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Study of the Natural Density Formation in JET and ASDEX Upgrade

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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 re ects device-specic dierences as regards recycling induced fuelling and beam fuelling. This paper presents evidence for a dierent 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 constitute 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). 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. This paper presents evidence for a dierent view, namely that at suciently low fuelling rates the plasma density becomes independent of the particle sources. This would imply the existence of 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.

The wall recycling induced particle source is largely unknown and dicult to control. Therefore the direct verication 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 this argument is as follows: Knowing all parameters that determine a tokamak discharge, viz. the machine parameters (MPs) (R, a, κ, ...), the discharge parameters (DPs) (B_t, q_ψ ,...) as well as the power to the plasma (P_{in}) 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

$$n = n(MP; DP; P_{in}; \dot{N})$$

Due to the insucient 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 sucient, provided that in the underlying database $\dot{N}$ is not correlated with the MPs, DPs or P_{in}. There are two areas where this requirement is not or possibly not fullled:

(i) The majority of empirical data are obtained in experiments which were performed at constant beam energy. In that case $\dot{N}_{beam} \propto P_{in}$ holds, where $\dot{N}_{beam}$ is the beamfuelling rate. Experimental data 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 otherwisexed 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 arst 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 consider data from JET and ASDEX Upgrade.

2. NATURAL DENSITY 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_l, etc.), toroidaleld 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 ux measured by the D_α photon flux Γ_{D_α}. As pointed out, we are free to choose any plasma quantity, but due to the close relation between Γ_{D_α} and wall fuelling the disappearance of any Γ_{D_α}-dependence will be particularly convincing.

Some simplications, the detailed justication of which are discussed elsewhere [3], can be made:

(i) In a JET and ASDEX Upgrade database there is naturally little variation of A and κ and we therefore completely ignore any dependences on these variables.

(ii) Following Ref. [2] we characterize the plasma shape by the single parameter $1 + \delta_u$, where δ_u is the the upper triangularity.

(iii) To take into account potentially dierent impurity levels we replace the heating power by the net input power $P_{in} = P_h - P^{tot}_{rad}$, where P^{tot}_{rad} is the total radi©ted power. Finally, P_{in} is replaced by the mean power flux across the separatrix $q_\perp$ ($q_\perp = (P_{heat} - P^{tot}_{rad})/O_p$, where O_p is the plasma surface) to simplify the discussion of Sec. 4.

Summarizing our discussion, we should now seek a scaling of n_{ND} in terms of R, B_t, q_{95}, $q_\perp$, $1 + \delta_u$ and Γ_{D_α}. However, a virtually vanishing Γ_{D_α}-dependence would be sensitively aected even by minor discrepancies in the calibration of the D photon ux diagnostics of JET and ASDEX Upgrade. In order not to be mislead by this, we thereforerst check the D_α-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:

$$n^{JET}_{ND,\,fit} = 4.38\ \frac{B_t^{0.65-0.11}\,(1+\delta_u)^{0.93-0.25}\,\Gamma_{D_\alpha}^{0.017-0.067}}{q_\perp^{0.017-0.0.079}\,q_{95}^{0.60-0.17}} \tag{1}$$

$[10^{19}\,m^{-3}$. MW, T, $10^{17}\,s^{-1}m^{-2}sr^{-1}]$, where the exponents are given with their 95% condence intervals. The Γ_{D_α}-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 ournal scaling by doing a regression for R, q_{95}, B_t, $q_\perp$ and $1 + \delta_u$ on the full JET and ASDEX Upgrade database:

$$n_{ND,\,fit} = 9.77\ \frac{q_\perp^{0.014-0.0.064}\,B_t^{0.61-0.09}\,(1+\delta_u)^{1.00-0.22}}{q_{95}^{0.62-0.17}\,R^{0.57-0.14}} \tag{2}$$

Figure 1 illustrates the quality of thet and provides the range of q_{95}, B_t, P_{heat} and δ_u variations covered by the database. Despite the limited range of variation of the ASDEX Upgrade data, there is some evidence that the two machines scale in the same way.

