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PLASMA HEATING BY AN ELECTRIC BEAM IN A MAGNETIC MIRROR MACHINE

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We investigate the heating of a plasma by an electron beam in an adiabatic trap with mirror ratio R = 5.25 in a wide range of experimental conditions. We obtain a hot plasma with T = 50 keV and $nT = 2\times 10^{15}$ eV/cm^2 and detached from the wall. The dependence of nT on the magnetic field is found to be resonant. The maximum of the resonance curve shifts toward stronger magnetic fields when the initial plasma density is increased. The efficiency of plasma heating increases continuously with increasing electron-beam energy. The lifetime of the hot component of the plasma agrees with the time of electron escape from the trap as a result of collisions with the neutral plasma component. In certain cases, an instability arises in a quietly decaying plasma and is accompanied by a sharp dip in nT and by a burst of microwave and x-ray emission.

IT has been previously established in investigations of plasma heating by an electron beam that the efficiency of heating in a mirror machine ("probkotron") increases greatly with increasing mirror ratio [1, 2] and also on going from a configuration with local mirrors to a configuration with extended mirrors [3]. The present investigation was carried out with apparatus redesigned with allowance for these facts.

DESCRIPTION OF APPARATUS

The apparatus comprises a mirror machine with extended mirrors (Fig. 1). The mirror ratio used in most experiments was 5.25. The maximum magnetic field at the center of the device was 2 kOe. The vacuum-chamber diameter is 40 cm. The electron gun 2 with lanthanum-hexaboride cathode (12 mm dia) produces a current up to 18 A at 25 kV. A rectangular voltage pulse of 100 μsec duration is applied to the gun. The electron beam is directed along the axis of the apparatus.

Plasma injector 6 comprises a set of hydrogen-impregnated titanium washers mounted behind the mirror at a certain distance from the axis. It produces a cold plasma with maximum density 10^{12} cm^{-3}. Probe 5 is located on the system axis to record the electron-beam current.

The following measuring apparatus was used in the experiment: diamagnetic probe 8, microwave interferometer 3, camera obscura 7 to photograph the hot plasma by x-radiation; the hard x-radiation passing through the camera wall was registered by photomultiplier 4 with Na I(Tl) crystal. An electron-optical converter (not shown in Fig. 1) was also used.

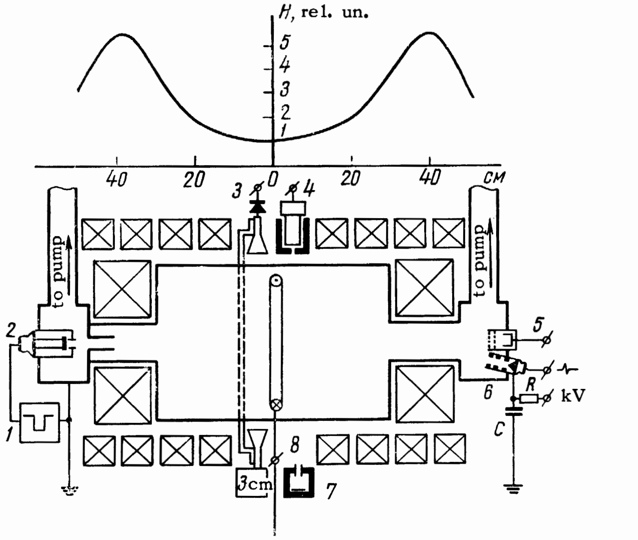

FIG. 1. Diagram of setup: 1—high-voltage pulse generator, 2—electron gun, 3—microwave interferometer, 4—bremsstrahlung recorder, 5—grid probe, 6—plasma injector, 7—camera obscura, 8—diamagnetic probe. The upper part shows the distribution of the magnetic field along the axis of the apparatus.

EXPERIMENTAL RESULTS

Passage of the electron beam through the plasma produces in the latter a group of hot electrons with energy exceeding that of the primary-beam electrons. This phenomenon was first observed in [4]. The concentration of the hot electrons in various experiments constitutes a small percentage of the total plasma density. Thus, the plasma obtained after the interaction with the electron beam is a two-component one. The components differ appreciably in density and in temperature.

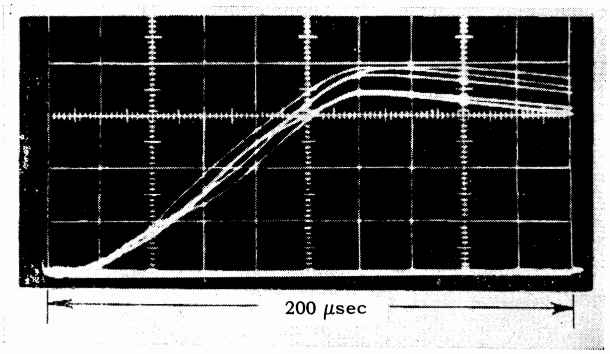

FIG. 2. Series of diamagnetic signals. Magnetic field H = 925 Oe, accelerating voltage U = 25 kV, beam current J = 10 A.

