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Development of the electron acceleration process and dynamics of micropinch plasma

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Based on the results of the experiments and numerical estimates, the authors hypothesize that the direction of propagation of the flow of high-energy electrons in a micropinch discharge is determined by the freezing of magnetic field lines into the plasma flow and the magnetization of electrons accelerated to high energies.

Keywords: micropinch discharge, plasma, acceleration processes.

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Micropinch is a microscopic plasma object that is formed in direct high-current (~ 100 kA) pulse discharges of *Z*-pinch type in the medium of heave elements, where the mode of plasma pinching by magnetic field of discharge current is implemented effectively, and features achievement of substance density and temperature, which are record-high for discharges. Another frequently used name for this object is „hot spot" (HS) [1,2]. The phenomenon of micropinching is rather a result of discovery, than an invention or a theoretic prediction [3]. A requisite condition for the micropinching is the achievement of some threshold current in the discharge, which is defined by the composition of elements in the discharge plasma. Authors of [4], based on the experimental results obtained with the use of multiframe shadowgraphy and records of x-ray line emission of multicharged ions with nanosecond timeŕesolution, suggested a hypothesis that micropinching is formed as two successive processes: slow magnetohydrodynamic compression (with a duration of several tens of nanoseconds) and fast, but not adiabatic compression (with a duration of less than 1 ns). Nearly at the same time a theoretical model of fast radiation compression was suggested [5], within which, based on the „runaway" electron model in turbulent plasma described in [6], authors of [7] showed that electrons can accelerated only in a strong longitudinal ohmic field, which is generated in the constriction under the conditions of anomalously high plasma resistance caused by its turbulization. Generation of the electron beam is started before the maximum compression and continued at the stage of plasma expansion, the time-integral spectrum of fast electrons reaches energies of about 300 keV. Later on the model of radiation compression was confirmed primarily due to the unique capabilities of high-resolution x-ray diffraction spectroscopy [8,9]. At the same time, authors of [10] reported that in a relatively low-current vacuum discharge (17 kA, 10 kV) in the atmosphere of electrode material (Fe) erosion products initially arising under the impact of a pulse of high-power ($10^{10}-10^{12}$ W/cm^2) laser emission, they have found the effects of micropinching structures formation and generation of electron beams with energies of up to 90 keV similar to the situation taking place in high-current discharges. However, the author state that in their view the acceleration of electrons may not be related to the pinching phenomenon. It should be noted that value of the threshold current for the micropinching phenomenon in ferrum plasma is ~ 50 kA according to both the model-based calculation and the experimental data [5,11]. In addition, the energy spectrum of epithermal electrons emitted from the discharge undergoes a stepwise change when the current amplitude becomes higher than some critical value [11].

To find out additional information on the interrelation between the compression processes of the constriction area and the development of accelerating processes in the plasma of micropinching discharge, the authors attempted to intervene into this process. The authors applied a combined current source composed of a capacitor battery and a forming line with variable length connected in parallel.

The discharge took place at an initial vacuum of at least 10^{-2} Pa in products of material erosion of coaxial electrodes (ferrum), one of which (inner high-voltage electrode) had a conical geometry, and another (outer earthed electrode) had a cylindrical geometry. The current achieved in the discharge was as high as $60-100$ kA. The current source was implemented as a battery of low-inductance high-voltage capacitors of IK-50-3 type connected to a discharging device through a forming line. The role of forming line was played by an assembly of parallel coaxial high-voltage cables SR-50-9-11 in amounts of 8 cables per capacitor in the battery. The maximum number of capacitors used in the battery was 4 pieces. The discharge initiated by supplying foreplasma from an auxiliary low-current erosion-type source into the interelectrode gap (Fig. 1). There

