Revisiting H, D, T studies of L-H transition in JET

E. R. Solano[1], E. Righi[2], E. Delabie[3], J.C. Hillesheim[4], C.F. Maggi[4], P. Carvalho[5], M. Chernyshova[6] and JET contributors
EUROfusion Consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, UK
[1]Laboratorio Nacional de Fusión, CIEMAT, Madrid, Spain; [2]European Commission, Brussels, Belgium; [3]Oak Ridge National Laboratory, Oak Ridge, TN 37831-6169, USA; [4]CCFE, Culham Science Centre, Abingdon, UK; [5]Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Lisbon, Portugal; [6]Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland

Much of the information on the isotope scaling of the L-H transition power threshold, P_{LH}, in JET is derived from early experiments in Hydrogen (H), Deuterium (D) and Tritium (T) with C wall (JET-C) [1]. In those experiments, mostly from 1997, the JET tokamak had the MarkIIA divertor, depicted in Fig. 1, with CFC divertor tiles. Also shown in Fig 1 is the present divertor configuration, JET-ILW, with tungsten (W) or W-covered CFC tiles in the divertor. Various experiments have studied P_{LH}(H) and P_{LH}(D) in JET-C [2,3] and JET-ILW [4], and have shown considerable variability in P_{LH} associated with divertor geometry**,** divertor strike point configuration, Carbon vs. ILW, Neutral Beam Injection (NBI) vs. Radio Frequency heating (RF) and plasma current or q_{95}, particularly for Hydrogen.

In JET-ILW L-H transition experiments the density is kept constant by feedback control of the fuelling rate, while the power is ramped up at approximately 1 MW/s. For fixed geometry and field we can observe different types of transitions as the electron density of the initial L-mode increases: gradual, sudden and sudden preceded by dithering. Shown in Fig. 2 are some examples of L-H transitions in the JET-ILW. Gradual transitions are observed at the lowest densities, they are often triggered by sawteeth. Sometimes each sawtooth ratchets the edge T_e until an L-H transition with a steady M-mode appears [5]. In gradual transitions it is

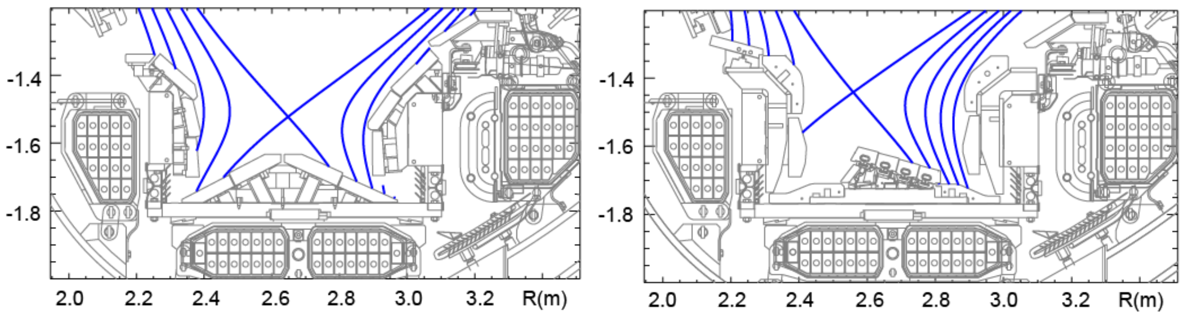
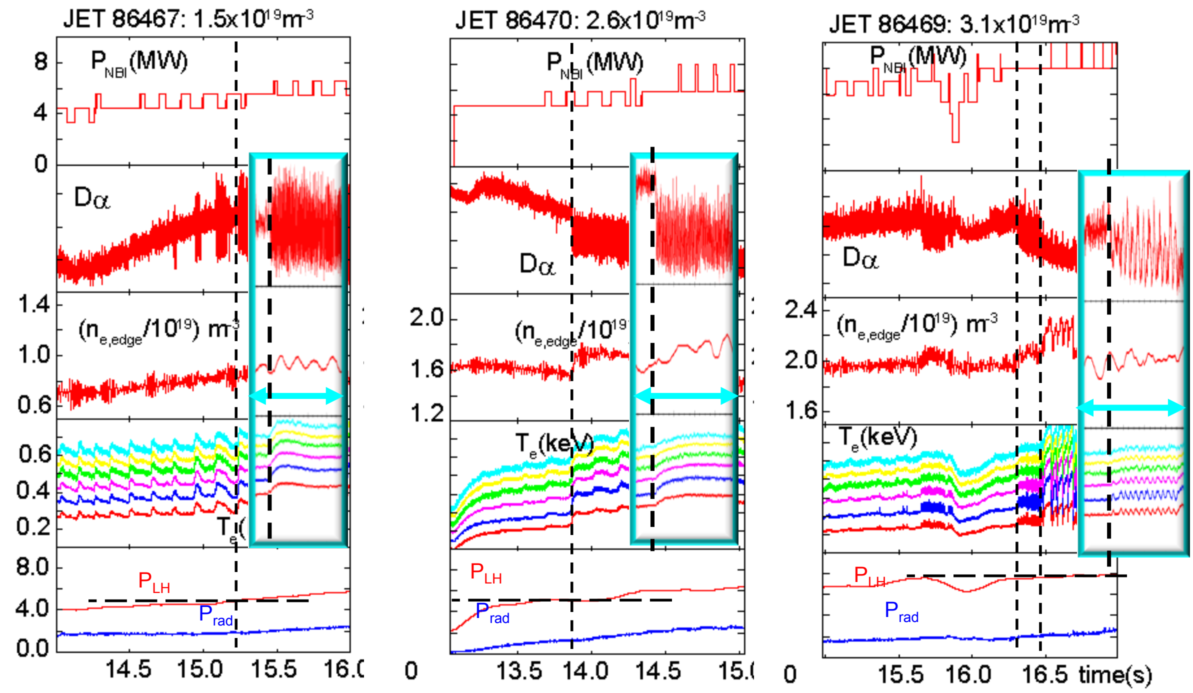