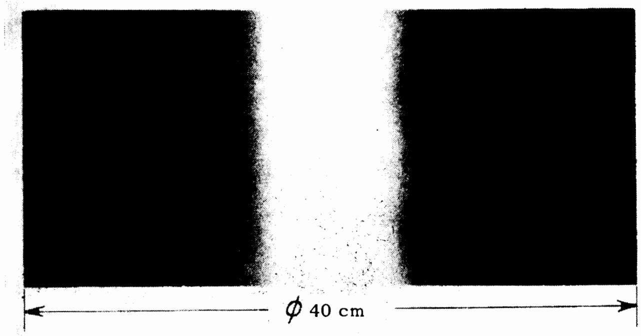

FIG. 4. X-ray photograph of the plasma.

It is of interest to ascertain the conditions on which the parameters of the hot-component of the plasma depend. In our experiment we varied the electron-beam current and velocity, the magnetic field, and the density of the primary plasma over a sufficiently wide range.

A series of diamagnetic-signal oscillograms is shown in Fig. 2. They show that the results are well reproducible from experiment to experiment. The section of the oscillograms from the start of the sweep to the maximum characterizes the process of accumulation of a hot plasma during the beam injection time, after which the plasma decays slowly. The visible drop of nT on the oscillogram does not actually represent plasma decay, but is determined entirely by the time constant of the RC integrating network used in our experiments. The decay constant nT due to plasma escape amounts to 20 msec.

Comparing the time variation of nT and the density (Fig. 3), we see that after the electric beam is turned off a decrease in density by one order of magnitude does not affect the value of nT. Consequently, a denser but colder plasma makes no noticeable contribution to nT, and this quantity is determined only by the hot electrons.

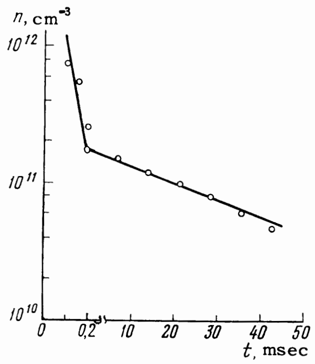

FIG. 3. Variation of the plasma density with time. Magnetic field H = 825 Oe, accelerating voltage U = 25 kV, J = 10 A. Sweep rate changes after 0.2 msec.

To determine nT it is necessary to know the cross section of the hot plasma. To this end we took x-ray photographs, of the plasma with the camera-obscura. As seen from Fig. 4, the hot plasma is detached from the walls, and the x-rays are generated inside the volume. Photometric reduction of the photographs obtained in different magnetic fields yields the same value, 10 cm, for the hot-plasma diameter. The diameter of the plasma in visible light is 18 cm. The maximum value of nT calculated from the diamagnetic signal reaches 2×10^{15} eV/cm^3 at the optimal magnetic field. The temperature of the hot component of the plasma, determined from the spectral distribution of the hard x-rays, amounts to 50 keV in this case. From the measured nT and T we get a value 4×10^{10} cm^{-3} for the hot-plasma density. This is approximately one-third the density at instants of time close to the inflection point (Fig. 3). The discrepancy is due to ionization of the neutral gas by the hot-plasma electrons in the chamber of the apparatus.

We can make the following estimates: The ionization increases the density by a factor $[n_0 \langle \sigma v \rangle \tau + 1]$, where n_0 is the neutral-gas concentration, $\tau = \frac{1}{2} L (M_i/T)^{1/2}$ is the time of escape of the secondary electrons from the trap, M_i is the ion mass, and L is the length of the trap. Putting $n_0 = 10^{12}$ cm^{-3}, $\langle \sigma v \rangle = 5 \times 10^{-8}$ cm^3/sec, and T = 1 eV at $n_{hot} = 4 \times 10^{10}$ cm^{-3}, we get 1.5×10^{11} cm^{-3} for the total density. This agrees with the density at the inflection point.

By experimenting in magnetic fields of different intensity, we have noted that the magnetic field has a strong influence on the plasma heating. Quantitative measurements have shown that the heating efficiency depends in resonant fashion on the magnetic field. Changes in the beam current, in its velocity, and in the density of the initial

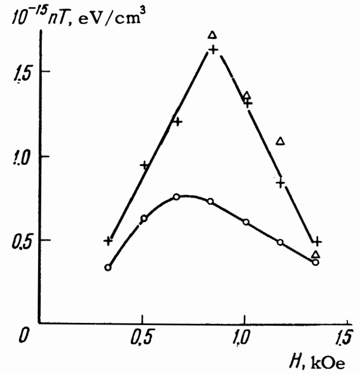

FIG. 5. Plasma heating vs. magnetic field at different electron-beam currents. O) 5 A, +) 10 A, △) 15 A. Accelerating voltage U = 25 kV.

plasma do not change the character of this dependence.

