Alternative method for characterization of inter ELM edge profiles of type-I ELMy H-modes in ASDEX Upgrade

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Introduction

To increase the stored energy in an H-Mode plasma it is convenient to increase the plasma pressure within the edge transport barrier (ETB), since the core pressure directly scales with the one at the edge due to stiff temperature profiles [1]. The ITER standard scenario works with an electron pressure of about 70kPa at the plasma edge. Yet, this prediction is not based on the understanding of first principle physics, but on extrapolations from available measurements.

In the ETB on spacial scales of a few centimeters n_e and T_e change by 1-2 orders of magnitude and form a pedestal, which seperates core plasma and scrape off layer (SOL). It is experimentally challenging to resolve the pedestal with sufficient resolution on time scales lower than the ELM frequency. The edge diagnostics at ASDEX Upgrade are constantly improving and have reached high enough spatial and temporal resolution to draw reliable conclusions about the shape of the edge pedestal during a whole ELM cycle [2].

An accurate and reliable method to characterize the edge pedestal data is essential for the ability to test theoretical models. The gradients of n_e, T_e and T_i in the pedestal and the width of the pedestal are of special interest for most theories and should be determined very accurately from the measured data.

The most common method to characterize the edge pedestal is based on a modified hyperbolic tangent function mtanh (see e.g. [3]). The advantages of this method are a suitable definition of the pedestal parameters even for few data points and a better comparability between different machines where the same method is applied. The main disadvantage originates from the combined fit of core, pedestal and SOL plasma with a symmetric function, which can lead to systematic errors for the pedestal parameters [4].

In this paper a new method is discussed, which aims to avoid the systematic errors introduced by the mtanh fitting. First results obtained with the new method are presented.

Two-line method

The shape of kinetic inter ELM plasma edge profiles shows two pronounced changes in the gradient for most cases. The inner core region has rather small gradients due to high turbulent transport. Within the experimental uncertainties the gradient is constant outside of $\rho_\text{p} \sim 0.85 - 0.90$ up to the pedestal top. In the pedestal steeper gradients are observed, because the

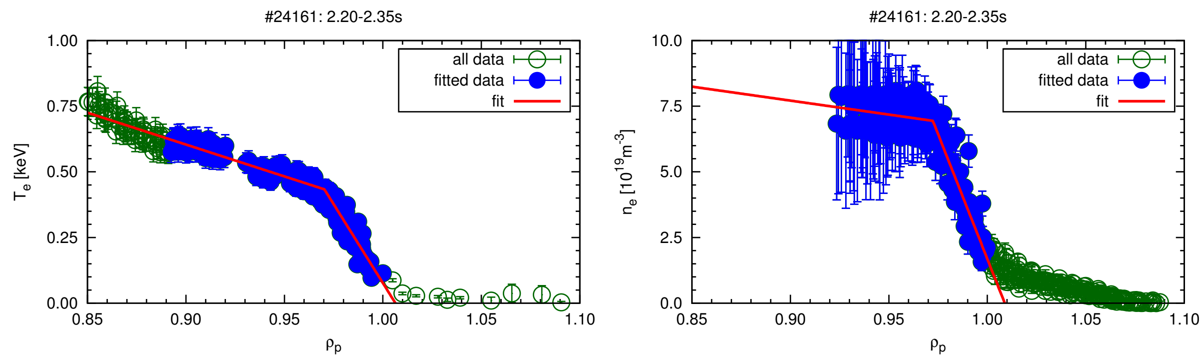

Figure 1: Typical inter ELM profiles of T_e (left: ECE and TS) and n_e (right: Li-Beam and TS) aligned with TS and fitted with Equation (1) in the pedestal region.

