

# COMPARISON OF THE H-MODE PEDESTAL DENSITY AND ITS UNDERLYING PHYSICS ON JET AND ASDEX UPGRADE

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## Introduction

The density profile in the plasma edge has a large impact on core performance as well as particle and power exhaust in a future reactor. Nevertheless, the values of pedestal and separatrix electron density,  $n_{e,ped}$  and  $n_{e,sep}$ , can usually not be predicted without experimental input, mainly due to the not well-known cross-field transport in the scrape-off layer (SOL) and edge transport barrier (ETB) regions. Consequently, a size scaling of these parameters is not available so far. Direct

measurements of the edge electron density profile shape are hampered by radial position uncertainties with respect to the separatrix. This is particularly problematic in the H-mode, where steep gradients convert the radial uncertainty in large absolute errors. In addition, the magnetic mapping may be affected by edge currents not being correctly taken into account by the magnetic reconstruction. To overcome these problems in spatial profile allocation, physics models have to be used to reduce the radial uncertainty by applying model assumptions<sup>1,2</sup>. In the following, the experimental situation in both experiments will be briefly reviewed, and comparisons of edge density data shown.

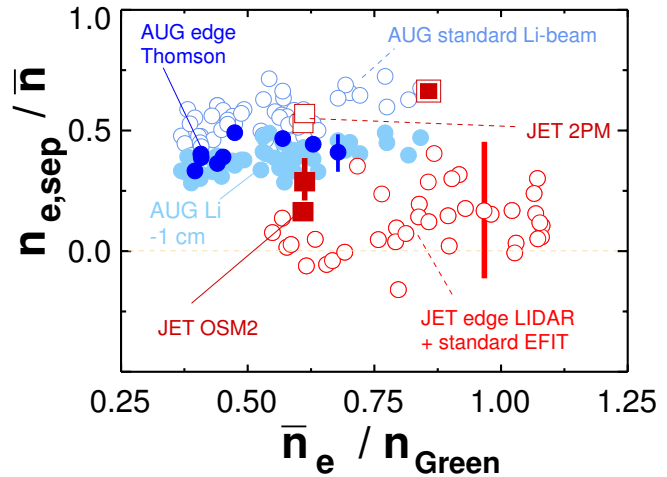


Figure 1: Comparison of normalized H-mode separatrix densities in JET and AUG versus the Greenwald fraction obtained by various diagnostics.

## Edge density profile measurements in JET and ASDEX Upgrade

Various data for the normalized separatrix density in JET and ASDEX Upgrade (AUG) are compared in Fig. 1 also showing typical error bars. The Greenwald fraction is used as ordering parameter, since  $n_{e,sep} / \bar{n}_e$  is generally observed to rise with gas puff or ELM frequency, respectively. The most reliable results in AUG are obtained with the edge Thomson scattering system in combination with dedicated radial plasma sweeps<sup>1</sup>. To determine the temperature and density profile shapes, a box car Bayes-filter<sup>3</sup> with 2 mm radial width is applied to a few hundred data points measured by 6 lasers with 20 Hz repetition frequency each at 4 radial

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channels. Typical results for two H-mode discharges with weak and medium gas puffing are shown in Fig. 2. 2-point modelling is used to check the radial position with respect to the separatrix by comparison of  $T_{e,Thomson}$  and  $T_{e,u}$ . Typically,  $T_{e,u}$  from 2-point modelling and the experimental midplane separatrix temperature agree very well, corresponding to a radial uncertainty  $\delta T/\nabla T$  of less than 3 mm. The high quality Thomson measurements represent a longer time interval ( $\approx 1$  s) necessary for the radial sweep. Routine and temporally resolved measurements are obtained from the lithium beam diagnostics. However, no direct check of the radial position is possible in this case due to the lack of the simultaneous temperature measurement. Uncertainties of the radial position turn into a corresponding error of  $n_{e,sep}$ . Comparison of Li-beam and Thomson data suggest a radial inward shift of the Li-beam measurements by 1 cm, leading to lower separatrix densities<sup>4</sup>.

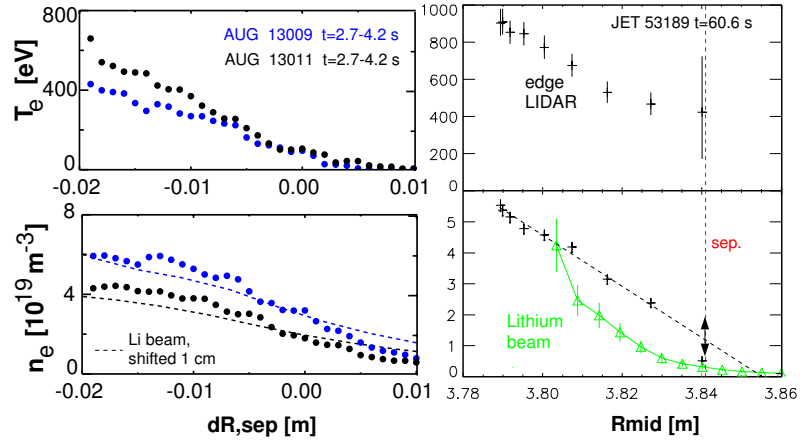


Figure 2: Edge profile measurements in AUG and JET H-modes with Thomson and Li-beam diagnostic.

