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PTRANSP: Predictive Integrated Tokamak Modeling

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The PTRANSP integrated modeling code [1] is used to compute predicted temperature and toroidal angular rotation frequency profiles. These profiles are compared with experimental data. Comparisons are carried out for H-mode, hybrid and negative central shear discharges in the DIII-D tokamak [2]. The PTRANSP simulations use the new MMM08 model for transport [3], the PEDESTAL module for the H-mode pedestal width and height [4], and the NCLASS module for neoclassical resistivity, bootstrap current and ion thermal neoclassical transport [5]. The NUBEAM module [6] is used with 50,000 Monte Carlo particles to compute neutral beam injection heating, torque, and current drive. Statistics are computed based on the comparison between predicted profiles and experimental analysis data. The PTRANSP simulations of the DIII-D discharges presented in this paper are used in a companion paper to investigate angular momentum confinement [7].

The MMM08 Multi-Mode transport model incorporates a recently advanced version of the Weiland model for transport driven by ion drift modes [8] as well as the transport driven by electron temperature gradient modes [9]. A computation of the toroidal angular momentum diffusion and convection, which can be either inward or outward, is included in the new Weiland model. The computation of momentum fluxes involves a non-linear resonance due to the inclusion of a Coriolis force term in the perturbed ion momentum equation. Since the resonance that appears in the diagonal part of the ion thermal diffusivity occurs at a different frequency than the corresponding resonance in the toroidal momentum diffusivity, the ratio of momentum to thermal diffusivity can be larger than unity in central regions of the plasma where the drift-mode growth rate is small. The net flux of toroidal momentum is often inward (toward the magnetic axis) because the inward pinch is frequently larger than the outward momentum diffusion.

Results of predictive PTRANSP simulations are compared with TRANSP analysis of experimental data for sixteen DIII-D discharges. The comparisons are carried out for time slices during quasi-steady state phases of the discharges. A single time slice is considered for twelve of the discharges; whereas, two or three time slices are considered for four discharges (125229,

