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Abstract

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INTERACTION OF HIGH-DENSITY PLASMA BUNCHES WITH MAGNETIC FIELDS

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One of the methods of creating and confining hot plasma for the purpose of obtaining a controlled thermonuclear reaction is the method of external injection into a magnetic trap of a previously created plasma ($^{1-4}$).

For an understanding of the complex phenomena that occur when traps are filled with plasma, the study of the simplest forms of interaction of plasma jets with magnetic fields may be of substantial importance; for example, the entry of a plasma jet into an increasing longitudinal magnetic field and the impact of a jet on a wall formed by a strong transverse field. The present paper presents the results of several experiments investigating these cases of interaction.

The plasma source was an injector analogous to the Marshall injector (^{5}). The properties of the plasma bunches obtained with the injector used are described in (^{6}). In most experiments the injector operating regime was chosen so that the mean velocity of the deuterium plasma bunches was $v_0 \approx 6.6 \cdot 10^6$ cm/sec, the plasma concentration $n_0 \approx (2 \div 3) \cdot 10^{15}$ cm^{-3}, the total energy $Q_0 \approx 100$ J, and the mean plasma conductivity $\sigma \approx 10^{14}$ CGSE. The plasma bunches propagated inside a quartz tube 10 cm in diameter. At a distance of 50 cm from the injector, coils were placed in which strong magnetic fields could be produced. At this distance the plasma bunches had the form of jets 30–40 cm long.

In experiments in which the passage of plasma through a longitudinal field was studied, its intensity could be brought up to 30 kOe. The mean value of the field gradient $\partial H/\partial z$ in the direction of motion of the jet was equal to $0.053 H_{\max}$ Oe/cm. The period of variation of the field was 580 μsec, and it was switched on in such a way that the plasma jet passed through the coil when the field had its maximum value. During the time of flight of the jet through the region occupied by the field, its intensity changed by less than 1%.

The velocities with which the plasma jets penetrated through the magnetic barrier formed by a strong longitudinal field increasing in space were measured by a spectroscopic method and by magnetic probes, with which it was possible to register the expulsion of the magnetic field by the plasma. The results of these measurements amount to the following. Upon interaction with the field, deformation of the jet occurs. As H is increased from 0 to 18 kOe, the leading

Fig. 1

Figure 1: Fig. 1

front of the jet decreases its velocity only slightly, by merely 25-30%, whereas the velocity of that part of the jet which most strongly expels the magnetic field falls by a factor of 2-3, decreasing to $(2 \div 3) \cdot 10^6$ cm/sec. Some part of the plasma of the jet undergoes complete braking and is reflected from the magnetic barrier. The reflected plasma was distinctly observed at $H \geq 3$ kOe. It moved toward the incident jets with a velocity of about 10^6 cm/sec. The intensity of the emission, both of the spectral lines of deuterium and of the continuous spectrum, of the reflected plasma increased with increasing H, which indicates, in particular, an increase in the concentration of particles in the reflected bunch.

The total energy of the plasma jet that passed through the magnetic barrier and the radial distribution of the energy density in the jet were determined by a calorimetric method for various values of H. The results of these measurements are presented in Fig. 1. The values of the jet diameters shown in the figure were obtained as the half-widths of the energy-density distribution curves. The decrease in the amount of energy that passed through the barrier is explained by the braking of particles entering the increasing field and by reflection of part of the plasma jet from the barrier. At $H = 18$ kOe, only 30% of the initial energy of the jet penetrates through the barrier.

Fig. 1

As the experiments showed, the transparency of the barrier is determined not only by the magnitude of H, but also by the value of the field gradient $\partial H/\partial z$. Measurements carried out at two values of the gradient ($\partial H/\partial z \simeq 0.04 H_{\max}$ Oe/cm and $\partial H/\partial z \simeq 0.08 H_{\max}$ Oe/cm) showed that, for identical $H_{\max}$, the barrier with the larger gradient is less transparent. The radial distributions of the energy density also differ substantially in these two cases. For the smaller gradient a higher energy density near the axis is characteristic.

As high-speed SFR-camera photography of the process showed, the plasma jet enters the increasing longitudinal field in the form of a well-defined luminous cone, which, in a homogeneous section of the field, changes into a jet of almost constant diameter; its value agrees well with the results of the calorimetric measurements. At the exit from the coil the jet diameter again increases (Fig. 2).

The process of interaction of the jet with the field is always accompanied by an increase in the intensity of the light emission from the plasma. This applies especially to the region of entry into the field, where, as a result of the increasing reflection of plasma with increasing H, a "plasma cushion" is formed. The brightness of the glow of the jet that has overcome the barrier decreases as the field increases. Noticeable penetration of the jet through the barrier is observed even when

$$H = 30 \text{ kOe.}$$

In this case the ratio

$$\frac{H^2}{8\pi} : \frac{\rho_0 v_0^2}{2} \simeq 150 \div 200$$

(ρ_0 is the initial plasma density).

Often the photographs show a violation of the axial symmetry of the plasma jet. Photography in the longitudinal direction showed that the cross section of the jet, as a rule, is not a circle, but has the form of a rosette. The instability of the surface of the plasma jet has the same form as the instabilities that arise in fast θ-pinches. The presence of instability can introduce difficulties into the interpretation of the results of many measurements.

