Multiply charged plasma-point ions

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The singularities of the emission of multiply charged ions with charges up to $z = 25$ from high-temperature "plasma points" of a low-inductance spark are investigated. The existing theoretical premises concerning the nature of plasma points are analyzed.

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1. INTRODUCTION

The formation of superdense plasmoids in a low-inductance spark, which is one of the modifications of pinched discharges, has recently attracted the attention of many research groups. The experiments have shown that the density of the plasma formations reaches $n_e \sim 10^{21}$ cm^{-3}, the temperature $T_e \sim T_i \sim 10$ keV, and their onset is accompanied by the hard x-ray and microwave emission usually observed in such discharges. A distinguishing feature of the plasmoids of a low-inductance spark is that they are of microscopic size ($\sim 10^{-3}$ cm), and as a result they have been named plasma points (PP). It was shown in Ref. 3 that the parameters of PP are strongly influenced by ion-sound oscillations that are excited in them, and it was emphasized that in this case the radius of the plasma column reaches the size of the Larmour radius of the ion in the discharge magnetic self-field.

The main feature of the PP, in our opinion, is that the ions are produced in them with an unusually high charge. Registration of emission of hydrogenlike and heliumlike ions from PP of elements of the iron group has been reported,[1] and emission of ions with charge up to 25 was observed in Ref. 4. The present paper is devoted to investigation of the features of the decay of PP and the evolution of the energy and spatial distributions of the ions emitted thereby.

2. MEASUREMENT PROCEDURE, PARAMETERS OF APPARATUS

The discharge circuit of the low-inductance spark consisted of a high-voltage capacitor short-circuited by electrodes secured in a vacuum chamber. One of the electrodes had an opening for the free flight of the plasma along the axis of the electrode system, and the second was bullet-shaped. The inductance of the discharge circuit was ~ 80 nH. The capacitance of the capacitor used in most experiments was 12 μF, and the initial voltage was 10–15 kV. The discharge was initiated by a laser pulse focused on the end-face of the bulletlike electrode, so that by simply changing the material of the electrodes it was possible to change the elemental composition of the plasma ions. To inject into the interelectrode gap ions of dielectrics or of materials that are difficult to machine, an insert of the corresponding material was placed in the bulletlike electrode. The energy of the triggering laser pulse was ~ 1 J, and the duration was 30 nsec. Deviation of the energy of the triggering pulse by several times from the indicated value, in any direction, led to a lowering of the stability of the reproducibility of the PP. The current reached the maximum value (≈ 120 kA) at 1.5 μsec after the start of the discharge. The current at the instant of the formation of the PP was ~ 100 kA. A block diagram of the experimental setup is shown in Fig. 1.

To investigate the decay products of the PP we used a time-of-flight mass spectrometer with a magnetic energy analyzer. The particles were recorded with a secondary electron multiplier.[5] The pressure in the vacuum volume was maintained at a level of 3×10^{-6} Torr, thereby excluding recombination of the ions when they passed through the drift space of the mass spectrometer. For a more correct measurement of the ion-emission parameters, the recording apparatus of the mass spectrometer was calibrated by the procedure described in Ref. 6.

Simultaneously with the investigation of the emission of ion beams, we registered the parameters of the discharge current and its derivative with the aid of Rogowski loops operating in the corresponding regime. We registered also hard x rays, using a standard procedure (lead filter, scintillator, photomultiplier). This has made it possible to establish that the PP are produced in the discharges. X-ray photographs of the PP were taken with a pinpoint camera whose hole (approximate dimension 10 μm) was covered with an aluminum-foil filter. The measurements of the intensity of the neutron radiation were made with a Hansen-McKibben counter with preliminary slowing down of the neutrons.[7]

3. REPRODUCIBILITY OF THE POSITIONS OF THE PP

A time-of-flight mass spectrometer with a magnetic energy analyzer can analyze ions by energy, by charge, and by mass. However, in one discharge it is possible to obtain only one point of an ion energy distribution of a given type. For sufficiently reliable reproducibility of the entire distribution,

