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V. F. Demichev, V. D. Matyukhin

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Abstract

Full Text

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Study of the Properties of Fast-Moving Plasma Clots

(Presented by Academician L. A. Artsimovich, 9 XI 1962)

In the present work we discuss the results of experiments on studying the properties of plasma clots obtained by means of an electrodynamic injector of the coaxial type.

The principle of electrodynamic acceleration of plasma was described by L. A. Artsimovich et al. (^{1}). Recently, in connection with the problem of filling magnetic traps with hot plasma, much attention has been given to this question (^{2}-^{4}).

The experiments were carried out on an electrodynamic accelerator analogous to Marshall' s injector (^{2}). The velocity of the plasma clots, their energy, momentum, and other properties depended on the operating regime of the injector, which was determined by the initial voltage on the capacitor bank U_0, the quantity M and kind of injected gas, and also by the delay time Δt between the instant of injection and the instant of gas breakdown. In the course of operation U_0 was varied from 3 to 15 kV; Δt, from 150 to 250 μsec; M, from 0.1 to 1.2 cm^3 of gas (at atmospheric pressure). Hydrogen, deuterium, and helium were used in the experiments. Most of the experiments were carried out with deuterium at $\Delta t = 200$ μsec and $M = 1.0$ cm^3. The reproducibility of the measurement results under a constant regime was sufficiently good: deviations from the mean value did not exceed 10%.

Fig. 1. A $-l_1 = 22$ cm; B $-l_2 = 90$ cm

By means of the magnetic-probe method it was established that the primary breakdown of the gas occurred in the region of the injection holes. The plasma shell that formed left the injector with a velocity the greater, the higher U_0 was and the smaller M was. On leaving the injector, the clot possessed its own current. The magnitude of this current depended on the phase at which the clot left the injector and rapidly decayed with distance from it. In some regimes the

Fig. 2

Figure 2: Fig. 2

magnetic probes recorded an H_z-component of the magnetic field in the emitted clot.

The inclusion of a special spark gap, short-circuiting the capacitor bank at the end of the first half-period of the current, eliminated the appearance of secondary clots emerging from the injector at the end of the second and subsequent half-periods of the current.

The plasma clot emerging from the injector moved along a porcelain tube with an internal diameter of 10 cm and a length of 120 cm. Its velocity v was measured by recording the magnetic flux $\Delta\Phi$ displaced by it. For this purpose, in two or three places along the length of the tube, local longitudinal steady magnetic fields $H = 100 \div 200$ Oe were created. Fields of such strength did not exert any noticeable braking action on the clot,

therefore, from the time taken for the clot to traverse the distance between the two coils, its velocity v could be determined. In Fig. 1, together with the current and voltage oscillograms, oscillograms of $\Delta\Phi$ are shown for two distances l from the injector.

From the magnitude of the displaced matrix flux, the lower limit of the conductivity of the clot was estimated as $\sigma_{\text{min}} \simeq 10^{14}$ CGSE. A finite value of the conductivity led to some distortion of the shape of the oscillograms of the displaced magnetic flux; however, the errors in measuring the velocity were insignificant.

Fig. 2. $A - l_1 = 5$ cm; $B - l_2 = 40$ cm; $V - l_3 = 75$ cm

The longitudinal dimensions of the clots near the injector, Δl_1, and at a distance of 75 cm from it, Δl_2, were estimated from the half-width of the $\Delta\Phi$ signals and the measured velocities. From these same measurements the mean values of the velocities of longitudinal expansion of the clots, $v_\parallel$, were obtained. The results of measurements for various values of U_0 are given in Table 1.