Fig 1, left: divertor and separatrix geometry of the JET-C divertor, MkIIA, during H, D, T, D+T campaigns in 1997. Divertor tiles were CFCs.
Fib 1,right: diverto geometry of JET-ILW, since 2011. This separatrix configuration is rfefered to as V5 or VH. Divertor tile at outer strike is solid W, others are W-covered CFCs.

*See the author list of E. Joffrin et al. accepted for publication in Nuclear Fusion Special issue 2019, https://doi.org/10.1088/1741-4326/ab2276



ST crashes, ratcheting $T_{e,ped}$, no n_e rise, increasing H duration, M-mode

Sudden L-H, M-mode, no dithers

Dithers followed by sudden L-H and M-mode, ELMs

Fig. 2: types of L-H transitions. the L-H transition time is marked with a black dashed line. Left: Gradual. Centre: Sudden. Right: Dithering. The insets show 100 ms windows. Observe that in the gradual transition n_e barely rises, and in the dithering transitions T_e and D_α exhibit periodic behaviour before the final transition.

often hard to detect a rise of $n_{e,ped}$, possibly because the target L-mode is largely unfuelled, to achieve a low density transition. Above a certain density value, transitions can be either sudden or dithering. Sudden transitions can also be sawtooth triggered, but now there is clear pedestal formation for both n_e and T_e immediately after the transition. At higher densities dithering transitions are commonly observed: the plasma can have multiple L-H transitions, until finally the power is sufficient to maintain a steady H-mode. For given plasma species, toroidal field and divertor+separatrix geometry it may not be possible to explore all 3 regimes. For instance, with B_{tor}=1.8 T in a HT configuration in Hydrogen only gradual and dithering transitions were observed. Here it must be mentioned that it is difficult to reduce the density in this configuration, in part because the outer strike is quite far from the divertor pump. For the same conditions in Deuterium, only sudden and dithering transitions were observed: presumably, we could not reach sufficiently low densities. In summary, in JET-ILW dithers are characteristic of a medium-high density range, typically gradual transitions are seen at low n_e, sometimes sudden transitions are seen near $n_{e,min.}$ Dithers are only observed in the low density branch of the power threshold when they are due to loss of coupling by the ICRH antennas, which can happen when density drops at the SOL upon entering the H-mode.

From now on let us consider solely the dataset with toroidal field B_{tor}=1.8 T of historical and recent L-H transition experiments at JET, which is the only one that contains a density scan for all 3 isotopes. For simplicity, in this paper we use the shorthand $P_{LH}=P_{aux(thermal)}+P_{ohmic}-dW/dt$. Shown in Fig. 3 are the L-H power thresholds in various cases: H, D and T. Marked in magenta are the regions for each type of transition. Note first in the recent data that $n_{e,min}$ is lower for D than it is for H, and the expectation is that it will be lower yet in T. The most striking feature of the historical data is that there is barely any variation on the target density for the Tritium shots. We observe that most of the historical data was taken at lower n_e than present data, and that no dithering transitions were observed. This leads us to believe that the in the old H, D, T dataset the high n_e branch was never reached. Having said that, our original assumption that all dithering transitions in JET-ILW correspond to the high

