20th International Symposium on High-Current Electronics

SHCE

IEEE NPSS
NUCLEAR & PLASMA SCIENCES SOCIETY

Chairman	Nikolay Ratakhin,	Institute of High Current Electronics, Tomsk, Russia
Co-Chairman	Gennady Remnev,	Institute of High-Technology Physics, TPU, Tomsk, Russia
Program Chairman	Edl Schamiloglu,	University of New Mexico, Albuquerque, USA
Program Co-Chairman	Alexander Batrakov,	Institute of High Current Electronics, Tomsk, Russia

Program Committee

Efim OKS	Institute of High Current Electronics SB RAS, Tomsk, Russia
Alexander SHISHLOV	Institute of High Current Electronics SB RAS, Tomsk, Russia
Vladimir KOSHELEV	Institute of High Current Electronics SB RAS, Tomsk, Russia
Alexander KIM	Institute of High Current Electronics SB RAS, Tomsk, Russia
Gennady REMNEV	Institute of High-Technology Physics, TPU, Tomsk, Russia
Victor TARASENKO	Institute of High Current Electronics SB RAS, Tomsk, Russia

International Advisory Committee

Stanislav CHAYKOVSKY	Institute of Electrophysics UB RAS, Ekaterinburg, Russia
Vasily GLUKHIKH	D.V. Efremov Scientific Research Institute of Electrophysical Apparatus, St. Petersburg, Russia
Evgenij GRABOVSKI	Troitsk Institute for Innovation and Fusion Research (TRINITI), Russia
Alexander KIM	Institute of High Current Electronics SB RAS, Tomsk, Russia
Francis LASSALLE	Centre d'Etudes de Gramat, Gramat, France
Alexander LITVAK	Institute of Applied Physics RAS, Nizhny Novgorod, Russia
Pavel LOGATCHOV	Institute of Nuclear Physics, Novosibirsk, Russia
Efim OKS	Institute of High Current Electronics SB RAS, Tomsk, Russia
Mikhail PETELIN	Institute of Applied Physics RAS, Nizhniy Novgorod, Russia
Vladislav ROSTOV	Institute of High Current Electronics SB RAS, Tomsk, Russia
Sergey RUKIN	Institute of Electrophysics UB RAS, Ekaterinburg, Russia
Marek SADOWSKI	Soltan Institute for Nuclear Studies, Warsaw, Poland
Victor SELEMIR	All-Russian Research Institute of Experimental Physics, FSUE RFNC – VNIIEF, Sarov, Russia
Valentin SMIRNOV	National Research Institute "Kurchatov Institute", Moscow, Russia
Valery SHPAK	Institute of Electrophysics UB RAS, Ekaterinburg, Russia
Victor TARASENKO	Institute of High Current Electronics SB RAS, Tomsk, Russia
Vasily USHAKOV	National Research Tomsk Polytechnic University, Tomsk, Russia
Yuriy USOV	National Research Tomsk Polytechnic University, Institute of Nuclear Physics, Tomsk, Russia
Mikhail YALANDIN	Institute of Electrophysics UB RAS, Ekaterinburg, Russia
Yuriy YUSHKOV	National Research Tomsk Polytechnic University, Institute of Nuclear Physics, Tomsk, Russia

Conference topics

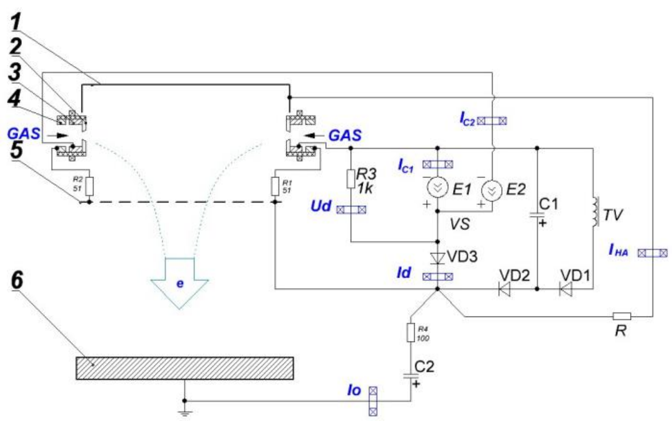
Intense electron and ion beams
Pinches, plasma focus and capillary discharge
High power microwaves
Pulsed power technology
Pulsed power applications
Discharges with runaway electrons

THE REACTION OF ARC DISCHARGE PARAMETERS TO THE SELECTION OF ELECTRONS FROM THE EMISSION PLASMA IN AN ELECTRON ACCELERATOR WITH A MESH PLASMA CATHODE[1]

M.S. VOROBYOV, N.N. KOVAL, S.YU. DOROSHKEVICH, S.A. SULAKSHIN

HCEI SB RAS, Academichesky av., Tomsk, 634055, Russia, E-mail: vorobyovms@yandex.ru, phone:8(382-2)-492-683

In the electrode system of an electron source with a plasma cathode, which allows the generation of a pulse-periodic electron beam of a large cross section from vacuum to the atmosphere through the outlet foil window, investigations have been made of the effect of electron extraction from the emission plasma on the parameters of a low-pressure arc discharge in which this plasma is generated. The work of the plasma cathode in different modes of electron beam generation is compared, namely, with the use of both a wide-aperture two-electrode electron-optical system (EOS) characterized by high beam current losses on the ribs of the support grid and a multi-aperture two-electrode EOS, when a metal mask is installed on the emission mesh with a configuration of holes that repeats the configuration of the holes in the support grid, and the electron beam is a superposition of electron beamlets formed by separate emission structures, the plasma boundary of which is also stabilized by a fine-structure metal mesh. Under the experimental conditions, the selection of electrons from the emission plasma leads to an increase in the voltage in the interelectrode gap between the cathode and the hollow anode of the plasma emitter, whose "voltage-addition" depends on the conditions of generation of the emission plasma (pressure and type of working gas, the ratio of the anode area of the discharge to the emission area), the area of the emission structures and the cell size of the used emission mesh.



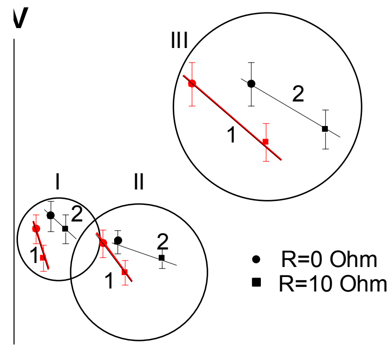


Fig. 1. Scheme of the electron accelerator "DUET": 1 - hollow anode of the main discharge; 2 - ferromagnetic insert of a plasma source; 3 - hollow cathode of a plasma source; 4 - ignition electrode of a plasma source; 5 - emission mesh; 6 - accelerating electrode

Fig. 2. Dependence of the voltage of arc discharge U_d on the extraction coefficient α of electrons from the plasma emitter. Experimental conditions p = 40 mPa, accelerating voltage U_0 = 100 kV, resistance in the hollow anode circuit R = 0, 1, 5, 10 Ohm: 1 – mesh size h=0.4 mm, mask with holes of 12 mm; 2 - mesh size h=1 mm, mask with holes of 12 mm, 3 - mesh size h = 0.4 mm, without mask

REFERENCES

[1] *S.P. Bugaev, Yu.E. Kreindel, P.M. Shcanin //* Large-Cross-Section Electron Beams. – Moscow, Energoatomizdat, 1984 (in Russian)
[2] *V.A. Burdovitsin, E.M. Oks. //* Laser and Particle Beams. – 2008. – T. 26. – №4. P.619-635.
[3] *N.N. Koval, Yu. E. Kreindel, V.S. Tolkachev, P.M. Schanin. //* IEEE Trans. Electr. Insul.. 1985. Vol. El-20. P.735-737.
[4] *S.W.A. Gielkens, P.J.M. Peters, W.J. Witteman, P.V. Borovikov, A.V. Stepanov, V.M. Tskhai, M.A. Zaivjalov, V.I. Guschenets, N.N. Koval. //* Rev. Sci. Instr. 1996. Vol.67, №7. P.2449-2452.
[5] *V.N. Devyatkov, N.N. Koval //* Journal of Physics: Conference Series 552, 2014, 012014 doi:10.1088/1742-6596/552/1/012014.

[1] The work was supported by the grant of Russian Foundation for Basic Research (Projects No 17-08-00627).

FEATURES OF PLASMA CATHODE GRID STABILIZATION IN THE PRESENCE OF INTENSE ION FLUX FROM ACCELERATING GAP[1]

V.N. DEVYATKOV, N.N. KOVAL

IHCE SB RAS, 2/3 Akademichesky Avenue, Tomsk, 634055, Russia, vlad@opee.hcei.tsc.ru, +7(3822)491713

The electrode voltage of the main discharge gap U_d was measured in a grid-stabilized plasma-cathode electron source (Fig. 1*a*) which is based on a constricted low-pressure arc [1], operates at a longitudinal magnetic field of 0.02–0.05 T, and produces a pulsed (200 µs) electron beam with a current of 50–300 A and energy of up to 15 keV. The measurements of U_d were taken for emission grids differing in mesh size under changes of the gas (Ar) pressure and conditions influencing the ion current from the acceleration gap to the plasma cathode. The pressure dependences of U_d obtained for different mesh sizes (Fig. 1*b*) were compared and analyzed for correlation with maximum operating currents attained in the source. With no electron emission from the plasma cathode, the voltage U_d coincided with the operating arc voltage. The study demonstrates the following. According to research data [2], the emission of electrons from a grid plasma cathode can change both the value and the polarity of U_d. Our experiments suggest that the variation in U_d with increasing the gas pressure p and discharge current I_d is governed not only by the ion current to the plasma cathode but largely by the grid stabilization conditions at the cathode plasma boundary and that controlling the voltage U_d allows one to efficiently control the operation stability of the plasma cathode. The maximum beam current (limited by breakdown of the acceleration gap) depends not only on the absolute value of the ion current to the plasma cathode but mostly on the potential of grid electrode *5* (Fig. 1*a*) with respect to the anode plasma of the arc discharge as a factor which also influences U_d. The voltage range $U_d \geq 0$ greatly increases the probability of cathode spots appearing at electrode *5* (from the side of the discharge system), and this almost inevitably leads to a breakdown of the acceleration gap [2]. Decreasing the grid mesh size decreases the dependence of U_d on p and I_d (Fig. 1*b*, curves *5*, *6*). The decrease in the ratio I_b/I_d, in this case, can be compensated by increasing the gas pressure, which causes almost complete switching of the discharge current from grid electrode *5* to the acceleration gap.

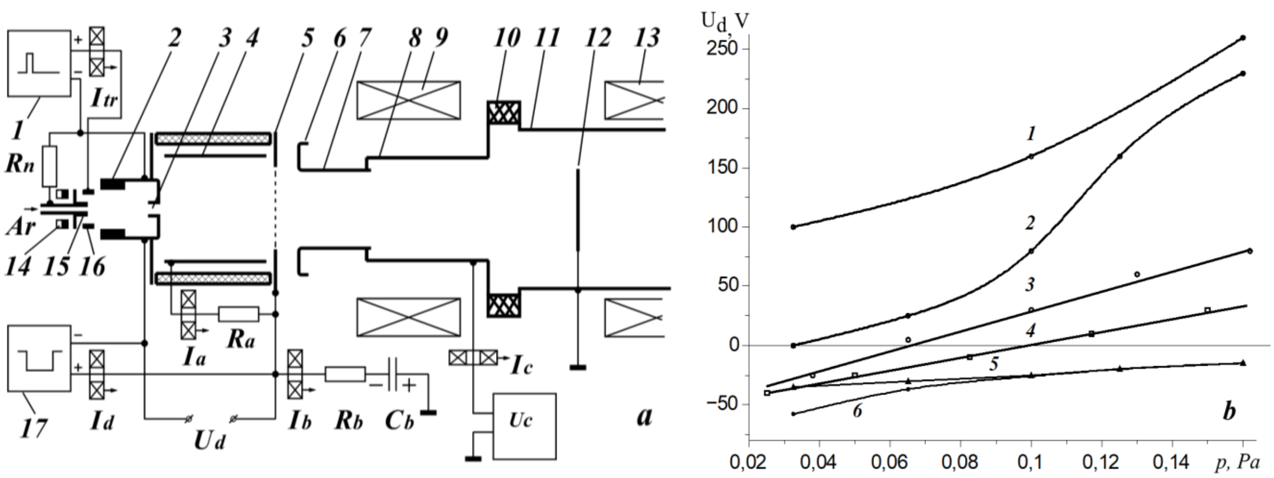


Fig. 1. Experimental setup (*a*): *1,17* – power supplies, *2,15* – Mg cathodes, *3* – constriction channel, *4* – anode insert, *5* – main discharge anode with grid window, *6–8,11* – drift tube, *10* – insulator, *12* – collector, *9,13* – solenoids, *14* – permanent magnet, *16* – anode of ignition discharge. Dependences of U_d on p for different mesh sizes (*b*): *1,2* – 0.45 mm, *3,4* – 0.33 mm, *5,6* – 0.15 mm at I_d = 50 A (*2,4,5*) and I_d = 200 A (*1,3,6*).

REFERENCES

[1] *Devyatkov V.N.,Vorobyov M.S.,Koval N.N., Shugurov V.V.* // J. Phys. Conf. Ser., – 2015. – 652. P. 012066-012071.
[2] *Devyatkov V.N., Koval N.N.* // J. Phys. Conf. Ser. – 2014. – 552. P. 012014-012019.

[1] This work was supported by the IHCE SB RAS State Task (project of fundamental scientific research of the SB RAS II.9.5.1 2017-2020 year).

TRANSPORT AND FOCUSING OF AN ELECTRON BEAM IN LOW-IMPEDANCE ROD PINCH DIODES

S.A. SOROKIN

Institute of High Current Electronics SB RAS, 2/3 Akademichesky Ave., Tomsk 634055, Russia, s.sorokin@rambler.ru, +7(3822)491617

An experimental study was made of the possibilities of transporting and focusing an electron beam in a low-impedance rod pinch diode initially shorted by a set of radial wires, when the place of contact between the wires and the rod is removed from the tip of the rod many times the diameter of the rod. In the experiment, effective transport of the electron beam to the anode tip is also realized with a curved rod.

GENERATION OF INTENSE ION BEAMS AT THE 13 MEV LEVEL ON THE HERMES-III ACCELERATOR[1]

Timothy J. RENK

Sandia National Laboratories
PO Box 5800, Albuquerque, NM 87185-1182 USA, tjrenk@sandia.gov, 1-505-845-7491

The HERMES-III accelerator (18 MV, 700kA, 40 ns) is located at Sandia National Laboratories in Albuquerque, NM USA. It uses Inductive Voltage Adder (IVA) architecture to drive a magnetically insulated transmission line (MITL) with a 34-ohm vacuum impedance. In normal operation, the load is a Bremsstrahlung diode operated in negative polarity, from which an intense electron beam can be extracted for gamma generation. The relatively high output voltage makes HERMES attractive as a source for high-energy ions which could be used, among other applications, for generating neutrons from high-cross section metal targets. Such beams of both protons and lithium were previously generated on HERMES 1 at the 16 MV level, but in positive polarity with the induction cavities reversed. To preserve the dominant negative polarity mode, ion beams now must be generated in negative polarity, with the resultant beams propagated to a target inside the MITL.

A self-field diode was chosen (no external field coils), so as to incorporate as much of the MITL flow (2/3 of the total available current) into the diode load. Previously, low-impedance diodes have typically been operated with the use of high-voltage interfaces, not IVAs. An example is the pinch-reflex ion diode (~2 ohms) designed by the Naval Research Laboratory (USA). Here, the diode must be compatible with the 34-ohm MITL impedance. A radial rather than axial cathode is used, and diode impedance is deliberately undermatched so as to capture the incoming MITL flow as useful diode current.

The development of this radial ion diode will be discussed, along with the diagnostic package used to characterize the ion beam. At present, this includes Faraday cups, Rogowski coils, shadowbox/witness plates, and calorimeters used to estimate ion current from energy deposited at the target location. Initial experiments indicate an estimated diode voltage in the 13 MV range, with MITL flow fully incorporated into the diode, consistent with PIC code predictions. Additional campaigns are planned, and latest results will be discussed.

REFERENCES

[1] *D. L. Johnson, J.A. Alexander, J.J. Ramirez, J.P. Corley, G.J. Denison, J.W. Poukey, T.R. Lockner, S.E. Rosenthal, and C. Ruiz* // Hermes-III Positive Polarity Experiment, 7th IEEE Pulsed Power Conference, (Monterey, CA, 11-14 June 1989) 32.

[1] Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

MODERN HIGH INTENSE H- SOURCES FOR ACCELERATORS.

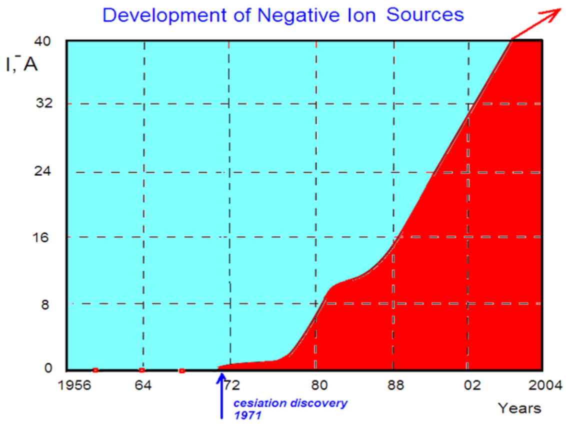
V. DUDNIKOV*

*Muons, Inc. 552 N. Batavia Ave. Batavia IL 6510 USA

Dvg43@yahoo.com

A review of modern high intense H- ion sources for accelerators are presented. Cesiation effect, a significant enhancement of negative ion emission from gas discharges with decrease of co-extracted electron current below negative ion current was observed for the first time by location into discharge chamber a compound with one milligram of cesium on July 1, 1971 in Institute of Nuclear Physics (INP), Novosibirsk, Russia [1]. This observation become a basis for development of surface plasma negative ion source (SPS) [2,3]. Efficiency of negative ion generation was increased sufficiently by invention a geometrical focusing [4]. Magnetron-planotron with geometrical focusing SPS are discussed. Converter SPS [5] are reviewed. Semiplanotron SPS [4] are discussed. Penning discharge SPS [6,7], RF pulsed and CW SPS are reviewed [8,9,10]. History of negative ion source development are reviewed [11].

Large development projects include the SPS for the Large Hadron Collider (LHC) and for the International Thermonuclear Experimental Reactor (ITER). The development and fabrication of injectors with cesiated SPS has become a billion dollar scale industry.



Progress in development of negative ion sources (beam intensity v.s. time)

REFERENCES

[1] *V. G. Dudnikov, "Method of negative ions production", SU Author sertificat,* M. Кл.H 01 J 3/0,4, 411542, filed 10/III,1972, http://www.findpatent.ru/patent/41/411542.html

[2] *Yu Belchenko, G. Dimov, V. Dudnikov, Physical principles of surface plasma source operation,* Symposium on the Production and Neutralization of Negative Hydrogen Ions and Beams, Brookhaven, 1977 (Brookhaven National Laboratory (BNL), Upton, NY, 1977), pp. 79–96;

[3] *Yu. Belchenko, G. Dimov and V. Dudnikov, Powerful Injector with surface plasma source,* NUCLEAR FUSION,14(1),113-114 (1974).

[4] *V. Dudnikov, Yu. Belchenko, Journal de Physique,* v. 40, p. 477, (1979).

[5] *R. L. York and Ralph R. Stevens, Jr., "A cusped field H- ion source for LAMPF",* IEEE Transactions on Nuclear Science, Vol. NS-30, No. 4, (1983).

[6] *V. Dudnikov, Surface Plasma Source with Pennig Geometry,* Proc. 4th All-Union Conf. on Charged Part. Accel., Moscow, 1974, V.1, p.323.

[7] *G. I. Dimov, G. E. Derevyankin, V. G. Dudnikov,* IEEE Trans. Nucl. Sci., NS24, No3 (1977).

[8] *R. F. Welton, V. G. Dudnikov, B. X. Han, S. N. Murray, T. R. Pennisi, R. T. Roseberry, M. Santana, and M. P. Stockli,* AIP Conf. Proc. **1515**, 341–348 (2013).

[9] [1]*R. F. Welton, A. Aleksandrov, V. G. Dudnikov, B. X. Han, S. N. Murray, T. R. Pennisi, M. Piller, Y. Kang, M. Santana, and M. P. Stockli, "A look ahead: Status of the SNS external antenna ion source and the new RFQ test stand",* AIP Conference Proceedings 1655, 030002 (2015).

[10] *V. Dudnikov, R. P. Johnson, B. Han, et al., "Features of radio frequency surface plasma sources with a solenoidal magnetic field",* AIP Conference Proceedings 1869, 030023 (2017).

[11] *Vadim Dudnikov, "Forty years of surface plasma source development",* Rev. Sci. Instruments 83, 02A708 (2012).

A SUBMICROSECOND HIGH-CURRENT ELECTRON BEAM SOURCE WITH AN EXPLOSIVE-EMISSION CATHODE AND AN AUXILIARY DISCHARGE INITIATED BY A PRE-PULSE [1]

A.A. ZHERLITSYN, N.V. TSOY

Institute of High Current Electronics SD RAS, 2/3 Academichesky ave., Tomsk, 634055, Russia, andzh@oit.hcei.tsc.ru

In widely used electronic source circuits based on diodes with preliminary plasma filling, additional auxiliary discharge electrodes and separate generators are used to power the auxiliary discharge with its charging and triggering system. Technically, a simpler version is a circuit in which the potential auxiliary discharge electrode and the diode cathode are combined. In this case, two voltage pulses with a time delay are applied to the electrode in series. The first pulse (pre-pulse) is intended to initiate the emission on the cathode and the auxiliary discharge before the second primary pulse is applied. Under certain conditions, a pre-pulse leads to an increase in the electron beam current (double-pulse effect [1]).

An approach, in which double-pulse effect is used, has been studied with reference to a diode with a submicrosecond electron beam duration at a voltage level of 100-300 kV. The diode is composed of an explosion-emission blade cathode and a flat anode. As a generator, a low-resistance (wave resistance ~1 Ohm) linear transformer driver (LTD) with air insulation is used. The LTD stages are made of a capacitive energy storage of 80 nF with a charging voltage of 80 kV. An additional discharge circuit with its own 3.2 nF energy storage is used in each LTD stage to generate pre-pulse. The main and additional capacitive energy storages are charged from a common charging unit and commutated with a controlled time delay from a trigger source.

The use of the pre-pulse has allowed a reduction in the diode resistance on the pulse front to a few Ohms. We have also managed to improve matching of the diode with the generator and increase the efficiency of the energy output from a low-resistance capacitive storage to the electron beam. The thermal imaging measurements of the electron beam profile showed that the presence of the pre-pulse does not disrupt the uniformity of the electron beam.

REFERENCES

[1] *Mesyats G.A., Proskurovskiy D.I.* // Technical physics letters – 1971. – 13(1). – P.7-10.

[1] The reported study was funded by RFBR according to the research project № 17-08-01189-a

REALIZARTION OF A LOW ENERGY STATE OF AN ELECTRON BEAM IN A UNIFORM CHANNEL

M.I. FUKS*, N.F KOVALEV**, E. SCHAMILOGLU*

* Departmnet. of Electrical and Computer Engineering, University of New Mexico, Albuquerque, NM 87131-1356, USA
** Institute of Applied Physics Russian Academy of Sciences, Nizhny Novgorod, Ulyanov str.46, 603950, Russia

Earlier was shown that between two virtual cathodes (VCs) in a channel that consists three smooth tubes with different radii but with common axis a low energy state of an electron beam appears with potential close to the potential of a real cathode [1]. Such result creates imagination that such the state could be realized only in irregular channel. Using a particle-in-cell code MAGIC [2] was found that such the state appears very quickly, about 2 ns after forming VCs (Fig.1).Results of simulations indicate also that for forming of the state necessary to use reflections of electrons that happen in [1] from planes in VCs, where velocity of electrons v = 0. At the present report we demonstrate a possibility to form the state in a uniform channel.

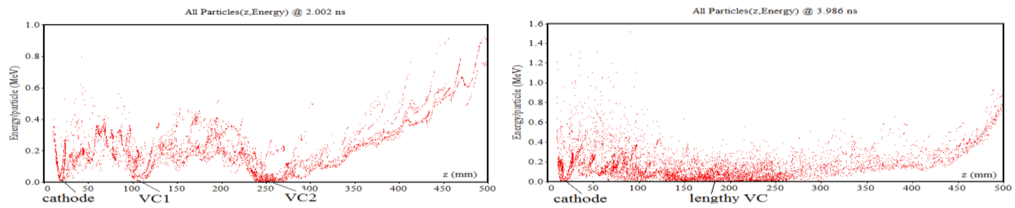


Fig.1. Forming the low energy state between two VCs in the channel that consist 3 tubes with different radii.

Let's replace the second VC by a magnetic mirror. Using adiabatic invariant $p_\perp^2/H$ = const it is possible to increase the magnetic field H so that a transverse momentum $p_\perp$ becomes equal to the total momentum $p = mc\gamma\beta$, where m is electron mass; c is the light speed; $\beta = v/c$; v is electron velocity; $\gamma = (1-\beta^2)^{-0.5}$.

Then using representation $p^2 = p_\perp^2 + p_{ii}^2$ we find that longitudinal momentum $p_{ii} = 0$. As it is shown in [3], it means that all electrons reflect from the mirror. In computer simulations the main criteria for this were absence of deposit of electrons on a surface with anode potential and on the output window. In [4] was shown that after VC Fedosov current is realized as from the real cathode [5] that gives a possibility to replace the first VC by a real tubular cathode taking into attention that on the cathode surface also $v = 0$.

We suppose that forming the low state happens so: when all electrons reflect from the mirror they go to the cathode, decelerate in the electric field up to $v = 0$ at the cathode and then accelerate in the same electric field to opposite direction. Since near the cathode these electrons have space charge, it partly decrease electron emission, which is added electrons to the reflected beam from the cathode. As result, the beam becomes denser and slower as, for example, a particle with fixed energy $W = mv^2/2$ becomes slower when its mass m is increased. Computer simulations show (Fig.2) several frames that demonstrate how decrease longitudinal momentum $p_z(t)$ on time t for each reflection up to establishment the low energy state.

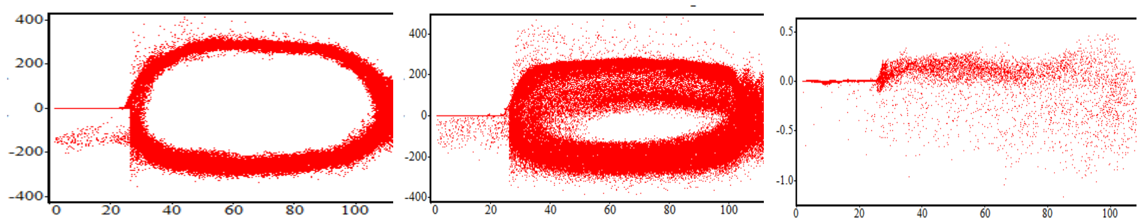


Fig.2. Selective frames, which demonstrate the temporal decrease of longitudinal momentum of electrons as result of successive reflections from the magnetic mirror and the VC.

REFERENCES

[1] *M.I. Fuks, S. Prasad, and E. Schamiloglu* // IEEE Trans. Plasma Sci., vol. 44, No.8, pp. 1298-1302, 2016.
[2] User-Configurable MAGIC for Electromagnetic PIC Calculation.
[3] *L.A.Artcimovich* // Controlled thermonuclear reactions (in Russian), Moscow, Physmatgiz, 1961.
[4] *N.F. Kovalev* // JTP –{in Russian}, vol.72, no.7, pp.112 – 116, 2002.
[5] *A.I. Fedosov, E.A. Litvinov, S.Ya. Belomytsev et. al. // Izv. VUZov. Physica–{in Russian}, no. 10, pp.134--138, 1977.*

3D NUMERICAL MODELING OF ULTRARELATIVISTIC PARTICLE BEAMS WITH CROSSING ANGLE[1]

M.A.BORONINA, *V.A. VSHIVKOV*

Institute of Computational Mathematics and Mathematical Geophysics SB RAS,
prospect Akademika Lavrentjeva, 6, Novosibirsk, 630090, Russia, boronina@ssd.sscc.ru

We present a new algorithm for numerical simulation of beam dynamics in the modern supercolliders, where the beams move with ultrarelativistic ($\gamma\sim10^3$-10^5) speeds and collide with crossing angle (~20 mrad). In case of critical charge densities the colliding beams may disrupt and the problem of beam stability arises.

We consider the fully three-dimensional dynamics of charged particle beams in self-consistent electromagnetic-fields in vacuum. A standard approach for the numerical simulations of beam-beam effects is considering each beam as a number of slices of particles and the interaction as interaction among the slices. The two-dimensional forces of each slice influence the motion of particles of the opposite beams when the longitudinal coordinates of slices from different beams coincide. This quasi-three dimensional approach is extensively used, but the effective incorporating of large crossing angles of colliding beams is complicated.

Our model is fully three-dimensional and allows overcoming these difficulties automatically. The model is based on the solution of Vlasov-Liouville equation and Maxwell equations with the particle-in-cell method. We use leap-frog scheme and the Villancenor-Buneman currents calculation. The algorithm is parallel and is based on a mixed decomposition to achieve the effective performance in case of strongly focused thin beams.

We present the numerical results for single-passage beam interaction with different beam configurations. Comparison with analytical solutions in case of their existence is shown. The methods can be applied for other problems of plasma physics and astrophysics.

REFERENCES

[1] *M.A Boronina, V.A. Vshivkovs //* J. Plasma Phys. – 2015. – 81. – 495810605.
[2] *M.A. Boronina, V. D. Korneev, V.A. Vshivkov //* Proc. of IPAC2014, Dresden, Germany. – 2014. – MOPME027.
[3] *M. Boronina, V. Vshivkov, E. Levichev, S. Nikitin, V. Snytnikov //* Proc. of Particle Accelerator Physics. – 2007. – 3366-3368.

[1] This work was supported by the Russian Scientific Foundation, project no. 16-11-10028.

TABLE-TOP SOURCE OF ACCELERATED BEAMS OF METALLIC IONS FOR ION IMPLANTATION

O. I. SHIPILOVA, V. P. DRESVYANSKY**, E. F. MARTYNOVICH**, A.L. RAKEVICH**, S.P. GORBUNOV* ,V L PAPERNY**

**Irkutsk State University, 1, K.Marx Str.,Irkutsk, 664003,Russia, paperny@math.isu.runnet.ru, +7(914)9333884*

*** Irkutsk Branch of the Institute of Laser Physics SB RAS, 664033,Irkutsk, Russia*

The parameters of the beams of copper and silver ions generated by a miniature (20*20*20 cm^3) fast low-voltage vacuum-spark discharge (duration 1 μs, voltage up to 2.5 kV, current <10 kA) are investigated. The optical characteristics of the areas of LiF and KCl crystals irradiated by beams of accelerated ions were measured. It is shown that the number of ions in the beam is about 10^{14}, the beam diameter at a distance of 10 cm from the anode is about of 3 cm. The ions implanted in the crystal matrix form a layer of luminescent centers several tens of nanometers in thickness. Thus, the investigated discharge can be used for the tasks of microelectronics, photonics, nanotechnologies.

[1] This work was supported by the RFBR (grant #17-02-00572)

A FOREVACUUM PLASMA ELECTRON SOURCE FOR PROCESSING DIELECTRIC SURFACES[1]

A.A.ZENIN, I.YU. BAKEEV*, A.S. KLIMOV*, YU.G. YUSHKOV***

** Tomsk State University of Control Systems and Radioelectronics, Russia, Tomsk, 40 Lenina ave., 634050*

*** Institute of High Current Electronics SB RAS, 2/3 Academichesky Ave., Tomsk, 634055, Russia*

Applying low-energy high-current electron beams for processes of modification and dimensional processing functional materials has a wide interest, since such processes significantly improve initial parameters of the material, such as microhardness, corrosion resistance, reducing the coefficient of friction [1]. In the last decade, the so-called forevacuum plasma sources of electrons have developed significantly, the feature of which is the possibility of generating electron beams in the pressure range of 1-100 Pa. This unique advantage opens the possibility of direct processing of non-conducting materials, such as ceramics, polymers, borides, etc. [2-3].

This paper describes a plasma electron source designed to form a continuous electron beam in the forevacuum pressure range. The operation of the source is based on the emission of electrons from a glow discharge plasma with a hollow cathode. As a result of the studies carried out, it is shown that a change in the geometry of the discharge gap can lead to an increase in the efficiency of electron extraction from the plasma of the hollow cathode. On the basis of research, the electron beam with record parameters for the forevacuum range was obtained: the current beam is 250 mA, the electron energy is 20 keV, the beam power is of the order of 5 kW.

The achieved electron beam parameters and the ability of the source to function in the forevacuum pressure range make it possible to effectively use it for electron beam modification of surfaces and dimensional processing of non-conductive materials.

REFERENCES

[1] Rotshtein *V.P, Proskurovsky D.I, Ozur G.E, Ivanov Y.F, Markov A.B.* // Surface and coating technology. – 2004. – Vol. 180. P: 377-381.

[2] *Burdovitsin V.A, Klimov A.S, Oks E.M,* // TECHNICAL PHYSICS LETTERS. – 2009. – Vol: 35, Issue: 6. P. 511-513.

[3] Yushkov *Y.G., Tyunkov A.V., Oks E.M., Zolotukhin D.B.* // Journal of Applied Physics. – 2016. – Vol. 120. P. 233302.

[1] This work was supported by Russian Science Foundation (grant № 18-08-00539).

ION BEAMS OF LOW-PRESSURE GLOW DISCHARGE IN TRANSVERSE SUPERSONIC GAS FLOW

DANIS ISRAPHILOV

Naberezhnye Chelny Institute, Kazan Federal University, Naberezhnye Chelny, Russian Federation, diisraphilov@yandex.ru

Article presents a model for the realization of a glow discharge at low pressures due to the organization of supersonic gas flow in a limited region of discharge chamber. A model of flow regime of a supersonic flow in a vacuum chamber is described. Results of experiments on realization of a glow discharge at low pressures due to the organization of a transverse supersonic gas flow are showen.

COMPARETIVE RESEARCH OF ENERGY AND CURRENT DENSITIES OF PULSED ELECTRON BEAM[1]

I.S. EGOROV, A.V. POLOSKOV, M.V. SEREBRENNIKOV, A.A. ISEMBERLINOVA

Tomsk polytechnic university, 30 Lenin ave., Tomsk, 634050, Russia, egoris@tpu.ru, +7 3822 60-64-05

The energy density and current density of pulsed electron beam were measured for the same geometry conditions. Electron beam pulse was generated by ASTRA-M [1] accelerator (up to 450 kV of accelerating voltage, up to 0.5 kA of beam current, 150 ns of beam pulse duration at FWHM). Sectioned calorimeter [2] has been used to capture the distribution of the energy in beam cross-section. Faraday cup have been used to catch the statistics of the beam current for the same areas and geometry of the beam cross-section. It was found that the relations between energy and current density of the beam differ for cross-section areas. The current pulse has been recalculated to the charge, transported by the beam. Thus, different average kinetic energy of the electron has been estimated for different areas of cross-section. Obtained results are important for practical applications of pulsed electron beams.

REFERENCES

[1] *Egorov I., Esipov V., Remnev G., Kaikanov M., Lukonin E., Poloskov A.* // Proceedings of the 2012 IEEE International Power Modulator and High Voltage Conference.˜ 2012. 716-719.

[2] *Egorov I., Serebrennikov M., Isakova Y., Poloskov A.* // Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment.˜ 2017.˜ 875. 132-136.

[1] Calculations and statistics analyzation were supported by RFBR grant #18-32-00184 mol_a. Empirical experiments with the ASTRA-M accelerator were carried out at Tomsk Polytechnic University within the framework of Tomsk Polytechnic University Competitiveness Enhancement Program grant.

INVESTIGATIONS OF THE SPACE-TIME STABILITY OF A LARGE CROSS SECTION ELECTRON BEAM GENERATED BY AN ACCELERATOR WITH A MESH PLASMA CATHODE[1]

M.S. VOROBYOV, S.S. KOVALSKY, N.N. KOVAL

HCEI SB RAS, Academichesky av., Tomsk, 634055, Russia, E-mail: vorobyovms@yandex.ru, phone:8(382-2)-492-683

In an electron source with a mesh plasma cathode on the basis of a low-pressure arc discharge, a study was made of the spatiotemporal stability of a pulsed-periodic beam of a large cross section (750×150) mm^2, outputed into the atmosphere through an outlet foil window. The research was carried out using an automated system that allows real-time measurements with the ability to visualize the data on a computer. This system allows to ensure the accuracy of measurements no worse than ± 2% and differs from the known analogues in compactness, reliability and simplicity of design. The use of this system made it possible to investigate the distribution of the current density over the beam cross-section in a wide range of its parameters, such as beam energy, beam current, and beam current pulse duration. A satisfactory agreement between past and present experimental data is shown. The use of this system for measuring the current density distribution along the beam cross section makes it possible to substantially increase the accuracy of the design of the scientific experiment, and, consequently, the speed of debugging and the repeatability of the technological process.

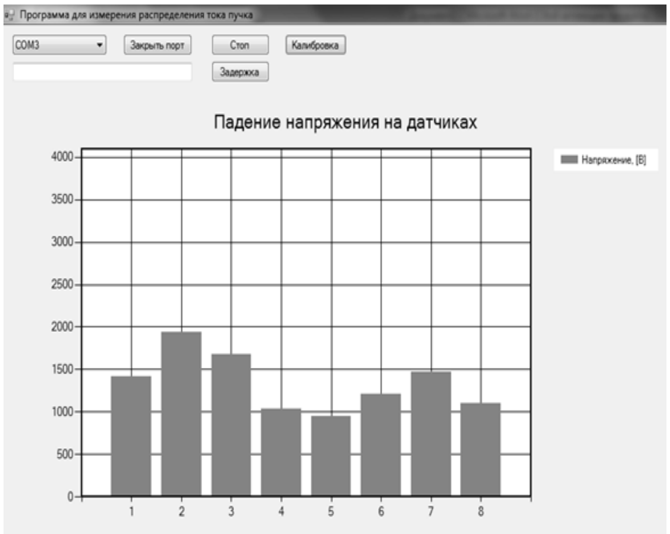


Fig. 1. Demonstration of real-time visualization of the beam current density distribution along its longitudinal side.

REFERENCES

[1] *S.P. Bugaev, Yu.E. Kreindel, P.M. Shcanin //* Large-Cross-Section Electron Beams. – Moscow, Energoatomizdat, 1984 (in Russian)

[2] *N.N. Koval, Yu. E. Kreindel, V.S. Tolkachev, P.M. Schanin. //* IEEE Trans. Electr. Insul.. 1985. Vol. El-20. P.735-737.

[3] *S.W.A. Gielkens, P.J.M. Peters, W.J. Witteman, P.V. Borovikov, A.V. Stepanov, V.M. Tskhai, M.A. Zaivjalov, V.I. Guschenets, N.N. Koval. //* Rev. Sci. Instr. 1996. Vol.67, №7. P.2449-2452.

[4] *Abroyan M.A., Kosogorov S.L., Nabokova I.V., Uspenskii N.A., Chumichev V.A., Shapiro V.B., Shvedyuk V.Ya.* // Instr. and Exper. Techn.. 2007. T. 50. № 4. P. 530-533.

[5] *Ponomarev A.V., Pedos M.S., Mamontov U.I., Gusev A.I., Scherbinin S.V. //* Instr.s and Exper. Techn.. 2015. T. 58. № 4. P. 499-504.

[6] *M. S. Vorobyov, N. N. Koval, and S. A. Sulakshin //* Instrum. and Experim. Techn. 2015. Vol. 58. No. 5. P. 687–695.

[7] *M. S. Vorob'ev, N. N. Koval' //* Technical Physics Letters. 2016. Vol. 42. No. 6. P. 574–576.

[1] The work was supported by the grant of Russian Foundation for Basic Research (Projects No 17-08-00627).

FORVACUUM PLASMA ELECTRON SOURCE OF A RIBBON BEAM FOR A PLASMA DISCHARGE GENERATING[1]

A.S. KLIMOV*

* *Tomsk State University of Control Systems and Radioelectronics, 40 Lenin ave,. Tomsk, 634050, Russia, E-mail: klimov@main.tusur.ru, phone: 8-905-990-52-41*

Electron-beam plasma is widely used in various material treatment technologies [1]. The parameters of beam plasma can be controlled in a wide range. Variation of electron beam current and energy, as well as composition of gaseous atmosphere, enables variation of plasma density and temperature. Due to low temperature of electron component and relatively high concentration beam plasma is used for etching of thin (monoatomic) surface layer [2].

The research presents results of plasma formation (>50 sq.cm) obtained by electron beam ionization of gas in the forevacuum pressure range. An upgraded source was used for electron beam generation, which allowed obtaining ribbon electron beam with no transmitting magnetic field [3]. The influence of electron beam parameters on the parameters of beam plasma was determined. The results of alumina ceramics treatment with a beam plasma ions flow are given.

REFERENCES

[1] *D.R. Borisa, T.B. Petrova, G.M. Petrov, S.G. Walton // J. Vac. Sci. Technol. – 2017. – A 35. Pp. 01A104*

[2] *S.G. Walton, D.R. Boris, S.C. Hernández, E.H. Lock, Tz.B. Petrova, G.M. Petrov, R.F. Fernsler // J. Solid State Sci. Technol. - 2015. - 4(6), pp. 5033-5040.*

[3] *Klimov A.S., Oks E.M., Zenin A.A. // Russian Physics Journal – 2018. – 60 (9). pp. 1501–1508.*

[1] This work was supported by the Ministry of Education and Science of the Russian Federation, grant No. 3.9605.2017/8.9.

STUDY OF PLASMA FORMATION IN A PLANAR TYPE ION DIODE WITH SELF-MAGNETIC ISOLATION[1]

A.V. STEPANOV, V.I. SHAMANIN*, G.E. REMNEV**

**Tomsk Polytechnic University, Lenina avenue, 30, Tomsk, 634050, Russia, stepanovav@tpu.ru, 89095465057*

One of the sources of high-power ion beams is a planar ion diode with isolation by external or self-magnetic field [1, 2]. Due to the simplicity and reliability of the design, this type of diodes is widely used in applied research [3-6]. The explosive plasma generation on the cathode surface under a bipolar voltage pulse is accompanied by a loss of the electron current from the anode-cathode region of the diode. The electron current characteristics depending on the operation mode of diode and the energy supplied are presented. Investigation of the cathode emission surface and distribution of the ion current density at the output of the diode along the cathode surface were carried out. The ion current density reaches 15-25 A/cm^2 at the outer edge of the cathode, and 5-8 A/cm^2 - in the central region. The area of emission surface of the cathode is approximately 25-30% of the total cathode area. Electron loss current in the matching mode of diode reaches 6.5 kA. The influence of the loss current electrons on the parameters of the ion diode is shown.

REFERENCES

[1] *I.F. Isakov, V.N. Kolodii, M.S. Opekunov, V.M. Matvienko, S.A. Pechenkin, G.E. Remnev, Yu. P. Usov //* Vacuum. – l991. - V. 42 (1). p. 159.

[2] *G.E. Remnev, I.F. Isakov, M.S. Opekounov, G.I. Kotlyarevsky, V.L. Kutuzov, V.S. Lopatin, V.M. Matvienko, M-.Yu. Ovsyagnikov, A.V. Potyomkin, V.A. Tarbokov //* Surface and Coatings Technology. – 1997. – V. 96. p. 103-109.

[3] *V. V. Uglov, G. E. Remnev, A. K. Kuleshov, V. M. Astashinskii, M. S. Saltymakov //* Russian Journal of Non-Ferrous Metals. – 2013. – V. 54(4). P. 349–354.

[4] *G.E. Remnev, A.M. Lebedynskiy, V.N. Legostaev, S.K. Pavlov, A.V. Petrov, E.V. Smolyanskiy, A.V. Stepanov //* Plasma Sciences (ICOPS). IEEE International Conference. – 2015. DOI: 10.1109/PLASMA.2015.7179531.

[5] *G.E. Remnev, V.A. Shulov //* Laser and Particle Beams. -1993. –V. 11. p. 707.

[6] *H.A. Davis, G.E. Remnev, R.W. Stinnett, K. Yatsui //* Mater. Res. Bull. – 1996. – V. 21. p. 58.

[1]This work was supported by State Project Nauka (Science) no. 3.8212.2017/BP

AN ANODE-LAYER PLASMA THRUSTER AS PLASMA OPTICAL SYSTEM FOR AN INTENSE ELECTRON BEAM TRANSPORT[1]

A.S. BUGAEV, V.I. GUSHENETS*, E.M. OKS***

**Institute of High Current Electronics, 2/3 Akademichesky Avenue, Tomsk, 634055, Russia, gvi@opee.hcei.tsc.ru*
***State University of Control Systems and Radioelectronics, 40 Lenin Avenue, Tomsk, 634050, Russia*

We report the recent experimental results on high-current wide-aperture non-relativistic electron beam manipulation and transport in a plasma-filled optic system (POS). The plasma –filled system is formed by the grid-bounded plasma emission surface in vacuum arc electron source and open (gridless or electrodeless) boundary of an anode plasma in the transport channel. Various types of plasma sources are available for generating anode plasma [1]. Among those, anode-layer plasma accelerator or thruster have attracted great interest for their high ionization probability, allowing one to obtain high plasma densities at relatively low gas flow rates. The plasma source concept presented in this publication is based on an Institute of Physics (NAS of Ukraine) toroidal plasma device [2]. Other an attractive feature anode-layer thruster is spatial configuration of a scattered magnetic field. The latter is similar to the field configuration of a single magnetic lens; therefore, the device has a focusing effect on the transported electron beam.

The geometry of plasma-filled optic system with a vacuum arc plasma electron emitter is shown in Fig. 1.

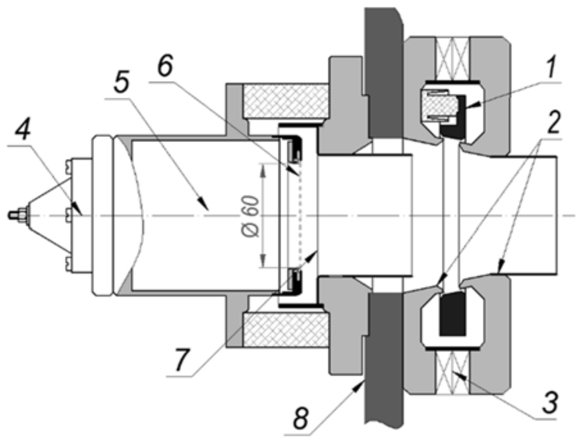


Fig. 1. Plasma-filled optic system with electron emitter. Anode-layer thruster: anode 1, cathode 2, and permanent magnets 3. The plasma electron emitter: arc plasma generator 4, hollow anode 5, emissive electrode 6, accelerating electrode 7, and header flange 8.

It is known that plasma thruster provides three discharge modes: (1) a low-current mode with a collimated ion beam at relatively low pressures and currents of several tens of milliamperes (ion generation mode); (2) a high-current plasma mode at higher pressures and currents from several amperes (plasma generation mode); and (3) an arc mode with a cathode spot. The plasma mode was studied in detail by measuring the plasma density, floating potential, and plasma electron temperature with a double Langmuir probe. And that's why. At first, in the plasma mode, the enhanced electric breakdown strength of the accelerating gap of the POS beam formation was detected for transported electron beam with current 100 A and energy 20÷35 keV. Secondly, under certain experimental conditions, a twofold increase of electron extraction from a plasma emitter was observed.

REFERENCES

[1] *A.S. Bugaev, V.I. Gushenets, Yu.A. Khuzeev, E.M. Oks, G.Yu. Yushkov //* 19th International Symposium on Discharges and Electrical Insulation in Vacuum (ISDEIV).-2000.- 2. - 629-632
[2] *A. Dobrovolskiy, S. Dunets, A. Evsyukov, A. Goncharov, V. Gushenets, I. Litovko, E. Oks //* Review of Scientific Instruments. - 2010. – 81. – №2. - 02B704.

1 This work was supported in part by the grants of Russian Foundation for Basic Research 16-08-00370-A and 18-08-00113-A. The authors are grateful to A. A. Goncharov and its colleagues from Institute of Physics NAS of Ukraine for kindly providing plasma lens.

THE USE OF PERMANENT MAGNETS FOR THE TREATMENT OF MASSIVE WORKPIECES WITH A HIGH-CURRENT ELECTRON BEAM

P.P. KIZIRIDI, G.E. OZUR, E.V. YAKOVLEV

**Institute of High Current Electronics, SB RAS, 2/3 Academichesky Ave., Tomsk, 634055, Russia, E-mail: kiziridi_pavel@mail.ru, phone: +7(3822)492052*

Low-energy, (up to 40 keV), high-current (up to 25 kA) electron beams of microsecond duration are widely used for the surface treatment of metallic materials by pulsed melting [1−3]. The beam transport to the target is usually performed in a guide magnetic field produced by pulsed solenoid. However, at the treatment of massive workpieces, the beam defocusing caused by the pulsed character of the solenoid field may take place. Actually, if the thickness of the treated workpiece exceeds the skin depth of the pulsed magnetic field penetration into the workpiece, so this magnetic field is partially ejected from it and magnetic field lines flow around the treated workpiece. This divergence of the magnetic field lines means defocusing of the beam, decreasing of its energy density, so the melting of the surface layer becomes impossible. Since the skin depth decreases with the increase of material conductivity, so the beam defocusing appears, first of all, for high conducting materials (copper, alumina, etc). Taking into account that for most of metals and alloys, the thermal conductivity is proportional to the electrical conductivity, it is clear that it becomes difficult to melt the surface layer.

We have solved this problem as follows. The beam defocusing was eliminated by placing of the permanent magnet shaped as a ring or square frame on the surface of the workpiece to be treated (Fig. 1). At this, the magnetic field induction vector on the surface of magnet, B_{mag}, looking to the cathode of electron gun, should be in opposite direction with the induction vector of the pulsed magnetic field provided by solenoid, B_{sol}. In this case, the vector of magnetic field of permanent magnet inside the ring (frame) has a significant component coinciding with those of pulsed solenoid and easily penetrating into a workpiece.

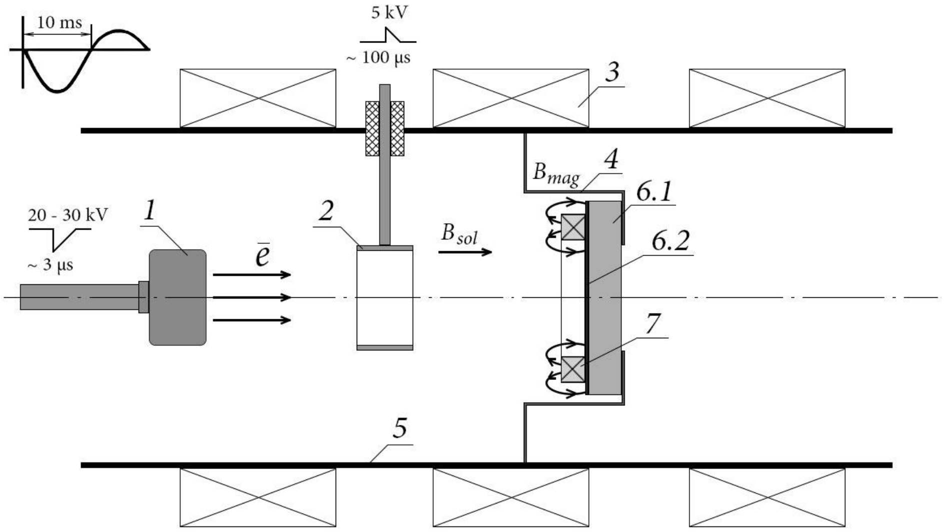


Fig. 1. Treatment of massive workpieces. *1* – cathode; *2* – anode; *3* – pulsed solenoid; *4* – holder of the workpiece; *5* – body of electron gun; *6* – workpiece (in the experiments the workpiece consisted of two parts: thick disk 6.1 and thin plate 6.2); *7* – permanent magnet.

Experiments have shown successful treatment of copper and alumina thick workpieces according to the scheme given in Fig. 1.

REFERENCES

[1] *G.E. Ozur and D.I. Proskurovsky //* Plasma Physics Reports. − 2018. − vol. 44. − No. 1. − pp. 18–39.
[2] *Guangwei Guo, Guangze Tang, Xinxin Ma, Mingren Sun, G.E. Ozur* // Surface & Coatings Technology. − 25 August 2013, vol. 229. − pp. 140−145.
[3] *Y. Uno, A. Okada, K. Uemura, T. Furukawa, P. Raharjo, K. Karato* // Precision Engineering. − 2005. − vol. 29. − pp. 449−455.

THE FORMATION OF A PLASMA ANODE IN A PENNING DISCHARGE CELL COMBINED WITH A PLANAR MAGNETRON[1]

P.P. KIZIRIDI, G.E. OZUR, L.A. ZULKOVA

* *Institute of High Current Electronics,2/3 Akademichesky Ave., Tomsk, 634055, Russia,* kiziridi_pavel@mail.ru

The uniformity of low-energy (up to 40 keV) high-current (up to 25 kA) electron beam (LHEB) formed in a gun with explosive-emission cathode and plasma anode is one of the key parameters for surface modification of materials, especially when solving problems associated with the formation of surface alloys from pre-deposited coatings. The electron and ion current densities in the double layer, in which the electron beam is formed, are related by Langmuir formula: $j_e = j_i (M/m)^{1/2}$. On the face of it, to ensure homogeneity of the LHEB density $j_e(r)$, it is necessary that the ion current $j_i(r)$ be homogeneous over the cross section of the plasma anode. However, the research and operational experience of high-current electron guns have shown that, passing through a homogeneous plasma channel in a guide magnetic field, the beam is transformed and acquires the maximum current density in the near-axis region [1]. To compensate this negative "focusing" effect, it is necessary to create a plasma anode with an increased density of ions at the periphery.

For this purpose, we developed a new electron gun [2] based on hybrid discharge matching an annular Penning anode and a planar magnetron built into an explosive-emission cathode (Fig. 1), which at the initial stage of the plasma anode formation makes it possible to obtain an annular "cloud" of cathode plasma [3]. This plasma contributes to the formation of plasma anode with the required particle density distribution, which, in turn, provides better beam uniformity.

The paper presents the characterization of the plasma anode formed in this discharge. The decreasing of the time delay of the transition of pulsed Penning discharge into high-current stage was observed if the magnetron discharge started before Penning discharge. The results of measurements performed with the help of a set of Langmuir probes have shown the possibility of a plasma anode formation having a maximum particle density at the periphery (Fig. 2). First tests of the LHEB energy density are also presented.

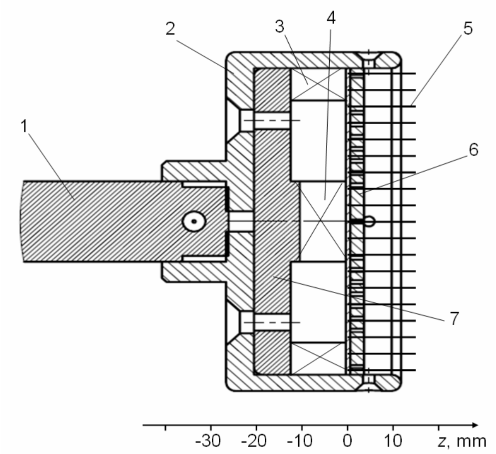


Fig. 1. Cathode assembly. 1 − cathode holder; 2 − fixture; 3 − ring permanent magnet Ø76×Ø60×12 (Nd-Fe-B); 4 − disc permanent magnet Ø20×10 (Nd-Fe-B); 5 − emitter; 6 − cathode substrate; 7 − magnetic citcuit.

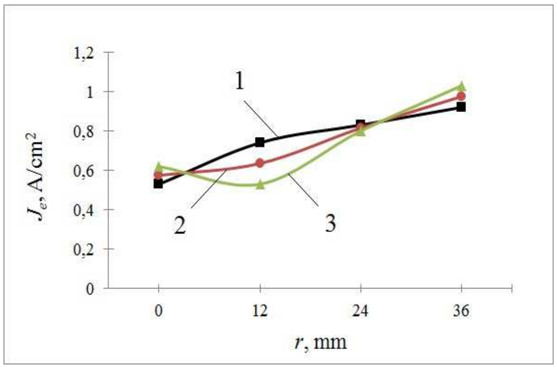


Fig. 2. The current density distribution of plasma electrons along the column radius at different instants of time from the beginning of the Penning discharge current pulse: curve 1 - 150 µs, 2 - 175 µs and 3 - 200 µs

REFERENCES

[1] *Nazarov D.S., Ozur G.E., Proskurovsky D.I.* // Instruments and Experimental Techniques (in Russian) – 1996 – vol. 4 – pp. 83-88.

[2] *Kiziridi P.P., Ozur G.E.* // Vacuum – 2017 – vol. 143 – pp. 444-446.

[3] *P. P. Kiziridi, G. E. Ozur, L. A. Zyul'kova, S. A. Popov, S. A. Shevelev, and M. A. Alekhin.* // Technical Physics, 2017, Vol. 62, No. 11, pp. 1643–1650. © *Pleiades Publishing, Ltd., 2017.*

[1] This work was supported by Russian Foundation for Basic Research (grant #16-48-700239-r_sibir-a)

PARAMETERS OF PLASMA BUNCHES GENERATED BY PULSED SURFACE FLASHOVER ON KCL AND PTFE AT 100 KV[1]

P.A. MOROZOV, R.V. EMLIN, V.V. LISENKOV, I.F. PUNANOV

Institute of Electrophysics, 106 Amundsena street, Yekaterinburg, 620016, Russia, lfd@iep.uran.ru, +7-343-267-88-26

Development of small pulsed plasma thrusters now is focused on achievement of higher values of efficiency, precision, and particle flow speed [1, 2]. One of the methods to stimulate plasma acceleration is vacuum surface flashover at higher voltages (more than 100 kV). Also, in order to improve parameters of plasma flow, it is an attractive idea to use nanosecond pulses because of higher rate of power input into propellant. In addition, in this mode there is a possibility to decrease the level of the stored energy down to 3-5 J and increase the pulse frequency up to 100 Hz and higher.

In this work we study plasma bunches generated by high-voltage vacuum surface flashover in linear configuration. The measured values are full ion charge, ionization degree, propellant loss, and thrust. We used potassium chloride, Teflon and polyethylene as samples. Generator voltage is 100 kV, stored energy is 5 J, and maximum current is 3.5 kA. Pulse duration is 25 ns.

We were interested in specific features of current flow which are determined by the differences in mechanisms of surface flashover in cases of anode- and cathode-initiated process. Thus, we obtained the waveforms of current and voltage across the discharge gap for both polarities of sharpened electrode.

We analyzed the full ion charge, propellant ionization degree, propellant loss, and thrust of the plasma bunch in terms of using of tested materials in discharge units of high-frequency pulsed plasma thrusters, paying attention to dependence of these values on chemical structure of the materials.

Also, we used a model based on the heat equation to calculate thrust, full energy of the bunch, charge efficiency and energy efficiency for dielectric materials of several chemical classes taking into account thermodynamical and electrophysical parameters of the given materials. The calculations were carried out for two sequential stages of the breakdown process (initiation and high-current discharge). We obtained values of thrust and full energy of the bunch which are in good accordance with the measured values.

REFERENCES

[1] *Zun Zhang and Haibin Tang* // Investigations on the Flowing Pulsed Plasma of a 20 J Pulsed Plasma Thruster. Proceedings of the 33rd International Electric Propulsion Conference, 2013. IEPC-2013-147.

[2] *Shintani K. et al* // Trans. JSASS Space Tech. Japan, 2009, Vol. 7, No. ists26, pp. Pb_147-Pb_154.

1 This work was supported by the Russian Foundation for Basic Research (project No 18-08-00185)

HIGH-INTENSITY PULSED ION BEAM FOCUSING BY ITS OWN CHARGE[1]

A. PUSHKAREV, A. PRIMA*, X.P. ZHU**, L. DING**, Q. ZHANG**, C.C. ZHANG**, YU. ISAKOVA*, M.K. LEI***

** National Research Tomsk Polytechnic University, 30, Lenin Ave, 634050 Tomsk, Russia, aipush@mail.ru*
*** Surface Engineering Laboratory, School of Materials Science and Engineering and Key Laboratory of Materials Modification by Laser, Ion, and Electron Beams (Ministry of Education), Dalian University of Technology, Dalian 116024, China*

The results of a study on focusing of high intensity pulsed ion beam (HIPIB) in a self-magnetically insulated diode at the TEMP-6 (120 ns, 200-250 kV) accelerator are presented. Ion space charge neutralization and focusing properties of HIPIBs are investigated in the relation to beam divergence and transport to a focal plane in a series of pulses. It is obtained that the concentration low energy electrons in an ion beam 1.3-1.5 time exceeds the concentration of ions. Use of an additional metal mesh in the transportation region of ions allows an increase in concentration of the accompanying electrons. The effect of additional focusing of ions by its own charge is discovered. With an increase in density of negative total charge (electrons and ions) of a beam the total divergence (the sum of divergences in vertical and horizontal planes) decreases from 11.4° to 5°. It leads to an increase in the energy density in the focus at total energy reduction by a factor of 1.5. The statistical shot to shot analysis of main parameters of an ion beam is conducted at the diode operation with an additional metal mesh.

[1] This work was supported by Russian Foundation for Basic Research, projects no. 16-48-700012 and 17-08-00067 and by the National Science Foundation of China under Grants Nos. 51371043, 51621064, National Basic Research Program of China (973 Program) under Grant No. 2015CB057306, the Fundamental Research Funds for the Central Universities under Grant No. DUT16JJ (G)01, and High-end Foreign Experts Recruitment Program of China under Grant No. GDW2017210029

NUMERICAL SIMULATION OF EOS WITH A LARGE-AREA PLASMA CATHODE WITH MESH STABILIZATION OF THE EMISSION-PLASMA BOUNDARY[1]

V.T. ASTRELIN, ***, A.N. KOZYREV**, V.M. SVESHNIKOV**, ***, M.S. VOROBYOV*****

**Budker Institute of Nuclear Physics SB RAS, av.Acad.Lavrentiev 11, Novosibirsk, 630090, Russia, e-mail: V.T.Astrelin@inp.nsk.su, phone: +79139459097*
***Institute of Computer Mathematics and Geologocal Physics SB RAS, av.Acad.Lavrentiev 6, Novosibirsk, 630090, Russia*
**** Novosibirsk State University, Pirogova str. 2, Novosibirsk, 630090, Russia*
***** Institute of High Current Electronics SB RAS, Akademichesky Avenue 2/3, Tomsk, 634055, Russia*

To irradiate large surfaces and significant gas volumes by electrons, an accelerator with a plasma emitter takes an important place [1]. The paper discusses some issues of numerical two-dimensional modeling of stationary electron beams generated in electron-optical systems (EOS) with a plasma electron emitter. The plasma parameters define the model boundary conditions for the potential and the electric field on the emission surface. The shape of the surface is found from the condition of continuity of the electron beam emerging from the plasma and entering the EOS. The characteristics of the emission flux through the plasma surface are determined by the parameters of the plasma and the input of the EOS by the conditions for the electric potential and the field at the boundaries of the system. The obtained relations are realized in the numerical code of ERA-DD [2].

In the code, the solution of the Poisson equation for the potential is achieved on a rectangular quasi-structured locally modified grid by the finite volume method with approximation of the boundary conditions on the grid nodes adjacent to the boundary. Near the emission surface of the plasma, a near-cathode region is allocated with an analytical representation of the parameters of the emission flux and potential. The surface of the plasma deformed during the solution of the problem is given by segments of circles with variable parameters. The accuracy of this representation is sufficient to describe the emission through a fine-scale cathode mesh.

Electronic flows in the model are taken into account in the hydrodynamic approximation. Their simulation is carried out by the method of current tubes. The shape of the electron trajectories is calculated by numerical integration of the equations of motion in the electric and magnetic fields of the system. The contribution of the space charge of the current tubes to the mesh cells is found from solving the equation of the flow continuity. The local density of the current flowing into the EOS is determined in the numerical solution of the one-dimensional Poisson equation in the quasi-plane gap. The considered small thickness virtual gap is located inside the near-cathode region by the plasma surface and parallel to it boundary. The potentials are given at the boundaries of the gap, and the electric field is given on the plasma surface.

The solution of the self-consistent problem of the formation in the EOS of a beam of electrons emitted by the plasma surface is found numerically and includes three main tasks: 1) calculating the potential by solving the Poisson equation using internal iterative process; 2) calculation of trajectories and space charge; 3) finding the shape of the plasma surface in external iterative process.

The testing of the code algorithms was carried out by comparing them with analytical solutions and with the results of numerical simulation by the POISSON-2 code [3].

The work was partially financed within the framework of the Comprehensive Program of Basic Research of the Siberian Branch of the Russian Academy of Sciences "Interdisciplinary integration studies" (Project of SB RAS No. 10, 2018-2020).

REFERENCES

[1] *Vorobyov M.S., Koval N.N., Sulakshin S.A.* An electron source with a multiaperture plasma emitter and beam extraction into the atmosphere // Instruments and Experimental Techniques. 2015. V. 58. No 5. P. 687-695.

[2] *D.O. Belyaev, A.N. Kozyrev, V.M. Sveshnikov.* Application package ERA-DD for solving two-dimensional boundary value problems on quasi-structured grids // Vestnik NSU. 2010. T. 8, No. 1. P. 3-11 (in Russian).

[3] *V.T. Astrelin.* Features of solving problems of plasma emission electronics in POISSON-2 software package // Progress in Applied Physics (Uspekhi prikladnoi fiziki), Volume 1, 2013, No. 5, p.571-573 (in Russian)

[1] The work was partially supported by the Ministry of Education and Science of the Russian Federation and by Siberian Branch of the Russian Academy of Sciences, Comprehensive program fundamental research of the SB RAS "Interdisciplinary integration studies", Project SB RAS No. 10

DEVELOPMENT OF THE PLASMA GENERATOR ON THE PARTIAL DISCHARGE OF LOW VOLTAGE

E.A. YAKOVLEV, A.D. MEKHTIYEV*, V.V. YUGAY*, O.V.ALDOSHINA*, L.A. ZINOVYEV***

** Karaganda state technical university, Mira Boulevard, 56, Karaganda, Republic of Kazakhstan, oxi80-07@mail.ru, tel.87079217912*

*** Private Institution "Information Technologies". Alikhanova, 1, Karaganda, Republic of Kazakhstan*

The partial (sliding) discharge plays a large role in power industry at operation of high voltage power lines. It represents breakdown of gas in the presence of a dielectric. Numerous experiments were made at high tensions and larger speeds of change of current [1]. At the same time it was revealed that the partial discharge is a source of strong ionizing radiation and has a wide number of appendices. In particular, it allows to switch currents in several megaamperes at a voltage up to 100 kV. On the other hand it represents a problem for high-voltage isolation of power lines.

In work [2] the partial discharge arising in electric equipment at much more low voltage (200-300 V) are described. Such discharge is the negative factor reducing endurance of an equipment and demanding costs of their detection and neutralization. In the same work the radiation of the partial discharge is described. The maximum of a radiation spectrum lies in the ultraviolet area on a wavelength of 280 - 400 nanometers. Small part is radiated in the visible range of a spectrum of 400 - 450 nanometers.

The purpose of work is development of a pulse plasma generator on the low voltage partial discharge. It will allow to use the cheap low-voltage equipment to its power supply.

The specified objectives are achieved by the fact that:

- the gap between the cathode and the dielectric case is done minimum;
- the internal surface of a dielectric between the anode and the cathode is modified by a covering a layer of the substance reducing breakdown voltage;
- the source of impulses with the raised steepness of the forward front is used.

Advantage of the offered plasma generator is use for power supply of low voltage. It leads to reduction in cost and simplification of a feed circuit of a plasma generator.

Modification of a surface of a solid dielectric facilitates emergence of the partial (sliding) discharge. Breakdown voltage at the same time goes down several times.

Pulse power supplies of low frequency (0,1 Hz) and the industry frequency are developed for power supply of a plasma generator. As an analog of such sources schemes of pulse relaxation generators for processes of electroerosive mascining of metals, RC-generators and static generators of impulses are considered.

Pulse RC-generators on voltage of 1000 V and a pulse repetition rate of 0,1 Hz with the steepness of the forward front of an impulse 5.10^7 V/s and the static generator of impulses on voltage of 1000 V and a pulse repetition rate of 50 Hz with the steepness of the forward front 2.10^5 V/s are developed.

Experiments on studying of development of the partial (sliding) discharge with attenuation at the 1st stage and with transition to the second stage are made. Experiments on studying of stages of the complete and incomplete partial discharge are also made.

Sizes of different options of a plasma generator: length is 40 mm, diameter of the channel is 6 mm; length is 60 mm, diameter of the channel there are 12 mm.

LIST OF REFERENCES

1. Electric discharge on a surface of a solid dielectric. P.1. Features of development and existence of the surface discharge. / A.N. Grigoriev, A.V. Pavlenko, A.P. Ilyin, etc.//News of the Tomsk Polytechnic University. 2006. V. 309. No. 1. Pages 66-69.

2. Partial discharges and methods of their measurement. / A.M. Andreyev, A.E. Monastyrsky, Yu.V. Solovyov, etc. SPb.: EIPK, 2010, - 48 pages.

NUMERICAL SIMULATION OF LOW-CURRENT VACUUM ARC PLASMA JET IN STRONG AXIAL MAGNETIC FIELD[1]

D.L. SHMELEV*, I.V. UIMANOV*, V.I. ORESHKIN**

*Institute of Electrophysics, UB, RAS, Ekaterinburg, 620016, Russia, Shmelev@iep.uran.ru, +73432678781
**Institute of High Current Electrons, SB, RAS, 634055 Tomsk, Russia

The plasma of high-current vacuum arcs in vacuum interrupters with axial magnetic fields (AMF) greater than 15-20 mT/kA consists of unmixed plasma jets emitted by separate cathode group-spots. Therefore, the study of such a separate plasma jet is important for understanding the operation of the interrupter as a whole. Plasma jets in strong AMF have been extensively studied experimentally. It was shown that for interelectrode gaps in the order of 1 cm (typical for vacuum interrupters) the secondary plasma, which appears mainly near the anode, strongly influences the formation of the plasma jet.

The present paper is devoted to computer simulation of the plasma jet emitted from one group-spot in a strong AMF, taking into account the secondary plasma arising from the sputtering of electrodes and the incomplete sticking of the incident ions. Using the previously developed hybrid model [1], the generation of secondary plasma and the interaction of the secondary plasma with the plasma emitted by the cathode spot were studied. It is shown that the plasma jet in the interelectrode gap of several millimeters in size with the applied AMF is a plasma core surrounded by a halo of neutral atoms. The appearance of the jet calculated in the framework of the model is qualitatively consistent with the experimental data (Fig.1).

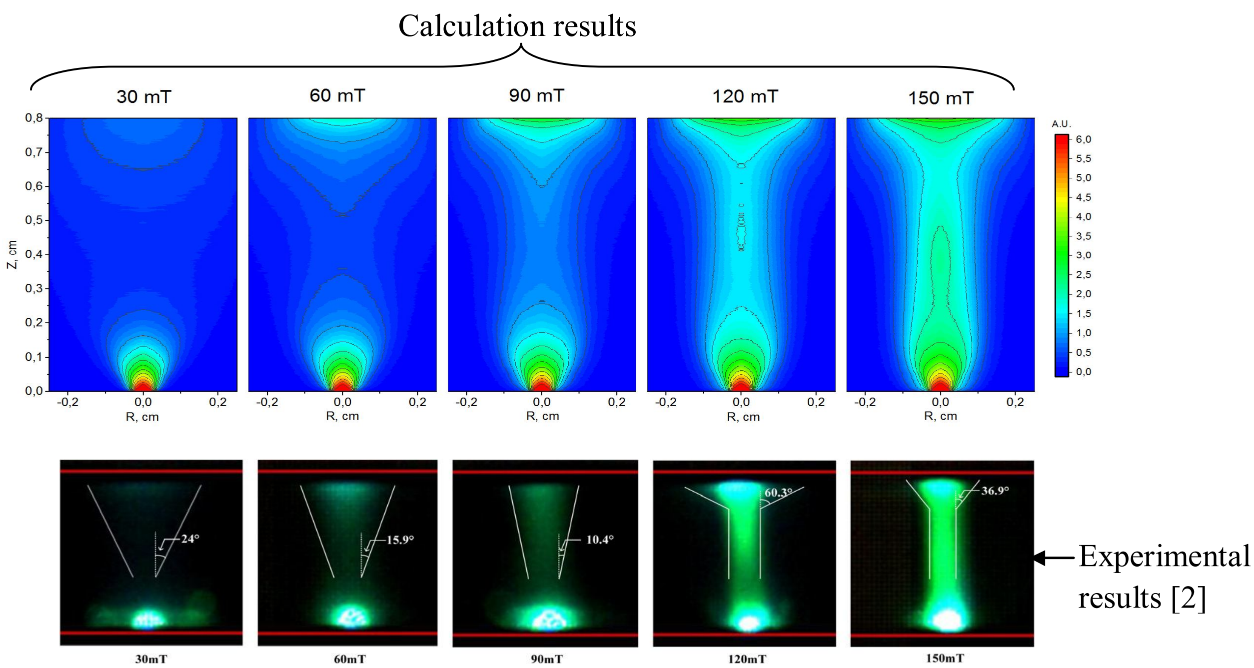


Fig. 1. Comparison of calculated plasma jet appearance (current 60 A) with experimental results [2] for different applied AMF. There is shown total luminosity – summarized over energies with Abel transform.

REFERENCES

[1] *D.L. Shmelev, I.V. Uimanov* // IEEE Trans. Plasma Sci. – 2015. – V. 43 – pp *2261-2266*
[2] *C. Wang, Z. Shi, B. Wu, Z. Gao, S. Jia, L. Wang* // J. Phys. D: Appl. Phys.. – 2016. – V. 49 – № *135203*.

[1] This work was supported by the Russian Fundamental Research Foundation under Awards: 18-08-00547 A

THE MEASUREMENT OF ION FLUX PARAMETERS TIME DEPENDENCE[1]

I.L.MUZYUKIN

*Institute of Electrophysics of the Ural Division of the Russian Academy of Sciences, 106 Amundsen, Ekaterinburg, 620016,Russia, plasmon@mail.ru

The author studied the time-dependant nature of ion flux generation in nanosecond range by means of multi-channel energy-mass analyser. The results obtained are the waveforms of arc current, discharge voltage and ion flux for two or three energy-to-charge ratios and several mass-to-charge ratios.

The electrode setup is widely used for vacuum arc studies which call for pure conditions and the absence of additional plasma source affect. In this case for persistent discharge initiation we used a manipulator capable of changing the mutual position of igniting electrode and cathode. The measurements were made after cathode cleaning with a hundred of long (>50 μs) discharge pulses. Cathode is made of copper. The distance between the anode and cathode is 1 mm.

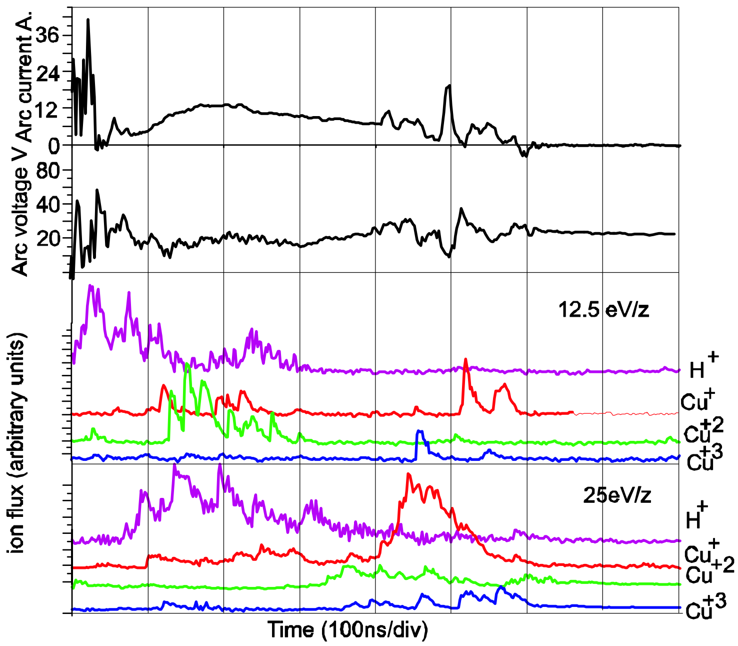


Fig. 1. Combined waveforms of current and arc voltage and ion fractions current for the second electrode circuit(b) (Low energy range).

The basis of ion flux is constituted by 10-30 ns elementary emissions. These elementary emissions may be related to micro-explosions on cathode surface (ectons). The ion emission combinations may form both subsequent emission groups and 100-150 ns super-emissions. The occurrence of super-emissions most probably precedes non-stabilities in arc current and the attempts of the discharge to extinct. Amplitude Fourier spectrum dependence is close to Brownian random process dependence.

[1] The work was performed under state assignment (theme No. 0389-2014-0005) and supported in part by the Russian Foundation for Basic Research (grants Nos. 16-08-01099, 17-02-00346, 15-08-01648, 17-08-01282, and 16-08-00604), RAS Presidium (program No. I.9P), and RAS UB (project No. 15-17-2-33).

GENERATION OF JETS AND DROPS BY THE CATHODE SPOT OF A VACUUM ARC[1]

I.V. UIMANOV*, G.A. MESYATS**

* Institute of Electrophysics, UB RAS, Ekaterinburg, 620016, Rissia
** P.N. Lebedev Physical Institute, RAS, Moscow 119991, Russia

The explosion of liquid-metal jets produced during the formation of a crater on the cathode of a vacuum arc is the basic mechanism of the initiation of individual cells in the cathode spot [1]. To analyze the processes involved, a two-dimensional axisymmetric model is proposed that describes the generation of quasi-one-dimensional liquid-metal jets during the growth of azimuthal instability of the liquid-metal rim of a cathode microcrater [2, 3]. The simulation input data are the jet diameter, propagation velocity, and temperature, which are calculated using a previously developed semiphenomenological model of crater formation [4]. In the context of the proposed model, the jet formation has been simulated for different modes of melt splashing from a crater [5] without considering the jet interaction with the cathode spot plasma. It has been shown that in the “active splashing” mode, a jet of almost constant diameter, longitudinal velocity, and temperature is formed. The head of the propagating jet transforms into a spherical drop due to surface tension. This is accompanied by the excitation of a capillary wave, which propagates to the jet base and harmonically modulates its diameter. In the “inertial splashing” mode with the melt velocity near the jet origin decreasing with time, a jet with a longitudinal velocity gradient is formed (see Fig. 1.). The velocity gradient acts to elongate the jet (reduce its diameter) and causes the drop-shaped head to separate away from the jet and the entire jet to break away from the crater. As the jet further propagates, it breaks into drops. It has been demonstrated that the jet breakup and its breakaway from the cathode are due to the Rayleigh–Plateau instability that occurs when the length of the modulated jet becomes equal to a capillary wavelength satisfying the instability criterion.

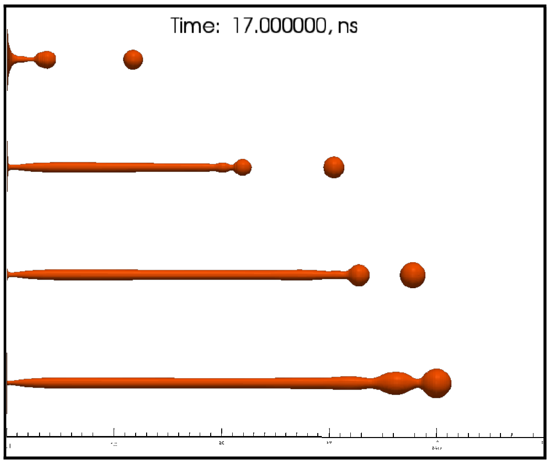


Fig. 1. Simulation of the generation of jets and drops by the cathode spot of a vacuum arc with Cu cathode.

REFERENCES

[1] *Mesyats G. A.//* Cathode Phenomena in a Vacuum Discharge: The Breakdown, the Spark, and the Arc. - Nauka, Moscow, 2000.

[2] *M. A. Gashkov, N. M. Zubarev, O. V. Zubareva, G. A. Mesyats and I. V. Uimanov //* Journal of Experimental and Theoretical Physics. – 2016. – Volume 122. – № 4. Pages. 776–786.

[3] *M.A. Gashkov, N.M. Zubarev, G.A. Mesyats, and I.V. Uimanov //* Pis’ma Zh. Tekh. Fiz. Physics. – 2016. – Volume 42. – № 16. Pages. 48–55.

[4] *Mesyats G.A. and Uimanov I.V. //* IEEE Transactions on Plasma Science. – 2017. – Volume 45. – № 8. Pages. 2087–2092.

[5] *Mesyats G.A and Uimanov I.V. //* IEEE Transactions on Plasma Science. – 2015. – Volume 43. – № 8. Pages. 2241–2246.

[1] This work was supported by the Russian Fundamental Research Foundation under Award 16-08-01099, Award 17-02-00346 and by the Theme of the State Task under Grant 0389-2014-0005.

INFLUENCE OF RADIATION-INDUCED DEFECTS ON THE OVERHEATING OF A METAL TARGET [1]

Y.I. ISAKOVA, A. PRIMA*, X.P. ZHU**, L. DING**, Q. ZHANG**, A.I. PUSHKAREV*, M.K. LEI***

** Tomsk Polytechnic University, 30, Lenin Ave, Tomsk, 634050, Russia*
*** Dalian University of Technology, Liaoning Sheng, Dalian Shi, Ganjingzi Qu, Dalian 116024, China*

The results of an experimental study on heating of a metal target by a high-intensity pulsed ion beam, which is formed by the TEMP-6 accelerator [1] (200 - 250 kV, 120 ns) are presented. The composition of the beam includes carbon ions (85%) and protons; the energy density in the focus is 5-12 J/cm^2, the target heating rate is above $3*10^{10}$ K/s. The temperature of the target was measured using the thermal imaging diagnostics [2] in a homogeneous heating mode over the target cross section (target diameter is smaller than the diameter of the ion beam) and nonuniform heating (the target size is much larger than the diameter of the ion beam). The studies were carried out on targets with a thickness of 75-200 μm made of stainless steel, titanium, brass, copper and tungsten. The temperature was measured after 0.1 s after irradiation, which corresponds to homogeneous heating of the target along the depth. Simulation of the temperature distribution along the depth in the near-surface layer of the target and the duration of temperature equalization by its depth are performed. Our investigations showed that the average temperature of the small target and the temperature of the large target in the focus are much higher than the ablation threshold of the target material. The analysis of the mechanism of the target overheating is carried out. It is shown that the effect of the target overheating during ion beam irradiation is attributed to the formation, migration and subsequent annealing of radiation-induced defects formed during high-intensity pulsed ion beam irradiation.

REFERENCES

[1] *X.P. Zhu, M.K. Lei, and T.C. Ma, Rev. Sci. Instrum.* ***73****, 1728 (2002).*
[2] *Y.I. Isakova and A.I. Pushkarev, Instruments Exp. Tech.* ***56****, 185 (2013)*

[1] This work was supported by Russian Science Foundation via grant no. 17-79-10140

GENERATION OF PLASMA AND ION BEAM BY VACUUM ARC WITH COPPER-CHROMIUM CATHODES[1]

*V. FROLOVA****, *A. NIKOLAEV***, *E. OKS****, *G. YUSHKOV**

**Tomsk State University of Control System and Radioelectronics, 40 Lenin Ave., Tomsk, 634050, Russia,*
Frolova_Valeria_90@mail.ru, +7(3822)491776
***High Current Electronics Institute, SB RAS, 2/3 Academichesky Ave., Tomsk, 634055, Russia*

Plasma and ion beam produced by vacuum arc are widely used in processes of plasma coating deposition and ion beam implantation for surface modification. Multicomponent cathodes containing several elements allow one to obtain plasmas or mixed ion beams with several types of ions [1,2]. This extends the capabilities of ion-plasma and ion-beam equipment making it possible to coat complex films or to implant of the surface simultaneously with ions of different materials. To use such cathodes for the above purposes, it is necessary to know the composition and the ion charge state distribution of the vacuum arc plasma. This article presents such studies using model cathodes made of chromium and copper composition with different ratios of these elements in them. The choice of such cathode material is related, among other things, with the fact that such an alloy is widely used in vacuum circuit breakers.

For investigation of plasma properties an ion emission method was used. Plasma of vacuum arc was generated in discharge system where both electrodes, i.e. cathode and anode, were made from copper-chromium composition. The vacuum arc plasma was generated in the gap between the cathode and the anode and then flowed through a small hole in the anode into a hollow electrode with an emission grid. From the plasma surface, a limited emission grid was used to select ions and an ion beam was formed at an accelerating voltage of 10-30 kV. The mass-to-charge ion beam composition was measured by a time-of-flight spectrometer. The the composition and the ion charge state distribution of the vacuum arc plasma were determined from the measured time-of-flight data for the ion beam. The effect of the vacuum arc parameters and composition of the cathode materials is discussed.

REFERENCES

[1] *Savkin K.P., Yushkov Yu.G., Nikolaev A.G., Oks E.M., Yushkov G.Yu.* // Review of Scientific Instruments – 2010. – V.81. – № 2. 02A501.

[2] *Nikolaev A.G., Oks E.M., Savkin K.P., Yushkov G.Yu., Frolova V.P., Barengolts S.A.*// Journal of Applied Physics – 2014. - V. 116, - № 21. 213303.

[1] This work is supported by the Russian Science Foundation under grant # 18-19-00069.

MEASUREMENT OF THE TEMPERATURE OF ALUMINUM WITH A TITANIUM COATING IN A HIGH-SPEED PULSE OF AN ELECTRON BEAM[1]

A.D. TERESOV, T.V. KOVAL**, P.V. MOSKVIN*, CHAN MI KIM AN**, N.N. KOVAL**

**Institute of High Current Electronics SB RAS, Akademichesky Ave., 2/3, Tomsk, 634055, Russia, tad514@sibmail.com, +7(3822)47-17-13*

***National Research Tomsk Polytechnic University, Lenin Ave., 30, Tomsk, 634050, Russia*

The mechanical and operational properties of materials are largely determined by the regime of electron beam effect, as well as material characteristics such as the maximum heating temperature, thermal cycle, melting and crystallization rates [1]. Therefore, measuring the surface temperature with high-speed electron beam action opens up opportunities, like studying the processes of heating, melting, evaporation of materials, and controlling the technological parameters of the modification in order to obtain predetermined properties of materials after electron-beam modification.

The paper presents the results of experimental temperature measurements of the target surface from aluminum and aluminum with a titanium coating in a high-speed pulse of an electron beam and the results of a numerical simulation of the electron-beam effect. Mathematical modeling of thermal processes includes the construction of a physics-mathematical model that is adequate to the experimental conditions and is described by the heat equation, taking into account the phase transition, the temperature dependence of the thermophysical coefficients and the boundary conditions on the surface of the sample.

In the experiment, the sample was fixed on the surface of the manipulator table and placed in a vacuum chamber of a pulsed electron beam facility «SOLO» [2, 3]. For pulse measurement of temperature on the surface of samples, a high-speed infrared pyrometer Kleiber KGA 740-LO with a measurement range (300-2300) C in the spectral range (2-2.2) μm was used. Voltage from thermocouple were measured with a Fluke 175 multimeter. In addition to the pulse temperature values, the oscillograms of currents in discharge cell and accelerating gap were recorded simultaneously with the Rogowski coils and the accelerating voltage with the Aktak ACA-6039 high-voltage probe (1:1000).

Measurement of the surface temperature of samples in a high-speed pulse of an electron beam (energy density 10–25 J/cm^2) and numerical calculations carried out with allowance for phase transitions showed that the surface heating rate is affected by the energy characteristics of the electron beam and the dynamics of the beam power density distribution on the surface of the sample [4].

The surface temperature of aluminum with a titanium coating (1 μm) depends linearly on the energy density at the front of the beam current, unlike an uncoated aluminum sample. This increases both the surface heating rate and the energy density of the beam (25 J/cm^2), when the metal plasma of the sample material begins to affect on transportation of the electron beam. Comparison of the experimental and calculated temperatures makes it possible to evaluate the influence of these processes on the energy deposition and to determine the dynamics of the beam power density distribution on the target in the high-speed pulse.

The method for measuring of pulse temperature and the use of numerical simulation of the thermal fields in the sample opens the possibility of controlling the main technological parameters of the electron beam effect in order to obtain predetermined properties of the material surface.

REFERENCES

[1] *Rotshtein V., Ivanov Yu., Markov A.* // Material surface processing by directed energy techniques.– Paris: Elsevier, 2006. 763 p.

[2] *Grigoryev S.V., Devyatkov V.N., Koval N.N., Teresov A.D.* // Pis'ma v zhurnal tekhnicheskoy fiziki.– 2010.– vol. 36.– № 4. pp. 23-31 [in Russian].

[3] Koval N.N., Grigoryev S.V., Devyatkov V.N., Teresov A.D., Schanin P.M. // IEEE Trans. Plasma Sci.– 2009.– vol. 37.– № 10. pp. 1890–1896.

[4] *Devyatkov V.N., Koval N.N.* // Izv. vuzov. Fizika.– 2016.– T.59.– №9/2. pp. 49–52 [in Russian].

[1] This work was supported by Russian Science Foundation (project No. 14-29-00091).