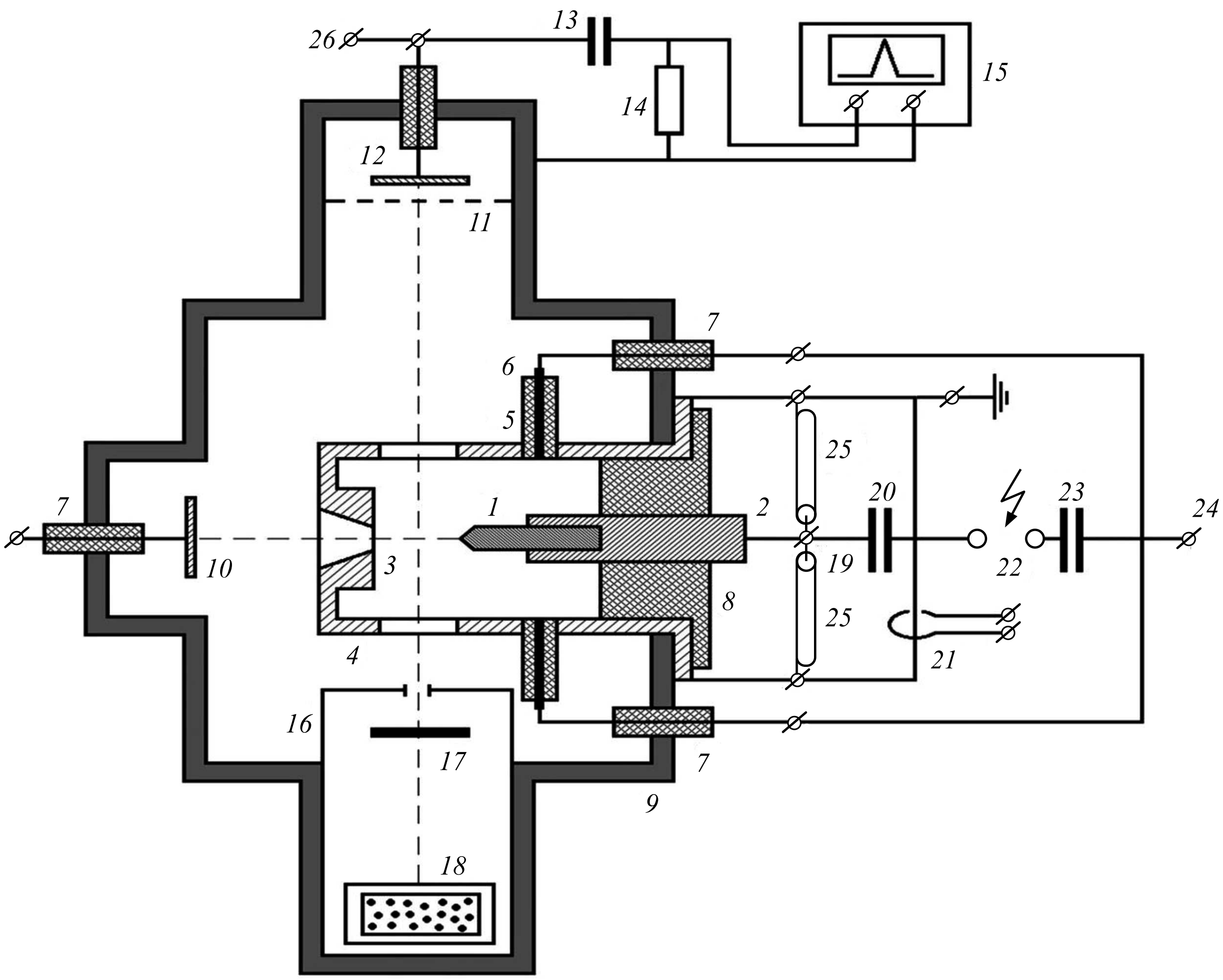
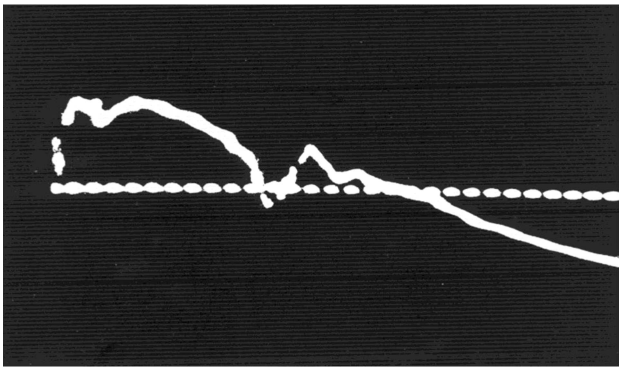


