EUROFUSION WPJET1-CP(16) 16560

A Huber et al.

The effect of the isotope on the H-mode density limit

Preprint of Paper to be submitted for publication in
Proceedings of 26th IAEA Fusion Energy Conference

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

The effect of the isotope on the H-mode density limit

A. Huber[1], S. Wiesen[1], M. Bernert[2], S. Brezinsek[1], A. V. Chankin[2], G. Sergienko[1], V. Huber[3], P. Abreu[4], A. Boboc[5], M. Brix[5], D. Carralero[2], E. Delabie[6], T. Eich[2], H.G.Esser[1], C. Guillemaut[4], S. Jachmich[7], E. Joffrin[8], A. Kallenbach[2], U. Kruezi[5], P. Lang[2], Ch. Linsmeier[1], C. G. Lowry[9,10], C. F. Maggi[5], G.F. Matthews[5], A.G. Meigs[5], Ph. Mertens[1], F. Reimold[1], J. Schweinzer[2], G. Sips[9,10], M. Stamp[5], E. Viezzer[2], M. Wischmeier[2], H. Zohm[2], JET contributors* and ASDEX Upgrade Team

EUROfusion Consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, UK
[1]Forschungszentrum Jülich GmbH, Institut für Energie- und Klimaforschung – Plasmaphysik, Partner of the Trilateral Euregio Cluster (TEC), 52425 Jülich, Germany
[2]Max-Planck-Institut für Plasmaphysik, D-85748 Garching, Germany
[3]Forschungszentrum Jülich GmbH, Supercomputing Centre, 52425 Jülich, Germany
[4]Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade Lisboa, PT
[5]CCFE, Culham Science Centre, Abingdon, OX14 3DB, UK
[6]Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA
[7]Laboratory for Plasma Physics, ERM/KMS, B-1000 Brussels, Belgium
[8]CEA, IRFM, F-13108 St Paul-lez-Durance, France
[9]European Commission, B1049 Brussels, Belgium
[10]JET Exploitation Unit, Culham Science Centre, Abingdon OX14 3DB, UK
See the Appendix of F. Romanelli et al., Proc. 25th IAEA FEC 2014, St Petersburg, Russia
E-mail contact of main author: A.Huber@fz-juelich.de

Abstract. In order to understand the mechanisms for the H-mode density limit in machines with fully metallic walls, systematic investigations of H-mode density limit plasmas in experiments with deuterium and hydrogen external gas fuelling have been performed on JET-ILW, and results have been compared with one another.
The observed H-mode density limit on JET in D- as well as in H-plasmas demonstrates similar operation phases: the stable H-mode phase, degrading H-mode, breakdown of the H-mode with energy confinement deterioration accompanied by a dithering cycling phase, followed by the L-mode phase. Independently of the isotopic effect, the total radiated power as well as the radiation power in the main chamber (Prad, bulk) stays almost constant during the H-mode phase until the H-L transition. The density limit is not related to an inward collapse of the hot discharge core induced by overcooling of the plasma periphery by radiation. It was observed in D- and H-plasmas that neither detachment, nor the X-point MARFE itself, do trigger the H-L transition and that they thus do not present a limit on the plasma density. It is the plasma confinement, most likely determined by edge parameters, which is ultimately responsible for the H-mode DL.
Although the operation phases are identical for D- and H-plasmas, the DL shows a strong dependence on the isotopic mass effect, the DL is up to 35% lower in the H-plasma than in the deuterium plasma. Basically, the density limit in H mode on JET-ILW is nearly independent of the power in the range of observed heating powers in D-plasma and in H-plasma correspondingly.
The measured Greenwald fractions are found to be consistent with the predictions from a theoretical model based on MHD instability theory in the near-SOL.

1. Introduction

Tokamak operation at high density with a partially or fully detached divertor is considered as the baseline scenario for ITER [1], DEMO [2] and future fusion power plants. The establishment of a detached divertor at densities close to the Greenwald limit n_{GW} [3] is mandatory for maximising the fusion power and for successful operation of future reactors to reduce the heat loads on plasma-facing components, in particular on the divertor target plates, to an acceptable level and to reduce the tungsten sputtering. Despite substantial efforts to quantify the density limit in machines with fully metallic walls, such as JET and AUG tungsten [4], not all underlying mechanisms responsible for the H-L transition are fully understood yet. In particular, the influence of isotopic effects can lead to a significant impact on the density limit (DL). In this contribution, we investigate the isotopic effect on H-mode density limit in the fully metallic machine JET-ILW.