ANALYSIS OF LIQUID METAL JET DEVELOPMENT DURING THE FORMATION OF CRATERS IN A VACUUM ARC CATHODE SPOT[1]

M.A. GASHKOV, G.A. MESYATS*'**, I.V. UIMANOV*, N.M. ZUBAREV*'***

**Institute of Electrophysics UB RAS, Amundsena str. 106, Yekaterinburg, 620016, Russia, gashkov@iep.uran.ru, +7(343)267-87-96*
***Lebedev Physical Institute RAS, Leninsky ave 53, Moscow, 119333, Russia*

As is known, the cathode spot is a source of liquid metal jets and droplets that plays an important role in the self-sustained operation of vacuum arc discharge. The jets and droplets are formed when liquid metal is extruded by the pressure of explosive plasma out from craters formed on the cathode [1]. A jet formation mechanism has been proposed [2], which is based on the development of azimuthal instabilities on the boundary of liquid expelled from craters. According to [3], this is a capillary instability of the Rayleigh–Plateau (RP) type. However, we cannot exclude that the Rayleigh–Taylor (RT) instability is also operative, since the characteristic times of RP and RT instabilities are comparable.

In the current work, we have continued the study of the dynamics of molten metal during crater formation in the cathode spot of vacuum arc discharge in the wide range of cell currents, times of current flowthrough a cell, and crater diameters. According to our assumptions, at the initial stage, a liquid-metal ridge is formed around the crater. This process has been numerically simulated in [4], where a hydrodynamic model that includes experimentally obtained characteristics of the cathode spot plasma interacting with the cathode, such as the pressure exerted by the plasma on the cathode and the power dissipated in the cathode, has been developed. At the final stage, the motion of liquid metal loses axial symmetry, which corresponds to a tendency toward jet formation. The development of azimuthal instabilities of the rim is analyzed in terms of dispersion relations for surface waves; estimations of the time of liquid metal jets formation and their most probable number are done.

REFERENCES

[1] *Mesyats G.A., Zubarev N.M.// J. Appl. Phys.* – 2013. – 113. – 203301.
[2] *Gashkov M.A., Zubarev N.M., et al.// J. Exp. Theor. Phys.* – 2016. – 122. – 776.
[3] *Gashkov M.A., et al. // Tech. Phys. Lett.*. – 2016. – 42. – 852.
[4] *Mesyats G.A., Uimanov I.V. // IEEE Trans. on Plasma Science*. – 2017. – 45. – 2087.

[1] This work was performed in the framework of state programs 0389-2015-0023 and 0023-2016-0004 and supported by in part by the Russian Academy of Sciences (program of the Presidium of RAS No. 11 and program of the Presidium of UB RAS, project No. 18-2-2-15) and by the RFBR (projects No. 17-08-00430, 17-02-00346). The work of one of the authors (M.A.G.) was supported by the RFBR (project no. 18-38-00313).

INVESTIGATION OF THE DISTRIBUTION OF CURRENT DENSITY IN THE CROSS-SECTION OF THE ELECTRON BEAM PRODUCED BY MULTI-APERTURE DIODE AND TRANSPORTED IN GUIDING MAGNETIC FIELD[1]

I.V. KANDAUROV, V.V. KURKUCHEKOV*,***

** Budker Institute of Nuclear Physics SB RAS, av. Acad. Lavrentiev 11, Novosibirsk, 630090, Russian Federation*
e-mail: I.V.Kandaurov@inp.nsk.su
*** Novosibirsk State University, Pirogova str. 2, Novosibirsk, 630090, Russian Federation*

Intense pulsed electron beams of moderate (20-200 keV) energy are used for modifying the surface layer of metal items in order to impart new physical and chemical properties unattainable with traditional technologies. Along with this, such beams are applicable for simulating transient thermal loads on plasma-facing components in the ITER Tokamak and future thermonuclear devices. For applications involving electron-beam treatment of materials, it is important to have an information on the distribution of the beam flux over irradiated target, as well as on the possible local flux density inhomogeneities associated, for example, with the technique of producing the beam. In our experiments on the newly developed electron beam test facility BETA [1] we employed an X-ray imaging technique [2] for measuring the cross-sectional current density distribution in a wide-area (ca. 50 cm^2) electron beam (10 – 60 A, 50 – 100 kV, 0.15 – 0.3 ms) produced in the plasma emission source with multi-aperture beam optics. The beam consisted of 241 individual beamlets arranged in hexagonal order at a distance of 5 mm inside a circle ca. 80 mm in diameter. An initial diameter of each beamlet was 2 mm. The beam passed in a guiding magnetic field (ca. 10 mT) onto a metal target located at 85 cm downstream the source, and an X-ray footprint of the beam was registered with 2D imaging diagnostic on a single-shot basis.

Experiments have shown that despite the initially discrete nature of the beam, quite homogeneous footprints without a noticeable beamlet structure can be obtained. This fact was also confirmed by the structure of the melting print on the target surface. This result is due to the presence of angular divergence of electron beam velocities owing to which radial oscillations of the beamlet envelope occur during the beam passage in a magnetic field. The spatial period of oscillations was ca. 0.6 m for typical experimental parameters (~10 mT, ~100 keV). Aligning the antinodal point of the beamlet envelope with the target plane by varying the guiding magnetic field and / or accelerating voltage, a quasi-homogeneous beam footprint can be obtained. Moreover, it was found that spatial periodicity of the beam structure is irreversibly smeared when the transported electron current is sufficiently large (≥ 20 A) due to the effect of uncompensated space charge of the beam. The space-charge compensation factor was also estimated registering the angle of the beam rotation during transportation to the target.

REFERENCES

[1] *L N Vyacheslavov et al.* // Phys. Scr. 2018 **93** 035602
[2] *I V Kandaurov et al* // J. Phys.: Conf. Ser. 2017 **830** 012032

[1] This work was financially supported by Russian Science Foundation (project №17-79-20203). Maintenance of the experimental facility was partially financed within the framework of the Comprehensive Program of Basic Research of the Siberian Branch of the Russian Academy of Sciences "Interdisciplinary integration studies" (Project of SB RAS No. 10).

AUTOMATIC PROBE DIAGNOSTIC SYSTEM FOR PULSE PLASMA ELECTRON SOURCE[1]

N.N. KOVAL, S.S. KOVALSKY, P.V. MOSKVIN

**Institute of High Current Electronics, 2/3 Akademichesky avenue, Tomsk, 634055, Russia,*
pavelmoskvin@mail.ru, +7(3822)491713

The paper presents a developed system of probe measurements for the diagnostics of emission plasma of a pulsed low-pressure arc discharge in a magnetic field under conditions of efficient electron selection. The developed system differs from analogs by the presence of two alternative methods for probe characteristics measuring and the ability to automate the measurement and processing of data.

It is known that the effective emission of electrons from the plasma cathode of an electron source change the plasma parameters, primarily by changing its potential. Under the conditions of an axial magnetic field presence, the emissive probe makes it possible to measure the plasma potential with a sufficient reliability [1]. The system allows to measure the plasma potential both with a cold Langmuir and a direct-emission probe. The system provides possibility of a smooth adjustment of the heating current, automatic cut-off of the filament just before the measurement to reduce the measurement error and increase the signal-to-noise ratio, it has the galvanic isolation to enable high voltage measurements with respect to the "ground" (25 kV) and saving data in a format that is convenient for further processing with a PC is presence.

The developed system was tested in experiments on measuring a plasma potential in a discharge cell of plasma cathode electron source with grid stabilization of the emission plasma boundary. A low-pressure arc discharge with a cathode spot is formed between three coaxially located electrodes: an annular AlSi cold cathode with an area of ~25 cm^2, a cylindrical niobium hollow cathode of 200 cm^2 and a cylindrical anode, one of whose bases is covered by a flange with an emission aperture of 40 mm. Apertures is covered by metal mesh to extract electrons into the accelerating gap. A cathode spot is initiated on the annular cathode. The spot exists for 200 μs, which is the main supplier of electrons. A hollow cathode is connected to the ring cathode through a 5 Ohm resistor, which helps to prevent the formation of cathode spots on it. The area of the anode is about 1000 cm^2, of which about 200 cm^2 is the end part which perpendicular to the magnetic field. The similar discharge cell is described in detail in [2].

By the method of divergence of the I-V characteristics of the emitting and cold probes and by the floating potential method, the behavior of the potential of the emission plasma is measured both in the absence of extraction of electrons from it and in the case of effective emission.

REFERENCES

[1] *Sheehan J. P., Raitses Y., Hershkowitz N., Kaganovich I., Fisch N. J. //* Phys. Plasmas. – 2011. – Vol. 18. Issue 7. P.073501

[2] *Grigoriev S.V. Moskvin P.V. //* Izv. vuzov, fizika. – 2016. – Vol. 59. – № 9-2. P. 59–62.

[1] The work was supported by the Russian Foundation for Basic Research (Projects No 18-42-703010).

10,11B ION BEAM PRODUCTION, FORMATION AND ACCELERATION AT THE CYCLOTRON DC-60[1]

I.A. IVANOV, V.V. ALEXANDRENKO**

** Institute of Nuclear Physics ME RK, Abylai khan av.2/1, Astana, 010000, Kazakhstan, igor.ivanov.inp@gmail.com, +77753032212*

Nowadays, special requirements are imposed at the accelerators of charged particles according to the types of ions, their energy, intensity, and other various parameters of the beam. To the solve a various research problems in the field of nucleosynthesis of the Universe are very important to study the reactions between light nuclei with 1p-shell nuclei with energy near Coulomb barrier. Very big interesting in this task is use a boron beam like a incident particle. Thus, to solve this problem, it was necessary to product a beam of boron ions with an energy of 1.75 MeV/nucleon at the cyclotron DC-60.

To solve this problem the methods of ion beams production proven at the ECR source using metal organic compounds MIVOC (Metal Ions from Volatile Compounds). The method based on the use of metal compounds (metallocenes) with high vapor pressure at room temperature. For producing ions of boron were used Carbonara $C_2B_{10}H_{12}$. The volatile compound $C_2B_{10}H_{12}$ has a vapor pressure of about 1-2 Torr at room temperature [1]. Using the standard exhaust systems and MIVOC method for the ECR ion source obtained the range of boron ions. Figure 1 shows the obtained spectrum of boron ions on the cyclotron.

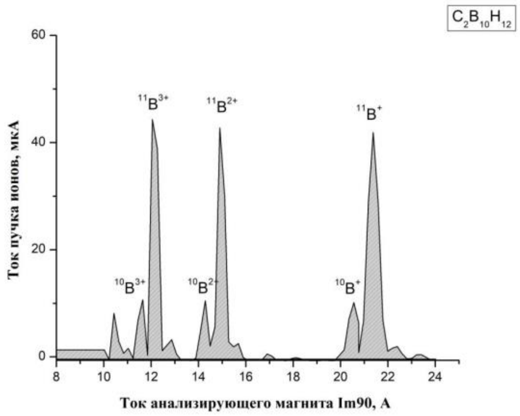


Fig. 1. Spectrum of 10,11B after optimization of ECR-source

Beams of boron ions were accelerated in cyclotron at 4th harmonic at 16.626 MHz frequency of HF-generator. Transportation of ion beams was carried out using standard ion-optical systems. Table 1 shows the produced intensities of ion beams at the source and after acceleration, as well as the transmission coefficients.

Table 1 – Intensities of ion beams and coefficient of transmission

Type of ion	Beam current ECR, μA	Extracted beam current, μA	K, %
10B2+	15.6	0,30	1,90
11B2+	24.2	0.70	2.85

REFERENCES

[1] *Hannu Koivisto // The MIVOC method for the production of metal ion beams. Dissertation work: Finland, 1998.*

[1] This work was supported by Ministry of Energy of the Republic of Kazakhstan under project “Development of technology for obtaining new ions at the accelerator DC-60. Improvement of methods of control and control of the ion beam”.

ACCELERATED ION BEAMS AND METHODS OF RESEARCH ON THE PHYSICAL UNITS OF THE CYCLOTRON DC-60[1]

V.V. ALEXANDRENKO, I.A. IVANOV*, M.V. ZDOROVETS*, M.V. KOLOBERDIN*, S.G. KOZIN*, Y.K. SAMBAYEV*, A.E. KURAKHMEDOV**

** Institute of Nuclear Physics ME RK, Abylai khan av.2/1, Astana, 010000, Kazakhstan, vitasqnx@rambler.ru, +77772733312*

DC-60 heavy ion accelerator [1], put into operation in 2006, according to its specifications - spectrum, charge and energy of accelerated ions, has the high scientific, technological and educational potential. The highest possible universality both by spectrum of accelerated ions and acceleration energy and regimes build in DC-60 heavy ion accelerator designing. The new interdisciplinary research complex based on cyclotron DC-60 makes it possible to create a highly-developed scientific-technological and educational environment in the new capital of Kazakhstan.

Since then became available and accelerated the multi-charged ions in the range from lithium to xenon with energies from 0.4 MeV/nucleon to 1.75 MeV/nucleon which are successfully used to perform a number of scientific and technical tasks in the field of nuclear physics, radiation physics of solid state, nanotechnology and other fields of science. The table 1 shows the main parameters of the resulting ion beams with energy of 1.75 MeV/nucleon at the cyclotron DC-60.

Table 1 – Intensities of ion beams in the ECR source and after acceleration in cyclotron, μA

Type of ion	Beam current ECR, μA	Extracted beam current, μA		Type of ion	Beam current ECR, μA	Extracted beam current, μA
$^{7}Li^{1+}$	110	2.25		$^{31}P^{5+}$	20	0.58
$^{11}B^{2+}$	24	0.70		$^{32}S^{6+}$	61	0.80
$^{12}C^{2+}$	140	2.51		$^{40}Ar^{7+}$	45	2.00
$^{14}N^{2+}$	120	3.20		$^{40}Ca^{7+}$	50	1.35
$^{16}O^{3+}$	86	1.50		$^{56}Fe^{10+}$	16	0.30
$^{20}Ne^{4+}$	76	2.08		$^{84}Kr^{15+}$	28	1.50
$^{24}Mg^{4+}$	46	1.14		$^{132}Xe^{22+}$	16	0.40

At the accelerator DC-60 was developed a system of energy measurement using the time-of-flight method for the reliability of the obtained energy of ion beams. The method consists in the fact that one and the same "microbanch" is consistently two scintillation detectors positioned in the course of the ion beam at a known distance. The time between signals from two detectors is measured and knowing the flight base, the ion energy is calculated. According to the measurements, the difference in the measured and calculated ion energies varies in the range of ± 0.04 MeV/nucleon. The error in the measurement of energy is estimated to be no worse than ± 3% [2].

To irradiate the samples under study on the problems of solid state physics at different temperatures, high-temperature heating systems (up to 700 ˚C) and a low-temperature holder (nitrogen temperature) were developed and put into operation.

Thus, the obtained beams of accelerated ions, the methods of measurement, the diagnostics and methods of irradiation of samples at the cyclotron DC-60 are relevant for solving problems in the field of radiation physics of solid state during the simulation of reactor and thermonuclear irradiation of structural materials.

REFERENCES

[1] *M. Zdorovets, I.A. Ivanov, M. Koloberdin, S. Kozin, V. Alexandrenko, E. Sambaev, A. Kurakhmedov, A. Ryskulov. Accelerator complex based on DC-60 cyclotron //* Material of XXIV Russian particle accelerator conference RUPAC 2014 (Obninsk, Russia, 6-10 October 2014). – P. 287- 289.

[2] *I.A. Ivanov, M. Zdorovets, M. Koloberdin, V. Alexandrenko, S. Kozin, Sambaev, A. Kurakhmedov, Yu. Teterev. A measure of the energy of accelerated ions by the method of time-of-flight for the heavy-ion accelerator DC-60 // Bulletin of ENU. – Astana, 2017. – №2(117). – p.188 – 195.*

[1] This work was supported by Ministry of Education and Science of the Republic of Kazakhstan under project IRN: AP05133476 “The comparative study of the fine structure in the area of damage of metals and the alloys irradiated with ions of metals and inert gases”.

CHALLENGES AND APPROACHES TO RADIATION HARDNESS CONTROL OF ELECTRONIC COMPONENTS TO IN-SPACE HIGH-ENERGY PARTICLES EXPOSURE

V. S. ANASHIN[*], *P. A. CHUBUNOV*[*], *A. E. KOZIUKOV*[*], *G.A. PROTOPOPOV*[*], *A.S. KONYUKHOV*[*]

[*]*JSC United Rocket Space Corporation – Institute of Space Device Engineering (JSC URSC – ISDE), Russian Federation.*

All spacecrafts operate in orbits or in outer space under influence of harsh environment of space ionizing radiation. The presence of ionizing radiation in space has been known since the very beginning of satellite and space exploration era. From the stand point of origin, we can highlight mainly three sources of ionizing radiation. Depending of the source the types and characteristics of high-energy particles may differ. The most missions operate in different near-earth orbits where the significant effect is caused by charged energy particles of Earth radiation belts. The typical particles for this environment are protons (low- and medium-energy – from hundreds keV to hundreds MeV) and electrons (from 10 keV to 10 MeV). The other source is solar events with high-energy protons up to 10 GeV and ions with Z from 2 to 28. And the last one is Galactic cosmic rays with high-energy protons of 10 GeV and ions with Z from 2 to 92. The lifetime of spacecrafts and its systems and subsystems almost fully depends on the hardness of electronic components to space radiation.

For modern very large scale integrated circuits (VLSIC), power MOSFETs, linear and optoelectronic devices heavy ions from solar and galactic cosmic rays are the most critical, as they induce single event effects (SEE) leading to errors and failures in these devices. SEEs are such effects, the cause of which is the interaction of a single charged particle with sensitive region of a device. Such effects have a stochastic nature and are not related to radiation “history” of the device. For modern electronic components with large scale integration, one hit of a single charged particle into a sensitive volume of the device is sufficient enough to cause a failure or upset in its functionality. Depending on various reasons, different effects, both irreversible (hard) and reversible (soft), may occur. The most common soft SEEs are: SEU (Single Event Upset) and SEFI (Single Event Functional Interrupt) and SET (Single Event Transient). Hard (catastrophic) effects are: SEL (Single Event Latchup), SEB (Single Event Burnout) and SEGR (Single Event Gate Rapture). VLSICs usually suffer from SEL and SEU, as well as SEFI in case of complex modification. MOSFETs typically are influenced by SEB and SEGR, and for linear devices SET is the most common effect, while optoelectronic devices may experience failures and upsets of all types. For this reason electronic components with hardness level above required, estimated from the spacecraft lifetime and mission environment, shall be used. To ensure these requirements ground SEE testing with heavy ion accelerators are performed.

A number of heavy ion test facilities have been created under The Branch of JSC «United Rocket and Space Corporation» – «Institute of Space Device Engineering» authorizing, on the base of cyclotrons U400 and U400M (FLNR, JINR, Dubna city, Moscow region), which have differential in the composition of output ions and their energy, the radiation area, range of temperatures, changeover time from one ion to another, vacuum pumping time. Currently our test facilities provide tests of all electronic component functional classes on hardness to all types of SEE. The test facilities allow us to irradiate items with LETs from 1 to 100 MeV×cm^2/mg, ranges in Si from 30 to 2000 μm, and irradiation area up to 200×200mm. The purpose of the test is to obtain experimental cross section dependence of SEE from linear energy transfer (LET) of heavy ions energy in the wide range of LET. The irradiation is carried out using described facilities until the registration level reaches more than 100 SEEs or until the destructive failure occurs or until the fluence is 1E+7 cm^{-2}. Long lifetime assurance of a spacecraft in terms of radiation hardness is achieved by using electronic components with guaranteed (by test results) radiation hardness level to all types of SEEs, that exceeds specified requirements. To clarify anticipated radiation hardness level, radiation environment impact should be monitored during the mission. For this purpose corresponding instruments are developed. Nevertheless, these instruments require designing sensitive detectors for monitoring high-energy particles with high accuracy. Carrying out tests for electronic components hardness assurance to all types of possible effects with high informative value (the determinative tests with large set of electrical parameters), with validity (the only usage of admissible (simulating) tests methods on the metrologically-certified and highly–precise (the discrepancy is less than 10 %) test facilities) in the critical temperature environment and in bias conditions is essential.

Our organization has all necessary methods and facilities for radiation hardness control and assurance of candidate spacecraft electronics of all functional classes. We are looking forward to further cooperation.

THREE-DIMENSIONAL SIMULATION OF THE ELECTRON BEAM INTERACTION WITH MODULATED DENSITY PLASMA[1]

E.A. GENRIKH, E.A. BERENDEEV**, G.I. DUDNIKOVA****

** The Institute of Computational Mathematics and Mathematical Geophysics SB RAS, Lavrentyev Ave., 6, Novosibirsk, 630090, Russia*

** The Institute of Computational Mathematics and Mathematical Geophysics SB RAS, Lavrentyev Ave., 6, Novosibirsk, 630090, Russia, evgeny.berendeev@gmail.com , phone: 8 (383) 330-96-65*

****-The Institute of Computational Technologies SB RAS, Lavrentyev Ave., 6, Novosibirsk, 630090, Russia.*

One of the perspective directions in the terahertz radiation obtaining is the generation of electromagnetic radiation near the plasma frequency in a plasma-beam system. The experiments on the electromagnetic waves generation (0.1-0.5 THz) during the injection of high-current electron beams into the plasma at the GOL-3 facility in the Institute of Nuclear Physics SB RAS showed significant increasing in the radiation efficiency (~ 1%) in the regime when the transverse dimensions of the system comparable with the length of the emitted waves [1]. In the linear theory, the mechanism of a plasma antenna for generating terahertz radiation was proposed [2].

The continuous injection of a beam into a plasma channel with a longitudinal density modulation provides a high efficiency (up to 10%) of the emission at a plasma frequency. It is assumed that the inhomogeneity of the plasma density plays a key role in the conversion of the beam energy into electromagnetic radiation.

The main problem of linear theories is that they do not take into account many factors such as instability which plays an important role in the real plasma. Therefore it is necessary to create a numerical model that takes into account nonlinear effects. In this paper, the three-dimensional numerical model is created for simulation of beam-plasma interaction. It is fully kinetic model based on Particle-In-Cell method. Numerical experiments for different beam and plasma parameters have been performed using computer systems with parallel architecture. Estimates of the radiation efficiency for the initially homogeneous plasma and for longitudinal density modulation are obtained.

REFERENCES

[1] *A.V. Arzhannikov, A.V. Burdakov, V.S. Burmasov, et al.* // Physics of Plasmas. 2014. Vol. 21. 082106.

[2] *I.V. Timofeev, E.P. Volchok, and V.V. Annenkov* // Physics of Plasmas. 2016. Vol. 23. 083119.

1 This work was supported by the Russian Foundation for Basic Research (project №16-01-00209). Simulations are performed at the Siberian Supercomputer Center SB RAS and using computational resources of Novosibirsk State University.

INVESTIGATION OF PLASMA POTENTIAL AND CONCENTRATION DYNAMICS IN PLASMA ELECTRON EMITTER BASED ON A LOW-PRESSURE ARC DISCHARGE[1]

P.V.MOSKVIN, E.A.PROSKURINA**

**Institute of High Current Electronics, 2/3 Akademichesky Avenue, Tomsk, 634055, Russia, lena_prosk94@mail.ru, +7(3822)491713*

Electron sources with a plasma cathode gradually find their applications in a surface treatment of materials. The introduction of electron sources into real production lines imposes special demands on the stability of operation and the repeatability of operation regime of these complex devices. The parameters of the operation can be dependent on a variety of factors, for example, on the evaporation of a material under the influence of an intense electron beam. Plasma sources of electrons are less sensitive to the residual atmosphere in the vacuum chamber and the evaporation of the material than, for example, thermionic sources. However, it can not be said that there is no complete dependence.

A significant influence on the stability of work, in particular on the electrical strength of the accelerating gap, is influenced by the plasma in the anode region of the sources. It can be a plasma anode, which is created by a separate discharge, or created by the beam itself, or by a parasitic discharge when working in forevacuum pressures. Another cause that provokes the formation of cathode spots and the breakdown of the accelerating gap may be the growth of the plasma potential with the effective extraction of electrons.

The present work is devoted to study of concentration and potential dynamics of the electron emitter cathode plasma under the influence of external factors for the emitter: gas pressure, ion flux into the discharge cell. The operation of the emitter was studied at a pulse duration of 250 μs, an accelerating voltage of up to 15 kV, a discharge current of up to 500 A.

It is shown that the plasma potential of a discharge cell relative to the anode when electrons are extracted from it mainly depends on the pressure of the working gas in the cell. This is due to the existence of a flow of ions into the discharge cell and, possibly, a change in the extraction coefficient up to 100%. The concentration of the cathode plasma in this case is established during the discharge current front even at an accelerating voltage of 3 kV. It is noted that in the absence of extraction, the process of increasing the plasma concentration in the discharge cell can last tens of microseconds.

[1] The work was supported by the Russian Foundation for Basic Research (Projects No 18-42-703010).

COMPUTER SIMULATION OF THE INTERACTION OF SINGLE-TORCH SYSTEM AND THE SEVERAL CAPILLARY TORCHES [1]

*S.V. RYZHKOV**, *V.V. KUZENOV**, K.V. POLYAKOV**

**Bauman Moscow State Technical University, 2 Baumanskaya Street, 5, 1, Moscow, 105005, Russia, E-mail: svryzhkov@bmstu.ru, +7(499)263-65-70*

***N.L. Dukhov All-Russian Research Institute of Automatics, Sushchevskaya Street, 22, Moscow, 127055, Russia*

Computer simulation for an array of pulsed plasma jets **-** capillary discharge with an evaporating wall is presented. The main models and methods, developed for radiation magneto gas dynamics and tested numerically using different tasks (like the target plasma for magnetized target fusion, coaxial magneto plasma accelerator, flow around different geometric bodies, etc.) [1-13] are described.

The high-order scheme, of course, will lead to numerical oscillations in cases where the pattern used crosses the gas-dynamic discontinuity, since polynomial approximation loses accuracy in this case. To avoid oscillations in TVD (total variation diminishing) schemes near the discontinuities and extremes of the solution, an automatic transition to a first-order accuracy scheme is performed, using nonlinear function-dependent constraints, which depend on the solution. They are defined in such a way that the total variation of the solution does not increase; the fulfillment of this property guarantees the preservation of monotonicity: if the solution was monotonous on the old time layer, it will remain so at a new moment in time. The use of limiters, however, introduces a significant numerical viscosity. As a result, the solution of problems involving, for example, propagating waves with a multitude of minima and maxima, may require the use of a very detailed grid.

In contrast to this, ENO (essentially non-oscillatory) schemes preserve the order of accuracy on smooth extremes of the solution. The basic idea underlying them is quite simple. To avoid interpolation through discontinuities, one of the possible patterns selects one on which the solution is the smoothest. As the indicator of smoothness, the values of the separated differences of the corresponding order are used.

A nonlinear quasi-monotone compact-polynomial difference scheme of higher order of accuracy is developed and implemented. The distribution $Y(\xi)$ of the gasdynamic parameters, which is "restored" within the computational cell, is based on a polynomial of the 7th degree. The main part of the polynomial (the first two terms) is determined in a separate way. It is determined on the basis of the Lagrange-Burmann expansion near discontinuities. It is possible to construct formulas of the necessary order for the reconstruction of gas-dynamic quantities on the faces of cells from the values of their average values.

REFERENCES

[1] *Sivkov A., Saygash A., Kolganova J., Shenenkov I.* // IOP Conference Series: Materials Science and Engineering. – 2014. - Vol. 66, Issue 1. – 012048.
[2] *Kuzenov V.V., Ryzhkov S.V.* // Problems of Atomic Science and Technology. – 2013. – No. 4 (86). – P. 103-107.
[3] *Kuzenov V.V., Ryzhkov S.V.* // Bulletin of the Russian Academy of Sciences. Physics. – 2016. – Vol. 80, No. 5. – P. 598–602.
[4] *Ryzhkov S.V.* // Plasma Physics Reports. – 2011. – Vol. 37. – P. 1075–1081.
[5] *Kuzenov V.V., Ryzhkov S.V.* // Journal of Physics: Conference Series. – 2017. – V. 815. – P. 012024.
[6] *Kuzenov V.V., Ryzhkov S.V.* // Mathematical Models and Computer Simulations. – 2018. – Vol. 10, No. 2. – P. 255–264.
[7] *Kuzenov V.V.* // Physics of Atomic Nuclei. – 2017. – V. 80, No. 11. – P. 1683–1686.
[8] *Kuzenov V.V., Polozova T.N., Ryzhkov S.V.* // Problems of Atomic Science and Technology. – 2015. – No. 4 (98). – P. 49-52.
[9] *Kuzenov V.V., Ryzhkov S.V.* // Problems of Atomic Science and Technology. – 2013. – No. 1 (83). – P. 12-14.
[10] *Kuzenov V.V., Ryzhkov S.V.* // Journal of Physics: Conference Series. – 2017. – V. 830. – P. 012124.
[11] *Kuzenov V.V., Ryzhkov S.V., Frolko P.A.* // Journal of Physics: Conference Series. – 2017. – V. 830. – P. 012049.
[12] *Sivkov A., Ivashutenko A., Shanenkova Y., Shanenkov I.* // Advanced Powder Technology. – 2016. – Vol. 27. – P. 1506-1513.
[13] *Sivkov A., Shanenkova Y., Saigash A., Shanenkov I.* // Surface and Coatings Technology. – 2016. – Vol. 292. – P. 63-67.

[1] This work was supported by the Ministry of Education and Science of the Russian Federation (Project No. 13.5240.2017/8.9)

PLASMA CHANNEL PARAMETERS IN HIGH-PRESSURE HYDROGEN[1]

M.E. PINCHUK, A.A. BOGOMAZ, A.V. BUDIN, A.G.LEKS, N.K. KURAKINA, A.A POZUBENKOV

[*]Institute for Electrophysics and Electric Power of Russian Academy of Sciences, Dvortsovaya nab., 18, St.-Petersburg, 191186, Russia

Based on x-ray [1,2], optic [3] and contact [3,4] diagnostics the plasma channel parameters of discharge at dense hydrogen were considered. The discharge with current up to 2 MA and current rise rate ~10^{10} A/s at pressure up to 30 MPa were researched. A physic mechanisms of most deep channel contraction on current rise stage of the discharge and oscillations of discharge channel radius were suggested.

Soft X-ray radiation radiation were registered for discharge with current amplitude of 1200 kA at initial hydrogen pressure of 5 and 7 MPa. Near current maximum the fluctuations of SRX from the channel have been registered. Estimations of such oscillations were made. Speed of current channel contraction, channel radius and its oscillation amplitude for current amplitude of 500-1200 kA were measured by magnetic probe with coordination with optic photostreaks.

The electric field strength in discharge channel and near electrode voltage drops were determined by comparison of channel radius oscillations with synchronous voltage changing. Satisfactory agreement for the estimations was received. Oscillation amplitudes are needed for calculation of X-ray intensity modulation. Channel plasma parameters were determined for maximal contraction moment.

REFERENCES

[1] A.A. Bogomaz, A.V. Budin, V.V. Zabrodskii, I.V. Kuznetsova, S.Yu. Losev, M.V. Petrenko, M.E. Pinchuk and Ph.G. Rutberg. // Instruments and Experimental Techniques. 2008. Vol. 51. No. 5, pp. 744–747. DOI: 10.1134/S0020441208050163

[2] M.E. Pinchuk, A.A. Bogomaz, A.V. Budin, L.A. Shirochin, M.A. Polyakov, A.G. Leks, S.Yu. Losev, Ph.G. Rutberg. // Instruments and Experimental Techniques. 2010. Vol. 53. No. 5. pp. 723–727. DOI 10.1134/S0020441210050192

[3] *A.A. Bogomaz, M.E. Pinchuk, A.V. Budin, A.G. Leks, V.V. Leont'ev, A.A. Pozubenkov, N.K. Kurakina. //* Journal of Physics: Conference series, 2016, v.774, n1, p.012186, DOI: 10.1088/1742-6596/774/1/012186.

[4] *M.E. Pinchuk, A.V. Budin, V.V. Leontev, A.G. Leks, A.A. Bogomaz, Ph.G. Rutberg, A.A. Pozubenkov. //* Izvestiya Vuzov. Fizika. 2014, Vol. 57, No. 12-2, pp. 240-244.

1 The work was performed under the Program of Fundamental Researches of the Presidium of the Russian Academy of Sciences n31 "FUNDAMENTAL RESEARCHES OF PHYSICAL AND TECHNICAL PROBLEMS OF ENERGY DEVELOPMENT"".

THE SLOW RELAXATION OF NON-EQUILIBRIUM STATE IN METAL TARGET EXITED BE PICOSECOND ELECTRON BEAM: INTERFEROMETRIC AND SIMULATION STUDIES [1]

S.V. BARAKHVOSTOV, A.I. LIPCHAK*, N.B. VOLKOV*, V.P. TARAKANOV**, S.I. TKACHENKO***, I.S. TURMYSHEV*, A.P. YALOVETS****.*

**Institute of Electrophysics UB RAS, 106 Amundsen Street, Yekaterinburg, 620016, Russia, nbv@iep.uran.ru, +7(343)2678660*
***Join Institute of High Temperatures RAS, 13/19 Izhorskaya Street, Moscow, 125412, Russia*
****Moscow Institute of Physics and Technology (state university), 9 Institute Lane, Dolgoprudny Moscow Region, 141701, Russia*
*****South Ural State University, 76 Lenin Avenue, Chelyabinsk, 454080, Russia*

Intensive picosecond e-beams are an interesting and promising tool for studying fast nonlinear processes in metals [1]. The aim of the work is to study both experimentally and theoretically a long-time (slow) relaxation processes in a metal targets after picosecond e-beams exposure. The experiments were carried out on EXCITOR experimental setup [2, 3]. It was designed on the basis of “RADAN 300- 303” a compact high voltage generator with double-pulse-forming line and resonant Tesla transformer [4]. The coaxial line with impedance $Z_{w\_}$= 50 Ω along with adjustable peaking and chopping discharge gaps filled with nitrogen at pressure of 40 atm were used to sharp and to short generator voltage pulses. E-beam was formed in a vacuum chamber at pressure of 10^{-4} Torr. A cone copper cathode having sharpen edge with radius of 2 mm was used in the experiments. A copper plates with thickness (d) of 0.1 and 3 mm were used as anode; one its surface was mirror like. The gap between cathode and anode equal to 2 mm was used in all experiments. It corresponds to e-beam current maximum amplitude after passing through two copper foils with a total thickness of 36 μm for the voltage amplitude of e-beam pulse equal U_{peak} = - (142±2) kV with duration $FWHM_U$ = (416±16) ps. The following parameters of the beam current pulse recorded by current collector based on Z_w = 50 Ω impedance Faraday cup were obtained: I_{peak} = - (13.85±0.55) A, $FWHM_I$ = 198±6 ps. The beam parameters at the front side of the anode equal to: $I_{peak}^{(calc)}$= - 175 A and $FWHM_I^{(calc)}$ = 321 ps were reconstructed using the electromagnetic relativistic PIC code KARAT [5] which used geometry of the interelectrode gap and the current collector corresponded to the experimental one. The maximum value of the mean electron energy is equal to $<W>^{(calc)}$ = 213.73±6.54 keV in this case.

Slow relaxation of non-equilibrium state in metal target exited be picosecond electron was investigated on experimental setup using interferometer displacement technique. The displacement of the mirror surface of the target (anode) back side under the influence of e-beam excited wave processes in the target was obtained by recording system based on Michelson's interferometer. It was established that the displacement of the back surface of the anode with a thickness d = 0.1 mm (1) begins with a time delay t_d = 0.22 ± 0.03 μs and for d = 3 mm (2) with a delay time t_d = 1.4 μs. The back surface of the anode shifted by $\Delta x \approx 1.3$ μm at t = 15 μs (d = 0.1 mm thick) and by $\Delta x \approx 1.26$ μm at t = 75 μs (d = 3 mm). Simulation of the slow dynamics of metal excited by an e-beam with the characteristics mentioned above was carried out using the BETAIN2 software package [6] in the approximation of elastic and plastic continuous media. This was done to analyze the physical mechanisms of slow relaxation of a non-equilibrium metal state excited by the picosecond e-beam. The results of the simulation are qualitatively and quantitatively consistent with experimental one. The spatial fields of tensions, deformations and temperatures were calculated. Comparison of the experimental and numerical results allows one to conclude that weak non-linear wave processes in metal are responsible for the slow relaxation of the non-equilibrium state excited by the picosecond e-beam.

REFERENCES

[1] *N.B. Volkov, N.D. Kundikova, A.Ya. Leivi, et al //* Techn. Phys. Lett. – 2007. – V. 33. – No 1. P. 69-72.
[2] *K.A. Nagayev, S.V. Barakhvostov, I.L. Muzyukin, et al //* Izv. vuzov Fizika. – 2014. – V. 57. – No 11/3. P. 96-99.
[3] *S.V. Barakhvostov, N.B. Volkov, K.A. Nagayev, et al //* in XIII Zababakhin Scientific Talks (International Conference March 20-24, 2017, Snezhinsk, Russia). Abstracts. – 2017. P. 114-115.
[4] *G.A. Mesyats, M.I. Yalandin //* Phys. Usp. – 2005. – V. 48. – P. 211-229.
[5] *V.P. Tarakanov //* User’s Manual for code KARAT. – Springfield, VA: Berkley Research Associates, Inc., 1992.
[6] *A.P. Yalovets, N.B. Volkov, V.S. Krasnikov, et al //* in Proc. 10th Int. Conf. on Modification of Materials with Particle Beams and Plasma Flows. – 2010. P. 221-227

[1] This work carried out within the state order No 0389-2015-0023 and under the partial financial support from Russian Foundation for Basic Research (grant No 16-08-00466).

STRUCTURAL CHANGES AND PECULIARITIES OF SODIUM MELTING CURVE AT HIGH PRESSURES[1]

N.B. VOLKOV, E.A. CHINGINA**

**Institute of Electrophysics UB RAS, 106 Amundsen Street, Yekaterinburg, 620016, Russia, nbv@iep.uran.ru, +7(343)2678660*

The melting curve of sodium has temperature maximum (T_m = 1000 K with P=28.3 GPa) was found experimentally with use Bridgman diamond anvils cells [1, 2]. In pressure range of 28.3 < P < 100 GPa the melting point of T_m decreases to ambient temperature. Analyzing deciphered information of sodium difractograms, authors [2, 3 concluded that there is metal structural transition at pressure increasing. Thus, in pressure range of 65 < P< 80 GPa, there is a transition from bcc to fcc structure, and sodium has the fcc structure at pressures 80 < P < 100 GPa. On the basis of the experimental data of shock-wave compression sodium [4], it is possible to conclude structural transitions have no effect on the form of adiabatic curve. This conclusion refers to the pressure ranges, corresponding to the conditions of the experiments [1-3]. The single-phase sodium phenomenological equation of state (EOS), we offered in [5], considers a lattice anharmonicity. This EOS describes the adiabatic curve with a high precision both in solid and in liquid state of sodium. In our work [6], within two-phase approach for the description of liquid state we use cluster model, and for the description of sodium solid state we use the EOS from [5]. According to the cluster model, the local structure of liquid sodium consists of large and small clusters near the melting curve. Large clusters have a structure close to structure of solid sodium near the melting curve. Small clusters are monatomic and are concentrated near the cluster bounds. Using this approach, we obtained the agreement of theoretical and experimental data of the melting curve with a reasonable degree of accuracy in the pressure range $0 \le P \le 20$ GPa [7]. The purpose of the offered work is to discuss an importance of structural transitions of sodium in formation of the melting curve features near the maximum and on the site with $dT_m/dP<0$.

As the main method, as in [7], we use the computing experiment produced by the LmtART 7 software package [8]. The dynamics of a lattice was computed using a linear response method within a well-known density functional theory. We use both single-phase approach – a well-known Lindeman criterion, and two-phase approach to obtain a melting curve. Within two-phase approach the polycluster model for the description of the structure of liquid sodium, similar to a model offered A.S. Bakai [9] for the description of amorphous solids is used.

REFERENCES

[1] *E. Gregoryanz, and et al //* Phys. Rev. Lett. – 2005. – V. 94. – No 18. Art. No 185502.
[2] *E. Gregoryanz, and et al //*Science. – 2008. – V. 320. – P. 1054-1057.
[3] *C.L. Guillaume, and et al //* Nature Physics. – 2017. – V. 7. - P. 211-214.
[4] *A.A. Bakanova, I.P. Dudoladov, and R.F. Trunin //* Sov. Phys. Solid State. – 1965. – V. 7. – P. 1307.
[5] *N.B. Volkov and E.A. Chingina //* Izv. vuzov Fizika. – 2014. – V. 57. – No. 12/2. P. 146-151.
[6] *N.B. Volkov and E.A. Chingina //* J. Phys: Conf. Series. – 2015. – V. 653. – Art. No 012084.
[7] *N.B. Volkov and E.A. Chingina //* J. Phys: Conf. Series. – 2017. – V. 830. – Art. No 012036.
[8] *S.Y. Savrasov //* Phys. Rev. B. – 1996. – V. 54. – No 23. P. 16470-16486; Program LMTART for electronic structure calculations. // Reprint cond-mat/0409705. – 2004.
[9] *A.S. Bakai //* Polycluster Amorphous Solids. – Moscow: Energoatomizdat, 1987.

[1] This work carried out within the state order No 0389-2015-0023 and under the partial financial support from Russian Foundation for Basic Research (grant No 16-08-00466).

ULTRAFAST SKIN LAYER EXPLOSION AT SURFACE MAGNETIC FIELD RISE RATES OF MORE THAN 4 MG/NS[1]

S.A. SOROKIN

Institute of High Current Electronics SB RAS, 2/3 Akademichesky Ave., Tomsk 634055, Russia, s.sorokin@rambler.ru, +7(3822)491617

The results of experiments on the ultrafast explosion of the skin layer of a metallic conductor are presented at a rise rate of the magnetic field at its surface more than 4 MG/ns. Conducting rods with radii of 0.5-1.0 mm are driven with 2 MA current of the high-current generator. Plasma with density 10^{16}-10^{17} cm^{-3} is preliminarily injected in the area of the rod load using a set of radial plasma guns. The $\boldsymbol{J}\times\boldsymbol{B}$ force sweep up the injected plasma along the rod. The plasma motion velocity at the rod surface is close to the Alfvén velocity and the rise time of the magnetic field on the surface of the rod can be estimated as the plasma current skin depth divided by the Alfvén velocity. The estimated surface magnetic field rise rates are more than 4 MG/ns. At this rise rate of the magnetic field, the surface explodes in a subnanosecond time in the regime of a high surface energy factor. The dense plasma of the surface is heated to a temperature of about 100 eV or more, generating a short pulse of soft x-ray radiation.

[1] This work was supported by the Russian Foundation for Basic Researches, project no. 18-08-00155.

RESEARCH OF NEAR ELECTRODE PHENOMENA AT ELECTROLYTE DISCHARGE

D.L. KIRKO*

*National Research Nuclear University MEPhI, Kashirskoe sh., 31, Moscow, 115409 Russia,
E-mail: dlkirko@mephi.ru, phone: +7(495)7885699-9813

Discharge in the electrolyte is accompanied by the appearance of a glow near the electrodes in the presence of a current in a fluid medium [1,2]. The existence of these discharges is associated with the appearance of various electric oscillations [1-4]. These discharges are used to modify the surfaces of materials and a polish of metal surfaces with a complex shape. It is of interest to study the effect of a discharge influence at the microrelief of a metal surface.

In this research for the experiments we used dielectric vessels with volume 100-400 cm^3 and electrolytes based on sodium carbonate, sodium hydroxide and potassium hydroxide. As a cathode rods of tungsten and titanium with diameter 1-3 mm were used, and a anode was made by stainless steel and molybdenum plates 0.1-0.5 mm thick. A full-wave rectifier with voltage 0-250 V and frequency of 100 Hz was selected for the power supply. The volt-ampere characteristics of the discharge for the electrolytes used in the electrolyte concentration range C=0.05-0.8 M (Na_2CO_3 concentration C=1 M: 106 g per 1 liter of distilled water) were obtained in the work. A research was made of the nature of the vibrational processes depending on the electrolyte used. For each electrolyte the most characteristic frequencies were obtained and spectra of electric oscillations in the range 10 kHz-150 MHz were constructed. The noise components of the oscillations in the range 100-400 kHz were studied in more detail. The generation of these oscillations can be associated with the appearance of electron cyclotron and ion cyclotron plasma waves in the discharge plasma at characteristic wavelengths in the region λ=1-40 mm.

The possible relationship between the recorded oscillation frequencies and break-down phenomena in the near-cathode region of the discharge was researched. The spark break-down model of an electrolyte medium containing gas bubbles is a more likely mechanism. With this process it is possible to generate electric oscillations with characteristic frequencies ν=1-50 MHz. At discharge currents in the range 0.5-1.5 A a strong heating of the liquid occurs and the formation of intense convective currents was observed. When approaching the maximum current, the motion of the plasma becomes turbulent. Due to the use of an external magnetic field 10-300 G plasma fluxes acquire a rotational velocity component.

The effect of discharge plasma influence at the surface microrelief of electrodes was made in the work. The surface of the electrodes was examined with the help of electron microscopes. On the surface of titanium cathodes objects with a shape close to spherical form with sizes of 3-40 μm and smaller irregularly formations with sizes 0.1-2 μm are observed. The elemental composition of the surface of the electrodes was investigated. As a result of the thermal action of the discharge plasma it seems that the process of titanium oxidation on the cathode surface and the formation of titanium dioxide microspheres are possible. At the same time, on the surface areas with a microporous structure with characteristic pore sizes in the range 0.2-1 μm are presented.

REFERENCES

[1] *Al.F. Gaisin, R.T. Nasibullin //* Plasma Phys. Rep. – 2011. – Volume **37**. – pp.896-903.
[2] *F.M. Kanarev //* Low temperature electrolysis of water. – Krasnodarsk Univ., Krasnodar, 2010.
[3] *D.L. Kirko, A.S. Savelov, I.V. Vizgalov* // Russian Physics Journal. – 2013. – Volume **55**. – №11, – pp.1243-1247.
[4] *D.L. Kirko //* Technical Physics. – 2015. – Volume **60**. – №4. – pp.505-509.

DELAYED PLASMA FORMATION ON TITANIUM OR ZIRCONIUM–COATED COPPER OR DURALUMIN CONDUCTORS[1]

I.M. DATSKO, N.A. LABETSKAYA*, S.A. CHAIKOVSKY**, D.V. RYBKA*, V.A. VANKEVICH**

**Institute of High Current Electronics SB RAS, 2/3 Akademichesky Av., Tomsk, 634055, Russia*
***Institute of Electrophysics UD RAS, 106 Amundsen St., Ekaterinburg, 620016, Russia*
datsko@ovpe.hcei.tsc.ru, (3822) 491-677

Studies of a skin explosion of homogeneous and double-layer cylindrical copper and duralumin conductors with the titanium or zirconium coatings were carried out. Titanium and zirconium conductivity and their sublimation energy density have similar values, but the zirconium ion mass is twice the titanium ion mass.

The experiments were carried out on a terawatt high-current MIG generator with the current amplitude up to 2.5 MA and the current rise time of 100 ns. The formation of plasma on the surface of the conductor were recorded with a four-frame optical camera with an exposure time of 3 ns. The internal structure of plasma at the conductor surface formed during the electrical explosion was studied with the X-ray radiography. The X-ray radiograph was based on the use of the X-pinch with $h\nu > 0.8$ keV at exposure 2 - 3 ns.

It was shown that a delays of the plasma formation on the surface of copper and duralumin conductors with a sprayed zirconium or titanium layer are comparable to each other. In the experiments we used copper conductors with a conductivity ratio of a homogeneous conductor and a sprayed layer of 26-27. The conductivity ratio of a homogeneous duralumin conductor and sputtering was 8.2 and 8.5 for Zr and Ti, respectively. In the presence of the magnetic field up to 300 T, the plasma formation on the surface of the double-layer conductors starts 400 ns later in comparison with a copper conductor and 250 ns later in comparison with a duralumin conductor. As the magnetic field increases up to 350-400 T, the delay in plasma formation decreases to 35 ns. A significant difference in the expansion velocities of the Ti and Zr surface plasmas of the double-layer conductors was not observed.

Thus, the delay in plasma formation is determined by the conductivity ratio of the main and the sprayed material at close values of the energy density sublimation of the latter. The expansion velocity of the near-sprayed layer plasma weakly depends on an ion mass of the sprayed material. This fact indirectly confirms the calculated data pointing out that the current density through sprayed material is insufficient for ohmic heating up to the explosion. Apparently this can be explained with the location of the maximum current density inside the main conductor with higher conductivity.

[1] This work was supported by the Russian Foundation for Basic Research (grants № 16-08-00658 and № 18-08-00728) and Program for Basic Research of the Presidium of RAS (PBR RAS) "Fundamentals of pulsed high-current emission electronics"

OPTIMIZATION OF DOUBLE SHELL NEON GAS-PUFF WITH OUTER PLASMA SHELL FOR EFFICIENT GENERATION OF K-SHELL RADIATION[1]

R.K. CHERDIZOV, F.I. FURSOV, V.A. KOKSHENEV, N.E. KURMAEV, N.A. LABETSKAYA, A.V. SHISHLOV

Institute of High Current Electronics SB RAS, 2/3 Akademichesky Ave., Tomsk, 634055, Russia
E-mail: rustam.k.cherdizov@gmail.com

Studies of Z-pinch plasma as a soft X-ray source were carried out on the GIT-12 generator (4.7 MA, 1.7 μs) in the IHCE SB RAS, Tomsk [1]. The main purpose of the research was optimization of load parameters for efficient generation of the neon K-shell radiation in the microsecond implosion regime. A new type of a Z-pinch load, a gas-puff with an outer plasma shell, was tested. An electromagnetic valve with separate inside volumes formed a gas-puff consisting of an annular outer shell and an inner central jet. In the experiments, the diameter of the annular shell was 80 mm or 100 mm, and the diameter of the inner jet was 20 mm. The outer plasma shell was generated by 48 plasma guns located at the diameter of 350 mm. The radiative characteristics of the neon plasma were obtained at varying initial load parameters - the gas-puff mass and the gas injection time. At optimized load parameters, the neon K-shell yield exceeded 14 kJ/cm, and the K-shell radiation power reached 1 TW/cm at the peak implosion current of 3.5-3.6 MA. In comparison with the triple neon gas-puff [2], the radiation yield increased by 20%, and the radiation power grew more than 2.5 times. Thus, a gas-puff with an outer plasma shell can be considered as a promising load for generation of the K-shell radiation of high-Z materials at the microsecond implosion regime, since the conducted experiments have demonstrated its higher efficiency compared to the traditional gas-puff loads.

REFERENCES

[1] *A.V. Shishlov, R.K. Cherdizov, F.I. Fursov, V.A. Kokshenev, N.E. Kurmaev, A.Yu. Labetsky* // Russian Physics Journal. – 2016. – Volume 59, Issue 9/3. – Pages 160-163.

[2] *A.V. Shishlov, R.B. Baksht, S.A. Chaikovsky, et al.* // Plasma Devices Oper. – 2005. – Volume 13, Issue 2. – Pages 81-85.

[1] This work was supported by RFBR Grant # 18-08-01132-a

Z-PINCH IMPLOSION SIMULATIONS: SINGLE AND NESTED WIRE ARRAYS AT ANGARA-5-1 [1]

O. G. OLKHOVSKAYA , V. A. GASILOV, P. V. SASOROV

Keldysh Institute of Applied Mathematics (Russian Academy of Sciences), Miusskaya sq., 4
Moscow, 125047, Russia, email: olkhovsk@gmail.com, tel.: +7 499 2207224

Multiwire array implosion is simulated in a series of numerical experiments with 3D models carried out by means of RMHD code MARPLE-3D (Keldysh Institute of Applied Mathematics). The aim is to explore plasma instabilities arising at the plasma ablation ending and developing up to the final stage of the wire array implosion. Different configurations of wire arrays are investigated. Cylindrical and quasispherical wire arrays were studied, as well as single and nested array designs are considered. Plasma emission is reproduced via prolonged plasma ablation model including spatial nonuniformity of plasma production rate consistent with experimental X-ray images of lower plasma emission areas. The distinction of wires in nested arrays is implemented.

The numerical results are compared with the experimental data obtained at Angara-5-1 facility (TRINITI, Troitsk). The qualitative and quantitative agreement of the simulation results with experimental data [1, 2] and theoretical estimates [3] is shown.

It is demonstrated that dedicated design of the electrodes, the wire array, and the mass distribution along the wires results in very compact spherical bright radiation source in the centre of the array. The use of quasi-spherical arrays, nested arrays, conical insertions on electrodes, profiling of the linear mass of wires makes it possible to create a compact SXR source with a high power density. Linear mass distribution $m(\theta) \sim 1/\sin^2(\theta)$ (where θ is the poloidal angle) along the length of the wires in a quasi-spherical array provides the increase in the radiation power density by a factor of ~ 3 as compared to quasi-spherical compression without mass profiling, and by almost 7.5 times in comparison with the cylindrical array.

Two-cascade nested array design allows a stable compact compression. Between the cascades a shock wave is formed, which damps the inhomogeneities of the plasma jets. The effect is also observed when the external and internal cascades are of the same material. The decrease in the trailing mass is more significant in the case of a quasi-spherical array.

The formation of magnetic flux breakthroughs during wire array implosion is also reproduced, and preconditions for a tearing instability forthcoming are detected.

Our further plans include:

• Full-scale wire array modeling in order to investigate the development of tearing instability due to the axial inhomogeneity of plasma formation and the breakthrough of magnetic flux into the wire array interior. This study requires computations on extra fine meshes in order to reproduce essentially different-scale processes (the formation of "magnetic bubbles", etc.).

• Modeling of mixed arrays, including polymer filaments and porous materials.

REFERENCES

[1] *Mitrofanov K.N., Aleksandrov V.V., Gritsuk A.N., Grabovski E.V., Frolov I.N., Laukhin Y.N., Oleinik G.M., Ol'khovskaya O.G. // Plasma Physics Reports.* – 2016. – Volume 42. – № 9. Pages 834-858.

[2] *Mitrofanov K.N., Aleksandrov V.V., Grabovski E.V., Ptichkina E.A., Gritsuk A.N., Frolov I.N., Laukhin Y.N.Plasma Physics // Plasma Physics Reports.* – 2014. – Volume 40. – № 9. Pages 679-704.

[3] *P. Sasorov // 6th Intern. Conf. on Dense Z-Pinches. AIP Conf. Proc. – 2006. – Volume 808. – Page. 81.*

[1] This work was supported by RFBR grant 16-02-00112-a. The computations were carried out using the equipment of the shared research facilities of HPC computing resources at Lomonosov Moscow State University, supercomputers MVS-100K/MVS-10P at Joint Supercomputer Center of the Russian Academy of Sciences (JSCC RAS), and supercomputers K100/K60 at KIAM RAS.

VOLT-AMPERE CHARACTERISTICS OF HIGH-FREQUENCY ARC DISCHARGE. DEVELOPMENT OF THE GENERALIZED EQUATION IN THE CRITERION FORM.

A.F. KOKORIN

40 let komsomola 32a-41, Yekaterinburg, 620072, RF, a.f.kokorin@urfu.ru, +79089099061

Methods of similarity theory are currently developed in relation to the analysis of arc discharges constant current and industrial frequency current. But, as it was shown in work /1/, the high-frequency arc discharge at high pressures has much in common with the constant current arc discharges. Dependencies resolved with respect to certain values, for example, dimensionless voltage, thermal efficiency, etc., allow to make calculations related to the design of plasma torches with fairly good accuracy.

When using the methods of similarity theory, it is necessary to comply with a number of requirements, the most important of which are as follows: the discharge is carried out in geometrically similar plasmatrons; the power supply conditions are the same; the gas temperatures at the entrance to the discharge chamber are not significantly different; the temperature of the walls and electrodes inside the discharge chamber are the same; the conditions of kinematic similarity are fulfilled.

Criteria of similarity and dimensionless numbers from the substitution in the equations of dimensional variables describing the processes in the discharge, dimensionless variables. Replace the produce division of variables on scale factors /2/. The criteria can be combined to produce new ones. Using dimensionless criteria is inconvenient, since scale factors are not always possible to choose. Therefore, they move to dimension complexes when all scale factors are taken out and included in the total scale factor. This total coefficient is determined from the analysis of a large number of experimental data.

As a rule, the criteria dependences are chosen as the product of the degrees of the criteria numbers.

In this work, we used the following criteria numbers: the criteria of arc voltage; energy criterion; Reynolds number; Knudsen number; criterion arc length.

Presentation of experimental data was carried out by the formula:

$$\frac{Ud}{I} = A\left(\frac{I^2}{Gd}\right)^{\alpha}\left(\frac{L}{d}\right)^{\beta}(pd)^{\gamma}$$

where: A-the size factor constant for the considered range of parameters changes;

d - the diameter of the discharge tube.

To determine the coefficient A and power indices α, β, γ, the data on 92 experiments were approximated by the equation:

$$\ell n\left(\frac{Ud}{I}\right) = \ell nA + \alpha \ell n\left(\frac{I^2}{Gd}\right) + \beta \ell n\left(\frac{L}{d}\right) + \gamma \ell n(pd)$$

The correlation analysis was carried out for the experimental data and the equation of volt-ampere characteristics of high-frequency arc discharge was obtained:

$$U = 1484 I^{-0,44} G^{0,72} d^{-0,45} p^{-0,17}$$

where: U-voltage; I - the discharge current, G - the air flow; d - the diameter of the discharge channel; h - the gas pressure.

The value of the relative standard deviation of the experimental data from the regression line in the range of discharge parameters: discharge current (1,2-16)A, air flow (1,7 - 4,6)10^{-3} kg/s, pressure (10^5 - 10^7)Pa, discharge tube diameters (9-20) 10^{-3}m, was in the range(20-25)%.

[1] *Kokorin// Izv.vuzov Physics.- 2014.- № 3/2. – S. 138-141.*

[2] *Principles of calculatton of linear-circuit plasma generators//Edited by M.F.Zhukov. – 1979. – S.148.*

REQUIREMENTS TO SPRAYED COATINGS FOR DELAYING OF PLASMA-FORMATION AT SURFACE ELECTRIC EXPLOSION OF DOUBLE-LAYER CONDUCTORS [1]

N.A. LABETSKAYA, D.V. RYBKA*, I.M. DATSKO*, V.A. VANKEVICH*, S.A. CHAIKOVSKY***

**Institute of High Current Electronics SB RAS, 2/3 Akademichesky Av., Tomsk, 634055, Russia*
***Institute of Electrophysics UD RAS, 106 Amundsen St., Ekaterinburg, 620016, Russia*
natalia@ovpe2.hcei.tsc.ru, (3822) 491-677

A skin electrical explosion results in the plasma formation on a conductor surface. In some cases, it is an undesirable effect, for example, from the point of view of magnetic isolation of vacuum transmission lines. Methods for delaying plasma formation were proposed in [1]. The report discusses issues related to the delay in the onset of plasma formation in the process of the surface electrical explosion of homogeneous and double-layer conductors in magnetic fields with an induction of 200-400 T.

The report presents experimental data obtained on the MIG facility [2] (current amplitude up to 2.5 MA, current rise time ~ 100 ns) about electric explosion of conductors made of copper, aluminum, duralumin D16T, steel 3, and stainless steel 12X18H10T. The conductors were coated half-length by materials with a higher specific resistivity (titanium, zirconium, molybdenum, and bismuth). The coatings with a thickness up to 100 μm were deposited by vacuum evaporation [3, 4]. Dielectric coatings from zirconium oxide were also used. The capability to delay the onset of plasma formation on the surface of copper, duralumin, and aluminum conductors coated with titanium or zirconium under a magnetic field induction up to 400 T was shown experimentally. The criteria for selection of coating materials, which allow realization of a significant delay in plasma formation under the indicated experimental conditions, are proposed.

REFERENCES

[1] *G.A. Shneerson // JETP Letters. – 1992. – V.18. – №6. Pp.18-21.*
[2] *A.V. Luchinskii, N.A. Ratakhin, V.F. Fedushchak, A.N. Shepelev // Rus. Phys. Jour. – 1997. – Vol.40. – №12. Pp. 1178-1184.*
[3] *N.N. Koval, Yu.F. Ivanov, I.V. Lopatin, Yu.H. Akhmadeev, V.V. Shugurov, O.V. Krysina, V.V. Denisov // Russian Journal of General Chemistry. – 2015. – №85. Pp. 1326-1338.*
[4] *A.A. Solov'ev, N.S. Sochugov, K.V. Oskomov, S.V. Rabotkin // Plasma Physics Reports. – 2009. – Vol.35. – №5. Pp. 399-408.*

[1] This work was supported by Russian Foundation for Basic Research, grant № 16-08-00658.

STUDY OF INTERACTION OF PULSED JETS GENERATED BY ATMOSPHERIC DISCHARGE [1]

*V.V. KUZENOV**, S.V. RYZHKOV*, K.V. POLYAKOV**

**Bauman Moscow State Technical University, 2 Baumanskaya Street, 5, 1, Moscow, 105005, Russia, E-mail: svryzhkov@bmstu.ru, +7(499)263-65-70*
***N.L. Dukhov All-Russian Research Institute of Automatics, Sushchevskaya Street, 22, Moscow, 127055, Russia*

Despite the importance of pulsed plasma jets for different applications (nuclear fusion, propulsion, neutron generator and ion source), the effect of multiple-jet interactions remains poorly understood. Numerical simulation for interaction of pulsed plasma jets generated by atmospheric capillary discharge [1-13] is presented.

The plasma source is based on a plasma jet established at the end of a capillary discharge at atmospheric pressure. Interaction between the pulsed plasma jets and the shock wave/contact boundary layer is analyzed. Regimes of plasma jet outflow of capillary discharge with evaporating wall are modeled. Note that the plasma jet for magneto-inertial fusion must be created in a vacuum environment. Preliminary results on a pulsed capillary discharge are presented. Main properties of capillary discharge plasma are discussed.

A capillary discharge with an evaporating wall, namely array of pulsed plasma jets is considered. The structure of an underexpanded supersonic jet that expires from the plasma channel of the capillary discharge with an evaporating wall is investigated. The turbulent viscosity and thermal conductivity coefficients are calculated using the equations of the Coakley model. Numerical simulation is performed and spatial distributions of plasma pressure, and temperature for an array of three pulsed plasma jets at different moments of time are obtained.

The gas dynamics of interaction of three pulsed jets, created by a capillary discharge with evaporating wall is considered. The jet-to-jet interaction, the geometric parameters of the jet array, and the effect of Mach number are investigated. The radiation and gas dynamic processes occurring in an array of plasma jets that expire into the space are numerically investigated. High-order compact finite differences are applied and gas dynamic calculations are performed. A two-dimensional radiation magnetogasdynamics code is used to investigate the characteristics of capillary discharge channel for 1-4 jets. All the main gas-dynamic and radiative parameters of the jet array have been calculated.

REFERENCES

[1] *Sivkov A., Saygash A., Kolganova J., Shanenkov I.* // IOP Conference Series: Materials Science and Engineering. – 2014. - Vol. 66, Issue 1. – 012048.
[2] *Kuzenov V.V., Ryzhkov S.V.* // Problems of Atomic Science and Technology. – 2013. – No. 4 (86). – P. 103-107.
[3] *Kuzenov V.V., Ryzhkov S.V.* // Bulletin of the Russian Academy of Sciences. Physics. – 2016. – Vol. 80, No. 5. – P. 598–602.
[4] *Ryzhkov S.V.* // Plasma Physics Reports. – 2011. – Vol. 37. – P. 1075–1081.
[5] *Kuzenov V.V., Ryzhkov S.V.* // Journal of Physics: Conference Series. – 2017. – V. 815. – P. 012024.
[6] *Kuzenov V.V., Ryzhkov S.V.* // Mathematical Models and Computer Simulations. – 2018. – Vol. 10, No. 2. – P. 255–264.
[7] *Kuzenov V.V.* // Physics of Atomic Nuclei. – 2017. – V. 80, No. 11. – P. 1683–1686.
[8] *Kuzenov V.V., Polozova T.N., Ryzhkov S.V.* // Problems of Atomic Science and Technology. – 2015. – No. 4 (98). – P. 49-52.
[9] *Kuzenov V.V., Ryzhkov S.V.* // Problems of Atomic Science and Technology. – 2013. – No. 1 (83). – P. 12-14.
[10] *Kuzenov V.V., Ryzhkov S.V.* // Journal of Physics: Conference Series. – 2017. – V. 830. – P. 012124.
[11] *Kuzenov V.V., Ryzhkov S.V., Frolko P.A.* // Journal of Physics: Conference Series. – 2017. – V. 830. – P. 012049.
[12] *Sivkov A., Ivashutenko A., Shanenkova Y., Shanenkov I.* // Advanced Powder Technology. – 2016. – Vol. 27. – P. 1506-1513.
[13] *Sivkov A., Shanenkova Y., Saigash A., Shanenkov I.* // Surface and Coatings Technology. – 2016. – Vol. 292. – P. 63-67.

[1] This work was supported by the Ministry of Education and Science of the Russian Federation (Project No. 13.5240.2017/8.9)

X-RAY SOURCES ON THE BASE OF X- AND PZ-PINCHES[1]

A.P. ARTYOMOV, A.G. ROUSSKIKH*, V.I. ORESHKIN*,**, S.A. CHAIKOVSKY*,***, A.S. ZHIGALIN*, A.V. FEDUNIN**

**Institute of High Current Electronics SB RAS, 2/3 Akademichesky Ave., Tomsk, 634033, Russia, aap545@gmail.com,*
***National Research Tomsk Polytechnic University, Tomsk, Russia*
****Institute of Electrophysics, Ural Branch, Russian Academy of Sciences, Ekaterinburg, Russia*

Analysis of X-ray sources characteristics obtained on the base of X- and PZ-pinches is presented. X-pinch is a type of multiwire load of pulse power generators those wires are crossed in the shape of the letter "X". When current with amplitude no less than 100 kA and rise rate more than 1 kA/ns flows through this load the wire's substance in the crossing area becomes completely ionized. After that in this place the neck with length 300 − 500 μm is formed. Implosion of the neck leads to the formation of micro-instabilities that develop into 1 - 3 hot spots. These micro hot spots radiate intensively in soft X-rays during of 1 - 2 ns [1-3]. In the case of PZ-pinch the current of main pulse power generator flows through plasma that has been generated by a high-current vacuum arc discharge beforehand. PZ-pinch is small Z-pinch that formed in the generator's interelectrode gap with width only 1.3 - 1.5 mm due to PZ-pinch works similar to the X-pinch [4].

Experiments with X- and PZ-pinch were carried out on compact pulse power generator XPG (250 kA, 220 ns) [3 - 5]. The data about the sources size, duration, power and spectral characteristics of the X-ray radiation pulses were obtained. The X-pinch has a more stable source size and an X-ray yield from shot-to-shot, and also makes it possible to obtain backlight images with a higher spatial resolution in comparison with the PZ-pinch, especially in the spectral region $h\nu > 3$ keV. At the same time an X-pinch wires burn out after each shot and after that it is necessary to open the generator vacuum chamber to install a new load. The plasma gun can stable works within of 30-100 shots depending on the cathode and the insulator materials. Thus, PZ-pinch allows you to make a set of backlight images with high spatial resolution without necessary to open generator vacuum chamber after each shot. It makes PZ-pinches a good alternative of the X-pinches in the X-ray pulse radiography.

References

[1] *Zakharov S M, Ivanenkov G V, Kolomenskii A A et al // Sov. Tech. Phys. Lett* – 1982. – Volume 8. Pages. 1060-1063.
[2] *Oreshkin V I, Chaikovsky S A, Artyomov A P et al // Phys. Plasmas.* – 2014. – Volume. 21. – №. 10. Pages. 102711.
[3] *Mesyats G A, Shelkovenko T A, Ivanenkov et al // JETP.* – 2010. Volume. 111. Pages. 363–370.
[4] *Russkikh A G, Shishlov A V, Zhigalin A S et al // Plasma Sources Sci. Technol.* – 2011. Volume. 20. Pages. 035011.
[5] *Ratakhin N A, Fedushchak V F, Erfort A A et al // Rus. Phys. J.* – 2007. – Volume. 50. – № 2. Pages. 193-198.

[1] This work was supported in part by the Russian Foundation for Basic Research (grant No. 18-08-00728 and No. 17-08-00131).

INVESTIGATION OF ELECTRICAL OSCILLATIONS IN PLASMA OF VACUUM SPARK

D.L. KIRKO, O.A. BASHUTIN*, P.P. SIDOROV*, A.S. SAVJOLOV**

**National Research Nuclear University MEPhI, Kashirskoe sh., 31, Moscow, 115409 Russia,*
E-mail: dlkirko@mephi.ru, phone: +7(495)7885699-9813

In plasma-focus type devices various studies are carried out on pinching the plasma shell [1,2]. Intensive radiation of this discharge in the visible and ultraviolet ranges of the spectrum is used to create installations for X-ray lithography. In certain regimes different high-frequency oscillations arise in the discharge plasma [3]. The study of these oscillatory processes is important for understanding the stability of the plasma. To operate the vacuum spark a capacitive energy storage device and an ignition circuit with a triggering spark gap are used. The capacity of the capacitor bank is 20 μF at charging voltage 5-20 kV. The distance between the electrodes is 4-5 mm. The anode has a pointed shape, and the cathode is a cylinder shape with a hole in the center. Electrodes from steel, iron and copper were used in the experiments. The working pressure in the chamber is 10^{-4}-10^{-5} Torr. The discharge current is in the range of 100-150 kA with a discharge period 6.0 μs.

The inclusion of a discharge leads to a strong current flow and the evaporation of the anode. A strongly compressed pinch is formed on the axis of the system, surrounded by a more rare shell. Pinch discharge is associated with the appearance of the current drawing and the emergence of intense high-frequency oscillations in the range 1-140 MHz. The appearance of electrical oscillations occurs from the beginning of the current pulse at the time of plasma formation. Investigations of high-frequency signals were carried out using magnetic probes. The following basic frequencies of oscillations were recorded: 4.1±0.1 MHz, 12.3±0.2 MHz, 34±1 MHz, 47±1 MHz, 108±0.2 MHz. On the basis of the data obtained a spectrum of high-frequency oscillations of the discharge current was constructed. According to the calculations the frequencies of oscillations of 1-120 MHz registered in the experiments will be in the range of low-frequency branches of plasma waves [4]. For the frequencies observed in the experiments the lengths of the plasma waves are in the range $2\cdot10^{-2}$ cm-0.3 cm.

Spectroscopy in the visible and ultraviolet ranges of the spectrum was used in investigations of the peripheral plasma of the vacuum spark. In the spectrum there are intense lines of ions of iron, nitrogen and oxygen. Using the hydrogen lines H_α and H_β the plasma temperature for different discharge modes was calculated by the relative intensity method. The plasma temperature values are in the range of 9200-9500 K. According to the Stark broadening of these hydrogen lines the value of the plasma concentration near the cathode $n_e=(3.2\pm0.3)\cdot10^{16}$ cm^{-3} was calculated. Surfaces of electrodes are exposed to strong currents and intense plasma waves. These surfaces were examined by means of electron microscopes. On the surface of the electrodes there are various wave-like structures with dimensions of 30-200 μm. At the same time in some places a fine-grained granular structure with cell sizes in the range of 0.3-0.5 μm is observed. A ring structure with a period of 0.1-0.2 mm was previously found on the surface of the iron cathode. The size of this ring structure is close to the lengths of plasma waves observed in experiments. This allows us to make an assumption about the connection of plasma waves and the process of formation of the ring structures.

REFERENCES

[1] *A.G. Rousskikh, R.B. Baksht, A.S. Zhigalin, V.I. Oreshkin, S.A. Chaikovsky, N.A. Labetskaya //* Plasma Phys. Rep. – 2012. – Volume **38**. – №8. – pp.595-607.

[2] *O.A. Bashutin, E.D. Vovchenko, E.I. Dodulad, A.S. Savjolov, S.A. Sarantsev* // Plasma Phys. Rep. – 2012. – Volume **38**. – № 3. – pp.235–243.

[3] *D.L. Kirko, A.S. Savelov //* Russian Physics Journal. – 2015. – Volume **57**. – №11. – pp.1455-1458.

[4] *N.A. Krall, A.W. Trivelpiece //* Principles of plasma physics. – Academic, New York, 1973.

RADIOGRAPHY OF THIN METALLIC FOILS EXPLOSION IN VACUUM [1]

A. S. ZHIGALIN, A. G. ROUSSKIKH*, V. I. ORESHKIN*,**, A. P. ARTYOMOV*, R. B. BAKSHT**

** Institute of High Current Electronics SB RAS, 2/3 Academichesky ave., Tomsk, 634055, Russia,*
E-mail: Zhigalin@ovpe2.hcei.tsc.ru
*** National Research Tomsk Polytechnic University, pr. Lenina 30, Tomsk, 634050 Russia*

This paper presents the experimental results of the explosion of thin metal (Al, Cu, and Ni) foils at a current density of $(0.5 - 1)\times10^8$ A/cm2. This work is a continuation of Ref.1, with a better temporal resolution. The experiments were carried out on the experimental complex that includes: XPG – 1 and XPG – 2 high-current generators [2] (the current pulse amplitude up to 250 kA, the rise time of 180 ns), WEG – 2 generator [3] (the current pulse amplitude up to 50 kA, the rise time of 300 ns) and two-frame soft X-ray backlighting. The WEG -2 generator was used to explode the investigated foil. Charge voltage of the WEG – 2 generator varied from 15 to 25 kV. The XPG–1 and XPG–2 radiographs were used to obtain the exploding foil image. During the experiments, two successive frames of the exploding foil were recorded, with a delay between frames from 5 to 50 ns. The frames of the exploding foil were registered both perpendicularly and parallel to the foil plane.

REFERENCES

[1] *Zhigalin A.S., Rousskikh A.G., Oreshkin V.I., et. al. // Journal of Physics: Conference Series – 2014. – V. 552. – 012027*

[2] *Artyomov A. P., Fedyunin A. V., Chaikovsky S. A., et. al. // Instruments and Experimental Techniques. – 2013. – V. 56. – № 1. 66-71.*

[3] *Rousskikh A.G., Oreshkin V.I., Zhigalin et. al. // Phys. Plasmas. – 2010. – V. 17. – №. 3. – 033505.*

[1] This work was supported by the Russian Foundation for Basic Research (Grant # 17-08-00459) and by project: "Phase transformations in thermophysics and in physics of high energy densities" of complex program of Basic Research Scientific Research SB RAS.

USING OF B-DOT PROBE FOR Z-PINCH PLASMA DIAGNOSTICS [1]

A. G. ROUSSKIKH, A. S. ZHIGALIN*, V. I. ORESHKIN*,**,R. B. BAKSHT**

** Institute of High Current Electronics SB RAS, 2/3 Academichesky ave., Tomsk, 634055, Russia,*
E-mail: Zhigalin@ovpe2.hcei.tsc.ru
*** National Research Tomsk Polytechnic University, pr. Lenina 30, Tomsk, 634050 Russia*

We present experiments performed on the IMRI-5 generator (450 kA, 450 ns) with a metallic gas-puff Z-pinch with a power-law density profile. The experiments were carried out in a preembedded axial magnetic field Bz0 that was varied from 0 to 0.6 T. To determine the initial pinch radius r0, we used the function r(t) that was found from the time dependence of the pinch inductance L(t). The time-dependent inductance L(t), in turn, was determined as a function of load voltage Vload(t) and pinch current I(t). The function r(t) was verified by a B-dot probe diagnostics. Measurements showed that for the "first shot" the initial radius of the metallic gas-puff Z-pinch decreased from 4 cm at Bz0 = 0 to 2.1–1.7 cm at Bz0 = 0.15 T. We believe that the decrease it r0 is related to the field effect on the ion gyroradius.

[1] This work was supported by the Russian Science Foundation (grant No.16-19-10142).

DEVELOPMENT OF MODEL OF THE VACUUM ARC CATHODE EROSION BASED ON RADIOGRAPHIC INVESTIGATION[1]

A.G. ROUSSKIKH, A.V. FEDYUNIN, A.P. ARTYOMOV*, A.S. ZHIGALIN*, V.I. ORESHKIN*,***

**Institute of High Current Electronics SB RAS, 2/3 Academichesky ave., Tomsk,634055, Russia, russ@ovpe2.hcei,tsc.ru*
***National Research Tomsk Polytechnic University, Lenina ave., 30, Tomsk, 634050, Russia.*

The work is devoted to a quantitative description of the aluminum cathode erosion during the vacuum arc discharge burning. The model development is based on experimental data obtained by means of electrophysical and radiographic methods. The results of the simulation are compared with the quantitative estimates of the distribution of the cathode vapor linear density obtained with radiographic investigations of the vacuum arc plasma jet. Experiments on radiography were carried out at the IMRI-5 current generator [1] with the amplitude of the arc discharge current in the range of 300 – 350 kA. The current of the arc discharge was a damped sinusoid with a half-period of 1.35 μs. A compact pulsed x-ray radiograph based on the X-pinch [2] is a device developed in HCEI SBRAS, which allows radiographic studies of rapidly changing plasma objects in the soft X-ray spectral range (hν ≈ 0.5 ÷ 3 keV).

REFERENCES

[1] *A.G. Rousskikh, A.S. Zhigalin, V.I. Oreshkin, N.A. Labetskaya, S.A. Chaikovsky, A.V. Batrakov, G.Yu. Yushkov, and R.B. Baksht* // Physics of Plasmas. ─ 2014. ─ Vol. 21. ─ 052701.

[2] *A. P. Artyomov, A. V. Fedyunin, S. A. Chaikovsky, A. S. Zhigalin, V. I. Oreshkin, N. A. Ratakhin, and A. G. Rousskikh* // Instruments and Experimental Techniques. ─ 2013, ─ Vol. 56. No. 1. pp. 66–71.

[1] This work was supported by Russian Foundation for Basic Research, grants No. 17-08-00131-a and No. 18-19-10142-a.

RADIOGRAPH PR-PZP-M1 BASED ON PZ-PINCH[1]

A.G. ROUSSKIKH, A.V. FEDYUNIN, A.P. ARTYOMOV*, A.S. ZHIGALIN*, V.I. ORESHKIN***, V.V. DANILOV***, M.A. HOLOPOV***, V.V. KURKUCHEKOV***, A.C. POPOV***, M.G. ALTUHANOV***, A.V. BURDAKOV***, C.C. POPOV***, YU.A. TRUTNEV***, D.I. SKOVORODIN****

**Institute of High Current Electronics SB RAS, 2/3 Academichesky ave., Tomsk,634055, Russia, russ@ovpe2.hcei,tsc.ru*
***National Research Tomsk Polytechnic University, Lenina ave., 30, Tomsk, 634050, Russia.*
****Budker Institute of Nuclear Physics of SB RAS, 11, Acad. Lavrentieva Pr., Novosibirsk, 630090, Russian Federation*

The work is devoted to the description of a compact pulsed X-ray radiograph developed in the HCEI SB RAS. A compact pulsed facility allows for the radiography [1] - [10] of fast-moving plasma in the soft X-ray spectral range (hν ≈ 0.5 ÷ 3 keV). The compact pulsed nanosecond generator (KING) occupying a laboratory area of 0.5 square meters, was designed based on low-inductance capacitor-switch assemblies. KING is a low-inductance capacitor bank consisting of four HCEIcap 60-0.25 capacitors equipped with its own trigger each. The maximum operating voltage of the capacitors is 60 kV, the capacitance of each capacitor is 0.25 μF. The total battery capacity is 1 μF. The capacitors are connected in parallel to the common low-inductive transmission line connected to the load. The inductance of the generator without a flexible transmission line is 9.5 nH, which provides a rising current of 160 ns. The total inductance of the battery of capacitors with switches and the transmission line and the plasma load is 15.5 nH. The circuit inductance makes it possible to provide the generator current with an amplitude of 210 kA, with a rise time of 220-225 ns via a plasma load (with a charging voltage of 43 kV).

The radiation source is a metal plasma jet with a longitudinal dimension of 1.3 mm compressed by the own magnetic field of the KING current (Point Z-Pinch) [11]. Experimental studies of the effect of the PZ-pinch initial parameters on the pulse duration and the radiation source size were carried out. Investigation of the characteristics of the created radiograph showed that when working with a PZ-pinch in a spectral range of 3 ÷ 4 keV, radiation pulses of duration 2 ÷ 3 ns can be obtained, with the radiation source being 10-12 μm in size. A clear illumination of photographic film (film optical density D = 1) of the brand "Mikrat" or RF-3 at a distance of 100 cm in the spectral range of 1 ÷ 3 keV for 30 shots without a opening of the injector assembly was achieved. Thus, the work of a pilot sample of a small radiograph of a soft X-ray range based on a KING generator and a PZ-pinch load has been demonstrated. With the help of a direct radiography scheme it was shown that, due to the small size of the radiation source, it is possible to obtain pictures of plasma and other objects with micron spatial and nanosecond temporal resolutions. The small dimensions of the radiograph greatly expand the scope of its use. The ability to transport the facility and use it together with other devices opens up the possibility of carrying out a wide range of experiments related to the study of fast plasma processes.

REFERENCES

[1] *T.A. Shelkovenko, S.A. Pikuz, and D.A. Hammer //* Plasma Phys. Reports. – V. 42. – Issue 3. – pp. 226–268. – 2016.
[2] *A.P. Artyomov, A.V. Fedyunin, S.A. Chaikovsky, A.S. Zhigalin, V.I. Oreshkin, N.A. Ratakhin, and A.G. Rousskikh, //* Instrum. Exp. Tech. – Vol. 56. – No. 1. – pp. 66–71. – 2013.
[3] *J.D. Douglass, S.A. Pikuz, T.A. Shelkovenko, D.A. Hammer, S.N. Bland, S.C. Bott, and R.D. McBride //* Phys. Plasmas. – **14**. – 9. – 2007.
[4] *D. Kalantar and D. Hammer//* Rev. Sci. Instrum. – **66**. – 779. – 1995.
[5] *S.A. Pikuz, T.A. Shelkovenko, V.M. Romanova, D.A. Hammer, A.Y. Faenov, V.A. Dyakin, and T.A. Pikuz //* Rev. Sci. Instrum. – **68**. – p. 740. – 1997.
[6] *T.A. Shelkovenko, S.A. Pikuz, A.R. Mingaleev, and D.A. Hammer //* Rev. Sci. Instrum. – **70**. – pp. 667-670. – 1999.
[7] *D.B. Sinars, T.A. Shelkovenko, S.A. Pikuz, J.B. Greenly, and D.A. Hammer //* Phys. Plasmas. – **7**. – pp. 1555-1563. – 2000.
[8] *S.A. Pikuz, D.B. Sinars, T.A. Shelkovenko, K.M. Chandler, D.A. Hammer, G.V. Ivanenkov, W. Stepniewski, and I.Y. Skobelev, //* Phys. Rev. Lett. – **89**. – 035003. – 2002.
[9] *S.V. Lebedev, F.N. Beg, S.N. Bland, J.P. Chittenden, A.E. Dangor, M.G. Haines, K.H. Kwek, S.A. Pikuz, and T.A. Shelkovenko //* Phys. Plasmas. – **8**. – 3734. – 2001.
[10] *V. Alexandrov, I. Frolov, M. Fedulov, E. Grabovsky, K. Mitrofanov, S. Nedoseev, G. Oleinik, I. Porofeev, A. Samokhin, P. Sasorov et al. //* IEEE Trans. Plasma Sci. – **30**. – 559. – 2002.
[11] *A.G. Russkikh, A.V. Shishlov, A.S. Zhigalin, V.I. Oreshkin, S.A. Chaikovaskii and R.B. Baksht //* Plasma Sources Sci. Technol. – 2011.– 20. – 035011.

[1] This work was supported by Russian Foundation for Basic Research, grants No. 17-08-00131-a, No. 18-19-10142-a. and by project: "Phase transformations in thermophysics and in physics of high energy densities" of complex program of Basic Research Scientific Research SB RAS.

SIMULATION OF THE SPECTRAL LINE PROFILES IN THE KRYPTON SPECTRUM EMITTED FROM A CURRENT SHEET PLASMA

*E.V. KORYUKINA**, *V.I. KORYUKIN***

**National Research Tomsk State University, 36 Lenin Avenue, Tomsk, 634050, Russia, evk@phys.tsu.ru, (3822) 52-98-52*
***Siberian State Medical University, 2 Moskowski Trakt, Tomsk, 6334055, Russia*

Spectroscopic methods play important role in plasma diagnostics. The application of these methods allows us to analyze processes taking place in plasma and to find such plasma parameters as the temperature and density of particles in the plasma. These parameters can be estimated from the intensities and profiles of spectral lines emitted from the plasma. However, none of existing theoretical methods for calculating plasma parameters from spectroscopic data is a universal one, because all methods have rather limited application field. The computer simulation of the emission spectra combined with traditional methods of plasma diagnostics enables us to analyze processes taking place in plasma in the best way.

In this work, the simulation of the krypton spectrum emitted from the plasma of the current sheet is carried out. The current sheets were observed in the experimental device CS-3D [2], where the sheets were formed after the application of the magnetic field with an ***X*** line to plasma produced by a theta-pinch discharge. It was supposed in [2] that a circularly polarized alternating electric field could be generated inside the current sheet. Based on this assumption, we have simulated the behavior of the krypton emission spectrum emitted from the current sheet plasma in the framework of the method of the energy matrix diagonalization of an atom in an electric field [1]. Our calculations have confirmed the presence of a circularly polarized alternating electric field inside the current sheet. This electric field efficiently influences the behavior of the intensities and profiles of spectral lines. As the influence of the electric field leads to the shifting and splitting of spectral lines, the spectral line profiles noticeably depend on the electric field strength (Fig. 1). The dependence of the profiles on the electric field frequency is rather weak.

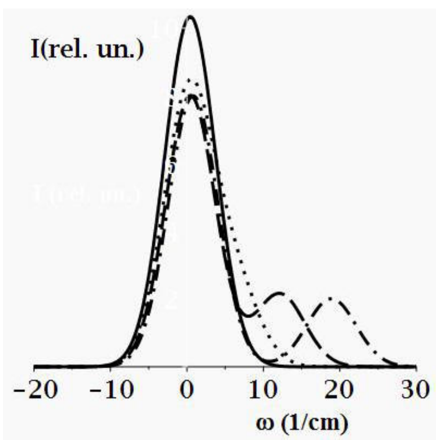


Fig. 1. Dependence of the profile of the $5d[1/2]_1$–$5p[1/2]_1$ spectral line on the electric field strength F (щ=10^3 MHz): solid – F=40 kV/cm; dot – F=80 kV/cm; dash – F=120 kV/cm; dash-dot – F=160 kV/cm.

The results of the simulation have allowed us to reveal the presence of the circularly polarized alternating electric field inside the plasma of the current sheet and analyze the influence of the electric field on the positions, intensities and profiles of spectral lines of the krypton atom emitted from the current sheet. Additionally, in the framework of the suggested theoretical approach, the dependence of the spectral line profiles on the temperature of Kr atoms has been also investigated.

REFERENCES

[1] *E.V. Koryukina //* J. Phys. – 2005. – D38. – № 17. 3296–3303.
[2] *A.G. Frank, V.P. Gavrilenko, N.P. Kyrie, and E. Oks //* J. Phys. – 2006. – B39. – № 24. 5119–5129.

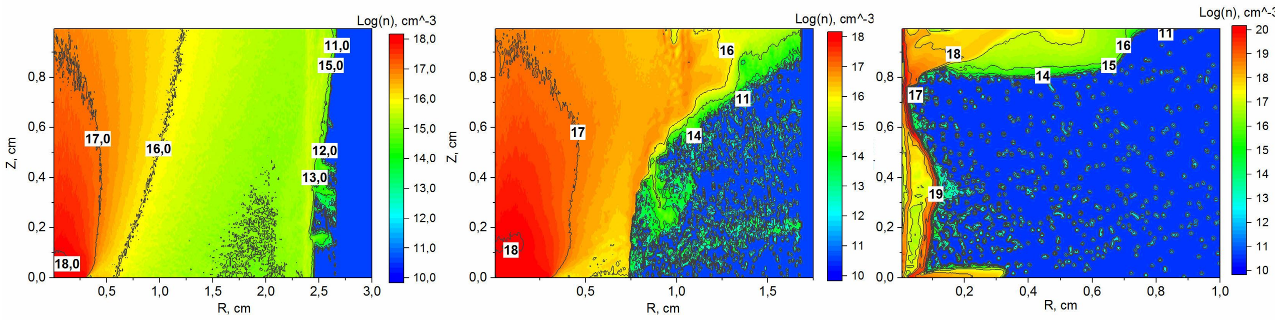
HYBRID MHD/PIC SIMULATION OF BISMUTH GAS-PUFF Z PINCH IMPLOSION[1]

D.L SHMELEV, V.I. ORESHKIN**, S.A. CHAIKOVSKY**

**Institute of Electrophysics, UB, RAS, Ekaterinburg, 620016, Russia, Shmelev@iep.uran.ru, +73432678781*
***Institute of High Current Electrons, SB, RAS, 634055 Tomsk, Russia*

We present the hybrid MHD/PIC simulations of the time evolution of a bismuth gas-puff z pinch in external axial magnetic field (AMF). Recent experiments with IMRI-5 generator (450 kA, 450 ns) [1], performed with plasma liner produced by 80 kA vacuum arc burning on bismuth cathode, shown the certain effect of an axial magnetic field on radiation energy produced during z pinch implosion. When AMF of 0.3 T was applied to the pinch, the radiation energy was about twice that generated without AMF.

In order to perform the numerical simulation of gas puff z pinch a hybrid model was developed. The hybrid model treats the electrons as a massless fluid and ions as macroparticles. The macroparticle dynamic is calculated with the use of PIC method. Ion-ion Coulomb collision is considered with the use of MC method. The radiation transfer of bismuth plasma was accounted in the framework of P1 method. The interelectrode gap pumping by plasma of 8 μs 80 kA bismuth arc with the following plasma implosion by 450 kA/ 450 ns current pulse in different external AMF was modeled (Fig.1). The obtained results are in a reasonable agreement with the experimental results [1].



t=200 ns t=400 ns t=510 ns

Fig. 1. Contour plot of Bi ion density distribution at different time instant during pinch implosion, AMF -0.3 T.