Figure 5 shows the dependence of nT on the magnetic field for three values of the electron-beam current. On changing from 5 A to 10 A, the maximum of nT shifts somewhat towards stronger magnetic fields, and its value more than doubles. Further increase of the beam current does not shift the position of the maximum and produces practically no change in its magnitude. A small shift of the maximum at large currents is due, as will be shown below, to a certain increase of the plasma density by additional ionization of the neutral gas by the stronger beam.

In[5], the plasma was heated by an electron beam under conditions when the plasma and cyclotron frequencies were close. In our experiments, the optimal heating conditions were obtained at $\omega_p = 4\omega_H$ for the center of the trap. The numerical ratio of ω_p to ω_H is highly arbitrary, inasmuch as the cyclotron frequency varies by a factor more than 5 along the trap, and the plasma frequency is calculated from a density that is averaged over the plasma cross section. To check on the equation $\omega_p = 4\omega_H$ we plotted nT against the magnetic field at another mirror ratio.

Figure 6 shows the results for two different values of R. At the lower mirror ratio (R = 3.14) nT decreases, but the position of the maximum of this curve practically coincides with the maximum for R = 5.25. In both cases we have $\omega_p = 4\omega_H$ for the center of the trap.

The ratio of ω_p to ω_H was checked further at different initial plasma densities. As before, we plotted nT against the magnetic field. The essential factor in these experiments was that the maxima of nT shifted towards stronger magnetic fields with increasing initial-plasma density. The values of the magnetic field for the maximum of nT, the plasma densities, and the corresponding cyclotron and plasma frequencies are listed in the table.

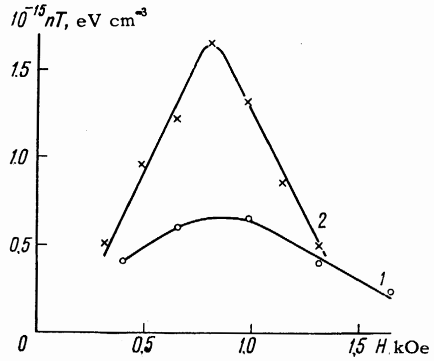

FIG. 6. Plasma heating vs. mirror ratio: 1) R = 3.14, 2) R = 5.25.

n, cm^{-3}	H, Oe	ω_p, sec^{-1}	ω_H, sec^{-1}
$0{,}5\cdot 10^{12}$	660	$4.1\cdot 10^{10}$	$1.1\cdot 10^{10}$
$1{,}6\cdot 10^{12}$	1000	$7{,}1\cdot 10^{10}$	$1.7\cdot 10^{10}$
$3{,}2\cdot 10^{12}$	1350	$1{,}0\cdot 10^{11}$	$2.4\cdot 10^{10}$

The values obtained for the frequencies show that the relation $\omega_p = 4\omega_H$ remains in force in this experiment, too. Thus, the existence of resonant heating of electrons, with a maximum at $\omega_p = 4\omega_H$ is an established experimental fact, for which we have no explanation as yet.

It is of great interest to ascertain how the electron density and temperature vary individually with varying magnetic field. Direct measurement of hot-electron concentrations is a very difficult task. The temperature measurements, however, were made for several values of magnetic fields by determining the spectral distribution of the hard x rays (Fig. 7). With increasing magnetic field, the electron temperature first increase and then reach a plateau. The start of the plateau occurs in the magnetic-field region at which nT has a maximum. The dependence of the hot-electron density on the magnetic field can be obtained by

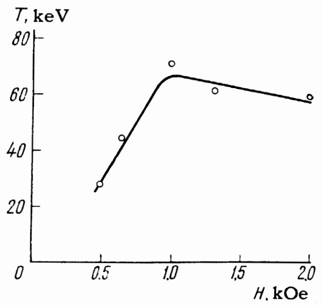

FIG. 7. Dependence of the electron temperature on the magnetic field. Accelerating voltage U = 25 kV, J = 10 A.

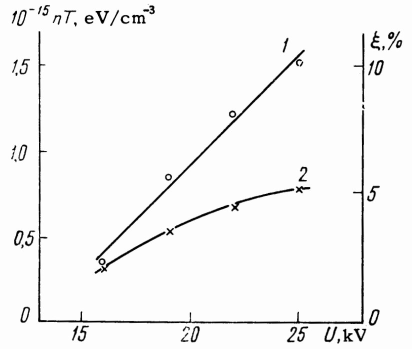

FIG. 8. Dependence of plasma heating on the electron-beam energy. Magnetic field H – 825 Oe, J = 10 A; curve 1–nT, curve 2–ξ.

dividing nT from Fig. 6 (curve 2) by the temperatures at the corresponding magnetic fields, taken from Fig. 7. It turns out that in weak magnetic fields the density remains practically constant, but starting with the values of the magnetic field near the maximum of nT it begins to decrease rapidly.

