DISTRIBUTION OF "HOT" ELECTRONS IN A PLASMA HEATED BY AN ELECTRON BEAM IN A MAGNETIC-MIRROR MACHINE

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Heating of a plasma in a magnetic-mirror machine by an electron beam is studied. It is shown that the heating occurs in the central part of the trap, where the mirror ratio does not exceed 3. The temperature of the hot electrons grows linearly with the plasma radius. The electron beam loses not less than 13% of its energy in the plasma.

In experiments on plasma heating by an electron beam, it was observed that the efficiency of heating increases with increasing mirror ratio[1,2], and also on going over to a smooth variation of the magnetic field along the trap[3]. For a further study of the obtained relationships, the PN-3 installation was constructed (see Fig. 1). The stainless steel vacuum chamber 1, with gaskets of indium and teflon, was evacuated to a pressure (1—3) $\times 10^{-7}$ Torr. A quasistatic magnetic field with a half-period 20—30 msec was produced by discharging a capacitor bank. The profile of the field is shown in Fig. 1. The field at the center of the trap was chosen close to 850 Oe, at which the plasma heating is the most effective[4]. A coaxial injector similar to that described in[5] was used to fill the trap with plasma. The titanium electrodes were saturated with deuterium. The electron beam was injected 100—300 μsec after operation of the plasma gun, when the plasma density decreased to 10^{12} cm^{-3}. The duration of the injection was 100—600 μsec. The beam current was 4—5 A at an energy of about 20 kV.

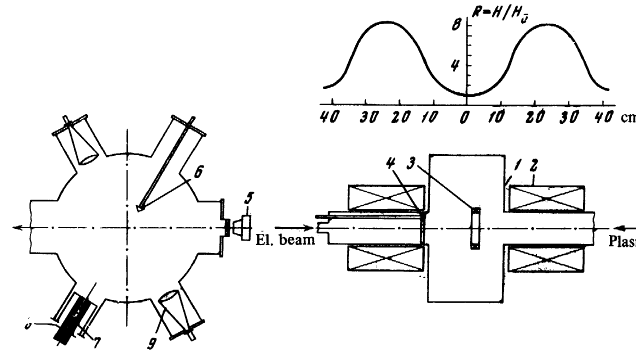

FIG. 1. Diagram of PN-3 installation: 1—vacuum chamber, 2—magnetic-field coil, 3—diamagnetic probe, 4—teflon ring, 5—photographic camera, 6—aluminum target, 7—lead collimator, 8—copper filter, 9—horn antenna. On the right is shown a plot of the magnetic field.

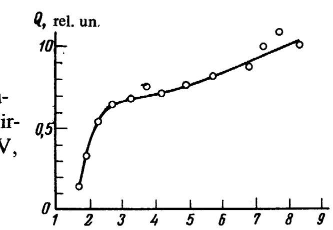

FIG. 2. Dependence of the diamagnetic signal on the effective mirror ratio. H_0 = 870 Oe, U_e = 17 kV, I_e = 4 A.

As is well known, in the case of beam heating the plasma contains relatively few "hot" electrons with energies of tens and hundreds of keV. These are the ones making the main contribution to the heating (nT) of the plasma. To verify how the hot electrons are distributed along the trap, a teflon ring 4 was inserted into the chamber from the side of the magnetic mirror. The electron beam passed freely through the opening in the ring, whereas the plasma column was cut off on the end. The signal from the diamagnetic probe 3 changed little until the ring reached a distance 10 cm from the center of the trap. Further insertion of the ring caused a rapid decrease of the signal. This indicates that the heating occurs in the central part of the mirror machine. The cooling of the plasma by the ring is equivalent to its escape from the trap along the force lines. By moving the ring we vary the effective mirror ratio $R = H_{pr}/H_0$, where H_0 and H_{pr} are the values of the field at the center of the trap and in the region of the probe. Figure 2 shows the dependence of the diamagnetic signal on R. The sharp break of the curve shows that it is far more preferable to construct a trap with a mirror ratio 3—3.5. By moving the oils 2 apart, we increased the mirror ratio to 12.5; however, the value of nT was not increased thereby.

