DISPERSION OF A PLASMA CURRENT SHEATH

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1. Experiment

The pulsed plasma accelerator with electrodes of coaxial geometry [1] and a storage capacitor with an energy of 25 kJ (working voltage 6 kV, maximum discharge current 400 kA) generated dense plasma clusters which were ejected from the accelerator gap with a velocity of $(2.5\text{-}3)\cdot 10^4$ m/sec at a working gas (Ar) pressure of 20 mm Hg. The emergence of the plasma occurred at the moment of the maximum discharge current, so that part of the current could be carried out along with the plasma and circulate inside it for some time. Dimensions of the coaxial electrodes: The inner one had a diameter of 10 and the outer one 17 mm; the length of the accelerator gap was 300 mm, the inner electrode being 150 mm shorter than the outer one. The electrodes were made of molybdenum impregnated with copper to reduce their erosion.

The photography of the plasma formation after ejection from the coaxial electrodes was carried out with an SFR-2M streak camera in the mode of framewise filming with a frequency of $1.25\cdot 10^6$ frames/sec. A characteristic SFR-gram is presented in Fig. 1. At the exit from the electrodes the emission front is almost flat, but then it becomes peaked. The luminous region consists of a head part, expanding intensely in the radical direction with a velocity of $\sim 5\cdot 10^3$ m/sec, and a "tail," a conical formation which does not vary its transverse dimensions.

The separation of the head part from the "tail," whose length is then about 5 cm, occurs about 5 μsec after the ejection of the plasma. After separation the head part somewhat increases its velocity in the longitudinal direction.

In order to study the internal structure of the flow, we carried out interferometry of the plasma on a Mach–Zehnder interferometer with a ruby laser illuminator operating in the giant-pulse mode (frame exposure of ~ 20 nsec). The interpretation was carried out on a computer using an Abel transformation. The electron density $N_e \cdot 10^{-17}$ as a function of the radius R at different times is shown in Fig. 2. It should be noted that interferograms in the region of the front of the head part are not subjected to interpretation (evidently because of strong turbulence) and also that in Fig. 2c, the head part passed outside the field of view of the interferometer. The electron density at the axis is $(1\text{-}3)\cdot 10^{18}$ cm^{-3} and it declines toward the periphery. The bridge between the head part and the "tail" at the moment of separation, corresponding to a minimum electron concentration ($4\cdot 10^{17}$ cm^{-3}), is seen in Fig. 2c.

One can attempt to explain the experimental data obtained by using the scheme of plasma ejection presented in Fig. 3. In the plasma a discharge current flows which is partially carried out beyond the electrode cut (Fig. 3a, b). With further movement of the plasma stream the current in the head part closes into a loop (Fig. 3c), as a consequence of which it acquires additional acceleration in the axial direction and separates from the "tail." The part of the current remaining inside the electrodes continues to perform the ejection of the plasma formed both by ionization of the residual gas and by erosion of the electrode material.

The current carried out by the head part can be estimated if one assumes that all the pressure behind the front of the radial shock wave excited by the expanding plasma is determined by the magnetic field within the plasma. This gives a current of ~ 80 kA, i.e., about 20% of the maximum value of the discharge current.

The initial mass of the cluster is also needed for further calculations. It can be roughly estimated as follows. From calculations on the basis of Fig. 2a, one can conclude that the total number of electrons in the plasma cluster at the moment of its emergence from the nozzle was not less than $\sim 10^{19}$. If we take the average charge of the Ar ions as two, which generally corresponds to the temperature and pressure of the plasma, then there should be $\sim 5\cdot 10^{18}$ ions in the cluster and its mass should be about $3\cdot 10^{-7}$ kg, which corresponds to about 15% of the mass of gas which is inside the coaxial electrodes in the initial state.

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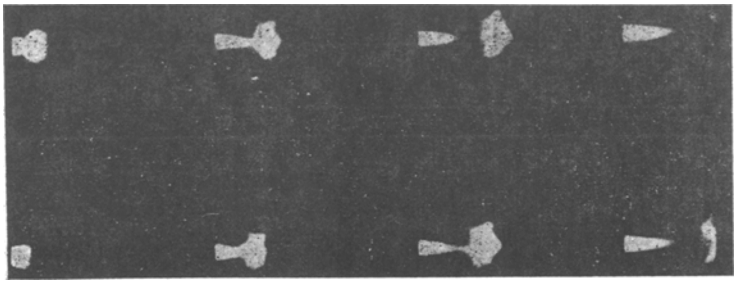