Here are also given the mean values of the velocity of transverse expansion of the clots, $v_\perp$, obtained from calorimetric measurements. It is seen from the table that $v_\perp$ is always smaller than $v_\parallel$. This is understandable, since $v_\perp$ is determined mainly by the thermal velocities of the ions in the clot, whereas $v_\parallel$ also depends on the spread of the longitudinal velocities of the ions arising in the process of acceleration of the clot. The accuracy of these estimates is low, but quite sufficient to assert that the thermal velocities of the ions in the clot increase with increasing U_0, while remaining, however, much smaller than the longitudinal velocity of the clot v. For $U_0 = 7$ kV, the thermal energy of the clot, for example, amounts to only 2–3% of its kinetic energy.

Table 1

U_0, kV	v, cm/sec	Δl_1, cm	Δl_2, cm	$v_\parallel \cdot 10$, cm/sec	$v_\perp$, cm/sec
3	$2.7 \cdot 10^6$	5	19	$3 \cdot 10^5$	–
4	$4.5 \cdot 10^6$	8	20	$5 \cdot 10^5$	–
5	$6.1 \cdot 10^6$	10	35	$1 \cdot 10^6$	$0.7 \cdot 10^6$
6	$7.8 \cdot 10^6$	12	52	$1.5 \cdot 10^6$	–
7	$1.0 \cdot 10^7$	15	65	$3.3 \cdot 10^6$	$1.3 \cdot 10^6$
10	$1.3 \cdot 10^7$	–	–	–	$2.8 \cdot 10^6$

In some operating regimes of the injector, characterized by a comparatively small amount of injected gas, the plasma clot separates into two, and sometimes into a larger number of individual clots moving with substantially different velocities. The splitting occurs gradually and becomes completely distinct at distances l = 70–100 cm from the injector (Fig. 2). The velocity of the first of the separated clots (we call it the forerunner) exceeds the velocity of the second, main clot by several times and depends more strongly on U_0. For example, when U_0 was increased from 7 to 10 kV, the velocity of the forerunner v' increased from $1.8 \cdot 10^7$ to $4.5 \cdot 10^7$ cm/sec, whereas the velocity of the main clot v'' changed only from $9 \cdot 10^6$ to $1.1 \cdot 10^7$ cm/sec. With an increase of U_0 to 12–15 kV, the velocity of the forerunner increased to 10^8 cm/sec.

The mechanism of formation of forerunners may be connected with shock-wave phenomena in the injector: with detachment of the front part of the plasma shell by a shock wave moving with increasing velocity into a region of decreasing density. It is also possible that the formation of the forerunner is connected with the phenomenon of strong compression of the plasma (“pinch effect”), which is observed as it exits the injector.

The energy Q of the plasma clots was measured by the calorimetric method. Because plasma was strongly reflected from metallic planes, deep sectional ···

nitrided copper cylinders with a length-to-diameter ratio of $3 \div 5$. Such calorimeters absorbed practically all the energy of the plasma entering them.

As the voltage U_0 increased, the energy of the plasma clots also increased. At $U_0 = 5$ kV it was ~ 100 J, and at $U_0 = 12$ kV it reached 2000 J. The energy distribution over the transverse cross section of the clot, also measured by the calorimetric method, changed at the same time, acquiring a sharper maximum at the center, reaching $15 \div 20$ J/cm^2.

When two or more plasma clots were present, the energy of each of them was measured with the aid of a thermal probe developed by Yu. G. Prokhorov (^{5}). Its principle of operation consists in recording the infrared radiation of a thin platinum foil heated by the incident plasma clot. The platinum foil used by us, of thickness 6 μ, provided a time resolution of the probe no worse than 1 μsec. The

Fig. 3

Figure 3: Fig. 3

magnitude of the signal from the thermal probe is related in a known way to the amount of energy delivered to the probe up to a given instant of time. Fig. 3 shows a typical oscillogram of the signals from the thermal probe W_T and the magnetic probe $\Delta\Phi$, located at the same place. Here there are two clots moving with different velocities. The step on the oscillogram W_T clearly separates the energies of the first and second clots. From the known energies and velocities the masses of the clots were determined. Knowledge of their dimensions made it possible to find the average values of the particle concentration in each of them.

