Pedestal Density Prediction for Tokamaks

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Introduction

The confinement in the high confinement mode (H-mode) tokamak plasma is strongly affected by the edge region of the plasma, the so-called pedestal. Therefore, predicting the pedestal properties is vital for the optimization of the tokamak reactor design for efficient production of fusion energy. The pedestal pressure can be predicted by the EPED model [1] that has been validated against experimental data on several devices. However, the EPED model does not predict how the pressure is divided between the density and temperature. Instead, it takes the pedestal density profile as an input. Here we present a simple model to predict also the density pedestal and show its validation against JET, AUG, DIII-D and MAST-U experiments. We also show predictions for future tokamaks such as JT-60SA, ITER and STEP and discuss the sensitivities of the model to the unknown or poorly known quantities.

Density pedestal prediction model

The prediction model is described in detail in [2]. For brevity we outline only the main features of the model here. In the model the radial profile of the electron density $n_e(r)$ in the pedestal region is predicted. It balances the radial diffusion with a coefficient $D_{ped}(r)$ against both low energy Franck-Condon (created by molecular dissociation) and high energy charge exchange neutrals $n_{FC}(r)$ and $n_{CX}(r)$, which themselves are modelled with a simple convection model. We have three equations:

$$\nabla.\left(D_{ped}\nabla n_e\right) = -n_e(\,n_{FC} + n_{CX})S_i \quad (1)$$

$$\nabla.\left(V_{FC}n_{FC}\right) = -n_e(\,n_{FC}S_i + n_{FC}S_{CX}) \quad (2)$$

$$\nabla.\left((V_{CX}n_{CX})\right) = -n_e\left(\,n_{CX}S_i - \frac{1}{2}n_{FC}S_{CX}\right). \quad (3)$$

Here, S_i and S_{CX} are the ionization and charge exchange rates and depend on the electron

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**See the author list of E. Joffrin et al 2024 Nucl. Fusion 64 112019 temperature, and, $V_{FC,r} = \sqrt{8E_{FC}/\pi^2 M_i}$, with $E_{FC} \sim 3\ eV$, and $V_{CX,r} = \sqrt{2T_i/\pi M_i}$.

The plasma particle diffusivity in the pedestal D_{ped} in this model is composed of three components $D_{ped} = D_{NC} + D_{KBM} + D_{TG}$. The neo-classical diffusivity is defined as $D_{NC} = 0.05\frac{\rho_s^2 c_s}{a}$, the kinetic ballooning mode turbulence driven turbulence that has a threshold form:

$$D_{KBM} = \begin{cases} C_{KBM}(\alpha - \alpha_{crit})\frac{\rho_s^2 c_s}{a}, \alpha > \alpha_{crit}, \\ 0, \alpha < \alpha\_crit \end{cases} \quad (4)$$

where α is the normalized pressure gradient, α_{crit} is the critical pressure gradient to trigger the KBM and C_{KBM} is a free parameter defining the amplitude of the KBM particle diffusivity. Finally the temperature gradient turbulence driven diffusivity is proportional to the heat diffusivity in the form $D_{TG} = \left(\frac{D}{\chi}\right)_{TG}\frac{P_{tot,e}}{Sn_e\nabla T}$, where $\left(\frac{D}{\chi}\right)_{TG}$ is a free parameter. It is estimated that this could vary between 0.02 and 0.1 [3]. In the testing we set this parameter to 0.05 that gives good fit with JET data and then keep it fixed for all other devices.

The boundary conditions for the model are the experimentally measured core gradient $\nabla n_e|_{core}$, and $n_{e,sep}, n_{FC,sep}, n_{CX,sep}$, which are the plasma, Franck-Condon neutral and charge-exchange neutral densities at the separatrix. The value of $n_{e,sep}$ is taken from the experiment, $n_{FC,sep}$ is set to $10^{15} m^{-3}$ for other devices, but for DIII-D we use the LLAMA [4] measured neutral densities. $\frac{n_{FC,sep}}{n_{CX,sep}} = 10$ is assumed.

Experimental validation

The model is tested using two methods. One is to use the experimental temperature profiles (needed to calculate D_{TG}) and the other is to predict pedestal temperature alongside with the density using the EPED model. We call these methods the "standalone" and "Europed" as the temperature pedestal is pressure is predicted with the density using the Europed code [5].

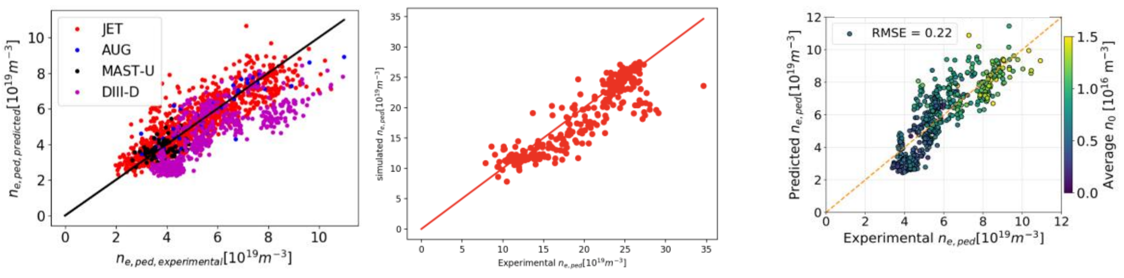

Figure 1. The predicted versus experimental density pedestals for JET, AUG, MAST-U and DIII-D with (left), C-Mod (middle), all with fixed separatrix density of 10^{15} m^{-3} and DIII-D with separatrix density taken from the LLAMA diagnostic (right). Tthe colour represents the measured neutral density at the separatrix.

