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Density Limit of H-Mode Plasmas on JET-ILW

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ABSTRACT

High-density discharges on JET with ITER-like Wall (ILW) have been analysed with the aim of establishing a mechanism for the H-mode density limit (DL) and compared with experiments in the JET carbon material configuration. The density limit is up to 20% higher in the JET-ILW than in the JET-C machine. The observed H-mode density limit is found close to the Greenwald limit. It is sensitive to the main plasma shape and is almost independent of the heating power. 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, the so-called 'dithering H-mode".

It was observed that detachment, as well as the X-point MARFE itself, does not trigger the H-L transition and thus does not present a limit on the plasma density and that it is the plasma confinement which is ultimately responsible for the H-mode DL.

1. INTRODUCTION

The H-mode density limit, the maximum plasma density accessible before back transition from the H-mode to the low confinement mode (L-mode), is one of the most fundamental operational boundaries for fusion devices [1]. Access to high density is highly desirable for the construction of a profitable thermonuclear reactor [2] from the point of view of maximising the fusion power since it scales quadratically with the density.

High-density high-confinement mode (H-mode) plasmas with a partially detached divertor are the baseline scenario for operation of ITER in high fusion gain regimes ($Q_{DT} \geq 10$) with plasmas at a density of 85% of the Greenwald density limit (GDL) scaling [1] and high energy (~ 350MJ) [3]. The establishment of a detached divertor at densities close to the Greenwald limit (n_{GDL}) is mandatory 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 sputtering of tungsten.

In the present paper, we investigate the physics mechanisms that lead to H-mode density limit and correspondingly to the H-L back transition. Dedicated H-mode density limit experiments have been performed during JET campaigns with the ITER-like wall (JET-ILW) [4] at densities close to the Greenwald limit in two magnetic field configurations. These experiments have been compared with experiments in the Carbon wall configuration (JET-C) which were operated under similar experimental conditions.

2. H-MODE DENSITY LIMIT EXPERIMENT IN THE JET TOKAMAK WITH ITER-LIKE WALL

2.1 H-MODE DENSITY LIMIT ON JET WITH THE ITER-LIKE WALL

H-mode density limit experiments with the ILW have been performed at $B_T \approx 2.7T$, Ip = 2.5MA, safety factor $q_{95} = 3.36$ in low and high-triangularity magnetic equilibria by varying the additional NBI-power from 8 to 20MW. Figure 1 shows the time evolution of a typical H-mode density limit discharge in JET-ILW in low-triangularity magnetic equilibria (average triangularity of $\delta = 0.22$). 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, confinement remains at a constant level of $H_{98Y} = 0.65$ up to about $n_e/n_{GDL} = 0.9$. Further gas puffing leads to moderate increase of the density, but the confinement deteriorates strongly down to $H_{98Y} = 0.56$ and the discharges usually make a back transition into the L mode. The H- L transition constitutes an effective undisruptive density limit (the H mode density limit) for an H-mode plasma. Beyond $n_e/n_{GDL} = 0.9$ during H-mode phase with confinement deterioration 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 the Figure 3. The ELMs might trigger the L-mode period during the dithering.

The sequence of these transitions we will call 'dithering H-mode'. The dithering cycles can be seen as a modulation of the BeII signal in the divertor. Therefore, the evolution of a gas fuelled, high density H mode discharge can be described by three main stages as shown in Figure 1: a Type I ELM phase, then a dithering cycling phase with energy confinement deterioration, followed by the L-mode phase. Dithering cycles, , have been firstly observed on ASDEX Upgrade during the gradual increase of the heating power P_{heat} close to the L-H power threshold (P_{thr}) [5] prior to final transition into the H-mode. Recently it has been reported in [6] that at plasma larger densities P_{thr} is reduced at least by ~ 30% with JET-ILW compared to JET-C. However it is found to be sensitive to variations in main plasma shape. In our experiments we operate far away from the L-H power threshold (scaling) with $P_{loss}/P_{thr} \approx 2$, where the $P_{loss} = P_{heat} – dW_{dia}/dt$ is the loss power. The repetitive H-L-H transitions close to the H–L transition boundary have been also observed in JT-60 [7] and ASDEX Upgrade.