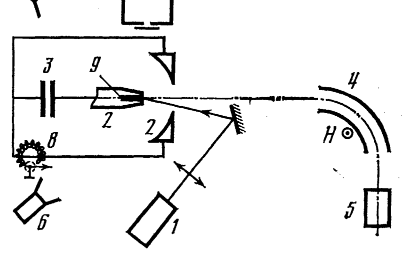

FIG. 1. Block diagram of setup. 1) pulsed laser, 2) electrodes, 3) capacitor, 4) magnetic energy analyzer, 5) secondary electron multiplier, 6) x-ray recorder, 7) Hansen-McKibben counter, 8) Rogowski loop, 9) interchangeable insert, 10) pinpoint camera.

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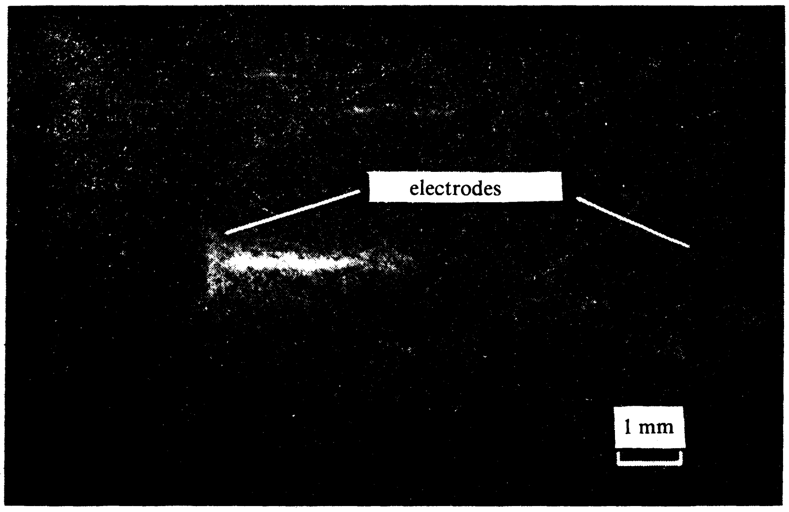

FIG. 2. Integrated pinpoint-camera photograph.

approximately 100 discharges are needed. Consequently, we actually obtain the average distributions of the ions in energy and in charge. To study by means of such a procedure, e.g., the spatial characteristics of the ion emission, it is therefore necessary to have information on the reproducibility of the position of the PP over approximately such a set of discharges. This makes it possible to separate effects due to the change of the PP position from discharge to discharge from effects that result from physical features of the decay of the PP itself. Figure 2 shows the resultant plasma image obtained after 100 discharges with the aid of a pinpoint camera and x rays of hardness ~ 1 keV. It is seen that the longitudinal dimension of the brighter region of the pinpoint photograph is 2 mm, and the transverse is 300 μm, while its distance from the bulletlike electrode is ~ 0.5 mm. On the other hand, measurement of the PP size with the aid of the image obtained in one discharge yielded transverse and longitudinal dimensions $d \approx 20$ and $l \approx 40$ μm, respectively. This shows that the size of the glow region on Fig. 2 is governed by fluctuations of the PP positions. Examination of Fig. 2 reveals also a glow from the end surface of the bulletlike electrode, which in this experiment serves as the anode; this glow is apparently due to bombardment by accelerated electrons [23]. Knowledge of the PP sizes makes it possible to estimate the plasma electron density. In Ref. 3 was obtained a formula for the linear density of the PP electrons:

$$N_e \approx Mc^2/2\bar{z}^2e^2,$$

M and $\bar{z}$ are the mass and average discharge of the ion in the PP. Substituting $M \sim 10^{-22}$ g (ion of an iron-group element) and $\bar{z} \sim 10$, we obtain $N_e \sim 2\cdot 10^{15}$ cm^{-1} and $n_e = 4N_e/\pi d^2 \sim 10^{21}$ cm^{-3}. We note that the expression for the linear density of the electrons, as well as the last estimate, were obtained under the assumption that the greater part of the current flows through the PP. With the aid of the filter method we estimated the electron temperature at $T_e \sim 7$ keV. Assurance that the measurement is accurate enough is obtained by determining the temperature from the spectral distribution of the x rays in a quantum-energy region bounded on one side by the ionization energy of the hydrogenlike ions present in the plasma (~ 10 keV for iron-group elements), so that the influence of recombination of the intensity discontinuities is eliminated, and on the other hand by the quantum energy ~ 150 keV above which the radiation intensity is determined by the presence of fast electrons in the plasma.[1] In this experiment, the absence from the plasma of impurities with atomic weight exceeding 60 a.m.u. and correspondingly with ionization energies exceeding ~ 10 keV was monitored by the mass spectrometer. The estimated temperature agrees well with the published results of similar measurements[1,2,8] and with the Bennett relation at $N_e \sim 2\cdot 10^{15}$ cm^{-1} and $I \sim 100$ kA.

4. CHARACTERISTICS OF AXIAL JETS

The experiments have demonstrated the presence of intense ejection of matter along the axis of the electrode system. We registered in the plasma expanding in this direction carbon nuclei, 11-fold charged aluminum ions, 16-fold charged iron ions, etc., up to 25-fold lead and bismuth ions (the maximum charges of the registered ions increased monotonically with increasing atomic weight of the element.[4,9] By registering the hard x rays and the singularities of the signal, of the derivative of the discharge current simultaneously with the investigation of the parameters of the emitted ions, we were able to establish a one-to-one correlation between the formation of the PP and the observation of ions with $z \sim 10$–20. The energy distributions of the emitted ions revealed a monotonic increase of the maximum spreading energies with increasing mass of the element: ~ 60 keV for carbon, ~ 120 keV for aluminum, etc., up to ~ 300 keV for bismuth. It is interesting to note that the maximum spreading rates decreased accordingly: $\sim 10^8$, $\sim 9\times 10^7$, etc., down to 5×10^7 cm/sec. Figure 3 shows the energy and charge distributions of the Fe ions. It is seen that the ion-spreading energy increases with increasing charge, and the number of emitted ions decreases at the same time. The maximum energy of the registered ions reaches ~ 200 keV, whereas the average expansion energy of the plasmoid is about 15 keV.

It is of interest to note that spectroscopic investigations of x rays from PP (Refs. 1, 2, 8) have made it possible to observe in PP iron ions with $z = 25$, which is higher than the charge of the ions registered by us here. In our opinion, this

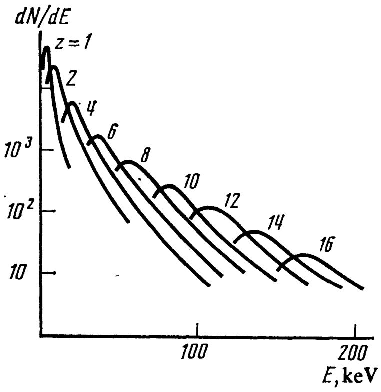

FIG. 3. Energy distribution of Fe ions of the axial plasma jet (the distributions of even charges and of $z = 1$ are shown).

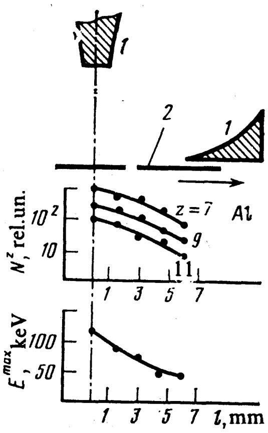

FIG. 4. Parameters of axial jet [1) electrodes, 2) movable diaphragm, N) number of ions, E_{max} maximum spreading energy].

is due not so much to recombination of the ions upon decay of the PP (the time that the ion stays in the PP is exceedingly short, 10^{-10} sec, see Sec. 7), as to the higher sensitivity of the spectroscopic procedure. The estimate assumed above for the average charge of the ions contained in the PP ($\bar{z} \approx 10$) is apparently confirmed by the following: the total number of ions emitted in the discharge, estimated from the mass spectrometer measurements, is $\sim 10^{14}$–10^{16} (the average charge of these ions is ≈ 3.5); the number of ions with charge more than 15–20 for elements with atomic number $\gtrsim 25$ is 10^{10}–10^{12}, whereas the number of ions contained in the PP is $\sim n_e d^2 l \bar{z}^{-1} \sim 10^{12}$. In addition, these estimates enable us to assess the contribution made by the low-temperature plasma surrounding the PP, to the observed ion emission.

