Local electron thermal conductivity in the Tuman-2A tokamak with a rapidly varying toroidal magnetic field

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In a discharge with magnetic compression the electron thermal conductivity starts out at the anomalously high value characteristic of a tokamak. In the course of the decompression the electron thermal conductivity decreases, approaching the neoclassical value. A possible reason for this behavior is discussed. The mathematical analysis of the experimental results is described briefly.

In the Tuman-2A tokamak[1,2] ($R = 40$ cm, $a_L = 8$ cm) the local transport coefficients are being studied under time-varying conditions, e.g., during the compression of the plasma by the toroidal magnetic field, in contrast with the measurements under steady-state conditions in most other tokamaks. The corresponding time evolution of the profiles $T_e(r)$, $n_e(r)$, and $w_{\rm rad}(r)$ (the radiative energy loss) is detected by means of the Thomson scattering of a laser beam, microwave interferometry, and a bolometric diagnostic method.

The current density distribution $j(r,t)$, which is required for an understanding of the local electron energy balance, is found through a numerical solution of the one-dimensional equation for the classical transport of a poloidal magnetic field B_p in a plasma for the case in which the conducting medium is in motion. The initial condition is the $B_p(r)$ profile for quasisteady ohmic heating with which the time-varying processes begin experimentally. The parameters of the equation are $V_r(r,t) = -0.5\dot{B}_T/B_T$, which is the radial velocity of the plasma caused by the time evolution of the toroidal field $B_T(t)$, and $D_M(r,t) = c^2/4\pi\sigma$, the magnetic field diffusion coefficient, both of which are determined from the experimental data. The conductivity is calculated with the toroidal correction in accordance with Ref. 3. To check the correspondence between the experimental data and the assumption that the B_p transport is of a classical nature, we calculated the emf ($\mathscr{E}_{\rm TR}$) developed by the transformer for the calculated distributions $B_p(r,t)$ and $j(r,t)$ and compared the results with the corresponding experimental values. The data found on $j(r,t)$ were used to solve the local heat-balance equation. From the solution we determined the effective electron thermal conductivity $\varkappa_{\rm eff}(r) = W_{tr}(r)/4\pi^2 Rr \nabla T_e$, where W_{tr} is the total heat flux carried by electrons across the lateral surface of a cylinder of radius r and length $2\pi R$ by the diffusion of heat and particles, and ∇T_e is the local temperature gradient.

This procedure was used to analyze the experimental results on the plasma compression twice each 0.5 ms (Ref. 2). In this experiment we obtained the most-comprehensive experimental data. Furthermore, the compression in this case yielded the most favorable results: an approximately adiabatic increase in $T_e(0)$ and $n_e(0)$, a slow decay of these properties in the postcompression stage, and an effective suppression of the oscillations by magnetic probes. The small value of $Z_{\rm eff}$ for the ohmic heating stage,

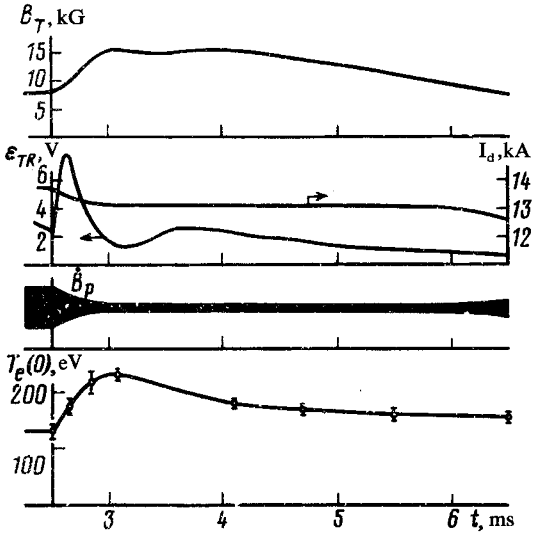

FIG. 1.

$Z_{eff} = 1.3$, is inconsistent with the suggestion that there is a significant anomalous behavior in σ. Furthermore, at such a low value of Z_{eff} we can essentially rule out any error in the determination of $j(r)$ due to a possible inhomogeneity of $Z_{eff}(r)$ distribution [in the calculations we assumed $Z_{eff}(r) = \text{const}$].

Figure 1 shows the time evolution of some of the discharge properties. The points on the $T_e\,(0,t)$ curve correspond to the times at which the complete profiles $T_e(r)$ were measured. The error in the $T_e(0)$ measurements is indicated. Comparison of the calculated and experimental values of $\mathcal{E}_{TR}$ confirms the suggestion that the B_p transport is classical.

Figure 2 shows calculated radial profiles $W_{tr}(r)$, $\varkappa_{eff}(r)$, and $q(r)$ (the safety factor) (curves 1, 2, 3, respectively) at three times: a) $t = 2.5$ ms; b) $t = 3.1$ ms; c) $t = 6.5$ ms. During the ohmic heating stage the $\varkappa_{eff}(r)$ profile has a maximum at the middle of the minor radius (Fig. 2a). Our calculations show that resonant magnetic surfaces with $q = 2$ and $q = 3$ fall in this region. This maximum may be due to the existence of magnetic islands. The compression erases the maximum (Fig. 2b). The flat radial profile of $\varkappa_{eff}$ and its magnitude in the postcompression stage of the discharge (as during the ohmic heating stage away from the maximum) correspond to ALCATOR scaling: $\varkappa \simeq 5 \times 10^{17}\ \text{cm}^{-1} \cdot \text{s}^{-1} \simeq \text{const}$ (see Ref. 4, for example).