2. Experiments

2.1. H-Mode density Limit Experiment in the JET Tokamak with ITER-like wall

To investigate the influence of isotopic effects on the DL, a series of experiments was started at JET in D- (with plasma currents I_p=1.75-2.5MA and toroidal magnetic fields B_T≈1.8-3.4T) and in H-plasmas (I_p=0.9-2.0MA and B_T≈1.3-1.8T) at varying input power levels in the low triangularity vertical target configuration with high deuterium/protium fuelling.

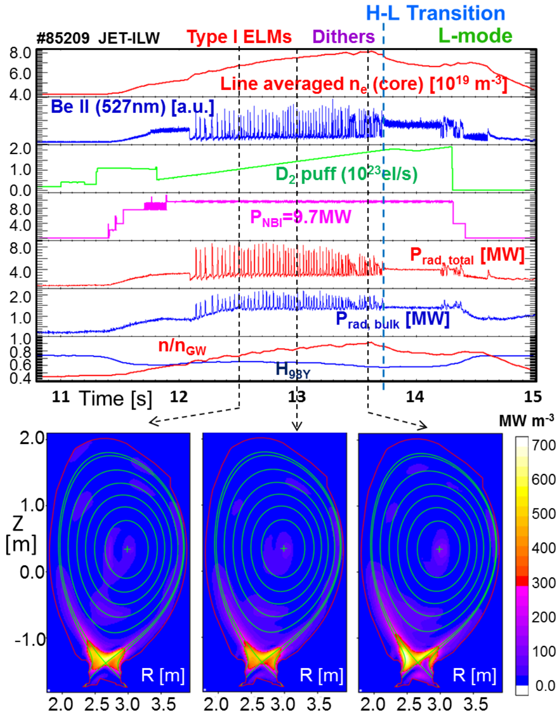

Fig.1 Time evolution of a typical H-mode density limit discharge on JET-ILW. Also shown are the poloidal radiation distributions during different time phases of the H-mode DL discharge. The total as well as the bulk radiation stays constant throughout the discharge.

Fig.1 shows the time evolution of a typical H-mode density limit discharge in JET-ILW in low-triangularity magnetic equilibria (average triangularity of δ=0.22). Deuterium external gas fuelling into the inner leg of the divertor with a rate of up to of 2×10^{23}D/s was used in this 10MW NBI-heated discharge to raise the plasma density up to density limit. The BeII fast emission signal in the outer divertor represents the ELMs behaviour during the density ramp. When the density is raised by gas puffing, the confinement factor remains at a constant level of H98Y=0.65 up to about n_e/n_{GW}=0.9. Further gas puffing leads to a moderate increase of the density, but the confinement deteriorates strongly down to H98Y=0.56 and the discharges usually make a back transition into the L mode. Prior to the final transition into the L-mode, type I ELMs are replaced by a sequence of H-L-H transitions, with short periods of H-mode embedded in the otherwise L-mode phase of the discharge, as shown in detail in Fig.3. The sequence of these transitions is what we will call 'dithering H-mode'. The dithering cycles can be seen as a modulation of the BeII signal in the divertor.

The energy losses due to radiation can cool down the confined plasma and thus cause the H-mode density limit. In previous studies at ASDEX Upgrade (AUG) and JET, both with a fully carbon covered wall, the density limit of H-mode has been attributed to the full detachment of the divertor [5] with a significant role of the radiation. However, in the JET-ILW as well in full-W ASDEX the poloidal radiation distribution as shown in Fig.1 for a JET H-mode DL pulse and the total radiated power as well as the radiation power in the main chamber ($P_{rad,bulk}$) stay almost constant during the H-mode phase until the H-L transition. Additionally, the radiation fraction, $\gamma_{rad} = \frac{P_{rad}}{P_{heat}}$, is low and is about 0.3 (0.4-0.6 for AUG). Therefore, the density limit is not related to additional energy losses from the confined region by radiation. It is also not related to inward collapse of the hot discharge core induced by overcooling of the plasma periphery by radiation. The effective ion charge, Z_{eff}, is ≈1.15 in the density ramp pulses. Replacement of the first wall and divertor walls by metallic materials reduced significantly the carbon levels [6], resulting in a reduced radiation and reduced Z_{eff}. Under cold detached divertor conditions with significant reduction of W sputtering, the tungsten is introduced into the plasma only during the ELMs. Beryllium is a much weaker radiator than carbon. A significant fraction of the radiation is caused by deuterium [6]. A MARFE (at the

X-point) does not appear before the H-L transition and, thus, is not related to the H-mode density limit.