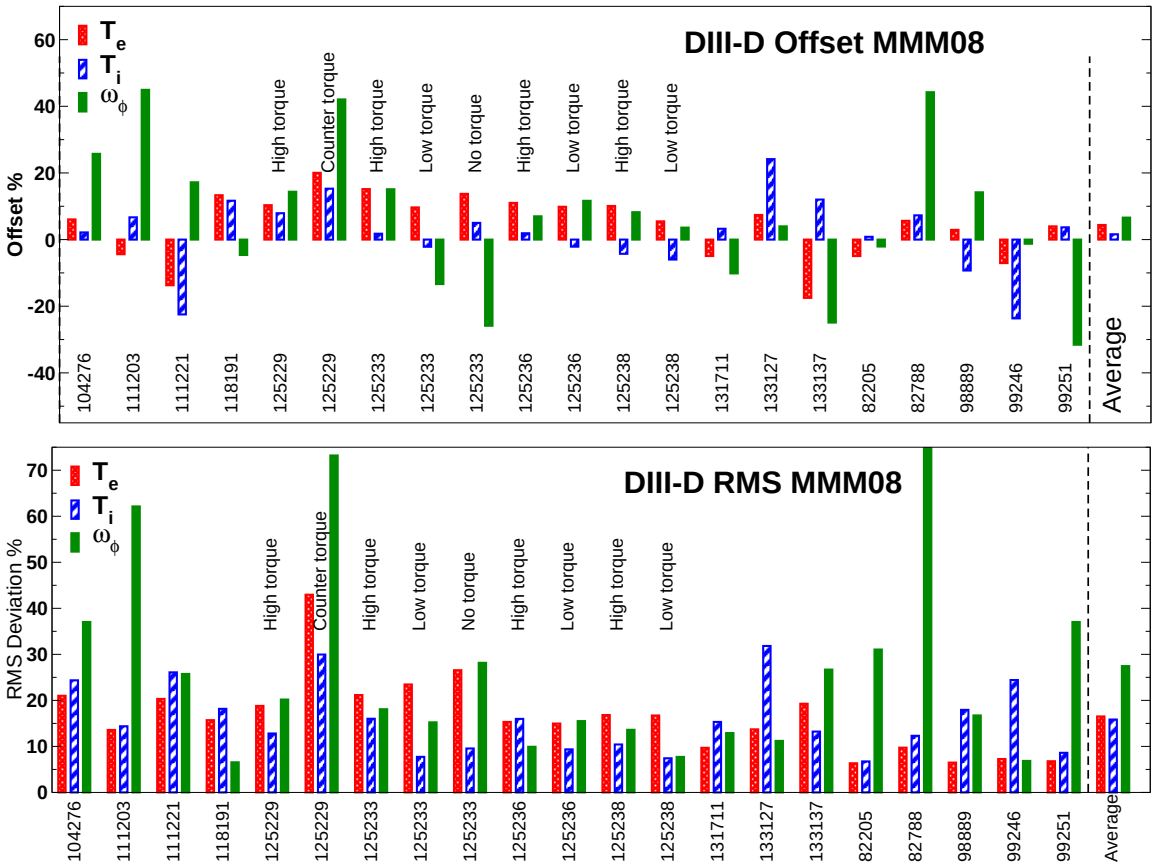

Figure 1: Normalized offset and RMS deviation computed from the difference between the PTRANSP electron temperature, ion temperature and toroidal angular frequency profiles and experimental data.

125233, 125236 and 125238) in which the neutral beam injected torque was varied while the heating power and other plasma parameters were held fixed [2]. The relative offsets and root-mean-square (RMS) deviations, shown in Fig. 1, for $j = 1,\ldots,N$ points across each electron temperature, ion temperature, and toroidal angular frequency profile are computed using

$$\text{Offset} = \left(\sum_j^N (T_j^{\text{sim}} - T_j^{\text{exp}})/N\right) \Bigg/ \sqrt{\sum_j^N (T_j^{\text{exp}})^2/N}$$

$$\text{RMS} = \sqrt{\sum_j^N (T_j^{\text{sim}} - T_j^{\text{exp}})^2/N} \Bigg/ \sqrt{\sum_j^N (T_j^{\text{exp}})^2/N}$$

where $N = 60$ for the results shown in Fig. 1.

The statistics are computed in the range $0 \leq r/a \leq 0.9$ for the temperature profiles and in the range $0.3 \leq r/a \leq 0.8$ for the rotation frequency profiles. For $r/a > 0.9$, the temperature profiles are controlled by the pedestal model rather than by transport. For $r/a > 0.8$, the toroidal rotation frequency is taken from experimental data in these simulations. In the region $r/a < 0.3$, where ion drift modes are generally stable, the momentum diffusivity is taken to be equal to the

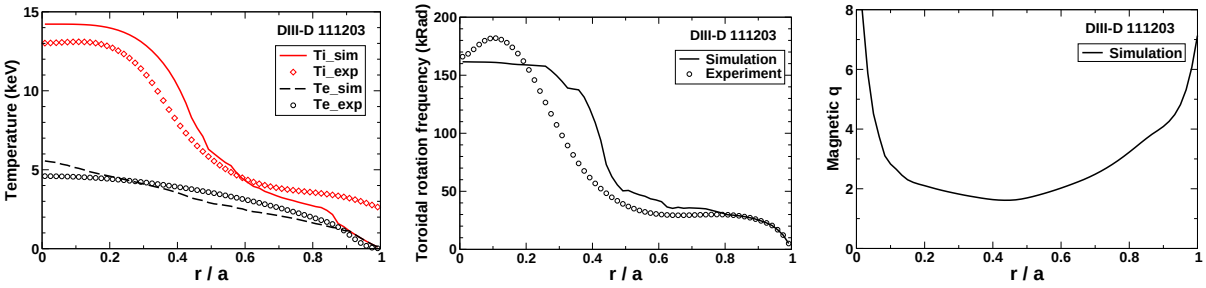

Figure 2: Simulation and experimental ion and electron temperature profiles (left panel), toroidal rotation frequency profiles (center panel), and magnetic q profile (right panel) for the DIII-D negative central shear discharge 111203.

neoclassical ion thermal diffusivity. The model for the momentum diffusivity in this region needs to be improved.