Figure 1. Schematic diagram of the experimental setup. *1* — inner electrode, *2* — inner current conductor, *3* — outer electrode, *4* — outer current conductor, *5* — dielectric bushing, *6* — ignitor electrode, *7* — bushing insulator, *8* — separating insulator, *9* — vacuum chamber, *10* — collector of charged particles with biased potential, *11* — anode of vacuum biplanar photodiode, *12* — cathode of vacuum biplanar photodiode, *13* — separating capacitor, *14* — load resistor, *15* — oscilloscope, *16* — camera-obscura objective, *17* — absorbing thin-film filter, *18* — photographic detector of x-ray radiation, *19* — connection of high-voltage source for battery charging in the circuit of main discharge, *20* — battery of capacitors in the circuit of main discharge, *21* — Rogowski coil, *22* — triggered spark gap, *23* — battery of capacitors in the ignition circuit, *24* — connection of high-voltage source for battery charging in the ignition circuit, *25* — forming line, *26* — connection of stabilized high-voltage source.

was a possibility to change polarity of the capacitor battery charging voltage.

The mode of discharge was monitored using 1) Rogowski coil in the mode of current derivative record; 2) vacuum biplanar photodiode recording the dynamics of emitted vacuum ultraviolet (VUV) and soft x-ray radiation; 3) collector of charged particles with biased potential (+60 V); 4) x-ray camera-obscura (recording range $\lambda < 0.3$ nm defined by thickness 0.1 mm of the filter made of berillium; spatial resolution of the object image was ~ 0.2 mm and defined by 0.15 mm diameter of the hole in the lead shield with a thickness of 0.18 mm). Note that the above-mentioned spectral range of x-ray radiation recording $\lambda < 0.3$ nm includes *K*-spectrum of the working element (ferrum). The mode of pinching up to formation of the micropinch was evidenced by the following: 1) arising of a drop (so called singularity) on the oscillogram of discharge current derivative in the first quarter of the period, i.e. knowingly before the polarity reversal of electrodes (Fig. 2); 2) synchronous recording of VUV pulse and soft x-ray radiation; 3) the fact od arising of a group of particles (plasma) moving with speeds of $\geqslant 4 \cdot 10^4$ m/s; 4) arising of a typical bright hole image in the absorbing diaphragm on the obscuragram, which is ofte called as an image of the „hot spot". Images of x-ray radiation sources were formed on a medical film of RM-K type with an emulsion layer thickness of ~ 0.03 mm, sensitivity of $\sim 30\,\mathrm{R}^{-1}$ in the unshielded variant and an average contrast (average gradient) of 3, proved itself to be sufficiently effective detector up to quantum energies of ~ 30 keV



1 μs

Figure 2. Oscillogram of signal from the Rogowski coil .

from among the most suitable for manual photoprocessing.

It is necessary to note that repeatability of the current oscillogram singularity, pulse of short-wave radiation recorded by the photodiode, the fact of recording of a group of particles with directed speed $\geqslant 4 \cdot 10^4$ m/s by the collector, and the character of images observed on obscuragrams turned out to be close to hundred percent, i. e. the above-mentioned characteristics repeated in nearly all discharges, total number of which was not less than two hundred.

Let us consider the sequence of x-ray obscuragrams recorded at different wavelength of the forming line. At a length of forming line of 1 m (at the moment of discharge initiation the inner electrode acts as anode, the outer electrode acts as cathode) formation of a micropinch is observed, which is recorded as a „hot spot". In addition, a luminance is observed in the above-mentioned x-ray range of the spectrum, presumably under the accelerated electron beam bombarding the inner electrode surface and peripheral plasma out of the constriction area (Fig. 3, *a*).