turbulent transport is suppressed here. At the pedestal bottom, the outer end of the steep gradient region, the SOL begins, it is outside of the magnetically confined region and therefore no significant gradient can be sustained. When the SOL is excluded from the analysis, two regions with distinct gradients remain, which are separated by the pedestal top. Considering this shape of the pedestal it is convenient to define the function

$$f(x) = \begin{cases} a_2(a_0 - x) + a_1 & \text{for } x \leq a_0 \\ a_3(x - a_0) + a_1 & \text{for } x > a_0 \end{cases} \tag{1}$$

where a_n are free parameters. A fit of the plasma edge from $\rho_p \sim 0.85 - 0.90$ up to the separatrix immediately yields the pedestal top position a_0, the pedestal top value a_1 and the mean gradient over the pedestal a_3, see Fig. 1). The width of the pedestal Δ is then $x_{sep} - a_0$. The position of the separatrix x_{sep} has to be determined separately. Although the separatrix position can be determined very accurately with equilibrium reconstruction using the magnetic data, the observed uncertainty of about 2% is not negligible on scales of the pedestal width. To determine the separatrix position directly from the profiles, the two point model [5] is used, which predicts $T_e(\text{sep}) = 100 \pm 20$ eV for an AUG H-Mode. In the case of n_e the position of the pedestal bottom coincides with $\rho_p(T_e = 100 \text{ eV})$ for all observed discharges.

Comparison of two-line and mtanh method

The mtanh method aims at providing a functional form of the plasma edge, which allows to derive the pedestal quantities. On the other hand, the two-line method defines the pedestal quantities directly. It has not the goal of resembling the exact shape of the plasma edge, but to give the best definition of pedestal top value, gradient and width possible within the uncertainties of the measurement. The mtanh method imposes a symmetry, namely the same absolute curvature at pedestal top and bottom. This is not always resembled in the experimental data of T_e and n_e as

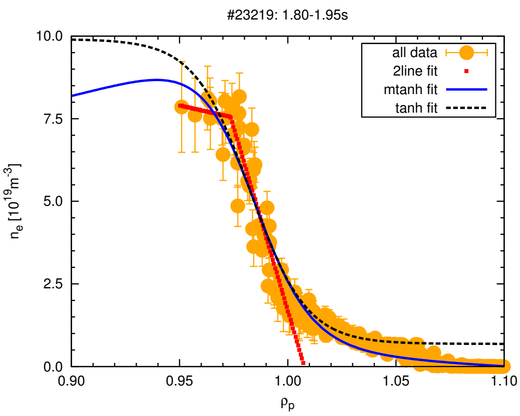

Figure 2: Example where the mtanh model fails. For n_e measurements the Li-beam diagnostic (circle,orange) was used at the edge and the DCN interferometer for the central plasma (not shown). Because of its symmetry the tanh fit (dashed,black) leads to far too high pedestal top values. The modified tanh (solid,blue) tries to match the interferometer data, but cannot compensate completely for the error in the tanh part. For comparison the two-line fit (dotted,red).

can be seen in Fig. 1 and 2. In case of the electron density, where this asymmetry is reinforced by high SOL n_e, pedestal top and width might be overestimated as illustrated in Fig. 2. This results in a large scatter and poor comparability with theory.

For a series of discharges with similar parameters reproducible pedestal parameters are expected. The pedestal parameters of 42 measurements with moderate gas fueling are determined by using the mtanh and the two-line model. The mtanh model yields a mean width $\Delta_{ne} = 1.8$ cm with a standard deviation of 0.8 cm, a pedestal top density $n_e^{top} = 7.6 \pm 0.9 \cdot 10^{19}$ m^{-3}, a temperature pedestal width $\Delta_{Te} = 1.9 \pm 0.5$ cm and $T_e^{top} = 0.38 \pm 0.09$ keV. With the two-line characterization the scatter is significantly reduced and becomes $\Delta_{ne} = 1.7 \pm 0.2$ cm, $n_e^{top} = 6.9 \pm 0.5 \cdot 10^{19}$ m^{-3}, $\Delta_{Te} = 1.7 \pm 0.3$ cm and $T_e^{top} = 0.43 \pm 0.03$ keV. Within the uncertainties one obtains the same pedestal parameters for both methods. However, the support for the theory that discharges with the same global parameters have the same pedestal parameters is stronger when using the results of the two-line method.

