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ABSTRACT
The natural H-mode density, i.e. the plasma density evolving in an H-mode discharge without active fuelling, reaches Greenwald fractions in JET typically higher than in ASDEX Upgrade.According to general thinking this reflects device-specic differences as regards recycling-induced fuelling and beam fuelling. This paper presents evidence for a different view, namely that at suciently low plasma fuelling rates any fuelling rate dependence of the plasma density vanishes and the plasma particle content is completely determined by the plasma itself. It is shown that this limit, which would constitutes an additional H-mode operational boundary, is reached in JET and ASDEX Upgrade natural density discharges and its scaling is determined. Possible overlapping with existing density limit scalings in next-generation tokamaks is discussed with a view to the potential implications for the H-mode operation window.

1. INTRODUCTION.
As is well known, the H-mode regime can be accessed in the absence of any gas inlet with a selfconsistently evolving density commonly referred to as the natural density" (ND). The present study was triggered by the observation of striking diferences between JET and ASDEX-Upgrade NDs. In ASDEX-Upgrade the ND is typically well below the Greenwald density, while it is systematically higher in JET and, for certain parameter combinations, may almost reach the Greenwald value. This raises the question of a size dependence of the ND and whether it may exceed the density limit in even larger machines, possibly implying a vanishing H-mode operation window.

According to general thinking the actual value of the ND is determined by the only two remaining particle sources, namely beam fuelling and wall induced fuelling, resulting from the interaction with the particle reservoir deposited in the surrounding walls through recycling. The latter is largely unknown and difficult to control and may even depend on the discharge history of a device. Therefore, in this picture an essential parameter that controls the ND is unknown, and this may explain why the investigation of the ND has gained little attention in the past.

This paper presents evidence for a rather different view, namely that at suffciently low fuelling rates the plasma density becomes independent of the particle sources. There would thus be a lower limit for the density which is no longer controlled by sources, but is completely determined by the plasma itself (natural density limit). It is shown here that it is actually adopted in JET and ASDEX Upgrade ND discharges. Of course, the surrounding walls still come into play in that they provide a reservoir for particles, but the amount of gas that is grasped is determined by the plasma. The limit density is then determined by well known and controllable parameters and its scaling can be determined by standard techniques.

From the previous discussion it is obvious that the direct verifcation of our hypothesis by a progressive reduction of the total plasma fuelling rate until its impact on density vanishes, is practically not feasible, and we have to rely on an indirect argument. The logic of thisargument is as follows: Knowing all parameters that determine a tokamak discharge, viz. the machine parameters (MPs) (R, a, k,...), the discharge parameters (DPs) (Bt, q_ψ,...) as well as the power to the plasma (Pin) and the plasma particle source ($\dot{N}$), one can, at least in principle, express any plasma quantity as a function of these parameters. For the line-averaged density, for instance, one has $n = n(MP; DP; Pin ;\dot{N})$ Due to the insufficient knowledge of $\dot{N}$ this relation is of limited practical use. One way to overcome this problem is to replace $\dot{N}$ by any plasma parameter that is in a one-to-one way linked with $\dot{N}$. In practical applications it is typically assumed that all dependences are of the power law type so that this condition is automatically met. One can then search for scalings of, for instance, n in terms of MPs, DPs, P_{in} and any other plasma parameter [1, 2]. If the $\dot{N}$ dependence vanishes in natural density discharges, a scaling for the natural density n_{ND} must exist which is entirely in terms of MPs, DPs and P_{in}. Thus, the existence of such a scaling is a necessary condition for our hypothesis to hold. It is also sufficient, provided that in the underlying database $\dot{N}$ is not correlated with the MPs, DPs or Pin. There are two areas where this requirement is not or possibly not fulfilled:

(i) The majority of empirical data are obtained in experiments which were performed at constant beam energy. In that case $\dot{N}$beam / Pin holds, where $\dot{N}$beam is the beam fuelling rate. Experimentaldata at dierent beam fuelling rates are required to remedy the problem.