With similar polarity of electrodes, but at a length of the forming line equal to 2 m, in addition to the luminance of the inner electrode surface, micropinch and peripheral plasma, a luminance of the outer electrode surface is observed (Fig. 3, *b*). Identical images are obtained with increase in the length of the forming line up to 3 m and arbitrary initial polarity of the electrodes (Fig. 3, *c* and *d*). Also, a similar image is formed at a length of the forming line equal to 1 m in the case when the inner electrode acts as cathode, the outer electrode acts as anode. A luminance of micropinch, peripheral plasma and the outer electrode is observed, while there is no luminance of the inner electrode. More over, formation of supersonic plasma flow can be noted (Fig. 3, *c*), which is directed outward the electrode system. A typical attribute of the supersonic flow blowing over the protrusion of the outer electrode tip is the formation of a standing shock wave recorded as a flow consolidation near the tip. Shape of the standing wave can be used to evaluate the Mach number [11]:

$$\mathrm{M} = 1/\sin(\theta/2), \tag{1}$$

where θ — angular opening of the cone formed by the shock wave.

The forming line, which capacitance with a length of 3 m is $C \approx 10^{-9}$ F, probably shunts the discharge and decelerates the development of accelerating processes related to the increase in ohmic resistance of the plasma and, as a consequence, with the increase in potential drop in the area of constriction. Presumably, in the interval between the first and the second compression a charging of the forming line takes place up to voltages of about 10^4-10^5 V and a delay occurs in the development of the accelerating processes in the plasma by a time interval of ~ 10, 20 and 30 ns depending on the length of the forming line:

$$\tau_{del} = (2L\varepsilon^{1/2})/c, \tag{2}$$

where L — length of the forming line, $\varepsilon = 2.3$ — dielectric constant of the insulator (polyethylene), c — speed of light in vacuum. The above-mentioned values of voltage surges as a result of the arising anomalous resistance of the pinch plasma are predicted by numerical evaluations made within the model of radiation compression [12] and matched with the measured energies of $10^4-3 \cdot 10^5$ eV emitted from the constriction plasma in the axial direction of fast epithermal electrons. Measurements were conducted by direct recording of the epithermal electrons flux [12–14] and by analysis of continuous x-ray radiation spectra [11,15,16].

It can be assumed that at the stage of transition from the first to the second compression a plasma flow is formed, which blows away „hot", i. e. accelerated, but fixed in a magnetic field electrons in the direction from the inner electrode to the outer electrode regardless of polarity of the electrodes, unless the process of acceleration is delayed till the moment when disappears the possibility of electrons „runaway " in the near-axial area of minimum magnetic field. Note that in Fig. 3, *a*, in addition to the image of the extended surface of the inner electrode, which rising is caused by the bombardment of the surface by sufficiently energetic electrons, an image of a local x-ray source is present on the tip of the inner electrode. The above-mentioned source is, presumably, the result of the electrode bombardment by electrons that have „run away" from the discharge plasma in the near-axial area of minimum magnetic field [17]. In Fig. 3, *b* no similar source is observed however the image of the inner electrode surface is still there, i. e. „hot" electrons bombard the electrode surface, but do not „run away"along the axis. Thus, a factor really exists that prevents „running away" of electrons in the near-axial area of minimum magnetic field. This factor can be the excitation of transversal oscillations of the plasma and arising of strong transversal electric microfields affecting the conditions of electron acceleration, which is evidenced experimentally [18–20].

