MAGNETIC FIELD CAPTURE AND PLASMA CONTAINMENT IN EXPERIMENTS WITH A COLLISIONLESS SHOCK WAVE

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It was shown in [1, 2] that collisionless shock waves can be excited in a rarefied plasma. Using magnetic probes and velocity plots, the motion of a wave was observed over the radius of a cylindrical plasma column, its cumulation at the axis of the system and the subsequent compression of the plasma by a cylindrical current sheet. When working with deuterium this stage of the process was accompanied by neutron radiation. Measurements of the wave velocity $3 \cdot 10^7 - 10^8$ cm/sec, the ion energy (1 – 10 keV), and the intensity of the neutron flux ($10^6 - 10^7$ per pulse) do not contradict the assumption of a thermonuclear mechanism for the neutron radiation.

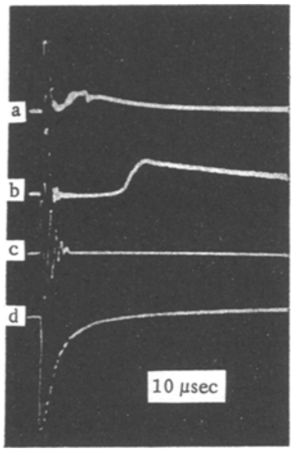

Fig. 1. a) X-radiation caused by electrons leaving through the end of the chamber; b) X-radiation caused by electrons leaving through the side wall of the chamber; c) shock coil current; d) neutron radiation.

The present communication gives some results of an investigation of the subsequent development of the process.

The experiments were carried out according to the following plan (for details see [2]). The vacuum chamber (a glass tube of diameter 16 cm) was situated on the axis of a quasi-stationary field trap $H_0 \sim 0.5$ kOe, T = 5 μsec); a shock coil of width 30 cm surrounded the chamber at the center of the system creating a variable field (H ~ 3–6 kOe, T ~ 1.4–2 μsec).

After filling the chamber with a previously ionized plasma (initial concentration $N_0 \sim 5 \cdot 10^{12} - 3 \cdot 10^{13}$ cm^{-3}), the field H was switched on, with a total damping time of 3–6 periods.

The investigations which were carried out revealed a series of properties which are apparently key properties in the understanding of the basic features of the development of the process after cumulation of the wave and the current sheet. These properties include the laws governing the neutron radiation, the charged particle flux detected at the chamber walls, and the structure of the magnetic field in the plasma volume. Thus, for example, the detection time for ions with energies ~10 keV and for the neutron radiation lasted from 10–15 μsec (Fig. 1d) to 100 μsec under optimal conditions when the damping time for the field H did not exceed 10–15 μsec.

Measurements of the spatial distribution of the intensity of neutron radiation show that the plasma volume which radiates is localized close to the shock coil and occupies a small volume of the trap.

The flux of fast electrons to the side wall of the chamber (detected by the γ-bremmstrahlung on the foil covering the scintillator) displays a maximum which appears significantly later than the total damping of H, shortly after the cessation of the neutron pulse (Fig. 1b).

A possible explanation of these facts may be connected with the appearance near the shock coil of a plasma structure stripped from the chamber walls in the course of several tens of μsec. Investigations carried out by means of miniature magnetic probes introduced into the plasma volume [2] indicate the formation, close to the coil, of a magnetic field structure which could, in principle, ensure the containment of the hot plasma.

It has been systematically observed that shortly after switching on the shock circuit (usually after cumulation of the wave and the current sheet) the magnetic fields in the plasma volume do not change sign, although current oscillations still exist in the shock circuit (Fig. 2). It is clear on the oscillograms, which are appended, that in this case opposing field directions are set up at different distances from the axis. This is a result which follows from the trapping of the field and the enclosing of the magnetic lines of force within the chamber. The formation of a similar closed-field configuration—an "ideal" trap—has been previously observed in θ-pinch experiments [3].

