High-Frequency Plasma Heating in a Closed Magnetic Trap

S. S. OVCHINNIKOV, S. S. KALINICHENKO, O. M. SHVETS AND V. T. TOLOK

Physico-technical Institute, Ukrainian Academy of Sciences

Submitted January 12, 1971; resubmitted July 15, 1971

Zh. Eksp. Teor. Fiz. 61, 2326–2329 (December, 1972)

Results are presented of an experimental investigation of the heating of a toroidal dense plasma performed by axially non-symmetric waves. Resonant excitation of ion cyclotron waves and subsequent thermalization of their energy by a magnetic shore result in efficient heating of the plasma. A mean ion energy up to 450 eV is obtained for a plasma density of $(2-5)\cdot 10^{13}$ cm^{-3}.

IT was shown earlier[1] that in a plasma situated in a toroidal magnetic trap it is possible to excite axially-symmetrical waves effectively by introducing the high-frequency power through exciting devices (ED) of different constructions. We describe here experiments on plasma heating by axially-asymmetrical ion-cyclotron waves. The thermalization mechanism was wave damping in a magnetic shore[2,3].

The experiments were performed with the "Omega" installation (Fig. 1a) which was described earlier[1]. A toroidal metallic vacuum chamber with minor diameter 200 mm and major diameter 800 mm is in a stationary magnetic field with maximum intensity up to 10 kOe. A plasma of density $1 \times 10^{13}-5 \times 10^{13}$ cm^{-3} was produced by an electron beam interacting with the working gas (hydrogen). The waves were excited by an ED (Fig. 1b) producing an alternating transverse magnetic field $\tilde{H}_\perp$ having a spatial periodicity along the plasma axis with a period $\lambda = 20$ cm, analogous to that described in[1]. A magnetic shore 30 cm long, with 25% attenuation of the field intensity, was produced along the torus at a distance of 100 cm from the ED.

To determine the optimal wave-excitation conditions, we measured the intensity of the alternating magnetic field $\tilde{H}_\perp$ over the radius of the chamber and the voltage $\tilde{U}_2$ on the receiving circuit, which was structurally similar to the ED and was located at a diametrically opposite point of the chamber.

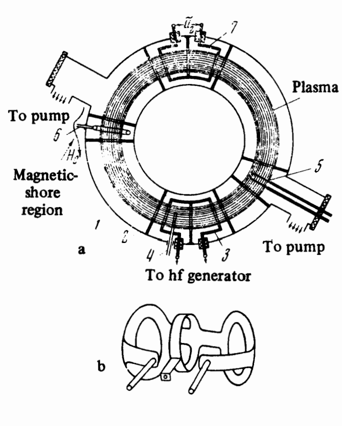

FIG. 1. a) Experimental setup: 1) vaccum chamber, 2) diaphragms, 3) exciting device, 4) high-frequency magnetic probe, 5) cathode of electron gun, 6) magnetic probe for the measurement of nT, 7) receiving device. b) Exciting device.

Figure 2 shows a typical dependence of the field $\tilde{H}_\perp$ on the chamber axis under the ED on the intensity of the containing magnetic field H_0 at a generator operating frequency 4.95 MHz. We see that the excitation of the ion-cyclotron wave has a resonant character with a maximum in the magnetic field above the ion-cyclotron-field value, in analogy with the case of axially-symmetrical waves[4]. Figure 2 shows the distribution of the high-frequency field intensity $\tilde{H}_\perp$ over the radius of the chamber in the absence of a plasma (b) and with a plasma in fields below the iron-cyclotron value ($H_0 = 3.2$ kOe) (c) and in a stronger field ($H_0 = 4.5$ kOe) (d). At magnetic fields below the ion-cyclotron field, no waves are excited in the plasma and the field penetrates little into the plasma. In the case of resonant excitation of ion-cyclotron fields, the intensity of the high-frequency field in the plasma under the ED increases and becomes higher than the vacuum value. The strength of the high-frequency current in the ED was maintained constant in these experiments.

Figure 3a shows plots of the voltage $\tilde{U}_2$ on the receiving circuit against the magnetic field for different values of the current in the ED; from these plots we can determine the coefficient of coupling between the ED and the plasma:

$$K_{\text{св}} = \sqrt{\frac{\tilde{U}_2}{\omega L I_1}},$$

where L is the inductance of the ED.

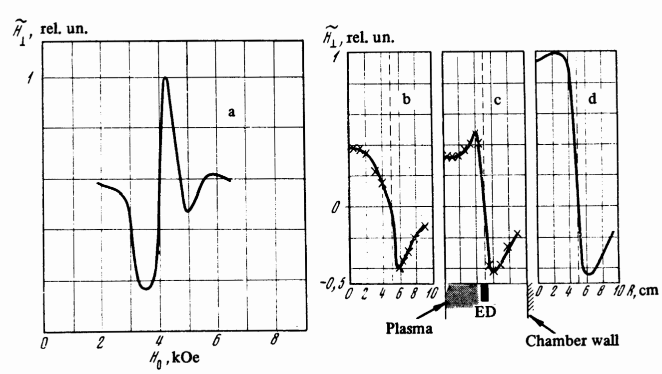

FIG. 2. a) Dependence of the field $\tilde{H}_\perp$ of the wave in the plasma on the magnetic field H_0; b, c, d) distribution of the field $\tilde{H}_\perp$ under the ED along the chamber radius.