3. JET BEAM ENERGY VARIATION AND VESSEL TEMPERATURE 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. Despite the dierent beam fuelling rates the at-top densities of the two discharges are identical in shape and magnitude [3].

One way to change the recycling-relevant wall properties and hence wall fuelling is to operate at dierent wall temperatures. Pairs of identical discharges have been performed at JET at wall temperatures of 200^o and 300^o. As in the case of beam fuelling variation, the at top densities are found to be identical in size and shape. However, there is a marked dierence in the Γ_{D_α} signals of the two discharges, providing evidence that the wall properties are indeed aected [3].

4. IMPLICATIONS FOR THE H-MODE OPERATION WINDOW

In this section we discuss the condition $\Phi \equiv n_{ND} = n_{DL} < 1$, 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 [4, 5]. Various scalings have been proposed for the H-mode density limit. We discuss as one example the scaling proposed by **B**orrass, **L**ingertat and **S**chneider [6], which provides a good description of JET and ASDEX Upgrade data [4, 5]. It results in

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

[10^{19} m^{-3}. MW m^{-2}, T, m]. As a second example we consider the empirical Greenwald scaling [7], which is widely used as a kind of reference:

$$\bar{n}_{GW} = 10 \frac{I_p}{\pi a^2} \quad (4)$$

[10^{19} m^{-3}. MA, T, m].

Extrapolation to ITER-like devices is, of course, our main concern. Generally the BLS scaling results in higher Φ values. 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_α = 80MW, P_h = 40MW, P_{rad} = 50MW and a plasma surface of 680MW)) we obtain, for example,

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

For ITER-FDR [8] parameters (R = 8:14m, a = 2:8m, B_t = 5:68T, I_p = 21MA, q_{95} = 3:1, δ_u = 0:31, $q_\perp$ = 0:15) we obtain similarly

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

These scaling results have to be interpreted with care. This is due to some intrinsic deciencies of the available data for both the natural density and density limit. In fact, there is a strong correlation between R and δ_u (see Fig.2), which makes a correct assessment of the size and triangularity dependences dicult. Unfortunately, this may strongly aect the predictions for ITER. Further experiments are in preparation on both JET and ASDEX Upgrade which will hopefully close this gap. Recent experiments at ASDEX Upgrade indicate an even stronger triangularity dependence than Eq. (2).

REFERENCES

[1]. BORRASS, K. et al., Nuclear Fusion **39** (1999) 843.

[2]. KALLENBACH, A. et al., 28th Conference on Controlled Fusion and Plasma Physics, 18-22 June 2001, Madeira, Portugal, paper p3.006.

[3]. BORRASS, K., et al., Natural density formation as an H-mode operational limit, Nucl. Fusion **42** (2002) 1-6.

[4]. MERTENS, V. et al., Nuclear Fusion **40** (2000) 1839.

[5]. BORRASS, K. et al., 28th Conference on Controlled Fusion and Plasma Physics, 18-22 June 2001, Madeira, Portugal, paper p2.006.

[6]. BORRASS, K. et al., Contrib. Plasma Phys. **38** (1998) 130.

[7]. GREENWALD, M., et al., Nucl. Fusion **28** (1988) 2199.

[8]. ITER Physics Basis Editors, ITER Physics Expert Group Chairs and Co-Chairs, ITER Joint Central Team and Physics Integration Unit, Nucl. Fusion **39** (1999) 2137.

