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Abstract

Full Text

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INVESTIGATION OF PLASMA ESCAPE THROUGH MAGNETIC SLITS OF TRAPS WITH A FIELD INCREASING TOWARD THE PERIPHERY

(Presented by Academician L. A. Artsimovich, 21 VI 1962)

Until now, the question of the influence of the region near the zero point of the magnetic field on the escape of charged particles from magnetic traps with a field increasing toward the periphery has remained unclear. In addition, there were no experimental data on the variation with time of the width of the magnetic slit. The purpose of the experiments described in this article was to clarify these questions.

All the experiments were carried out on the "Orekh" trap, a description of which is given in ([4]). The magnetic field of the trap is produced by 4 coaxially arranged coils. By combining the switching-on of the coils, one can obtain various forms of magnetic lines of force. The field form shown in Fig. 1a was used in earlier experiments ([1]-[5]) and is characterized by a relatively smooth change in the direction of the lines of force. Figure 1b presents the field form for oppositely directed switching-on of neighboring coils ("octupole"configuration). In this case the lines of force change direction sharply, which should promote detachment of the plasma clot from the field as it passes through the magnetic barrier. The octupole configuration is also distinguished by a still more rapid decrease of the field in the direction toward the center.

Fig. 1. Configuration of the lines of force of the magnetic field for quadrupole (*a*) and octupole (*b*) switching-on of the coils.

The maximum value of the magnetic-field strength at the periphery H_0 in both configurations is equal to 4000 oersteds. For plasma injection an electrodynamic

Fig. 2

Figure 2: Fig. 2

injector was used, designed by E. N. Braverman (^{6}) and used in (^{4}). The energy of the plasma clot was measured with a hollow cylindrical calorimeter with a system of partitions, moving along the axis of the chamber. The calorimeter diameter was 82 mm, its height 50 mm.

The time course of heat release to the wall was investigated with special bolometers whose resolving time was $3\,\mu$sec. The bolometer is a thermal resistance made of a bismuth-lead alloy, deposited by vacuum evaporation on oxidized aluminum foil $28\,\mu$ thick. The thickness of the oxide insulating layer is $1\,\mu$. The surface of the foil facing the plasma has no oxide layer. Bolometers of this type are described in (^{7}). In determining the width of the magnetic slit corresponding to different moments of time, a bolometer having a sensitive surface 1 mm wide was moved parallel to the axis.

system. To measure small heat fluxes in experiments with a highly rarefied plasma, sensitive germanium bolometers were developed, whose design is analogous to that of the bismuth bolometer. Time measurements at low plasma concentrations were carried out using a three-layer bismuth bolometer $0.2\,\mu$ thick, made on the basis of a collodion film. The side of the film facing the plasma was coated with a layer of silver $0.1\,\mu$ thick. The threshold sensitivity of such a device proved to be better than 10^{-5} J/cm^2.

Spectroscopic measurements were carried out on a Fabry–Perot standard crossed with an ISP-51 spectrograph. To determine the plasma concentration and estimate the electron temperature, Langmuir probes placed at the center of the chamber were used.

Fig. 2. Dependence of the width of the magnetic slit on time. 1 and 2 –octupole connection; 3 and 4 –quadrupole connection; 1 and 3 $-H_0 = 2000$ Oe; 2 and 4 $-H_0 = 4000$ Oe.

Plasma temperature. The electron temperature near the zero point of the magnetic field, obtained from probe characteristics, proved to be 15 eV. The ion temperature was determined from the Doppler broadening of the Ne II and C II lines and was ~ 10 eV at $H_0 = 4000$ Oe.

Change of the magnetic slit with time. After differentiation of the bolometric curves, the contours of the magnetic slit were constructed for different moments of time after the beginning of heat registration by the bolometer. The totality of experimental data for both configurations and two values of the magnetic-field strength is shown in Fig. 2. As is seen from the figure, for both configurations the slit width is greater at smaller values of the magnetic field. To explain the widening of the magnetic slit observed in the experiment, there is no need to invoke other broadening mechanisms besides the mechanism of

Figure 3 and Figure 4

Figure 3: Figure 3 and Figure 4

classical diffusion.

