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Scaling of density peaking in ELMy H–mode plasmas based on a combined database of AUG and JET observations

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The extrapolability of present plasma scenarios to ITER partly depends on whether the same shape of the density profile will be realized also in burning plasmas. The shape of the density profile has important consequences on both the plasma confinement and the plasma stability. In a burning plasma, with the same temperature profiles and the same volume averaged density, a peaked density profile produces larger amount of fusion power and bootstrap current with respect to a flat profile. On the other hand, a too peaked density profile might have negative consequences on both the MHD stability and central accumulation of heavy impurities. Recent experimental results in AUG and JET H–mode plasmas indicate that the density peaking is correlated with the plasma collisionality [1,2]. This observation might lead to the prediction that density profiles in the ITER standard scenario will not be flat, as usually assumed [3], but peaked, since ITER collisionality is expected to be as low as the lowest collisionalities achieved in present devices. However, as long as results from a single device are considered, collisionality is correlated with other plasma parameters, in particular the Greenwald fraction, the normalized ion Larmor radius ρ_* and the fuelling provided by the beams. For the first time, here we present an empirical scaling for the density peaking taking into account observations from more than one device. We show that by combining observations from different devices, while some correlations are indeed reduced, also additional uncertainties are introduced. The way we have adopted to overcome the limitations encountered is discussed. Multiple regression analyses are performed which confirm that in the combined database of AUG and JET observations, collisionality is the most relevant parameter in the regressions. Scalings for density peaking are proposed and ITER projections are discussed.

Definition of the regression variables

Our purpose is to express the density peaking in the form of a multivariable regression in terms of dimensionless plasma parameters. The physics plasma parameters ρ_*, ν and β, are considered with the following definitions,

$$\rho_* = 0.3225\ (m_{\rm eff}\,\langle T\rangle)^{0.5}\,/B_T/a\ , \quad \nu_{\rm eff} = 0.1\,Z_{\rm eff}\,\langle n_e\rangle\,R_{geo}/\langle T\rangle)^2\ , \quad \beta = 8\pi\langle nT\rangle/B_T^2 .$$

Geometrical plasma parameters like q_{95}, the edge triangularity δ are also considered. Given the small variation of aspect ratio and elongation in AUG and JET, these two parameters are not included. Note that in AUG and JET these parameters are very close to those of ITER. Moreover, the plasma size (the major radius R), despite dimensional, is also included in part of the analysis as device label, in order to check its significance in the regressions. The analysis takes into account the Greenwald fraction as well, and compares its effect with respect to that of collisionality. Finally dimensionless variables to describe the particle source are considered. We made the assumption that the particle source provided by wall neutrals can be neglected for core density peaking, and considered only parametrizations of the beam fuelling. The neutral beam heating and particle source profiles are computed for all the observations by the PENCIL code for JET data and the Monte Carlo FAFNER code for AUG data. Two different parameters are considered to describe the beam particle source. The first is directly the peaking of the beam particle source profile. The second provides more precisely a quantification of the contribution

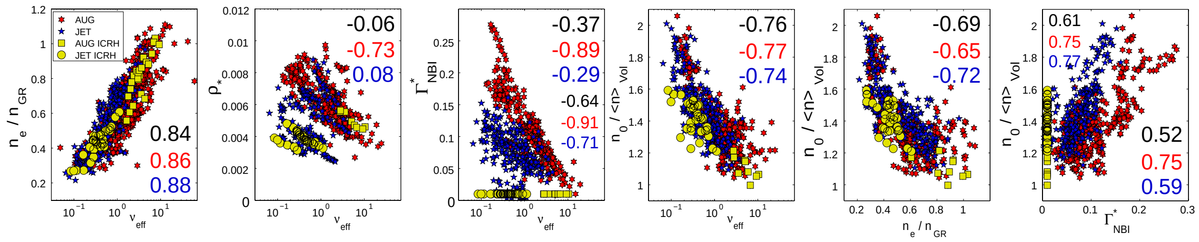

Fig. 1. *Univariable scatter plots among various plasma parameters. The numbers in the plots provide the related correlation coefficients, in black for the combined dataset, in red for the AUG data subset, in blue for the JET data subset. Smaller fonts used in plots involving the beam source parameter indicate the correlation coefficients over the subset of observations with* P_{NBI} / $P_{TOT} > 0.7$