(ii) As regards the recycling-induced fuelling rate $\dot{N}$ wall, it cannot be excluded that we accidentally select discharges with identical wall parameters, thus making the wall-induced fuelling rate a function of plasma parameters only.

Fortunately, a limited number of dedicated JET experiments exist where the beam or wall-induced fuelling rate is varied under otherwise fixed conditions, but the number is small and it would not be meaningful to include them in the statistical analysis. Instead the following procedure is adopted: In a first step the existing database is analyzed and it is shown that a scaling for n_{ND} of the required format exists. We then discuss in detail beam energy variation experiments and experiments where the wall conditions were deliberately changed.

In order to get information on the size dependence, we have to consider data from at least two machines. The choice of JET and ASDEX Upgrade was determined by easy access to background information on the diagnostic involved, which is mandatory in the light of some details associated with ND discharges.

The scaling issues are addressed in Sec. 2. In Sec. 3 JET beam energy variation and vessel temperature variation experiments are discussed to complement the results of Sec. 2. In Sec. 4 the implications of our findings are discussed with a particular view to thepotential of large tokamaks to operate in H-mode.

2. NATURAL DENSITY SCALING

2.1 JET NATURAL DENSITY DISCHARGES

ND discharges are not normally a key element of experimental programmes, but rather a byproduct of other activities. In JET the situation is relatively favourable. Density ramp-ups are typically realized by performing a sequence of discharges with constant, but successively increasing gas rates. Such a series normally starts with an ND discharge. Examples of such ramp-ups are density limit studies, so that the ND database basically covers the same parameter space as the density limit database and includes data in a wide parameter range and from dierent magnetic and divertor congurations. To minimize the potential impact of the plasma-wall interaction history attention is conned mainly to ND discharges performed at the beginning of an early shift. We also select discharges with a suciently long at-top phase to reach steady-state (5 to 10s). Densities are taken at the end of the at-top phase. The impact of wall loading with gas is relatively moderate in JET. It can be estimated from ND discharges performed at the end of a high-density gas scan, the densities of which exceed those performed prior to the scan by hardly more than 15 to 20%. This observation is in line with the results of dedicated wall loading experiments recently performed at JET.

2.2 ASDEX UPGRADE NATURAL DENSITY DISCHARGES

In ASDEX Upgrade the situation is less favourable. Unlike in JET, density ramp-ups are performed by continuously increasing the gas rate during a discharge, starting with relatively high rates. However, so-called standard discharges are routinely performed to check the machine conditions. They are good ND discharges and exist in large number, but, unfortunately, are always performed for the samexed set ofparameters. They show very little scatter and therefore provide at least a good database for the size scaling. In addition to these only a few good cases have been identied so far, so that the parameter range covered by the ASDEX Upgrade data is somewhat modest.

2.3 EMPIRICAL SCALING

In the absence of a clear understanding of the physics underlying the formation of the ND, the line-averaged density is chosen as a target. According to the discussion of Sec. 1, one should seek a scaling in terms of the major radius R, aspect ratio A, shaping parameters (elongation κ, upper triangularity δ_u, lower triangularity δ_ι , etc.), toroidal field B_t, safety factor q_{95} , heating power P_h and one other plasma parameter replacing the plasma particle source. Following Ref. [2] we choose for the latter the midplane recycling flux measured by the D_α photon flux $\Gamma_{D\alpha}$. As pointed out, we are free to choose any plasma quantity, but due to the close relation between $\Gamma_{D\alpha}$ and wall fuelling the disappearance of any Γ_D -dependence will be particularly convincing.