The radiation losses between ELMs tend to increase firstly during the Type I phase with following saturation at constant level of $\gamma = P_{rad}/P_{heat} = 0.3$ (averaged over ELMs $<\gamma> = 0.37$) for larger densities beyond $n_e/n_{GDL} = 0.6$. After the 'dithering H-mode'a back transition at t = 13.36s from H to L-mode is observed with $\gamma \approx 0.4$. The H-mode density limit is typically defined as the maximum of n_e that is reached at the H-L boundary. The maximum density achieved in the JET-ILW gas fuelled steady state ELMy H-mode, shown in Figure 1, is ~ 92% of the GDL.

The Figure 2 shows the plasma stored energy as function of the central averaged electron density. Here are shown two H-mode density limit discharges with identical magnetic field geometry heated with ≈ 9.8MW and 20MW NBI powers respectively. The different phases are marked: red – type I ELM phase; blue – dithering cycles phase; green – L-mode phase. During the Type I H-mode phase, the stored energy and the confinement stay constant, while 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 such that the pedestal pressure stays constant. This phase is called a stable H-mode, since the pressure, and thus, the confinement, stays constant while the density increases.

During the ‘dithering phase’, the density increases marginally and the T_e^{ped} cools down, degrading the pedestal pressure and leading to a reduction of the confinement and of the stored energy.

Shortly before the H-L back transition the 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 ditering cycling has been observed in the configurations with both strike points on the vertical targets and only occasionally or with very short duration of the dithering phases in the configuration with outer strike point positioned on the horizontal divertor plate. In this 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.

2.2 DITHERING CYCLES PRIOR TO THE INTO THE L-MODE

Investigation of the ‘dithering cycles’ phenomenon is of outmost importance for understanding the physics mechanisms that lead to H-mode density limit. Figure 3 shows details of the ‘Type I ELMs phase’ and ‘dithering cycling’ phase of the typical H-mode pulses in a magnetic field configuration with both strike points on the vertical divertor targets. The cycles can be seen as a modulation of the BeII signal in the divertor. 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, improvement in the energy confinement reduces the power conducted to the SOL and divertor, causing stronger detachment: a completely detached inner and at least partially detached outer divertor leg. Despite that, the plasma density both at the edge and in the core is seen sharply rising, reflecting significant improvement in the particle confinement demonstrating 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, does not shows any excursion during the dithering cycles and stays almost at the lowest value of ≈ 140eV. Thus, cold and dense pedestal during the H-phase increases the plasma pedestal collisionality leading to the transition from the plateau regime of the neoclassical transport to the Pfirsch-Schlüter one. This is in line with the explanation given in [8] that the GDL 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 plasma collisionality corresponds to the transition from the plateau regime to the Pfirsch-Schlüter one. 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). During the L-phases with the low edge density, the BeII-emission has large values while it decreases during the short H-mode phase together with the total radiation. The measurements with fast magnetic probe (dB/dt) show that the turbulence level is significantly increased when the L-phase develops during the dithers. Similar as 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. Also the n_e and T_e profiles, measured by the High Resolution Thomson Scattering (HRTS) system [9] in transient L-mode periods demonstrate similarity to the profiles after transition into the L-mode.

Additionally, Figure 3 shows the tomographic reconstructions of D_α- and D_γ-emissions as well as the D_γ/D_α ratio in the divertor region just before the H-L transition during the L-mode dithering cycling phase. Strong radiation patterns of hydrogen emission lines are located in the divertor region, inside the inner scrape-off layer (SOL), without any indication of the MARFE formation. The D_γ/D_α-ratio increases strongly up to level of ≈ 0.1 throughout the inner divertor plasma. This large ratio cannot be explained by radiation due to excitation processes where the ratio should be below 0.02 for $T_e \leq 5$eV indicating the strong contribution of recombination processes. The electron density at the inner strike point measured by Langmuir probes is about $\approx 7 \times 10^{19}$m^{-3}. At such a density and assuming that the main fraction of radiation is due to recombination, the estimated local T_e calculated from ADAS photon emission coefficients [10] is about 1.0eV. The electron temperature near outer strike points measured by Langmuir probes is about 12eV and the outer divertor thus is completely attached.