3. Characterisation of the H-mode density limit

3.1 Characterisation of the H-mode DL on JET-ILW

The evolution of a gas fuelled, high density H mode discharge in JET-ILW can be described by three main stages as shown in Fig.1: a Type I ELM phase, then a dithering cycling phase with energy confinement deterioration, followed by the L-mode phase. The impact of the phases on the plasma stored energy and the central line averaged electron density is shown in Fig.2. The characteristics of the phases and their impact on the electron density and temperature profiles (see Fig.2) are listed in the following:

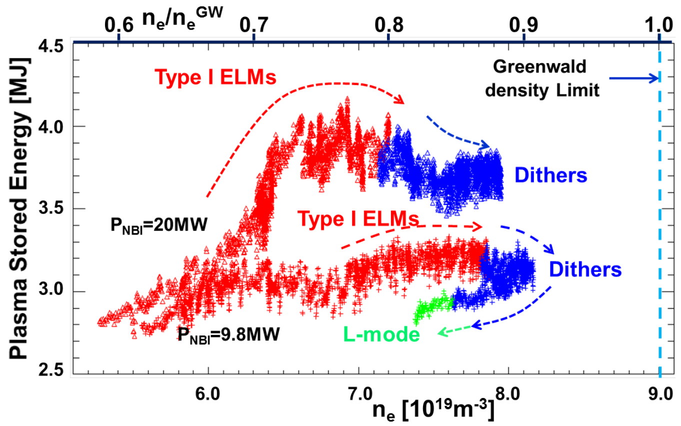

Fig.2 Plasma stored energy plotted versus the central averaged electron density. The main phases of the H-mode DL on JET-ILW.

Stable H-mode Before the dithering phase, the stored energy and the confinement stay constant whereas the density is increasing in the core and in the edge. At the same time, the pedestal temperature ($T_{e,ped}$) decreases during the gas ramp so that the pedestal pressure stays constant. This phase is called a stable H-mode, since the pressure, and thus the confinement, stay constant while the density increases.

Dithering cycling phase Two distinct sub-phases are identified in the 'dithering phase': an **early 'dithering phase'** with confinement degradation and a **late phase** with the breakdown of the H-mode.

Earlier dithering phase During the **earlier 'dithering phase'**, the density increases marginally and $T_{e,ped}$ cools down, degrading the pedestal pressure and leading to a reduction of the confinement and of the stored energy.

Late dithering phase Shortly before the H-L back transition during **the late dithers** a strong altering of the stored energy as well as a density drop by 15% have been observed, followed by the L-mode phase. The duration of the dithering phase varies, between the discharges in the database, from 0.1s to over 0.5s. Systematically the dithering cycling has been observed in the configurations with both strike points on the vertical targets but only occasionally, or with very short duration of the dithering phases, in the configuration with the outer strike point positioned on the horizontal divertor plate. In the latter configuration an increase of the fuelling source is associated with a transition from type I to small ELMs combined with dithering cycles, which finally leads to the back transition.

L-mode In the last phase, the density decreases over the full profile and the temperature further reduces.