In a JET and ASDEX Upgrade database there is naturally little variation of A and κ. We therefore completely ignore any dependences on these variables. Since next-generation devices will have aspect ratios and elongations not too far off those of JET and AS- DEX Upgrade and since possible implications for next-generation machines are our main interest, this is not a matter of particular concern

The role of triangularity is somewhat special in that variations of δ_u (upper triangularity) and/or δ_ι (lower triangularity) suffer from numerous device-related constraints. In the light of these limitations it seems appropriate to characterize triangularity (as a first step) by a single parameter such as δ_u, δ_ι or a simple combination of the two. δ_u seems to be a reasonable choice [2] and will be adopted in what follows. Since δ_u may be negative in ASDEX Upgrade, δ_u is replaced by $1+\delta_u$. (Whether the power law ansatz remains justied for $1 + \delta_u$ has to be checked a posteriori.)

To take into account potentially different impurity levels we replace the heating power by the net input power $P_{in} = P_h - P_{\mathrm{rad}}^{\mathrm{tot}}$, where $P_{\mathrm{rad}}^{\mathrm{tot}}$ is the total radiated power. Since the power dependence will be found to vanish virtually, these details are more of a cosmetic character. Finally, Pin is replaced by the mean power flux across the separatrix $q\perp$, ($q\perp = (P_{heat} - P_{\mathrm{rad}}^{\mathrm{tot}}) / O_p$, where O_p is the plasma surface) to simplify the discussion of Sec. 4.

In addition to the parameters discussed, there remain a vast number of others which could, in principle, have an impact: divertor congurations, higher-order shape parameters, plasma-wall distances, power deposition profiles, etc. To assess whether some of the scatter is due to such hidden dependences would require a more refined analysis exceeding the scope of the present paper. In any case the influence seems to be small and would probably not affect our conclusions.

Summarizing our discussion, we should now seek a scaling of n_{ND} in terms of *R, Bt,* q_{95}, $q\perp$, $1+\delta_u$ and D. Hovever, a virtually vanishing $\Gamma_{D\alpha}$-dependence would be sensitively affected even by minor discrepancies in the calibration of the D_α photon flux diagnostics of JET and ASDEX Upgrade. In order not to be mislead by this, we therefore first check the $\Gamma_{D\alpha}$- dependence separately on the subset of JET data ignoring any *R*-dependence. Using the usual assumptions of least-squares regression, we then obtain the empirical scaling

$$n^{JET}_{ND,fit} = \mathrm{x}4.38 \frac{B_t^{0.65-0.11}(1+\delta_u)\Gamma_{D_\alpha}^{0.93\pm0.25}}{q_\perp^{0.17\pm0.079}\, q_{95}^{0.60\pm0.017}} \qquad (1)$$

[10^{19}m^{-3}, MW, T, 10^{17}s^{-1}m^{-2}sr^{-1}] where the exponents are given with their 95% confidence intervals. The $\Gamma_{D\alpha}$-dependence obviously vanishes within the error bars.

Having demonstrated that $\bar{n}ND$ can indeed be described in terms DPs, MPs and Pin, we now obtain our final scaling by doing a regression for R, q95, Bt, q? and 1 + u on the full JET and ASDEX Upgrade database:

$$n_{ND,fit} = \mathrm{x}9.77 \frac{q_\perp^{0.014-0.064}\, B_t^{0.61\pm0.09}(1+\delta_u)^{1.00\pm0.22}}{q_{95}^{0.62\pm0.17}\, R^{0.57\pm0.014}} \qquad (2)$$

Equation (2) is complemented by information from Figs 1 and 2. Figure 1 illustrates the quality of the fit as well as the range of variation of the natural density. Figure 2 provides the range of q_{95}, B_t, P_{heat} and δ_u variations covered by the database. Figure 2 also confirms that the power law ansatz underlying Eqs (1) and (2) is indeed justified for all variables. Despite the limited range of variation of the ASDEX Upgrade data, there is some evidence that the two machines scale in the same way.

This section is concluded with a brief discussion of "density moments" other than line averaged density. Of particular interest is the pedestal density $n_{ND},_{ped}$.

