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PLASMA PARAMETERS FOR A COAXIAL INJECTOR

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A series of experiments with a coaxial plasma accelerator is described. The characteristic plasma parameters (front velocity, density profile, temperature) are given as functions of the operating regime. It is shown that a neutral gas moves ahead of the plasma front, while the tail of the plasma has a thermal character. The results are discussed.

Coaxial plasma accelerators have been the subject of numerous studies [1, 2, 3]. The results show that the simple obvious model in which the plasma is treated as a conducting fluid driven by a magnetic piston is incomplete. In fact, the acceleration process is more complex, and, in order to elucidate the actual mechanism, further studies of the initial stage of acceleration and the structural properties of the plasma leaving the injector are needed.

Here we present the results of experiments aimed at determining the relation between the plasma parameters and the accelerator operating regime.

Experimental Set-up and Some Initial Considerations

The experimental apparatus is shown schematically in Fig. 1. The parameters of the coaxial were selected so as to facilitate comparison of the experimental results with calculations based on the elementary model of the acceleration process (small ratio of accelerating electrode diameters, large capacitance of capacitor bank).

The discharge current was usually shorted near the maximum of the auxiliary discharger. The discharge period without shorting was 12×10^{-6} sec.

The gas was injected by means of two synchronous high-speed valves, which admitted 0.1-1 cm^3 of hydrogen at atmospheric pressure. The valves were located 0.25 m from the injector insulator.

The length of the accelerating electrodes after admission of the gas was 0.75 and 0.25 m, respectively, for the two variants of the accelerator studied.

The plasma moved along a metal tube 0.1 m in diameter, which connected the accelerator with the pumpout system.

Using various techniques (magnetic and Langmuir probes, voltage measurements along the coaxial, high-speed photography), we studied the motion of the current sheath in the injector and established that the acceleration process is unstable – there is a breakdown in acceleration such that with increase in voltage the point of discontinuity is displaced in the direction of decreasing length of the coaxial (Fig. 2). In the initial stage of acceleration (up to the discontinuity) the correspondence between the observed velocity of the current sheath and the calculated velocity is satisfactory. Beyond the discontinuity the rate of plasma formation diminishes, tending to some constant value independent of the applied voltage.

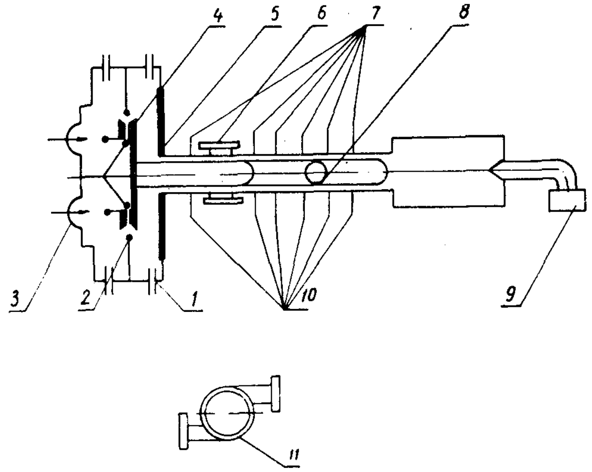

Fig. 1. Schematic of experimental apparatus: 1) capacitor bank, U = 10kV; C = 260 μF; 2) main discharger; 3) auxiliary discharger; 4) inner electrode, diam. 80 mm; 5) outer electrode diam. 100 mm; 6) inlet valve; 7) Langmuir probes; 8) optical interferometer windows; 9) mass spectrometer; 10) magnetic probes; 11) detail of valve arrangement.

In this case analysis of the Langmuir probe signals shows that along with a fall in velocity there is a rapid loss of particles from the plasma – toward the ends of the electrodes the column practically collapses.