3.2 Dithering cycles prior to the L-mode

Independently of the isotopic mass of the main plasma, it has been observed that the transition from H-mode to L-mode is not always an abrupt event but may exhibit a series of H-L-H transitions ("dithering H-mode"), or a gradual transition (which is orders of magnitude longer than the energy confinement time τ_E). Fig.3 shows the details of a 'dithering cycling' phase of typical JET H-mode pulses in a magnetic field configuration with both strike points on the vertical divertor targets. The cause of the repetitive H-L-H transitions must be the modulation of the plasma edge density, so that the sharp density rise during short H-mode periods, reflecting significant improvement in the particle confinement, triggers back H-L. During transient H-mode periods of the dithers, the inner divertor is completely detached and the outer divertor leg is at least partially detached. In spite of that, one observes that the plasma density both at the edge and in the core during the first sub-phase rises, reflecting a significant improvement in the particle confinement; it demonstrates that the detachment itself presents no limit on the plasma density and the H-L transition. The edge electron temperature, measured by the electron cyclotron emission (ECE) diagnostic [7], does not show any excursion during the dithering cycles and stays almost at the lowest value of ≈140eV. Thus, a cold and dense pedestal during the H-mode phase increases significantly the collisionality of the plasma pedestal. This is in line with the explanation given in [8,9] that the Greenwald DL could be explained from the requirements that, in the edge transport barrier, the radial pressure gradient does not exceed the ballooning stability threshold and the critical plasma collisionality. The duration of the transient L- and H-phases changes during the development of the dithers. The late dithers demonstrate longer L-phases (≈25ms) than the early ones (≈10ms) leading to the reduction of the ne even before the H-L transition because the short H-mode periods are not able to provide a full recovery of the density. During the L-phases with the low edge density, the BeII-emission has large values whereas it decreases during the short H-mode phase together with the total radiation. The measurements with fast magnetic probe (∂B/∂t) show that the turbulence level is significantly increased (see Fig.3b) when the L-phase develops during the dithers. Similar to those after the final transition into the L-mode, the broadband fluctuations, reflecting the significant anomalous transport, have been observed in the low confinement dithering phase. As was demonstrated in [10,4], during the dithering cycles the MARFE itself does not drive the H-L transition.

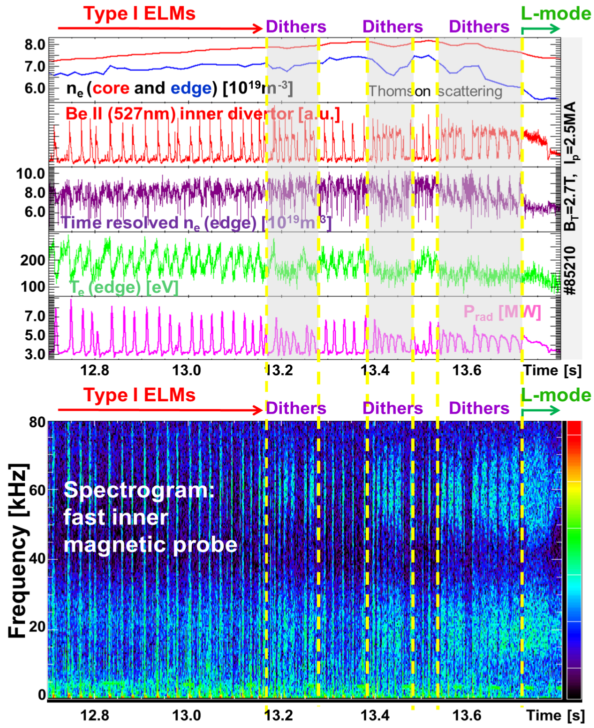

Fig.3 Characteristic time traces of the high density limit JET-ILW discharges for dithering cycles before the H-L transition: BeII-emission signal, pedestal density n_{edge} and temperature T_{edge}, total radiated power P_{rad} as well as power spectrum of a magnetic probe located inside the vessel on the high field side.

Dithering cycles have not been observed in the majority of the H-mode DL pulses on ASDEX Upgrade or, to be exact, only one DL pulse shows the dithering cycles. In contrary to AUG, on JET-ILW the density after H-L transition shows a strong reduction pushing the plasma again into the H-Mode operational space with the consequent improvement in the particle confinement. This leads subsequently to the increase of the density with the following H-L transition. On ASDEX Upgrade, however, the density increases after the H-L transition, driving the plasma away from the H-mode operational space.

