29th EPS Conference on Plasma Phys. and Contr. Fusion Montreux, 17-21 June 2002 ECA Vol. ***26B****, P-1.046 (2002)*

Isotope Effect on the L-mode Density Limit in ASDEX Upgrade

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1. Introduction

Extrapolation to ITER from present day tokamaks will involve a step in the ion mass of the fuel gas. Despite this, little attention has been paid so far to the isotope dependence of the H-mode density limit (DL). On the other hand, a rather complete understanding of the L-mode DL has been achieved over the past decade, including subtle effects such as the isotope dependence. Moreover, common elements have been identified in the physics underlying H- and L-mode DL. All this suggests investigating the isotope dependence in L-mode DL as a first step to a similar exercise in H-mode and as "testbed" for existing models.

An initial study of the isotope effect of the L-mode DL was performed in JET with the MarkIIA divertor [1]. A weak isotope dependence of the DL was found and, more interestingly, the experiments indicated a coupling between mass and net input power dependence of the DL, as predicted by the model described in Refs. [2] and [1].

The JET MarkIIA L-mode DL database was limited to discharges with fixed toroidal field ($B_t = 2.5$ T) and safety factor ($q_{95} \sim 4$). In the present study the parameter space has been expanded, by including ASDEX Upgrade (AUG) DL discharges from Divertor I (Div I) and Divertor IIb (Div IIb) [3] experimental campaigns in which ion mass (H, D), input power $P_{in,tot}$ and q_{95} were varied. In addition, the comparison of data from JET and AUG provides information on the machine size dependence of the DL.

Finally, due to the smaller plasma surface in AUG than in JET for similar heating powers, the variation in power flux across the scrape-off-layer (SOL) is expanded significantly compared to the initial study.

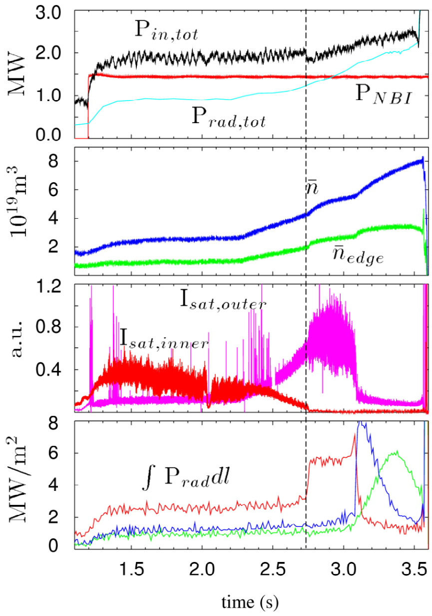

Figure 1. *Time traces of main plasma parameters for an AUG L-mode DL discharge in H with Div IIb (pulse #14710). The vertical line marks the time of the DL, coinciding with complete detachment in the inner divertor.*

2. L-mode gas scans in AUG: experimental issues and identification of the DL

Fig. 1 shows time traces of some key parameters in a typical AUG L-mode DL discharge (Div IIb). The plasma density is increased by gas fuelling at roughly constant $P_{in,tot}$ (Ohmic plus neutral beam heating, in analogy with the JET experiments) to the disruption limit. Gas injection is from the divertor valves, located at four different toroidal positions, so as to achieve uniform gas fuelling. The ion fluxes to inner and outer divertor targets, measured by Langmuir probes, initially increase and then drop to very low values (complete divertor detachment) as the density is increased, while the total radiated power $P_{rad,tot}$ increases monotonically. In ref. [1] it was observed that in JET the onset of the MARFE coincides with complete detachment at the inner divertor leg (marked by the vertical line in Fig.1). Subsequently, with increasing density, the MARFE moves to the inner wall and then a plasma disruption occurs. By the time of the disruption the outer divertor leg is also completely detached. These observations had led to two definitions for the density limit: i) the density at the time of the MARFE onset, which coincides with complete inner divertor detachment; ii) the density reached when the disruption occurs. Definition i) was adopted as the most adequate definition of DL [1] and we now apply it to the AUG L-mode DL discharges as well. Table 1 summarizes the parameter ranges covered by the AUG dataset.

