Low-power ECR heating in the T-10 tokamak

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A doubling of the electron temperature and of the total heating power level $P_{\mathrm{OH}} + P_{\mathrm{ECH}}$ resulted in virtually no decrease of the energy confinement time of electrons in the T-10 tokamak under the conditions $P_{\mathrm{ECH}} \simeq 330$ kW $q(a) \simeq 3.7$, and $\bar{n}_e \simeq 1.5 \times 10^{18}$ cm^{-3}.

Estimates of the losses associated with electrons trapped in the ripples of a toroidal field of a T-10 tokamak showed that these losses may become appreciable after the electron temperature in this device is raided to 5–6 keV.[1] To determine the effect of these losses on the observable losses in T-10, in particular, the dependence $\tau_E \sim P_{\mathrm{tot}}^{-0.6}$ for $P_{\mathrm{tot}}/P_{\mathrm{OH}}^0 = 3 - \infty P_{\mathrm{tot}}/P_{\mathrm{ECH}} + P_{\mathrm{OH}}$, [(where P_{OH}^0 is the ohmic heating before switching on of the electron-cyclotron heating (ECH)], it was necessary to accurately compare the results of the calculations with the measured $T_e r$ profiles and the energy times τ_E at various levels of rf power. In the first place, it was of interest to determine whether τ_E remains constant when the rf power is reduced to $\sim P_{\mathrm{OH}}^0$. Such a test was shown to be possible in Ref. 1, and also in experiments with the electron-cyclotron heating in a T-7 tokamak,[3] where it was shown that τ_{Ee}/μ_e remained constant under conditions of ohmic and auxiliary heating.

The electron-cyclotron heating at low power in T-10 tokamak was studied under typical working conditions with a plasma current $I_p \simeq \infty /,$ kA, the limiter radius $\alpha_L /$ cm, magnetic field $B_0 \simeq ,$ kG, and $n_e \sim \infty , \cdot \infty^{13}$ cm^{-3}. In the ohmic regime Z_{eff} had the values $<$ and the radiation losses did not exceed 50 kW ($\sim , \ P_{\mathrm{OH}}^0$). The automatic adjustment of the gas supply maintained the average plasma density when the ECH was turned on. The length of the discharge pulse was $\sim ,$ s.

The experiment with ECH was carried out with a single gyrotron which produced a central heating at the first harmonic of ECH of power up to 380 kW (λ /, mm, the length of the rf pulse ~, s, and a rise time of 0.3 ms). According to the data on the diamagnetic measurements, the energy content in the plasma during the ECH increased to ~∞ kJ ($\beta_p / \pm$, in the pulse No. 49965). The ion temperature T_i, measured from the charge-exchange atoms, remained virtually constant during the ECH. The temperature T_i was ~eV.

DIAGNOSTICS OF $T_c r$ PROFILES

The change in the electron temperature in the ohmic regime and in the ECH pulse was determined from the emission signals of the second harmonic of the ECH at six points around the plasma column. Under ohmic conditions these signals behaved uniformly as the current was rising. Their behavior became erratic, however, as the current I_p began to decrease. These changes in the ECP signals on the current decay curve were found to be connected with the displacement of the plasma column toward the outer surface of the torus, and also with the decrease in the field B_0 which decreased along with the current and the guiding field at the end of the T-10 discharge pulse. Analysis of the data on the column displacement, which were determined from the displacement of the density profile n_e, and the estimate of the decay of the field B_0 showed that in the time interval $\Delta T < 30$–40 ms after the beginning of the current decay, the change in the ECP signals is attributed to the displacement of the coordinate x of the radiation during a slight perturbation of the $T_e(r)$ profile. The coordinates x were shifted by as much as 6 cm because of the displacement and by ~7 cm because of the decay of the field.

