Effect of fuelling location on pedestal and ELMs in JET

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Since the introduction of the Tungsten (W) divertor in JET, as part of the ITER-Like Wall (ILW) project, we confirm the ASDEX-Upgrade finding that low fuelling, with associated infrequent large ELMs, can cause W sputtering and entrain W into the plasma [1], eventually cooling the plasma core. To avoid core W accumulation, typically large fuelling is used at JET, producing high ELM frequencies and smaller ELMs. On the other hand, large fuelling or low pumping are known to have a detrimental effect on confinement: H_{98}~0.8 has been typical in heavily fuelled 2 MA baseline plasmas, both with C wall [2] and ILW at JET [3].

It is possible that heavy fuelling localised in the divertor area drives the plasma towards detachment and cools the X-point, thereby affecting pedestal stability, and the speed at which the separatrix recovers from the ELM. To study this we varied the poloidal fuelling location in ILW plasmas with 2 MA, 2.3 T, $n_e/n_{e,Greenwald}$~0.65, 12-14 MW of NBI heating and medium fuelling levels. Two plasma shapes were studied: one with good pumping due to strikes near the pump duct, as shown in blue in Fig. 1, and a more conventional one with reduced pumping, in red in Fig. 1. D_α viewing lines of inner strike, X-point and outer strike are shown for blue shape.

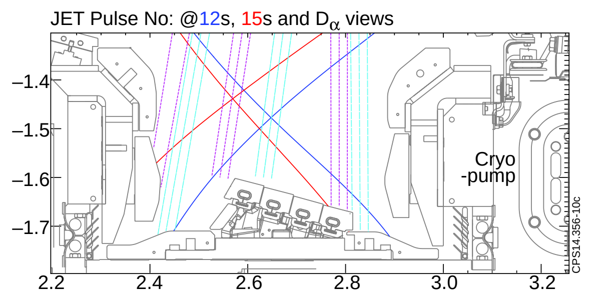


Fig. 1.: Blue and Red plasma shapes studied and D_α lines viewing inner strike, X-point and outer strike

Fuelling scans were carried out from various locations: inner strike divertor area, (iDIV, circles in next plot), upper low field side (uLFS, squares) and plasma top (Top, triangles). The divertor fuelling is toroidally distributed at source, uLFS is available at 1 toroidal location, top fuelling used 2 toroidal locations simultaneously.

*See Appendix of F. Romanelli et al, Proc. of 24th IAEA Fusion Energy Conference 2012, San Diego, USA

Shown in Fig. 2 are the ELM frequencies averaged for 1 s. Empirically we observe *in this scan* that when the ELM frequencies are lower than 40 Hz, sudden W influxes modify ELM frequencies and can even lead to loss of H-mode. In those cases we plot the ELM frequency 0.5 s before such events. When sufficient fuelling is applied the plasma can recover from transient W events and a healthy steady state can be reached. Because the cryo-pump is located in the divertor area, divertor fuelling is less efficient. Top fuelling is most effective at increasing f_{ELM}.

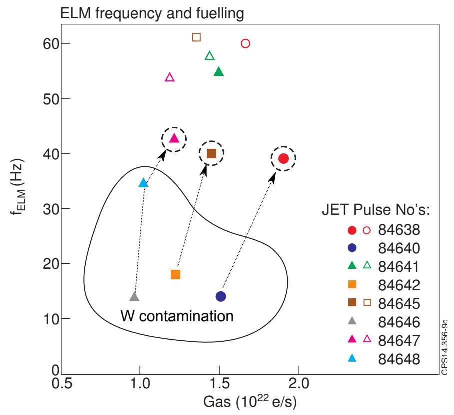


Fig. 2: ELM frequency achieved for different fuelling levels and locations. Solid symbol for blue shape, open for red.

Shown in Fig. 3 are the plasmas that had minimum fuelling required to avoid W accumulation, fuelling location and level noted at the top of each column. Divertor fuelling was insufficient to produce regular ELMs, it typically had colder pedestals and higher radiation. The time zoom shows that in many cases we observe "negative ELMs", drops in D_α after the ELM [3,4]. Negative ELMs are produced when a dense (> 10^{20} m^{-3}) cold (T_e<1-3 eV) plasma is being viewed, since then D_α is dominated by recombination [5]. When an ELM deposits energy in that plasma T_e rises and the recombination rate drops, leading to a reduced D_α. Later D_α may increase again as the plasma cools back down, or as n_e and T_e rise (possibly