to the density peaking provided by the beam particle source. Namely, by recasting the general diffusive law for the particle flux in the form

$$-\frac{1}{n}\frac{dn}{dr} = \frac{\Gamma}{nD} - \frac{V}{D}, \tag{1}$$

the local slope of the density profile in the LHS is expressed as the sum of the particle source contribution and the particle pinch contribution. The source contribution to the density peaking due to the beams can therefore be parametrized as follows,

$$\Gamma^*_{NBI} \doteq \frac{R\Gamma_{NBI}}{nD} = 2T\,\frac{\Gamma_{NBI}}{Q_{NBI}}\,\frac{Q_{NBI}}{Q_{TOT}}\left|\frac{R}{T}\frac{dT}{dr}\right|\,\frac{\chi}{D}.$$

Assuming that χ/D is a rather constant quantity (this is the strongest assumption of this procedure), all the other terms can be evaluated using the parameters available in the databases, like beam deposition profiles (or beam energy), total and beam heating powers (it has been assumed that all coupled RF power is absorbed inside $r/a = 0.5$), and the temperature profile peaking.

Definition of the response variable

The main difficulty encountered in combining observations from AUG and JET is related to a coherent definition and measurement of the regressed quantity, namely the density peaking (as well as for the regression variables). Different diagnostics for the density profiles might have small systematic errors which do not involve large uncertainties in the ITER prediction when considered alone, but which might cause extremely large uncertainties in the ITER predictions when combined with other diagnostics which might have systematic errors in different directions. This is reflected in particular in the ρ_* dependence. To make a clear example on this point, let assume that systematically JET density profiles are measured slightly more peaked than they actually are, and AUG density profiles slightly less peaked than they actually are. Of course as long as observations of a single device are considered these small systematic errors are reflected in a small overestimate or underestimate of the ITER peaking. If the measurements from the two devices are considered together in this form, they would artificially increase the ρ_* dependence of the peaking, with projections for ITER much more peaked than what should actually be.

To overcome this problem, we have applied a method to obtain values of density peaking from both AUG and JET derived with exactly the same procedure. First, we have observed that density profile measurements in JET show a better agreement between the Thomson scattering diagnostics and the interferometer line integrals than in AUG. On this basis we have assumed that JET profile reconstructions by SVD using both Thomson scattering and the interferometer measurements were more reliable than AUG measurements based on simple inversion of the interferometer. Second, we have computed the line integrals along the chords of the AUG interferometer of all the JET profiles of the database for a chosen AUG equilibrium. Third, again considering the same equilibrium, we have inverted the line integrals of the JET profiles by expressing the profiles as a linear combination of base functions for the profile shape. Finally, by the same method also all the AUG interferometry measured line integrals are inverted. In this way a set of density profiles, for both AUG and JET, reconstructed from the AUG interferometer line integrals by the same inversion method is obtained. Among the various possible definitions of density peaking, the definition $n_e(\rho_{pol} = 0.2) / \langle n_e \rangle_{Vol}$ is rather independent of the choice of the basis functions for the inversion, and strongly determined once all the line integrals are matched. For this reason we have adopted this definition of density peaking in our analysis. For example, we find that the RMSE between the original JET density peaking and the recalculated peaking is as small as 0.018.

