Tokamak Discharges with Electron Thermal Conductivity Near the Neoclassical One

V.M. Leonov

National Research Centre “Kurchatov Institute”, Kurchatov sq.1, Moscow, Russia.

E-mail contact of main author: leo@nfi.kiae.ru

Abstract. Results of predictive modeling of transport processes for several representative tokamak discharges with the Ohmic heating at high plasma density are presented. The main purpose was to verify the predictions of the neoclassical theory on the electron heat transport in these discharges, where the collisional transport is expected to be dominant and the transport anomality is minimal. This study shows that profiles of electron and ion temperatures measured in the considered experiments can be reasonably well reproduced in the frame of the neoclassical transport theory using the complete matrix of the neoclassical coefficients without an additional anomality of electron thermal conductivity. Therefore, the neoclassical coefficients of electron heat transport in tokamaks (not “pseudo-classical”) can be considered as minimal coefficients.

1. Introduction

At the development of plasma transport models it is very important to have the asymptotic transitions to the cases when transport coefficients are well described by some first principle based theory. For the ion component of tokamak plasma it is a transition to the results of the neoclassical theory (in Ohmically heated high density plasma). Another stable opinion was formed in characterizing the electron transport, as being principally anomalous. Conclusions of L. A. Artsimovitch [1], who analyzed the first tokamak experiments, are contributed to this. He called the electron thermal conductivity of the minimal level as “pseudo-classical” due to “classical” behavior of its parametric dependences despite of several times higher amplitude. This opinion was supported later by B. B. Kadomtsev [2] and by some other authors. Further experiments with the auxiliary plasma heating consolidated this opinion because they demonstrated that level of electron transport considerably exceeds the neoclassical predictions. However, first conclusions have been done as a result of simplified consideration of transport processes using diagonal terms of the transport matrix only. In addition, significant radiation of high-Z impurities from the plasma core typical for the first tokamak experiments and convective power losses were not accounted properly in transport analysis.

Analysis of the neoclassical formulas shows that non-diagonal terms of the neoclassical transport matrix is of the same order as the diagonal terms. So, it was interesting to analyze tokamak experiments with the Ohmic heating again using the complete neoclassical matrix to verify if electron thermal conductivity always exceeds significantly the neoclassical level. High density discharges where collisional transport is expected to be dominant and transport anomality to be minimal are most appropriate for this.

In this report transport processes for several representative tokamak discharges with the Ohmic heating at high plasma density are simulated in the predictive mode of the ASTRA transport code [3] using the complete matrix of the neoclassical transport coefficients. Results of simulations demonstrated that, taking into account the off-diagonal terms of the neoclassical transport coefficient matrix makes possible to reproduce the radial profiles of ion and electron temperatures in considered discharges in the frame of the neoclassical transport theory without suggestion on anomality of electron thermal conductivity.

2. The model

"Steady-state" transport simulations have been carried out using ASTRA transport code [3]. Transport equations for electron and ion components have been written as follows:

$$\frac{3}{2}\frac{\partial}{\partial t}(n_e T_e) + div(q_e + \frac{5}{2}\Gamma_e T_e) = P_{OH} - P_{ei} + P_{ei\Gamma} + P_{ei\mu} - P_{rad} \quad (1)$$

$$\frac{3}{2}\frac{\partial}{\partial t}(n_i T_i) + div(q_i + \frac{5}{2}\Gamma_i T_i) = P_{ei} - P_{ei\Gamma} - P_{ei\mu} - P_{cx} \quad (2)$$

where Γ_e and Γ_i are the fluxes of electron and ion plasma component, P_{OH} is the Ohmic heating power; P_{ei}, $P_{ei\Gamma} = \frac{\Gamma_e}{n_e}\frac{\partial p_i}{\partial r}$ and $P_{ei\mu} = \mu_i T_i A_{1i}$ is the heat exchange terms between electron and ion components due to electron-ion collisions, diffusion and viscosity; P_{rad} is the radiation power losses and P_{cx} is the losses of ion energy due to charge-exchange. For simulation of equilibrium we used 2D equilibrium equation of ASTRA in 3-momentum approximation with the fixed boundary.