REFERENCES

[1] *A. G. Rousskikh, A. S. Zhigalin, V. I. Oreshkin, V. Frolova, A. L. Velikovich, G. Yu. Yushkov, and R. B. Baksht //* Physics of Plasmas. – 2016. – 23. – № *063502.*

[1] The work was supported by Russian Science Foundation Project No. 16-19-10142.

ON INITIAL MASS DISTRIBUTION OF THE PLASMA LINER PRODUSED BY ARC PLASMA GUN IN EXTERNAL AXIAL MAGNETIC FIELD[1]

D.L SHMELEV, A S. ZHIGALIN**,*

**Institute of Electrophysics, UB, RAS, Ekaterinburg, 620016, Russia, Shmelev@iep.uran.ru, +73432678781*
***Institute of High Current Electrons, SB, RAS, 634055 Tomsk, Russia*

This paper is devoted to the simulation of expansion of plasma produced by arc-plasma-gun used in experiments [1, 2]. This expanding plasma forms liner, which compressed afterwards with the help of IMRI-5 generator (450 kA, 450 ns). Recent experiments [2] have revealed certain dependences of the initial liner radius and the liner compression velocity on the external axial magnetic field (AMF). An attempt to reconstruct initial distribution of plasma liner using the zero-dimension snowplow approximation has led to conclusion that the liner consists of the high-density bismuth core surrounded by the low-density carbon plasma [1]. In this paper we try to solve this inverse problem using 2D axial symmetric hybrid approach. Thus, at the first step we model the evolution of bismuth-carbon plasma ejected by the plasma gun to an interelectrode gap taking to account the AMF. At the second step, we calculate the compression of the obtained plasma liner by IMRI-5 current pulse and compare an experimental curve of the liner-radius-on-time with the calculated one.

In order to perform the numerical simulation of the plasma expansion and the followed liner compression a hybrid model was developed. The hybrid model treats the electrons as a massless fluid and ions as macroparticles. The macroparticle dynamic is calculated with the use of PIC method. Ion-ion Coulomb collision is considered with the use of MC method. The radiation transfer of bismuth plasma was accounted in the framework of P1 method. Modeling of the compression of the plasma consisting of heavy ions (Bi) and light ions (C) using the hybrid approximation showed that two closely located shock waves are formed near the compression front. A similar structure is observed in the experiments [1, 2].

REFERENCES

[1] *A. G. Rousskikh, A. S. Zhigalin, V. I. Oreshkin, V. Frolova, A. L. Velikovich, G. Yu. Yushkov, and R. B. Baksht //* Physics of Plasmas. – 2016. – 23. – № *063502.*

[2] *A. G. Rousskikh, A. S. Zhigalin, V. I. Oreshkin, and R. B. Baksht //* Physics of Plasmas. – 2017. – 24. – № *063519.*

[1] This work was supported by the Russian Fundamental Research Foundation under Awards: 17-38-50155

RESEARCH OF NEUTRON EMISSION FROM DEUTERIUM GAS-PUFF Z-PINCH ON THE GIT-12 GENERATOR AT CURRENTS OF 3 MA[1]

R.K. CHERDIZOV, F.I. FURSOV*, V.A. KOKSHENEV*, N.E. KURMAEV*, A.V. SHISHLOV*, J. CIKHARDT**, B. CIKHARDTOVA**, D. KLIR**, J. KRAVARIK**, P. KUBES**, K. REZAC**, G. N. DUDKIN***, V. N. PADALKO***, V. A. VARLACHEV****

** Institute of High Current Electronics SB RAS, 2/3 Akademichesky Ave., Tomsk, 634055, Russia*
E-mail: rustam.k.cherdizov@gmail.com
*** Czech Technical University in Prague, Faculty of Electrical Engineering, Technicka 2, 16627 Prague 6, Czech Republic*
**** National Research Tomsk Polytechnic University, 30 Lenina Ave., Tomsk, 634050, Russia*

The Z-pinch experiments were carried out at currents of 3 MA on the GIT-12 generator (4.7 MA, 1.7 μs) at the IHCE SB RAS in Tomsk [1][2]. The experimental load was composed of a single shell deuterium gas-puff with an outer plasma shell. The diameter of the gas-puff was 81 mm, and the injected linear mass was (60-75)±5 μg/cm. The plasma shell consisting of hydrogen and carbon ions was formed by 48 plasma guns at the diameter of 350 mm, and its linear mass density was about 5 μg/cm. The maximum neutron yield reached more than 10^{12} neutrons at a current level of 3 MA, and the neutrons with energies above 20 MeV were observed. This neutron emission was detected by different diagnostic techniques including calibrated scintillation time-of-flight detectors, bubble detectors, a silver activation detector, a Sodium Iodide and high-purity Germanium detectors with several threshold activation samples, such as Al, Cu, In, Nb, Zr [3][4]. This neutron detection equipment allowed us to obtain information about the yield, spectrum and anisotropy of the neutron emission by independent diagnostics methods.

REFERENCES

[1] *D. Klir, A.V. Shishlov, R.K. Cherdizov et. al.* // Plasma Physics and Controlled Fusion. – 2015. – Volume 57. – Pages 044005.

[2] *D. Klir, A.V. Shishlov, R.K. Cherdizov et. al.* // Physics of Plasmas. – 2016. – Volume 23. – Pages 032702.

[3] *R.K. Cherdizov, A.V. Shishlov, D. Klir, J. Cikhardt et. al.* // Journal of Physics: Conference Series. – 2017. – Volume 830, Issue 1. – Pages 012017.

[4] *J. Cikhardt, D. Klir, A.V. Shishlov, R.K. Cherdizov et. al.* // IEEE Transactions on Plasma Science. – 2017. – Volume 45, Issue 12. – Pages 3209-3217.

[1] This work was supported by the Grant Agency of the Czech Republic (Grant No.1607036S), the Czech Ministry of Education (Grant Nos. LD14089, LG15013, LTAUSA16084), the Ministry of Education and Science of Russian Federation (Grant No. RFMEFI59114X0001), the CTU (Grant No. SGS 16/266/OHK3/3T/13).

EFFECT OF THE GAS DISTRIBUTION ON IMPLOSION DYNAMICS AND THE K-SHELL YIELD OF THE NEON GAS-PUFFS WITH THE OUTER PLASMA SHELL[1]

A.V. SHISHLOV, R.K. CHERDIZOV, F.I. FURSOV, V.A. KOKSHENEV, N.E. KURMAEV, N.A. LABETSKAYA

Institute of High Current Electronics SB RAS, 2/3 Akademichesky Avenue, Tomsk, 634055, Russia, ash@ovpe2.hcei.tsc.ru, +7-3822-492-133

For almost forty years gas-puff Z-pinches have been investigated as a K-shell plasma radiation source [1]. A natural limitation that reduces the efficiency of such radiation sources is Rayleigh-Taylor instabilities that develop during implosion of the plasma shell. In the mid-90s, the idea of using load with structured gas density profiles [2, 3] to reduce the level of instabilities was adopted. Since then, various types of Z-pinch loads (solid fill gas puffs, multi-shell gas puffs, etc.) have been studied both theoretically and experimentally. The result of these efforts was the development of such load configurations that provide theoretically expected yields of the K-shell radiation at implosion times up to 200-300 ns [4, 5, 6]. Nevertheless, the problem of efficient generation of the K-shell radiation at microsecond implosion times requires further research.

A new type of load configuration, a gas puff surrounded by a plasma shell, has been employed in experiments on the GIT-12 generator (4.7 MA, 1.7 μs) at microsecond implosion times. Optimization of the load parameters in the experiments with deuterium Z-pinches allowed us to increase the neutron yield by an order of magnitude [7]. The experiments with neon gas puffs have also demonstrated that a gas puff with an outer plasma shell has higher efficiency as a K-shell plasma radiation source in comparison with the traditional gas-puff loads at microsecond implosion times [8].

In this report we present complementary studies on the effect of the gas distribution on implosion dynamics and the K-shell yield of the neon gas-puffs with the outer plasma shell.

REFERENCES

[1] *Giuliani J.L., Commisso R.J.* // IEEE Trans. Plasma Sci. - 2015 - vol. 43 - No. 8, pp. 2385-2453.
[2] *A.L. Velikovich, F.L. Cochran, J.Davis* // Phys. Rev. Lett. – 1996 - vol. 77, - No. 5, pp. 853–856.
[3] *F.L. Cochran, J.Davis, A.L. Velikovich* // Phys. Plasmas – 1995 - vol. 2 – No.7, pp. 2765-2772.
[4] *H. Sze et al.* // Phys. Rev. Lett. – 2005 - vol. 95, pp. 105001-1–105001-4.
[5] *J. S. Levine et al.* // Phys. Plasmas – 2006 - vol. 13 - No. 8, pp. 082702-1–082702-11.
[6] *R. J. Commisso et al.* // in Proc. 16th IEEE Pulsed Power Conf., Albuquerque, NM, USA, Jun. 2007, pp. 1773–1779.
[7] *D. Klir, et al.* // Physical Review Letters -2014- Vol. 112, 095001.
[8] *A.V. Shishlov, R.K. Cherdizov, F.I. Fursov, V.A. Kokshenev, N.E. Kurmaev, A.Yu. Labetsky* // Russian Physics Journal. – 2016. – Volume 59, Issue 9/3. – Pages 160-163.

[1] This work was supported by RFBR Grant # 18-08-01132-a

THE EFFECT OF THE PHASE STATE OF A METAL ON THE GROWTH OF THERMAL INSTABILITIES. [1]

V.I. ORESHKIN, K.V. KHISHCHENKO**, E.V. ORESHKIN***, A.G. ROUSSKIKH***

** Institute of High Current Electronics (IHCE), 2/3 Akademichesky Avenue, Tomsk, 634055, Russia, oreshkin@ovpe.hcei.tsc.ru, +73822492988*
***Joint Institute for High Temperatures (JIHT), Izhorskaya st. 13 Bd.2, Moscow, 125412, Russia*
****P.N. Lebedev Physical Institute (LPI RAS), Leninskiy Prospekt 53, Moscow, 119991, Russia*

It is known that in the initial stage of an electric explosion, after the metal has melted, the substance can be in three different phases: liquid; metastable liquid (superheated metal); two-phase region (biphase region: liquid + vapor). In this paper, a comparative analysis of the growth of thermal instabilities is carried out, depending on the phase in which the metal can reside. For each phase, the crose rate is determined. The dependences of the crose rate vs instability wavelength are plotted.

[1] This work was supported by RFBR grants No. 17-08-00459, 16-08-00969 and the draft of the Comprehensive Program of the FNI of the SB RAS.

ELECTRICAL EXPLOSION OF PROFILED CYLINDRICAL CONDUCTORS[1]

N.A. LABETSKAYA, I.M. DATSKO*, S.A. CHAIKOVSKY**, V.I. ORESHKIN*, D.V. RYBKA*, V.A. VANKEVICH**

**Institute of High Current Electronics SB RAS, 2/3 Akademichesky Av., Tomsk, 634055, Russia*
***Institute of Electrophysics UD RAS, 106 Amundsen St., Ekaterinburg, 620016, Russia*
natalia@ovpe2.hcei.tsc.ru, (3822) 492-133

The purpose of this work was an experimental investigation of the explosion of profiled cylindrical metal conductors at the following conditions: initial diameters of the conductor were 1, 2 and 3 mm and B-field values at the conductor surface were ~ 300, 400 or 800 T.

The experiments were carried out on the high-current generator MIG (the current amplitude up to 2.5 MA, the current rise time of 100 ns). The 3-step cylindrical axisymmetric conductors (made of duralumin, copper or titanium) were used as a generator load. The diameters of these steps were 3, 2 and 1 mm (the ends of the steps were smoothed to reduce the edge effects). The plasma formation at the conductor surface was recorded with the help of a four-frame optical cameral with an exposure of 3 ns per frame.

To estimate the brightness temperature of plasma in the black body approximation, the signals of the XRDs with bared aluminum cathodes were used. Each of the three XRDs received radiation from only one step of the generator's load. That was reached by means of a diaphragm system. The instant of rapid signal rise corresponded to the appearance of plasma with a temperature of about 2-2.5 eV on the conductor surface.

The experimental values of magnetic induction of 245 T (D16T), 180 T (Ti) and 350 T (Cu), when plasma with a temperature of about 2÷2.5 eV is formed on the conductor's surface (conductor’s diameter of 3 mm for duralumin and titanium material; and 2 mm for copper one), are rather well agreed with estimates of magnetic induction of the cylindrical conductor (270, 220 and 375 T, respectively).

The process of plasma formation on a surface of the step conductor is rather well described by the criterion offered for the uniform cylindrical conductor.

[1] This work was supported by Russian Foundation for Basic Research, grant № 16-08-00658

DELAYED LARGE-SCALE INSTABILITIES ON TI-COATED COPPER CONDUCTORS[1]

V.A. VANKEVICH, N.A. LABETSKAYA*, I.M. DATSKO*, V.I. ORESHKIN*, D.V. RYBKA*, S.A. CHAIKOVSKY**, V.V. SHUGUROV**

**Institute of High Current Electronics SB RAS, 2/3 Akademichesky Av., Tomsk, 634055, Russia*
***Institute of Electrophysics UD RAS, 106 Amundsen St., Ekaterinburg, 620016, Russia*
www_vlad_v@mail.ru, (3822) 492-133

The paper reports on experiments showing that Ti-coated copper conductors compared to bare copper conductors, are able to delay and suppress the growth of large-scale instabilities on their surface. The experiments were carried out on the high-current generator MIG (the current amplitude up to 2.5 MA, the current rise time of 100 ns). The plasma and the instabilities arising at the conductor surface were recorded with a four-frame optical camera (frame exposure of 3 ns). The internal structure of the substance of conductors formed during the development of instabilities was studied with the X-ray radiography in the quantum energy $h\nu$ range more 0.8 keV and 2 - 3 ns exposure. The X-ray radiograph was based on X-pinch.

The most considerable effect of suppression was found for Ti coatings of thickness 50 and 80 μm at a magnetic field of about 300 T. As the magnetic field at the conductor surface was increased to 350-400 T, the effect did occur but was less pronounced.

[1] The work was supported in part by the Russian Science Foundation, grant No. 16-19-10142.

MEASUREMENTS OF SUB-NANOSECOND PULSED ELECTROMAGNETIC WAVES BY STRIP-LINE SENSORS WITH LONG TRANSMITTING COAXIAL CABLE

V.M. FEDOROV, V.E. OSTASHEV, V.P. TARAKANOV, A.V. UL'YANOV

Joint Institute for High Temperatures of Russian Academy of Sciences (JIHT of RAS), Izhorskaya 13/2, Moscow, 125412, Russia, vmfedorov@ihed.ras.ru, +7-495-4857944

Antenna's sensors of strip-line types of the directional wave couplers are widely used at time-domain measurements of the electric-field (*E(t)*-field) pulses in traveling-waves. The strip-line sensors are employed to measure the *E(t)*-field in ultra-wideband electromagnetic waves (UWB EMP-wave) radiated from high power pulsed radiators. Advantages of the strip-line sensors are a simple design and a sensor output voltage identically a waveform of the *E(t)*-field pulse. Such sensors can have high time resolution $T_{SA,f}$ = 20-100 ps and allow to measure correctly the *E(t)*-wave during time-gap of $T_{SA,g}$ = 3-10 ns. The time-gap is determining by the strip-line design and length of line [1]. The coaxial cable is used to transmit the sensor voltage signal directly to a shielded box or room with a recording device with ~ 10 GHz frequency band. A limit of short length of the transmitting cable is about 1 m. The cable is used as a rule by flexible microwave coaxial cable (50 Ohm impedance, inner copper wire of D_c=1-2 mm diameter) with length L_{cab} up to 10 m. A transfer of the pulsed voltage with ~ 0.1 ns rise-time through the long cable is producing noticeable distortions of the pulse. These distortions are produced by a limited conductivity of cable conductors and dielectric losses. We take for example public data for two good cables with like attenuations: RK50-4-47C (Russia OKB KP, semi-rigged, D_c=1.7 mm, dielectrics with $\varepsilon = 2$ -Teflon tape) and TCF500 (Japan TOTOKU Co, flexible, dielectrics $\varepsilon = 1.4$ -extended Teflon (ePTFE) tape). These cables produce attenuations for a sine signals approximately by formula:

$$V_{out} \approx V_{in}\cdot\exp(-0.023\cdot f^{0.5}\cdot L_{cab})\cdot\exp(-0.0015\cdot f\cdot L_{cab}),\ \text{here } f\text{ –GHz, } L_{cab}\text{ –meter} \quad (1)$$

Attenuations by Eq.(1) are of ≈13% for length L_{cab}= 1.5 m and frequency f = 10 GHz, and attenuation of ≈ 20% for f = 5 GHz and L_{cab}= 4 m. We use these data to get the transient response of this cable. It is calculated with using a conversion to time-domain in Eq.(1) by the Laplace transform for first term and for second term by conversion with approximation of low attenuation:

$$V_{out}(t) \approx [1\text{-}0.07\cdot(T_{crl}/t)^{0.5}]\cdot[1\text{-}0.07\cdot\exp(-t/T_{cdl})]\ ,\ \text{here } T_{crl} = 11\cdot(L_{cab})^2,\ T_{cdl} = 38\cdot L_{cab}\text{ –in ps} \quad (2)$$

Rise-time to level of $V_{out}(t= T_{0.9}) \approx 0.9$ is $T_{0.9} \approx 40$ ps for cable length of 1.5 m by Eq.(2) and for cable length of 4 m is $T_{0.9} \approx 140$ ps ! These estimations clearly show the necessity to compensate the losses in cable by increase the sensor sensitivity for signals with rise-time~ 100 ps. Note, the Eq.(2) is correctly for time intervals of $t > T_{crl}/50$, an extended approximation was developed earlier in [2]. It uses a series application of a convolution of the transient response of type $V_i(t)$ =(1-(1-k_i)·exp(-t/T_i)) with number i=1…8.

The MsO4m microstrip sensor antenna was made with using PCBs technology. This sensor is non-symmetrical two-wire line. The signal line is copper foil (width ≈ 3 mm, length 45 cm) is plated on broad dielectric plate ($\varepsilon = 4.5$, thickness 1.5 mm, width 45 mm and length 50 cm). On backside dielectric plate is plated a foil of grounded electrode (width 45 mm, length 50 cm). A frontal edge (a place of sensor entry for EMP-wave) of the signal electrode is connected to the coaxial cable RK50-4-21 (Russia) of 4 m length. The MsO4m sensor design is included next "gain" additions: width of the signal electrode on frontal edge is increased on ≈ 1mm and the input height of an insertion layer over signal foil is ≈ 2 mm and they are decreased along 10 cm on *z*-axis. These insertions allow to increase the sensor sensitivity during a passing of wave front and to compensate of the cable losses.

The MsO4m microstrip sensor with transmitting cable of 4 m length was made to measure the *E(t)*-field in EMP wave with parameters: sensitivity 0.36 V/(kV/m), a rise-time $T_{SA,f} \approx 50$ ps and for time gap $T_{SA,g}$ = 4.2 ns. The sensor models were examined at the computer simulations and tested by the experiments. Non-stationary processes in the sensor were studied analytically and by numerical 3-D code "KARAT". These investigations show how a using of a hard correction more 20% for gain of high frequency harmonics to compensate an losses in the cable gave an parasitic oscillations in the $V_{MsO4m}(t)$ signal shape The experimental data and results by computer simulations are given in the report.

REFERENCES

[1] *V.M. Fedorov, V.E. Ostashev, V.P. Tarakanov, A.V. Ul'yanov//* 2015. High power radiators and E-field sensors for sub-nanosecond EM pulses" *Sympos.EMC2015-Dresden, Proc. IEEE:CPF15EMC-USB,* pp. 1127-1132

[2] *P.P. Deichuly, V.M. Fedorov, A.A. Yazenko//* 1986. Preprint 86-56, Institute of Nuclear Physics, Novosibirsk, Russia

GENERATION OF ULTRA-WIDEBAND AND MESOBAND PULSES BY USING RADIAL FORMING LINES

V.A. BALDYGIN, I.N.GRIGORIEV, M.B. KRUCHENOV,V.P.LISITSYN, I.A. MYSIN, M.G. NIKIFOROV

Corporation "NPP"ERA",Zavodskaja 5, Istra, Moscow region, 143501, Russia,lisitsyn@istranet.ru,+74959206175

A series of pulsed high-voltage systems consisting of generators of high-voltage pulses and radiators has been developed.Primary circuits of generators use pulse transformers of various design: without cores and with cores made of nanocrystalline alloys, amorphous iron, and electrotechnical steel. In the output stages of the generators, radial forming lines [1-3] are used that are connected with the coaxial transmission linesandswitched by a multi-spark ring discharge in a hydrogen medium with a pressure of 100 atm.

Mathematical modeling of electromagnetic processes of subnanosecond duration in three-dimensional space allowed optimizing the geometry of output stages. The calculations were confirmed by experimental testing:oscilloscopicrecording the output pulses and measuring their amplitude-time parameters.

By varying the wave resistances of the radial formingline and transmission coaxial line, one can obtain subnanosecond pulses of unipolar, bipolar and oscillation forms on the load. The pulse duration varies within the range (0.1 ... 10) · 10^{-9} s. The amplitude of the pulses of the output voltage in some devices exceeded 1 MV. A peak power of more than 10 GW at a load of 60 Ohm has been achieved (Fig. 1). Frequency modes of operation with pulse repetition frequency up to 500 Hz are realized. The duration of bursts of pulses is from 1 to 5 seconds.

The developed impulse systems were used for the radiation of ultra-wideband and mesoband electromagnetic pulses by means of TEM horns, modified horn and parabolic antennas(Fig.1). The maximum value of the effective potential E · r (E is the peak value of the electric field strength, r is the distance to the observation point in the far zone) was 18 MV.

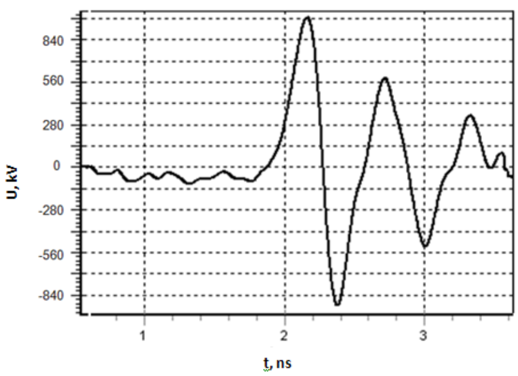


Fig. 1.The oscillogram of voltage impulse at 60 Ohm load and the photo of impulse systems withparabolic antenna

REFERENCES

[1] *V.A. Baldygin, M. G. Nikiforov* //Russia Federation Patent.– №2206175. –2001.
[2] *V.A. Baldygin, , A. A. Beloshapko, O. V. Davydov, V. P. Lisitsyn, M. G. Nikiforov* //Prikladnaja Fizika.–2001.–№ 4. 11-14.
[3] *V. P. Lisitsyn M. G. Nikiforov* //Russia Federation Patent –№23824385. –2008.

CHERENKOV KA-BAND OSCILLATOR WITH 45% EFFICIENCY OF BEAM-TO-MICROWAVE POWER CONVERSATION

R.V. TSYGANKOV, I.K. KURKAN, A.V. GUNIN, V.V. ROSTOV

Institute of High Current Electronics, Siberian Branch, Russian Academy of Sciences, 2/3 Akademichesky Avenue Tomsk 634055 Russia, tsygankov@lfe.hcei.tsc.ru, 8(3822)49-17-24

The paper describes the study of a new relativistic microwave Cherenkov generator of the millimeter wavelength range with the transverse dimension of the electrodynamic system D≈2.5λ, where D is the average diameter of the slow wave system, and λ is the wavelength of the radiation. The investigations were carried out with a high-current SINUS-200 electron accelerator at a voltage of 470 kV and an electron beam current of 3.8 kA. The use of several, complementing each other, mechanisms of selection of parasitic waves provides stable microwave generation at a specified frequency of 36.4 GHz. The microwave power in the experiment is 804 MW with 45% beam-to-microwave power conversion.

A HIGH-POWER SOURCE OF ULTRAWIDEBAND RADIATION WITH REFLECTOR ANTENNA

E.V. BALZOVSKY, YU.I. BUYANOV, V.P. GUBANOV, A.M. EFREMOV, V.I. KOSHELEV, E.S. NEKRASOV, A.S. STEPCHENKO

Institute of High Current Electronics SB RAS, 2/3 Akademichesky Ave., Tomsk 634055, Russia, koshelev@lhfe.hcei.tsc.ru

In this work, we investigated the characteristics of the radiation source of UWB pulses with linear polarization based on the irradiation of a parabolic reflector by a compact UWB combined antenna, excited by a bipolar voltage pulse of the amplitude up to 100 kV and duration of 1 ns at a pulse repetition rate of 200 Hz. The developed source is intended for testing electronic systems, radar with high spatial resolution, and sounding objects and dielectric media.

The generator of bipolar pulses (Figure 1) of the developed source consists of a monopolar pulse generator 1 and a bipolar voltage pulse former 2. To increase the operating frequency of the SINUS-160-40 high-voltage monopolar pulse generator from 100 to 200 Hz, with retaining the stored energy in the forming line, the rating of the power supply has been doubled, the power of the gas blowdown system and the efficiency of the cooling system have been increased. In a sharpening switch, conical electrodes with a rounded top are used instead of spherical ones. Continuous operation mode of the generator at an output voltage of 340 kV and repetition rate of 200 Hz with instability of the breakdown voltage of 1% was realized.

The pulse former presents an open-circuit line including a decoupling inductor, four forming lines, and two switches. A possibility to adjust smoothly the amplitude of an output bipolar voltage pulse in the range from 100 to 200 kV by changing the nitrogen pressure in the former in the range from 30 kg/cm^2 to 80 kg/cm^2 is provided. The pulse length is 1 ns by the level of 0.1 of the amplitude value. The dispersion of the amplitude of bipolar pulses is not more than 3-4% at the pulse repetition frequency equal to 200 Hz.

The feed element of a parabolic offset reflector is made in the form of a combined antenna [1], presenting a combination of radiators of electric and magnetic types which are fed by pulses with the necessary time delays and united by a common coaxial input. By the level of VSWR = 2, the matching band of the feed is 0.38-2.4 GHz. The antenna shows the best matching with the feeder at the frequencies about 1 GHz. Close to this frequency, maximum spectrum energy of bipolar voltage pulses of the length 1 ns is concentrated. To prevent electric breakdown between electrodes, the antenna is placed into a hermetic polyethylene container filled with SF_6-gas.

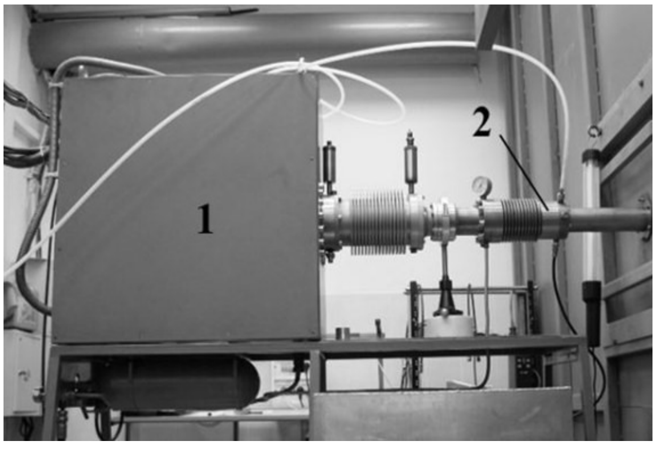


Fig. 1. Bipolar pulse generator.

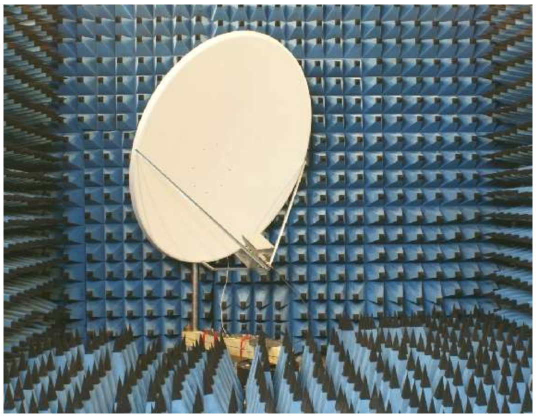


Fig. 2. Reflector with the feed antenna at the rotating support in anechoic chamber.

REFERENCES

[1] *Yu.A. Andreev, Yu.I. Buyanov, and V.I. Koshelev* // J. Commun. Technol. Electron. – 2005. – Vol. 50. – No. 5. – pp. 535-543.

CHARACTERISTICS OF AN ULTRAWIDEBAND 8×8 ARRAY OF CYLINDRICAL HELICAL ANTENNAS[1]

YU.A. ANDREEV, V.I. KOSHELEV, S.S. SMIRNOV

Institute of High Current Electronics SB RAS, 2/3 Akademichesky Avenue, Tomsk, 634055, Russia, andreev@lhfe.hcei.tsc.ru

Characteristics of an ultra-wideband (UWB) 8×8 array of cylindrical helical antennas were investigated in the paper. The array is supposed to be installed as radiator in a high-power source of UWB radiation with elliptical polarization. A cylindrical equidistant helical antenna optimized to radiated 1-ns bipolar pulses was used as the array elements. Spectrum maximum of this pulse corresponds to the frequency of 1 GHz. The chosen antenna geometry provides the axial radiation mode near this frequency. Parameters of the array elements corresponded to the following values: the mean diameter of the helices was $2b = 9.6$ cm, the turn-to-turn distance was $S = 6.7$ см. Conductors of the antennas were made as a tube of the diameter $a = 1$ cm. The number of turns was $N = 6$. The array elements were installed on a ground plate of the dimensions 1.41×1.41 m. The distance between the inputs of helical antennas both vertically and horizontally was d =18 cm. Possible variants of reciprocal rotation was studied for the helices in a 2×2 array, which was 1/16 of a real array. The geometry of the identical rotation of the helices was chosen.

A test pulse of the voltage -29 V/+25 V and length 1 ns entered the feeder system input [1] of the antenna array (Fig. 1). The waveform of the pulse was distorted insignificantly at the feeder system output (input of the array elements) and the pulse amplitude was -2.75 V/+2.85 V at the symmetrical dividing by all channels.

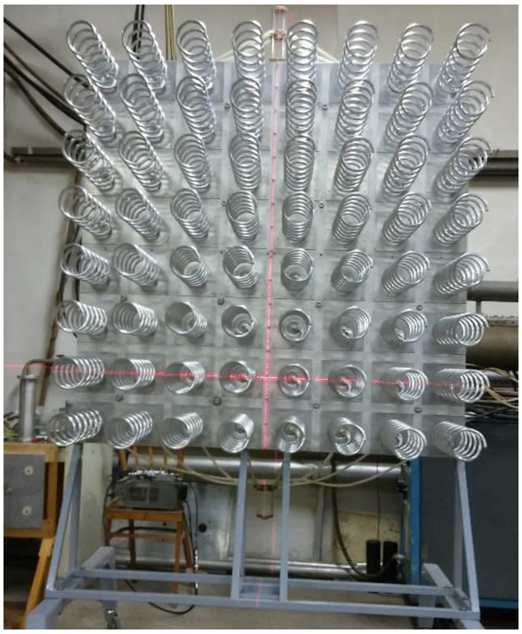


Fig. 1. The 8×8 array of cylindrical helical antennas.

REFERENCES

[1] *V.I. Koshelev, V.V. Plisko, and K.N. Sukhushin //* Ultra-Wideband, Short Pulse Electromagnetics 9. – 2010. – pp. 259-267.

[1] The work was supported by the Russian Foundation For Basic Research (Project No. 16-08-00297).

SOME CHARACTERISTICS OF ULTRA-WIDEBAND 2×2 COMBINED ANTENNA ARRAY

*Y.A. ANDREEV**, *E.V. BALZOVSKY**, *V.N. KORNIENKO***, *Y. XIE****, *S. WANG****

**IHCE SB RAS, Akademichesky ave. 2/3, Tomsk, 634055, Russia, andreev@lhfe.hcei.tsc.ru*
***IRE RAS, Mokhovay st. 11 bilding 7, Moscow, 125009, Russia*
**** Xi'an Jiaotong University, West Xianning road 28, Xi'an, 710049, China*

The influence of the different types of geometry of the 2×2 antenna arrays on the characteristics of their radiation was studied in the work. Combined antennas optimized for 1ns high voltage bipolar pulse radiation and modernized combined antennas with Klopfenstein impedance taper of TEM-horn [1] were used as elements of antenna arrays. Antenna arrays (2×2) of combined antennas and Klopfenstein combined antennas were designed and fabricated. During experiments, all elements of the arrays have been excited simultaneously through symmetrical power dividers. The 2×2 combined antenna array was exactly the 1/16 of a high power 8×8 combined antenna array intended for radiation of ultra-wideband pulses with a 4.3 MV effective potential [2]. The 2×2 Klopfenstein combined antenna array was excited with monopolar voltage pulses with 1 ns duration and 2.2 kV amplitude.

A possibility to increase the peak electric field E_p of radiated pulse of the Klopfenstein combined antenna array in the boresight direction φ, δ = 0° (φ - azimuth angle, δ - elevation angle) by changing the array geometry was investigated first of all. For this purpose, the influence of the aperture height increase by d_v and the gap increase between the antenna array column d_h on the E_p value were investigated. The peak field E_p dependence on the additional array height d_v for the Klopfenstein combined antenna array is presented in Fig. 1. The value d_h = 0 cm in this experiment.

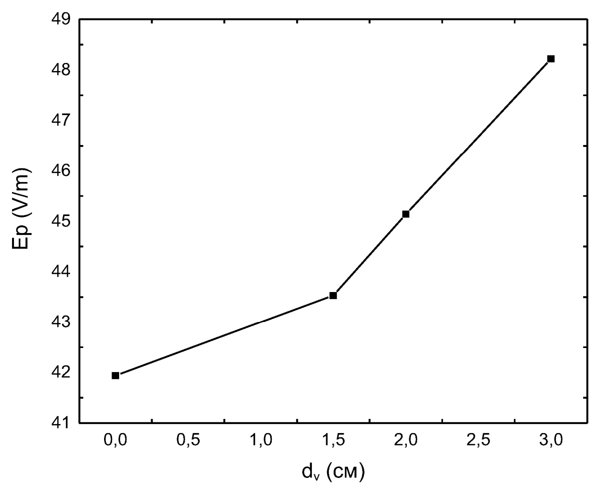


Fig. 1. The peak field E_p versus the additional aperture height d_v in the Klopfenstein combined antenna array.

The possibility to radiate ultra-wideband pulses with tunable narrow band suppression part in its spectra was studied with the combined antenna array. The tuning of the suppression band was realized by mechanical changing of the combined antenna array geometry.

REFERENCES

[1] *Shao-fei Wang,Yan-zhao Xie //* IEEE Trans. Antennas Propag. – 2017. – Vol. 65 – № 12. – pp. 6960-6967.
[2] *A.M. Efremov, V.I. Koshelev, B.M. Kovalchuk, V.V. Plisko, and K.N. Sukhushin //* Laser and Particle Beams. – 2014. – Vol. 32 – № 3. – pp. 413-418.

BULK RESONANCES IN SLOW–WAVE STRUCTURES WITH HIGH RATIO OF DIAMETER TO RADIATION WAVELENGTH

V.A. CHAZOV, M.P. DEICHULY, V.I. KOSHELEV

Institute of High Current Electronics SB RAS
2/3 Akademichesky Ave., Tomsk, 634055, Russia
vadim.chazov.2017@mail.ru

Application of overmoded slow-wave sructures (SWS) in the devices of MWCG type [1] allows obtaining multigigawatt power levels of microwave radiation. Theoretical investigations of the structure of electromagnetic fields of overmoded periodic SWSs are presented in this paper. Using the scattering matrix method [2], the numerical simulation of electrodynamic characteristics of single–section SWSs was carried out. The waveguide diameter was assumed to be invariable while the period of diaphragming (d) varied. Axially symmetric modes were considered. Results were obtained for the following ratio of the diameter to the radiation wavelength: $D/\lambda = 4$, $D/\lambda = 8$, and $D/\lambda = 16$. To study the synchronous addition of the surface wave of the TM_{01} mode with the modes TM_{04}, TM_{08}, and TM_{016}, respectively, is of interest. The possibility to realize bulk resonances in these structures is demonstrated. The distribution of the electric energy density in the fields of this type was obtained. The influence of the section length and diaphragm height on the structure of the field of the first longitudinal resonance was considered.

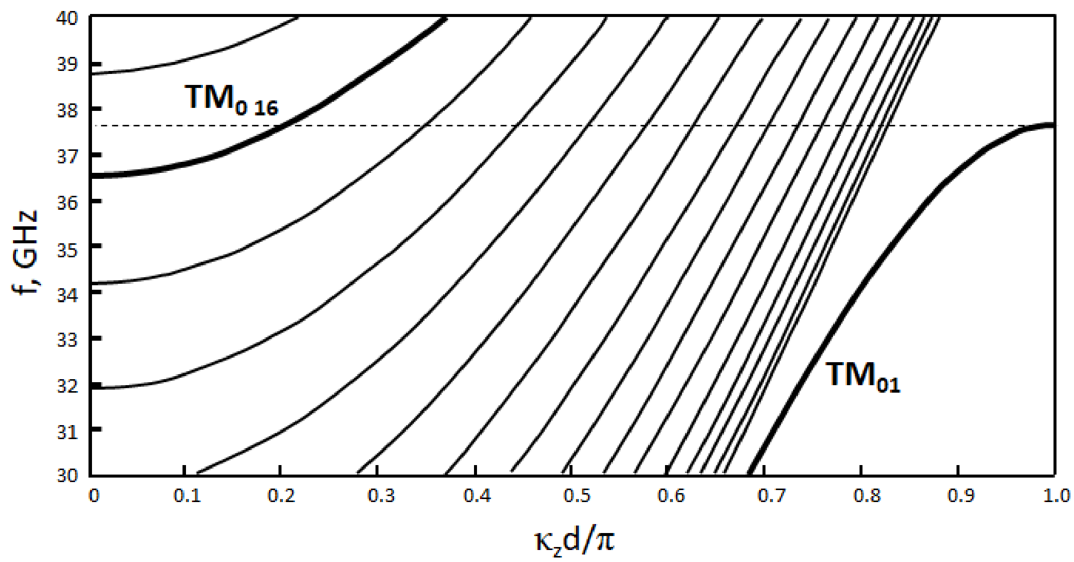


Fig. 1. Dispersion characteristics of symmetric TM-modes of a periodic corrugated waveguide with $D/\lambda = 16$.

REFERENCES

[1] *S. P. Bugaev, V. A. Cherepenin, V. I. Kanavets, A. I. Klimov, A. D. Kopenkin, V. I. Koshelev, V. A. Popov, and A I. Slepkov* // IEEE Trans. Plasma Sci. – 1990. – vol.18. – No. 3. pp. 525 – 536.

[2] *M. P. Deichuly, V. I. Koshelev, and V. A. Chazov* // Rus. Phys. J. – 2017. – vol.60. – No. 8. pp. 1379 – 1385.

AZIMUTHALLY NONUNIFORM PERIODIC WAVEGUIDES AND SLOW-WAVE STRUCTURES FOR GENERATION OF LINEARLY POLARIZED RADIATION

M.P. DEICHULY, V.I. KOSHELEV

Institute of High Current Electronics SB RAS
2/3 Akademichesky Ave., Tomsk, 634055, Russia
koshelev@lhfe.hcei.tsc.ru

Numerical simulations of electrodynamic characteristics of azimuthally nonuniform periodic waveguides and slow-wave structures were carried out. The surface of the waveguides is formed by two sectors of diaphragms separated by the sectors of a smooth tube. Two variants of an azimuthally nonuniform periodic waveguide were considered. In the first variant (Fig. 1a), the radius of sectors of the smooth tube is equal to the radius of the diaphragm base, and in the second one (Fig. 1b) it is equal to the radius of the top of the diaphragms.

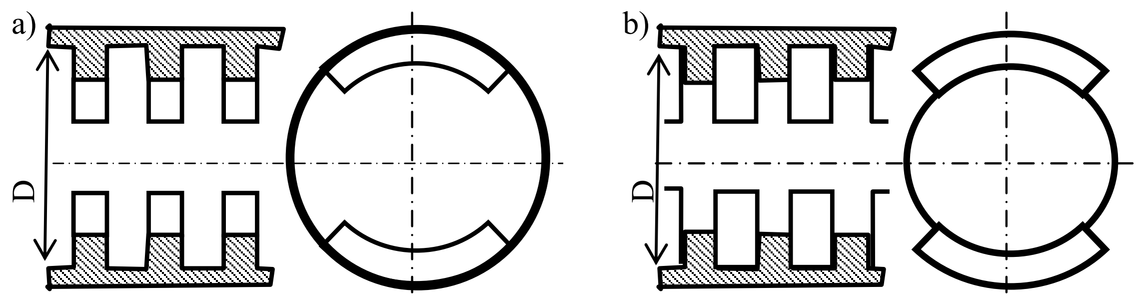


Fig. 1. Geometry of two variants of an azimuthally nonuniform waveguide.

The first variant of the waveguide was used in a multiwave Cherenkov generator for obtaining high-power linearly polarized radiation [1]. Calculations of the electrodynamic characteristics were carried out using the scattering matrix method [2]. The dispersion characteristics of the complex modes of an infinite waveguide of the first and second variant were obtained. The examples of the eigen fields (resonances) in finite slow-wave structures are presented. Note that it is difficult to use the name of the modes agreed for symmetrical waveguides in case of an azimuthally nonuniform waveguide, since the complex mode is represented by a set of modes of each cell. The number of variations of the field in azimuth can be different at different radii.

Particular attention was made to the investigation of lower modes in an overmoded ($D/\lambda \approx 4$) waveguide near the π-mode of oscillations. Here, $D = 13$ cm is the waveguide diameter, λ is the wavelength. It is shown that there are pairs of waves that have a similar picture of the field force lines and differ in the polarization direction by 90º.

Comparisons of the Q-factor of resonances in one-section slow-wave structures of two types were made at different angular length of the diaphragms.

Methods for suppressing resonances of the modes that can compete with the lower complex mode are under discussion. Excitation of this particular mode with the polarization directed from one sector of diaphragms to another is required in a multiwave Cherenkov generator to obtain high-power linearly polarized radiation.

REFERENCES

[1] *M.P. Deichuly, and V.I. Koshelev //* Commun. Technol. Electron. – 2013. – Vol. 58. – No. 8. pp. 828–839.
[2] *M.P. Deichuly, V.I. Koshelev, and V.A. Chazov //* Rus. Phys. J. – 2017. – Vol. 60. – No. 8. pp. 1379–1385.

NANOSECOND FRONT DYNAMICS AND RF OSCILLATION GENERATION IN A TRANSMISSION LINE WITH NONLINEAR CAPACITORS

P.V. PRIPUTNEV, I.V. ROMANCHENKO, V.V. ROSTOV, O.B. KOVALCHUK, V.V. BARMIN

Institute of High Current Electronics SB RAS, 2/3 Akademichesky Ave., Tomsk, 634055, Russia, E-mail: priputnevpavel@gmail.com, Phone: +7(382-2) 491991

Nonlinear transmission lines (NLTLs) are known to be used for pulse sharpening and RF generation for quite a long time and are still being studied for those purposes [1-4]. There are two types of such transmission lines. They are lines with continuous nonlinear material such as ferrite [1,2] and lumped lines with nonlinear elements such as nonlinear capacitors [3,4].

This report represents the results for the nanosecond pulse distribution in NLTL with nonlinear capacitors which capacitance drops with the increase of biasing voltage experiments. Pulse sharpening capabilities of such lines is limited by the cut-off frequency of the line. That means that pulse rise time reduction is also limited by the cut-off frequency. When the sharpened front length goes below the value limited by cut-off frequency the oscillation excitement is observed. The experimental results for pulse sharpening and RF oscillations generation are presented for a transmission line fabricated from commercially available components. The problem of matching the line impedance with a resistive load is discussed.

REFERENCES

[1] *V.V. Rostov, N.M. Bykov, et. Al.* // IEEE Transactions on Plasma Science. – 2010. – Vol. 38. – NO. 10. – P. 2681-2685.
[2] *I.V. Romanchenko, P.V. Priputnev, V.V. Rostov* // Journal of physics: conference series. – 2017. – Vol. 830.
[3] *D.M. French, B.W. Hoff, S. Heidger, D. Shiffler* // Pulse Power Conference. – 2011.
[4] *L.P. Silva Neto, J.O. Rossi, J.J. Barroso, E. Schamiloglu* // IEEE Transactions on Plasma Science. – 2016. – Vol. 44. – NO. 12. P. 3424-3431.

COUPLE COEFFICIENTS OF WAVES OF MAGNETIZED THIN-WALLED HIGH CURRENT ELECTRON BEAMS

N.F. KOVALEV, M.B. GOIKHMAN, A.V. GROMOV, A.V. PALITSIN

Institute of Applied Physics Russian Academy of Sciences, Nizhny Novgorod, Ulyanov str.46, 603950, Russia, kovalev@appl.sci-nnov.ru, +78314367810

Edged explosive emission cathodes are used in relativistic microwave electronics for formation of tubular thin-walled electron beams. For analysis of various regimes of generation and amplification it is convenient to introduce a concept of eigen or normal electron waves. Such method allows us to consider appearance of generation as a reradiation of waves with different signs of kinetic potentials. In the report an explanation for the kinetic potential is given and a method of its calculation for different systems is developed. As a result, a method of transverse sections is generalized for Cherenkov's microwave devices. A scheme of calculation of reradiations on different irregularities makes it possible to calculate amplification (including crestatron one) and small-signal regimes of generation.

PLASMA ULTRA-WIDEBAND AMPLIFIER OF RELATIVISTIC ELECTRON BEAM NOISE[1]

D.E. DIAS MIKHAYLOVA, I.E. IVANOV*, P.S. STRELKOV*, D.V. SHUMEIKO*, V.P. TARAKANOV*****

**Prokhorov General Physics Institute, Russian Academy of Science, Moscow, 119991 Russia, diasmikhaylovade@mail.ru, +7(499)135-63-87*
***Joint Institute for High Temperatures, Russian Academy of Sciences, Moscow, 125412, Russia*
****National Research Nuclear University "MEPhI", Moscow, 115409, Russia*

Ultra-wideband high power microwave sources are well-known [1]. Principle of these sources are based on radiation of short high-voltage video pulse with duration approximately 1 ns. Middle frequency of signals spectra, obtained in these sources, depending on video pulse duration, and usually are less than 1 GHz. To increase signal frequency one have to reduce video pulse duration. However reducing the pulse width results in a decrease of microwave signal energy. Energy of signals obtained in such sources with one antenna are usually less than 0.2 Joules. In plasma ultra-wideband microwave source signal spectra is defined only by plasma density, it is independent of voltage pulse duration. This allows us to receive microwave signals with durations of 200-300 ns. Moreover, it is possible to change frequency in each pulse of the electron beam current by changing plasma density. Principle of plasma ultra-wideband microwave source based on amplification of relativistic electron beam noise (electron energy 500 keV, beam current 2 kA, cathode voltage pulse duration 500 ns). Ultra-wideband microwave pulses $2\Delta f / (f_{min} + f_{max}) > 0.9$ were obtained. Spectrum of one of these signals is shown in fig.1.

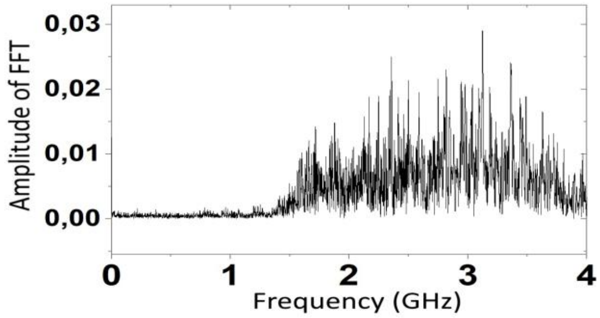


Fig. 1. Spectrum of signal obtained at plasma ultra-wideband microwave source.

Energy of microwave signals was 6-9 Joules. Signals duration was 200-300 ns. Middle frequency of signals was changed from 1,7 GHz to 4 GHz. Here middle frequency is defined as such frequency that the energy of microwave signals with frequencies less than middle frequency equals energy of microwave signals with frequencies more than middle frequency. Dependence of the middle frequency in GHz on plasma density in arb. units shown in fig.2.

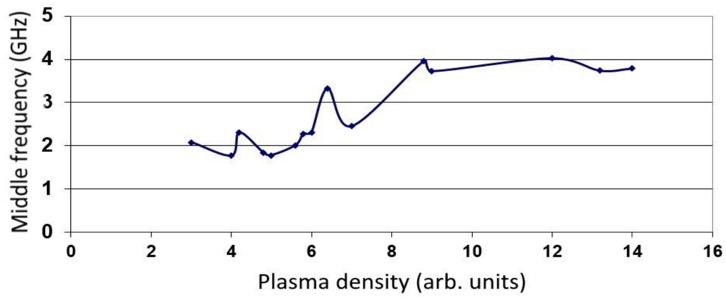


Fig. 2. Dependence of the middle frequency in GHz on plasma density in arb. units.

REFERENCES

[1] *V.P. Belichenko, J.I. Buyanov, V.I. Koshelev //* Ultra-wideband impulse systems. – Novosibirsk: Nauka, 2015.
[2] *P.S. Strelkov, I.E. Ivanov, D.V. Shumeiko //* Plasma Physics Reports. – 2016. – Vol. 42. – № 7. 644-648.

[1] This work was supported by the Russian Foundation for Basic Research, project no 16-08-00439.

FORMATION OF MULTI-WAVE COHERENT RADIATION BY RELATIVISTIC ELECTRONIC FLOWS IN OVERSIZE ELECTRODYNAMIC STRUCTURES

V.A. CHEREPENIN [1], *V.N. KORNIENKO* [1], *V.I. KOSHELEV* [2]

[1] *Kotelnikov's Institute of Radioengineering and Electronics RAS, Mochovaya st. 11,Moscow, 125009, Russia, E-mail korn@cplire.ru phone +7(495)6297678*
[2] *IHCE SB RAS, 2/3 Akademichesky Avenue, Tomsk, 634055 Russia*

The mechanisms of formation of coherent radiation of relativistic electron beams in oversized electrodynamic structures are considered by the method of numerical experiment. Particular attention is paid to the multi-wave Cherenkov generator (MVCG) [1].

The studies were carried out with a number of computational algorithms in which the motion of charged particles was described by the PIC method, and the field dynamics was determined both by means of integral relations for the electromagnetic field and by the method of finite differences in the solution of the three-dimensional Maxwell equations in the space-time representation.

For the simulation, the computing resources of the Interagency Supercomputer Center were used.

As a result of the investigations carried out, it was shown that coherent radiation in the system arises even if the electron beam parameters deviate significantly from the ideal (monoenergetic, axially symmetric and so on). We observed coherent radiation even in the case when the beam had a finite width and a strong density inhomogeneity in the azimuthal coordinate.

Conditions were found under which the transverse structure of the radiation field has an axially symmetric form.

In most of considered cases, the output power level reached ten of GW in the three-centimeter wavelength range (Fig.1)

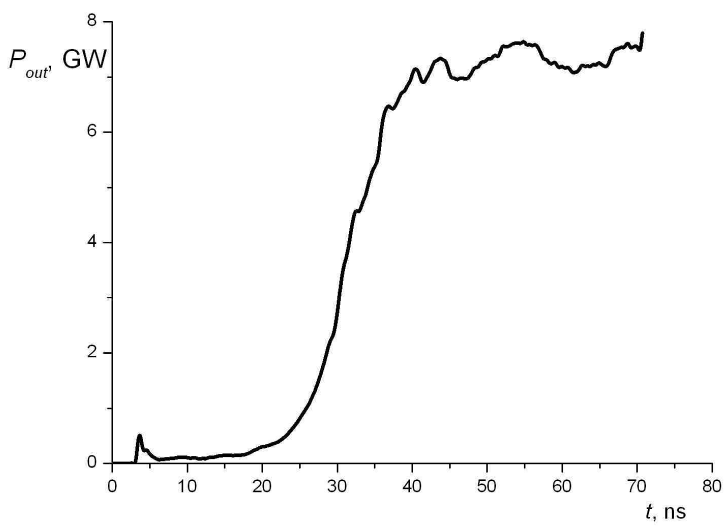


Fig. 1. output power versus time.

Thus, the physical conception of the generation processes in oversized electrodynamic structures has been largely clarified.

REFERENCES

[1] *S.P.Bugaev, V.I.Kanavets, V.I.Koshelev, V.A.Cherepenin.* // Relativistic multiwave microwave oscillators. –Novosibirsk: Nauka, 1991.

INVESTIGATION OF THE CHARACTERISTICS OF ELECTRODYNAMIC STRUCTURES OF MULTIWAVE CHERENKOV GENERATORS USING NUMERICAL METHODS FOR SOLVING NONSTATIONARY PROBLEMS OF ELECTRODYNAMICS

V.A. CHEREPENIN, V.N. KORNIENKO

Kotelnikov's Institute of Radioengineering and Electronics RAS, Mochovaya st. 11,Moscow, 125009, Russia, E-mail korn@cplire.ru phone +7(495)6297678

Previously, it was shown that the operating mode of MVHG can significantly change with small changes in the shape of the electrodynamic structure (ES) of the device [1]. As a result, it becomes necessary to develop a method that makes it possible to analyze electromagnetic fields excited in a particular ES. We note that the ES has finite dimensions in all three coordinates and a complicated shape of the boundary.

We proposed and implemented the following algorithm for obtaining the necessary characteristics. It consists of three steps.

In the first step, using the numerical method for solving the nonstationary Maxwell equations, six components of the electromagnetic field are calculated at observation points located on a line parallel to the axis of the device and remote from it by a distance equal to the initial radius of the electron beam. The fields in the ES are excited by a short longitudinal current, which has the form of a hollow cylinder whose axis coincides with the axis of the ES. The current moves along the longitudinal axis with a velocity equal to the initial velocity of the electron beam.

The second step is to calculate the complex frequency spectrum of the field at each observation point. At the final step of the algorithm, a spatial spectrum over the longitudinal wave number is computed for all observation points for each frequency.

The result of the algorithm is represented as a dependence of the amplitude of the oscillations on the value of the frequency and the longitudinal wave number, which is an analog of the dispersion characteristics of the ES.

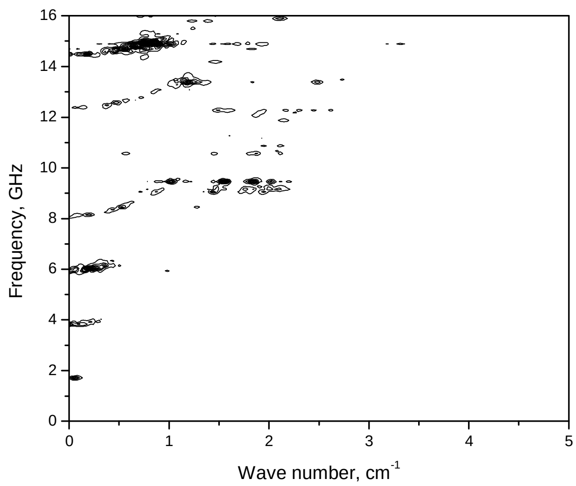


Fig. 1. Dispersion characteristics calculated for the E_z field component.

Fig.1 presents an example of calculation according to the proposed algorithm of the ES characteristic, the parameters of which are similar to the parameters of the ES, which was used in [2]

REFERENCES

[1] *V.A.Cherepenin, V.N.Kornienko* // Izv.VUZov "PND". – 2012. – V.20. - № 6. P.118-123.

[2] *S.P.Bugaev, V.I.Kanavets, V.I.Koshelev, V.A.Cherepenin.* // Relativistic multiwave microwave oscillators. –Novosibirsk: Nauka, 1991.

INTERFERENCE SWITCH OF A SUPERCONDUCTING RESONANCE MICROWAVE COMPRESSOR [1]

S.N.ARTEMENKO, G. M. SAMOYLENKO
Tomsk Polytechnic University, 30 Lenina str., Tomsk, 634050, Russia
sgm@tpu.ru, 3822-417451

We propose a superconducting interference switch of a resonance microwave compressor on the basis of a waveguide H-plane tee, whose lateral arm contains a switching cavity having controllable parameters and based on another H-plane tee. The transmission coefficient of the switch is evaluated for the case of controlling the Q-factor and/or resonance frequency of the switching cavity externally. It is shown that the proposed switch can ensure high-efficiency transmission of the stored energy to the load at a minimal value of the controlling parameter (compared with the known solutions).

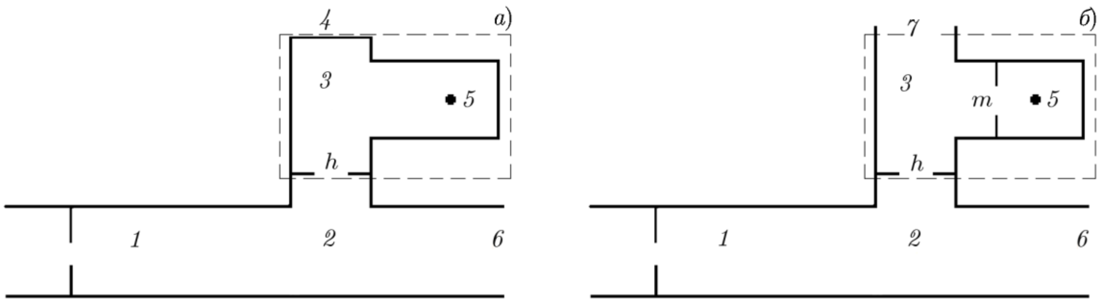


Fig. 1. Scheme of the resonance microwave compressor with a switching cavity based on the H-plane tee: the output control by frequency variation (a), the output control by simultaneous variation of the frequency and Q-factor (b), the superconducting storage cavity (1), the main H-plane tee (2), the superconducting switching cavity (3), the short-circuitor (4), the electron gun (5), output 1 (6), output 2 (7), and h and m are the transmission coefficients of the coupling elements.

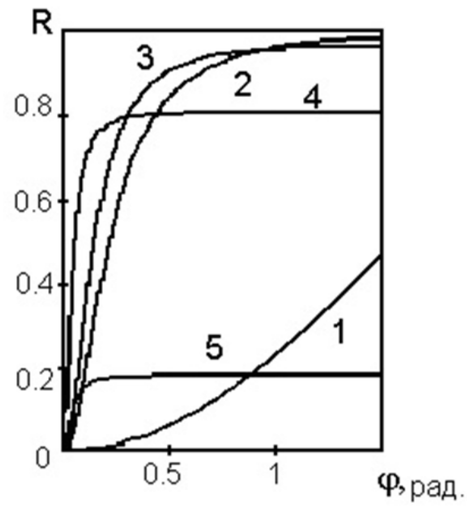


Fig. 2. Transmission coefficients of different versions of the interference microwave switch as functions of variations in the electric length of the switching volume: the conventional scheme of the switch with a half-wave short-circuited switching side arm [1] (1), the scheme with a switching cavity [2] (2), the scheme from Fig. 1a (3), and the scheme from Fig. 1b (4 and 5, where 4 shows output1 and 5 shows output 2).

REFERENCES

[1] *A.N.Didenko Yu.G.Yushkov//* High-Power Nanosecond Microwave Pulses [in Russian], Energoatomizdat, Moscow, 1984
[2] *S.N.Artemenko, G.M. Samoilenko//* Radiophys. Quantum Electron., 2014, **57**, No. 1, 20

[1] This work was partially supported by the Competitiveness Improvement Program of Tomsk Polytechnic University.

INTERFERENCE MICROWAVE SWITCH WITH AUTOMATIC PERFORMANCE CONTROL

S.N. ARTEMENKO, S.A. GOREV, S.A. NOVIKOV, YU.G. YUSHKOV

Tomsk Polytechnic University, 30 Lenin str., Tomsk, 634050, Russia, snartemenko@mail.ru , +73822417451

Operation characteristics of an output interference switch affect considerably output pulse parameters of a microwave compressor. The natural objective is the increase of switch operation efficiency. The proposed design is a traditional waveguide tee of H-type [1] but connected into the transmission type cavity formed by the direct tee arms. The longitudinal size is limited by two irises positioned in the direct arms symmetrically about the side arm of the tee. This layout provides the standing wave node at the side arm connection area at the transmission operational mode. Thus the power feeding the side arm and accompanying losses would decrease.

At these operational conditions the switch transmission factor as a function of losses value in the side arm was determined. The factor versus losses characteristics showed that the forming of the continuous standing wave in the transmission type cavity with the node at the side arm connection area increased the switch transmission factor. Early experiments at high power level were performed and they proved the switch transmission efficiency increased at dynamic operation mode as well. It is expected the similar efficiency increase can be reached in the interference microwave switch where the T-junction of H-type is made of moderately oversized waveguides. The report presents results of experimental tests of the microwave switch of increased efficiency at low and high power levels.

REFERENCES

[1] *I.J. Altman // M*icrowave Circuits, Van Nostrand. – 1964.

[2] *V.A. Avgustinovich, S.N. Artemenko, A.A. Zhukov //* Technical Physics Letters. – 2013. – Vol. 39. – 5. PP. 402-404.

STUDY OF SWITCHING PROCESS IN OVERSIZED INTERFERENCE MICROWAVE SWITCH

S.N. ARTEMENKO, S.A. GOREV, V.S. IGUMNOV, S.A. NOVIKOV, YU.G. YUSHKOV

Tomsk Polytechnic University, 30 Lenin str., Tomsk, 634050, Russia, snartemenko@mail.ru , +73822417451

The X-band oversized T-type H-tee of an interference microwave switch [1] was used in the experimental study of the gaseous plasma discharge switching processes. The switching efficiency as a function of plasma channel parameters has a threshold nature. Conditions for highest efficient switching were found. The envelope of the microwave pulse of higher amplitude, as shown in fig. 1, corresponds to these conditions. Comparison of simulation results for the switching process in the oversized microwave interference switch with data of its experimental tests was made. It was shown the switching is most efficient if the plasma channel length is compared to the half-wavelength in a waveguide. It was assumed the dominant process contributing to switching over to the transmission state of the oversized interference switch is changing of the discharge tee arm eigenfrequency.

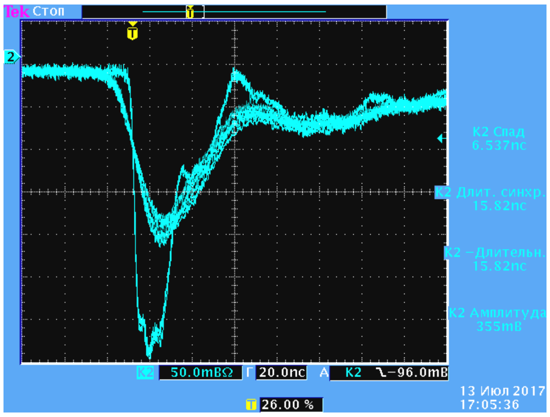


Fig. 1. Waveform envelopes of the microwave compressor output pulses when passing the threshold length of the plasma channel (pulse of smaller amplitude – the channel lengths is less than the threshold value, higher amplitude – the channel length is equal to the threshold).

REFERENCES

[1] *V.A. Avgustinovich, S.N. Artemenko, A.A. Zhukov* // Technical Physics Letters. – 2013. – Vol. 39. – 5. PP. 402-404.

GENERATION OF TERAHERTZ RADIATION BY ELECTRON BEAM-PLASMA INTERACTION[1]

G.I. DUDNIKOVA*, E.A. BERENDEEV**, A.A. EFIMOVA**, V.A. VSHIVKOV**

*Institute of Computational Technologies SB RAS, Lavrentiev ave.6, Novosibirsk, 630090, Russia, dudn@ict.nsc.ru, 3833309772
** Institute of Computational Mathematics and Mathematical Geophysics SB RAS, Lavrentiev ave.6, Novosibirsk, 630090, Russia

At present, the search for new methods of generation electromagnetic radiation in the terahertz frequency range has emerged as one of the most promising rapidly developing areas of research in science and engineering, including medical diagnosis and security. One of the modern solutions of the problem is the generation of electromagnetic (EM) waves due to the interaction of high-current relativistic electron beams with plasma. Since in this case the radiation frequency is comparable with the plasma frequency, it can be easily adjusted by simple changing the plasma density. The efficient terahertz electromagnetic emission was produced during the injection of relativistic electron beams into plasma in laboratory experiments at the GOL-3 facility INP SB RAS [1].

In this paper the mechanisms of the high efficiency of energy transfer from the relativistic electron beam to the EM radiation in turbulent regime of collisionless plasma are investigated on the base of computer simulation. The kinetic approach for ion and electron plasma components, as well as for electron beam, was used in 2D numerical model with the real mass ratio of charged particles [2]. A parallel electromagnetic particle-in-cell (PIC) code UMKA2D3V [3] was applied to simulate beam-plasma system for parameters close to the parameters of laboratory experiments at GOL-3 facility. Regimes of injection of one electron beam into the plasma and the counter injection of electron beams were considered. Computational experiments under different value of plasma density, beams current and energy, external magnetic field, as well as different species of plasma ions was performed using modern computer systems with massively parallel architecture.

The efficiency of generated electromagnetic radiation for the uniform plasma density, as well as for the regimes of the predetermined density modulation was studied. Estimates of the amplitude of the wave excited by the beam in plasma are obtained; the spectrum of electromagnetic fields in plasma and in vacuum is calculated. Numerical experiments have shown that the self-consistent modulations of the plasma density that arise under the action of a plane beam-driven waves, as well as the angle of the beam entrance to the plasma with respect to the direction of the external magnetic field, play the main role in the generation of EM radiation. If plasma has a longitudinal density modulation, such a system is able to radiate electromagnetic waves as a dipole antenna [4]. This radiation mechanism is based on the conversion of an electron beam-driven potential plasma wave on the periodic previously perturbation of plasma density. Numerical modeling allowed us to find the beam-plasma interaction modes with high efficiency (up to 10%) of the terahertz radiation. It is shown that the injection of the colliding electron beams into the plasma results in generation electromagnetic emission near the second harmonic of plasma frequency due to direct collision of beam-driven waves (Fig.1).

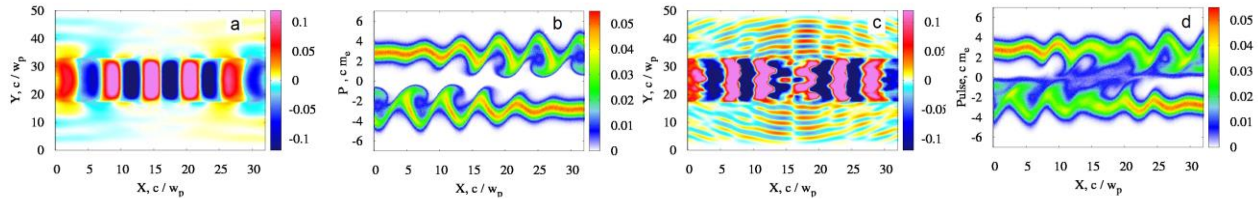


Fig. 1. The maps of electric field $E_z(x, y)$ (a,c) and phase spaces (x,P_x) counter electron beams (b,d) at t=48, 240. The coordinate (x,y), the momentum of the electron beam, P_x, and the time, t, are represented in units of c/ω_p, m_ec, $1/\omega_p$, respectively. Here c is light velocity, m_e - electron mass, ω_p- plasma frequency.

REFERENCES

[1] *A.A. Ivanov, A. V. Arzhannikov, A.V. Burdakov, et al. //* Phys. Plasmas.- 2015.- 22- 122302.
[2] *I.V. Timofeev, E.A. Berendeev, G.I. Dudnikova //* Phys. Plasmas.- 2017.- 24. -9.- 093114.
[3] *E. Berendeev, G. Dudnikova, A. Efimova, V. Vshivkov //* Lecture Notes in Computer Science.- 2017.- 10187.- 227-234.
[4] *I.V. Timofeev, V.V. Annenkov and A.V. Arzhannikov //* Phys. Plasmas.-2015.- 22, 113109.

[1] This work was supported by Russian Science Foundation under Project No. 16-11-10028

RF PULSE GENERATION IN TRANSMISSION LINE WITH DISCHARGE GAPS AND CROSS-LINK CAPACITORS

P.V. PRIPUTNEV, I.V. ROMANCHENKO, V.V. ROSTOV

Institute of High Current Electronics SB RAS, 2/3 Akademichesky Ave., Tomsk, 634055, Russia, E-mail: priputnevpavel@gmail.com, Phone: +7(382-2) 491991

Nonlinear transmission lines (NLTLs) with dispersion have been studied for RF generation for quite a long time. Those transmission lines use different nonlinearities, e.g. magnetic or electric nonlinearity [1-3]. In all those approaches RF generation phenomenon can be separated on two different process. They are pulse sharpening and processes connected with influence of the transmission line dispersion on the formed shock front [4].

In the present work the possibility of RF pulse generation in a transmission line with discharge gaps and cross-link capacitors is discussed using Rompe-Weizel model for resistance of the discharge gap dynamics [5]. Shock front formation and conditions for effective RF generations are studied.

REFERENCES

[1] *N. Seddon, C.R. Spikings, J.E. Dolan* // Pulsed power conference. – 2007. 16th IEEE International.
[2] *I.V. Romanchenko, et. Al.* // The review of scientific instruments. – 2012. Vol. 83(7).
[3] *H. Ikezi, J.S. Degrassie, J. Drake* // Applied physics letters. – 1991. – Vol. 58(9). – P. 986-987.
[4] *A.M. Belyantsev, et. Al.* // Tech. phys. – 1995. – Vol. 40(8). – P. 820-826.
[5] *R. Rompe, W. Weizel* // Zs. Physic. – 1944. Vol. 122. – P.636-639.

HIGH-VOLTAGE TRANSITIONS FROM THE COAXIAL OUTPUT OF THE GENERATOR TO THE TEM HORN ANTENNA

L A. BUSYGINA, A.A. CHUMAKOV, V.P. LISITSYN, M.G. NIKIFOROV

Corporation "NPP"ERA", Zavodskaja 5, Istra, Moscow region, 143501, Russia,lisitsyn@istranet.ru,+74959206175

Installations, which radiate high power electromagnetic fields, usually have high-voltage pulse generators with a coaxial output. Therefore, connecting the generator to a common radiator – to a TEM horn, which have "strip" input, required high-voltage transition. Known transitions use the principle of gradual conversion of the geometry of the cross-section of the line while maintaining the uniform wave impedance [1]. The outer conductor of the coaxial line is cut, move apart and a flat part is inserted into the gap. The smaller size has a transition [2], in which the outer conductor does not move apart, and the inclined flat part is embedded in the cut pipe of the outer conductor of the coaxial.

The coaxial output of a generator is usually filled with oil, so an important part of the transition is a dielectric vessel with oil in which the transition conductors and the initial part of the TEM horn are located. The dimensions of the high-voltage transition are determined, basically, by the necessary insulating distance between the conductors at the output of the transition over the surface of the dielectric vessel. To increase the distance and improve the characteristics of transition, the "cover" of the dielectric vessel is made spherical or in the form of a "gable roof". We successfully designed and fabricated a series of transitions for generators that generate voltage pulses with amplitude of hundreds of kV and with nanosecond and subnanosecond rise times.

The geometry of the transitions was optimized using three-dimensional numerical computations using a created by author conformal FDTD code. The presence of a program that allows conformal modeling the complex geometry of conductors and dielectrics has made it possible to create a unique high-voltage transition with a voltage doubling. The transition consists of a tee, each output arm of which is an intermediate coaxial-strip transition. Intermediate transitions are connected to two intermediate horns, which create a TEM wave in the main horn (Fig. 1). Conductors of the transitions and intermediate horns are minimized in size and placed in oil inside a conical dielectric vessel with a spherical cover. The diameter of the vessel is 0.98 m, the length is 0.84 m. The coaxial input has an internal diameter of the outer conductor of 160 mm and a wave impedance of 30 Ohm. The applied voltage is a monopulse with amplitude of about 1 MV, with a subnanosecond rise time and duration of several ns. The pulse amplitude of the output voltage exceeds 2 MV. The transition is connected to the TEM horn radiator (Fig.1).

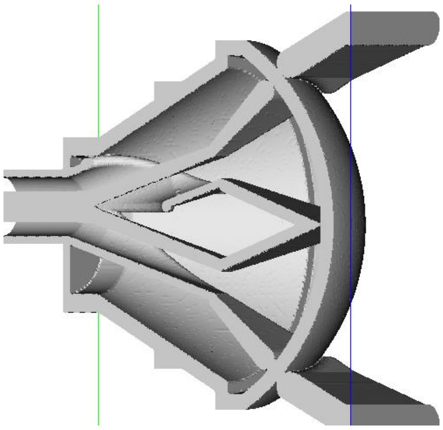


Fig.1.The calculated geometry of the transition, and the photo of high power impulse installation with transition and antenna

REFERENCES

[1] *E.G. Farr, G.D. Sower, C.J. Buchenauer //* Sensor and Simulation Note.–№371.–1994.

[2] *LA. Busygina, M.G. Nikiforov, V.P. Lisitsyn, A.A. Chumakov //* Russian Federation Patent.–№2292099. –2005.

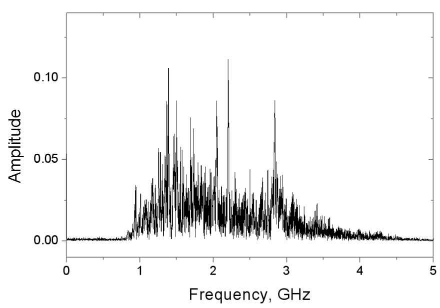
SPECTRA OF RADIATION OF A PLASMA RELATIVISTIC MICROWAVE OSCILLATOR[1]

I.E. IVANOV

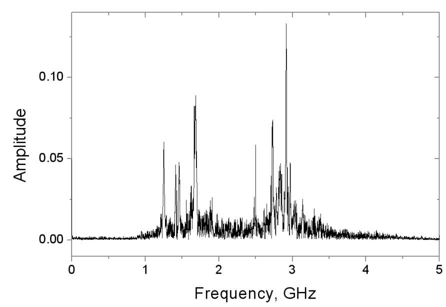
38 Vavilov St.r, 119991 Moscow, +7, Russia, iei@fpl.gpi.ru,+7 (499) 135-4148

In [1], the experimentally obtained spectra of a plasma relativistic microwave oscillator in the range up to 3 GHz were compared with numerical simulations of such spectra using the KARAT code. The main regularities in the variation of spectra during a pulse were explained. In the present work, the change in the emission spectra is studied as a function of the resonator length *L*. The one boundary of resonator was metallic disk. The slope of this disk changes the radiation spectrum. The duration of the microwave pulses varied from 300 to 450 ns, the energy reached 15 J. A correspondence was obtained between the geometric length of the resonator and the length determined from the registered frequency peaks of the spectra. The main regularities in the variation of the spectra for various configurations of the resonator are explained.

Spectral analysis of microwave pulses was carried out by the method of discrete Fourier transformation of oscillograms of the microwave signal over the entire time interval of the pulse of 800 ns. The sampling rate of the oscillograms is 16 ps, the bandwidth of the recording oscilloscope Tektronix TDS 7404 is 4 GHz. The spectra obtained for different *L* and different slopes of the metallic disk were analyzed. The figure shows examples of spectrum changes for a perpendicular (a) and inclined (b) disk for the same plasma density.



(a)



(b)

An inclined disk creates an anisotropy in the resonator, which leads to a simplification of the spectrum, to mode selection. Noise generation is largely suppressed. The change in the spectrum during the pulse was analyzed by the instantaneous frequency method. Under certain conditions, generation can occur either at one or two frequencies. In the latter case, first generation occurs at a higher frequency, and then a transition to a lower frequency occurs. A jump to another frequency is apparently associated with a change in the plasma density during the pulse.

REFERENCES

[1] *I.L.Bogdankevich, I.E.Ivanov, O.T.Loza, A.A.Rukhadze, P.S.Strelkov, V.P.Tarakanov, D.K.Ulyanov //* Plasma Phys. Reports, 2002, vol.28, № 8, pp.690-698.

[1] This work was supported by the Foundation for Basic Research; project no 16-08-00439

HIGH-POWERED 100-NANOSECOND CAPACITOR-SWITCH ASSEMBLIES [1]

I.V.LAVRINOVICH, D.V.MOLCHANOV*, N.V.ZHAROVA**

**Institute of High Current Electronics SB RAS, 2/3 Akademichesky ave., Tomsk, 634055, Russia, lavrivan@mail.ru, 8(3822)492335*

New capacitor-switch assemblies (CSA) with high absolute and specific output power are developed. The design of new assemblies is similar to the design of assemblies developed earlier in the IHCE SB RAS [1]. They consist of a hollow cylindrical capacitor, inside which is a gas switch. But, unlike previous models, this assembly contains not one, but two capacitors are charged by different polarity, which are high-voltage terminals are connected to a common three-electrode gas switch, which trigged on the basis of field distortion. Such a design provides a compact arrangement of capacitors and an switch and, as a consequence, a small total inductance of the discharge circuit of the CSA.

Specification of the developed capacitor-switch assemblies is presented. The prospects of using the developed CSA for the construction of compact LTD cavity and powerful pulse generators are shown.

REFERENCES

[1] *I.V. Lavrinovich, N.V. Zharova, M.G. Bykova //* Izv. Vyssh. Uchebn. Zaved., Fiz.. – 2012. – 55. – № 10/3. 253-255.

[1] This work was supported by Russian Science Foundation (project №17-79-20292)

MEGAAMPERE LOW-INDUCTANCE CROWBAR BASED ON A PLASMA SWITCH [1]

V.A.. KOKSHENEV, N.E. KURMAEV, F.I. FURSOV, R.K. CHERDIZOV

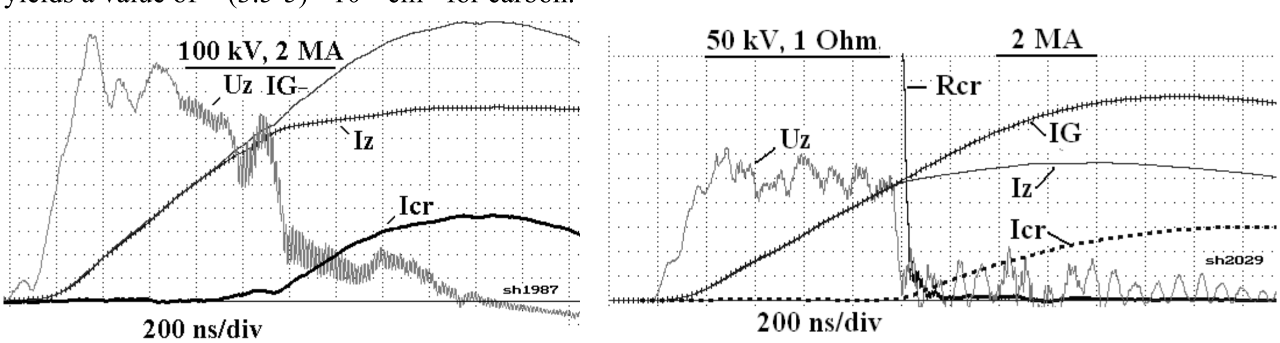
Institute of High Current Electronics SB RAS, 2/3 Akademichesky Avenue, Tomsk, 634055, Russia, vak@oit.hcei.tsc.ru, +7-3822-492-908

In novel experiments with Z-pinches, the efficiency of energy transfer to the load does not exceed 20-25% [1]. There is a problem of protecting the elements of the generator and diagnostic tools in the area of the load from destruction while utilizing the remaining energy. In the paper, the possibility of realizing the mode of the crab on the GIT-12 generator with the help of a plasma switch installed in a magnetically insulated transmission line (MITL). The pressure of the incident plasma stream should be sufficient to overcome the pressure of the transverse magnetic field ($\rho v^2 > H^2/8\pi$). Estimates show that for a magnetic field B ~ 0.5 T (H ~ 4 kA / cm) at a plasma velocity of 5 cm / μs, its density should be at least 2×10^{-8} g / cm^3 (for C^+ ~ 2×10^{15} cm^{-3}).

Plasma guns (PG) with a discharge over the surface of polyethylene in a capillary are investigated for a plasma switch. The diameter of the capillaries was 0.5 or 1 mm, length – 5, 10, 15 mm. The current in 1 PG varied from 8 to 18 kA with a front of 1-1.3 μs. Plasma streams with a density of up to 5×10^{-8} g / cm^3 and a velocity of up to 5 cm / μs are obtained.

Two designs of the crowbar based on the plasma switch were tested. In design 1, the switch was formed by planar plasma sources of 8 PG in each. The current amplitude in each PG is ~ 18 kA with a rise time of 1.3 μs. The installation of 4 such sources on a prefabricated electrode of a central node with a diameter of 1.5 m made it possible to obtain a mode of the crowbar with a current cut off by an amplitude of up to 2 MA from the load with an inductance of 60 nH (Fig. 1a, shot 1987). A limited number of planar sources on a large diameter did not allow the full realization of the low-inductance crowbar switch.

In the design 2 of the switch, 16 PGs were formed (a capillary is 0.5mm / 15mm), set evenly along the azimuth at a diameter of 380 mm in the MITL with ρ = 10 Ω. In Fig. 1b shows oscillograms of the crowbar mode with a load cut off by an inductance of 25 nH from the generator. In this shot (# 2029), the plasma flow rate dropped from ~ 5 cm / μs to 4.1 cm/μs when moving in a magnetic field increasing from 0.39 T to 1.13 T for a time of 600 ns (at # 2030 to 3.7 cm / μs change in the magnetic field from 0.7 T to 1.5 T for a time of 680 ns). Estimation of the plasma injection concentration from the measured braking of the bunch yields a value of ~ (3.5-5) $\times10^{15}$ cm^{-3} for carbon.



a **b**

Fig. 1. Oscillograms of current *Icr* and voltage *Uz* for a crowbar switsh: a – design 1 (L_z=60 nH), b – design 2 (L_z=25 nH). *IG*, *Iz* - generator and load currents, *Rcr* - spark gap resistance.

REFERENCES

[1] *Oreshkin V.I. // Pisma Zh. Tekh. Fiz. – 2013. – Vol. 39. – №15. P. 1-11.*

[1] This work was supported by the RFBR (Project No. 18-08-00568-a).

MARX GENERATORS FOR RECTANGULAR MICROSECOND VOLTAGE PULSES PRODUCTION AT A CONSTANT ARBITRARY RESISTIVE LOAD

E.N. ABDULLIN, G.F. BASOV

Institute of High Current Electronics SB RAS, 2/3, Academichesky ave., Tomsk, 634055, Russia,
E-mail: abdullin@lhfe.hcei.tsc.ru, phone: 8-3822-491913

The paper presents the description of the electrical schemes and design elements of two variants of the Marx generator allowing forming rectangular microsecond voltage pulses at an arbitrary constant resistive load. The air-isolated Marx generator consists of 6 stages assembled on the basis of artificial long lines. The wave impedance of the lines is 4.2 Ω, the electric length is 5 μs, the charging voltage is up to 50 kV. To eliminate the reflections, each line is supplied with a matched load and presents an analogue of the Vvedensky scheme [1]. Switching on the stages in series by the generator operation and connection of the matched loads to the lines is made by means of one or two blocks of discharge gaps. The generator variant with one block of the gaps is shown in Fig. 1. The generator provides obtaining close to rectangular pulses of voltage up to 200-250 kV and length of 5 μs at the arbitrary constant resistive load. In the variant of the generator with two blocks of the gaps, it is possible to obtain close to rectangular voltage pulses with adjustable duration up to 10 μs corresponding to the double electric length of the lines at the arbitrary constant resistive load.

Fig. 1. Generator variant with matched loads and one block of the gaps

REFERENCES

[1] *Auslander V.L., Ilyin O.G., and Shenderovich A.M. // Pribory I Tekhnika Eksp. – 1963. – № 2. P. 173-174 (In Russian).*

SOS DIODE BASED ON P-TYPE SILICON (P-SOS)[1]

A. G. LYUBLINSKIY, E. I. BELYAKOVA, I. V. GREKHOV

Ioffe Institute, 26 Polytechnicheskaya, St.Petersburg, 194021, Russia, Alexander.Lyublinsky@mail.ioffe.ru, +7-812-297-3145

The fast interruption of the current with a density up to several tens of kilo-amperes per square centimeter by switching from forward to reverse direction through a silicon $p^+p^/N_0n^+$-diode with a deep (150-200 μm) $p^/N$-junction was discovered in Institute of Electrophysics, Ekaterinburg and named SOS-effect (SOS – Semiconductor Opening Switch) [1]. The numerical simulations of this effect were made in [2-4]. The simulations show that the current interruption begins from the formation of sharp peak of high electric field in n^+-region near N_0n^+-boundary. This peak rises fast up to the value close to breakdown level, but then the position, width and amplitude of this peak remain practically unchanged during the further commutation process. The power current interruption and voltage increase across SOS diode are determined mostly by the following fast expanding high electric field domain in $p^/$-region, fed by the flow of free holes removed from the plasma. At the moment of maximum pulse voltage on SOS diode, there are two high electric field domains with the amplitudes up to 150-200 kV/cm, wide in $p^/$-region and sharp in n^+-region, separated by 50-60 μm thick high density electron-hole plasma in base layer. Therefore, while the power current is interrupted by SOS diode and switched into the parallel connected load, $p^/N$-junction and most of base layer are filled in by the plasma. At the final stage of the commutation process this plasma is removed through the high electric field regions and $p^/N$-junction recovers.

The further investigations in our laboratory show that several drawbacks and unwanted effects are inherent to the current interruption process by SOS diode, including:

a) The high electric field domains collide close to N_0n^+-boundary and far from $p^/N$-junction, because the domain formed in $p^/$-region moves much faster than that of in n+-region due to the difference in electron and holes mobility. But the diode switching-off process is not finished at this moment, because $p^/N$-junction should recover and triangular-like electric field should be formed on it. Therefore, it is preferable if high electric field domains collide just on pn-junction. Otherwise, additional time is required for of the carrier displacement and reconfiguration of the electric fields.
b) The remain high density plasma stored in too thick base layer and next removed through the high electric field regions significantly increases the total commutation losses.

These effects reduce the efficiency of SOS diode operating as a powerful opening switch. Therefore, new $p^+P_0n^+$ semiconductor structure named p-SOS diode has been suggested. The first experimental evidence and theoretical study of SOS-effect in the diode based on p-type silicon have been presented in [5-7]. p-SOS diode shows better performance, i.e. shorter switching-off time and significantly lower (1.5 times) commutation losses in comparison with conventional SOS diode. The high electric field domains collide just on P_0n^+-junction, and thus, the first above mentioned drawback has been eliminated. The current article describes further investigation of p-SOS diode with reduced thickness of the base layer. The thin base layer excludes excessive plasma between the high electric field domains at the final stage of the switching-off process. By this way, the contribution of the second mentioned drawback in the total losses is reduced. The observed commutation losses in such p-SOS diode are lowered two times more, and the pulse voltage on the load increases in more than 1.5 times in the same operation regime. The attained pulse amplitude significantly exceeds the static breakdown voltage of the considered diode structure. The computer simulation revealed new effect in the electric field domains dynamics responsible for this outstanding result. It was shown that two high electric field domains collide and form rectangular-like common electric field just on P_0n^+-junction, which allows to get up to double pulse voltage on the diode structure.

REFERENCES

[1] *Yu. A. Kotov, G. A. Mesyats, S. N. Rukin, A. A. Filatov // Dokl. Akad. Nauk, 1993, 330, p.315.*
[2] *S. N. Rukin, S. N. Tsyranov // Semiconductors, 2009, 43, p.957.*
[3] *S. K. Lyubutin, S. N. Rukin, B. G. Slovikovsky, S. N. Tsyranov // Semiconductors, 2012, 46, p.519.*
[4] *A. Engelko, H. Bluhm // J. Appl. Phys., 2004, 95, p.5828.*
[5] *I. V. Grekhov, A. G. Lyublinskii, I. A. Smirnova // Technical Physics, 2015, 60, № 11, pp. 1677–1681.*
[6] *I. V. Grekhov, A. G. Lyublinskii, E. I. Belyakova // Technical Physics, 2016, 61, № 3, pp. 424–427.*
[7] *N. I. Podolska, A. G. Lyublinskiy, I. V. Grekhov // Technical Physics, 2017, 62, № 12, pp. 1787–1790.*

[1] This work was supported by Russian Science Foundation (project no. 14-29-00094)

EFFECT OF VOLTAGE RISE RATE AND TEMPERATURE ON THE SWITCHING OF HIGH-VOLTAGE SILICON THYRISTORS [1]

S.N. TSYRANOV, A.I. GUSEV*, S.K. LYUBUTIN*, S.N. RUKIN*, O.E. PERMINOVA***

** Institute of Electrophysics UB RAS, 106 Amundsen Str., Yekaterinburg, 620016, Russia,*
E-mail: serg@iep.uran.ru,+79193886860
*** Ural Federal University, 19 Mira St. 19, Yekaterinburg, 620002 Russia*

Operation of the thyristor-based switches triggered in impact-ionization wave mode has been investigated. The thyristor switch contained tablet thyristor with DC operating voltage of 2.4 kV, and diameter of silicon wafer of 32 mm. At applying across the switch a triggering pulse with a voltage rise rate dU/dt of over 1 kV/ns the thyristors transition time to conductive state was less than 1 ns. In this work effect of voltage rise rate and temperature on the switching process of a thyristor is investigated.

In experiments the voltage rise rate on thyristor structure of dV/dt varied in the range of 0.5 to 10 kV/ns, temperature of structure of T – from 25 to 200 ^{0}C. These two factors affect on the switching process in opposite manner. Increasing the dU/dt values leads to increasing the switching voltage and decreasing the switching time. Quite the reverse, increasing the structure temperature has a negative effect on the switching process. It was found that the voltage rise rate dU/dt at the triggering stage was the main factor affected on the thyristors switching characteristics: switching voltage, time of switching the thyristor from the blocking state to the conducting state and value of the residual voltage.

The following results were obtained.

At dV/dt > 8 kV/ns the switching effect existed up to T ~ 200 ^{0}C.