Table 1. *Summary of parameter ranges covered in the AUG L-mode DL database.*

Div type	**I_p (MA)**	**B_t (T)**	**q_{95}**	**isotope**	**$q_\perp$(MW/m^2)**
Div I	0.6 – 0.8	2.0 – 2.1	4.0 – 5.0	H, D	0.016 – 0.059
Div IIb	0.6 – 0.8	2.0	3.8 – 5.2	H, D	0.006 – 0.027

Due to the reduced L-H power threshold in Div IIb compared to Div I , the L-mode operational window in Div IIb is very narrow, especially in D plasmas. This limits the extent of our scans, particularly in terms of input power. The situation is slightly better in H, due to the higher L-H power threshold. As a consequence of the low additional heating which can be used, compatible with the L-mode regime, the Ohmic power can contribute significantly to the total input power. This establishes an internal correlation between input power and other discharge parameters (e.g. I_p, B_t), which has to be taken into account in the analysis of the data.

Another issue of concern is the correct evaluation of $P_{rad,tot}$. In AUG this is calculated from tomographic reconstruction of the radiated power fluxes measured by various bolometer LOS covering the plasma cross section [4]. This technique is prone to higher error bars at high density/low power (up to 30% compared to 10% in standard discharges). Errors in the calculation of $P_{rad,tot}$ propagate unfavourably in the calculation of the net input power, $P_{net} = P_{in,tot} - P_{rad,tot}$, , which is one of the key parameters in the scaling of the DL (see Section 3) and this is possibly the main source of uncertainty in the dataset.

3. Scaling of the density limit

Plasma discharge parameters that may influence the DL include the net input power P_{net}, the safety factor q_{95} and the toroidal field B_t. In comparing different devices the machine size dependence, which can be expressed in terms of the major radius R, need also be considered. An additional parameter is the mass of the fuelling gas m. Other parameters, such as divertor geometry, plasma triangularity and elongation may also play a role.

The limited variety of AUG L-mode DL discharges available and the fact that some of the parameters are not independent do not allow a full statistical regression of the data. We therefore adopt the strategy of comparing the experimental data with existing DL models. The model described in Refs. [2] and [1] is currently the only candidate that predicts the isotope dependence of the DL and has been successful in the interpretation of the JET data [1]. In this model, complete divertor detachment defines a limit on the upstream separatrix density n_S^{det} . From the equations of a two point model applied to the region upstream of the gas target, assuming Bohm perpendicular transport and showing that at complete detachment the Mach number and the sheath transmission coefficient at the gas target entrance are only functions of the ion-neutral transverse collisionality, a class of scalings is obtained for n_S^{det}:

$$n_S^{det} = C\, q_\perp^{\,x}\, B_t^{\,5/16}\, m^{\,0.8\,x-0.16} / (q_{95} R)^{\,11/16-x} \qquad \text{(Eq. 1)}$$

where $q_\perp = P_{net}/A_{plas}$ is the power flux across the separatrix, with A_{plas} [m^2] the plasma surface. C and x remain undetermined within the model and have to be provided by the experiment.

Since the DL is a limit on the upstream separatrix density, we should use this parameter in our studies. For the JET MarkIIA L-mode discharges, however, routine measurements of n_S were not available and therefore the edge line averaged density was used, with the implicit assumption of direct proportionality between the two quantities [1]. The improved edge diagnostic capabilities in AUG with Div IIb have allowed us to check the validity of this assumption experimentally, as shown in Fig. 2. The value of n_S is derived using an analytic edge transport model fit to high resolution edge T_e and n_e radial profiles measured by Thomson scattering [5]. Within the error bars, n_S/n_{bar} ~ 0.4 at the DL over the whole density range spanned in the dataset. We note also that this ratio shows no isotope dependence. These results give us confidence in the choice of n_{bar} as target density to be used in the comparison with the model, thus allowing a simultaneous fit of both AUG and JET data.

The result of the regression of the JET and AUG data to the class of scalings expressed by Eq. 1 is shown in Fig. 3. A best fit to the entire dataset is obtained with x = 0.33 ± 0.03 (χ^2 = 0.14). Both machines are well described by the same scaling, except for a small number of AUG discharges in Div IIb (the symbols with smaller font in Fig. 3), for which the measured density exceeds the model prediction.