Following consideration of [4], neoclassical electron heat fluxes were taken in the form:

$$q_e + \frac{5}{2}\Gamma_e T_e = -K_{an} n_e T_e (\varepsilon^{1/2} \rho_{e\Theta}^2 / \tau_e)\{K_{12}(1 + \frac{T_i}{Z_i T_e})\frac{n_e'}{n_e} + (K_{22} - \tfrac{3}{2}K_{12})\frac{T_e'}{T_e} + (1 - K_o)K_{12}\frac{T_i}{Z_i T_e}\frac{T_i'}{T_i}\} - $$

$$- n_e T_e K_{23} \varepsilon^{1/2} \frac{cE_{II}}{B_p} \quad (3)$$

where K_{an} is the neoclassical thermal conductivity enhancement factor (K_{an} =1 corresponds to the case with pure neoclassical electron thermal conductivity) , coefficients K_{mn} are defined in [4]. The neoclassical ion thermal conductivity coefficient taking account of finite aspect-ratio and effects of impurities [5] has been used in simulations of ion heat fluxes. Boundary temperatures were taken from the experiments under consideration.

We used experimental radial profiles of plasma density because the modeling of the particle balance required special consideration. Plasma fuelling by deuterium neutrals from the boundary was simulated using the kinetic equation in the slab approximation. Flux of the cold neutrals to the plasma boundary was fitted to produce power losses from the ion component near the plasma boundary with the charge-exchange and convection to be the main energy losses there. It has been suggested that the particle fluxes through some magnetic surface are equal to the ionization source inside this surface, calculated using density of neutrals.

Modelling of impurity behaviour was performed by the ZIMPUR code [6] simulating the dynamics of the charge states, transport and radiation of impurities. Neoclassical impurity fluxes were simulated using NCLASS code [7]. The impurity source was defined as the impurity neutral flux on the plasma boundary. The value of this source was fitted to provide the necessary impurity contamination in plasma or Z_{eff} value or radiation power, which were known from the experiments under consideration. To reproduce experimental profiles of $Z_{eff}(\rho)$ and $P_{rad}(\rho)$ some small anomalous pinch of impurities $V_p = -(0.1 - 0.2)\cdot(\rho/\rho_{max})^{1.5}$ (m/s) have been added.

3. Result of simulation of tokamak discharges.

As an example some tokamaks discharges with Ohmically heated plasma of high density are under consideration. In these discharges collisional transport is expected to be dominant and transport anomality is minimal. Discharges of IOC (Improve Ohmic Confinement) type can be considered here. In this discharges improved confinement relative to standard discharges with the saturated confinement are observed [8]. They were obtained by some reduction of gas flux to the plasma boundary or in high density discharges following the pellet injection. For example, radial profiles of electron (T_e) and ion (T_i) temperatures for IOC scenario of ASDEX tokamak [8] are presented in FIG.1.