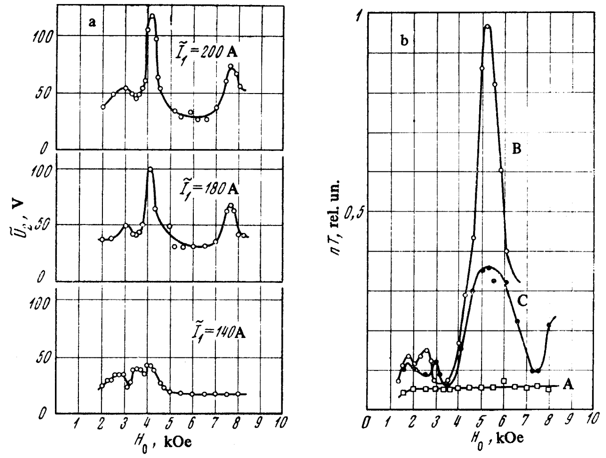

FIG. 3. a) Dependence of receiving-circuit voltage $\tilde{U}_2$ on the magnetic field H_0 at different values of the current I_1 in the ED. b) Dependence of the plasma pressure nT on the magnetic field: A) of a preformed plasma, B) in the magnetic shore, C) in the absence of a shore.

Under the experimental conditions, in the absence of a magnetic shore, K_c reached a value 0.25. The load on the ED differed little in this case from the vacuum load (the equivalent series resistance was r = 0.4 ohm). It should be noted that the coupling between the exciting device and the plasma is maximal in fields $H_0 > H_{ic}$ and $H_0 > 2\ H_{ic}$ (i.e., in fields corresponding to the excitation of ion-cyclotron waves for atomic and molecular hydrogen (see Fig. 3a). The coupling coefficient at small currents in the exciting device (from the measurement level to a value $I_1 \approx 140$ A) is 0.12—0.18, and at large currents it increases somewhat. The increase of the coupling with increasing current is probably due to the fact that the plasma boundary approaches the exciting device, as a result of the additional ionization of the gas by the strong high-frequency field on the periphery of the discharge (measurements of the density profile over the cross section have shown that at large currents in the ED the distribution becomes more step-like). In the presence of a magnetic shore of depth 25% and length 30 cm, the coupling between the receiving and exciting devices is decreased because of the wave damping in the shore, and the load on the ED increases to r = 4 ohm at resonant excitation of the wave. The power fed into the plasma reached in this case 120—150 kW. When a shore with a field drop larger than 25% and length 15 cm is produced ("steep shore") the ED load and the power transferred to the plasma decrease.

Figure 3b shows plots of the plasma pressure nT measured with the magnetic probe in the region of the magnetic shore. Plot A corresponds to measurement of nT of a plasma preformed by an electron beam; the two others were obtained following high-frequency heating: B) for a shore with field decreased by 25% and C) in the absence of a shore. The presence of a maximum of nT in the absence of a shore is due to the damping of the wave in the corrugations of the magnetic field, which have a magnitude on the order of 13%. The presented plots show that in high-frequency heating nT increases by a factor of several times ten compared with the initial value (the density remains practically unchanged when a high-frequency field is applied to a preformed plasma).

The absolute value of nT, obtained from the readings of the diamagnetic probe, gives a value that is approximately 5—8 times lower than the value of nT obtained from measurements by other methods (microwave diagnostics, analyzers of the transverse energy and of the flux of fast neutral particles, double probes). This is probably due to the conducting diaphragms that are located close to the probe, and also to the paramagnetic effect produced by the large flux of plasma particles to the glass body of the diamagnetic probe.

Measurements of the transverse energy of the ions by means of the analyzer described in[3] have shown that in the region of the maximum the average ion energy reaches 450 eV. These measurements are in good agreement with the average energy obtained from the velocity distribution of the flux of charged neutral particles leaving the plasma.

It should be noted that nT of the plasma increases only in the region of the magnetic shore. This is apparently connected with the fact that during the course of thermalization the ions acquire mainly a transverse energy and are captured in a local magnetic trap. The time of containment of the plasma in the toroidal trap without rotational transformation is too short to permit conversion from transverse to longitudinal energy. In a number of experiments, the high-frequency power was fed to 2 ED operating simultaneously. This has made it possible to increase the power input into the plasma.

Thus, the experimental results demonstrate the feasibility of effectively heating a dense plasma in closed magnetic traps by means of axially-asymmetrical ion-cyclotron waves.

The use of a large number of ED makes possible the increase in plasma power input that is needed for the heating of a dense plasma in large volumes. The radial distribution of the wave field (Fig. 2) gives grounds for hoping to be able to heat plasmas having a large transverse cross section.

In conclusion, the authors thank V. I. Kurilko for valuable remarks during the course of the work, P. I. Kurilko for taking part in the experiment, and V. I. Osmakov and V. V. Bronnikov for preparing the experimental apparatus.

[1]S. S. Ovchinnikov, S. S. Kalinichenko, O. M. Shvets and V. T. Tolok, ZhETF Pis. Red. 12, 277 (1970) [JETP Lett. 12, 187 (1970)].

[2]T. H. Stix and P. W. Palladino, Phys. Fluids 1, 446, 1958.

[3]O. M. Shvets, V. F. Tarasenko, S. S. Ovchinnikov and V. T. Tolok, in the book Vysokochastotnye svoĭstva plazmy (High-Frequency Properties of Plasma), Kiev, Naukova dumka, 1967.

[4]V. I. Kurilko and O. M. Shvets, in the book Vzaimodeĭstvie zaryazhennykh chastits s plazmoĭ (Interaction of Charged Particles with Plasma), Kiev, Naukova dumka, 1967.

Translated by J. G. Adashko
243