In fact, our main focus is the relation between natural density and density limits and there are indications that the H-mode density limit is actually a limit of the pedestal density [3, 4]. We determine $n_{ND},_{ped}$ for a selection of JET points using core Lidar data. A problem arises through the fact that ND profiles may be rather peaked at lower densities, which makes it difficult to identify the pedestal position from the noisy and poorly resolved Lidar data. The data therefore have to be interpreted as preliminary. In Fig. 3 $n_{ND},_{ped}/n_{ND}$ is plotted versus n_{ND}. Despite the caveats there is evidence that $n_{ND},_{ped}/n_{ND}$ approaches unity with increasing density. This is a rather interesting point. Flattening of the density prole is systematically observed in density scans when the density limit is approached [3, 4]. Figure 3 indicates that this is not simply a consequence of the strong boundary particle source associated with massive gas puffing.

3.0 SUPPLEMENTARY STUDIES

3.1 JET BEAM ENERGY VARIATION EXPERIMENTS

Dedicated beam energy experiments have been performed on JET which provide independent variation of the beam fuelling rate. Otherwise identical discharges were conducted with beam energies of 80keV and 140keV including pairs with no gas inlet. As an example we consider discharges 45741 (80keV) and 45722 (140keV) (P_h = 7:1MW, B_t = 2:0T, I_p = 1:8MA, δ_u/ι = 0:2/0:3). Despite the different beam fuelling rates the flat-top densities of the two discharges are identical in shape and magnitude (Fig. 4). It is interesting to note that effects are seen at moderate gas rates which again vanish at high gas rates. This is completely in line with our picture: At zero gas rate the beam fuelling rate is below the threshold. At medium gas rates the total fuelling rate is above the threshold,
but external and beam fuelling are still comparable, so that variation of beam fuelling has a visible effect. At high gas rates external fuelling dominates and the impact of beam fuelling becomes negligible.

3.2 JET VESSEL TEMPERATURE VARIATION EXPERIMENTS

One way to change the recycling-relevant wall properties and hence wall fuelling is to operate at different wall temperatures. Pairs of identical discharges have been performed at JET at wall temperatures of 200° and 300° In Fig. 5 the flat-top density profiles of discharges 52987 (200°) and 52735 (300°) are shown as examples. As in the case of beam fuelling variation, the two profiles are found to be identical in size and shape. In Fig. 5 $\Gamma_{D\alpha}$ is plotted for the two discharges. There is a marked difference between the two discharges, providing evidence that the wall properties are indeed affected. In complete analogy with Sec. 3.1 effects are seen at medium gas rates which again vanish at high gas rates.

4. IMPLICATIONS FOR THE H-MODE OPERATION WINDOW

In this section we discuss the conditions for $\phi \equiv n_{ND}/n_{DL} < 1$ to hold, where n_{DL} is the H-mode density limit. It is not a priori clear what happens in a device where $\phi > 1$, but it is natural to expect that $\phi < 1$ is a prerequisite for the existence of an H-mode operation window. This is suggested by, in particular, the fact that the H-mode density limit seems to coincide with the high-density H-mode operation boundary [3, 4].

Various scalings have been proposed for the H-mode density limit. We discuss as one example the scaling proposed by Borrass, Lingertat and Schneider [5], which provides an excellent description of JET and ASDEX Upgrade data [3, 4]. It results in (Eq. (7) of Ref. [5])

$$\bar{n}_{BLS} = 41.4 \frac{q_\perp^{0.09\pm0.064} \ B_t^{0.53}}{(q_{95} \ R)^{0.88}} \tag{3}$$

$[10^{19}m^{-3}, MWm^{-2}, T, m]$. It is basically a limit for the pedestal density, but at the limit density proles are found to be at so that no distinction between theline averaged and pedestal densities has to be made.

As a second example we consider the empirical Greenwald scaling [6], which is known to give a crude description of H-mode density limit data and is widely used as a reference scaling:

$$\bar{n}_{GW} = 10 \frac{I_p}{\pi a^2} \equiv 15.9 g \frac{B_t}{q_{95} R} \tag{4}$$

$[10^{19}m$, MA, T, m], where $g = q_{95}/q_c$ ($qc = \frac{2\pi}{\mu_0} \frac{a^2 B_t}{R I_p}$ being the cylindrical q) is determined by the plasma shape (elongation, triangularity). The Greenwald scaling is generally interpreted as a scaling for the line averaged density.