One drawback of the two-line method is that it only provides mean gradients for the pedestal. Maximum gradients are relevant for most stability theories. However, they do not differ significantly from the mean gradients within the experimental uncertainties.

Results

The two-line method was applied to a considerable range of ASDEX Upgrade type-I ELMy H-modes. Discharges were selected with $I_p = 0.6 - 1.1$ MA, $B_t = 1.8 - 2.8$ T, $P_{heat} = 5 - 12$ MW, $q_{95} = 3 - 7$, $\delta = 0.2 - 0.3$ and a radial sweep of the plasma column in order to improve the resolution with virtual lines of sight. Only profiles were used, which are at least 4 ms after the previous and 1.5 ms before the next ELM. In this interval the pedestal is not influenced by the ELM instability [2].

One of the most recent pedestal models is the EPED1 model [6], which predicts a $\beta_{p,ped}^{0.5}$ dependency of the pedestal width Δ_{ped}. At DIII-D it is found to be $\Delta_{ped} = 0.076\beta_{p,ped}^{0.5}$ when using the mtanh method [7]. Where $\beta_{p,ped} = 4\mu_0 n_{e,ped} T_{e,ped} \bar{B}_p^{-2}$ and the pedestal width is the mean of Δ_{ne}

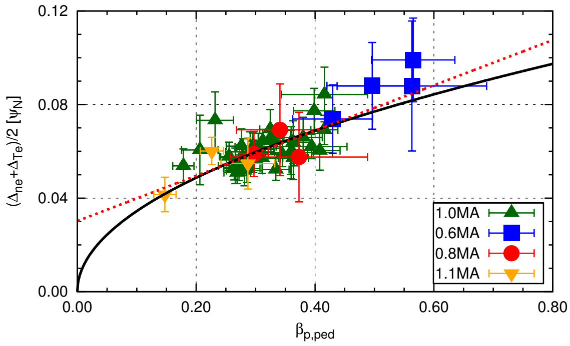

Figure 3: Mean pedestal width of T_e and n_e plotted against $\beta_{p,ped}$. Both $\beta_{p,ped}^{0.5}$ (solid, black) and $\beta_{p,ped}^{1.0}$ (dashed, red) fit to the data.

and Δ_{T_e} measured in normalized poloidal flux coordinates. The result for the AUG database is shown in Fig. 3. The data fits to $\Delta_{ped} = 0.11\beta_{p,ped}^{0.5}$. However, within the available range of $\beta_{p,ped}$ this cannot be distinguished from a linear correlation. The pedestal in AUG is found to be wider than it is in DIII-D. This is most likely not a side effect of the analyzing method, since the tanh method tends to lead to higher pedestal widths instead of smaller ones as observed.
The above analysis was performed in normalized poloidal flux coordinates ψ_N, however, if e.g. gyro orbit effects would play a role in the pedestal formation, real space coordinates would be more appropriate. The choice of the coordinate system will influence the outcome of the analysis, since $\partial\psi_N/\partial r$ is not independent of $\beta_{p,ped}$, but varies by about 40% where the $\beta_{p,ped}^{0.5}$ correlation would yield 70% rise in the pedestal width. Therefore, in real space the pedestal width correlation with $\beta_{p,ped}$ is less pronounced.

When looking at T_e and n_e individually similar behavior of the pedestal in density and temperature is visible in real space. In both cases the pedestal width is around 1.7 ± 0.3 cm, whereas the mean gradient is rising proportional to the pedestal top value by a factor of 2.4. However, within the uncertainties the temperature pedestal width shows a correlation with the pedestal top pressure P_e^{top} and the poloidal magnetic field B_p. The density width shows the correlation with B_p as in the case of T_e, but no trend with P_e^{top}. This is consistent with mtanh analysis [8].

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