MONTE-CARLO SIMULATION OF THE IONIZATION PROCESSES FOR DISCHARGES IN THE LEFT BRANCH OF PASCHEN'S CURVE*

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The paper deals with the development of the simulation methods as applied to the low-pressure discharges in which the reduced electric field *E*/*p* is extremely high and there exists a problem for the correct description of the ionization processes in the classical electron avalanches. In some conditions, the electron free path for ionization can be comparable with the interelectrode gap so that the notion of electron avalanche is not applicable at all. Typical examples are the discharges in the so-called pseudospark switch and in the plasma sources of electron and ion beams [1].

It seems that one of the computer codes that would be applicable for discharge modeling in such conditions is the PIC/MC xoopic [2, 3]. This code offers a possibility to compute the spatial and temporal distribution of electric field self-consistently with the temporal changing of the excess space charge of electrons and ions. The block taking account the ionization processes is based on the Monte-Carlo method. One of the advantage is that the computer program has the open code and we are able to modify the primary data on the cross sections and the calculation algorithm in accordance with the particular problem, which is solved [4].

Here we use the above code for calculation of the impact ionization coefficient α, the electron drift velocity and the electron diffusion coefficient *D* in the electron avalanches in nitrogen. The range of calculations covers the ratio *E*/*p* ≤ 1000 V/(cm·Torr). An example of calculation of the coefficient α is presented below.

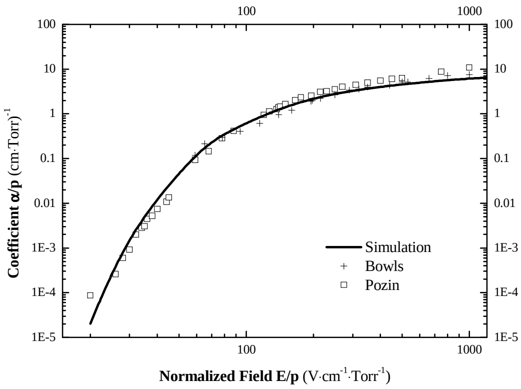

Fig. 1. Coefficient α from simulation (nitrogen, 20 Torr) and experiments [5].

Formally speaking, even for extremely high reduced electric fields we have a reasonable agreement with the experimental data. However, the interpretation of the results in terms of the electron avalanches for *E*/*p*≥ 1000 V/cm leads to incredibly high electron diffusion coefficient and electron temperature at a level of $kT_e \approx 30$ eV, i.e. larger than the ionization potential [4]. The data on spatial distribution of electrons in the gap, obtained with a usage of Monte-Carlo simulation, show that for a moderate *E*/*p* values the electron cloud is located inside the gap and has a spherical shape. As for the high *E*/*p*, we can hardly speak of the electron avalanche in its generally accepted representation. Here the electron cloud does not have space and time to take shape in the gap. The physical reasons for the described effect and the features of ionization at high *E*/*p* are discussed in detail in the present paper.

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PLASMA TRANSFER AS A WHOLE*

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Sunce the first systematic studies of the beginning of the last century, the concept of local ionization-recombination equilibrium is dominant in describing the balance of charged particles of gas discharge plasma. Calculations of the characteristics of gas discharge plasma are based on models of local equilibrium [1], whereas fields observed experimentally at high pressures that are low for ionization are explained by the multi-stage processes of particle production in the bulk [1, 2]. However, electron and ion fluxes coming from the near-electrode layers at moderate and, especially, atmospheric pressures, are sufficient to ensure the balance of particles in the discharge plasma without ionization in the bulk [3]. Moreover, if we consider the motion of charged particles of the positive column in detail, it is easy to see that even in a classical discharge at low pressures (0.01-1 *Torr*) particles with different signs of charges recombining on the walls in the selected tube cross-section (S) come from different parts of the discharge (Fig. 1). The positive ions (i) moving in the cross-section under the action of ambipolar diffusion simultaneously have a velocity component directed from the anode. The electrons (e) coming to the tube walls together with these ions arrive from the cathode side, and the overwhelming number of electrons generated in the cathode layer pass through the entire tube volume to the anode practically without losses. Only at low pressures (of the order of 0.01 *Torr* and less) the areas of generation and death of particles can be comparable with each other, although this is also quite questionable, since the mean free path becomes comparable to the radius of the tube and the physical meaning of the concept of local balance is lost.

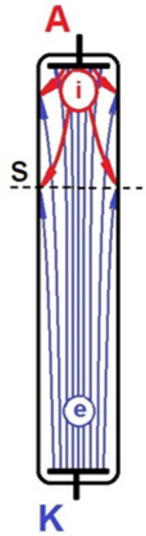

Fig. 1 Diagram of the motion of charged particles in a tube.

In our papers we show [4-7] that at moderate and atmospheric pressures not only fluxes from the electrode side determine the longitudinal structure of the discharge, but also the plasma transfer as a whole [8], together with the thermal potential nT and the plasma electric field energy potential $\rho\varphi$ determine the transverse structure of the discharge. Moreover, bulk ionization and recombination losses are not considered. It is shown that the atmospheric pressure stationary discharge [9, 10] exists only in a well-heated gas when molecular ions are absent and the losses are determined by ambipolar diffusion [11].

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PREBREAKDOWN CURRENTS IN THE TWO-SECTIONED COLD-CATHODE THYRATRON AND THEIR ROLE IN MECHANISM OF STATIC BREAKDOWN*

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The data on measuring the prebreakdown currents and the static breakdown voltages as applied two-sectioned sealed-off thyratron TPI1-10k/50 are presented [1]. Schematic of the thyratron and illustration of the method of measurement are shown in Fig. 1.

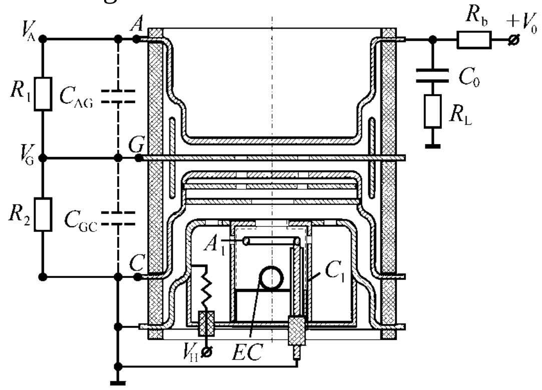

Fig. 1. Schematic of experiment. *A* – main anode, *C* – main cathode, *G* – gradient electrode, V_H – voltage at the heater of hydrogen reservoir. C_0 = 10 nF, R_b = 7.5 MΩ, capacitance of the upper section C_1 = 40 pF, capacitance of the lower section C_2 = 29 pF.

In the experiments, we measured the prebreakdown currents, the static breakdown voltages in the thyratron as a whole V_{br} and the breakdown voltages and prebreakdown currents in the separate sections of the device. The summary of the data are shown in the table below, where V_{br1} is the breakdown voltage of the upper section, V_{br2} is the breakdown voltage of the lower section. V_{Acr} is a critical anode voltage with which the static breakdown voltage at the lower section would be achieved if the voltage over the sections were distributed in accordance with the capacitances C_1 and C_2.

V_H, В	6.0	6.1	6.2	6.3
V_{br}, кВ	> 45	42	24	17
V_{br1}, кВ	> 45	32	20	14
V_{br2}, кВ	20	10.5	9	6
V_{Acr}, кВ	34	17.8	15.9	10.2

The static breakdown voltage of the upper section of the device is higher than that for the lower section. Then when we increase the voltage V_0, the prebreakdown current initially appears in the lower section. In the conditions of absence of the resistive divider R_1-R_2, we revealed that the prebreakdown current leads to effect of redistribution of the anode voltage over the sections. The essence of the effect can be illustrated, for example, by the data shown in the column V_H = 6.1 V.

When the anode voltage approaches to V_{Acr} = 17.8 kV, the prebreakdown current starts flowing in the lower sections. This means that certain resistance of the discharge R_d is connected in parallel with capacitance C_2. The capacitance is discharged via R_d, so that the voltage V_1 decreases and the prebreakdown current disappears. We have the situation when the voltage V_2 turns out to be lower than V_{br2}. Further increasing of the anode voltage results in stabilization of the voltage V_2 and an increase in the voltage V_1. The breakdown occurs when the static breakdown voltage is achieved both at the upper and lower sections. Due to this effect the maximum possible breakdown voltage of the device is realized ($V_{br} = V_{br1} + V_{br2}$).

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MECHANISM OF HIGH EFFECTIVE GENERATION OF ELECTRON BEAMS IN HIGH-VOLTAGE DISCHARGE IN HELIUM AND ITS MIXTURES WITH NITROGEN AND OXYGEN.*

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High-voltage discharges in helium and its mixtures with oxygen for a long time are used to generate electron beams (EB) in medium-pressure gases. Nevertheless, the question of the most important properties of such discharges, in particular, the current-voltage characteristics, the efficiency of the generation of electron beams, the mechanisms of electron emission from cold cathodes, and the effect of helium purity on these parameters are debated up to this day. In this report, studies of the current – voltage characteristics and the efficiency of generation of EB in discharges in helium and its mixtures with nitrogen and oxygen have been conducted.

Studies were conducted in carefully outgassed cells with helium of purity no worse than 99.999%. It turned out that under these conditions, the I – V characteristic with a pressure of more than 10 Torr, as the voltage rises, realizes an exponential law of the I – V characteristic, then slows down its growth until a falling portion is obtained, and at a voltage higher than 1.5 kV, the rapidly increasing characteristic with current density $I = U^y$ with the value of y = 5-15. The appearance of the current – voltage characteristics in the initial region is explained by the exponential dependence of the Townsend multiplication factor α on the voltage U. As U increases, the growth of α slows down, passes a maximum, and then α rapidly decreases. The emission of electrons in the initial segment is carried out under the action of ions, metastable atoms and photons and weakly depends on U. At U> 500-600V, electron runaway from the cathode fall region begins to play a significant role, which, together with the fall of α, leads to a fall in the IVC. At U> 1.5 kV, an electron beam is formed, the photo-illumination of the cathode by resonant VUV radiation is amplified, and the current – voltage characteristic again acquires a rapidly increasing character. At U> 3.5kV, due to the predominance of photoemission, the efficiency of generation of EBs reaches 85%.

The introduction of oxygen or nitrogen in small quantities (less than 2%) dramatically increases the discharge current --- up to two orders of magnitude and, at a helium pressure of less than 4 Torr, increases the efficiency of generation of EF. This increase is associated with a large value of <γ> - kinetic emission under the action of fast molecular particles. In turn, the high value of <γ> is due to the interaction of fast heavy particles with the surface layers of cathodes doped with these particles. The results obtained make it possible to interpret from the unified point of view the entire diversity of the I – V characteristics in the discharges both in pure helium and in mixtures with molecular gases and to determine the conditions for achieving highly efficient generation of EB.

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FEATURES OF THE DISCHARGE DEVELOPMENT UNDER THE ACTION OF A TRIGGER PULSE IN THE TRIGGER UNIT OF SEALED-OFF COLD-CATHODE THYRANRON*

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Currently, high-current switching devices based on low-pressure hollow-cathode pulsed discharge (so-called pseudospark switches) are widely used [1-5]. The design and principle of operation of these switches are close to those of a classical hot-cathode hydrogen thyratrons. However, these devices do not have a hot cathode. Therefore, pseudospark switches are often called cold-cathode thyratrons or thyratrons with a grounded grid [6–8].

As in the case of classical thyratrons, a range of operating pressures of the switch corresponds to 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 thyratron and for external discharge triggering a considerable pre-breakdown electron current is required [6-8]. For the case of external triggering, this current is provided due to a special trigger unit that is placed in the main cathode cavity. Various types of the trigger units are presented, for example, in [2, 9, 10].

By now, the sealed-off metal-ceramic devices have been developed and manufactured. The first devices have been described in the review [9]. Currently, these devices are commercially produced in the Pulsed Technology Ltd. (Ryazan, Russia, http://www.pulsetech.ru). Different triggering methods have been employed in these devices. In particular, in the thyratrons of the TPI type, the trigger unit is based on an auxiliary glow discharge [2, 10].

The operation conditions of the auxiliary glow discharge substantially affect the thyratron characteristics as a whole [10-13]. In particular, this concerns the breakdown voltage, the time delay of breakdown in the main discharge gap with respect to the triggering pulse, and the pulse repetition rate. Therefore, considerable attention is paid to the choice of the operating modes of the auxiliary discharge and the design of the electrode system of the device.

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, auxiliary glow discharge ignition occurs over the “long path” and suitable discharge burning and ignition voltages are provided. Different schemes of auxiliary discharge powering and triggering schemes were tested. Features of the auxiliary discharge development under the action of a trigger pulse were investigated.

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EFFECT OF STREAMER VELOCITY ON THE CHARACHTERISTICS OF DYNAMIC DISPLACEMENT CURRENT*

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Currently, great attention is paid to research of streamer discharges in non-uniform electric fields [1–3]. Despite significant progress, there are still many unexplained phenomena and effects. It is known that breakdown in the gap with a high level of overvoltage occurs as a result of propagation of a large-sized streamer (ionization wave) [2, 4]. In this case, when the streamer is formed and moves along the gap, the current caused by the redistribution of the electric field (dynamic displacement current, DDC) flows through it [4]. It is evidently that the rate of the redistribution of the electric field should be determined by the propagation velocity of the streamer and the change in its shape. Therefore, the DDC magnitude is related to the streamer velocity. The results of the simulation aimed at finding the relationship between the dynamic displacement current and streamer velocity are presented in this study. The simulations were performed with the KARAT code [5], based on the analytical axisymmetric model of the conductive channel moving at a given velocity [6] and having a finite conductivity. The xoopic code [7] was used to verify the model. The actual parameters (dimensions and velocity) of a conductive channel estimated from the experimental data obtained using a four-channel ICCD camera was used in the simulation. An experimental setup (diode, detectors, etc.) used in the analytical estimates and modeling, completely repeated that used in the experiment. The analytical model confirmed the experimentally observed fact: the flow of significant current in a circuit and the voltage drop across a diode, depending on the parameters of the conductive channel. In the moving cathode model, the start of the channel motion and the time instant corresponding to the gap bridging were selected in accordance with the experimental dynamic displacement current waveform. The result obtained with the KARAT code is presented in Fig. 1a. The calculations were performed for two modes: constant V_{const} and dynamic V_{dyn} speed of a moving channel (Fig. 1b). The results of simulations (V_{dyn}, Fig. 1a) performed with the model implying the dynamic streamer velocity confirm the experimentally observed features of streamer motion in a "point-to-plane" gap, as well as the corresponding voltage drop across the diode and the DDC magnitude.

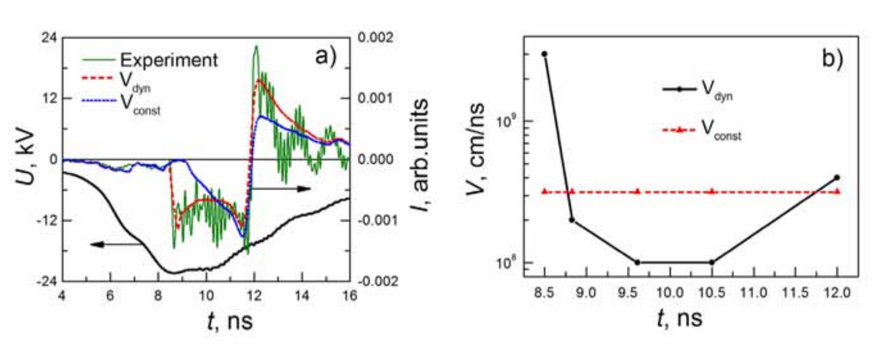

Fig. 1. a) Waveforms of the voltage across the gap, the dynamic displacement current obtained in experiment, as well as the dynamic displacement current obtained in simulations: V_{const} – model with the constant streamer velocity; V_{dyn} – model with the dynamic streamer velocity. b) Streamer velocities. V_{dyn} – dynamic streamer velocity; V_{const} – constant streamer velocity.

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RESISTANCE OF SPARK CHANNELS IN AIR IN UNIPOLAR AND OSCILLATORY DISCHARGES *

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Spark gaps are often used to commute energy at discharge of a capacitive storage on a load [1-3]. An understanding of the way in which the resistance of the spark channel varies as a function of time is important, not only for better comprehension of gas discharges but also in various applications where electric sparks are used as fast switches [4]. However, the experimental data available in the literature on the temporal variation of the resistance of spark channels are scanty [5]. Moreover, in most of these studies, the current pulse durations are shorter than 10 µs. It was shown in [3] that the switch energy losses provide critical impact on the overall circuit efficiency. A detailed review on existing models for spark resistance is given in [5] also. A vast majority of models are outdated and describe more or less only the resistance on a rising part of the current pulse. In some applications oscillatory regime (underdamped sinusoidal) has to be realized for the capacitor bank discharge, in particular, for a pulsed electromagnetic forming technology [6]. In this paper the arc resistance measurements have been done for new geometry of coaxial switch with closed loop rotating arc. Different operations regimes have been investigated with wide variation in the current-voltage amplitudes and pulse duration (up to 3 ms). 1D arc model has been developed for calculation of the arc resistance, valid for both the oscillatory and unipolar regimes of capacitor bank discharge. The results of numerical calculations are compared with experimental results.

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STREAMER START OF APOKAMPIC DISCHARGE*

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The apokampic discharge is a relatively new object of research, useful for laboratory modeling of transient light phenomena of the middle atmosphere [1-3] and potentially interesting for the development of plasma technologies for various purposes.

As our studies have shown, at pressures of ~ 400 Torr, several thousand breakdowns of the discharge gap are required to form an apokamp, which was due to with the need to heat the discharge channel. In addition, at low air pressures (100–450 Torr), glow traces were observed, resembling in form streamer coronas, the appearance of which preceded the apokamp grow. The article purpose is to investigate this phenomenon in detail and formulate a hypothesis about the streamer coronas effect on the apokamp development at low air pressures.

A pulsed discharge was ignited between steel pointed electrodes located at an angle of 140º relative to each other. One electrode was high-voltage, and the second had a capacitive decoupling with the ground. The power source provided a voltage pulse with an amplitude of $8 < U_p < 13$ kV and a pulse repetition frequency of $30 < f < 50$ kHz.

The electrodes were placed in a flask, the pressure in which could be adjusted from 760 to 80 Torr. The time course of the voltage was recorded near the electrode with capacitive decoupling using a capacitive divider, and the current between the electrodes was a shunt. The signals from the divider and shunt were fed to a TDS-3034 oscilloscope (Tektronics, Inc.).

A typical apokamp formation scenario under the conditions of our experiment was as follows: when five to ten voltage pulses are applied to the electrodes, a pulsed spark discharge is ignited in the gas discharge gap. With the subsequent increase in the number of pulses N, a discharge channel is formed, an increase in its diameter and bending occurs. When the number of pulses $N \geq 1500$, an apokamp is formed at the site of maximum bending.

The decrease in pressure entails an increase in the length and an increase in the intensity of the streamer coronas, which means that ionization increases in the space between them. It is also noted that when the pressure changes to the larger side, the streamer coronas are displaced by the bases closer to the point of maximum bending of the channel, and when it is lowered, they are similarly shifted towards the electrodes. Consequently, the larger the p, the higher the probability of formation of the apokamp (with a fixed U_p) without participation of the streamer coronas as an intermediate stage.

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COMPUTER SIMULATION OF HIGH CURRENT VACUUM ARC WITH DEVELOPED ANODE SPOT *

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High current vacuum arc (HCVA) is an arc with current in the order of several kiloamperes. Such kind of arcs is typical for vacuum interrupters or circuit breaker. At the moderate current, the main source of plasma in HCVA is multiple cathode. However, when the current increases to a certain threshold value, the anode becomes another plasma source. The bright, well defined spot appears at the anode surface. This phenomenon is known as the anode spot [1]. Unlike the cathode spot, there seems to be nothing mysterious about the anode spot operation. Anode surface is heated by heat flux from the interelectrode plasma up to a temperature at which the saturated vapor pressure becomes higher than the total pressure of near-anode plasma. After that, the anode vapor starts to flow into the interelectrode gap, where the vapor is rapidly ionized. A dense relatively cold plasma blob appears at the anode as a result of the mentioned processes. The plasma blob temperature is considerably smaller than the interelectrode plasma temperature, the density of plasma blob is much higher than the interelectrode plasma density and the average charge state of the blob ions is about one. Thus, the anode plasma blob looks much brighter than the interelectrode plasma (Fig.1).

The processes described above were self-consistently modeled using a hybrid model based on that developed earlier [2] (Fig. 1). The hybrid model allows to direct simulate the evaporation (including Knudsen layer), ionization and charge exchange. The results obtained in the framework of the model are consistent with the known experimental results at least qualitatively.

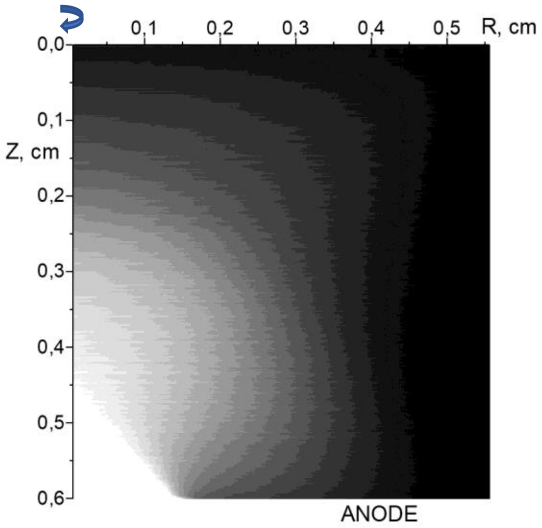

Fig. 1. Calculated HCVA appearance at the stage of well-developed anode spot. Arc current is 2 kA, surface temperature in the anode center is about 2.1 kK.