4. Role of Detachment in H-mode density limit

The H-mode density limits in earlier experiments on JET-C demonstrate a good agreement between experiment and the model developed by Borrass et al. [11]. According to this model, the onset of the H-mode density limit is related to the plasma detachment at the divertor plates between ELMs. The H-mode density limit in the machine with the ILW shows larger values (>20%) than predicted by Borrass, indicating in this latter case that the H-L transition cannot be explained by the detachment. Fig. 4 shows the observations made in the divertor of JET-ILW during the approach to the limit in the H-mode density limit discharge. The time traces show measurements of the pedestal density n_{ped} and pedestal temperature T_{ped}. As well as the integrated ion saturation current to the outer divertor and the local saturation current at the outer strike point. The lower envelope of the saturation currents indicates the roll-over into detachment during the inter-ELM period in the outer divertor at time t=14s. After t=14s the outer divertor is at least partially detached. At 15s the Dγ-emission rapidly increases in the outer divertor. At the same time, the Dγ/Dα-ratio increases strongly up to the level of ≈0.1 throughout the outer divertor plasma, indicating a strong volume recombination. Additionally, the ion flux to the outer divertor reduces and reaches at t=15s the degrees of detachment DoDpeak≈5.0 and DoDint≈3.0. Thus, after t=15s the outer divertor is fully detached. Despite the fully detached inner and outer divertor the density in the core and at the edge is raised for a long-time period after the outer divertor is fully detached, until the H-L transition. Thus, detachment and subsequent MARFE if any do not trigger the H-L transition.

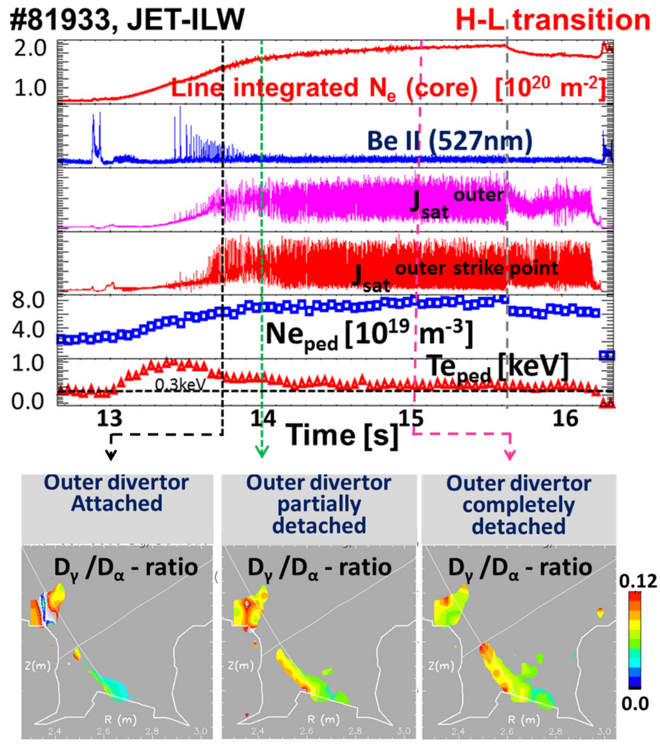

Fig.4 Tomographic reconstructions of D_γ/D_α ratio (bottom) in the divertor region during three phases of the H-mode density limit discharge.

A similar conclusion delivers the observation at ASDEX Upgrade [12]. In full-W AUG, the complete detachment sets in after the H-mode DL and, thus, the detachment does not play a key role in the physics of the H-L transition.

5. Impact of the isotopic effects on the Density Limit

Although the operation phases are identical for D- and H-plasmas, the DL shows a strong dependence on the isotopic mass effect, as show in Fig.1. The DL is up to 35% lower in the H-plasma than in the deuterium plasma (Fig.5) and it is well predicted by the Goldston model discussed later. Both plasma discharges have been carried out in a similar vertical target magnetic field configuration with I_p/B_T=1.9MA/1.8T and q_{95}=2.8.

6. Impact of the input heat power on the Density Limit

The impact of the input heat power on the H-mode density limit at JET in D-plasma has been analysed in the experiments by varying the input heating power. The heating scan does not

