Mechanism of plasma heating by an electron beam in a probkotron machine

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We investigated the connection between the efficiency with which the high-temperature electron component of a plasma is heated by an electron beam in a probkotron machine and the spectrum of the excited oscillations. The experimental results offer evidence against the heating mechanism proposed by the authors of [4, 5].

It is known that electron-beam interaction with a cold plasma in a probkotron machine produces in the plasma a group of electrons with average energy greatly exceeding the energy of the primary beam. The macroscopic laws governing beam heating have been adequately investigated.[1,2] Most of the regularities can be understood within the framework of the diffusion model proposed by Ryutov.[2,3] This circumstance can be regarded as an indirect confirmation of the initial premises of the theory.

Another point of view concerning the mechanism of beam heating is contained in[4,5], where the authors state that the heating is produced by stochastic cyclotron resonance in the inhomogeneous magnetic field of the probkotron. The principal experimental facts advanced in favor of this heating mechanism is the observed temporal correlation between the x-ray flashes and the radiation in the region of the cyclotron frequencies of the probkotron. This alone, however, is insufficient to determine which oscillations are responsible for the plasma heating. To this end it is necessary to demonstrate that the excitation of one oscillation spectrum or another correlates with the increased energy content of the plasma.

In this paper we investigate the connection of the x-ray flashes at cyclotron and plasma frequencies with the energy content of the high-temperature component of the plasma, and ascertain the role of the magnetic mirrors in the beam-heating mechanism.

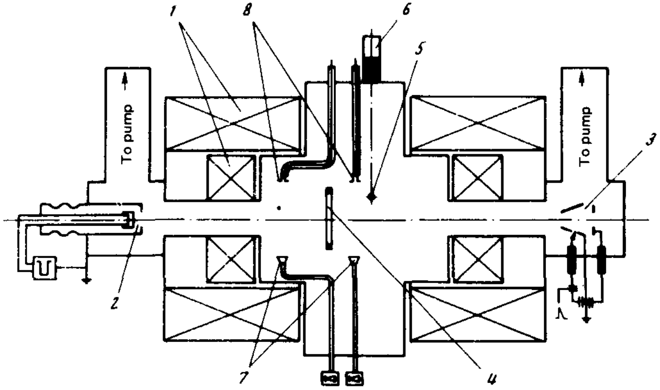

FIG. 1. Schematic diagram of installation: 1—magnetic-field coils, 2—electron gun, 3—plasma injector, 4—diamagnetic probe, 5—target needle, 6—x-ray pickup, 7—horn antennas, 8—dipole antennas.

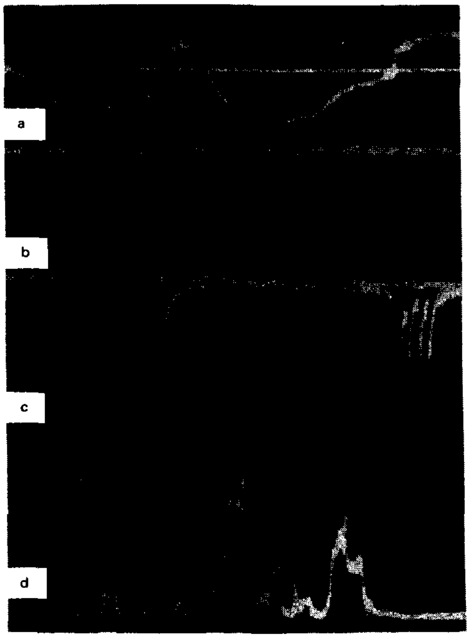

FIG. 2. Oscillograms plotted in one experiment: a—differential diamagnetic signals, b—radiation at $\lambda = 10$ cm, c—hard x rays, d—radiation at $\lambda = 1.5$ cm. $H_{min} = 1$ kOe, $H_{max} = 5$ kOe, beam current $I = 10$ A, beam energy $U = 20$ keV, plasma concentration $n = (1-2)\times 10^{12}$ cm^{-3}, sweep duration $\tau = 50$ μsec.