Combining Eqs (3) and (4) with Eq. (2) we get, respectively,

$$\phi_{BLS} = 0.24 \frac{B_t^{0.08} R^{0.31} \ q_{95}^{0.26} (1+\delta)^{1.00}}{q_\perp^{0.076}} \tag{5}$$

[*MW, m, T*] and

$$\phi_{GR} = \frac{0.61}{g} \frac{q_\perp^{0.014} R^{0.43} \ q_{95} (1+\delta_u)^{1.00}}{B_t^{0.39}} \tag{6}$$

[*MW, m, T*]. To make Eq. (5) meaningful it is mandatory that ND profiles flatten as in gas-fuelled discharges, when n_{ND} approaches nBLS. Some evidence that justies this assumption was given at the end of Sec. 2.3 (see Fig. 3).

Extrapolation to ITER is, of course, our main concern. The $q\perp$ dependences are negligible in Eqs. (5) and (6) and the of q_{95} ITER will not differ from typical values in current tokamaks. The main difference to present-day machines will be in size and field. To interpret the R and Bt dependences in Eqs (5) and (6) correctly, one has to take into account that in standard tokamaks (i.e. tokamaks based on tape-wound pure-tension D-shaped coils with aspect ratios between 3 and 4), one has roughly B_t^{max} $[T]/R[m]$ 0:8 1:2, where B_t^{max} is the maximumeld on axis [7]. Unlike present experimental tokamaks, ITER will have to operate at the highest possible B_t, so that any B_t-dependence actually establishes an additional size dependence. In this sense we have a positive size dependence of ϕ_{BLS}, while ϕ_{GR} is virtually size-independent. In both cases the δ_u-dependence is dominant. Note, however, that the shaping factor *g* in Eq. (6) increases with triangularity so that the δ_u-dependence is somewhat weaker in ϕ_{GR} than in ϕ_{BLS}. In conclusion, one would expect the BLS scaling to be more critical than the Greenwald scaling. This is indeed confirmed by numbers obtained for the recent ITER design points. For ITER-FEAT parameters (R = 6:2m, a = 2:0m, B_t = 5:3T, I_p = 15:0MA, q_{95} = 3:2, δ_u = 0:33, $q\perp$ = 0:10 (estimated from $P\alpha$ = 80MW, P_h = 40MW, P_{rad} = 50MW and a plasma surface of 680MW)) we obtain, for example,

$$\phi_{BLS}^{ITER-FEAT} = 1.00 \text{ and } \phi_{GR}^{ITER-FEAT} = 0.52$$

For ITER-FDR [8] parameters (*R = 8.14, a = 2.8m,* B_t *= 5.68,* I_p*= 21MA,* q_{95} *= 0.31,* δ_u *= 0.31,* $q\perp$ = 0.15) we obtain similiarly

$$\phi_{BLS}^{ITER-FDR} = 1.05 \text{ and } \phi_{GR}^{ITER-FDR} = 0.63$$

3. SUMMARY AND CONCLUSIONS

We have investigated the density formation of JET and ASDEX Upgrade H-mode discharges in the so-called natural density limit, i.e. in the absence of external fuelling. It has been shown that the plasma density becomes independent of the particle source, if the strength of the latter drops below a certain value and that this limit is actually reached in well-conditioned JET and ASDEX Upgrade natural density discharges. At this limit the plasma particle content is completely determined by machine parameters, discharge parameters and heating power and thus, following conventional wording, constitutes an operational limit in the H-mode operation space. The existence of this operational limit is the main result of the present study.