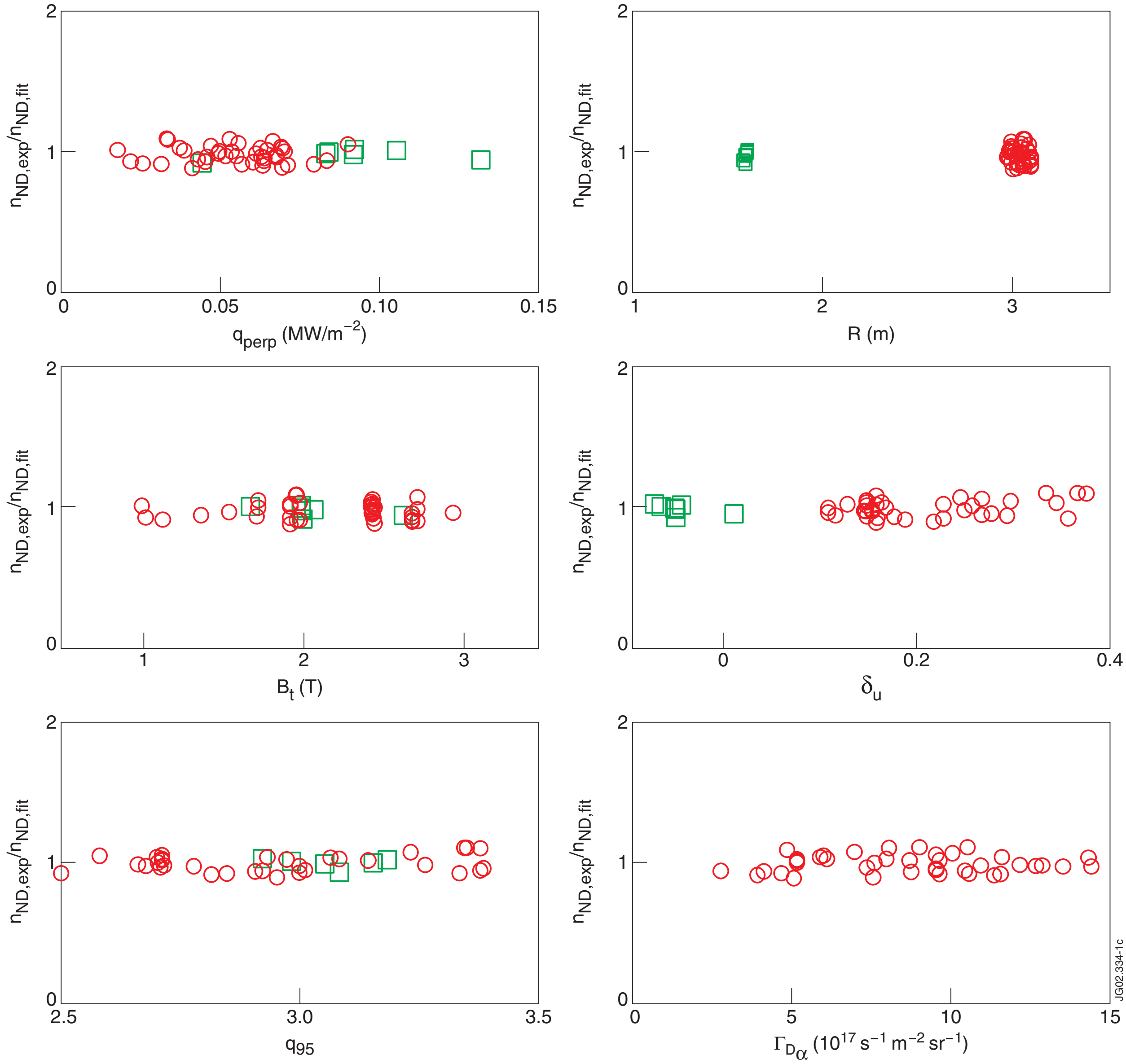

Figure 1: Experimental natural densities $n_{ND;exp}$ from JET (circles) and ASDEX- Upgrade (squares) over $n_{ND;fit}$ calculated from Eq. (2) versus mean power flux across the separatrix $q_\perp$, toroidaleld B_t, safety factor q_{95} at the 95% flux surface, major radius R, upper triangularity δ_u and D_α photon ux $\Gamma_{D\alpha}$.