2.3 ROLE OF DETACHMENT IN H-MODE DENSITY LIMIT

High density discharges in JET-ILW have been analysed with the objectives of establishing a mechanism for the H-mode density limit. At densities close the Greenwald limit the inner divertor is completely detached during the stable H-mode in-between ELMs. The outer divertor is at least partially detached. The radiation patterns of hydrogen emission lines as well as Be emission does not show any indication of the MARFE formation. These experiments confirm findings reported in the paper [11], where an extensive analysis of the divertor detachment has been performed in the H-mode density limit experiment at high triangularity. It is shown in that work that the density in the core and at the edge is rised for a long-time period after the outer divertor is fully detached. Thus, detachment and subsequent MARFE if any do not trigger the H-L transition as it is also observed at ASDEX Upgrade [12]. This experimental evidence supports the view of the earlier observation on JT-60U with [7] that it is the plasma confinement which is ultimately responsible for the H-mode density limit.

2.4 IMPACT OF THE INPUT HEAT POWER AND PLASMA SHAPE ON THE DENSITY LIMIT

The impact of the input heat power on the H-mode density limit has been analysed in the experiments by varying neutral beam auxiliary heating NBI-power from 6 to 20MW in low ($B_T \approx 2.7$T, $I_p = 2.5$MA, $q_{95} = 3.36$, averaged $\delta = 0.22$, the location of the inner and outer strike points on the vertical targets) and high-triangularity magnetic equilibria ($B_T \approx 3.0$T, $I_p = 2.0$MA, $q_{95} = 4.6$, averaged $\delta = 0.42$, the location of the inner and outer strike points on the vertical target and horizontal target correspondingly). Figure 4 shows the measured Greenwald fractions as a function of total heating power obtained in these experiments. The H-L transition in the pulse with P_{NBI} = 20MW at high-δ has not been succeeded. Because the density increase during the dithering phase is very marginal, we used here the maximum reached density during the dithering cycles. A density limit close to the GWL is found: 0.9 for low-δ and 1.05 for high-δ configuration. The investigated density limit is up to 15% higher in the high-δ divertor geometry than in the pulses with strike points on the vertical targets at low-δ. The observed H-mode density limit is sensitive to the main plasma shape and is almost independent of the heating power. At ASDEX Upgrade, however, the H-mode density limit is reported to be independent of the triangularity but shows an increase with heating power [12].

2.5 COMPARISON OF THE H-MODE HIGH DENSITY OPERATION IN JET-C AND JET-ILW

In Figure 5 two density limit pulses (#81933-beryllium/tungsten wall; #76292-carbon wall) with ITER-like and Carbon wall are compared. Both plasmas (2.0MA/ ≈ 3.0T) were heated with ≈ 10MW NBI. Similarly to the L-mode experiments [11], the density limit was higher when the experiment was performed in the fully metallic machine: n_e/n_{GDL} = 1.05 with ILW versus n_e/n_{GDL}= 0.9 with C-wall. In contrast to JET-ILW, the total radiated power in JET-C is always increased during the density rise until the H-L transition. On the other hand, the radiation power with the ILW tends to increase during the Type I phase with following saturation at constant level of $\gamma = P_{rad}/P_{heat} = 0.45$ during the small ELMs phase. In general, the radiation fraction is always higher in the JET-C than in the JET-ILW. The Carbon levels are much lower than in JET-C, resulting in reduced Z_{eff}≈ 1.15 versus ≈ 1.75 in JET-C and in a lower P_{rad} up to the H-L transition. To reach the density limit in JET-ILW, essentially larger puffing rates than for the JET-C machine are required.