Fig. 1

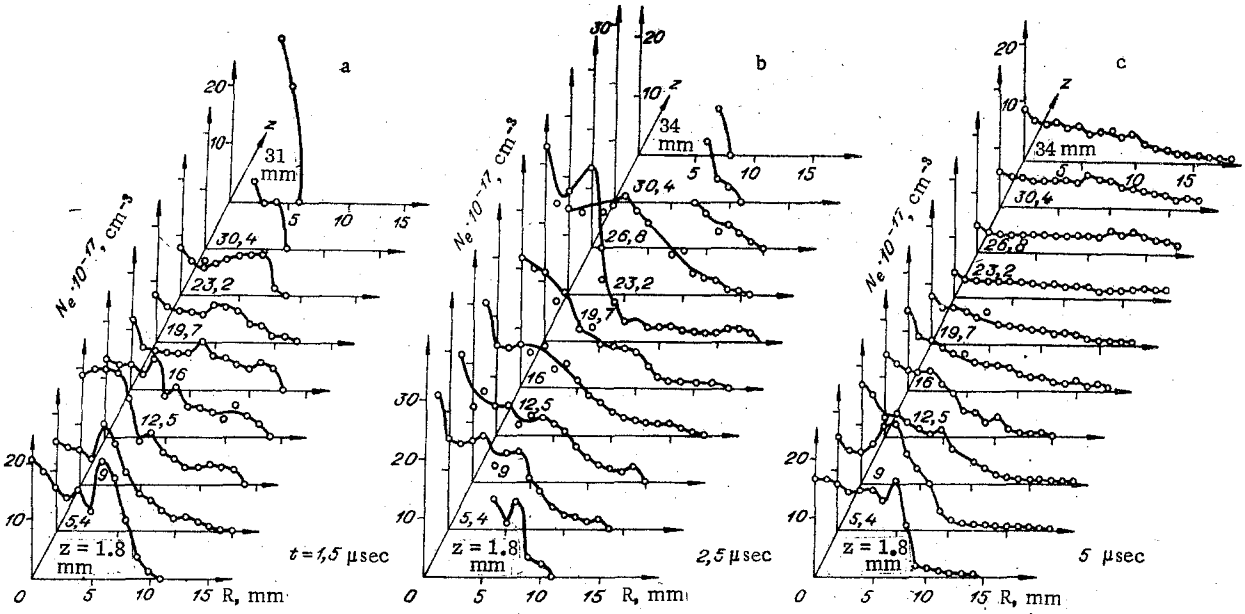

Fig. 2

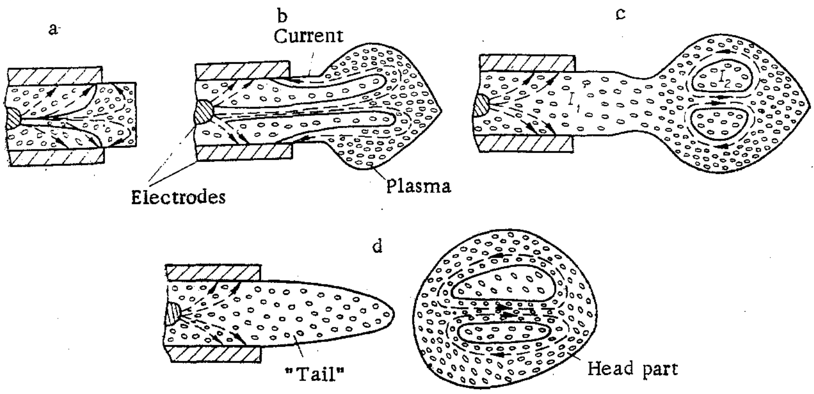

Fig. 3

2. Calculation of Dispersion

Model and Calculation Method. The mathematical model described below was intended for the statement of the problem of the dispersion of just the head part of a cluster. Calculation of the dynamics of the tail part becomes possible after one is able to obtain information about the inflow of mass from the accelerator into the tail part and the current distribution in it.

It is proposed to model the dispersion of the head part of a cluster in the following way. The cluster is represented in the form of a plasma current sheath, depicted in Fig. 4. In the approximation of an infinitely conducting plasma the equations of motion and energy of the sheath have the form

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial r}+v\frac{\partial u}{\partial r}+\frac{1}{\rho}\frac{\partial p}{\partial r}=0,$$
$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial r}+v\frac{\partial v}{\partial z}+\frac{1}{\rho}\frac{\partial p}{\partial z}=0, \tag{2.1}$$
$$\frac{\partial \varepsilon}{\partial t}+u\frac{\partial \varepsilon}{\partial r}+v\frac{\partial \varepsilon}{\partial z}+\frac{p_g}{\rho}\left[\frac{1}{r}\frac{\partial}{\partial r}(ru)+\frac{\partial v}{\partial z}\right]=0,$$

where r and z are the radial and axial coordinates, respectively; u and v, radial and axial velocity components; ρ, density; p_g, gas pressure; p, pressure; ε, specific internal energy.