For a better understanding of the processes that occur during the stage of the PP decay, it was of interest to investigate the spatial characteristics of the ion emission. In the first run of the experiments we investigated the angular distributions of the spreading of the ions. To this end, a special bellows transition piece was constructed, which enabled us to rotate the discharge chamber relative to the drift tube of the mass spectrometer. Experiment has shown that the spreading of the multiply charged ions is isotropic within an angle of 15° around the tip of the bulletlike electrode. The restriction of the angle between the direction of the analysis and the electrode axis to a value 7.5° was due to the difficulty of rotating the discharge chamber and admitting at the same time the discharge-initiating laser radiation.

The setup for the second run of these experiments is clear from Fig. 4. A diaphragm with an opening of 1 mm diameter could be moved in a direction perpendicular to the axis of the electrode system. It is clear that at a selected position of the diaphragm only ions from a definite section of the plasmoid could travel to the recording apparatus. The dimensions of these sections were close to the diaphragm diameter, the distance from the plasma to the diaphragm was much less than the distance to the ion recorder. In these experiments, the bulletlike electrode was made of aluminum. Study of the spreading of the ions along the discharge axis by the described procedure has shown that the bulk of the ions with higher charges is emitted from a region of approximately 4 mm diameter that is symmetrical about the electrode axis. The size of the region from which ions with smaller charges were emitted increased with decreasing ion charge and reached 6–7 mm. The number of ions emitted from regions located 4–5 mm away from the discharge axis was smaller by approximately an order of magnitude than from central regions. A similar relation was observed also for the ion spreading energies (the ions emitted from the peripheral regions have energies up to 50 keV, as against up to 120 keV from the central regions). Since the ions with the larger charges should be produced in the region of the hottest and densest plasma (at the PP), it can be stated that the size of the region in which they are produced does not exceed $\sim 20\ \mu$m. Taking into account the fluctuations of the position of the PP from discharge to discharge in the course of the study of the energy distributions of the ions, we would obtain, in the case of free expansion of the ions, a radiating region of size $\sim 300\ \mu$m. The substantial excess of the recorded effective size of the emitting region over the size of the zone in which the PP are produced, as well as the observed dependences on the ion charges, is apparently due to two factors: (a) the appreciable curvature of the ion trajectories upon decay of the PP, owing to the influence of the plasma-confining magnetic field; (b) to the possible formation of ions with low charges in the peripheral regions of the plasma.

5. TRANSVERSE SPREADING

Observation of anisotropy of the expansion of the PP ions was reported earlier.[9] It was found that the energies of the spreading aluminum ions in a direction perpendicular to the discharge axis reach only 25 keV (as against 120 keV along the axis). The number of ions emitted in a solid angle subtended by the entrance slit of the mass spectrometer, in the case of spreading perpendicular to the axis, is smaller by approximately an order of magnitude than in the case of spreading along the axis. However, the maximum attainable charge states of the ions registered for both directions were identical. Generalizing the foregoing results and recognizing that the total solid angle of the ions spreading perpendicular to the axis is several times larger than for spreading along the axis (see Fig. 1), we find that the ions carry away in a direction perpendicular to the axis approximately 10% of the total energy lost by the PP to particle emission.

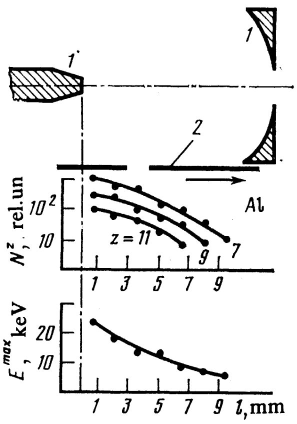

FIG. 5. Transverse spreading [1) electrodes, 2) movable diaphragm, N) number of ions, E_{max}) maximum spreading energy].

