Plasma heating at the electron cyclotron resonance in the T-10 tokamak

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Experiments on plasma heating at the frequency of the electron cyclotron resonance are reported. The nominal microwave power pumped into the tokamak was about 500 kW. The heating efficiency ranged from 60% to 90%, depending on the conditions. The increase in the electron temperature reached $\Delta T_e = 0.6$–0.9 keV.

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Experiments have been carried out to study plasma heating at the frequency of the electron cyclotron resonance in the T-10 tokamak. The microwave source was a gyrotron complex[1] in which each of the four gyrotrons ($\lambda = 3.6$ mm) provided an output power up to 200 kW in a pulse with a length Δt up to 0.15 s. The microwave power was pumped into the tokamak chamber on the side of the weaker longitudinal magnetic field; about 70% of the power was carried by the ordinary wave, and the rest by the extraordinary wave. The beam was focused to the center of the cross section of the plasma column to reduce refraction.

The experiments on the electron cyclotron heating were carried out at a current $J_p = 220$–240 kA in a deuterium plasma; the radius of the plasma column, set by a movable graphite limiter, was $a_L = 34$ cm. The electron density averaged over a diameter lay in the range $\bar{n}_e = (2.5$–$4.0) \times 10^{13}$ cm^{-3}; the magnetic field at the axis of the plasma column was $B_T = 30$ kG and corresponded to the first harmonic of the electron cyclotron resonance.

It was found in the course of the experiments that the heating efficiency and the thermal insulation of the plasma during the electron cyclotron heating depend on the discharge conditions, so that we are reporting all results for two distinct sets of conditions. In case I, the chamber was previously cleaned by a glow discharge, and the level of light impurities was low; in general, the values of $\bar{n}_e$ were lower than in case II, corresponding to the conditions after the chamber had been cleaned by an induction discharge.

The results show that the changes in the torus loop voltage U, in the paramagnetic flux Φ during the microwave pulse, and in the time constant (τ) for the decay

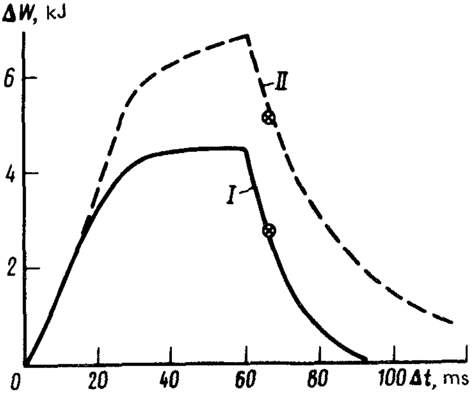

FIG. 1. Time dependence of the increase in the plasma energy, $\Delta W = \Delta n T$, during the heating for the two cases studied.

of Φ are 1.5–2 times higher in case II than in case I. We may thus conclude that the efficiency of the electron cyclotron heating is higher, and the absorbed microwave power is confined better, in case II. Figure 1 shows the change in the plasma energy, ΔW, caused by the electron cyclotron heating in these two cases.

Let us determine the primary measures of the electron cyclotron heating:

$$\delta\eta = \frac{P_{\text{mic}}}{P_{\text{ex}} + P_{\text{ord}}}, \tag{1}$$

$$\tau'_E = \frac{W}{P_{\text{ohm}} - dW/dt}. \tag{2}$$

Here η is the heating efficiency, P_{mic} is the power absorbed in the plasma, P_{ex} is the power pumped into the plasma in the form of the extraordinary wave, P_{ord} is that pumped into the plasma in the form of the ordinary wave, W is the internal energy of the plasma, P_{ohm} is the ohmic power, and τ'_E is the total energy confinement time, determined after the microwave pulse. The microwave power absorbed in the plasma was determined from the energy balance equation

$$P_{\text{mic}} = \Delta W / \tau'_E + dW/dt + \Delta P_{\text{ohm}}, \tag{3}$$

where $\Delta P_{\text{ohm}} = J_p \Delta U$ is the change in the ohmic power during the heating. The basic discharge parameters in cases I and II are shown along with the measures of the electron cyclotron heating in Table I, where values found from x-ray measurements are

TABLE I.

Case	$\bar{n}_e$ 10^{13} cm^{-3}	$T_{e0}(0)$ keV	τ_{E0} ms	P_{ex}, kW	P_{ord}, kW	P_{mic}, kW	Δt ms	$\Delta T_e(0)$ keV	ΔW kJ	ΔP_{ohm}, kW	η %	τ_E ms
I	2.8	1.5	40	150	350	320	60	0.9^*–1.0	3.7–3.8^*	120	64	25
II	3.8	1.2	45	150	350	450	60	0.5^*–0.6^*	6.8	230	90	36

marked with an asterisk, while the subscript 0 refers to parameters determined before the microwave pulse. Table I gives two values of $\Delta T_e(0)$ for case I, in which the distribution $T_e(r)$ was determined both by Thomson scattering and from x-ray spectra (Fig. 2). The two values found for this electron temperature increase agree well. Using the measured profile $T_e(r)$ and $n_e(r)$ in case I, we calculated ΔW, the increase in the internal energy of the plasma; the results agree well with the diamagnetic measurements, as can be seen from Table I. For case II the increase in the internal energy of the plasma during the electron cyclotron heating was determined only from the diamagnetic measurements.

We see from the table that the heating efficiency is quite high. The highest efficiency was achieved in case II, where η was 90%. The power pumped in with the ordinary wave was absorbed completely in the interior of the plasma column; some of the power carried by the extraordinary wave was also absorbed, apparently because of a depolarization of the microwave radiation upon reflection from the chamber wall.

