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Testing H-mode Pedestal and Core Transport Models Using Predictive Integrated Modeling Simulations

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H-mode Pedestal Models

Models are developed to predict the temperature and density at the top of the pedestal at the edge of type 1 ELMy H-mode plasmas in order to provide the boundary conditions needed for integrated predictive simulations [1]. In the model presented here, the width of the temperature pedestal, Δ, is assumed to be determined by a combination of magnetic and flow shear stabilization of drift modes, $\Delta = C_W \rho s^2$, where s is the magnetic shear, ρ is the ion gyro-radius and C_W is a constant of proportionality chosen to optimise the agreement with experimental data. A constant pressure gradient, limited by the ideal MHD ballooning mode limit, is assumed so that the normalized critical pressure gradient is given by

$$\alpha_c \equiv -2\mu_o R q^2 (\partial p / \partial r)_c / B^2 = 0.4 s (1 + \kappa_{95}^2 (1 + 5\delta_{95}^2)), \qquad [1]$$

where the magnetic q and shear s are evaluated one pedestal width away from the separatrix; R is the major radius, and B is the toroidal magnetic field. The dependence of α_c on elongation and triangularity at the 95% magnetic flux surface, κ_{95} and δ_{95}, is described by the geometrical factor included in Eq. (1). The pedestal pressure is the product of the pedestal width times the critical pressure gradient, which, after some algebra results in the following expression for the pedestal temperature:

$$T_{\text{ped}}[\text{keV}] = 1.89 C_W^2 \left(\frac{B}{q^2}\right)^2 \left(\frac{M_i}{R^2}\right) \left(\frac{\alpha_c}{n_{\text{ped}19}}\right)^2 s^4, \qquad [2]$$

where $n_{\text{ped }19}$ is the electron density at the top of the pedestal in units of 10^{19} m^{-3}.

The magnetic q has a logarithmic singularity at the separatrix and it is a function of plasma elongation and triangularity near the edge of the plasma. At one pedestal width away from the separatrix, the magnetic q is approximated by

$$q = \frac{0.85 a^2 B}{I_{\text{MA}} R} \frac{1 + \kappa_{95}^2 (1 + 2\delta_{95}^2 - 1.2\delta_{95}^2)(1.17 - 0.65 a/R)}{[1 - (a/R)^2]^2} \left[\left(1 + \left(\frac{r}{1.4R} \right)^2 \right)^2 + 0.27 \left| \ln\left(\frac{1-r}{a} \right) \right| \right], \qquad [3]$$

where $r = a - \Delta$ is the position of the top of the barrier [2]. The magnetic shear, $s = (1/q)(\partial q/\partial r)$ is computed using Eq. (3) and is then reduced by the effect of the bootstrap current. Since the pedestal width is needed to compute the magnetic *q*, *s*, and α_c, and since the pedestal width is a function of the pedestal temperature, the right side of Eq. (2) depends nonlinearly on the pedestal temperature, T_{ped} and a non-linear equation solver is required to determine T_{ped}.

The coefficient C_W in the expression for the pedestal width is determined by calibrating the model for the pedestal temperature against 533 data points for type 1 ELMy H-mode plasmas obtained from the International Pedestal Database version 3.1 (http://pc-sql-server.ipp.mpg.de/Peddb/) using discharges from ASDEX-U, DIII-D, JET, and JT-60U tokamaks. It is found that the value $C_W = 2.42$ yields a minimum logarithmic RMS deviation of about 32% for this data. The comparison between the pedestal temperature from this model and experimental data is shown in Fig. 1. It is found that a simple empirical expression for the pedestal density $n_{ped} = 0.71\bar{n}$, where $\bar{n}$ is the line-averaged plasma density, results in a pedestal density that fits the 533 data points with a logarithmic RMS deviation of 12%, as shown in Fig. 2.

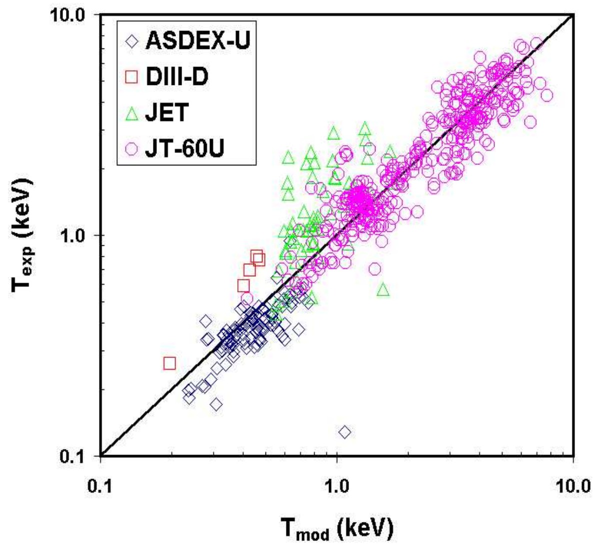

Figure 1: Predicted pedestal temperature compared with 533 experimental data points from the database.