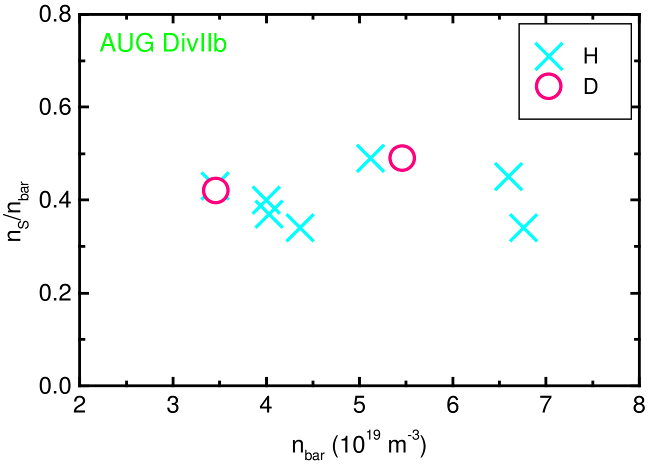

Figure 2. *Ratio of separatrix to central line averaged density, n_S /nbar, vs central line averaged density at the DL for AUG Div IIb L-mode DL discharges in which separatrix density measurements were obtained.*

The reason for these discrepancies is not yet understood. The ouliers fall into two groups: the H pulses at high input power and the D pulses at q_{95} = 4. For the former we observe that these discharges are transiently in H-mode as soon as the NB heating is

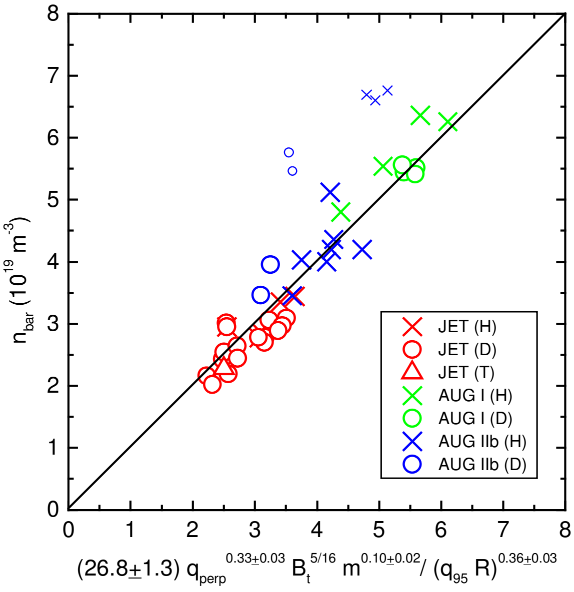

Figure 3. *Measured central line averaged density at the DL versus scaled density. The points in smaller font are the outliers found in the AUG Div IIb dataset.*

applied, and then revert into L-mode as the plasma density is increased with gas fuelling. It is not clear if this transition into H-mode is the cause for the high DL. Since we measure no density peaking in these discharges (which are included in Fig. 2), it is possible that the reason for this discrepancy originates in the plasma edge and not in the core. For the latter discharges, a relatively high plasma density (obtained with feedback gas control) is needed during the Ohmic phase in order to avoid the L-H transition. This leads to MARFE formation just before the NB heating is applied. With additional heating power flowing in the SOL, the divertor plasma reattaches and then later, with increasing plasma density, a second detached phase with MARFE occurs. We are uncertain as to whether proximity to the DL prior to the additional heating phase may bring the discharge transiently to a higher density than that which would be obtained with a monotonic gas ramp. A second attempt at these discharges with lower density in the Ohmic phase produced an H-mode, due to the better vessel conditioning at that time. Experiments with reversed Ip/Bt, planned for the near future, may help to clarify these points, since in these plasmas the L-H power threshold is expected to be higher than in the forward direction.

In conclusion we note that the weak isotope dependence of the L-mode DL found in JET is confirmed in AUG, as well as the coupling of net input power and ion mass dependence at the DL, which in the model originates from the ion-neutral collisionality at the ionization front in the divertor. In addition, the machine size dependence of the DL has been verified for AUG and JET discharges.nfviewer Finally, in AUG discharges with Div IIb we have been able to measure the direct proportionality between n_S and n_{bar} at the DL, which was so far implicitly assumed in the comparison of the experimental data with the DL model.

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