The installation is shown schematically in Fig. 1. The magnetic field was produced by a system of coils (1). The magnetic field intensity at the center of the trap could reach 2 kOe, and in the mirrors 10 kOe. An electron gun (2) and a plasma injector (3) were placed at the ends of the installation. We measured the diamagnetism of the plasma, the x-radiation, and the microwave radiation in the cyclotron and plasma frequency bands. The differential diamagnetic probe (4) had a time resolution not worse than 10^{-6} sec. The x rays from the target needle (5) were registered with a scintillation pickup (6). The pickup was screened with lead, and the radiation from the target needle entered the crystal only through a narrow collimator opening. The x rays from the volume of the plasma were not registered at this sensitivity level. The electromagnetic radiation from the plasma near the frequencies $2\omega_{pi}$ and ω_H were received respectively by a horn antenna (7) and a dipole antenna (8). The antennas were placed at the center of the installation in the region of the first mirror in the path of the beam.

Figure 2a shows an oscillogram of the diamagnetic signal, which is determined by the rate of change of the energy content of the plasma. It is seen on this oscillogram that at certain instants of time there is an abrupt decrease of the energy content of the plasma. At the same instants, intense radiation flashes at the cyclotron frequencies (oscillogram 2b) and of x rays from the target needle (oscillogram 2c) are observed. Since these flashes (their number depends on the cold-plasma concentration) are always accompanied by a decrease rather than an increase of the energy content of the plasma, they can naturally have no bearing whatever on the plasma heating. It becomes therefore obvious that the stochastic cyclotron mechanism of plasma heating by a beam, which is based exclusively on observation of correlations between the x rays and the excitation of the oscillation spectrum in the cyclotron-frequency region, is not borne out by experiment. In fact, the results of the proponents of the stochastic cyclotron mechanism pertain not to heating but to the observation of instability of a plasma heated in fields of oscillations of an *entirely different type*. Similar instabilities were observed earlier in a plasma with hot electrons.[6]

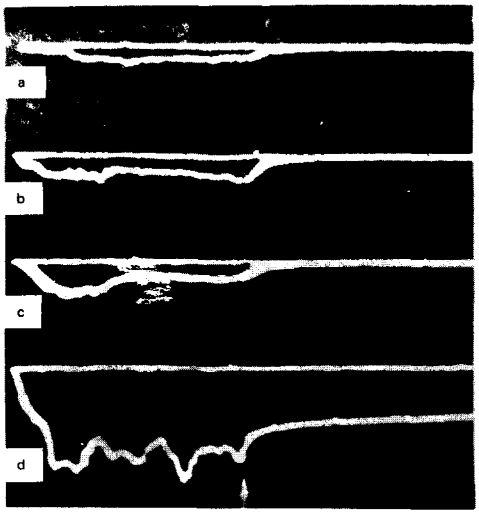

FIG. 3. Oscillograms of integral diamagnetic signals: a—$R_e = 2$, $R_m = 2$; b—$R_e = 2$, $R_m = 5$; c—$R_e = 5$, $R_m = 2$; d—$R_e = 5$, $R_m = 5$. $H_{min} = 1$ kOe, $I = 10$ A, $U = 20$ keV, $n = (1-2)\times 10^{12}$ cm^{-3}, $\tau = 500$ μsec. The instant when the gun is turned off is indicated by the arrow.

During the heating stages (lower sections of the oscillogram 2a), radiation is observed at double the plasma frequency $2\omega_{pi}$ (oscillogram 2d). This is evidence of the development of intense Langmuir oscillations in the plasma. It is most probable that the heating of the electrons to high temperatures occurs in fields of just these oscillations.

Figure 3 shows a series of oscillograms of the integral diamagnetic signal (the energy content of the plasma) at different mirror-ratio combinations. Four combinations were realized: a) $R_e = 2$, $R_m = 2$; b) $R_e = 2$, $R_m = 5$; c) $R_e = 5$, $R_m = 2$; d) $R_e = 5$, $R_m = 5$, where R_e is the mirror ratio on the electron-gun side, and R_m is the mirror ratio on the opposite end of the probkotron. In Figs. 3a, b, c, the diamagnetic signals hardly differ from one another. In the case of Fig. 3d, the picture is radically altered—the energy content of the plasma is greatly increased and its temperature rises, as can be seen from the prolonged confinement of the plasma after the beam is turned off. It follows from these experiments that the mirror ratio on the two ends of the probkotron plays an essential role in the mechanism of heating with a beam. In the stochastic cyclotron heating model it is assumed that the plasma electrons acquire energy in the region of the decreasing magnetic field of the first mirror in the path of the electron beam, while the second mirror serves only to trap the electrons.

Even in this respect, however, the heating model developed in[4,5] is not confirmed experimentally.

In conclusion the authors thank D.D. Ryutov for useful discussions.

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