OPERATION FEATURES OF THE PULSE PENNING ION SOURCE IN THE TRANSITION PRESSURE RANGE

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The ExB gas discharge (penning discharge) is widely used in various fields of science and technology [1]. In particular the penning discharge is effectively used in ion sources (IS) for the miniature linear accelerators [2].

There are several modes of the penning discharge combustion depending on the physical parameters (anode voltage, magnetic field magnitude, working gas pressure) [3]. The discharge mode significantly affects the potential and the electron density distributions inside the discharge cell as well as the speed of discharge development and, as the consequence, the ion beam density and the efficiency of the ion extraction. For the stable operation of the IS the linear dependence of the discharge current (and the extracted ion current) on the working gas pressure is required. For the pulsed IS it is also important to insure the rectangular shape of the extracted current pulse with short leading and trailing edges, which do not change its shape in a given pressure range [4]. Therefore, the “transition” mode of combustion characterized by the decrease in the discharge current (and the extracted ion current), followed by a sharp exponential increase in current with a gradual increase in pressure is especially undesirable. The pressure range in which the conditions for the "transition" mode are realized depends on the magnitude of the magnetic field, the anode voltage and the geometric parameters of the discharge cell and is usually in the range of ~ 0.5 – 10 mtorr.

The paper presents the results of experiments studying the dependence of discharge and extracted currents on the pressure of pulsed penning IS, which was described in [5]. A comparative analysis of the amplitude-time and current-voltage characteristics of IS for the various anode voltage amplitudes, pulse repetition rates, pulse durations, magnitudes (and configurations) of the magnetic field is presented. The obtained results reveal the existence of different (stable and unstable) discharge modes depending on the operating conditions of the power supply system and the pressure range of the working gas (deuterium). The features of current waveforms in the transitional pressure range 0.5-2 mTorr (see figure 1) are defined.

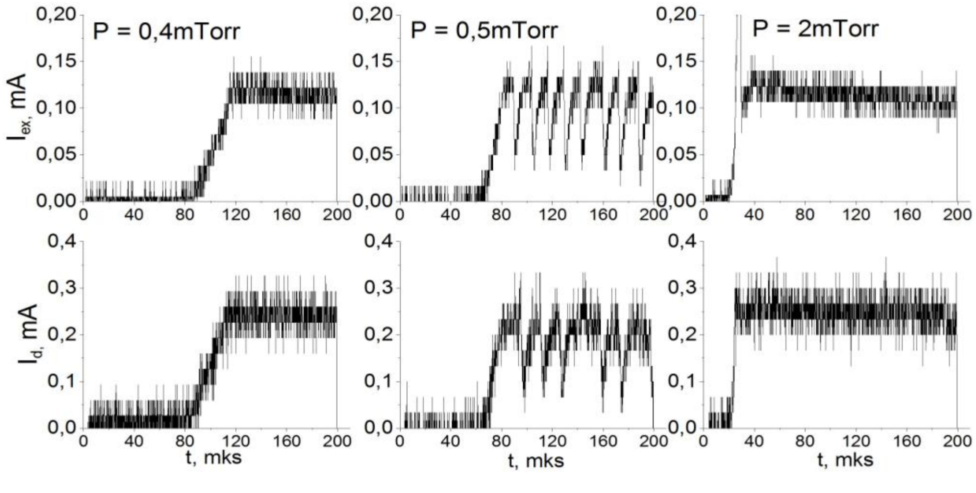

Fig. 1. Current pulse waveforms examples in the transient pressure range (I_d - discharge current, I_{ex} - extracted ion current). The anode voltage is 2 kV, the frequency is 600 Hz and the duration is 200 μs.

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ATMOSPHERIC PRESSURE PLASMA GENERATOR FOR MODIFICATION OF NITRILE BUTADIENE RUBBER SURFACE*

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The atmospheric pressure discharge like a "plasma jet" which operates in the flows of nitrogen N_2 as well as carbon dioxide CO_2 were investigated. The peculiarities of plasma generator operation with different materials of discharge system electrodes were investigated also. It was experimentally determined that the use of a tantalum cathode and a copper anode delivered stabile operating of the discharge. Exactly at these electrode materials the dependences of the discharge voltage vs the discharge current were obtained.

The optimal operating conditions were as follows: both N_2 and flow CO_2 rate of – up to 5 l/min; operating mode - DC or pulse; discharge voltage magnitude – about 600 V; discharge current magnitude – about 80 mA; pulse duration – up to 10 µs; pulse repetition rate – up to 200 kHz. The single Langmuir probe was used for diagnostics at these discharge parameters. As the result of probe diagnostics, the values of the electron temperature T_e and plasma density n were obtained. T_e was about 1.75 and 5 eV and n was about $9\cdot10^{10}$ and $1\cdot10^{10}$ cm^{-3} for N_2 and CO_2 plasmas respectively.

This plasma generator was used for modification of the nitrile butadiene rubber (NBR) surface modification. After plasma treatment, the structure and tribological properties the surfaces of NBR samples were studied. The criteria for influencing the friction resistance reduction and mechanical wear of the NBR surface were determined.

PLASMA SOURCES AND EQUIPMENT

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ABOUT THE PULSE MODES OF CORONA GLOW AREA*

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Corona discharge is one of the varieties of gas equipment, and its use can often be found in electrostatic filters, as well as in electro-gas-dynamic automation devices. Usually, a corona discharge is observed under conditions of sharply inhomogeneous electric fields [1, 2], in which a high field strength is achieved and its rapid decline with increasing distance from the ionization site, which prevents electrical breakdown of the gas-discharge gap.

The purpose of this work is to determine the current modes and the corona discharge form in air using an electrode with a small curvature radius.

The studies were carried out in atmospheric air ($p \approx 760$ Torr), with a constant voltage of both various sizes polarities. For the local electric field amplification, a thin needle 5 cm long, 0.32 mm in diameter, a tip radius of 40 μm and a tip angle of 9.5° was used as a high-voltage electrode. The corona discharge was ignited both at a separate electrode and between the tip and flat electrodes with a discharge gap of 1 to 4 cm. A flat electrode measuring 16x16 cm was used to facilitate the registration of the corona discharge current. The voltage at the electrode was supplied from high-voltage DC sources of positive or negative polarities with voltage $U_p \leq 25$ kV. Using a TDS 3034 oscilloscope (Tektronics, Inc.), the time characteristics of the voltage and discharge current were recorded.

At a positive voltage and an interelectrode gap of 2 cm, the ignition of a corona discharge was observed with $U_p \approx 5$ kV. At the electrode a «low-luminous cloud» appeared, the size and intensity of which grow with increasing voltage. $U_p < 9.8$ kV provoked the formation of streamer coronas, the length of which increased, in consequence of which they reached a flat electrode at voltages of about 13 kV. An increase in voltage above 15 kV led to the formation of a diffuse (glow) discharge, and then a spark discharge.

The amplitude of the discharge current pulses for positive polarity reached ~ 700 μA, which is two orders of magnitude greater than the negative one. This difference is explained by the absence of a streamer corona at a negative voltage polarity. The results of size measurements of the spherical-like corona glow area with a negative polarity showed that its dimensions also increase with grow voltage, but have a larger diameter than the positive-polarity corona with an equivalent voltage. The minimum ignition voltage of the negative corona was ~ 3.1 kV with an interelectrode gap of 2 cm.

The peculiarity of the negative-polarity spherical corona is the registration of repetitively pulsed current pulses (Trichel's pulses), following with a high frequency in a wide voltage range. The amplitudes of the discharge current pulses with negative polarity didn’t change significantly with increasing voltage, but the pause between the pulses decreased. It can be noted that the current pulse duration at half-height with a negative voltage on average was about 180 ns in the voltage range of -3.1 ... -12 kV, and at positive-polarity voltages, in the range of 11.2-13.6 kV, this value was ~ 250 ns.

Studies of the corona discharge emission spectra confirmed that the bands of the second positive nitrogen system in the UV area of the spectrum have the greatest intensity.

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PLASMA PARAMETERS OF DUAL DEEP OSCILLATION MAGNETRON SPUTTERING SYSTEM[1]

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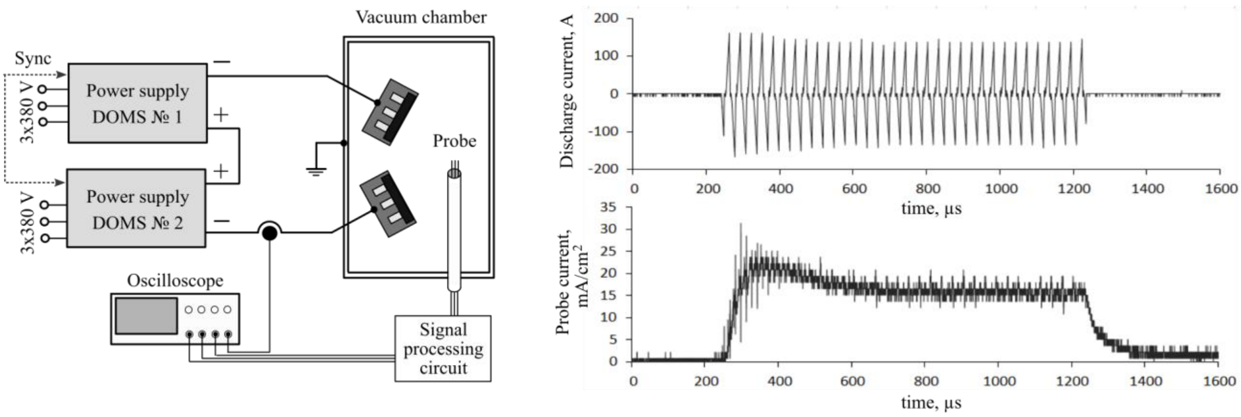
Deep oscillation magnetron sputtering (DOMS) is a new type of high power pulsed magnetron sputtering technology (HPPMS or HIPIMS) that allows to prevent the formation of arcs in the processes of reactive magnetron sputtering [1,2]. The report presents the results of an experimental study of the discharge formed by dual magnetron sputtering system (DMSS) with aluminum targets in the DOMS regime. To power the dual DOMS discharge, high-power bipolar microimpulse packages are used, which form a macroimpulse with a duration of 1000 ÷ 3000 μs, as shown in Fig. 1,b. Figure 1,a shows the connection diagram for DMSS, pulse power supply and measuring devices. Plasma parameters, such as electron temperature, electron concentration, the floating potential, plasma potential and ion current density on the probe were measured using triple and single Langmuir probes. Their dependences on the parameters of the discharge pulse power supply (voltage and current amplitudes, current density and power density on the target) were established. The use of dual DOMS regime allowed 5-fold increase of the discharge current density and 20-fold increase of the discharge power density, relative to DC and middle-frequency magnetron sputtering. The plasma concentration at a distance of 12 cm from the target surface reached a value of $7 \cdot 10^{11}$ cm^{-3}, and ion current density – 18 mA/cm^2. The decrease in the sputtering rate of aluminum by 70% together with an increase in the ion current density caused an increase in the degree of ion impact on the substrate, which is determined by the ratio of the ion flux density to the neutral atom flux density. In dual DOMS regime, this parameter is equal to 0.28, whereas, in traditional sputtering modes with the same average discharge power, it was approximately 0.01.