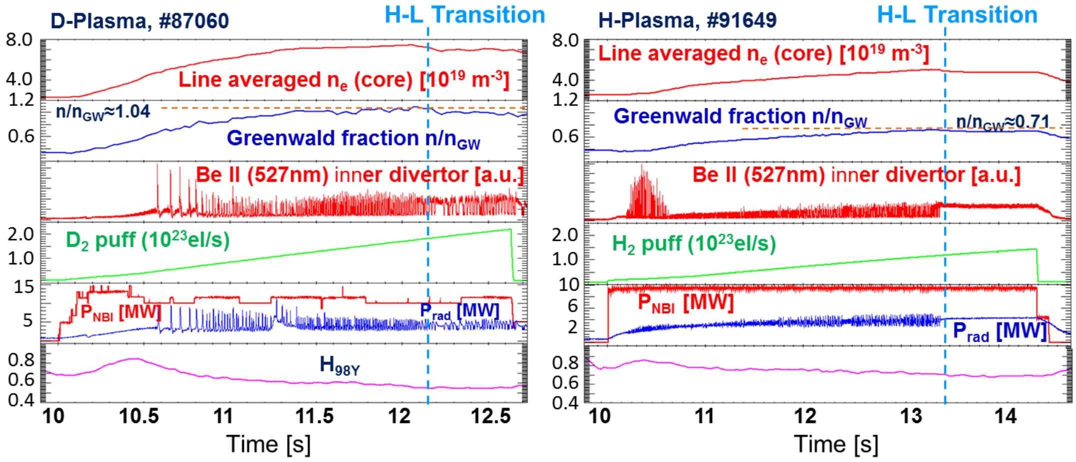

Fig.5 Time traces during a typical density ramp experiment on JET-ILW with D-plasma (left) and H-plasma (right). The time when the H-mode DL sets in is marked by the dashed lines.

include a variation of the heating source. Only the intrinsic Ohmic heating and NBI heating were used. A discharge with RF wave heating (ICRH) was not carried out. Fig.6a shows the measured Greenwald fractions as a function of the total heating power obtained in these experiments. These D-plasma pulses have been performed in low -triangularity magnetic equilibria at B_T≈2.7T, I_p=2.5MA, q_{95}=3.36, average δ=0.22 with location of the inner and outer strike points on the vertical targets. Basically, the density limit in H mode on JET-ILW is nearly independent of the power at higher heating power beyond 8MW and the corresponding densities only approach in this configuration a Greenwald fraction of about f_{GW}=0.9. Nearly the same findings have been observed in H-mode DL experiments with H-

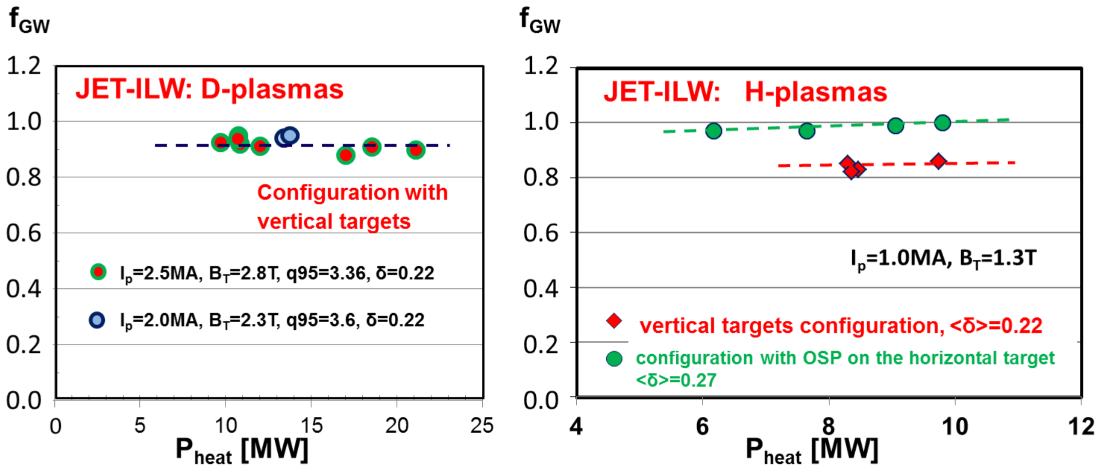

Fig.6 Dependency of the Greenwald fraction at the H-mode DL on the total heating power for JET-ILW in D-plasma (left) and H-plasma (right).

plasma. Fig.6b represents the result which was obtained by varying the NBI heating power from 6MW to 9.4MW at constant plasma current and safety factor for the full-metallic JET in two configurations: vertical target configuration and the configuration with the location of the inner and outer strike points on the vertical target and horizontal target. The achieved densities are nearly constant or show very little increase with the heating power. The density limits reached in the experiments shown in Fig6 a and b demonstrates only the dependence on

P_{heat}, they cannot be compared with each other because of strong differences in main plasma parameters. The expected H-mode DL in D-plasma at I_p=1.0MA and B_T=1.3T is f_{GW}≈1.2.