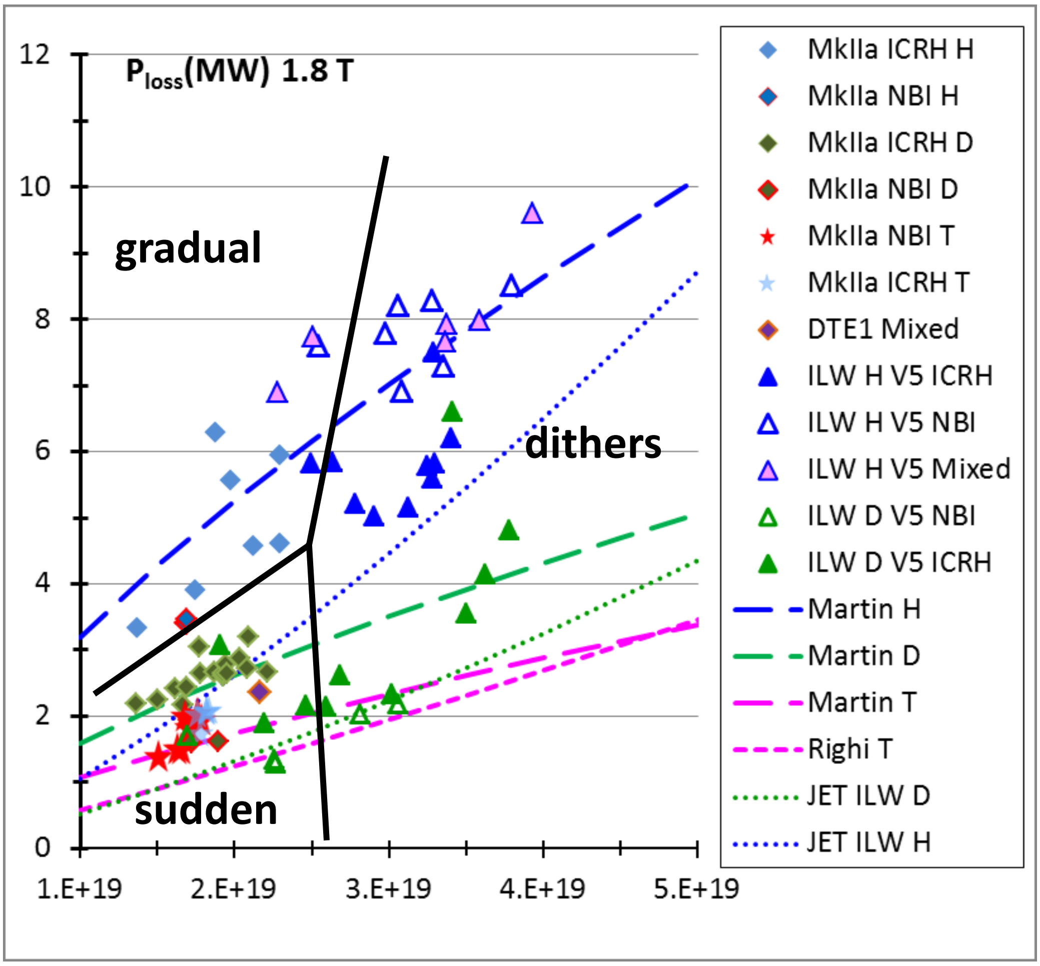


Fig. 3: P_{L-H} for various L-H transition experiments at 1.8 T in JET. The black solid lines delimit the types of L-H transition: gradual, sudden and dithering.

density branch of the power threshold has proven incorrect, some dithers can be present even in the low density branch. There simply appears to be a minimum density below which transitions are either gradual or sudden, without dithers. We will continue investigating this, it may be related to the relationship between particle and energy confinement time.

Let us now consider the scaling laws, assuming, as was done at the time, that the old data could be fitted by a single scaling law. Shown in Fig 3 with broad dashed lines are the Martin scaling laws for H, D, T, with their assumed A^{-1} isotope dependence [6]. They are not too different from the Righi scaling laws. Reanalysing the old P_{LH} data, and using $P_{Martin} = 0.0488 n_{e20}^{0.717} B_t^{0.803} S^{0.941}$ [5] as a convenient metric, we find that $P_{LH}^{Old}(D, RF) \cong P_{Martin}$, while $P_{LH}^{Old}(H, RF \,\&\, NBI) \cong 1.6\, P_{Martin}$. In Tritium the data is in a very narrow density range, (1.5-1.8)×10^{19} m^{-3}, lowest n_e with NBI, higher with RF, with different slopes, so the n_e scaling of $P_{LH}^{Old}(T)$ is quite uncertain, with $P_{LH}^{Old}(T)$ values falling between (0.67-0.9)×P_{Martin}. In the JET-ILW new scaling laws have been derived for D [7], $P_{LH}^{ILW}(D) = 0.046\, B^{0.85} n_{e20}^{1.31} S$. They are also displayed in Fig 3 as dotted lines. They capture the minimum P_{LH} for H and D in JET-ILW, but the density trend appears to be slower in the scalings than in the data in this Horizontal Target low field dataset.

For scaling to high field it is especially important to investigate the low field point, since it can heavily influence extrapolations. One implication of this study is that we should plan broad density scans in the forthcoming T and DT isotope campaigns at JET. We hope to look further into the effect of shape, since in JET-ILW it has been shown that P_{LH} can be twice as high for Vertical Target or Corner configurations.

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Acknowledgements: 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 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. Additionally, this work was supported in part by the Spanish National Plan for Scientific and Technical Research and Innovation 2017-2 020, grant number FIS2017-85252-R.