(a) (b)

Fig. 1. a) Experimental setup; b) Waveforms of target current and ion current density on the probe.

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PLASMA SOURCES AND EQUIPMENT

PLASMA SOURCE FOR GENERATION OF AUXILIARY ANODE PLASMA IN ELECTRON SOURCE WITH GRID PLASMA CATHODE*

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Intense electron beams sources are used in technologies for material surface treating. Insufficient electrical strength of the accelerating gap is the limiting factor of the introduction of plasma electron sources into the industry. In the paper [1], the authors used a discharge in the field of electron beam transportation to solve this problem, which allowed pre-ionization of the working gas before the start of beam generation.

In this work, we used an electron source with grid stabilization of the emission plasma boundary with a grid diameter of 40 mm and an operating beam current of up to 300 A [2]. The electron source is placed in an external magnetic field of 50 mT, in which studies of the operation of the discharge cell were carried out to create an auxiliary anode plasma based on an electrode system with a closed electron drift. The discharge cell had an annular anode with an inner diameter of 95 mm, located between two cathodes-magnetic conductors and a hollow cathode, the role of which was performed by the drift tube of the source. This discharge cell was introduced into the drift space of the electron beam at a distance of 10 mm or 70 mm from the emission grid of the plasma cathode, providing a discharge current of up to 3 A. It is shown that the most successful arrangement is the configuration of the electrodes of the auxiliary discharge cell, which is 70 mm from the emission grid. In this case, there is a constructive additional cathode, which can flaw the discharge current. Due to this, a plasma is created in the drift space, which makes it possible to close the current not only to the anode of the discharge cell, but also to the collector. As a result, the discharge current increases many times.

It has been established that even a weak discharge current (up to tens of milliamperes) makes it possible to reliably initiate the main arc discharge of the plasma cathode with a lower working pressure, reaching 7.2×10^{-3} Pa.

It was also established that the presence of the auxiliary discharge of several amperes makes it possible to improve the conditions for the generation of an electron beam at a low (less than 1.6×10^{-2} Pa) pressure in the first 15 μs of the source work. First of all, the improvement is due to the disappearance of high-frequency oscillations of the beam current.

In addition, the use of the auxiliary plasma anode reduces the training time of the accelerating gap due to ionic cleaning of the emission grid, which opens up new technological possibilities for electron sources of this type.

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PLASMA GENERATION IN THE ARC DISCHARGE WITH A THERMIONIC CATHODE IN CURRENT STABILIZATION CONDITIONS*

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The features of the operation of the plasma generator with a thermionic and hollow cathodes “PINK” in the discharge current stabilization conditions are investigated. The possibility of not completely closing of the thermionic electrons current into the external circuit under these conditions is shown. In this case, the electron current closes inside the device, inverting the hollow cathode current increasing the thermal load on the electrodes (fig. 1). The effect of the filament current intrinsic magnetic field on the discharge voltage waveform is also shown [1]. The main characteristics of the plasma in different phases of the filament current were also investigated.

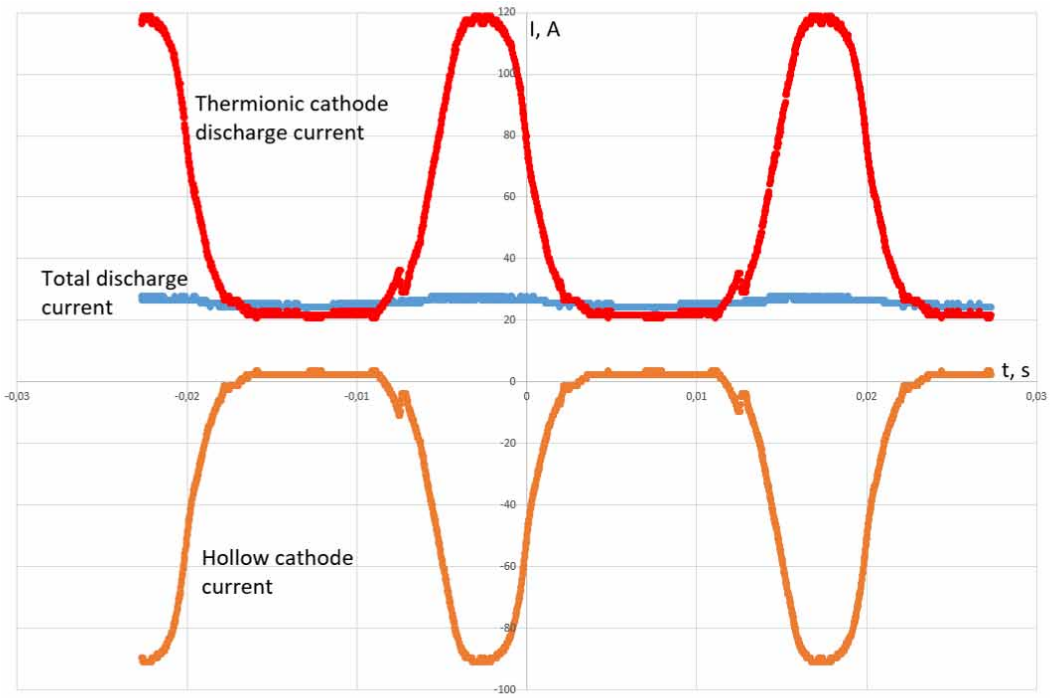

Fig. 1.Typical PINK current diagram.

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LOW-TEMPERATURE PLASMA GENERATION IN A NON-SELF-SUSTAINED GLOW DISCHARGE WITH A HOLLOW CATHODE OF EXTENDED AND COMPLEX SHAPE*

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A new method for processing the inner walls of curvilinear extended cavities, including pipes has been developed. A two-stage system for plasma generation at low pressure (0.2 – 1 Pa), was used. The main non-self-sustained glow discharge with a hollow cathode generates a working plasma in the cavity being treated. An auxiliary discharge plasma produced by the "PINK" plasma generator [1-3], was the source of electrons for stable ignition and burning of the main discharge. The curvilinear extended cavity for plasma generation was a tube made of stainless steel 12X18H10T (AISI 321) with a total length of 300 mm and an internal diameter of 25 mm, bended over at an angle of 90° in the middle. The inner surface of the tube was a hollow cathode of a non-self-sustained glow discharge, and the anode was a tungsten rod 4 mm in diameter, inserted through the end of the pipeline for a length of 40 mm. To determine the uniformity of inner surface nitriding, 5 samples of the same steel with a diameter of 6 mm were placed at an equal distance from each other. In the experiment on nitriding, the main non-self-sustained glow discharge burned at a voltage of 200 V and a current of 4 A, and the auxiliary discharge current of the plasma generator "PINK" was 2 A. The pressure of the gas mixture (Ar:N2 = 10:1) was 1 Pa. In this discharge burning mode, the temperature throughout the curved pipeline was in the range of (600 – 650) °C. After nitriding for an hour, the thickness of the modified layer was (50 – 60) µm, and the surface hardness increased from 2.6 GPa to 7 GPa. The proposed discharge system allows to achieve good homogeneity (Fig. 1) of the temperature distribution (± 3% of the average value) and the thickness of the modified layer (± 8.5 % of the average value).

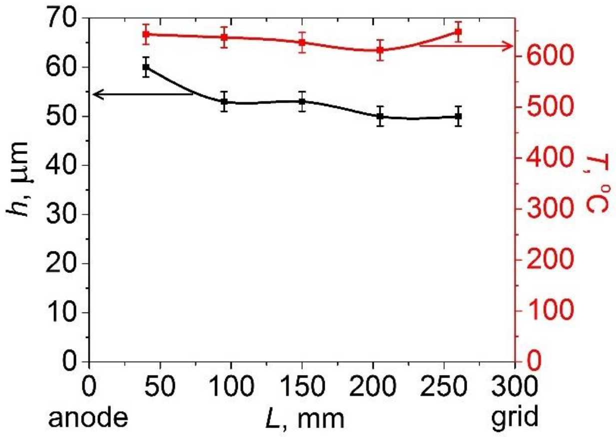

Fig. 1. The dependence of the distribution along the length of the cavity L of the thickness of the nitrated layer h and the temperature T in the curved cavity.

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ELECTRON BEAM GENERATION WITH VARIABLE CURRENT AMPLITUDE DURING ITS PULSE IN A SOURCE WITH A GRID PLASMA CATHODE*

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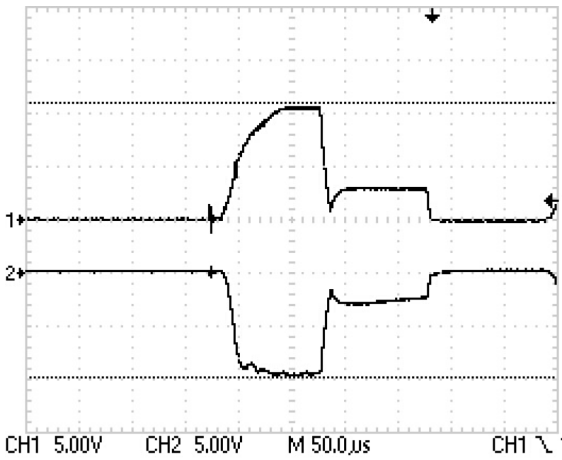
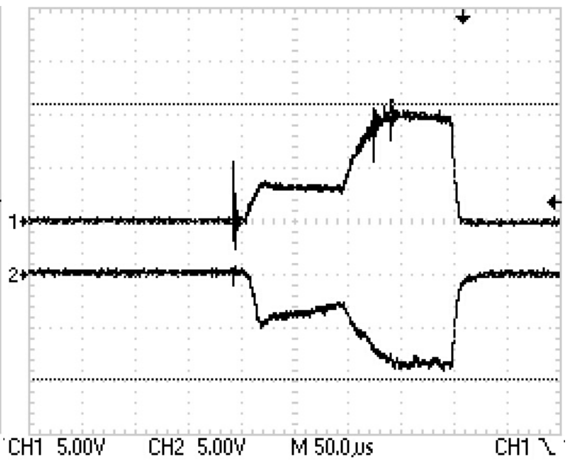
In electron sources with grid plasma cathodes, the boundary of the emission plasma is stabilized by a fine-structured grid, the cell size of which is comparable to the size of the Langmuir layer [1]. The correct choice of the cell size of the emission grid allows to stabilize of the emission plasma boundary, reaching a wide range of adjustment of the parameters of the generated electron beam with a weak dependence of these parameters on each other [1, 2]. Since the beam current amplitude is most often controlled by a proportional change of the discharge current in the plasma cathode, which allows to change the emission plasma concentration, this paper is investigated the possibility of generating the electron beam having variable amplitude by predicting the change in the discharge current amplitude during its pulse.