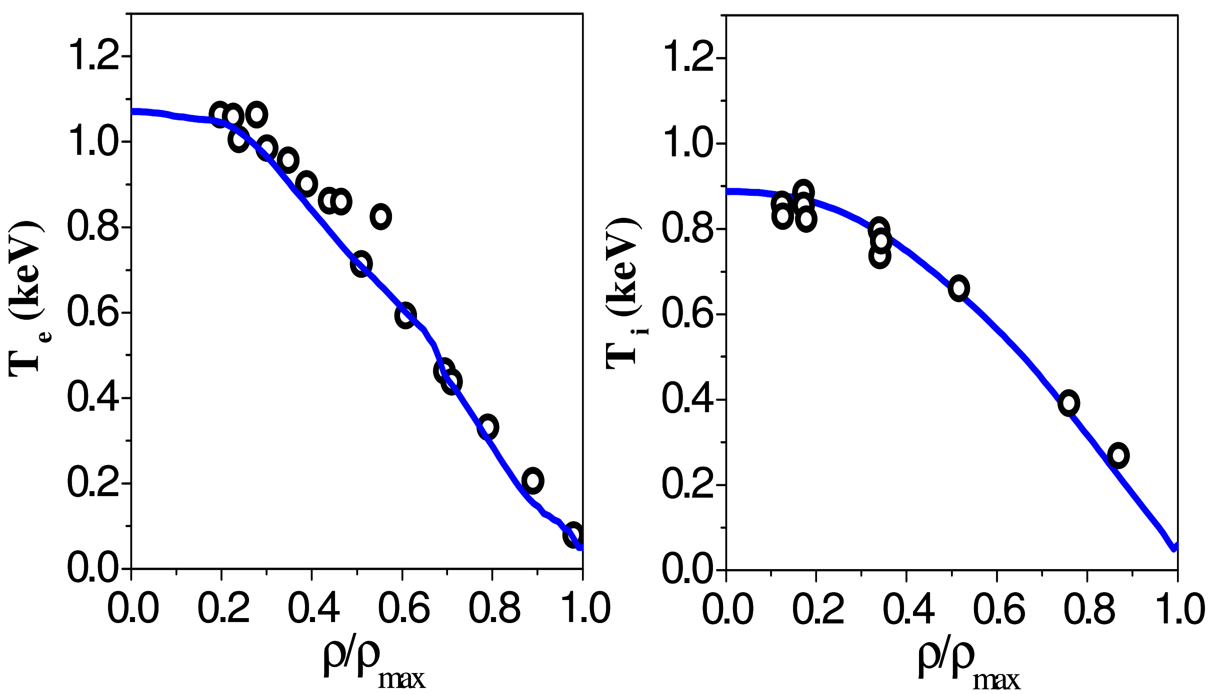

FIG. 1. Comparison of experimental [8] and simulated radial profiles of electron and ion temperatures for ASDEX discharge.

The main parameters of this scenario are the toroidal magnetic field $B_o = 2.17$ T, plasma current $I_p = 0.38$ MA and average electron plasma density $\langle n_e \rangle \sim 5\cdot10^{19}$ m^{-3}. Simulated profiles are shown by blue lines and experimental points are shown also. One can see the fairly good agreement between simulation results (using neoclassical transport with the enhancement factor K_{an} = 1) and experimental points for both electron and ion temperatures.

One of the main difficulties of the analysis of high density discharges is caused by the strong collisional coupling of ion and electron components and close values of their temperatures. Therefore, it is often difficult to distinguish which component is responsible for changes in plasma transport. However, in this discharge good agreement is found for both electron and ion temperatures. Attempts to increase the electron heat conductivity higher than the neoclassical level staying inside the experimental errors interval required reduction of the ion heat diffusivity below the neoclassical one, because in the other case both temperatures in the central plasma regions will be smaller their experimental values. So, we can conclude that in this case heat transport can be described in the frame of the neoclassical theory ($K_{an} \approx 1$) not only for the ion component but for the electron component also.

FIG.2. demonstrates comparison of experimental and simulated radial profiles of electron and ion temperatures for TEXTOR discharge of IOC type [9]. Main tokamak and discharge