The relation between the natural density boundary and the density limit has also been discussed with a view to possible overlapping of the two and the obvious implications for the existence of an H-mode operation window. An empirical natural density scaling was derived from JET and ASDEX Upgrade and the relation to existing density limit scalings was discussed in terms of the "proximity" parameter ϕ, where ≥ 1 would indicate a natural density exceeding the density limit. The Greenwald and BLS scalings were considered explicitly. Generally the BLS scaling results in higher ϕ values. For ITER (FEAT and FDR) ϕ_{BLS} parameters come close to unity but ϕ_{GR} is lower by a factor of about two.

While the existence of a natural density H-mode operational limit has a solid empirical basis, the scaling results have to beinterpreted with great care. This is due to some intrinsic defficiencies of the available data for both the natural density and density limit. As regards the ND database a major concern is the strong correlation between R and δ_u (see Fig. 2), which makes correct assessment of the size and triangularity dependences dicult. Unfortunately, this may strongly affect the predictions for ITER. In fact, while R (and B_t) increases by a factor of about two when going from JET to ITER, near-ITER δ_u values are already obtained in JET. Also, with data from only two machines, systematic errors in the density data, unfortunately not unusual, may indicate a nonexisting size dependence. A more subtle question is whether the plasma shape is properly described by the single parameter δ_u. Generally a wider ASDEX Upgrade database would be desirable, including data from high-triangularity congfigurations, to clarify these issues. Finally, our scaling is incomplete in that some parameters are not covered at all or only poorly covered by our database (aspect ratio, heating method and heat deposition prole, impact divertor conguration, etc.).

As regards the density limit set by the high density H-L boundary, considerable progress has been made in recent years in determining its empirical scaling and in understanding the underlying physics [3,4,5], the only remaining question being the impact of triangularity. Though there are indications that the high-density H-L boundary depends only weakly, if at all, on triangularity, the existing database is insucient to resolve this issue. Dedicated experiments are in preparation on both JET and ASDEX Upgrade which will hopefully close this gap.

In summary, the preceding discussion leads us to the following conclusions: For the Greenwald scaling we are on the safe side, but this is not particularly relevant in the light of the failure of the Greenwald scaling to describe empirical findings [4]. For the BLS scaling, which has proved to be an excellent description of existing JET and ASDEX Upgrade data, the situation is marginal. In the light of the uncertainties discussed this means that we may be on the safe side, but it may also well be that we have a problem in next-generation devices. Further investigations along the lines discussed should therefore be performed with priority.

ACKNOWLEDGEMENTS

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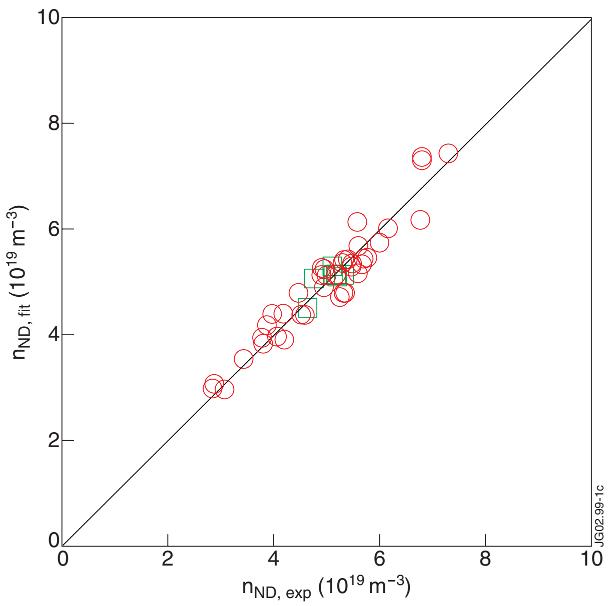

Figure 1: Density $n_{ND,fit}$ calculated from Eq. (1) versus experimental natural densities $n_{ND,exp}$ from JET (circles) and ASDEX Upgrade (squares).

