New results on the local electron thermal conductivity in the T-10 tokamak

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As the longitudinal magnetic field in the T-10 tokamak is raised from 1.5 to 3 T (and the safety factor at the limiter radius is raised to 5), the electron thermal conductivity κ_e decreases by a factor of three or four in the interior of the plasma column. Auxiliary heating of the electrons increases κ_e.

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In recent research on the heat loss from tokamak plasmas, the total energy confinement time τ_E remains of interest, but local characteristics of the transport processes are receiving progressively more attention.[1-5] In particular, an increased effort is being made to determine the local value of the electron thermal conductivity.

In earlier experiments in the T-10, with a longitudinal magnetic field $B_T = 1.5$ T and with a safety factor $q(a_L) = 2$ at the limiter radius, it was found[2,3] that the measured profile of the electron thermal conductivity, $\kappa_e(r)$, agrees with the scaling law proposed in Refs. 1 and 4:

$$\kappa_e(r) = 10^{20} \frac{T_e^{1/2}}{q(r)\, R} (r/R)^{7/4} \tag{1}$$

(T_e is in electron volts). When the electron temperature T_e was raised by auxiliary microwave heating of the electrons at the second harmonic of the electron cyclotron resonance,[5] it was found that κ_e varies no faster than T_e^a with $|a| \leqslant 0.5$. This result, which was found upon a small change in T_e ($\Delta T_e \cong 300$ eV) and under conditions similar to those described in Ref. 3, correlated with the constancy of the energy confinement time τ_E and was consistent with the scaling law in (1).

In the experiments reported in the present letter, it proved possible to study the T_e dependence of κ_e upon a much greater increase in T_e, $\Delta T_e \cong 1$ keV, achieved through microwave heating at the fundamental frequency of the electron cyclotron resonance.[6] It was observed that in the steady stage of the ohmic heating the electrons in the interior of the plasma column have a very low thermal conductivity, quite different from that predicted by (1).

The conditions in these experiments differed from those in Refs. 2, 3, and 5 in that the longitudinal field was stronger ($B_T = 3$ T) and the safety factor was $q(a_L) = 5$ at $a_L = 34$ cm. Figure 1 shows the basic characteristics of these discharges. The conductivity κ_e was measured during the steady stage of the discharge, at a

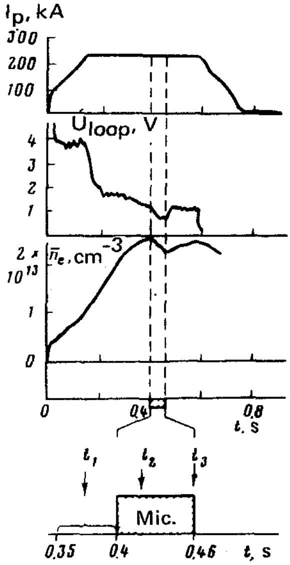

FIG. 1. Basic discharge characteristics. Shown at the bottom is the temporal sequence of the plasma diagnostic measurements carried out for the calculations of κ_e.

plasma current $I_p = 220$ kA, at a torus loop voltage $U_{\rm loop} = 1.2$ V, and at the average electron density $\bar{n}_e = 2.8 \times 10^{13}$ cm^{-3} (this is the density averaged over the diameter of the plasma column). The energy confinement time τ_e increased to 40 ms during the ohmic heating, in contrast with the 24 ms reported in Ref. 5. We observed no sawtooth oscillations of the soft x-ray emission intensity.

The battery of diagnostic methods described in Refs. 2 and 3 was supplemented with measurements of the x-ray emission spectrum in two perpendicular directions (with an averaging time $\Delta t \cong 50$ ms) and with measurements of $T_e(r,t)$ by a filter method. The conductivity τ_E was determined from measurements of the plasma diamagnetic signal.