At dV/dt < 1 kV/ns the switching effect disappeared at T > 120 ^{0}C.

This work continues the research started in [1-2].

REFERENCES

[1] *Gusev A.I , Lyubutin S.K. , Rukin S.N. and Tsyranov S.N. //* Semiconductors. - 2016. - Volume 50. - №3. p. 394-403.
[2] *Gusev A.I , Lyubutin S.K. , Rukin S.N. and Tsyranov S.N. //* Semiconductors. - 2017. - Volume 51. - №5. p. 649-656.

[1] This work was supported by the RFBR under projects number 17-08-00203, 17-08-00406 and 18-08-01390

COMPRESSION CHARACTERISTICS OF THE SLIT AND CAPILLARY EPTRONS[1]

P.A. BOKHAN, P.P. GUGIN, M.A. LAVRUKHIN, D.E. ZAKREVSKY

A. V. Rzhanov Institute of Semiconductor Physics SB RAS, pr. Lavrentieva 13, Novosibirsk, 630090, Russia, lavrukhin@isp.nsc.ru

At present, interest to the research and development of nano- and subnanosecond powerful high-voltage switches, capable to function with high pulse repetition frequency (~10-100 kHz and more), is rather high. Particularly, it is due to the application of such switches in self-terminated lasers pumping power supply.

The results of the detailed research of the new type of the switch, which is based on the construction composed from capillary or slit part and part which implements «open discharge», are presented. This type of switches previously was named Eptron [1].

Semiconductor generator was used to form primary high-voltage (up to 20 kV) pulses with durance 0.1 — 2 μs. The load was constructed from low-inductance resistors with a total value of 10 – 330 Ohm.

Researches were carried out with different gaseous medium (helium, neon, argon, hydrogen), the pressure was in the range of 0.1-10 Torr. Ability of this switches to function with pulse repetition frequency more than 100 kHz in burst mode, with primary voltage pulses duration less than 0.5 μs, was demonstrated (fig.1.). In this case pulse compression degree amounts to 10^3 and current rise time equals ~ 0.5-2 ns.

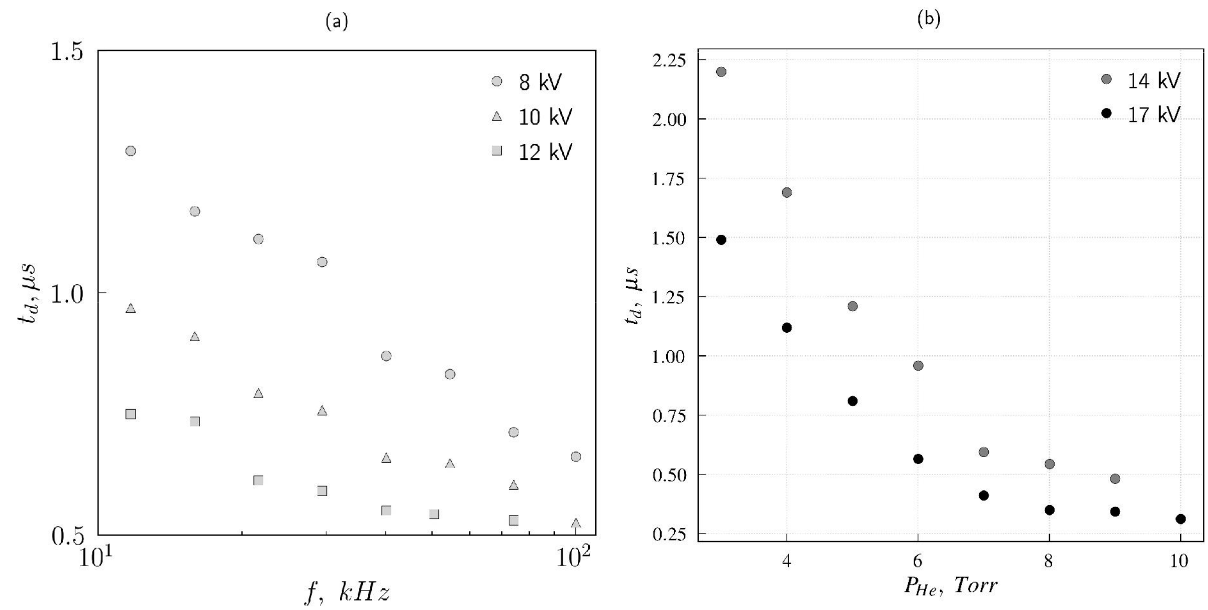


Fig. 1. Slit (a) and capillary (b) eptron discharge delay time τ_d dependence on pulse repetition frequency for various voltages, (a) P_{He}=10 Torr, (b) f=16 kHz.

REFERENCES

[1] *P.A. Bokhan, P.P. Gugin, M.A. Lavrukhin, Dm.E. Zakrevsky* // AMPL-2017. - Abstract Book. - Tomsk. - 2017. - P. 131.

1 This work was supported by RSF project № 14-19-00339.

TWO STAGE SUBNANOSECOND OPEN DISCHARGE BASED GENERATOR IN THE REGULAR PULSES MODE [1]

P. A. BOKHAN, P. P. GUGIN*, M. A. LAVRUKHIN*, DM. E. ZAKREVSKY**

Institute of Semiconductor Physics, Siberian Branch, Russian Academy of Sciences, pr. Akademika Lavrent'eva 13, Novosibirsk, 630090, Russia, gugin@isp.nsc.ru

Generation of high-power nano- and subnanosecond pulses is a challenge in various fields of science and technology. In particular, advances in pulsed gas lasers currently limited by the lack of equipment capable of forming high-current high-voltage pulses with a rise time of about 1 ns in the regular pulses mode at frequencies up to tens of kilohertz [1].

The report presents the results of an experimental study of the "open" discharge based sharpener - kivotron [2]. The experiments were carried out in the regular pulses mode in the frequency range 1-12 kHz (Figure 1a) at the voltage of up to 25 kV. The set of 20 low-inductance ceramic resistors of 5-50 Ohms was used as a load. The prototype of the pulse generator (Figure 1b) consisted of a primary transistor high-voltage pulse generator (VT_1, Tr_1), a matching circuit (L_1-C_2-L_2) and a two-stage sharpener based on kivotrons K_1, K_2 loaded on R_{load}.

The working capacitance C_3 at the first stage of the sharpener was charged by the pulse with edge of 35-50 ns, after which the first stage, operating at a pressure of 3-5 Torr of helium, recharged the working capacitance of the second stage C_4 during ~5 ns. The second stage, working at a Helium pressure up to 20 Torr, provided voltage pulse edge 0.1-0.2 ns and a duration up to 1.5 ns at a current up to 2 kA on the active load depending on the load and the applied voltage. The maximum average power in this experiment was 0,5 kW. It was also investigated the possibility of generating rectangular pulses of subnanosecond duration using the Blumlein scheme on artificial lines in the second stage. Figure 1c shows a typical oscillogram of a rectangular current pulse in a such mode.

In conclusion, the work demonstrates the possibility of creating generator of high-current subnanosecond pulses based on a kivotron capable of operating in the regular pulses mode with a frequency of at least 12 kHz and high average power and pulse conversion efficiency.

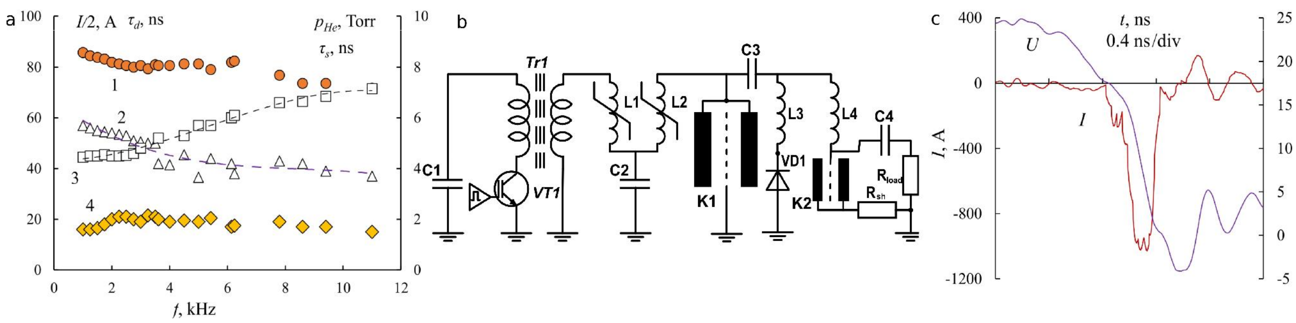


Fig. 1. a. The first stage kivotron experimental curves: 1-current, 2-discharge delay time, 3-Helium pressure, 4-switching time; b. Experimental device circuit; c. Typical oscillogram at the second stage in Blumlein mode.

REFERENCES

[1] *P.A Bokhan., P.P. Gugin, Dm. E. Zakrevsky, M.A. Lavrukhin, M.A. Kazaryan, N.A. Lyabin //* Quantum Electronics. - 2013. - 43. - 715.

[2] *P.A. Bokhan, P.P. Gugin, D.E. Zakrevskii, and M.A. Lavrukhin //* Technical Physics. - 2015. - 60. - 1464.

[1] This work was supported by RFBR № 17-08-00121.

CORONA PREIONIZED HIGH-CURRENT CLOSING SWITCH FOR REPETITIVELY OPERATED 300 KV DOUBLE-FORMING LINE (BLUMLEIN)

E.G. KRASTELEV[*], A.V. NASHILEVSKI[**], D.V. PONOMAREV[**], G.E. REMNEV[**], A.A. SEDIN[*]

[*]*Joint Institute for High Temperatures, Russian Academy of Sciences, 13/19 Izhorskaya str., Moscow, 125412, Russia, ekrastelev@yandex.ru, 89167956495*
[**]*Tomsk Polytechnic University, 30 Lenina ave., Tomsk, 634050, Russia*

A high-current self-breakdown gas switch stabilized by corona preionization was developed for closing of 300 kV repetitively operated at 10 pps water insulated double-forming line (Blumlein) of a nanosecond electron accelerator. The switch is installed at the end of the Blumlein and is used for closing of outer of two coaxial lines. High stability of the self-breakdown voltage (within ±1%) at fast charging of Blumlein (during ≈1.4 µs) is achieved by gas preionization in the spark-gap by additional pulsed corona discharge. The spark-gap electrode system includes two main toroidal electrodes and an additional corona needle that is located in the cavity of one of them (negative during the operation). It combines two parallel gas discharge gaps – the main spark gap and an additional corona discharge gap. Separating the functions of the spark and corona gaps makes it possible to optimize the geometry of the electrodes of each gap and provide both the ability to switch high currents and high dynamic characteristics for a long operating time. Dried air is used as a working gas at pressure of 3-4 atm (abs.). Gas blowing system includes 4 gas inlets located at outer flange supporting the high voltage insulator (water-gas interface) and one outlet in the cavity of the grounded main electrode. This scheme of gas flow protects the insulator from deposition of electrode erosion products and minimizes gas flow (≈20 l/min) for stable operation of the switch by removing of the hot gas throw the cavity of the grounded electrode.

The design of the switch together with the main results of the working tests will be presented and discussed.

UPGRADE OF THE PULSE TRANSFORMER URT-0,5M ACCELERATOR[1]

M.E. BALEZIN, S.YU. SOKOVNIN* **, A.A. ANDREEV**, F.V. AVERIN****

**Institute of Electrophysics Ural Division Russian Academy of Sciences, 106 Amundsen Str., Ekaterinburg, 620016, Russia, e-mail: mk@iep.uran.ru, +73432678782*

***Ural Federal University, 19 Mira Str., Ekaterinburg, 620002, Russia*

**** Ashinskiy Iron and Steel plant, 9 Mira Str., Ash, 456010, Russia*

Important element of the URT-0,5M accelerator (0,5 MEV, 50 ns, 1 kW) [1] is the pulse transformer with the core from permalloy 50NP 20 μm thick. This core is rather expensive, not easily accessible and has rather non-uniform geometrical and magnetic characteristics from batch to batch.

Therefore the core of the transformer was replaced with 2 magnetic conductors 1B-M (saturation induction at least 1,56 T) TU 14-123-233-2012 [2] the K375x305x25 size from the fast-tempered ribbon from magnetically soft amorphous alloy AMET-1SR developed and released by Ashinskiy iron and steel plant. The geometrical sizes of the old and new core are identical.

This material in case of rise speed of induction 5 T/μs and induction range 2,5 T has magnetic field strength within 900-1100 A/m. Each ring of the core 25 mm high is constructive consists of parts 5 mm high without insulation which are spliced and insulated from each other by spacers from film glass-cloth Izofleks-191.

It is set that after changeover parameters of the accelerator did not change and it steadily works with pulse repetition rate up to 200 pps. At the same time the cost of a magnetic conductor 1B-M is approximately ten times lower than cost of permalloy core.

REFERENCES

[1] *S.Yu. Sokovnin, M.E. Balezin, I.A. Buldakov, V.A. Skotnikov, S.V. Tscherbinin // News of higher educational institutions. Physics. – 2007. – №10/2. – p. 188-191.*

[2] *A.V. Akimov, P.V. Logachev, A.A. Korepanov, F.V. Averin, O.V. Savinova, G.L. Mamaev, S.L. Mamaev // PTE. – 2012. - №10. – p. 129-134.*

[1] This work was performed within a support of the Russian Science Foundation project No 16-16-04038.

COMPACT LTD CAVITY ON THE BASIS OF NEW CAPACITOR-SWITCH ASSEMBLY [1]

*I.V.LAVRINOVICH**, *D.V.MOLCHANOV**, *D.RYBKA**, *A.P.ARTYOMOV**

**Institute of High Current Electronics SB RAS, 2/3 Akademichesky ave., Tomsk, 634055, Russia, lavrivan@mail.ru, 8(3822)492335*

The project of compact linear transformer driver (LTD) cavity on the basis of the new capacitor-switch assembly "HCEIcsa 160-0.1" [1] is presented. In accordance with the project, the LTD cavity contains twelve capacitor-switch assemblies (CSA) connected in parallel to the matched load. Also, the LTD cavity contains cores with a total cross section of 90 cm^2, made of a 30 μm thick band of amorphous alloy of 2NSR (analog of Metglass). According to the estimations, when all CSAs are synchronously switched, they will provide in a matched load equal to 0.067 Ohm a current pulse with an amplitude of 1.1 MA with a rise time of ̴100 ns, which corresponds to a pulsed power of 80 GW. The outer diameter of the cavity will be approximately 1 meter, the height of 0.45 m. The small overall dimensions of the cavity in combination with a high level of output power promise good prospects for its application. Such a compact LTD cavity can be used in laboratory studies both as an independent driver for various low-impedance loads, and as a standard element for constructing more powerful pulse accelerators.

REFERENCES

[1] *I.V. Lavrinovich, D.V.Molchanov, N.V. Zharova//* Report at the EFRE 2018 #S4-O-003501

[1] This work was supported by Russian Science Foundation (project №17-79-20292)

INVESTIGATION OF POWER TRANSISTOR PARAMETERS FOR DESIGN HIGH-FREQUENCY HIGH-VOLTAGE SWITCHES[1]

CH. G. ANTIPOVA, V.YU. KHOMICH*, I.E.REBROV**

**Institute for Electrophysics and Electric Power RAS, 18, Dvortsovaya naberezhnaya, Saint- Petersburg, 191186, Russia, rbrv.igor@gmail.com, +74991351195*

Recently, high-voltage pulse technology has widely used in medicine and biotechnology [1]. Thus, the problem of forming highly oriented polymer materials of biomimetic design can be solved through the high-voltage pulse generators. By using this technique, it is possible to obtain materials with specified morphology by electrospinning for two-dimensional and layer-by-layer three-dimensional printing [2].

Such semiconductor switching elements as MOSFETs and insulated gate bipolar transistors (IGBTs) are advantageously distinguished by their ability to operate at a high pulse repetition frequency, low power and simple control schemes. However, such operating parameters as the maximum voltage and the current rise rate of an individual transistor are insufficient to obtain wide-ranging devices [3]. Therefore, high-voltage switches based on assemblies of a parallel-serial connection of transistors are used in pulse generators with a relatively small peak power (one to hundreds of megawatts), voltages of tens of kilovolts, high repetition frequencies (10 kHz and more) and short switching times. In addition, the task of commutators construction with a repetition frequency of 100 kHz or more imposes to the transistor more stringent requirements for switching the maximum voltages in a very short time at a high efficiency [4].

In this work, we analyzed the efficiency and operation speed of IGBTs and MOSFETs in circuit with a full discharge of the storage capacity. The study was conducted on 17 models of commercially available transistors of IR, APT (Microsemi), Infineon, IXYS, and others with a range of blocked voltages of 900-1200 V and pulse currents of more than 40 A and storage capacitor of 500pF to 4 nF.

During the experiment, voltage had been measured over the transistor at the switching process (with the TESTEC Elektronik TT-HV250 probe). Together with the current shunt signal it was fed to the LeCroy Waverunner 104Xi oscilloscope. Such parameters as the current amplitude, the rise time 10 to 90% and the full width at half maximum were measured. The efficiency of the power device was estimated as the ratio of the energy stored in the capacitor to the energy transmitted through the load.

Comparison of experimentally obtained values of electrophysical parameters for 17 models of transistors shows that the energy of losses decreases with increasing maximum attainable current and gate voltage. And besides, the rise time of the pulse for the set of transistors has a much lower effect on the efficiency. However, within the limits of one transistor these quantities are close correlated to the gate-emiiter voltage of the power device. In this regard, transistors with an extended permissible gate voltage range provide more variability in the design of high-frequency high-voltage switches.

Thus, it was revealed that the MOSFET ipw90r120c3, the IGBT irg 7^{th} and 8^{th} series distinguished from all discrete switches by their maximum current, pulse width and efficiency. IGBT apt45 and apt75 are favorably differing by the rise rate of the pulse. Such types of transistors are most suitable for the design of high-frequency high-voltage pulse generators.

REFERENCES

[1] Fridman G. et al. Applied Plasma Medicine // Plasma Processes Polym. 2008. Vol. 5, № 6. P. 503–533.

[2] T. E. Grigoriev, A. V. Kashin, K. I. Lukanina, I. E. Rebrov // Anniversary XV Kurchatov Interdisciplinary Youth Scientific School, a collection of annotations. – 2017. Vol. 1. P. 132-132.

[3] Khomich V. Yu., Malashin M. V., Moshkunov S. I., Rebrov I. E., Shershunova E. A.// European Power Electronics and Drives Journal. – 2013. - T. 23. № 4. P. 51-54.

[4] S. I. Moshkunov, I. E. Rebrov, V. Yu. Khomich // Izvestia Vyshich Uchebnych Zavedeniy. Fizika. – 2016. - T. 59. № 9-3. P. 110-113.

[1] This work was supported by RSCF № 17-79-10470

LEWIS TRANSFORMER WITH SEQUENTIAL ADDER [1]

KLADUKHIN V.V., NOVOSELOV A.A.

Institute of Electrophysics, Ural Branch, Russian Academy of Sciences, ul. Amundsena 106, Yekaterinburg, 620016, Russia, laepr@iep.uran.ru, +7 (343) 267-87-88

This paper is devoted to generation of nanosecond power pulses with rectangular shape by summarizing identical partial pulses distributed across two-wire transmission lines. The paper shows the transition from Lewis generators [1] use coaxial transmission lines and lumped summator to pulse generators based on transmission lines and spread sequential summators made as a chain of summarizing elements with linearly slowing coupling coefficient. Variants of summarizing elements are given. Numerical simulation of partial currents summation in coupled and partially coupled modes, influence of mismatch on output pulses shape, results were investigated. Peculiarity of pulses generation using transistor switches and short transmission lines were discussed.

[1] *Lewis A.D. // Electronic Eng. – 1955. – V. 27. pp. 448 – 450.*

[1] This work was performed as part of State Task №0389-2015-0026

PULSED POWER GENERATOR BASED ON SEQUENTIAL ADDER AND DOUBLE FORMING LINES [1]

KLADUKHIN V.V., KHRAMTSOV S.P.

Institute of Electrophysics, Ural Branch, Russian Academy of Sciences, ul. Amundsena 106, Yekaterinburg, 620016, Russia, khramtsov@iep.uran.ru, +7 (343) 267-87-88

The paper describes the power pulse generation with rectangular shape by summarizing identical partial pulses formed on double forming lines. The transition from stacked coaxial-line Fitch generators using double forming lines and lumped summator [1] to a scheme of generators that uses double forming lines and spread sequential summators. The operation of generator in matched and mismatched modes were investigated. A dependence of insufficient match and output pulse shape is shown. Some possible designs of generators are given. A possibilities of an approach by example of realization of six-sections quasi rectangular pulse forming generator with the following parameters: pulses duration - 100 ns, power 3.5GW, voltage up to 600kV were shown. The generator uses standard coaxial cables KVI-100, controlled multi-gap gas switch and combined isolating choke based on Ferroxcube ferrites and amorphous strip AM3.

[1] *Fitch R.F., Howell V.T.S. // Proc. IEE. – 1964. – V. 111. – № 4. pp. 849-855.*

[1] This work was performed as part of State Task №0389-2015-0026

CONTROLLED AUTOWAVE MULTI GAP SWITCH [1]

KLADUKHIN S.V., NOVOSELOV A.A.

Institute of Electrophysics, Ural Branch, Russian Academy of Sciences, ul. Amundsena 106, Yekaterinburg, 620016, Russia, novoselov@iep.uran.ru, +7 (343) 267-87-88

This paper describes a scheme (model) of a controlled switch that consists of commutation chain made by sequential connection of identical threshold items. These items are covered by longitudinal capacitive couplings realizes autowave process of overvoltage propagation. Controlled switches with the wide range of capabilities can be made on the basis of this scheme. Switching dynamic processes simulation results with the controlled pulse applied to one side of switch are shown. The design of a multigap gas switch based on the specified scheme that provides guaranteed triple overvoltage on the gaps is described. The design of the switch uses transparent lattice electrodes that promotes ionization of neighbor gas gaps through ultraviolet illumination and runaway electrons. Voltage and current on the gaps of switch, dynamics and a structure of electrical fields in the area of lattice electrodes are given.

[1] This work was performed as part of State Task №0389-2015-0026

A TRIGGERED MULTI-GAP SWITCH WITH A HIGHLY NON-UNIFORM ELECTRIC FIELD AT NEGATIVE POTENTIAL ELECTRODES [1]

A.A. ZHERLITSYN, E.V. KUMPYAK

** Institute of High Current Electronics SD RAS, 2/3 Academichesky ave., Tomsk, 634055, Russia, andzh@oit.hcei.tsc.ru*

The paper describes the design and test results of an electrically triggered multi-gap switch of planar geometry operating in the air at atmospheric pressure. The switch is designed to be used in pulse-periodic generators with a charging voltage of up to 100 kV without oil insulation and a high-pressure gas medium.

When a capacitive energy storage is charging, the voltage in the multi-gap switch is evenly distributed between the intermediate electrodes by a high-resistance voltage divider or due to inter-electrode capacitances. With a planar switch, the capacitance between the intermediate electrodes and the ground becomes significant, which disturbs the uniform distribution of the voltage. We studied an approach in which a sharply-uniform configuration of the electric field in the gaps of the switch provides ignition of the corona discharge in the process of pulsed charging of the capacitive energy storage. The corona discharge current provides a uniform distribution of voltage between the intermediate electrodes of the switch. In addition, the corona discharge provides a more stable generation of initiating electrons in the discharge gaps. As a result, we obtained a 1-σ jitter at the level of ~1 ns.

[1] The reported study was funded by RFBR according to the research project № 18-08-00159-a

PECULIARITIES OF USING THE CHARGING COILS IN FAST LTD CAVITIES

V.M. ALEXEENKO,**, S.S. KONDRATIEV*, V.A. SINEBRYUKHOV*, S.N. VOLKOV*, A.A. KIM**

** Institute of High Current Electronics SB RAS, Tomsk, Russia*
*** National Research Tomsk Polytechnic University, Tomsk, Russia*

The fast LTD cavity with oil insulation contains a number of identical bricks, each brick consists of the spark gap switch and two storage capacitors that are charged in opposite polarity. Usually the capacitors of same polarity in different bricks are connected in parallel by charging resistors made of ~10 mm diameter polyethylene tubes that are filled with $CuSO_4$ water solution. These charging resistors are needed to protect the capacitors in the case several cavity switches prefire.

After some number of shots, inside such charging resistors the gas bubbles begin to grow, its size increases with the number of shots. As the size of the bubble becomes comparable with the tube diameter, the electrical breakdown may appear inside the bubble resulting in the destruction of the tube. In this case the conductive $CuSO_4$ water solution flows into the oil and the cavity must be repaired. To avoid such faults, the charging liquid resistors should be replaced after each ~10^4 shots [1]. This replacement increases the service cost of the large generators containing numerous LTD cavities.

To avoid these problems, in [2] the charging (and trigger) resistors were replaced with the coils made of the resistive metal wire with practically unlimited lifetime. But the authors do not describe what are the requirements to these coils, and what must be the range of their parameters.

In our report we present simulation results of the LTD cavity with the coils in the charging circuit. These results allow to determine the requirements to the charging coils, and to suggest proper materials for their production.

REFERENCES

[1] *Kim A.A., Mazarakis M.G., Sinebryukhov V.A., Volkov S.N. Alexeenko V.M, Kondratiev S.S., Vasiliev S.V.*// Proc. IEEE 20th Pulse Power Conference.- Austin, Texas, USA.- 2015.- pp.196-199

[2] *Zhou Lin, Li Zhenghong, Wang Zhen, Liang Chuan, Li Mingjia, Qi Jianmin, and Chu Yanyun*//Phys.Rev.Accel.Beams. – 2016. – v.19. – 030401

NUMERICAL MODEL OF THE HCEI SWITCH FOR THE FAST LTD CAVITIES[1]

*V.M. ALEXEENKO**, **, *S.S. KONDRATIEV*, V.A. SINEBRUKHOV*, S.N. VOLKOV**

** Institute of High Current Electronics SB RAS, Tomsk, Russia*
*** National Research Tomsk Polytechnic University, Tomsk, Russia*

The LTD cavity includes large number of the spark gap switches, then detailed model of such switch is important for the development of the LTD generators. The existing model [1] predicts the performance of the LTD switch only after the sparks in its gaps appear. In this paper, the new model of the LTD switch is presented, which expands the model [1] by taken into account the influence of the trigger pulse characteristics on such parameters of the switch closure as the time it needs to close, and its jitter. This new model is useful to predict the performance of the switch in different trigger circuits.

REFERENCES

[1] *A.A. Kim, V.G. Durakov, S.N. Volkov, A.N. Bastrikov, B.M. Kovalchuk, V.A. Sinebryukhov, S.V. Frolov, V.M. Alexeenko, L. Véron, M. Toury, C. Vermare, R. Nicolas, F. Bayol, C. Drouilly.//* Известия Вузов. Физика. – 2006. –том 49. – №11.Приложение. – стр. 297

[1] This work was supported by RFBR #18-38-00199

A COUPLED-LINE VOLTAGE DIVIDER FOR RECORDING HIGH-VOLTAGE NANOSECOND PULSES

A. M. EFREMOV

Institute of High Current Electronics, Siberian Branch, Russian Academy of Sciences, 2/3 Akademichesky AvenueTomsk 634055, Russia, efremov@oit.hcei.tsc.ru

To record bipolar nanosecond pulses, ultrawideband voltage dividers are required. Coupled-line dividers [1] having a wider frequency band than the capacitive ones, fit these requirements.

Fig. 1,a illustrates the design of a voltage divider installed into a coaxial path of the transmitting line with the wave impedance of 12.5 Ω. It consists of the upper arm (main transmitting line) and the lower one (measuring line). The measuring line was a double-faced foil-coated fibre-glass plastic of the total length 0.25 мм installed on the internal surface of a 65-mm diameter case. The measuring line is short-circuited at the end. The main line of the divider is formed by a central conductor *4* and a potential plate of the fibre-glass plastic. An attenuated voltage pulse is removed from the fibre-glass plastic plate and is recorded by an oscilloscope through a connector. To prevent the input of the voltage wave into the recording circuit through a slot between the ground plate of the fibre-glass plastic and a case, a thin copper-foil tube *2* is installed into the case hole. One end of the tube is soldered to the ground plate, and another end is expanded and pressed with the case connector. A polyamide insulator *1* is housed into the connector case. The connector was tested under the pressure of up to 100 atm and temperature up to 60 degrees.

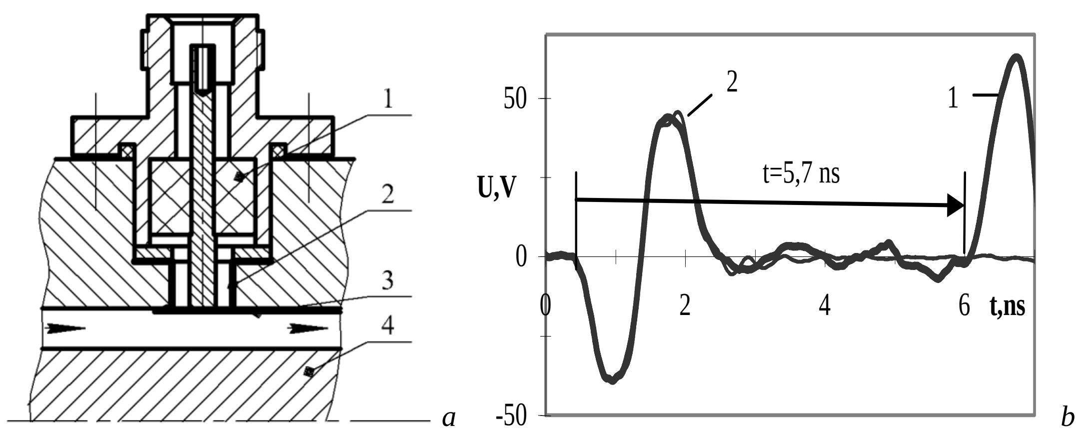


Fig. 1.

Fig.1,b presents the waveforms of a pass-through pulse *2* and a pulse from the divider *1* restored with the coefficient ≈77. A confidence time interval of recording this divider is no more than 5.7 ns. It is determined by the double run of the wave along the measuring line. The voltage divider was used to record bipolar pulses of the amplitude up to 100 kV and length of 2 ns. Similar designs of the dividers were used in the lines with the wave impedance of 50 Ω for transmitting bipolar pulses of the amplitude up to 80 kV and length of 2 and 3 ns [2]. The lines had the length of 750 mm and internal diameter of 16 mm. An attenuation factor of the dividers was ≈70 at the confidence time interval of the reliable recording equal to 9 ns.

REFERENCES

[1] *Efremov A.M., Koval'chuk B.M //* Instruments and Experimental Techniques.-2004.-T. 47.-№ 1. C. 61-62.
[2] *A. M. Efremov, V. I. Koshelev, V. V. Plisko, and E. A. Sevostyanov //* Review of Scientific Instruments. – 2017. – 88. 094705.

NEW GAS SWITCH OPERATING CHARACTERISTICS OF LOW-INDUCTANCE CAPACITOR-SWITCH ASSEMBLY [1]

D. V. MOLCHANOV, I. V. LAVRINOVICH, A. P. ARTYOMOV, D. V. RYBKA

IHCE SB RAS, 2/3 Akademichesky ave., Tomsk, 634055, Russia, cyborgevo2@gmail.com, 8(3822)492335

A new three-electrode gas switch was developed which operates on the "field distortion" principle. One is designed to work in assembly with two low-inductance capacitors, which have operating voltage of ±80 kV, amplitude of the discharge current - about 100 kA and rise time is about 100 ns. On the laboratory bench, the dependences of operate delay time and jitter on the applied voltage in the operating pressure range from 3 atm. to 10 atm. are investigated. Small standard deviation of the triggering time of the surge gap allows to switch a large number of low-inductance capacitor-switch assemblies simultaneously. The obtained operating characteristics of the switch demonstrate the possibility of using it in the LTD technology.

[1] This work was supported by Russian Science Foundation (project №17-79-20292)

STATISTICAL REGULARITY IN LTD TECHNOLOGY

A.A. KIM, V.M. ALEXEENKO*,**, S.S. KONDRATIEV*, V.A. SINEBRUKHOV*, S.N. VOLKOV**

** Institute of High Current Electronics SB RAS, Tomsk, Russia*
*** National Research Tomsk Polytechnic University, Tomsk, Russia*

The LTD technology shows promise for applications that need high-power, high-voltage, high-current output pulses, because it does not require any pulse compression to achieve the short pulse length (<<1us), and because the LTD accelerator may operate in the IVA-mode. One of the requirements to the IVA-mode is that the successive cavities should fire one after the other with the delay the electromagnetic wave propagates between them along the accelerator output line. Since the length of the LTD cavity is ~25 cm, the neighboring cavities should be delayed by ~0.83 ns at vacuum insulation of the line, and by ~7.7 ns at water insulation of the line.

Each LTD cavity includes up to ~40 parallel bricks, each brick with its own spark gap switch, then the jitter of these switches determines the possibility for the cavities to fire with the delay suggested above. Since usually the accelerator load locates in vacuum, vacuum insulation of the output line is preferable because it does not require any plastic interface in the vicinity of the load. But at vacuum insulation the cavity jitter must be minimal to allow the LTD accelerator to operate in the IVA-mode.

In the report we present simulations indicating that the cavity jitter may be expressed as a function of the switch jitter and the brick quantity. This result is discussed in respect to the jitter of the LTD module consisting of multiple series cavities, and to the jitter of the LTD accelerator consisting of multiple parallel modules.

A COMPACT HIGH-CURRENT "FIELD-DISTORTION" GAS SWITCH WITH INCREASED LIFETIME OF SHARP TRIGGER ELECTRODE[1]

Y.A. BYKOV, V.F. FEDUSCHAK, E.G. KRASTELEV, A.A. SEDIN

Joint Institute for High Temperatures, Russian Academy of Sciences, 13b.2 Izhorskaya str., Moscow, 125412, Russia, Yrka.2@mail.ru, 8(916)2664168

A compact 40 kV, 80 kA low-jitter triggered gas switch of "field distortion" type was developed for low inductance "switch-capacitor" modules consisting of two capacitors of 0.35 μF and one switch. The electrode system of the switch includes two main electrodes with toroidal working surface and a disk type trigger electrode. The outer and inner diameters of grounded main electrode are equal to 32 mm and 16 mm, and for the high-voltage electrode they are equal to 22 mm and 9 mm respectively. The trigger electrode in form of hollow rod, gradually turning into a sharp-edged disk, is inserted through the cavity of the grounded electrode. The air at pressure up to 4 atm is used as insulating gas. A stable operation for a long time without degradation of dynamic parameters (time delay, jitter), which is resulted from erosion of sharp edge of the trigger electrode, was achieved by the decreasing of its diameter and removing the disk edge from zone between the tops of the main electrodes. Based on results of electric field calculations and preliminary experiments the diameter of the trigger electrode was chosen equal to 15.8 mm, less than the diameter of inner cavity of 16 mm of the grounded toroidal electrode. The shape of the trigger electrode corresponds to the equipotential surface for a given (by a resistive divider) potential of 1/3 of switch voltage U. For this condition the axial position of the disk edge is 0.8 mm from the top of the grounded electrode and 3.8 mm from the top of the high voltage electrode. Switch tests showed that for positive polarity of applied voltage U of 0.75 of self-breakdown voltage U_{sb} and negative trigger pulse of 2/3U the total time delay including the rise time of trigger pulse of 15 ns is about 27 ns and jitter is ≈1 ns. For $U=0.6U_{sb}$ they are increased to 32 ns and 2 ns respectively. The set of 10 modules is routinely used for driving 20 stages 800 kV linear transformer for fast (≤300 ns) charging of water insulated PFL of a high-current nanosecond accelerator [1]. A stable simultaneous operation of all 10 switches with the maximal deviation of closing time within ±5 ns is observed. No degradation of the switch parameters were registered for more than 200 pulses.

REFERENCES

[1] *Yu.A. Bykov, E.G. Krastelev, G.V. Popov, A.A. Sedin, V.F. Feduschak //* Journal of Physics: Conference Series 830. – 2017. – 012021.

[1] This work was supported by the Russian Science Foundation (project 16-15-10355)

SENSOR OF MEGAAMPERE RANGE CURRENT WITH RISETIME UP TO 100 TA/S

V.A. KOKSHENEV

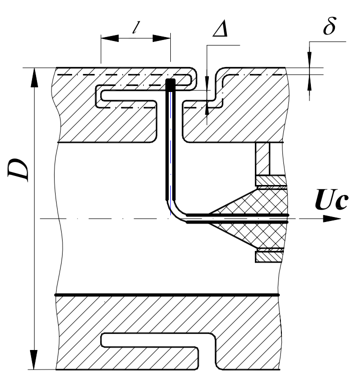
Institute of High Current Electronics SB RAS, 2/3 Akademichesky Avenue, Tomsk, 634055, Russia, vak@oit.hcei.tsc.ru, +7-3822-492-908

In high-power pulse systems it is necessary to measure currents of the mega-ampere range having a pulse front from 10^{-6} s to 10^{-8} s. The use of Rogowski's coil is not always possible for technological and electrophysical reasons. Known are sensors in the form of shielded magnetic loops (B-dot) [1], which measure the derivative of the current in the local region. The GIT-12 installation successfully uses sensors in the form of an inductive groove for measuring *dI/dt*. In this paper, the characteristics of sensors from materials satisfying (necessary) the requirements are considered, the design of sensors of different modifications used for measuring currents with an amplitude of up to 10 MA and a slew rate up to 10^{14} A / s are presented.

The current sensor in the form of an inductive groove (Fig.1) can have a small inductance $L \leq 0.1$ nH and allows to remove the dielectric from the region of formation and registration of the signal. With its help, it is possible to register current on both the external and internal (potential) electrodes. For current form $I(t) = I_0 \cdot \sin(\omega t)$, the current flows in the skin layer $\delta(\text{cm}) \cong 10^4(\rho T/4\mu)^{1/2}$, where ρ – $\Omega\cdot$cm, $T = 2\pi/\omega$ – s, μ – relative permeability of the material. The U_C signal from such a sensor is the sum of two quantities $U_C = U_L + U_R$, where $U_L = LdI/dt$ is inductive, and $U_R = RI(t)$ is the active component. Integration of the quantity $DI = U_C(t)/L = dI/dt + I(t)\cdot R/L$ gives the current $I_C(t) = I(t) + I_R(t)$, which, in addition to the true value of $I(t)$, has an additive $I_R(t)$, associated with the process time parameters and the characteristics of the groove material. This leads to a measurement error $I_R(t)/I(t) \cong (7{,}85\cdot 10^3/\Delta)\cdot(\rho\mu T/4)^{1/2}\cdot(t/T/4)$. Thus, to reduce the measurement error, it is necessary to use a nonmagnetic material with high conductivity.

Evaluation of the measurement error is made for $\Delta >> l$, D and very high frequency. Taking into account the magnetic flux inside the conductor with $\mu \sim 1$ leads to an increase in L and a decrease in the measurement error in $[1+5033(\rho T/4)^{1/2}]$ times. With this correction in the table, the characteristics of the sensors from commonly used materials – stainless steel (SS), copper (Cu) and aluminum (Al) are given. For an iron groove ($\mu \sim 10^3$), the error in measuring the amplitude of a current can be 100% or more, and the transition from SS to Cu reduces the error by 6.5 times. An analysis for the exponential current showed that the measurement error in this case is of the same order of magnitude. When using the parameter $\tau = L/R \cong \pi\cdot 10^{-5}\cdot\Delta\cdot(T/\rho)^{1/2}$ in the above expression for *DI*, the current is calculated using formula (1):

$$I(t) = \exp(-t/\tau_{DI})\int_0^t (DI)\exp(t/\tau_{DI})dt\,. \qquad (1)$$



Table

Material	Cu		Al		SS	
ρ, Ω·cm	$1.75\cdot 10^{-6}$		$2.8\cdot 10^{-6}$		$75\cdot 10^{-6}$	
T/4, s	10^{-6}	10^{-7}	10^{-6}	10^{-7}	10^{-6}	10^{-7}
δ, cm	0.0132	0.0042	0.0167	0.0053	0.0866	0.0274
I_R/I, % Δ=0.5cm	2.63	0.8	3.28	1	15	5.26
τ=*L/R*,μs Δ=0.5cm	24	7.6	19	6	4	1.3

Fig. 1. The design of the current sensor based on the inductive groove

REFERENCES

[1] *W. A. Stygar et al //* in Proc. of the 11th IEEE Int. Pulsed Power Conf. – NJ, 1997. – P 591.

ALTERNATING MAGNETIC FIELD DIFFUSION IN THE INDUCTIVE MEASURING PROBE OF CIRCULAR CROSS-SECTION[1]

G.SH. BOLTACHEV*, S.A. CHAIKOVSKY*,**

*Institute of Electrophysics, UB of RAS, Amundsen str. 106, Ekaterinburg, 620016, Russia, grey@iep.uran.ru, +7 (343) 2678820
**Institute of High Current Electronics, SB of RAS, Akademichesky ave. 2/3, Томск, 634055, Russia, chaikovsky@iep.uran.ru

The influence of the diffusion of an alternating magnetic field ($B_0 = B_m \sin(\omega t)$) into a toroidal single-turn measuring probe of circular cross-section on the measurement accuracy of external field amplitude (B_m) is investigated. Owing to the known skin-effect the magnetic field is ejected partly from the probe and as a result the field amplitude in the space enveloped by the probe coil is changed. The problem on the diffusion of a magnetic field into a measuring probe is solved by analytical methods within simplifying assumptions and numerically for the general case. The probe heating is neglected. The conditions, which are corresponded to a static limit, i.e., when the skin-layer depth (δ_s) is large in comparison with measuring probe sizes, and to a dynamic limit, when $\delta_s \to 0$, are analyzed analytically. In the framework of the numerical solving procedure the space distributions of the magnetic field and the current distributions into the probe cross-section are obtained.

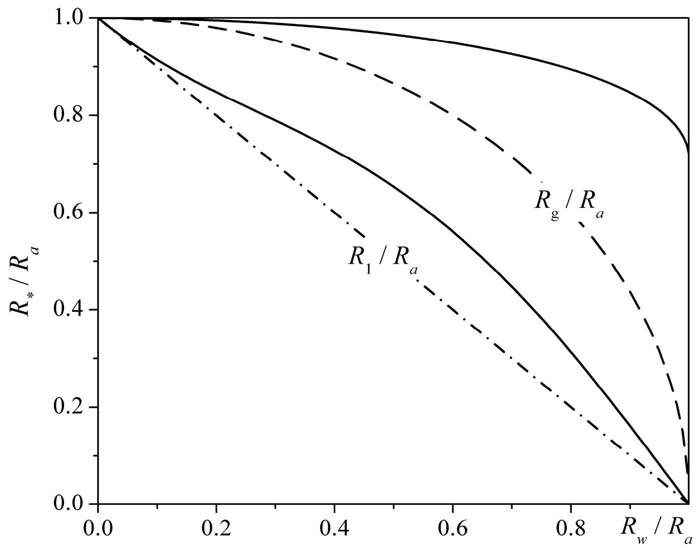


Fig. 1. The "dividing" radius at static limit (upper solid line) and at dynamic limit (lower solid line) in accordance with analytical solutions obtained vs. the radius of the probe cross-section. The dashed line is the geometrical mean radius of the measuring coil, the dotted line is the inner (minimal) radius. The upper figure border, at value of unit, corresponds to the arithmetic mean radius of the coil.

The magnetic flux Φ being measured by the probe is determined by a "dividing" radius R_* so that $\Phi = B_0 \pi R_*^2$. Figure shows the dividing radius values (solid lines), which correspond to analytical solutions obtained for static and dynamic limits. For the sake of viewing simplicity all size quantities are presented in a reduced form using the arithmetic mean (R_a) of the maximal (R_2) and minimal (R_1) radii of the probe ($R_a = (R_1 + R_2)/2$). For comparison the geometrical mean radius $R_g = (R_1 R_2)^{1/2}$ is also showed. It can be seen that with decreasing the measuring coil thickness, i.e., when wire radius $R_w \to 0$, the dividing radius R_* tends to the arithmetic mean R_a value at any ratio of the skin-layer depth (δ_s) and the probe sizes. In the opposite case, at relatively small values of the inner diameter of the measuring coil, i.e., when $R_w/R_a \to 1$, the dividing radius is distinctly smaller than the value of R_a, even at the static limit. At the conditions corresponded to the strong skin-effect the difference increases essentially (see the lower solid line at the figure) and can result in a serious error concerning the measuring magnetic field. In the general case (between the limit curves presented) the dividing radius values are calculated numerically and fitted by a two-parameter function $R_*/R_a = f(R_w/R_a, \delta_s/R_w)$, which is easy-to-use for experimental data processing.

[1] This work was performed as a part of State Task No. 0389-2015-0026 and supported in part by RFBR Grant No. 16-08-00277.

A STUDY OF SHOCK WAVE REGULATION TECHNOLOGY BASED ON PULSED DISCHARGE IN WATER [1]

RONGYAO FU[1,2,3], YAOHONG SUN[1,2,3], XUZHE XU[2,3], YINGHUI GAO[2,3], PING YAN[1,2,3]

[1] Chinese Academy of Sciences, Beijing, 100049, China
[2]Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing, 100190, China
[3]Key Laboratory of Power Electronics and Electric Drive, Chinese Academy of Sciences,Beijing,100190,China
E-mail: furongyao@mail.iee.ac.cn, phone: +86 01082547119

The pulsed discharge technology has relevant requirements for the frequency and amplitude of the shock wave in the application fields such as underwater detection and seismic exploration. The main frequency and magnitude of the shock wave directly determine the propagation distance and the exploration resolution. In this paper, a regulation technology of trigger discharge in time series was proposed through a new type of source system. The rising edge, amplitude and pulse width of discharge current can be can adjusted in a certain range through the technology, and different kinds of shock waves can be gotten. Based on the mathematical relations of discharge current and shock wave in the past references, the circuit simulation of sixteen discharge systems is carried out. Each discharge source is 2kJ, and the maximum discharge current is 10kA. The simulation result shows the feasibility of the shock wave control technology.

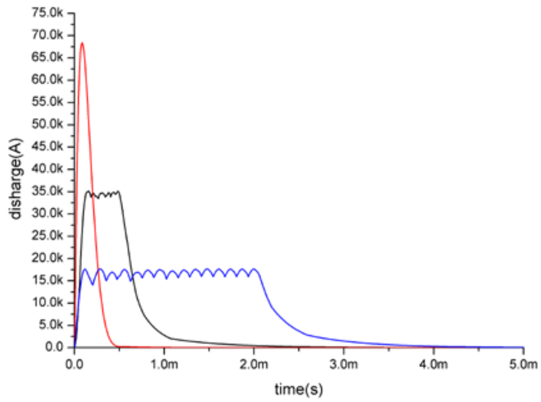


Fig.1 Shock waves of different current

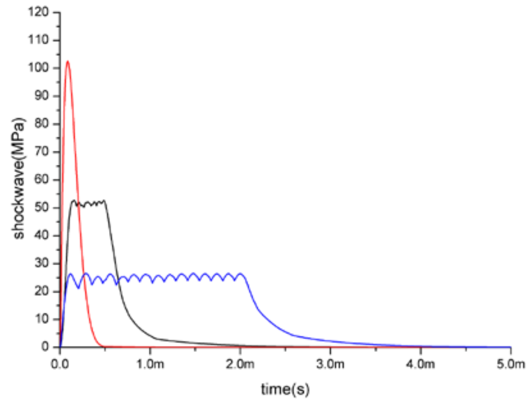


Fig.2 Shock waves of different shapes

Fig.1 Different current waveforms caused by trigger discharge in time series
Fig.2 Different shock waves caused by different different current

REFERENCES

[1] *Touya G, Reess T, Pécastaing L, et al. Development of subsonic electrical discharges in water and measurements of the associated pressure waves[J]. Journal of Physics D Applied Physics, 2006, 39(24):5236-5244(9).*
[2] *Martin J, Reess T, Ferron A D, et al. Influence of hydrostatic pressure and temperature on the water dielectric strength and on the dynamic pressure wave[C]// Power Modulator and High Voltage Conference. IEEE, 2012:370-373.*
[3] *Maurel O, Reess T, Matallah M, et al. Electrohydraulic shock wave generation as a means to increase intrinsic permeability of mortar[J]. Cement & Concrete Research, 2010, 40(12):1631–1638.*

[1] This work was supported by by the National Natural Science Foundation of China according to the Contract No. 51577176.

AL-SI ALLOOY MULTILAYER STRUCTURE FORMATION AFTER ELECTRO-EXPLOSIVE ALLOYING WITH YTTRIUM OXIDE POWDER

V.E. GROMOV , A.M. GLEZER** , Y.F. IVANOV*** , S.V. KONOVALOV**** ,*
*A.A. KLOPOTOV***** , Y.A. RUBANNIKOVA**

**Siberian State Industrial University, Kirov street, 42, Novokuznetsk, 654006, Russia,*
e-mail: gromov@physics.sibsiu.ru, telephone: +73843 462277; +79059663458
***National University of Science and Technology (MISIS), 4 Leninskiy Ave., 119049 Moscow, Russia*
****Institute of High Current Electronics of the Siberian Branch of the RAS, 2/3, Academicheskii Ave., 654052, Tomsk, Russia*
*****Samara National Research University, 34 Moskovskoye Shosse, 443086, Samara, Russia*
******Architecture and Building Tomsk State University, 2 Solyanaya Sq., 634050, Tomsk, Russia*

Today, aluminium alloys are essential in a wide range of industries, such as aircraft and motor car construction, and the manufacture of electrical, railway and other equipment. In recent years, researchers have shown an increased interest in alloys based on the Al-Si system (silumin) [1,2]. This is used as a base in state-of-the-art aluminium foundry alloys, due to its advantageous combination of casting, mechanical and other special operational properties. There are a number of important differences between aluminium and silumin, with the latter being more resistant to corrosion in a humid atmosphere and salt water. It competes successfully with ferrous metals, substituting for or replacing them completely in traditional fields, due to its good handling properties, relatively high levels of physical and mechanical properties and wear resistance. The issue of enhancing the mechanical and strength properties of silumin has therefore grown in importance. This study therefore aims to research the elemental and phase composition and defect substructure state of a eutectic Al-Si alloy subjected to electro-explosion alloying with yttrium oxide powder. Plates of a eutectic Al-Si alloy (silumin) (11.1 Si, 0.58 Mg, 2.19 Cu, 0.92 Ni, 0.25 Fe, 0.029 Mn, 0.047 Ti, 0.005 Cr, balance Al (weight %)) were analysed. Samples took the form of 10×10×5 mm plates. Surficial alloying of silumin with yttrium oxide was achieved using an electro-explosion setup (EVU 60/10M).

Transmission electron microscopy (TEM) of thin foils (JEM-2100F, JEOL) was used to identify the structure and element composition of the modified silumin layer.

A multilayer structure is formed, consisting of a surface layer (layer 1), interlayers (layers 2 and 3), and an interjacent layer (layer 4). Of these layers, layer 2 is the widest, with a thickness of approximately 900 nm, while layer 1 is the thinnest, with a thickness of 100 nm. The most likely causes of the formation of a multi-layer structure include a gradient in the temperature field, variations in the elemental composition, and a gradient in the cooling speed.

These results indicate that the foil section under consideration is a multi-elemental alloy, and that its basic elements are O, Al, Y, Si and Ti. The most likely arrangement of these elements within the material to be analysed was revealed by the mapping method, the results of which show that O and Y atoms are mostly located in layers 1, 2 and 4, atoms of Al in layer 3, and atoms of Si and Ti in layers 1–3.

From the experimental data, it is apparent that layers 1 and 2 have a columnar structure, with the transversal sizes of columns ranging between 60 nm and 75 nm. The transversal sizes of the columns in layer 2 are between 250 nm and 600 nm. Indexing of a micro-electron diffraction pattern shows that these layers are formed by yttrium oxide, Y_2O_3 .

Layers 1 and 2 contain inclusions of the second phase. These are round particles, ranging between 5 nm and 12 nm. Indexing of the micro-electron diffraction pattern presented in Fig. 1b indicates that these particles are aluminium silicates with composition $Al_2 SiO_5$.

Layer 3 has a nanocrystalline structure, with crystalline particles ranging between 5 and 10 nm. The crystals are combined in disoriented regions of between 80 and 150 nm. Indexing of the micro-electron diffraction pattern of this structure reveals reflexes of aluminium oxide with composition Al_2O_3, and aluminium silicate with composition Al_2SiO_5.

Layer 4 has a nanocrystalline structure, in a similar way to layer 3, with crystalline particles of up to 50 nm. Diffraction microanalysis of layer 4, with subsequent indexing of a micro-electron diffraction pattern, reveals reflexes of yttrium aluminide with composition Y_3Al_2 and yttrium silicate with composition $Y_2Si_2O_7$.

REFERENCES

[1] *A. Dziadon, R. Mola, L. Blaz* // Mater. Characterization 118 (2016) 505-513.
[2] *K. Gawdzinska, K. Bryll, D. Nagolska* // Archives of Metallurgy and Mater. 61 (2016) 177-181.

FEATURES OF PROCESS OF AVALANCHE SWITCHING OF SILICON THYRISTORS AT HIGH TEMPERATURE[1]

S.N. TSYRANOV*, O.E. PERMINOVA**

** Institute of Electrophysics UB RAS, 106 Amundsen Str., Yekaterinburg, 620016, Russia,*
E-mail: serg@iep.uran.ru,+79193886860
*** Ural Federal University, 19 Mira St. 19, Yekaterinburg, 620002 Russia*

Operation of the high-power thyristor switching in the impact-ionization mode was studied by numerical simulation methods. Effect of voltage rise rate and temperature on the switching process in a conductive state of Si thyristors is investigated. In the calculations, trigger pulses with voltage rise rates dU/dt varied in the range of 0.5 to 10 kV/ns were applied to the thyristor with bias voltage U_0 = 2.2 kV. The thyristor switch contained tablet thyristor with DC operating voltage of 2.4 kV, and diameter of silicon wafer of 32 mm. In the calculations, temperature of the silicon wafer of T varied from 25 to 200 ^{0}C.

Theoretical researches of switching process of thyristors in comparison with data of experiments allowed establishing the following.

1) Temperature increase leads to decrease in intensity of processes of ionization and for maintaining of ionization rate sufficient for start of an impact-ionization wave, increase in amplitude of an electric field is necessary. It leads to increase in switching voltage of the thyristor with increase in temperature.

2) Increase in temperature leads to rise of equilibrium thermal concentration of electrons and holes in a thyristor. Electron concentration has big value in a neutral part of a n-base whereas in the space charge region (SCR) near the n-p junction it is insignificant. Holes concentration in the SCR is much higher than electrons and it is close to the equilibrium concentration corresponding temperature of thyristor structure. At a temperature over 50 ^{0}C concentration of thermal holes in the SCR begins to exceed characteristic value ~ 10^9 cm^{-3} and start of the impact-ionization wave is carried out by these holes.

3) At a temperature over 140 ^{0}C concentration of thermal holes is compared to doping level in the n-base, what leads to the considerable changes of distribution of an electric field in the SCR. With increase in holes concentration for achievement in SCR of amplitude of an electric field, sufficient for start of the impact-ionization wave, smaller voltage is required. About temperature of ~ 140 ^{0}C of switching voltage of the thyristor reaches a maximum, as this mechanism of the voltage reduction begins to compensate increase in voltage, being a consequence increases in amplitude of an electric field necessary for maintenance of intensity of ionization processes in case of temperature increase. This work continues the research started in [1-2].

REFERENCES

[1] *Gusev A.I , Lyubutin S.K. , Rukin S.N. and Tsyranov S.N. //* Semiconductors. - 2016. - Volume 50. - №3. p. 394-403.
[2] *Gusev A.I , Lyubutin S.K. , Rukin S.N. and Tsyranov S.N. //* Semiconductors. - 2017. - Volume 51. - №5. p. 649-656.

[1] This work was supported by the RFBR under projects number 17-08-00203, 17-08-00406 and 18-08-01390

INDUCTIVE ENERGY STORAGE FOR POWER SUPPLY OF PLASMA CATHODES ON THE BASIS OF LOW PRESSURE ARC DISCHARGE[1]

S.YU. DOROSHKEVICH, V.N. DEVYATKOV, N.N. KOVAL, M.S. VOROBYOV, V.V. YAKOVLEV

HCEI SB RAS, Academichesky av., Tomsk, 634055, Russia, E-mail: vorobyovms@yandex.ru, phone:8(382-2)-492-683

Examples are given of the use of power supplies with inductive output, the load for which is plasma cathodes based on a low-pressure arc discharge. In accordance with the different design of the plasma cathodes used, which can differ not only in geometry, but also in the number of cathode units or in the conditions for generating an electron beam, various circuit solutions for inductive power supplies are considered. The simplicity of the design, the relatively high efficiency (which is related to the possibility of recuperation of the residual energy not given to the load in the primary storage device), as well as the an open-circuit voltage independent of the discharge current make it possible to provide more stable operation of the plasma cathode (in comparison with, for example, sources on the basis of the capacitive storage), and, accordingly, the electron sources as a whole. The examples of solving several customer-specific problems, reflected in the technical specification for the power supply (remote control of beam parameters: amplitude, duration and repetition frequency of beam current pulses, a wide range of discharge currents 10 ÷ 450 A, short current front ≈30 A/μs; ensuring a flat top drop of ± 5-10% in the indicated range of discharge currents and pulse duration up to 500 μs, etc.). Additional possibilities of using electron sources with inductive power supply circuits of a mesh plasma cathode based on a low-pressure arc discharge are considered.

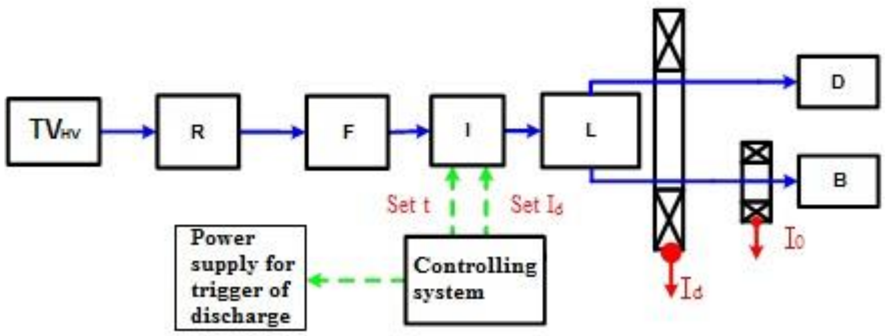


Fig. 1. Block diagram of the discharge power supply: TV_{HV} - high-voltage separation transformer; R - rectifier; F - filter; I - inverter; L - throttle; D - load when the discharge current is closed through the hollow anode; B - load, when the discharge current closes through the accelerating gap (electron beam). Dotted lines marked the connection on the fiber.

REFERENCES

[1] B.Yu. Semyonov. Silovaya electronica: ot prostogo k slojnomu. // Moscow: Solon-press. 2005. 412 p. (in Russian)
[2] *S.P. Bugaev, Yu.E. Kreindel, P.M. Shcanin //* Large-Cross-Section Electron Beams. – Moscow, Energoatomizdat, 1984 (in Russian)
[3] *V N Devyatkov and N N Koval // J. Phys.: Conf. Ser. 2014. V.552. P. 1-4.*
[4] *S. Petrov // Silovaya electronica. 2009. No. 5. P. 74-81.* (in Russian)
[5] *V.O. Oskirko, N.S. Sochugov, A.P. Pavlov // Instruments and Experimental Techniques. 2014. Vol. 57. No. 5, P. 594–600.*
[6] *M. S. Vorobyov, N. N. Koval, and S. A. Sulakshin //* Instrum. and Experim. Techn. 2015. Vol. 58. No. 5. P. 687–695.

[1] The work was supported by the grant of Russian Science Foundation (Projects No 14-29-00091).

FULLY SOLID STATE HIGH VOLTAGE PULSE GENERATOR FOR THYRATRON REPLACEMENT[1]

P. P. GUGIN, M. A. LAVRUKHIN, V. A. KIM

Institute of Semiconductor Physics, Siberian Branch, Russian Academy of Sciences, pr. Akademika Lavrent'eva 13, Novosibirsk, 630090, Russia, gugin@isp.nsc.ru

A nano- and submicrosecond high-voltage pulses solid-state generator with low-voltage power supply designed for tubes and thyratrons replacement for pulse gas lasers pumping and similar tasks was developed and investigated. The results of generator testing in the copper bromide vapor laser pumping circuit with direct and capacitive pumping with a voltage up to 12 kV, pulse repetition frequency up to 100 kHz and a pulse edge 50-100 ns, as well as a primary pumping of "open" and capillary discharge based sharpener with a voltage up to 25 kV, pulse repetition frequency up to 100 kHz, and a pulse edge 200-500 ns are presented.

The generator is a set of parallel-connected forward single-ended quasi-resonance converters connected by a common single-turn primary winding of a step-up transformer made on a ferrite core. The current and rate of its increase is determined by the number of converters and the leakage inductance of the transformer. MOSFET and IGBT transistors can be used as switches in the converters, depending on the specific conditions. To reduce the leakage inductance, the primary winding is formed of a copper foil casing, and the secondary winding is consisted of several parallel windings uniformly distributed around the perimeter of the core. Interwinding insulation can be made of quartz or ceramic parts, which excludes its degradation under the action of the high frequency electric field. The optimum load for this generator is capacitance, because in this case resonant energy transfer from the primary storage device to the load with switching on and off of transistors at zero current is realized.

The main advantages of such scheme in comparison with the common serial connection scheme is the absence of the need for accurate voltage balancing between individual keys, higher reliability due to parallel rather than serial connecting of transistors, and the absence of a high voltage power supply. An additional voltage increase is possible due to the serial connection of the secondary windings of several generators.

[1] This work was supported by RSF project № 14-19-00339.

EFFECT OF ELECTRON-BEAM POLISHING OF ELECTRODES ON HOLD-OFF AT PULSED DC AND MICROWAVE ELECTRIC FIELDS IN VACUUM

A.V. BATRAKOV, I.K. KURKAN, E.V. NEFEDTSEV, S.A. ONISCHENKO, V.V. ROSTOV, R.V. TSYGANKOV

Institute of High Current Electronics SD RAS, 2/3 Academichesky ave., Tomsk, 634055, Russia, alexander.batrakov@yahoo.com

Unlike DC and pulsed DC electric fields, microwave fields cause multipactoring when prebreakdown processes become more complicated. Besides field emission, breakdown strength becomes lowered by gas desorption and its ionization. Rare microwave plasma emits charged particles impacting electrode surfaces and causing secondary emission. That is why degasation of surfaces is as important as smoothing and cleaning. We used electron-beam surface remelting as a technology of surface finishing. The treatment allows one to smooth and to clean surface perfectly. The experimental study involves both the voltage and current measurements and high-speed imaging.

IMPACT OF SNUBBER CIRCUIT INDUCTANCE ON DAMPING LATE CURRENTS IN A PULSED POWER CIRCUIT[1]

H.S. GROVER*, F.P. DAWSON*

*University of Toronto, 27 King's College Circle, Toronto, M5S 1A1, Canada, harpreet.grover@mail.utoronto.ca, +1-647-646-3930

The discharge in a repetitively pulsed TEA discharge gas laser begins its lasing cycle by being homogenous in nature but quickly (10s of ns later) transitions into filamentary mode due to instabilities. This filamentary discharge presents a very low impedance path for the pulsed power circuit and so the current continues to oscillate (resonance) until all of the circuit energy is exhausted. This post lasing remnant circuit energy causes electrode erosion [1] and additional stresses on the thyratron. Ideally, all of the initially stored energy must be deposited in the homogenous discharge at the optimum pumping intensity but there are limits to achieving this, since the discharge instabilities respond to the current density [2]. Therefore, it is very difficult to avoid the filamentary arc discharge mode but efforts can be focused on reducing its intensity.

A snubber circuit can be deployed across the main energy storage capacitor in a pulsed power circuit to dissipate some portion of the remnant circuit energy. The snubber circuit consists of a series string of HV diodes and a series resistor. The diodes become forward biased when the storage capacitor voltage reverses polarity. At the onset time of diode conduction, the discharge is already in the filamentary mode.

The large number of diodes placed in series (to block the initial charge voltage) occupies physical space and thus a parasitic inductance is created within the diode assembly. This inductance value in conjunction with the choice of snubber resistance value can have a significant impact on the post filamentary energy dissipated in the discharge column and in particular the amount of electrode erosion. The following figure shows the total energy dissipated by the snubber circuit in each lasing cycle with a single snubber assembly (dashed curve-about 1.4uH total snubber inductance) and with two snubber assemblies placed in parallel (solid curve – about 1uH total effective snubber inductance). The effective snubber resistance for the two paralleled circuits is the same as the single snubber circuit.

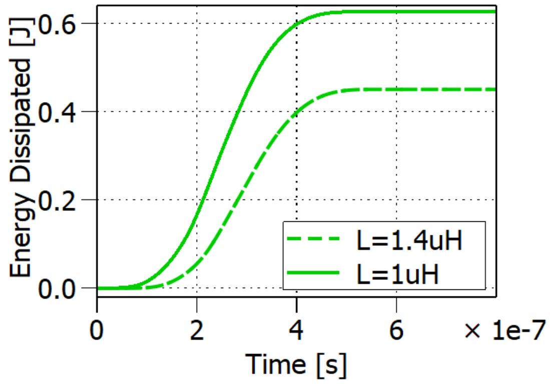


Fig. 1. The total energy dissipated in the snubber circuit [Joules] versus time [sec] for two different parasitic inductance values that were experimentally determined.

From Figure 1, lowering the inductance in the snubber leads to larger energy dissipation in the snubber resistance. Efforts are underway to build a new diode assembly which significantly reduces the assembly parasitic inductance and thus transfer the dissipated energy from the discharge column to the snubber circuit. Experiments have confirmed that a higher dissipation by the snubber results in reduced laser pulse instability and a longer gas lifetime.

REFERENCES

[1] *J. Feldman and E. Williams //* Applied Scientific Research, Section B. – 1962. – Volume 10. – pp. 7-22.

[2] *Y. Korolev and G. Mesyats //* Physics of pulsed breakdown in gases. – Yekaterinburg: URO-PRESS, 1988.

[1] This work was supported by LightMachinery Inc. and NSERC Canada.

NUMERICAL SIMULATION OF COMMON VACUUM DIODE LOAD OF «GAMMA-4» FACILITY

S.YU. PUCHAGIN, V.S. GORDEEV*, K.V. STRABYKIN*, E.A. CHERNYSHEV*, R.P. TRUNTSEVA**

** Russian Federal Nuclear Center – All-Russian Research Institute of Experimental Physics*
FSUE «RFNC-VNIIEF»,37 Mira avenue, Sarov, Nizhni Novgorod region, 607188, Russian Federation,
e-mail: otd4@expd.vniief.ru, fax: (83130)44569

Four-module electrophysical facility «Gamma-4» aimed at producing bremsstrahlung pulses with duration ~50 ns has been built in RFNC-VNIIEF [1]. The operating mode of the facility in which all its accelerating modules are connected in-parallel to the common vacuum diode is under consideration in the paper. In this mode it is planned to increase the X-ray energy density as compared to the mode in which every module has its own separate vacuum diode load. The original variant of the common vacuum diode load was presented in [2]. Numerical optimization of the common vacuum diode design for «Gamma-4» facility has been performed. The criterion of the optimization process was increasing the efficiency of energy and power transmission from accelerating modules to the load. It is shown that the impedance of the diode can be decreased to required value ~0.7 Ohm (matched mode) by changing cathode configuration and adding central anode post. According to the results of simulation it should lead to the rise of the energy and power transmission efficiency by ~30% as compared to the original design of the load.

REFERENCES

[1] *N.V. Zavyalov, V.S. Gordeev, A.V. Grishin et al.* «Design of «Gamma-4» electro-physical facility» // Proceedings of international conference «XVI Khariton's Topical Scientific Readings». Powerful pulsed electro-physics. Collection of reports. Sarov, 2014, pp.32-37

[2] *N.V. Zavyalov, V.S. Gordeev, A.V. Grishin et al.* «Computational justification of the common vacuum diode load for «Gamma-4» experimental facility» // Proceedings of international conference «XVIII Khariton's Topical Scientific Readings». High-power density physics. Collection of reports. Sarov, 2017, pp.136-139

PREDICTIONS OF BREMSSTRAHLUNG DOSE OUTPUT OF «GAMMA-4» FACILITY

S.YU. PUCHAGIN, K.V. STRABYKIN*, V.S. GORDEEV*, R.P. TRUNTSEVA*, E.A. CHERNYSHEV*, A.N. ZALYALOV**

** Russian Federal Nuclear Center – All-Russian Research Institute of Experimental Physics*
FSUE «RFNC-VNIIEF»,37 Mira avenue, Sarov, Nizhni Novgorod region, 607188, Russian Federation,
e-mail: otd4@expd.vniief.ru, fax: (83130)44569

Four-module electrophysical facility «Gamma-4» aimed at producing bremsstrahlung pulses with duration ~50 ns has been built in RFNC-VNIIEF [1]. The facility is planned to be used in two modes. In the first one the accelerating modules are fully electrically independent and each of them ends with separate vacuum diode. In the second one the modules are connected in-parallel to the common diode load to increase the X-ray power density.

The results of calculations of absorbed dose distribution in the near-field are presented for two mentioned operating modes of the facility. The calculations have been made with the aid of S-007 Monte-Carlo code [2] designed in RFNC-VNIIEF. The distributions of absorbed dose in air volume 20x100x100 cm behind the aluminum vacuum barrier have been received.

REFERENCES

[1] *N.V. Zavyalov, V.S. Gordeev, A.V. Grishin et al.* «Design of «Gamma-4» electro-physical facility»// Proceedings of international conference «XVI Khariton's Topical Scientific Readings». Powerful pulsed electro-physics. Collection of reports. Sarov, 2014, pp.32-37

[2] *A.K Zhitnik E.N. Donskoy, S.P. Ognev et al.* S-007 technique using Monte Carlo method of coupled linear equations of neutron, gamma quantum, electron and positron transfer // VANT. Ser.: Mat. Mod. Fiz. Proc. 2011. No 1. pp. 17-24. (in Russian)

STUDY OF MULTI CHANNEL MODE OF GAS-FILLED HIGH VOLTAGE DISCHARGER TRIGGERED BY FIELD DISTORTION[1]

I.S. EGOROV, I.V. BELYUGA

Tomsk polytechnic university, 30 Lenin ave., Tomsk, 634050, Russia, egoris@tpu.ru, +7 3822 60-64-05

Three electrode gas-filled discharger has been tested for commutation of Blumlein of TEMP-2M [1] ion accelerator. A multi-channel discharge mode with triggering by field distortion has been captured in the gap between triggering electrode and anode (Fig. 1). The field distortion has been realized by rapid change of the triggering electrode potential at the moment of saturation of a reactor connecting the trigger and grounded anode.

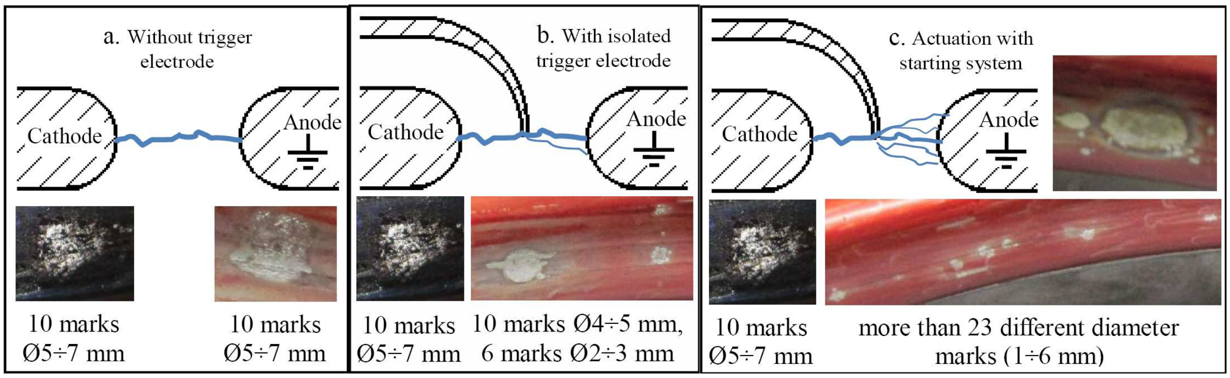


Fig. 1. The marks of discharge channels for different electrode systems after 10 commutations

The tested controllable mode demonstrates less dependence of the commutated voltage from the gas pressure. This feature can be utilized for stabilization of the pulse-to-pulse parameters of the discharger in high repetition rate mode.

REFERENCES

[1] *G. E. Remnev, I. F. Isakov, M. S. Opekunov et al.* // J. Surface and Coatings Technology, 1997, 96, No1. 103-109.

[1] Empirical experiments are carried out at Tomsk Polytechnic University within the framework of Tomsk Polytechnic University Competitiveness Enhancement Program grant.

STUDY OF PROCESS OF AVALANCHE SWITCHING OF SILICON THYRISTORS WITHOUT BIAS[1]

O.E. PERMINOVA, S.N. TSYRANOV***

** Ural Federal University, 19 Mira St. 19, Yekaterinburg, 620002 Russia,*
E-mail: perminova_oe@mail.ru, +79193958322
*** Institute of Electrophysics UB RAS, 106 Amundsen Str., Yekaterinburg, 620016, Russia*

Operation of the high-power thyristor switching in the impact-ionization mode was studied by numerical simulation methods. Effect of voltage rise rate and temperature on the switching process in a conductive state of Si thyristors without bias voltage is investigated. In the calculations, trigger pulses with voltage rise rates dU/dt varied in the range of 0.5 to 10 kV/ns were applied to the thyristor without bias voltage. The thyristor switch contained tablet thyristor with DC operating voltage of 2.4 kV, and diameter of silicon wafer of 32 mm. In the calculations, temperature of the silicon wafer of T varied from 25 to 200 ^{0}C .

Theoretical researches of switching process of thyristors without bias voltage in comparison with data of experiments allowed establishing the following. When switching the thyristor without bias voltage processes of impact ionization occur at the same time in two regions of n-base – in the part of a base filled with the majority carriers and in the space charge region (SCR) near the n-p junction. It is important to note that while in SCR the impact-ionization front is formed, in the part of a base filled with the majority carriers, processes of ionization occur in each point of area. During switching process the contribution of SCR is small both on the rate of votage reduction, and on voltage amplitude, not exceeding 30% of total voltage on the thyristor. At a temperature over 180 ^{0}C, owing to increase in concentration of thermal carriers in the thyristor, ionization processes occur only in SCR. It leads to increase in duration of switching process and increase in residual voltage, which is created in a n-base out of SCR. However, despite it if voltage rise rates rather big also exceeds value of ~ 9 kV/ns, the effect of fast switching of the thyristor exists up to 200 ^{0}C.

Comparing of process of thyristor switching with bias voltage (mode I) and without it (mode II) was shown by the following. In case of room temperature switching voltage in the mode II is less, than in the mode I, and at a temperature over 50 ^{0}C switching voltage in the mode II it is compared and even begins to exceed it in the mode I. In the thyristor in the mode I the impact ionization processes occur only in SCR where impact-ionization front is formed, which passes through the structure of a device and uniformly fills its area with dense electron–hole plasma. During propagation of an impact-ionization front across base of the thyristor of value of amplitude of an electric field, speed of filling of a base with plasma and concentration of plasma in it reach higher values in the mode I than in the mode II. It is necessary to emphasize that such distinction exists at an identical voltage is also a consequence of different geometry of distribution of an electric field in a thyristor basis: in the mode I the field is concentrated in SCR, and in the mode II the field is distributed in all base. This work continues the research started in [1-2].

REFERENCES

[1] *Gusev A.I , Lyubutin S.K. , Rukin S.N. and Tsyranov S.N. //* Semiconductors. – 2016. – Volume 50. – №3. p. 394-403.
[2] *Gusev A.I , Lyubutin S.K. , Rukin S.N. and Tsyranov S.N. //* Semiconductors. – 2017. – Volume 51. – №5. p. 649-656.

[1] This work was supported by the RFBR under projects number 17-08-00203, 17-08-00406 and 18-08-01390

AUXILIARY GLOW DISCHARGE WITH HOLLOW CATHODE AND HOLLOW ANODE IN THE TRIGGER UNIT OF COLD-CATHODE THYRATRON[1]

N.V. LANDL, Y.D. KOROLEV, V.G. GEYMAN, O.B. FRANTS, G.A. ARGUNOV, I.A.SHEMYAKIN

Institute of High Current Electronics, Akademichesky Ave. 2/3, Tomsk, 634055, Russia, landl@lnp.hcei.tsc.ru

Since the end of 1980s, considerable interest has been generated to a new type of low-pressure high-current switching device with a cold cathode (the pseudospark switch) [1–5]. A range of operating pressures of the switch corresponds to the conditions of the left branch of Paschen's curve when the electron free path for ionization is much in excess of the electrode separation. For both self-breakdown of the main gap of the switch and for external discharge triggering a considerable pre-breakdown electron current is required [2, 4]. This current is provided due to a trigger unit that is placed in the main cathode cavity [3].

Various types of the trigger units are used in the switches [2, 3, 6]. One type of the trigger devices is based on an auxiliary low-current hollow-cathode glow discharge. In the sealed-off thyratrons, that are produced commercially, trigger unit consist of hollow cathode and ring anode. For reduction of auxiliary discharge ignition and burning voltages, a special high emissivity tablet is used. It represents a cylinder that is fabricated from powder materials by means of hot-pressing and sinter technology and is placed at the bottom of the cavity of auxiliary discharge. Unfortunately, the tablet composition effects to the parameters of the auxiliary discharge. In turn, the conditions of the auxiliary discharge burning determine the rating characteristics of the switch itself [7].

In this report, the data on the regimes of the auxiliary glow discharge with a hollow cathode and hollow anode are presented. As a distinct from the sealed-off thyratrons with the ring anode of a trigger unit, current investigations were carried out with the sealed-off and demountable thyratrons with modernized trigger unit without high-emissivity tablet. The electrodes of the modernized trigger unit represent two cups, faced to each other by open sides. Two discharge regimes were observed: the so-called hindered glow discharge and the conventional glow discharge. A model of the current sustainment in a hollow-cathode discharge is proposed. Instead of the conventional secondary emission coefficient, the model uses a generalized emission coefficient that takes into account not only ion bombardment of the cathode, but also the emission current from an external source [4, 8]. The results of calculations agree well with the experimental data.

REFERENCES

[1] *K. Frank and J. Christiansen.* // IEEE Trans. Plasma Sci. –1989. – vol. 17 – pp. 748-753

[2] *Yu.D. Korolev and K. Frank.* // IEEE Trans. Plasma Sci. – 1999. – vol. 27. – pp. 1525-1537

[3] *V.D. Bochkov, V.M. Dyagilev, V.G. Ushich, O.B. Frants, Y.D. Korolev, I.A. Shemyakin, K. Frank //* IEEE Trans. Plasma Sci. – 2001. – V. 29. – No. 5. – pp. 802–808.

[4] *Yu.D. Korolev, O.B. Frants, N.V. Landl, I.A. Shemyakin and V.G. Geyman.* // IEEE Trans. Plasma Sci. – 2013. – vol. 41. – pp. 2087-2096

[5] *B.L. Meena, S.K. Rai, M.S. Tyagi, U.N. Pal, M. Kumar and A.K. Sharma.* // J. Phys. Conference Series – 2010. – vol. 208. – article number 012110

[6] *Yu.D. Korolev, N.V. Landl, V.G. Geyman, O.B. Frants, A.V. Bolotov, //* AIP Advances. – 2017. – vol. 7. – No 7. – article number 075116

[7] *Yu.D. Korolev, N.V. Landl, V.G. Geyman, O.B. Frants, I.A. Shemyakin, V.S. Kasyanov, A.V. Bolotov, //* Plasma Physics Reports. – 2018. – vol. 44. – No 1. – pp. 112-120

[8] *Yu.D. Korolev, N.V. Landl, V.G. Geyman, O.B. Frants, I.A. Shemyakin, V.O. Nekhoroshev //* Plasma Physics Reports. – 2016. – vol. 42. – No 8. – pp. 799-807

[1] This work was supported by the Russian Science Foundation under the Grant # 14-19-00139

METHODS OF TRIGGERING FOR THE COLD-CATHODE THYRATRON WITH NANOSECOND OPERATION STABILITY[1]

G.A. ARGUNOV, N.V. LANDL*, Y.D. KOROLEV*, V.G. GEYMAN*, O.B. FRANTS*, P.A. BAK**, A.V. AKIMOV***

**Institute of High Current Electronics, Akademichesky Ave. 2/3, Tomsk, 634055, Russia, argunov.grigory@yandex.ru*
*** Budker Institute of Nuclear Physics, Acad. Lavrentieva Pr., 11, Novosibirsk, 630090 Russia*

At present, there is a great interest to the high-current low-pressure switching devices with the hollow cathode (pseudospark switches) for different applications [1-3]. The design and principle of operation of these switches are close to those of a classical hot-cathode hydrogen thyratron. However, these devices do not have a hot cathode, that is a great advantage from a viewpoint of a device lifetime. Therefore, pseudospark switches are often called cold-cathode thyratrons or thyratrons with a grounded grid [3, 4].

Under certain conditions, it is possible to achieve a very short delay time to breakdown of the main gap of a cold-cathode thyratrons relative to the triggering pulse, the jitter in delay time being within a few nanoseconds [4, 5]. This allows one to use such thyratrons in complex electrophysical systems consisting of a large number of devices operating in parallel. As an example, thyratrons are used in the scheme of a pulsed modulator of a linear inductive accelerator with the maximum voltage of 2.5 MV [6, 7]. The scheme uses 96 TPI1-10k/50 cold-cathode thyratrons with the maximum current of 10 kA and an anode voltage of up to 50 kV, which are switched on in parallel.

A range of operating pressures of the switch corresponds to the conditions of the left branch of Paschen's curve. Under such conditions the electron free path for ionization is much in excess of the electrode separation. For both self-breakdown of the main gap of the switch and for external discharge triggering a considerable prebreakdown electron current is required [8]. For the external triggering, this current is provided due to a special trigger unit that is placed in the cathode cavity of the main gap [4, 8, 9].

Various types of the trigger units are used in the switches. One type of the trigger units is based on an auxiliary low-current hollow-cathode glow discharge. In the commercially produced sealed-off thyratrons, trigger unit consist of hollow cathode and ring anode. For reduction of auxiliary discharge ignition and burning voltages, a special high emissivity tablet is used.

The tablet composition effects on parameters of the auxiliary discharge and on rating characteristics of the switch itself [3]. In particular, depending on the regime of the auxiliary discharge and the tablet composition the delay time to breakdown in the main gap of the thyratron relatively to the trigger pulse varies from pulse to pulse.

In this report the results of investigation of sealed-off prototype of cold-cathode thyratron with modernized trigger unit are presented. As a distinct from the commercially produced sealed-off thyratrons, in the thyratron under investigation electrodes of the trigger unit represents two cups, faced to each other by open sides. As a result, discharge ignition occurs over the “long path” and suitable discharge burning and ignition voltages are provided. Different triggering schemes were tested. It is show the ability of prototype operation with the nanosecond stability at high anode voltages.

REFERENCES

[1] *J. Zang, X. Liu. //* Physics of Plasma. – 2018. – vol. 25. – No 1. – article number 013533.
[2] *J. Vieker, K. Bergmann //* Journal of Physics D - Applied Physics. – 2017. – vol. 50. – No 34. – article number 345601.
[3] *Yu.D. Korolev, N.V. Landl, V.G. Geyman, O.B. Frants, I.A. Shemyakin, V.S. Kasyanov, A.V. Bolotov, //* Plasma Physics Reports. – 2018. – vol. 44. – No 1. – pp. 112-120
[4] *V.D. Bochkov, V.M. Dyagilev, V.G. Ushich, O.B. Frants, Y.D. Korolev, I.A. Shemyakin, K. Frank //* IEEE Trans. Plasma Sci. – 2001. – V. 29. – No. 5. – pp. 802–808.
[5] *Yu.D. Korolev, N.V. Landl, V.G. Geyman, A.V. Bolotov, V.S. Kasyanov, V.O. Nekhoroshev, S.S. Kovalsky //* IEEE Trans. Plasma Sci. – 2015. – V. 43. – p. 2349
[6] *P. V. Logachev, G. I. Kuznetsov, A. A. Korepanov, A. V. Akimov, S. V. Shiyankov, O. A. Pavlov, D. A. Starostenko, and G. A. Fat'kin //* Instrum. Exp. Tech. – 2013. – V. 56. – p. 672
[7] *A. V. Akimov, V. E. Akimov, P. A. Bak, V. D. Bochkov, L. T. Vekhoreva, A. A. Korepanov, P. V. Logachev, A. N. Panov, D. A. Starostenko, and O. V. Shilin //* Instrum. Exp. Tech. – 2012. – V. 55. – p. 218
[8] *Y.D. Korolev, K. Frank //* IEEE Trans. Plasma Sci. – 1999. – V. 27. – p. 1525.
[9] *N.V. Landl, Y.D. Korolev, O.B. Frants, V.G. Geyman, A.V. Bolotov //* J. Phys.: Conf. Series. –2015. – V. 652. – 012050.

[1] This work was supported by the Integrated Program for Basic Research of SB RAS "Interdisciplinary integration studies" on 2018-2020., the project "Study of low-pressure high-current pulsed discharges and the development of the switch prototype for the parallel switching in accelerator LIU-20"

INVESTIGATION OF ARC MOTION IN RAILGUN GAS SWITCH IN OSCILLATORY REGIME OF DISCHARGE

A.V. KHARLOV, *E.V. KUMPYAK, G.V. SMORUDOV, N.V. TSOY*

Institute of High Current Electronics 2/3 Academichesky Ave., 634055, Tomsk, Russia, akharlov@lef.hcei.tsc.ru

Discharge of a capacitive storage on a load with unipolar pulse is employed for pumping of powerful lasers and also for feeding of electromagnetic launchers, and pulsed high magnetic field facilities. Spark gaps are often used to commute energy on a load. Triggered spark gaps with electrodynamical acceleration of spark channel were developed and investigated by Kovalchuk and colleagues for the unipolar pulse mode [1-3]. In some applications oscillatory regime (underdamped sinusoidal) has to be realized for the capacitor bank discharge. In particular, it is valid for a pulsed electromagnetic forming (EMF) technology, which is used for assembling welding, cutting, and forming the details of products in various branches of industry [4]. Spark gaps, developed for unipolar discharge, cannot directly be employed in under-damped (oscillatory) regime, because at current transition through zero the arc channel could stop motion and ignite at initial place on the following half period. Process of the arc ignition and motion became more complicated in the oscillatory regime of capacitor bank discharge. Compact gas switch, intended for operation in oscillatory (low damping) regime of discharge, was introduced in [5]. It is two-electrode switch with electrodynamic acceleration of a spark channel and a matched series injection trigger generator. Two operations regimes have been investigated, namely “fast” regime with current amplitude ~ 160 кA, total charge ~ 12 C, period of oscillations 60 µs, full pulse length ~ 400 µs and “slow” regime with current amplitude ~ 30 кA, total charge 18 C, period of oscillations 360 µs, full pulse length ~ 3 ms. The spark gap is designed for 50 kV charging voltage, at a current up to 200 kA, and up to 20 C charge transfer.

Two main objectives were pursued in this work: 1. develop test bed on base of the switch [5] for investigation of the spark channel motion for the oscillatory regime of capacitor bank discharge; 2. Investigate arc motion by use of optical and electrical probes depending on the current and charge transfer in wide operation range and compare it with simulations.

In this report we present the test bed shematics and results of the tests.

1. *B. M. Kovalchuk, A. V. Kharlov et al // Rev. Sci. Instrum.* – 2008. – 79. – 053 504.
2. *B. M. Kovalchuk, A. V. Kharlov et al. //* IEEE Transactions on Plasma Science – 2008. – 36. – 2651-2657.
3. *B. M. Kovalchuk, A. V. Kharlov et al // Rev. Sci. Instrum. – 2015. –**86**, –123 504*
4. *V. Psyk, D. Risch, B.L. Kinsey, A.E. Tekkaya, M. Kleiner. Journal of Materials Processing Technology. – 2011. – **211,** p. 787.*
5. *A. V. Kharlov, B. M. Kovalchuk,. E.V. Kumpyak, and N. V. Tsoy. Journal of Instrumentation – 2017. – **12** JINST T10009*

* Work supported by a Russian Foundation for Basic research grant 18-08-01209

DESTRUCTION FEATURES OF STEEL INDUCTORS WITH NITRIDED WORKING SURFACE UNDER STRONG MAGNETIC FIELD GENERATION[1]

PAVEL RUSSKIKH, A.V. SPIRIN, S.N. PARANIN, D.S. KOLEUKH, V.I. KRUTIKOV

Institute of Electrophysics UB of RAS, Amundsen str. 106, Yekaterinburg, 620016, Russia, russkikh_p@inbox.ru, +7(343)267-88-27

Poor durability of tool coils (inductors) for magnetic pulsed treatment of hard metals, e.g., steel welding, is the main technical problem in this pulsed technology. Usually, coil failure occurs at working surface where material is subjected to intense thermo-mechanical stresses due to pulsed current concentration at surface layer. It is supposed that modifying the inductor current-carrying layer, changing its conductivity and strength, may improve the inductor performance [1]. We consider structural steels as alternative inductor materials instead of high strength copper-based alloys due to their low cost, high strength, easy machining, and applicability to plasma nitriding. Electrical and mechanical properties of nitrided structural steels and their durability in pulsed high magnetic field are the key aspects of the study.