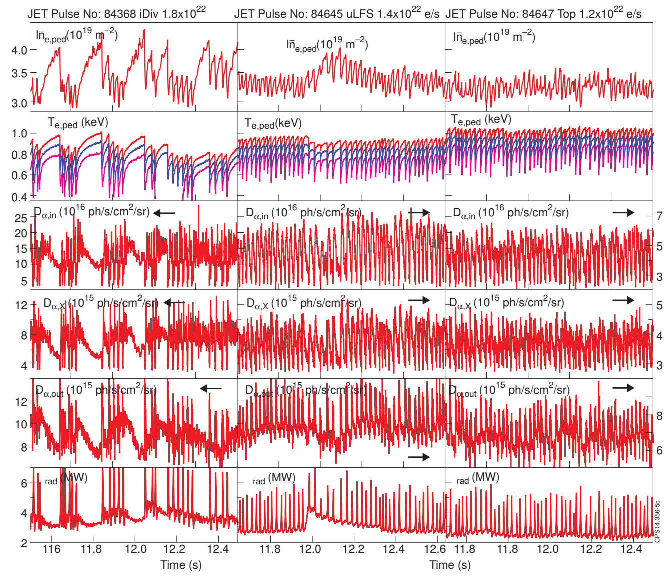
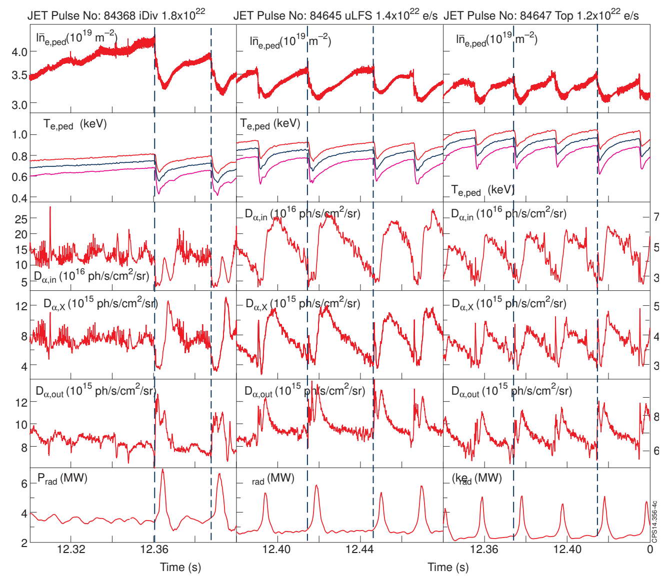


Fig. 3a) for blue shape and divertor, upper LFS and top fuelling: pedestal density, temperature, D_α from inner strike, X-point and outer strike views, total radiation.



b) time zoom to show negative ELMs

elsewhere along the line of sight) in between ELMs. Modelling D_α evolution along a line of sight is very complex. Nevertheless, we can use the observation of "negative ELMs" as an indicator of cold plasma, particularly at the X-point. In that sense we see that in iDiv fuelled plasmas the inner strike and the X-point are cold, while the outer strike is not. uLFS fuelling exhibits negative ELMs only at the inner strike. Top fuelling has mostly positive ELMs. Langmuir probes shows signs of inboard detachment, slightly more so for divertor fuelling [6].

In steady plasmas in the blue shape H_{98}~0.8-0.9. In the low pumping red shape there is no apparent effect of puffing location: considerably colder pedestals and low confinement, H_{98}~0.75 are observed in all cases, together with negative ELMs, even when the ELM frequencies are sufficient to control W.

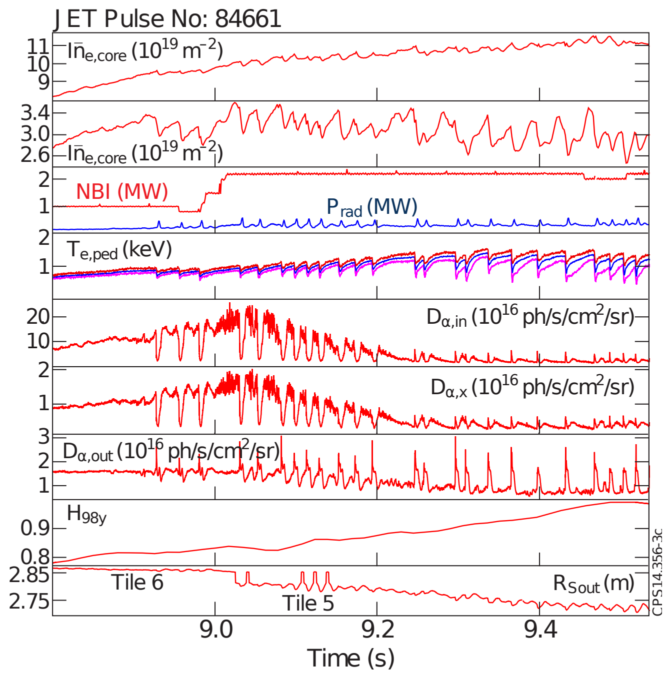


Fig. 4: evolution of D_α from negative to positive ELMs, together with change in $T_{e,ped}$

In a different series of pulses, meant to study the difference between hybrid and baseline plasmas [7] we find more dynamic situations. For instance in Fig. 4 we see that as power is increased inner strike and X-point ELMs change from negative to positive. At the same time pedestal temperatures and H98y increase.