Figure 5 shows that the transition from Type I to small ELMs (or to Type III ELMs in the case of JET-C) is accompanied by an increase of the edge collisionality ν*(neo) at the pedestal. The edge collisionality ν*(neo) [13] approaches extremely high values (up to ν*(neo) ≈ 3.5 at DL) for the pulse with JET-ILW directly after Type I-to-small-ELMs transition, indicating a much denser and cooler pedestal than in the JET-C (ν*(neo) ≈ 1.5 at DL).

The n_e profile, measured by HRTS system, develops during the density rise completely different in JET-C and JET-ILW pulses. In contrast to the JET-ILW machine, during the gas fuelling in carbon environment the $\langle n_e \rangle$ saturates while the n_{ped} increases monotonically up to the H-L transition. The n_e profile approaches the flattening with density close to the GWL.

In the case of the JET-ILW, the n_e profile is flat even at Type I-Small ELMs transition. Practically n_{core} has the same values as n_{ped} during the entire phase of density rise. The n_e profile stays flat until H-L transition.

CONCLUSIONS

Dedicated H-mode gas fuelled Density Limit-experiments have been performed during JET recent experimental campaigns with the ITER-like wall by varying the additional NBI-power from 8 to 20MW. The H-mode density limit was found close to the Greenwald empirical scaling (n_{DL}/n_{GDL} = 0.9 ÷ 1.05). In addition, 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 in the so-called ‘dithering H-mode” accompanied by energy confinement degradation. In gas fuelling ramp discharges, three operational phases have been identified: the stable H-mode phase, then a dithering cycling phase or the regime of small ELMs combined with dithering cycles with energy confinement deterioration, followed by the L- mode phase. During the first phase, the stable H-mode phase, the pedestal pressure, and thus, the confinement, stays constant while the density increases. During the ‘dithering phase’, the density increases marginally and the T_e^{ped} cools down degrading the pedestal pressure leading to the reduction of the confinement and of the stored energy.

During the transient H-mode periods of the dithers, improvement in the energy confinement reduces the power conducted to the SOL and divertor, causing stronger detachment: completely detached inner and at least partially detached outer divertor leg. Despite that, the plasma density both at the edge and in the core is seen sharply rising, reflecting significant improvement in the particle confinement.

The metallic machine operates with a much denser and cooler pedestal than the JET-C machine. Essentially, larger puffing rates are required to reach n_{DL} in the full metal machine than were needed for the JET-C machine due to changes of recycling at the Be/W wall. It was observed that detachment, as well as the X-point MARFE itself, does not trigger the H-L transition and thus does not present a limit on the plasma density. In the range of total heating powers of 6-20MW, no dependence of the density limit n_{DL} on the heating power was observed. But it depends on the magnetic field configuration: n_{DL}/n_{GDL} = 1.1 in high- triangularity magnetic equilibria with q_{95} = 4.6 and the location of the outer strike on the horizontal plate and n_{DL}/n_{GDL} = 0.9 in low-triangularity equilibria with q_{95} = 3.36 and strike points on the vertical targets.

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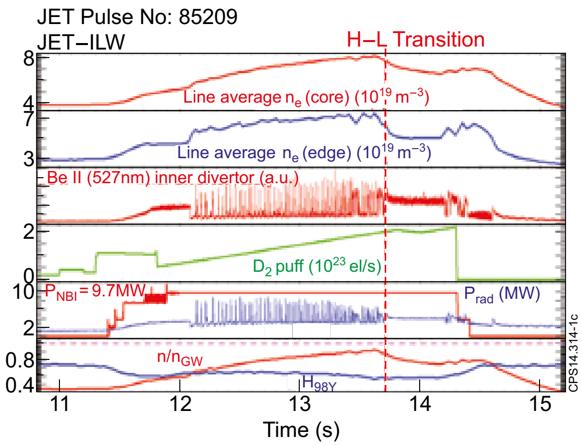

Figure 1: Time evolution of a typical H-mode density limit discharge.