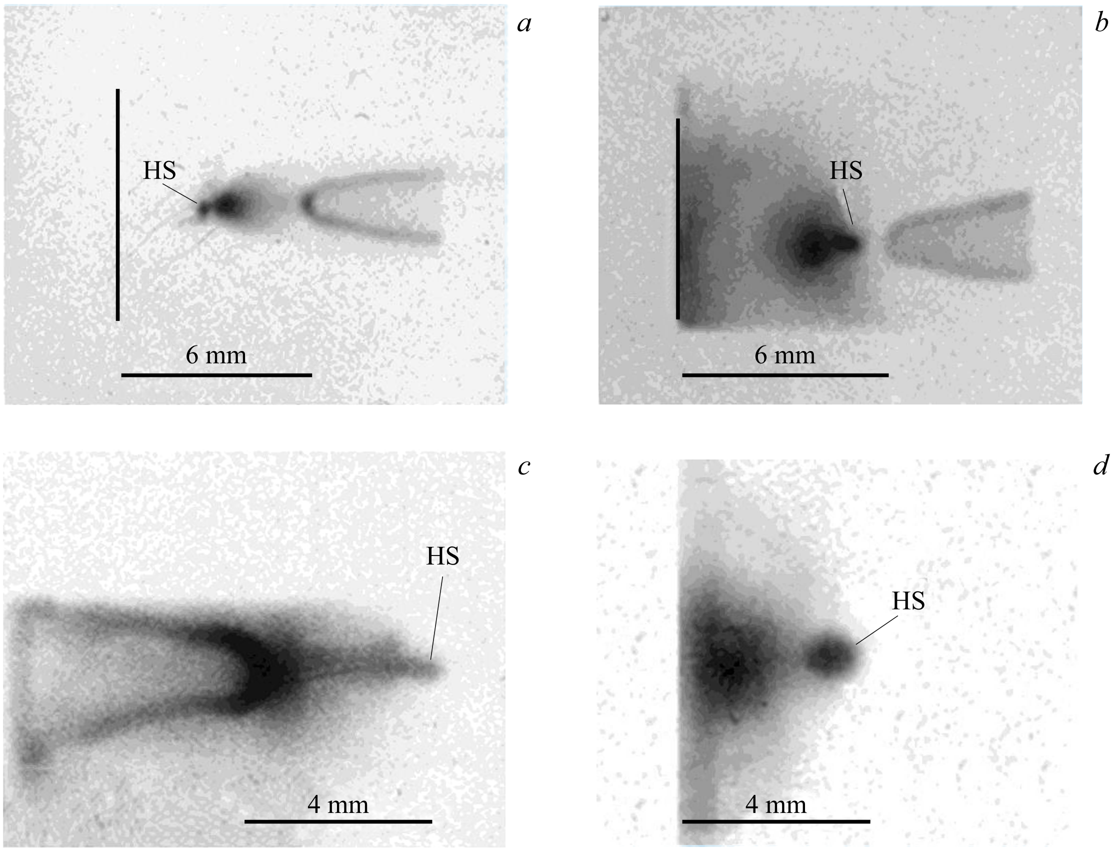


Figure 3. X-ray obscuragram of the interelectrode gap recorded under the following conditions: at the moment of discharge initiation the inner electrode acted as anode, the outer electrode acted as cathode, length of the forming line was 1 m (*a*), 2 m (*b*) and 3 m (*c*); at the moment of discharge initiation the inner electrode acted as cathode, the outer electrode acted as acted as anode, length of the forming line was 3 m (*d*). Obscuragrams *a–c* were recorded with one discharge, obscuragram *d* was recorded as a result of exposure during a series of ten discharges.

The study of behavior of the discharge plasma temperature based on the measurements with sufficiently high time-resolution of spectral characteristics of continuous x-ray radiation of the discharge plasma shows that at the stage of transition from the first to the second compression the temperature of the electron component can be as high as ~ 10 keV [11]. Electric conductivity of the plasma will be [21]:

$$\sigma = 2 \cdot 10^{-2} T_e^{3/2}/(\Lambda Z) \approx 3 \cdot 10^8\,\Omega^{-1} \cdot \mathrm{m}^{-1}, \quad (3)$$