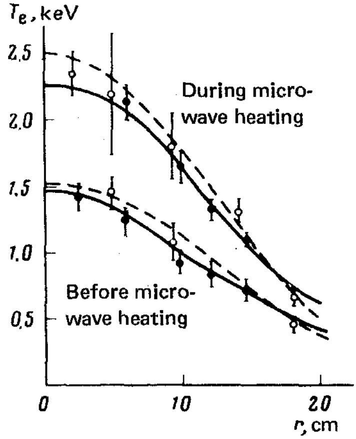

FIG. 2. Dashed curves—The radial profile $T_e(r)$ determined by Thomson scattering before and during the microwave heating; solid curves—the same, but as determined by the x-ray method.

Figure 2 shows radial profiles of the electron temperature, $T_E(r)$, in the steady stage of the ohmic heating. The results found by the diagnostic methods, Thomson scattering and x-ray spectroscopy, agree. The values of κ_{el} in this stage of the discharge ($t = t_1$; Fig. 1) was determined from the energy balance equation

$$< Q_{\text{ohm}} > \, = \, < Q_{ei} > + < Q_{rad} > - \, r\,\kappa_e \left(\frac{dT}{dr}\right)_r , \qquad (2)$$

where $\langle Q\rangle \equiv \int_0^r Q(r)c\,dr$. These calculations yield $\kappa_{\text{el}} = (0.4 \pm 0.2)\,10^{17}\ \text{cm}^{-1}\cdot\text{s}^{-1}$, and this conductivity varies only slightly over the part of the plasma cross section which was studied ($x \equiv r/a_L < 0.5$).

The indicated upper limit on this value, which was determined quite reliably, is one-third the value predicted by scaling law (1) for the region $0.25 \leqslant x \leqslant 0.4$ in the plasma, and it is roughly four times the neoclassical value κ_e^{neo} in the plateau region[7]:

$$\kappa_e^{neo} \cong 10^9 \, \frac{T_e^{3/2}\, q(r)\, n_e(r)}{B_T^2 R} \qquad (3)$$

(T_e is in electron volts, and B_T is in gauss). It follows from (2) that in this calculation method the experimental value of κ_e is determined from a heat flux which also includes the flux caused by electron diffusion. The actual values of κ_{el} could thus be only lower.

When microwave power was pumped into the plasma, the increase in T_e which we detected in the central part of the plasma was much larger than that of Ref. 5: $\Delta T_e(0) = 0.8 - 1$ keV (Fig. 2). In contrast with Ref. 5, τ_E decreased from 40 to 26 ms during the microwave heating. We observed a decrease in n_e at the center of the plasma and a slight increase at the periphery.[6]

The thermal conductivity during the microwave heating was determined from an equation similar to (2), but with a term $\langle Q_{\text{mic}}\rangle$ (the microwave power absorbed by the plasma) added to the left side. The average power $\langle Q_{\text{mic}}\rangle$ was determined from the derivative $d(nT)/dt$, measured by various methods. The results calculated for κ_e at various times during the microwave heating are given in Table I (for $0.25 \leqslant x \leqslant 0.4$) and in Fig. 3.

TABLE I.

conditions κ_e, in units of 10^{17} cm$^{-1}\cdot$s^{-1}	ohmic heating	microwave heating	
	κ_{el} ($t = t_1$)	κ_{e2} $t = t_2 = 410$ ms (laser , r = 12 cm)	κ_{e3} $t = t_3 = 460$ ms (x-ray)
κ_e^{expt}	0.4 ± 0.2	1.2 ± 0.4	1.3 ± 0.3
κ_e from (1)	1.6 . . . 2.3	2.6 ± 0.2	2.4 . . . 2.8
κ_e^{neo}	0.06 . . . 0.12	0.13 ± 0.04	0.1 . . . 0.2

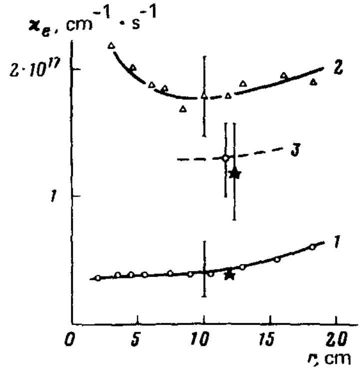

FIG. 3. 1–The profile $\kappa_e(r)$ in the inner part of the plasma before the microwave heating; 2–after the microwave heating; 3–the value of κ_e calculated with allowance for the escape of particles; *–data obtained from laser measurements.