Figure 1 shows the characteristic oscillograms of the discharge current and the beam current obtained at the electron source «SOLO» included in the list of unique installations of Russia «UNICUUM». It can be seen from the oscillograms that the above-described advantage of plasma cathodes makes it possible to obtain electron beams with both a falling and a rising current amplitude of the beam during its pulse.

The obtained electron beam generation regimes open up new possibilities for using this source for both scientific and technological purposes.



a)



b)

Fig. 1. Осциллограммы тока разряда (*1*) и тока пучка (*2*), полученные в источнике электронов с сетчатым плазменным катодом «СОЛО». Масштаб: по вертикали – 100 А/дел., по горизонтали – 50 мкс/дел..

Fig. 1. Oscillograms of the discharge current (*1*) and the beam current (*2*), obtained in the electron source «SOLO» with a grid plasma cathode. Scale: vertical - 100 A/div., horizontal - 50 µs/div.

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IMPROVING THE UNIFORMITY OF THE DISTRIBUTION OF PLASMA CONCENTRATION IN THE NON-SELF-SUSTAINING LOW-PRESSURE GLOW DISCHARGE WITH A HOLLOW CATHODE[1]

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Electron-ion-plasma technologies for modifying the surface of materials due to their environmental friendliness and the feasibility of processing effects unattainable for other methods are widely used in industry [1]. In a number of works it was shown that the rate of nitriding in the plasma of low pressure discharges (≈ 1 Pa) can increase up to several times as compared with nitriding in an anomalous glow discharge [2-3]. This is due to the better cleaning of the surface of products from oxide layers in the plasma of low pressure discharges due to higher ion energy. However, to date, low pressure discharges have not found wide application for the chemical-thermal treatment of large-sized products due to problems in scaling, i.e. difficulties of homogeneous plasma generation in large vacuum volumes. A non-self-sustaining low-pressure glow discharge with a hollow cathode with the injection of an electron current of up to several tens of amperes makes it possible to achieve a plasma concentration of about 10^{18} cm^{-3} at a pressure of about 1 Pa with a degree of radial non-uniformity of about 13% in the volume of the vacuum chamber ~ 0.2 m^3, measuring about 600 × 600 × 600 mm [4]. In this work, studies were conducted to determine the effect of the hollow cathode material, the shape and location of the glow discharge anode on the azimuthal distribution of plasma concentration in the hollow cathode volume. During the experiments, hollow cathodes of steel grade 12X18H10T, titanium grade VT1-0 and with a surface coated with titanium nitride were used. The experimental results showed a significant influence of the shape and location of the anode on the degree of non-uniformity of plasma concentration.

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THE FORMATION OF POWERFUL PLASMA BUNCHES IN HIGH-CURRENT PLASMA GUNS WITH A DISCHARGE ON THE SURFACE OF THE DIELECTRIC*

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The paper presents the results of a study of the characteristics of plasma flows formed by high-current discharges over the surface of a dielectric capillary made of polyethylene, teflon and ceramics. In the experiment, the diameter and length of the capillary, the amplitude of the current (from several kA to tens of kA), the rate of current rise (τ_f – 250 ns, 420 ns, 1200 ns), the form of the current (oscillatory or aperiodic discharge mode) were varied. The optical and probe diagnostics were used to measure the plasma flow velocity. The probes were placed at a distance of 80, 130, 180 mm from the plasma guns (PG) (Fig. 1). The plasma flow velocity was measured by the time shift of the characteristic parts of the signals from the two probes. For optical diagnostics, a two-frame electron-optical complex "Nanogate Frame-9" with an exposure time of 20 ns was used.

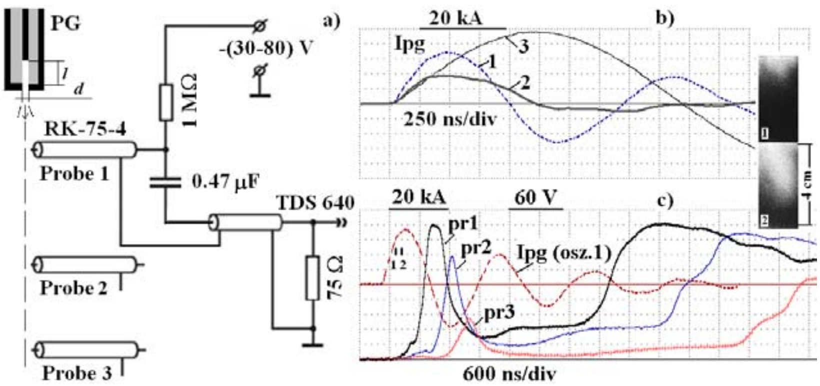

Fig. 1. Probe measurement scheme – a), discharge current forms in PG – b), characteristic signals from probes at Upr = – 60V for current form 1 – c), on the right – frames of 1.2 “Nanogate 2”, taken with an exposure of 20 ns at intervals of 180 ns.

In [1], the results of experiments with capillaries made of polyethylene for the rising current edge of ~ 1.2 µs are shown (osc. 3, Fig. 1). In the present work, the results for the rising current edge are ~ 0.4 µs (osc. 1, fig. 1). For capillaries with a length of l = 5, 10, 15 mm c d = 1.5 mm at a constant voltage on the power source Uc = 50 kV for a current of 7.3 kA, the speed of the first bunch (osc. pr1-pr3, fig.1, c) is constant within the measurement error. An increase in current to 13.4 kA leads to a synchronous increase in the average velocity for all lengths from ~ 11 to 13 cm / µs. For l = 15 mm, an increase in the voltage Uc from 40 kV to 55 kV (ΔUc = 5 kV) with an increase in the current in the capillary from 5.9 kA to 8.1 kA leads to a linear increase in the average speed by ~ 1.25 times (from 10 to 12.5 cm / µs). At a current of 10.7 kA (Uc = 40 kV) the speed is ~ 13/5 cm / µs, at a current of 13.4 kA (Uc = 50 kV), v ~ 14.5 cm / µs. Thus, an increase in the current in the capillary by ~ 2.3 times led to an increase in speed by 1.45 times ($v \sim I^{1/2}$). With a current in the capillary of ~ 7.2 kA, the transition from the oscillatory mode with a front of 420 ns (osc. 1, fig. 1, b) to aperiodic with a front of 250 ns (osc. 2, fig. 1, b) did not lead to a significant change in velocity.

For a teflon capillary with copper electrodes (d = 3.5 mm, l = 15 mm, I = 30 kA, τ_f – 420 ns), the main flow has a speed of ~ (4.5-5) cm / µs, a jet opening angle of ~ 20°, $n \sim 10^{15}$ cm^{-3}. For corundum (Al2O3, d = 2.2 mm, l = 5 mm, I = 7.4 kA, τ_f – 420 ns) with Al electrodes when injected from a 2 mm hole with a speed of ~ (4.4-5) cm / µs, using a mixer Laval nozzle type – v ~ (5.8-6.4) cm / µs. In both cases, the amplitude of the blower, having a speed of v ~ 10 cm / µs and a half-height duration of $\tau_{1/2}$ ~ 300 ns, drops sharply after 2-3 operations.

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THE DISTRIBUTION OF PLASMA PARAMETERS ALONG THE AXIS OF THE HOLLOW ANODE IN THE PLASMA ELECTRON EMITTER *

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Low pressure discharges (≈ 1 Pa) are used to harden the surface of materials and products in order to increase their lifetime [1]. A non-self-sustained discharge with a hollow cathode with the injection of an electron current of up to tens of amperes makes it possible to achieve a plasma concentration of about 10^{18} cm^{-3} at a pressure of 1 Pa with a radial inhomogeneity of about ± 13% in the volume of the vacuum chamber of ~ 0.2 m^3. The dimensions of vacuum chamber are about 600 × 600 × 600 mm [2].

However, in a system with an extended hollow cathode with a large length-to-diameter ratio of the hollow cathode (> 1.5) with a relatively small area of the output aperture of the emitting electron source, from which electrons are injected into the main glow discharge, an increase of inhomogeneity is noted. Electron injection can be performed not from the emission center of a small area located in the plane of one of the walls of the hollow cathode, but inside the hollow cathode from a relatively large area in order to reduce the inhomogeneity of the glow discharge plasma parameters. As an implementation of this concept, a system with a grid long cylindrical emission electrode was assembled. In this system, the injection of electrons is performed through the emission electrode to the cathode walls, due to which an increasing of the homogeneity can be achieved. The grid long cylindrical emission electrode is the anode of the electron source.

In this paper, plasma generation processes in a hollow long cylindrical grid anode of a non-self-sustained arc discharge with heated and hollow cathodes were investigated. The distributions of plasma parameters of a non-self-sustained low-pressure arc discharge were measured along the axis of the hollow anode. The effect of electron injection into the pulsed main non-self-sustained glow discharge on the parameters of an arc plasma in a hollow anode was determined.

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PLASMA SOURCES AND EQUIPMENT

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PROFILE FORMATION OF EMISSION CURRENT OF GRID PLASMA CATHODE IN A LONGITUDINAL MAGNETIC FIELD*

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The design of a gas-discharge system of a plasma grid cathode, designed to work with a pulsed electron source [1] that generates an intense low-energy electron beam transported in a longitudinal magnetic field, has been presented. The two-stage gas-discharge system, which includes the 1,3 initiating and main low-pressure arc discharge electrodes 3,5-8, generating an emission plasma, provides a discharge current of at least 500 A with a current pulse duration of 20-250 μs. An electron source with a presented plasma cathode allows generating a pulsed intensive (with a nominal current of up to 300A and a maximum of up to 500 A) a low-energy (up to 25 keV) electron beam transported in a longitudinal magnetic field of 0.02-0.05 T.

A feature of the gas-discharge system of the plasma cathode is the work in a non-uniform longitudinal magnetic field (5-30 mT), penetrating into it from the beam transport area, which can lead to compression of the discharge. By optimizing the geometry of the electrodes, the location and orientation of additional permanent magnets in the discharge system, a steady initiation and stable operating (without current interruptions) of the main discharge in the working range of the gas pressure (Ar) $(2\text{-}8)\cdot10^{-2}$ Pa has been achieved. A stable attachment of cathode spots on the Mg-insert surface of the discharge cathode and an axially symmetric discharge current flowing around the redistributing electrode 7 in a longitudinal magnetic field has been observed. Installing an electrode 7 with a large diameter provides an efficient redistribution of the discharge current over the surface of the emission grid 8. The initial distribution of the emission current over the beam section is controlled by changing the conditions of the discharge current flow around the electrode 7, which is achieved by adjusting the magnetic field penetrating the discharge system. When a beam is transported in a magnetic field, the profile of the electron beam changes with the formation of a maximum current density in its central part. By correcting the initial current distribution obtained from the plasma cathode (forming the beam profile close to the ring one), it is possible to eliminate the indicated maximum and to obtain a beam with a diameter of up to ≈ 35 mm with a heterogeneity of ± 10% of the average value.