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MODELING OF PLASMA JET OF VACUUM ARC WITH COPPER-CHROMIUM CATHODE UNDER ACTION OF STRONG AXIAL MAGNETIC FIELD *

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The high-current vacuum arc (HCVA) with composite copper-chromium electrodes is appeared in vacuum interrupters with external axial magnetic field (AMF), which are widely used in the world. Thus, the measurement and modeling of the plasma properties those are typical for interelectrode plasma of HCVA with AMF is in high demand. Recently [1], ion charge state composition of HCVA plasma in the dependence on time, average current density and AMF was measured. It was found that the ion average charge state comparatively weakly depends on the average current density. The average charge state increases with the AMF increase as expected, but for AMF more than 0.8 T, the increase in the charge state slows down.

It is known that the plasma of HCVA under the action of AMF greater than 15-20 mT/kA consists of unmixed plasma jets emitted by separate cathode group-spots. Thus, in order to obtain the plasma parameters typical for HCVA with strong AMF is enough to simulate a single plasma jet originated from the cathode group-spot. The present paper is devoted to computer simulation of the plasma jet emitted from one group-spot on composite coper-chromium cathode 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 [2], the generation of secondary plasma and the interaction of the secondary plasma with the plasma emitted by the cathode spot were studied. It was shown that secondary plasma considerably influences on the parameters of the primary plasma including ion charge composition. The plasma parameters of the jet calculated in the framework of the model is qualitatively consistent with the experimental data.

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ON POSSIBLE REASONS OF POSITIVE NEAR-ANODE VOLTAGE DROP IN HIGH-CURRENT VACUUM ARC*

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There are experimental evidences that under certain conditions a positive anode voltage drop occurs in the near-cathode region of the high-current vacuum arc (HCVA) [1], although the exact location of the potential drop is not determined experimentally. Some researchers believe that this positive voltage drop is inside the anodic plasma sheath [1, 2], moreover, they suggest that this positive drop is the cause of the anode spot appearance. However, in [3, 4] it is shown that for the plasma parameters typical for HCVA the anode voltage drop inside the anode plasma sheath remains negative even at a current density higher than the electron thermal current density. The reason for that is the formation in the near-anode plasma of the electron shifted Maxwell distributions with the velocity shift corresponding to the electron current velocity. At this condition the anode plasma sheath voltage drop remains negative at any current. Despite this conclusion the positive near-anode voltage drop formation is still possible. This may not necessarily be a voltage drop in the sheath. A geometric-ohmic voltage drop in the thin near-anode plasma layer aroused due to current constriction is also possible. In this paper, MHD and kinetic approaches have been used to study various possible scenarios for the formation of the positive voltage drop both in the anode plasma sheath and in the near-anode plasma region of HCVA. In particular, it was demonstrated the formation of the positive voltage drop in the anode plasma sheath when the radius of current constriction become less than the electron coulomb collision mean free path.

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SIMULATION OF THE GENERATION OF JETS AND DROPS BY THE CATHODE SPOT OF A VACUUM ARC*

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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. 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.

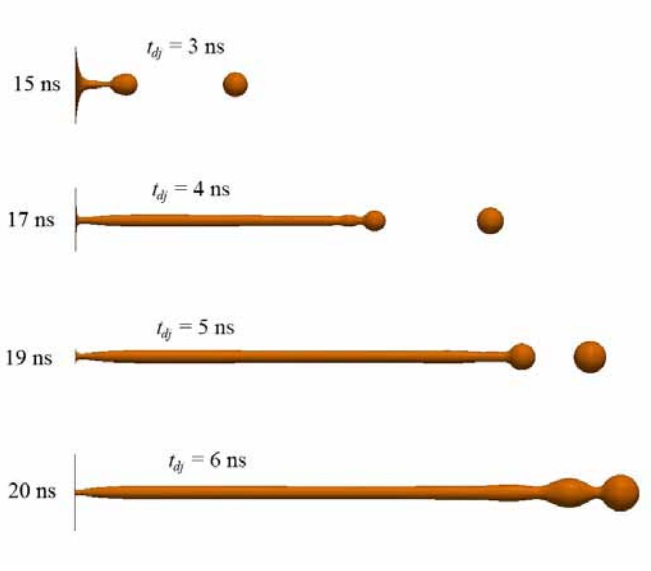

Fig. 1. Jet disintegration into drops and its separation from the crater in the inertial melt splashing mode.

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MODEL OF THE CONVECTIVE THERMAL DESORPTION OF DEUTERIUM AND FORMATION OF PLASMA ION COMPOSITION IN A PULSED VACUUM ARC DISCHARGE WITH A METAL DEUTERIDE CATHODE*

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Although the development and use of neutron tubes with arc source of deuterium ions has been developed for nearly half a century, the mechanism of desorption of hydrogen isotopes from deuterated cathode in arc discharge is not studied yet. Today, it is considered that the main suppliers of deuterium ions in plasma of arc source are cathode spots [1]. In this work the numerical model based on the cellular structure of the cathode spot of a vacuum arc has been developed to describe the process of desorption of deuterium and the formation of the ion composition of plasma of a vacuum arc source with a $ZrD_{0.67}$ cathode (see Fig. 1). It was shown that deuterium and zirconium are almost completely ionized in the plasma jet of the cell at a distance of ~ 10 μm from the cathode. In this case, the number of deuterium ions in the mixture of deuterium ions and all zirconium ions is determined by their atomic fluxes from cathode craters and is ~ 44%. However, taking into account the desorption flow from the periphery of cathode spot cells and ionization in the plasma of the group cathode spot, this value can reach ~ 80%.

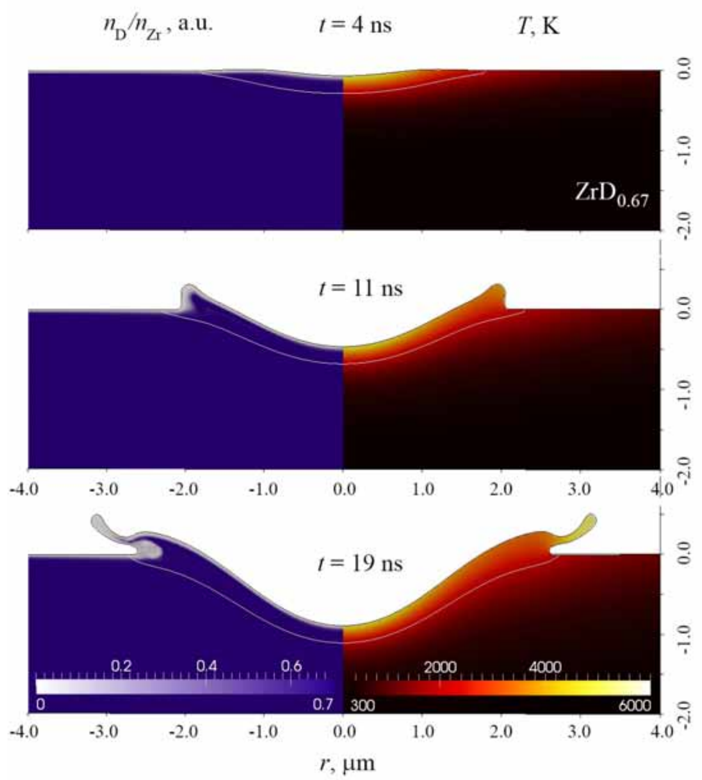

Fig. 1. Temperature distribution and deuterium concentration in the $ZrD_{0.67}$ cathode during the crater formation.

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A HIGH-CURRENT PULSED VACUUM ARC PLASMA SOURCE*

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The vacuum flashover discharge is intensively explored for a long time [1]. It acts as a source of multiply charged plasma [2]. The results of the plasma ion flow study with high temporal resolution and the electrode erosion dependences on the amplitude of the current pulse are presented in the research. A coaxial plasma source with a 1 mm distance between the cathode and the anode was used. The cathode was made of copper and had a diameter of 2 mm. Steel and molybdenum were used as anode materials. Anode ring with a diameter of 2 cm has a 2 mm outlet. Polyethene was used as a dielectric. The plasma source was placed in a vacuum chamber, which was pumped to a pressure of about 10^{-4} mm Hg. In order to make a vacuum arc, a pulse generator based on a system of capacitors was used. The generator can create pulses with an amplitude of up to 12kV and a half-height duration of 10μs.

Plasma parameters were taken using two identical probes connected with an oscilloscope. This method allows analyzing both the spatial and temporal structure of the ion flow. The probe was in a grounded housing with an input aperture of 9 holes with a diameter of 200 μm. The collectors were located at a distance of 15 cm and angles of 0°, 15°, 30°, 45° and 60°. For each combination of parameters, an averaged waveform was obtained. It was also carried out numerical integration over the angles to calculate the total ion current fig 1.

The main ion flow reaches the detector in 3.5 μs. Almost all ionic current is distributed in solid angle up to 60°. The maximum current density is achieved at an angle of 30° for the steel anode and at 0^0 for molybdenum. The presence of a strong peak in the ion current oscillograms reveals the formation of an intense plasma wave directly behind the leading front of the expanding plasma.

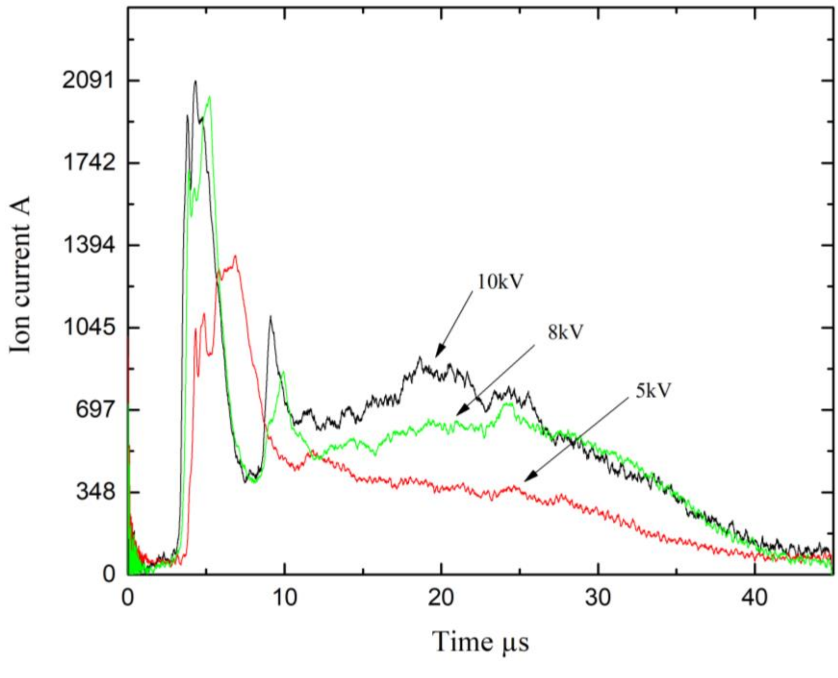

Fig. 1. Integral ion current dependence through the surface of a hemisphere with a diameter (15 cm) on time, Mo anode.

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ABOUT LIMITATIONS IN HYBRID MODELS APPLICATION FOR STUDY OF AN ELECTRONS AVALANCHE IN PULSED GAS DISCHARGE OF HIGH PRESSURE*

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The paper analyses the details of the application of the hybrid model for calculation of the formation of high-pressure gas discharge in conditions where the transition of electrons into runaway mode is possible. Usually in hybrid models, PIC-MC method is used only for calculation of runaway electrons, and the standard hydrodynamic approach is used for calculation of plasma electrons. However, electron concentration is low at the initial stage of discharge formation, so application of hydrodynamic model is incorrect because the motion of individual electrons is crucial until the avalanche reaches critical size. In this paper, the characteristics of such motion are investigated using Monte-Carlo simulation in 3D-configuration to estimate limitations of hybrid model application. The investigation is important for correct description of initial stage of high pressure pulsed discharges and for calculation of electron transition into runaway mode.

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INVESTIGATION OF PLASMA ION COMPOSITION GENERATED BY HIGH-POWER IMPULSE MAGNETRON SPUTTERING (HIPIMS) OF GRAPHITE*

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Amorphous carbon diamond-like (DLC) films are characterized by a high content of diamond-like C-C bonds (70-90%) that explains their high hardness (up to 50 GPa), high IR transparency (up to 90%) and other properties [1]. Diamond-like coatings are deposited by vacuum-arc cathode sputtering, pulsed laser deposition, deposition from an ion beam (i.e. by methods creating high-density carbon ions flow), but all these methods do not allow the deposition of amorphous carbon (a-C) films on large-area substrates. In the case of magnetron sputtering of graphite, it is possible to deposit a-C coatings on large-area substrates, however, the plasma produced in this case has a low (less than 10%) degree of ionization, and the resulting films have a low hardness (5-10 GPa) even with a negative voltage bias applied to the substrate [2]. High-power impulse magnetron sputtering (HiPIMS) used to increase the density of the plasma produced in this case (up to 10^{13} cm^{-3}) and the fraction of ionization of sputtered material – carbon (up to 70 %) [3]. It makes possible to increase the ion bombardment of the growing film by applying a negative bias HF potential to the substrate, which allows deposition of DLC coatings.

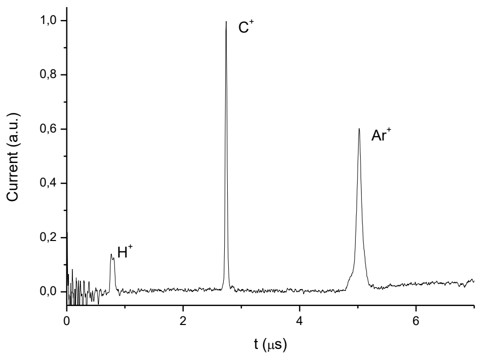

Fig. 1. Output signal of time-of-flight analyzer for HiPIMS of graphite at the discharge current of 30 A, pressure of 1 mtorr, pulse duration of 22 μs, and ion accelerating voltage of 15 kV

Parameters of plasma, generated by HiPIMS of graphite, depend on properties of magnetron discharge. In [4] it was shown, that self-sputtering of graphite characterized by abrupt increase of discharge current. It can be related to change in the plasma ion composition: carbon ions should be the majority. The purpose of this research was to measure the ion composition of plasma during HiPIMS of graphite. To measure it, a linear axially-symmetric time of-flight spectrometer with flight length of 1.2 m and radial focusing of analyzed ions, having a secondary electron multiplier detector was used. Output signal of the time-of-flight analyzer depends on discharge parameters – argon pressure, discharge current and pulse duration. In figure 1, one can see dependence of current of time-of-flight analyzer on time from analysis start and its interpretation. For the discharge current of 30 A and argon pressure of 10^{-3} Torr the particle fractions are the following – H^+ is 9%, C^+ is 33%, Ar^+ is 58%. Increase of discharge current to 70 A leaded to growth of C^+ fraction up to 60% that results from more intense sputtering of the graphite cathode. This trend was observed both for 20 μs and for 30 μs pulse width. Decrease of argon pressure down to $3 \cdot 10^{-4}$ Torr leaded to reduction of C^+ fraction down to 13%, which is related to less intense sputtering. Thus, using of time-of-flight analyzing of plasma ion composition generated by HiPIMS of graphite one can choose optimum discharge pressure and current – both of them should be maximized.

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SPUTTERING KINETICS OF GRAPHITE TARGET IN HIGH-POWER IMPULSE MAGNETRON DISCHARGE* (HIPIMS)

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Magnetron sputtering makes it possible to deposit coatings on substrates of a large area, since magnetron systems can be extended (up to 3 m), and the substrate can be scanned. That makes magnetron sputtering more technological procedure than vacuum-arc evaporation or laser sputtering of materials. However, the plasma produced in this case is characterized by a small (less than 10%) degree of ionization of sputtered material. Therefore, the deposited coatings have a columnar and porous structure [1], and in the case of graphite sputtering the deposited amorphous carbon (a-C) films are graphite-like and have a hardness of 5–10 GPa even when negative bias is applied to the substrate [2]. Pulsed high-power magnetron sputtering (HiPIMS) is used to increase the density of the resulting plasma (up to 10^{13} cm^{-3}) and the degree of ionization of the sputtered material (up to 30-50%). This allows increasing the ion bombardment of the growing film when a negative bias potential is applied to the substrate to overcome the above disadvantages. Unfortunately, the consistent theoretical model of pulsed high-power magnetron sputtering (HiPIMS) materials has not been proposed yet. It is the task of this work.

Here the original zero-dimensional theoretical model of a magnetron high-current discharge (used in HiPIMS) is formulated. When modeling, the dense plasma region near the cathode and the vast plasma region in the volume of the magnetron chamber will be artificially separated. The main theoretical task is to simulate a dense plasma that forms the plasma-chemical composition, while the surrounding plasma can be described in terms of the well-known complementary model of Brenning [3].

The proposed theoretical approach based on a nonstationary spatially averaged (zero-dimensional) model of the region of intensive ionization of a magnetron discharge [4]. It accounts for the dynamics of electrons, neutral atoms and positive single charged ions of carbon and argon. To consider the plasma composition accurately we implement large number of low-pressure plasma-chemical bulk reactions (impact electron ionization, Penning processes, diffusion, recharging, etc.) as well as boundary reactions (losses at walls). At the mathematical level, the model consists a set of particle balance equations and the electron temperature balance equation describing the behaviour of quasi-neutral multi-component HiPIMS discharge plasma. Main result of theoretical simulation is the estimation of optimal parameters for the experimental setup intended for obtaining a dense plasma with the desired composition.

Theoretical work is complemented by the experimental measurements of plasma parameters and ion composition using the Langmuir probes and the time-of-flight spectrometry.

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TEMPERATURE GRADIENTS IN TARGETS WITH HIGH-INTENSITY IMPLANTATION AND THEIR INFLUENCE ON THE CHARACTERISTICS OF ION-MODIFIED LAYERS*

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This paper is devoted to the study of the gradient temperature field dynamics and distribution in the metal targets irradiated with high-intensity beams of gas and metal ions. The investigations concerned ion implantation modes with the ion beam current density from several tens of mA/cm^2 up to A/cm^2 were investigated.

The ion beam power was additionally varied due to the change of ion energy in the range from 0.6 to several keV and the pulse duty factor in the range of 0.2–0.8. The integral temperature of the target was measured with an electrically isolated thermocouple. To measure the dynamic change in the local temperature on the irradiated target a high-temperature pulse pyrometer KLEIBER 740-LO was used.

The problem of temperature evolution and metal sample melting under the exposure of a high-intensity repetitively pulsed ion beam was solved numerically using the heat conduction equation written in cylindrical coordinates.

Analysis of the experimental data obtained with the use of electrically isolated thermocouple, pulse pyrometer, and numerical simulation revealed the presence of significant gradient temperature fields both over the surface and along the depth of targets irradiated by high-intensity ion beams.

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INSTANT VALUES OF THE MAIN PLASMA PARAMETERS OF THE NON-SELF-SUSTAINED ARC DISCHARGE WITH THERMIONIC CATHODE *

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The probe studies of the plasma of a non-self-sustained gas arc discharge was carried out. Plasma generation by a generator “PINK” with a combined thermionic and hollow cathode [1] was carried out. The plasma parameters were studied using a single cylindrical Langmuir probe. The instantaneous values of the electron concentration and temperature, as well as the plasma potential, are obtained. The dependence of the basic plasma parameters not only on the characteristics and conditions of discharge burning (discharge and cathode heating currents, discharge voltage, operating pressure, gas), but also on the phase of the cathode heat current is shown.

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EFFECT OF THE DISCHARGE AREA MAGNETIC FIELD ON THE MASS-CHARGE COMPOSITION OF TWO-COMPONENT ION BEAM*

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The use of the cathode consisting of two metals in the vacuum arc ion source allows the generation of two-component ion beams. The generation of two-component metal ion beams in the vacuum arc source was investigated using a copper-chromium cathode as model material [1]. In this paper the investigation of the effect of up to 1 T induction axial magnetic field generated in the discharge region of the ion source with the copper-chromium cathode on a mass-charge composition of the ion beam. The magnetic field application is shown results in the charge state increase for the both metals in the cathode. The ion beam current increase at the constant discharge current in the presence of the magnetic field is shown to be associated with the focusing of the plasma flux along the magnetic field lines during the magnetization of plasma electrons and the retention of ions by the potential of negatively charged plasma. When the magnetic field is applied, a ratio of the copper and chromium ion proportion was found to be corresponded to the ratio of their atoms in the cathode of the vacuum arc source. The presented results may be useful in practice, for example, to the discharger electrode surface modification by creating copper-chrome cover with different atomic proportions.