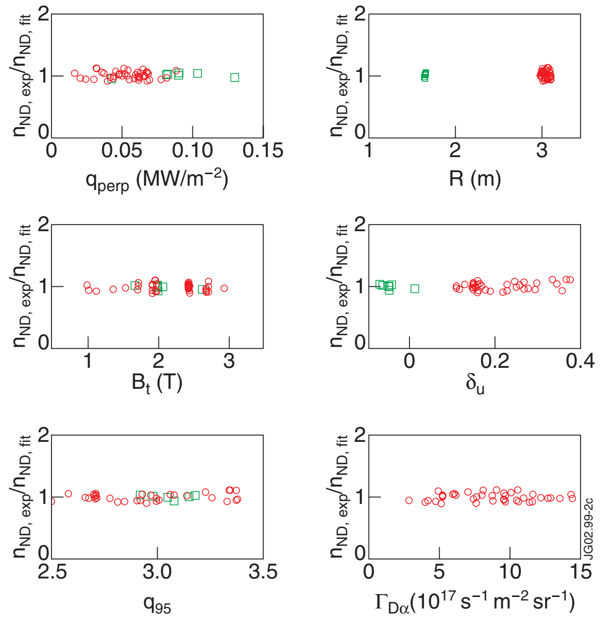

Figure 2: Experimental natural densities $n_{ND,exp}$ from JET (circles) and ASDEX-Upgrade (squares) over $n_{ND,fit}$ calculated from Eq. (2) versus mean power ux across the separatrix $q_{\perp}$, toroidaleld B_t, safety factor q_{95} at the 95% ux surface, major radius R, upper triangularity δ_u and D photon flux ΓD_{α}.

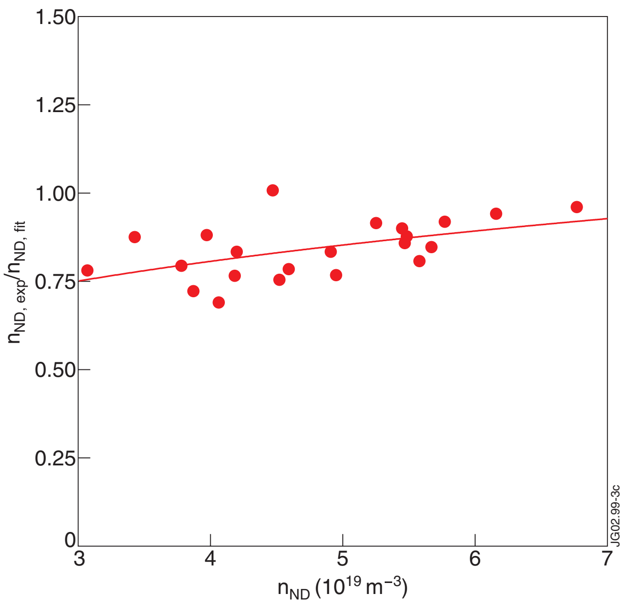

Figure 3: $n_{ND,ped}/n_{ND}$ versus n_{ND} for a selection of JET points. $n_{ND;ped}$ and nND are the pedestal and line averaged densities determined from core Lidar data. The solid line is the standard least- squares regressiont. $n_{ND,ped}/n_{ND}$ approaches unity with increasing n_{ND}.