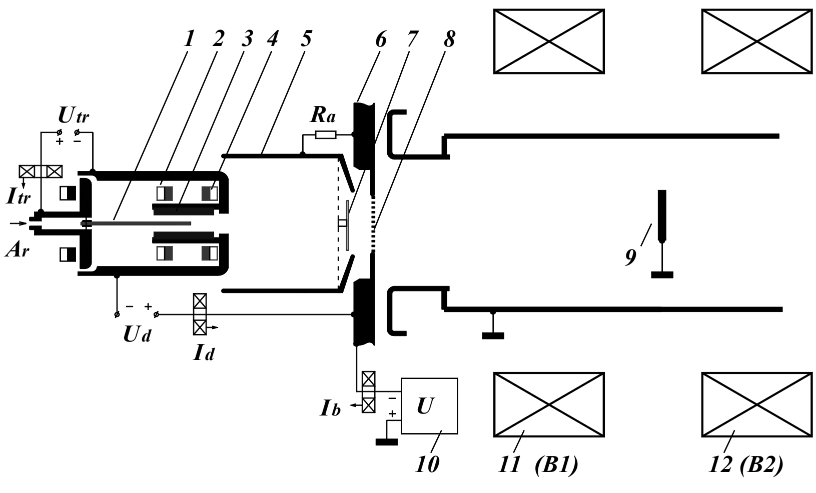

Fig. 1. Experimental setup: *1* – anode of ignition discharge, *2,4* – permanent magnets, *3* – Mg cathodes, *5* – anode insert, *6* – main discharge anode, *7* – redistributive electrode Ø 40 mm, *8* – emission grid window Ø 50 mm, *9* – collector, *10* – high voltage power supply, *11,12* – solenoids. *Utr* – ignition discharge power supply, *Ud* – main discharge power supply.

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THE DEFLECTION OF A WIDE ELECTRON BEAM FROM THE LONGITUDINAL AXIS OF THE SOURCE WITH A PLASMA CATHODE AND PLASMA ANODE*

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The interaction of the electron beam with the target leads to intense gas desorption, evaporation of contaminants from the target surface, to the melting of the target, as well as to ionization of the vapors by the electron beam, forming a collector plasma. These pairs can reach the emission electrode, contaminating its surface, therefore, reduce the electrical strength of the accelerating gap [1]. The presence of a collector plasma leads to the formation of an ion flow, which either charges dielectric inclusions on the grid, or causes a violation of the layer stabilization of the emission plasma boundary, which also reduces the electrical strength of the accelerating gap [2].

To eliminate this problem in this work, it was decided to carry out the deflection of the electron beam from the longitudinal axis of the source. In the experiments, an electron source with a plasma cathode with grid stabilization of the boundary of the emission plasma and a plasma anode, the boundary of which is open, was used. The dotted line circled the developed magnetic system of the electron beam deflection, consisting of solenoids 1-5 and sector tap 6. Solenoids 7, 8 are located on the drift tube for transporting the beam.

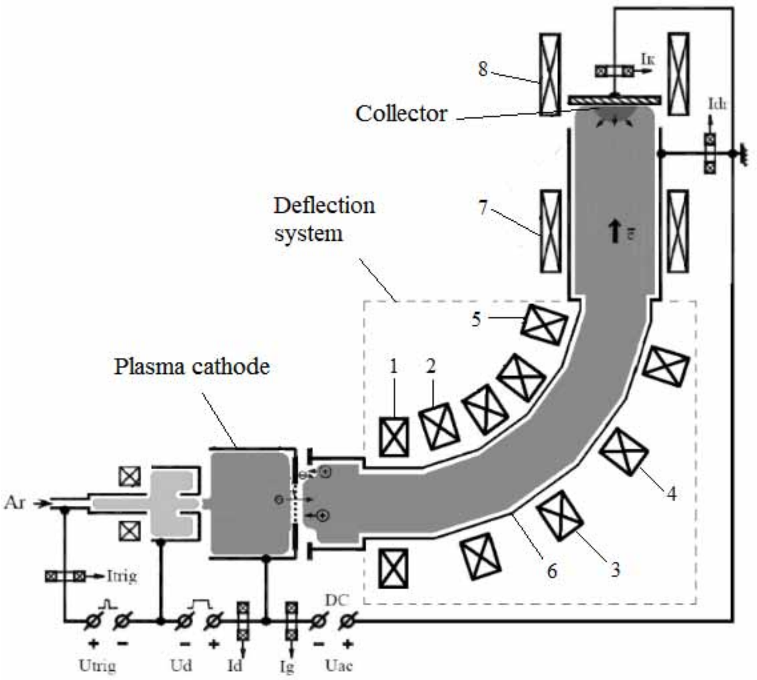

Fig. 1. Scheme of a pulsed beam installation with a plasma cathode

It was experimentally shown that the introduction of an electron beam deflection system into the design of the source described allows an increase in the electrical strength of the accelerating gap up to 6 times, and thereby expand the limiting parameters of the electron beam. It was also found that there are different mechanisms of electrical breakdown of the accelerating gap: the first is associated with the total energy content of the beam, and the other with the violation of the stabilization of the boundary of the emission plasma.

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OPTICAL EMISSION STUDY OF PLASMA VORTEX RINGS AT ATMOSPHERIC PRESSURE AIR*

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Reactive turbulent vortex rings are traditionally of scientific interest, in particular, in the tasks of intensification of combustion processes [1], interaction with flames [2]. It was reported about the formation of plasma vortex rings during the expansion of a pulsed plasma jet in atmospheric air [3]. The optical emission of such structures considerably exceeds the time of the energy deposition. The physical properties of such multiphase vortex flows are generally poorly studied.

The paper presents the results of high-speed optical emission study of plasma vortex rings. The device for generating is similar to described in [3]. The spectrums were recorded using a high-speed CMOS spectrometer with a resolution of 1.5 nm and a frequency of 1400 fps. The emission spectrums in the time interval up to 11 ms after the start of the outflow were registered. Fig.1 shows the recorded spectrums corresponding to 0.725 and 4.60 ms.

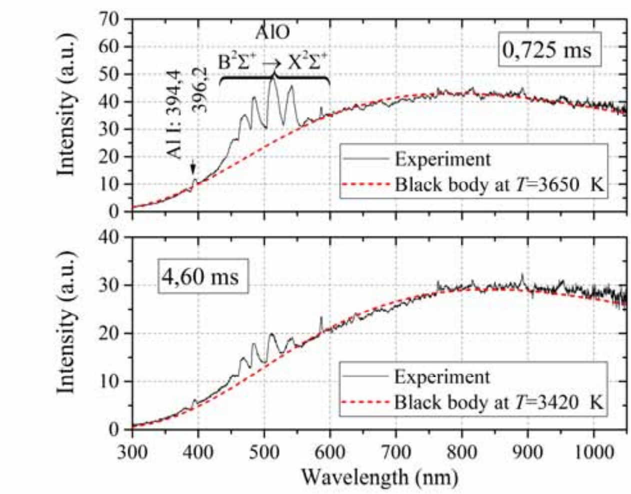

Fig. 1. The emission spectrum of plasma vortex ring

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HIGH-SPEED IMAGING PYROMETRY OF PLASMA VORTEX RINGS AT ATMOSPHERIC PRESSURE AIR*

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Under certain conditions, the pulsed injection of plasma jets into atmospheric air leads to the formation of large-scale vortex plasma structures. Their afterglow time considerably exceeds the energy deposition times [1]. Interest in such formations is largely due to the prospect of creating high-intensity optical radiation open-sources [2]. For the construction of theoretical models of such objects, it is necessary to know their temperature characteristics.

The present study is concerned with investigation of temperature dynamics of plasma vortex rings. A pulsed electrothermal plasma generator based on a localized electrical explosion of wire was used to generate the vortex rings.

Studies were conducted using a developed high-speed imaging pyrometer. The system based on high-speed monochrome camera Videosprint (NPK Videoskan, Russia) and optical filters with transmission maximum wavelength at 475 nm and 16 nm FWHM. The spectral sensitivity is located in the spectral band regions of AlO that makes it possible to detect regions with the most active reactions. Fig. 1 shows the temperature map of the vortex ring in the late stage of its afterglow.

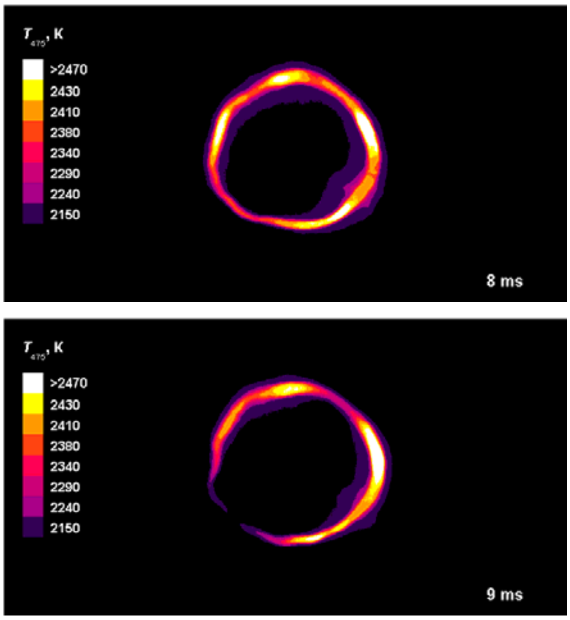

Fig. 1. Spatial temperature map of plasma vortex ring.
Frame size - 0.75 x 0.4 m.

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FOIL LINER IMPLOSIONS WITH A NANOSECOND RISE TIME OF CURRENT THROUGH THE LINER*

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Experiments on implosion of aluminum foil liners with a diameter of up to 2 mm were carried out on the high-current MIG generator (2 MA, 80 ns) with a current rise time through the liner of about 1 ns. To reduce the rise time of the current through the liner to 1-2 ns, the liner area is pre-filled with plasma with ion density of 10^{16} -10^{17} cm^{-3}. Fast current switching to the liner is realized in the process of sweeping the injected plasma by the generator current (J × B force) in the "snow plow" mode [1]. Since the acceleration time of the liner with the initial radius r_0 to a given velocity v is about $\tau = 3r_0/v$, reducing the rise time of the current through the liner and, therefore, the liner implosion time allows to reduce its radius. The Rayleigh-Taylor (P/T) instability has the most destructive effect on the process of liner implosion. In the linear stage of P/T instability development, the increment of longitudinal perturbations is $\gamma = (kg)^{0.5}$. Here k is the perturbation wave vector; g is the liner acceleration. For a fixed wave vector k, the determining growth of perturbations during the liner acceleration time τ integral $\int\gamma dt \propto \gamma\tau \propto \tau g^{0.5} \propto \tau(v/\tau)^{0.5} \propto \tau^{0.5}$ is proportional to the square root of the liner acceleration time τ to a given velocity v. In addition, it is well known that the most dangerous are perturbations with a wavelength λ close to the thickness of the liner Δ. This is due to the increment increases with decreasing λ, and the perturbations with $\lambda < \Delta$ in the nonlinear stage of their development go into saturation mode. With a constant liner mass per unit of its length $m = 2\pi r_0 \Delta\rho$ (ρ is the density of the liner material) its thickness is $\Delta \propto 1/r_0 \propto 1/\tau \propto 1/k$ and in this case $\int\gamma dt \propto \tau$. That is, reducing the time of liner acceleration to a given velocity and a corresponding decrease in its initial radius leads to an increase in the stability of the liner implosion. Note that reducing the initial radius of the liner implies a corresponding decrease in its final radius. This reduction may be, for example, proportional with a fixed degree of the liner radial compression or higher due to a higher degree of the liner radial compression because of the above-mentioned stabilization of the liner implosion.