Bivariate correlations

Fig. 1 shows a selection of scatter plots. The corresponding correlation coefficients are quoted in the figure, in black for the combined database, in red for only AUG data, in blue for only JET data (those in smaller fonts indicate the correlation coefficients for the subset with $P_{NBI} / P_{TOT} > 0.7$). The combined database is composed of 277 JET observations and 343 AUG observations. We observe that while correlations with ρ_* are strongly reduced by combining observations from the two devices, the correlation between ν_{eff} and the Greenwald fraction remains rather large. Collisionality turns out to be the parameter which has the largest bivariate correlation with density peaking in the combined dataset. However, both the Greenwald fraction and the beam particle source parameter Γ^*_{NBI} show very large correlations with density peaking. Finally, a very strong correlation coefficient (-0.91) between collisionality and the beam particle source parameter in AUG plasmas heated with NBI only is found. This correlation is reduced by considering plasmas from the two devices. At the same value of collisionality, JET plasmas have a particle source parameter Γ^*_{NBI} which is on average smaller than AUG plasmas.

Multivariable statistical analysis

Let us consider the vector of observations of the regressed variable Y and N vectors of regression variables X_j. A linear or logarithmic multivariable regression expresses Y in the forms

$$Y = c + \sum_j a_j X_j \qquad \text{or} \qquad Y = C\,\Pi_j X_j^{a_j}\,.$$

According to [4], we define the following parameter to describe the statistical relevance StR_j of the parameter X_j in the linear regression for Y, $StR_j = a_j \times \mathrm{STD}(X_j)$, where with STD we indicate the usual standard deviation. Analogously for a logarithmic regression, $StR_j = a_j \times \mathrm{STD}(log(X_j))$. In this way StR_j estimates the variation of the (logarithm of the) regressed variable for one standard deviation variation of the (logarithm of the) regression variable X_j. The larger StR_j is, the higher is the relevance of the variable X_j in the regression for Y. Besides this parameter, we have also considered an estimate of the statistical significance of each regression variable, $StS_j = a_j/\Delta a_j$, where with Δa_j we consider the 90% confidence interval of the regression coefficient a_j. Table 1 shows the statistical relevance normalized to the maximum value obtained in each regression for a set of plasma parameters. Different regression models are considered. Regressions which include the collisionality and exclude the Greenwald fraction N_{GR}, and which include the Greenwald fraction and exclude the collisionality, as well as regressions which include both these plasma parameters, are considered. Moreover, for comparison, models which, besides the dimensionless variables, include as well a device label (namely the geometrical major radius) are analysed. A set of considerations and conclusions can be drawn. In all the regression models which include collisionality, collisionality is found to be the parameter with the largest statistical significance and the largest statistical relevance. Comparable RMSE is found when the device label is included or excluded. In regression models which include collisionality and exclude the major radius, rhostar is found to have a negligible statistical significance and statistical relevance. In regression models which include the Greenwald fraction and exclude collisionality, the device size is found to play a more important role, through a larger statistical relevance of ρ_* and/or the major radius. The signs of the regression coefficients indicate that at the same Greenwald fraction, the density peaking is larger in JET than in AUG. In regression models which exclude collisionality and include the Greenwald fraction, the beam particle source parameter is found to have a larger statistical relevance. Finally, in regression models which include both collisionality and the Greenwald fraction, density peaking is found to increase with increasing Greenwald fraction, namely at fixed collisionality. Finally, if the weight of ICRH points is increased in the regression, the RMSE of regressions which exclude collisionality increase more than those of regressions which include collisionality.

Γ^*_{NBI}	$\ln \nu_{eff}$	N_{GR}	ρ_*	β	q_{95}	δ	$T_{e2}/\langle T_e \rangle$	R_{geo}	RMSE
0.78	−1		0.19	−0.43	−0.11	−0.15	0.05	0.44	0.113
0.55	−1		−0.06	−0.24	−0.13	−0.03	−0.02		0.114
1		−0.56	0.21	−0.31	0.06	−0.17	−0.09	0.89	0.121
0.80		−1	−0.50	0.13	0.00	0.17	−0.24		0.126
0.64	−1	0.27	0.29	−0.49	−0.11	−0.21	0.05	0.42	0.112
0.49	−1	0.13	−0.01	−0.27	−0.13	−0.06	−0.02		0.114