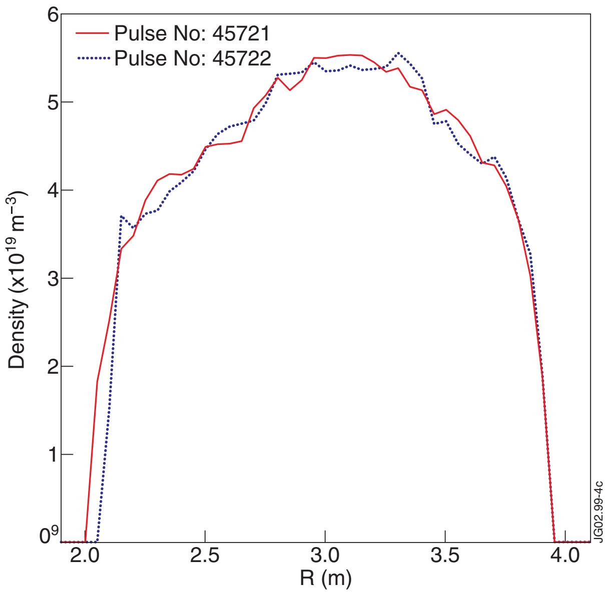

Figure 4: Flat-top density proles (Lidar) of JET Pulse No: 45741 (solid lines) and 45722 (dashed lines) with beam energies of 80keV and 140keV, respectively. All other parameters are identical (P_h=7.1MW, B_t=2.0T, I_p=1.8MA, $\delta_{u/l}$ = 0.2/0.3). Each discharge is the average of three adjacent (in time) profiles to avoid misleading by the Lidar noise.

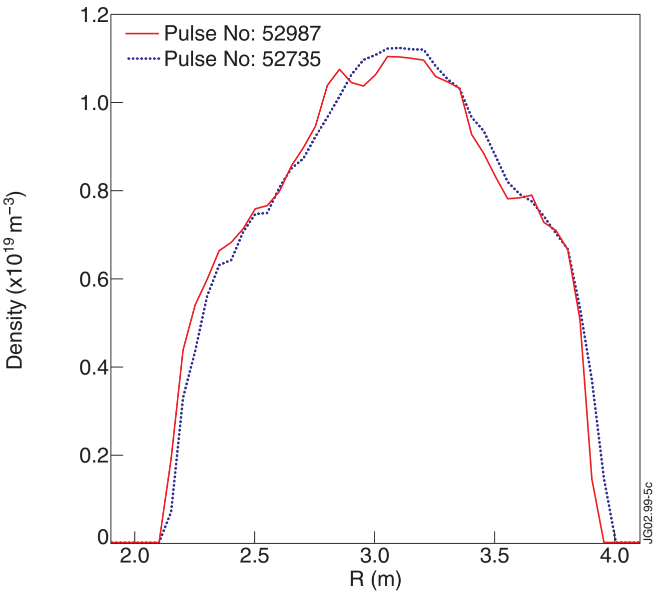

Figure 5: Flat-top density proles (Lidar) of JET Pulse No's: 52987 (solid lines) and 52735 (dashed lines) with wall temperatures of 200^o and 300^o, respectively. All other parameters are identical (P_h=14MW, B_t=2.7T, I_p=2.5MA, $\delta_{u/l}$ = 0.5/0.4). Each discharge is the average of three adjacent (in time) proles to avoid misleading by the Lidar noise.

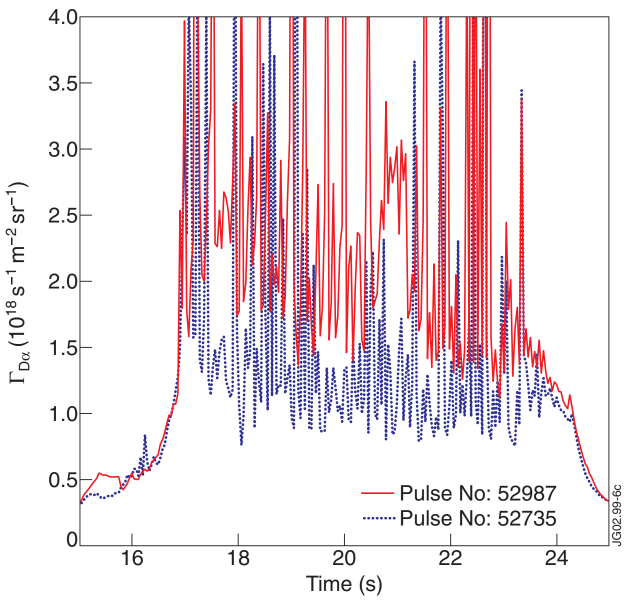

Figure 6: Midplane Dα photon flux for JET Pulse No's: 52987 (solid lines) and 52735 (dashed lines) with wall temperatures of 200^o and 300^o, respectively (see also Fig.5).