In the present study we have performed experiments aimed at determining the localization of the region that emits the ions perpendicular to the axis. The procedure for these experiments was similar to that described in the preceding section and it is clear from Fig. 5. The diaphragm had an opening in the form of a slit 1.5 mm wide and 10 mm long, and was oriented to be able to observe ion emission from plasma regions with dimension ~ 1.5 mm along the discharge axis. The experiments have shown that the bulk of the ions is emitted by an interelectrode-space section adjacent to the bulletlike electrode and 2–3 mm long, i.e., precisely by the section in which the PP is produced. The number of ions with larger charges emitted from this section exceeded by 10–100 times the number of ions emitted from regions farther from the bulletlike electrode (Fig. 5). Accordingly, the maximum ion spreading energies decreased from 25 to 6 keV.

6. INFLUENCE OF POLARITY

The influence of the polarity of the electric field in the discharge gap on the characteristics of the ion spreading is of great importance. Thus, e.g., Plyutto and co-workers[10] registered emission of fast ions ($E \gtrsim 1$ MeV) from a plasma diode only in the case when the electric field polarity was such as to hinder the spreading of the ions in the observation direction. It was precisely this fact that led to the conclusion that the decisive influence in this effect is exerted by formation of the electron beam (the field is accelerating for the electrons) and that the ions are subsequently accelerated in the field of this beam. Ions were thus obtained with energies exceeding by several dozen times the initial voltage. For PP ions the ratio of the spreading energy (up to 300 keV) to the initial voltage (~ 10 kV) reaches 30, i.e., it is close to that observed in the cited references; therefore the question of the influence of the polarity in the decay of PP becomes even more interesting. The electric-field polarity in the gap between the electrodes was reversed by reversing the sign of the charging voltage, i.e., either a positive or a negative voltage was applied to the bulletlike electrode. In most PP investigations in which the discharge was initiated by a laser, a positive voltage was applied to the central (bulletlike) electrode. When the polarity is reversed, the initiating laser plasma is produced on an electrode having not positive but negative polarity, affecting adversely the conditions needed for the formation of the PP. The experiments have shown, however, that PP are produced even in these cases, and consequently the chosen procedure can be regarded as correct.

The study of the ion emission parameters along the discharge axis has shown that the basic characteristics (number, charge, spreading energy) were approximately the same for both cases. Consequently, the ion acceleration mechanism in the PP case differs from that observes in Ref. 10 and is connected not so much with the polarity of the initial voltage as with the processes that take place in the core of the dense plasma. This conclusion was confirmed by an experiment in which capacitors of various sizes were used (3–24 μF), and the charging voltage was chosen such that the current amplitude remained unchanged. It was observed that despite the variation of the initial voltage on the electrodes, the characteristics of the ion emission remained practically unchanged. At the same time, experiments at constant voltage and variable current have shown that with increasing current the charges, number, and energies of the emitted ions increase. Thus, the main factor that determines the parameters of the PP and influences their decay is not the value and polarity of the initial voltage, but the strength of the discharge current.

The characteristics of the discharge circuit used for the foregoing experiments lie in the range of the parameters at which PP were observed in most investigations: $C \sim 1$–30 μF, $I \lesssim 250$ kA, $U \lesssim 20$ kV, and $L \lesssim 100$ nH. The appreciable difference between the properties of a low-inductance spark and the effects observed in Ref. 10 with apparatus of apparently similar construction is due to the high working voltages used in these investigations (0.1–1 MV). This has obviously led to the appearance of "runaway particles" (formation of an electron beam) and the relatively tenuous initial plasma, and hindered the formation of a high-temperature plasma.

