

Analysis of High-Resolution ASDEX Upgrade Edge Plasma Profiles

J. Neuhauser, D.P. Coster, V. Dose, J.W. Kim, B. Kurzan, H. Murmann,
H. Salzmann, R. Schneider, W. Schneider, J. Schweinzer, R. Wunderlich
and the ASDEX Upgrade Team

*Max-Planck-Institut für Plasmaphysik, EURATOM Association
D-85748 Garching, Germany*

Introduction

The experimental tokamak edge data base is still rather incomplete and suffers from large error bars, especially for the most interesting high power, high performance discharges, where e.g. Langmuir probes can no longer be applied near and inside the separatrix. The lack of experimental data is aggravated by the inherent complexity of the edge region making a routine analysis in terms of physical model parameters like cross field transport coefficients, critical gradients etc. rather cumbersome. A simple empirical scaling approach as applied for global confinement may be questionable because of too many hidden parameters. Improved diagnostics as well as interpretation tools are therefore required to remedy the situation. In this contribution, we present recent progress on ASDEX Upgrade with respect to high resolution H-mode electron temperature (T_e) profile measurements around the separatrix as typical for the problem. We discuss the accuracy and characteristics of the experimental profiles obtained by edge Thomson scattering and describe different approaches and tools for their analysis in terms of physical models and mechanisms. Emphasis is put on the correlation across the separatrix and the resulting similarities in pedestal and hot scrape-off layer (SOL) scaling.

Apparatus

The quasi-continuous vertical YAG-Thomson scattering system of the poloidal divertor tokamak ASDEX Upgrade [1] ($R \approx 1.65\text{m}$, $a \approx 0.5\text{m}$, $b \approx 0.8$; $B \leq 3.5\text{T}$, $I_p \leq 1.4\text{MA}$; $P_{\text{NI}} \leq 20\text{MW}$) consists of six parallel, vertically launched YAG laser beams of 2 mm radial width adjacent to each other. The scattered light is detected through a radial port via 16 channels. If positioned at the outer edge this results in vertically and radially staggered scattering volumes, each with 2 mm radial width and 25 mm height (35 mm vertical gaps in between). Only up to 5 channels lie in the edge plasma and from those only 1-3 channels have a local poloidal angle to the curved flux surface below a few degrees as required to keep the effective radial resolution in the few mm range without the need for complicated signal unfolding. The system usually measures bulk plasma profiles with the 20 Hz lasers equally spaced in time, i.e. about 8 ms time resolution. For specific purposes, e.g. in elmy plasmas, the 6 lasers can be fired in a short pulse train (min. separation 50 μs) yielding a nearly instantaneous profile consisting of 6 to 18 radial points (depending on the number of selected channels) with 20 Hz repetition. Sweeping of the separatrix position during a discharge plateau phase, the high time resolution allows one to construct high resolution profiles ranging from the pedestal region out to the scrape-off layer wing.

Profile characteristics

A rather instructive, quasi-stationary case to start with is an H-mode discharge with well separated type-I elms ($f_{\text{elm}} \approx 80\text{ Hz}$) at medium line average density $n_{\text{av}} \approx 4.5 \cdot 10^{19} \text{m}^{-3}$ (separatrix density $n_{\text{sep}} = 1.8 \cdot 10^{19} \text{m}^{-3}$), high current and with a heating power not too far above H-mode threshold. Fig. 1 shows such a discharge scenario with approximately constant plasma parameters over a 5s plateau (#10814, 1MA, -2T, $q_{95} = 3.2$, 2.5MW $\text{D}^0 \rightarrow \text{D}^+$). The outer separatrix is slowly shifted during the plateau by 2.5 cm, away from the wall initially, then back again. The lasers are fired in packages ($\Delta t = 100 \mu\text{s}$) with 20 Hz repetition. The two most appropriate vertical channels were chosen, two obviously bad lasers were excluded and a