We plotted the energy content of the plasma Q = nTS against its radius. Here S is the cross section area of the plasma column. To this end, a set of teflon rings of different diameter was inserted inside the probe 3 by removing in succession the rings by means of a lever, we varied the cross section of the plasma without breaking the vacuum. Instead of using rings, the cross section of the plasma can be limited by means of probe 6, which is inserted radially into the chamber. The results obtained by both methods are identical. This means that owing to the azimuthal and axial drift, all the hot electrons reaching the boundary of the plasma strike the probe. Figure 3 shows a plot of Q(r). The solid line was calculated in accordance with the formula $Q = \pi r^2 \overline{nT}$, where $\overline{nT} = 8 \times 10^{14}$ eV/cm^3. We see that nT does not vary with the plasma radius, and that the increase of the energy content is due to the increase of the plasma cross section.

Figure 4 shows the dependence of the x-radiation intensity I_R on the depth of the insertion of the probe

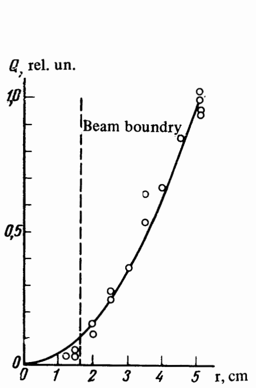

FIG. 3

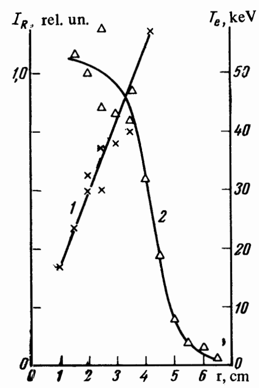

FIG. 4

FIG. 3. Dependence of the diamagnetic signal on the radius of the plasma column. The circles denote the experimental points, the solid curve is based on the formula $Q = nT\pi r^2$, where $nT = 8 \times 10^{14}$ eV/cm^3; $H_0 = 800$ Oe, $U_e = 18$ kV, $I_e = 5$ A.

FIG. 4. Dependence of the temperature of hot electrons (curve 1) and of the intensity of the bremmstrahlung from the probe (Fig. 2) on the depth of emersion of the probe. $H_0 = 870$ Oe, $U_e = 20$ kV, $I_e = 4$ A. The radial distance is measured from the chamber axis.

(curve 2). The limit of the "hot" plasma is very strongly delineated. This result agrees with the deceleration of the growth of Q with increasing plasma radius above 5 cm. In order to estimate the electron temperature, copper plates 8 of different thickness (up to 1.4 mm) were inserted into the slot of the collimator 7. The obtained radiation-attenuation curve was compared with that calculated for different T_e. The calculation is similar to that described in[6]. Curve 1 of Fig. 4 shows that the temperature of the hot electrons increases linearly with the radius of the plasma. An analysis of the radiation spectrum shows that even near the beam boundary there is a noticeable fraction of electrons whose energy exceeds by several times the energy of the beam electrons. From absolute measurements of the radiation intensity from the probe it follows that at a plasma radius of 1 cm the hot electrons carry away, across the magnetic field, about 13% of the beam energy. This figure determines the minimum losses of beam energy in the plasma.

Ryutov proposed a beam-heating theory[8] to explain the results of[2,4,7]. According to this theory, a small fraction of the electrons is knocked out of the beam. The beam itself generates Langmuir oscillations in the surrounding cold plasma. The knocked-out electrons interact with the oscillations, drift towards the wall of the chamber, and are simultaneously accelerated. The larger the diameter of the diaphragm encompassing the beam, the longer the drift time and the higher the temperature and the energy content of the electron-hot plasma. The threshold dependence of the heating on the mirror ratio is attributed by Ryutov to the anisotropy in the distribution of the Langmuir oscillations. From the value of the mirror ratio corresponding to the break in the curve on Fig. 2 it is possible to find the angle between the axis of the trap and the generator of the cone within which the oscillations propagate. It turns out to be close to 55°.

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