Electron heat balance in ohmic H-mode with Internal Transport Barrier in TUMAN-3M

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An Internal Transport Barrier has been found in the ohmically heated H-mode plasma in the TUMAN-3M [1]. The ITB was observed on the electron temperature and density profiles. As a result of the transport suppression the plasma density increased dramatically. The increase in the density was accompanied by some decrease in the central electron temperature $T_e(0)$ and saturation of the energy content W. The transport analysis has been performed in order to study the evolution of the electron heat balance through the ITB formation and to clarify the reason for $T_e(0)$ reduction in the conditions of increasing density. The results of the transport simulations are presented in this paper.

Experimental observation of the T_e decay during the density increase

Typical plasma parameters in the shot with ITB were as follows: $R_0=0.53$ m, $a_l=0.23$ m, $B_t=0.7$ T, $I_p=150$ kA, $T_e(0)=450$ eV, $T_i(0)=180$ eV, $\bar{n}=(1.5 \div 5) \cdot 10^{19}$ m^{-3}. The evolution of the electron temperature profile $T_e(r)$ was measured with Thomson scattering and SXR techniques, the density profile n(r) was measured by multichannel microwave interferometer. The TS measured T_e profiles in the ohmic H-mode with ITB are shown in fig.1. The steep gradient zone is seen nearby r=14 cm (0.65a) on the profiles taken on 68 ms and 77 ms, when averaged density was $3.4 \cdot 10^{19}$ m^{-3} and $4.4 \cdot 10^{19}$ m^{-3}, correspondingly. This steep gradient is considered as indication of ITB formation. The feature of the profiles is the pronounced decrease in $T_e(0)$ from 460 eV on 68 ms to 370 eV on 77 ms. The decrease is in agreement with SXR behavior. Figure 2 shows evolution of the SXR emission measured along the chords inwardly shifted for 3 cm (SXR#4) and 9 cm (SXR#6) during the density ramp. The line of sight of SXR#4 detector is close to the magnetic axis. It is seen that SXR#4 intensity decreases while density increases from 68 to 80 ms, see top window in fig.2. Taking into account n^2 factor in SXR intensity one can conclude some decrease in $T_e(0)$.

Electron heat balance evolution

Electron heat balance was analyzed using transport code ASTRA [2]. In order to derive source term in the 1-D heat balance equation the poloidal magnetic field diffusion equation was solved using neoclassical resistivity and experimental $T_e(r)$ profiles. Measured loop voltage was used to check the calculated j(r) evolution. The heat balance equation was solved taking into account ohmic power input P_{oh}, electron-ion energy exchange P_{ei} and radiation losses P_{rad}, which were estimated to be less than 10% of P_{oh}. In the simulations $T_i(r,t)$ was assumed to be $T_i(0,t) \times (n_e(r)/n_e(0))$ with $T_i(0,t)$ measured by neutral particle analyzer.
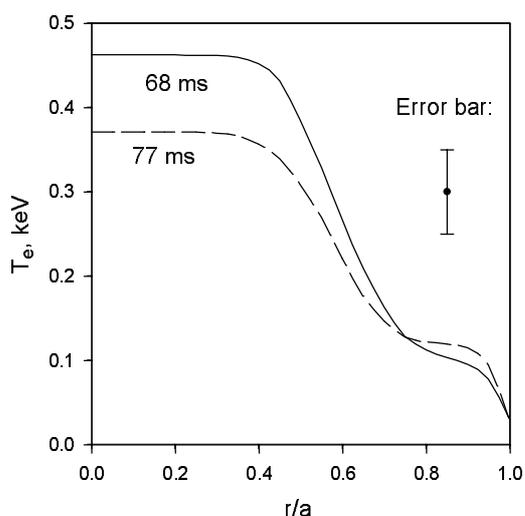
Fig.1 TS electron temperature profiles measured on 68 and 77 ms in the ohmic H-mode with ITB.
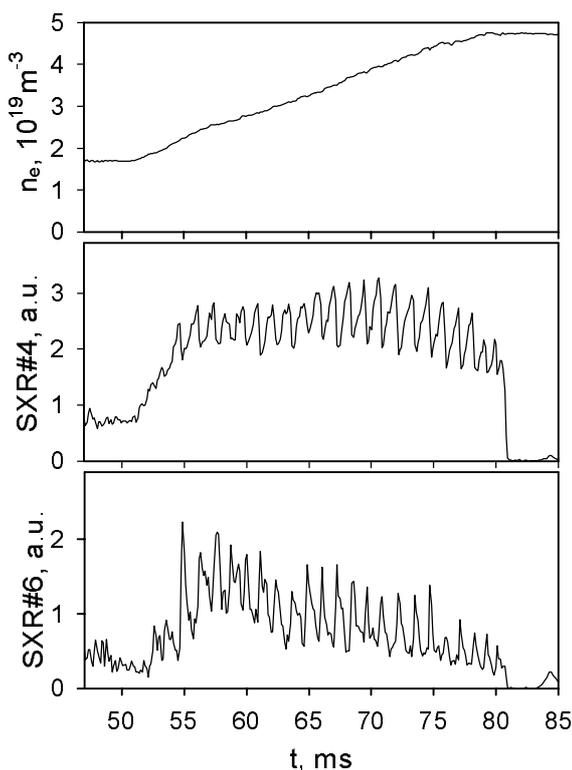