The influence of the external medium (Ar in the state before the start of the discharge) was taken into account using a snowplow model [1]. Such a simplification was justified by the necessity of estimating, if only in a first approximation, the effects of the presence of an external medium. Moreover, the presence of some uncertainty in the conditions of the problem (the amount of matter in the calculated part of the cluster, the amount of current carried out, etc.) gave an additional reason to be confined to this approximation.

For closure of the system (2.1) we used tables of the thermodynamic functions of Ar kindly presented by I. B. Rozhdestvenskii. From these tables the functions $p=p(\rho, \varepsilon)$ and $T=T(\rho, \varepsilon)$ were obtained in the form of second-degree polynomials, and these were used in the calculation.

The system (2.1) was solved using a modified method of particles in cells [2]. For this the plasma sheath was divided into cells of an Eulerian grid of one layer in space (see Fig. 4). The number of cells was gradually increased in the process of deformation of the sheath. In calculating the pressure acting on the boundary of any cell, we took into account both the gas pressure of the cell adjacent to the calculated cell and the magnetic pressure. The matter of each cell was modeled by 1000 particles in the transfer calculation. The boundaries of the sheath were traced cell by cell in accordance with the maximum and minimum values of the coordinates of the particle found in (or carried into) a given cell.

Initial and Boundary Conditions. At the starting time the sheath was taken as a disk compressed in the shock wave of the plasma. The flow parameters of the Ar being compressed beyond the shock wave front were determined from data obtained in the experiment on the plasma flow velocity, which was $3 \cdot 10^4$ m/sec. Under these conditions, the degree of compression proved to equal about 10. The total discharge current, also measured in the experiment, comprised 400 kA and was constant. The plasma temperature in the cluster was $T=8 \cdot 10^4$°K, while $\rho=0.45$ kg/m^3 and $p_g=3.9 \cdot 10^7$ Pa. The sheath had an initial axial velocity $v_0=3 \cdot 10^4$ m/sec and $u_0=0$.

The boundary conditions were determined by the following considerations. The pressure outside the sheath was $2.6 \cdot 10^3$ Pa and $\rho=0.04$ kg/m^3. Inside the sheath at a distance r from its axis the pressure beyond the current bridge was purely magnetic and was determined by the expression

$$p_m=\frac{\mu_0}{2}\left(\frac{I_i}{2\pi r}\right)^2,$$

regardless of the configuration of the cavity, where I_i is the current flowing through the bridge (a plasma column); μ_0 is the magnetic permeability of a vacuum. Inside the current bridge there is only gas pressure, equal to the magnetic pressure at its surface.

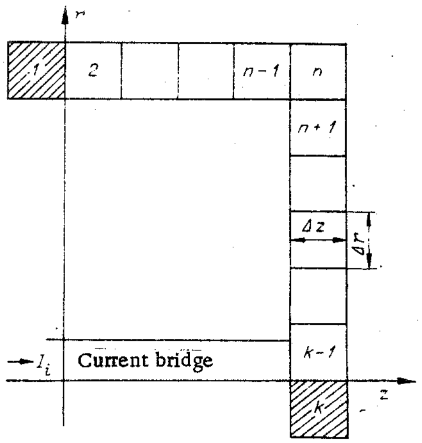

Fig. 4

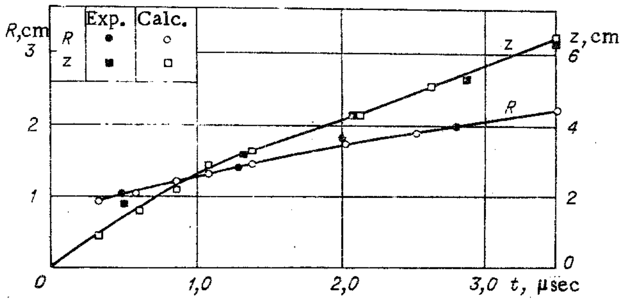

Fig. 5

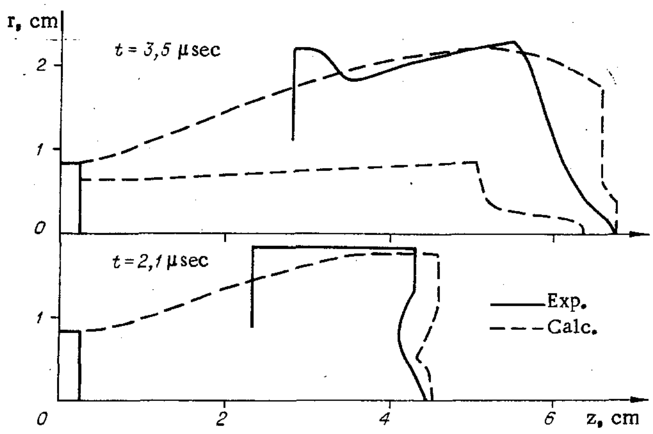

Fig. 6

To model the flow of matter from the accelerator in cell 2 (see Fig. 4) the initial conditions were maintained. Cells 1 and k were fictitious, simulating boundary conditions of the "rigid-wall" type. The initial thickness of the head was assigned in accordance with the amount of matter forming the cluster. The outer radius of the disk was 8.5 mm.