During the magnetic decompression, however, while B_T is falling, a zone with extremely low values $\varkappa_{eff} < 2 \times 10^{17}\ \text{cm}^{-1} \cdot \text{s}^{-1}$ arises in the central part of the plasma column (Fig. 2c). The experimental manifestation of this effect is that the high value of T_e at the center of the plasma remains nearly constant throughout the decompression. Even when B_T is restored to its precompression level, $T_e(0)$ remains significantly higher than its original value. The contribution of the energy to the central zone in this stage of the discharge, on the other hand, decreases significantly because of the expansion of the current channel, the decrease in $j(0)$, and the magnetic adiabatic cooling.

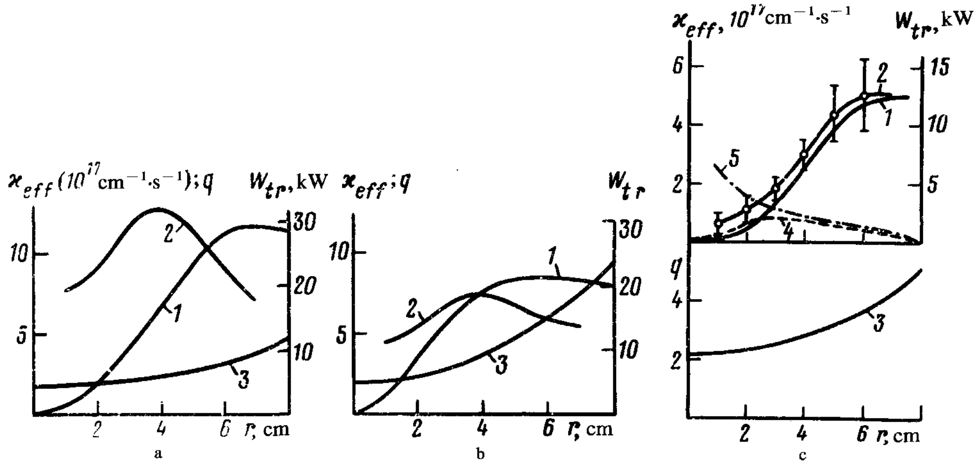

FIG. 2.

In order to discuss such small values of $\varkappa_{\rm eff}$ we need to know the error in the determination of $\Delta\varkappa_{\rm eff}$. This error depends on several factors, which play different roles in different stages of the discharge. For the period before the beginning of decompression, we have $\Delta\varkappa_{\rm eff} \simeq (1\text{–}2)\times 10^{17}$ cm^{-1}·s^{-1}, and at the end of the discharge $\Delta\varkappa_{\rm eff}$ is lower (Fig. 2c).

Let us compare these low values of the thermal conductivity with the predictions of the neoclassical theory.[5] According to Ref. 5, the specific heat flux in the electron component for the plateau regime consists of the three components

$$\Gamma^{neo} = \Gamma_c^{neo} + \Gamma_p^{neo} + \Gamma_I^{neo} = -3D_e n \nabla T_e - 3D_e n \times$$

$$\times [T_e(\nabla n/n + 1{,}5\nabla T_e/T_e) + T_i(\nabla n/n + 1{,}5\nabla T_i/T_i)] - 4{,}37 D_e j B_p/c,$$

where $D_e = 1.8\times 10^{26}\, qT_e^{3/2}/RB_T^2$ (cgs units, with $T_{e,i}$ in energy units). The first two terms here are respectively the conduction heat flux and the heat flux due to the diffusion of particles (including thermodiffusion). The third term is the heat flux carried by the particles moving toward the center of the plasma column due to the current flow in the plasma. Estimates of these three components for the conditions in Fig. 2c and for $0<r<3$ cm show that $|\Gamma_I^{\rm neo}|$ exceeds the sum of the two other components: $\Gamma^{\rm neo}:\Gamma_c^{\rm neo}:\Gamma_p^{\rm neo}:\Gamma_I^{\rm neo}:\simeq 1:3.5:(-5)$. Since the total heat flux is smaller in magnitude than its components, the accuracy of the approximation used in Ref. 5 is important: If this accuracy is not good enough, both the value of $\Gamma^{\rm neo}$ and its sign will be incorrect.

It appears important, however, that the experimental heat fluxes for the case under consideration here are comparable in magnitude to the individual components of the neoclassical heat flux. That this is true can be seen in Fig. 2c, which shows the neoclassical analogs of W_{tr} and $\varkappa_{\rm eff}$: $W_{tr}^{\rm neo} = 4\pi^2 Rr(\Gamma_c^{\rm neo} + \Gamma_p^{\rm neo})$ (curve 4) and $\varkappa_{\rm eff}^{\rm neo} = W_{tr}^{\rm neo}/\nabla T_e$ (curve 5).

In an attempt to find the reason for the appearance of such a low electron thermal conductivity in this tokamak, we compare the values of $\varkappa_{\rm eff}(r)$ and $q(r)$ in Fig. 2. We see that in the region with low values of $\varkappa_{\rm eff}$ there are no integer resonances. Where such resonances do exist, $\varkappa_{\rm eff}$ has a typical tokamak value, $\varkappa_{\rm eff} \gtrsim 5\times10^{17}$ cm$^{-1}\cdot$s^{-1}. A similar linkage between $\varkappa_{\rm eff}$ and the presence of resonant surfaces was observed in the T-10 tokamak.[6] It may be that the existence of integer resonant surfaces in the plasma causes an anomalous electron transport. If, on the other hand, broad zones without such resonant surfaces form in a tokamak, the transport loss will approach the neoclassical level in these zones.

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