Fig.2 Density behavior and evolution of the SXR emission along the inwardly shifted chords SXR#4 - shift 3 cm, SXR#6 - shift 9 cm.

The analysis has shown the formation of two regions of reduced transport in the early stage of the shot [1]. Figure 3 presents the radial distribution of the effective thermal diffusivity coefficient on 68 and 77 ms. Also $\chi_e^{eff}(r)$ in ordinary ohmic regime is given for comparison in fig.3. The first region of reduced transport was found to be near the edge, r>0.9 a. It corresponds to the transport barrier which is characteristic for the standard H-mode. The other region of reduced transport was in the plasma core and appeared as a consequence of the ITB formation. The core and edge transport barriers are separated by a zone with enhanced electron transport. The simulations allowed to conclude that the electron thermal diffusivity decreases by a factor of 10 within the ITB region. In spite of significant decrease during the ITB formation the χ_e^{ITB} exceeds the neoclassical coefficient χ_e^{neo} [3] by an order of magnitude. Temporal evolution of the $\chi_e^{eff}(0.65a)$ is shown in fig.4. Also in this figure the $\chi_e^{neo}(0.65a)$ is presented.

During the ELM-free period following the transition into the ohmic H-mode with the ITB the electron density increases from $1.7 \cdot 10^{19}$ to $(4\text{-}5) \cdot 10^{19}$ m^{-3}. At high density the electron-ion equipartition time decreases substantially. As a result the energy transfer from electrons to ions becomes essential part of the electron heat losses. The simulated temporal evolution of the input power P_{oh} and of the power transfer from electrons to ions P_{ei} is presented in fig.5. At high density P_{ei} is close to P_{oh} resulting in the reduction of the net power input into electron component. In these conditions the effective cooling of the electrons was found while χ_e^{eff} does not change much, see figs.3&4. The results of the transport simulations allow to explain the observed decay in $T_e(0)$, figs.1&2.

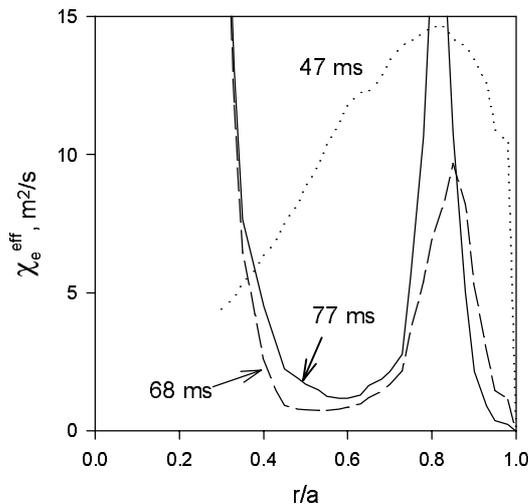*Fig.3 Effective electron thermal diffusivity calculated on 68 and 77 ms in the ohmic H-mode with ITB. χ_e^{eff} in ordinary ohmic regime is given for comparison - 47 ms.*
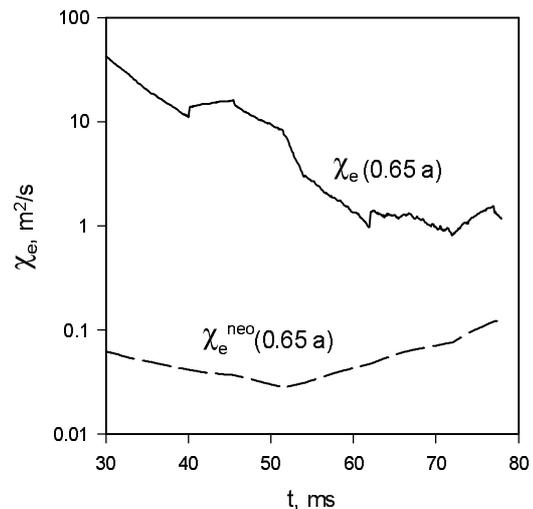
Fig.4 Evolution of the electron thermal diffusivity χ_e^{eff} at r=0.65a in the ohmic H-mode with ITB.