few obvious outliers were dropped. The remaining 406 data points are shown together in fig. 1 (right), with lasers and channels coded by colours and numbers, resp. For this plot each individual Te profile has been re-mapped onto a mid plane radial scale with the instantaneous nominal (magnetically determined) separatrix position as origin. A box car filter with 2 mm width has been applied to determine the mean profile shape (black dots). Bayesian statistics together with experimentally estimated Te errors has been adopted as a tool for proper outlier recognition and weighting in the filter [2]. The edge density profile determined by the Li-beam diagnostic [3] (including elms again) is less steep and varies nearly linear from $1 \cdot 10^{19}$ to $2.8 \cdot 10^{19} \text{ m}^{-3}$ over the Te data range plotted. A time resolved Te and ne profile analysis over the elm cycle exhibits a gradient variation of the order of 10 % not discussed here in detail (though the rare elms still contribute to the scatter in the Te profiles shown). Inspection of the mean profile reveals a steep linear gradient zone ($\approx 450 \text{ eV/cm}$) inside the nominal separatrix with a smooth transition into the SOL ($\lambda_T \approx 2..3 \text{ mm}$ from log plot). We emphasize that, while the relative error of the nominal separatrix position between laser pulses may be around 1 mm, the estimated absolute error can be easily 5 times as high.

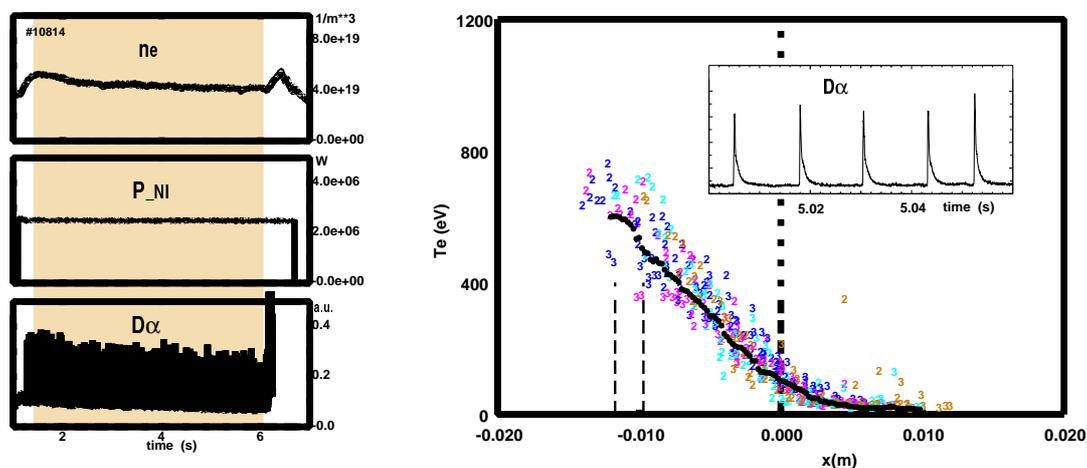


Fig.1: H-mode discharge with well-separated elms. Left: Time traces of density (n_e), neutral injection heating power (P_{NI}) and divertor $D\alpha$ -emission. A radial separatrix scan is performed during the shaded interval. Right: Measured edge electron temperature profile relative to the nominal separatrix position. The dots are mean values by obtained from a box car Bayes-Filter with 2 mm radial width.

As a second, rather extreme example we chose a gas puffed high power, high density H-mode discharge close to the empirical density limit with stepwise ramp-up of neutral injection heating to 15MW (#11821, 1MA, -2.5T). Discharges at this power and density level suffer already from reduced global confinement, but have otherwise highly desirable edge features, e.g. frequent, densely spaced elms, increased SOL width and marginally detached divertor plasma. A 400 ms radial in-out separatrix scan in the second half of the last four power steps (7.5, 10, 12.5 and 15MW) has been made similar to the above one (except for the shorter duration). The most obvious difference to the first example is that the temperature scatter is much larger, though the same hardware and analysis has been applied. The reason behind is obviously the macro turbulence produced by the frequent elms.

As a third typical example for comparison we may look at an L-mode plasma in hydrogen at moderate power and medium density (#11275, 1MA, -2.5T, $q_{95}=4.2$, 3.5 MW $H^0 \rightarrow H^+$). Here, the mean Te profile varies smoothly over the whole radial range considered with gradients substantially lower than for the corresponding H-mode in deuterium (first example).