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SIMULATION OF ELECTRON BEAM GENERATION WITH A CONSTANT, RISING AND FALLING BEAM POWER DURING ITS PULSE*

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To generate pulsed (hundreds of microseconds) intense (hundreds of amperes) electron beams, two methods are most often used to apply a high voltage to the accelerating gap: 1. Using a high-voltage artificial forming line, the energy from which is completely taken during the beam current pulse; 2. The use of high-voltage capacitor battery with its partial discharge. The second method is most popular due to the possibility of generating an electron beam with a wider range of pulse durations. However, when using a high-voltage capacitor bank and a constant amplitude of the beam current, the voltage across the accelerating gap has a linearly falling shape, and, therefore, the power of the electron beam is linearly decreased during its pulse. Most often, attention to this phenomenon is not emphasized, since with the electron energy in the beam varying in the range of 10–30 keV, their depth of penetration is substantially less than the depth of impact of this beam on any inorganic material (units of microns Vs hundreds of microns). In the material science calculations, the electron energy is most often assumed to be constant, and accordingly, it is considered that the beam power is also constant during the pulse, and the change in the accelerating voltage can be neglected. However, such an assumption can be made not always, since in intensive modes the accelerating voltage can change by 50% or more.

In this work, the operation of an electron source with a plasma cathode was simulated, where a capacitor battery is used as a high-voltage generator. The calculations were performed with the aim of obtaining an electron beam, the power of which is either constant during its pulse, or has a linear increase or decrease.

The calculations confirm the uniqueness of plasma electron sources, and also open up additional possibilities for the use of such sources for both scientific and technological purposes.

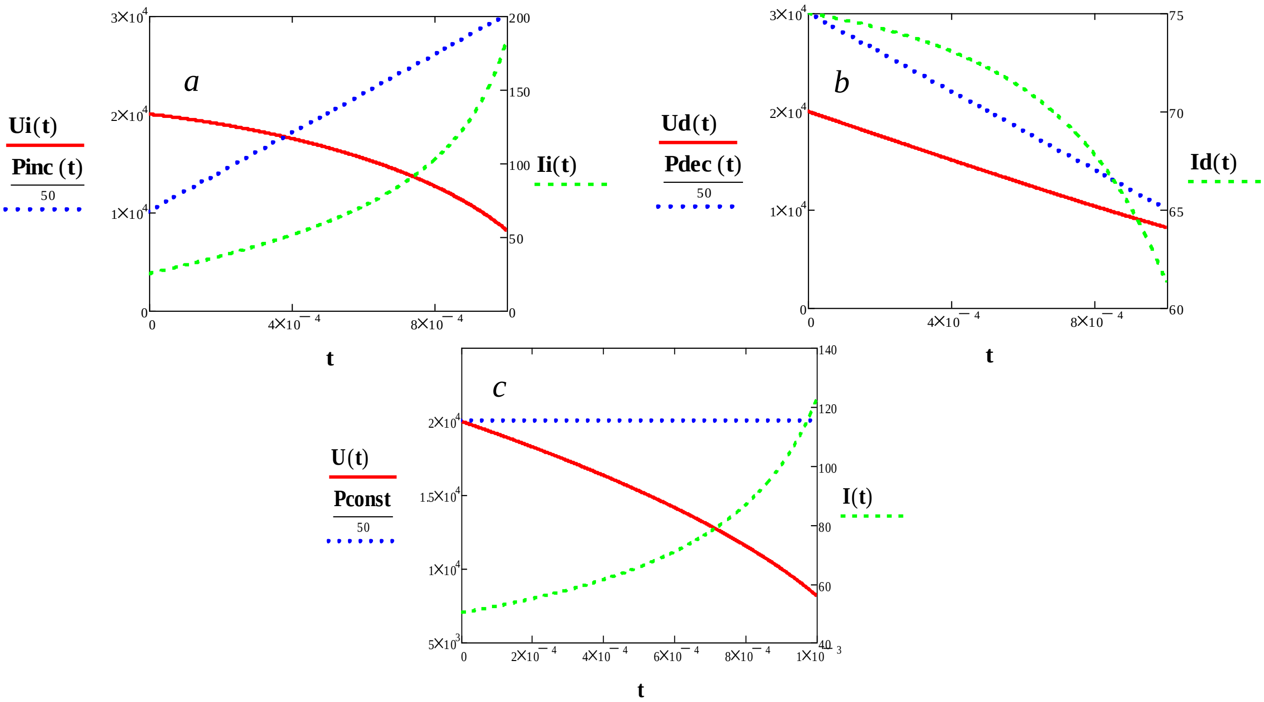

Fig. 1. Oscillograms of the currents and voltages of the capacitor to obtain the rising (a), falling (b) and constant (c) power at the load with a total energy of the beam content of 1 kJ by duration of 1 ms.

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MEASUREMENT OF PLASMA PARAMETERS IN A HYBRID DC+HIPIMS MODE OF MAGNETRON SPUTTERING*

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Direct current (DC) magnetron sputtering is the most basic and inexpensive type of magnetron sputtering. But during DC magnetron sputtering the plasma concentration is low (about 10^9 cm^{-3}), and its ionic component is represented mainly by the ions of the working gas (Ar^+). In high-power impulse magnetron sputtering (HIPIMS) plasma density could be as high as 10^{12} cm^{-3}. However, a significant disadvantage of HIPIMS is the reduction in the films deposition rate compared to DC sputtering. Different ways have been offered to improve deposition rate, for example, pulse waveform modulation [1]. Another perspective approach is hybrid technology, known as hybrid DC + HIPIMS co-sputtering process [2].

In this work the plasma parameters in DC + HIPIMS mode of magnetron sputtering have been investigated. Hybrid mode (DC + HIPIMS) of the magnetron sputtering was realized at an average power of 500 W, applied to a planar magnetron with a Cu target. The main parameters that changed during the experiments, were frequency of high current pulses (100 Hz and 500 Hz) and average power of DC discharge in hybrid mode DC + HIPIMS. Wherein the total average discharge power and the duration of high current pulses are remained unchanged and were of 500 W and 100 μs, respectively. During the experiments such plasma parameters as electron energy distribution function, plasma density, electron temperatures, plasma and floating potential were measured with movable Langmuir probe. Typical waveforms of discharge voltage and current in HIPIMS (250 W, 500 Hz, 100 μs) + DC (250 W) mode at a pressure of 0.3 Pa are shown in Fig. 1,a. An example of the waveforms of the discharge current and the ion current per probe (bias voltage of -80 V) in the HIPIMS (500 W, 100 Hz) mode are shown in Fig. 1,b.

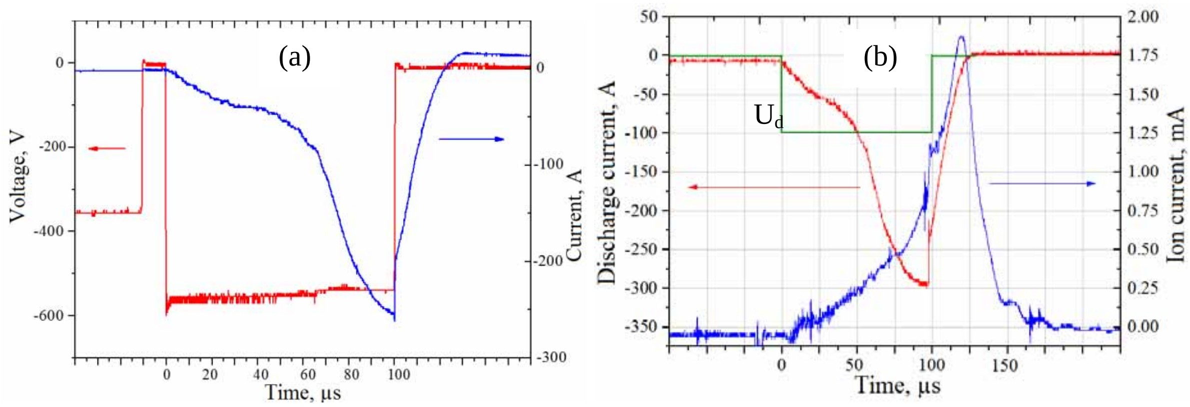

Fig. 1. Waveforms of discharge voltage and current in HIPIMS (250 W, 500 Hz, 100 μs) + DC (250 W) mode at a pressure of 0.3 Pa (a). An example of the waveforms of the discharge current and the ion current per probe (bias voltage of -80 V) in the HIPIMS (500 W, 100 Hz) mode (b).

It is shown that the electron density in the DC + HIPIMS mode is about 1-2 orders of magnitude higher than with DC magnetron sputtering. Moreover, it can be regulated by the frequency and amplitude of high-current pulses. During a high-current pulse in the plasma, the number of metal ions increases and the discharge goes into self-sputtering mode. This is confirmed by the change in the slope of the current-voltage characteristics of the discharge and the increase in the rate of growth of the discharge current on the oscillograms. The transition to the self-sputtering mode occurs when the discharge current reaches 50–100 A, which corresponds to a target power density of 350–700 W/cm^2. With a high content of metal ions in plasma, its electron temperature decreases due to the fact that metal atoms have much lower excitation and ionization potentials by electron impact than argon atoms.

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ABOUT CHANGES IN THE PHYSICOCHEMICAL PROPERTIES OF AQUEOUS SOLUTIONS USED AS A LIQUID ELECTROLYTE CATHODE*

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The gas discharge between liquid electrolyte cathode and metal anode was experimentally investigated. Aqueous solutions of sodium chloride, potassium chloride, sodium sulfate, sodium hydroxide, and potassium hydroxide were used as the electrolyte cathode. The experiments used the original approach, which was proposed in paper [1].

The essence of the experiments was as follows. The discharge was ignited and its combustion was maintained at a constant current (I = *const*). Stable discharge burning was provided by the use of inverter power supplies. The decrease in the aqueous solution was compensated by the addition of distilled water (solvent). The working volume of the aqueous solution during the combustion of the gas discharge remained unchanged (V_s = *const*). The volume of solvent added ΔV was comparable to the working volume of the electrolyte V_s.

In fig. 1 as an example, some results are presented. As can be seen, the specific electrical conductivity of aqueous solutions of alkali metal salts (sodium chloride, potassium chloride, sodium sulfate) increases, and alkali (sodium and potassium hydroxides) decreases.

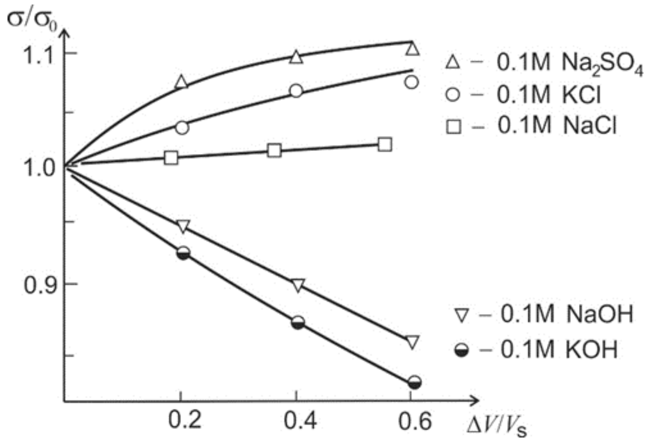

Fig. 1. Changes in electrical conductivity of aqueous solutions used as liquid electrolyte cathode. V_s = 5.0 l. I = 7.5 A.

In the experiments, alkalization of aqueous solutions of alkali metal salts (sodium chloride, potassium chloride, and sodium sulfate) was observed. The concentration of hydroxide ions in the aqueous solution increased. The solution was enriched with more mobile ions. This fact explains the increase in the electrical conductivity of aqueous solutions of alkali metal salts (sodium chloride, potassium chloride and sodium sulfate).

A decrease in the electrical conductivity of aqueous solutions of alkalis (sodium and potassium hydroxides) indicates of removing of sodium and potassium ions into discharge region.

Thus, it has been established experimentally that, despite significant solvent dilution, the specific electrical conductivity of aqueous solutions of alkali metal salts and alkalis varies slightly. The paper analyzes the mechanism of this phenomenon. The main elements of the mechanism were revealed: 1) drip removal of ions from the electrolyte due to cathode sputtering; 2) drift of positive alkali metal ions to the cathode and their return to the electrolyte; 3) alkalization of aqueous solutions of alkali metal salts.

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SOME FEATURES OF THE ELECTRIC DISCHARGE WITH THE ANODE AS A LIQUID ELECTROLYTE FLOW*

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Electric discharge between a liquid electrolyte anode and a metal cathode was experimentally investigated. Sodium chloride solutions in distilled water were used as electrolyte.

The aim of the work was to study the properties of electric discharge with liquid electrolyte anode at elevated currents. The study was conducted in the range of currents of 0.1-3.5 A. Electric power was supplied from a three-phase rectifier through a C-L-C filter.

Electric discharge was created with use of various embodiments of electrode assemblies.

In one embodiment, the body *1* of anode assembly was made of a dielectric material in the form of an elongated hollow body (fig.1). Inside the cavity was mounted metal electrode *2* from a palladium-tungsten alloy. The electrolyte flowed out of a narrow slot *3*, made on the housing *1*. The tubular metal cathode *4* was located coaxially with the anode housing in different positions: with horizontal displacement ($x \neq 0$) and without displacement ($x = 0$). The displacement of electrodes relative to each other contributed to the formation of a voluminous plasma *5*. As can be seen from the oscillograms *6*, presented, during the burning of the discharge, current and voltage pulsations occurred.

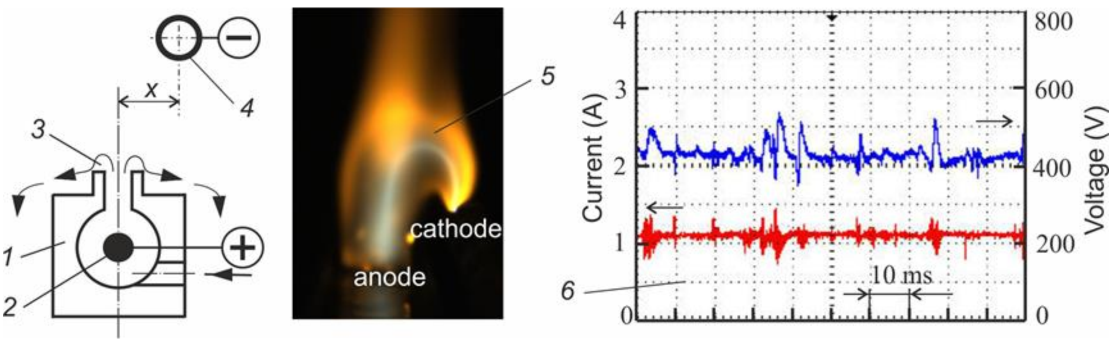

Fig. 1. Diagram of discharge assembly, photo of discharge, oscillogram of current and voltage. $x = 14$ mm. The molar concentration of an aqueous solution is 0.1 mol/l. Instant photo taken with exposure 0.2 ms.

In this case the peculiarities of electrical discharge which were shown with an increase in current and an increase in the interelectrode distance vertically were found, and also when the concentration of the aqueous solution was changing - an anode.

With an increase current in the discharge gap, a contracted channel was formed. It is noteworthy that contracted channel adjoined liquid anode without changing the brightness of the glow.

On the high-speed video frames contracted channel was in a single copy. With increasing discharge current channel was expanded. Spectral studies have shown that the radiation spectrum contains intense Balmer hydrogen lines. It can be noted that discharge radiation has common features with the emission of a plasma column near metal cathode in the water flow [1].

Increasing distance between electrodes was led to disruption of spatial stability of the plasma column. The physical picture of the phenomena was almost the same when using aqueous solutions with different concentrations.

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AXIAL DISTRIBUTION OF PLASMA ION COMPOSITION IN PLANAR MAGNETRON DISCHARGE*

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In a planar magnetron discharge with a target diameter of 50 mm the axial distribution of plasma ion composition was measured. The mass-to-charge measurements were made by using a modified quadrupole mass spectrometer. Experiments were carried out with copper target and argon as operating gas. The measurements were carried out along the magnetron axis at a distance from 10 to 30 cm from the target. The operating pressure varied in the range from $7\cdot10^{-4}$ to $2\cdot10^{-3}$ Torr at a magnetron discharge current from 50 to 300 mA. It is was shown that the distribution of argon and copper ions along the axis has a nonmonotonic character.

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PLASMA GENERATION DELAY ON THE SURFACE OF COPER AND DURALUMIN CONDUCTORS WITH DIELECTRIC COATING*

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Studies of the skin explosion of homogeneous and double-layer cylindrical copper and duralumin conductors with a dielectric coating of zirconium dioxide (ZrO_2) were carried out. Previously [1, 2] at the amplitude of magnetic field induction on the surface of a conductor up to 400 T, it was shown that due to the double-layer structure of a conductor with an outer layer of lower conductivity (copper and duralumin conductor with a deposited titanium layer) a significant plasma formation delay was observed for titanium layer thicknesses more than 20 μm. For the outer layer, it is possible to use other materials with more than 15 times lower conductivity and with sublimation energy, which is comparable with the sublimation energy of the electrode material in magnitude [3]. The conductivity of dielectric coatings is much less than that for any metallic, therefore it was expected to obtain large delays before the beginning of plasma formation at the surface with coating of lower thicknesses. The experiments were carried out on a high-current MIG generator with current amplitude up to 2.5 MA and a rise time of 100 ns. The plasma generated on the conductor surface was imaged using a four-frame optical HSFC Pro camera with a frame exposure time of 3 ns. The internal structure and density of the plasma on the surface of the conductor formed during an electrical explosion is supposed to be investigated using X-ray radiography. The X-ray radiograph was based on the use of the X-pinch with hν > 0.8 keV at exposure 2 – 3 ns. In addition, vacuum photoemission diodes recorded a surface plasma reaching a temperature of ~ 2 eV in the black-body approximation. The coating deposition was carried out on an ion-plasma QUINTA facility. Unfortunate The internal structure and density of the plasma on the surface of the conductor formed during an electrical explosion is supposed to be investigated using X-ray radiography. ly, the synthesis of dielectric coatings on the surface of metals with a large curvature (cylinder diameter 1–3 mm) led to the formation of internal stresses in the coatings and their cracking. Therefore, the deposition of zirconium dioxide films without cracks with a thickness more than 7.5 μm was not possible. Multilayered coatings with alternating layers of ZrO_2 (0.9 μm) and Zr (0.1 μm) were more crack-resistant. Due to technological complexity, we formed the coatings with layers number up to 16 for our experiments. A delay in the onset of plasma formation on a dielectric-coated part of the load of up to 70 ns was obtained with a field induction of up to 300 T compared with that for a pure copper or duralumin conductor. At the field increases to 350-400 T, the plasma formation delay decreases and it is about 30 ns.

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SIMULATION DIFFERENT SCENARIOS OF TRANSITIONS BETWEEN DIFFERENT MODES OF CURRENT TRANSFER TO ELECTRODES OF DC DISCHARGES*

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A DC gas discharge is inherently an open system, far removed from thermodynamic equilibrium. Due to the nonlinear nature of the processes and the presence of near-electrode layers in such a system, many unstable states are manifested and self-organization of various dissipative structures occurs [1,2]. These processes are determined by some critical values of control parameters, both external and internal, depending on the properties of the medium. The development of instabilities, especially near critical currents, often qualitatively and quantitatively changes the structure of the discharge, leading to new combustion regimes. It is worth noting that the discharge of atmospheric pressure is characterized by a fairly rapid heating of the gas to significant temperatures at low currents. In this case, a glow discharge without proper cooling of the electrodes quickly contracted and passes into an arc.

A qualitative picture of the current-voltage characteristics of a low-pressure gas discharge for low pressure is given in many monographs on plasma physics, which describes the different modes of burning discharges and transitions into each other. However, its full qualitative projection on the behavior of discharges of atmospheric pressure is not obvious. At the same time, it is clear that it is impossible to model DC discharges in a wide range of discharge currents with a description of the nucleation and formation of various types of instabilities without considering the processes occurring at the boundary of the "gas-discharge plasma-electrode".

In connection with the foregoing, in the framework of a single extended hydrodynamic model, various modes of burning of direct current discharges were numerically studied in a wide range of discharge currents and various scenarios of transients and formation of current spots on electrodes were described.

In particular, results were obtained that demonstrate different scenarios for the transition from a normal TR to an arc: with a section on the I–V characteristic corresponding to the anomalous TR and without it. The variants are demonstrated in which round, annular as well as their combination current spots on the electrodes are realized in the normal mode of burning discharges. For the arc mode of discharge discharge, the results with diffusion and contracted current spots on the cathode are presented, depending on the cooling options.