At ASDEX Upgrade, however, the H-mode density limit shows an increase with heating power **[12].** The possible explanation of the different dependence on the P_{heat} could be that the fuelling efficiency by gas puff is reduced at high densities and only a small fraction of the fuelled gas reached the confined region. In comparison to the gas puff, the fuelling rate by the AUG NBIs (≈10^{21}D/s versus 10^{22}D/s by gas puffing) is relatively large and it is not negligible because the major part of the injected D atoms are delivered directly into the confined region. This may explain the increase of f_{GW} with the increase of the NBI heating power on AUG. On the JET machine, the puff rate (≈10^{23}D/s) is two orders of magnitude larger than the rate of the injected neutral D-atoms (≈10^{21}D/s) and the fuelling by NBI is thus negligible.

8. Comparison with the theoretical model

In the paper **[13]** the author**,** R.J.Goldston, suggests that the H-Mode and, more generally, the Greenwald density limit may be caused by an MHD instability in the SOL close to the separatrix, rather than originating in the core plasma or pedestal. This idea has been triggered by observations showing that the ballooning parameter $\alpha \equiv -Rq^2\beta'$, derived from the heat flux width, almost linearly increases with f_{GW} until detachment occurs. The ballooning α parameter was derived [13] under the assumption that the pressure gradient scale length at the separatrix is approximately equal to the experimentally measured λ_q ($\alpha \equiv -Rq^2\beta/\lambda_q$). Assuming that the SOL β limit is defined by criticality to MHD instability, characterized as $\alpha_{crit} \sim C_\alpha(1+\kappa^2)^\gamma$, the Goldston model gives

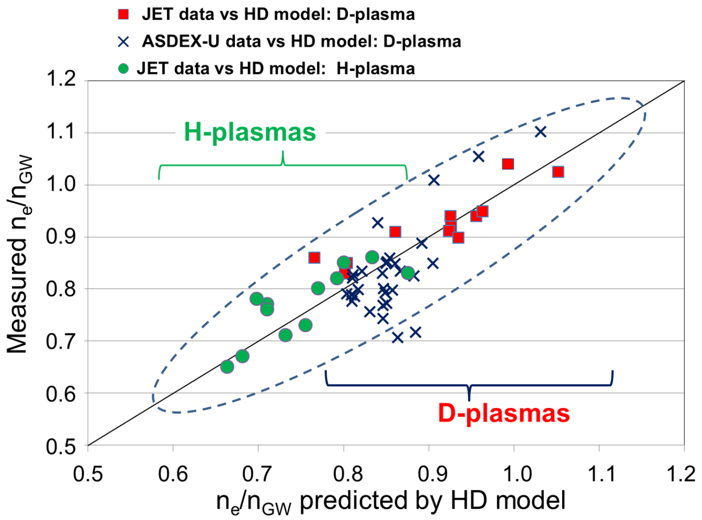

Fig7. Experimental measurements of the Greenwald fraction, n_e/n_{GW}, in gas fuelled H-Mode DL discharges in JET-ILW and AUG tokamaks, plotted against the Goldston model [5]. Filled circle symbols represent the result in H-plasmas on JET-ILW.

$$f_{GW,Goldston} = 8.13 \cdot C_\alpha \frac{\bar{n}}{n_{sep}} \left(\frac{q_{cyl}RB}{a} P_{SOL}\right)^{-1/8} (1+\kappa^2)^{\gamma-3/2} \left[\frac{2\bar{A}}{(1+\bar{Z})}\right]^{9/16} \left(\frac{Z_{eff}+4}{5}\right)^{-1/8}$$

where q_{cyl} is the cylindrical approximation for the safety factor, κ is plasma elongation, a and R the horizontal minor and major radiuses, P_{SOL} is the power which crosses from the core region into the SOL, $\bar{n}$ *and* n_{sep} are the separatrix and the line-averaged densities. Generally speaking, f_{GW} shows little variation with key parameters. On the contrary, it shows a relatively strong dependence on the average atomic mass, $\bar{A}$, of the plasma species.