Additional experiments were carried out on an injector with the length of the center electrode reduced to 0.25 m. Measurements of the magnetic field inside the injector with magnetic probes showed that in the initial stage of acceleration there were no changes, though the changes in the parameters of the plasma emerging from the injector were substantial.

It was observed that the plasma leaves the injector not as an integral mass but as separate jets, whose number and front velocity depend essentially on the mass of the admitted gas, when the voltage supply to the electrodes is held constant with respect to the moment of admission. The current is trapped by the plasma front and quickly relaxes as the plasma moves down the channel. At a distance of the order of 130 cm from the end of the center electrode the trapped field has practically disappeared.

For this variant the curves in Fig. 2 (indicated by the dashed lines) do not have a point of inflection. Evidently, at the end of the center electrode conditions are created that result in further acceleration of the plasma formation leaving the injector.

In subsequent experiments we concentrated our attention on the parameters of the plasma moving along the plasma guide. Basically, we studied such parameters as the density, velocity, and temperature of the plasma and their dependence on the injector operating regime.

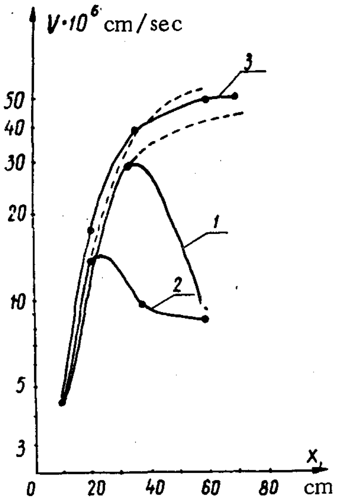

Fig. 2. Velocity of plasma front as a function of distance along the electrodes for different voltages U_b on capacitor bank: 1) U_b = = 5kV; 2) U_b = 7 kV; 3) theoretical curve. The dashed parts of curves 1 and 2 correspond to the case of a shortened center electrode.

Experimental Methods and Results

To determine the particle concentration in the plasma leaving the injector, we used the Michelson optical interferometer described in [4]. The optical windows of the interferometer were situated 130 cm from the end of the center electrode.

This interferometer enabled us to study the behavior of the plasma structure as the parameters that govern accelerator operation were varied. Figure 3 gives the density profiles along the length of the plasma formation as a function of the mass of the admitted gas. It is plain from the figure that efforts to improve plasma parameters by reducing the mass of admitted gas hold little promise; the increase in velocity is limited by the entrainment of electrode material. The pronounced gaseous tail associated with the plasma is obviously connected with vaporization of the electrode surfaces. As the mass increases above some limit, the plasma formation loses its compactness and strongly expands, while its velocity diminishes.

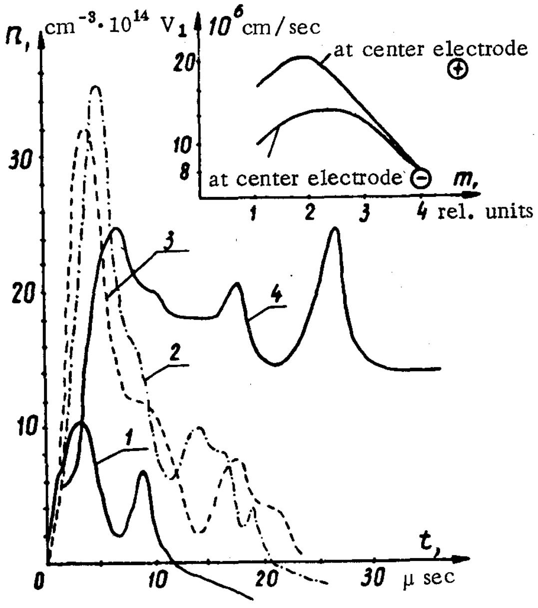

Fig. 3. Density profiles and plasma front velocity as a function of the mass of admitted gas. The mass increases smoothly from 1 to 4.

From this it follows that for a given accelerator design there is a certain optimum mass of the admitted gas for which acceleration is best realized.