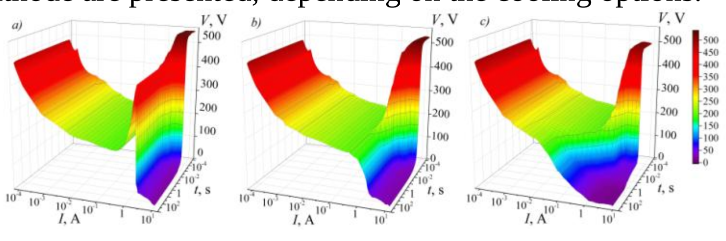

Fig.1. The evolution of the current-voltage characteristics of DC in the case of three different options for cooling the electrodes

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EFFECT OF SUPERSONIC GAS FLOW ON THE STRUCTURE OF THE GLOW DISCHARGE.*

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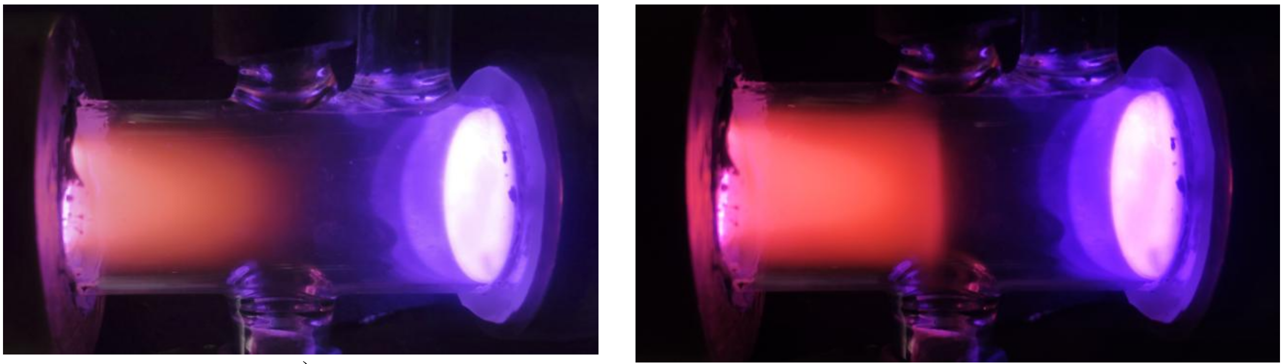
The development of methods and mechanisms for controlling the distribution of the characteristics of a gas-discharge plasma is relevant both from the point of view of studying the fundamental problems of plasma physics and from the point of view of numerous practical applications. In our recent work, the idea of changing the density of neutral particles in a gas-discharge gap by creating a supersonic gas flow was proposed. This, in turn, determines the localization of both the near-electrode zones and the positive column of a glow discharge.

In this paper, the methodological studies of these ideas are continued. For experimental studies, a discharge chamber of molybdenum glass of cylindrical geometry with water-cooled copper electrodes was performed. The interelectrode distance was 50 mm, and the diameter of the discharge tube was 30 mm. In a tube in a perpendicular to the direction of the axis of the tube, Laval micro-nozzles and a diffuser were placed. A diffuser through a vacuum hose was connected to the receiver. During the experiment, a vacuum was created in the receiver and a supersonic flow was made through the discharge zone. Figure 1 shows a photograph of the discharge during the experiment.



a) b)

Fig. 1. Glow discharge glowing at a pressure of 7 Torr: a) in the quiescent air; b) in the supersonic air flow. The cathode on the right, the anode on the left, the nozzle in the center below

As can be seen from Fig. 1, the supersonic flow strictly defines the zone of localization of the positive column. To the region of supersonic flow, we see Faraday dark space. In a fairly wide range of gas pressure and discharge currents, this localization is preserved.

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STUDY OF IONIZATION WAVES IN A PULSE DISCHARGE IN ARGON[1]

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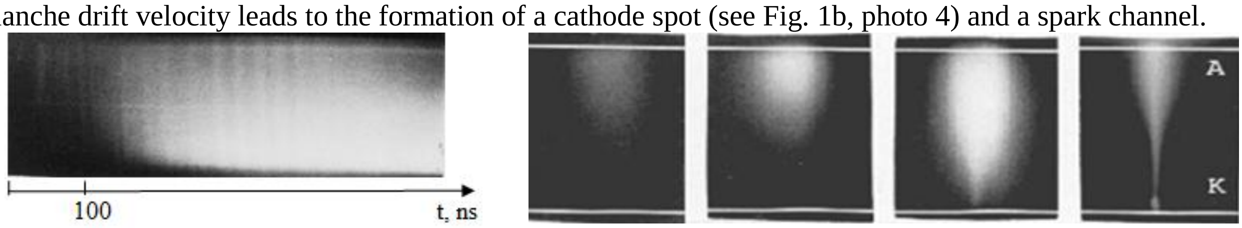
In this paper, an experimental and numerical study of the features of formation and development at the initial stages of breakdown of both the ionization fronts of the luminescence and the physical processes that cause the volumetric discharge instability in atmospheric pressure Ar is performed. The 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.



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)

A two-dimensional axisymmetric calculation of the development of ionization waves in argon at atmospheric pressure was performed. The discharge was ignited between two parallel plates with a radius of 2 cm and an interelectrode distance of 1 cm. The voltage on the electrodes was constant throughout the calculation and was 25 kV. The calculation model includes the particle balance equation for electrons, atomic and molecular ions, lower excited levels of Ar ($1s_5$), Ar ($1s_4$), Ar ($1s_3$), Ar ($1s_2$), highly excited levels of Ar (hl) (combining 2p, 2s , 3d, 3p in one level) and excimers. In total, more than 130 reactions were considered. The constants were taken from and determined by the electron temperature, which was found from the solution of the equation for the electron energy. The self-consistent electric field was found from the Poisson equation. The calculation was performed according to an explicit scheme with the second order of accuracy in time and space. The convergence of the solution was confirmed by the coincidence of the calculated values on different grids. In the interelectrode gap, the grid was uniform, along the radius - with thickening. The initial concentration was set on the axis of the discharge gap by a Gaussian function with a maximum concentration of electrons and atomic ions 10^7 cm^{-3}.

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OPTICAL AND KINETIC CHARACTERISTICS OF A PULSED DISCHARGE IN ARGON WITH ALUMINUM VAPOR AT ATMOSPHERIC PRESSURE[1]

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The study of the space-time dynamics of a pulsed discharge formation in atmospheric pressure argon in centimeter inter electrode gaps (with an initial electron concentration in the interval n_0 ~10^7cm^{-3} and insignificant over voltages *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}.

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.

In this paper, we consider the electron drift in argon with aluminum vapor in order to study the effect of the concentration (or fraction) of aluminum on the electron transfer coefficients. The computational experiment is based on the consideration of an ensemble of electrons that do not interact with each other, whose motion is determined by given fields and instantaneous collisions with atoms. The collision model is based on the random number generation procedure, i.e., the Monte Carlo method takes into account the energy balance of electrons based on elementary acts, including in inelastic collisions.

A model of collisions of ions with gas atoms, taking into account the resonant ion exchange, polarization and short-range (gas-kinetic) interaction, is constructed. On the basis of experimental data on ion mobility and the results of modeling collisions of ions with atoms of their own gas in a uniform electric field, the cross sections for resonant charge exchange of ions of noble gases, aluminum and copper were calculated. The influence of the electric field, the temperature of the buffer gas atoms and the percentage composition of the gas mixture on the ion velocity distribution function was investigated.

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STUDY OF IONIZATION WAVES IN A PULSE DISCHARGE IN HELIUM[1]

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The paper presents the results of experimental and numerical studies of the formation and development of an ionization wave in atmospheric pressure helium.

The experimental setup and research methods are given in [1]. The voltage across the gap varied in the range 3-20 kV. The voltage and discharge current were recorded, respectively, by an ohmic divider and a low-inductance shunt using digital oscilloscopes such as Aktakom and Tektronix. The space-time development of the discharge was filmed by a photoelectric recorder FER2-1. Preliminary ionization of the gas (n_0~10^8 cm^{-3}) was achieved by irradiating the gap through the grid anode with UV light from an external spark discharge. The 1 cm long test gap was formed by a mesh anode and a solid cathode 4 cm in diameter made of stainless steel.

Of greatest interest are the experimental results of direct observations of the dynamics of the formation of a discharge with spatial and temporal resolution in the nanosecond time range, obtained using FER2-1.

It was established experimentally that the first recorded luminescence occurs at the anode after the application of an external field, which then propagates as a diffuse luminescence to the cathode with a characteristic speed of ~ 10^7 cm /s. The glow front is not uniform, the intensity decreases from the discharge axis to the periphery, which indicates a higher intensity of ionization processes on the discharge axis. After the arrival of the luminescence front at the cathode, the discharge passes into the next phase, the phase burning phase.

At low breakdown voltages U0 <6 kV, a discharge is formed with a high emission uniformity and burning duration. At voltages U0> 6 kV and current densities $j \geq 40$ A/cm^2, plasma channels are attached to the cathode spots in the cathode region. With an increase in the number of cathode spots, the appearance of a spark channel in the gap is delayed, and many thread-like channels are formed. It has been established that with an increase in the energy input to the pre-ionization source, the uniformity and stability of the volume discharge increases. At very high overvoltages $U_0 \geq 12$ kV, the discharge is ignited in the high-current diffusion mode.

To describe the discharge, a two-dimensional axisymmetric diffusion-drift model of the motion of electrons and ions is used together with the Poisson equation.

It is shown that the formation of a discharge occurs during the development of a cathode-directed ionization wave, which is confirmed both by the results of numerical simulation and the results of experimental studies of the spatial-temporal dynamics of the development of the initial stages of the discharge. The transverse inhomogeneity of the gas pre-ionization forms an inhomogeneous ionization front wave developing from the central gap. The non-uniformity of pre-ionization of gas both along and across the discharge gap leads to non-uniformity of the electron concentration distribution across the discharge gap, therefore, the ionization wave front is not flat, but has an elongated shape. The rate of the ionization front decreases from the center of the discharge gap to the periphery.

As the cathode approaches, the field strength at the ionization front also increases, and the intensity of the ionization processes increases accordingly. With a decrease in the preionization electron concentration, the formation time of the ionization wave increases, respectively, and the discharge formation time.

The study of the kinetic processes of formation of a plasma column in gas He at a pressure of 1 atm in a non-uniform discharge based on a two-dimensional model has been performed. The initiation of 1-3 cathode spots, with a distance between them of 0.5 cm, was carried out by distorting the surface of the cathode at local points, which created an increased field strength in the region of the cathode. The calculated space-time distributions of the electron concentration and field are obtained. The development of a discharge with increasing electron concentration in the range 10^6–10^8 см$^{-3}$ is considered. The dependence of the width of the plasma column on the energy introduced into the discharge is revealed.

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STUDY OF THE TEMPERATURE INFLUENCE ON STRUCTURAL-PHASE CHANGES IN PORCELAIN CERAMICS PRODUCTION

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Insulating porcelain ceramics (PC) plays an important role in the wide transportation and safe use of electricity. Porcelain ceramics have not only high mechanical properties, but also high voltage properties [1-3]. At present, many high voltage insulators do not meet the requirements, resulting in frequent firefighting and safety precautions. In addition, electric current losses cause economic inefficiency. Solving this problem has become one of the main research areas of scientists in the last decade. In this regard, special attention is paid to study the complex internal microstructural-phase changes in porcelain ceramics, improvement of functional qualities. PC is a complex mixture consisting of silicon and aluminum oxides. The degree of relative percentage of oxides affects the properties of porcelain ceramics, which requires additional research. Therefore, the aim was to study the effect of temperature on the structural-phase changes in the production of porcelain ceramics.

As a result, porcelain ceramics was prepared based on the local raw materials of the Kyrgyz Republic. Main chemical composition is: kaolin 45%, porcelain stone 28%, clay 20% and feldspar 7% [4].

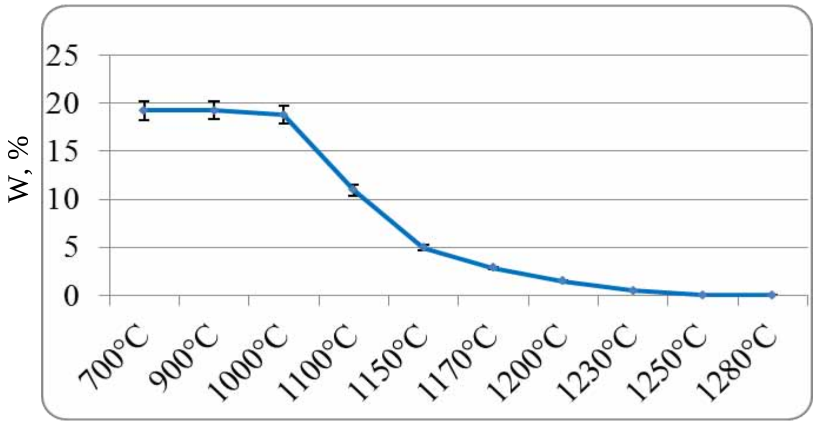

Fig. 1. Curve of change of the water absorption (W,%) of PC prototypes depending on their firing temperatures

Samples of ceramics was studied for water permeability at the temperatures of 700-900 °C. When the temperature reached 1280 °C water absorption decreased to 0.01%, and the volume decreased by 30%. This was due to the phase exchange, pore destruction, reduced size and weight, and the increase in density. PC obtained after the thermal treatment was studied using the X-ray pattern lines. It was found that it consisted of monoclinic and orthorhombic mesh. A new phase was observed on the X-ray spectra. Tensile strength of PC rose by 1.4% after heat treatment.

The effective mode of obtaining the porcelain ceramics was established along with the determination of regularities of structural-phase changes, the effect of temperature on the typical structure and mechanical properties and a harmonious combination of the vitreous phase with other phases.

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CHARACTERIZATION OF MAGNETRON PLASMA USING OPTICAL SPECTROSCOPY AND COLLISIONAL-RADIATIVE MODEL OF NITROGEN *

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Collision-radiative models (CRM) are widely used to determine the parameters of low-temperature plasma using optical spectroscopy [1]. Most of these models are global, i.e. describe the kinetics of spatially averaged quantities. In the case of discharges in nitrogen and nitrogen-containing gas mixtures, these models can be both relatively simple [2] and very complex, including hundreds of different reactions [3], depending on pressure, ionization degree and other conditions.

The magnetron discharge is characterized by low pressure and a relatively high ionization degree. In this case, the processes involving electron impact play the major role and some of the other processes may be neglected thus simplifying the model. On the other hand, the magnetron discharge has a spatial non-uniformity, which may question on the applicability of the global model.

In this work, we propose a method for determining plasma parameters of a magnetron discharge in nitrogen, based on global-local CRM and direct fit of synthetic emission spectrum to the experimental one. The global part of the model describes the kinetics of states with a longer lifetime, which can emerge in regions with a denser and hot plasma, and is transferred to the observation region. The local part of the model describes the states making the main contribution to radiation. The model takes into account the following processes: 1) excitation / quenching of N_2 states by electron impact; 2) excitation / quenching of metastable states by electron impact; 3) dissociation of N_2 due to electron impact; 4) optical transitions between the N_2 states; 5) vibration-vibrational and vibration-translational energy exchange processes for the ground $N_2(X)$ and metastable $N_2(A)$ states; 6) excitation of the N_2 states due to the collision of molecules in the metastable state $N_2(A)$; 7) quenching due to collisions with heavy particles; 8) quenching due to diffusion and collisions with the walls of the vacuum chamber; 9) sputtering of target atoms and compound molecules; 10) chemisorption of atoms and gas molecules on the walls of the chamber and the target of the magnetron; 11) recombination of gas atoms with chemisorbed atoms on the surface covered by the compound.

Using this technique, we investigated the plasma in a laboratory installation for reactive sputter deposition of titanium oxynitrides at several pressures and powers. The rise of the discharge power leads to the increase of rotational temperature determined by contours of the first positive (FPS), second positive (SPS) and first negative (FNS) emission band systems. The temperatures determined by FPS and SPS are noticeably higher than the temperature for FNS. This may be due to the large contribution of collisions of heavy particles to the formation of the corresponding excited states. With increasing pressure, the global and local concentrations decrease, as well as the global electron temperature. A similar dependence of electron temperature and density on pressure was also observed in [4] and may be associated with an increase in diffusion flux across the magnetic field. With increasing power, an increase in electron concentration and a drop in global temperature are observed. A similar result was obtained in [5] and our previous works. Such dependence can be related to the ohmic heating mode [6].

The results are generally consistent with our previous studies of the magnetron discharge in this setup, and with the results of other authors. In addition, we evaluated the degree of dissociation of nitrogen molecules in two ways: theoretical and experimental. These estimates are in good agreement, especially at high discharge power.

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MEASURING THE EXPANSION VELOCITY OF PLASMA FORMED DURING ELECTRICAL BREAKDOWN ALONG AN EXPLODING AL FOIL IN A MEDIUM OF DISORBATED GASES*

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This paper presents experimental results on measuring the plasma expansion velocity formed during electrical breakdown along an exploding Al foil. Electrical breakdown occurs in the environment of a mixture of gases desorbed from the surface of the foil when it is heated by the flowing current. Aluminum foil had the dimensions: length 20 mm, thickness 6 microns, width varying from 0.93 to 1.05 mm. Foil explosion was carried out by a sinusoidal current with a period of oscillation of 1780 ns. The current amplitude varied depending on the charging voltage (U_c = 10, 20, and 30 kV) of a 0.25 μF capacitor and was about 6.5, 14, and 22 kA, respectively.

The plasma expansion velocity was measured using three electric probes under the earth potential and located at the edges and in the middle of an exploding foil. The distance from the foil to the probes varied from 2 to 16 mm. In the experiments, the time of appearance of the signal on the probes was measured relative to the moment of breakdown along the foil. Measuring the time of flight of the plasma from the foil to the probes, and knowing the distance to the probes, the plasma expansion velocity was calculated.

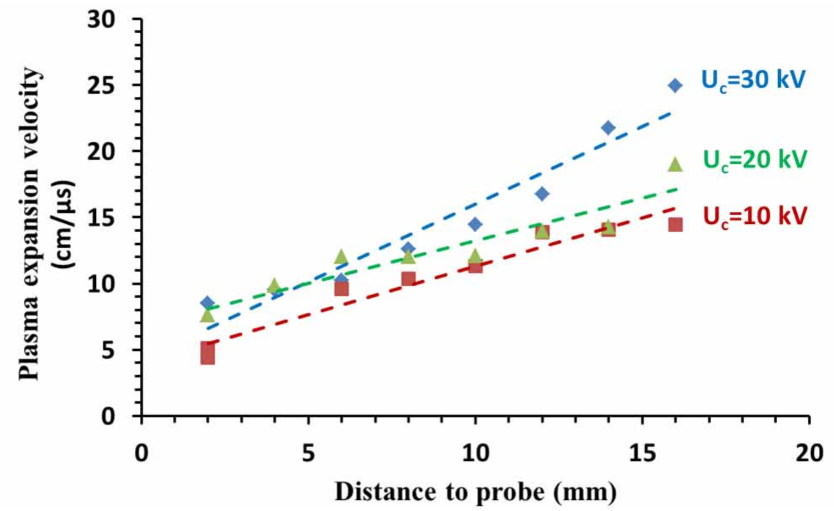

Fig. 1. The expansion velocity of plasma formed during the breakdown along the exploding aluminum foil at different capacitor charging voltages.

In addition to probe measurements, in this work, we recorded the optical images of an exploding foil and the glow of expanding plasma with four frame camera HFSC-Pro with an exposure time of 3 ns. These studies allowed us to get an idea of the shape of the forming plasma envelope and measure the rate of expansion of the bulk of the desorbed gases and metal vapors as a function of time. In addition, ideas were obtained about the processes occurring in the near-electrode regions at the moment of the occurrence of a breakdown.

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THE MECHANODIFFUSION MODEL OF THE INITIAL STAGE OF PARTICLES FLOW INTRODUCTION PROCESS IN A TARGET SURFACE*

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The paper presents a coupled mathematical model of the initial stage of particles penetration in the metal surface in non-isothermal approximation. It is assumed that the implanted material there is sufficient energy to generate mechanical disturbances into target surface at the interaction moment. And mechanical disturbances effect on the redistribution of diffusion of implanted particles.

The simplified one-dimensional model includes the heat conduction equation (1), equation of implanted component balance (2) and the motion equation (3):

$$\rho C_\sigma \frac{\partial T}{\partial t} + \alpha_T T \frac{\partial \sigma}{\partial t} = -\frac{\partial \mathbf{J}_q}{\partial x} \tag{1}$$

$$\rho \frac{\partial C}{\partial t} = -\frac{\partial \mathbf{J}}{\partial x} \tag{2}$$

$$\rho \frac{\partial^2 u}{\partial t^2} = \frac{\partial \sigma}{\partial x} \tag{3}$$

The govering relations correspond to the theory of generalized thermoelastic diffusion:

$$\mathbf{J} = -\rho D \frac{\partial C}{\partial x} + BC \frac{\partial \sigma}{\partial x} - t_D \frac{\partial \mathbf{J}}{\partial t} \tag{4}$$

$$\mathbf{J}_q = -\lambda_T \frac{\partial T}{\partial x} - t_q \frac{\partial \mathbf{J}_q}{\partial t} \tag{5}$$

$$\sigma = E\left[\varepsilon - \alpha_T \left(T - T_0\right) - \Delta\alpha\left(C - C_0\right)\right] \tag{6}$$

The model takes into account the finiteness of relaxation times of heat and mass fluxes and the interaction of waves of different physical nature — impurity concentration, stresses (strain) and temperature. The problem was solved numerically with using the double sweep method. The Fig.1 presents examples of coupled problem solving for materials system - Mo(Ni).

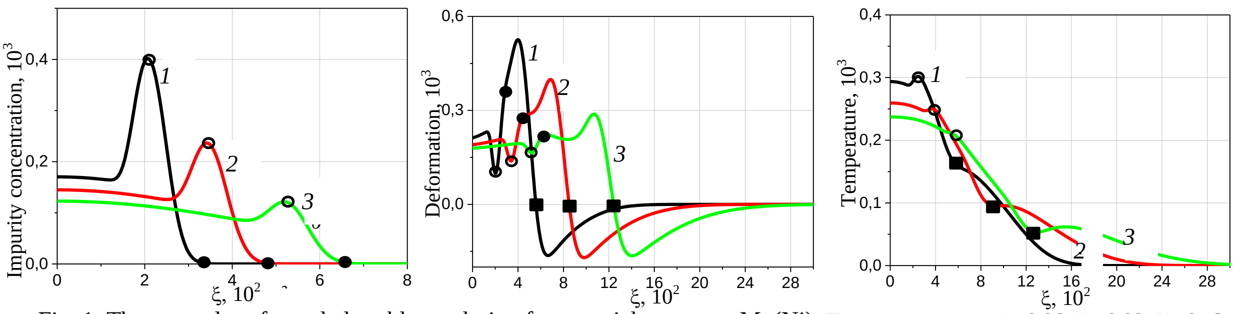

Fig. 1. The examples of coupled problem solution for materials system - Mo(Ni). Time moments, τ : *1* – 0,06, *2* – 0,09, *3* – 0,13

It is shown that the interaction of waves of different physical nature leads to the distribution of temperature and concentration do not correspond to the classical ideas (Fourier and Fick laws). The work demonstrated the distortions in the deformation and temperature waves which are the result of the interaction of the studied processes.