A considerable increase in the ion concentration in the plasma jet entering the magnetic field is indicated by the strong broadening of the spectral lines of deuterium associated with the Holtsmark effect. Figure 3 presents the distributions of the ion density n_i along the axis of the magnetic field for two values of $H_{\max}$. The quantities n_i were determined from the half-width of the D_β line according to

Fig. 2

$H_{\max} = 12$ kOe

0 μsec. 2.7 μsec.

5.4 μsec. 8.1 μsec. 18.9 μsec.

35.1 μsec. 43.2 μsec.

Fig. 4, a

v $\oplus H$

mirror

0 μsec. 2.7 μsec.

5.4 μsec. 8.1 μsec. 10.8 μsec.

13.5 μsec. 16.2 μsec.

Fig. 4, b

v H

0 μsec. 2.7 μsec. 5.4 μsec.

8.1 μsec. 10.8 μsec. 13.5 μsec. 16.2 μsec.

Fig. 3

Figure 2: Fig. 3

work (7) and had the character of a certain average value over the entire process, which is connected with the integral method of obtaining spectrograms. In the initial sections of the n_i curves, the growth of the ion concentration is well explained by the radial compression of the plasma ($n_i \sim 1/D^2$). The reflection that then begins distorts this dependence and leads to the appearance of a maximum on the n_i curves. At $H = 6$ kOe, as can be seen from Fig. 3, the ion concentration in the jet increases by more than a factor of 10 in comparison with the concentration at $H = 0$. At $H = 24$ kOe this ratio increases to ~ 30 ($n_i \simeq 6 \cdot 10^{16}$ cm^{-3}).

Fig. 3

The action on a moving plasma of a magnetic field varying in space is analogous to the processes occurring in fast θ-pinches, i.e., to the compression of a stationary plasma by a field increasing in time. From this point of view this process was considered by L. A. Artsimovich (8). This consideration makes it possible to obtain an idea of the factors that affect the behavior of a plasma entering a longitudinal magnetic field. From it, in particular, it follows that the condition for "deep penetration" of a plasma jet into a magnetic field should have the form

$$\frac{a_0^2}{L^2}\frac{H^2}{4\pi\rho_0 v_0^2} < 1. \tag{1}$$

Here a_0 is the initial radius of the jet, and L is the longitudinal dimension of the region in which the field builds up. Consequently, one may expect strong penetration of the plasma through the magnetic barrier even in the case when $H_{\max}^2/8\pi > \rho_0 v_0^2/2$, if the ratio a_0^2/L^2 has such a value that inequality (1) is satisfied. For the conditions of our experiment, inequality (1) reduces to the following:

$$\frac{H_{\max}^2}{4\pi\rho_0 v_0^2} < 50. \tag{2}$$

However, as was already indicated, penetration of the plasma through the magnetic barrier was observed even at $H_{\max}^2/4\pi\rho_0 v_0^2 \simeq 150 \div 200$. This discrepancy is explained by the fact that inequality (1) was obtained under idealized assumptions; in particular, the finite conductivity of the plasma was not taken into account.

As a result of the finite conductivity, partial mixing of the plasma with the field occurs, which is confirmed by the results of magnetic-probe measurements. This circumstance facilitates the passage of the jet through the region of strong field. For the same reason, the diameter of the plasma jet changes somewhat more slowly than predicted by the theory.

It follows from inequality (1) that the transparency of the magnetic barrier must depend on the field gradient $\partial H/\partial z \simeq H/L$. This dependence, as already indicated, is qualitatively confirmed by the experiment.

It could be assumed that when a plasma jet strikes a magnetic wall created by a transverse field, complete reflection of the plasma from the field will take place if the inequality $4\pi\rho_0 v_0^2/H_{\max}^2 < 1$ is satisfied. In -

In reality, however, photographs obtained with the aid of an SFR, as well as calorimetric measurements, reveal that even at a very small value of the indicated ratio the plasma can pass through the field. In this case not the entire jet penetrates into the strong field; rather, at its front there arises a comparatively thin tongue, which then turns into a plasma sheet oriented along the field and, bending and losing velocity, as if slips between the lines of force. In Fig. 4a the plasma sheet is shown in two projections: from the side and from below (in the lower part of the photograph). Here $v_0 \simeq 10^7$ cm/sec, $n_0 \simeq 10^{15}$ cm^{-3}; the field strength during the process shown in the figure varied from ~ 3 to ~ 9.6 kOe; the thickness of the plasma sheet is $\delta \simeq 1$ cm. As the field strength increases, δ decreases.

Reflection of the plasma from the magnetic barrier was observed for a comparatively large ratio of the field energy to the specific energy of the plasma jet (Fig. 4b). Here $v_0 \simeq 10^7$ cm/sec; $n_0 \simeq 10^{15}$ cm^{-3}; $H_{\max} = 12$ kOe; $4\pi\rho_0 v_0^2/H_{\max}^2 \simeq 0.03$. The explanation of these facts must be based on taking into account the finite conductivity of the plasma σ. L. A. Artsimovich considered the conditions under which a plasma jet can pass through a magnetic barrier formed by a transverse field. According to this consideration, the plasma tongues formed as a consequence of the instability of the leading front of the decelerating jet can penetrate into the field if the condition is satisfied

$$\frac{\sigma\delta^2}{12c^2}\,\frac{H_{\max}^2}{L} < \rho_0 v_0. \tag{3}$$

Here L is the effective length of the region over which the field increases in the direction of motion of the jet. For our case $L \simeq 10$ cm. The results of the experiments do not contradict the condition given above.

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Note: Figure translations are in progress. See original paper for figures.