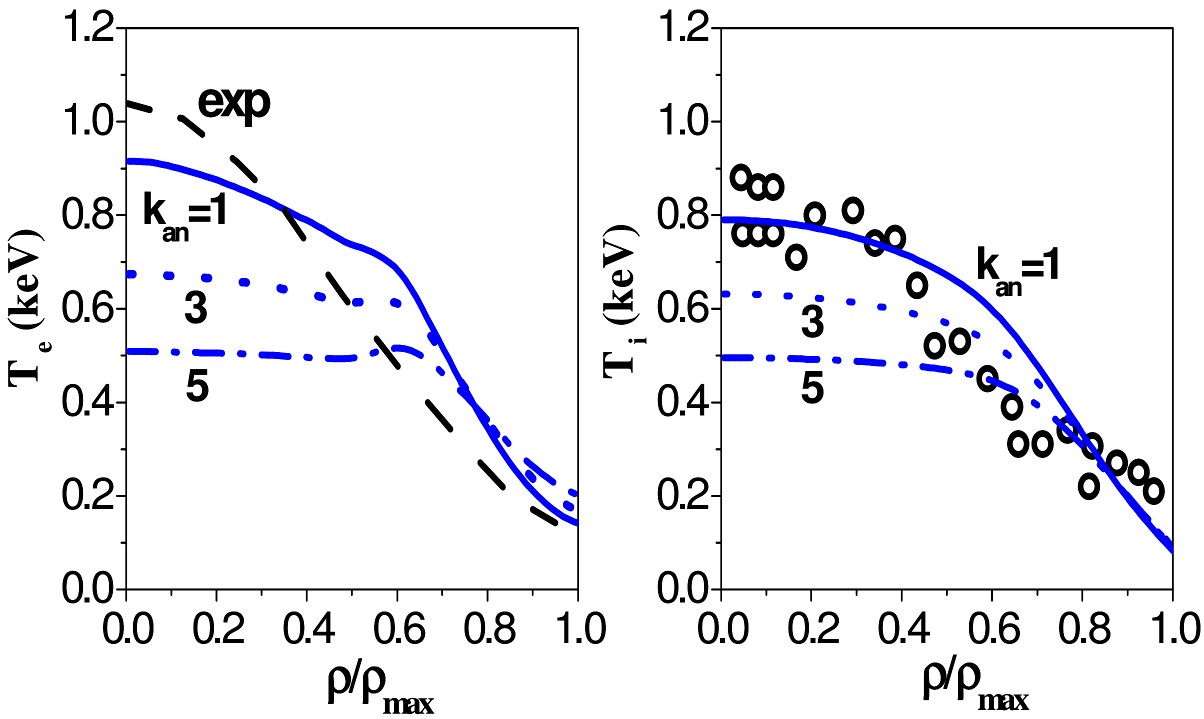

FIG. 2. Comparison of experimental [9] and simulated radial profiles of electron and ion temperatures for TEXTOR discharge.

parameters are very similar to the previous case. Experimental profile of electron temperature is shown in figure by black dashed line. Blue lines present results of simulation using different values of K_{an} anomality coefficient. One can see that reasonable agreement within a factor of about 2 in K_{an} is registered between simulation results and the experimental data. Big discrepancy of central values of $T_e(0)$ and $T_i(0)$ with the experimental data are following the increase of electron heat anomality coefficient K_{an} higher than 3. When $K_{an} = 5$, values of $T_e(0)$ and $T_i(0)$ are about a factor of two smaller than the experimental points. The main contribution of thermal conductivity would be most appreciable in the confinement region of plasma column $0.3 \leq \rho_N \leq 0.7$ (where $\rho_N = \rho / \rho_{max}$), because sawteeth sometimes occur for $\rho_N \leq 0.3$ and convection and elementary processes typically have large influence at $\rho_N > 0.7$. For example, in FIG. 2 at $K_{an} = 1$ only about 26% of power from the electron component is lost through the electron thermal conductivity at $\rho_N \sim 0.7$. At $\rho_N \leq 0.6$ this value increases to

50% and more. That is why the main change in temperatures is registered in central regions of plasma column ($\rho_N \le 0.6$). Increase of K_{an} results in increase of this contribution. Attempts to compensate difference between central calculated and experimental temperatures at K_{an} higher than 3 required reduction of the ion thermal conductivity to the level much lower than the neoclassical value (5-10 times).

Experimental and simulated radial profiles of electron temperature for TFTR discharge after injection of 5 deuterium pellets [10] are shown in FIG. 3. For this discharge Bo = 4.9 T,

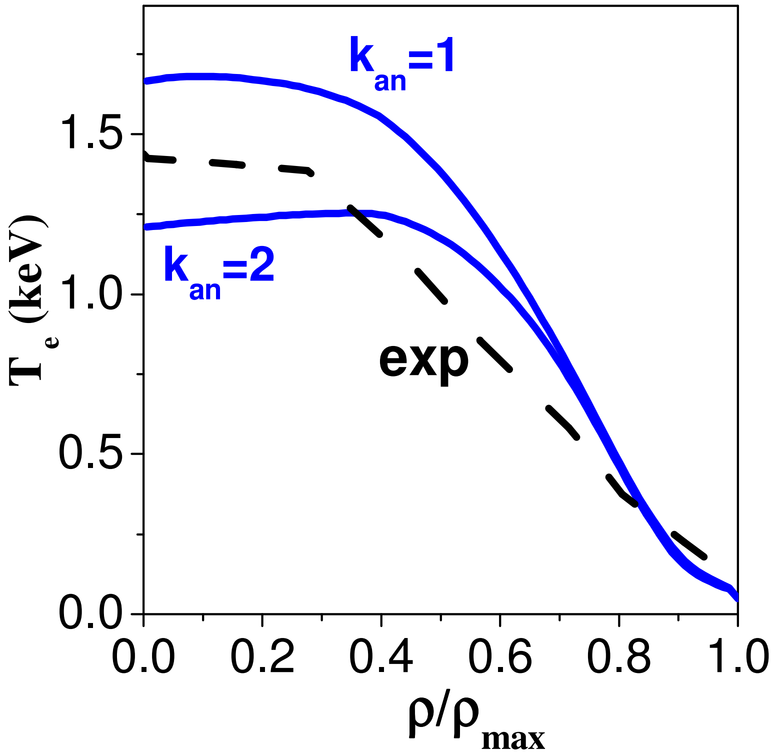

FIG. 3. Comparison of experimental [10] and simulated radial profiles of electron temperature for TFTR discharge after injection of 5 deuterium pellets.