Fig. 3

Measurements carried out with the thermal probe showed that the energy of the precursor can greatly exceed the energy of the main clot, while its density is, as a rule, an order of magnitude smaller than the density of the main clot. The longitudinal dimensions of the clots, determined from the time during which they released energy to the thermal probe and from their velocities, agree well with the dimensions determined from the half-widths of the $\Delta\Phi$ signals.

The integral momentum P of the plasma clots was measured by a ballistic method. The same deep cylinder that served as the calorimeter was used as the pendulum. Since the plasma was practically not reflected from the deep cylinder, its momentum could be considered equal to the total momentum of the plasma clots.

Simultaneous measurement of the momentum and energy, as well as of the velocities of the clots, made it possible to determine their average masses and densities, if no more than two clots were present. Good agreement was obtained with measurements made with the aid of the thermal probe. The results of the measurements are given in Table 2. The operating regimes of the injector were chosen so that a clear splitting of the clots occurred. All quantities with a single-prime index refer to the precursor, and those with a double-prime index to the main clot.

From the measured values of the velocities v', v'', the momentum P, and the energies Q, Q', Q'', the average values of the masses m' and m'', the densities n', n'', and the total numbers of particles N' and N'' of both clots were calculated. In all calculations the thermal energy and the radiation energy of the clots were neglected in comparison with their kinetic energy.

Spectroscopic measurements were made only in certain operating regimes of the injector, in which the clots had comparatively

low velocities ($v \lesssim 10^7$ cm/sec) and a relatively high plasma density. No afterglow was observed under such regimes. Only lines of the Balmer series of deuterium were found on the spectrograms. No impurity lines were observed in

Figure 4

Figure 4: Figure 4

the visible part of the spectrum, which is explained by the low electron temperature of the plasma. The ion concentration n_i in the blobs was estimated from the broadening of the D_β line, associated with the Holtsmark effect.

Fig. 4. 1 $-v \simeq 10^7$ cm/sec; 2 $-v \simeq 5 \cdot 10^6$ cm/sec

The average value of n_i, determined according to Ref. (6), was in the range $5 \cdot 10^{14}$ to $2 \cdot 10^{15}$ cm^{-3}.

The results of optical and magnetic measurements showed that the head part of the blob has the highest degree of ionization.

In connection with the measurement of energy it has already been mentioned above that, when plasma blobs strike a flat metallic surface, only part of their energy is transferred to this surface. Photographs from high-speed filming showed that the interaction of plasma blobs with a metallic surface leads to the formation of a shock wave, which moves toward the incoming blob and serves, as it were, as a screen that prevents the plasma from freely reaching the metal surface.

Quantitative estimates of the fraction of the blob energy transferred by it to the metallic surface were made by the calorimetric method. The results of these measurements are given in Fig. 4, where along the ordinate is plotted the fraction of the blob energy η transferred to the metallic surface, and along the abscissa—the energy density q in the incident blob. The operating regime of the injector was selected throughout so that the change in energy occurred mainly due to a change in the plasma density. The velocity of the blobs was kept constant, equal to $5 \cdot 10^6$ and 10^7 cm/sec. The results presented indicate that, when measuring the energy of plasma blobs with a density of the order of 10^{15} cm^{-3}, the reflection phenomenon must already be taken into account.

Table 2

U_0, kV	v', cm/sec	v'', cm/sec	Q, J	Q', J	Q'', J	P, dyn/sec	m', μg	m'', μg	n', cm^{-3}	n'', cm^{-3}	N'	N''
5	$1.7 \cdot 10^7$	$6.6 \cdot 10^6$	50	15	33	100	1.0	11.0	10^{14}	10^{15}	$3 \cdot 10^{17}$	$3.3 \cdot 10^{18}$
10	$4.5 \cdot 10^7$	$1.1 \cdot 10^7$	1350	900	400	1140	9.5	64.0	$3 \cdot 10^{14}$	$5 \cdot 10^{15}$	$3 \cdot 10^{18}$	$1.9 \cdot 10^{19}$

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