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Exploring the physics of a high-performance H-mode with small ELMs and zero gas puffing in JET-ILW

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Recent experiments in JET-ILW have been successfully exploring a high-performance H-mode scenario with no gas dosing at low q_{95} ($I_p = 3$ MA, B_t=2.8 T, $q_{95} = 3.2$) and low triangularity, with peak neutron rates reaching values of 3.6×10^{16} s^{-1}. This was enabled by operation at very low gas fueling, which is challenging in JET with the metal wall due the need to control the W influx into the core region. By starting H-mode operation at high density, applying a high level of gas injection early during the NBI heating phase to avoid ELM-free phases, it was possible to reduce the gas puffing to very low levels ($\approx 10^{21}$e/s), achieving a high performance, low density regime (called no-gas regime in the rest of the text) with averaged $n_e \approx 3 \times 10^{19}$ m^{-3} and Greenwald fraction of ≈0.35, amongst the lowest ever achieved in JET-ILW. Operation at such low densities allows decoupling ions from electrons, resulting in higher T_i/T_e than what obtained in conventional ELMy H-modes at higher densities and similar heating power.

One of the best examples of this no-gas scenario (#94900) is shown in Fig. 1, compared to the reference ELMy H-mode discharge (#94777) at similar heating power. Both discharges are heated by 20 MW of neutral beam injection (NBI) and up to 4 MW of ion cyclotron resonance heating (ICRH). In discharge #94900 the gas puffing is switched off at 8.5 s, resulting in a strong decrease in edge density (from 7×10^{19} m^{-3} to 2×10^{19} m^{-3}) and a significant increase in the density profile peaking. This is accompanied by an increase in pedestal temperatures ($T_{e,ped}$ ≈1.5 keV, $T_{i,ped}$ ≈2 keV), enhanced toroidal rotation ($v_{tor,0}$ ≈450 km/s), improved core ion confinement ($T_{i,0}$ ≈15 keV, $T_{i,0} \approx 2 \times T_{e,0}$) and ELMs substantially smaller and faster than those of the reference with gas fuelling (f_{ELM} ≈60 and 25 Hz respectively). In the no-gas phase, the ion temperature, stored energy and neutron rate continuously increase until the appearance of a core MHD mode (n=4) triggered by a sawtooth crash (see sharp drop in the neutron rate at 10.5 s, Fig. 1(e)), suggesting the performance is limited by MHD rather than transport. It must be noted that this MHD event does not lead to a disruption, the discharge survives and is landed safely. Density and radiation remain essentially constant after the gas puff is switched off, indicating particle transport is fast enough to provide adequate density and impurity control. This behavior differs from what observed in the hot-ion H-mode developed in JET-C(1) where density and radiated power increased constantly during long ELM free periods, eventually leading to a radiation collapse and back transition to L-mode.

Despite the absence of gas puffing and strong electron density peaking of the no-gas scenario, which typically lead respectively to an increase in W source and to strong inward impurity convection, central impurity accumulation does not take place, the temperature of the outer target and the total radiated power are comparable to the reference discharge. Both discharges also show very similar 2D radiation patterns, with strong localization on the LFS midplane at ψ_N>0.8 and very low central values. Due to the much lower electron density at the pedestal top, the no-gas discharge reaches similar radiated power to the reference with a factor 4 increase in mid-Z (Ni/Fe/Cr/Cu) and high-Z (W) impurity concentrations, which in turn are the cause for the increased LOS-integrated Z_{eff} measurement (Fig. 1(c)). Due to the strong localization of these impurities on the LFS midplane, their increased concentration does not affect the plasma center where Z_{eff} remains < 1.4 as in the reference, so core dilution is also kept under control.