Mechanism of plasma escape from the trap. To determine the influence of the region near the zero point of the magnetic field on the escape of charged particles from the trap, heat fluxes through the magnetic slits were studied as a function of the position of the calorimeter in the vacuum chamber. The presence of a calorimeter inside the magnetic trap leads to recombination of charged particles on its surface. Thus, in this case the surface of the calorimeter represents, as it were, an additional "internal slit" through which plasma escape takes place. The area of this slit exceeds the area of the magnetic slits by several times. If the charged particles, before leaving the trap, enter the region of weak magnetic field near the center, then the introduction of a calorimeter into this region should lead to a sharp drop in the heat flux through the magnetic slits. If, however, the charged particles are tied to the magnetic field and their escape from the trap along the lines of force is due to collisions, then the introduction of the calorimeter will decrease the heat flux through the slits as the calorimeter intersects an ever larger number of those lines of force with which the particles are associated.

Experiments carried out for the octupole configuration indicate that in this case the first mechanism of escape is realized (Fig. 3). Placing the calorimeter at the center of the chamber causes the plasma flux through the magnetic slit to become practically equal to zero. Such a result can be explained only by the assumption of plasma outflow from the region with weak field, where $W_\perp/H$ is not conserved. The dimensions of this region

can be estimated by formula (6)

$$r \approx \sqrt{\frac{mvc}{ea_1}}$$

and amount to $\sim$ 5 cm (a_1 is the first coefficient in the expansion of H_z). A calorimeter placed near the injector records the energy of all the injected plasma, while at positions below the region where the adiabatic invariant is not conserved, as in the quadrupole configuration, the calorimeter records the fast clump not captured in the trap (4).

Fig. 3. Dependences of the heat flux through magnetic slits and of the heat flux to the calorimeter on the position of the calorimeter for the octupole field configuration

Fig. 4. Dependences of the heat fluxes through a magnetic slit on the position of the calorimeter for the octupole (1) and quadrupole (2) configurations

An independent check on the validity of the assumption that the adiabatic invariant is lost near the zero-field point is provided by experiments in which the heat receiver is placed in the upper annular slit formed when the coils are connected in the octupole mode. Placing the calorimeter at the center of the trap leads to a two- to threefold decrease in the heat flux into the upper slit (Fig. 3). Such a decrease is not a consequence of the calorimeter intersecting those field lines with which the particles are associated, since the topology of the magnetic field is such that not a single field line going from the injector into the upper annular slit intersects the calorimeter placed at the center.

When plasma is injected into a trap with a quadrupole configuration, a different picture is obtained. The heat loss into the side slit remains unchanged until the upper edge of the calorimeter reaches the midplane of the trap. The heat flux to the calorimeter, when the calorimeter is positioned below the midplane, likewise does not change. Subsequently, as the calorimeter is moved upward, when it intersects an ever increasing number of field lines running from the injector to the side slit, the heat flux into the side slit decreases (Fig. 4). At the same time, the heat flux recorded by the calorimeter increases. Thus, when the plasma is connected in the quadrupole mode, the plasma captured in the magnetic field escapes along the field lines.

The difference in the mechanisms of plasma loss for the octupole and quadrupole configurations is apparently due to two main reasons:

1. In the quadrupole configuration the plasma clump travels a longer path in a magnetic field of one direction, as a result of which the field has time to mix with the plasma.

2. The greater curvature of the field lines in the octupole configuration promotes detachment of the plasma from the field lines after passing through the barrier.

At densities below 10^{12} cm^{-3}, when the mean free path exceeds the dimensions of the apparatus, the lifetime of the plasma captured in the magnetic field should be determined by ion-ion collisions and increase as the concentration decreases. To reduce the initial plasma concentration, the injector was moved 30 cm away from the entrance to the trap, and the portion of hydrogen intro-

could pass through the fast-acting valve into the injector, was reduced to 0.1 cm^3. Under these conditions, with a quadrupole configuration, the energy-flux density into the lateral slit decreases exponentially with a time constant of 150-200 μsec. Increasing the initial hydrogen pressure to $\sim 10^{-4}$ mm leads to a decrease in the heat flux into the magnetic slit because of recharging. (Recall that at $n = 10^{14}$ cm^{-3} the lifetime is determined by the hydrodynamic outflow of the plasma and is 60-70 μsec. (4).)

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