Measurements show that the trapped field is of order of magnitude H, and that the structure indicated usually lasts considerably longer than the damping time of H and is of the same order as the duration of the neutron flux (Fig. 2). The trapped field is modulated with period T (as long as H is comparable with the strength of the trapped field). The period of modulation points to the periodic compression, by the field of the external coil, of the internal trap which is being formed. The envelope of the neutron signal has a similar modulation.

After the current in the shock coil ceases the amplitude of the trapped field decreases slowly, which is apparently connected with spreading of the trap volume and the dissipation of the field. The intensity of the neutron radiation in this region also decreases monotonically, which should be the case when the trap spreads due to the increase of N_i and T_i.

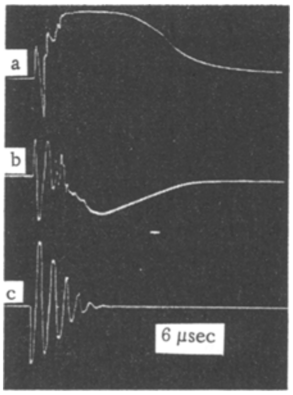

Fig. 2. Signals from magnetic probes located in the plasma close to the coil at distances: a) ~0.25 R, b) ~0.9 R from the axis of the chamber, c) current in the shock coil.

The radial spreading of the trap should lead to the escape of the hot plasma, which it contains, to the walls of the chamber, and to the disappearance of the closed-field configuration. This may be the cause of the observed delayed maximum of the electron flow to the side wall of the chamber (Fig. 1b).

Moreover, the character of the signal from the scintillation gauge detecting the electrons which leave along the field H_0 (Fig. 1a), does not contradict the idea of an internal trap explained above. Actually, the flux of "longitudinal" electrons is significantly weakened when the flow of electrons to the side wall of the chamber is most prolonged (Fig. 1b), i. e., effective confinement of the plasma by the trapped field takes place.

It should be noted that the introduction of a magnetic probe into the plasma appreciably lowered the intensity and duration of the neutron flux, and this substantially limited the possibilities of quantitative measurements. For this reason a detailed investigation of the magnetic field structure, requiring the simultaneous use of several probes, was carried out with helium (oscillogram in Fig. 2), although the basic characteristics of the process in working with deuterium were preserved in their entirety.

Our hypothesis concerning the containment mechanism for a hot plasma requires supplementation to account for the balance of pressures over the cross section of the chamber, since the internal trap with a pressure $H^2/8\pi$ exists for a long time after the opposing interaction from the field of the shock coil has disappeared.

Apparently we must seek an explanation of this fact in the formation of a cylindrical plasma sheet close to the chamber wall, which imparts to it the pressure of the trapped field. The existence of a plasma layer close to the wall is convincingly demonstrated by its screening action; magnetic measurements do not reveal any field at the external wall of the chamber (after the cessation of the current in the shock coil), when the field inside the chamber is fixed in the immediate proximity of the walls (Fig. 2b).

In this case the time during which the trap exists should be connected with the diffusion of the field trapped in a volume of radius R through a layer with skin thickness δ adjacent to the wall

$$t \sim \frac{R}{\delta} t_s \qquad \left(t_s = \frac{\delta^2}{C^2} 4\pi\sigma\right)$$

(t is the skin time, σ is the conductivity of the layer).

Estimates show that the values of t observed in the experiment (several tens of microseconds) correspond to the presence of a layer of thickness less than 1 cm with a temperature of the order of tens of electron volts.

The relatively high temperature of the layer adjacent to the wall can be maintained on account of the dissipation of the diffusing field.

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REFERENCES

1. R. Z. Sagdeev, "On the fine structure of a shock front propagating across a magnetic field in a rarefied plasma," Zh. tekh. fiz. vol. 31, p. 1185, 1961.

2. A. M. Iskol'dskii, R. Kh. Kurtmullaev, Yu. E. Nesterikhin, and A. G. Ponomarenko, "Experiments with a collisionless shock wave in a plasma," ZhETF, vol. 47, no. 2(8), 1964.

3. H. A. B. Bodin, et al., "The influence of the trapped field on the characteristics of a magnetically compressed plasma (thetetron)," Nucl. Fusion Suppl. p. 2, 521, 1962.

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