1.5d analytic model fit (least square and Bayesian)

As a first step on the way to a full 2d numerical model fit we use analytic solutions of a 1d radial heat conduction equation across the separatrix with parallel electron heat conduction loss along open field lines ($\sim T^{7/2}$) as a local sink outside the separatrix ('1.5d model'). An analytic solution for the SOL at a given power across separatrix has been presented in [4] for the radial

transport coefficient $n\chi$ independent of radius. Simple analytic solutions exist also if $n\chi \sim T^\alpha$, where $\alpha=1$ at roughly constant density and magnetic field is equivalent to Bohm diffusion. As in earlier work [5, 3] we choose the constant $n\chi$ and the Bohm-like model solutions (and a simple exponential profile with power conservation as additional condition) as SOL fit functions. These SOL solutions are continued into the closed field line plasma assuming constant gradient and hence continuous transport across the separatrix consistent with the above experimental observation and also with typical radial correlation lengths of few cm in numerical 3d turbulence simulations [6]. B2-Eirene code simulations [7] are used to derive geometry correction factors relative to the circular cross section models. With the measured temperature profile relative to the nominal separatrix and the power flow across the separatrix as input, a new, corrected separatrix position and the absolute transport coefficients are obtained from the fits. If applied to the first H-mode example (see fig. 1), the separatrix correction is in the millimeter range and the temperature decay lengths at the new separatrix is 2 mm or smaller for all three models. Repeating the procedure for all examples mentioned above (all with $I_p=1\text{MA}$), we get a small data set and can look for scalings. The most obvious and robust H-mode trend is $n_{\text{sep}}/\lambda_T \approx \text{constant}$, nearly independent of power from 2.5 to 15MW, as shown in fig 2. For comparison, the L-mode value is much lower, a higher triangularity H-mode plasma (not in this paper) yields a factor 1.5 higher n_{sep}/λ_T (fig. 2). An earlier data set [5] with a current scan from 0.6 to 1.2 MA at constant power (5 MW $D^0 \rightarrow D^+$) gives $n_{\text{sep}}/\lambda_T \sim (I_p)^\beta$, with β slightly above one. Altogether, these trends are similar to the critical pedestal gradient scaling inside the separatrix [8], a fact which is not surprising in view of the strong correlation across the separatrix as stated above and the fact that n_{sep}/λ_T is roughly proportional to the electron pressure gradient at the separatrix (because of relatively constant T_{sep} and $\lambda_n > \lambda_T$). A similar trend has been obtained earlier by regression analysis of an older ASDEX Upgrade data set contained in the ITER edge database [9].

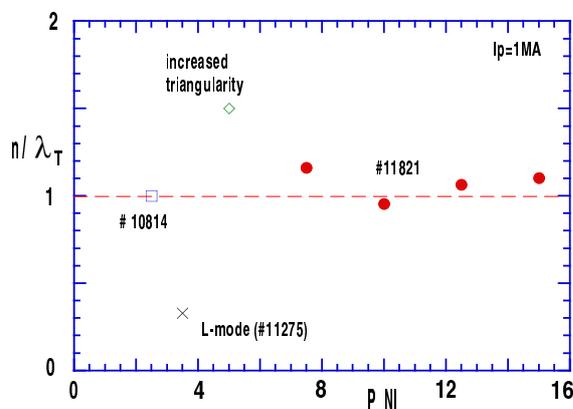


Fig. 2. Scaling of $n_{\text{sep}} / \lambda_T$ [10^{22} m^{-4}] with heating power P_{NI} for H-mode plasmas at low and increased triangularity (and one L-mode case for comparison) as obtained from a $n\chi = \text{const.}$ model fit to Thomson electron temperature data in the separatrix vicinity (about $\pm 1\text{cm}$).