The work concerns an experimental observation of destruction features of massive single-turn coils of several steel grades, including 30ХГСА, 40Х, 50ХГА, 38Х2МЮА, 3Х2В8Ф, 4Х5В2ФС, and У8А, which had an inner channel surface modified by ion plasma nitriding at low temperature (400–500°C). The coils without plasma treatment were also studied for comparison. Electrical resistivity of nitrided steels and resistivity temperature dependence as compared with untreated steels has been investigated. A microstructure and microhardness profiles across near-surface layer of treated and untreated inductors, applied for high magnetic field generation, has been studied. The coils were designed as duplex cylindrical inserts (magnetic flux concentrators, field shapers) having an inner channel of 10 mm in diameter and placed for testing inside an outer coil. Magnetic field of 50 T in amplitude and rising time 6 μs inside the concentrators was generated by the outer coil. Experimental and analytical methods used and previous results on durability testing of some steel coils are described in [2].

In contrast to the just thermal treated steels, the brittle rupture of the inner surface as the microcrack network was observed for nitrided samples (*Fig. 1*). It is considered to be the main mechanism of failure of the inductors with modified surface during the first several pulses; the following destruction is caused by the "saw effect" – spark erosion due to the crack vicinity overheating by high pulsed current (peak current was about 800–900 kA). Failure of the inductors without plasma treatment occurs after the tens of pulses due to the residual deformation as furrows which is caused by instability of inductor channel surface under the action of high magnetic field pressure. Further this furrows, directed along the inductor channel (transversely to the current), result in straight cracks formation. Thus, the inductors of different steels with and without plasma treatment were compared on durability in pulsed high magnetic field.

Fig. 1. Inner channel view of nitrided and without plasma treatment inductors after testing (B=50 T). Durability is in brackets.

REFERENCES

[1] *Shneerson G.A., Dolotenko M.I., Krivosheev S.I. //* Strong and superstrong pulsed magnetic fields generation. – Berlin/Boston: Walter de Gruyter GmbH, 2014.

[2] *Spirin A., Krutikov V., Koleukh D., et al. //* Journal of Physics: Conf. Series. – 2017. – V. 830. – 012080.

[1] This work was performed within the state task No. 0389-2015-0025, partly financed by RFBR grant No.16-08-00919, and research project of RAS program No.18-2-2-8).

INITIATION OF PARTIAL DISCHARGES IN OIL SHALES

A.A. BUKHARKIN*, S.M. MARTEMYANOV*

* *Tomsk Polytechnic University, Lenina street 30, Tomsk, 634050, Russia, amplexor@ya.ru, 89138862206*

Oil shales have been considered for several decades as a fuel-energy and chemical-technological raw material. However, environmentally safe, cost-effective and universal technology for the development of shale deposits is not exists. Technologically, one of the simplest methods of producing the deposit is to heat the rock to the temperature of the thermal transformations of the heavy organic components of the formation into lighter and volatile ones directly underground. From a technical point of view, heating by the current of an industrial frequency that flows directly into the rock is optimal. Due to the high resistance of the rock [1], such a method of thermal conversion is possible if the conductive channel is created directly in the formation.

In the vast majority of cases, an increase in temperature and partial discharges (PD) lead to an increase in the conductivity of dielectrics and weakly conducting materials [2]. Partial discharges occur in places of high local stresses and lead to a treeing, i.e. the growth of tree-like discharge structures (dendrites), and subsequent breakdown [3]. It is technically and energetically inexpedient to perform a thermal breakdown of industrial volumes of oil shale in underground conditions. Thus, the PD plays the main role in the formation of a conducting channel for the thermal conversion of rock.

The characteristics of the PD are affected by the structure and electrophysical properties of the individual components of the material. Microscopy of oil shales and experiments on the initiation of the PD in the rock (Table 1) were carried out.

Table 1. Experiments data.

Series 1				Series 2			
U_{PD}, V	L, mm	E_{PD}, V/mm	q_0, pC	U_{PD}, V	L, mm	E_{PD}, V/mm	q_0, pC
500	51	9,8	0,34	860	210	4,1	0,97
530	54	9,8	0,24	590	192	3,1	0,52
570	49	11,6	0,67	850	202	4,2	0,65
500	45	11,1	0,54	850	204	4,2	0,44
640	50	12,8	0,43	800	198	4,0	0,81
610	51	12,0	0,22	820	200	4,1	0,36
500	45	11,1	0,92	760	205	3,7	0,28
500	46	10,9	0,3	820	203	4,0	0,41
750	52	14,4	0,51	Average			
700	55	12,7	0,5	793,75		3,9	0,6
Average							
580		11,6	0,5				

U_{PD} – PD inception voltage; L – interelectrode distance; E_{PD} – average PD inception stress; q_0 – average value of the apparent charge of a single initial PD.

Due to the significant heterogeneity and very heterogeneous structure, the rock possesses semiconductor properties [4]. As a result, the voltage and the average stress of the PD inception low. In addition, the determining factor of PD initiation is precisely the value of voltage, not stress. This distinguishes partial discharges in oil shales from the PD in dielectrics.

REFERENCES

[1] *V. V. Lopatin, S. M. Martemyanov // Russian Physics Journal. – 2012. – Volume 55. – № 5. pp511-515.*

[2] *A.I. Dolginov // Tekhnika vysokikh napryazheniy v elektroenergetike.* – M., "Energiya", 1968.

[3] *L.A. Dissado, J.C. Fothergill //* Electrical degradation and breakdown in polymers. – Peter Peregrinus Ltd., London, United kingdom, 1992.

[4] *Dortman N.B. // Fizicheskiye svoystva gornykh porod i poleznykh iskopayemykh (petrofizika). Spravochnik geofizika. Izdaniye 2.* – Nedra, Moskva, 1984.

STUDY ON SERIES OF MULTI THYRISTOR FOR HIGH VOLTAGE AND REP-FREQUENCY POWER SUPPLY

YINGHUI GAO, JING HAN, KUN LIU, YAOHONG SUN, PING YAN

Institute of Electrical Engineering, Chinese Academy of Sciences Key Laboratory of Power Electronics and Electric Drive No 6 zhongguancun beiertiao , Beijing, 100190

In resent years, high-voltage microsecond discharge technology was used to collect the high resistivity dust and get better effect of dust removal. But the high-voltage microsecond electrostatic precipitators is hard to be developed, because the power supply needs to have the higher output power, higher output voltage and microsecond period pulsed width. Figure 1 showed the topology of the high-voltage microsecond electrostatic precipitator. It is realized by a microsecond pulsed power supply superimposed on a high-voltage DC power. The current and voltage waveforms of the high-voltage switch were showed in figure 2.

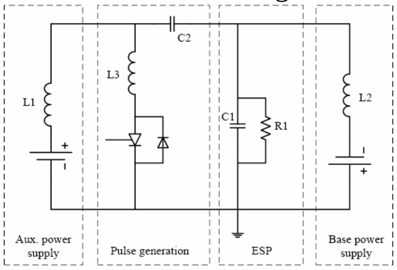


Fig. 1. Topology circuit of the high-voltage microsecond electrostatic precipitator.

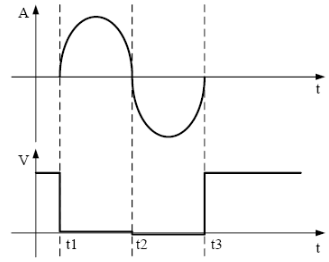


Fig. 2. The current and voltage waveform of the high-voltage switch.

In the study of electrostatic precipitator pulse power supply [1-2] , a 60kV pulse power supply is needed. The output pulse width of the pulse power supply should no more than 150us and the output current should reach 500A. The repeat frequency of the pulse power supply should be 100Hz. Based on these demand, a 20kV high-voltage switch model was studied firstly, which is the technical exploration of the final 60kV high voltage switch.

According to the waveform shows in figure2, at the same time, considering of the withstand voltage and reverse recovery time, the thyristor was selected [3-4] . The switch is composed of twenty 1800V-800A thyristor in series, and each thyristor connect with an 1800V-800A diode in reverse parallel. The structure of the 20kV switch is showed in figure 3. The 20kV high-voltage switch was tested in a test circuit and figure 4 is the current and voltage waveforms of the switch.

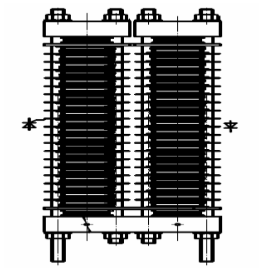


Fig. 3. Structure of the 20kV switch.

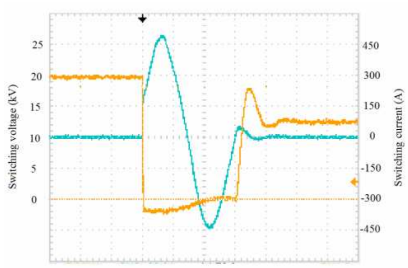


Fig. 4. Current and voltage waveforms of the 20kV high-voltage switch.

The 20kV high switch worked well. In the near future, we will development a 60kV pulse power supply using three 20kV high switches in series. In addition, less pulse width with the series technology of thyristors is wanted to be obtained.

REFERENCES

[1] *Grass, N., Hartmann, W., and Klockner, M.,* "Application of different types of high-voltage supplies on industrial electrostatic precipitators," IEEE Transactions on Industry Applications, vol. 40, no. 6, pp. 1513-1520, 2004.

[2] *Grass, N., Hartmann, W., and Klockner, M.,* "Microsecond pulsed power supply for electrostatic precipitators," in IEEE 2001 Industry Applications Conference, 2001, pp. 2520-2524.

[3] *Welleman, A.; Waldmeyer, J.; Fleischmann, W.,* "Semiconductor components & solid state switches for pulsed power applications," in 2004, pp174-177.

[4] *Huang, A.Q.; Motto, K.; Yuxin Li,* "Development and comparison of high-power semiconductor switches," in 2000 Power Electronics and Motion Control Conference, 2000, Vol. 1, PP. 70-78.

[5] *Nishikawa, K.; Okino, A.; Watanabe, M.; Hotta, E.; Ko, K.-C.; Shimizu, N.* "High rep-rate operation of pulsed power modulator using high voltage static induction thyristors," in IEEE 2001 Pulsed Power Plasma Science Conference, 2001, pp.44.

THE USE OF NANOSECOND ELECTRON BEAM FOR THE EGGS SURFACE DISINFECTION IN INDUSTRIAL POULTRY[1]

S. Yu. SOKOVNIN ** ***, I.M. DONNIK*, I.A. SHKURATOVA****, A.S. KRIVONOGOVA* ****,*

A.G. ISAEVA ****, M.E. BALEZIN* *** R.A. VAZIROV* ***

**Urals State Agrarian University, 42 Karl Liebknecht Str., Yekaterinburg, 620075, Russia, e-mail: sokovnin@iep.uran.ru, +73432678782*
***Ural Federal University, 19 Mira Str., Yekaterinburg, 620002, Russia*
****Institute of Electrophysics Ural Division Russian Academy of Sciences, 106 Amundsen Str., Yekaterinburg, 620016, Russia*
*****Urals State Scientific Research Institute of the Veterinary Medicine, 112A Belinsky Str., Yekaterinburg, 620142, Russia*

Development of technology bases of egg disinfection using of surface irradiation is executed by the nanosecond electron beam. The essence of technology is that in case of shell eggs irradiation by the accelerated electron beam due to matching of electrons energy is chosen such profile of distribution of the absorbed dose in the product that in case of irradiation to destroy all kinds of microorganisms, including pathogenic (salmonellas, yersiniya, clostridia, toxigenic stocks of colibacillus, cocci, fungi), both on the shell surface, and in its pores and the air camera, up to the putamen. At the same time irradiation of the protein is practically not made by the accelerated electrons but only at the expense of the arising bremsstrahlung.

Were made experiments on shell eggs irradiation on the frequency nanosecond URT-0,5 [1] accelerator (electron energy up to 500 keV, pulse width about 50 ns, pulse repetition rate up to 200 pps). Was executed determination of absorbed dose distribution on depth in polyethylene was carried out by method of a gray wedge, and also using of the film dosimeter measurement of electron beam absorbed dose on the shell surface and under the shell, and also under the absorber layer (polyethylene 80 microns thick). For determination of absorbed dose distribution of bremsstrahlung in egg was used TLD-500 thermoluminescent dosimeters.

The received results allow to draw the conclusion that in case of irradiation by the electron beam with absorbed dose level 5 kGy, it's enough for the full disinfection of the surface and pores of egg shell, the absorbed dose in the egg at the expense of bremsstrahlung won't exceed 0.08 Gy which can't have essential action on protein.

Is made irradiation of shell eggs batch in plastic packaging the size of 100 pieces which were pledged in an incubator together with an inspection lot of not irradiated egg. The percent of deductibility of eggs and survival of chickens of pilot and control batches were identical that it specifies lack of significant radio biological effect from irradiation of egg internal structures [2]. The received chickens were grown up within the 5 weeks. It is established that the chickens who are grown up from the irradiated egg have no essential differences in development. According to the obtained results, it is proposed to use this sterilization method for eggs in industrial poultry farming.

REFERENCES

[1] *S.Yu. Sokovnin, M.E. Balezin // Radiation Physics and Chemistry. -2018-V.- 144- p. 265-270..*
[2] *Sokovnin S.Yu., Krivonogova A.S., Isaeva A.G., Shkuratova I.A., Donnik I.M., Drozdova L.I. // International Journal of Advanced Biotechnology and Researc. -2017- V. - 8 - I - 2 - p.680-686*

[1] This work was performed within a support of the Russian Science Foundation project No 16-16-04038.

PHYSIOLOGICAL MECHANISMS OF NANOSECOND REPETITIVE PULSED MICROWAVE EXPOSURE ON THE ORGANISM

ANNA V. KEREYA[,**], MICHAEL A. BOLSHAKOV[*,***], LUBOV P. ZHARKOVA[*,***], OLEG P. KUTENKOV[*], VLADISLAV V. ROSTOV[*]*

[*]Institute of High-Current Electronics SD RAS, Academic avenue, 2/3, Tomsk, 634055, Russia, E-mail: kereya21@mail.ru, tel: +7 3822 493191,
[**] Siberian state medical university, Moscow highway, 2, Tomsk, 634050, Russia
[***] National research Tomsk state university, str. Lenin, 36, Tomsk, 634050, Russia

The brain plays the most important role in the regulation of all physiological functions of the body. White adipose tissue is an important neuroendocrine organ, it can change the activity of the brain through its biologically active substances, and therefore, it can influence functioning of the body. Reasoning from the foregoing, our aim was to study the effects of nanosecond repetitive pulsed microwaves (RPMs) on the brain and epididymal adipose tissue of mice locally, and to find the dependence on the pulse repetition frequency.

40 outbred white male mice with a weight of 25–30 g were used for our experiments. The experiments conformed to all ethical rules and standards for treatment of animals. Within 10 days, the region of the mice head and epididymal adipose tissue was daily exposed to a single irradiation with 4000 RPM pulses at a peak power density of 1500 W/cm^2 and repetition frequency of 6, 8, 13, 16, and 22 Hz. The RPM source was a laboratory generator based on a MI-505 magnetron (carrier frequency 10 GHZ, pulse duration 100 ns). To provide a local exposure, the body of the mice was covered with a radiation-absorbing material. The irradiation time was varied from 3 to 20 min depending on the pulse repetition frequency. The effect of RPM exposure was estimated from the changing of: behavioral responses and general motor activity of mice by the open field-test; neuronal activity of brain structures by the level of early response protein (c-fos); the mass of some organs and epididymal adipose tissue.

The research data allows the conclusion that direct nanosecond RPM irradiation of the brain changed brain activity. That effects appeared as a significant multidirectional changes in behavioral responses, in the dynamics of general motor activity, in the neuronal activation of the hypothalamus and the reticular formation, in feed intake, in the mass of animals and internal organs including epididymal adipose tissue, as well as in the content of hormones of corticosterone and leptin. Furthermore, direct nanosecond RPM irradiation of the epididymal adipose tissue significantly changed the state of laboratory mice. Specifically, the RPMs were able to change the morphometric parameters of the adipose tissue itself, change the content of leptin and corticosterone in the blood serum, as well as change the behavioral responses of animals. The pulse repetition frequencies of 6, 13 and 22 Hz were the most effective physiologically.

The results allow suggesting a possible physiological mechanism of the RPMs action on the body of mice. Under this mechanism, the hypothalamus and the hippocampus as well as a number of biologically active substances, associated with the functioning of adipose tissue, participate in the formation of body reactions. All of the revealed reactions indicates a potentially adverse influence of RPMs on the mice body, even to the development of stress. This should be taken into account in the practice of the operation of nanosecond RPM sources.

The work was supported by the program of the Presidium of the Russian Academy of Sciences No.10 "Powerful ultrashort electromagnetic pulses, as well as their interaction with objects and media."

A HIGH-CURRENT NANOSECOND ELECTRON ACCELERATOR MIR-M FOR BIOMEDICAL RESEARCH[1]

Y.A. BYKOV, V.F. FEDUSCHAK*, A.V. IVANOV**, E.G. KRASTELEV*, A.A. SEDIN*, A.M. SHISHKIN**, V.P. SMIRNOV**

**Joint Institute for High Temperatures, Russian Academy of Sciences, 13/19 Izhorskaya str., Moscow, 125412, Russia, Yrka.2@mail.ru, 8(916)2664168*

***Russian Scientific Center of Roentgenology, 86 Profsoyuznaya str., Moscow, 117997, Russia*

A high-current electron accelerator MIR-M for biomedical studies of the reaction of healthy and tumor tissues, as well as cell cultures, exposed to X-ray radiation with extremely high dose rate - up to 100 MGy/s at absorbed doses of 0.5 to 20 Gy in the single pulse, was developed and constructed. The main parameters of the accelerator are the next: accelerating voltage – up to 800 kV, peak current – up to 50 kA, e-beam pulse duration - ≈80 ns. The pulsed power system of the accelerator includes primary energy storage in form of 10 compact low-inductance modules, each of them consisting of two capacitors and one switch, 20-stages linear pulsed transformer, water insulated pulse forming line, self-breaking main water switch and a stepped transformer line. Several different in design diodes were constructed for experiments with horizontally or vertically oriented X-ray beams. Anodes made of 100 μm Ta foil are used as converters of X-ray radiation together with located downstream carbon layer of 0.5-1 mm thick for capturing electrons that have passed through the foil. The desired cross-section of the X-ray beam is defined by Pb-collimators integrated in the anode unit of the diodes. Two methods of dose measurements are used in experiments: TLD dosimeters DTG-4 calibrated at dose of 7 Gy by Rokus-AM (60Co-based therapeutic gamma source) and Gafchromic EBT 3 films (Ashland, USA) processed using DoseLab 6.5 (Moebius Medical Systems, USA).

The design and parameters of the main systems and elements of the accelerator together with the methods of measurements and first results of a comparative analysis of the effects of irradiation in vivo and in vitro using therapeutic devices (X-ray therapy apparatus T-200 with a dose rate of 11 mGy/s and apparatus "Rokus-AM" with a dose rate of 8.4 mGy/s) and accelerator MIR-M will be presented and discussed.

[1] This work was supported by the Russian Science Foundation (project 16-15-10355)

COMPARISON OF ACCELERATION FOR DIFFERENT METALLIC FLYERS ON THE ANGARA 5-1 INSTALLATION[1]

S.I. TKACHENKO[*,**], *G.M. OLEINIK*[*], *E.V. GRABOVSKI*[*], *A.N. GRIBOV*[*], *A.O. SHISHLOV*[*], *K.V .KHISHCHENKO*[***]

**"State Research Center of Russian Federation Troitsk institute for innovation end fusion research. Pushkovykh street, vl. 12., Troitsk, Moscow, 108840, Russian Federation*
***Moscow Institute of Physics and Technology (State University), 9 Institutskiy per., Dolgoprudny, Moscow Region, 141700, Russian Federation*
****Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya 13 Bldg 2, Moscow 125412, Russia*

On the Angara-5-1 installation the megabar pressure is generated by the magnetic field produced by the current up to 6 MA and the linear density up to5 MA/cm (see Figure 1). In loading of the sample by high pressure one can study the dynamic characteristics of substances at sub-microsecond processes [1]. The acceleration experiment of the flyers made from duralumin, copper and titanium were carried out. The numerical simulation in frame of MHD model with semiempirical equation of state [2] was carried out to estimate the parameters of the flyer made from these metals at the action on it the current with a linear density of ~ 4.5 MA/cm. The time dependencies of the velocity for different layers of flyers and the distribution of the temperature, density, pressure and current density in different time over its thickness were obtained. A comparison of the simulation results and experimental data is presented and we can state that numerical results are in good agreement with experimental ones. It was obtained velocity up to 10 km/s during the investigations with duralumin flyer with a thickness of ~ 0.6–0.8 mm.

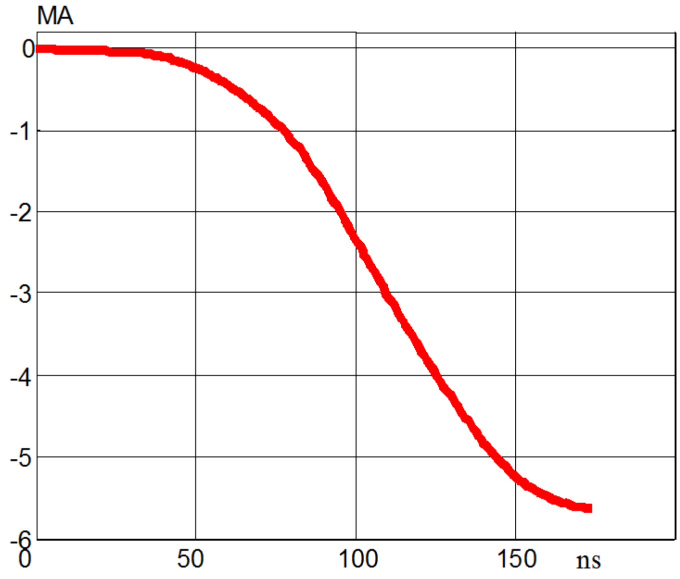


Fig. 1. The time dependence of the current obtained by the miniature probe near the load

REFERENCES

[1] *G.I. Kanel, S.V. Razorenov and V.E. Fortov* // Shock-Wave Phenomena and the Properties of Condensed Matter – New York: Springer, 2004.
[2] *V.E. Fortov, K.V. Khishchenko, P.R. Levashov and I.V. Lomonosov* // Nucl. Instr. Meth. Phys. Res. A – 1998. – Volume. 415. Page. 604

[1] This work is funded by the Russian Science Foundation under Grant 16-12-10487

ALL SOLID-STATE MODULARIZED SPARKER USED FOR METALLIC ORE EXPLORATION[1]

Y. SUN,** , X. XU* , R.FU*,** , P. YAN*,***

**Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing 100190, China*
***University of Chinese Academy of Sciences, Beijing 100049, China*

The seismic exploration was mainly used for detecting the information of the underground structure and stratum. Because most of the metallogenic belt of metal ores are in the orogenic belt, the surface and subsurface geological conditions are very complicated, the conventional seismic exploration techniques (such as dynamite source, vibrator, airgun, sparker[1], etc.) can not meet such applications.

In this paper, a new type of all solid-state modularized sparker was presented, which consists of four pulsed power modules (50kJ per module at 10kV, total stored energy of 200kJ). Each module mainly consists of an isolated diode, a pulse capacitor, a thyristor switch, a freewheeling diode and a discharging electrode. Compared with the dynamite source, the main frequency of the seismic wave generated by the sparker is higher, which indicates that higher detecting resolution can be obtained. The seismic profile based on the field experiments shows that the detecting depth is more than 2000m.

REFERENCES

[1] *Yaohong Sun, Ping Yan, etc.* A High-power Sparker and its Applications. Power Modulator Symposium, 2006. P.508-5 86310.

[1] This work was supported by National Natural Science Foundation of China (51277171), National R&D Projects for Key Scientific Instruments (ZDYZ2012−1−06).

INTENSIFICATION OF THE OUTPUT OF CHEMICAL ELEMENTS FROM ORE IN CONDITIONS GLIDING DISCHARGE[1]

LI HONGDA, S.A. SOSNOVSKIY**, V.I. SACHKOV***, B.B. KUDABAYEV****, M.A. KAZARYAN*****,*

*V.G. ROZDOLSKIY*******

**Ph.D., Shenyang Polytechnic University, assistant professor, 6 Nanping Middle Rd, Hunnan Qu, Shenyang Shi, Liaoning Sheng, Shenyang, 110168, China*

***Candidate of Physical and Mathematical Sciences, Senior Researcher«Innovative-technology center» of Siberian physical-technical institute of Tomsk state university, Novosobornaya sq. 1, Tomsk, 634050, Russia, ssa777@mail.ru, +7(913)815-98-04*

**** Doctor of Chemical Sciences, head «Innovative-technology center» of Siberian physical-technical institute of Tomsk state university, Novosobornaya sq. 1, Tomsk, 634050, Russia*

*****Leading engineer, Engineering School of New Manufacturing Technologies, Tomsk Polytechnic University, Lenin Ave. 30, Tomsk, 634050, Russia*

******Doctor of Physical and Mathematical Sciences, Leading Researcher, The Lebedev Physical Institute of the Russian Academy of Sciences (LPI RAS), 53 Leninskiy Prospekt, Moscow, 119991, Russia*

*******Master of Scienc, Engineering School of Nuclear Technology, Tomsk Polytechnic University, Lenin Ave. 30, Tomsk, 634050, Russia*

"Thermal" spark discharges, seldom appliedfor water treatment, are characterized with high, up to 20000 ˚C, temperature in the discharge channel and may be used for the initiation of high-temperature reactions. Electric discharge in oxygen-nitrogen mixtures inevitably results in the formation of nitrogen oxides, i.e., NO, NO_2, N_2O_3, and N_2O_5, forming aqueous nitrite- and nitrate-anions. The accumulation of the anions, may occur useful in treatment of process solutions. The main discharge products in the "air-solution" system are active oxidizers: short-living particles O, OH, HO_2, capable to influence the solutions directly during the electrodischarge treatment. The more stable discharge products, first of all, nitrogen compounds can accumulate in solutions and provide their higher activity for a longer time.The electrical discharge in the air induces the formation of nitrogen oxide NO which is oxidized by oxygen in the air and the active discharge particles to NO_2, N_2O_3, and N_2O_5 in the gas phase. When dissolved in water, nitrogen oxides form nitric (HNO_3) and nitrous (HNO_2) acids.

The experimental device includes the reactor with mechanical stirrerand the high-voltage pulse generator. The reactor is placed onto the 3-L tank containing solutions and ore to be treated. The factors influencing the characteristics of the discharge and, thus, the production of anions, were electric conductivity and initial pH of solutions. The treatment of solutions with electric discharges results in the decreased pH due to accumulation of nitric acid. The temperature of the solutions in experiments stabilized around 20 ˚C at the ambient temperature of 16 to 20 ˚C. The time of treatment was varied from 20 to 60 min, during which thesolution passed the discharge zone for a few times. The inner space of the reactor is open for pressure equalizing. The gas and liquid mixing conditions remained constant in all experiments. The electrode system was composed of high-voltage and earthed electrode. The solid-state magnetic pulse generator was used in the discharge generation. The generator consists of a thyristor pulse shaper followed by a high voltage step-up transformer and magnetic compression stages. Was used gliding discharge at atmospheric pressurewith mechanical stirring of the liquid phase.

The current and voltage waveforms were registered with the oscilloscope Tektronix TDS2014 using low-inductance resistive current sensor and high-voltage divider. The energy released in the electrode systems was calculated by integrating the current and voltage oscillograms. The energy of the pulse was determined by the energy accumulated in the generator's storage capacitor. The concentration of nitrite-ions was measured colorimetrically. The nitrate concentration was measured with the glass ion-selective electrode. The concentration of ozone in the gas phase was measured using gas analyzer ; aqueous ozone was determined iodometrically. The treatment of solutions "thermal" spark discharge results in accumulation of both nitrates and nitrites. This is determined by a slow oxidation of primary nitrogen monoxide and predominant accumulation of NO and NO_2 in the gas phase.

The sum accumulation rate of aqueous nitrogencontaining anions for the spark discharge is from 2 to 4 times higher than for the pulsed corona and dielectric barrier ones, have a potential in initiating reactions in process solutionsat an intensification of allocation of chemical elements from ore in a liquid phase.

[1] This work was supported by obtained within the framework of the state task of the Ministry of Education and Science of the Russian Federation, project N°. 10.3031.2017 / 4.6 and with the support of the TSU Competitiveness Enhancement Program.

METHODS FOR INCREASING THE BREAKDOWN VOLTAGE IN THE COLD-CATHODE THYRATRON[1]

N.V. LANDL, Y.D. KOROLEV, V.G. GEYMAN, O.B. FRANTS, G.A. ARGUNOV, V.S. KASYANOV, V.O. NEKHOROSHEV

Institute of High Current Electronics, Akademichesky Ave. 2/3, Tomsk, 634055, Russia, landl@lnp.hcei.tsc.ru

At present, there is a great interest to the high-current low-pressure switching devices with the hollow cathode (pseudospark switches) for different applications [1-4]. The design and principle of operation of these switches are close to those of a classical hot-cathode hydrogen thyratron. However, these devices do not have a hot cathode. Therefore, pseudospark switches are often called cold-cathode thyratrons or thyratrons with a grounded grid [4, 5].

As in the case of classical thyratrons, a range of operating pressures of the switch corresponds to the conditions of the left branch of Paschen's curve. Under these conditions the electron free path for ionization is much in excess of the electrode separation. For both self-breakdown of the main gap of the switch and for external discharge triggering a considerable pre-breakdown electron current is required [6].

On the other hand, the presence of a pre-breakdown current is the major reason preventing the voltage of a thyratron breakdown from being increased [7]. One of the solutions to this problem is the use of so-called blocking electrodes [8, 9]. Their aim is to block the charge carriers produced in the cathode cavity to be extracted on the blocking electrode rather than in the main discharge gap. The blocking electrodes are commonly introduced into the region of the main gap or hollow cathode. However, there are no such electrodes in the serially-produced sealed-off devices.

Another method for method for increasing the breakdown voltage is the use of a multi-stage structure of the main gap [5]. To do so, a few gradient electrodes are introduced into the main gap, which separate it into several sections. The sections are formed so as to make the breakdown voltage of each section comparable to that of the main gap of a single-stage thyratron. As a result, the high voltage applied to the thyratron anode is distributed between the stages in such a way that the pre-breakdown current is generated in the main gap at a higher voltage.

One of the effective methods for breakdown voltage increasing is the use of a pulsed charging. Due to the pulsed charging high overvoltages can be achieved at the thyratron main gap. The shorter charging time allow higher overvoltage.

In this work a number of methods for increasing the breakdown voltage of the cold-cathode two-sectioned sealed-off thyratron TPI1-10k/50 thyratron (maximum current 10 kA for anode voltage up to 50 kV) are proposed and tested. It is shown that due to the forced distribution of the voltage between the thyratron sections and pulsed charging the breakdown voltage can be increased up to the 50%/

REFERENCES

[1] *J. Zang, X. Liu. //* Physics of Plasma. – 2018. – vol. 25. – No 1. – article number 013533.

[2] *N. Kumar, R.P. Lamba, A.M. Hossain, U.N. Pal, A.D.R. Phelps, R. Prakash //* Applied Physics Letters. – 2017. – vol. 111. – No 21. – article number 213502.

[3] *J. Vieker, K. Bergmann //* Journal of Physics D - Applied Physics. – 2017. – vol. 50. – No 34. – article number 345601.

[4] *Yu.D. Korolev, N.V. Landl, V.G. Geyman, O.B. Frants, I.A. Shemyakin, V.S. Kasyanov, A.V. Bolotov, //* Plasma Physics Reports. – 2018. – vol. 44. – No 1. – pp. 112-120

[5] *V.D. Bochkov, V.M. Dyagilev, V.G. Ushich, O.B. Frants, Y.D. Korolev, I.A. Shemyakin, K. Frank //* IEEE Trans. Plasma Sci. – 2001. – V. 29. – No. 5. – pp. 802–808.

[6] *Y.D. Korolev, K. Frank //* IEEE Trans. Plasma Sci. – 1999. – V. 27. – pp. 1525.

[7] *N.V. Landl, Yu.D. Korolev, V.G. Geyman, O.B. Frants, G.A. Ardunov* // Russian Physics Journal. – 2017. – V. 60. – No. 8. – pp. 1269-1276

[8] *V. D. Bochkov, A. V. Kolesnikov, Y. D. Korolev, et al.* // IEEE Trans. Plasma Sci. – 1995. – V. 23. – No. 3. – pp. 341-346.

[9] *M. Stetter, P. Felsner, J. Christiansen, et al.* //// IEEE Trans. Plasma Sci. – 1995. – V. 23. – No. 3. – p. 283.

[1] This work was supported by the Russian Science Foundation under the Grant # 14-19-00139

RESEARCH DISINFECTIVE EFFECT OF JOINT ACTION OF THE NANOSECOND ELECTRON BEAM AND PLASMA RADIATION OF THE GAS DISCHARGE[1]

S.YU. SOKOVNIN, **, ***, A.S.KRIVONOGOVA*, ****, A.G.ISAEVA*, ****, M.E. BALEZIN*, ****

**Urals State Agrarian University, 42 Karl Liebknecht Str., Yekaterinburg, 620075, Russia,*
e-mail: sokovnin@iep.uran.ru, +73432678782
***Ural Federal University, 19 Mira Str., Yekaterinburg, 620002, Russia*
****Institute of Electrophysics Ural Division Russian Academy of Sciences, 106 Amundsen Str., Yekaterinburg, 620016, Russia*
*****Urals State Scientific Research Institute of the Veterinary Medicine, 112A Belinsky Str., Yekaterinburg, 620142, Russia*

Was investigated the combined action by the nanosecond electron beam (NEB) and plasma radiation of nanosecond gas discharge of high pressure to study t he possible synergy sterilizing effect. Plasma radiati on was carried out by the the GVI-150 [1] generator which loading was a discharge camera. Pulse repetition rate of the generator operation was 37 pps, distance from electrodes cutoff to processed samples ~ 5 cm.

For research of bactericidal action of pl asma radiation on the m icrofloor of eggs wer e used food table eggs. They were laid down in plastic containers o n 10 pieces. On the fe eding table plas tic containers are tossed through a work space of installat ion (by electrodes cutoff), being irradiated by plasma. To except UV radiation losses in container material the cover w as not closed. After processing cont ainers with eggs overturned and eggs irradiated with plasma radiation on the other hand.

Experiments on irradiation by NEB were made on the pulse and periodic nanosecond accelerator URT-0,5 [2] (electrons energy up to 500 ke V, a pulse dur ation 50 ns, pulse repetition rate up to 200 pps). In t he course of the experiments the acceler ator worked in the modes in case of the charge voltage 30 kV. On the feeding table plastic containers on 10 eggs are tossed through the work space of installation, being exposed to radiation by NEB, uniform on width.

At first batches of eggs w ere irradiated by plasma radiation, and then the by NEB. The time container spent under plasma radiation changed from 0 to 5 minutes, the absorbed dos e (AD) of different batches changed from 0 to 5 kGy.

Was investigated survival of standard representatives of opportunistic and pathogenic microflora on the egg surface at the combined processing by nanosecond electron beam and plasma radiation. Researches were conducted by rines test fr om the egg surface with the subsequent crops on st andard nutrient mediums, a thermostat control, allocation of pure cultures and identification of microorganisms.

Were used standard strains of microorganisms Salmonella. Carried out crops on dense nutrient medium (Endo's circle) from cultivation of 5 billion/ml. Right after crops petrie disches exposed by NEB with the AD 1,2,3 and 5 kGy. Experiment was made in 3 parallels, control tests were in the same conditions, as skilled, but weren't processed by NEB. After radiation dishes w ere placed in the the rmostat and incubated at t he temperature 35-37 °C within 24 h ours. Further ca rried out calculation of colonies number on nutri ent mediums (KOE).

Is received the big data array on jo int action of NEB and plas ma radiation for several ty pes of widespread microorganisms. Is found the synergetic effect of NEB influence and plasma radiation on microorganisms of the sort Klebsiella: at AD of NEB 3 kG y these m icroorganisms are sowed when processing by plasma 0-1 minute, and at 3-5 minutes perish – in these tests there is no growth.

REFERENCES

[1] *Соковнин С.Ю, Балезин М.Е., Булдаков И.А., Заякина О.М. // Abstracts Russian-Chinese Workshop "Perspective Plasma Technologies PTT-2007", Томск - 2007- с.38-39.*

[2] *S.Yu. Sokovnin, M.E. Balezin // Radiation Physics and Chemistry. -2018-V.144- p.265-270..*

[1] This work was performed within a support of the Russian Science Foundation project No 16-16-04038.

RESEARCH OF LUMINOPHORES AFTERGLOW UNDER INFLUENCE OF PULSED X-RAY RADIATION OF NANOSECOND DURATION

A.S. CHEPUSOV, A.A. KOMARSKIY*, S.R. KORZHENEVSKIY*, Y.I. MAMONTOV**, A.V. PONOMAREV**

**Institute of Electrophysics, 106 Amundsena St., Ekaterinburg, 620016, Russia, apon@iep.uran.ru, +79226133593*
***Ural Federal University, 19 Mira St., Ekaterinburg, 620002, Russia*

The work describes an investigation of afterglow of various luminophores under influence of pulsed X-ray radiation of nanosecond duration. As a source of radiation a pulsed X-ray “Yasen-01” apparatus is applied. Maximum impulse current of an X-ray tube is 150 A. Maximum electron energy is 120 keV. Half-height pulse duration of an X-ray burst is about 15 ns. A pulse repetition rate is up to 4 kHz.

Two types of X-ray luminophores based on gadolinium oxysulfide Gd2O2S:Tb and cesium iodide CsI have been investigated. The novelty of the work is use of a fast-acting solid-state semiconductor photomultiplier. It allows recording changes of luminophores luminosity in the nanosecond time range. The photomultiplier is characterized by having two discreet outputs for measuring quickly and slowly time-changing light flows. Presence of two signal outputs allows recording changes of luminophores luminosity both during fast nanosecond excitation and during long-time afterglow.

Obtained data about the nature of afterglow of investigated luminophores makes it possible to select the best one for use in conjunction with a pulsed X-ray apparatus with a high pulse repetition rate.

GENERATOR OF POWERFUL CURRENT PULSES FOR ELECTROSTIMULATED DRAWING PROCESS[1]

*V. A. KUZNETSOV *, E. A. KUZNETSOVA *, V. E. GROMOV*, D. A. KOSINOV *, A. P. SEMIN **
** Siberian State Industrial University, Kirov street, 42, Novokuznetsk, 654006, Russia, e-mail: gromov@physics.sibsiu.ru, telephone: +73843 462277; +79059663458*

For the intensification of wire drawing processes of difficult to deform alloys the generator of powerful current pulses is necessary. The diagram of economical and high speed pulse generator with the thyristor converter application is given. The generator forms the single pole current pulses of sinusoidal form with 120 μs duration, up to 500 Hz frequency and up to 10 kA amplitude. The principle of generator operation is based on the periodical discharge of the precharged capacitor to low ohmic load. For the pulse amplitude value control the two-circuit system of subordinate current control is realized. The internal circuit of the automatic control system is organized as the circuit of current charge control and the external circuit – the control of capacitor charge voltage. In connection of high operation speed of transient processes at electrostimulated drawing the control of the parameters by hand is practically impossible and it resulted in the necessity of creation of the automated speed operational systems of drawing parameters' control.

The system of electrostimulated drawing parameters (the temperature in the zone of deformation and drawing force) forming the control signal to the generator of powerful current pulses is presented. For the realization of possibility of pulse amplitude regulation and the increase in its power, two nonreversive unidirectional thyristor convertors connected in series and enabling to obtain the variable voltage at power capacitors are used in the charge device instead of the non-variable source of direct current.

One of the inherent factors in the electro-plastic effect should be the low temperature in the zone of deformation, usually not more than 250-300 0C. The increase in temperature results in the change in the properties of the material being processed, most often as in plastic deformation with heating. In this case the change in the plasticity of the metal is amenable to the other physical laws. So, in electro-stimulated drawing it is necessary to the keep watch on the temperature in the zone of deformation allowing no its increase.

With the aim of increasing the reliability and quality of electrostimulated drawing process with the use of powerful current pulse generator the automatic control system of elecrtrostimulated drawing process (SAUESV) containing the single circuit system of draw force regulation as well as the delayed temperature feedback in the zone of deformation is realized. The dependences of change in draw force and temperature on the frequency of pulse repetition are obtained according to the results of carried out laboratory investigations and computations using the well-known and ingenious techniques. It is known that in motion of wire the efficiency of electro-plastic effect as well as the temperature in the zone of deformation will change in connection with the decrease of time while the deformed part of wire is current effected. In order to simplify SAUESV the dependences of force and temperature on the frequency of current pulses are linearized in the processes of wire motion.

Model SAUESV in «Matlab-Simulink» medium is made for the analysis of modes of operation at of electrostimulated drawing with the use of control system. The model is adequate to real parameters obtained in the processes of electroplastic effect investigation. The designed model enabled to improve the technical characteristics and modes of system operation. The block diagram, the model of the system in Matlab-Simulink medium, the oscillograms of transient processes are represented.

The uncontrolled decrease in the rate of electro motor results in the increase in temperature before the beginning of the cutting off. In this case the temperature stabilizes out a prescribed (maximum) level under the insignificant decrease in the force of drawing. At the regaining of the required rate the optimal process of electrostimulated drawing is restored.

The single circuit system of automatic control of draw force with flexible temperature feedback in the zone of deformation enables to optimize the modes of operation as well as to increase the reliability of electrostimulated drawing process. The system is introduced to industry at elecrostimulated wire drawing.

[1] This work was supported by project No. 16-32-60048 mol_a_dk

HARDWARE PROVISION OF ELECTROSTIMULATED MACHINING OF METALS

V.A.KUZNETSOV , V.E.GROMOV , E S.KUZNETSOVA , A.YU.GAGARIN , D.A.KOSINOV , YU.RUBANNIKOVA

Siberian State Industrial University, Kirov street, 42, Novokuznetsk, 654006, Russia,
e-mail: gromov@physics.sibsiu.ru, telephone: +73843 462277; +79059663458

The progress in the development of the modern metal working technologies is connected with the application of electric currents of the high density [1]. Especially, it is concerned with the metallurgical, aircraft, automobile and aerospace branches of industry. In shaping of the metal parts the current effects are the multiple-factor ones and they consist in the decrease of forces in metal working, the flow stresses, the increase in plasticity, the acceleration of ageing and recrystallization, the decrease in the grain size, the decreasing in the residual stresses, the decrease in the elastic recovery [2]. It is concerned with the processes of forging and rolling [3], drawing, metal working, joining of materials, sintering, sheet forging.

In spite of the intensification of deformation the reliable experimental and theoretical ideas of the processes of plastic deformation are very limited and the physical nature of metal plastification effect is studied not evidently. It retards the application of the promising phenomenon in metal shaping technology. The solution of problems in the investigation of the mechanisms of developed electrostimulated plastic deformation and its practical application in metal shaping is possible only with the use of the sources of powerful short current pulses.

For the electrostimulated metal working the different sources of direct, alternating and pulse current with different forms and parameters of frequency, duration and amplitude depending on the concrete type of production, the technological process, the material are used.

A promising approach to the shaping of steel is the use of powerful unipolar current pulses with the following characteristics: amplitude 10–15 kA; pulse frequency up to 400 Hz; pulse length up to 100 μs. The widespread industrial use of this technique is hindered by the low efficiency of the corresponding pulse generators, which also draw considerable power from the ac grid and are not sufficiently controllable. In the present work, a generator of powerful unipolar current pulses that is free of those defects is described. It includes a charging system connected to power capacitors; and a thyristor switch that discharges the capacitors to a low-resistance load. To reduce the power drawn from the grid, the generator includes a recharging device based on a thyristor, which is connected to a reverse-parallel thyristor switch. To permit regulation of the pulse amplitude and increase its power, the uncontrollable dc source in the charging system is replaced by two irreversible thyristor converters in series. That permits control of the voltage at the power capacitors. To optimize capacitor charging, a two-loop subordinate control system regulates the parameters of the pulse generator: the external control loop governs the voltage charging the capacitors, while the internal control loop governs the charging current. MATLAB Simulink software is used to create a model of the proposed generator. The model corresponds to the actual pulse generator used at Siberian State Industrial University to investigate the electrostimulated plastic deformation of metals and alloys. The model permits improvement in the characteristics of the pulse generator and its operating conditions. A benefit of the proposed generator over its counterparts is that the power drawn from the grid is considerably reduced, while the voltage charging the capacitor may be regulated in the range up to 600 V, with pulse frequencies up to 400 Hz. The generator may be used industrially—in particular, in rolling mills when drawing steel wire that is hard to deform.

REFERENCES

[1] *Ruszkiewicz B J, Grimm T, Ragai I, Mears L and Roth J T* 2017 J. of Manufacturing Science and Engineering 139 110801 (1-15)

[2] *Gromov V E, Zuev L B, Kozlov EH V i Cellermaer V YA* 1996 Elektrostimulirovannaya plastichnost' metallov i splavov M.: Nauka 293

[3] *Li X, Wang F, Li X, Zhu J and Tang G* 2016 Mater. Sci. Technol. 33(2) 215–219

NANOSTRUCTURAL WEAR-RESISTANT COATINGS SYNTHESISING ON MARTENSITE STEEL BY SURFACING

*V.E. KORMYSHEV**, S.A. NEVSKII* , V.E. GROMOV* , YU.F. IVANOV** , S.V. KONOVALOV*** , YU.A. RUBANNIKOVA**

**Siberian State Industrial University, Kirov street, 42, Novokuznetsk, 654006, Russia,*
e-mail: gromov@physics.sibsiu.ru, telephone: +73843 462277; +79059663458
***Institute of High Current Electronics of the Siberian Branch of the RAS, Tomsk, 2/3, Academicheskii Ave., 654052, Russia*
****Samara National Research University, Samara, 34 Moskovskoye Shosse, 443086, Russia*

This paper focused on the study of synthesising nanostructural wear resistant coatings and identifying mechanisms of their strengthening. Steel Hardox 450 is used as the base material. An elemental composition of the steel and the deposited metal is given in Tables 1 and 2.

Table 1 Elemental composition of steel Hardox 450 (chemical composition of metal in the ladle, Wt.%, iron is Bal.)

C	*Si*	*Mn*	*Cr*	*Ni*	*Mo*	*B*	*P*	*S*
0.19-0.26	0.7	1.60	0.25	0.25	0.25	0.004	0.025	0.010

Table 2 Elemental composition of the surfacing wire (Wt.%, iron is Bal.)

C	*V*	*Cr*	*Nb*	*W*
1.4	1.0	7.0	8.0	1.2

It is shown that a high-strength surface layer ≈ 6 mm thick is synthesised by weld deposition, and microhardness of this layer varies from 9.5 GPa to 11.5 GPa. Microhardness of the material diminishes fast in a direction away from the deposited metal surface, reaching a level of 6.5 GPa. Therefore, the deposited layer is twice as hard as the base metal with the deposited layer thickness of ≈6 mm. Wear factor of the deposited layer is $V = 95.1 \times 10^{-6}$ mm^3/N·m, and that of steel is $V = 0.69 \times 10^{-6}$mm^3/N·m as the tribological testing the base and deposited metal demonstrates. Friction factors are 0.259 and 0.104 for the deposited metal and base, respectively.

The study on the defect substructure of steel Hardox 450 has revealed that it is a polycrystalline aggregate based on α-phase. In bulk α-phase grains a lamellar structure dominates, being apparently the result of martensite transformation. A sub-grain structure is infrequently registered. Secondary phase particles are detected in bulk lamellae, on boundaries of lamellae and sub-grains. We have identified these particles as iron carbide Fe_3C.

The study outcomes of the defect substructure of the deposited material are in line with the data of the X-ray phase analysis. The principal phase is α-phase. It has a martensite structure. Indexing micro electron diffraction patterns of the martensite structure, we reveal retained austenite (insert), arrows indicate reflexes of retained austenite) which is located on the boundaries of martensite crystals in the form of long inter-layers.

Oxides and carbides were detected. It is quite distinct that particles of special carbides are round, dimensions of the particles vary from one to tens nm. Carbide phase particles are located on the boundaries and in bulk martensite crystals.

The structure of the contact area between deposited and base metals is like the base steel structure in many parameters. The martensite structure is identified. In martensite crystals, there is a dislocation substructure in the form of chaotically distributed dislocations and dislocation spheres.

THE USE OF METHOD OF STANDARD MIXTURES FOR INVESTIGATION OF SULFUR-CONTAINING IMPURITIES CONVERSION IN PULSED CORONA DISCHARGE PLASMA[1]

I.E. FILATOV, D.L. KUZNETSOV, V.V. UVARIN

Institute of Electrophysics of the Ural Branch of the Russian Academy of Sciences, 106 Amundsen street, Yekaterinburg, 620016, Russia, fil@iep.uran.ru, +73432678767

Sulfur-containing impurities (sulfur dioxide SO_2, carbon disulfide CS_2, carbonyl sulfide COS etc.) are toxic components of exhaust gases from various industrial enterprises. Since SO_2 and COS are main products of CS_2 conversion in air, simultaneous removal of all three components is an important problem. We proposed to use a pulsed corona discharge to remove CS_2 from the air [1].

It was experimentally determined that specific energy expenditures to remove carbon disulfide vary in the range of 4–40 eV/molecule, depending on carbon disulfide concentration. Moreover, a mutual influence of CS_2, SO_2 and COS on the efficiency of the removal of all three toxic components was discovered. In order to optimize the pulsed corona discharge processing of air mixtures, a method of standard mixtures is proposed [2]. Essence of the method is to process mixtures with specially selected compositions by the discharge, then to obtain dependencies of toxic impurities concentrations on specific energy deposited into gas mixture, and, finally, to determine relative reactivities of all toxic components for various mixture compositions.

Paper [1] shows that four main atmospheric-pressure air mixture compositions should be taken into account. In our experiments we prepared the following mixtures: mixture I contained 8500 ppm of CS_2, 1500 ppm of SO_2, and 1600 ppm of COS; mixture II contained 2000 ppm of CS_2, 350 ppm of SO_2, and 400 ppm of COS; mixture III contained 120 ppm of CS_2, 1700 ppm of SO_2, and 1200 ppm of COS; mixture IV contained 700 ppm of CS_2, 6200 ppm of SO_2, and 4200 ppm of COS. Concentration dependencies were obtained and relative reactivities of CS_2, SO_2 and COS were determined for these mixtures. Fig. 1 shows that relative reactivity of CS_2 (k_{1j}) has a maximum value in all cases except for mixture I, which corresponds to maximum total concentration of sulfur-containing impurities. A relative reactivity of COS (k_{3j}) has a maximum value for mixture I. On the contrary, energy yield G of CS_2 for mixture I has a maximum value (16.5 molecules/100 eV) and exceeds twice the value of energy yield of COS. Relative reactivity of COS (k_{3j}) decreases strongly with the decrease in total concentration, while one of SO_2 (k_{2j}) varies insignificantly.

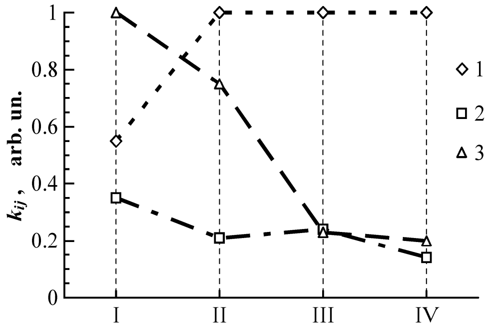


Fig. 1. Relative reactivities k_{ij} of CS_2 (1, i = 1), SO_2 (2, i = 2), and COS (3, i = 3) for mixtures I, II, III, and IV (j is the type of toxic impurity with a maximum value of relative reactivity for each mixture).

It should be noted that relative reactivities are not in correlation with energy yields. The reason is that energy yield is a characteristic of energetic efficiency of the removal process, while relative reactivity shows the efficiency of the use of active plasma particles in conversion processes.

Thus, the method of standard mixtures demonstrates that the efficiency of CS_2 conversion processes depends not only on energetic characteristics of the processing, but also on the efficiency of the use of various active plasma particles.

References

[1] *D.L. Kuznetsov, I.E. Filatov, and V.V. Uvarin* // Tech. Phys. Lett. - 2016. - Vol. 42. - No. 8. P. 820–823.
[2] *I.E. Filatov, V.V. Uvarin, and D.L. Kuznetsov* // Tech. Phys. Lett. - 2016. - Vol. 42. - No. 9. P. 927–931.

[1] This work was supported by the state task (theme No. 0389-2014-0006) and by the Russian Foundation for Basic Research (project No. 17-08-01212).

CHARACTERISTICS OF HIGH-PRESSURE NANOSECOND DISCHARGE IN METHANE-CONTAINING GAS MIXTURES[1]

I.E. FILATOV, D.L. KUZNETSOV, V.V. UVARIN

Institute of Electrophysics of the Ural Branch of the Russian Academy of Sciences, 106 Amundsen street, Yekaterinburg, 620016, Russia, fil@iep.uran.ru, +73432678767

Pulsed gas discharges of various types are widely used in studies on plasma chemistry of methane [1,2]. Usually, the pressure of the gas medium does not exceed 1 bar. The efficiency of methane conversion generally increases with increasing pressure, and the use of short nanosecond discharges allows to provide a volumetric nature of the effect even at high pressures of the gas mixture, to realize high specific energy inputs to the plasma medium. In this paper we studied the discharge parameters at pressures up to 6 bar.

One of the main reactions of methane conversion is "dry reforming", the reaction between CH_4 and carbon dioxide ($CH_4 + CO_2 = 2CO + 2H_2$). Therefore, we investigated mixtures of these gases.

The generator of high-voltage pulses SM-4H with the following parameters was used as the discharge power source: voltage pulse amplitude - 240 kV, current pulse amplitude - up to 3.5 kA, pulse duration - 10-25 ns, pulse repetition frequency - up to 50 Hz.

The discharge was carried out in a cylindrical chamber with an internal diameter of 80 mm and a volume of 10^3 cm^3. A corona, diffuse or spark discharge was realized depending on the geometry of the electrodes, pressure and composition of the mixture. We measured the current, the discharge voltage; the excited volume was estimated by the glow of the discharge. The input energy was defined as the integral of the product of the discharge current and voltage.

In our experiments, the dependences of the discharge current, voltage, pulse length, specific energy inputs in the gas on the pressure, composition of the mixture, the geometry of the electrodes were determined. Thus, for a typical initial CH_4/CO_2 1:1 mixture and diffuse discharge, the average specific energy inputs into gas per 1 pulse varies from 6 mJ/cm^3 to 0.8 mJ/cm^3 when the pressure varies from 2 to 6 bar (Fig. 1). An increase in pressure shortens the pulse drop and decreases the relative portion of the energy input in the low-voltage stage of the discharge (at the voltage pulse decay).

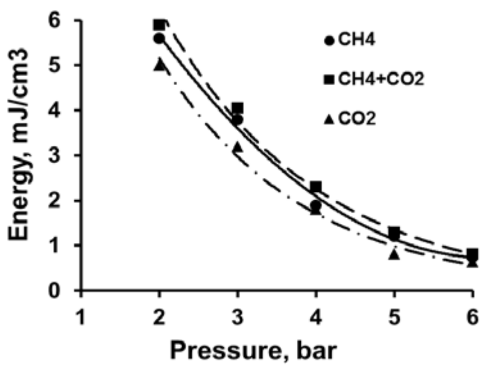


Fig. 1. Average specific energy inputs into gas per 1 pulse as a function of pressure for different gases. The ratio of the components in the mixture CH_4 and CO_2 – 1:1. Diffuse discharge, gap – 25 mm.

The data obtained are required to determine the specific energy consumption for methane conversion that will allow to estimate correctly the efficiency of the discharge technology of natural gas processing.

References

[1] *P.D.G. Maqueo, M. Maier, M.D.G. Evans, J. Bergthorson and S. Coulombe1* // ISPC 23 Book of Extended Abstracts. 2017. P.806-809.

[2] *Gi Sung Bea, Chung Jun Lee, Dae Hoon Lee and Teagyu Kim* // ISPC 23 Book of Extended Abstracts. 2017. P.840-842.

[1] This work was supported by the state task (theme No. 0389-2014-0006).

THE EFFECT OF ELECTRONEGATIVE ADDITIVES ON AIR CLEANING FROM VAPORS OF UNSATURATED VOCS BY PULSED CORONA DISCHARGE[1]

I.E. FILATOV, D.L. KUZNETSOV, V.V. UVARIN

Institute of Electrophysics of the Ural Branch of the Russian Academy of Sciences, 106 Amundsen street, Yekaterinburg, 620016, Russia, fil@iep.uran.ru, +73432678767

Parameters of the impulse corona discharge significantly depend on the addition of electronegative impurities to the working gas mixture. It has been shown that halogen-containing compounds, such as CCl_4 and the like, with a content in gas mixtures even in an amount of 1000 ppm or less significantly reduce both the current of the pulsed corona discharge and the energy input to the gas mixture [1]. This effect is explained by the attachment of electrons to electronegative molecules. A study of the effect of such additives on the processes of air purification from vapors of unsaturated (i.e. containing in their composition a double C=C bond) volatile organic compounds (VOCs) was made. It was found that, despite the decrease in the discharge current and energy input, the addition of electronegative compounds leads to a evident increase in the energy efficiency of the VOC removal process. In the case of using a pulsed corona discharge of amplitude 110-120 kV and duration of 15-20 ns, it was found that the addition of 0.085% CCl_4 to air reduces energy consumption by removing the unsaturated compound perchlorethylene (PCE) at a concentration of 0.09% by more than two times (from 12 to 6 eV / molecule at a purification rate of 63%) [2].

Figure 1a illustrates the process of PCE removal from dry air (curve 1) by corona discharge. The addition of CCl_4 significantly increased the energy efficiency of the cleaning process (curve 2), while the concentration of CCl_4 did not significantly change (curve 3).

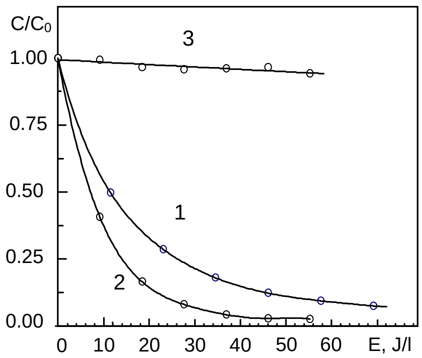


Fig. 1. Plots of relative concentration C/C_0 of PCE vs. specific discharge energy E in gas mixtures based on dry air C_0(PCE) = 840 ppm without CCl_4 and (2) C_0(PCE) = 840 ppm with addition of 890ppm CCl_4; (3) variation of CCl_4 concentration for $C_0(CCl_4)$ = 890 ppm in first case [2].

More extensive studies have shown that other halogen-containing compounds, freons, etc. can act as electronegative impurities the same way. As unsaturated VOCs, MMA vapor, styrene and mixtures thereof were tested. In all cases, the effect of increasing the efficiency of VOC removal was clear. The mechanism of the active influence of electronegative impurities is discussed.

The found regularities will be useful for investigating the properties of a gas-discharge plasma and for developing new technologies for cleaning air from toxic impurities.

References

[1] *D.L. Kuznetsov, I.E. Filatov, and V.V. Uvarin // J. Phys.: Conf. Ser.* - 2018. - Vol. 946. - P. 012169.

[2] *I.E. Filatov, V.V. Uvarin, and D.L. Kuznetsov //* Tech. Phys. Lett. - 2017. - Vol. 43. - No. 12 . - P. 1140–1143.

[1] This work was supported by the state task (theme No. 0389-2014-0006) and by the RFBR (project No. 17-08-01212).

MITOCHONDRIAL MEMBRANE PERMEABILITY AFTER NANOSECOND ELECTROMAGNETIC PULSED EXPOSURE[1]

LUBOV P. ZHARKOVA, ILYA V. ROMANCHENKO, MICHAEL A. BULDAKOV, PAVEL V. PRIPUTNEV, MICHAEL A. BOLSHAKOV, VLADISLAV V. ROSTOV

Institute of High current electronics SB RAS, Tomsk, Russia
National research Tomsk state university, Tomsk, Russia

The reduction of the rate of mitochondrial respiration and conductivity of the mitochondrial suspension to alternating current of β-dispersion, the increase of mitochondrial swelling after exposure to high-frequency electromagnetic radiation with nanosecond pulses were shown previously (Zharkova, EFRE 2017). The effect depended on the intensity of the electric field, the number of pulses and pulse repetition frequency.

The purpose of the presented study was to find possible mechanisms of nanosecond pulses influence on the mitochondria of different cell types. The mitochondrial respiration essentially depends on the state of its inner membrane and permeability to ions. Therefore, the possibility to induce electric pores and/or to open permeability transition pores in the mitochondria (mPTP) of normal and tumor cells by the action of electromagnetic nanosecond pulses was studied in the work.

The experiments were conducted on isolated mitochondria of mice hepatocytes, as well as fibroblasts mitochondria and tumor cells (HeLa, K562). Mitochondrial and cell suspensions were exposed to electromagnetic radiation from: a) a pulse generator based on the MI-505 (10GHz, peak power density of 18kW, pulse duration of 100 ns) and b) от RF generator with pulse generation due to excitation of gyromagnetic precession in a nonlinear transmission line with saturated ferrites (0.6-1.0 GHz, pulse duration of 4 -25 ns and amplitude of electric field of 0. -36 kV/cm). The pulse repetition rates of both sources were in the range of 8-25 Hz. The effect was estimated by the fluorescence intensity of Calcein-AM in mitochondria (MitoProbe Transition Pore Assay Kit, Invitrogen, USA).

It was shown that both types of radiation with all used regimes did not change the intensity of Calcein-AM fluorescence. It is supposed that the exposure to nanosecond pulses does not induce the opening of already existing pores in mitochondrial membranes (mPTP). Therefore, the increase in the conductivity of mitochondrial membranes, shown earlier, can be explained by increase in nonspecific permeability due to loosening of the membrane lipid matrix.

[1] The work is supported: in part by the Russian Foundation for Basic Research (grant No. 16-38-60040), in part by IHCE SB RAS Project 2018 No.10.

PHYSIOLOGICAL STRESS RESPONSES TO NANOSECOND PULSED-PERIODIC MICROWAVE

KNYAZEVA I.R.[1,2], MEDVEDEV M.A.[1], KUTENKOV O.P[2], VASILEV A.V.[1], GOROKHOVSKY A.A.[1], ROSTOV V.V.[2]

[1]Siberian State Medical University, 2 Moskovsky trakt, Tomsk, 634055, Russia, e-mail: knyazeva_irekle@mail.ru, +7(3822)901101(1670)

[2]Institute of High Current Electronics, Siberian Branch, Russian Academy of Sciences, 2/3 Akademichesky Avenue, Tomsk 634055, Russia

Electromagnetic radiation, including microwave radiation, is highly integrated into people's lives and has an impact on different body systems. As a consequence, it is necessary to study the effects of electromagnetic radiation on the human body in detail. Especially intensively in recent years, there has been an increase of the level of pulsed microwave radiation that has used in communication systems. The question of the stress of this radiation is important, and corticosteroids (cortisol and corticosterone) can be used as an indicator of stress.

Therefore, the purpose of this study was to evaluation of corticosterone in the blood serum after irradiation by a nanosecond repetitive pulsed microwave.

The experiments were performed in compliance with all ethical norms and rules on 30 white male mice, weighing 20-25 g. The animals were divided into five groups of 6 mice each. Mice from the sham-irradiated group were subjected to the same manipulations except irradiation. Mice were irradiated for 5 days daily once a day (4000 pulses per session) with repetition frequencies 8, 13, 16 and 22 pulse per second (pps). Laboratory generators based on the MI-505 magnetron served as repetitive pulsed microwaves sources. (Russia, 10 GHz, 180 kW, pulse duration is 100 ns, peak power density 1500 W/cm^2, average power flux density 1.5 mW / cm^2). Effects of exposure were assessed by the level of corticosterone in the blood of irradiated and sham-irradiated mice with the help of an enzyme immunoassay.

The positive correlation was found between the repetition rate of microwave pulses and the level of corticosterone. After exposure to the frequency 13 and 16 pps, the level of corticosterone increased 3.3 and 2.5 times respectively as compared with the sham-irradiated group. Irradiation with a frequency 22 pps resulted in a significant decrease of the content of corticosterone. The frequency 8 pps did not have a statistically significant effect. Since corticosterone is an indicator of stress, it can be concluded that the frequency 8 pps does not exert a significant stress effect, the frequencies 13 and 16 pps have a significant stressor effect, and a frequency 22 pps contributes to the chronicity of stress, because there is no adequate response to high impulse activity.

The analysis of own and few reported data allows to conclude that mechanisms of biological effect of repetitive pulsed microwave are nonspecific. Earlier we have shown that repetitive pulsed microwave can produce a variety of biological effects indicative of oxidative stress (it changes the oxidative modification of lipids and proteins [1] and have an influence on the level of reactive oxygen species in mice hepatocytes [2]). The possibility of a stressful effect was confirmed in this study. The level of corticosterone indicates the presence of stress.

REFERENCES

[1] *M.A. Bolshakov, V.V. Rostov, M.S. Korovin, et al.,* // Biophysics. - 2005. - V.50 (1). - P. 104-109.
[2] *L. P. Zharkova, I. R. Knyazeva, V.V. Ivanov, et al.* // Tomsk State Univ. Bulletin. - 2010. - V.333. - P. 161-163.

DIELECTRIC BARRIER DISCHARGE PLASMA JET IN ARGON AND HELLIUM[1]

M.E. PINCHUK, **, O.M. STEPANOVA*, **, A.V. LAZUKIN**, ***, A.M. ASTAFIEV*, ***

**Institute for Electrophysics and Electric Power of Russian Academy of Sciences (IEE RAS), Dvortsovaya nab., 18, St.-Petersburg, 191186, Russia, pinchme@mail.ru, +7-812-315-17-57*

***St.-Petersburg State University, Medical Faculty, Universitetskaya nab. 7/9, St. Petersburg, 199034, Russia, o.m.stepanova@spbu.ru*

****National Research University Moscow Power Engineering Institute, Krasnokazarmennaya 14, Moscow 111250, Russia*

An atmospheric pressure plasma jet based on dielectric-barrier discharge (DBD plasma jet) is widely used for applied research in biomedicine. It is usually formed from a noble gas flow passed through a discharge gap. To feed a plasma generator we used high-voltage sinusoidal power supplies with a frequency of 7.5, 30 and 80 kHz. Helium and argon plasma jets at laminar and turbulent gas flow regimes were obtained. Quartz tubes with inner diameters of 3.6, 5.58 and 7.49 mm and wall thickness of 1 mm served as a dielectric barrier. They were equipped by an electrode system “inner rod – outer ring”. The inner electrode was made from a copper wire of 1.5 mm in diameter and placed inside the tube along its center line at the distance of 7.5 mm from the edge of the tube. The outer electrode was made from a copper foil strip of 5 mm wide wrapped around the tube at the distance of 5 mm from its edge. Some additional details about the set-up can be found in [1].

Electrical diagnostics results of the DBD atmospheric pressure plasma jets in helium and argon are presented. The features of the formation of plasma jets in these gases are considered. Two distinct spatial regions, a main discharge and a plasma jet, can be distinguished. Energy distribution between the two regions has been studied using volt-coulomb characteristics measured with a compensating circuit for the geometric capacity of the discharge gap.

REFERENCES

[1] *O. Stepanova, O. Rybalchenko, M. Pinchuk, A. Astafiev, O. Orlova, V. Spodobin, A. Kudryavtsev.* // Plasma Medicine. 2017. Vol. 7, № 3, pp. 187-200. DOI: 10.1615/PlasmaMed.2017019064

1 This work was supported by the Russian Foundation for Basic Research (grant no. 16-08-00870).

INFLUENCE OF THE SUPPLY VOLTAGE FREQUENCY AND ELECTRODE SYSTEM CONFIGURATION ON THE LENGTH OF MICRODISCHARGES IN THE SDBD[1]

A.V. LAZUKIN, I.V. SELIVONIN**, M .E . PINCHUK***, I.A. MORALEV**, S.A. KRIVOV**

**National Research University Moscow Power Engineering Institute, Krasnokazarmennaya 14, Moscow, 111250, Russia, lazukin_av@mail.ru, +7 495 362-75-60*
***Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya 13, Moscow, 125412, Russia*
****Institute for Electrophysics and Electric Power of RAS, Dvortsovaya nab., 18, St.-Petersburg, 191186, Russia*

Previously, the effect of the supply voltage frequency on the microdischarge length and the area of the discharge region for the surface dielectric discharge with axisymmetric electrode configuration (discharge from disc edge of 16 mm in diameter). was investigated in [1]. In such discharge arrangement the microdischarges do not experience appreciable restrictions, both from opposite and from adjacent microdischarges.

In this paper we considered both the influence of the supply voltage frequency (50 and 200 μs cycle duration), and the features of the self-organization of microdischarges caused by a change in the configuration of the electrode system to the above parameters. Two electrode configurations were used. The first one was a classical asymmetric configuration with 1 mm strip exposed electrode (aluminum foil of 50 μm thickness). The second one was a three-electrode system with two parallel 1 mm strip exposed electrodes located 4.5 mm apart. In the first case, the propagation and evolution of microdischarges are affected by the adjacent microdischarges, in the second case both by the adjacent microdischarges and by the counter-moving ones.

A high-speed photography was used in this work (we used the ICCD camera Andor iStar DH720). The discharge region was photographed separately for the positive and negative half-waves of the supply sinusoidal voltage at values from 2.3 to 3.4 kV (RMS) at frequencies of 5 and 20 kHz. Exposure and start of the camera was adjusted by current shunt signal. The features of the propagation and evolution of the microdischarge for both configurations were estimated both from single photographs and from integral (accumulation of many half-period images on the camera chip / exposure is equal to 100 periods of supply voltage) images (estimation by the light emission border).

It was shown in the case of two-electrode configuration the discharge region length was greater for a higher frequency: it was 4.5 ± 0.3 mm at 20 kHz and 3.5 ± 0.2 mm at 5 kHz. In the case of three-electrode configuration, on the negative half-wave of the supply voltage the restriction of the discharge with two parallel strips was occurred regardless of the supply voltage frequency at 2.7-2.8 kV. On the positive half-wave at a frequency of 20 kHz the discharge restriction occurs at 2.5 kV.

REFERENCES

[1] *Lazukin A.V., Pinchuk M.E., Stepanova O.M., Krivov S.A.* // Izvestiya Vuzov. Fizika. 2016. 59. No 9-3. 257-260

[1] This work was supported by the Russian Foundation for Basic Research (grant no. 16-08-00870).

MULTICHANNEL HIGH-FREQUENCY GENERATOR OF SAWTOOTH PULSES FOR ELECTROHYDRODYNAMIC FLOWS FORMATION[1]

CH. G. ANTIPOVA, V.YU. KHOMICH*, I.E.REBROV**

**Institute for Electrophysics and Electric Power RAS, 18, Dvortsovaya naberezhnaya, Saint- Petersburg, 191186, Russia, rbrv.igor@gmail.com, +74991351195*

Electrohydrodynamic actuators have found wide application in aeronautics because of the fast response time, due to the high frequency of operation, as well as the high efficiency of converting the input energy into the energy of flow [1, 2]. In the presented work, a high-frequency generator of sawtooth pulses was developed and investigated. The main application of the generator being developed (fig. 1a) is the acceleration of a weakly ionized gas by a traveling field for electrohydrodynamic flows formation in atmospheric pressure air by plane electrode systems [3]. A specialty of such systems is a small interelectrode distance, but a high electric field strength. The principle of ion traveling acceleration is the synchronous change of the electric field strength with the spatial arrangement of the ion cloud [4]. If the ion moves faster or slower, it falls under the decelerating potential difference and it is deionized at the corresponding electrode.

Pulse generators with low peak power [5], but operating at high repetition rates (10 kHz or more) are suitable to power such systems. The choice of the optimum frequency and shape of the signal is determined by the attainment of the maximum possible speed with a high efficiency of conversion of electrical energy into kinetic.

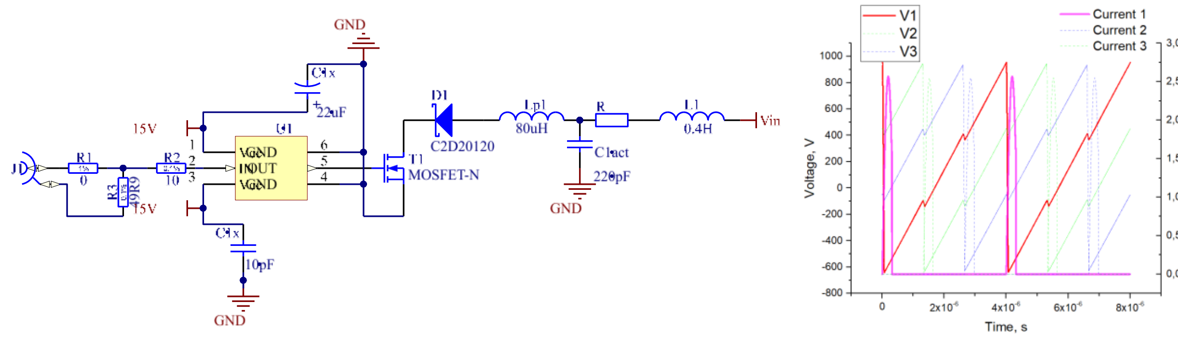


Figure 1a - High-frequency pulse generator circuit (1 phase). C1x-array of power capacitors driver transistor. R1-R3 - matching resistors, J1 - coaxial input from the master oscillator, D1 - Schottky diode, L1 - throttle, C1act - capacitances parallel to the actuator, Lp parasitic inductance. b - Voltage and current of generator 1kV of sawtooth signal with frequency f = 250 kHz on actuator with load C = 220 pF.

The operation modes of the generator were investigated. Electrophysical parameters of elements loss assessment that were difficult to calculate, for example, losses in the inductor core, switching losses in the key and diode had been measured.

During the study, voltage and current oscillograms on the load at different pulse repetition rates and power consumption from power supply had been measured (Fig. 1b). The phase shift was controlled by changing the delay of the channels in the lead generator. A voltage of 1 kV at a repetition frequency up to 250 kHz, a current up to 2.5 A in sawtooth pulses and up to 1 MHz in quasi-sinusoidal mode was achieved.

REFERENCES

[1] Chernyshev S.L. et al. // Aerospace Science and Technology. 2016. Vol. 59. P. 155–161.
[2] Rebrov I.E., Khomich V.Y., Yamshchikov V.A. // Tech. Phys. 2016. Vol. 61, № 8. P. 1130–1134.
[3] Aleshin B.S. et al. A Multidischarge Actuator System for Power Electrohydrodynamic Action on the Boundary Layer of Aerohydrodynamic Surfaces // Technical Physics Letters. 2017. Vol. 43, № 1. P. 64–66.
[4] Schlitz D.J. Microscale ion driven air flow: Ph.D. United States -- Indiana: Purdue University, 2004. 226 p.
[5] S. I. Moshkunov et al.// Izvestia Vyshich Uchebnych Zavedeniy. Fizika. – 2016. - T. 59. № 9-3. P. 110-113.

[1] This work was supported by RFBR № 17-08-01409 A

REGULATOR SETTINGS EFFECT FOR HIGH-CURRENT ELECTRONICS ON FUNCTIONAL EFFICIENCY OF GAS CLEANING SYSTEM FILTERS

M.YU. NIKOLAEV, V.V. MAKAROV**, O.P. KUZNETSOVA****

**Omsk State Technical University, Mira, h. 11, Omsk, 644050, Russian Federation, makarov@omgtu.ru, +79136298281*

***Omsk State Technical University, Mira, h. 11, Omsk, 644050, Russian Federation*

****Omsk State Technical University, Mira, h. 11, Omsk, 644050, Russian Federation*

A problem in electric gas purification is gas cleaning from dust with high specific resistivity; the last is the Ekibastuz coal ash, the Republic of Kazakhstan. Electrostatic precipitators operate due to two basic electro physical processes: charging the particles of the cleaned flue gas with corona ions and moving the charged particles to the precipitation electrode under the electrostatic force. An optimal mode of corona electrodes shaking should maintain a layer of dust on the corona elements, where the corona current provides the most effective dust trapping in the electrostatic precipitator, and the control algorithms optimization of the electrode shaking mechanisms maintains the optimal operating mode, as it is the most important task [1, 2]. To optimize bag filters operation and regeneration system efficient operation, it is necessary to determine permanently the dew point where dust particles adhere to the electrostatic precipitator element, and it makes the control system operation of electro pneumatic valves, that provide impulsive supply of compressed air to the electrostatic precipitator, ineffective. An important task for this electrostatic precipitator type is to solve an optimization problem of the bag filter operation temperature mode.

According to electrostatic precipitators in operation, the following was stated:

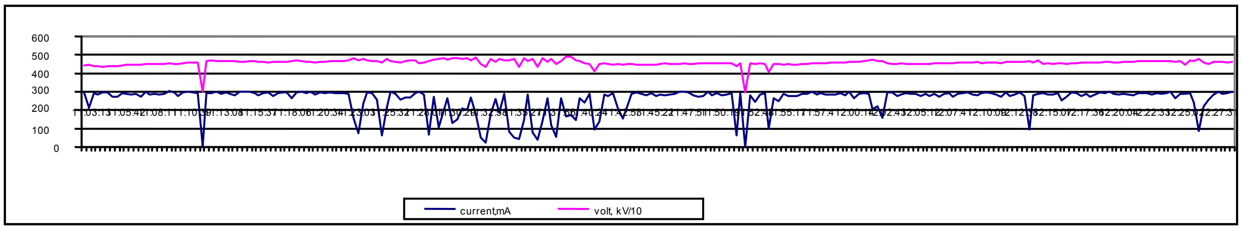


Figure 1. Trends of dust meter readings

Nature of curves for semifields proves that there is back corona on the electrostatic precipitators and it is necessary to apply intermittent power supply for these semifields and to maintain voltage on electrostatic precipitator electrodes by means of algorithms of digital voltage regulators (DVR) control near the inflection point of volt-ampere characteristics. Trends of dust meter readings, current transducers and voltage probes when passing from the mode with transmission of pulses (2/8, 2/6) to the mode of continuous supply of voltage pulses with frequency 100 Hz are shown in Figure 1 graphs. When supply voltage with an intermittent forms the relative dust-ash carryover decreases twice [4].

Application of dust meters based on electro optical sensors EOS-2, installed on the exhaust passes after precipitator housings organizes feedback on the control system and detuning the optimum operating modes of the control systems for operation of precipitators for cleaning flue gases of various types [3]. There is an opportunity to install automated process control systems for gas purification and constant monitoring of dustiness of TPP piped gas.

REFERENCES

[1] *Zacharenko V.A., Shkaev A.G. //* Improving the efficiency of dust and gas purification of industrial enterprises. Russia is young: advanced technologies – into industry! 2015. №2. P.32-35.

[2] *Zacharenko V.A.* // Methods and means of contactless telemetry for the tasks of thermal control in industry. Omsk, 2014.

[3] *Zacharenko V.A., Shkaev A.G., Saifutdinov R.N. //* Optoelectronic sensor for dust and gas emissions. Sensors and systems. 2003. №12. P.27-29.

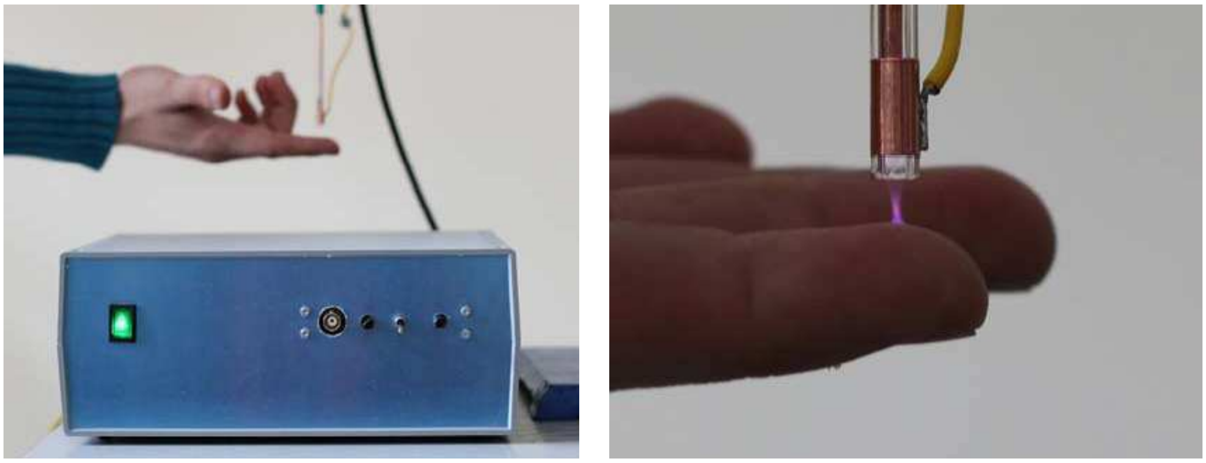
[4] *Makarov V.V., Kuznetsova O.P., Nikolaev M.Yu.* // The effect of electric exposure on the gas cleaning systems filter efficiency (Влияние электрического воздействия на эффективность работы фильтров систем газоочистки) // XII International Conference Radiation-thermal Effects and Processes in Inorganic Materials; Materials Science and Engineering. 2017. Vol. 168. DOI: 10.1088/1757-899X/168/1/012005

COMPACT HIGH VOLTAGE PULSE GENERATOR FOR DBD PLASMA JETS[1]

S.I. MOSHKUNOV, N.A. PODGUYKO, E.A. SHERSHUNOVA

Institute for Electrophysics and Electric Power, Russian Academy of Sciences, Dvortsovaya nab.18, St.-Petersburg, 191186, Russia, E-mail: podguyko.nikolay@mail.ru, phone: +78123151757

Compact low-power high voltage pulse generator for DBD plasma jets was developed and assembled (fig.1). There is a function of voltage pulse value and PRR regulation with the fascia control panel of the generator. The voltage amplitude can be set at the level of 0 – 6 kV. There are two frequency bands: 10 Hz – 100 Hz and 100 Hz – 1 kHz. The high voltage pulses of 12 us duration have nanosecond rise and fall time (20 ns). The maximum power consumption is 100 W. The generator is powered by 220 V, 50 Hz. The overall dimensions of the device – 105x260x180 mm, its weight is less than 2 kg.



a) b)

Fig. 1. Compact low-power high voltage pulse generator for DBD plasma jets: a) pulse generator common view, b) DBD plasma jet operation

The generator consists of: a DC high-voltage source board, a switch driver board, two high-voltage composite solid-state switches connected by a half-bridge scheme and a control board.

The board of the DC source is assembled according to the standard scheme: a full-wave rectifier circuit, a half-bridge inverter with MOSFET-transistors controlled by PWM controller operating at 200 kHz frequency, a step-up transformer, a voltage multiplier [1].

The driver board consists of two drivers, creating current pulses in the control loops of the switches by the input control pulses.

High-voltage composite solid-state switches are realized by a set of six series-connected 1200 V IGBT-transistors, controlled by means of the transformer coupling of their gates and the driver's current loops [2, 3].

The control board is a two-channel low-voltage pulse trigger generator. The pulse frequency can be changed by means of the toggle switch (switching between the bands) and the variable resistor (for smooth adjustment). The delay time between the trigger pulses, determining the duration of the output high-voltage pulse, is fixed. In addition, the voltage level can be changed by means of an extra variable resistor.

REFERENCES

[1] *S. Moshkunov, V. Khomich and E. Shershunova* / A Compact Source of Flash-Corona Discharge for Biomedical Applications // Technical Physics Letters – 2018. – V. 44. No 1. 84-86.

[2] *E. Shershunova, M. Malashin, S. Moshkunov, V. Khomich* / Diffuse DBD in Atmospheric Air at Different Applied Pulse Widths // Acta Polytechnica. – 2015. – V. 55. – No. 1. 59-63.

[3] *M. Malashin, S. Moshkunov, V. Khomich, and E. Shershunova* / A high-voltage semiconductor rectangular-pulse generator for powering a barrier discharge. // Instruments and Experimental Techniques – 2016. – V. 59. No 2. 226-230.

[1] This work was supported by Russian Foundation for Basic Research, grant N. 16-08-01037

TWO-CHANNEL HIGH-VOLTAGE GENERATOR OF RECTANGULAR PULSES FOR ELECTROSPINNING ORIENTED FIBERS[1]

A.V.KASNIN, I.E.REBROV**

**Institute for Electrophysics and Electric Power RAS, 18, Dvortsovaya naberezhnaya, Saint- Petersburg, 191186, Russia, rbrv.igor@gmail.com, +74991351195*

In the course of the work, a two-channel generator of high-voltage high-frequency pulses was developed and assembled for electrospinning nanofiber materials. It creates a periodic voltage switching on two electrodes with times from 100 nanoseconds to hundreds of milliseconds. To ensure a directional fiber laying during the electrospinning process, the voltage pulses were in the form of a square wave with 180^0 phase shift between the receiving electrodes.

The generator consists of two synchronized low-voltage driving generators (1) AKIP-3409, allowing to change the period of the output high-voltage signal; two drivers (2) controlling the opening and closing of four high-voltage switches (3) [1,2] and galvanically isolating the low-voltage and high-voltage part of the system [3]. Drivers are powered by voltage sources of 12 and 300V, GPR-6030D and GPR-30H10D respectively. Each driver controls two switches connected to one electrode (4). The high voltage is generated by the Spellman SL2000 (5) source and fed to the input of commutators 3_1 and 3_2 [4]. The formation of high-voltage pulses arriving at the electrode occurs due to the alternate opening and closing of the keys.

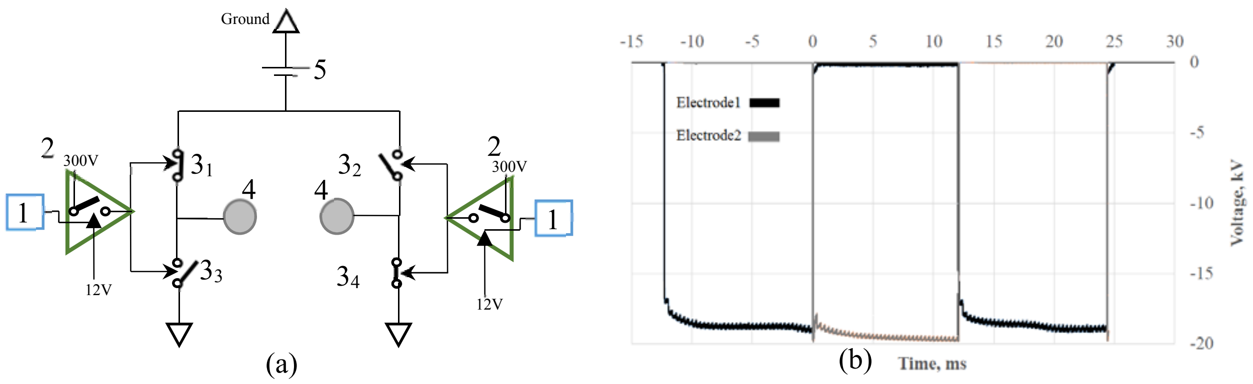


Fig.1. a) Schematic of the generator; b) Voltage oscillogram on two electrodes

The created architecture of the generator allows changing the frequency, pulse duration, number of phases for obtaining complex structured biomimetic matrices with several orientations.

REFERENCES

[1] *S. I. Moshkunov, I. E. Rebrov, V. Yu. Khomich //* Izvestia Vyshich Uchebnych Zavedeniy. Fizika. *– 2016. - T. 59.* № 9-3. *P. 110-113.*

[2] *T. E. Grigoriev, A. V. Kashin, K. I. Lukanina, I. E. Rebrov* // Anniversary XV Kurchatov Interdisciplinary Youth Scientific School, a collection of annotations. – 2017. Vol. 1. P. 132-132.

[3] *Khomich V. Yu., Malashin M. V., Moshkunov S. I., Rebrov I. E., Shershunova E. A.//* European Power Electronics and Drives Journal. – 2013. - T. 23. № 4. P. 51-54.

[4] *Khomich V. Yu., Moshkunov S. I., Rebrov I. E.* // SPEEDAM 2016 - Proceedings. – 2016. - P. 919-923.

[1] This work was supported by RSCF № 17-79-10470

EXPERIMENTAL INVESTIGATION OF LINEAR THERMAL EXPANSION OF HOPG NEAR ITS MELTING POINT[1]

V.N. SENCHENKO, R.S. BELIKOV

Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya St. 13 Bldg 2, Moscow, 125412, Russia, roman.belikov@phystech.edu, +79268705441

At this point experimental data on the isobaric expansion of pyrolytic graphite in the temperature region above 3300 K are extremely few. Meanwhile, such data are necessary for constructing wide-range equations of state for carbon [1], as well as for studying the thermophysical properties of a graphite crystal.

A method involved allows studying the density of graphite in the high-temperature region up to the melting point at high static pressure and is considered in detail, for example, in [2]. Using this method an isobaric dependence of the linear thermal expansion of pyrolytic graphite was experimentally determined in the temperature range 3300-4800 K at a pressure of 1 kbar in directions parallel and perpendicular to the basal plane.

Highly oriented pyrolytic graphite (HOPG) of two types with grain-boundary angle of 0.8° and 3.5° produced by «Atomgraph» was used in the experiments. The high density of this material made it possible to measure thermal expansion up to the melting point without destruction of the samples (even in two-phase region).

The temperature of the sample was measured by brightness pyrometry, the brightness temperature was recalculated into the true one under the assumption of a constant emissivity in the investigated temperature range 3300-4800 K, the value of the emissivity was taken from [3]. During the experiment the current and the voltage drop over the sample were also measured. Therefore, knowing the mass of the sample, it was possible to obtain the value of the deposited energy. The obtained values of the enthalpy change of graphite during the heating up to the melting point corresponded to the data presented in the literature [4].

In a few experiments it was possible to continue heating the sample of pyrographite after the beginning of the melting plateau, i.e. some data on the pyrolytic graphite density in a two-phase region was obtained. It should be noted that the measurement technique involves certain difficulties due to active sublimation of graphite at high temperatures.