7. LIFETIME

One of the methods of high-temperature-plasma diagnostics, which makes it possible, knowing certain parameters, to estimate its lifetime, is the determination of the intensity of neutron emission. Registration of the neutron yield (10^5 per discharge) from a formation similar to the low-inductance spark was reported in Ref. 11. The discharge was initiated by injecting batches of the gas in the interelectrode space through a special opening in one of the electrodes. Neutron emission was observed upon injection of deuterium. The energy stored in the discharge bank amounted in this case to ~ 1 kJ. Can it be assumed that PP from which neutrons are emitted are produced when deuteron is injected and a discharge develops in this apparatus?

As indicated above, the main difference between PP and other types of pinched discharges is apparently the presence of multiply charged ions in the latter. Using the result of Ref. 12, in which the radiation loss from a plasma containing multiply charged ions was calculated, we can obtain for a plasmoid having the same parameters as a PP an estimated cooling time $\sim 10^{-10}$ sec. As will be shown below, this is close to the lifetime of the PP, and the estimate is evidence that the multiply charged ions exert a significant influence on the parameters of the PP. It is precisely the presence of multiply charged ions in the plasma, where a constriction is produced in the plasma column, which stimulates intense radiation from the plasma and leads to formation of a plasmoid of microscopic size.

At the same time, as shown in Ref. 3, the presence of multiply charged ions in the plasma makes it easy to satisfy the conditions necessary for the buildup in the plasma of ion-sound oscillations. For example, the usual requirement $n_e T_e \gg n_i T_i$ is easily satisfied in PP, since $\bar{z} \approx 10$ and $n_e \gg n_i$. Therefore, at a definite stage of plasma compression (when the plasma-column radius becomes equal to the Larmor radius of the ion revolution in the magnetic field of the discharge current[3]) that the turbulence is excited. The discharge current (see Ref. 3) is then given by

$$I \approx 2\bar{z}eN_e(T/M)^{1/2} \sim N_e e c_s,$$

where c_s is the propagation velocity of the iron-sound oscillations, i.e., a quasilinear turbulence regime is apparently realized.[13] This is precisely the development stage, determined by radiative cooling and by the quasilinear turbulence, which corresponds apparently to the plasma parameters given in most studies of PP. The transition to the next stages with higher noise level in the plasma leads apparently to the decay of the PP. The reasoning above shows that the presence of multiply charged ions in PP plays the principal role. Consequently, no PP could be produced in the next z-pinch modification described in Ref. 11 upon development of a discharge in deuterium.

To change the neutron yield from the PP we used in the present study the following procedure. The insert in the central electrode was made of titanium deuteride with equal contents of deuterium and titanium. Upon focusing of the laser pulse on the insert, a batch of material containing both deuterium and a heavy element (Ti) was injected into the space between the electrodes, thereby guaranteeing the production of multiply charged ions and of PP in the discharge. The neutron flux was measured by a registration system based on the Hansen-McKibben counter, with preliminary deceleration of the neutrons.[7] The location of the counter relative to the discharge chamber, and also calibration against a standard source, ensured a system sensitivity $\sim 3\times 10^3$–10^4 neutrons/discharge. The experiments performed by this procedure have shown that the sensitivity of the recording apparatus is insufficient to observe neutrons. This provides an upper bound of the PP lifetime. Indeed, the neutron yield from a plasmoid with PP parameters can be estimated from the formula

$$N_n \sim {}^1/_2 n_D^2 \langle\sigma v\rangle \tau d^2 l,$$

where n_D is the deuteron density, $\langle\sigma v\rangle = (1\text{–}7)\times 10^{-19}$ cm^3 sec^{-1} for $T = 5$–10 keV [14], $n_D \approx 10^{20}$ for $\bar{z} \approx 10$, $n_e \sim 10^{21}$ cm^{-3}, and with an equal content of deuterons and titanium ions in the plasma. Substituting for N_n the neutron-detection threshold of the recording apparatus, we obtain for

$$\tau < \frac{3\cdot 10^3}{0.5 n_D^2 \langle\sigma v\rangle d^2 l} \sim (10^{-10} \div 10^{-9}) \text{ sec.}$$

At the same time it is obvious that

$$\tau > \frac{d}{c_s} \sim \frac{d}{((\bar{z}+1)T/M)^{1/2}} \sim 3\cdot 10^{-11} \text{ sec},$$

since the oblong form of the PP is evidence that the plasma is kept to some degree from spreading transversely (for pure inertial confinement we have $\tau = d/c_s$). Combining the last two inequalities we can assume that $\tau \sim d/(T/M)^{1/2} \sim 10^{-10}$ sec.