Results of Calculation and Comparison with Experiment. The first variants of the calculations, made with the condition that the total discharge current passes through the sheath while its mass equals the original mass of gas in the accelerator, showed the unsatisfactory nature of these assumptions. The radial expansion of the sheath and its axial movement proved to be overstated by two to three times in comparison with the experiment.

The variant with a zero current and a full mass also proved to be unsatisfactory. The axial movement of the sheath considerably exceeded the values obtained from the experiment and, moreover, the overall configuration of the sheath differed strongly from the experimental configuration.

An analysis of the results of the first variants of the calculation made it possible to conclude that the current through the sheath comprises a fraction of the total discharge current, while the mass of the sheath is also some fraction of the mass of gas in the accelerator. And this prompted us to make the estimates given in Sec. 1.

The best agreement with experiment was obtained when the fraction of current captured by the sheath was 20% of the discharge current, which corresponds to the estimate of Sec. 1, and the fraction of the mass of the sheath out of the mass of gas in the accelerator was the same, which does not differ too much from the estimate of Sec. 1.

The time dependences of the radial expansion and axial movement of the sheath are shown in Fig. 5, and the experimental points are also plotted here.

Figure 6 allows one to compare the sheath configuration calculated under these assumptions with the configuration of the head part obtained from the experiment.

From an analysis of Figs. 5 and 6 it is seen that the experiment and calculation are in good agreement. It should be noted that the analysis of the experiment revealed certain characteristic features of the dispersion of the sheath: the presence of a peak at the center of the sheath and the almost constant velocity of axial movement of the cluster, established after $t \approx 1$ μsec and equal to about half of v. It turned out that the calculation also caught these subtle effects: The calculated configuration also has a peak, while an almost constant axial velocity of movement of the cluster is established after $t \approx 1$ μsec and equals about $0.5v_0$.

We note that these effects do not develop in a calculation of the dispersion with a zero current (by inertia). The head of the disk remains flat, while the velocity of axial movement, like the velocity of radial expansion, decays monotonically.

The explanation for the above-mentioned effects may be the following. Up to $t \approx 1$ μsec, the gas of the surrounding medium "raked up" by the central part of the cluster retards the dispersion. But subsequently, a mode of dispersion is evidently reached such that the interaction of the "raked-up" mass, the rarefaction wave outrunning the gas from the central zone of the cluster to the periphery, and the magnetic pressure provides for the above-noted constancy of the axial velocity. The absence of this effect in the radial motion is due to the fact that the magnetic pressure, declining quadratically with radius, has considerably less effect on the side wall of the sheath.

The formation of a peak at the center can be explained by the fact that the magnetic pressure is highest in this region, while the inertia of this part of the sheath is comparatively high (the radial flow of matter is still slight).

Thus, the results obtained through the numerical experiment made it possible not only to calculate the kinetics of the motion of the cluster but also to show that the cluster (at least its head part) consists of a plasma current sheath expanding under the action of magnetic pressure.

In conclusion, one can add that the results of the calculation provided information which is not exhausted by the data of Figs. 5 and 6. The calculation made it possible to trace the thickness of the plasma sheath and the thermodynamic parameters averaged over its thickness. It was found, e.g., that by a time of 3-3.5 μsec the temperature of the sheath along the wall varies slightly and is within the limits of $7.5 \cdot 10^4 \pm 10\%$°K. The pressure and density increase monotonically along the direction toward the head and vary within the limits of $0.4 \cdot 10^7 < p < 1.4 \cdot 10^7$ Pa and $0.04 < \rho < 0.17$ kg/m^3. The pattern of the distribution of thermodynamic quantities over the surface of the sheath is nonmonotonic and is due to the nonequilibrium of the distribution of magnetic pressure and to the influence of the rarefaction wave, which is appreciable by this time. The head proves to be cooler than the wall (owing to the raking up of cool matter of the surrounding medium). The average pressure at the head is 10^7 Pa and the density is 0.16 kg/m^3.

Thus, the results of the experimental–numerical investigation of the dispersion of a plasma cluster revealed a number of important phenomena and made it possible to give the following picture of the dispersion. The plasma flying out of the accelerator forms two sharply differing regions adjacent to each other:

1. A head part, consisting of a sheath with a mass of ~0.2 of the mass of the cluster and within which a current, comprising about 20% of the discharge current, travels through a current bridge. This part disperses under the action of the magnetic and gas pressures. The head part has a tendency toward the formation of a peak at the center of the cluster.

2. A tail part, consisting of a plasma jet of variable cross section, which moves in the axial direction.

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