This work presents data on the measurement of the linear thermal expansion of pyrolytic graphite in the temperature range 3300-4800 K under isobaric conditions at a static external pressure of 1 kbar. Analysis of the obtained experimental data shows that the dependence of the relative density of pyrolytic graphite agrees with the data [5], obtained for nonisobaric heating, and also with computation data [1, 6].

REFERENCES

[1] *Khishchenko K.V., Fortov V.E., Lomonosov I.V.* // Int. J. Thermophys. – 2005. – V. 26. – P. 479–491.
[2] *Senchenko V.N., Belikov R.S.* // J. Phys.: Conf. Ser. – 2017. – V. 891. – P. 012338.
[3] *Basharin A.Yu., Pahomov I.S., Scheindlin M.A.* // High Temp.-High Press. – 1991. – V. 23. – P. 543.
[4] *Bergman G.A., Buchnev L.M., Petrova I.I., Senchenko V.N., Fokin L.R., Chekhovskoi V.Ya. and Sheindlin M.A.* // Tables of standard reference data GSSSD 25–90. – 1991. – P. 12.
[5] *Kondratyev A.M., Korobenko V.N., Rakhel A.D.* // J. Phys. Condens. Matter. – 2016. – V. 28. – P. 265501.
[6] *Kerley G.I., Chhabildas L.C.* // Sandia report SAND2001-2619. – 2001. – P. 50.

[1] This work was supported by the Russian Science Foundation (grant No. 14-50-00124).

EXPERIMENTAL INVESTIGATION OF THERMORADIATIVE PROPERTIES OF REFRACTORY MATERIALS[1]

V.N. SENCHENKO, R.S. BELIKOV, P.A. KONOVALOV

Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya St. 13 Bldg 2, Moscow, 125412, Russia, roman.belikov@phystech.edu, +79268705441

The experiment is focused on studying the thermoradiative properties of refractory materials at high temperatures, particularly in the melting region. Experimental investigation of these properties is necessary for solving the problems of high-temperature engineering and energetics, primarily in connection with the creation of new heat-protective materials for aerospace equipment and aircraft engines operating at extremely high temperatures, for innovative plasma processing technologies, and for designing next-generation nuclear reactors.

Refractory carbides, in particular TaC, HfC and their mixtures, have anomalously high melting temperatures of the order of 4000 K (which is higher than the melting point of the most refractory metal - tungsten) and retain high strength and durability under extreme thermal loads.

At the moment there is practically no data on the thermoradiative properties of these carbides at extremely high temperatures that can arise in emergency operation regimes of the equipment in the literature, which makes it difficult to model and control such regimes.

Knowledge of the thermoradiative properties of high-temperature materials is extremely important, both in experimental thermophysical studies and in industry. Today, in fact, only in the scientific laboratory of the Institute for Experimental Physics, Austria, methods of fast current heating and polarimetric method are used to measure optical constants for metals at high temperatures [1, 2].

The novelty of the proposed approach consists in using for studying of the high-temperature thermoradiative properties of refractory carbides in the melting region a complex approach combining high-speed spectroscopy with methods of rapid heating by a plasma jet and a current pulse.

The experimental setup is described in detail in the article [3], the modification of this setup consists in the use of the high-speed Avaspec-2048 spectrometer, which makes it possible to study the spectra of thermal radiation in the range 0.5-1.1 μm.

Measurements of thermoradiative properties will essentially improve the accuracy of temperature measurement in the study of thermophysical properties of carbides and will make it possible to refine the solutions of problems of heat transfer by radiation and conduction, which describe heating of materials to extremely high temperatures.

The results obtained can be useful for solid state physics, the calculation of thermodynamic properties in the melting range, high-temperature power engineering and plasma heat treatment.

REFERENCES

[1] *Seifter A., Sachsenhofer F., Pottlacher G.* // Int. J. Thermophysics. – 2002. – Vol. 23. – No. 5.
[2] *Boivineau M., Pottlacher G.* // Int. J. Materials and Product Technology. – 2006. – Vol. 26. – Nos. 3/4. – P. 217-246.
[3] *Senchenko V.N., Belikov R.S.* // J. Phys.: Conf. Ser. – 2017. – V. 891. – P. 012338.

[1] This work was supported by RFBR (Grant 18-08-00923).

PRODUCTION OF HIGH-PURITY QUARTZ CONCENTRATE BY ELECTRICAL PULSE FRAGMENTATION

L.G. ANANYEVA, S.S. ILENOK*, M.V. KOROVKIN*, E.V. KUMPYAK**, A.A. ZHERLITSYN***

**National Research Tomsk Polytechnic University, 30 Lenin Ave., Tomsk, 634050, Russia, mvk@tpu.ru*
***Institute of High Current Electronics SD RAS, 2/3 Academichesky ave., Tomsk, 634055, Russia*

The demand for pure and highly pure raw quartz materials has increased in recent years due to the need for production of ceramic materials, silicon carbide (SiC) and silicon nitride (Si_3N_4) products, as well as for production of silicon and nanomaterials for various and special applications. Considering the depletion of traditional deposits of pure quartz, the problem of using abundant quartz rocks in industry attracts a lot of attention. According to the literature data [1, 2], promising sources of quartz can be the quartzites in the “Bural-Sardak” (Buryat Republic, Russia) and “Antonovskoye” (Western Siberia, Russia) deposits that contain 97...99% of SiO_2. The special purity of these quartzites is due to their unique conditions of formation.

Production high-purity quartz concentrate from initially dense chemically pure quartzites requires special methods of rocks grinding with a minimal addition of a "hardware" contaminating material. An attractive method is the electrical pulse fragmentation, where a high-voltage discharge is used as a grinding tool. We studied the material and element composition of impurities in electrical pulse method of fragmentation. The fragmentation was carried out at a pulse-periodic generator with the pulse repetition rate of 5...10 Hz; the energy stored in a high-voltage capacitive storage of up to 500 J and the voltage level of up to 300 kV. The electrodes of the fragmentation chamber are made of stainless steel. The working medium is water. The regime of fragmentation ensures the production of quartz concentrate with a grain size of 0.01...0.5 mm in a series of 1000 pulses from a pre-prepared lump quartz with a fraction size ~25 mm.

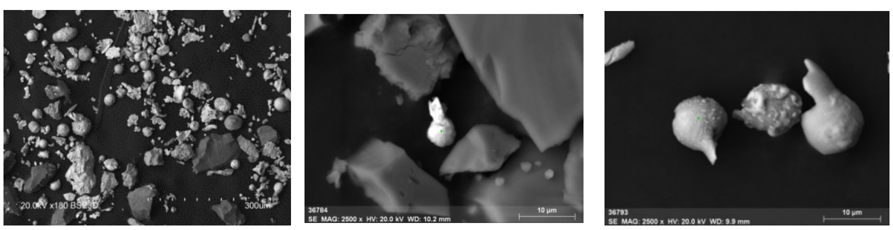


Fig. 1. Shape and size of the particles of quartz concentrate and "hardware iron" after fragmentation.

Element	[norm. wt.%]
Carbon	0
Oxygen	19,30845
Silicon	0,326285
Chromium	18,97082
Iron	56,07997
Nickel	5,314476
Sum	100

Composition of «hardware iron»

The analysis of quartzites before and after fragmentation was carried out with both optical microscope and scanning electron microscope Hitachi S-3400N with energy dispersive spectrometer Bruker XFlash 4010 for semi-quantitative X-ray analysis, which makes it possible to determine the element composition of micro-grains. In an initial sample of quartzite, no inclusions of accessory minerals and other impurities were observed. As a result of the electrical pulse fragmentation, the quartz grains of various shapes with a characteristic shell-like fracture were obtained, including melted ones: both pure and with particles of pure iron adhering to them. There was also a presence of foreign non-magnetic impurities of a complex composition Fe-Cr-Ni-Cu-Al and Fe-Ni-Cr, sometimes with an admixture of Mn, in the form of separate grains of various shapes: teardrop, spherical, lamellar, stalactite-like in size 1...30 μm. The magnetic fraction is represented by individual grains and grains of quartz with iron hydroxide films; the shape of the grains of the magnetic fraction is different: dendritic, lamellar, acicular, rounded, etc. (Fig. 1). To obtain high-purity quartz concentrate, it is necessary to increase the erosive and abrasive wear resistance of the fragmentation chamber electrodes, for example, by nitriding the steel in a low-pressure arc discharge or by using technically pure iron for magnetic separation of contaminants.

REFERENCES

[1] *A.I. Nepomnyashchikh, B.A. Krasin, I.E. Vasilieva, I.A. Eliseev, V.P. Eremin, S.I. Popov, V.V. Sinitsky, V.A. Fedoseyenko, A.M. Spiridonov, E.I. Vorobyov, V.A. Gnilusha. Silicon for solar energy* // Izvestiya of Tomsk Polytechnic University. – 2000. – V.303, Iss.1. –P.176-190.

[2] *Korovkin M.V., Ananyeva L.G., Ginsar V.E., Razva O.S. Production of pure raw quartz by enriching quartzites* // IOP Conference Series: Earth and Environmental Science. – 2015 – Vol.24, 012017. – P.1-5.

NUMERICAL SIMULATION OF SPRAK CHANNEL DYNAMICS IN RAILGUN SWITCHES

A.V. KHARLOV

Institute of High Current Electronics 2/3 Academichesky Ave., 634055, Tomsk, Russia, akharlov@lef.hcei.tsc.ru

Discharge of a capacitive storage on a load with unipolar pulse is employed for pumping of powerful lasers and also for feeding of electromagnetic launchers, and pulsed high magnetic field facilities. Spark gaps are often used to commute energy on a load. Triggered spark gaps with electrodynamical acceleration of spark channel were developed and investigated by Kovalchuk and colleagues [1, 2]. Later two-electrode spark gap with inductive coupling in a triggering circuit [3] was introduced with sharp extension in operation range and charging voltage. In some applications unipolar pulse is not feasible and oscillatory regime (underdamped sinusoidal) has to be realized for the capacitor bank discharge. In particular, it is valid for a pulse magnetic method, which is used for assembling welding, cutting, and forming the details of products in various branches of industry [4]. Spark gaps, developed for unipolar discharge, cannot directly be employed in under-damped (oscillatory) regime, because at current transition through zero the arc channel could stop motion and ignite at initial place on the following half period. Process of the arc ignition and motion became more complicated in the oscillatory regime of capacitor bank discharge. Two main objectives were pursued in this work: 1. develop and test simulation model of a the spark channel motion in linear rail geometry for the oscillatory regime of capacitor bank discharge; 2. Investigate arc motion and electrodes heating depending on the current and charge transfer in wide operation range. A simple and effective model has been developed by Kharlov [5] to study in complex both arc motion and electrodes erosion in linear or coaxial rail geometry in high pressure gas for high current and high charge transfer pulses. Self-consistent treatment of plasma motion and electrodes heating has been employed. But in model [5] approximation with constant arc mass has been accepted, which is not very accurate assumption. This paper upgrades model [5] by incorporation of self-consistent treatment of the ablation on the electrodes and taking into account temperature dependence of main thermal parameters and radiation transfer from a plasma channel, which is quite important for consideration of the energy deposition in electrodes and hence electrodes erosion and degradation. It should be noted that the term ‘ablation’ means to the authors a combination of two processes: melting and simultaneous removal of melted material. Good agreement with the experiment is observed in considered range of parameters.

REFERENCES

1. *B. M. Kovalchuk, A. V. Kharlov et al // Rev. Sci. Instrum.* – 2008. – 79. – 053 504.
2. *B. M. Kovalchuk, A. V. Kharlov et al. //* IEEE Transactions on Plasma Science – 2008. – 36. – 2651-2657.
3. *B. M. Kovalchuk, A. V. Kharlov et al // Rev. Sci.* Instrum. – 2015. –**86**, –123 504
4. *V. Psyk, D. Risch, B.L. Kinsey, A.E. Tekkaya, M. Kleiner. Journal of Materials Processing Technology. – 2011. –* ***211,*** *p. 787.*
5 . *A . V . K h a r l o v //* IEEE Transactions on Plasma Science– 2010. – 38. – 2474-2478.

* Work supported by a Russian Foundation for Basic research grant 18-08-01209

PLASMA CHEMICAL PURIFICATION OF FLUE GASES USING PULSED ELECTRON BEAMS[1]

R.V. SAZONOV, G.E. KHOLODNAYA, D. V. PONOMAREV

Tomsk Polytechnic University, 2a Lenin Avenue, 634028, Tomsk, Russia, E-mail: sazonr@mail.ru

It is known that 2017 is officially declared the Year of Ecology in Russia. The purpose of this decision is to draw attention to the problematic issues that exist in the environmental protection field and to improve the state of the Russia's environmental security. A particularly acute environmental problem, both in Russia and abroad, is air pollution. The enterprises of ferrous and non-ferrous metallurgy, chemistry and petrochemistry, construction industry, energy, and fuel industry particularly affect air pollution. Thermal power plants (TPP) pollute atmospheric air with oxides of hydrocarbon, nitrogen, and sulfur.

Currently, there are a significant number of methods (sorption, catalytic, carbamide, ammonium magnesite, etc.) and technologies (technologies for the separation of sulfur dioxide from waste gases, Ebara technology), which make it possible to purify TPP flue gases from harmful constituents. The effectiveness of these measures is quite high, but a significant disadvantage is the high cost of equipment and operation, as well as the complexity of technological processes. In addition, all equipment is designed for high performance. An alternative to the above-described process for low-power enterprises may be the organization of plasma-chemical binding of harmful components of flue gases with the initiation of the process by a pulsed electron beam.

The paper presents the results of studies of the SO2 removal process due to the formation of ammonium sulphate as a result of a plasma-chemical reaction initiated by a pulsed electron beam. A laboratory stand which consists of a TEA-500 pulsed electronic accelerator (electron energy (varying) is 200-450 keV, beam current is 10 kA, current pulse duration (at half-amplitude) is 60 ns) and a plasma-chemical reactor. The proposed method for cleaning flue gases is based on plasma-chemical reactions initiated by a pulsed electron beam. A mixture of gases (N2, O2, H2O, SO2, NH3) is injected into the plasma chemical reactor, then a pulsed electron beam is injected. The energy of the electrons is transferred to the components of the gas mixture. The electrons interact with the gas, producing ions and radicals, excited atoms and molecules: N2+, N+, O2+, O+, H2O+, OH+, H+, N2+, O2+, N, O, H, OH, etc. These types of active particles take part in various chemical reactions, including reactions that bind polluting chemicals with the formation of solid compounds, which can be removed by filtration.

[1] This work was supported by Russian Science Foundation, research project No. 17-73-10269.

STUDY OF ELECTRODE SPOTS FROM A SPARK DISCHARGE WITH THE HELP OF INTERFERENCE MICROSCOPE[1]

I.V. BEKETOV, A.V. BAGAZEEV*, E.I. AZARKEVICH**, D.S. KOLEUKH**

** Institute of Electrophysics of the Ural Branch of the Russian Academy of Sciences, Amundsena str., 106, Ekaterinburg, 620016, Russian Federation*

***Ibid., azarkevich@iep.uran.ru, +7-912-612-9838*

In the course of work on production of nanopowders by the spark discharge method [1], in order to study the nature and mechanism of erosion of electrodes in a spark discharge, experiments were carried out to obtain discharge spots on the electrode surface after single discharges in an air atmosphere at normal pressure. The tested electrode was a cylinder of St3 steel with a diameter of 17 mm with a polished surface. The stored energy of the capacitor in experiments varied from 26 to 92 J, the discharge current was 10–20 kA, the period of current oscillations was 1.5–2.6 μs.

The spots were studied with the help of an interference microscope – the NewView 5010 surface analyzer (Zygo Corp., USA). The relief of the discharge spot is a system of craters separated by shafts. The processing of the microscope data made it possible to determine the shape and dimensions of craters and shafts, the statistical characteristics of their ensemble, and their relationship with discharge parameters.

As a result of analysis of the relief of discharge spots for different parameters of a spark discharge, the following is established.

1) The trace from the discharge looked like a large circular spot 1.2–2.4 mm in diameter, around which was a circle of small spots with diameter of 3.5–5.7 mm.

2) Discharge parameters – the stored energy, the charge flowing through the electrode, the current action integral, the square of the current amplitude – are correlated with each other, therefore any of them can be taken as the influencing factor on which the crater characteristics depend. In this study, the stored energy is taken as a factor.

3) The area of the discharge spot is proportional to the stored energy. The mass of metal, eroded from the electrode by the pulse, is also proportional to the stored energy. Therefore, erosion from a unit area of the spot, at a first approximation, does not depend on the energy and is equal to 0.384 μg/mm^2, which corresponds to a layer with a thickness of 0.049 μm.

4) Average specific characteristics of large spots such as the share of the area occupied by craters (55%), the density of the craters location (411 mm^{-2}), and the mean thickness of the layer of the moved metal (0.35 μm), at a first approximation, do not depend on the discharge parameters. The number of craters per spot is approximately proportional to the area of the spot.

5) The characteristics of craters – volume, area, depth, diameter – have a fairly wide distribution. The distribution of volumes and areas is close to normal-logarithmic one, and distribution of depths – to normal one. The median values of the characteristics of the craters, calculated from all the experiments, are equal: volume – 441 μm^3, mass – 3.44 ng, area – 790 μm^2, diameter – 31.7 μm, depth – 1.73 μm. Median values increase weakly with increasing stored energy. By geometric properties, the shape of the crater is on average close to the cone.

6) The median values of the characteristics of craters of small spots located on the periphery are 1.5–2 times smaller than for craters of a large spot. Therefore, it can assume that the current density at the periphery of the discharge is much smaller than in its central region, and the main source of the material from which the nanoparticles are formed is the central region of the discharge spot.

REFERENCES

[1] *D.S. Portnov, I.V. Beketov, A. Larranaga, A. Martinez-Amesti, G.V. Kurlyandskaya //* Vacuum. – 2016. – V. 132. P. 1-4.

[1] This work was supported by the Program of the Presidium of the Russian Academy of Sciences #11.

THE INSTALLATION FOR PRODUCTION OF METAL AND OXIDE NANOPOWDERS BY THE SPARK DISCHARGE METHOD, AND ITS TESTING[1]

I.V. BEKETOV, A.V. BAGAZEEV*, E.I. AZARKEVICH**, A.D. MAXIMOV*, A.I. MEDVEDEV*, A.I. BEKETOVA**

** Institute of Electrophysics of the Ural Branch of the Russian Academy of Sciences,*
Amundsena str., 106, Ekaterinburg, 620016, Russian Federation
***Ibid., azarkevich@iep.uran.ru, +7-912-612-9838*

A number of applications of nanopowders (for example, in medicine) imposes a requirement for as much particle dispersity as possible. Herewith, one expects from the methods of obtaining nanopowders not so much high performance, low energy consumption and cost, as for the quality of nanopowders. One of the promising methods for production of nanopowders with particles in the range of few nanometers is the synthesis of nanoparticles in the process of a spark discharge in a gas [1]. The Institute of Electrophysics of the UB RAS has been developing this technology in recent years [2, 3].

The report describes the latest modernization of the installation that implements this method, which allows expanding the range of materials used; increasing the stability of operation; providing ease of operation, etc. There are two interelectrode gaps in the new reaction chamber, with the gap geometry being varied within a wide range (gap size, shape and dimensions of electrodes). The electrical part of the installation contains a high-voltage power supply with an output voltage of up to 25 kV and a current of 100 mA, a storage capacitor of the IK-100-0.1 type, a discharge chamber with electrodes, a discharge current sensor, a voltage divider. The inductance of the discharge circuit is about 0.65 μH. The repetition rate of the discharge pulses is set by the ignition pulse generator (22 kV, 0.05 J), and can vary from 10 to 1000 Hz.

The aerosol formed by the discharge is carried away from the discharge chamber by the working gas flow created by the compressor (gas flow rate is up to 70 l/min). Particles of the product (less than 100 nm in size) are deposited on a porous stainless steel filter. Larger particles and agglomerates are trapped by the cyclone.

Preliminary experiments on the production of powders of metal oxides: titanium, iron, copper, and aluminum were carried out on the developed installation. Synthesis of nanoparticles was carried out in an air flow. The charging voltage varied from 10 to 22 kV and the discharge repetition rate was from 18 to 87 Hz. The produced powders were analyzed by XRD, BET, and also by electron microscopy (TEM and SEM).

The product is nanopowders of metal oxides with a predominant phase, respectively: TiO_2, Fe_3O_4, CuO and Al_2O_3. The mean particle size calculated from the specific surface is weakly dependent on the discharge parameters and is 6−8 nm for Ti and Fe, 10−15 nm for Al and Cu.

The main factors affecting the erosion of electrodes and the yield of the product are the material of the electrodes and the stored energy of the capacitor. In order of increasing erosion, the metals studied are arranged in a row: Ti, Fe, Cu, Al. The loss of the mass of the electrodes and the product yield are approximately proportional to the stored energy. The productivity of the installation depends, in addition to these factors, on the discharge repetition rate, and reached 0.5 g/h for Al at 33 Hz. The energy consumption were from 10 (Al) to 23 (Ti) MJ/g.

The spark discharge method is remarkable for the purity of the product, and it is suitable for any current-conducting material. The mean particle size can be controlled in certain range via the energy per spark. The productivity per installation can be increased by using a larger number of discharge gaps connected in series, and by an increasing the repetition rate of discharges.

REFERENCES

[1] *T.V. Pfeiffer, J. Feng, A. Schmidt-Ott* // Advanced Powder Technology. – 2014. – V. 25. P. 56-70.
[2] *D.S. Portnov, I.V. Beketov, A. Larranaga et al.* // Vacuum. – 2016. – V. 132. P. 1-4.
[3] *G.V. Kurlyandskaya, D.S. Portnov, I.V. Beketov et al*. // Biochimica et Biophysica Acta. – 1861 (2017). – P. 1494-1506.

[1] This work was supported by the Program of the Presidium of the Russian Academy of Sciences #11.

DEVELOPMENT OF A POWERFUL HIGH-VOLTAGE POWER SUPPLY FOR 30 KV

Y. A. BYKOV, V.F. FEDUSCHAK, K.V. GORBACHEV, Y.I. ISAENKOV, V.A. STROGANOV

Joint Institute for High Temperatures, Russian Academy of Sciences, 13/2 Izhorskaya str., Moscow, 125412, Russia
Yrka.2@mail.ru, 8(916)2664168

The developed high-voltage power supply for 30 kV with a power of 30 kW is designed for fast charging of high-voltage capacitors (charging speed up to 30 kJ/s) and pulse generation circuits in modulators of general purpose. The power supply is designed using the pulse width modulation (PWM) of an asymmetric half-bridge circuit of a resonant inverter. The source consists of a resonant inverter and a step-up transformer. The inverter is a half-bridge resonant LC converter with the switching of power IGBT switches at zero current. The oscillation frequency of the LC circuit is up to 20 kHz.

The secondary winding of the step-up transformer is designed as separate modules consisting of a winding and a bridge-circuit rectifier on high-frequency diodes. The output voltage of each module is up to 2 kV. The winding wire is designed to work with a current of up to 1 A. The serial connection of single modules allows to obtain an output voltage of up to 30 kV at a current through a load of 1 A.

This work is devoted to designing a high-voltage power supply and describing its operation principle. The features of the chosen scheme are substantiated, the reviews of power elements in the current market and their description are presented. The results of model tests are shown.

EXPERIMENTAL INVESTIGATION OF EXPLODING THE SURFACE OF CONDUCTORS BY A MULTIMEGAGAUSS MAGNETIC FIELD WITH A MICROSECOND RISE TIME

V.A.. KOKSHENEV, N.E. KURMAEV, F.I. FURSOV, R.K. CHERDIZOV*

Institute of High Current Electronics SB RAS, 2/3 Akademichesky Avenue, Tomsk, 634055, Russia, vak@oit.hcei.tsc.ru, +7-3822-492-908

For the microsecond current front, the behavior of conductors from various materials with a magnetic field intensity on their surface of several MA/cm is investigated. In such modes, plasma formation takes place on the electrode surface with its subsequent expansion into the gap. This leads to a decrease in the efficiency of energy transportation to the load, but it can be used to implement the mode of the crowbar with the disconnection of the load node from the generator. According to available literature data, the sublimation energy for copper is attained at ~ 2.8 MA/cm, which can be obtained with a current of 4 MA at a diameter of no more than 0.5 cm. The operating mode of the GIT-12 generator with loads of 3-4 mm in diameter and up to 2.5 cm in length provided a current of up to 4.5 MA with a front ~ 1.7 μs.

The samples of stainless steel (SS), aluminum (Al) and copper (Cu) in diameters of 4 or 3 mm in the form of a rod or tube with a wall thickness b from 0.25 mm to 1 mm were tested. The wall thickness was chosen from the estimate of the thickness of the skin layer for linear diffusion of the magnetic field into the conductor $\Delta \cong (c^2\rho\tau_f / 4\pi)^{1/2}$, where ρ is the resistivity of the material, τ_f is the current front. For $\tau_f \cong$ 1 μs, the thickness of the skin layer for copper is ~ 0.12 mm, for aluminum ~ 0.15 mm, for stainless steel ~ 0.85 mm.

The boundary values of the magnetic field intensity above which there is an explosion of the conductor surface are established and the explosion velocities of the explosion products for the front of the current (1 - 1.5) μs are determined. For a copper rod ∅ 3.6 mm at currents up to Id = 3.4 MA/1130 ns, which corresponds to a magnetic field strength of Hs ~ 3 MA/cm, there is practically no glow of the surface, there is only an image of the contact region. After the explosion, the surface disperses at a velocity u ~ 1.7 mm/μs. For a stainless rod ∅ 4 mm Hs ~ 2.2 MA/cm, the expansion velocity u ~ 4 mm/μs, for a tube with wall thickness b = 1 mm – u ~ 5.5 mm/μs. For an aluminum rod ∅ 3 mm, the propagation velocity in different sections (strata) was u~(3-5) mm/μs with a current change from $Id1$=3 MA/1020 ns to $Id2$ =3.5 MA/1250 ns.

The method of increasing the maximum magnetic field intensity before a conductor explosion with the use of composite samples was tested [1]. Fig. 1 illustrates the positive effect of this method. In the area where the copper rod is inserted, there is no surface expansion at a magnetic field intensity of at least H = 3.1 MA/cm. When the diameter of the composite sample was reduced to 3 mm, the magnetic field intensity was H ~ 4 MA/cm (magnetic field induction ~ 5 MG and pressure ~ 100 GPa).

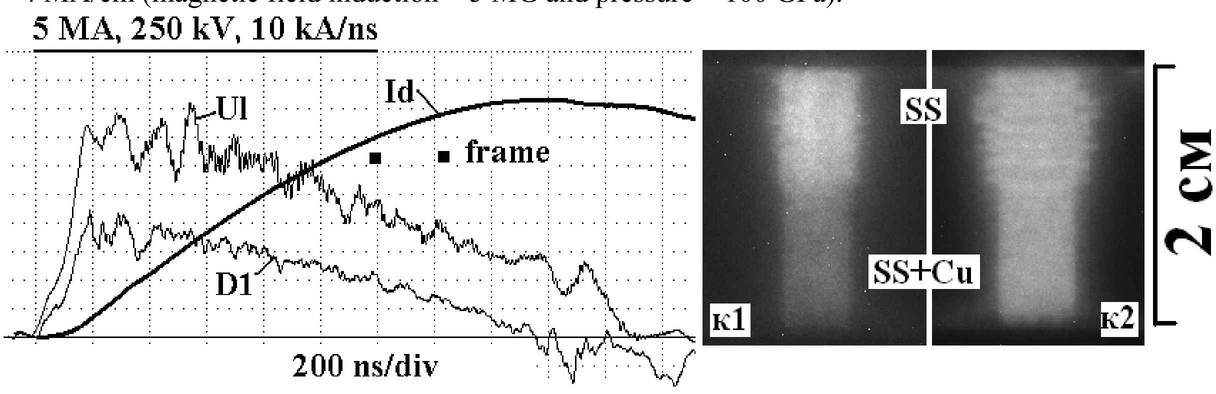


Fig. 1. Oscillograms of the load current Id, its derivative D1 and the voltage Ul for a two-layer conductor [SS ∅ 4 mm + (SS tube ∅ 4/3 mm + Cu ∅ 3 mm)]. On the right, frame-by-frame sample images obtained with the help of "Nanogate-2". The frame times with 10 ns exposure are shown in squares.

REFERENCES

[1] *Chaikovsky S. A. et al // Phys. Plasmas. – 2014. – V.21. – 042706.*

NUMERICAL INVESTIGATION OF SUBNANOSECOND PULSES AMPLIFICATION IN THE GAS AMPLIFIER OF THE THL-100 LASER SYSTEM[i]

A.G. YASTREMSKII, N.G.IVANOV, V.F. LOSEV

Institute of High Current Electronics, Siberian Branch Russian Academy of Sciences, Akademicheskii prosp. 2/3, 634055 Tomsk, Russia; e-mail: ayastremskii@yandex.ru

THL-100 hybrid laser systems presently being developed at the Lebedev Physics Institute(Moscow) and the Institute of High Current Electronics, Siberian Branch, Russian Academy of Sciences (Tomsk). These system includes a Ti:sapphire femtosecond front end and a photo dissociation XeF(C–A) amplifier. The mirror system of the gas amplifier consists of input, and output window and 31 mirrors. The pulse power THL-100 14 TW [1], record for the visible region (λ=475 nm), was obtained in 2013 with a pulse duration of 50 fc and an input beam energy of 0.7 mJ. In 2017, the output energy is increased to 3.2 J [2] and it is shown that the amplifier operates in saturation mode. A further increase in energy is possible only with an increase in the pumping energy or the number of passes of the active region by the laser beam. However, in this case, the intensity of the laser radiation increases, which can cause destruction of the mirrors.

The main goal of the work is to study the influence of pumping energy and the number, dimensions and position of the mirrors of the gas amplifier of the THL-100 laser system on the energy and time characteristics of a laser beam. To reduce the intensity of radiation, the duration of the laser beam was increased to 250 ps. The energy and duration of the pump pulse were 270 J and 330 ns, respectively.

The investigation results of the gas amplifier pumping energy increase on the energy and intensity of laser

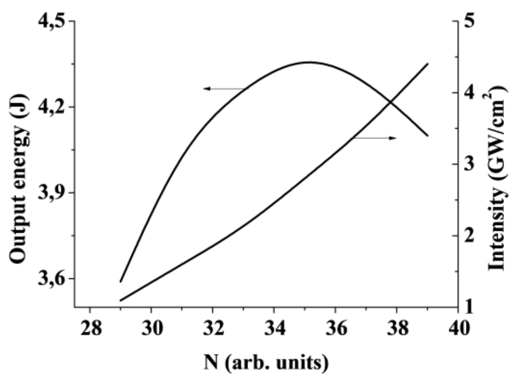


Fig. 1. Output energy and intensity, depending on the number of laser beam passes in the amplifier

radiation were presented. The dynamics of change in the energy and intensity of laser radiation with an increase in the number of passes of the laser beam in the amplifier from 29 to 39 was investigated.

REFERENCES

[1] *S.V. Alekseev, A.I. Aristov, N.G. Ivanov, B.N. Koval'chuk, V.F. Losev, G.A. Mesyats, L.D. Mikheev, Yu. N. Panchenko, N.A. Ratakhin//* Quantum Electronics. - 2012.- V. 42 - №5 - P.377.

[2] *S.V. Alekseev, N.G. Ivanov, M.V. Ivanov, V. F. Losev, G.A. Mesyats, L.D. Mikheev, Yu.N. Panchenko, N.A. Ratakhin, A.G. Yastremskii.//* Quantum Electronics - 2017.-. V. 47 - №3 - P.184.

[i] This work was supported by the Russian Foundation for Basic Research (Projects 18-08-00407 and 18-08-00383).

STUDY OF ELECTRON INTERACTIONS WITH LIQUID WATER AND PROCESSES RELATED TO SUB-NANOSECOND ELECTRICAL BREAKDOWN[1]

Z. BONAVENTURA*, P. BÍLEK*, T. HODER*, M. ŠIMEK**

*Masaryk University, Faculty of Science, Department of Physical Electronics, Kotlářská 2, 611 37 Brno, Czech Republic.
**Department of Pulse Plasma Systems, Institute of Plasma Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic

Initiation of electric discharge in dielectric liquids such as water can be caused either by formation of gaseous bubbles (when the system is driven by high-voltage waveforms of microsecond duration) or due to creation of cavitation voids in case of very-steep high-voltage pulses with sub-nanosecond rise times. Presence of these deformations prolong mean-free path of electrons, which can then gain enough energy for excitation/ionization/dissociation of water molecules.

We propose to use Geant4-DNA [1, 2] toolkit for studies of elementary processes related to interaction of accelerated electrons with liquid water. The Geant4-DNA provides a complete set of models describing the step-by-step physical electromagnetic interactions of electrons with liquid water. These models describe both the cross sections and the final states of the physical interactions, with a full description of the interaction products, taking into account the molecular structure of liquid water. Geant4-DNA electron models for the calculation of ionization and excitation cross sections are based on the Emfietzoglou model [3] of the dielectric function of liquid water. The dielectric function approach is currently the state-of-the-art technique for modeling the energy-loss of electrons in the condensed phase [4].

The aim of our work will be to study elementary processes related to interaction of accelerated electrons with liquid water. Geant4-DNA provides appropriate tools for simulations of different liquid-water characteristics during electrical breakdown such as: electron-penetration-range computation [5], electron slowing-down spectra [6] and radiation-chemistry modeling [7]. These tools enable us determination of electrical-breakdown characteristics of liquid water, which will be confronted with experimental data acquired in point-plane electrode geometry [8, 9].

REFERENCES

[1] *M.A. Bernal et al*., Physica Medica: European Journal of Medical Physics **31** 8, (2015) 861–874.
[2] *S. Incerti et al*., Medical physics **37** 9, (2005).
[3] *D. Emfietzoglou* Radiat. Phys. Chem., **66**, 373 (2003).
[4] *Emfietzoglou et al*., Int. J. Radiat. Biol., **88**, 22 (2012).
[5] *Z. Francis et al*., Applied radiation and isotopes **69** 1, (2011) 220–226.
[6] *S. Incerti et al*., Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, **397**, (2017) 45–50.
[7] *M. Karamitros et al*., Progress in nuclear science and technology **2** (2011), 503–508.
[8] *M. Šimek et al*., Book of Contributed Papers of 15th International Symposium on High Pressure Low Temperature Plasma Chemistry (HAKONE XV) p. 405-407 (2016).
[9] *M. Šimek, et al*., Plasma Sources Science and Technology **26** 7, (2017) 07LT01.

[1] This work has been supported from the Czech Science Foundation research project 18-04676S.

DISCHARGE CHAMBER GAS DYNAMICS WITH MOVING CONTACT[1]

N.K. KURAKINA * **, *M.E. PINCHUK* * **, *A.V. BUDIN**, *A.A. SMIRNOVSKY****, *V.E. KUZNETSOV**, *A.A. KISELEV**

**Institute for Electrophysics and Electric Power of Russian Academy of Sciences, Dvortsovaya nab., 18, St.-Petersburg, 191186, Russia, e-mail: rc@iperas.nw.ru, +7 (812) 3151757*

***Research and Production Company "UniLabs", Zagorodnyi pr. 37/70 liter A office 12-H , St.Petersburg 191180, Russia, e-mail: mail@unilabs.tech*

****Peter the Great Saint-Petersburg Polytechnic University, Polytechnicheskaya, 29, Saint-Petersburg 195251, Russia*

The gas filling of the discharge chamber during opening contact system is investigated. A supersonic flow of the compressed gas was blowed into the chamber through the arc. The movable contact moved due to the gas pressure inside the discharge chamber. The experimental set-up is intended for investigation of arc processes, erosion of electrodes and degradation of insulating materials in gas current circuit breakers [1].

For numerical simulation an open package OpenFOAM was used with the swak4foam library. The methods for creating a model with the elements of grid reconstruction taking into account model assumptions are described. The results of calculation of gas-dynamic parameters are given: pressure fields, velocities, temperature and their time dependence. The pressure equalization in the chamber is investigated when the necessary contact opening speed was achieved for effective arc extinguishing in the range of 20-25 m/s by the time moment of 4 ms with the boost pressure of the gas within 2-3 MPa.

REFERENCES

[1] *A.V. Budin, M.E. Pinchuk, V.E. Kuznetsov, V.V. Leont'ev, N.K. Kurakina.* // Instruments and Experimental Techniques. 2017. vol. 60. № 6. pp. 837-842. DOI: 10.1134/S0020441217060033.

1 The work was performed under the Program of Fundamental Researches of the Presidium of the Russian Academy of Sciences n31 "FUNDAMENTAL RESEARCHES OF PHYSICAL AND TECHNICAL PROBLEMS OF ENERGY DEVELOPMENT"'. Also the work is partially supported by Russian Foundation for Basic Research (grants 16-08-00767-a).

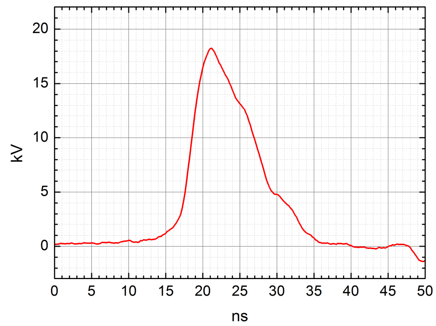
COMPACT HIGH VOLTAGE DSRD-BASED GENERATORS OF NANOSECOND PULSES FOR DISCHARGE AND MEDICAL APPLICATIONS

A.G. LYUBLINSKIY, A.F. KARDO-SYSOEV

Ioffe Institute, 26 Polytechnicheskaya, St.Petersburg, 194021, Russia, Alexander.Lyublinsky@mail.ioffe.ru, +7-812-297-3145

Two types of new designed high voltage nanosecond pulse generators are presented. They are based on Drift Step Recovery Diodes (DSRD) – semiconductor devices discovered in Ioffe Institute [1]. The detailed description of DSRD physical principles and operation were presented in [2, 3]. In spite of DSRD are widely used and many pulse generators have been already designed [4, etc.], novel demands and application areas encourage continuous research in this field. The design and operation of two types, namely, burst mode pulse generator and rectangular waveform pulse generator are described.

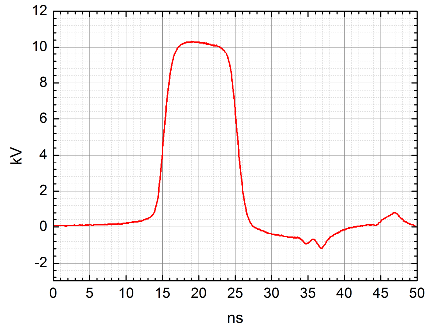
The first one is NPG-18/100k burst mode high voltage nanosecond pulse generator. The repetition rate within the burst has been increased up to 100 kHz, which significantly extends the ability of the generator. Burst mode and high repetition rates are vital for plasma-assisted burners, ignition systems and combustion control in gas turbines, aircraft or internal combustion engines, etc. Very promising application is air-breathing plasma jet propulsion and the thruster based on magneto-plasma flux compression (MPC) for stratospheric flights. The photo, output pulse waveform and main parameters are shown in Fig.1.



Amplitude – regulated 13-18 kV
Output impedance – 75 Ohm
Rise time – less than 4ns
Pulse width (FWHM) – 9 ns
Max. frequency – 100 kHz (burst)
4 kHz (continues mode)
Pulses within burst – up to 4000
Digital control of amplitude, frequency and number of pulses
Size – 248x90x250 mm^3

Fig. 1. The photo, output pulse and main parameters of NPG-18/100k high voltage burst mode nanosecond pulse generator.

The second one is NRG1001 rectangular waveform high voltage nanosecond pulse generator. It implements DSRD-based opening switch and current charging line instead of widely-know solution based on closing switch and voltage-charged pulse forming network (PFN), which should be initially pre-charged to a high voltage. The main benefits of new approach are nanosecond and sub-nanosecond rise/fall times as well as high voltage output pulse generation with using of low voltage power supplies only. Therefore, compact and effective pulse generators can be made. NRG1001 has been designed for medical application, but it can be used in other areas, for example, Pockels cell drivers and kicker systems for e-beam control. NRG1001 includes special circuit for damping the reflected pulses and can operate with unmatched load.



Amplitude – regulated 3-10 kV,
1-10kV with external divider
Output impedance – 50 Ohm
Load – 50 Ohm or high impedance
Rise/fall times – 2 ns
Pulse width (FWHM) – 10 ns
Max. repetition rate – 1 kHz
Size – 248x90x250 mm^3

Fig. 2. The photo, output pulse and main parameters of NRG1001 rectangular waveform high voltage nanosecond pulse generator.

REFERENCES

[1] *I.V. Grekhov, V.M. Efanov, A.F. Kardo-Sysoev, et al. // Sov. Tech. Phys. Let., 1983,* ***9****, (7), p. 435.*
[2] *I.V. Grekhov // Solid-State Electronics, 1989,* ***32****, (11), pp. 923–930.*
[3] *I.V. Grekhov, G.A. Mesyats // Physics – Uspekhi, 2005,* ***48****, (7), pp. 703–712.*
[4] *S.V. Korotkov, Yu.V. Aristov, A.K. Kozlov, et al. // Instruments and Experimental Techniques, 2012,* ***55****, (5), pp. 605–607.*

GENERATION OF LASER RADIATION IN THE PUMPING DISCHARGE OF KRF-LASER WITH CHANNELS[1]

*YU.N. PANCHENKO, S.A. YAMPOLSKAYA, A.G. YASTREMSKII**

** Institute of High Current Electronics SB RAS, 2/3 Akademichesky ave., Tomsk, 634055, Russia, E-mail: s_yampolskaya@yahoo.com, phone: 8 (3822) 49-17-52*

Often, for various applications, an important requirement is the compact dimensions of an electric-discharge excimer laser. In this case, in order to obtain sufficient laser parameters, it is necessary to increase the specific (per unit volume) energy of laser radiation. This is possible only at high pumping power and high content of halogen donor in the working mixture. Under such conditions, the pumping discharge of excimer lasers, in general, and the KrF laser, in particular, is highly unstable. During its duration discharge passes from a volume discharge to a discharge consisting of one or several channels with high conductivity. The transition to the channel form stops generation of laser.

In [1], the results of a study of the development of the pump discharge of Krf-laser with a channel, obtained by metod of 2D modeling, were presented. It was shown that before the spark stage, the channel passes through the stage of the diffuse channel and at this stage, conditions are created optimal for obtaining a high specific power of laser radiation.

The purpose of the presented work was to determine the influence of pumping conditions, such as, the charge voltage, the duration of the pump pulse, the total discharge current for the duration of the discharge in the diffuse channel stage t_d. It was shown that t_d depends weakly on the pumping conditions and is ~ 20 ns. In connection with this, the pump pulses with a duration of 30 - 40 ns are the most effective from the point of view of obtaining the maximum specific energy of the radiation and the efficiency of the laser.

REFERENCES

[1] *S. A. Yampol'skaya, A. G. Yastremsky, Yu. N. Panchenko, A. V. Puchikin, S. M. Bobrovnikovs* // Russian Physics Journal. – 2018. – Vol. 60. – № 9. 1623-1629

1 This work was supported by the Interdisciplinary Integration Studies SB RAS Grant No. 161

OPTICAL PROPERTIES OF $Si_XTi_YC_ZO_W$ COMPOSITE NANOPOWDER OBTAINED BY PULSED PLASMA CHEMICAL METHOD[1]

G.E. KHOLODNAYA, F.V. KONUSOV*, R.V. SAZONOV*, D.V. PONOMAREV*, M.I. KAIKANOV***

**Tomsk Polytechnic University, 2a Lenin Avenue, 634028, Tomsk, Russia, E-mail: galina_holodnaya@mail.ru*
***National Laboratory Astana, Nazarbayev University, Kabanbay batyr ave. 53, Astana, 010000, Kazakhstan*

This paper presents the results of an experimental investigation on the optical properties of the $Si_xTi_yC_zO_w$ nanopowders, produced by the pulsed plasma chemical method. Pulsed plasma chemical synthesis is realized on the laboratory stand, which consists of a plasma chemical reactor and TEA-500 pulsed electron accelerator. Main parameters of the electron beam are as follows: kinetic energy of electrons is 400-450 keV, half-amplitude pulse duration is 60 ns, total energy of the beam is up to 200 J, beam spot-size is 5 cm in diameter.

The spectrum of the diffuse reflection coefficient R(hν) was measured using the AvaSpec-2048-2 (Avantes) spectrometer with the AvaLight-DHS light source (deuterium and halogen-tungsten lamp) and an integrating sphere. To determine a crystal structure of the nanopowder, the common technique of X-ray phase analysis was used. The reaction products were analyzed using a DRON-07 diffractometer. The morphology of the particles was studied using the the JEOL-II-100 electron microscope. Composition of nanopowder was identified using the optical absorption spectrum in the IR region. The application of this method for the study of the nanodispersed particles enables to make a volumetric analysis of the sample, since the penetration depth of the IR-radiation (several μm) exceeds a geometrical size of the particles. To perform this analysis, the Nicolet 5700 FT-IR spectrometer was used.

The main physical and chemical properties of the obtained composites (morphology, chemical, elemental and phase composition) were studied. The morphology of the $Si_xTi_yC_zO_w$ composites is multiform. There are large round particles, with an average size of above 150 nm. Besides, small particles with an average size in the range of 15 to 40 nm also presents in synthesized powder. The morphology of small particles is in the form of crystallites. In the $Si_xTi_yC_zO_w$ synthesized composite, the peak with a maximum of 946 cm^{-1} was registered. The peaks in this region of IR spectrum are typically responsible for the deformation of atomic oscillations in the Si-O-Ti bond, which indicates the formation of the solid solution in compound. The composites consist of two crystal phases – anatase and rutile. The prevailing phase of the crystal structure is rutile.

[1] This work was supported by the MES of RK grant “Pulsed plasma-chemical synthesis of new generation TiO2 photo catalysts”.

DEVELOPMENT OF DISCHARGE AND GENERATION CHARACTERISTICS OF CU-NE AND CUBR-NE LASERS WHEN EXCITED BY PULSES WITH A SHORT FRONT[1]

P.A. BOKHAN, P. P. GUGIN, M. A. LAVRUKHIN, DM. E. ZAKREVSKY

Institute of Semiconductor Physics, Siberian Branch, Russian Academy of Sciences, pr. Akademika Lavrent'eva 13, Novosibirsk, 630090, Russia, lavrukhin@isp.nsc.ru

It was shown in [1] that up to the pulse repetition frequency (PRF) *f*~16 kHz, the power of laser generation of a Cu-Ne laser increases in proportion to f when excited by pulses with a front ~ 1 ns. In [1] active elements of the FSUE "Istok" production with cold emission cathodes were used. In the case of cold non-emission cathodes, there is a delay in the development of the discharge, which can adversely affect the lasing characteristics. The reason is that the initial conductivity of the plasma is significantly different for the near-electrode regions and the active zone (AZ) of the laser tube. Therefore, a pre-breakdown low-voltage stage of voltage on the AZ occurs, during which the parasitic population of the metastable states of the copper atom occurs. To study the effect of this phenomenon on the generation characteristics of a Cu laser, we made a tube of BeO ceramics with an internal diameter of 2 cm and a length of 50 cm. The tube is equipped with a built-in heater, which made it possible to work in a train of pulses without changing the thermal regime with variations in the PRF in the train. For a comparative study, a quartz tube 30 cm in length and 1 cm in diameter was also designed to work with the CuBr-Ne mixture. The laser was excited in two ways: when the capacitance was discharged through the thyratron, followed by a magnetic compression of the pulses, and when the capacitance was discharged through a kivotron with rising fronts τ~1 ns. In this case, the pulse parameters were stored up to *f*=13 kHz without changing the switching characteristics. To achieve large *f*, the kivotron was filled to a lower pressure, which made it possible to operate *f* = 28 kHz with a front *τ*~3 ns. For even larger PRF, an eptron that retains its switching characteristics at least *f*=100 kHz is used for working with a CuBr laser, requiring lower currents.

The figure shows the dependence of 1 shows the lasing characteristics (output power) of a Cu laser at a working capacity of 1.1 nF and a voltage on a thyratron of 16 kV, the operating temperature of the tube is 1550 °C, and the neon pressure is 45 Torr. Curve 2 shows the efficiency of the laser in relation to the energy stored on the primary capacitance. Dependences 3,4 show the same parameters for the case of commutation by a kivotron with *τ*~1 ns. To achieve the same power at *f*=3 kHz, the initial voltage at the working capacitance was 17 kV, so the efficiency at this PRF is lower than with the use of magnetic compression. There is a significant difference in the generation characteristics when using different ways of feeding the laser. To achieve a high repetition rate, a kivotron with *τ*~3 ns was used. In this case, up to *f*=7kHz, the generation power is practically the same as for the case with *τ*~1 ns. However, at large f, the lasing power growth slows down, and it does not reach the same value even at high repetition rates (curve 5). Qualitatively similar results were obtained for a CuBr-Ne laser.

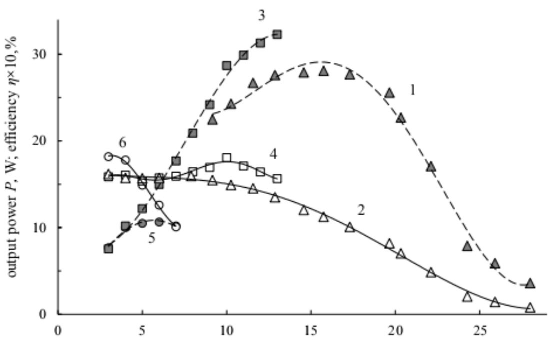


Fig.1. Output power (1;3;5) and efficiency (2,4,6) of a *Cu* laser versus frequency *f.* 1,2 - *τ*~3 ns; 3,4 - *τ*~3 ns; 5,6 - followed by a magnetic compression.

REFERENCES

[1] *Bokhan P.A., Gugin P.P., Zakrevskii D.E., Lavrukhin M.A., Kazaryan M.A., Lyabin N.A.*// Quantum Electron. - 2013. - 38. - 715.

[1] The study was supported by Russian Foundation for Basic Research (№ 17-08-00121).

CHARACTERIZATION OF THE ABLATIVE ANODE MICRO-CATHODE VACUUM ARC THRUSTER[1]

D.B. ZOLOTUKHIN, **, S. HURLEY**, M. KEIDAR***

**Tomsk State University of Control Systems and Radioelectronics, 40 Lenina St., Tomsk, 634050, Russia, ZolotukhinDen@gmail.com*

***The George Washington University, 800 22nd Street, Northwest Washington, DC, 20052, United States of America*

Microcathode vacuum arc thrusters (µCATs) developed by The George Washington University are compact (several cm-scale) low weight (up to 300 g) pulsed (single pulse length 10-100 µs) plasma-propulsive engines of micro-Newton thrust level, which are gaining popularity in small satellites like CubeSats [1]. Small satellites are becoming widely used by private companies and universities; partially, CubeSats equipped by µCATs have been enrolled in space missions like CANYVAL-X [2] and BRICsat-P [3]. Such thrusters typically consist of central cathode, and annular anode separated by a ceramic dielectric coated by conductive film. The thrust is produced as a result of expelling the plasma particles created in result of pulsed arc discharge between the electrodes. Typically [4], the coaxial configuration of µCAT, with central cathode and annular anode, both made of low-weight metals, is used. However, the configuration of µCAT with ablative central anode made of light metal with high vapor pressure and low melting temperature (as copper or brass) looks very promising since it theoretically allows increasing thrust-to-power ratio by the more effective utilization of electron current during arcing pulse. Therefore, the goal of the present work was the characterization of µCAT with an ablative anode. We measured the ion-to-arc current ratio, ion velocity and electrode mass erosion rates for µCATs in ablative and non-ablative anode configurations. We found the presence of the anode ablation effect; this fact in combination with the higher ion-to-arc current rate and ion velocity, in comparison with non-ablative µCAT, allows one to expect the higher thrust for the same electrical power provided to thruster.

REFERENCES

[1] *M. Keidar, T. Zuang, A. Shashurin, G. Teel, D. Chiu, J. Lucas, S. Haque, L. Brieda // Plasma Physics and Controlled Fusion. – 2015. – 57. – № 1. 014005(1-10).*

[2] *See NASA webpage for additional mission details: https://www.nasa.gov/feature/goddard/2016/nasa-engineer-awaits-launch-of-cubesat-mission-demonstrating-virtual-telescope-tech*

[3] *S. Hurley, G. Teel, J. Lukas, S. Haque, M. Keidar, C. Dinelli, J. Kang // Transactions of JSASS, Aerospace Technology Japan. – 2016. – 14. – ists30. Pb157-Pb163.*

[4] *J. Kolbeck, M. Keidar, A. Anders // 52nd AIAA/SAE/ASEE Joint Propulsion Conference. – 2016. 1-15.*

[1] This work was supported by a Vector Space Systems and NASA DC Space Grant Consortium.

TRIGGERED SPARK-GAP SWITCH WITH GAS CIRCULATION FOR REPETITIVELY OPERATED MULTISTAGE MARX GENERATOR [1]

A.S. YUDIN*, S.M. MARTEMYANOV*, A.A. BUKHARKIN *, I.V. BUGAEV*, E.G. KRASTELEV**

*Tomsk Polytechnic University, 30 Lenina ave., Tomsk, 634050, Russia, tevn@hvd.tpu.ru
** Joint Institute for High Temperatures, Russian Academy of Sciences, 13/19 Izhorskaya str., Moscow, 125412 Russia

A column type set of spark-gap switches for 12-stage 5 kJ Marx generator repetitively operated with rep-rate up to 10 pps was developed and constructed. The Marx generator design (peak voltage of 600 kV at 50 kV charging) meets the requirements of applications in electro-discharge technologies like a concrete construction crashing, removing of concrete surface layers, drilling and cutting of stones [1]. The column of Marx switches includes one triggered switch and eleven self-breakdown two-electrode gaps. A long-time of operation of the switches is provided by an intensive gas circulation through the column and its cooling. High stability of the dynamic parameters (stable pulsed self-breakdown voltage and a small discharge time delay) is achieved by the gas preionization in the spark gaps by additional corona discharges.

The design of the spark-gap electrode system is based on the scheme reported in [2] in which the main electrodes have a toroidal geometry and an additional corona needle is located in the cavity of one of them (negative during the operation). Such electrode system combines two parallel gas discharge gaps – the main spark gap and an additional corona discharge gap. The spark gap is formed by toroidal electrodes with a large working surface which provides a long-time operation of the switch. Configuration of the corona discharge gap with axial needle and the cavity of the opposite electrode meets the requirements of corona set up prior to the spark breakdown between the main electrodes and excludes its transition to the spark form. The sketch of the first triggered spark-gap switch given in figure 1. The results of experimental tests including the measurements of electrodes erosion provide the estimations for electrode life-time of 10^6 pulses and periodical service-time of $5{\cdot}10^4$ pulses. The design of the switch and its main elements together with the results of the experimental tests will be presented and discussed.

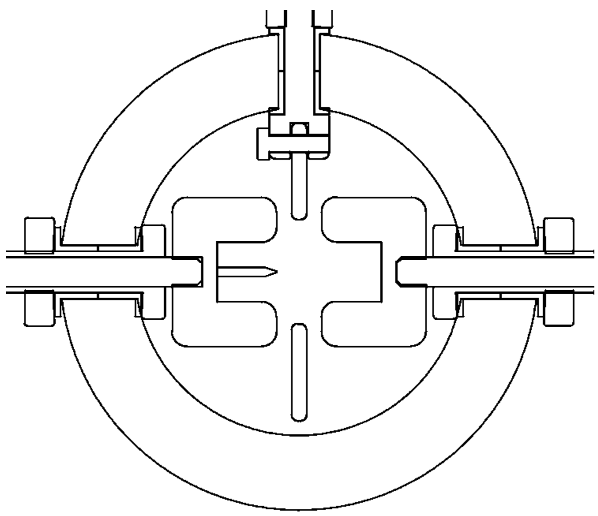


Fig. 1. Sketch of the first triggered spark-gap switch

REFERENCES

[1] *B. V. Semkin, A. F. Usov, and V. I. Kurets // The principles of electric impulse destruction of materials (in Russian),Kola Science Centre of the Russian Academy of Sciences. Saint Petersburg, Russia: Kola Peninsula, 1995,[Online]. Available: http://www.kolasc.net.ru/spark/download/Binder2.pdf*

[2] *Yu. A. Bykov and E. G. Krastelev. Gas Spark Switches with Increased Operating Life for Marx Generator of Lightning Test Complex // Physics of Atomic Nuclei, 2016, Vol. 79, No. 14, pp. 1614–1618.*

[1] This work was supported by RFBR project № 16-48-700278.

APPLICATION OF IONIZING RADIATION FOR THE PROTECTION OF GRAIN FROM PESTS AND DISEASES

*T.V. CHIZH**, *N.N. LOY**, *A.N. PAVLOV**, *M.S. VOROBYEV***

**RIARAE, Obninsk, 249032, Kaluga region, Kiev highway, 109 km, Russia,*
Phone: +7(910)526-45-95, e-mail: taras.chizh@rambler.ru
***IHCE SB RAS, Tomsk, 634055, 2/3 Akademichesky Avenue, 2/3, Russia*

Insect pests of grain are ubiquitous and cause great damage to agricultural products during storage. They cause not only large losses of grain, but also its spoilage, reduce quality of flour and the feed value of grain fodder, mixed fodder [1].

To ensure reliable disinfestation of seeds in our country, chemicals are traditionally used – contact insecticides. The use of chemicals (fumigation) is not always effective against internal contamination of products, and its widespread use leads to the emergence of forms of pests resistant to the chemicals used [2].

In addition, after harvesting, the surface of the seeds remains the causative agents of fungal and bacterial diseases, which, after sowing seeds in the soil, affect plants, exerting a depressing effect on the development of plants, thereby reducing crop productivity.

Therefore, now the efforts of many scientists and specialists focused on the search for new seed disinfection methods without the use of pesticides. Radiation disinfestation and disinfection of agricultural products compared with existing chemical methods has undoubted advantages: pollution of the environment is excluded; in the irradiated products there are no residues of pesticides, economically advantageous [3-5].

Studies on presowing seed irradiation on an electron accelerator at doses of 1, 5, and 8 kGy, dose rates of 100 and 500 Gy per impulse, made it possible to establish that presowing irradiation of barley seeds at doses of 5 and 8 kGy (dose rate 100 Gy per impulse) and doses of 1 and 5 kGy (a power of 500 Gy per impulse) reduces its incidence of helminthosporiosis (*Helminthosporium sativum* P., K. et B) of barley by 3.2 and 2.1 times, and the prevalence of the disease is 3.0 and 1.4-2.3 times, respectively (Table 1).

Table 1

Effect of irradiation on damage to barley seeds by Helminthosporium sativum, %

Dose, kGy	Dose rate, Gy/imp.	Damage	Prevalence
0 (control)	-	17.00	36.33
1.0	100	14.00	29.33
5.0	100	5.33	12.00
8.0	100	5.33	12.00
1.0	500	8.00	26.00
5.0	500	8.17	16.00
8.0	500	16.00	34.00
HCP_{05}		5.82	11.11

In this way, the effectiveness of using electron irradiation to suppress the viability of pathogens has been experimentally proven.

REFERENCES

[1] *Zakladnoy G., Saulkin V.* Detection of insect pests of grain stocks without sampling // Mixed feed, No. 8. 2011. P. 57-58.
[2] *Champ B.R., Dyt, C.E.*, 1976. Report of the FAO global survey of pesticides susceptibility of stored grain pests. FAO Plant Production and Protection Series No. 5, Food and Agriculture Organization of the United Nations, Rome, 297 pp
[3] *Tuncbilek A.S.*, 1995. Effect of 60 Co gamma radiation on the rice weevil, Sitophilus oryzae (L.). Anzeiger fur Schadlingskunde Pflanzenschutz, Umweltschutz 68, 37±38.
[4] *Lapidot M., Saveanu S., Padova R., Ross I.* 1991. Insect Disinfestation by Irradiation. Insect Disinfestation of Food and Agricultural Products by Irradiation. Proceedings IAEA, Vienna, 103 pp.
[5] *Ahmed M.* 2001. Disinfestation of stored grain, pulses, dried fruits and nuts, and other dried foods. p. 77–112. In: “Food Irradiation Principles and Applications” (R. Molins, ed.). Wiley, New York.

FEATURES OF THE DISCHARGE IGNITION IN THE TRIGGER UNIT OF COLD-CATHODE THYRATRON[1]

N.V. LANDL, Y.D. KOROLEV, V.G. GEYMAN, O.B. FRANTS, G.A. ARGUNOV, A.V. BOLOTOV

Institute of High Current Electronics, Akademichesky Ave. 2/3, Tomsk, 634055, Russia, landl@lnp.hcei.tsc.ru

Currently, there is a great interest to the high-current low-pressure switching devices with the hollow cathode (pseudospark switches) for different applications [1-4]. The design and principle of operation of these switches are close to those of a classical hot-cathode hydrogen thyratron. However, these devices do not have a hot cathode, that is a great advantage from a viewpoint of a device lifetime. Therefore, pseudospark switches are often called cold-cathode thyratrons or thyratrons with a grounded grid [4, 5].

A range of operating pressures of the switch corresponds to the conditions of the left branch of Paschen's curve. Under such conditions the electron free path for ionization is much in excess of the electrode separation. For both self-breakdown of the main gap of the switch and for external discharge triggering a considerable pre-breakdown electron current is required [6]. For the external triggering, this current is provided due to a special trigger unit that is placed in the cathode cavity of the main gap [5-7].

The trigger unit is intended for the generation of high-density plasma inside the main cathode cavity at the certain instant of time. This plasma is generated due to the application of a trigger pulse between the main cathode cavity and one of the electrodes of the trigger unit. As a result, the ignition of the high-current trigger discharge with a current of about 10 A in the main cathode cavity occurs. Then an electron flow is extracted from this trigger discharge plasma into the main gap, so that the high-current discharge in the main gap is initiated in accordance with the mechanism described in [6].

This report deals with the investigation of the features of trigger discharge ignition in a two-sectioned sealed-off prototype of cold-cathode thyratron TPI1-10k/50 with the modernized trigger unit based on auxiliary glow discharge. As a distinct from the commercially produced sealed-off thyratrons, in the thyratron under investigation electrodes of the trigger unit represents two cups, faced to each other by open sides. Data on the delay times to trigger discharge ignition and to discharge ignition in the main gap relative to the trigger pulse application are obtained. The ability of prototype operation with the nanosecond stability at high anode voltages is shown.

REFERENCES

[1] *J. Zang, X. Liu. //* Physics of Plasma. – 2018. – vol. 25. – No 1. – article number 013533.

[2] *N. Kumar, R.P. Lamba, A.M. Hossain, U.N. Pal, A.D.R. Phelps, R. Prakash //* Applied Physics Letters. – 2017. – vol. 111. – No 21. – article number 213502.

[3] *J. Vieker, K. Bergmann //* Journal of Physics D - Applied Physics. – 2017. – vol. 50. – No 34. – article number 345601.

[4] *Yu.D. Korolev, N.V. Landl, V.G. Geyman, O.B. Frants, I.A. Shemyakin, V.S. Kasyanov, A.V. Bolotov, //* Plasma Physics Reports. – 2018. – vol. 44. – No 1. – pp. 112-120

[5] *V.D. Bochkov, V.M. Dyagilev, V.G. Ushich, O.B. Frants, Y.D. Korolev, I.A. Shemyakin, K. Frank //* IEEE Trans. Plasma Sci. – 2001. – V. 29. – No. 5. – pp. 802–808.

[6] *Y.D. Korolev, K. Frank //* IEEE Trans. Plasma Sci. – 1999. – V. 27. – pp. 1525.

[7] *N.V. Landl, Y.D. Korolev, O.B. Frants, V.G. Geyman, A.V. Bolotov //* J. Phys.: Conf. Series. –2015. – V. 652. – 012050.

[1] This work was supported by the Russian Science Foundation under the Grant # 14-19-00139

DETERMINISTIC MODELLING OF THE RUNAWAY ELECTRON BEAMS FORMATION IN HIGH-PRESSURE NANOSECOND GAS DISCHARGES

V.Y. KOZHEVNIKOV, **, A.V. KOZYREV**, N.S. SEMENIUK**, A.O. KOKOVIN***

**Institute of Electrical and Electronics Engineers, 501 Hoes Lane, Piscataway, NJ 08855, USA, Vasily.Y.Kozhevnikov@ieee.org*
***Institute of High Current Electronics, 2/3 Akademichesky ave., Tomsk, 634055, Russian Federation*

This paper introduces a review of modern theoretical modelling of high-pressure nanosecond gas discharges with strongly non-equilibrium and non-Maxwellian electron component represented by runaway electrons. Unlike the widely used today in the computational plasma physics particle-in-cell (PIC) methods, the methodology we utilize is based on deterministic macroscopic (fluid) and kinetic theoretical approaches. Fluid models describe gas discharges of various kinds in terms of averaged variables (moments) of the electron distribution function. In spite of high reliability of such approach, it has serious limitations connected with general shortcomings of macroscopic models, like impossibility to describe dynamics of minor particle group with high energies.

Contrariwise, kinetic models operate with a distribution function itself, providing comprehensive information about the evolution of ensemble of particles in phase space. Since the distribution function is submitted to the Boltzmann equation, its solution become complicated from both analytical and numerical points of view, especially when the Boltzmann equation is coupled with the electric or electromagnetic field equations. As in dense gases the runaway electron generation is always associated with a non-Maxwellian electron distribution, so it requires the using of kinetic approach in order to describe the generation of runaway electrons accurately.

We propose an alternative way [1], [2] to treat such problems that combine prospective advantages of macroscopic and kinetic modelling. In our hybrid approach, the dynamics of discharge plasma is described following the fluid model equations, and then we solve Boltzmann kinetic equation for runaway electrons only using the background of previously computed discharge plasma parameters. Such approach allows combining of two- or three-dimensional accurate macroscopic discharge simulation with one-dimensional kinetic investigation of the runaway electron beam characteristics. The correctness of this approach is justified by the experiment showing that the fraction of runaway electrons does not exceed 1-2% in high-pressure discharges [3].

As an example of the hybrid approach application, we simulate a nanosecond discharge in high-pressure gas diode having tip-to-plane configuration of a discharge gap [3]. The discharge in this two-dimensional axisymmetric configuration is calculated in the framework of two-moment drift-diffusion macroscopic model. The characteristics of runaway electrons are calculated using one-dimensional Boltzmann equation on the symmetry axis of the problem. It was shown that fast electron energy spectrum behind the anode foil is broadband. Due to the specific diode design and the sharp front edge of the applied voltage pulse, the resulting spectrum contains significant fraction of electrons with energies above the maximum of applied voltage value. This physical phenomenon is also known as electrons with "anomalous" energies [4]. The existence of "anomalous" spectrum component significantly expands the capabilities of possible practical applications, e.g. in low-dose industrial radiography. The calculated pulse of runaway electron current and the energy spectrum are in a good agreement with the some experimental measurements.

REFERENCES

[1] *V.Yu. Kozhevnikov, A.V. Kozyrev, N.S. Semeniuk // EPL. – 2015. – 112. – № 1. P. 15001.*
[2] *A.V. Kozyrev, V.Yu. Kozhevnikov, M.I. Lomaev, D.S. Sorokin, N.S. Semeniuk, V.F. Tarasenko // EPL. – 2016. – 114. - № 4. P. 45001.*
[3] *V.F. Tarasenko et al. // Runaway Electrons Preionized Diffuse Discharges. – Nova Science Publishers Inc., 2014.*
[4] *A. Kozyrev, V. Kozhevnikov, N. Semeniuk // EPJ Web of Conferences. – 2018. – 167. – P.01005*

SIMULATION OF STREAMER DISCHARGES[1]

N.YU. BABAEVA, G.V. NAIDIS

Joint Institute for High Temperatures RAS, Izhorskaya 13, Moscow 125412, Russia, gnaidis@mail.ru, +79263717579

Electric phenomena in various dense media (high-pressure gases, dielectric liquids, semiconductors) are often accompanied with formation of ionization waves - streamers, having luminous fronts that move with velocities up to 10^{10} cm/s [1-3]. The ionization waves are key elements in pre-breakdown processes, they appear in various kinds of pulsed electrical discharges (coronas, volume and surface dielectric barrier discharges, lightning leaders, etc.). Phenomena related with fast propagation of luminous plasma objects have been observed in sprite discharges in the upper atmosphere [4] and in cold atmospheric-pressure plasma jets [5]. Recently, similar luminous plasma plumes (so-called apokamps) have been discovered in repetitive pulsed discharges (when one electrode is at high voltage and the other is at a floating potential) [6]. Streamer characteristics can vary in a wide range, depending on external conditions: density of the medium, parameters of applied voltage pulse, etc. In particular, streamer radii are larger at lower medium densities, being typically about several micrometers in liquids, of an order of millimeter in atmospheric-pressure gases, and reaching hundreds of meters in sprite streamers in the upper atmosphere, at altitudes of 60-80 km. In cold plasma jets, streamers (so-called plasma bullets), guided along the jet axis, with annular luminous fronts are often observed.

For evaluation of streamer characteristics, a number of approaches have been presented. Some helpful information, e.g. on similarity conditions, is obtained in the framework of analytical consideration. However, a detailed description of streamer dynamics and structure can be obtained only on the basis of numerical modeling. In this report, a review of simulation results, concerning specific streamer properties in the wide range of conditions mentioned above, is presented; these results are compared with available experimental data. A discussion of characteristics of streamers in high-pressure gases, formed at application to discharge gaps of voltage pulses with high amplitudes and very short (subnanosecond) rise times and allowing to obtain wide plasma channels [7], is given. Possible effects on parameters of produced plasma of fast (runaway) electrons and x-rays generated at streamer development are considered.

REFERENCES

[1] *Yu.P. Raizer //* Gas Discharge Physics. Springer, 1991.
[2] *A.N. Lagarkov, I.M. Rutkevich //* Ionization Waves in Electric Breakdown of Gases. Springer, 1994.
[3] *V.Ya. Ushakov, V.F. Klimkin, S.M. Korobeynikov //* Impulse Breakdown of Liquids. Springer, 2007.
[4] *V. P. Pasko, J. Qin, S. Celestin //* Surv. Geophys. – 2013 – V. 34. – P. 797.
[5] *X. Lu, G.V. Naidis, M. Laroussi, K. Ostrikov //* Phys. Rep. – 2014 – V. 540. – P. 123.
[6] *V.F. Tarasenko, E.A. Sosnin, V.S. Skakun, V.A. Panarin, M.V. Trigub, G.S. Evtushenko //* Phys. Plasmas – 2017 – V. 24. – P. 043514.
[7] *G.V. Naidis, V.F. Tarasenko, N.Yu. Babaeva, M.I. Lomaev //* Plasma Sources Sci. Technol. – 2018 – V. 27. – P. 013001.

[1] This work was supported by the Russian Foundation for Basic Research under Grant 17-52-16002.

X-RAY AND VUV REFLECTOMETRY AND METROLOGY OF PLASMA RADIATION SOURCES

A.P. SHEVELKO

P.N. Lebedev Physical Institute of the RAS, Leninsky Pr. 53, Moscow, 119991, Russia,
Email: apshev51@gmail.com, phone +7 499 1326951

Recently quantitative (absolute) measurements of intensities in soft X-ray and vacuum ultraviolet (VUV) spectral ranges acquire special significance. Particularly important are these measurements for studies of radiation heating of targets in inertial confinement fusion and for developing of new radiation sources for various practical applications (EUV nanolithography, microscopy of biological objects in the "water window" spectral range, etc.). This requires the development of new calibration and metrology methods.

Traditionally synchrotron radiation is considered as "a calibration source #1." Synchrotron radiation facilities allow calibration of spectrometer elements with a high accuracy and in a wide spectral range. Nevertheless there are also some essential restrictions and disadvantages too. Another approach is the use of various laboratory X-ray and VUV reflectometers. An example could be found in ref.[1] when the VUV reflectometer based on capillary discharge plasma source and grazing incidence monochromator was used for calibration of diffraction grating reflectivities and photographic film and CCD detector sensitivities.

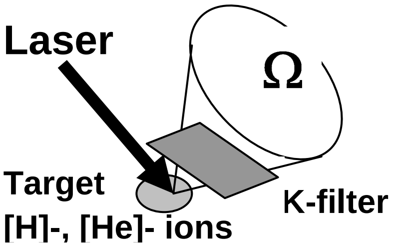


Fig. 1. Scheme of the method of monochromatisation.

For X-ray calibration of focusing crystal spectrometers it is necessary to use a quasi-monochromatic, with a large solid angle of divergence beams. For this purpose a special method are developed using X-ray fluxes from laser-produced plasmas [2]. This method uses a special combination of the laser target elements and K-absorption filters. The laser targets with average atomic numbers $Z_A \approx 10 \div 20$ are selected to ensure the excitation of hydrogen ([H]-) and/or helium-like ([He]-) ions (spectral range λ=0.2 ÷1.0 nm) in laser-produced plasmas. The selected K-absorption filters transmit light in a narrow spectral range which only contains the resonance lines of [H]- and [He]-like ions. Other spectral lines of these ions are located beyond the K-edge and completely absorbed by the filter. The resonance lines of ions with lower ionization degrees ([Li]- and others) occupy the long-wavelength range and are also completely absorbed by the filter. Experimental and theoretical studies have shown that, in the fluxes formed, the degree of monochromatisation $\lambda/\Delta\lambda$ may reach ~100 at the radiation contrast ratio of 5 ÷ 10 and angular divergence of $\Omega\sim\pi$ sr. As a result, the maximum measured value of the parameter $\eta=\Omega\cdot\lambda/\Delta\lambda$ constituted ~300. Another advantage of this method is its simplicity: the tuning of the working wavelength requires only a change of the laser target and K-filter. Such a change can be made without vacuum violation in the chamber. So the use of this method ensures absolute *in situ* calibration of spectrometers at different wavelengths. This method will be used for absolute calibration of X-ray focusing crystal spectrometers and their elements.

REFERENCES

[1] *I. I. Sobelman, A. P. Shevelko, O. F. Yakushev, L. V. Knight, R. S. Turley//* Quantum Electronics. – 2003. 33. -3-6.
[2] *A.P. Shevelko.//* Quantum Electronics. -2016. -46. -845-847.

RUNAWAY ELECTRON BEAMS AND X-RAY RADIATION GENERATED DURING DISCHARGES IN AIR AT RISE TIMES OF VOLTAGE PULSE OF 500 AND 50 NS [1]

V.F. TARASENKO*, CH. ZHANG**, I.D. KOSTYRYA*, J. QIU**, D.A. SOROKIN*, P. YAN**, E.KH. BAKSHT*, T. SHAO**

*Institute of High Current Electronics SB RAS, Tomsk, 634055, Russia
E-mail: VFT@loi.hcei.tsc.ru, phone: +7 (3822) 491-685
**Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing 100190, China

The parameters of runaway electron beams and X-ray radiation generated at long-pulse discharges in atmospheric-pressure air were investigated. All studies were performed at two setups. The first setup included a metal gas diode connected to a voltage pulse generator of the SLEP-150M type [1]. To increase the rise time of the voltage pulse a peaker was removed from the coaxial line. A 20-cm-length segment of the high-voltage coaxial line with the impedance of 100 Ω was charged with a pulse transformer.

The second setup included a solid-state pulse generator SPG200N produced pulses with nanosecond duration and operated in repetitive mode [2]. In the experiments, high-voltage pulses with the rise times of 500 and 50 ns were applied to an interelectrode gap. The gap geometry provided nonuniform distribution of the electric field strength.

It was founded that at the voltage pulse rise time of 500 ns and the maximum breakdown voltage U_m for 1-cm-length gap a duration (FWHM) of a runaway electron beam current pulse shrinks to 0.1 ns. A decrease in the breakdown voltage under conditions of a diffuse discharge leads to an increase in the FWHM duration of the electron beam current pulse up to several nanoseconds. Waveforms of beam current pulses with different FWHMs and the scintillator luminescence caused by X-ray radiation are presented in Figure 1.

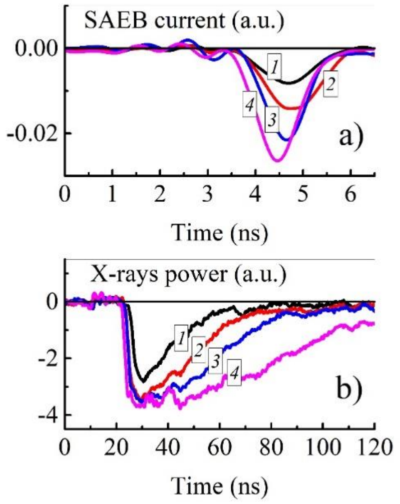


Fig. 1. Waveforms of the RAEB current behind the anode made of kimfol film (*a*) and X-ray radiation with a 30-µm-thickness Al anode foil (*b*). 15.1-mm-diameter ball-shaped cathode. The gap width is 22 mm.

It was shown that when the rise time of the voltage pulse is of 500 ns and the diffuse discharge occurs in the gap, the FWHM duration of the X-ray radiation pulse could reach ≈ 100 ns.

It was established that at a pulse-periodic diffuse discharge fed by high-voltage pulses with the rise time of 50 ns, an energy of X-ray quanta and their number increase with increasing breakdown voltage. Wherein the parameter U_m/pd is saved.

REFERENCES

[1] *Kostyrya I.D. & Tarasenko V.F.* // Plasma Phys. Rep. – 2015. – V. 41. – P. 269 –273.
[2] *Zhang C., Shao T., Yu Y., Niu Z., Yan P. & Zhou Y.* // Rev. Sci. Instrum. – 2010. – V. 81 – P 123501.

[1] This work was supported by RFBR according to the research project No. 18-52-53003_GFEN_a and by the National Natural Science Foundation of China according to the Contract No. 1171101226.

MAIN PARAMETERS OF THE HIGH-PRESSURE GAS-DISCHARGE PLASMA FORMED IN STRONGLY OVERVOLTAGED GAPS[1]

D.A. SOROKIN, V.S. RIPENKO*, M.I. LOMAEV*,***

**Institute of High Current Electronics, 2/3 Akademichesky Ave., Tomsk, 634055, Russia, SDmA-70@loi.hcei.tsc.ru*
***National Reasearch Tomsk State University, 36 Lenina Ave., Tomsk, 634050, Russia*

Dense non-equilibrium low-temperature plasma realized in gaseous mediums at atmospheric pressure and more is of interest as a basis for devices and technological processes that allow solving various tasks in the most diverse aspects of human activity [1]. A promising tool allowing to form a plasma object with above mentioned properties is runaway electron preionized diffuse discharge (REP DD). At pressures of different gases in the gap of several atmospheres, this discharge can have diffuse form (avoiding the constriction) during the entire burning time (Fig. 1) [2]. Data on the main plasma parameters (electron density N_e, electron T_e and gas T_{tr} temperature, reduced electric field strength E/N, etc.) is extremely important from both the point of view of developing the theory REP DD phenomenon and determining the possibilities of REP DD plasma use.

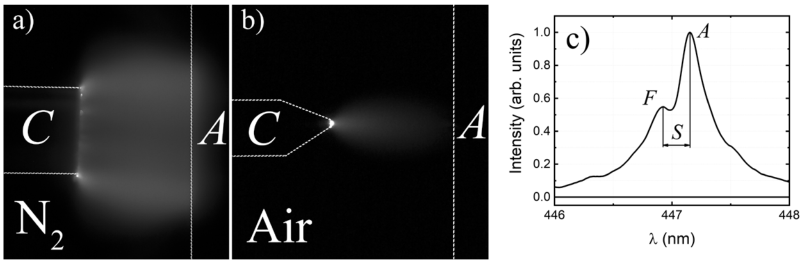


Fig. 1. Integral images of the REP DD plasma glow in atmospheric-pressure nitrogen (a) and air (b). Voltage pulse of negative polarity with an amplitude of 55 kV and a rise time of ~ 0.7 ns. *C* – potential cathode with a small radius of curvature: 6-mm-diameter tube (a) and cone with an apex angle of 60° (b) . *A* – flat grounded anode. Gap widths are 8 mm (a) and 5 mm (b). Spectral line of He I at wavelength of 447 nm from the plasma of REP DD in atmospheric-pressure helium ( ). *F* – peak of the forbidden component (2^3P–4^3F, 447.0 nm). *A* – peak of the allowed component (2^3P–4^3D, 447.15 nm). *S* – spectral distance between peaks of the allowed and forbidden components.

The main problem in this case is in choice of techniques suited for diagnostic of such plasma. There are many techniques which applicability depends on the values of the measured parameters, the state of the plasma and so on. Among them, the techniques of optical emission spectroscopy (OES techniques) can be emphasized. The main advantage of OES techniques is that they are contactless and do not introduce perturbations into the investigated medium. Earlier, the first attempts to measure the parameters of REP DD plasma formed in pulsed mode have been already made [2].

This paper continues the research cycle, aimed at selecting techniques for diagnostics of the plasma formed at high pressure, proving the possibility of their use, as well as determining the parameters in the plasma of REP DD ignited in pulsed and pulse-periodic modes in atomic or molecular gases and their mixtures. Using the technique based on measuring the spectral distance *S* between peaks of the 2^3P–4^3F forbidden (*F*, 447.0 nm) and 2^3P–4^3D allowed (*A*, 447.15 nm) components of the spectral line of a helium atom He I at a wavelength of 447 nm (Fig. 1) [3], the electron concentration in in discharge plasma was measured. For example, N_e in the plasma of the diffuse discharge in pure He is ~ 10^{15} cm^{-3}. This result is in good agreement with that obtained previously using the Stark broadening technique [2]. Applying the technique consisting in measuring the ratio $R_{391/394}$ of peak intensities of the ionic N_2^+ (391.4 nm) and molecular N_2 (394.3 nm) bands of the second positive system of a nitrogen molecule [4], T_e and E/N in the REP DD plasma were measured. In addition, using the ultrafast streak camera equipped with monochromator, the time behavior of the electron temperature and reduced electric field was obtained. By registering the rotational and vibrational distributions of electronic-vibrational-rotational bands of radiation, vibrational T_v, rotational T_r and gas T_{tr} temperatures in the discharge plasma were measured.

REFERENCES

[1] *Edited by Paul K. Chu and Xin Pei Lu //* Low temperature plasma technology: Methods and applications. – CRC Press, 2013.
[2] *Edited by V.F. Tarasenko // Runaway Electrons Preionized Diffuse Discharges.* – Nova Science Publishers, Inc., 2014.
[3] *A. Chernichowsky and J. Chapelle //* J. Quant. Spectrosc. Radiat. Transfer. – 1985. – 33. – No. 5. – 427-436.
[4] *Nassar, H., Pellerin, S., Musiol, K., Martinie, O., Pellerin, N., Cormier, J. - M. //* J. Phys. D: Appl. Phys. – 2004. – 37. – No. 14. – 1904-1916.

[1] This work was supported by the Russian Science Foundation (the project No. 17-72-20072).

OPTICAL CHARACTERIZATION OF PULSED PLASMA JET AND JET ARRAY[1]

R. WANG, Y. ZHAO, C. ZHANG, T. SHAO

Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing 100190, China,
E-mail: st@mail.iee.ac.cn, phone: +86010-82547114

Pulsed plasma jets have attracted considerable interests recently due to their various applications, such as surface modification, biological decontamination, combustion and environmental protection. By grouping multiple plasma jets together ensures large area treatment. In order to improve the performance of plasma jet or jet array, the physical properties should be well understood. This work will review the spatial-temporal evolution of plasma bullets and emission intensities in microsecond pulsed plasma jet and jet array performed by our group. It is found that pulse parameters, especially pulse rise time, pulse width and pulse polarities have a significant influence in plasma bullet behaviors. These parameters will influence the electric field intensity and thus determine the plasma bullet behaviors. The distribution of He emission and O emission are mainly located near the nozzle and travel in a slow speed. In the contrary, the distribution of N_2 and N_2^+ emission travel in a faster speed and reach a very far distance. By comparing the emission distribution, it is found that the plasma bullet formation is due to the fast travelling speed of N_2 and N_2^+ . Six

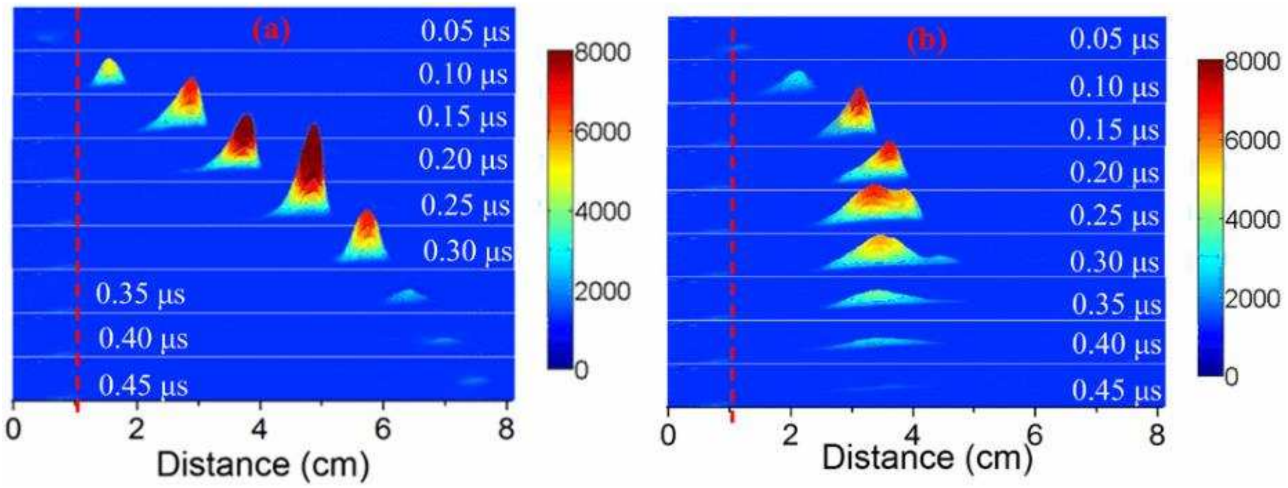


Fig. 1. Spatial-temporal distribution of the N_2 emission in open air in the (a) positive and (b) negative plasma jets. The photographs weretaken at 0.05 µs increments. The exposure time was 5 ns, and the number of accumulation was 5 000.

individual plasma jets are grouped together to increase the treatment area. The effect of electrode configuration, gas flow rate, pulse frequency and jet distance on the plasma jet array behavior are well studied. The homogenous discharge is obtained under certain parameters. The jet interaction mechanism is studied by ICCD camera, optical emission and schlieren images.

REFERENCES

[1] *R. Wang, K. Zhang, Y. Shen, C. Zhang, W. Zhu & T. Shao.* // Plasma Sources Science Technology-2016.-V.25-P. 015020.
[2] *R. Wang, H. Sun, W. Zhu, C. Zhang, S. Zhang & T. Shao.* // Physics of Plasmas-2017-V. 24-P. 093507.

[1] This work was supported by the National Natural Science Foundation of China under Contract Nos. 51637010, 51507169, and 11611530681.

GENERATION OF RUNAWAY ELECTRON BEAM IN NANOSECOND PULSED DISCHARGE BY USING DIFFERENT ELECTRODE MATERIALS [1]

C. ZHANG, D.A. SOROKIN**, H. BAI*, V.F. TARASENKO**, P. YAN*, E. KH. BAKSHT**, T. SHAO**

** Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing 100190, China*
E-mail: st@mail.iee.ac.cn, phone: +86-10-82547114
***Institute of High Current Electronics SB RAS, Tomsk, 634055, Russia*

Supershort avalanche electron beam (SAEB) generated in inhomogeneous subnanosecond discharge in a small gap at different pressures is vital for fundamental understanding of pulsed breakdown kinetics [1, 2].

In this paper, the investigation of effect of the cathode materials on the parameters of SAEB current pulse registered behind the anode foil were carried out in two diodes fed by nanosecond pulses at elevated pressure.

In the first diode, the pulsed power generator of SLEP-150M type produces triangular-shaped voltage pulses with the amplitude of ~ 110 kV, the rise time of 1.6 ns and the FWHM of 3-5 ns in 12 mm gap with anode of 10-µm-thickness Al foil. Experiential results showed that the highest amplitudes of beam current pulse are observed for stainless steel cathode in figure 1a. When *pd* is large, the cathode material barely has influence on the SAEB current. Otherwise, the cathode material affects the amplitude of the SAEB current pulse.500 and 50 ns were applied to an interelectrode gap. The gap geometry provided nonuniform distribution of the electric field strength.

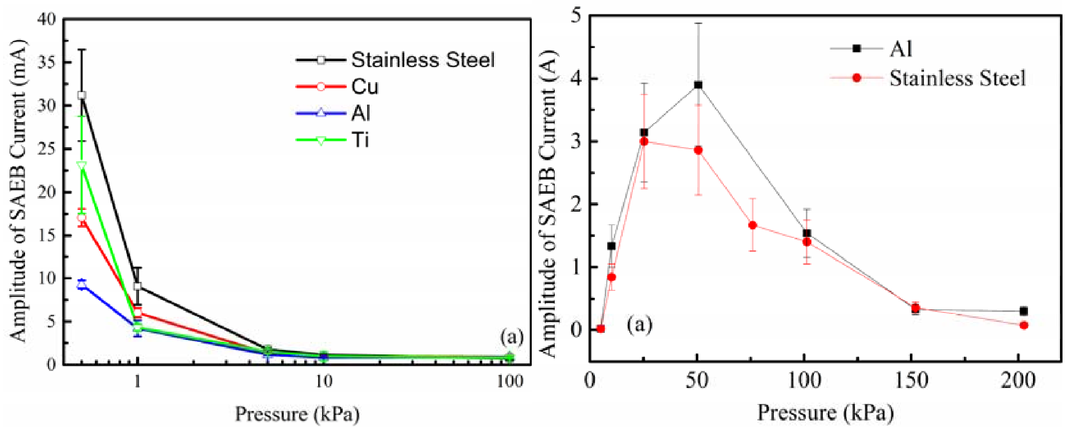


Fig. 1. Amplitude of the SAEB current behind the anode made of 10-µm-thickness Al film (*a*) dependence of the amplitude of the SAEB current pulse on the gas pressure at different cathode materials in the first diode (*b*) Dependence of the amplitude and FWHM of the SAEB current pulse on the gas pressure at different cathode materials in the second diode.