* This work was performed within the frame of the Fundamental Research Program of the State Academies of Sciences for 2013-2020, line of research III.23.

SIMULATION OF HIGH-PRESSURE GAS BREAKDOWN UNDER CONDITIONS OF SPATIALLY NON-UNIFORM INITIAL IONIZATION AND TEMPERATURE*

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The paper presents the results of numerical simulation of the extended atmospheric pressure discharge in configuration of the tip-to-plane diode (Fig.1.). The simulation is based on a modern hydrodynamic model of a discharge plasma in a pure O_2 medium at low average electric field strengths ~ 10 kV/cm. A voltage pulse with an amplitude of 100 kV with a duration of 2.5 μs and a leading front of 800 ns was applied to the electrodes with an interelectrode distance of 10 cm through the ballast resistance 10 kΩ. The following plasma chemical reactions for an electronegative gas were taken into account: ionization by electron impact with the formation of an O_2^+ ion, attachment of electrons with the formation of an O_2^- ion, direct dissociation of the molecule with the formation of atomic oxygen, and ion-ion recombination. It was investigated how different initial conditions (the presence of a weakly ionized plasma channel or a given temperature profile on the discharge axis) affect the initiation of a breakdown and the formation of a subsequent discharge structure (Fig. 2). The results of the calculations make it possible to qualitatively explain how the relaxing plasma generated by the previous pulse can influence the process of development of the discharge when the next voltage pulse is applied. These results will be used later to construct qualitative models of repetitively pulsed discharges with complex spatial geometry, for example, the apocampic discharge [1].

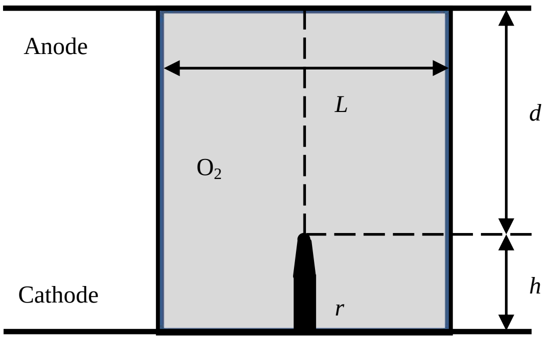

Fig. 1 – The computational domain configuration (h = 10 mm, L = 100 mm, d = 100 mm, r = 2 mm).

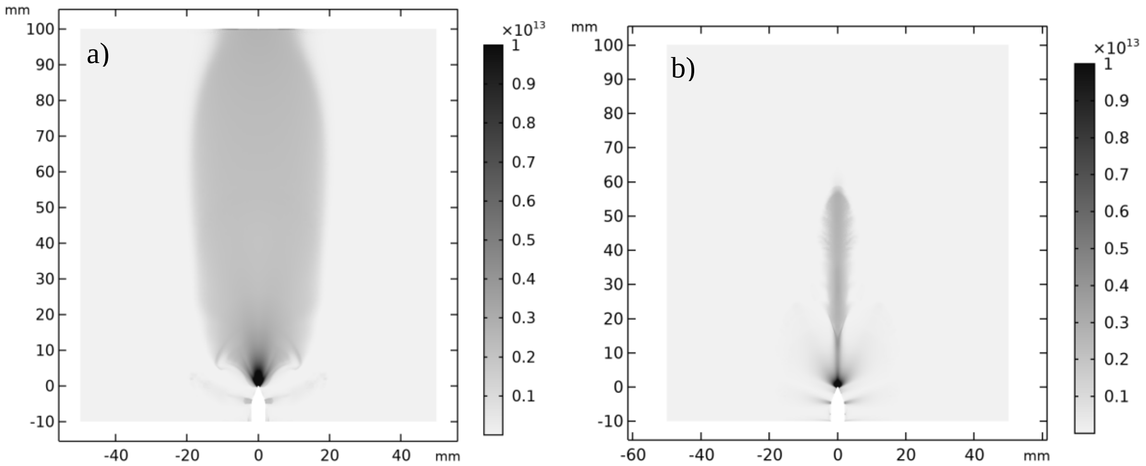

Fig. 2 – Spatial distribution of the O_2^+ number density (scale in cm^{-3}) for gas discharge a) without and b) with a Gaussian pre-ionization channel with an initial maximum concentration of positive ions of 10^{11} cm^{-3} in the center of the channel and a characteristic spatial parameter r_0 = 0.5 mm for the 400 ns time point.

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NEW METHOD OF CONDENSED SYSTEMS IGNITION BY LASER RADIATION*

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The dependence of the ignition delay time of high-energy materials (HEM) on the laser power is of practical importance in the design and calculation of HEM initiation systems (igniters, fuses, detonators), for evaluating the HEM explosion hazard under external thermal effects, and also used in determining the macrokinetics parameters of the ignition process by solving the inverse problem of chemical kinetics. In the experimental determination of the HEM ignition characteristics, optical furnaces or lasers with continuous or pulsed radiation are used [1, 2].

During HEM ignition by laser radiation, a significant factor is the uneven distribution of the density of the radiant heat flux over the surface of the irradiated HEMs sample. This is due to the presence of several types of transverse oscillations (modes) TEM_{mn} in an open laser resonator. The irregularity of the radiation flux density leads to the appearance of "hot" areas of uncontrollable dimensions on the HEMs sample surface, in which ignition is initiated. This leads to a large variation in results when measuring the ignition delay time.

This report presents a new method for determining the ignition characteristics of HEMs samples by laser radiation, which ensures the uniform distribution of the heat flux density over the surface of the sample during its ignition. The method consists of measuring the ignition delay time of a cylindrical HEMs sample when continuous laser radiation is applied to its end surface with a beam diameter equal to the sample diameter. The HEMs sample is pressed into a cylindrical tube. Before applying laser radiation, a rotational motion of the sample is created around its axis of symmetry with a constant angular velocity.

A theoretical estimate of the required angular velocity of sample rotation was performed, which averaged with a given error of the radiation flux density over the sample surface:

$$\omega \geq \left(\frac{q_0}{\Delta T_*}\right)^2 \frac{1}{2n\lambda\rho c},$$

where ω is angular velocity of the sample, rad/s; q_0 is average heat flux density of laser radiation, W/m^2; ΔT_* is the value of non-uniform heating of the sample surface, K; n is a number of radiation modes in the cross-section of the laser beam; λ is a thermal conductivity coefficient of the sample material, W/(m·K); ρ is a density of the sample material, kg/m^3; c is specific heat of the sample material, J/(kg·K).

The calculation of the heat flux density from the surface of the rotating sample into the environment was carried out according to the formula [3]:

$$q_S = \frac{\lambda}{R}\left(T_S - T\right)\cdot 0.329\sqrt{2\,\mathrm{Re}_\omega \mathrm{Pr}},$$

where q_s is heat flux density, W/m^2; R is disk radius, m; T_s is the surface temperature of the disk, K; T is ambient temperature, K; $\mathrm{Re}_\omega = \rho\omega R^2/\mu$ is rotational Reynolds number; μ is a coefficient of dynamic viscosity of the environment, Pa·s; $\mathrm{Pr} = \mu c_p/\lambda$ is Prandtl number; c_p is isobaric heat capacity of the environment, J/(kg·K).

The results of experiments on ignition HEM (pyroxylin) by CO_2-laser radiation with and without rotation of the sample are presented.

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AIR BREAKDOWN IN THE FIELD OF TRAVELING TEM-WAVE ASSISTED BY RUNAWAY ELECTRONS*

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An experiment was performed to study the breakdown of atmospheric air in the electric field of a traveling TEM-wave by dynamic reflectometry method. As a discharge gap, an air insulation gap of a 45-Ohm coaxial short-circuited line with a length of 40 cm was used. Breakdown localization was provided by replaceable inserts into the central electrode representing discs with a semi-toroidal edge and serving as electric field enhancer. The ledge with a height of 1.5 mm and 1 mm thickness, as well as a thinner 50-μm foil-made one, did not make significant inhomogeneities in the line with a radial clearance of 12.5 mm. Local impedance misalignments along the coaxial duct from subnanosecond RADAN generator (110 kV, 1 ns, 0.2 ns front) to the short-circuited line end did not exceed ±1 Ohm. The time of the double propagation of the wave between the insert and the short-circuited end of the line was 1.5 times longer than the pulse duration. This made it possible to use the method of dynamic reflectometry [1,2] and to obtain data on the dynamics of the breakdown in the electric field of a known magnitude and shape.

Reference mode when a gap in the region of the discharge is closed by the metal disk, gives the exact temporal reference of the investigated reflection. The principle is that when studying the development of the breakdown at the open end of the line it is very difficult to determine the real three-dimensional geometry of the electric field, part of the pulse energy is radiated into space and the front of the reflected pulse will be distorted. In the study of two-dimensional design load is only the dynamic resistance of the discharge that is in parallel with the wave impedance of the line, which gives the opportunity to analyze the rates of the voltage collapse, current rise, and discharge resistance.

When using a voltage pulse with an amplitude of –(80-110) kV, a 50-μm thin foil insert into the central electrode provided an electric field amplification sufficient not only to fulfill the field criterion for the thermal electrons runaway in the region of strong field distortion, but also to support the runaway mode of these accelerated particles in the rest of the radial gap [3]. Runaway electrons (RE) were recorded through a window in the outer line electrode by means of a collector sensor placed behind an aluminum foil filter or fine mesh. The voltage of -80 kV was the threshold for RE appearance. As the voltage amplitude increased, these particles were recorded from pulse to pulse without misses, which indicated a uniform emission along the enhancer circumference.

As a result, it was shown that the presence of RE leads to a multiple acceleration of the voltage collapse in comparison with the breakdown development without RE participation. The discharge resistance after 1 ns was noticeably lower (~10 and ~50 Ohms, respectively). The dependence of the discharge resistance on the RE current indicates their significant role in the pre-ionization of the gas. The collapse of the voltage began after the emission of RE and was further delayed at least for the time of their acceleration to the anode. Measurements with foil filters of different thickness showed that within accuracy of the registration the energy of the RE flow did not exceed the value determined by the voltage amplitude in the line. Thus, for 1 ns exposure at electric field strength of ~95 kV/cm, the noticeable delay of the pulse breakdown of atmospheric air is guaranteed. The obtained data demonstrate the possibilities of reflectometry for the study of fast processes in hard-to-investigate places.

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INVESTIGATION OF DEPENDENCE OF THE COMPOSITION OF CATHODE MATERIAL IONS IN LOW-CURRENT VACUUM ARCS ON THE CURRENT VALUE*

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The dependence of the average charge state of copper ions on the arc current value was investigated. The experiment was carried out in the range of discharge currents from 1.8 to 40 A. As opposed to the previous study [1], quasi-rectangle current pulses formed by a LC-line were used. Therefore the estimation of the actual current value was more accurate. Pulse duration was about 2 µs. The pulsed electrostatic gate was used to exclude from analysis the plasma flux formed at the ignition mode of the discharge. The charge composition of ions was obtained via the Thomson spectrometer with automated recording and processing of spectrograms.

The use of the electrostatic gate showed that the impact of the nonstationary processes corresponding to the gap breakdown stage is not significant. In Fig. 1. the diagram obtained with 4 µs gate located below the second one (without the gate), since the gate cut-off efficiency increases with the ion charge. However the trend lines of the dependences are almost parallel. The average charge variation with an increase in the arc current is determined by a remarkable difference between the growth rate of the quantity of Cu+ ions and the ions with the +2 charge and higher. The quantity of the multiply charged ions increases with the current considerably faster. And the arc current value, and therefore the quantity of emission centers, probably is an essential factor influencing the plasma charge state. Since the charge state of the cathode material ions depends on the quantity of simultaneously operating explosive emission centers, it can be supposed, that ionization processes take place in the plasma layer above the cathode spot and at least at the distances sufficiently larger than 1 µm. Probably it occurs due to plasma density increasing with the quantity of cathode spot cells, when an interaction between the plasma jets of different cells takes place. Concentration of hydrogen ions in the arc plasma can affect the ionization of cathode material ions, especially in the current range lower than 15 - 20 A in case of copper cathode. However probably it is not a predominant factor.

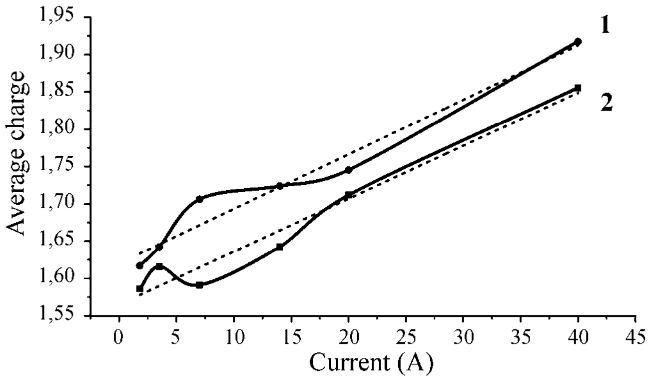

Fig. 1. Dependences of average charge of copper ions on discharge current with trendlines. 1 - Disabled gate; 2 - 4 µs gate pulse duration.

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DEPENDENCE OF THE PLASMA COMPOSITION IN THE LOW-CURRENT VACUUM ARC DISCHARGE WITH THE CUCR CATHODE ON THE CURRENT VALUE AND SURFACE CONDITIONS *

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At the moment there are investigations that show a corresponding of vacuum arc plasma composition to the elemental composition of the CuCr cathode material at the discharge current values about 500 A [1]. And also there are investigations of low-current vacuum arcs which demonstrate a tendency of cathode spots to appear mostly on the chromium grains when the grains are sufficiently large, and absence of the tendency when the grains size is in nanometer range [2, 3]. From this fact a hypothesis of the prevalence of the chromium ions in the low-current vacuum arc plasma on the CuCr cathode and the equivalence the fraction of chromium ions to the fraction of chromium in the cathode material at higher currents was derived. Dependence of the mass-charge composition of the ion flux from the plasma of the vacuum arc with the cathode made of CuCr on a value of the discharge current was investigated via the Thomson spectrometer with automatic signal registration and analysis. The microsecond arc was formed in a millimeter gap between CuCr cathode and copper anode under high vacuum conditions. The arc current was changed within the range from a few to tens of ampere. At the highest current range the plasma composition corresponded the elemental composition of the cathode surface. E.g. Fig.1. shows one of the experimental results. The sample used in the experiment has about 56% of chromium atoms and 44 % of copper atoms on the surface. This values corresponds the fractions of the ions of copper and chromium obtained at the arc current 75A. The surface analysis was made by means of the scanning electron microscope. The fraction of the chromium ions significantly decreased with the arc current decreasing below 30 A. There was noticeable increasing of the fraction of the chromium ions in the plasma at the discharge currents near the threshold values for the cathode materials. The effect appeared on coarse-grained non-melted cathode surfaces, and vanished after a multiple arcing. Therefore both of the effects described in [1-3] were confirmed. And the background of the effects was the increase of the copper ions fraction with the current decrease.

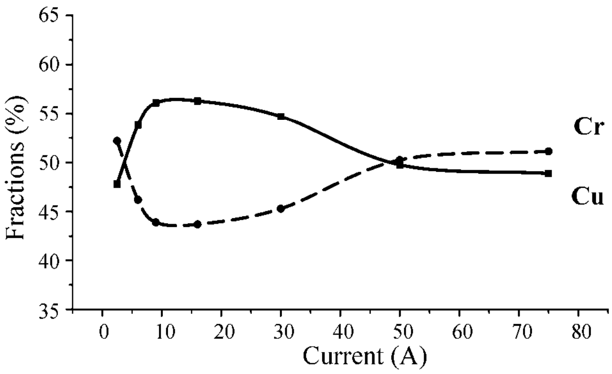

Fig. 1. Aggregated percentages of copper and chromium ions in the registered cathode material ion flow depending on the arc current value. Ascending current values.

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INVESTIGATION OF FEATURES OF CRATER FORMATION ON THE CATHODE SURFACE IN THE SHORT VACUUM DISCHARGE *

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The complex investigation (ion erosion, droplet erosion, crater formation) of a short (10-100ns) vacuum arc discharge has been carried out. The using of the short discharge time made it possible to examine in detail the evolution of cathode erosion. The cable generator with several pulse durations (8ns, 18ns, 45ns, 100ns) was used. The short vacuum discharge was burned on multi-pin tungsten cathode. The discharge was ignited by needle anode, which was moved over cathode surface. The discharge current, ion current was recorded and quantity of droplets was estimated for each discharge pulse. The dependence of averaged values of total ion charge and droplets amount on pulse duration was achieved. The erosion traces on cathode surface was analyzed. Three types of erosion traces can be distinguished: deep craters, rudimentary crater and melted erosion areas. The formation of the deep craters began at the durations exceeding 20ns. The form of these craters suggests that the current was constricted in a very small area which radius was less than 2mkm.

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DISTRIBUTION OF PLASMA POTENTIAL NEAR THE INFINITE CHAIN OF DUST PARTICLES *

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Solid micron-sized particles which are immersed in low-temperature plasma obtain a great charge (Zd = 10^3 -10^5e). Ions accumulate around such particles and an ion cloud is formed. Such systems had been already thoroughly investigated [1]. It can be confidently stated that the task of determination of the self-consistent distribution of ions and electrons around isolated dust particles is solved fully. With the solution of this problem, the following arises – how to numerically determine the self-consistent distribution of the potential around a cluster of dust particles.

Based on the modification of the code used in [2], the authors of this paper have considered at a qualitative level the distribution of a self-consistent potential around an infinite one-dimensional chain of dust particles oriented along the Z-axis. The potential in this system was determined by the following formula:

$$U(r,\theta) = -\frac{\tilde{Q}}{r} - \sum_k \frac{\tilde{Q}}{r_{k,2}} - \sum_k \frac{\tilde{Q}}{r_{k,1}} + \int \frac{n(r',\theta')d^3r}{|r-r'|} + \sum_k \int \frac{n(r',\theta')d^3r}{|r_{k,1}-r'|} + \sum_k \int \frac{n(r',\theta')d^3r}{|r_{k,2}-r'|}, \quad (1)$$

$$r_{k,1}{}^2 = (D^2 + r^2 - 2kdz), \quad r_{k,2}{}^2 = (D^2 + r^2 + 2kdz), \quad (2)$$

where $\tilde{Q}$ - dimensionless dust particle charge, D - interparticle distance.

Based on the data obtained, the dependence of the dust particle charge on the interparticle distance is presented, and a comparison with the case, where the dust particle is isolated, is made.

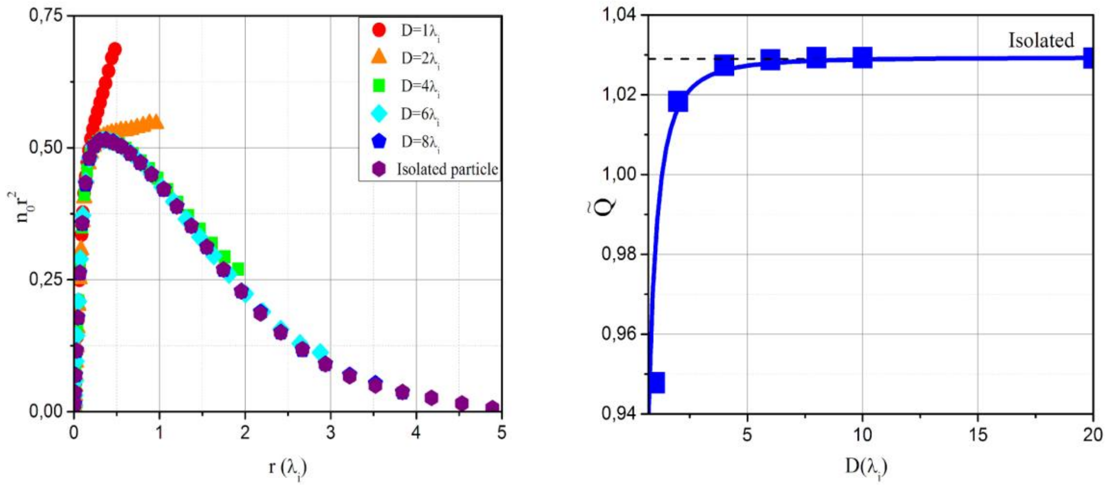

Fig. 1. The zero (isotropic) term $n_0(r)r^2$ of the expansion of the space charge density in the Legendre polynomials (left) and the charge of dust particles Q (D) (right) for different interparticle distances D.

From the analysis of the data obtained, it follows that the charge of each individual dust particle decreases, with the decrease of the interparticle distance, which is in a good agreement with the numerous experiments. A particle can be considered isolated at an interparticle distance greater than six Debye ion lengths.