The paper presents experimental results for shots with 8-µm-thick aluminum foil liners. Liners with initial diameters from 0.65 mm to 2.0 mm were used. With the rise time of the current through the liner 1-2 ns, the implosion time of such liners ranged from 7 ns to 35 ns. Dynamics of the liner Implosion was numerically calculated using a 0-dimensional model and assuming that the current instantaneously switches to the liner at the time of the first radiation peak (associated with the fast explosion of the skin layer on the surface of the liner and the formation of a layer of high-temperature dense plasma [2]). A satisfactory agreement between the experimental and calculated times of liner implosion is noted. This indirectly confirms that the time of the current switching to a 10-mm-long liner does not exceed 2-3 ns.

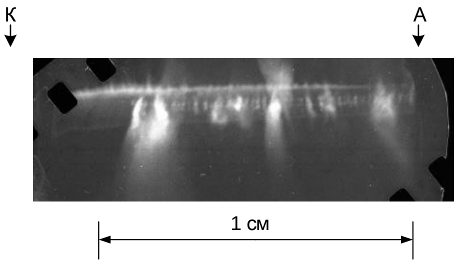

Fig. 1. Side-on time-integrated soft x-ray image for a shot with a 0.65-mm diameter, 8-mm length aluminum liner. The image shows emission from the surface of the liner, and on-axis formed pinch.

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EVAPORATION OF POLYCRYSTALLINE SILICA-ALUMINIUM CATHODE IN CATHODIC ARC VACUUM DISCHARGE

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Introduction. The most widely used technologies of silica and silica containing coating production are the sol-gel, CVD methods, magnetron sputtering in vacuum [1] and ion-beam sputtering. Alternative method for continuously coating is the evaporation with vacuum cathodic arc in arch-like magnetic field (steered arc) [2, 3, 4]. This method provides with high film density, fine film adhesion, high performance without thermal cracks of the cathode. At present vacuum arc discharge on silica cathode in the arch-like magnetic field is studied insufficiently. The report is devoted to the investigation results of the magnetic field influence on the discharge parameters and erosion products composition of the silica-aluminum cathode.

Experiment. The work was carried out with the butt cathodic arc evaporator with cathode diameter 150 mm [2]. The discharge current was from 19 to 25 V, induction magnitude of arch-like magnetic field varied from 0 to 13 mT. The characteristics of macroparticles were investigated within thin films on the substrates placed on 240 mm from the cathode surface with the help of confocal and atomic force (AFM) microscopes.

Results. It was shown that increasing of magnetic field induction from 0 to 13 mT leads to discharge voltage changing from 19 to 25 V. At that tame the cathode spots motion velocity increases from 1.5 to 5 m/s. Further increasing of magnetic field induction leads to the discharge instabilities. Increasing of the spots motion velocity provides with cathode erosion rate decreasing from $5.3 \cdot 10^{-8}$ to $3.2 \cdot 10^{-8}$ kg/C (in 1,6 times) (Fig. 1).

The statistical characteristics of the macroparticles on the substrate and in the plasma flow were obtained. It was shown that increasing of the magnetic field induction on the cathode surface decreases particles number on the substrate up to 1.5-2 times. At the same time the decreasing of mass fraction of the particles in the coating from 0.3 to 0.2 takes place (Fig. 2). It was shown that most of macroparticles mass is transferred with the droplets in plasma of 0 to 0.8 um diameter.

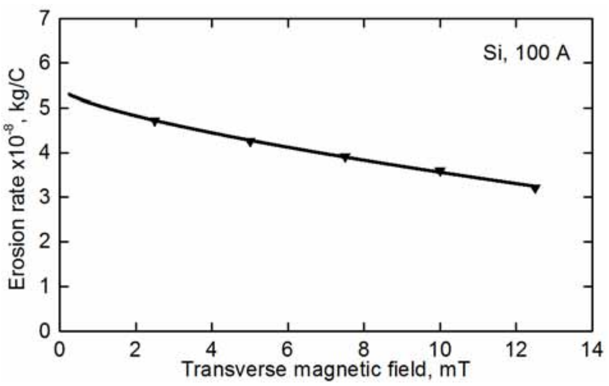

Fig. 2. Decreasing of silica-alumina cathode erosion rate with increasing of magnetic field

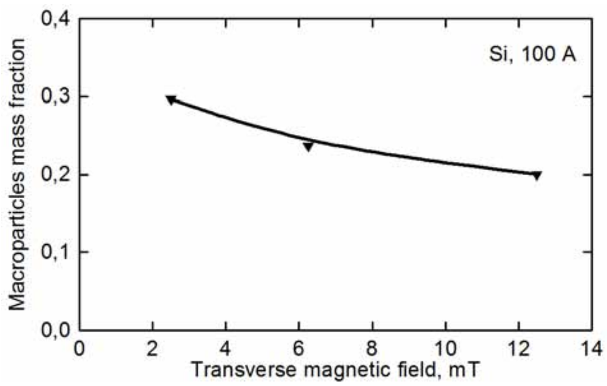

Fig. 3. Decreasing of macroparticles mass percentage in coatings with increasing of magnetic field

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EXPERIENCE OF FORMATION OF COMBINED LOW ENERGY ELECTRON-ION BEAMS IN PLASMA SOURCES OF CHARGED PARTICLES

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One of the methods to increase the efficiency of ion sources used for deposition of thin-film layers of metals, semiconductors and dielectrics is the use of high-current electron emitters to support ionization processes and ensure stable discharge burning, compensation of both the volume charge in the beam, and the surface charge on the formed film. Currently, thermal emitters are used for these purposes [1]. However, under conditions of intense ion fluxes, the resource of such emitters is limited due to intense ion bombardment. Therefore, the search for these purposes of non-termal emitters of electrons is quite relevant. Low-energy electron beams are also of interest for the implementation of plasma-chemical processes and technologies for deposition of films and coatings for various purposes using alternate or simultaneous thermophysical electron and modifying ion effects.

In systems with a plasma emitter, the production of low-energy compensating electron beams is possible either due to energy recovery or by creating optimal conditions for the formation of such beams directly at the source. In the formation of electron beams of the required geometry in systems with a plasma emitter, the position and shape of the emitting plasma surface are decisive. They, in turn, are determined by the plasma parameters, the characteristics of the beam-forming system (the potential and geometry of the forming electrodes), and the magnitude of the reduced field strength accelerating the electrons.

The paper shows the possibility of forming combined electron-ion beams in a single multi-bit structure that does not contain incandescent elements. The design of the electrode structure of an electron-ion source, consisting of two gas-discharge cells of the “Penning” type [2] connected in series (along the axis), is proposed. It is shown that the interrelation of separately controlled discharges in the structure contributes to an increase in the degree of gas ionization under reduced pressure, as well as to the formation of double electric layers in the plasma, ensuring the formation of combined ion-electron flows in a single structure. This is achieved by creating conditions for the electron beam to drift through the entire part of the electrode structure, which ensures the formation of the ion current of the source, and contributes to an increase in the degree of gas ionization in this region. In addition, the deceleration of the electron beam in the gap of ion acceleration ensures the return of electrons that have lost some of their energy to the ionization of the gas to the region of the formation of the ion-emitting plasma. This contributes to an increase in the density of the ion emission current.

The possibility of separate control of the accelerating voltages of electrons and ions in the developed structure provides for regulation in a wide range of ratios of the energies of electrons and ions, as well as the densities of their currents in the electron-ion beam. This expands the range of possible technological application of the electron-ion beam source.

The results of the research indicate the promising application of the developed structure for the design of technological sources of combined electron-ion beams.

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PLASMA SOURCES AND EQUIPMENT

PULSED JETS FOR DENSE PLASMA GENERATION IN AN EXTERNAL MAGNETIC FIELD [1]

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The calculation of pulsed jets of a capillary discharge with an evaporating wall is presented. A plasma source [1-17] based on a plasma jet formed at the end of a capillary discharge at atmospheric pressure is considered.

A mathematical model of a system of pulsed plasma jets flowing into a submerged space, based on the equations of radiation plasma dynamics, written in arbitrary curvilinear coordinates, is developed. Radiation and gasdynamic processes arising in a system of capillary discharges with an evaporating wall, which expire in a submerged space, are numerically investigated. Calculations of all the main gasdynamic and radiative parameters of a capillary discharge system with an evaporating wall are made. A numerical simulation are carried out and spatial distributions of pressure, temperature, velocity and Mach number in a pulsed jet of a capillary discharge and a system of pulsed jets of a capillary discharge with an evaporating wall at different points in time are obtained.

These jets flow from an array of capillary discharges located nearby with an evaporating wall. The interaction of the peripheral parts of pulsed plasma jets emanating from a capillary discharge with an evaporating wall affects external shock waves separating the plasma of each capillary discharge with the evaporating wall from the gaseous medium (air) in the submerged space. In this region, two shock waves collide with a noticeable increase in the values of gasdynamic parameters in the interaction zone (pressure and density increase approximately two times). At the same time, outside the interaction zone (for a given time point), the thermo-gasdynamic parameters of a capillary discharge with an evaporating wall correspond to the values in the plume of a single capillary discharge. Note that all noted phenomena require further detailed and comprehensive study.

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TANDEM ANALYZER OF PLASMA FLOW IONS BY ENERGY, MASS AND CHARGES*

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The main areas of application of ion analyzers for energy, mass and charge are the study of the surface of solids, the study of the structure of matter and the processes of interaction in collisions of particles in gases and plasma, in particular, with the location of the analyzer in the area occupied by the plasma.

In our case, it is proposed to perform energy, mass and charge analysis in a tandem of successively located energy analyzers with retarding potential (RFA) and Wien linear filter (WF), and ion detection is performed on a detector located at the output of the tandem of two analyzers (Fig. 1a). The sequence of analyzers in tandem can be reversed: linear WF – RFA (Fig. 1b).

