Application of modified Canonical Profiles Transport Model (CPTM) to DIII-D and MAST pulses simulation

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The tendency of tokamak plasma temperature and pressure profiles to conservation under different external influences has been discussed since early eighties [1, 2]. This effect is often considered as plasma *self-organization* and the relative profiles are called as *stiff*. In the late eighties the quantitative measure of the profiles stiffness appeared as a factor standing in front of the difference in temperature (or pressure) gradient and the *critical gradient* in the expressions for heat and particle fluxes in Canonical Profiles Transport Models [3]. Experiments devoted to the ion temperature profile stiffness evaluation in JET have revealed new features, consisting in stiffness variation with radius and its dependence on toroidal rotation velocity [4]. These observations provided challenge for CPTM modification.

In the framework of CPTM model the heat flux in the electron ($k = e$) or ion ($k = i$) channel is presented in the form [5]

$$q_k = -\kappa_k^{PC}\, T_k(T_k'/T_k - T_c'/T_c)\, H(-\,(T_k'/T_k - T_c'/T_c)) - \kappa_k^0\, T_k' + {}^3/_2\, T_k\Gamma_n.$$

Here T_k is electron or ion temperature, $T' = \partial T/\partial\rho$, ρ is normalized magnetic radius, T_c is the canonical temperature profile, κ_k^{PC} is the stiffness of the temperature profile, *PC* index means "Profile Consistency", $H(x)$ is the Heaviside function, $H(x) = 1$ for $x > 0$, $H(x) = 0$ for $x < 0$. The value κ_k^0 is the coefficient of thermal conductivity, determined by processes not related to the effect of profile consistency (for example, neoclassical effects, averaged description of MHD mixing in sawtooth oscillations). The last term describes the convective heat flux, proportional to the particle flux Γ_n. For κ_k^{PC} the following expression is used:

$$\kappa_k^{PC} = \alpha_k^{mod}/M\,(1/A)^{3/4}\, q(\rho{=}1/2)\, q_{cyl}\, T_k^{1/2}(\rho{=}1/4)\,\bar{n}/B\,(3/R_0)^{1/4}.$$

The following "practical" units are used here: κ_k^{PC} is in 10^{19} m^{-1}s^{-1}, M is the relative ion mass, q is the safety factor, $A = R_0/a$ is the aspect ratio, T_k is in keV, $\bar{n}$ is the chord-averaged plasma density in 10^{19} m^{-3}, B is the toroidal magnetic field in Teslas, R_0 is the major plasma radius in m, $q_{cyl} = 5a^2B/R_0I$, a is minor plasma radius in m and I is the plasma current in MA.

The factor α_i^{mod} is now taken in the form

$$\alpha_i^{mod} = \alpha_i\, S(\rho)\, G(v_{tor})$$

with $\alpha_i = 5$ and two additional factors describing the ion profile stiffness dependency on radius and toroidal rotation velocity at $\rho = 0.5$. The model modification just consists in the addition of these two factors, while in the standard model version $S = G = 1$. For the electron heat flux the model standard version is always used: $\alpha_e^{mod} = \alpha_e = 3.5$.

Recently new efforts to determine the ion temperature profile stiffness have been performed in DIII-D [6]. Presented experimental data allow one to evaluate the ion incremental thermal conductivities

$$k_i^{j\ \mathrm{inc}} = -dq_i^j / d(\mathrm{grad}\ T_i^j); \qquad (j = 1, 2, 3, 4)$$

in shots with high and low toroidal rotation velocity at four radial points: $\rho = 0.4$, 0.5, 0.6 and 0.7 (Fig. 1). The high and low rotation velocities at mid-radius are $v_{tor} \sim 1.2$ - 1.6 and $v_{tor} \sim$ 0.6 - 0.8 $\times 10^5$ m/s, respectively. According to these experimental data the coefficients S and G may be presented in the form

$$S(\rho) = \min[S_{max}, \exp(7\rho - 4.9)]; \qquad G = (0.7 / v_{tor})^{1.6}.$$

The $S(\rho)$ graph in comparison with incremental thermal conductivities normalized at the point $\rho = 0.7$ for both high and low rotation data sets is presented in Fig. 2.