It should be noted that the density profiles shown in Fig. 3 correspond to the case where the capacitor bank is shorted with the aid of an auxiliary discharger near the current maximum. Using a shorting discharger enables us sharply to reduce the tail part of the plasma formation, which is enriched by impurities due to combustion of the accelerator insulator material during succeeding discharge half-periods. Figure 4 illustrates the effectiveness of the shorting discharge.

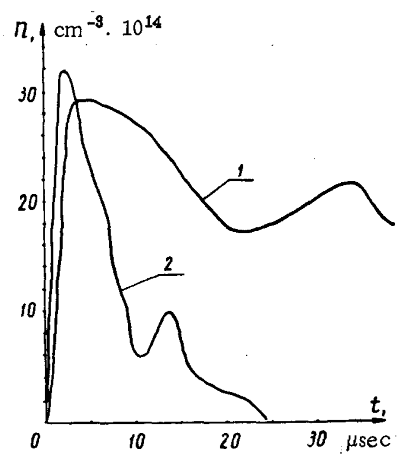

Fig. 4. Effectiveness of operation of discharger. 1) Oscillatory discharge; 2) capacitor bank shorted close to current maximum.

The plasma parameters were investigated as functions of the applied voltage. As may be seen from Fig. 2, the velocity increases with increase in voltage, while as the interferograms show, the density profile varies little with time. This means that the energy supplied to the plasma increases sharply with voltage, as verified by calorimetric measurements.

In relation to the acceleration mechanism great importance attaches to the determination of the transverse velocity of particles in the plasma, i. e., its temperature. We determined the temperature by a method based on the study of supersonic flow past an obstacle. The ion temperatures of the plasma, measured in this way, are not less than 50 eV at injector voltages of 5-7 kV.

An important and interesting property of the plasma structure was detected by means of these temperature measurements. During the first $(1.5\text{-}2)\cdot 10^{-6}$ sec a neutral gas, or more precisely, a plasma with a very low degree of ionization, precedes the plasma (Fig. 5). The temperature of the neutral gas is the same as that of the plasma front.

In determining the temperature by the method proposed it is of the utmost importance to find plasma velocity and the energy distribution of the particles. The velocity of the plasma front was measured with Langmuir probes and by tying in interferograms by irradiating the slit with the light from a short spark, triggering of which was synchronized with the beginning of the discharge current. The energy distribution along the length of the plasma formation was studied with a rotary mass spectrometer, similar to that described in [5], with the assistance of N. L. Alinovskii.

We found that the velocity of the plasma front decreases with motion along the plasma guide. Mass-spectrometric measurements showed that with increase in the lag between admission of the gas and triggering of the main discharger the impurity concentration in the plasma increases; accordingly, all the experiments described above were conducted with an optimally fixed delay, which for our accelerator was $270\cdot 10^{-6}$sec. The front of the plasma formation contains only a small amount of impurities. The concentration increases toward the tail. The presence of impurities is conditioned by the decomposition products of the diffusion pump oil and the injector insulator, and the concentration is reduced when the shorting discharge is used.

The tail part of the plasma formation is the residual plasma that leaves the injector after the first quarter of the discharge current due to the excess gas-kinetic pressure. In the absence of a confining magnetic field considerable numbers of particles are lost from this part of the plasma formation, evidently because of the ratio of the longitudinal and transverse velocities of the particles, which is close to unity [6]. The absence of a characteristic compression shock in flow past an obstacle is also evidence of the random distribution of the particles forming the plasma tail. Thus, it is possible that by using plasma guides of sufficient length we can free the plasma from impurities. The application of a longitudinal magnetic field leads to a sharp decrease in particle losses from the tail of the plasma (Fig. 6) during transport.

Discussion of Results

The results show that a single current sheath moves in the direction of the accelerator outlet and that its width increases with time. In the initial stage of acceleration the experimental data are in good agreement with the calculations.