We find in general that at medium fuelling levels hot pedestals and good confinement are associated with a hot X-point. Whether this is related to SOL flows, as suggested in [8], is not known. Another possible interpretation is that a hotter separatrix enables the pedestal top to be hotter for a given limiting gradient. But it is also possible that a hotter pedestal produces larger energy pulses that burn through the cold plasma at the X-point and produce positive ELMs.

Returning to Fig. 3 note that in the case of uLFS fuelling at 12 s there is a sudden rise in radiation, which slowly decays afterwards. It is due to a sudden W influx, captured by a spectroscopic camera as a flash of W I light (400.8 nm), shown in Fig. 6. Coincidentally $T_{e,ped}$ drops and $n_{e,ped}$ rises, until they recover their previous values. We interpret this as evidence of a direct effect of W influx on pedestal temperature, until the W is flushed out of the pedestal region by the ELMs, but there may also be an effect of the increase in core radiation. There are various examples such as this one in our pulses, displaying a consistent pattern.

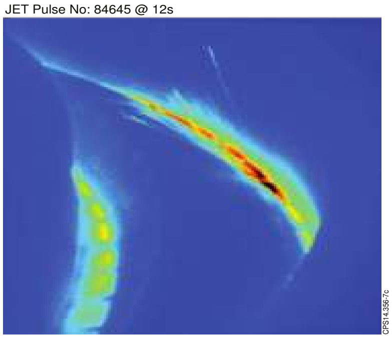


Fig. 6: shower of W sparks originating near the outer strike point, following a combined sawtooth and ELM event, responsible for triggering radiation increase and $T_{e,ped}$ drop at 12 s in 84645, shown in Fig. 4

In a different example, shown in Fig.7, we do have IR measurements at the outer strike, now in the red shape. Here the arrival of a sawtooth pulse (bringing in core impurities and fast ions) triggers a W event that increases radiation at the plasma edge (shown in the edge bolometry channels) and lowers $T_{e,ped}$. Note that the ELMs themselves are affected, their amplitude is smaller during the W and radiation event, and ELM duration is longer (it changes from 3 to 7 ms in IR). Eventually the various ELMs expel W from the pedestal region (bolometry shows that some of it moves inward, some outward). When the next sawtooth cleans the core, the plasma returns to its previous state.

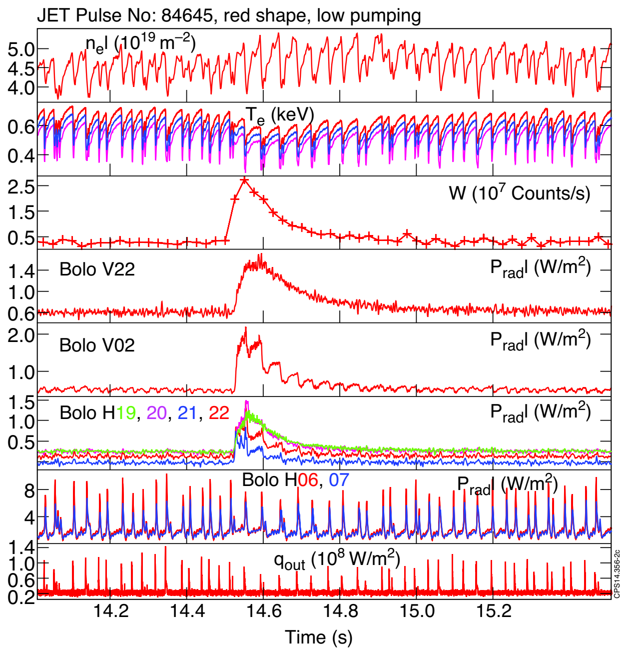


Fig. 7: effect of W influx on pedestal

In conclusion: in a well pumped shape, poloidal location of fuelling can affect SOL and f_{ELM}, top pumping being most efficient at achieving stationary clean plasmas. With sufficiently low fuelling and/or strong pumping evidence of hot X-points correlates with higher $T_{e,ped}$ and higher confinement in these JET plasmas in ILW. We also show how transient W events temporarily increase P_{rad} in the pedestal, reduce $T_{e,ped}$ and modify ELMs.

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