Electron thermal conductivity and diffusion in a tokamak

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The dependence of the electron thermal conductivity in a tokamak on the toroidal ratio r/R and on the major radius R is discussed. It is shown that the energy lifetimes of electrons measured in different devices agree with the dependence $\tau_{Ee} \sim R^3$. It is also shown that the experimental data are consistent with the dependence $D \approx k\chi_e$, where $k \approx 0.1$.

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Analysis of the energy balance of electrons performed in a number of experiments using tokamaks[1,2] indicated that the coefficient of electron temperature conductivity χ_e increases greatly along the radius of a plasma column, whereas the product $\chi_e n_e$, where n_e is the electron density, varies slightly along the radius and has approximately the same value in different devices $\sim 5 \times 10^{17}$ cm^{-1} • sec^{-1}.[3] It would seem that these data exclude the strong dependence of χ_e on any parameter except n_e and are in agreement with the "Alcator" similarity relation for the energy lifetime of electrons $\tau_{Ee} \sim n_e a^2$ (Ref. 4) (a is the minor radius of the column).

Recent experiments on the T-11 facility[5,6] showed, however, that τ_{Ee} depends weakly on a ($\tau_{Ee} \sim a^{\alpha}$, where $\alpha \approx 0.2$-0.5) and that the product $\chi_e n_e$ satisfies the dependence $\chi_e n_e \sim q^{-1} R_e^{0.5} r^{1.75}$ ($q = rB_0/RB_\omega$, B_ω is the magnetic field of the current at the radius r, B_0 is the toroidal magnetic field, R is the major radius of the torus, and T_e is the electron temperature). Using these data and the experimental evidence that the anomaly of the electron thermal conductivity $\langle \chi_e \rangle / \langle \chi_e^{\mathrm{NEO}} \rangle \approx$ const in the ohmic-heating mode when $\langle \nu_e^* \rangle \approx$ const, we can obtain the following expressions for χ_e and τ_{Ee}

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TABLE I.
A comparison between the measured values of τ_{Ee} and those calculated according to Eq. (2)

Device	R cm	a cm	$q(a)$	$\bar{n}_e$ (10^{13} cm^{-3})	$\langle T_e \rangle$ eV	Z_{eff}	τ_{Ee}^{exp} msec	τ_{Ee}^{calc} msec
T-11 [6]	70	12,5	2,5	1,5	150	~1	2,4	2,4
T-11 [6]	70	20	2,5	1,5	160	~1	2,8	2,7
T-10 [7]	150	24,5	2	2	460	4	12	14
PDX [8]	150	38	3,1	1,5	320	~1	23	22

$$\chi_e \approx 10^{20} \frac{\sqrt{T_e}}{n_e qR} \left(\frac{r}{R}\right)^{7/4}, \tag{1}$$

$$\tau_{Ee} \approx 3{,}5 \times 10^{-21} \left(\frac{a}{R}\right)^{1/4} q(a) \frac{\bar{n}_e R^3}{\sqrt{\langle T_e \rangle}}. \tag{2}$$

Here χ_e^{NEO} is the neoclassical temperature-conductivity coefficient of electrons in the region of infrequent collisions, $\langle \nu_e^* \rangle = (R/a)^{3/2}\, qR/\langle \lambda_e \rangle$, λ_e is the free path length of electrons, and the angle brackets denote averaging over the cross section of the column. The numerical coefficients in Eqs. (a) and (2) were selected from the best agreement with the results of the measurements on the T-11 device, T_e is in eV, R is in cm, and $\bar{n}_e$ is the average density of electrons along the column's diameter in cm^{-3}.

A strong dependence of χ_e on the toroidal ratio r/R and on the radius R given by Eq. (1), which leads to the dependence $\tau_{Ee} \sim R^3$, is consistent with the data obtained using other devices. As seen in Table I, the dependence (2) can account for the noticeable difference in the values of τ_{Ee} obtained in the T-11 and T-10 devices for similar values of a, $\bar{n}_e$, and $q(a)$.

The data in Table I were obtained in regimes with a low plasma density, in which the energy loss was determined by the electron thermal conductivity and the parameter of the electron collision ν_e^* in the middle of the column's radius was $\lesssim 1$.

We attempted to determine in the experiments using T-11 the contribution of the electron thermal conductivity and the total energy loss for moderate and high plasma density and for $\nu_e^* > 1$. We measured the integral energy lifetime τ_E of the plasma in a broad range of $\bar{n}_e$ for two values of the column's radius $a = 20$ cm and $a = 12.5$ cm. We investigated the hydrogen plasma with a low impurity content (the effective ion charge $Z_{\text{eff}} \approx 1$, the ratio of the power of the radiation loss and the loss due to charge exchange to the power of the ohmic heating P_{rad}/P_Ω was $\leqslant 0.15$ both for low and high plasma density). The thermal energy of the plasma column was determined from the measurements of the diamagnetic plasma effect.