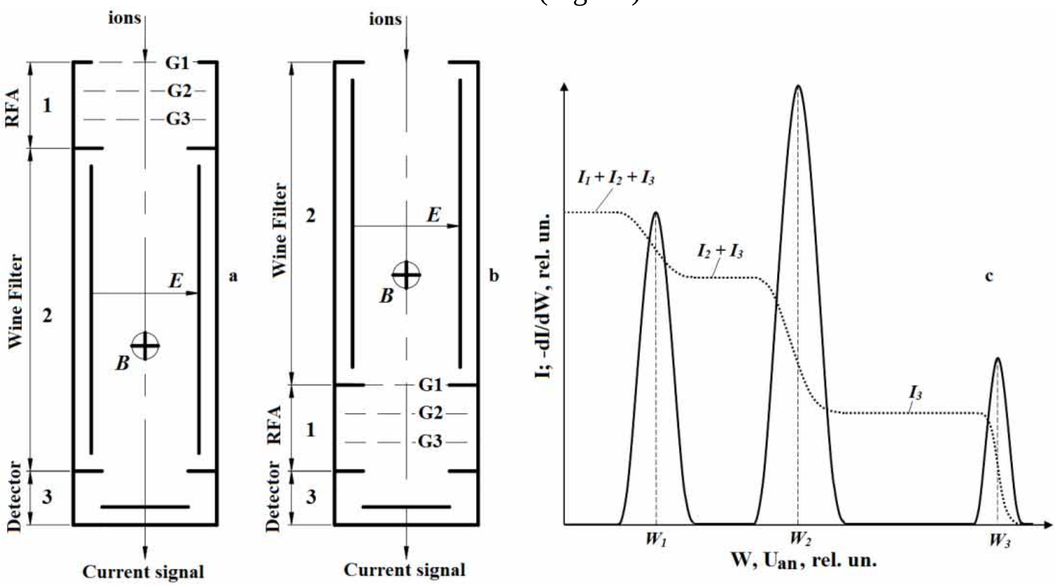

Fig. 1. Tandem analyzer of plasma flow ions by energy, mass and charges: a, b – analyzer options; c – for option Fig. 1a current I of the detector when registering a three-component flux of ions having a wide energy spectrum W with masses m_1, m_2 and m_3 at a fixed setting WF and changing the potential of the analyzing (G3) grid U_{an} RFA from zero to the value $eU_{an.max}$ ensuring locking of all the incident ions flow; $\boldsymbol{E}$ – electric field strength; $\boldsymbol{B}$ – magnetic field induction.

Let there be ions of three masses m_1, m_2, and m_3 in the flow, with $m_1 < m_2 < m_3$. On the detector, the mass ions m_1 will not disappear until the decelerating field of the G3 RFA grid reflects the ions of mass m_1 with energies from the initial minimum $W_{min.1}$ to the tuning energy WF $W_0 + \Delta W$, where ΔW is the energy resolution of WF. On the delay curve $I = f(U_{an})$, the current in these conditions will be defined as $I = I_1 + I_2 + I_3$ (see Fig. 1c). With a further increase in U_{an}, the ions of mass m_1 leave the area of the WF tuning, the signal from these ions disappears. On the delay curve, the amplitude of the current decreases to the level $I = I_1 + I_2$. For even larger values of U_{an}, the contribution from the ions with mass m_2 will disappear and the ion current will be determined only by the current of particles with mass m_3. The current from the detector will become zero at $eU_{an} \geq W_{max.3} + \Delta W$. On the delay curve, the current steps will be visible, the number of which is equal to the number of different masses of the ions in the incident flow – 3 in our case.

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A CALIBRATION METHOD FOR PHOTOELECTRIC RADIATION DETECTORS FOR MEASURING HIGH-INTENSITY PULSED SOURCES

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With the development of high-intensity pulsed radiation sources (RS) such as laser and flash lamps the task of detecting the temporal nature of the radiation power was actualized. In this case the following requirements on radiation detectors are imposed: high temporal resolution (no more than 0.1 of light pulse rise time), long-term stability, reliable calibration technique with a relatively small error.

Pyroelectric sensors with a wide variety of receiving surfaces sensitivity and long-term stability are the most widely used for laser radiation measuring. However, in case of continuous-spectrum flash lamp the broad spectral range of the detected radiation and inconstancy of the spectral sensitivity complicate the interpretation of measurement results.

To study the radiation parameters of continuous lamps, photodiode based radiometers with a built-in integrated amplifier are widely used. Calibration methods for such detectors are simple and have a small error (≈ 5%). The low temporal resolution and absolute sensitivity of the detector, as well as the presence of an integrated amplifier, do not allow the recording of high power short pulses.

On the other hand, photodiodes themselves have a high temporal resolution and the selection of sensitivity for any RS is not a laborious task. A wide choice of the spectral sensitivity ranges makes it easy to personalize a problem solving and to calculate the emissivity of the RS with a relatively small error.

However, the calibration of such detectors is a time-consuming task, requiring a reference high-intensity radiation source with a known spectral distribution. The error of such methods is usually at the level of 15%.

This article describes a method for calibrating a photodiode device for detecting high-intensity radiation pulses using continuous lamps. The method based on using an attachable integrated amplifier with a calculated and confirmed by measurements time constant. Based on the value of the detector's sensitivity (obtained during calibration) and time constant, the correlation coefficient between the radiation power and the photodetector response is mathematically obtained.

This technique was tested on the example of a xenon flash lamp with a half-height pulse duration of ≈ 55 μs.

POWERFUL SOURCE OF VUV-UV RADIATION BASED ON NANOSECOND VOLUMETRIC DISCHARGE

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When applying a high-voltage subnanosecond pulse (< 1 ns) to a coaxial matched low-inductance gas chamber at an air pressure of 1 atm, a powerful volumetric discharge is obtained emitting in the VUV-UV range.

To form a volume discharge, a modernized generator (250 kV) with a pico-nanosecond (0.1–5.0 ns) pulse duration and a current of 5 kA with a pulse repetition rate of 0.1–12.5 Hz is used. This device, like the previous one [1], is made according to the hybrid Tesla generator scheme, where the output circuit capacity is divided and its components C1 and C2 form a two-stage Marx generator. Unlike the device [1], the components C1 and C2 of the Marx generator have a special design and their capacity is adjustable. These capacitors are charged in the first semi-period of the Tesla generator operation. The VUV-UV spectrum and the kinetics of intense flares were measured in the spectral range of 12 – 200 nm using the complex (VMS-1, PEM-142, PEM-31, p-i-n diode FDUK-1UVSKM, Tektronix TDS3032B). The duration of VUV-UV plasma pulses < 1 nc is achieved in air, Ar and He at a pressure of 1.0–1.5 atm. The emission spectrum of emission of a powerful volumetric gas-discharge plasma source has a VUV boundary about 12 nm. A preliminary analysis of the experimental results shows that the spectral maximum of plasma emission lies in the range of ~ 25–30 nm and the surface power density is about 10^7 W/cm^2 at a stored energy of the discharge of 200 mJ.

In the volumetric discharge mode, plasma emission is observed only in the VUV-UV spectral range. A different picture takes place in the development of a streamer mode of the discharge over the nanosecond duration of the generator. In this case, the spectrum of less intense radiation of the plasma is located in the visible range. Such a significant difference in the energy, spectral and kinetic characteristics of the volumetric and streamer discharges is explained by the magnitude of the discharge gas volume. The discharge streamer has a cross-section of 1–3 μm, a large length, but a very small discharge volume. Therefore, the resistance of the streamer channel is significant; the discharge decay time reaches 300 ns and the discharge power drops sharply. Since the radiating volume of the streamer is small, the unexcited volume of gas effectively absorbs the VUV-UV radiation of the streamer and its spectrum is observed only in the visible spectral range. On the contrary, for the case of a volumetric gas discharge, with the same length of the discharge gap, its volume (~2 cm^2) exceeds by eight orders of magnitude the volume of the streamer and occupies the entire active zone of the chamber. In this case, the dynamic resistance of a volume discharge becomes negligibly small, the duration is <1 ns and its power is more than four orders of magnitude higher than the power of the streamer discharge.

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PULSED FIELDS INFLUENCE ON PIG ION SOURCE PERFORMANCE

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Penning ion sources (PIG IS) with self-sustained discharge have some disadvantages particularly expressed in pulsed or frequency regimes. It seems interesting to investigate the possibility of its pulsed magnetic field modulation by appropriate coils with rather large pulsed currents [1]. These fields may trigger the Penning discharge at its initial absence. However, the attempt to simply place an ordinary PIG IS into a solenoid can hardly bring to success due to the field "scinning" and the conductors as well as magnetic materials availability inside the IS [2].

But if instead of coils plane spiral antennas playing roles of PIG IS cathodes are used the difficulties noted above disappear. At that the antenna metal may contact plasma and γ-processes are significant but may also be isolated from it and in this case the discharge excitation occurs only due to the volume ionization (α-processes). Using different types of coils without contact with plasma one may get capacitively coupled plasma (CCP) instead of inductively coupled (ICP) and the decisive role will play just the curl electric field, not magnetic [3]. In fact both are significant but their mutual effect differs in different antennas and currents configurations.

To trigger discharge antennas shown in fig. 1 have been investigated. The estimating fields calculations have been made for antenna (a) at the discharge of the 20 nF capacitor charged to IS anode potential (3 kV) in the RLC contour. Active resistance of this contour R=0.2 Om, its inductivity L=0,5 μH is appreciated with the help of the on-line calculator [4] at the turns number – 8, external diameter – 19.8 mm, wire diameter 1 mm and distance between turns 0.2 mm. Different combinations of the capacitor coupling to the antennas being IS cathodes are examined: both are always at the earth potential (keys – spark-gaps are located between the capacitor and the cathodes); one or both of them are in the initial moment at the anode potential; currents directions during the pulse are the same or opposite. In the later case the pulsed magnetic fields form the monocasp trap. Variants with auxiliary constant magnetic field or without it are investigated.

The calculated pulsed fields – magnetic as well as curl electric one have been used to plasma characteristics estimation according to the method presented in the "plasma module" [2]. These estimations have been made for different hydrogen pressures in the cell of 3 cm length, 2 cm anode height and 60 mT inductivity static magnetic field. This plasma module doesn't allow one to calculate the discharge (anode) current and the extracted ion current determined by ion optics. That's why the presented experimental data for different configurations allow one to appreciate advantages and shortcomings of this PIG IS pulsed performance concept.

Fig. 1. Spiral (a) and twin (b) antennas as well as double spiral antenna.