At JET, the best radial resolution ( $\sim 1$  cm)<sup>5</sup> is provided by the Lithium beam diagnostics but the results are not routinely available. Edge LIDAR measurements are routinely available with 1 Hz repetition frequency, but the gradients in H-mode edge can usually not be resolved due to the limited spatial resolution ( $\sim 3$  cm) of the system<sup>5</sup>. The Li-beam and edge LIDAR systems have essentially different geometries but use similar EFIT reconstruction for magnetic midplane mapping. The accuracy of such reconstruction is about 2 cm. The data points shown in Fig. 1 exhibit the large scattering expected from a radial mapping uncertainty of 2 cm in combination with steep gradients. The values of  $n_{e,sep}$  were obtained by a linear fit of the data in the edge region. The negative values stem from the extrapolation to  $R_{sep}$  and reflect the mapping errors. The relatively large uncertainty of magnetic mapping in JET is partly caused by the iron core, which makes magnetic reconstruction difficult.

A different approach to determine the midplane electron density is to use target probe data and apply a 2-point model for mapping into the midplane. The power flux in the electron channel is taken from Langmuir probes, while the total power flux is either taken from  $P_{heat}-P_{rad}$  or thermocouple measurements<sup>6</sup>. Spitzer parallel resistivity is used to calculate the upstream  $T_{e,u}$ , the upstream density is obtained from pressure balance and  $T_e$  and  $n_e$  at the target. Consequently, 2-point modelling is applicable only for attached conditions. A more sophisticated extension of the 2-point model is the onion-skin model (OSM), which takes into account radiation and collisionality effects. The most accurate separatrix density values in the H-mode in JET are believed to be those obtained by the actual OSM2 model, provided that  $n_e$ ,  $T_e$  profiles at the target have been obtained using strike point sweeping. As shown in

Fig. 1, OSM2 gives significantly lower separatrix densities compared to the 2-point model for low densities, but very similar values for high densities. This difference is attributed to the large  $T_i/T_e$  values at low density. OSM modelling of upstream  $n_{e,sep}$  based on target Langmuir probes is not available for AUG Div II due to concerns about Langmuir probe reliability for the very low field line pitch angles.

### Correction of the JET edge LIDAR temperature measurement

In AUG, the simultaneous measurement of  $T_e$  and  $n_e$  by the Thomson scattering diagnostic is optionally used to correct the separatrix position with 2-point model  $T_{e,sep}$  to improve the derived  $n_{e,sep}$ . Typical values of  $T_{e,sep}$  are around 100 eV in AUG and JET. JET edge LIDAR yields often much larger values of  $T_{e,sep}$  (see Fig. 2), which is partly understood as an instrumental effect: The LIDAR evaluation assigns the measured values of electron temperature and density to the radial position which corresponds to the center of the radial interval where photons are collected. If an electron density gradient is present, the LIDAR detector receives more photons from the region of higher density, leading to a shift of the effective measurement position towards the region with higher density. For the usual case of a decreasing density towards the edge, this leads to an overestimation of the temperature. Fig. 3 shows a modelling of this effect using the simplified assumption of temperature averaging in the detection system to be proportional to the photon number. In the typical example shown, the measured  $T_e$  of 200 eV corresponds to true 100 eV. If this value is used e.g. in the 2-point model, higher values of the the separatrix density are obtained. The procedure described above makes the higher  $T_e$  values seen by the edge LIDAR more plausible, but can finally not lead to accurate values of separatrix parameters due to the lack of spatial resolution.

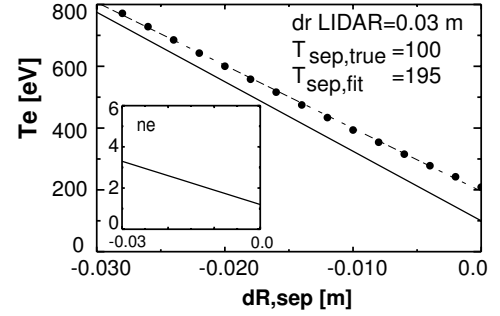


Figure 3: Simulation of apparent temperature overestimation of edge LIDAR caused by a density gradient.