Ion energy balance evolution

As it is shown above at high density the essential part of the input power is lost through the ion component. Nevertheless, no significant increase in the $T_i(0)$ was observed during the density ramp stage. Unfortunately ion temperature profile $T_i(r)$ was not measured in this experiment. Therefore it is difficult to estimate the degree of anomaly in the ion energy losses. In order to get the desired estimation we have compared the experimental ion energy confinement time τ_{Ei}^{exp} with the neoclassical expression τ_{Ei}^{neo} obtained in [4]. τ_{Ei}^{exp} was calculated using collisional energy transfer term P_{ei} and the following assumption for ion energy content $W_i = 3/2\int T_i^{exp}(0)\cdot(n^2(r)/n(0))\cdot dV$. Note that a charge exchange losses were not included into the consideration. Therefore τ_{Ei}^{exp} underestimates the characteristic time of the ion thermal diffusivity. In fig.6 the temporal evolution of the τ_{Ei}^{exp} and τ_{Ei}^{neo} is shown.

The figure allows to make two conclusions on the ion transport. First, there is no improvement in the ion thermal diffusivity after transition into the ohmic H-mode with ITB. Moreover the ion energy confinement substantially drops during the density ramp stage (from 6-8 ms to 2-3 ms). Second, the temporal behavior of the τ_{Ei}^{exp} is similar to that of τ_{Ei}^{neo}: significant drop with increasing density. Obviously, the subtraction of charge exchange losses may reduce discrepancy in absolute values of τ_{Ei}^{exp} and τ_{Ei}^{neo}. This means that the ion energy confinement time in the considered high density regime is restricted by the neoclassical thermal diffusivity.

Conclusions

Formation of Internal Transport Barrier in the ohmic H-mode in TUMAN-3M results in the significant reduction of electron thermal diffusivity at r=0.65a (factor of 10). In the conditions of increasing density the collisional transfer increases to the level close to the ohmic power input resulting in noticeable decrease in $T_e(0)$.
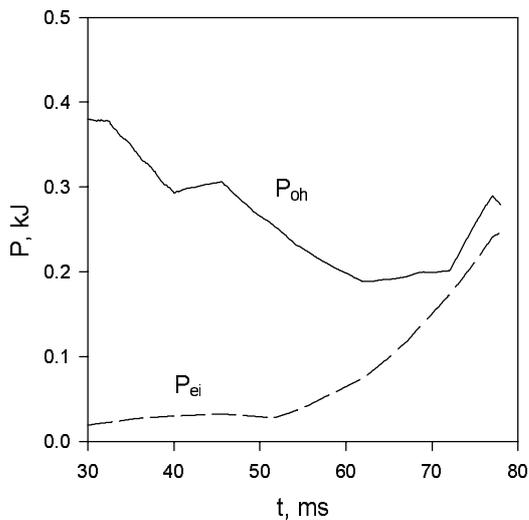
Fig.5 Temporal evolution of the ohmic input power P_{oh} and energy transfer from electrons to ions P_{ei} in the ohmic H-mode with ITB.
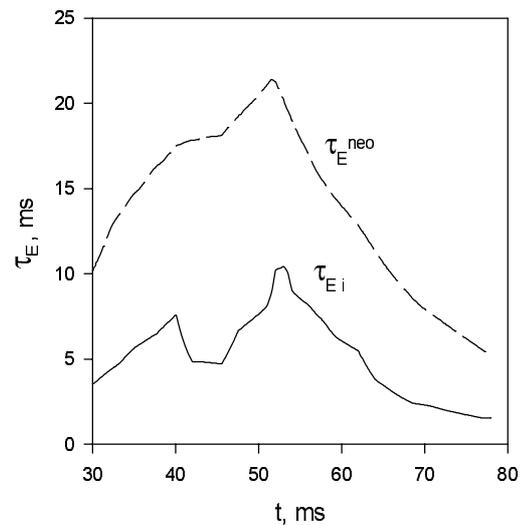
Fig.6 Comparison of the experimental ion energy confinement time τ_{Ei}^{exp} and neoclassical estimation τ_{Ei}^{neo} [4].

The ion energy thermal diffusivity is close to the neoclassical one in the both ordinary ohmic and ohmic H-mode regimes. This results in absence of improvement in the ion energy confinement after transition into the ohmic H-mode.

The saturation of the global energy confinement in the ohmic H-mode with ITB at high density is explained by neoclassical ion energy losses.

Acknowledgments

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