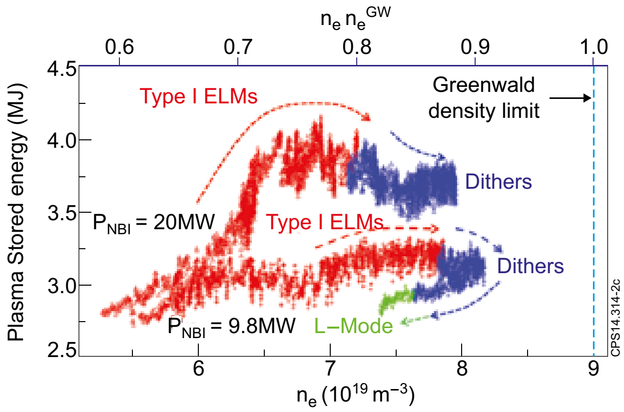

Figure 2: Plasma stored energy plotted versus the central averaged electron density.

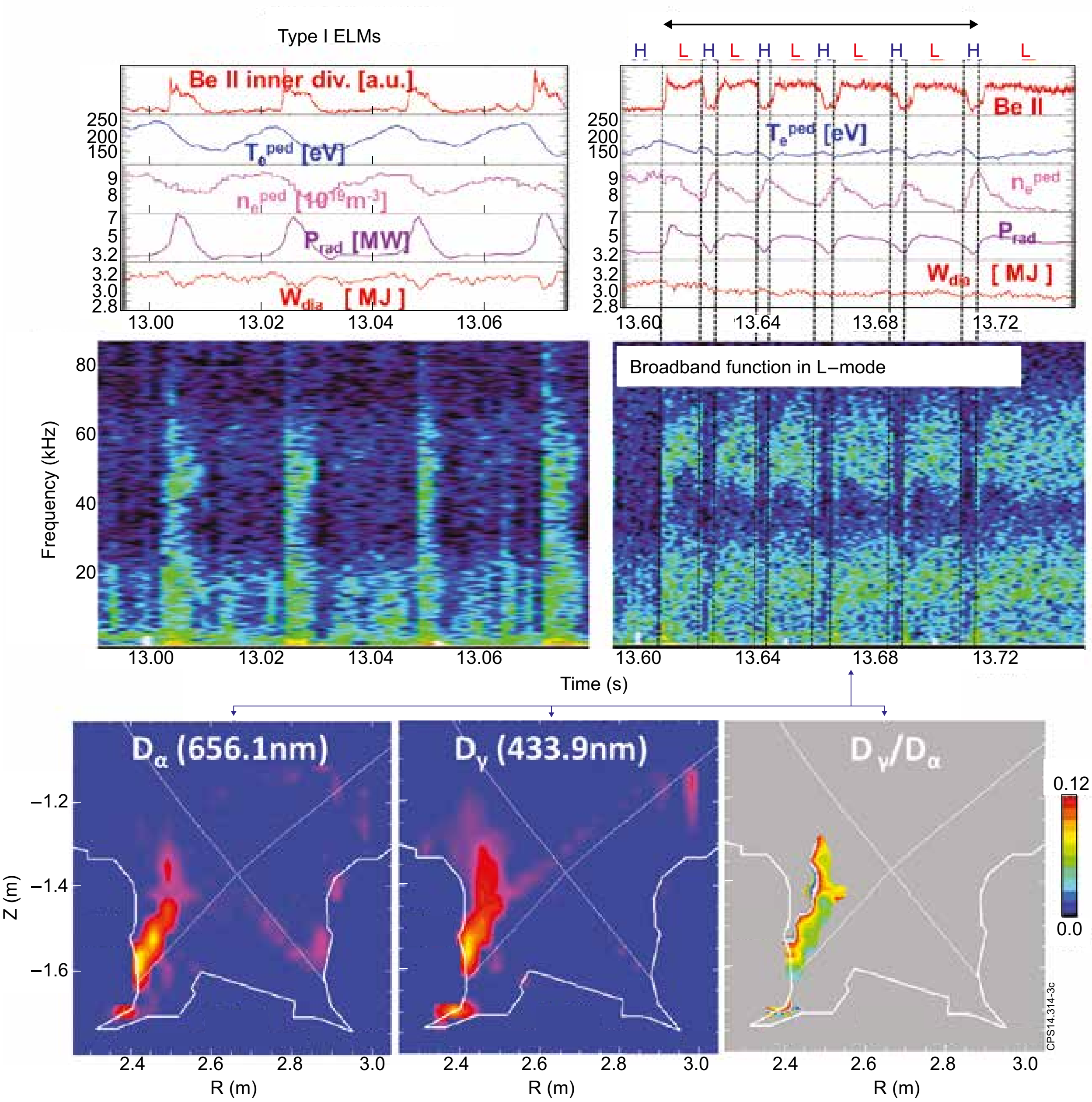

Figure 3: Characteristic time traces of the high density limit discharges for stable H-mode phase (left) and dithering cycles before the H-L transition (right): BeII-emission signal, pedestal density n_{ped} and temperature T_{ped}, total radiated power P_{rad}, plasma stored energy W_{dia} as well as power spectrum of a magnetic