8. APPLICATION OF THE THEORY OF EQUILIBRIUM RELATIVISTIC BEAMS TO PP

An equilibrium structure of a cylindrically symmetrical relativistic beam that is uniform along the z axis was considered earlier in Refs. 2 and 15–19. It was shown that under certain assumptions the particles can condense to the axis until the transverse dimension of the beam becomes of the order of the Bohr radius, and until the density corresponds to degeneracy of the electrons ("linear atom"). A classical and quantum analysis of collisionless emission of electrons, which can arise when they interact with the boundaries of the beam upon its condensation, was presented in Refs. 16 and 17. The stability of the predicted beam structures was considered in Refs. 18 and 19, where experimental conditions under which it would be possible to observe a linear atom were also described. In all these papers are indicated the following conditions for the onset of a linear atom in a beam:

$$N_i - (1-\beta^2)N_e > T_e(1-\beta^2)^{1/2}/e^2, \tag{1}$$

$$N_e - N_i > T_i/e^2, \tag{2}$$

where N_e and N_i are the linear densities of the electrons and ions, and β is the ratio of the velocity of the electron current to the speed of light. Thus, an essential assumption is the presence in the beam of an uncompensated electron charge. The electrons are held together by magnetic attraction, and the ions by electrostatic attraction of the space charge of the electrons, and on the whole, the beam tends to become compressed by the collective-interaction forces.

The studies mentioned are of interest since they predict the possibility of extremal conditions of the existence of matter in relativistic beams. In Refs. 2 and 16–21, however, they attempted to use the theory developed for a direct explanation of the onset of PP. Such an application of this theory is apparently not quite correct, since it was developed for a beam that is infinite along the z axis. Allowance for the finite linear dimensions of the PP ($\sim 10^{-3}$ cm!) makes it automatically necessary to take into account the spreading, along the discharge axis, of the excess negative charge that presumably arises in the PP zone for some reason. Using Maxwell's equations, it is easy to show that the charge density ρ produced in a medium with conductivity σ will spontaneously decrease in accord with the law

$$\rho = \rho_0 \exp(-4\pi\sigma t),$$

i.e., the characteristic fall-off time of the PP is $t_0 = 1/$

$4\pi\sigma \sim 10^{-18}$ sec, shorter by many orders of magnitude than the lifetime of a plasmoid. Consequently, there can be in practice no excess negative charges in the PP zone, and the mechanism proposed in the considered papers for beam confinement cannot be applied to PP.

9. CONCLUSION

The experimental results obtained in the present research can be partially explained by the model proposed in [20, 21], where the dynamics of the development of a constriction in a plasma column in a z pinch is considered, with account taken of the particle expulsion effect. The calculation was carried out within the MHD framework and has shown that in the course of compression the linear density of the plasma decreases by a factor 10–100 compared with the initial value. The velocity of the forced-out jet of matter along the discharge radius amounts to $\sim 7\times 10^7$ cm/sec. The forcing-out of matter is symmetrical relative to the constriction and does not depend on the polarity of the electric field. The estimate in these papers have shown that owing to the particle ejection from the region of the constriction, the Larmor radius of the ion becomes comparable with the radius of the plasma pinch in the constriction. Continuation of the analysis of the process within the MHD framework is in general not valid, and it is necessary to use a mixed model of the plasma, namely, kinetic with respect to ions, and MHD with respect to electrons. It is precisely this situation which is apparently realized in PP, in which the plasma column is compressed to the size of the Larmor radius of the ion.[3,8] The mixed plasma model, as applied to the plasma focus, was considered by Imshennik.[22] However, by virtue of a number of features of the PP, particularly the short lifetime communsurable with the time of one Larmor period, the extension of the results of that study to include PP is apparently impossible, and further development of the theory is necessary.

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