The temperature profiles were calculated with the code ASTRA. The RMS deviations of calculated ion temperature profiles from the experimental ones were minimized in the runs by

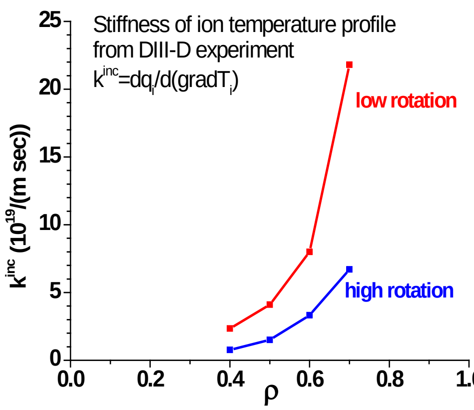

Fig. 1. Incremental heat conductivity coefficients in the cases of low and high toroidal plasma rotation velocity in DIII-D.

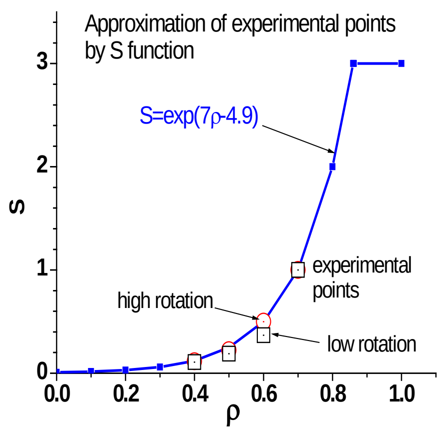

Fig. 2. Function $S(\rho)$, approximating the experimental stiffness values for low and high rotation normalized at radial position $\rho = 0.7$.

means of the boundary value $T_i(a)$ and the parameter κ_i^0 variations. The deviations were integrated inside the interval $0 < \rho < 0.8$. The modeling results with $S_{max} = 3$ for the pulse #145455, presented in Fig. 3, confirm that the model modification allows one to obtain much better results in comparison with the standard version. Figure 4 presents the normalized ion temperature R_0/L_{Ti} and canonical temperature R_0/L_{Tc} gradient profiles for the same pulse ($L_T = (T' / T)^{-1}$). Following the $S(\rho)$ decrease the ion temperature gradient increases in the core region $\rho < 0.8$. However, the maximal R_0/L_{Ti} values do not exceed 8, while the values $R_0/L_{Ti} \sim$ 15 – 20 are typical for ITBs. That's why the decrease of ion temperature profile stiffness in the core region in DIII-D cannot be attributed to ITB.

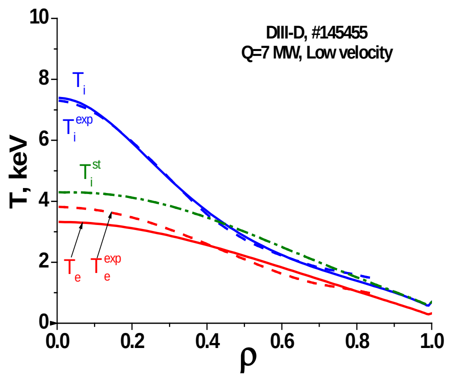

Fig. 3. Simulated (solid lines) and experimental (dashed lines) electron and ion temperature profiles. The ion temperature simulated by standard CPTM is plotted with dash-dot line.

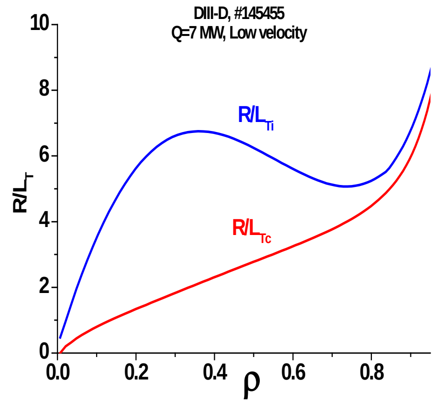

Fig. 4. Simulated ion R_0/L_{Ti} and canonical temperature R_0/L_{Tc} normalized gradient profiles.