In the second diode, triangular-shaped voltage pulses had an amplitude of the incident voltage wave of ~ 50 kV, the rise time of 0.7 ns and the FWHM of 1 ns. A decrease in the amplitude of the SAEB current pulse at gap spacing of 5 mm with anode of 10-µm-thickness Al begins at nitrogen pressures of 100 kPa and 50 kPa, respectively.

Therefore, comparing the SAEB parameters obtained using different experimental setups, it is necessary to consider the parameters of the voltage pulses, the gas diode design, as well as the design and material of the electrodes.

REFERENCES

[1] *Tarasenko V. F., Burachenko A. G. & Baksht E. Kh.* // J. Phys.: Conf. Ser. *– 2017. – V. 927. – P. 012063.*
[2] *Zhang C., Tarasenko V. F., Gu J., Baksht E. Kh., Beloplotov D. V., Burachenko A. G., Yan P., Lomaev M. I., & Shao T. // Phys. Rev. Accel. Beams – 2016. – V. 19 – P. 030402.*

[1] This work was supported by the National Natural Science Foundation of China under Contracts 51777204 and 1171101226 and by the RFBR under Contract 18-52-53003.

ON INSTABILITY OF THE OVERVOLTAGE REGIME OF THE OPEN DISCHARGE IN D2 GENERATING HIGH-ENERGY RUN-AWAY ELECTRONS[1]

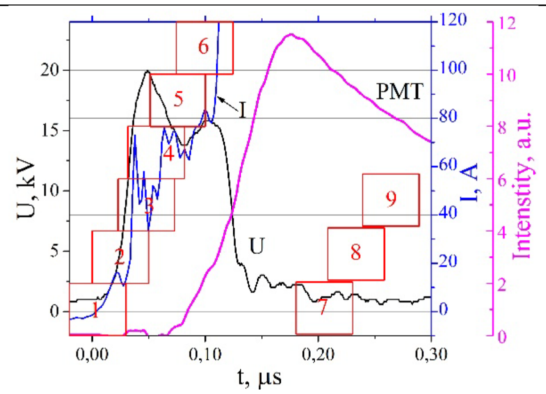
<u>YU.S. AKISHEV</u>,**, V.B. KARALNIK*, A.V.PETRYAKOV*, N.I.TRUSHKIN**

**SRC RF TRINITI, Pushkovykh Str.-12, Moscow, Troitsk, 108840, Russia, akishev@triniti.ru, +74958415236*

***NRNU MEPhI, Kashirskoe shosse-31, Moscow, 115409, Russia*

Strongly overvoltage open discharges in a narrow gap (2-3 mm) between the solid cathode and the grid anode are widely used for generation of the pulsed high-current beams of run-away electrons with energy up to 100 keV. Strongly overvoltage (SO) regime is unstable and the discharge tends to transit into low-voltage (LV) regime with a high-current. We studied experimentally this transition by example of the three-electrodes open discharge in deuterium (D_2) at low pressure (about 0.5-2 Torr) being powered by stepwise voltage with amplitude up to 25 kV [1]. The usage of the auxiliary third electrode allows one to get more stable operation of the open discharge. Our findings are shortly resumed in figure 1. It was revealed that, first, the SO open discharge does not constrict but contrariwise increases his cross-section and brightness up to the transition into the LV regime and, second, the bright cathode current spot(s) happen after the SO→ LV transition and therefore they cannot be a reason initiating this transition because the cathode spots in itself do not shunt the gap - they can only initiate the streamers (thin current filaments) which can propagate from the cathode towards the anode.

However, the propagation of streamers towards the anode requires the existence in the gap of the intensive direct ionization of neutrals by the electron impact. In fact, the extremely high electric field at the cathode in the overvoltage regime (E/N reaches of huge magnitude of 10^5 Td and even more) leads to that the electrons have immediately become the run-away electrons which have the extremely low efficiency of the impact ionization. This is a reason why the propagation of streamers towards the anode is impossible in the overvoltage regime.



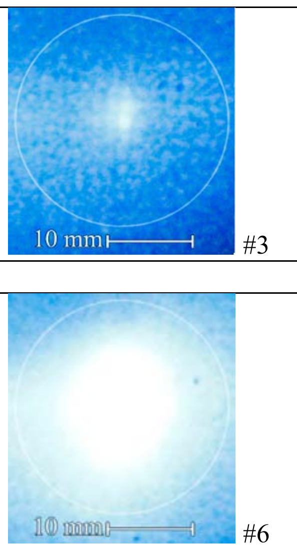


Fig.1. The set of the discharge images (right) taken by a fast multi-frame camera and correlated with the current-voltage waveform (left). The white circle in each shot depicts the boundary of the cathode. The exposure time of each shot is 50 ns. The enumerated time moments marked in the current-voltage waveform correspond to those at which the enumerated images were taken. Gas - D_2, P = 2 Torr, U = 20 kV.

We have developed 1D mathematical model taking into account the most important processes that can happened in the overvoltage open discharge and have done the proper numerical calculations for the conditions corresponding to the performed experiments. Main goal of these calculations was to find out the processes responsible for the SO → LV transition. The obtained results will be presented in the extended version of the report.

REFERENCES

[1] *Yu S Akishev, V B Karalnik, M A Medvedev, A V Petryakov, N I Trushkin, A G Shafikov //* IOP Conf. Series: Journal of Physics: Conf. Series **927** (2017) 012070 doi:10.1088/1742-6596/927/1/012070

[1] This work was supported in full by the Russian Science Foundation (Grant № 16-12-10458)…

CHANGES OF THE PLANE ANODE SURFACE UNDER DIFFERENT REGIMES OF DISCHARGE IN NONEQULIBRIUM ELECTRIC FIELD[1]

M.A. SHULEPOV, M.V. EROFEEV*, S.E. ZATSEPINA*, V.S RIPENKO*, V.F. TARASENKO*, K.I. ALMAZOVA**, A.N. BELONOGOV**, V.V. BOROVKOV**, E.V. GORELOV**, V.I. KARELIN**, I.V. MOROZOV**, A.A. TRENKIN**, S.YU. HARITONOV***

** Institute of High Current Electronics, Siberian Branch, Russian Academy of Sciences, 2/3 Akademichesky Ave., Tomsk, 634055, Russia, MixShlp@yandex.ru, +79539264117*

***State Corporation on Atomic Energy "Rosatom" Federal State Unitary Entity "Russian Federal Nuclear Center – All-Russian Scientific and Research Institute of Experimental Physics", 37 Mira Ave., Sarov, 607190, Russia*

The impact of different regimes of atmospheric air discharge on a copper surface was studied. The experiments were carried out with pin-to-plate electrodes configuration at different conditions such as discharge gaps, voltage and current magnitudes, their pulse duration, which allowed one to form diffuse and spark discharges, as well as transitional volume discharge with anode spots. The present work continues studies of [1].

The dependence of the impact character of discharge type on anode surface has been defined. It is shown, that diffuse discharge does not leave visible autographs on the plane anode, however its surface exposed to cleaning and the surface free energy is increased in the plasma-processed region. In the transitional regime from diffuse to spark discharge, when the anode spots already formed on the surface, a uniformly distributed erosion craters were observed in the processed region (Figure 1a).

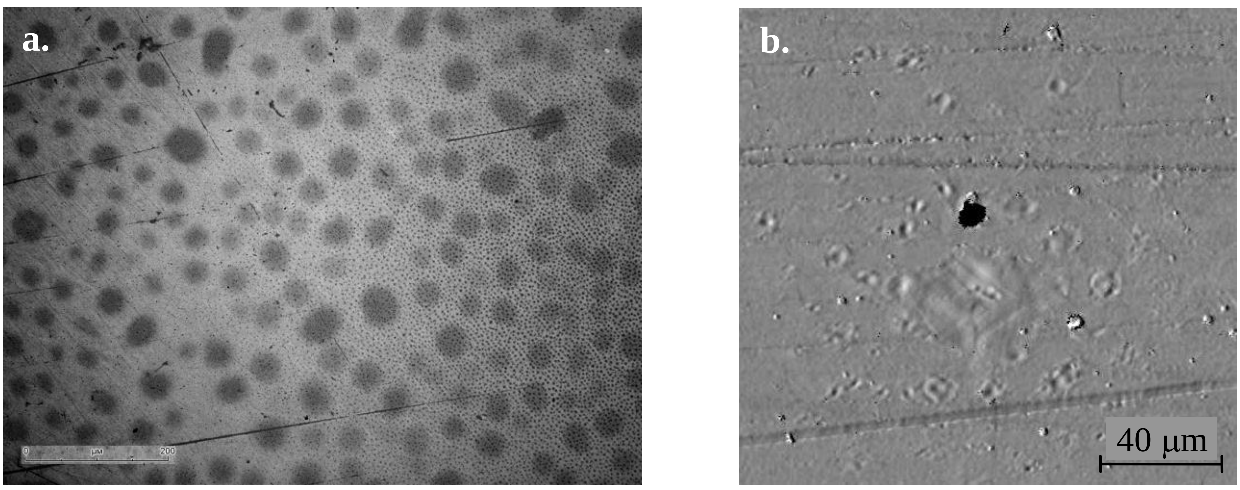


Fig. 1. Photographs of discharge autographs in presence of: a.- transitional volume discharge with anode spots, b.- spark discharge.

The spatial microstructure of a spark discharge with a current amplitude of 1.5 kA and its attenuation duration of 2 μs was investigated; it was formed in the gap point-plane in the air of atmospheric pressure. The method of a shadow photography was used to record the microstructure dynamics from unities up to tens of nanoseconds including the development of a large number of micro channels from the point into the discharge gap, their branching and radial expansion. It was defined that the area of the discharge influence on the surface of a plane electrode is an aggregate of a large number of erosion micro craters (Figure 1b); their forms and dimensions were obtained.

REFERENCES

[1] *E.Kh. BakSht, O.M. Blinova, M.V. Erofeev, V.I. Karelin. et al. // Plasma Physics Reports, – 2016. – V42. – № 9. p. 876–886*

[1] The work is performed in the framework of the State task for HCEI SB RAS (project #13.1.4).

DYNAMICS OF A POSITIVE STREAMER IN ATMOSPHERIC PRESSURE AIR IN A SHARPLY INHOMOGENEOUS FIELD UNDER THRESHOLD CONDITIONS FOR BREAKDOWN OF A GAP[1]

*M.I. LOMAEV**,**, *D.V. BELOPLOTOV**, *V.F. TARASENKO**,**, *D.A. SOROKIN**

**Institute of High Current Electronics, Siberian Branch, Russian Academy of Sciences, 2/3 Akademichesky Ave., Tomsk, 634055, Russia, Lomaev@loi.hcei.tsc.ru, (3822) 492-392*

***National Research Tomsk State University, 36 Lenin Ave., Tomsk, 634050, Russia*

At present, much attention is paid to the study of a streamer forming at high overvoltage, whose transverse dimensions are comparable to the interelectrode distance [1 - 3]. The purpose of this work is to investigate by the method of high-speed four channel ICCD camera the formation of a streamer in a highly non-uniform electric field at threshold conditions for breakdown with simultaneous recording of the voltage at the gap and the dynamic displacement current caused by the redistribution of the electric field strength in the gap.

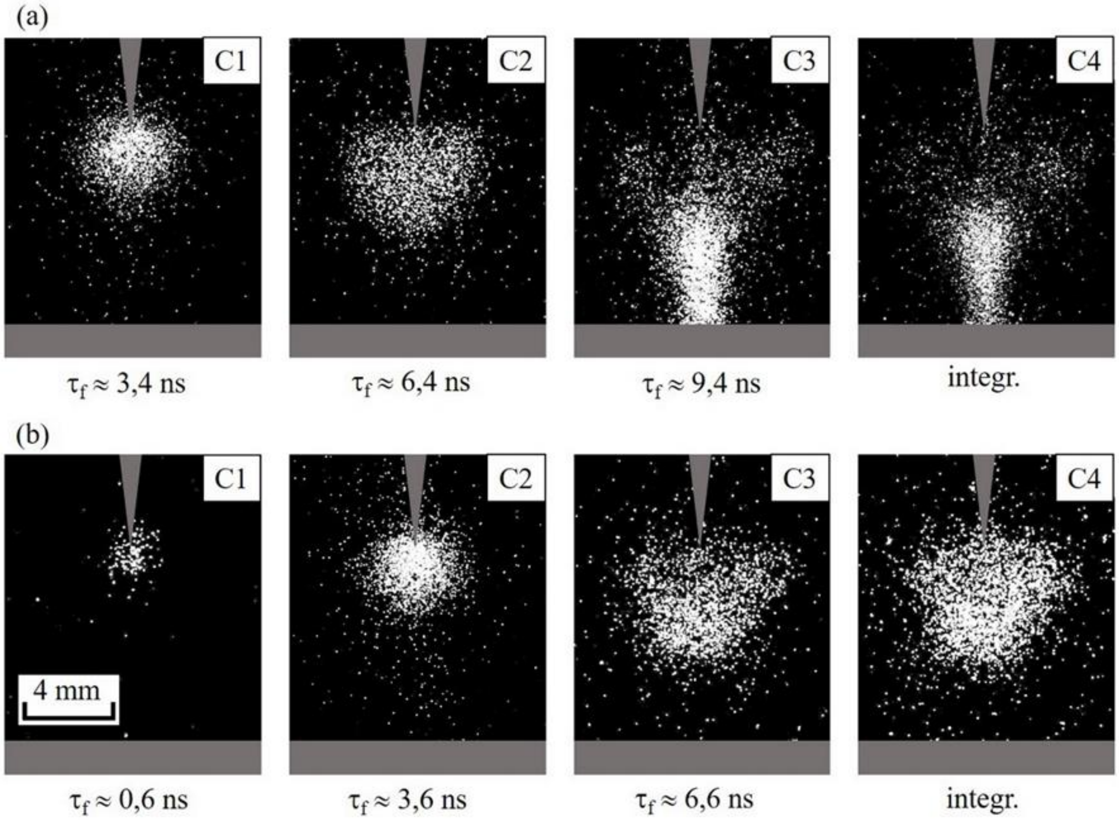


Fig. 1. Images of the streamer luminescence in atmospheric pressure air. (a) The case when the streamer crossed the gap during the voltage applying to the gap. (b) The case when the streamer did not crossed the gap. C1, C2, C3, C4 - channel numbers of the ICCD camera. τ_f is the time interval for which the glow was formed.

It is found that under these conditions a spherical streamer forms (Fig. 1). In the case of gap overlap the streamer transformed into a cylindrical one (Fig. 1a). The oscillograms of the dynamic displacement current, caused by the redistribution of the electric field intensity during the formation of the streamer, are registered. From the data obtained, the time variation of the electric field strength near the grounded cathode is determined.

REFERENCES

[1] *P. Tardiveau, L. Magne, E. Marode, K. Ouaras, P. Jeanney and B. Bournonville //* Plasma Sources Sci. Technol. – 2016. – 25. 054005.

[2] *N.Yu. Babaeva, G.V. Naidis //* IEEE Transactions on Plasma Science. – 2016. – 44. – 6 . 899-902.

[3] *D.V. Beloplotov, V.F. Tarasenko, D.A. Sorokin, and M.I. Lomaev* // JETP Letters. – 2017. – 106. – 10. 653–658.

[1] This work was supported by the Russian Science Foundation (Project No. 17-72-20072).

DIFFUSE DISCHARGE IN SF_6 AND ITS MIXTURES WITH H_2, D_2 AND C_2H_6 FORMED BY NANOSECOND VOLTAGE PULSES IN NON-UNIFORM ELECTRIC FIELD [1]

D.V. BELOPLOTOV, M.I. LOMAEV*,**, V.F. TARASENKO*,**, A.N. PANCHENKO*, **, N.A. PANCHENKO*, ****

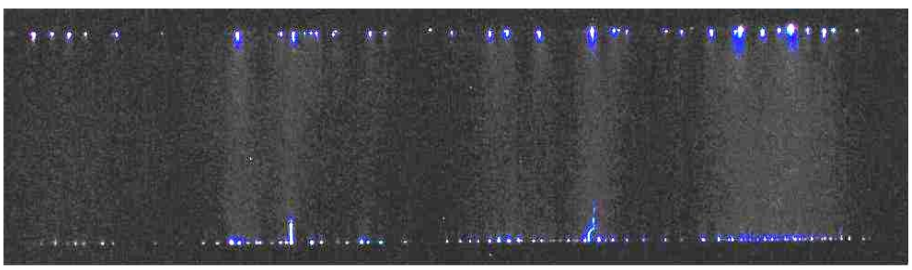
**Institute of High Current Electronics, Siberian Branch, Russian Academy of Sciences, 2/3 Akademichesky Ave., Tomsk, 634055, Russia, Lomaev@loi.hcei.tsc.ru, (3822) 492-392*
***National Research Tomsk State University, 36 Lenin Ave., Tomsk, 634050, Russia*
****Tomsk State University of Control Systems and Radioelectronics, 40 Lenin Ave., Tomsk, 634050, Russia*

Electronegative SF_6 gas is widely used in electrical installations as gas insulation [1]. s is due to its high electrical strength, which significantly exceeds the electrical strength of nitrogen and air. Volume self-sustained discharge in SF_6 with small additions (less than 10%) of different gases is used for various technological applications, in particular, in microelectronics for etching semiconductor materials [2]. Also a volume discharge in mixtures with SF_6 is used for excitation of non-chain chemical lasers on HF (DF) molecules.

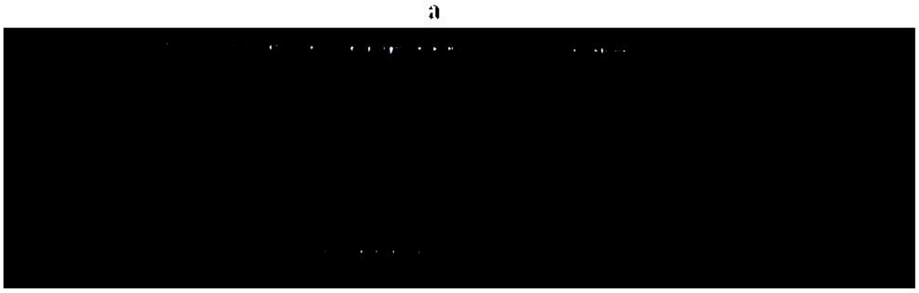
Diffuse discharges formed in electrode systems with an inhomogeneous electric field (between blades, pins, etc.) when high-voltage pulses with short rise-time were applied was proposed to call Run-away Electron Preionized Diffuse Discharge (REP DD).

The aim of this work is to study parameters of REP DD in SF_6 and SF_6 with additives of other gases between two extended electrodes with a small radius of curvature.

It was shown that diffuse discharge can be formed in SF_6 at elevated pressure between blade electrodes with length of 30 cm (see Fig. 1). It was also confirmed that in a sharply non-uniform electric field a beam of run-away electrons is generated and that the gap breakdown occurs due to ionization waves which begin on electrodes with small radius of curvature.



a



b

Fig. 1. Images of diffuse discharge in SF_6 obtained at pressure of 0.04 (a) и 0.05 МПа (b).

Laser action in the IR spectral region was obtained in SF_6 -$H_2(D_2)$ mixtures. The laser output up to 110 mJ was easily achieved which corresponds to ultimate intrinsic efficiency (with respect to deposited energy) of 10%.

REFERENCES

[1] *I.M. Bortnik //* Physical properties and electrical strength of elegas. – Moscow, Energoatomizdat, 1988 (in Russian).
[2] *Seung-Ju Oh, Hyo-Chang Lee, and Chin-Wook Chung //* Physics of Plasmas. – 2017. – 24. – 1. 013512, 6 p.
[3] *E.H. Baksht, A.G. Burachenko, I.D. Kostyrya, M.I. Lomaev, D.V. Rybka, M.A. Shulepov, and V.F. Tarasenko //* Journal of Physics D: Applied Physics. – 2009. – 42. – 18. 185201, 9 p.

[1] The work is performed in the framework of the State task for HCEI SB RAS, project #13.1.4.

INFLUENCE OF FREQUENCY AND VOLTAGE TO APOKAMP DISCHARGE DYNAMICS AT MODERATE PRESSURES[1]

E. KH. BAKSHT, E. A. SOSNIN*,**, V. S. SKAKUN*, V. A. PANARIN*, V. F. TARASENKO*,**, AND V. S. KUZNETSOV**

**Institute of High Current Electronics, 2/3 Akademichesky ave., 634055 Tomsk, Russia*
***National Research Tomsk State University, Tomsk 634050, Russia*

Two years ago, we found that an extended diffuse jet is formed at a pulse-periodic discharge approximately perpendicular to the point of bend of the bright current channel. We call this phenomenon apokamp discharge (using the Greek words από (from) and καμπη (bend, turning)). To date, it has been shown that by its properties (spectral, morphological and electrophysical) is similar to the blue jets and starters phenomenon, which have place at moderate and low air pressures of Earth atmosphere [1].

In this paper, we investigated the dynamics of apokamp discharge formation at air pressure of ~ 120 Torr at different voltage pulse frequencies (10 < f < 56 kHz) and the values of the voltage amplitude from 6.5 to 10 kV. To do this, we used an installation similar to that described in [1].

The apokamp dynamics was recorded using four-channel high-speed camera with a minimum frame exposure of 3 ns (PCO AG HSFC-PRO). The camera was triggered by pulse generator (BNC 565) with different delays relative to the rise of current in the gap. As a result a new facts about apokamp discharge formation were revealed:

1) increasing of voltage from 6.8 to 8.5 kV leads to increasing of plasma bullets velocity in apokamp from 120 to 170 km/s, respectively (see Fig. 1);

(2) velocity rate of plasma bullets is almost doubled to ~ 220 km/s with a frequency reduction from 56 to 10 kHz.

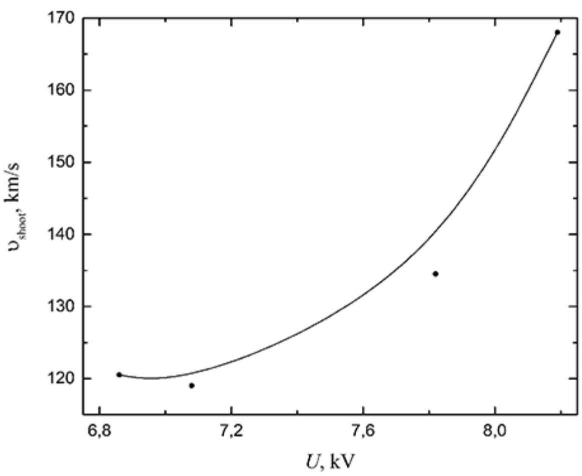


Fig. 1. The dependence of plasma bullets velocity in apokamp on discharge voltage for air pressure of 120 Torr.

The obtained data are in accordance with the results of measurements of the velocities of plasma bullets obtained earlier [1, 2]. In addition, they are a new argument confirming the affinity of apokamp discharge in air at moderate pressures and atmospheric transient luminous phenomena – blue jets, which have place form at the upper boundary of thunderclouds at an altitude of 17 km, reach altitudes from 18.1 to 25.7 km, and propagate at a velocity of 27 to 153 km/s.

This means that in order to obtain long blue jets in the atmosphere, there is no need for increased breakdown frequencies in atmospheric cloud layers.

REFERENCES

[1] *Sosnin E.A., Baksht E.Kh., Panarin V.A., Skakun V.S., Tarasenko V.F. // JETF Letters. – 2017. – Vol.105. – P. 641-645.*
[2] *Sosnin E.A., Naidis G.V., Tarasenko V.F., Skakun V.S., Panarin V.A., Babaeva N.Yu. // JETP. – 2017. – Vol.125. – P. 920-925.*

[1] The work is performed in the framework of the State task for HCEI SB RAS, project #13.1.4.

SPECTRAL PYROMETRY OF PLASMA VORTEX RINGS AT ATMOSPHERIC PRESSURE AIR

L.Y. VOLODIN, A.S. KAMRUKOV, E.Y. KOTOVRASOV

Bauman Moscow State Technical University, 2-ya Baumanskaya ul., 5, str.1, Moscow, 105005, Russia, volodinlu@yandex.ru, +7(906)0817253

Under certain conditions, the pulsed injection of plasma jets into atmospheric air leads to the formation of large-scale vortex plasma structures with an afterglow time considerably exceeding the energy deposition times [1]. Interest in such formations is largely due to the prospect of creating high-intensity open-source optical radiation sources. For the construction of theoretical models of such objects it is necessary to know their temperature characteristics.

The paper presents the results of spectral-emission analysis applied to the temperature characteristics of plasma vortex rings. The device for generating is similar to described in [1]. The spectra were recorded with a Solar S100 spectrometer with a resolution of 1.5 nm in the frequency survey mode with a frame interval of 710 μs. The radiation spectrum was registered in the time interval from 5 to 11 ms after the start of the outflow.

In the registered emission spectra, on the background of the continuum, there are atomic lines of aluminum and excitable impurities that form part of the material of the plasma-forming element (aluminum foil) - sodium and potassium, as well as molecular bands AlO (transition $B^2\Sigma^+ \rightarrow X^2\Sigma_+$) and FeO ("orange" system).

Fig.1 (a) shows the recorded spectrum corresponding to ~ 6 ms, and in Fig.1 (b) - the same spectrum, reconstructed in the Wien coordinates. Quasilinear sections correlate with the black body emission. The presence of two sections indicates a temperature inhomogeneity [2]: a less heated region (1) with a temperature T = 2610 ± 10 K and a heated region with a temperature T = 3390 ± 40 K (2).

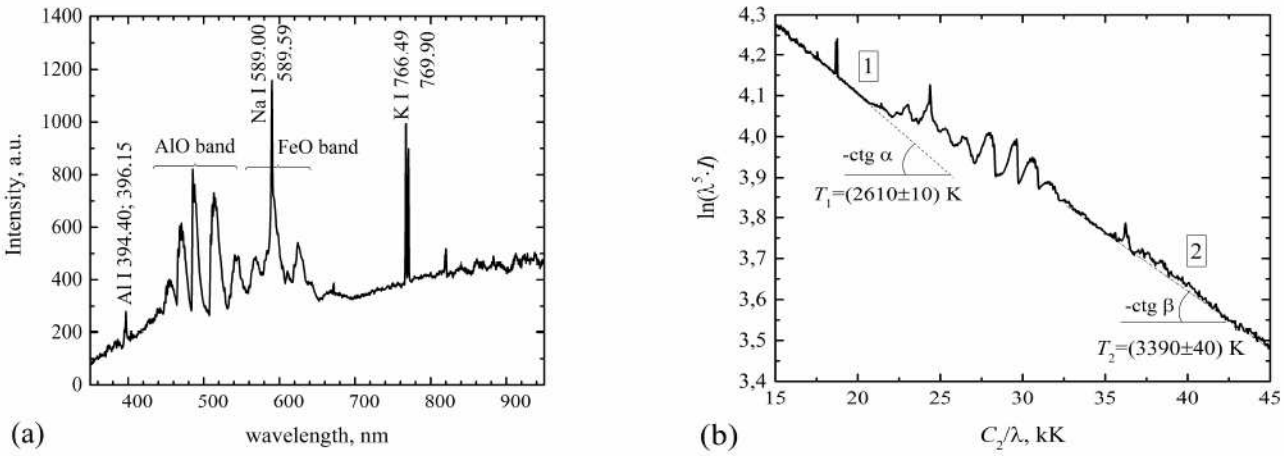


Fig. 1. (a) The emission spectrum of plasma vortex ring at 5.5 ms; (b) the same spectrum in the Wien coordinates.

Comparing the experimental and model AlO spectra, the temperature of the rotational and vibrational transitions was estimated, which was Tr = Tv = 3400 K.

REFERENCES

[1] *M.N. Zharnikov, A.S. Kamrukov, I.V. Kozhevnikov et al* // Tech. Phys. – 2008 – V. 53. – No 5. 571-578.

[2] *A.N. Magunov* // Tech. Phys. – 2010. – V. 55. – No 7. 78-82.

FILAMENTATION OF SPARKS IN AIR DISCHARGE[1]

E.V. PARKEVICH[1, 2], *M.A. MEDVEDEV*[1, 2]

[1]*Lebedev Physical Institute, RAS, Moscow, Russia*
[2]*Moscow Institute of Physics and Technology, Dolgoprudny, Moscow Region, Russia*
parkevich@phystech.edu

In this paper, we present the results of the study with a high spatial and temporal resolution of the initiation and evolution of spark channels formed in air discharge at atmospheric pressure. A multichannel laser probing was used to obtain quantitative information on the parameters of spark channels plasma. The investigations were carried out at the experimental setup with a high-voltage generator launched by an ignition laser beam with the jitter of ~ 1 ns . The generator provided output voltage pulses with their amplitude up to 20 kV and pulse duration up to 30 ns with the rise time of ≈ 4 ns and the maximum generator current of ≈ 500 A. The Lotis LS-2151 Nd: YAG laser emitting at 1064 nm and 532 nm with the pulse energy up to 80 mJ was used. At 532 nm the pulse duration (full width at half magnitude, FWHM) was 70 ps. To implement the laser probing a 6-channel 18-frame optical system for simultaneous recording of interference, shadow and schlieren images of the discharge gap in each optical channel was developed. The average delay time between adjacent channels was ≈ 2 ns. The spatial resolution in each channel was about ≈ 3–4 μm. The discharge was studied using the "pin-to-plane" electrode geometry. The wires with the diameter of several tens of microns were used as the cathode. The use of the point cathode provided both achievement of a strong field near the cathode and initiation of the discharge at the particular region. Moreover, the adjustment accuracy of the optical system focused at the developing spark channel was improved. It was established that approximately 1 ns after the breakdown (with sharp increase of the discharge current) clots of plasma appear at the top of the pin-cathode. Then, one or more highly ionized spark channels directed towards the anode are formed from these clots. The average rate of the spark channel expansion in the longitudinal direction achieves 70 ± 5 μm/ns and the current density achieves $j \sim 10^6$ A/cm^2. The current density was estimated on the assumption that the discharge current flows through the developing spark channel. It was shown by interferometry that the electron density in the developing spark channel can be as high as $N_e = 5\times10^{19}$ cm^{-3} [1].

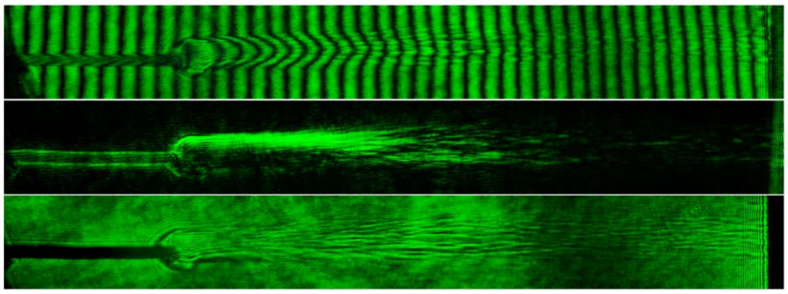


Fig. 1. The typical interferogram (*a*), schlirien-image (*b*) and shadowgram (*c*) of anode-directed spark channel developed from the top of copper wire (Ø50 μm). The cathode is on the left. The gap between the wire and the plane anode is 2 mm.

The formation of filaments at the top of the developing anode-directed spark channel was recorded (see Fig.1). It was established that the filament diameter is 5–30 μm and their growth rate in the longitudinal direction is $v \sim 10^8$ cm/sec. The number of filaments observed in the stage of their growing to the anode is on the average $N \sim 10$ and, as the discharge develops, increases by several tens. It was found that the electron density in filaments can reach $N_e \sim 10^{19}$ cm^{-3} when it was possible to trace on interferograms the individual filaments with diameter of about ~ 10 μm. The current density in filaments achieves $j \sim 10^6$ A / cm^2. The analysis of the plasma parameters of filaments showed that they can have a significant effect on the discharge parameters. Thus, the filaments growth and the increase in their number inside the discharge gap can lead to the change in the total conductivity of the discharge gap as well as the discharge current and, as a consequence, the time of the voltage drops inside the gap.

REFERENCES

[1] *E.V. Parkevich and etc. //* JETP – 2018. – Vol. 126 – №3. Pages.423-430.

[1] The experimental study in this work was supported by the Russian Science Foundation (grant No. 14-22-00273). The development of the optical recording system was partially supported by the Russian Foundation for Basic Research (grants No. 17-08-01690; 18-32-00566).

RUNAWAY ELECTRONS FROM STREAMER BREAKDOWN IN SHORT OVERVOLTED GAPS IN AIR AT ATMOSPHERIC PRESSURE: SIMULATION STUDY[1]

Z. BONAVENTURA*, O. CHANRION**, A. BOURDON***, AND T. NEUBERT**

*Masaryk University, Faculty of Science, Department of Physical Electronics, Kotlářská 2, 611 37 Brno, Czech Republic.
**Technical University of Denmark, National Space Institute (DTU Space), Elektrovej Bygning 327, 2800 Kgs. Lyngby, Denmark.
***LPP, CNRS, Ecole polytechnique, UPMC Univ Paris 06, Univ. Paris-Sud, Observatoire de Paris,
Université Paris-Saclay, Sorbonne Universités, PSL Research University, 91128 Palaiseau, France

The runaway electron mechanism is of great importance for the understanding of the generation of x- and gamma rays in atmospheric discharges [1]. Runaway electrons play also an important role for breakdown and discharge development in laboratory conditions [2, 3]. Both nanosecond discharges in an inhomogeneous electric field and atmospheric discharges are characterized by the presence of X-rays and runaway electrons [4]. Firstly, we discuss the runaway threshold definition with a particular interest in the influence of the angular scattering for electron energy close to the threshold [5]. We focus on the runaway mechanism and we compare the outcome of different Fokker–Planck and Monte Carlo models with increasing complexity in the description of the scattering. The outcome is particularly important for the acceleration of thermal electrons to the runaway regime. Secondly, we present we present 2D axisymmetric 'beam-bulk' model for the production of runaway electrons in high-pressure discharges. The model is built on our previous work [6], where we have studied the production of runaway electrons by streamers using a 1.5D 'beam-bulk' model. The main idea of the model remains identical and is based on the fact that streamer discharges can produce runaway electrons from their tip [7, 8]. The fluid model is based on the work of [9]. The model solves for the drift-diffusion equations for positive and negative ions and for electrons of energy below 100 eV. The particle model is inherited from the work of [8, 10], it is based on the classical PIC-MCC approach in which particles are followed in cells forming a mesh used to map the force fields. We use this model to study discharge breakdown appearing in a negative point-to-plane gap submitted to very high voltage pulse. The results show the effect of high energy electrons on discharge development. While overtaking the discharge front, the high energy electrons pre-ionize the gas ahead and leave a trace of secondary seed electrons that in turn facilitate discharge propagation. Characteristics of fast electrons generated in the region of enhanced electric field ahead of the discharge propagating front are studied in detail.

REFERENCES

[1] *J.R. Dwyer et al*., Space Sci. Rev. 173 (2012), 133–196.
[2] *P. Tardiveau, et al*, J. Phys. D: Appl. Phys. 42 (2009) 175202.
[3] *E. Marode et al*., Plasma Sources Sci. Technol. 25 (2016) 064004.
[4] *I. D. Kostyrya and V. F. Tarasenko*, Plasma Physics Reports 41 3 (2015) 269–273.
[5] *O. Chanrion et al*., Plasma Phys. Control. Fusion, 58, (2016) 044001.
[6] *O. Chanrion et al*., Environ. Res. Lett. 9 (2014) 055003.
[7] *G. D. Moss and V. P. Pasko, N. Liu, and G. Veronis*. J. Geophys. Res. , 111 (2006) A02307.
[8] *O. Chanrion and T. Neubert* (2008), Journal of Computational Physics. 15(15):7222–7245.
[9] *F. Pechereau et al*., Plasma Sources Sci. Technol. 21, (2012) 055011.
[10] *O. Chanrion and T. Neubert* (2010), J. Geophys. Res., 115, A00E32, doi:10.1029/2009JA014774.

[1] This work has been supported from the Czech Science Foundation research project 18-04676S.

FORMATION OF DIFFUSE DISCHARGES IN ATMOSPHERIC PRESSURE AIR[1]

N.YU. BABAEVA, G.V. NAIDIS

Joint Institute for High Temperatures RAS, Izhorskaya 13, Moscow 125412, Russia, nybabaeva@gmail.com, +79680687775

It is usually believed that photoionization is the main factor responsible for the formation of precursor electrons ahead of the streamer front. In this work, theoretical and two-dimensional computational studies of a streamer discharge are performed using Monte Carlo technique for the simulation of high-energy electrons emitted from cathode surfaces. The influence of these electrons on the character of the discharge formation is considered.

The model, *nonPDPSIM*, used in this paper is a t wo-dimensional code which is executed on unstructured numerical meshes [1]. In the model, energetic secondary electrons emitted from surfaces are treated by the kinetic Electron Monte Carlo Module (EMCM). EMCM integrates the trajectories of the fast electrons. The trajectories of such electrons are tracked until they cross the boundary of the computational region (chamber wall) or their energy becomes less than the average electron energy in the volume. The energies of fast electrons are recorded to compute electron energy distributions (EEDs). From the EEDs, electron impact source functions and sources of secondary electrons are computed.

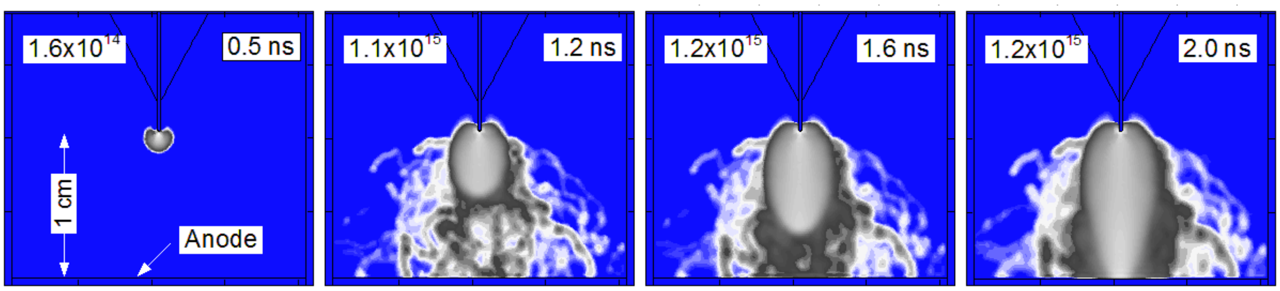


Fig. 1. Streamer evolution in a point-to-plane geometry: pre-ionization is created only by fast electrons emitted from point cathode and the region of high electric field in the streamer head while photoionization is excluded. The electron density (cm^{-3}) is plotted over 5 decades log scale which enables to see the tracks of fast electrons. The maximum electron density is indicated in each frame.

A negative streamer is initiated in a point-to-plane 1 cm gap by applying high-voltage pulses of nanosecond duration to the point cathode. Fast electrons are periodically emitted from the surface of the cathode with weight coefficients proportional to the rate of secondary electron emission during ion or photon bombardment of the cathode. The evolution of the discharge is shown in Fig. 1 for the 2 ns pulse duration, 0.3 ns rise and 0.5 ns fall time and a peak voltage -70 kV. The background ionization is created by fast electrons emitted from the point cathode. Fast electrons are also produced in the streamer head where the electric field is high enough to accelerate the electrons at this location.

We analyze factors which determine transition to diffuse forms of discharges in air. In particular, we present patterns of streamers calculated with and without account for photoionization or pre-ionization by fast electrons. It is concluded that diffuse discharges can be formed due to preliminary gas ionization by fast electrons.

REFERENCES

[1] *N. Yu. Babaeva, Ch. Zhang, J. Qiu, X. Hou, V. F. Tarasenko, Tao Shao // Plasma Sources Sci. Technol. -2017- V. 26, -P. 085008.*

[1] This work was supported by the Russian Foundation for Basic Research under Grant 17-52-16002.

CONDITIONS FOR GENERATION OF RUNAWAY ELECTRONS IN A GAS DIODE WITH A STRONGLY NONUNIFORM ELECTRIC FIELD[1]

G.A. MESYATS, M.I. YALANDIN**, N.M. ZUBAREV***

**Lebedev Physical Institute, RAS, Leninskii pr. 53, Moscow, 119991, Russia*
***Institute of Electrophysics, UB, RAS, ul. Amundsena 106, Yekaterinburg, 620016, Russia*
E-mail: nick@iep.uran.ru, phone: +7(343)2678776

A sufficient condition for generation of runaway electrons in a uniform field is that its strength is above the threshold value (E_r) determined by the parameters of the gas [1] ($E_r \approx 450$ kV/cm for nitrogen and air at atmospheric pressure). The feature of laboratory studies of generation of runaway electrons is often a sharp inhomogeneity of the electric field in the interelectrode gap (cathodes in the form of a needle or a blade are used for the local enhancement of the field). In this case, the field exceeds the threshold value only in a small vicinity of the working surface of the cathode, and to answer the question on the possibility of runaway electrons, it is necessary to examine their motion at the periphery in the region of low fields.

In the present work, the conditions for generation of runaway electrons in a gas diode with a sharply nonuniform electric field are investigated for a "tubular edge cathode–planar anode" discharge gap [2]. For calculations, it is assumed that the field strength decreases with the distance z from the edge of the cathode as $z^{-1/2}$ that corresponds to the parabolic approximation of the cross section of the cathode edge. In recent Letter [3] it was shown that the equations of motion of electrons in the gas can be solved analytically for such a field strength distribution. The analysis of the solutions allows us to formulate the conditions for runaway of electrons at the periphery in the region of weak field which supplement a classical condition $E_0 > E_r$ of runaway electrons in the cathode region. Here E_0 is the strength of the macroscopic field at the edge (the microscopic field on the cathode determined by the presence of various microinhomogeneities on the surface can be one or two orders of magnitude higher than the macroscopic field E_0, thus ensuring conditions for field emission [1]). The new condition for runaway has the form

$$U > \sqrt{2DE_rU^*} \,,$$

where D is the interelectrode distance, U^* is the parameter weakly depending on the interelectrode distance ($U^* \approx 2.7-3.0$ kV for distances in the range of 6-26 mm). According to developed theory confirmed by experiments, just this condition, rather than the classical condition, will determine the transition of electrons to the runaway regime for the strongly sharpened edge of the cathode. The threshold value of the rounding radius of the cathode edge for the use of different criteria of run away is $R^* = U^*/E_r \approx 60-67$ μm (this estimate corresponds to nitrogen at atmospheric pressure).

REFERENCES

[1] *Yu.D. Korolev and G.A. Mesyats* // Field Emission and Explosion Processes in Gas Discharge. – Nauka, Novosibirsk, 1982 [in Russian].
[2] *G.A. Mesyats, M.I. Yalandin, A.G. Reutova, K.A. Sharypov, V.G. Shpak, and S.A. Shunailov* // Plasma Phys. Rep. – 2012. – Vol. 38. – p. 29.
[3] *N.M. Zubarev, G.A. Mesyats, and M.I. Yalandin* // JETP Letters. – 2017. – Vol. 105. – No. 8. – pp. 537–541.

[1] Theoretical part of the work was supported by the State Task 0389-2015-0023, by the RAS research program No. 11 and, in part, by the RFBR grant No. 17-08-00430. Experiments were performed following to the RAS research program No. 10.

I-V CHARACTERISTICS AND EFFICIENCY OF ELECTRON BEAMS GENERATION IN A CONTINUOUS "OPEN" DISCHARGE[1]

P. A. BOKHAN

Institute of Semiconductor Physics, Siberian Branch, Russian Academy of Sciences, pr. Akademika Lavrent'eva 13, Novosibirsk, 630090, Russia, bokhan@isp.nsc.ru

The operating features of an "open" discharge OD in the continuous and quasicontinuous (τ=1...3.5 ms) combustion conditions are investigated. Cells with *Ti*-cathodes were used. Molybdenum grids with geometric transparency μ_1=65 % and μ_2=87 %, with a characteristic hole size δ=0.2 mm and a working diameter of 12 mm were installed at a distance l=0.65 mm from the cathode. At a distance from the grids L=20 mm, the collector of electrons CE was placed. Thermal sensors and ohmic heaters were located on the CE and the side wall of the cell, which made it possible to measure, with an accuracy of up to 5%, the power of the electron beam EB, release on the CE and scattered in the drift space DS between the grid and the CE.

Two methods of connecting cells to a power supply have been studied. In the first case, the grid and CE were grounded through the current-measuring shunts. In the second case, the voltage was applied between the cathode and the CE, and the grid-anode was under the floating potential. In both cases, the I-V characteristic of the discharge in the range of helium pressures p_{He}=15...30 Torr, which are optimal for the generation of EB, is Z - shaped. As the operating voltage increases, the current-voltage characteristic is initially close to the I-V characteristic of the normal and weakly anomalous discharges. Then, depending on the pressure, at a voltage of 300...500 V there is a sharp drop in current. For the case with grounded anode and a pressure p_{He}=30 Torr, the current decreases 40 times, from 15 mA to 350 µA. Then, from a voltage U=1.5...2.2 kV, a new current growth begins, accelerating as the voltage rises. If we characterize the I-V characteristic by the dependence $j \sim p^x U^y$, then in the range U=2.5...3 kV, the value may be as y=10 for the variant with the floating anode potential and y=15 for the grounded anode. A further increase in U leads to a slowing of the growth rate of the current due to heating of the working gas. When fed with rectangular pulses for a floating potential option, the parameter y stabilizes at y=15, and for a grounded anode, starting at a current of ~4 mA and up to 50 mA, the voltage is almost independent of current, i.e. $y \to \infty$. The parameter x, depending on the conditions, varies in the range x=1.5...7 and unlike the parameter y it always is positive.

In a wide range of conditions, the energy efficiency η of the EB generation is measured. The largest measured value η_{exp}=83% was achieved for the case of a grounded anode with p_{He}=30 Torr and $U\approx$4 kV. Taking into account the transparency of the mesh, μ_2=87%, the internal efficiency of the generation of EBs is $\eta_{in}\approx$95%, and the power dissipated is distributed almost equally between the CE and the working gas in the DS. Within the accuracy of the measurement, η_{exp} practically coincides with the efficiency, determined from the ratio between the anode and collector currents (~83% and ~86%, respectively). For the case of the floating potential of the anode, η is much smaller and amounts to $\eta_{exp}\approx$70% and $\eta_{in}\approx$80%, which is explained by the injection of ions from the DS into the accelerating gap and, correspondingly, by a much larger fraction of the ion current in the total discharge current. It is due to the fact that the grid potential with respect to the potential of the plasma in the DS, measured with probes, can exceed 100 V.

The listed features of the OD function entirely fit the hypothesis of its photoelectronic nature, realized at U>2 kV. In this case, the power of the EB expended in the DS for excitation of the resonant states of helium is sufficient to generate such a number of resonant VUV photons, at which the photodischarge is self-maintaining one, and the charge multiplication in the discharge gap is negligible.

[1] The study was supported by Russian Foundation for Basic Research (№ 17-08-00121).

COMPARATIVE STUDY OF THE CHARACTERISICS OF ANOMALOUS AND "OPEN" DISCHARGE IN HELIUM [1]

P. A. BOKHAN

Institute of Semiconductor Physics, Siberian Branch, Russian Academy of Sciences, pr. Akademika Lavrent'eva 13, Novosibirsk, 630090, Russia, bokhan@isp.nsc.ru

The "open" discharge OD realized in small gaps between the solid cathode and the grid anode, almost immediately after the first implementation in 1980, became the subject of lively discussions. In this paper, comparative studies of anomalous discharge AD and OD in identical cells for a continuous and quasi-continuous (millisecond) mode of operation have been carried out. The cells for the OD with the distance between the cathode and the anode grid l=0.65 mm and different characteristic grid cells size δ=0.2; 0.4; 1 mm were used. At a distance of 20 mm from the nets, an electron collector was installed. For AD, the same dimensions are observed, but there are no grids. In all cases, the working diameter of the cathode was 12 mm. The experiments were carried out with both helium of M5 purity and with small impurities of O_2 and N_2. To determine the efficiency of electron beam EB generation, the energy deposition was measured both in the drift space between the cathode (or grids) and the collector of electron CE, and scattered on the CE. The experiments were carried out in carefully degassed and trained cells.

The I-V characteristic both in AD and in OD have a different character depending on the pressure of helium. For p_{He}<5 Torr in AD and p_{He}<10 Torr in OD, they have a smooth increasing character, and the current density j is much smaller than in AD with the generation of EB in the *He-O*$_2$ discharge [1]. With increasing pressure, the character of the I-V characteristic changes abruptly. Depending on $j(U)$, three different regions clearly differ. In the first of them, at lower voltages U and j, the I-V characteristic of all the cells is close. Then, depending on p_{He} and power conditions, at a certain value of j (from 0.5 to 10 mA/cm^2) the current with increasing voltage first ceases to depend on U, and in the range U~400...1500 V the falling I-V characteristic is realized. In AD, in the dependence $j \sim p^x U^y$, the value of y in this case is slightly negative. In the OD, depending on the size of δ, the character of the I-V characteristic acquires a pronounced *Z*-shaped dependence. The smaller the value of δ, the deeper the fall in j occurs in this region. In a cell with δ=0.2 mm and at p_{He}=30 Torr, the current at U=2 kV is 40 times smaller than at U=400 V.

After the region with decreasing I-V characteristic in a certain region, ΔU j does not depend on U and then the I-V characteristic again acquires an increasing character. The smaller the size δ, the more rapidly the current increases with increasing U. In AD, the parameter y reaches the value y=4, and in the OD with δ=0.2 at j=5 mA/cm^2, the voltage with increasing current ceases to increase, i.e. $y\to\infty$, to the value j~50 mA/cm^2. From this point the I-V characteristic for both AD and OD has a clearly pronounced increasing character. For discharges in *He* c with an admixture of O_2 or N_2 (1-2%), the I–V characteristic of all discharges has always an increasing character, with identical current densities realized at much lower p_{He} than in pure *He*. At U>2 kV, the dependence of the energy efficiency of EB generation was measured in AD in *He-O*$_2$ mixtures, the values of η_{exp} and $j(U)$ obtained are close to the results of [1]. In pure *He*, to obtain the same value of j in AD, the helium pressure is much higher than in [1]. In the OD, the smaller δ, the higher p the current is equal to the current in AD. The efficiency of EB generation increases with decreasing size δ and at δ=0.2 mm is practically equal to the geometric transparency of the mesh μ, and the internal (i.e., taking into account μ) value η_{exp}~95% as compared with η_{exp}~50...75% for AD.

All the above features of discharges are explained in terms of the emission characteristics of cathodes. With lowered U in pure *He* and for any U in mixtures, emission is dominated by the action of heavy particles. As U grows in pure *He*, conditions are realized for the runaway of electrons and the formation of EB. Therefore, the influx of ions into the cathode begins to decrease. This phenomenon is more noticeable for the OD, so it implements a deep fall of j with increasing U. With a further increase in U and increased of the power of the EB, which is scattered in the drift space between the cathode and the CE, is sufficient to realize a self-sustained photoemission discharge due to the resonant *He* photons.

[1] *J.J. Rocca, J.D. Meyer, M.R. Farrell, and G.J. Collins //* J. Appl. Phys. – 1984. - 56. - 790.

[1] The study was supported by Russian Foundation for Basic Research (№ 17-08-00121).

SUBNANOSECOND SWITCHING DEVICES BASED ON AN "OPEN" DISCHARGE [1]

P.A. BOKHAN, I.V. SCHWEIGERT**, DM.E. ZAKREVSKY**

* *Rzhanov Institute of Semiconductor Physics, SB RAS, Novosibirsk630090, Russia*
** *Khristianovich Institute of Theoretical and Applied Mechanics, SB RAS, Novosibirsk 630090, Russia*
phone: +7(383)3331091, E-mail: zakrdm@isp.nsc.ru

The paper presents the results of theoretical and experimental research of a new generation of subnanosecond and picosecond switches based on the "open" discharge OD and its combination with other types of discharges. A classical OD is realized between the cathode and the anode, behind which is located the drift space DS. In the DS, the energy of fast electrons accelerated in the discharge gap is released. Due to the fact that a significant part of the electron energy is spent on excitation of the resonant states of the working gas, an intense VUV cathode illumination is realized, which ensures an independent discharge character at a sufficiently high pressure of the working gas, usually helium. In work [1,2], the perspectives of using the OD as a fast key - a device allowing to pass into a high-conductivity state in subnanosecond and picosecond times - is shown.

Typical are the constructions of cells with the generation of colliding electron beams of EB -kivotron. In this case, they contain two accelerating (discharge) gap, located symmetrically with respect to either one common grid, or gaps have each its grid, located some distance from the grid of another gap. A special case is the coaxial arrangement of the cathode and the grid-anode, in which the generation of counter propagating EBs is also realized. The fastest are switches with flat electrodes, which have one common grid. Attained values of the functioning by separately achieved parameters: the rate of current rise to 500A/ns cm^2; operating voltage U up to 100kV; switching time τ_s - voltage reset time on the switch up to 100ps; the degree of pulse compression $S=\tau_d/\tau_s$ is the ratio of the delay in the development of the discharge τ_d to τ_s to 40 and the repetition rate of f to 100kHz. A significant disadvantage of the kivotrons is that high f are achieved by lowering the working pressure, which is accompanied by an elongation of the leading edge of the pulse of the generated voltage and a decrease in the degree of its compression.

Further development of the concept of the kivotron is a device that represents a combination of "open" and capillary discharges integrated in one working volume - an eptron. The design is a cuvette with a discharge gap, a cathode-mesh anode (a conventional kivotron), in which an OD is generated and a converging EB is generated. On the side of one of the ends of the cuvette, an additional discharge structure is connected, on the outside of which an anode is mounted. In general, a kivotron may have a coaxial and planar structure, and an additional discharge structure may be a coaxial or slotted capillary. Typical values of functioning by separately achieved parameters: operating voltages U up to 20kV; switching time τ_s up to 100ps; the compression ratio of pulses S to 1000, the pulse repetition rate to 100kHz.

The theoretical study included modeling the processes of interaction of electrons with atoms and ions of the working gas, the interaction of heavy, including fast particles, as well as the processes of electron emission under the action of ions, fast atoms and photons. A discussion in the description and interpretation of the properties of these devices is the question of the mechanisms of electron emission. According to our ideas, the main mechanisms responsible for ultrafast breakdown are photoemission under the action of resonant photons having a large Doppler shift due to the high energy of fast atoms. In the final stage of breakdown, the secondary electron emission plays the dominant role.

A critical analysis of the current data on the electron emission coefficients due to the action of heavy particles is carried out and it is concluded that the data [3] are inapplicable for describing the discharge in pure helium.

An experimental study of the conditions under which, both in the abnormal discharge and in the «open» discharge, including the continuous discharge, becomes photoemission. The data obtained unambiguously testify to the photoemission mechanism of electron emission during ultrafast breakdown of discharge gaps.

REFERENCES

[1] *Bokhan P.A., Gugin P.P., Zakrevsky D.E., Lavrukhin M.A. //* Techn. Phys. Lett. – 2012. – 38. – 383.
[2] *Schweigert I.V., Alexandrov A.L., Bokhan P.A., Zakrevsky Dm.E. //* Plasma Sources Science and Techn. – 2015. – 24. – 044005.
[3] Hayden H.C., Utterback N.G. // Phys. Rev. – 1964. – 135. – A1575.

[1]The study was supported by RSF project № 14-19-00339.

MECHANISM OF RUNAWAY ELECTRON GENERATION AT GAS PRESSURES FROM A FEW ATMOSPHERES TO SEVERAL TENS OF ATMOSPHERES [1]

S.N. IVANOV*, N.M. ZUBAREV*,**

*Institute of Electrophysics, Amundsena Str. 106, Ekaterinburg, 620016, Russia, E-mail: stivan@iep.uran.ru, phone:+7(343)2678824.

**Lebedev Physical Institute, Leninskiy Prospekt 53, Moscow, 119991, Russia, E-mail: nick@iep.uran.ru, phone:+7(343)2678776.

The mechanism of runaway electron (RAE) generation at gas pressures (p) from a few atmospheres to several tens of atmospheres is proposed. According to this mechanism, the electrons transfer into the runaway mode in the enhanced electric field zone that arises between a cathode micro protrusion – a source of field-emission electrons – and the region of the positive ion space charge accumulated near the cathode in the tails of the developing electron avalanches. As a result, with a time delay required for the formation of the enhanced field zone, RAEs are generated, which produce ionization in the gas volume. This process determines the breakdown delay time.

Specific features of the formation dynamics of the space charge region at different gas pressures have been analyzed. At gas pressures of a few atmospheres, the space charge arises due to the avalanche multiplication of the very first field-emission electron. In this case, the initiating electrons are emitted from the cathode with time intervals on the order of the time t_c during which the number of charge carriers near the cathode micro protrusion increases to a level at which the space charge electric field becomes comparable with the external field. According to our estimates, at pressures of several tens of atmospheres, the space charge forms as a result of superposition of many electron avalanches with a relatively small number of carriers in each. At these pressures, the time intervals between emissions of individual electrons from the cathode become much shorter than the time t_c.

The formation of a region with an uncompensated ion space charge near a cathode micro protrusion leads to the enhancement of the electric field near the cathode and an increase in the field emission. The field emission ensures the influx of electrons into the gap between the micro protrusion and the space charge region. This leads to the enhancement of gas ionization near the boundary of the space charge region, due to which it rapidly expands toward the cathode. As a result, the electric field is enhanced up to values greater than E_{cr}/p (E_{cr} – the threshold value of the electric field intensity (E) required for RAE generation [1, 2]), which are sufficient for the electrons to pass into the runaway mode. The potential drop across the gap between the cathode and the space charge region allows the RAEs to gain an energy of a few kiloelectronvolts, due to which they continue to run away after entering the region with the weak (with E/p a lot less than E_{cr}/p) average field. As a result, an RAE beam forms under the conditions in which runaway criterion [1, 2] is certainly not satisfied in the average field.

Experimentally RAEs were registered in an initially homogeneous electric field in nitrogen at a pressure of 40 atm in paper [3]. In these experiments, the breakdown of the discharge gap occurred at the front of the applied high voltage pulse. The reduced electric field strength at the start of the breakdown (i.e. estimated at the upper limit) was 36-38 V/(cm Torr): i.e. all the previously known criteria [1, 2, 4, 5] for transition of electrons into runaway mode were not fulfilled in these conditions.

The authors are grateful to Academician G.A. Mesyats for stimulating discussions.

REFERENCES

[1] *Yu. D. Korolev and G. A. Mesyats* // Physics of Pulsed Breakdown in Gases. – Ural Division of Russian Academy of Sciences, Ekaterinburg, 1998.
[2] *L. P. Babich* // High-Energy Phenomena in Electric Discharges in Dense Gases: Theory, Experiment, and Natural Phenomena. ISTC Science and Technology Series, Vol. 2. – Futurepast, Arlington, VA, 2003.
[3] *S. N. Ivanov* // J. Phys. D: Appl. Phys. – 2013. – 46. – 285201.
[4] *A. V. Kozyrev, Yu. D. Korolev, G. A. Mesyats, and Yu. N. Novoselov* // Book of Abstracts "VI All-Union Conference on Physics of Low-Temperature Plasmas" (Leningrad, USSR, 1983), p. 228–230.
[5] *A. N. Tkachev and S. I. Yakovlenko* // Tech. Phys. Lett. – 2003. – 29(8). – 683–686.

[1] This study was full-filled in the frame of state tasks N 0389-2015-0023 and 0023-2016-0004. This work was partially supported by the Russian Fund for Basic Research (grants N 17-08-00430-a, N 16-08-00466-a), the Presidium of the Russian Academy of Sciences under program N 11 "Basics of Pulsed High-Current Emission Electronics", and the Ural Branch of the Russian Academy of Sciences under the program "Physical Models, Theories, and Devices" (project N 18-2-2-15).

THE EFFECT OF THE MICRO-STRUCTURE OF CATHODE SURFACE ON THE GENERATION OF RUNAWAY ELECTRONS IN A FORMING CATHODE LAYER OF SELF- SUSTAINED HIGH PRESSURE GAS DISCHARGE.[1]

V.V. LISENKOV, **, S.N. IVANOV*, Yu.I. MAMONTOV**, I.N. TIKHONOV***

**Institute of Electrophysics UD RAS, 106 Amundsena st., Yekaterinburg, 620016, Russia, lisenkov@iep.uran.ru, +73432678779*
***Ural Federal University, 19 Mira st., Yekaterinburg, 620002, Russia*

The paper presents the results of theoretical and experimental studies of the generation of runaway electrons emitted from micro-inhomogeneities, which form local amplification of the electric field. The installation described in [1] was used in the experimental studies. The presence of runaway electrons was experimentally detected in the pressure range of 1-40 atm. In our opinion, the generation of runaway electrons occurs in the near-cathode region at the stage of discharge formation.

The problem was solved by Monte Carlo method in 2D geometry. Nitrogen and hydrogen were taken as investigated gases. The calculation results showed that the passage through small sized region with amplified electric field near micro-spike or another inhomogeneity could help electrons to transfer into runaway mode, especially at gas pressures above 10 atm.

In our opinion, generated runaway electrons can pre-ionize the gas medium and provide the formation of the initial discharge phase in volume form. On the other hand, in the case of the formation of self-sustained volume discharge in a pre-ionized gas, the runaway electrons are able to initiate the development of instability in the forming cathode layer, which can subsequently lead to the contraction of discharge.

REFERENCES

[1] *Ivanov S.N. //* J. Phys. D: Appl. Phys. – 2013. – V. 46. – P 285201 (6pp).

[1] This study was full-filled in the frame of state task № 0389-2015-0023. This work was supported by RFBR, Grant 16-08-00894.

STUDY OF HIGH-PRESSURE GAS DIODE SWITCHING PROCESS IN SUBNANOSECOND TIME SCALE [1]

S.N. IVANOV, V.V. LISENKOV

Institute of Electrophysics, Amundsena Str. 106, Ekaterinburg, 620016, Russia, E-mail: stivan@iep.uran.ru, phone:+7(343)2678824.

In papers [1-3], it was shown that in nitrogen at pressures between 5 and 40 atm and in hydrogen at pressures between 5 and 50 atm in the sub-nanosecond range at the same time, there are two mechanisms for initiating of self-sustained subnanosecond discharge: the initiation of discharge by field emission from cathode micro protrusions and volume initiation by runaway electrons (RAEs). The electrons transfer into the runaway mode in the forming cathode layer [4], which formation requires some time. In this time, the anode directed ionization wave (IW), which is the result of drift multiplication of field emission electrons, have time to move away from the cathode at a short distance. Then, the RAEs beam outruns the front of this IW and pre-ionize gaseous medium. Further movement of the IW front is caused by the development of electron avalanches from the secondary electrons arising in the gas volume due to pre-ionization of the gas by RAEs, which leads to a significant increase in the speed of propagation of the IW front. This results in a dynamic capacity (anode – IW front), the charging current of which can cause a voltage drop in the discharge gap already at the stage of development of the conductive column (when the plasma has not yet reached the anode). Previously, for breakdown in the nanosecond region of time, such experimental conditions were not reported [5]. The process of gap switching starts only after the entire interval is covered by plasma.

We have analyzed this situation. The discharge gap was modeled as a parallel-switched capacitor of variable capacitance and a circuit consisting of a series-connected discharge current generator and a variable resistor (with resistance varying according to the change in the conductivity of the plasma channel). The results of the calculations showed a good agreement with the experimentally obtained voltage and current waveforms.

REFERENCES

[1] *S. N. Ivanov, K. A. Sharypov* // Technical Physics Letters. – 2016. – 42(3). 274–277.
[2] *S. N. Ivanov, K. A. Sharypov* // Technical Physics. – 2015. – 60(10). 1478–1482.
[3] *S. N. Ivanov, V. V. Lisenkov* // Plasma Physics Reports. – 2018. – 44(3). 369–377.
[4] *N. M. Zubarev, S. N. Ivanov* // Plasma Physics Reports. – 2018. – 44(4). 445–452.
[5] *Yu. D. Korolev and G. A. Mesyats* // Physics of Pulsed Breakdown in Gases. – Ural Division of Russian Academy of Sciences, Ekaterinburg, 1998.

[1] This study was full-filled in the frame of state task № 0389-2015-0023. This work was partially supported by the Russian Fund for Basic Research (grants N 16-08-00894-a, N 16-08-00466-a) and Federal Agency of Scientific Organizations under the program of fundamental studies “Physical models, theories, and devices” of the Ural Branch, Russian Academy of Sciences (grant N 18-2-2-15).

DYNAMICS OF THE ELECTRON ENERGY DISTRIBUTION FUNCTION IN AN INHOMOGENEOUS ELECTRIC FIELD [1]

V.V. LISENKOV*, **, YU.I. MAMONTOV**

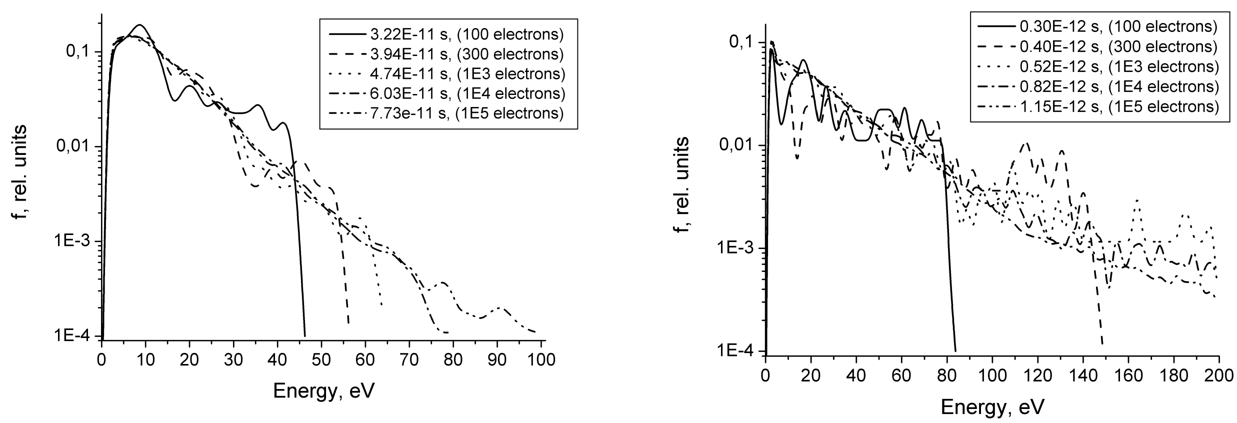
*Institute of Electrophysics UD RAS, 106 Amundsena st., Yekaterinburg, 620016, Russia, lisenkov@iep.uran.ru, +73432678779
**Ural Federal University, 19 Mira st., Yekaterinburg, 620002, Russia

In the paper, the formation of electron avalanches was simulated using Monte-Carlo method in inhomogeneous electric field of micro-spike located on the cathode surface. Nitrogen was taken as the test gas. The motion of each electron in the avalanche was modeled taking into account all the main elastic and inelastic collisions. For modeling, micro-spikes of height h and base $0.5{\cdot}h$ were used. To avoid singularities, the vertex of the cone was rounded with a hemispherical radius of $0.01{\cdot}h$. The spatial structure of the electric field was calculated using Laplace equation.

Figure 1 shows the electron energy distribution functions at different points of time that correspond to the different number of electrons in the avalanche. The calculations were performed for the micro-spike with $h = 10$ µm and gas pressures of 1 atm (a) and 10 atm (b). For correct comparison, the same ratio $E_m/p = 150$ kV/(cm·atm) was taken. The average electric field strength in the gap was defined as $E_m = U/d$ (U – voltage, d – gap).

Figure 1 shows that at the beginning of avalanche ionization, the electron energy distribution function changes distinctly with the increase in the number of electrons in the avalanche. With a further increase in the number of electrons to ~ 10^4-10^5, the distribution function tends to a quasi-equilibrium state. This process is faster at a pressure of 10 atm compared to a pressure of 1 atm, despite the fact that at a pressure of 10 atm, quasi-equilibrium distribution is achieved only at >10^5 electrons in the avalanche.

An interesting fact is that at a pressure of 10 atm, the transfer of electrons to runaway mode was detected, and at a pressure of 1 atm, the runaway electrons were not detected.



a) b)

Fig. 1. Electron energy distribution functions at different points of time and different number of electrons in the avalanche.
a) pressure 1 atm; b) pressure 10 atm

[1] This work was supported by RFBR, Grant 16-08-00894

DYNAMICS OF PULSE DISCHARGE IN ATMOSPHERIC PRESSURE ARGON[1]

V.S. KURBANISMAILOV, S.A. MAIOROV**,***, O.A. OMAROV*, G.B. RAGIMKHANOV*, TERESHONOK D.V.****

**Dagestan State University, str. M. Gadjieva 43a, Makhachkala, 367000, Russia, E-mail: gb-r@mail.ru*
***A.M. Prokhorov General Physics Institute of the Russian Academy of Sciences, Vavilova Str. 38, Moscow, 119991, Russia*
****Joint Institute for High Temperatures of the Russian Academy of Sciences, IzhorskayStr.13, Moscow,125412 Russia*

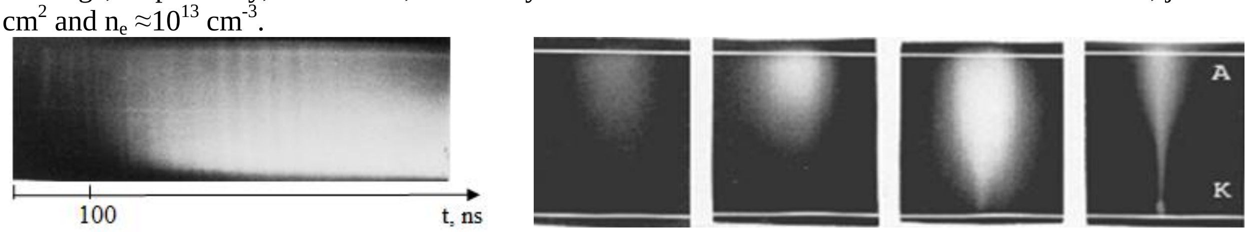
In this paper, an experimental and numerical study of the features of formation and development at the initial stages of breakdown of both the ionization fronts of the luminescence and the physical processes that cause the volumetric discharge instability in atmospheric pressure Ar is performed. The investigations were carried out in short intervals (d = 1 cm), with a discharge area s = 12 cm^2 at voltages in the range from a statistical breakdown (Ust = 6.8 kV at d = 1 cm, p = 1 atm) to hundreds of percent of overvoltages (up to 20 kV) in a preionized gaseous medium with electron concentration $n_0 \sim 10^7$cm^{-3}. The experimental setup is similar to that described earlier in Refs.[1].

In the experiments, discharge diagnostics included the recording of voltage and discharge current on the discharge gap (respectively ohmic divider and low-inductance shunt) using digital oscilloscopes such as Aktakom and Tektronix, photographing the integral glow of the discharge, as well as photographing spatio-temporal patterns of glow of the gap using a photoelectric recorder (FER-2).

In Fig. 1 successive shots of the development of the discharge in argon, obtained during preionization, are shown. When the initial concentration of electrons is created in the interval $n_0 \cdot 10^7$ cm^{-3} and insignificant overvoltages, the first recorded luminescence appears at the anode by the instant of a sharp increase in current at an electron concentration ~ 10^{12}-10^{13} cm^{-3} and propagates to the cathode with a velocity ~ (2-5) · 10^7 cm/s. The speed is determined from the photos of the slit scan (see Fig. 1a).

As the emission front approaches the cathode, the electron concentration at the wave front increases and reaches values of 10^{13}-10^{14} cm^{-3}. At this stage, the discharge current has a value of 1-10 A. The overlapping of the discharge gap by an ionization front with a velocity an order of magnitude greater than the electron avalanche drift velocity leads to the formation of a cathode spot (see Fig. 1b, photo 4) and a spark channel.

In time, the overlap of the glow corresponds to the beginning of a sharp drop in voltage across the gap. At this stage, respectively, the current, its density and electron concentration are of the order: I ≈ 1 A; j ≈ 10^2 A / cm^2 and $n_e \approx 10^{13}$ cm^{-3}.



a) b)

Fig.1. Space-time frames for the formation of a spark channel in argon with gas preionization in the gap (anode –in the top, cathode – in the bottom, d = 1 cm, p = 760 Torr, Ust = 10 kV)

Thus, the analysis of frame-by-frame patterns of discharge formation in argon in a wide range of changes in the initial conditions shows that, the formation of a homogeneous plasma column is preceded by the sequence of the following stages:

a) the appearance of the first visible glow near the anode;
b) propagation of the glow front to the cathode;
c) voltage drop across the discharge gap with the advent of the emission front to the cathode;
d) the formation of the cathode and anode layers, as well as the plasma column.

REFERENCES

[1] *Kurbanishmailov V.S., Omarov O.A., Ragimkhanov G.B. et.al.* .//Plasma physics reports. - 2016. - Vol. 42. - № 7. - P. 687-698.

[1]The experimental part was supported by the Russian Foundation for Basic Research, project № 18-08-00075a. The theoretical part was supported by the President of Russia Scholarship for young scientists, project № 3812.2016.1.

ELECTRONDRIFT CARACTERISTICSIN ARGON WITH IRON VAPOR: COEFFICIENTS OF MOBILITY, IONIZATION AND RUNAWAY[1]

V.S. KURBANISMAILOV, S.A. MAIOROV**,***, O.A. OMAROV*, G.B. RAGIMKHANOV**

**Dagestan State University, str. M. Gadjieva 43a, Makhachkala, 367000, Russia, E-mail: gb-r@mail.ru*
***A.M. Prokhorov General Physics Institute of the Russian Academy of Sciences, Vavilova Str. 38, Moscow, 119991, Russia*
****Joint Institute for High Temperatures of the Russian Academy of Sciences, IzhorskayStr.13, Moscow,125412 Russia*

The properties of a gas-discharge plasma in a mixture of an inert gas in the presence of metal vapors are of great interest for variety of applications [1]. In addition, the process of formation and development of a pulsed discharge in aninterelectrode gap can also be accompanied by sputtering of electrode [2].Metal vapor, even at low concentrations, due to the lower ionization potential, significantly affect the kinetics of the discharge. In this paper, we consider, as an example, the drift of electrons in Ar with Fe vapor.Note, that Cu vapor lasers are widely used, but theoretical and numerical resultsleave many questions [3,4,5].

The electron drift characteristics in argon with iron vapors are calculated and analyzed at reduced electric field strength in the range E / N = 1 - 2000 Td. The influence of the iron concentration on the kinetic characteristics of the discharge: the drift velocity, the average electron energy, the diffusion and mobility coefficients, the ionization frequency, and Townsend ionization coefficients is studied. Stoletov constant is also calculated. Particular attention is paid to the electron runaway effect.

A comparison of the electron distribution function with Maxwell and Druyvestein distributions is given. It is shown that even minor additions of iron atoms to argon, starting with a fraction of a percent, strongly influence the discharge, in particular, on the characteristics of inelastic processes.

In Fig. 1(left) shows the dependence of the drift velocity of the electrons, and in Fig. 2 (right))the coefficient of electron runaway from the reduced electric field strength E / N in pure argon, iron vapors and also in argon/ferrum mixture with 0.1%, 1%, 2%, 5%, 10% and 50% iron atoms content.

The results of the calculations give a fairly complete picture of the mechanism of the effect of small additions of iron vapors on the characteristics of a gas discharge. The most interesting and important fact from the practical point of view is a strong increase in the ionization frequency with an insignificant (on the order of fractions of a percent) addition of iron fumes. In addition, it should be noted that in this case, iron atoms will predominantly be ionized, respectively, iron ions will be mainly represented in the discharge.

It is shown that even small additions of copper atoms to helium, starting with a fraction of a percent, strongly influence the discharge, especially on the characteristics of inelastic processes.

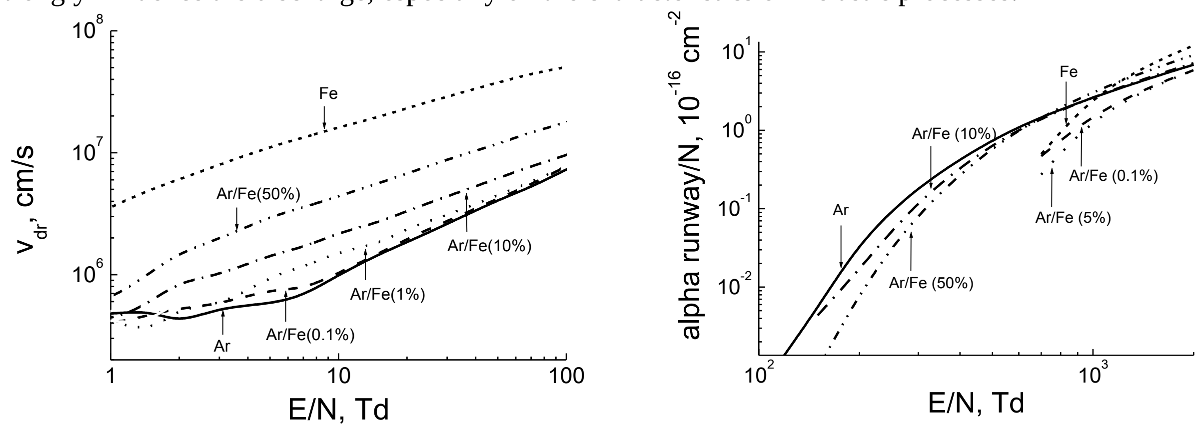


Fig. 1

REFERENCES

[1] *Tarasenko V.F., Yakovlenko S.I. //*Physics - Uspekhi. -2004. - Vol.174. - №9. - P.953-971.
[2] *Kurbanishmailov V.S., Omarov O.A., Ragimkhanov G.B. et. al.//*Plasma physics reports. - 2016. - Vol. 42. - № 7. - P. 687-698.
[3] *Babich L.P.//*Physics - Uspekhi. - 2005. - Vol.175. - №10. - P.1069-1091.
[4] *Ulyanov K.N.//* High temperature. - 2005. - Vol.43. - №5. - P. 645-656.
[5] *Stahl A., Hirvijoki E., Decker J., Embréus O., and Fülöp T.//* Physical Review.Letters -2015. –Vol. 114. – P. 115002.

[1]This work was supported by the Russian Foundation for Basic Research, project № 18-08-00075a.

IMPULSE DISCHARGE IN ARGON IN THE SPRAY MODE OF THE MATRIX OF THE SUBSTANCE OF THE ELECTRODE[1]

V.S. KURBANISMAILOV, S.A. MAIOROV**,***, O.A. OMAROV*, G.B. RAGIMKHANOV**

**Dagestan State University, str. M. Gadjieva 43a, Makhachkala, 367000, Russia, E-mail: gb-r@mail.ru*
***A.M. Prokhorov General Physics Institute of the Russian Academy of Sciences, Vavilova Str. 38, Moscow, 119991, Russia*
****Joint Institute for High Temperatures of the Russian Academy of Sciences, IzhorskayStr.13, Moscow,125412 Russia*

The study of the space-time dynamics of a pulsed discharge formation in atmospheric pressure argon in centimeter interelectrode gaps (with an initial electron concentration in the interval n_0 ~10^7cm^{-3} and insignificant overvoltages *W*~ (10-100%) show that during the formation of a discharge, the first recorded luminescence occurs on anode, which propagates to the cathode at a velocity of ≈ $2\text{-}5\cdot10^7$ cm/s [1]. As the emission front moves toward the cathode, the electron concentration in it increases and reaches values of ~10^{13}-10^{14} cm^{-3}.

At this stage, the discharge current has a value of 1-10 A. The overlapping of the discharge gap by the ionization front leads to the formation of a cathode spot and a spark channel (see Fig. 1, frame 4). The temperature of the cathode flare, estimated from the relative intensity of the spectral lines of argon in 30-40 ns, is 4-5 eV. The temperature of the electrons of the diffuse channel, tied to the cathode spot, is ~ 1-2 eV. After 30-40 ns, the cathode flare begins to stretch over the external field and assumes the shape of an elongated ellipse, and a spark channel sprouts from the cathode spot deep into the gap.

We have carried out investigations of the emission spectra from the near-cathode plasma of the discharge in atmospheric pressure argon. It has been established that with the formation of a cathode spot, the spectrum of the near-cathode plasma is characterized by intense lines of the cathode material *AlII* 396.1 nm, 394.4 nm, 280.1 nm, 281.6 nm with high excitation potentials and an intense continuum in the 260-360 nm range. The lines of aluminum ions are recorded simultaneously with the onset of a sharp current increase and reach a maximum value in 20-30 ns. After 30 ns from the onset of sharp current growth, the Stark half-width of the 480.6 nm argon line is 0.5-0.6 nm, and the line 422.8 nm ≈ 0.5 nm. These half-widths correspond to an electron density of ~ 10^{19} cm^{-3}, and after 20 ns the concentration decreases to a value of $2\cdot10^{18}$ cm^{-3}.

The effect of a longitudinal magnetic field on the emission spectra of a cathode plasma of a discharge is investigated. It is established that with an increase in the strength of the magnetic field the maximum radiation energy shifted to the short-wave region of the spectrum: at H = 0, λ_{max} = 420 nm, at H = 140 kOe - 400 nm, at H = 200 kOe - 380 nm. Thus, in the magnetic field the intensity of continuous radiation increases, the brightness of the ion lines in the ultraviolet region also increases: *ArII* 280.6 nm, *ArIV* 280.9 nm and lines of the electrode material *Al*-280.1 nm, 281.6 nm.

At the stage of slow channel expansion, i.e. from the moment t = 500 ns, the intensity of continuous radiation decreases, the intensity of ionic lines also decreases, while the brightness of the lines of neutral argon is 394.89 nm, 392.9 nm and aluminum lines *AlI* - 302.9 nm, 308.2 nm; *AlII* - 281.6 nm, 280.1 nm increases. In the longitudinal magnetic field, from the moment t = 700 ns, the emission of *ArI* lines 394.89 nm strongly increases; *ArII* 280.6 nm; *ArIV* 280.9 nm and aluminum 281.6 nm; 280.1 nm; 309.27 nm and 308.216 nm, while the intensity of the lines in the visible range of the spectrum decreases with increasing magnetic field strength.

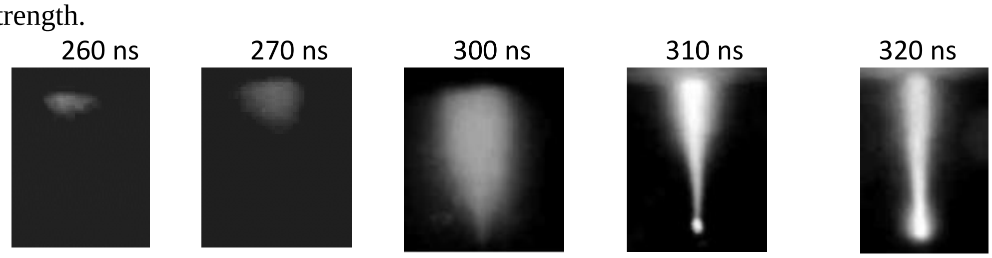


Fig.1. Photos of the glow at different times ((E / p = 10.53 V / cm · Torr)

REFERENCES

[1] *Kurbanismailov V.S., Omarov O.A., Ragimkhanov G.B.et al. //*Plasma physics reports. - 2016. - Vol. 42. - № 7. - P. 687-698.

[1]This work was supported by the Russian Foundation for Basic Research, project № 18-08-00075a.

SUBNANOSECOND BREAKDOWN OF A POINT-TO-PLANE GAP AT NEGATIVE AND POSITIVE POLARITIES[1]

D.V. BELOPLOTOV, D.E. GENIN*, D.V. SHTANGOVETS**, V.F. TARASENKO**

** Institute of High Current Electronics, 2/3 Akademicheskii Ave., Tomsk, 634055, Russia, rff.qep.bdim@gmail.com*
*** National Research Tomsk State University, 36 Lenin Ave., Tomsk, 634050, Russia*

In gas discharge physics it is known that the breakdown voltage of gaps with an asymmetric distribution of the electric field strength (e.g., point-to-plane gap) depends on the polarity of voltage pulses. In a quasistatic electric field the breakdown voltage with a negative pointed electrode is approximately twice as high as with a positive one [1]. This effect was called the "polarity effect". The reason for the polarity effect is the shielding of the negative pointed electrode by a cloud of immobile positive ions. In case of the positive pointed electrode, electric field strength is amplified by ions. Due to the development of pulse technology and the widespread use of nanosecond voltage pulsers, more attention was paid to high-voltage nanosecond discharges at high overvoltage. In such discharges, inversion of polarity effect was observed: the breakdown voltage with the negative pointed electrode was less than with the positive one [2–6]. However, at high pressure the ordinary polarity effect was observed [5]. In [5, 6], it was suggested that the inversion of the polarity effect is due to the large time of formation of explosion-emission centers on a flat cathode. Currently, there is no clear understanding of the causes of the inversion of the polarity effect. In this work results of experimental investigations of the influence of polarity on breakdown characteristics in different gases as well as with different cathodes with UV irradiation are presented.

REFERENCES

[1] *Yu.P. Raizer //* Gas discharge Physics. – Berlin, Germany: Springer-Verlag, 1991.
[2] *Yu.F. Potalitsyn // Pulse Discharges in Insulators, G. A. Mesyats, Ed.* Novosibirsk, Russia: Nauka Publishers. 1985. pp. 77–80.
[3] *L.P. Babich, and T.V. Loiko //* Proceedings of XX International Conference on Phenomena in Ionized Gases. Pisa, Italy. – 1991. – V. 2. – P. 46.
[4] *L.P. Babich //* High-Energy Phenomena in Electric Discharges in Dense Gases. – Arlington, TX, USA: Futurepast, 2003.
[5] *T. Shao, V.F. Tarasenko, Ch. Zhang, D.V. Beloplotov, W. Yang, M.I. Lomaev, Zh. Zhou, D.A. Sorokin, and P. Yan. //* Phys. Lett. A. – 2014. – V. 378. – P. 1828–1833.
[6] *D.V. Beloplotov, V.F. Tarasenko, M.I. Lomaev, D.A. Sorokin //* IEEE Trans. Plasma Sci. – 2015. – V. 43. – P. 3808–3814.

[1] This work was supported by RFBR according to the research project №18-32-00103

STREAMERS IN A GAP WITH AN INHOMOGENEOUS ELECTRIC FIELD STRENGTH DISTRIBUTION FILLED WITH ATMOSPHERIC PRESSURE AIR[1]

V.F. TARASENKO, G.V. NAIDIS**, D.V. BELOPLOTOV*, M.I. LOMAEV*, D.A. SOROKIN*, N.YU. BABAEVA***

** Institute of High Current Electronics, 2/3 Akademicheskii Ave., Tomsk, 634055, Russia, rff.qep.bdim@gmail.com*
***Joint Institute for High Temperatures, Izhorskaya 13, Moscow, 125412, Russia*

At present great attention has been given to the study of a nanosecond breakdown in an inhomogeneous electric field at high overvoltage [1–7]. The breakdown occurs due to formation and propagation of one or more streamers. [3–7]. The number of streamers depends on a kind of gas, pressure, an interelectrode distance, a shape of the pointed electrode, and an overvoltage level. Streamer velocity is of the order of 1 cm/ns [5, 6]. The formation of streamers with large transverse dimensions at high pressures in an inhomogeneous electric field was observed in a number of experimental studies [3–7]. The simulation also indicates the formation of streamers with large transverse dimensions [6, 8]. However, detailed studies of the dynamics of the formation of such streamers at high overvoltage were not carried out.

In this work the results of a detailed experimental study and simulation of the formation of single positive streamers with large transverse dimensions in air at atmospheric pressure in a point-to-plane gap at high overvoltages are presented. The dynamics of the streamer formation was studied with a four-channel ICCD camera. The data on streamer velocity, electric filed strength on the streamer front, radiation dynamics of the N_2 (C–B) band were obtained by the numerical simulation based on the standard model [8], including the two-dimensional balance equations for charged particles and the Poisson equation for the electric field.

It was established that a dynamic displacement current is registered during the streamer propagation. It is assumed that the value of the one depends on the streamer velocity. On this basis, the maximum streamer velocity is reached at the initial and final stages. The average streamer velocity is ≈0,8 cm/ns. The transverse dimension of the streamer is comparable with the interelectrode distance. Results of the simulation have been shown that a streamer velocity depends on a radius of curvature *R* of the pointed electrode. The smaller *R*, the slower streamer. The streamer velocity depends on its length. The streamer velocity rapidly increases near the pointed electrode, decreases in the middle of the gap, and again increases as it approaches the flat electrode. The maximum electric field strength at the streamer front was observed at the initial and final stages of the streamer propagation. The calculated two-dimensional radiation profiles qualitatively coincide with the images taken with the ICCD camera.

REFERENCES

[1] *S. Yatom, V. Vekselman, J.Z. Gleizer, Ya.E. and Krasik //* J. Appl. Phys. – 2011. – V. 109 – P. 073312.
[2] *V.F. Tarasenko (ed.) //* Runaway Electrons Preionized Diffuse Discharges. – New York: Nova Science Publishers, Inc., 2014.
[3] *A.Yu. Starikovskii //* IEEE Trans. Plasma Sci. – 2011. – V. 39. – № 11. – P. 2602–2603.
[4] *P. Tardiveau, L. Magne, E. Marode, K. Ouaras, P. Jeanney, and B. Bournonville //* Plasma Sources Sci. Technol. – 2016. – V. 25. – № 5. – P. 054005.
[5] *D.V. Beloplotov, M.I. Lomaev, D.A. Sorokin, and V.F. Tarasenko //* Russ. Phys. J. – 2017. – V. 60. – № 8. – P. 40–45.
[6] *G.V. Naidis, V.F. Tarasenko, N.Y. Babaeva, and M.I. Lomaev //* Plasma Sources Sci. Technol. – 2018. – V. 27. – P. 013001.
[7] *D.V. Beloplotov, V.F. Tarasenko, D.A. Sorokin, and M.I. Lomaev //* JETP Letters. – 2017. – V. 103. – № 10. – P. 653–658.
[8] *G.V. Naidis, and N.Y. Babaeva //* IEEE Trans. Plasma Sci. – 2016. – V. 44. – № 6. – P. 899–902.