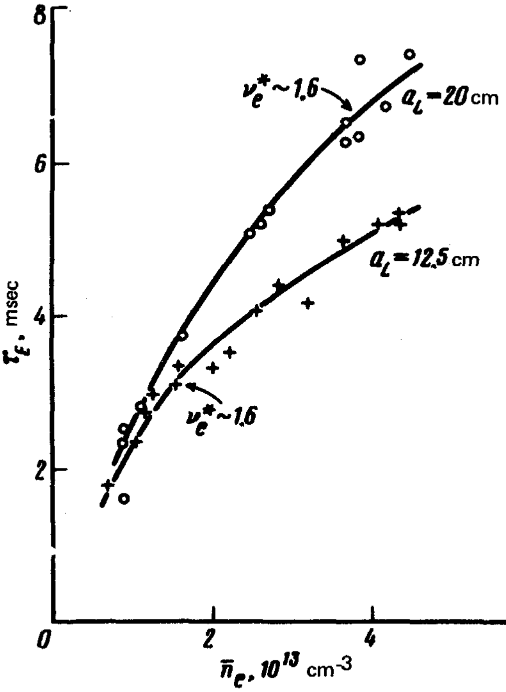

FIG. 1. Dependences of τ_E on $\bar{n}_e$ for two radii of the plasma column in T-11. $B_0 = 9.4$ kG, $q(a) \approx 2.5, a = a_L$ is the radius of the limiting diaphragm.

The results of the measurements are shown in Fig. 1. We can see that the obtained dependences of τ_E on $\bar{n}_e$ are almost linear for low values $\bar{n}_e \lesssim 1.5 \times 10^{13}$ cm^{-3}. As $\bar{n}_e$ increases, both dependences diverge noticeably from the linear values, and when $a = 12.5$ cm the deviation from the linear law $\tau_E \sim \bar{n}_e$ is stronger (the experimental curve in this case is approximated by the dependence $\tau_E \sim \sqrt{\bar{n}_e}$). The indicated peculiarities in the behavior of τ_E can be accounted for by the increasing role of the ion thermal conductivity in the energy balance of the plasma arising from the increase of $\bar{n}_e$ and ν_E^* assuming that the energy lifetime of electrons follows the dependence (9) at high plasma density. This is illustrated in Table II, in which the measured values of τ_E are compared with the calculated values of τ_{Ee} and τ_{Ei}^{NEO} for two values of the column's radius at $\bar{n}_e \approx 4 \times 10^{13}$ cm^{-3}. Table II also gives the cal-

TABLE II.

a cm	$\langle T_e \rangle$ eV	$\langle T_i \rangle$ eV	τ_E msec	τ_{Ei}^{NEO} msec	τ_{Ee} msec	$P_i^{NEO}/P_{\mathrm{OH}}$	P_e/P_{OH}
20	125	105	6,8	11	7,8	0,3	0,46
12,5	100	85	5,0	3,8	7,8	0,6	0,32

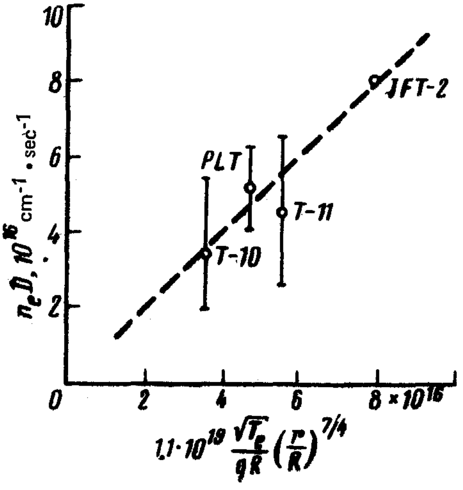

FIG. 2. Values of Dn_e measured in T-10 (Ref. 7), JFT-2 (Ref. 9), PLT (Ref. 10), and T-11, as a function of the product 0.11 $\chi_e n_e$.

culated parts of the electron P_e/P_{OH} and ion P_i^{NEO}/P_{OH} energy losses. In the calculation of the energy lifetime of ions τ_{Ei}^{NEO} and of the ratio P_i^{NEO}/P_{OH}, we have used an approximation formula for the neoclassical coefficient of ion temperature conductivity proposed by P. N. Yushmanov, $\chi_e^{NEO} = \chi_i^{PS} + \chi_i^{PL}/(1 + \chi_i^{PL}/\chi_i^{B})$ (χ_i^{PS} is the Pfirsch-Schlüter-Shafranov coefficient, and χ_i^{PL} and χ_i^{B} are the Galeev-Sagdeev coefficient for the region of the intermediate and rare collisions, respectively). If at $a = 20$ cm and $\nu_e^* \sim 1.7$ the losses due to neoclassical ion thermal conductivity are $\sim 30\%$ of the total energy losses, then at $a = 12.5$ cm and $\nu_e^* \sim 8$ the neoclassical ion losses become dominant. Table II shows that the remaining energy losses are close to those due to electron thermal conductivity calculated from Eq. (2). Thus we can conclude that Eqs. (1) and (2) can be used to describe the electron energy loss in a broad range of $\bar{n}_e$ and $\nu_e^* \approx 0.2 - 8$.

We have ignored above the energy loss due to plasma diffusion. This is apparently justifiable in the analysis of the energy balance of electrons, since the diffusion coefficient D is approximately an order of magnitude lower than χ_e (Fig. 2). If the tendency $D \approx 0.1\ \chi_e$, which is evident in Fig. 2, will be confirmed in the future experiments, then the losses of charged particles must influence noticeably the energy balance of ions in the region $\nu_e^* \lesssim 1$ in the ohmic heating modes and in the region $\nu_e^* \lesssim 0.1$, produced as a result of strong ($P_{ADD} \sim 10\, P_{OH}$) additional plasma heating.

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