Behavior of the ion temperature during electron cyclotron heating in the T-10 tokamak

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The behavior of the ions during microwave heating of electrons at a power ~ 1 MW in the T-10 tokamak was studied. The results confirm that the energy transfer from electrons to ions is by a Coulomb mechanism.

The basic thrust of the program on auxiliary plasma heating in the T-10 tokamak is electron cyclotron heating at the first harmonic of the resonant frequency. The microwave source is a set of six gyrotrons, each having a power of 200 kW and a pulse length $\lesssim 100$ ms (Ref. 1).

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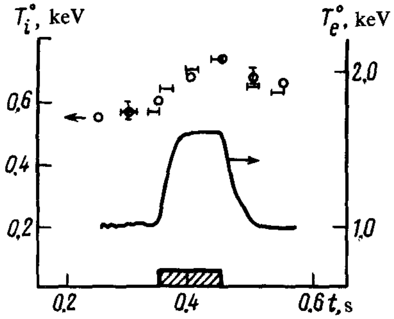

FIG. 1. Time evolution of the electron and ion temperatures at the center of the plasma during microwave heating in a regime with $I_p = 280$ kA, $B_t = 32.8$ kG, $\bar{n}_e = 3.6 \times 10^{13}$ cm^{-3}, and $P_{\rm MW} = 0.9$ MW. Horizontal bars—data on charge exchange; circles—neutron measurements; solid curve—measurements of the electron temperature at the second harmonic of the electron cyclotron radiation; hatching—duration of the microwave heating.

In this letter we report a study carried out to optimize the conditions for ion heating at a fixed microwave power deposition in the plasma. The heating of the ions is, of course, a result of an interaction of the ions with heated electrons.

We studied the behavior of the plasma electrons and ions in a regime with a current $I_p \cong 300$ kA, a longitudinal magnetic field $B_t \cong 30.0$ kG, and an average electron density $n_e = (0.5\text{–}4) \times 10^{13}$ cm^{-3} by measuring and second harmonic of the electron cyclotron radiation, the energy spectra of the charge-exchange atoms, and the yield of fusion neutrons. These measurements were carried out for various positions of the zone of resonant absorption of the microwave power.

Figure 1 shows the results of the measurements of the electron and ion temperatures at the center of the plasma during microwave heating in one of the regimes studied.

Figure 2 shows the set of results of measurements of the central ion temperature at the end of the microwave heating under various conditions, set primarily by varying the plasma density, which has the consequence of changing the electron temperature during microwave heating at a fixed power.

The function $\Delta T_i / T_i^0$ crosses zero, and the two branches of this function correspond to an increase and a decrease in the ion temperature as a result of the microwave heating of the electrons. This behavior of $\Delta T_i / T_i^0$ corresponds to a Coulomb law for

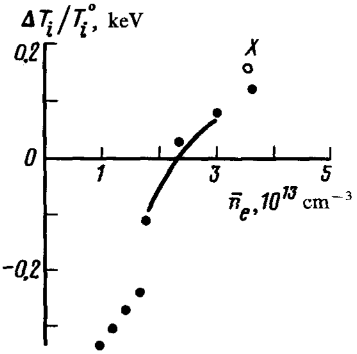

FIG. 2. Relative increase in the central ion temperature by the end of the microwave heating versus the average plasma density at a fixed microwave power ($P_{\rm MW} \cong 0.9$ MW). Filled circles—Resonant zone at the center of the plasma; open circle and cross—resonant zone displaced outward and inward from the center of the plasma, by $\Delta r = -9$ cm and $\Delta r = 12$ cm, respectively; solid curve—theoretical.

energy transfer from electrons to ions,[2] and the negative and positive branches of $\Delta T_i/T_i^0$ in Fig. 2 are attributed to the nonmonotonic behavior of the Coulomb power on the electron temperature. According to this law, at $T_e > 3T_i$ the energy transfer from electrons to ions begins to fall off with increasing T_e, giving rise to a region of negative values of $\Delta T_i/T_i^0$. A simple calculation based on a Coulomb energy transfer from electrons to ions and constant coefficients for the heat loss due to ions during the microwave heating of the electrons (this assumption is valid at least near vanishing values of $\Delta T_i/T_i^0$) leads to a good agreement with the experimental data (Fig. 2). This agreement, however, tells us only that the functional dependences of the experimental quantities agree with a Coulomb energy-transfer law, since Q_{ei} could, in principle, differ from the Coulomb value Q_{ei}^C in absolute value (in order to satisfy the ion energy balance in both the ohmic-heating regime and the auxiliary-heating regime, the coefficients of the ion energy transport must differ from the values corresponding to Coulomb transfer by an equal factor). This uncertainty can be eliminated by analyzing the rate of increase of the ion temperature during the microwave heating. This rate depends on the absolute value of the energy transferred from electrons to ions.

We see from Fig. 1 that the electron temperature increases much more rapidly than the ion temperature during the microwave heating. Using the ion energy balance equation in the form

$$\frac{3}{2}\frac{\Delta}{\Delta t}(nT_i) = k\,(Q_{ei}^{*} - Q_{ei}^{0}) = k\,\Delta Q_{ei},$$

where Q_{ei}^0 and Q_{ei}^* are the Coulomb energy transfer to ions during ohmic and auxiliary heating, and k is a proportionality factor, and carrying out some straightforward calculations, we conclude that in absolute value the actual energy transfer from electrons to ions differs from the Coulomb value by a factor of 1–3 (the range reflects the uncertainties in the measurements of the rate of increase of the ion temperature).

As the zone in which the microwave power is absorbed is moved away from the center of the plasma, we find that the increase in the central electron temperature is less pronounced, and the profile of this temperature becomes flatter at a given microwave power.[1] As a result, the electron temperature deviates less from the ion temperature than it does in the case of central heating, and, as follows from the Coulomb law for energy transfer, we observe a more efficient heating of the ions, which depends only slightly on just where the microwave absorption zone is moved (Fig. 2).

In summary, these results provide evidence for a classical Coulomb transfer of energy from electrons to ions during microwave heating of the electrons.

We wish to thank our many colleagues who are involved in the program of microwave heating in the T-10 for assistance in this study.

[1] V. V. Alikaev *et al.*, in: Tenth International Conference on Research on Plasma Physics and Controlled Fusion, IAEA-CN-44/F-1-1, London, 12–19 September, 1984.

[2] P. E. Stott, Plasma Phys. **18**, 251 (1984).

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