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SPACE CHARGE SHEATH NEAR DIELECTRIC TARGET, IRRADIATED BY ELECTRON BEAM*

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Measuring the potential of a dielectric target irradiated by an electron beam can be considered as an independent task due to the many options in which it arises. It should be recognized that a single solution does not seem to exist. In this paper, we consider one of the options that is realized when a dielectric is irradiated by an electron beam with an energy of 2–10 keV and a current density of 1–10 mA/cm^2 in a forevacuum, i.e. in the pressure range of 1-100 Pa [1]. In this case, the electron beam forms a plasma column, clearly visible to the naked eye (Fig. 1). The plasma column is separated from the target by a dark gap representing the area of potential drop, i.e. space charge sheath. Experiments performed with a metal target showed that a change in the negative potential at the target affects the length of the sheath. This circumstance allowed us to associate the length of the sheath with the potential of the target and thus propose a method for determining the potential of the dielectric target. As shown by experiments conducted with an isolated metal, as well as with dielectric targets, the target potential is determined by a set of factors, of which the most important are the target material and the electron beam energy (Fig. 2). This indicates the connection of the target potential with the secondary emission properties of its material.

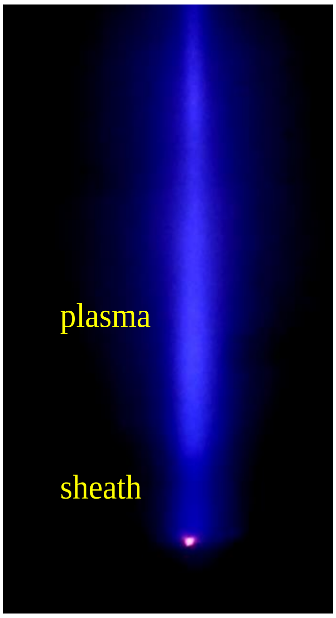

Fig. 1. View of beam and sheath.

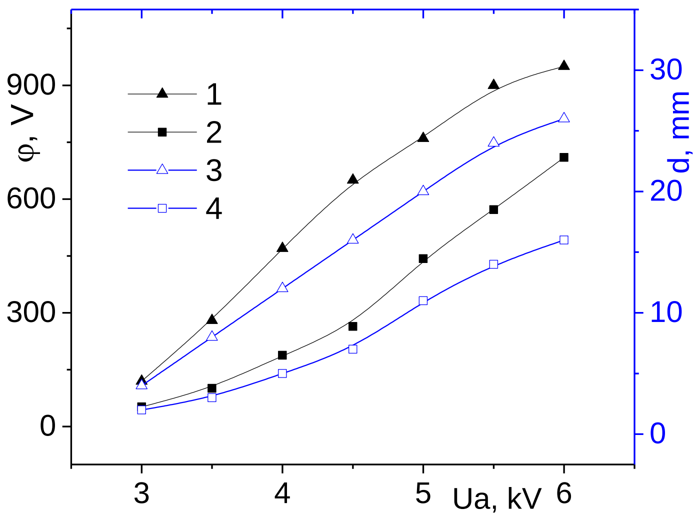

Fig. 2. The potential φ (1, 2) of the target and the thickness d (3, 4) of the layer as a function of the accelerating voltage Ua for isolated titanium (1, 3) and quartz (2, 4) targets.

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THE EMISSION SPECTRA OF GAS MIXTURES PLASMA INDUCED BY THE PRODUCTS OF $^{6}Li(n,\alpha)^{3}H$ NUCLEAR REACTION*

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The main processes in the plasma created by reactor irradiation are similar to processes in a gas-discharge recombining plasma. The research of optical radiation of the nuclear-excited plasma induced by products of nuclear reactions is interest for development of an alternative outlet method of energy from the nuclear reactor, creation of ionizing radiation detectors as well as creation of one of diagnostics of high-temperature plasma in fusion reactors [1].

This work presents the results of the reactor experiments to study the spectral-luminescent characteristics of noble gases and their binary mixtures in a 200-975 nm spectral range, with excitation gaseous media by products of $^{6}Li(n,\alpha)^{3}H$ nuclear reaction. The reactor experiments was held on the LIANA experimental bench, located in a stationary reactor hall, at a flux of thermal neutrons of $1.44 \cdot 10^{14}$ n/cm^{2}s.

Lithium layer (with enrichment by ^{6}Li – 7.5%) with a thickness of about 0.05 mm was applied to the inner surface of 12 mm diameter and 150 mm length tube. The tube with lithium layer was connected with the tube of 20 mm diameter and 600 mm length, sealed at the end by the flange with optical vacuum input. An output of light emission was implemented with the collimator with a quartz lens, inside the ampoule device (AD) and connected with the fiber-optic cable through the optical vacuum input. Light emission from the ampoule device got into the QE65Pro (Ocean Optics) spectrometer's input through the 10 m length fiber (P600-10-UV-VIS) and was recorded as a luminescence spectrum on the hard disk of PC.

Lines of 2p-1s-transitions of atoms (Paschen notations) prevail in spectra of clean noble gases. Strong molecular bands were observed in the binary mixtures of noble gases. Molecular bands observed in the emission spectra of paired mixtures of inert gases, were identified [2] as the transitions between states of heteronuclear ionic molecules. A powerful band in Kr-Xe mixture with maximum at 491 nm (figure 1) and the weaker band in Ar-Kr with maximum at 642 nm were observed in experiments. Not only transitions from $Ar^{+}(^{2}P_{1/2})Xe$ level at 329 and 506 nm, but also from Ar^{+}(2P3/2)Xe level at 346 and 545 nm, weak band at 349 nm were observed in Ar-Xe mixture. This result strikingly differs not only from the case of radioisotope pumping but also from the case of excitation by ion beam for the same degree of pumping power [3]. A possible explanation could be the quenching of Ar^{+}(2P1/2)Xe level to an underlying level in the presence of high xenon content, but during ion pumping transitions from $Ar^{+($2P3/2)Xe level are also absent in Ar(445 Torr)-Xe(50 Torr) mixture [3]. Band in the region 663 nm, which could correspond to the transition from Kr^{+}(2P3/2)Xe, was absent in Kr-Xe mixture.

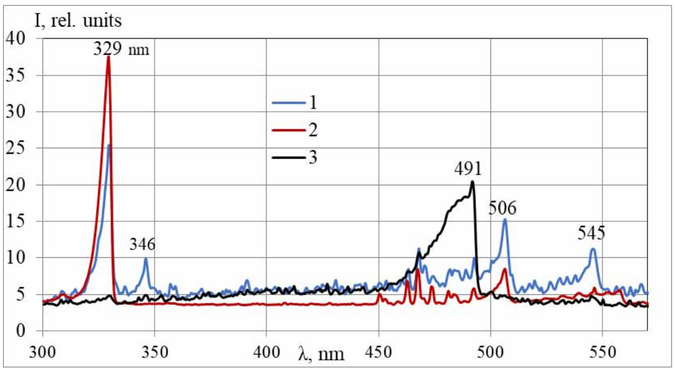

Fig. 1: Luminescence spectra of mixtures of Ar(690 Torr)-Xe(68 Torr) (1), Ar(600 Torr)-Xe(6 Torr) (2) and Kr(380 Torr)-Xe(380 Torr) (3) under excitation at the nuclear reactor (1,3) and by beam of argon with 70 MeV energy (2).

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THE FORMATION OF TUNGSTEN CARBIDES IN BEAM-PLASMA DISCHARGE OF CH_4 ON THE TUNGSTEN SURFACE

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At present, tungsten is supposed to be used as the divertor of a thermonuclear reactor facing the plasma, and beryllium and carbon-containing materials can be used as the first wall material [1].

Since beryllium will be used as the first wall, when a helium, formed as a result of a thermonuclear reaction, is exposed to it, the reaction takes place:

$$^{9}Be + {}^{4}He \rightarrow {}^{12}C + n, \quad (1)$$

Due to the processes of physical and chemical sputtering of carbon materials, the plasma will be contaminated with carbon and hydrocarbon impurities. In plasma, these impurities will be ionized by energy electrons and, then, together with hydrogen isotopes, implanted into tungsten. In this case, depending on the conditions of the plasma action, both carbon films and carbides may form on the surface of the tungsten divertor.

The presence of carbon accumulated in this way highlights the carbidization process of tungsten in a separate area of research. To date, studies on the formation of carbon films and tungsten carbides have been carried out by obtaining thin films of carbon and carbides (W_2C, WC) using various methods, such as magnetron sputtering [2], in plasma arc discharge [3], irradiation of tungsten with a stream of hydrogen plasma with the addition of carbon [4], chemical precipitation of carbon from the gas phase [5], or evaporation of carbon [6].

The appearance of carbon in the chamber of the thermonuclear reactor entails a number of problems [4]. By acting on the surface of the divertor in a mixture with hydrogen plasma, carbon can penetrate into the volume of the divertor and along with hydrogen ions contribute to erosion and the formation of porous layers on the surface of tungsten, as well as under certain conditions, the formation of carbides (W_2C, WC). Japanese scientists conducted research on this problem [4]. They studied the behavior of carbon on the surface of tungsten when the sample was irradiated with a deuterium ion beam with different carbon contents and changes in the beam parameters (energy, fluence) and sample temperature.

All experimental work on the deposition of a carbon coating in a plasma discharge of methane was carried out on a simulation bench with a beam plasma installation.

For the development of methods for coating the surface of tungsten, two programs have been developed. This is a program of experiments, which determined the conditions, processes and modes of operation of PBI under which the coating occurs. The second program defines methods for materials science studies, which include sample preparation, sample annealing, SEM, EDS, and X-ray phase analysis.

As a result, experiments were carried out in which samples of the brand SVI-1 (analog WY-20) were irradiated in the mode of a beam-plasma discharge in methane medium, at various values of the ion energy and the surface temperature of the sample.

As a result of materials research, the presence of a network of microcracks, erosion on the surface of tungsten samples was found, and the carbon content in the surface layer of the samples was determined in the range from 6 to 10% mass. X-ray phase analysis revealed the presence of carbide (WC) and half-carbide (W2C) tungsten peaks on samples W-12 and W-13.

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ELECTRIC ARC PLASMATORCH OF A TWO-CHAMBER SCHEME WITH REVERSE POLARITY OF ELECTRODES CONNECTION*

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The current density in the cathode region of an electric arc in an environment of molecular oxygen-containing gases is about 10^4 A / cm^2, and volts is the equivalent of heat flux into the cathode $U_E \approx 10$ V [1]. Thus, the heat flux density in the cathode reaches 10^5 W / cm^2. No method of cooling the electrode, except for thermal emission, is unable to divert this level of heat flux density without destroying it. Due to the presence of oxygen in the plasma gas, it is impossible to use tungsten thermocathodes, and thermochemical cathodes made of zirconium or hafnium that can work in an oxygen-containing atmosphere have an operating current of up to 300 A and a limited lifetime of continuous operation. Therefore, a common way to ensure the efficiency of the cathode in the environment of oxygen-containing gas is the dispersion of heat flux over its working surface by gas or magnetic scanning of the cathode portion of the electric arc column. In this case, copper is most widely used as an electrode material due to high heat and electrical conductivity. In this case, the typical level of specific erosion of the cathode in an air atmosphere is $\langle G \rangle = 1.5\ 10^{-9}$ kg/C.

Studies of cathode erosion in an environment of an oxygen-containing gas — air were carried out in a two-chamber plasma torch. Earlier studies [1] of erosion of a copper cathode in a two-chamber plasma torch with direct polarity for switching on the electrodes showed that the level of specific erosion has the usual value for air $\langle G \rangle = 1.5 \cdot 10^{-9}$ kg / C.

Data on work with reverse polarity of connection are absent, therefore, experiments were conducted in a two-chamber plasmatorch with reverse polarity of switching on the electrodes and self-adjusting arc length. The scheme of the plasma torch is shown in Fig. 1.

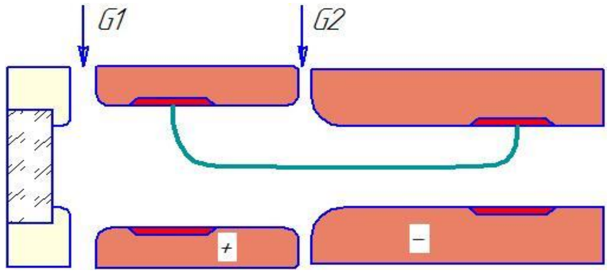

Fig. 1. Scheme of a two-chamber arc plasma torch with the connection with reverse polarity

The diameter of the channel of the internal electrode of the plasma torch - anode was 30 mm, and the diameter of the channel of the output electrode of the plasma torch - cathode was 20 mm. Air consumption through the swirlers is 20g / s, the operating current is 240 A. According to the results of more than 20 hours of experiments, it was found that there is no progressive increase in the thickness of copper oxides in the cathode arc channel characteristic of the output electrode — the anode with a direct polarity of the two-chamber plasma torch.

When the polarity of the switching of the plasmatorch electrodes was reversed, the voltage level was 660 V, which is 30% higher than the voltage level when the electrodes were turned on directly. Thus, the reverse polarity of the connection of a two-chamber plasmatorch with equal power provides a more than twofold increase in the service life of the plasma torch in comparison with the direct polarity of its connection. The level of specific erosion of the cathode was $\langle G \rangle = 8 \cdot 10^{-10}$ kg / C, which is two times less than the typical level of erosion of the cathode in an air atmosphere.

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NUMERICAL INVESTIGATION OF THE SURFACE BARRIER DISCHARGE IN THE AIR*

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The dielectric barrier discharge, as is known, has two forms of development: volume and surface. In a volume discharge, the gas layer in which the discharge develops is located between the dielectric-coated electrodes. In the surface discharge, when two electrodes of different widths are separated by a dielectric, it lies directly on the surface of the dielectric. The smaller electrode, to which a voltage is applied, and at the edge of which a discharge develops, will be called a high-voltage or working electrode. The potential of the opposite will be considered zero.

An intensive study of the surface barrier discharge began only a few years ago due to its promising use for controlling the laminar-turbulent transition and the position of air flow separation zones near solid surfaces by changing the parameters of the boundary layer.

In recent years, various models and numerical experiments based on them have appeared, which allow predicting the parameters of a surface barrier discharge depending on external conditions. It should also be noted that researchers are looking for ways to control the parameters of barrier discharges, including in the case of surface organization [1-2]. Accordingly, existing models and their numerical implementations are being developed.

In this regard, the aim of the presented work was to simulate the simplest version of the implementation of the surface barrier discharge in air at atmospheric pressure in the case of positive polarity applied voltage. Air is a multi-component molecular gas characterized by a vast set of elementary processes occurring on varied spatial and time scales. This is why the choice of a plasma-chemical model depends on the formulation of the problem.

In this work, air was considered as a mixture of nitrogen and oxygen (77% N_2, 23% O_2). Here, we applied a set of plasma-chemical reactions developed in other work [3], which considered only positive and negative molecular ions O_2^+ and O_2^- of air and six reactions containing these ions (table 1).

To perform a numerical simulation a fluid model of electrical discharge was formulated [1]. It is based on density balance equations for electrons, positive and negative ions, electrons heat balance equation, which takes into account not only the volume processes, but also the spatial transfer by conduction and the Poisson equation for finding a self-consistent electric potential. The mobility and diffusion coefficients for electrons, as well as some constants of the inelastic processes involving them, are calculated by convolving the electron distribution function, with the cross section. In this work the electron distribution function is assumed Maxwellian.

Preliminary numerical calculations have been carried out, demonstrating the formation of a streamer structure of the discharge in the case of the application of a positive potential to the working electrode. The dynamics of electron density and electric potential for a streamer form of discharge is presented.

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THE INTERRELATION BETWEEN OF THE GEOMETRY OF THE CHANNEL OF THE FLARE DISCHARGE AND ENERGY CHARACTERISTICS

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A high frequency flare discharge burning at atmospheric pressure is a plasma channel which surrounded by faint diffusion shell. The flow of high frequency current and the main energy release occurs in the zone of the discharge channel. Therefore, the physical characteristics of the flare discharge are determined by the size and shape of its channel.

The most important characteristic of the discharge is a thermal power. However, to date measurements of the thermal power of the discharge have been carried out, as a rule, without specifying the length of its channel. . In addition, the measurements were limited to the study of discharges with a power not exceeding 200 ... 300 watts. We also note that the lack of reliable experimental data on the relationship between the length of the discharge channel and its thermal power makes it difficult to verify existing theoretical models [1] of the discharge.

This paper presents the results of measuring the thermal power of a flare discharge burning in air , argon, and helium at atmospheric pressure, depending on the length of its channel. The thermal power was determined by summing the heat losses at the discharge electrode, the heat losses in the discharge chamber, and the heat flow of the discharge plasma in the axial direction.
The measurement results for a flare discharge burning in air are presented in Figure 1. As can be seen from the figure, the dependence of the discharge thermal power on the length of its channel is linear.

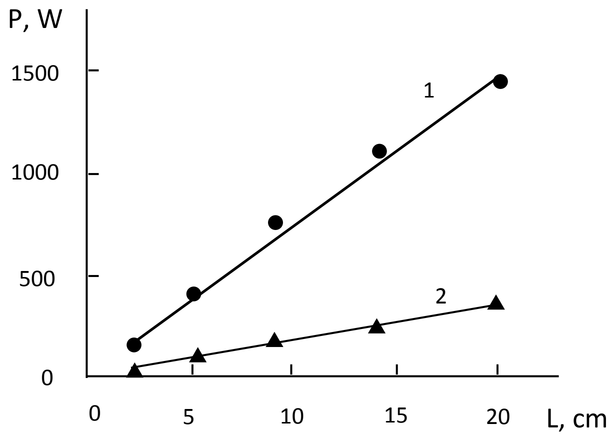

Fig . 1. The dependence of the thermal power of the flare discharge burning in the air from the length of his channel. 1 - total heat power ; 2 - heat losses on the electrode .

The dependence of the heat loss at the electrode on the length of the discharge channel has a similar character. Note that in the case of a flare discharge burning in air, the heat loss at the electrode is 12 ... 15% of the total discharge power. At the same time, for a flare discharge burning in helium, this value is 7 ... 8%. This difference is apparently due to the small value of the gas temperature of the helium plasma.

From the results of the measurements, it also follows that the discharge power is proportional to the cross-sectional area of its channel. Therefore, the diameter of the flare discharge channel is proportional to the square root of its thermal power. Note that this dependence is confirmed by the results of experimental measurements by other authors.

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PHENOMENA AT THE ELECTRODE SURFACES AND LOCALIZATION OF VOLUME DISCHARGES IN SMALL–SIZED SEALED–OFF TEA–CO_2 LASERS

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1. Introduction

Creation of sealed–off TEA–CO_2 lasers with a long time of working is directly connected with remaining of spatial homogeneity of a volume discharge, in plasma of which pumping is effected. Under the influence of the volume discharge in the laser mixture a large number of secondary compositions are accumulated. These compositions initiate a regeneration of the volume discharge into local one and limiting a lifetime of small–sized TEA–CO_2 lasers at a level of $10^3 \div 10^4$ pulses [1].

Regeneration of active mixtures with the help of catalysts enable to rise a lifetime up to $(1 \div 6)_* 10^6$ pulses. A localization of the volume discharge after $(1 \div 6)_* 10^6$ pulses is present in conditions of a very low CO_2 dissociation and low O_2 concentration and some other secondary compounds correspondingly.

These facts show that a localization of the volume discharge is defined not only by the ionization processes in a gas medium but also by the processes at the electrode surfaces. The present work is devoted to investigation of interrelations between a microstructure of electrode active surfaces with their autoemissive characteristics, a spatial structure of the volume discharge plasma and the resource of the small–sized sealed–off pulse–periodical TEA–CO_2 lasers.

2. Experimental investigations

All investigation works have been done with a TEA–CO_2 laser container with 10 independent gaps used to ignite a volume discharge. Al, Mg, stainless–steel, Ni, Cu, Mo, Ti, Ta, Nb and W are used as electrode materials. A volume discharge of nanosecond duration and an energy density W =150÷250 $mJ_* cm^{-3}$ was excited simultaneously in all gaps with a pulse repetition rate F =40 Hz. A condition of the electrode active surfaces before the influence of plasma of the volume discharge on them and after a definite number of current pulses of the volume discharge was controlled by an optical microscope Carl Zeiss (m≤500) or a raster electronic microscope JOEL–7 (m≤5000).

Autoelectronic currents were measured in a separate chamber ($P \leq 10^{-7}$ mm Hg). In the same chamber an electronic work function from electrode active surfaces was defined by a method of a “vibrating condenser” according to a contact potential difference. This value made it possible to define a coefficient of amplification of the electrical field and an area of emissive centers on the basis of the Fowler–Nordheim equation [2–4].

The values of the coefficient β increase in the same materials, where the most noticeable changes in the surface microstructure are observed. So, influence of plasma of the volume discharge on the electrode surface results in change in the surface microstructure and increase in local electrical fields. If the autoelectronic current gains values at which a thermal destruction of the autoemitter happens then in this point a local channel begins to form.

Increase in geometrical dimensions of microinhomogeneities at the electrode surfaces results in autoelectronic currents from these zones of the surfaces and initiates a formation the emission centers at them as a result of a transfer from the autoelectronic emission to an explosive one [3, 4].

The results pointed show to a definite role of the autoelectronic phenomena in destruction of the spatial homogeneity in plasma of the volume discharge. The same results indicate to a necessity of making electrodes of materials, which more stable to the influence of plasma of the volume discharge.