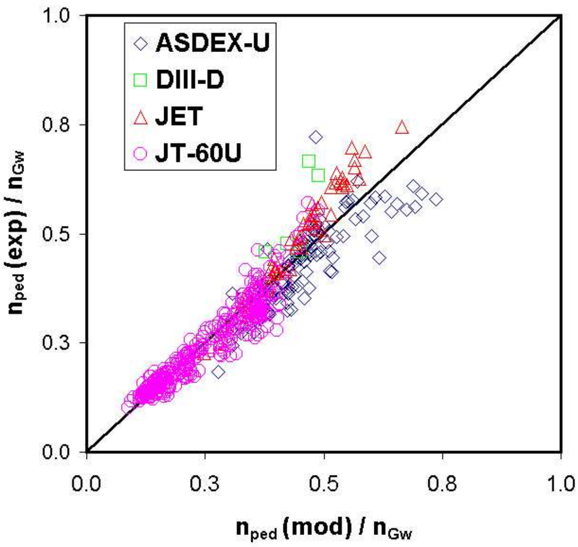

Figure 2: Predicted pedestal density compared with 533 experimental data points, normalized by the Greenwald density.

The model for the pedestal temperature, described above, is used to provide the boundary conditions in simulations of H-mode discharges in the BALDUR integrated predictive modeling code. The standard Multi-Mode model [3] is used as the core transport model in these simulations. It is found that the overall agreement between the simulated profiles and experimental data when the model is used to predict the edge temperature and density is of the order of 10%, which is comparable to the results obtained when experimental values are used to provide the boundary conditions in the simulations. In Figures 3 and 4, results obtained from simulations using the pedestal model for T_{ped} are compared with experimental data for the profiles in 12 H-mode discharges.

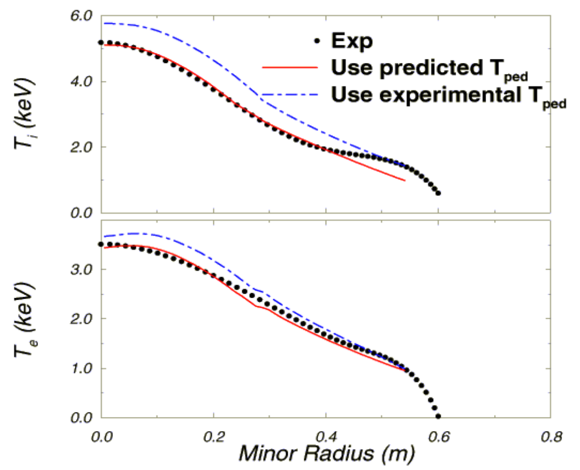

Figure 3: Example of simulation results compared with experimental data for T_i and T_e profiles in DIII-D 81321 using predicted or experimental values for T_{ped}.

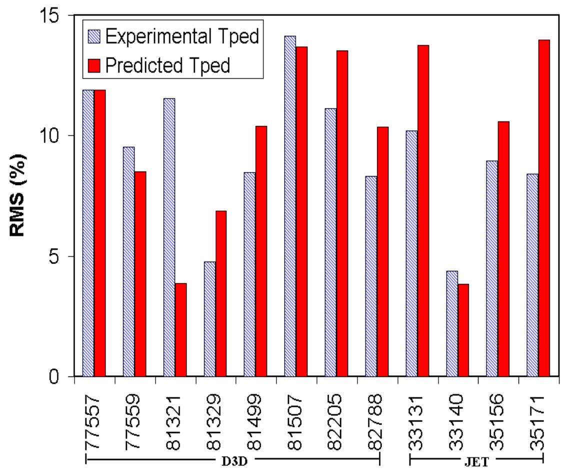

Figure 4: The RMS deviation between the simulation results for the T_i profiles and the experimental T_i profiles for eight DIII-D and four JET discharges.

Simulations of ITER and FIRE

The pedestal model was then applied to simulations of ITER, with R = 6.2 m, a = 2.0 m, I_p = 15 MA, B = 5.3 tesla, κ_{95} = 1.7, δ_{95} = 0.33, and FIRE with R = 2.14 m, a = 0.6 m, I_p = 7.7 MA, B = 10 tesla, κ_{95} = 1.77, δ_{95} = 0.4. It can be seen in Fig. 5 that the predicted pedestal temperature is inversely related to the pedestal density. The density is normalized by the Greenwald density, $n_{Gw} = I_p/(\pi a^2) = 1.19\times10^{20}$ m^{-3} for ITER and = 6.92×10^{20} m^{-3} for FIRE.