A positive offset indicates that the simulation over-predicts the profile. When the offset is small, the RMS deviation characterizes how well the shape of the simulation profile agrees with the experimental profile. The average offsets are less than 10%, indicating that the PTRANSP simulations somewhat over-predict the experimentally measured profiles. The average RMS deviation for the rotation frequency profile is 27%, and there is a large scatter in results from one discharge to the next.

Profiles are shown in Fig. 2 for DIII-D discharge 111203, which has negative magnetic shear in the plasma center. A sharply defined internal transport barrier can be seen both in the simulation and experimental ion temperature and toroidal rotation frequency profiles (left and center panels) near the radius of minimum magnetic q ($r/a \approx 0.45$), where the magnetic shear passes through zero. Ion drift mode transport is strongly suppressed by the combined effects of low magnetic shear and flow shear stabilization in this region. There is no transport barrier evident in the simulated and measured electron temperature profiles (lower curves in left panel). The electron thermal transport is driven primarily by the electron temperature gradient mode, which is not suppressed by low magnetic shear or high flow shear in the MMM08 transport model. In this particular discharge, the rotation frequency offset and RMS deviations are relatively large (45% and 62%). This is a consequence of the slight difference in the position of the internal transport in the simulation compared with the experimental data.

The temperature and toroidal rotation frequency profiles are shown in Fig. 3 for a discharge in which the neutral beam injected torque was in the direction opposite to the plasma current (negative torque). The rotation frequency profile indicates a mild and diffuse internal transport barrier in the region $0.4 < r/a < 0.55$. It is seen that the toroidal rotation frequency is negative (opposite to the plasma current) throughout the plasma and that the simulation over-predicts the magnitude of the rotation frequency in the central part of the plasma. In other discharges,

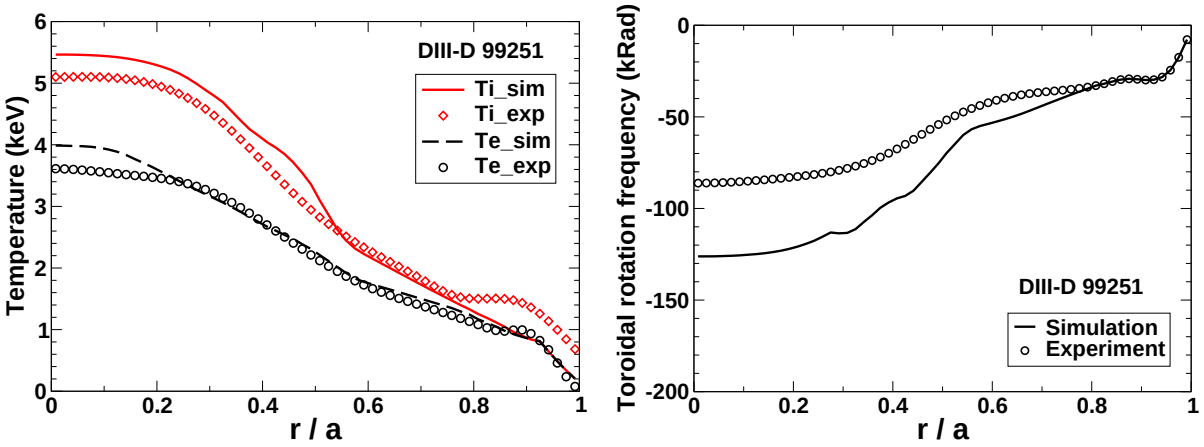

Figure 3: Ion and electron temperature profiles (left panel) and toroidal rotation frequency profile (right panel) from a PTRANSP simulation of DIII-D negative torque discharge 99251 compared with experimental data.

it is found that high torque and correspondingly high toroidal rotation frequency alone are not enough to produce an internal transport barrier. The central rotation frequencies is between 100 and 150 kHz in many of the high torque discharges that show no indication of an internal transport barrier.

Statistics presented in this paper provide a quantitative measure of validation for PTRANSP simulations using the MMM08 transport model. These statistics, however, are an imperfect measure of agreement in negative central shear discharges in which the predicted internal transport barrier has approximately the same height as the experimentally observed barrier but at a somewhat different minor radii.

References

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