The resource of the TEA–CO_2 laser with electrodes of Al is 2.5 hours or $2_* 10^5$ pulses. When the electrodes made of nickel were used the resource is 56 hours. It is significantly exceeds 10^6 pulses. The largest resource is gained in the laser with electr5odes made of Ta. In this laser the resource is 110 hours which significantly exceeds 10^7 pulses.

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HIGH–VOLTAGE PULSE GENERATORS FOR EFFECTIVE PUMPING OF SUPER–ATMOSPHERIC PRESSURE CO_2–LASERS

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Effective excitation of super–atmospheric pressure volume discharges, pumping of CO_2–lasers at super–atmospheric pressures and effective generation of "runaway electrons" can be realized by using of very high voltage pulses with nanosecond rise times [1, 2].

The present work is devoted to describing construction of some types compact pulse generators with amplitude of voltage pulses up to 200 kV, rise–times about 10 nanoseconds and pulse energy per pulse up to 20 J.

The electrical scheme one of that pulse generators images in Fig.1. There are 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 pulse 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 condensers 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 of volume discharge between the main electrodes A–C.

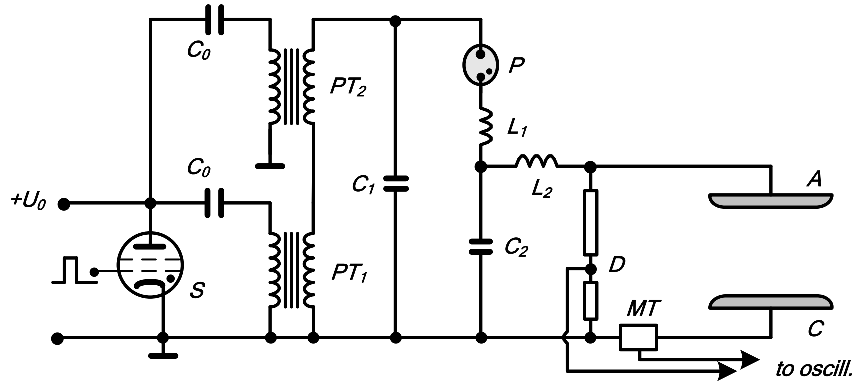

Fig.1. Electrical scheme of high–voltage generator with two pulse transformers

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 volume discharge forming in CO_2–laser mixtures at super–atmospheric pressures.

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METHODICS FOR ELECTRICAL DIAGNOSTIC OF THE PLASMA JET FORMED IN THE LOW-CURRENT PLASMATRON*

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Currently, plasma jets based on the atmospheric-pressure discharges are attracting increasable attention [1–3]. Frequently, the gas-discharge system for obtaining a plasma jet using the discharge in a gas flow are called a plasmatron. The electrodes of plasmatron are configured to allowing the gas to flow through the discharge region [1–4]. Thus, the heated flow of weakly ionized gas, so-called “plasma jet”, forms in the plasmatron nozzle [1–4].

This paper deals with the investigations of the plasma jet generated by using the atmospheric-pressure glow discharge in a vortex airflow with the electrode configuration corresponding to coaxial plasmatron. The discharge is supplied from the high-voltage DC voltage source. The ballast resistor is used for limiting discharge current at level less than 0.2 A. The air mass flow rate is varied from 0.1 g/s up to 0.3 gm/s. In these conditions, the mainly part of a total discharge current in plasmatron flows via the constricted positive column of the glow discharge and only a small fraction of electrical current is flowing through the jet volume.

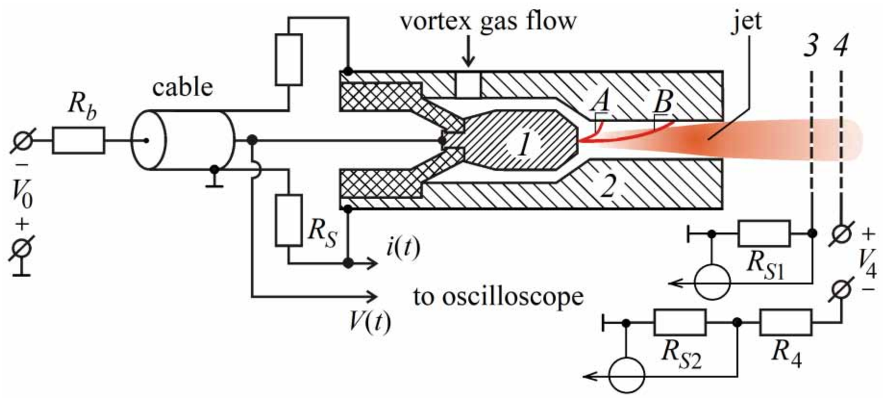

Fig. 1. Circuit of the experimental arrangement for diagnostic of the plasma jet. The discharge is sustained between the cathode of plasmatron 1 and the grounded anode 2 (a length of the plasmatron nozzle l = 20 mm, an inner diameter of the nozzle D = 5 mm). The system of additional diagnostically electrodes *3* and *4* are used to collect the currents flows through the jet volume. A, B – the positions of positive column (schematically). A typical DC voltage V_0 = (3 – 5) kV, $V_4 \leq 3$ kV, R_b = (20 – 42) kΩ, R_4 = 100 kΩ. The discharge burning voltage $V(t)$ is measured by the TDS-1012B oscilloscope with the high-voltage probe. The low-inductance shunts R_S = 1 Ω, R_{S1} = 1 kΩ and R_{S2} = 10 kΩ are used for the current signals measurement.

In the experiments the currents in the system of diagnostic electrodes is measured. The obtained data allow to concluding that the electrical current flowing through the jet volume forms due to electrons that can drifted from the discharge plasma region. It shown that the jet current magnitude is determined by the gas flow rate, by the discharge channel position and by the characteristics of the discharge in the plasmatron. The methodic for estimate the electron density in the jet volume has been proposed. Based on experimental data, the estimated value of the electron density in the jet is not less 10^9 cm^{-3}. At such value of electron density, the electric field distortion by the space charge of electrons can lead to the current self-limitation through the jet.

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THE EFFECT OF POLARITY ON THE FORMATION OF STREAMERS IN AN INHOMOGENEOUS ELECTRIC FIELD*

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It is well known that the polarity of voltage pulses affects the formation dynamics and parameters of a streamer. The effect of polarity is especially pronounced in the gaps with asymmetric distribution of the electric field strength. Breakdown voltage at positive polarity is less than at negative one (polarity effect) in conditions of slowly varying electric fields [1]. A negative electrode is the shielded by a cloud of immobile positive ions. As a result, higher electric field is required for the development of a negative streamer. Furthermore, with low overvoltage, a positive streamer develops faster than the negative one. In nanosecond discharges with high overvoltage levels, the inversion of polarity effect is observed: breakdown voltage at positive polarity becomes higher than at negative one [2–4]. In recent paper it was shown that at subnanosecond breakdown of a 1-cm tube-to-plane gap, the positive streamer appears later than the negative one [5]. As a result, the voltage at positive polarity increases to large values. However, the effect of polarity on a streamer velocity has not been studied in [5].

This paper presents the results of experimental studies of the effect of polarity on the streamer velocity at various voltage amplitudes. In the experiments, nanosecond voltage pulses were applied across an 8.5 mm point-to-plane gap filled with air and nitrogen at a pressure of 100 kPa. The formation of positive and negative streamers has been experimentally studied using a HSFC-PRO four-channel ICCD camera. Waveforms of voltage and discharge current pulses were also recorded. The propagation velocity of streamers was estimated by a dynamic displacement current (DDC) [6]. It was found that the negative streamer crosses the gap faster than the positive one (Fig. 1). This may be due to the features of the streamer shape near the pointed electrode, as well as the mechanism of gas pre-ionization before the streamer front.

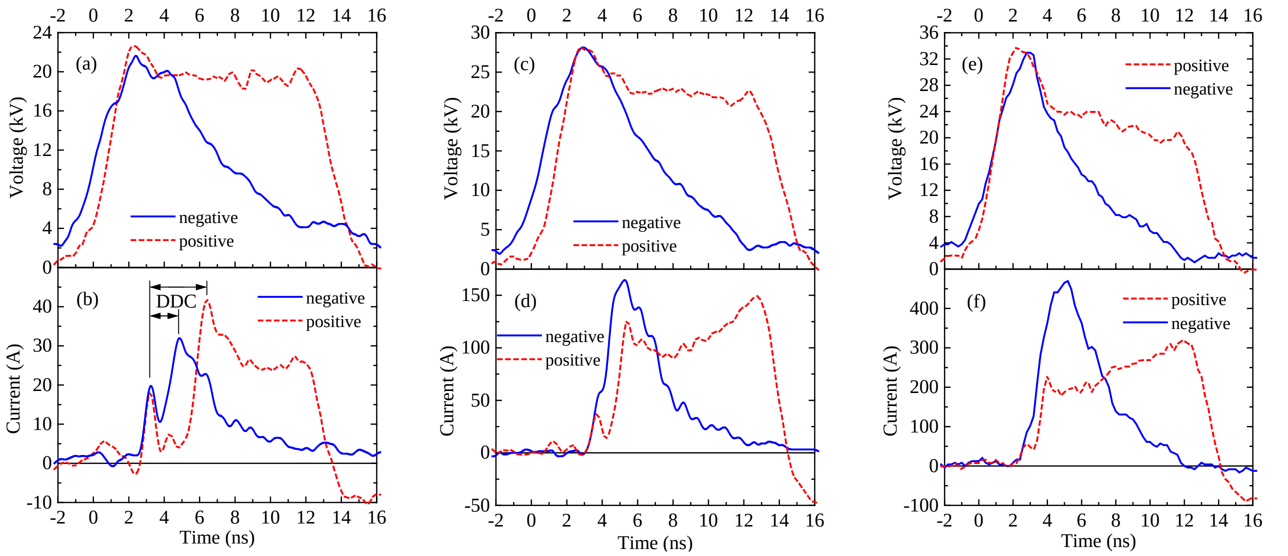

Fig. 1. Waveforms of (a, c, e) voltage and (b, d, f) current during discharge in atmospheric pressure air at different voltage amplitudes and polarities.

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ON THE INFLUENCE OF A CATHODE SHAPE ON THE PARAMETERS OF CURRENT PULSES OF RUNAWAY ELECTRON BEAMS AT APPLYING VOLTAGE PULSES WITH A RISE TIME OF 200 NS*

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Runaway electron beams generated during the breakdown of gaps with a cathode having a small radius of curvature are currently obtained in various gases at pressures from hundreds of Pa to thousands of kPa. Their parameters were measured in different conditions with a high temporal resolution [1]. However, such measurements were carried out under conditions of high overvoltages when applying voltage pulses with a subnanosecond and nanosecond front duration. In practical applications, voltage pulses with a rise time of 10^{-7}–10^{-6} s are widely used [2]. There are very few data on direct measurements of the parameters of runaway electron beams under these conditions. Noteworthy is the work [3] of 2018, in which studies were carried out with the rise time of ≈ 500 ns.

The purpose of this work is to study the influence of the cathode design on amplitude-time parameters of runaway electron beams at applying voltage pulses with the rise time of 200 ns.

The experimental studies were carried out on setup that allows measuring subnanosecond runaway electron beam current pulses with temporal resolution up to 100 ps. A GIN-35NP homemade voltage pulse generator was used. Different cathodes were used. The first one was made of a needle with a length of 5 mm, a base diameter of 1 mm, and a rounding radius of its tip of 75 µm. The second was tube with a diameter of 6 mm and a wall thickness of 100 µm. The third was made of a ball with a diameter of 14 mm. The grounded electrode was a plane. The gap width was 8.5 mm. The generator produces negative voltage pulses with an amplitude of up to 35 kV, the rise time of 200 ns, and a pulse duration $\tau_{0.5} \approx 270$ ns. To measure the parameters of a supershort avalanches electron beam (SAEB) [1], the grounded plane electrode was made of a grid. The SAEB current was measured with a 20-mm collector placed behind the grounded electrode. The grid had the mesh size of 400×400 µm and a transparency of 62%. In some experiments, a 2-µm kimfol ($C_{16}H_{14}O_3$) film coated with a 0.2 µm-thickness aluminum layer, as well as a 10-µm Al foil were used as the grounded electrode. The kimfol passes electrons with an energy of 10 keV and higher. The Al foil passes electrons with an energy above ≈40 keV. They were used as filters. The electrical signals from a capacitive voltage divider and the collector were recorded with a Keysight Tech MSOS804A digital oscilloscope (8 GHz, 20 GS/s). The bandwidths of a current shunt made of chip resistors and the 20-mm collector were no higher than 4–5 and 6 GHz, respectively.

It was found that the shape of the cathode significantly affects the duration of SAEB current pulse, its amplitude and shape. The largest amplitudes (≈ 90 mA) were observed with the tubular cathode at a pressure of air of 12.5 kPa. Saeb current pulse duration was $\tau_{0.5} \approx 130$ ps. Two pulses with different duration, amplitude and energy of electrons were observed with the needle cathode. When using the ball, the duration and amplitude of the beam current pulses were $\tau_{0.5} \approx 250$ ps and ≈ 4 mA, respectively.

Studies performed with a four-channel ICCD camera showed that the breakdown occurs via the development of streamers starting from the cathode. The diameter of the streamer depended on the radius of curvature of the cathode, and was the largest with the smallest radius of curvature (needle cathode). As the air pressure increased to 100 kPa, the amplitude of the beam current decreased.

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PARTICLE DYNAMICS IN QUADRUPOLE ALTERNATING CORONA DISCHARGE

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Particles dynamics inside alternating corona discharge electrodes of the trap was studied. Four electrodes were mounted parallel to each other at the corners of a square. At the electrodes prebreakdown alternating voltage was applied with phase π at neighboring electrodes. Uncharged Al2O3 microparticles were injected between the electrodes where they start gaining charges in alternating corona discharge. The frequency of the alternating voltage was 50 Hz and the strength of electric field was up to 30 kV/cm (peak-to-peak).

Under the assumption of wire-to-cylinder geometry of the electrodes and hydrodynamic model that takes into account the continuity equations govern the transport and the gain/loss balance of every species due to the chemical reactions with the Poisson equation a stationary corona discharge was simulated in oxygen [1,2] for different geometries, the distributions of positive and negative ions and electron were gained.

Using the distribution of electric field and concentration of ions and electrons in positive and negative corona discharges the particle's charges were calculated at every moment of simulation. Analyzing particle motion the areas of particle capturing (the geometric area, parameters of voltage and the geometry of electrodes, particles sizes and densities) and the dynamics of particles changes were found, Fig 1.

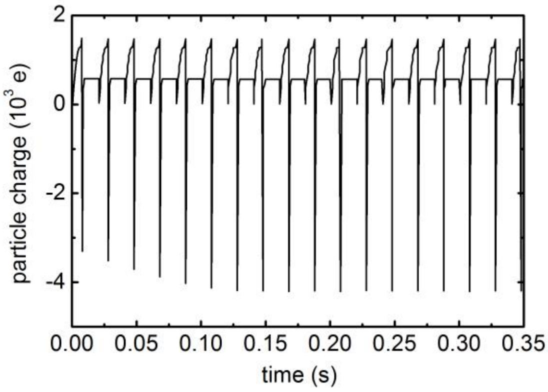

Fig. 1. The charge dynamics of 1μm Al2O3 captured inside quadrupole corona discharge.

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THE DYNAMICS OF IONIZATION WAVES FORMATION IN A TRANSVERSE NANOSECOND PLASMA-BEAM DISCHARGE WITH A SLOT CATHODE IN ARGON

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The paper presents the results of an experimental study and numerical simulation of the spatial-temporal dynamics of ionization processes in the gap between the electrodes and inside the cathode cavity during the formation of a nanosecond discharge in argon at pressures in the chamber from 1 to 10 Torr. The cathode had the shape of a cylinder with a diameter of 1.0 cm with longitudinal cuts 0.2 mm wide and 0.6 cm deep; the discharge area between the electrodes was limited by dielectric walls set at a distance of 0.2 cm from each other. Voltage pulses with an amplitude of 0.5 to 1.5 kV and a duration of about 100 ns were applied to the electrodes. The dynamics of the formation of the spatial structure of the discharge at various stages was experimentally investigated using high-speed photo-recording with a Princeton Instruments PI-MAX3 camera [1]. The correspondence between the density distribution of charged particles and the optical patterns of the discharge was established. A numerical model of the formation of a limited discharge in argon under various external conditions was constructed taking into account the influence of the charge deposited on the surface of the dielectric wall, the secondary electron emission coefficient from the cathode surface, and the influence of the space charge on the distribution of electric potential between the electrodes. The role of the surface charge deposited on the dielectric walls in the formation of the spatial structure of the discharge was established. The results of numerical simulation are compared with experimental data. It is demonstrated that the electron concentration in a discharge limited by dielectric walls is an order of magnitude higher than in an unlimited discharge under the same external conditions.

The general patterns of formation and development of a limited discharge in argon are discussed; the main physical processes affecting the dynamics and the spatial structure of the discharge are established.

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HOLOGRAPHIC INTERFEROMETRY FOR THE STUDY OF THE ELECTRIC EXPLOSION OF WIRES *

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Some experimental results of holographic interferometry [1] for the specification of an electric explosion of wires [2] are presented. "Slow" (during of 50…200 μs) electric explosions of thin (with an initial diameter of 20…50 μm) different metal titanium wires were characterized in air and argon atmosphere. An energy input from a capacitor into the wires was varied from 3 to 7 J. The process was studied with the double exposure laser (λ=532 nm) holographic interferometry.

The main features of the explosion were visualized at different times. A curvature of interference fringes indicated about a refractive index change (see Fig. 1.). So a generated shock wave (1), a shock compressed gas (2) and an extended high temperature explosion products (3) were found. At less times (<30 μs) an initial wire was still visualized (4). A complicated (with a heavy curvature of interference fringes) behavior of a refractive index in explosion products was explained by a presence of titanium small particles, neutral and ionized vapors, arc plasma, etc.

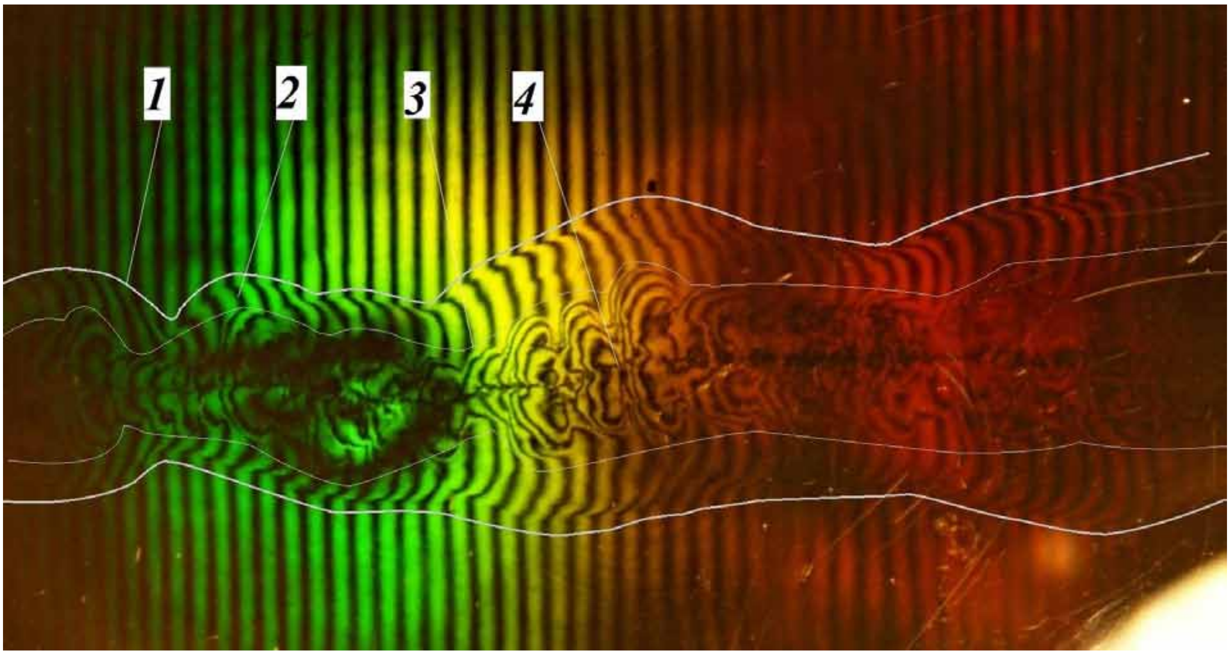

Fig. 1. Holographic interferometry pattern of titanium wire explosion at 20μs: 1 – shock wave front, 2 – shock compressed gas, 3 – explosion products and 4 – initial wire

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I-V CHARACTERISTICS AND EFFICIENCY OF ELECTRON BEAM GENERATION IN DISCHARGES, IN NITROGEN AND OXYGEN*

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Sources of electron beams (EB) with an EB of the keV-range energy based on a gas discharge typically use helium or argon, or their mixtures with oxygen. At the same time, there are practically no studies on the generation of EB in pure molecular gases, in particular, in nitrogen and oxygen. Such generators can be used in technological operations for nitriding and oxidation, for example, in semiconductor industries. Of particular interest is also the study of physical processes in high-voltage discharges in N_2 and O_2, the study of which may contribute to the expansion of possible applications.