$\Lambda \approx 10$ — the Coulomb logarithm, $Z \approx 10$ — average charge of ion. With duration of the stage in question equal to $\tau \leqslant 3 \cdot 10^{-8}$ s, and typical scale of plasma motion of $s \approx 10^{-4}$ m, equal to a value of about the constriction radius in the first compression, the following relationship is held:

$$s \gg (\tau/\mu_0\sigma)^{1/2}, \quad (4)$$

which is the condition of freezing of magnetic field [21]. Thus, the formation of a directed flow of plasma in the constriction can result in distortion of pattern of magnetic field lines carried away by the plasma flow. The accelerated electrons with energies of $\sim 10^4 - 10^5$ eV, arising of which is unambiguously connected with the formation of micropinch [11], are fixed in the magnetic field (except for the near-axial area):

$$r_L \approx 10^{-5}\,\mathrm{m} \ll s \approx 10^{-4}\,\mathrm{m}, \quad \lambda_{ei} \approx 1\,\mathrm{m}, \quad (5)$$

where r_L — the Larmor radius of fast electron, $\lambda_{ei} \approx Z/(n_e\sigma_{ei})$ — electron track length in the plasma, σ_{ei} — cross-section of the elastic electron scattering on ion, which value is evaluated (in Gaussian units) as [22]:

$$\sigma_{ei} = \pi\Lambda(Ze^2/2\varepsilon_e)^2, \quad (6)$$

where $\varepsilon_e \approx 10^5$ eV — average kinetic energy of epithermal electron, $Z \approx 10$, $n_e \approx 10^{26}\,\mathrm{m}^{-3}$ — electron concentration of the plasma after the first compression. In addition, the analysis of experimental and calculated data presented in the literature [23] allows stating that the cross-section of ionization of multicharged ions in the plasma by electrons with energies of $\sim 10^5$ eV is at least not greater than the cross-section of the elastic scattering.

The phenomenon of magnetic field lines carrying away by the plasma flow will, in turn, result in carrying away of the high-energy accelerated electrons by the plasma flow.

The analysis of images on obscuragrams suggest an idea the the main role in the process of formation of an anisotropic axial flow of plasma may be played by the process of radiation compression, because the duration of interval between the first and the second compressions is 30−70 ns according to model representations and experimental data [5,11].

At the moment of achievement of the maximum compression the resistance of the pinch is maximum as well. The resistance of constriction at the moment of maximum compression under conditions of low energy loss for radiation will be defined only by the plasma temperature in the constriction. At the transition to the mode of radiation compression an increase in plasma pinch resistance by several orders of magnitude takes place achieving a value of about 0.1 Ω in the first compression and 10 Ω in the second compression, and an increase in the accelerating resistive electric field up to $\sim 10^4$ and $\sim 10^6$ V, respectively. Thus, both the arising of accelerated electrons with the most high energies and the formation of anisotropic axial plasma flow presumably are inextricably linked with the phenomenon of radiation compression [12].

However, the recorded dynamics of the continuous x-ray radiation spectrum emitted by the micropinch discharges shows that the development of accelerating processes probably starts approximately 30 ns before the transition to the second compression [15], i e. the development of accelerating processes is in advance of the second compression. More over, it can be stated that the transition to the second compression becomes possible only due to the heating of plasma neck formed as a result of the first compression due to anomalous growth of its resistance, which results in increase in radiation losses of energy with the growth of electron temperature from initial 50 eV to 200−300 eV and above [11]. In the case of ferrum plasma (as it takes place in our experiments) with the above-mentioned temperature growth a channel of radiation energy losses opens in the *L*-spectrum as a result of the effective ionization of *L*-levels of ferrum atom, an increase in radiation intensity per unit volume and plasma lucency in this spectral range [5].

Authors of this work probably applied for the first time the active method of diagnostics of the processes running in a micropinch discharge. Based on the results of performed experiments and numerical evaluations, the authors hypothesize that the presence of forming line delays the process of electron acceleration in a quasistatic electric field of resistive nature in the area of constriction at the stage of transition to the radiation compression and results in an advanced formation of an anisotropic axial plasma flow. Due to the freezing of the magnetic field lines into the plasma flow and fixing of the accelerated to high energies electrons in the magnetic field the high-energy electrons are captured and carried away by the directed axial flow of the plasma. The obtained results are completely matched with the representations of the model of radiation compression.

Conflict of interest

The authors declare that they have no conflict of interest.

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