Using the following values for the free parameters of the model in the standalone simulations for JET, MAST-U, AUG and C-Mod: $\left(\frac{D}{\chi}\right)_{TG} = 0.05, C_{KBM} = 1, \alpha_{crit} = 2$ (JET, AUG, C-Mod) and α_{crit}=5 (MAST-U due to it being a spherical tokamak and having better stability against ballooning modes) and fixed $n_{FC,sep} = 10^{15} m^{-3}$ produces very good agreement with the experiments as shown in Fig 1.

For DIII-D we find that with the fixed value for $n_{FC,sep} = 10^{15} m^{-3}$ the predictions deviate from the experiment (Fig1., left). However, with the LLAMA-inferred neutral densities (derived from Ly-α emission measurements in the main chamber and taken as the average of the low and high field sides) the prediction accuracy is equally good as in the other devices.

The predictions using Europed in some cases lead to a feedback loop with the KBM constraint of the EPED model interacting with the KBM transport in the model. Therefore, we had to suppress the KBM part of the model and compensate that by increasing $\left(\frac{D}{\chi}\right)_{TG}$ to 0.5. With that, we obtain predictions with JET, AUG and MAST-U that have similar errors as those done using the standalone model. Both in standalone and Europed modelling, it was identified that the main sensitivity of the model was $n_{e,sep}$.

Predictions for future devices

Since the model worked well for the existing devices without having to change parameters between devices, we use it to predict the density pedestals for future tokamaks such as JT-60SA, ITER and STEP.

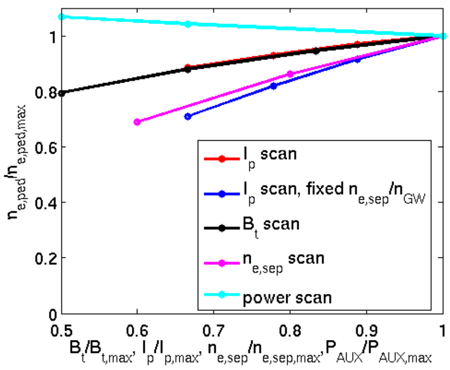

Figure 2. The relative sensitivity of the JT-60SA pedestal density prediction to the variation of I_p, B_t, heating power and $n_{e,sep}$.

For JT-60SA we predict the pedestals using Europed for the ITER-like baseline scenario with B_t=2T, I_p=4.6MA, β_N=2, P_{AUX} =30MW, Z_{eff}= 1.7 and $n_{e,sep} = 2.4 \times 10^{19} m^{-3}$. The prediction with these parameters gives $n_{e,ped} = 5.5 \times 10^{19} m^{-3}$. The sensitivities of the prediction to the global parameters is shown in Fig 2. As can be seen, the prediction is very robust for all other variations except $n_{e,sep}$.

For ITER we predict the density pedestal for the full current (15MA) plasma. The difference for JT-60SA is now that there is significant fusion power that contributes to the density pedestal prediction, which then in turn affects the plasma density and temperatures in the core, which then affects the fusion power. To take this into account, we use a very simple transport model used in [5] to predict JET DT plasmas assuming stiff temperature profiles in the core and density peaking proportional to $-\ln(\nu^*)$. The range of $n_{e,sep}$ used in the predictions was $3-7\times10^{19}m^{-3}$ [6]. Within that range $n_{e,sep}/n_{e,ped}$ increases from 0.3 to 0.5 as the $n_{e,sep}$ increases. At the same time the fusion power decreases significantly as shown in Fig. 3. meaning that the ITER fusion power is going to be sensitive to the separatrix conditions.

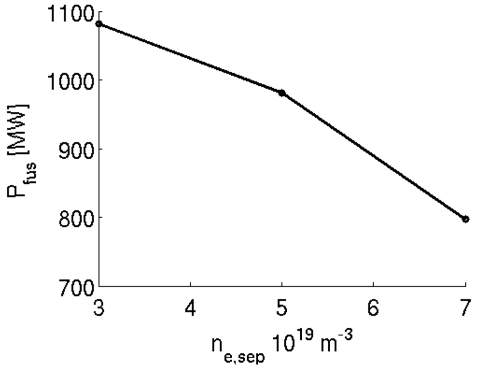

Figure 3. The predicted ITER and fusion power as a function of the separatrix density.

Finally, we predict the pedestal density for STEP fusion reactor with the following parameters B_t=3.2T, I_p=22MA, R=3.6m, a=2m, κ=3.0, P_{fus}=1.56GW [7]. Since STEP is mainly pellet fuelled, we test how sensitive the prediction model is to the core gradient as the pellets are supposed to be deposited inside the pedestal region increasing the density gradient there. We find that the pedestal density prediction decreases with the core gradient but then saturates at high gradients.

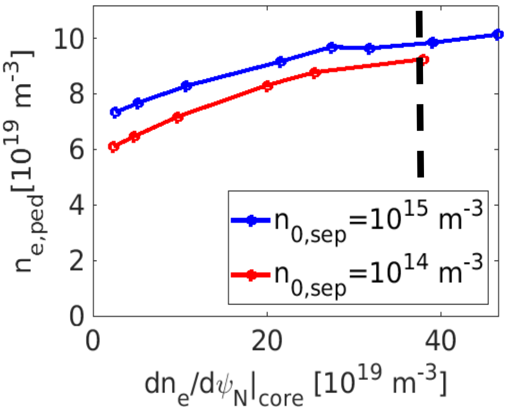

Figure 4. The predicted pedestal density for STEP as a function of the core density gradient for two values of separatrix neutral density. The vertical line shows the core gradient value used in the integrated modelling [7].

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