The studies were carried out in carefully degassed cells with a titanium cathode with a diameter of 12 mm and an interelectrode distance of 21 mm. Calibrated thermal sensors were installed to measure the efficiency of the generation of EB on the side walls of the cell and on the anode-collector of electrons. The potential measurement of the electric field in the cathode region was carried out using probes. It turned out that in N_2 and O_2, the current – voltage characteristics have a smoothly increasing form in the investigated voltage range of 0.5–6 kV and pressures of 20–200 mTorr. Already at $U > 1.5$ kV, the efficiency η of the generation of EB exceeds 50% and increases to 86% at $U = 6$ kV for discharge in O_2 and 79% for discharge in N_2.

The achievement of such high efficiency is explained from the standpoint of the mechanism of kinetic emission of electrons under the influence of fast neutral and ionized molecular particles with a total emission coefficient of $\langle\gamma\rangle = 6$ for discharge in O_2 and $\langle\gamma\rangle = 3.8$ for discharge in N_2. In turn, the high $\langle\gamma\rangle$ value is ensured by the effective interaction of fast molecular particles with the cathode surface. On the one hand, they saturate the surface layers to the level of packing density corresponding to the density of liquid oxygen and nitrogen. On the other hand, fast particles accelerated in the region of the cathode potential drop ionize nitrogen or oxygen in the surface layers, releasing electrons with subsequent emission. The greater magnitude of $\langle\gamma\rangle$ and the efficiency of generation of EB in oxygen is explained by the large ionization cross section of the O_2 molecule with fast O_2 and $O_2^{\ +}$ compared with the ionization cross sections of N_2, and fast N_2 and N_2^+.

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EMISSION CURRENTS FROM CATHODE WITH NANOSTRUCTURED TENDRIL BUNDLES

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Plasma-surface interaction is a key factor for realization of thermonuclear fusion with magnetic confinement. The experiments on plasma-wall interaction with tungsten have been carried out on linear simulators and tokamaks show that thin nanorods called “fuzz” can be formed on tungsten surfaces after helium plasma irradiation. The typical thickness of the fuzzed layer is ~1 μm, and the rod diameter is ~10 nm. It was demonstrated in [1] that in the case of fuzz formation frequency of unipolar arcing increases that leads to higher material erosion rate.

Recently it was shown [2] that nanostructured tendril bundles (NTB) demonstrated in fig. 1 can grow on the tungsten surface after neon or nitrogen addition to helium plasma. NTB can be several tens micrometers in height and about 10 μm in diameter near bottom. The NTB as a rule are separated by several hundred micrometers from each other and are formed from thin fuzz nanorods. The mechanism of NTB formation is not clearly understood [3,4] but in some way it is related to the sputtering and redeposition processes on surfaces covered by tungsten fuzz under plasma ions impact.

As for plasma-surface interaction with NTB covered cathode, it is of interest to investigate dynamics and parameters of emission currents in DC electric fields.

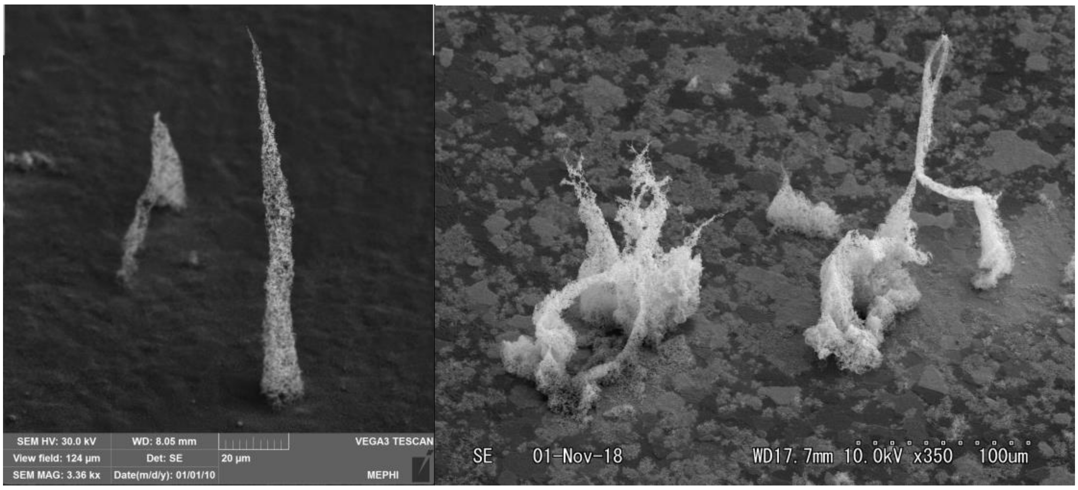

Fig. 1. Photos of different types of nanostructured tendril bundles on tungsten surface.

Field emission from samples with NTB was measured using vacuum diode device. Emission current of several nanoamperes was detected for electric fields lower than 1 kV/mm that is comparable with specially designed flat field emission cathode. Field enhancement factor and effective emission area were calculated using Fowler–Nordheim formula and compared for different types of the nanostructures. Transparent anode covered by luminophore was used for detecting of emission sites distribution on the surface and their dynamics during experiment. Emission sites positions were in strong correlation with position of the NTBs arrays on the cathode surface. In combination with analysis by scanning electron microscope and confocal laser microscope, this allows detection of nanostructures initiating of pre-breakdown currents. We have also seen a temporal evolution of emission currents and found that these currents do not directly relate to the evolution of NTB form. The possible reasons of such temporal currents behavior will be also discussed.

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STUDIES OF THE MECHANISMS FOR CONTROLLING THE SPATIAL PARAMETERS OF THIN PLASMA CHANNEL IN OPEN ATMOSPHERIC DISCHARGE*

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The project is devoted to a complex theoretical study of a new phenomenon in gas-discharge plasma physics - the so-called "apokamp discharge" (from the Greek "apo" + "kamp", that is, "from bending") [1]. Apokamp discharge is the phenomenon of formation in the open space of long and narrow plasma jet oriented perpendicularly to a short plasma column of a pulse-periodic contracted discharge.

The study included both experimental and theoretical parts. As a result of a series of experiments, the influence of an external electric field created by a grounded electrode on the formation and maintenance of the apokamp is shown. Note that the external field is the initiator of the jet, but does not affect its orientation in space. The average external electric field, at which a plasma jet grow up, is determined in experiment.

The model of the phenomenon is constructed in the framework of the hydrodynamic approach with drift-diffusion approximation. For the first time, the problem of a theoretical description of the appearance of a narrow plasma channel growing up perpendicular to the high-current channel of the main discharge has been solved. The effect of the weak external field on the formation and growth of the plasma channel is theoretically demonstrated.

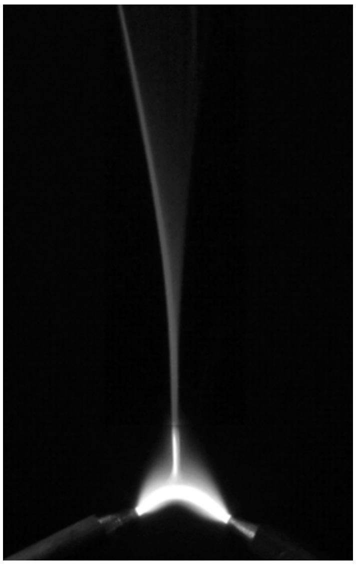

Fig. 1. Apokamp between a sharp-ended electrodes.

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SIMULATION OF THE EXPLOSION OF A SURFACE MICROPROTRUSION DURING A RADIO FREQUENCY BREAKDOWN

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The explosion of a surface microprotrusion under the action of a radio frequency electromagnetic field has been numerically simulated. It has been demonstrated that the microexplosion and the subsequent crater formation occur in much the same way as they do in the case of a dc field. The results obtained support the hypothesis that a dc vacuum breakdown and a breakdown initiated by an rf wave incident on a metal surface proceed by the same mechanism [1, 2].

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REGULATION OF THE AIR HIGH VOLTAGE AC PLASMA TORCH POWER BY SMALL AMOUNT OF METHANE*

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Already for a long time plasma torches are used for a wide range of areas: welding and cutting of metals and refractory materials; the application of protective coatings on various materials; obtaining nanodispersed powders of metals and their compounds; thermal neutralization of highly toxic organic waste; oil-free kindling of pulverized coal boilers of power stations.

In each case, the most important parameter of the plasma torch is its power. In most cases, the power of an electric arc plasma torch can be changed by several methods: electric current, voltage, mass flow rate of the plasma-forming mixture, composition of the plasma-forming mixture. Previously it was found that in plasma torches with a vortex stabilization of an electric arc for plasma-forming mixtures consisting of steam, carbon dioxide and methane, the power increased significantly with the additional methane [1]. This was due to the formation of hydrogen:

$$CO_2 + CH_4 = 2CO + 2H_2 \quad (1)$$

$$H_2O + CH_4 = CO + 3H_2 \quad (2)$$

The power of the plasma torch varied from 60 to 170 kW. In this case, the voltage drop across the electric arc was changed. This is due to a change in the electrical conductivity of the arc containing hydrogen and an increase in the intensity of heat exchange between the arc and the colder gas vortex stabilizing it.

The report deals with the AC three-phase high-voltage plasma torch [2]. A small amount of methane (up to 1%) was added to the main plasma gas. In this case, the following reaction took place in the electric arc burning zone:

$$CH_4 + 0.5O_2 = CO + 2H_2 \quad (3)$$

The plasma torch is powered by an alternating current power source with a 10 kV open circuit voltage [7]. The power supply consists of a high-voltage transformer (380/10000V), current-limiting inductances, a reactive power compensator and a system for continuous measurement of electric parameters.

However, unlike the mixture of methane with steam, the power of the plasma torch increased exponentially. Probably the main cause of this phenomenon is the decomposition of nitrogen oxides, the ions of which provide a significant portion of the electrical conductivity of the electric arc:

$$2NO + 2H_2 = N_2 + 2H_2O \quad (4)$$

The same experiments were carried out using a plasma torch with two inputs of plasma-forming gases [3]. Air was supplied to the near-electrode zone, and a mixture of air and methane was fed to the electric arc zone. In this case, the power change was significantly lower. This is since there is no hydrogen in the electrode area and the main sources of electrical conductivity are preserved. The results indicate that it is possible to control the power of the plasma torch without a significant change in the total flow rate of the plasma-forming mixture and its composition.

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TARGET TEMPERATURE MEASUREMENTS IN A PULSED MAGNETRON DISCHARGE IN TARGET MATERIAL VAPOR*

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Nowadays, magnetron sputtering plays one of the leading roles in deposition of thin films with outstanding physical properties and high quality. Comparing magnetron sputtering with other methods of physical vapor deposition, we can distinguish a number of significant drawbacks, one of which is the low efficiency of the film deposition process and low film growth rates. To eliminate the drawbacks of magnetron systems, various modifications of existing systems are being developed. One of such promising concepts is pulsed magnetron discharge in target material vapor [1, 2].

The main parameter to assess the effectiveness of the modified magnetron sputtering system is the deposition rate The deposition rate, in turn, is influenced by the shape of the current pulse profile, voltage, discharge temporal characteristics and temperature of the target [3]. The measurement of the target temperature is the most problematic part of the evaluation of parameters affecting the deposition rate.

There are two different ways to measure temperature: contact and non-contact [4–5]. At significantly high temperatures of heated objects, the use of the contact method for temperature measurement is complicated. Contactless temperature analysis in our case is also difficult, because of the rapid deterioration of optical transmission due to high speed of coating deposition.

As part of this work, a special shielding that allows optical emission measurements from hot Cu, Si, and Cr targets has been designed. Comparison of optical and contact temperature measurement methods has been performed. The methods and devices described in this contribution aim at investigating the dependence of the deposition rates of Cu, Si, and Cr films on the impulse shape of the discharge current and voltage, and the discharge plasma temporal characteristics.

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DBD PLASMA JETS IN ARGON AND HELIUM: STREAMERS PROPAGATION ALONG GAS FLOWS*

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Atmospheric pressure plasma jets (APPJ) are one of the most prospective sources of "cold" atmospheric plasmas that have been intensively developed for a wide range of biomedicine applications. To generate APPJ, we used a dielectric-barrier discharge, which was fed by an original high-voltage signal consisting of a superposition of 40 kHz bipolar square pulses and 300 kHz oscillating signals (Fig. 1(a)).

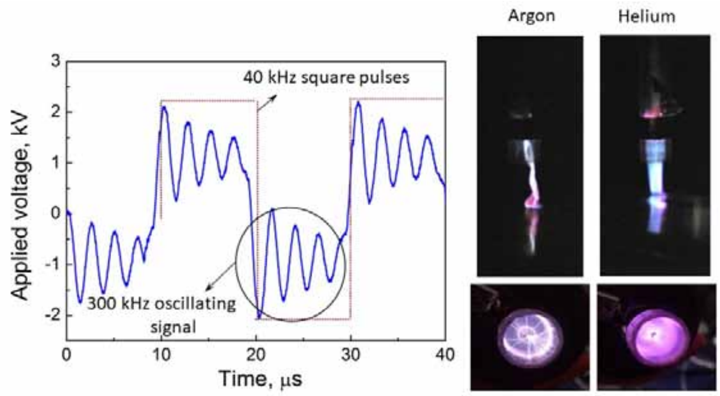

Fig. 1. High-voltage signal to feed a dielectric-barrier discharge in a helium flow (a); images of a dielectric barrier discharge in argon (left) and helium (right) flows (b).

DBD was ignited inside a quartz tube with a co-axial electrode system "inner rode – outer ring". The high voltage applied to the inner electrode, which was made of a copper wire 1.5 mm in diameter. The outer electrode made from a copper foil stripe was grounded. Gas flow was passing through the tube with the discharge with the gas flow rates of 1, 3, and 4.5 l/min, a plasma jet appeared in ambient air. Plasma jet is formed due to the ionization waves (streamers) propagation along the gas flow outside the discharge tube. The shape and geometrical sizes of the plasma jet depend on the combination of the applied voltage parameters and gas-dynamics conditions.

Argon and helium are two inert gases wide-spread in plasma technologies, which are used in APPJ-type generators to produce "cold" plasma flows. Owing to the different nature, the two gases provide DBD burning on the different regimes: diffusive and filamentary (Fig. 1(b)) [1]. Electrical diagnostics of the discharge was done along with the high-speed imaging of the plasma jets.

Electrical measurements suggest that diffusive nature of helium discharge gets along with the narrow single discharge current peaks of 10 mA at the positive and negative half-periods of the applied voltage, whereas the filamentary structure of argon discharge is recorded along with the numerous small peaks of the discharge current that almost indistinguishable against the displacement current.

The time-spatial behavior of the streamers along the helium and argon plasma jets has been described. For the helium plasma jet, a special step-by-step streamer propagation mechanism was recorded. It is valid when the applied voltage has a special shape with a voltage bias of oscillations. For the argon plasma jet, a branched structure of the streamers was observed. It is due to the filamentary regime of DBD burning in argon.

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THE METHOD OF SYNTHESIS GAS AND STEAM PYROLYSIS AT HIGH TEMPERATURES

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Recently, quite a lot of publications have been devoted to the improvement of methods and approaches to the use of hydrocarbons in the energy sector and other non-volatile industries. Consider a historical method of producing fuel based on steam pyrolysis. This method according to the official version belongs to Traverse Morris Williams (England, 1927). This water gas is obtained by blowing water vapor through a layer of hot coal or firewood. The reaction follows the $H2O + C \rightarrow H2 + CO$ equation with heat absorption - 132 kJ / mol.

As a known at temperatures approaching 1000 ° C, water is decomposed into hydrogen and oxygen. While the water in a fire heats up and evaporates, it takes a large amount of heat and acts as a "quencher", but as soon as the steam heats up above 400 ° C, the water turns into additional fuel. This method of obtaining energy is undeservedly forgotten and received its applied distribution only in the narrow field of metallurgy and in chemical synthesis - for the production of synthetic fuels, lubricating oils, ammonia, methanol, etc.

The main value of this method of producing fuel lies in its availability of investments and the simplicity of manufacturing working devices for the general population and production. Given the conditionally zero cost of water, as well as the way it is processed (decomposed), you can move from the concept of alternative fuel to the concept of increasing the efficiency of burning traditional fuel.

This article describes how to increase the efficiency of a coal (wood burning) stove or solid fuel boiler without using additional hydrocarbon energy resources. The principle of operation of the technology is quite simple: water from the tank (steam generator) is converted into steam with a high temperature (300–350 ° C) and is fed directly into the flame through a nozzle, acting as a kind of combustion catalyst, increasing the productivity of the heating installation.

REGIMES OF SUSTAINING THE HOLLOW-CATHODE GLOW DISCHARGE WITH THE HOT FILAMENT INSIDE THE CAVITY*

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Nowadays hollow-cathode low-pressure glow-type discharges are widely used for different applications [1-5]. In particular, such discharges are used for generation of charged particle beams, for surface modification, for generation of extreme ultraviolet radiation, in high-current switching devices (cold-cathode thyratrons), for generation of large volume plasmas and so on. The term "low-pressure" implies that the discharge conditions correspond to the left branch of the Pashens curve, i.e., the electron mean free path in terms of ionization exceeds the length of the discharge gap. Under these conditions, single electrons cannot initiate the gap breakdown.

The conventional approach to explain the mechanisms of sustaining of the low-pressure glow discharge implies that the main part of the discharge current at the cathode surface is carried out by ions and electrons are emitted from the cathode due to the ion bombardment [6]. To constructing the model of a hollow-cathode discharge the conventional secondary emission yield γ from the cathode material – the number of secondary electrons per one ion incident on the cathode surface is often used.

The coefficient γ formally takes into account only electron emission caused by the ion bombardment of the cathode surface as the secondary process. This coefficient is sometimes called the generalized emission yield, implying that it also takes into account the photoeffect. However, the coefficient γ can be used to describe the emission current caused by the photoeffect and ion bombardment only if both components of the emission current depend equally on the ion current. In most cases, such a situation is an exclusion rather than a rule and it is physically more justified to consider the electron photocurrent as a certain external current. Then, an external emission source should be introduced separately.

Such approach was proposed in [7-11]. In these papers the generalized coefficient of secondary emission Γ, that depends on external emission current and includes classical coefficient γ, was introduced. Based on this approach the explanations of discharge sustaining features in the main gap and in the trigger unit of the cold-cathode thyratron were done.

At the same time, there are other types of discharges for that the proposed approach for explanation of the mechanisms of current passage and discharge sustainment seems to be perspective. It can be spread to the discharges in devices for the modification of properties of material surfaces. In such devices, the low-pressure discharge is sustained and external emission current is set and changed artificially. In particular, to this type of discharge can be attributed the glow discharge with a hollow cathode and hot filament (thermionic cathode) inside the cavity [5, 12].

In this report the results of investigations of hollow-cathode glow discharge with the hot filament inside the cavity are presented. Current-voltage characteristics for the different filament currents were recorded. The regimes of discharge sustaining based on the model are interpreted. It is shown that the model agrees with experiments.

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INFLUENCE OF THE RESISTANCE OF SEMICONDUCTOR ON DELAY TIMES TO BREKDOWN IN A FLASHOVER BASED TRIGGER UNIT OF THE COLD-CATHODE THYRATRON*

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Currently, high-current switching devices based on low-pressure hollow-cathode pulsed discharge (so-called pseudospark switches) are widely used [1-5]. The design and principle of operation of these switches are close to those of a classical hot-cathode hydrogen thyratrons. However, these devices do not have a hot cathode. Therefore, pseudospark switches are often called cold-cathode thyratrons or thyratrons with a grounded grid [3, 6].

As in the case of classical thyratrons, a range of operating pressures of the switch corresponds to 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 thyratron and for external discharge triggering a considerable pre-breakdown electron current is required [7, 8]. For the case of external triggering, this current is provided due to a special trigger unit that is placed in the main cathode cavity. In the sealed-off thyratrons, that are produced commercially, trigger units are based on auxiliary glow discharge (TPI series) and on a discharge over a semiconductor surface (TDI series) [6].

Trigger unit is intended for plasma generation inside the thyratron cathode cavity at a curtain instant of time. To do this, a voltage pulse with an amplitude of several kilovolts (trigger pulse) is applied to one of the electrodes of the trigger unit. For the case of trigger unit based on discharge over the semiconductor surface, after application of a trigger pulse the current in a trigger circuit at the initial stage is flowing through the semiconductor body. Due to the current cathode spots arise in the place of contact of trigger electrode and semiconductor and surface discharge is initiated. At the further stage, surface discharge current is intercepted from the trigger unit to the main cathode cavity and due to the hollow cathode effect plasma is generated inside the cavity [9, 10]. Electrons are extracted from the plasma into the main gap that leads to initiation of the discharge in the main gap and thyratron triggering occurs.

Time interval from the application of trigger pulse to initiation of breakdown in the thyratron main gap is the delay time of thyratron triggering. This delay time consist of the delay time to initiation of surface discharge, delay time to interception of the surface discharge current to the main cathode cavity and delay time to discharge development in the main gap. In turn, the delay time to initiation of surface discharge have to depend on the value of semiconductor body resistance and on the trigger pulse amplitude and rise time.

In this report the results of investigation of the trigger unit based on a discharge over the semiconductor surface with different resistance of semiconductor body and different amplitudes of a trigger pulse are presented. Experiments were carried out with the sealed-off thyratrons of TDI series. Data on delay times to discharge initiation were obtained. Methods for reduction of the delay time to current interception to the main cathode cavity are proposed. Conditions of thyratron operation for that the delay times of thyratron triggering are minimal revealed.

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