An increase in electrode length leads to a breakdown in acceleration, apparently due to the structural properties of the moving current sheath [7].

The causes of the anomalously rapid decay of the plasma after the collapse of acceleration are not yet clear. The most probable cause is decay at the Alfven velocity v_A of the loop current formed as a result of breakdowns behind the accelerated plasma. The characteristic times of this decay $\sim \Delta/v_A$ (Δ is the electrode separation) are in good agreement with the experimental data.

When a shortened center electrode is used, the conditions created at the end cause further acceleration of the plasma which leaves the injector with a large current. The plasma then forms a sort of extension of the coaxial electrodes. The inner "electrode" of the plasma coaxial is strongly compressed by its self-magnetic field, and a configuration similar to that described in [8] is formed. Under these conditions we may get additional acceleration of the plasma leaving the injector.

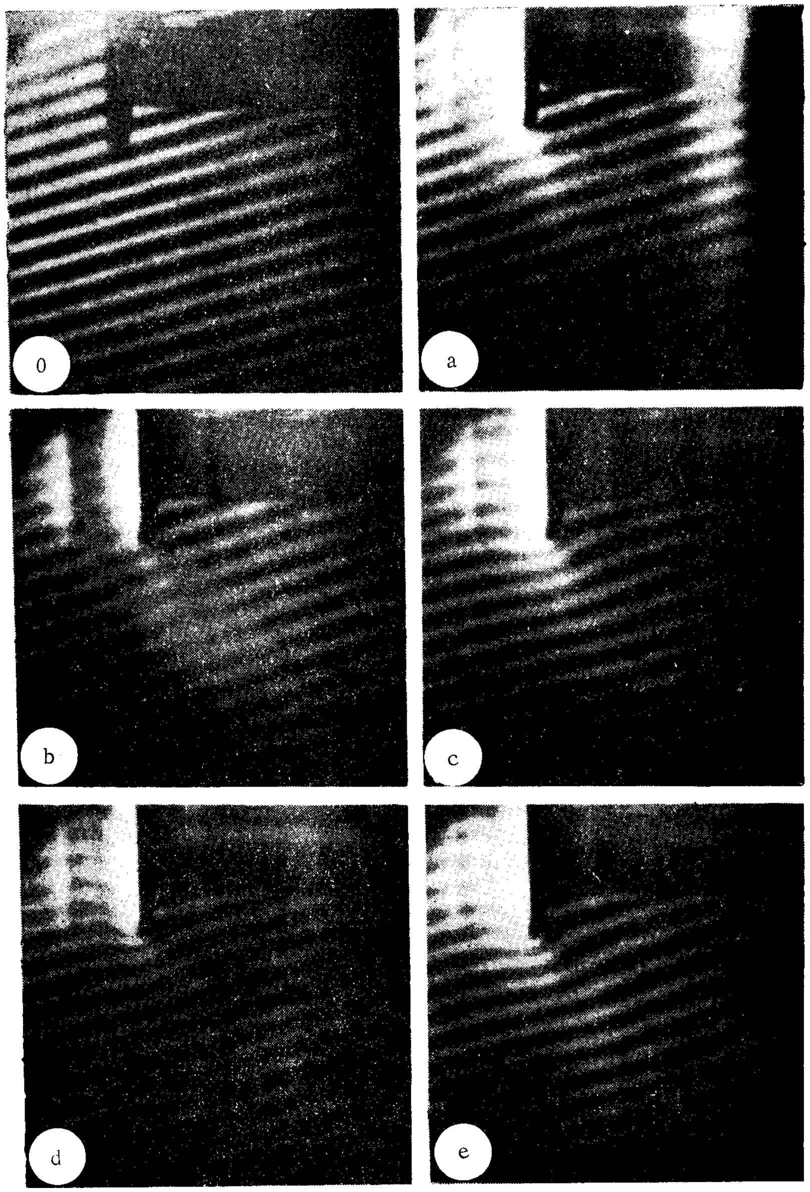

Fig. 5. Typical interferogram frames for plasma flow past an obstacle. Frames taken at $1 \cdot 10^{-6}$ sec intervals. In front the displacement of the interference bands corresponds to the neutral gas (a, b); in frames c, d, and e the displacement is associated with the plasma. The upper left-hand frame (0) shows the interference field.