Analysis of the ECP signals during the decay of $B_0 I_p$, carried out for two carefully studied pulses, Nos. 49963, 49965, has made it possible to accurately calibrate (~5%) six measuring channels and to find the relative profiles $T_e(r)$ for all the instants of time of these pulses without the use of other data on the distribution of $T_e(r)$. The absolute values of $T_e(r)$ were determined by fitting the calculated discharge voltage to the measured value under the assumption that $1.5 < Z_{\rm eff} < 2$. Numerical calculations have shows that $Z_{\rm eff}$ remains constant upon transition to the ECH regime and yielded values of ~1.6 for pulse No. 49963 and ~1.9 for pulse 49965. The values of $T_e(0)$ for the established stage of ohmic heating for pulse 49963 and before the ECH for pulse 49965 were close to 1.4 keV.

RESULTS OF MEASUREMENTS

Figure 1 shows plots of $T_e(r)$ and $n_e(r)$ for pulse 49963 obtained before, after, and during the EC heating. Auxiliary heating in this pulse was switched on during the unstabilized stage of ohmic heating ($t = 270$ ms), in which there were no sawtooth oscillations. The largest increase in the electron temperature of $T_e(0)$, by a factor of up to 2.7, was found to occur in pulse 49963 at the beginning of the ECH pulse relative to the stabilized ohmic level; the temperature rise decreased by a factor of 2.5 at the end of the ECH. In pulses 49964 and 49965, where the auxiliary heating was switched on 100 ms later, the increase in $T_e(0)$ was the same (~2.5) as that at the end of pulse 49963. In three pulses the electron temperature increased by approximately a factor of 2 in the average radii of the plasma column ($r/a = 0.4$–0.7).

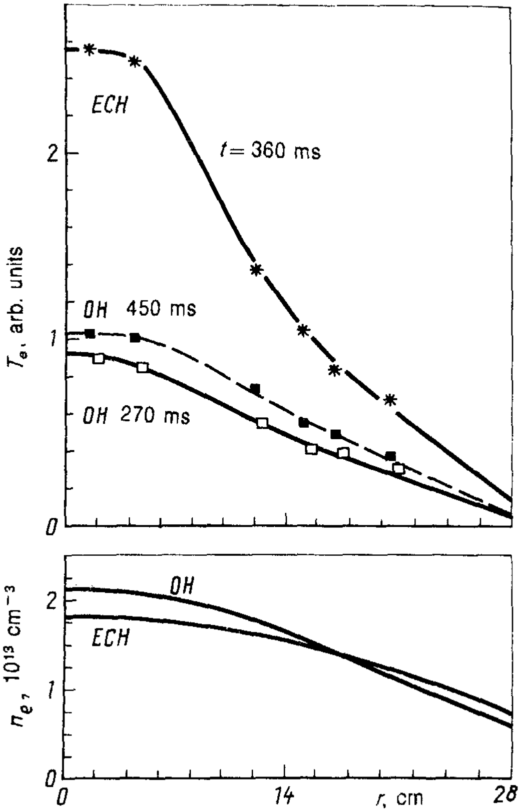

FIG. 1. Radial profile of the density and electron temperature under conditions of ohmic heating and ECR heating.

Figure 2 shows the plots of $T_e/T_e^{\rm OH}$ for the plasma, obtained from the ECH signals during the first 4.5 μs of the EC heating for pulse 49963. Note that the position of the maximum on the plots in Fig. 2 ($\Delta r \simeq 5$ cm, $R \simeq 149 \pm 5$ cm) corresponds to the expected position of the absorption zone of the rf power ($R \simeq 153$–155 cm). Note also that the $T_e/T_e^{\rm OH}$ profiles in pulse 49965, in which sawtooth oscillations were observed at the beginning of the ECH, were not as sharp as those in pulse 49963.

Despite the marked difference in the dynamics of the change of the $T_e(r)$ profiles at the beginning of the ECH in pulses 49963 and 49965, the increase in the electron energy ΔW_e calculated from these changes, with allowance for the $n_e(r)$ profiles, was found to be linear in time for ~ 5 ms in these two pulses. The ratios $\Delta W_e/\Delta t$ yielded the values $P_{\rm ECH} \simeq 340$ kW for pulse 49963 and ~ 320 kW for pulse 49965.