We see from Table I and Fig. 3 that the increase in T_e during the microwave heating is accompanied by an increase in the electron thermal conductivity in the interior of the plasma; this increase correlated with the decrease in τ_E. The values of κ_{e2} and κ_{e3} nevertheless remain appreciably lower than those predicted by scaling law (1). We should emphasize a distinction between our approach to the steady stage of the discharge and our approach to the microwave-heating stage. In the former case, the important point is the upper limit estimated for the experimental value of κ_{e1}, since it confirms that the thermal conductivity under these conditions is consideraly lower than that predicted by scaling law (1) and considerably lower than the results observed previously.[2,3,5] From this standpoint, it is not of fundamental importance to consider the diffusion flux, which only strengthens this assertion.

During the microwave heating, in contrast, the thermal conductivity increases, so that it is the lower limit on κ_e which is more important for making comparisons and drawing conclusions. Since we observe a decrease in the density n_e in this stage (Fig. 1), which implies the appearance of an additional heat flux (one not resulting from the thermal conductivity) in the central part of the plasma, thus flux was accordingly taken into account in calculating κ_{e2} and κ_{e3} (Fig. 3).

It is important to note that in the same series of experiments we observed discharges in which τ_e in the ohmic-heating stage was nearly the same as under the conditions which we are discussing here, but it fell off slightly during the microwave heating. As a rule, these discharges had relatively high values of n_e: $\bar{n}_e = (3.6 - 3.8) \times 10^{13}$ cm^{-3}. These differences in the behavior of τ_E in the microwave-heating experiments in the T-10 and the large differences between the values of κ_e under approximately the same conditions indicate that empirical scaling laws are of only limited applicability, because the specific mechanisms responsible for the energy transport in the plasma column have not yet been determined.

To put these results in a more systematic form, we will use the changes in the collision parameter $\nu_e^* = (r/R)^{-3/2}\, qR/\lambda_e$ (λ_e is the electron mean free path) under the conditions considered here. For the conditions of Refs. 2, 3, and 5, the parameter ν_e^* is typically less than 1 (~0.8) in the part of the plasma studied; in other words, the electrons are in a collisionless region, for which scaling law (1) was derived.[1,4] Under these conditions the values of κ_e measured in the T-10 agree with those expected on the basis of (1) (Refs. 2, 3, and 5).

For the discharge conditions described in this letter, the collision parameter shifts to the region $\nu_e^* > 1$ (~1.2-1.5) in the ohmic-heating stage. Here we observe κ_e values much lower than those predicted by (1), and there is an approach to the neoclassical values κ_e^{neo}.

This interpretation of the results in terms of the collision parameter leads to certain suggestions regarding the structure of κ_e. We write the thermal conductivity as consisting of two terms, anomalous and neoclassical, with the second term possibly having some numerical factor. The experimental data indicate that the region of ν_e^* near 1 is a transition region; specifically, as ν_e^* increases, there is a decrease in the anomalous component, while the "neoclassical" component becomes progressively more important. In this case, the increase in κ_e observed during the microwave heating results from not only an increase in the absolute value of T_e but also an increase in the anomalous component, since ν_e^* moves into the region $\nu_e^* < 1$ during the heating. In fact, the increase in the anomalous component may be more important than the increase in the absolute value of T_e.

The parameter ν_e^* can be used to characterize the position of the transition region in general terms. However, since we are dealing with the changes in the anomalous component of the thermal conductivity, it may be more appropriate to describe this region in terms of another parameter. This other parameter would have a structure similar to that of ν_e^* but would depend more strongly on (for example) the longitudinal magnetic field, since the value of B_T distinguishes the conditions of the present experiments from those of Refs. 2, 3, and 5.

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