As pointed out above, for $(1.5-2) \cdot 10^{-6}$ sec a neutral gas moves in front of the plasma. The possibility of the existence of a neutral gas in front of the current sheath in the initial stage of the discharge may be attributed to the fact that when voltage is applied to the electrodes with a certain delay relative to the admission of gas, the gas is able to spread for some distance along the electrodes. Breakdown usually develops in the section corresponding to the maximum gas density distribution, leaving the tail of the gas distribution in front of the current sheath. It is usually assumed that the current sheath "rolls up" the gas in front of it, ionizes it, and accelerates it ("snowball" model). However, according to calculations, at the experimentally attained plasma velocities, charge-exchange events predominate, since the probability of hydrogen atom ionization by collision with protons is a good deal less than the probability of charge-exchange. This means that the energy of the particles forming the leading part of the plasma is effectively extracted by the neutral atoms. The external manifestation of this effect is a reduction in the velocity of the plasma front along the length of the plasma guide and an expansion of the region occupied by neutrals. Estimates made with the aid of interferograms indicate that the total number of neutrals moving ahead of the plasma and the total number of charged particles in the plasma formation are comparable (~ 10^{19}). Hence, the energy of the neutral gas flux is comparable with the energy of the plasma, i.e., in order to create a high-speed gun we must exclude neutrals from the region ahead of the accelerated plasma front.

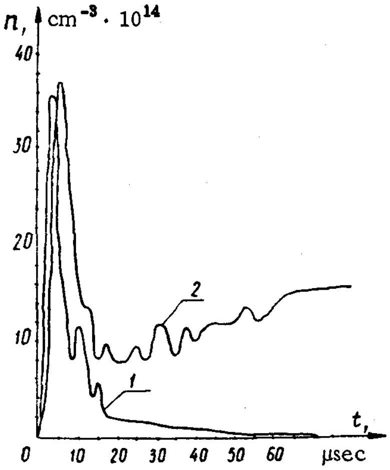

Fig. 6. Dependence of plasma density profile on method of transportation. 1) No guiding longitudinal magnetic field; 2) plasma moves in longitudinal field, B ≃ 0.1 weber/m^2.

The design of the accelerator described in this work was such that we were able to obtain plasmas with a total number of particles equal to ~ 10^{19}, an average energy of directional motion of the hydrogen atoms of about 300-500 eV, and an ion temperature of 70-100 eV. The impurity concentrations were small. As shown, given a long enough plasma guide, the tail of the plasma formation is freed of impurities, and the plasma can be used for further heating in various devices.

REFERENCES

1. J. Marshall, Phys. Fluids, 3, 135, 1960.
2. P. J. Hart, Phys. Fluids, 5, 38, 1962.
3. J. Osher, Phys. Rev. (L), 8, 305, 1962.
4. E. P. Kruglyakov, Yu. E. Nesterikhin, "A Michelson interferometer for plasma studies," (preprint), Novosibirsk, 1964.
5. H. P. Eubank, T. D. Wilkerson, RSI, 34, 12, 1963.
6. A. A. Kalmykov, S. A. Trubchaninov, V. A. Naboka, and L. A. Zlatopol'skii, ZhTF, 34, 1005, 1964.
7. J. Keck, Phys. Fluids, 5, 630, 1962.
8. V. I. Vasil'ev, V S. Komel'kov, B. V. Skvortsov, and S. S. Tserevitinov, ZhTF, 30, 756, 1960.

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