For elliptic plasmas with elongation κ, it could be adapted according to Ref. [14] $\alpha_{crit} \approx 0.4s(1+\kappa^2)$, where $s = d\ ln\ q / d\ ln\ r$ is the magnetic shear (typically s=2).
Experimental measurements of the H-mode density limit expressed in terms of the Greenwald fraction, f_{GW}, in both tokamaks, JET-ILW and AUG, are plotted against the f_{GW} derived from the

Goldston prediction (see Fig.7). The experimental results contain only data sets of the D-plasmas and H-plasmas (filled circle symbols) which correspond to plasma configurations with strike points on the vertical targets. The Goldston model gives a good agreement with recent measurements concerning the absolute value of f_{GW} as well as the dependence on main plasma parameters. Also the model predicts a strong dependence on the average atomic mass, $\bar{A}$, of the plasma species, $f_{GW} \propto \bar{A}^{\,9/16}$, which is confirmed experimentally on JET-ILW in D- and H-plasmas.

9. Extrapolation to ITER

Based on the above findings, it is possible to attempt a prediction of the density limit on ITER. The design values for ITER the baseline 15MA, Q=10 inductive H-mode burning plasma discharges [1] are as follows: R=6.2m, a=2.0m, κ=1.7, B_T=5.3T, I_p=15MA, q_{cyl}=2.42, Z_{eff}=1.6, n/n_{sep}=3. We assuming that ITER will operate in deuterium-tritium (D-T) mixtures using 50% of D and 50% of T and nominal operation of ITER with Q=10 corresponds to P_{SOL}=100MW. Inserting the above into the f_{GW} scaling predicted by Goldston, we find the estimates $f_{GW} \approx 1.03$. Note that ITER will operate with impurity seeding and that the scaling should be confirmed in dedicated experiments with impurity seeding.

Acknowledgement

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] Progress in the ITER Physics Basis, Edd., Nucl. Fusion 47 (2007) S1 sqq.
[2] ZOHM, H. et al., "On the physics guidelines for a tokamak DEMO", Nucl. Fusion 53 (2013), 073019.
[3] GREENWALD, M. et al., "Density limits in toroidal plasmas", Plasma Phys. Control. Fusion 44 (2002) R27.
[4] HUBER, A. et al., "Comparative H-mode density limit studies in JET and AUG", Nucl. Mater. Energy, submitted.
[5] BORRAS, K. et al., "A Scrape-off Layer Based Density Limit for JET ELMy H-modes", Contrib. Plasma Phys. 38 (1998) 130–135.
[6] BREZINSEK, S. et al., "Residual carbon content in the initial ITER-Like Wall experiments at JET", J. Nucl. Mater. 438 (2013) S303–S308.
[7] DE LA LUNA, E. et al., "Electron cyclotron emission radiometer upgrade on the Joint European Torus (JET) tokamak", Rev. Sci. Instrum. 75 (2004) 3831.
[8] TOKAR, M.Z.,"On Greenwald density limit in H-mode", Phys. of Plasmas 16 (2009) 020704.
[9] CHANKIN, A. V. and SAIBENEE, G., "Interpretation of density limits and the H-mode operational diagram through similarity parameters for edge transport mechanisms", Plasma Phys. Control. Fusion 41 (1999) 913–930.
[10] HUBER, A. et al., "Impact of the ITER-like wall on divertor detachment and on the density limit in the JET tokamak", J. Nucl. Mater. 438 (2013) S139–S147.
[11] BORRAS, K. et al.,"Recent H-mode density limit studies at JET", Nucl.Fusion 44 (2004) 752
[12] BERNERT, M. et al., "The H-mode density limit in the full tungsten ASDEX Upgrade tokamak", Plasma Phys. Control. Fusion 57 (2015) 014038 (12pp).
[13] GOLDSTON, R.J. et al.,"Theoretical aspects and practical implications of the heuristic drift SOL model", Journal of Nuclear Materials 463 (2015) 397–400.
[14] BATEMAN, G. et al., "Integrated predictive modeling of high-mode tokamak plasmas using a combination of core and pedestal models", Phys. Plasmas, Vol. 10, No. 11, 2003.