Another important parameter of the apparatus, besides the magnetic field, is the electron-beam power. In our experiments it was varied in two ways, 1) by varying the beam current at constant electron-gun accelerating voltage and 2) by varying the voltage at fixed current. It turns out that the heating depends on the method of supplying the energy to the plasma. When the beam current ranges from 5 to 15 A, the absolute magnitude of nT increases and reaches saturation. If we introduce the concept of efficiency given by the formula $\xi = nTV/JUt$, where V is the volume of the plasma and J, U, and t are respectively the current, accelerating voltage, and duration of beam passage, then the dependence of the efficiency on the beam current will have the following approximate appearance: on going from 5 to 10 A, the efficiency increases very slightly; further increase to 15 A, to the contrary, causes a noticeable drop in efficiency. This can be verified by simple calculation from the data of Fig. 5. The electron-gun voltage in these experiments was 25 kV.

The situation changes radically if the beam velocity is varied at a fixed current. Figure 8 (curve 1) shows nT as a function of the electron-gun accelerating voltage at a current of 10 A in the optimal magnetic field. Increasing the voltage by a factor of merely 1.5 more than triples nT. The same figure (curve 2) shows a plot of the heating efficiency. In this case the efficiency increases continuously, i.e., an increase of the energy contribution to the plasma by increasing the beam velocity is more favorable.

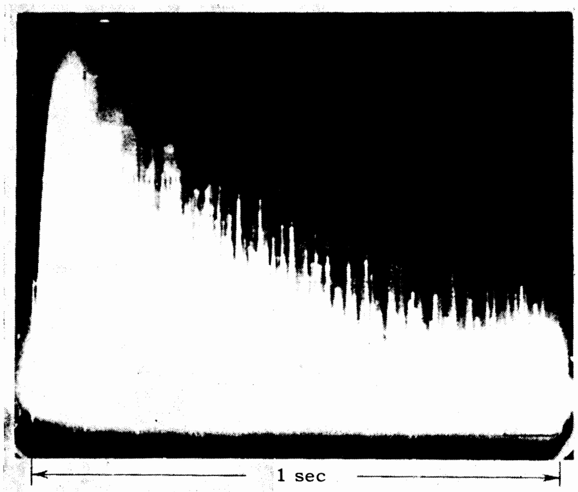

FIG. 9. Bremsstrahlung from plasma.

The hot component of the plasma exhibits in the overwhelming majority of cases no symptoms of instability. The density decreases slowly with a time constant $\tau = 30$ msec. This time is in satisfactory agreement with estimates of the lifetime in a trap for collisions with neutral gas. The presence of a long-lived hot plasma is confirmed also by the prolonged x-ray emission from the chamber (Fig. 9).

There are, however, cases when instabilities arise even in a quietly decaying plasma and lead to a sharp decrease in the density and in the diamagnetic signal. The disintegration of the plasma is always accompanied by a burst of x-ray and microwave emission. The oscillogram in Fig. 10 illustrates this phenomenon. Similar instabilities were observed in [1,6].

CONCLUSIONS

1. Our experiments have shown that the heating depends to a considerable degree on the magnetic field. There exists an optimal magnetic field at which the heating (nT) is maximal. The magnitude of this field is connected with the plasma

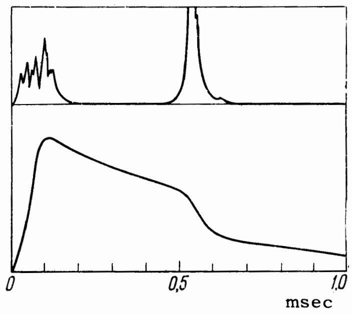

FIG. 10. Oscillogram illustrating instabilities in the plasma: top–x-ray emission, bottom–diamagnetic signal.

density by the relation $\omega_p = 4\omega_H$. This relation remains in force when the mirror ratio is changed.

2. The electron temperature of the hot component of the plasma more than doubles in a narrow range of variation of the magnetic field, and reaches a plateau. The hot-electron concentration, to the contrary, is at first practically independent of the magnetic field, but drops strongly once the region of the optimal magnetic field is reached.

3. The heating efficiency grows continuously with increasing electron-gun voltage. When the beam current increases, the efficiency remains practically constant. It is therefore more advantageous to increase the energy input to the plasma by raising the gun voltage.

4. The continuous increase of nT during the beam-injection time gives grounds for hoping to obtain large values of nT by simply prolonging the injection time.

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