Table 1. *Table of values of the Statistical Relevance, as defined by Eq. for various plasma parameters used as regression variables for the density peaking.*

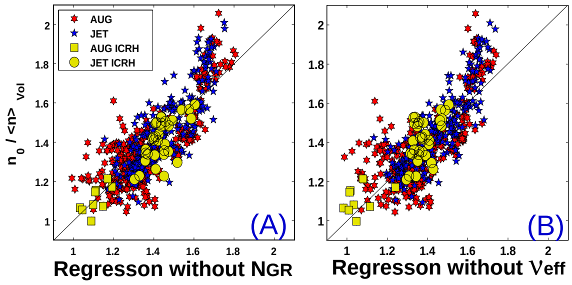

Fig 2. *Density peaking versus the scaling for the two regressions proposed, (A) excluding the Greenwald fraction, (B) excluding collisionality.*

Proposed scalings and ITER predictions

Different regression models are considered, in both the logarithmic and the linear forms. Here we propose two linear regressions, one which includes collisionality and excludes the Greenwald fraction, and one which excludes the collisionality and includes the Greenwald fraction (Fig. 2). For density peaking, the linear regression is prefered to the logarithmic one since it is deemed to be more appropriate to the physical nature of this regressed quantity, as shown by Eq. 1.

Of course, in these proposed scalings, only the statistically significant regression variables are used. The regression without using the Greenwald fraction reads

$$n_{e2}/\langle n_e \rangle_{Vol} = 1.350 \pm 0.023 - 0.115 \pm 0.008\, log(\nu_{\text{eff}}) + 1.171 \pm 0.162\, \Gamma^*_{NBI} - 4.410 \pm 1.311\, \beta,$$

with RMSE = 0.115 (90% confidence intervals for the regression coefficients are quoted). The regression without using the collisionality reads

$$\begin{aligned} n_{e2}/\langle n_e \rangle_{Vol} &= 1.778 \pm 0.077 - 0.624 \pm 0.060\, N_{GR} + 1.682 \pm 0.218\, \Gamma^*_{NBI} + \\ &\quad - 22.61 \pm 6.64\, \rho_* - 0.055 \pm 0.025\, T_{e2}/\langle T_e \rangle_{Vol} + 0.308 \pm 0.120\, \delta, \end{aligned}$$

with RMSE = 0.125.

These regressions, as well as analogous regressions in the logarithmic form, are applied for ITER predictions. For the ITER standard scenario, with the plasma parameters described in [3], and in particular $\langle T_e \rangle_{Vol} = 8$ keV and $\langle n_e \rangle_{Vol} = 10^{20}$ m^{-3}, and taking the beam particle source equal to zero, the first regression predicts the peaking $n_{e2}/\langle n_e \rangle_{Vol} = 1.45 \pm 0.04$. This corresponds to a value of R/L_n, namely the normalized logarithmic gradient at mid–radius, between 3 and 4. More in general, *all* linear or logarithmic regressions which include collisionality in the regression variables predict a peaked density profile for ITER, more precisely values of the peaking above 1.35. The proposed scaling which excludes collisionality in the regression variables, predicts the ITER peaking $n_{e2}/\langle n_e \rangle_{Vol} = 1.18 \pm 0.24$, namely a rather flat profile. More in general, scalings which exclude collisionality from the regression variables, predict flat density profiles for ITER, namely values of peaking below 1.2. In conclusion, we emphasize that the option of excluding collisionality from the regression variables cannot be motivated by any physical argument. A predicted value of density peaking for the ITER standard scenario between 1.4 and 1.5 is the final outcome of the present work.

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* *See Appendix of J.Pamela et al, Fusion Energy 2004 (Proc. 20th Int. Conf. Vilamoura, 2004) IAEA, Vienna (2004).*