Bayesian statistics, already applied above for filtering, has been extended also to function fitting as an alternative to the simple least square fit procedure. For large data sets this advanced statistics fit is much more time consuming, since the statistical contribution of an individual point is dependent on all others in a complex form. On the other hand, it has again clear advantages in outlier handling and model validity assessment. Applied to our examples, the fits obtained are not much different, but we get new and more reliable information on the data and model fit quality. For instance, for the H-mode example in fig. 1, the constant $n\chi$ model is much more likely than the Bohm-like one, a fact which to a large extent may be understood as a result of the constant pedestal gradient inside and the smooth transition into the SOL. In contrast, there is altogether a trend to the Bohm-like model for the micro-macro turbulent edge in the different power steps of the high power/density discharge #11821, possibly an indication for an upper turbulent transport limit.

We emphasise that all the fits above apply to the separatrix vicinity, typically 1 cm inside plus the hot SOL part outside. Quite different mechanisms seem to be effective in the cold SOL profile wing as derived by fitting Langmuir probe data [10]. Thomson scattering data have, however, large error bars in the far edge, giving little weight to these points in the fit. This

radial variation in diagnostic accuracy and dominant physical mechanisms on a centimetre correlation scale indicates an inherent problem of any such analysis: the result necessarily depends on the type of data and the radial window selected. This can cause severe scatter and discrepancies in intermachine data bases, if the data are not created and handled in a consistent way everywhere.

Automatic profile fitting with the B2.5 code

As mention in the introduction, the complexity of the edge requires highly sophisticated, at least 2d numerical code packages like B2-Eirene. Since their typical run times per case are of the order of weeks, they are still restricted to the study of a limited number of typical scenarios [7]. Downgraded versions with simpler neutral model, coarser grid and eventually artificial radiation, however, can be fast enough to allow for routine mid plane profile analysis, at least for cases where divertor details seem to be less important. First attempts in this direction have been made with the B2.5 code with a fluid neutral model. Appropriate iteration and control loops have been added, which essentially allow for the same fitting procedure and transport laws as explained above, just with the analytic solution replaced by the full 2d numerical solution. Fig. 3 shows the electron temperature profile fit (with pure deuterium plasma) for the H-mode discharge #10814 (compare fig. 1). The separatrix position correction found is less than 1 mm and $\chi \approx 0.2 \text{ m}^2/\text{s}$. These values are about equal to those obtained with the previous analytic model fit. Because of the weak radial density variation, the transport laws $\chi=\text{const.}$ and $n\chi=\text{const.}$ give nearly the same result. Stepwise more experimental input is added allowing for more output parameters to be determined.

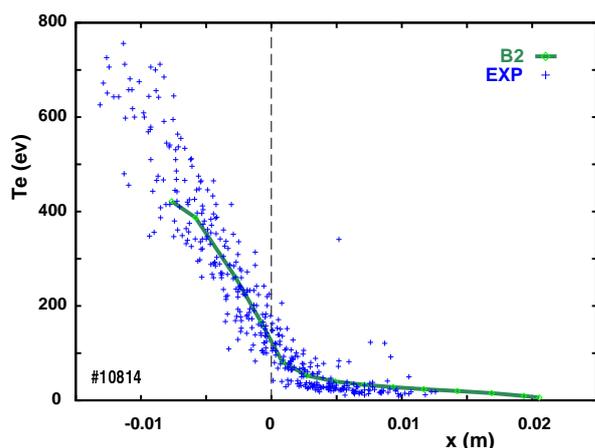


Fig.3: Transport analysis and separatrix correction with the 2d-code B2.5 for the H-mode discharge #10814, assuming χ independent of radius (pure deuterium plasma). The separatrix position correction is less than 1 mm and $\chi \approx 0.2$

Summary and conclusions

High resolution edge profiles have been measured at ASDEX Upgrade by Thomson scattering for a small number of discharges covering nevertheless a broad range of fusion relevant scenarios. The profiles have been analysed first by filtering and inspection, then by fitting 1.5 d analytic transport models with

free separatrix position using standard and Bayesian statistics and finally by an automatic profile analysis version of the 2-dimensional B2.5 code. A strong radial transport correlation across the separatrix into the power conducting layer seems to exist, which causes a striking similarity between hot SOL and pedestal gradient scaling.

References

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