The efficiency listed in the table for case II may be slightly too high because of the decrease in the internal inductance l_i of the plasma column during the heating. Analysis of various possible current profiles on the basis of the diamagnetic and x-ray measurements shows that the inductive component of the voltage, $(1/2)I_p\Delta l_i/\Delta t$, may reach 0.1–0.2 V. Allowance for this voltage component reduces $P_{\rm ohm}$ by 20–40 kW and puts the efficiency at 80–85%. The corresponding correction for case I is negligibly small.

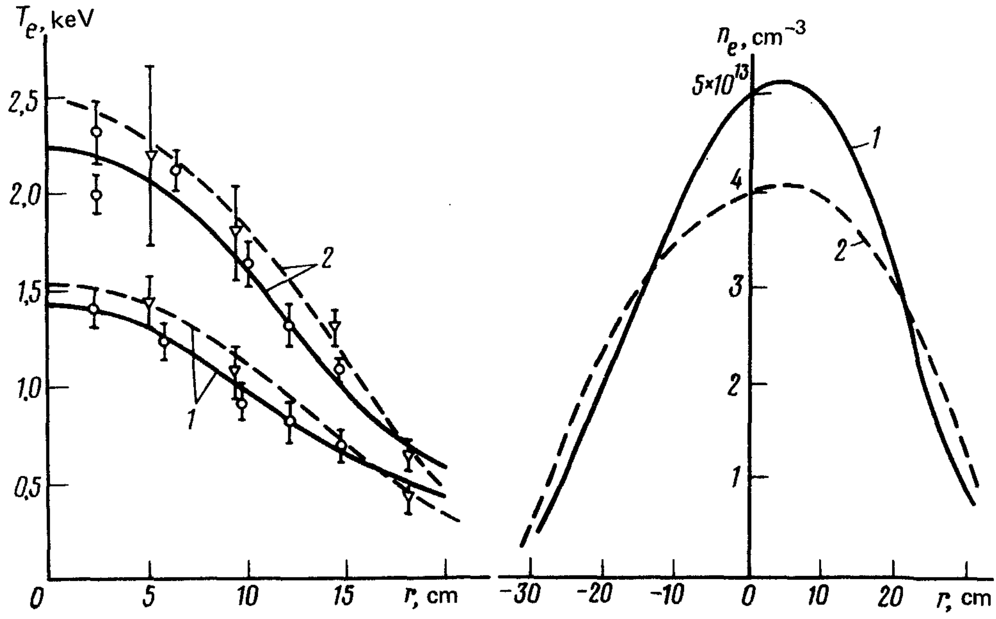

FIG. 2. Radial profiles of the electron temperature and density before (1) and at the end of (2) the heating pulse (case I).

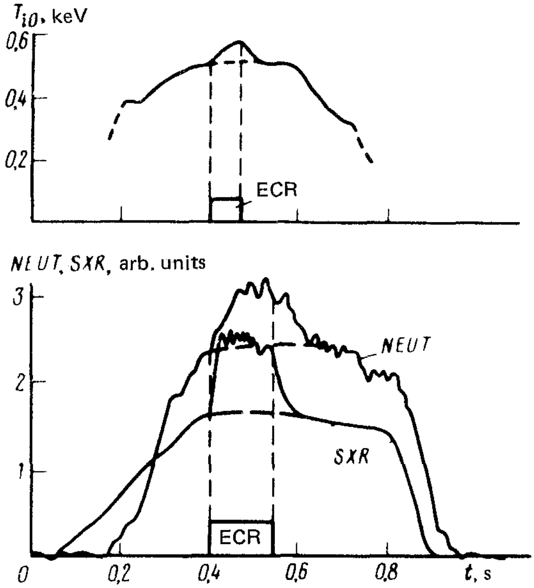

FIG. 3. Time dependence of the neutron and x-ray emission and of the ion temperature during electron cyclotron heating under the conditions corresponding to case II.

Study of the electron and ion components showed that 1) most of the electron heating occurs in the interior of the plasma column (Fig. 2), with ΔT_e reaching 0.6–0.9 keV at the center of the plasma, and 2) the ion heating is appreciable only in case II. The increase in the ion temperature, determined from the energy distribution of the charge-exchange atoms and the flux density of fusion neutrons, was about 100 eV, as expected under these conditions (Fig. 3).

We should also point out that the heating was accompanied by a decrease in the electron density near the axis of the plasma column. This effect was insignificant in case II but quite clearly expressed in case I (Fig. 2), where the decrease in $n_e(0)$ amounted to about 20%. It follows from measurements of the radiative-loss power P_R that the electron cyclotron heating is accompanied by an increase in P_{R0} by no more than 40 kW in case II and by about 80 kW in case I. This difference in the values of ΔP_R in these two cases, however, does not explain the difference between the corresponding values of τ'_E.

The differences between the values of τ'_E, ΔW, and η is cases I and II result primarily from the difference in the behavior of the electron thermal conductivity κ_e. The value of κ_e in the interior of the plasma column in case I increased by a factor of 3 or 4 during the heating and changed only slightly in case II.

Most of the measurements were carried out with a microwave pulse 60 ms long. In a final series of discharges, we tested the gyrotron complex at a pulse length of 150 ms. A rough idea of the heating at this pulse length can be obtained from the oscilloscope traces of the neutron and x-ray emission in Fig. 3. The neutron emission and thus the ion temperature increase throughout the pulse. The intensity of the soft x-ray emission increases to a steady-state level, perhaps implying that the electron temperature reaches a steady state.

In summary, these experiments in the T-10 tokamak show that electron cyclotron heating can be used successfully to heat plasmas in large fusion devices.

1. V. V. Alikaev *et al.*, Preprint IAÉ-3502/7, I. V. Kurchatov Institute of Atomic Energy, Moscow, 1981.

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