probe located inside the vessel on the high field side. Tomographic reconstructions of D_γ- and D_α emissions and D_γ / D_α ratio (bottom) in the divertor region during an L-mode dithering phase at t = 13.67s.

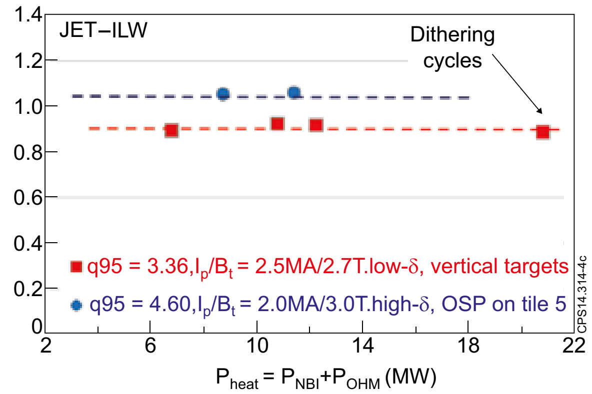

Figure 4: The H-mode density limit (Greenwald fraction) as a function of total heating power obtained in the JET-ILW.

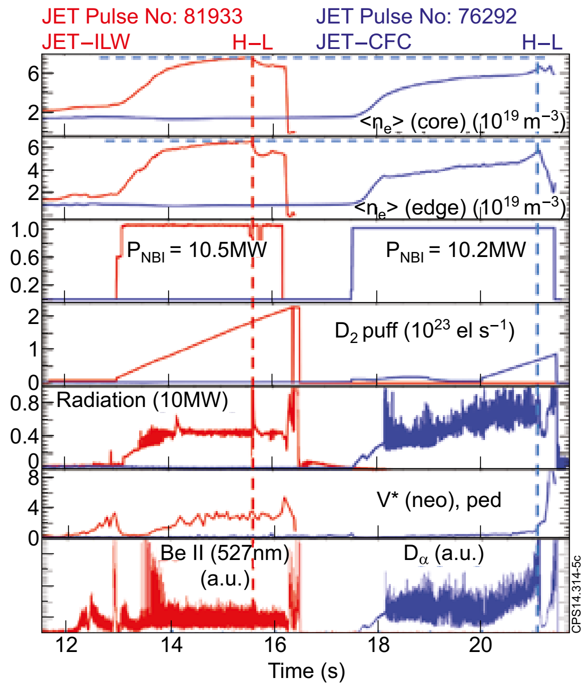

Figure 5: Comparison between two H-mode density limit pulses in JET-ILW and JET-C.