Ip = 1.6 MA, R / a = 2.4 m / 0.71 m and high enough average plasma density <ne>~$1.5{\cdot}10^{20}$ m^{-3}. In this case satisfactory agreement with experimental results is found to be at K_{an} between 1 and 2. Increase of K_{an} more than 3 causes, as in previous cases, strong difference between results of simulations and experiment in the central plasma column regions. In these regions thermal conductivity plays an appreciable role and its change can be registered.

Comparison of experimental and simulated radial profiles of electron temperature for Alcator-C discharge after deuterium pellet injection [11] is shown in FIG.4. Alcator-C tokamak is characterized with high toroidal magnetic field and high plasma density which achieve in this case B_o = 8.1 T and $\langle n_e \rangle \sim 2.9{\cdot}10^{20}$ m^{-3}. At so high magnetic field, the value of hyroradius in this tokamak is smallest comparing with other tokamaks. As in previous cases reasonable agreement is found between the experimental results and predictions of the neoclassical theory at K_{an} = 1. In this discharge about 40% of the Ohmic power is lost through the electron channel. In the plasma core about 50-90% of power is lost from the electron component with

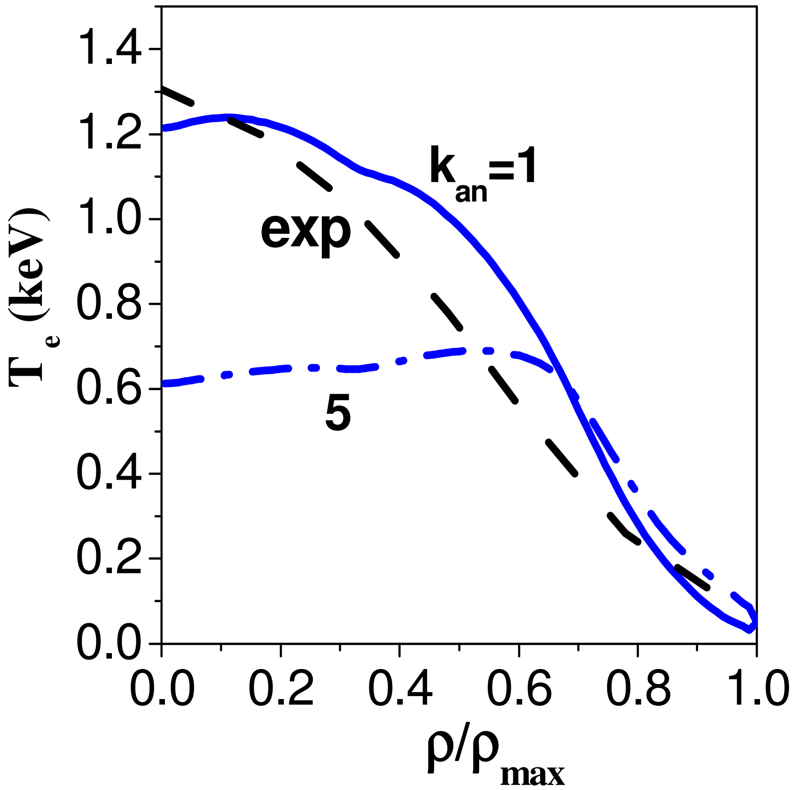

FIG.4. Comparison of experimental [11] and simulated radial profiles of electron temperature for Alcator-C discharge after pellet injection.

the electron thermal conductivity. That is why these losses are detectable and rise of anomality coefficient K_{an} higher than 3 results in appreciable difference of central electron temperature from the experimental one. In this case we also can conclude that temperature profiles could be modeled in reasonable agreement with the experiment using the neoclassical transport.

4. Summary

Results of predictive modeling of transport processes for several representative tokamak discharges with the Ohmic heating at high plasma density are presented. The main purpose was to verify predictions of the neoclassical theory relative to the electron heat conductivity for these discharges, where collisional transport is expected to be dominant and transport anomality is minimal.

This study shows that profiles of electron and ion temperatures measured in the considered experiments can be reasonably well simulated in the frame of the neoclassical transport theory using complete matrix of the neoclassical coefficients without suggestion on anomality of electron thermal conductivity (K_{an} ~ 1-2).

Therefore the neoclassical coefficients of electron heat transport in tokamaks (not "pseudo-classical") can be considered as minimal coefficients.

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