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*DEVELOPMENT OF ROTATING AMBIENT-AIR ARC JET FOR LOW-TEMPERATURE TREATMENT

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Recently plasma activated water (PAW) is attracting a lot of attention owing to a huge number of possible agriculture and medical applications such as seed germination promotion and disinfection.[1] There are many ways to produce PAW, such as atmospheric pressure plasma jets (APPJ) and dielectric barrier discharge (DBD); however, generation of this type of discharges typically requires expensive high voltage power supply and special gasses (such as He or Ar) to generate the plasma.[2] Turbulent gas flow and small size are making treatment of large targets and powders impossible. Moreover, requirement of special gasses and problems with scaling are limiting conventional DBD APPJ to laboratory studies and research applications. Taking into account problems described above, thermal arc discharges seem to be promising for the development of APPJ considering high density of plasma, wide range of possible parameters of the discharge and possibility of generation of the discharge in ambient air, which allows to perform plasma irradiation using simple experimental setup and reduce treatment costs. Moreover, arc discharge is easily scalable, which could be essential for medical and agricultural applications. However, the high temperatures of ambient-air plasmas lead to serious damages and burning of samples. To overcome the problems, we have developed portable rotating arc generator operated using ambient air flow and investigated the effects of experimental conditions on properties of the discharge and generated in the discharge species.

Arc discharge was generated using high-voltage transformer operated by a push-pull generator, diode rectifier and reservoir capacitor. Discharge gap was organized between rod and ring electrodes by placing tip of the rod electrode to a center of the ring electrode. Ring electrode was surrounded by toroidal magnets for rotation of the arc in the discharge gap. Custom cooling system was developed to prevent heating of the electrodes. Discharges were generated in ambient air with flow rate of air varied in a wide range.

Using the setup described above, it was succeeded to generate rotating arc discharge in ambient air at various flow ratios using small input power (below 50 W). Type of the discharge was changed from spark to low-current arc discharge with increase of input power. Change of type of discharge was clearly observed in the OES spectra and current and voltage waveforms. Discharge parameters and gas flow ratio were tuned to prevent the electrodes heating and keep gas at room temperature after the interaction with the plasma. It was succeeded to generate stable rotating arc discharge at small air flow ratio (0.25-1 slm) and low input power (35W). Low flow rate of air during operation allows to overcome problem with turbulence typically observed in conventional APPJs, which could be essential for treatment of large samples and powders.

Species generated in plasma were analyzed using optical emission spectroscopy (OES) and quadrupole mass spectrometry. Effect of input power and flow rate on the plasma parameters and generation of species were studied and optimized. Rotating arc jet was applied to treatment of water and concentrations of RONS in produced PAW were analyzed using VUV absorption spectroscopy and deconvolution of absorption peaks. It was found, that concentrations of RONS after treatment using ambient-air arc jet was more than 100 times higher than that of PAW produced using conventional APPJs operated with He gas and the same irradiation time.

Construction of the ambient-air rotating arc jet, effect of the experimental condition on concentrations of produced RONs and possible application of rotating arc jet to sterilization of the bacteria will be presented.

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Angular Distributions of Mass and Charge Flow in Plasma Beam Generated High-Voltage Nanosecond Surface Flashover in Vacuum

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In this work we studied the features of angular distributions of plasma flow generated by linear high-voltage nanosecond surface flashover in vacuum. We used the generator with glycerol-filled coaxial forming line. Parameters of the generator are as follows: impedance 25 Ω, stored energy 2 J, voltage 80 kV, voltage pulse duration in match-load mode 30 ns, pulse rise time 2 ns, discharge current 3 kA, current pulse duration 30 ns (first half wave). The samples used were polyethylene (PE), polymethylmethacrylate (PMMA) and polytetrafluorethylene (PTFE).

We measured the distribution of mass flow, density of ions current and ions speed. The distribution of mass flow was measured by the deposition of the flow on thin copper and mica plates. Ion current of plasma flow and ions velocity distribution were measured by the Faraday cup.

We obtained that for all the tested materials the flow of mass as well as the flow of charge are concentrated in thin layer in the equatorial plane (which is normal to the axis of the discharge). The full width of the angular distribution at half maximum is 10 degrees for meridional plane and 60 degrees for equatorial. Also, we observe asymmetry in distribution of ions flow in meridional plane. Probably, the anisotropy of plasma expansion may be caused by the geometry of the current path. In the work we discuss the plasma acceleration mechanisms which may be responsible for these distribution patterns.

POWER SUPPLY FOR OBTAINING THE LOW-TEMPERATURE PLASMA JET*

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In our days, the plasma jets and a plasma sources based on the atmospheric-pressure discharges in the gas flow attract considerable interest not only the researchers but and for the technology and medicine applications [1–7]. The common property for this kind of systems for obtaining the plasma jet is allowing the gas flowing through the discharge gap and a plasma area [1–8]. A wide variety of the electrode configurations, the gases types, and the discharges types are used in the atmospheric-pressure plasma sources [1–8].

The present paper describes results of the investigation of glow discharge burning modes when powered by the high-voltage power supply whit the reactive ballast intended for obtaining low-temperature plasma jet. In the considered system, plasma jet is obtained by using the DC glow-like discharge sustained in the non-steady-state low-current plasmatron with coaxial electrodes. Specialized power supply provides an output voltage up to 6 kV for initiate the discharge, and then realizes discharge current limiting mode. Maximal value of the glow discharge current limited at level about of 140 mA by impedance of inductive-resistive ballast. One of the significant differences of the investigated power supply system from the classical circuit with resistive ballast is the low-frequency modulation of the output voltage, which provides a significant ripple of the discharge current magnitude.

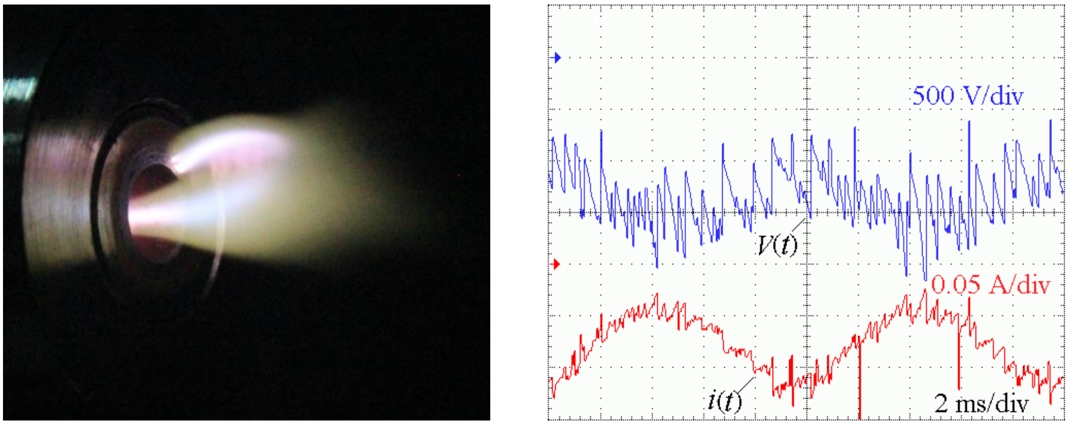

Fig. 1. Photography of plasma jet on the exit of plasmatron nozzle and the glow discharge burning voltage and current waveforms. $V(t)$ – discharge burning voltage, $i(t)$ – discharge current. The gas flow rate G(air) = 0.1 g/s.

Interpretation of the experimental data obtained as a result of the analysis of the waveforms of the discharge current and the discharge burning voltage allows us to reveal the specifics of the DC glow discharge sustaining when powered by the proposed supply system.

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PLASMA SOURCES AND EQUIPMENT

ONE–SEC PLASMA SOURCE FOR FLOW FORMING IN SMOLA DEVICE [1]

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The key problem of plasma confinement in open traps is the suppression of particle and energy losses from the ends. To solve this problem, the concept of screw plasma confinement was proposed [1]. It consists in the creating magnetic plugs moving in the reference system of plasma, whose motion relative to the plasma is created by rotating it in crossed electric and screw magnetic fields. This process is reversible and redirection of plugs movement out of device permits to accelerate the plasma. SMOLA device has been designed and developed for experimental verification of this confinement concept at the BINP SB RAS.

The present work is devoted to the study of the plasma source in the SMOLA device. This axisymmetric system creates a plasma jet by a magnetically insulated discharge with a hot LaB_6 cathode [2]. Using an infrared heater, the cathode is heated to T ~ 2000 K, and the electrons emitted by the cathode ionize and generate plasma with a density of n ~ 10^{13} cm^{-3} and T ~ 5 eV at a distance of 0.4 m from the gun anode. To optimize the transport and confinement of the plasma in the trap, it is important to monitor and regulate the primary parameters of the plasma jet. For this purpose, a diagnostic complex has been created. It includes measuring instruments for electrical parameters of discharge, vacuum, as well as power systems control for all high-power circuits.

In this work, the dependences of the plasma jet parameters on the initial conditions of the experiment will be presented, and the influence of the cathode heating, the amount of gas feeding, the amplitude of the cathode voltage on the plasma properties will be assessed.

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SWITCHING DEVICES - EPTRON WITH 100 KV OPERATING VOLTAGE AND A SUB-NANOSECOND SWITCHING TIMES*

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The results of experimental studies of the switching characteristics of the device with subnanosecond switching time, which combines two types of discharges: an open discharge as a plasma source and a capillary discharge which allows fast recovery of electrical resistivity in inter-pulse period and relatively high delay of the breakdown development after applying operating voltage. Two types of capillary structures were tested. First one had a coaxial structure with discharge cross-section 0.16×10 mm^2, assembled from flat circular discs that had 0.16×25 mm hole in the center and separating rings with internal diameter of 10 mm and 20 mm. The total length of the gap was 60mm, the length of separating discs and the capillary structure was 56 mm. Ceramic elements from BeO and ring elements from Al_2O_3 were placed outside the capillary structure in order to prevent outside discharges, this allowed device operation at a voltage up to 110 kV. Unlike [1], the capillary was located at the end of the coaxial kivotron outside. The second capillary structure differs from the first by enlarged slit size of 0.3×10 mm, which made it possible to exclude the effect of runaway electrons from the breakdown process.

Two types of the return conductor were used. First one was a wire conductor with a diameter of 3 mm, removed from the capillary by ~ 40 mm. Second had a coaxial structure with an external conductor diameter of 50 mm. It turned out that for both capillary structures the delay in the development of the breakdown was much greater in the case of the coaxial external conductor, which is associated with the development of a bias current that removes charges from the capillary wall. In other turn, the current-voltage and frequency characteristics of the capillary of the second type were much better. Thus, the working pressure of helium at U = 100 kV for the first capillary was ~ 2 Torr and for the second one equaled ~ 6 Torr. As a result, for the second type of capillary, discharge development delay time remained almost unchanged up to 10 kHz in a burst mode (10 pulses in a burst) with a switching power of 5 kW and up to 2 kHz in the regular pulse mode with a switching power of 1 kW.

PLASMA SOURCES AND EQUIPMENT

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IMPROVING PULSE REPETITION RATE WITH A COMBINATION OF CAPILLARY AND OPEN DISCHARGES*

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Results of experimental studies of the frequency and switching characteristics of devices that combine open discharge, used as a plasma source, and capillary or slit discharge, that provides fast recovery of electrical resistivity in the inter-pulse period, are presented. The difference from the previous work [1] is in the usage of devices with an external placement of capillary or slit discharge sections connected to the part in which open discharge (kivotron) is realized.