Table I gives the energy content in the plasma, W and W_e, and the Coulomb heat transfer, P_{ei}, before and after auxiliary heating, calculated from the measured $T_e(r)$ and $\bar{n}_e(r)$ profiles and from the model-based profile $T_i(r) \sim [1-(r/a)^2]^{1.5}$, which describes the regimes with low values of n_e in T-10 tokamak. As can be seen from Table I, the heat transfer P_{ei} is markedly lower than the heat transfer to the electrons, and the possible errors of $\sim 20\%$ in the data on the ion temperature could not appreciably affect the calculations of the energy balance in the electrons. Since the principal quantities in these calculations, W_e and $P_{\rm ECH}$, were normalized to the same $T_e^{\rm OH}(r)$

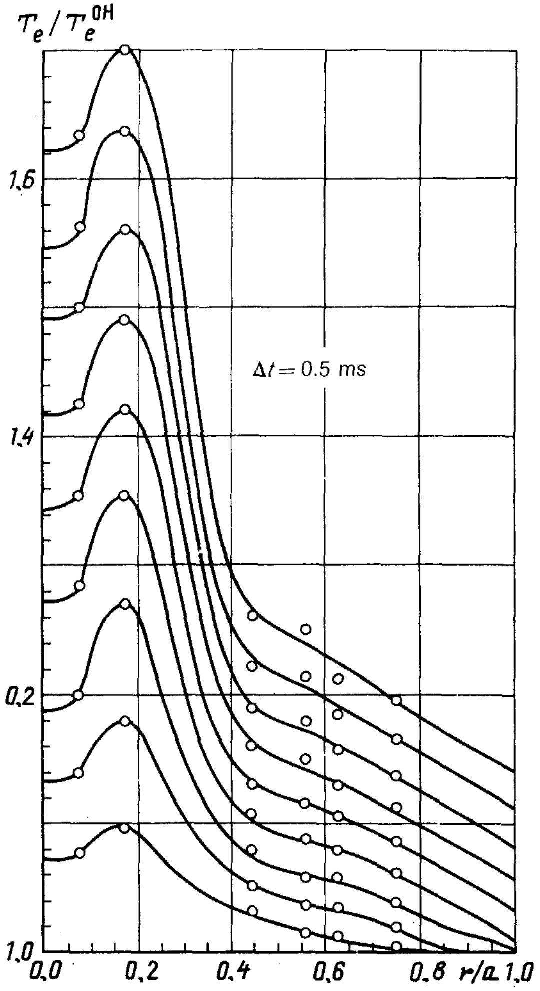

FIG. 2. Evolution of the $T_e(r)$ profile several milliseconds after applying auxiliary heating in pulse No. 49963.

profiles, the ratio of times τ_{Ee} and τ_E in the regimes with EC and ohmic heating in our calculations was determined within $\leqslant 10\%$.

As can be seen from Table I, after allowance for the decrease in $\bar{n}_e$ the decrease of τ_E and τ_{Ee} is very small ($\sim 10\%$) when the plasma heating in T-10 is doubled due to

TABLE I.

	$\bar{n}_e$	P_{tot}	P_{ei}	W_p	W_e	τ_E	$\tau_E/\bar{n}_e$	$\tau_{Ee}/\bar{n}_e$
	10^{13} cm^{-3}	kW		kJ		ms		
49963 OH	1.56	210	63	6.9	5.3	32	20.3	22.4
OH + ECH	1.43	440	57	11.4	10	26	18.2	18.4
49965 OH	1.69	210	71	6.9	5.1	32	19.1	21.2
OH + ECH	1.49	405	61	11.3	9.7	28	18.6	18.9

the ECH. This result shows the advantage of auxiliary EC heating with a diving power profile, which can account for small changes in the energy confinement time in the tokamak when the electron temperature is increased by a factor of 2–2.5 and when the loss factor $\chi_e \sim \sqrt{T_e}^{\,1}$ is increased relatively slightly.[1]

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[3] V. V. Alikaev *et al.*, in Plasma Phys. and Contr. Nucl. Fus. Res. Proc. 11th Int. Conf., Kyoto, 1986; Vol. 1, IAEA, Vienna, 1987, p. 533.

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