[1] This work was supported by the Russian Science Foundation, project no. 17-72-20072.

EXCITATION OF DIAMONDS BY A SUBNANOSECOND RUNAWAY ELECTRON BEAM WITH AN ELECTRON ENERGY OF UP TO 200 KEV GENERATED IN A NANOSECOND GAS DISCHARGE[1]

D.V. BELOPLOTOV, M.I. LOMAEV, V.F. TARASENKO, E.KH. BAKSHT, A.G. BURACHENKO, M.V. EROFEEV, E.I. LIPATOV

Institute of High Current Electronics, 2/3 Akademicheskii Ave., Tomsk, 634055, Russia
E-mail: rff.qep.bdim@gmail.com

As is known runaway electrons (REs) are generated in nanosecond gas discharges [1–3] as well as in tokamak-type setups during the current decay phase of disruptions [4, 5]. REs generated in a pre-breakdnown stage of nanosecond gas discharges play a fundamental role in their formation. REs provide a pre-ionization of a gas ahead a streamer front. It allows to form a diffuse discharge in different gases at atmospheric pressure and above [3]. Such discharges are sources of low-temperature non-equilibrium plasma which is applied in various fields (water treatment, surface treatment, plasma assisted combustion, flow control, radiation sources etc.) [6–9]. However, REs generated in tokamak-type setups have a negative effect. High-current RE beams melt and destroy walls of a vacuum vessel [5]. Electron energy range is wide. There are electrons with an energy of 10–100 keV to 1–10 MeV. Registration of such electrons is an actual task. Nowadays X-ray diagnostics are applied. However, there is a need for direct electron detection. This will allow a more complete study of the mechanism of their generation.

Different types of devices are developed to detect high-energy charged particles. Cherenkov detectors based on a diamond is the most widely used ones. Cherenkov radiation (CR) can be emitted by a transparent medium when electrons move in the one with velocity higher than the phase velocity of light. Intensity of the CR increases with a decrease in wavelength. There is a threshold electron energy for generation of the CR, which for a diamond is ≈50 keV. However, cathodoluminescence can be observed in a diamond under the action of high-energy electrons. This report presents the results of an experimental study of the spectral and amplitude-temporal characteristics of radiation of diamonds excited by a subnanosecond runaway electron beam with an electron energy of up to 200 keV generated in a nanosecond gas discharge. Experimental data were compared with the theoretical estimates of the CR spectrum. The results show that cathodoluminescence bands dominate in radiation spectrum of diamonds; the CR is no more than 10 percent of the total radiation energy [10]. The wavelength range of 225–350 nm can be used to register of the CR in IIa-type synthetic diamond excited by a RE beam with an electron energy of up to 200 keV.

REFERENCES

[1] *Yu.D. Korolev and G.A. Mesyats* // Physics of Pulsed Breakdown in Gases. – URO Press, Yekaterinburg, 1998.

[2] L.P. Babich // High-Energy Phenomena in Electric Discharges in Dense Gases. – Arlington, TX, USA: Futurepast, 2003.

[3] *V.F. Tarasenko (ed.)* // Runaway Electrons Preionized Diffuse Discharges. – New York: Nova Science Publishers, Inc., 2014.

[4] *P.V. Savrukhin and E.A. Shestakov* // Nuclear Fusion. – 2015. – V. 55. – №. 4 – P. 043016.

[5] *V.P. Budaev et al.* // Nuclear Materials and Energy. – 2017. – V. 12. – P. 418–422.

[6] *P.J. Bruggeman et al.* // Plasma Sources Sci. Technol. – 2016. – V. 25. – №. 5. – P. 053002.

[7] *I.V. Adamovich, I. Choi, N. Jiang, J.-H. Kim, S. Keshav, W.R. Lempert, E. Mintusov, M. Nishihara, M. Samimy and M. Uddi* // Plasma Sources Sci. Technol. – 2016. – V. 18. – №. 3. – P. 034018.

[8] *A.N. Panchenko, and N.A. Panchenko* // Atmospheric and Ocean Optics. – 2016. – V. 29. – №. 4. – P. 390–394.

[9] *M.A. Shulepov, M.V. Erofeev, V.S. Ripenko, and V.F. Tarasenko* // Journal of Physics: Conference Series. – 2017. – V. 830. – №. 1. – P. 012090.

[10] *D.A. Sorokin, A.G. Burachenko, D.V. Beloplotov, V.F. Tarasenko, E.Kh. Baksht, E.I. Lipatov, and M.I. Lomaev* // J. Appl. Phys. – 2017. – V. 122. – №. 9. – P. 093304.

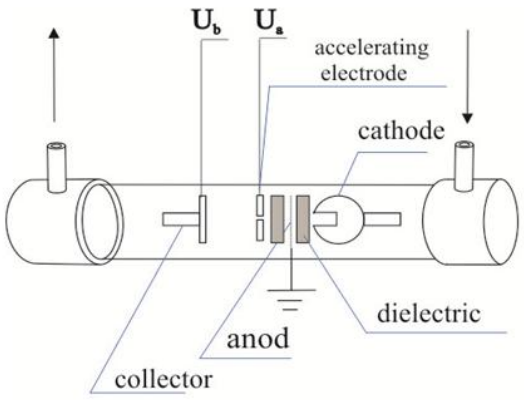
[1] This work was supported by the grant from the Russian Science Foundation, project # 18-19-00184

LOW-ENERGY IONS SOURCE OF PLANE GEOMETRY ON THE BASIS OF PLASMA-BEAM DISCHARGE WITH A SLOT CATHODE

N.A.ASHURBEKOV , K.O. IMINOV, G.SH SHAKHSINOV, A.R. RAMAZANOV

Dagestan State University, 43a M.Gajiev Str., Makhachkala, 367000, Russian Federation, nashurb@mail.ru, +78722675817

A pulsed nanosecond discharge with a slot cathode occupies a special place among all other types of gas discharges due to its unique properties. One of such properties is the possibility of band-shaped electron beams generation in the region of increased pressures in the forevacuum range [1]. In this paper, we present the results of experimental studies of the process of "plasma sheet" creating based on a ribbon electron beam formed in a nanosecond discharge with a slot cathode. A block diagram of the electrode system for plasma sheet formation and the corresponding optical picture obtained in neon are given in Fig. 1. The slot cathode and the flat anode are made of aluminum and placed at a distance of 0.5 cm from each other. An emission window of 0.5 cm × 5 cm closed off with a fine-grained tungsten grid is made in the anode. The magnitude of the accelerating voltage varied within the range of 1-1.5 kV at gas (neon) pressures in the chamber of less than 0.5 Torr. The ribbon electron beam formed in such a system is transported and received at a collector placed at a distance of 3 cm from the locking anode. Concurrently, a plasma sheet with an area of 5 cm × 3 cm and a thickness of about 0.5 cm is formed (Fig. 1b).



a)

b)

Fig. 1. Diagram of the electrode system (a) and the optical picture (b) of the plasma sheet.

Experimental studies of the conditions for the plasma sheet formation were performed depending on the gas pressure, the amplitude of the accelerating voltage pulses at the anode and the voltage at the collector. To study the degree of homogeneity of the plasma sheet, optical radiation was taken from the slot in the cathode, at the exit from the accelerating anode and from the center of the plasma sheet by applying diaphragms and photomultipliers. The duration of the radiation pulses at half-maximum in these regions was approximately 90 ns, 75 ns, and 70 ns, respectively. An estimate of the range of electrons accelerated in the cathode layer for these conditions gives a value of the order of 10 cm, hence, the area of the plasma sheet can be increased.

The possibility of using the resulting plasma sheet as a source of low-energy ions with an energy of about 1 eV emitted from the plasma sheet in the transverse direction is analyzed.

REFERENCES

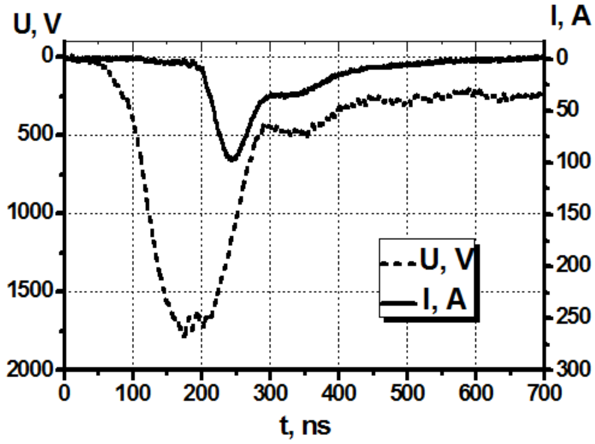
[1] *Ashurbekov N.A., Iminov K.O., Kobzev O. V., Kobzeva V.S. // Technical Physics. – 2010. – 55 – 8 . 1138.*

THE IMPACT OF THE DIELECTRIC BOUNDARY ON THE SPATIAL STRUCTURE AND PROPERTIES OF A NANOSECOND DISCHARGE WITH AN EXTENDED SLOT CATHODE

N. A. ASHURBEKOV, K. O. IMINOV, G.SH. SHAKHSINOV, A. R. RAMAZANOV

Dagestan State University, 43a M. Gajiev St., Makhachkala 367002, Russia, nashurb@mail.ru, +78722675817

The paper presents the results of an experimental study of the spatial structure and electrical characteristics of a nanosecond discharge with an extended slot cathode in helium [1]. General regularities in the formation of the spatial structure of the discharge when it is limited by dielectric walls installed along the electrodes are determined. Under the conditions of this work, the discharge area occupies a limited space 1.2 cm long, 0.2 cm thick and 40 cm wide (including the cavity inside the cathode). The limitation of the discharge in helium by dielectric walls leads to an increase in the amplitude of the pulses of the combustion voltage, the discharge current, with a simultaneous sharpening of these pulses front (Fig. 1). In addition, the redistribution of the intensity of the optical radiation inside the gap in the cathode and in the area between the cathode and the anode occurs in a limited discharge; and in a certain range of E/p values, the discharge column is focused along the center between the dielectric walls of the limiter (Fig. 1).



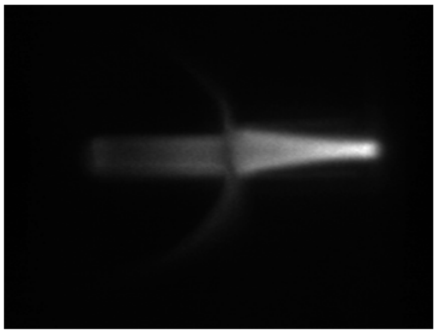


Fig.1. The oscillograms and the optical picture of a limited discharge

It is shown that the change in the spatial structure of the discharge with the localization of the discharge column at the center of the gap and the focusing on the anode surface, as well as the redistribution of optical radiation when the discharge is limited, is associated with a change in the distribution of the electric field and the concentration of charged particles in the gap due to the impact of the charge deposited on the surface of the dielectric limiter.

Estimates of the magnitude of the surface charge on the dielectric wall of the discharge chamber and its impact on the spatial distribution of the electric potential between the electrodes are made.

REFERENCES

[1] *Ashurbekov N A, Iminov K O, Popov O A, and Shakhsinov G S // Plasma Science & Technology. – 2017. – 19. – 3. 035401.*

SPECTRAL INSTRUMENTS FOR X-RAY AND VUV PLASMA DIAGNOSTICS

A.P. SHEVELKO

P.N. Lebedev Physical Institute of the RAS, Leninsky Pr. 53, Moscow, 119991, Russia,
Email: apshev51@gmail.com, phone +7 499 1326951

X-ray and VUV spectroscopy methods are the most informative diagnostic tools for investigation of high temperature plasmas. These methods allow determining of electron temperature and density, ionization stages and charge distribution, and other plasma parameters. Investigation of these plasma parameters needs developing of special schemes of spectrometers. For these purposes a set of spectral instruments are developed for x-ray and VUV spectroscopy of plasma sources in a spectral range of λ=0.1 ÷ 100 nm:
1) High efficiency very compact focusing crystal spectrometer (XRS-1), based on von Hamos scheme [1, 2];
2) Various modifications of compact off-Rowland grazing incidence diffraction spectrometers (GIS-1S, GIS-2S, GIS-3S);
3) Grazing incidence diffraction EUV spectrometer - monochromator (GISM) with a constant angle of deviation.

The spectrometers are equipped by various type of CCD detectors based on CCD linear arrays, fiber optical plates and phosphor layers. The use of other types of detectors (micro channel plates, photographic films, PIN diodes, streak cameras) is also possible due to the flat field plane of registration. Other perspective models of spectrometers are also considered. They include hard x-ray focusing crystal spectrometer for high repetition rate radiation sources (DuMond scheme), extra compact x-ray and EUV focusing crystal spectrometer (mica crystal and multilayer structures as dispersive elements, conical crystal), compact x-ray focusing crystal spectrometer (Johann scheme).

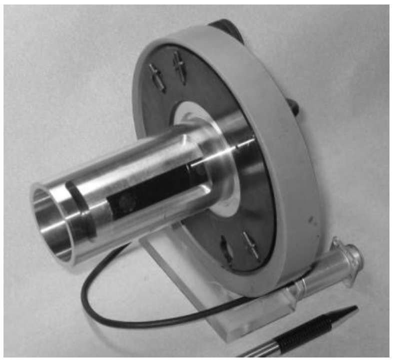


Fig. 1. XRS-1 (on the left) and GISM (on the right) spectrometers.

The unique features of these instruments are a capability of their absolutely calibration for metrology applications. Special original methods of the calibration are developed in x-ray spectral range [3]. Using x-ray spectroscopy methods these spectrometers could diagnose plasmas in a wide electron temperature range (T_e ~ 30 eV ÷ 1.5 keV). For this matter it is necessary to mention a new x-ray spectroscopy method of electron temperature measurements in plasmas of heavy elements [4]. The spectrometers are widely used for diagnostics and absolutely intensity measurements of various plasma sources: laser-produced plasmas including nano- and femto- second laser-produced plasmas, z-pinch plasmas including high power Z-pinch plasmas, capillary discharge plasmas, EUV sources intended for nanolithography.

REFERENCES

[1] *A. P. Shevelko* // Proc. SPIE -1998.-3406. -91-108.
[2] *A. P. Shevelko, Yu. S. Kasyanov, O. F. Yakushev, and L. V. Knight* // Rev. Sci. Instrum. -2002. -73. -3458-3463.
[3] *A.P. Shevelko* // Quantum Electronics. -2016. -46. -845-847.
[4] *A.P. Shevelko* // Quantum Electronics. -2011. -41. -726-728.

EFFECT OF THE PLASMA CHANNEL VELOCITY ON THE DIODE PARAMETERS DURING BREAKDOWN IN A HIGHLY INHOMOGENEOUS ELECTRIC FIELD [1]

S.YA. BELOMYTTSEV, A.A. GRISHKOV*, V.A. SHKLYAEV*,**, V.V. RYZHOV*,***

**Laboratory of Theoretical Physics, Institute of High Current Electronics, Russian Academy of Sciences, 2/3 Akademichesky Ave., 634055, Tomsk, Russia*
***Institute of High Technology Physics, National Research Tomsk Polytechnic University, 30 Lenin Avenue, 634050 Tomsk, Russia*

Here, continuing our research in the breakdown of a gas diode with a highly inhomogeneous electric field, we present an analytical model which relates the diode current and voltage to the plasma channel velocity from cathode to anode in an axisymmetric statement. It is shown that the voltages cross- and lengthwise the diode can differ greatly and that the difference increases as the channel moves faster. This effect should be taken into account when analyzing subnanosecond pulsed breakdowns in a highly inhomogeneous electric, otherwise a large discrepancy is possible between measured and actual diode voltage. The analytical model is based on charge conservation laws and Lorentz transforms for electric field strengths and coordinates and is verified using the KARAT particle-in-cell (PIC) and xoopic particle-in-cell/Monte Carlo (PIC/MC) codes. The simulation results agree well with the analytical model developed.

It is shown that the voltages cross- and lengthwise the diode, $U_\perp$ and $U_\parallel$, can differ greatly and that the difference increases as the channel moves faster:

$$U_\perp = \frac{2U_0}{1+\frac{v}{c}}, \quad (1)$$

$$U_\parallel = 2U_0\left(1-\frac{v}{c}\right), \quad (2)$$

$$I = \frac{2I_0}{1+\frac{c}{v}}. \quad (3)$$

Figure 1 shows the transverse voltage $U_\perp$, longitudinal voltage $U_\parallel$ and current I plotted as a function of plasma channel velocity from (1), (2) and (3), respectively. It is seen from the figure that for the channel velocity $v = 0$, the voltage in the line is equal to the voltage along the z axis $U_\perp = U_\parallel = 2U_0$ and the current in the line is $I = 0$, which corresponds to idle mode. For the channel velocity close to the velocity of light $v = c$, we have a matched load with voltage and current in the line equal to those in the incident wave: $U_\perp = U_0$ and $I = I_0$, which means the absence of electromagnetic wave reflection from the channel front. In this case, $U_\parallel = 0$ because the electromagnetic wave moves no faster than the plasma channel.

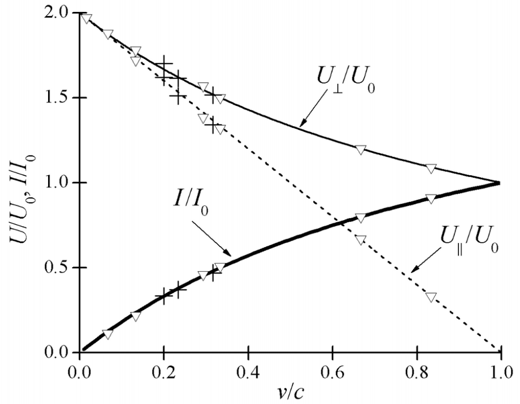


Fig. 1. Transverse and longitudinal diode voltage and diode current as a function of plasma channel velocity according to analytical model (lines), simulation results by PIC codes KARAT (∇) and xoopic (+).

[1] The results were obtained within the RSF grant (project No. 17-72-20072).

LUMINESCENCE OF CRYSTALS EXCITED BY A RUNAWAY ELECTRON BEAM AND BY KRCL EXCILAMP[1]

V.F. TARASENKO, D.V. BELOPLOTOV, A.G. BURACHENKO, E.KH. BAKSHT, D.A. SOROKIN, E.I. LIPATOV, M.I. LOMAEV

Institute of High Current Electronics SB RAS, Tomsk, 634055, Russia
E-mail: VFT@loi.hcei.tsc.ru, phone: +7 (3822) 491-685

Runaway electrons (RAEs) can adversely affect plasma heating in controlled thermonuclear research systems. Although this fact is well-known from theory. Recent research on tokamaks has focused much attention on RAEs as fast electrons add to the loss of energy and to the evaporation of vacuum chamber walls. Different types of devices are developed to detect high-energy electrons, and most widely used in tokamaks are Cherenkov-type detectors.

However some papers report, that in natural and synthetic diamonds, as well as in other crystals, the radiation at 200–800 nm excited by a pulsed electron beam of energy from several tens to several hundreds of kiloelectronvolts is mainly due to cathodoluminescence. In particular, this is observed for a subnanosecond electron beam known as a supershort avalanche electron beam (SAEB). Note that in SAEB excited polymethyl methacrylate Cherenkov radiation escapes detection [1].

The paper presents research data on cathodoluminescence, photoluminescence, and Cherenkov radiation at 200–800 nm excited in crystals with different refractive indices by a subnanosecond runaway electron beam and by KrCl excilamp radiation with a peak wavelength of 222 nm [2]. The data include spectral and amplitude-time characteristics measured with a resolution of up to ~100 ps for natural and synthetic diamonds of type IIa, sapphire, CsI, ZnS, CaF_2, ZrO_2, Ga_2O_3, $CaCO_3$, CdS, and ZnSe. Figure 1 shows the spectral energy density ρ(λ) as a function of wavelength for natural (*1*) and synthetic diamonds (*2*) excited by a SAEB.

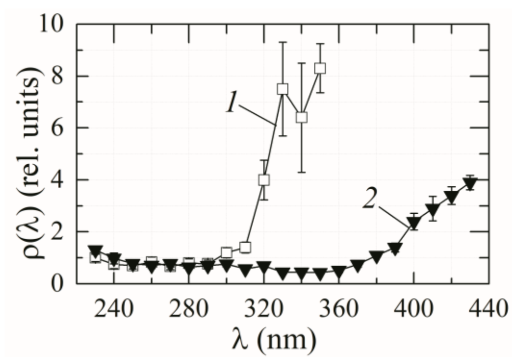


Fig. 1. Spectral energy density ρ(λ) vs wavelength for natural (*1*) and synthetic diamonds (*2*) excited by SAEB in mode #2, measured with MDR-23 monochromator and photomultiplier.

The dependencies take into account the sensitivity of the photomultiplier and the spectral transmission of the measuring optical elements. It is seen that for natural diamond at 230–310 nm and for synthetic diamond at 230–350 nm, ρ(λ) increases with decreasing λ. Our research shows that cathodoluminescence can greatly exceed Cherenkov radiation over a wide spectral range. The estimation suggests that the Cherenkov radiation energy in the emission spectrum 200–500 nm is ~0.1 % for natural and ~10 % for synthetic diamond.

The research suggests that cathodo- and photoluminescence should be accounted for in Cherenkov-type detectors of runaway electrons. The results can be useful for detecting high-energy electrons in tokamaks.

REFERENCES

[1] *Tarasenko V.F., Baksht E.Kh., Burachenko A.G., Beloplotov D.V. & Kozyrev A.V.* // IEEE Trans. Plasma Sci. – 2017. – V. 45. – P. 76 –84.

[2] *Sorokin D.A., Burachenko A.G., Beloplotov D.V., Tarasenko V.F., Baksht E.Kh., Lipatov E.I. & Lomaev M.I.* // Journal of Applied Physics. – 2017. – V. 122. – P. 154902.

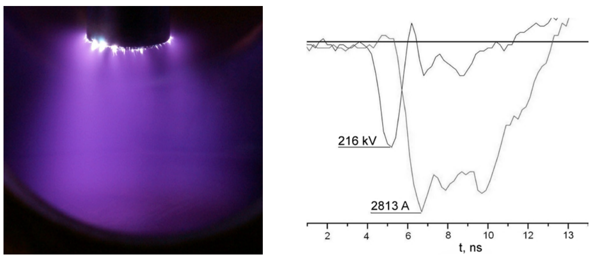
[1] Russian Science Foundation supported this work according to the research project No. 18-19-00184.

THE FORMATION OF THE DIFFUSE PLASMA OF A DISCHARGE IN AIR, NITROGEN AND ARGON AT ATMOSPHERIC PRESSURE ABOVE THE SURFACE OF LIQUID H_2O AND A CHANGE IN THE STRUCTURE OF H_2O UPON DISCHARGE PLASMA EFFECT[1]

D.A. SOROKIN, V.M. ORLOVSKII*, V.A. PANARIN*,*

**Institute of High Current Electronics, 2/3 Akademichesky Ave., Tomsk, 634055, Russia, SDmA-70@loi.hcei.tsc.ru*

Results of study of the dynamics of formation of a pulse discharge in nitrogen, argon and air initiated by a short-duration voltage pulse (rise time is less than 1 ns) and a discharge with an admixture of drinking water vapor in the gap are presented. It is shown that the diffuse discharge is formed due to avalanche multiplication of charges because of action of fast electrons and then supported by secondary breakdowns through ionized gas channels [1]. When placing heavy and drinking water on the anode, the discharge in the gap filled with air burns in the form of diffuse jets of conical shape starting with bright spots on the potential cathode. The discharge current at the initial stage has the same dynamics as the discharge in the air, but does not have a pronounced first peak (Fig. 1).



(a) (b)

Fig. 1. Integral image of the plasma glow at a discharge in atmospheric-pressure air (a) and waveforms of the voltage across the gap and discharge current (b).

Changes in the structure of H_2O when processing with atmospheric-pressure diffuse plasma formed in air, argon and nitrogen above the surface of liquid H_2O were obtained in the study of IR absorption spectra of liquid with a spectrometer FT-801. Analysis of absorption spectra in the IR range showed differences between the absorption spectra of irradiated and non-irradiated drinking water (Fig. 2.). Changes in the absorption spectrum of drinking water consisted in the fact that the band of valence oscillations of OH-groups expanded without pronounced maximums for the investigated liquid. It is assumed that these changes are due to the water clustering. Whereas the formation of water associates, the ordering of the three-dimensional volume grid of hydrogen bonds is due to the predominant formation of strong hydrogen bonds. Thus, the diffuse discharge plasma can be used to modify water and aqueous solutions.

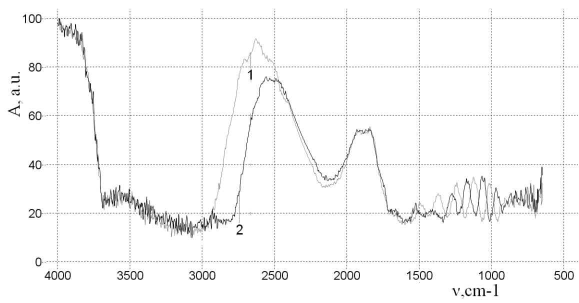


Fig. 2. Transmission spectrum of drinking water (1) and one after 1200 discharge realizations.

REFERENCES

[1] *Orlovskii V.M., Panarin V.A., Shulepov M.A. // Tech. Phys. Lett. – 2014. – 40 – № 7. 645-648.*

[1] This work was performed in the framework of the State task for IHCE SB RAS, project #9.5.2

BREAKDOWN PHASE IN STRONGLY OVERVOLTAGED GAPS FILLED WITH HIGH-PRESSURE GASES[1]

D.A. SOROKIN*, D.V. BELOPLOTOV*, V.A. SHKLAYEV*, A.A. GRISHKOV*, V.F. TARASENKO*, M.I. LOMAEV*,**

*Institute of High Current Electronics, 2/3 Akademichesky Ave., Tomsk, 634055, Russia, SDmA-70@loi.hcei.tsc.ru
**National Reasearch Tomsk State University, 36 Lenina Ave., Tomsk, 634050, Russia

The research of the breakdown phase of a gas-filled “tip-plane” gap fed by high-voltage pulses of positive and negative polarity with a rise time of several nanosecond and less were performed. In the experiments high-voltage discharge was ignited in diodes filled with air, nitrogen, methane, hydrogen, argon, neon, and helium at different pressures. There are several papers reporting about registration of streamers having ball-like form during the breakdown of air and nitrogen at reduced electric field strength E/p of ≈ 100 kV/cm·Torr [1, 2]. Nevertheless, the mechanism of formation of such streamers has not yet been established. Using optical methods (high-speed framing and electron optical chronography) and high-resolution experimental devices (four-channel ICCD camera and ultrafast steak camera equipped with monochromator), the phases of formation and propagation of streamer in the gap were investigated. An experimental setup is presented in Fig. 1.

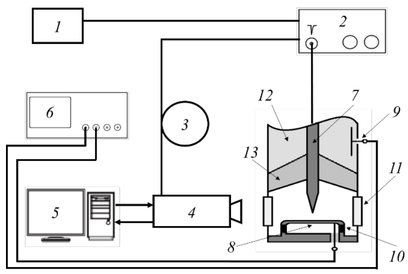


Fig. 1. Block diagram of the experimental setup. *1* – triggering generator; *2* – voltage pulse generator; *3* – delay line or generator; *4* – four-channel ICCD camera or streak camera; *5* – PC; *6* – oscilloscope; *7* – high-voltage electrode with a small radius curvature; *8* – flat grounded anode; *9* – capacitive voltage divider; *10* – current view resistor; *11* – side quartz windows; *12* – transformer oil; *13* – insulator.

By registering the dynamics of plasma glow, it was established that at both polarities of a voltage pulse in a wide range of pressures of the mentioned above gases a big size streamer is formed (Fig. 2ab). It was established that at a voltage rise rate of ~ 10^{13} V/s the streamer propagation speed is several centimeters per nanosecond and more. After the streamer reaches a flat grounded electrode, a diffuse discharge is realized in the gap. When the voltage pulse polarity is negative, a supershort avalanche electron beam is registered with collector behind the anode foil. Based on observed dynamics of the streamer formation and propagation, a mechanism of its development was suggested. For a number of conditions the numerical simulations of the dynamics of plasma glow were preformed. The results of the simulations are in good agreement with experimental data (Fig.2cd). In addition, it has been shown that first, the glow arises at some distance from the potential electrode with a small radius of curvature (Fig. 2c). This distance is reduced with increasing the gas pressure.

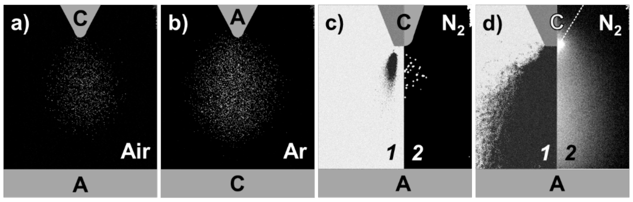


Fig. 2. Images of the plasma glow at pre-breakdown stage in air (a) and argon at atmospheric pressure and negative and positive polarity, respectively. Images of plasma glow obtained in the simulation (c, d; part *1*) and experiment (c, d; part *2*) for breakdown phase in nitrogen at pressure of 100 Torr. d) is corresponding to the moment after bridging of the gap by a streamer.

REFERENCES

[1] *A.Yu. Starikovskiy* // IEEE Trans. Plasma Sci. – 2011. – 39. – 2602.
[2] *P. Tardiveau, L. Magne, E. Marode, K. Ouaras, P. Jeanney, and B. Bournonville // Plasma Sources Sci. Tech. – 2016. – 22. – 054005.*

[1] This work was supported by the Russian Science Foundation (the project No. 17-72-20072).

THEORETICAL MODELLING OF FAST ATMOSPHERIC PRESSURE DISCHARGE IN GAS DIODE WITH PLANE-GRID CATHODE SYSTEM

A.O.KOKOVIN*, V. KOZHEVNIKOV**, A. KOZYREV*, N. SEMENIUK**, V. GOLIAK*

*Tomsk State University, 36 Lenin Ave., Tomsk, 634050, Russia
alexander.kokovin.desch@gmail.com, +7(913)113-29-78
**Institute of High Current Electronics, 2/3 Akademichesky ave., Tomsk, 634055, Russian Federation,

In this paper we numerically investigate nonstationary nanosecond gas discharge in the two-dimensional semi-periodic computational geometry of the gas diode with a plane-grid cathode system. Previously this configuration was studied experimentally as a source of intensive runaway electron beam.

The gas diode configuration we simulate is depicted in Fig. 1a. It consists of two parallel plane electrodes – cathode and anode, and cathode grid of parallel wires of the radius r = 0.1 mm arranged in parallel to plane electrodes. The anode is at the high-voltage potential supplied by the nanosecond power source with a simple 100 Ω ballast load, so the maximum of applied voltage is ten or more times greater than the static breakdown threshold. We use the diode configuration parameters from [1] where l = 3 mm, d = 4 mm, D = 4 mm (cathode grid period). The trapezium voltage pulse amplitude is U_0 = 140 kV, its pulse duration is about 1 ns and both edges are equal to 0.3 ns.

For the simplicity reasons the real diode (Fig. 1a) in our model is substituted by the two-dimensional semi-periodic in x-axis structure (Fig. 1b), since radial size of the diode is much larger than the wire grid period D of the cathode system. The semi-periodicity of the structure makes it possible to impose periodic boundary conditions along x-axis 1-4 and 2-3 boundaries, thereby reducing the computations only to the 1-2-3-4 area. The proposed simplification is approved by the specific experimental measurement conditions in [1], where the adjustable 3 mm diaphragm is placed between anode and current collector.

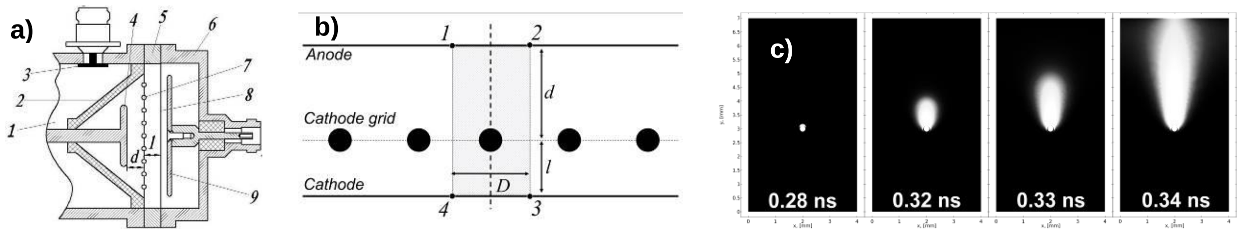


Fig. 1. The experimental (a) configuration of the gas diode: (1) high-voltage coaxial transmission line, (2) insulator, (3) capacitive divider for voltage pulse measurement, (4) anode, (5) steel ring, (6) collector chamber wall, (7) parallel wire grid array, (8) foil cathode, (9) runaway electrons current collector; (b) two-dimensional semi-periodic computational geometry: plane electrodes parallel to x-axis, the 1-2-3-4 area represents the simulation domain, where the periodic boundary conditions are applied at 1-4 and 2-3 sides to simulate infinite periodic structure in longitudinal direction; (c) plasma density profiles of the discharge propagation.

The discharge simulations are based on two-dimensional drift-diffusion macroscopic model including a number of electron and ion continuity equations coupled to Poisson's equation accounting the electrostatic field self-consistently [2]. We compute nitrogen plasma species reaction rates using BOLSIG+ code with the IST-LISBON cross-sections database. In addition, the discharge model consists the accounting of gas photoionization implemented in the way it proposed in [3]. We also include the autoelectron (field) emission [4] as an additional source of seed electrons from cathode in the model.

The obtained system of equations is solved numerically using COMSOL Multiphysics 5.2a finite element software. Nearly 52000 linear finite elements were employed and the number of degrees of freedom (DOF) was about 186 thousands. The discharge development is given in the sequence of still images at Fig. 1c.

REFERENCES

[1] *V.F. Tarasenko, I.D. Kostyrya, and D.V. Beloplotov //* Laser and Particle Beams. – 2015. – vol. 34. – no. 01. pp. 23–30.
[2] *E. Gogolides, H.H. Sawin //* Journal of Applied Physics. – 1992. – vol. 72. – no. 9. pp. 3971–3987.
[3] *A. Bourdon, V.P. Pasko, N.Y. Liu, S. Célestin, P. Ségur, E. Marode //* Plasma Sources Science and Technology. – 2007. – vol. 16. – no. 3. pp. 656–678.
[4] *R.H. Fowler, L. Nordheim //* Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences. – 1928. – vol. 119. – no. 781. pp. 173–181.

FORMATION OF 1.4-MEV RUNAWAY ELECTRONS FLOW IN AIR [1]

A.G. SADYKOVA, M.S. PEDOS*, S.N. RUKIN*, V. V. ROSTOV**, I.V. ROMANCHENKO**, A.F. SADYKOV***,*

K. A. SHARYPOV, V.G. SHPAK*, S. A. SHUNAILOV*, M. R. UL'MASCULOV*, M.I. YALANDIN*,*

** Institute of Electrophysics UD RAS, 106 Amundsen Street, Ekaterinburg, 620016, Russia, anuta@iep.uran.ru, +7(343)267-88-24*
***Institute of High Current Electronics SD RAS, Tomsk, 634055, Russia*
**** M.N. Mikheev Institute of Metal Physics UD RAS, 18 S. Kovalevskaya Street, Ekaterinburg, 620108, Russia*

Fulfillment the condition when the voltage rise time across air gap is comparable with the time of electron acceleration from the cathode to anode permits formation the flow of runaway electrons (RE) with a relativistic energy approaching to that determined by the amplitude of the voltage pulse. In the experiment, an all-solid-state pulsed power source providing the pulse compression and sharpening in a train of serially connected gyromagnetic nonlinear transmission lines (NLTL), was applied [1,2]. As a result, RE energy of at least 1.4 MeV was achieved with the use of minus 860-kV travelling voltage pulse. The pulse amplitude was doubled at the cathode of 2-cm-long air gap in an open end regime due to delay of conventional pulsed breakdown. Above mentioned record-breaking voltage pulse compressed and sharpened by cascade of NLTLs possesses unique characteristics. Within (0.1-0.9) pulse front levels, mean rate of the voltage rise and the rise time were ~7 MV/ns and 100 ps, respectively. Maximum rate of the voltage rise reaches 10 MV/ns. The width of the pulse was as shot as 120 ps (FWHM) and the peak power exceeds 15 GW across a 44-Ohm output terminal.

This is important, that listed parameters are record-breaking to-date for a gigawatt-range pulsed power machines in whole, and rather reproducible due to application of an all-solid-state switching/sharpening devices throughout entire power modulator. The achieved energy evidences that dynamic electric field was sufficient for all free secondary electrons derived in the gap by the primary RE come to runaway regime.

The authors note a contribution of Ural Federal University's electrophysics department to the possibility of performing test measurements using the Tektronix DPO73304D wideband oscilloscope.

REFERENCES

[1] *A. I. Gusev, M. S. Pedos, S. N. Rukin, S. P. Timoshenkov, S. N. Tsyranov //* Rev. Sci. Instrum. – 2017. – 88. – № 11. 114704.
[2] *M. R. Ulmaskulov, G. A. Mesyats, A. G. Sadykova, K. A. Sharypov, V. G. Shpak, S. A. Shunailov, and M. I. Yalandin //* Rev. Sci. Instrum. – 2017. – 88. – № 4. 045106.

[1] This work was supported by the IEP UB RAS budget subsidy (0389-2015-0026; P10), and, in part, by Russian Foundation for Basic Researches (grant No. 17-08-00608).

THE SPATIAL-TEMPORAL DIAGNOSIS OF 3-D MULTIPLE PULSED PLASMA JETS[1]

R. WANG, H. XU, Y. ZHAO, C. ZHANG, T. SHAO

Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing 100190, China
E-mail: st@mail.iee.ac.cn, phone: +86010-82547114

Pulsed plasma jet with advantages of low temperature, great flexibility and abundant reactive species, has been widely used in surface modification. In this work, six individual plasma jets are oriented in a circle and focused into one-spot. This structure is ideal for cylindrical subject treatment. The influence of pulse rise time on 3-D plasma jet array behavior is investigated. The interaction between plasma plume and subject is studied by monitoring the electrical characteristics, optical emission and plasma bullet evolution. It is found that, a short pulse rise time results higher discharge current and a faster luminous front travelling speed. There is obvious rejection between individual plasma jets when operate without any subject, but they will eventually focus in the central spot(figure1). However, by adding an insulating or metal subject, there is no sign of rejection. Besides, the metal subject can enhance the intensity and travelling speed of ionization front. Plasma bullet reflection effect is observed when touching with the metal surface. More details will be shown and discussed in the paper.

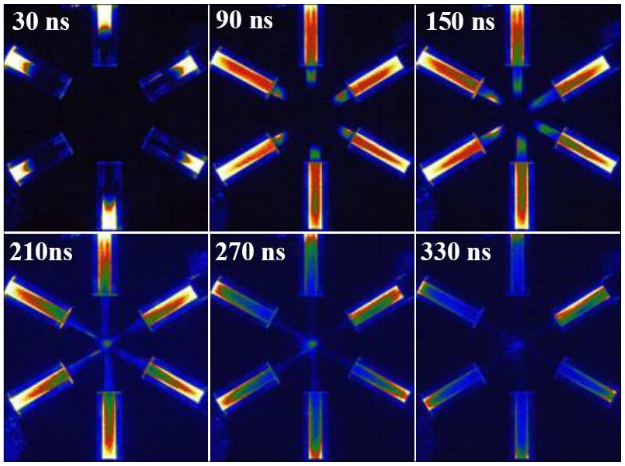


Fig. 1. Spatial-temporal evolution of 3-D pulsed plasma jets

[1] This work is supported by National Natural Science Foundation of China(51507169,11611530681, National Basic Research Program of China (973 Program)(2014CB239505-3)

STUDY ON CHARACTERISTICS OF MULTI-NEEDLE-TO-PLATE NANOSECOND-PULSE DIFFUSE DISCHARGE AT ATMOSPHERIC PRESSURE [1]

C. ZAHGN,***, Z. LI*,**, J. QIU*,***, X. CHEN*,***, P. YAN*,***, T. SHAO*,****

** Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing 100190, China*
E-mail: st@mail.iee.ac.cn, phone: +86-10-82547114
*** Industrial Technology Research Institute, Zhengzhou University, Zhengzhou 450001, China*
**** University of Chinese Academy of Sciences, Beijing 100084, China*

The nanosecond-pulse generator can realize a large area of diffuse discharge at atmospheric pressure in a multi-needle-plate electrode[1, 2]. Investigation on characteristics of nanosecond-pulse diffuse discharge at atmospheric pressure is essential for development of non-equilibrium plasma applications.

In this paper, a large-area diffuse discharge with a multi-needle-to-plate gap is generated by a nanosecond-pulse generator in a multi-needle-plate electrode structure in atmospheric air. The nanosecond pulses have a rise time of 100 ns and a full maximum at half maximum of 150 ns. Pulse repetition frequency (PRF) ranges from 100 to 1500 Hz. Transition process of the diffuse discharge is investigated by recording the voltage and current waveform under different PRFs. The voltage and pulse energy for maintaining diffuse mode are analyzed.

The experimental results show that when the gap spacing is 10 mm, the initial voltage and pulse energy for diffuse discharge are approximately 12 kV and 7 mJ, respectively. These values are almost the same for all PRFs. Discharge mode transitions from diffuse discharge to spark discharge appears when the applied voltage increases. The breakdown voltage decreases with the increase of the PRF. The calculated equivalent capacitance for the multi-needle-to-plate gap is 22.59 pF, Thus the calculated conduction current of the diffuse discharge ranges from 10~20 A, which is larger than that for the diffuse discharge with single needle-to-plate gap. In addition, the large area diffuse discharge with an area of 12 cm×20 cm could be maintained until the PRF increased to 1500 Hz when the gap spacing ranges from 1 to 3 cm in atmospheric air.

REFERENCES

[1] *C. Zhang, V. F. Tarasenko, T. Shao, et al. Bent paths of a positive streamer and a cathode-directed spark leader in diffuse discharges preionized by runaway electrons. Physics of Plasmas, 2015, 22(3): 033511.*

[2] *T. Shao, V. F. Tarasenko, C. Zhang,* et al. *Diffuse discharge produced by repetitive nanosecond pulses in open air, nitrogen, and helium. Journal of Applied Physics, 2013, 113(9), 093301.*

[1] Work supported by the National Natural Science Foundation of China under Contract No. 51477164.

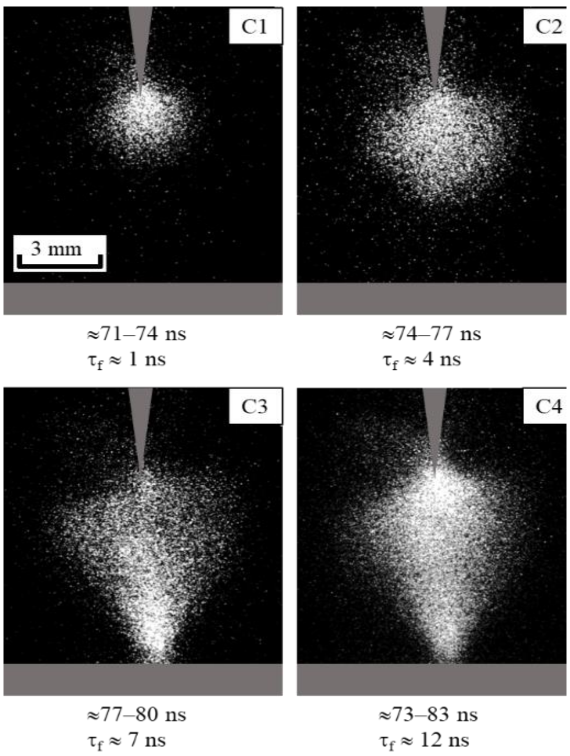
FORMATION OF A NEGATIVE STREAMER IN NITROGEN AND AIR IN A NON-UNIFORM ELECTRIC FIELD AT SUBMICROSECOND FRONT OF VOLTAGE PULSE[1]

M.I. LOMAEV,**, D.V. BELOPLOTOV*, V.F. TARASENKO*,**, D.A. SOROKIN**

**Institute of High Current Electronics, Siberian Branch, Russian Academy of Sciences, 2/3 Akademichesky Ave., Tomsk, 634055, Russia, Lomaev@loi.hcei.tsc.ru, (3822) 492-392*

***National Research Tomsk State University, 36 Lenin Ave., Tomsk, 634050, Russia*

Currently, much attention is paid to the investigation of high-voltage nanosecond breakdown at conditions of runaway electrons generation [1 - 4]. However, the mechanism of generation of runaway electrons, realized in the phase of breakdown, at atmospheric pressure of various gases and durations of the voltage pulse front of tens of hundreds of nanoseconds, remains poorly studied. In this paper, the results of the experimental study of the breakdown in nitrogen in a sharply inhomogeneous field are given for a duration of the voltage pulse front ≈ 200 ns.



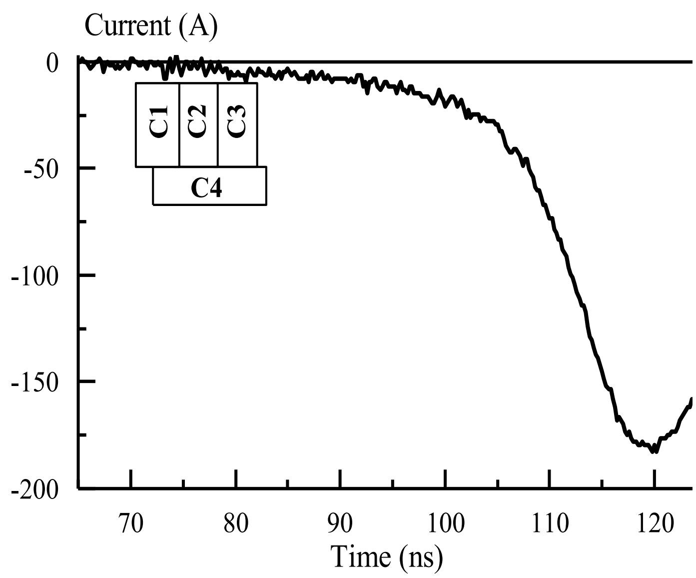


Fig. 1. Images of the streamer luminescence in atmospheric pressure nitrogen (left). The waveform of discharge current (right). C1, C2, C3, C4 - channel numbers of the ICCD camera. τ_f is the time interval during which a light emission profile was formed.

The experimental study is based on recordings by high-speed four-channel ICCD camera time-resolved light emission profiles and their complete correlation to voltage and current waveforms. It was found that at conditions under study a diffuse discharge is realized due to formation of a spherical streamer. Its diameter is comparable with an interelectrode distance. The mean propagation speed was registered to be of 0,12÷0,28 cm/ns. Amplitude of a runaway electron beam current registered behind a mesh anode was found to be of ones-tens mA.

REFERENCES

[1] *Edited by V.F. Tarasenko //* Runaway Electrons Preionized Diffuse Discharges. – Nova Science Publishers, Inc., 2014.
[2] *M.I. Lomaev, D.V. Beloplotov, V.F. Tarasenko, D.A. Sorokin //* IEEE Transactions on Dielectrics and Electrical Insulation. – 2015. – 22. – No. 4. 1833-1840.
[3] *E. Marode, Ph. Dessante and P. Tardiveau //* Plasma Sources Sci. Technol. – 2016. – 25. 064004.
[4] *N.Yu. Babaeva, C. Zhang, J. Qiu, X. Hou, V.F. Tarasenko and T. Shao //* Plasma Sources Sci. Technol. – 2017. – 26. 085008.

[1] This work was supported by RFBR according to the research project No. 18-52-53003_GFEN_a.

APOKAMP DISCHARGE AS A SOURCE OF NITROGEN OXCIDES[1]

E. KH. BAKSHT, E. A. SOSNIN*,**, V. S. SKAKUN*, V. A. PANARIN*, V. F. TARASENKO*,**, AND M. V. DIDENKO***

**Institute of High Current Electronics, 2/3 Akademichesky ave., 634055 Tomsk, Russia*
***National Research Tomsk State University, Tomsk 634050, Russia*

Two years ago, we found that an extended diffuse jet is formed at a pulse-periodic discharge approximately perpendicular to the point of bend of the bright current channel. We call this phenomenon apokamp discharge (using the Greek words από (from) and καμπη (bend, turning)) [1, 2].

The aim of this work is to determine the composition of the plasma decay products of atmospheric pressure apokamp discharge and to clarify the phenomenon conditions. For this purpose, we measured the temperature and spectral characteristics, NO_2 concentration in various modes of pulse periodic discharge between two tip-shaped electrodes.

It is found that pulse-periodic potential discharge, in relation to dissipation power can be responsible for mainly nitrogen oxides or ozone formation. There is a critical value of dissipation power for transformation of diffuse discharge to apokamp discharge. Simultaneously, due to the thermochemical reactions plasma discharge starts to produce nitrogen oxides (Fig. 1). Thus, the gas heating in pulsed-periodic discharge is one of the key factors to explain the apokamp mode formation. The obtained data about nitrogen oxides and ozone formation are in good agreement with theoretical and our experimental works [3, 4].

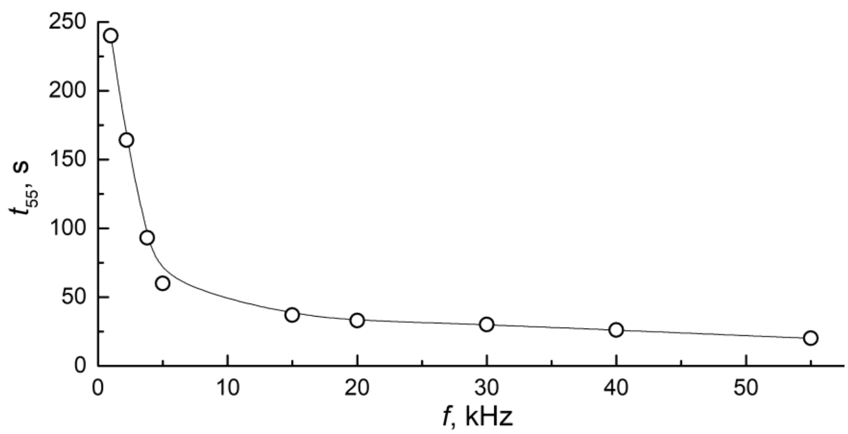


Fig. 1. Formation of NO_2 via voltage pulse frequency values at C = 5.5 pF, U_p ~ 11.3 kV, d = 7 mm. The t_{55} is period of time for achievement of set value of NO_2-analyzer (55 mg/m^3).

Decay products of atmospheric pressure plasma in air were applied to treating of wheat and rye seeds. In case of treatment period of time of 2 min and passive treatment of 1 min by plasma decay products the fungicidal activity has been revealed. It has been shown that the same treatment decrease fungi concentration on seeds surface at least two times. The main active substance of revealed effect is nitrogen dioxide.

REFERENCES

[1] *Skakun V.S., Panarin V.A., Pechenitsyn D.S. Sosnin E.A., Tarasenko V.F. // Russ. Phys. J. – 2016. – Vol.59. – P. 707-711.*
[2] *Sosnin E.A., Skakun V.S., Panarin V.A., Pechenitsin D.S., Tarasenko V.F., and Baksht E.Kh. // JETF Letters. – 2016. – Vol.103. – P. 761–764.*
[3] *Sosnin E.A., Baksht E.Kh., Panarin V.A., Skakun V.S., Tarasenko V.F. // JETF Letters. – 2017. – Vol.105. – P. 641-645.*
[4] *Sosnin E.A., Naidis G.V., Tarasenko V.F., Skakun V.S., Panarin V.A., Babaeva N.Yu. // JETP. – 2017. – Vol.125. – P. 920-925.*

[1] The work is performed in the framework of the State task for HCEI SB RAS, project #13.1.4.

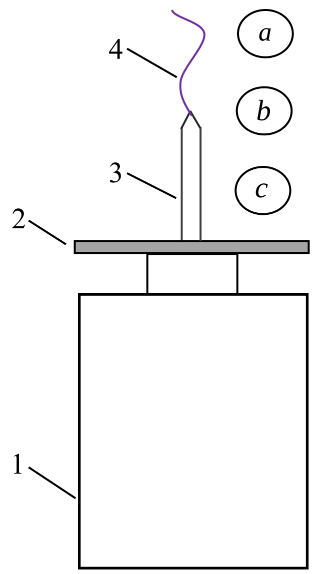
X-RAY AND OPTICAL RADIATION GENERATED DURING CORONA DISCHARGE IN AIR AT MICROSECOND RISE TIME OF VOLTAGE PULSE[1]

E.KH. BAKSHT, V.F. TARASENKO, E.A. SOSNIN, I.D. KOSTYRYA

Institute of High Current Electronics SB RAS, Tomsk, 634055, Russia
E-mail: BEH@loi.hcei.tsc.ru, phone: +7 (3822) 491-685

In atmospheric pressure air formation and decay of corona discharge diffuse "channels", as well as optical and x-ray radiation were investigated. A corona discharge was formed using a high voltage pulse generator, which was connected to a point electrode [1]. Modulate pulses (~290 kHz) of high voltage (~250 kV) with duration ~10 ms was used. Each modulate pulse consisted of a sine-wave signal with an oscillation frequency of ~290 kHz. The pulse repetition rate was 50 Hz.

X radiation was detected by the darkening of an X-ray Kodak RAR film 2497. The X-ray film was placed in a light and ray-proof envelop with a window 6 mm in diameter. The window in envelop was covered with a beryllium foil 15 µm in thickness (the long wave transmission end corresponded to energy of X-quanta of ~0.7 keV). In some experiments, the beryllium window was covered with an aluminum foil 10 µm in thickness or several layers of paper, including aluminum-metalized paper. The envelope was fixed on a disk *2* (see Fig. 1).



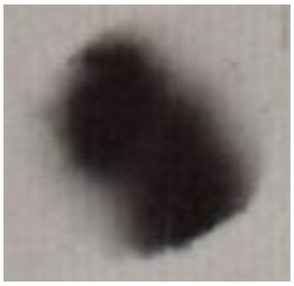


Fig. 1. Block-diagram of the setup: Tesla generator (*1*), metal disk (*2*), tip (*3*), corona discharge “channel” (*4*); *a*, *b*, and *c* are the points of location of the end face of the camera or spectrometer light guide for registering spectra in different regions of a corona discharge (on the left). X-ray film exposure is 11 min, the diameter of the exposed area is 6 mm (on the right)

It was determined that bends appeared on the diffuse “channels”. At the end of the voltage pulse the value of the bends increased. In the area of diffuse “channel” and at a distance from the plasma channel the bright glowing term was registered.

Soft X-ray radiation was registered from corona discharge due to the use of a thin beryllium filter and location of the envelope with the film on disk *2* near the tip (see Fig. 1). The generator operated for 11 min in these experiments.

REFERENCES

[1] *Kozyrev A.V. Kozhevnikov V.Y., Kostyrya I.D., Rybka D.V., Tarasenko V.F. & Schitz D.V. //Atmospheric and Oceanic Optics. – 2012. – V. 25. – P. 176-183.*

[1] This work was supported by RFBR according to the research project No. 18-52-53003_GFEN_a.

THE NEAR-CATHODE PROCESSES AND INITIATION OF SPARKS IN AIR DISCHARGE[1]

E.V. PARKEVICH[1, 2], M.A. MEDVEDEV[1, 2], A.V. AGAFONOV[1], S.I. TKACHENKO[2], A.V. OGINOV[1], T.A. SHELKOVENKO[1], S. A. PIKUS[1]
[1]Lebedev Physical Institute, RAS, Moscow, Russia
[2]Moscow Institute of Physics and Technology, Dolgoprudny, Moscow Region, Russia
parkevich@phystech.edu

In this paper, we present the date on parameters of near-cathode plasma formed at the cathode at the instant of gap breakdown obtained by laser probing methods (interferometry, shadow and schlirien-photography). The investigations were carried out at the experimental setup with a high-voltage generator provided output voltage pulses with their amplitude up to 20 kV and pulse duration up to 30 ns with the rise time of ≈ 4 ns and the maximum generator current of ≈ 500 A. The Lotis LS-2151 Nd: YAG laser emitting at 532 nm with the pulse duration (full width at half magnitude, FWHM) of 70 ps was used. To implement the laser probing a 6-channel 18-frame optical system for simultaneous recording of interference, shadow and schlieren images of the discharge gap in each optical channel was developed. An average delay time between adjacent channels was ≈ 2 ns. The spatial resolution in each channel was about ≈ 3–4 μm. The air discharge was studied using the "pin-to-plane" electrode geometry. The cathode was made of thin metal wires with the diameter of several tens of microns.

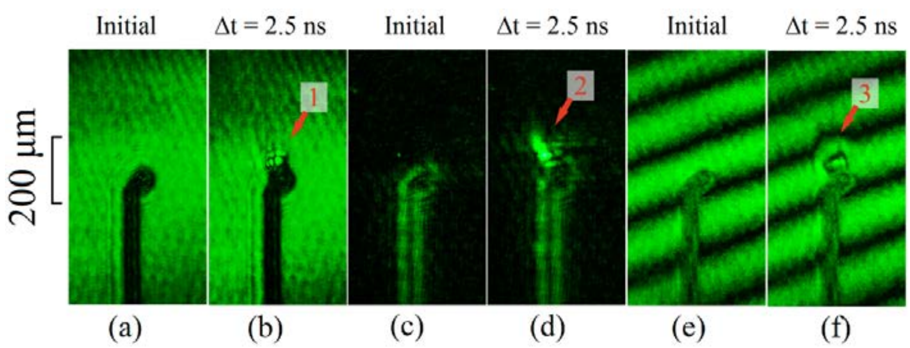


Fig. 1. Development of anode-directed spark channel from the top of gold wire (Ø50 μm): shadowgrams (*a*,*b*), schlirien-images (*c*,*d*), interferograms (*e*,*f*). Photos (*b*,*d*,*f*) were obtained after Δt = 2.5 ns from breakdown. Figures in photographs denote: 1 – dense plasma clot, 2 – areas of high ($\partial N_e/\partial x \sim 10^{22}$–$10^{24}$ cm^{-4}) gradients of electron density, 3 – developing spark channel.

It was established that opaque dense plasma clots (see Fig.1) with the size of about 10 μm are formed near the cathode surface approximately $\Delta t \sim 1$ ns after the gap breakdown (with sharp increase of the discharge current). Then, one or more highly ionized spark channels directed towards the anode are formed from these clots. These clots are most likely the erosion plasma formed of the cathode material. Analysis of the absorption and refraction of the laser radiation demonstrated that the observed formations can have the electron density greater than 10^{20} cm^{-3} and typical density gradients of ~ 10^{22}–10^{24} cm^{-4}. The obtained data indicate that the formation of the spark channel at the cathode surface can be associated with explosive electron emission [1]. The average rate of the spark channel expansion in the longitudinal direction is 70±5 μm/ns, in the transverse direction (near the cathode surface) the corresponding value is 30 ± 5 μm/ns. The current density is $j \sim 10^6$ A / cm^2. The electron density in the developing spark channel achieves the value of $N_e = 5\times10^{19}$ cm^{-3} that is higher than the number of molecules presented in air at atmospheric pressure 2.7×10^{19} cm^{-3}. Assuming that most of the current flows through the developing spark channel, the specific energy input near the cathode in terms of one molecule on average amounts to several tens of electron volts.

It should also be noted that the obtained data on the discharge gap breakdown are important for both development of the models regarding the conductivity of the spark channel and refinement of the existing ones.

References

[1] *Korolev Yu. D., Mesyats G.A.* Physics of pulsed breakdown in gases. Yekaterinburg. – Ural Division of the Russian Academy of Science, 1998.

[1]The experimental study in this work was supported by the Russian Science Foundation (grant No. 14-22-00273). The development of the optical recording system was partially supported by the Russian Foundation for Basic Research (grants No. 17-08-01690; 18-32-00566).

HIGH–VOLTAGE PULSE GENERATOR FOR "RUNAWAY ELECTRONS" SOURCES IN DENSE GASES

B.A. KOZLOV, N.S. KULIKOV

Gagarin str.59/1, Electronic Devices Dept. RSREU, Ryazan, 390005, RUSSIA, E–mail: kozlov.qe.ryazan@mail.ru

"Runaway electrons" use some scientists and engineers for many applications especially for generation of hard VUV– and roentgen radiation in dense gases. Such radiation can provide intensive pre–ionization of dense gas mixtures in inter–electrode gaps up to 10 cm and more before forming of high–current volume discharges [1, 2].

The present work is devoted to describing construction of compact pulse generator with pulse amplitude of voltage up to 200 kV, rise–time about 10 nanoseconds and pulse energy up to 20 J.

The electrical scheme of pulse generator images in Fig.1. We used two identical pulse transformers (PT_1, PT_2) and one high–current pseudo–spark switch (S) (TPI1–10k/50) (maximum voltage 50 kV, maximum current 50 kA). Primary circuits of both transformers were connected in parallel. Secondary circuits were connected sequentially. Transformation coefficients of each transformer were n = 10. The capacitance values of main condensers C_0 were in range 0.025–0.1 μF. Initial charging voltage that condensers can vary in range U_O = 10–30 kV. Secondary condenser C_2 (400–1200 pF) can charges from two pulse transformers up to 200 kV with rise–time about 1.5÷2 μs. We used very quick switching spark gap (P) (gas pressure in spark gap equal 100 Atm.) for minimal shortening of rise–time of high voltage pulses. The own time of switch–on this spark switch was less than 1 nanosecond. Condenser C_2 with capacitance 50–200 pF can charges more than 220 kV.

Voltage divider (D) and measurement transformer (MT) (they were constructed by recommendation in [3, 4]) ensure control of electrical parameters sliding spark discharge (SS) which we used for initial ionization working gases in TEA–CO_2 laser with active volume V = 8x8x70 cm^3.

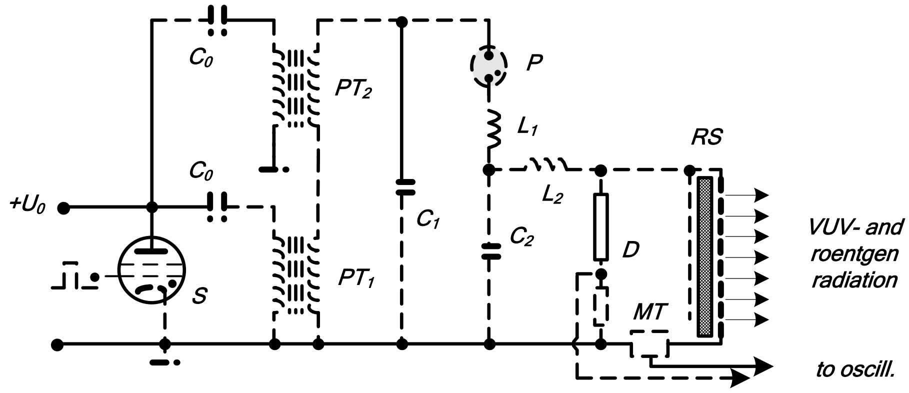


Fig.1. .Electrical scheme of high–voltage generator and intensive source of VUV– and roentgen radiation

The main results of our work are the next:

– realized a new variant of small–sized pulse generator on the base of two pulse transformers and high–pressure peaking spark switch with maximal amplitude of pulse voltage up to 200 kV and with rise–time about 10 nanoseconds;

– fulfilled preliminary experiments with initiation of volume discharge in TEA–CO_2 laser with active volume V = 8x8x70 cm^3.

REFERENCES

[1] V.F. Tarasenko, Editor // Runaway Electrons Preionized Diffuse Discharges. –Nova Publischers. New–York. 2014.
[2] S.L. Kulakov, A.A. Kuchinsky, A.G. Maslennikov at all. // Journal of Technical Physics. –1990. Vol. 60. –№ 12. Pp. 43–48.
[3] A.J. Shwab // Measurements on high voltages. –Springer–Verlag. Heidelberg. 1981.
[4] J.M. Anderson // Rev. Sci. Instruments. –1971. –№ 7. P. 915–926.

VOLUME DISCHARGES IN CO_2–LASER MIXTURES AT ATMOSPHERIC PRESSURE WITH HIGH ENERGY DENSITY

DO QUANG MANH, B.A. KOZLOV, MAI THE NGUYEN, N.V. SUKHORUKOVA

Gagarin str.59/1, Electronic Devices Dept. RSREU, Ryazan, 390005, RUSSIA, E–mail: kozlov.qe.ryazan@mail.ru

TEA–CO_2 lasers pumping realize in volume discharge plasma. Stable volume discharges with high density of pumping energy forms at intense initial ionization of gas mixture before breakdown gas discharge gap and effective reproduction of electrons in cathode region after breakdown [1–3]. Basic mechanism of electron reproduction in cathode region of discharges at current densities up to $j \le 10^2$ A/cm^2 is ion–electron emission. At $j \ge 10^2$ A/cm^2 auto–electron emission to take part significant fraction in total volume discharge current.

There was suggested to use carbon soot at cathode working surfaces for amplification of auto–emissive currents [4]. The carbon soot was manufacturing in separate reactor at the ignition of high–current arc discharge between graphite electrodes in helium atmosphere with total currents up to 700 A. The carbon soot contain carbon in some nano–structured forms [5].

The main goal of this experimental work – to determine conditions of increase energy density in volume pumping discharges in TEA–CO_2 lasers. It includes study of auto–emissive characteristic cathodes from Al, Cu, Ni, Mo, Ta, W and graphite with carbon films on their surfaces and volt–ampere characteristics of volume discharges in CO_2–laser mixtures at total pressure P = 1 Atm.

Voltage–current characteristics of the auto–electronic currents from cathode surfaces studied in separate vacuum chamber at total residual gas pressure $P \le 10^{-8}$ Torr. Auto–electronic characteristics in Fowler–Nordgeim coordinates give information about local amplification of electrical field coefficient [6] and can use for explanation of volume discharge current variations. The volt–ampere characteristics of volume discharges in CO_2–laser mixtures were studied in real inter–electrode gap of small–sized TEA–CO_2 laser. Geometrical parameters of discharge gap V = 18x0.8x0.8 cm^3, cathode surface S = 18x0.8 cm^2. Investigations of volume discharge characteristics were made on experimental set–up with pulse generator (pseudo–spark switch S, storage capacitor C_0, charging resistor R), active element of TEA–CO_2 laser (anode–cathode A–C and sliding spark preionizer SSP), control devices (voltage divider D and measurement transformer MT) (Fig.1).

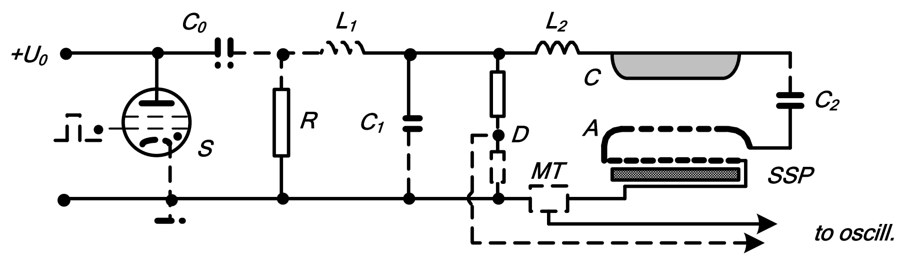


Fig.1. .Electrical scheme of high–voltage pulse generator and discharge gaps for initiation and forming of volume discharge

Thin layer from graphite soot on the cathode surfaces given the next results:
– auto–emissive currents increase in 2–10 times;
– maximal density of volume discharge currents achieve 400–600 A/cm^2;
– volume energy density increase from 250–400 mJ/cm^3 to 800–1200 mJ/cm^3.

REFERENCES

[1] G.A. Mesyaz // Pulse energetic and electronics. –Moscow. Nauka. 2004.
[2] V.N. Karnushin, R.I. Soloukhin // Macroscopic and molecular processes in gas lasers. –Atomizdat. Moscow, 1981.
[3] V.V. Osipov // Proceedings of SPIE. 1995. –Vol. 2916. Pp. 32–38.
[4] Do Quangh Man, Mai The Nguyen, B.A. Kozlov, N.S. Kulikov // Book of Abstracts International Conference AMPL–2017. –Tomsk, Russia. –2017. P. 37.
[5] Sidorov L.N. Editor // Fullerens. –Moscow. –Ekzamen. 2005.
[6] Slivkov I.N. // Processes at high voltages in vacuum. –Moscow. –Energoatomizdat. 1986.

PHYSICAL KINETICS OF ELECTRONS IN THE BREAKDOWN OF A LONG GAS-FILLED GAP WITH A LONGITUDINALLY INHOMOGENEOUS FIELD AND PRESSURE DISTRIBUTION[1]

V. S. GOLYAK, A. O. KOKOVIN*, V. YU. KOZHEVNIKOV**, A. V. KOZYREV*, N. S. SEMENIUK***

**Tomsk State University, 36 Lenin Ave., Tomsk, 634050, Russia*
***Institute of High Current Electronics, Siberian Branch of the Russian Academy of Sciences, 2/3 Akademichesky Ave., Tomsk, 634055, Russia*

The development of aircraft makes it necessary to study the atmospheric discharges. One reason is the powerful X-ray flashes occurs in the formation of "blue jets". The presented model is the first step to the theoretical study of this phenomenon. Its conditions close to natural. Namely, no uniform distributions for field and pressure take place. The diagram of the discharge model is shown in Fig.1. We use a circuit with a series-connected discharge gap and a charged capacitance. The gap is the spherical sector filled with nitrogen with a pressure gradient from 1.0 to 0.1 of atmospheric value (from cathode to anode coordinates).

High-energy electrons play an important role in atmospheric discharges. Therefore, it is necessary to use fundamental principles of electron physical kinetics. We numerically solved the system of equations includes the Boltzmann kinetic equation for the electron distribution function with the modeling collision integral, the continuity equation for the discharge current, and the Kirchhoff equation for the electric circuit. The numerical solution is carried out by grid difference schemes. The proposed method makes it possible to simulate an electrical breakdown with sufficient accuracy and to obtain such important characteristics as the discharge current, the distribution of the electric field in the gap, the energy spectrum of the electron component at any time. The proposed method for describing the discharge was successfully tested earlier for high-pressure discharges and showed good agreement with experiment [1]. An example of the possibilities of this method is shown in Fig.2. It demonstrates a phase portrait of the electron distribution function at a fixed time. Such information is available for any time.

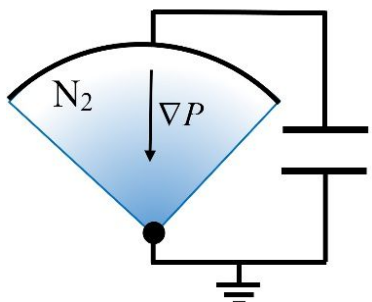


Fig. 1: Circuit diagram

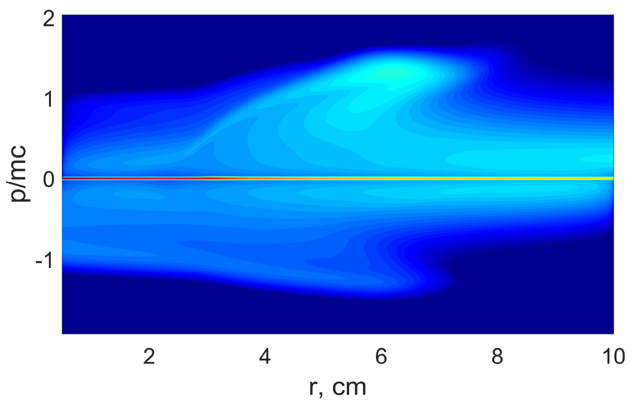


Fig. 2: Distribution function of electrons

REFERENCES

[1] *Tarasenko V., et al* // High Voltage. – 2017. – 2. – 49-55.

[1] The reported study was funded by RFBR according to the research project №18-38-00120

TWO MODELS OF THREE-COMPONENT HIGH-PRESSURE OXYGEN PLASMA

V. S. GOLIAK, V. YU. KOZHEVNIKOV**, A. V. KOZYREV*, N. S. SEMENIUK***

**Tomsk State University, 36 Lenin Ave., Tomsk, 634050, Russia*
***Institute of High Current Electronics, Siberian Branch of the Russian Academy of Sciences, 2/3 Akademichesky Ave., Tomsk, 634055, Russia*

The research is devoted to theoretical modeling of the kinetics of plasma particles in a pulsed electric discharge in atmospheric pressure oxygen. Despite the fact that such problems were solved many times earlier [1], new issues sometimes arise in their solution. One of these issues is addressed in the present study.

The physical kinetics was analyzed within the framework of the simplest model of oxygen plasma, which contained only three types of charged particles (positive and negative molecular oxygen ions O_2^+ and O_2^- and electrons e). A voltage pulse of rectangular shape with amplitude of 13 kV and duration of 2 μs using an electrical circuit with a resistance of 10 kΩ applied to the gap of 5 cm in length.

Calculations of two kinetic models have been made.

Reactions	Model "A"	Model "B"
Impact ionization	$e + O_2 \Rightarrow 2e + O_2^+$	$e + O_2 \Rightarrow 2e + O_2^+$
Attachment of electrons	$O_2 + e \Rightarrow O_2^-$	$e + O_2 + O_2 \Rightarrow O_2^- + O_2$
Ion-ion recombination	$O_2^+ + O_2^- \Rightarrow 2O_2$	$O_2^+ + O_2^- + O_2 \Rightarrow 3O_2$

It is found that in calculating the kinetics of the discharge, these models give different plasma compositions with similar electrical parameters of the discharge. Thus, in the "A" model, the discharge plasma is ion-ion, that is, the concentrations of O_2^- and O_2^+ ions are approximately equal to $2{\cdot}10^{12}$ cm^{-3}, and the concentration of free electrons is much smaller. In the model "B" the situation is different − plasma electron-ion, that is, the concentration of electrons and positive ions O_2+ approximately equal y $1.6{\cdot}10^{13}$ cm^{-3}, and the concentration of negative ions O_2^- not significant. At the same time dynamic voltage-current dependence in the two models do not differ very much. The figure shows graphs of *U(t)* and *I(t)* dependencies on the voltage-current phase plane.

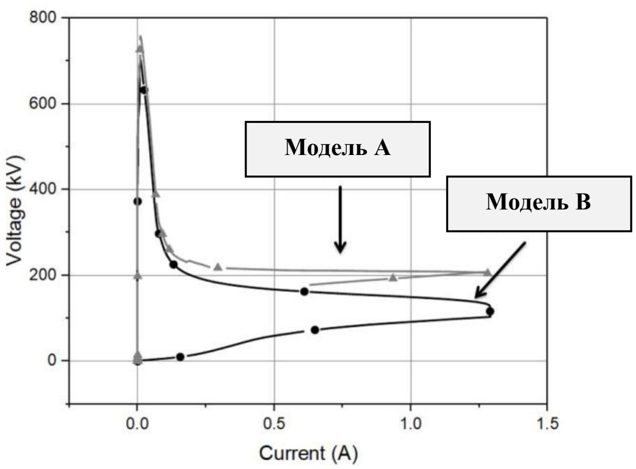


Fig. 1. Dynamic current-voltage characteristics of the first discharge pulse.

Note that in the experiment only current and voltage oscillograms are recorded, and they are used to restore the parameters of the plasma in the gap volume. Therefore, the main result of the work is that it is not always possible to draw an unambiguous conclusion from the current and voltage waveforms not only about the quantitative characteristics of the plasma, but sometimes it is impossible to even say what kind of plasma − electron-ion or ion-ion plasma − gives the observed electrical discharge characteristics.

REFERENCES

[1] *Raiser Y. P. Physics of gas discharge. Moscow: Science, 1987*
[2] *Wen Yan and Economou D. J. Simulation of a non-equilibrium helium plasma bullet emerging into oxygen at high pressure (250-760 Torr) and interacting with a substrate //* J. of Applied Physics. − 2016. − **120**. − 123304.

CRITICAL RUNAWAY ELECTRON AVALANCHE[1]

*E.V. ORESHKIN**

**P.N. Lebedev Physical Institute (LPI RAS), Leninskiy Prospekt 53, Moscow, 119991, Russia, oreshkin@lebedev.ru,+74991326614*

The X-ray and gamma-ray flares observed in the thunderstorm atmosphere of the earth are usually associated with the generation of runaway electrons (RE) in electric atmospheric fields. It is assumed that in avalanche discharges, which are observed in a t hunderstorm atmosphere, the main role is played by avalanche of RE, initiated by cosmic rays. In this paper, using the three-dimensional numerical calculations, the development regularities are investigated and the parameters of the critical avalanches are determined. It is shown that in air under conditions characteristic of thunderstorm atmospheric discharges, the number of electrons in the critical avalanche of RE can reach values of the order of 10^{18} particles.

[1] This work was supported by RFBR grant No. 16-38-60199; Scholarship of the President of the Russian Federation Grant No. SP-951.2016.1.

SPECTRAL CHARACTERISTICS OF FAST HEAVY PARTICLES IN AN OPEN DISCHARGE[1]

P.A. BOKHAN, P. P. GUGIN, M. A. LAVRUKHIN, DM. E. ZAKREVSKY

Institute of Semiconductor Physics, Siberian Branch, Russian Academy of Sciences, pr. Akademika Lavrent'eva 13, Novosibirsk, 630090, Russia, zakrdm@isp.nsc.ru

It was shown in [1,2] that in the breakdown of discharge gaps DG at high E/N in medium-pressure gases, the determining process of electron emission and, accordingly, superfast breakdown is photoemission under the action of resonant VUV photons. Depending on the geometry of the discharge gap, modes and conditions of discharge functioning, resonant states of atoms can have different excitation mechanisms. In the general case, the dependences $I{\sim}p^xU^y$ have a complicated form, determined by the change in the mechanism of the generation of VUV photons, in particular by an increase in the fraction in the excitation of the resonant states of the gas atoms by fast heavy particles appearing in DG. Experimental results together with modeling allow us to state that in a strong electric field typical for an "open" discharge OD, the fast atoms that appear as a result of charge exchange of ions excite a resonance state, which in turn, due to the Doppler effect, radiates at a frequency-shifted resonant radiation that is not subject to reabsorption, which initiates the rapid development of current.

Demonstration of the presence of fast atoms and an estimate of the energy of the emitting particles due to the Doppler Effect will confirm the above. Two types of cells based on OD with generation of colliding electron beams were investigated: - planar with round electrodes with a working area of 1 cm^2 with interelectrode distances of 3 mm and with a common mesh anode. The peculiarity of the cell consisted in the fact that each cathode was made of 2 fine-meshed grids with hole size of ~ 200 μm with a distance between them of 0.3 mm. This design of cathode structure allowed spontaneous emission through them. Another type was a planar cell with round *SiC* electrodes with a working area ~ 6 cm^2 with interelectrode distances of 3 mm and with a common network anode. Its distinctive feature was that the cathodes had through gaps of width 0.1 mm. In this case, spontaneous emission was recorded through a gap. The maximum energy of heavy particles was estimated from spectral measurements in the wings of the lines.

A study was made of the relative distribution of the radiation of the lines of the helium atom (λ=501.57 nm, the transition 3^1P_1-2^1S_0) and the helium ion (λ=655.98 nm, the transition $^2P^0{}_{1/2}$-$^2S_1$ or λ=468.57 nm transition, the $^2P^0{}_{3/2}$-$^2D_{5/2,3/2}$). The level 3^1P_1 is well excited by fast helium atoms. In this process, both a fast atom and an atom with a thermal velocity are excited with equal probability [3]. A fast atom radiates at a frequency shifted due to the Doppler effect. It is seen that: in the case when the field is weak (E/N≈3.3×10^{-15} Vcm^2) the line has no far wings, and the half-width Δλ≈0.42 Å is determined by the resolution of the monochromator; at E/N≈10^{-13} Vcm^2, radiation is observed in distant wings, and the line is asymmetric; the helium ion line is broadened more than the atom, which is explained by the lower average energy of fast helium atoms. From a comparison of the contours, it can be seen that the radiation in the wings of lines, the broadening of which is due to the Doppler effect, is recorded up to Δλ≈15 Å, which corresponds to particle energy up to 20 keV and closely to the applied discharge voltage.

REFERENCES

[1] *Bokhan P.A., Gugin P.P., Zakrevsky D.E., Lavrukhin M.A.* // Techn. Phys. Lett. – 2012. – 38. – 383.
[2] *Schweigert I.V., Alexandrov A.L., Bokhan P.A., Zakrevsky Dm.E.* // Plasma Sources Sci. Technol. – 2015. – 24. – 044005.
[3] *Kempter V., Veith F., Zehnle L.* // J. Phys. B: Atom. Molec. Phys. 1975. – 8. – 1041

[1] The study was supported by RSF project № 14-19-00339.

STUDY OF THE FORMATION TIME OF A SELF-SUSTAINED SUBNANOSECOND DISCHARGE AT HIGH AND ULTRAHIGH GAS PRESSURES [1]

S.N. IVANOV, V.V. LISENKOV

Institute of Electrophysics, Amundsena Str. 106, Ekaterinburg, 620016, Russia, E-mail: stivan@iep.uran.ru, phone:+7(343)2678824.

The formation times of self-sustained subnanosecond discharges in nitrogen at pressures of 1–40 atm and in hydrogen at pressures of 1–60 atm are analyzed in terms of the avalanche–streamer model. In experiments, a subnanosecond voltage pulse with an amplitude of 100 kV was applied to a 0.5-mm-long discharge gap with a uniformly distributed electric field (the curvature radii of both the cathode and anode ends were 1 cm). The rise time of the voltage pulse from 0.1 to 0.9 of its amplitude value was about 250 ps. Breakdown occurred at the leading edge of the pulse. The discharge formation time was measured at different gas pressures (*p*) with a step of 5–10 atm. Analysis of the experimental results shows that, in nitrogen at pressures of 10–40 atm (Fig. 1a) and in hydrogen at pressures of 20–50 atm (Fig. 1b), breakdown occurs earlier than the electron avalanche reaches its critical length and that the critical avalanche length lies in the range of (2–8) x 10^{-2} mm, which is one order of magnitude shorter than the discharge gap length. This means that the avalanche–streamer model is inapplicable in this case. The fast formation of a conducting plasma column under these conditions can be explained by ionization of gas by runaway electrons (RAEs). In this case, the conducting column develops as a result of simultaneous development of a large number of electron avalanches in the gas volume. The presence of RAEs in our conditions (RAEs were also registered in a uniform electric field at nitrogen pressures up to 40 atm) was observed in [1]. Thus E/p in the experiments described in [1] was about one order of magnitude lower than E_{cr}/p (E_{cr} – the threshold value of the electric field intensity required for RAE generation [2]). An increase in the hydrogen pressure from 50 to 60 atm leads to an abrupt increase in the discharge formation time by about 60%. As a result, the growth time of the electron avalanche to its critical length becomes shorter than the discharge formation time. In this case, the electrons cease to pass into the runaway regime and the discharge is initiated from the cathode only due to field emission from micro protrusions on its surface. Under these conditions, the discharge formation time is well described by the avalanche–streamer model. The transition to the streamer model of discharge development is accompanied by a significant (by 50%) increase in the pulse breakdown voltage. At the same time, the overvoltage of the discharge gap starts to rise.

We are grateful to Academician G.A. Mesyats, Corresponding member of RAS N.M. Zubarev, Professor Yu.D. Korolev for useful discussions of the results.

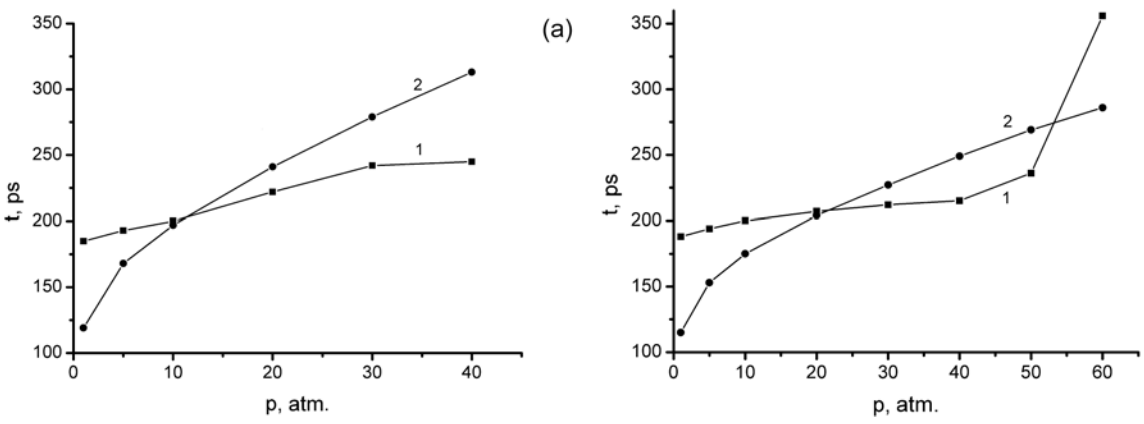


Fig. 1. The breakdown formation time (1) and the time of gaining the critical number of electrons in the avalanche (2) as function of gas pressure *p* for nitrogen (a) and hydrogen (b).

REFERENCES

[1] *S.N. Ivanov* // J. Phys. D: Appl. Phys. – 2013. – 46. – 285201.

[2] *Yu. D. Korolev and G. A. Mesyats* // Physics of Pulsed Breakdown in Gases. – Ural Division of Russian Academy of Sciences, Ekaterinburg, 1998.

[1] This study was full-filled in the frame of state task № 0389-2015-0023. This work was partially supported by the Russian Fund for Basic Research (grants N 16-08-00894-a, N 16-08-00466-a) and Federal Agency of Scientific Organizations under the program of fundamental studies "Physical models, theories, and devices" of the Ural Branch, Russian Academy of Sciences (grant N 18-2-2-15).

STUDY OF THE IONIZATION PROCESSES AT THE DELAY STAGE OF THE SUBNANOSECOND DISCHARGE IN HIGH-PRESSURE NITROGEN [1]

S.N. IVANOV, V.A. SHKLYAEV***

**Institute of Electrophysics, Amundsena Str. 106, Ekaterinburg, 620016, Russia, E-mail: stivan@iep.uran.ru, phone:+7(343)2678824.*

***Institute of High Current Electronics, Akademichesky Avenue 2/3, Tomsk, 634055, Russia, E-mail: shklyaev@to.hcei.tsc.ru, phone:+7(3822)491471*

In [1-3] it was shown that in nitrogen at a pressure (p) of 40 atm in the sub-nanosecond range two mechanisms of initiation of the self-sustained discharge operates simultaneously: the initiation of discharge by field emission from the cathode micro protrusions and volume initiation by runaway electrons (RAEs). Experiments were carried out in an initially homogeneous electric field. The breakdown of the discharge gap occurred at the front of the applied high-voltage pulse. In these experiments, the reduced electric field E/p at the beginning of the breakdown (that is, estimated at the upper limit) was 36-66 V/(cm Torr), which is significantly lower than required by the criterion of the transition of electrons into the runaway mode [4, 5].

In this paper in the first time, the development of ionization processes leading to breakdown in these conditions was numerically investigated. Self-consistent calculations were carried out taking into account the kinetics of electrons, including RAEs, and the dynamics of the electromagnetic field in the discharge gap in 2D approximation. Dynamics of both RAEs and slow electrons was calculated by particle-in-cell method using open-source code XOOPIC [6], which allows modeling of the breakdown development with account of electromagnetic field dynamics. Collisions accounting in the simulation were calculated using the Monte Carlo method. At the same time, all the main channels of electron energy losses, such as the excitation, ionization and elastic scattering, were taken into account. The dynamics of the electromagnetic field was calculated both in the gas diode and in the forming line, using a system of Maxwell's equations. The time of injection of the RAE beam was determined according to the method described in [7]. After that, the dynamics of the development of ionization processes in the discharge gap was analyzed by two methods: according to the dynamics of changes in the distribution of electric field intensity in the gap and according to the dynamics of changes in the distribution of the concentration of the second positive nitrogen system $C_3\Pi^u$. The results obtained in the analysis were compared with the results of discharge modeling under the same experimental conditions (with the same electrodes configuration and the length of the discharge gap, the rate of voltage increase on the gap, etc.) but in the absence of RAE beam; as well as with the experimentally obtained data [2, 3] of the breakdown delay time and the pulse breakdown voltage.

REFERENCES

[1] *S. N. Ivanov* // J. Phys. D: Appl. Phys. – 2013. – 46. – 285201.
[2] *S. N. Ivanov, K. A. Sharypov* // Technical Physics Letters. – 2016. – 42(3). 274–277.
[3] *S. N. Ivanov, V. V. Lisenkov* // Plasma Physics Reports. – 2018. – 44(3). 369–377.
[4] *Yu. D. Korolev and G. A. Mesyats* // Physics of Pulsed Breakdown in Gases. – Ural Division of Russian Academy of Sciences, Ekaterinburg, 1998.
[5] *L. P. Babich* // High-Energy Phenomena in Electric Discharges in Dense Gases: Theory, Experiment, and Natural Phenomena. ISTC Science and Technology Series, Vol. 2. – Futurepast, Arlington, VA, 2003.
[6] *J. P. Verboncoeur, A. B. Langdon, and N. T. Gladd* // Comput. Phys. Commun. – 1995. – 87(1–2). 199–211.
[7] *N. M. Zubarev, S. N. Ivanov* // Plasma Physics Reports. – 2018. – 44(4). 445–452.

[1] This study was full-filled in the frame of state task № 0389-2015-0023. This work was partially supported by the Russian Fund for Basic Research (grants N 16-08-00894-a, N 16-08-00466-a) and Federal Agency of Scientific Organizations under the program of fundamental studies “Physical models, theories, and devices” of the Ural Branch, Russian Academy of Sciences (grant N 18-2-2-15).