Two different device types were investigated. First one was a coaxial construction 50 mm long which consisted from alternate Al_2O_3 rings of 2 types with 8 mm outer diameter and inner of 1 and 5 mm respectively. The other one was a planar construction with a slit that had a cross section of 0.3 mm ×10 mm, assembled from Al_2O_3 plates with dimensions of 40 × 60 mm. In the last case a cooling radiator or a water cooling jacket can be placed directly on the slit wall and at the same time can be used as a return conductor with a minimum inductance of the order of ~ 20 nH.

With a coaxial capillary a planar open discharge cell without the counter propagating electron beams and a coaxial kivotron similar to [1] were used. With a slit construction a planar kivotron with a drift space of 10 mm was used.

It turned out that the removal of the capillary from the inside of the kivotron negatively affects the breakdown development delay and the rate of the electrical strength recovery after a pulse, reducing both parameters by more than an order of magnitude relative to [1]. The main difference between these options is the distribution of the electric field strength during of the voltage raising on the device, which in [1] prevented the straight propagation of electrons to the anode through the capillary, and the breakdown delay time increased. To solve this problem, a casing with the potential of the cathode was put on the outer capillary surface, which one also served as a return conductor with low inductance. In this configuration value of f = 100 kHz with U_a = 30 kV, p_{He} = 3.5 Torr in the case of planar and with p_{He} = 2.6 Torr in the case of coaxial device was achieved.

Device with a slit showed better characteristics than one with a capillary: lower switching time, higher repetition rates, longer delay time, lower residual voltage (≤5% with a the slit and ≤10% with a capillary).

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CREATION OF PLASMA COLUMN TO GENERATE THZ-RADIATION DUE TO ELECTRON BEAM-PLASMA INTERACTION *

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PLASMA SOURCES AND EQUIPMENT

Stable propagation of a kiloampers beam of relativistic electrons (E-beam) in a plasma column and collective deceleration of its electrons at plasma oscillations significantly depends on local plasma parameters. Requirements for plasma parameters are highly controversial. In particular, to form plasma current that ensures beam neutralization both in charge and in current density high plasma conductivity is required. On the other hand, it is necessary to provide an intense beam-plasma interaction at a high level of plasma oscillations that to be transformed into electromagnetic waves going out from plasma to surround space. Nevertheless, such level of plasma oscillations leads to turbulent pulsations of the electromagnetic field in the plasma, accordingly to significant decreasing of plasma conductivity and to breakdown of the current density neutralization for the E-beam. For pumping of plasma oscillations by the beam, it is required suitable plasma density with its acceptable homogeneity. At the same time, to localize the spatial region of maximum beam-plasma interaction on the installation length, one has to create necessary plasma density distribution along the axis of the column. In addition, for the effective transformation of the upper-hybrid oscillations pumped by the E-beam into electromagnetic waves, a plasma density gradient with a strictly specified angle with respect to magnetic field lines is required. We have constructed and are using the system for creation of the plasma column to carry out beam-plasma experiments at GOL-PET facility with taking into account the pointed circumstances. One has to mention at this activity we applied experience accumulated at the creation and operation of GOL-3 and GOL-3T facilities [1].

A high voltage discharge system to create the plasma column at the GOL-PET facility has the following structure. A vacuum chamber made of stainless steel is placed in a magnetic solenoid. The solenoid generates a magnetic field with induction that can be varied up to 4 T. The total length of the vacuum chamber is 300 cm and it is pumped out through its ends. At one end of the chamber, on the side of E-beam injection into the plasma, a quartz tube of 70 mm inner diameter with graphite diaphragms bounding the plasma column in diameter of 50 mm is installed inside the chamber. At the end of the quartz tube, where the E-beam is injected into plasma through a magnetic mirror with an induction up to 7 T, a dense cloud of krypton is fed by a pulse valve. This cloud serves as the cathode of a high-voltage (20kV) discharge. An anode electrode of a high-voltage discharge, which consists of two electrically insulated half-rings, is installed in the middle part of the quartz tube at 40 cm distance of from the point of beam entry. The inner diameter of the half-rings is the same as the inner diameter of quartz diaphragms. A high voltage pulse is supplied on these half-rings independently of each other. It allows creating a different distribution of the discharge current over the cross section of the column and thereby varying the plasma density distribution over its cross section with a diameter of 6 cm. Pulsed feeding by hydrogen into the chamber is carried out by pulse valves installed in its various sections along the length. By varying the delay between starting the discharge current and the moment of fast valves opening, one can obtain various configuration of the plasma density distribution along the length and the cross section of the plasma column. In providing experiments, we measure the current in the coils of the magnetic field and the currents flowing through the anodic semi-rings and through the plasma column in the vacuum chamber. During the discharge current with a duration of 10 μs, fast cameras recorded the optical glow that goes along the axis and across the plasma column. The plasma density distribution of the plasma column at eight points along its diameter was measured by 1.03 μm laser radiation scattering. Integral density value over the plasma column diameter is measured using an interferometer at a wavelength of 10.3 μm. Thus, in the course of experimental studies, various variants of plasma density distribution were obtained. The results of these studies are described in the present report.

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HIGH-CURRENT PULSE NON-SELF-SUSTAINED GLOW DISCHARGE WITH CURRENT UP TO 1 KA [1]

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In the pulsed combustion mode of a non-self-sustained glow discharge with a hollow cathode, the plasma concentration of about 10^{18} cm^{-3} at a pressure of about 1 Pa in the volume of the vacuum chamber ~ 0.2 m^3 was achieved while injecting an electron current of up to several tens of amperes [1]. The degree of plasma ionization in this case is about 1 %. Plasma with a higher degree of ionization is of considerable scientific and practical interest for the formation of electron beams of submillisecond duration with increased (tens of A/cm^2) and ion-plasma product treatment in chambers of large vacuum volumes (>0.1 m^3).

In this paper, the modes of plasma formation in a pulsed non-self-sustained glow discharge with a hollow cathode of about 0.2 m^3 with currents up to 1 kA at a current of injected electrons up to 200 A were investigated. As a result of the probe measurements of plasma parameters, their value in the center of the hollow cathode was obtained and the degree of plasma ionization was calculated.

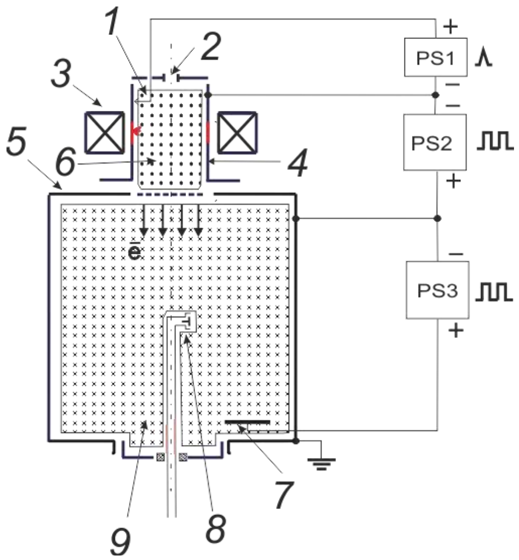

Fig. 1. The scheme of experimental installation. 1 - trigger, 2 – gas input, 3 – magnetic field coil, 4 – hollow cathode of auxiliary arc discharge, 5 – hollow cathode of main glow discharge, 6 – plasma of auxiliary arc discharge, 7 – anode of glow discharge, 8 – plane probe, 9 – plasma of glow discharge, PS1 – trigger power supply; PS2 – arc discharge power supply; PS3 – glow discharge power supply.

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SMALL ANODE DISCHARGE ION SOURCE

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Ion source modification is proposed for efficient production of ion beam and extending of operating Lifetime [1,2]. Ionization efficiency of the Bernas type ion source has been improved by using a small anode-thin rod, oriented along the magnetic field. The transverse electric field of small anode transport plasma by drift in crossed field to the emission slit. Optimization of the cathode material recycling is used to increase the operating lifetime. Optimization of the wall potential is used for suppression of flakes formation. A three-electrode extraction system was optimized for low energy beam production and efficient space charge neutralization. An ion beam with emission current density up to 60 mA/cm2 has been extracted from discharge in BF3 gas. Ion beams of ^{11}B isotope with intensity up to 6 mA for 3 keV, up to 11 mA for 5 keV, 18 mA for 15 keV have been transported through the analyzer magnet. Design of SAS ion source is shown in Fig. 1. Dependence of ^{11}B current on the discharge current for small anode ion source and for Bernas are presented in Fig. 2. Close solution is proposed in [3].

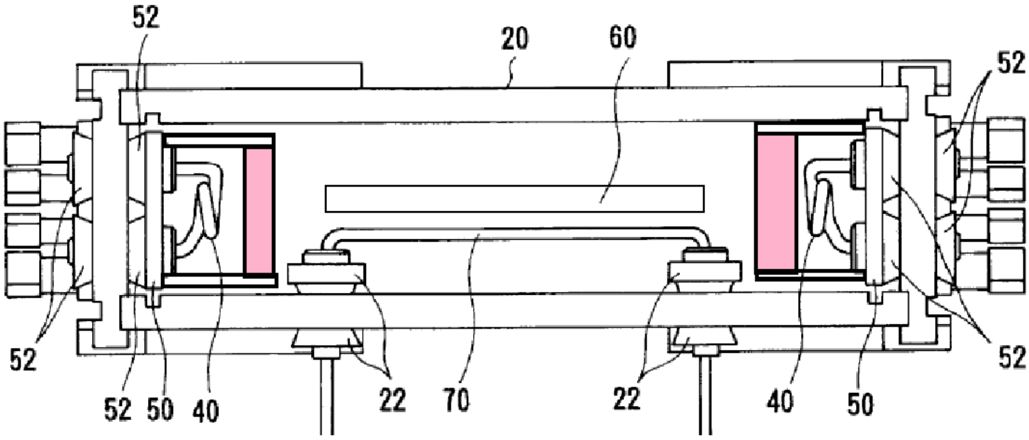

Fig. 1. Design of SAS ion source

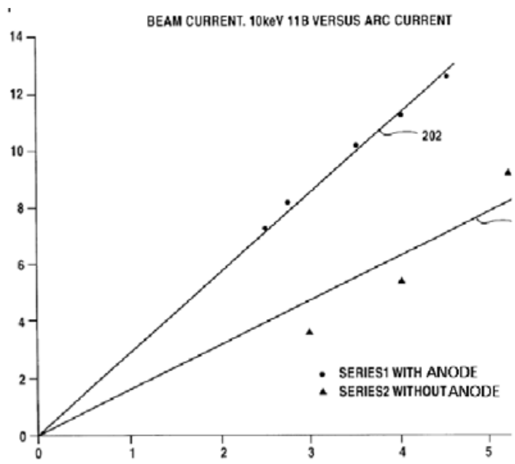

Fig. 2. Dependence of ^{11}B current on the discharge current for small anode ion source and for Bernas type ion source

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