### Relation of pedestal density and recycling

An alternative approach to characterise and compare the edge density uses the recycling taken from  $D_\alpha$  measurements and the line-averaged density as measure for the H-mode pedestal density<sup>8</sup>. Both are robust measurements and routinely available in AUG and JET. The main chamber recycling flux is related to an effective SOL density via a simple high recycling ansatz,  $n_{e,SOL} = 2.7 \cdot 10^9 m^{-2}s^{1/2} (\Gamma_{D\alpha}[m^{-2}s^{-1}])^{1/2}$ . This allows to write an expression for  $\bar{n}_e$  using SOL-related dimensionless parameters  $\rho^*$ ,  $v^*$ ,  $\beta$ , using the upstream temperature derived from a 2-point model and  $n_{e,SOL}$  as representative density. Analysis of 150 time slices yields

$$\bar{n}_e/n_{e,SOL} = 32.7 v^*{}^{0.285} \rho^*{}^{0.892} \beta_t^{-0.796} q_{95}^{-0.97} (\delta_{up} + 0.2)^{0.372} \approx \exp(w \cdot v_{in}/D) \quad (1)$$

In this form, the expression on the r.h.s. can be related to a density rise factor between SOL and pedestal, connected to a drift parameter  $v_{in}/D$  active over a radial range  $w$ . In dimensional units reads, Eq. 1 reads

$$\bar{n}_e = 3.3 \cdot 10^{17} \Gamma_{D\alpha}^{0.2445} P_{net}^{-0.263} q_{95}^{-0.944} B_t^{0.7} R_{geo}^{-0.607} (\delta_{up} + 0.2)^{0.372} \quad (2)$$

Particle transport calculations for the fuel ions with the STRAHL code for two well diagnosed discharges in JET and AUG are compared in Fig. 4. The code uses 1-d radially varying transport coefficients  $D$  and  $v$ , parallel losses are estimated by a parallel decay time. Hydrogen charge exchange is treated with a simple analytical model. The particle balance is treated via a chamber model including pumping and bypass times<sup>9</sup>  $\tau = V_{div}/S_{(pump,leak)}$ . Valve fueling is taken from the experiment, the radial SOL transport has been adjusted to match the measured  $D_\alpha$  recycling flux, which is the sum of main chamber recycling and divertor leakage neutrals. A passive wall with recycling coefficient of 1 is assumed. The STRAHL calculations reconcile the density rise factor  $\exp(w \cdot v_{in}/D)$  given by Eq. 1. Slightly lower values are obtained in the modelling in comparison to the scaling due to the effect of neutral fuelling inside the separatrix.  $D$ ,  $v$  are not determined independently, the relative influence of neutral fuelling depends on the absolute values and decreases with rising  $D$ ,  $v$  at constant drift parameter  $v/D$ .

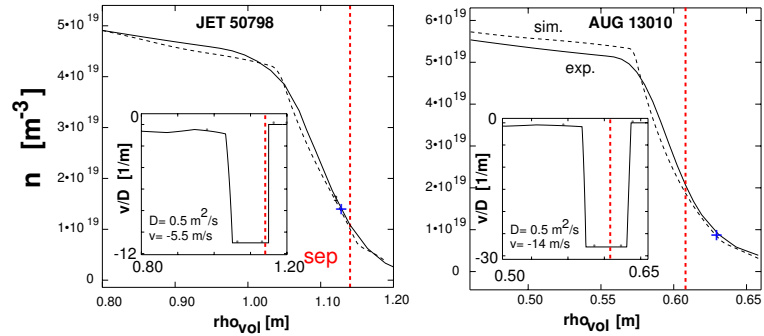


Figure 4: STRAHL modelling of density profiles in 2 well diagnosed JET and AUG discharges.

## Conclusions

Due to the large error bars involved, in particular caused by the magnetic mapping, a robust comparison of H-mode separatrix densities in JET and AUG is not possible so far. Comparing JET OSM2 results with AUG Thomson and shifted Li-beam measurements, similarly large fractions of  $n_{e,sep}/\bar{n}_e$  are obtained with strong gas puffing. At lower density/without gas puffing, the normalized separatrix density in JET appears to be lower compared to AUG. The steeper rise of the normalized density in JET with gas puff or, synonymously, ELM frequency compared to AUG is in accordance with published results<sup>7,2</sup>. For these low density conditions, the major part of the target power flux is carried by ions. An empirical scaling is given for the buildup of the pedestal density assuming main chamber recycling as the dominant particle source for JET and AUG which exhibits a strong positive dependence on upper triangularity. The steep edge density gradients are related to the presence of an inward particle pinch.

## References

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