The predictive pedestal model yields a pedestal density that is proportional to the average plasma density, which can be varied by controlling the plasma fuelling. The predicted pedestal pressure, then, varies by less than 20% as the density is varied. The alpha heating fraction $[P_\alpha/(P_\alpha+P_{aux}+P_\Omega)]$ predicted by the BALDUR code using the Multi-Mode transport model is shown as a function of the volume-averaged plasma density in Fig. 6. The ITER simulations ran for 300 seconds with auxiliary heating power P_{aux} = 40 MW and impurity concentration of 2% Be plus 0.12% Ar plus the accumulation of Helium ash, which remained below 2% in these simulations. At the ITER design point, $\langle n_e\rangle/n_{Gw}$ = 0.84, the pedestal temperature is 2.7 keV and the central ion temperature is predicted to be 20 keV, in these simulations. At the lowest density in this scan, $\langle n_e \rangle / n_{Gw} = 0.35$, the pedestal temperature is 6.7 keV and the central ion temperature is 29 keV. The FIRE simulations run for 21 seconds with 30 MW of auxiliary heating and an impurity concentration of 3% Be plus Helium accumulation. At the FIRE design point, $\langle n_e \rangle / n_{Gw} = 0.7$, the pedestal temperature is 2.3 keV and the central ion temperature is predicted to be 18 keV. The Multi-Mode model is moderately stiff, which provides burn control in these simulations.

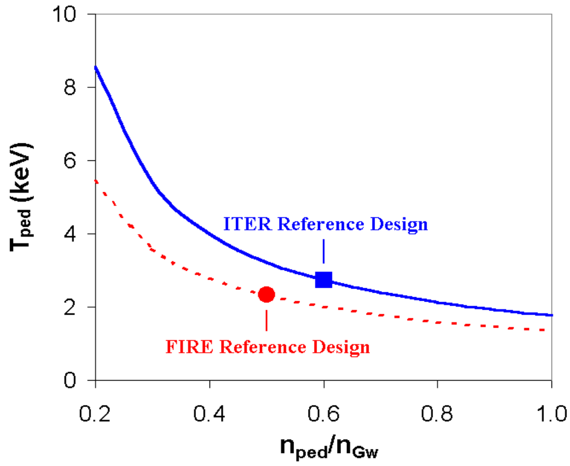

Figure 5: Predicted pedestal temperature as a function of normalized density for ITER and FIRE.

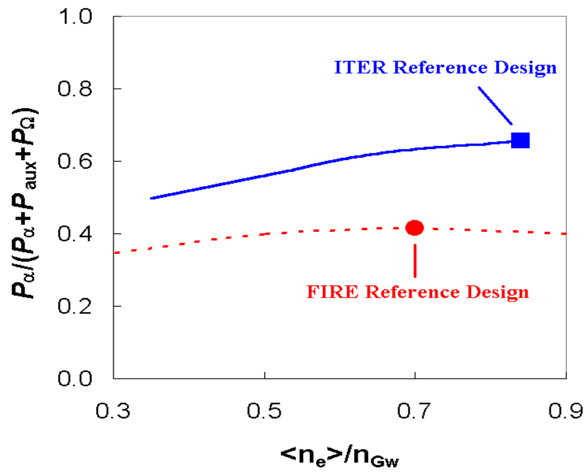

Figure 6: Alpha heating fraction as a function of normalized volume averaged plasma density for ITER and FIRE.

Conclusions:

A predictive model has been developed for the temperature and density at the top of the pedestal at the edge of type 1 ELMy H-mode plasmas. When the pedestal model is used together with the Multi-Mode model in the BALDUR code to carry out simulations of H-mode discharges in DIII-D and JET, it is found that the agreement between the simulated profiles and experimental profiles is about as good as when experimental data is used for the pedestal height. In simulations of ITER and FIRE, using these models, it is found that the alpha heating fraction is relatively insensitive to the plasma density because the pedestal temperature from the model is nearly inversely proportional to the pedestal density.

[1] T. Onjun, G. Bateman, A. H. Kritz, and G. Hammett, “Models for the pedestal temperature at the edge of H-mode tokamak plasmas,” to be submitted to Physics of Plasmas.

[2] M. Sugihara, Nuclear Fusion 40 (2000) 1743.

[3] G. Bateman, A. H. Kritz, J. E. Kinsey, A. J. Redd, and J. Weiland, Phys. Plasmas 5 (1998) 1793-1799.

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