The no-gas scenario exhibits remarkably good absolute and normalized performance, albeit transient, reaching peak values of H_{98} ≈1.4, β_N ≈2.2, W_{MHD} ≈9 MJ, and this is achieved at much lower collisonality ($\nu^*_{e,ped}$< 0.1, close to ITER values) than the reference ELMy H-mode at higher density. The electron pedestal pressure is also slightly smaller than the reference, albeit at lower density and higher temperature, but there is a significant increase in core electron and ion pressures, resulting in a 35% increase in global energy confinement at the maximum stored energy. Improved transport driven by the increase in sheared $E \times B$ flow [2] is thought to contribute to both the strong peaking of the density profile and the improved performance. Additional effects associated with the large population of fast ions present in these plasmas, as shown in [3], might also play a role in the overall improved thermal transport. The added impurity control is provided by the increased ion temperature screening enhanced by the extreme toroidal rotation [4].

An especially interesting feature of the no-gas regime is the marked reduction in ELM size compared to conventional ELMy H-mode plasmas. With the decrease in edge density the type I ELMs are replaced by very small ELMs at a much higher frequency. ELM size increases as the pedestal pressure increases, but remains significantly smaller than those obtained in the reference pulse at higher density and similar heating power. We note that in those conditions the link between ELM size and pedestal collisionality and/or edge density typically found for Type I ELMs is lost [5]. Both the electron density and temperature pedestals become wider, and there is a substantial reduction in the maximum ∇n_e as the edge density decreases, resulting in a lower maximum ∇P_e. Pedestal stability analysis indicates that the edge operating point is below the peeling-ballooning boundary, which might explain the absence of large type I ELMs. The underlying physics mechanisms responsible of the onset of these small ELMs are still a matter of ongoing investigation.

The new no-gas H-mode regime recently demonstrated in JET-ILW provides a valuable opportunity to study the confinement properties and ELM dynamics of high temperature plasmas with temperature and density profiles substantially different from those obtained in the conventional scenarios. With the aim of improving our understanding and increasing the accuracy of extrapolations for ITER, this scenario allows validating existing transport models and investigating the role of different physics mechanism involved in the observed improved energy confinement and impurity control.

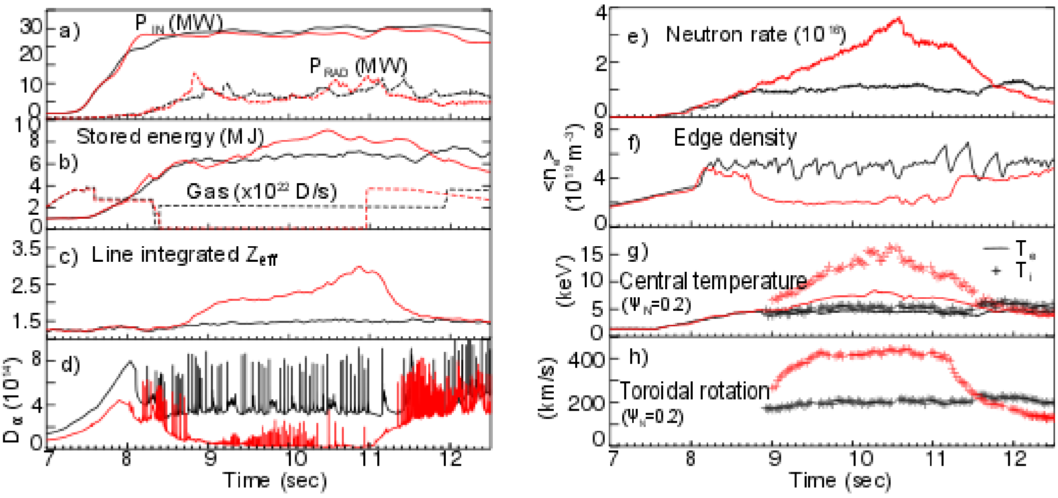

Figure 1: Comparison of a no-gas H-mode discharge (#94900) with a type I ELMy H-mode reference (#94777) with gas dosing during the main heating phase (Ip=3 MA, q_{95}=3.2, low δ, P_{NBI}=22 MW, P_{ICRH}=4 MW)

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