The ion temperature profile stiffness coefficients obtained on DIII-D were verified using MAST data. One of the common features of NBI heated MAST discharges is a rather high ion temperature gradient in the gradient zone with the effective ion heat diffusivity in the range of 1-3 m^2/s. Let us consider the pulse #28053 as an example. As can be observed in Fig. 5, the ion temperature exceeds the electron one after 220 ms, although the beam power deposited to ions remains lower than to electrons. The efforts to describe such temperature profiles behaviour as an ion ITB formation in the framework of standard version of the CPTM have been performed earlier. However, such efforts have brought to ion temperature profiles with narrow high gradient layer and very low heat diffusivity (sometimes below the neoclassical one) that disagree with measurements. Direct comparison of the pulse #28053 characteristics with those of the pulse #24600 with confirmed ion ITB [7] demonstrates considerable difference. In particular, in the initial phase heated with one 2 MW beam the ion thermal transport inside the ITB is on the neoclassical level and normalized ion temperature gradient ρ_s/L_{Ti} is in the range of 0.15 – 0.2 for the pulse #24600 (ρ_s is ion Larmor radius).

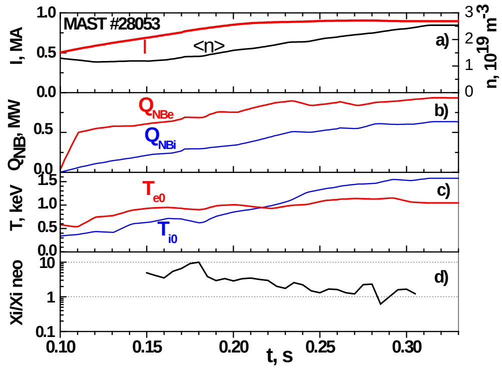

Fig. 5. Evolution of discharge #28053: a) current and volume-averaged plasma density, b) NBI power deposited to electrons and ions, c) central electron and ion temperatures (all TRANSP data), d) ratio of heat diffusivity to the neoclassical one in the point of maximal T_i gradient (ASTRA calculation).

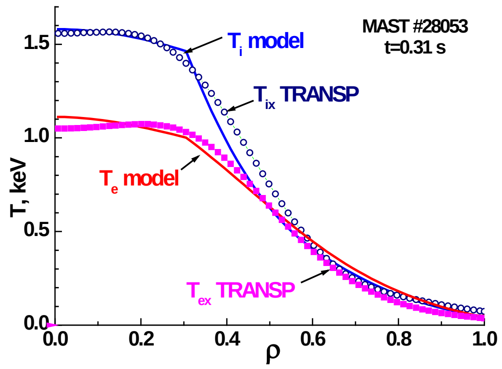

Fig. 6. Experimental (points) and calculated (solid lines) electron, T_{ex}, T_e, and ion, T_{ix}, T_i, temperature profiles at t = 0.31 ms.

In contrast, for the pulse #28053 the effective ion heat diffusivity is significantly above the neoclassical level during almost the whole time interval under study (Fig. 5) and normalized ion temperature gradient ρ_s/L_{Ti} does not exceed 0.08, and that is why this pulse cannot be considered as a pulse with ion ITB. The results of temperature profile modelling are presented in Fig. 6. This shot is in the L-mode, and the temperature boundary values for both electrons and ions were chosen as $T_{e,i}(a)$ = 0.05 keV. The minimization of the ion temperature deviation gives us $k_i^0 = 0.5\times10^{19}\mathrm{m^{-1}s^{-1}}$ and $S_{max} = 1$. The formation of increased ion temperature gradient zone $0.3 < \rho < 0.6$ is in connection with the deviation of ion temperature profile from the canonical one as well as for the DIII-D pulse, considered above (Fig. 4). Flat temperature profiles in the core are connected with MHD mixing.

In summary, the modified version of CPTM provides background for heat transport simulation in tokamaks with different geometry, especially in the cases of suppressed ion heat flux in the plasma core with no evidence of ion ITBs.

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