Overview of hybrid development in JET with ITER-Like Wall

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Since 2011 JET has operated with a Tungsten (W) divertor and a Beryllium (Be) main chamber to test first wall materials adopted for ITER [1]. The hybrid scenario [2], originally characterized by a low central shear q-profile and aiming at a moderate density (Greenwald fraction ~0.6), q_{95}~4, β_N>2.5 and H_{98y2} > 1.2, has been studied and developed with this new ITER like wall (ILW). The main difference with the former Carbon wall (C-wall) is the lack of an intrinsic edge radiator and the presence of metals radiating from the core. Tungsten accumulation is a major issue in Hybrid: it has recently been shown that the phenomenon is mainly associated with the peaking of the electron density profiles, typical of this regime, plus additional contributions coming from MHD and poloidal asymmetries [3]. Gas puffing and central ICRH heating are used to mitigate this effect which can degrade the performance or even lead to a disruption: the first increases the ELM frequency which helps in flushing out impurities and the latter has beneficial effects on neoclassical particle pinch via density pump out [4]. An optimization of the resonance position and minority concentration is needed for ICRH to be effective in impurity control: while this work has been successfully done in baseline H-mode, it needs further investigation for the hybrid case.

A reduced pedestal confinement is generally observed with the present metal wall. In the hybrid regime, this is partially compensated by a more peaked pressure profile which allows to recover typical C-wall performance (H_{98y2} ~1.2-1.4 with β_N ~ 3 for 2-3 s) [5]. Dedicated power scans, performed at constant current, field, shape and density, confirm that the power degradation is weaker than expected from H_{98y2} scaling [6]. A closer inspection of the data shows that this result is obtained only when the gas rate is reduced at the minimum level required for impurity control. A wider database, including plasmas with different engineering parameters, seems to indicate that the normalized pressure (β_N) is more relevant for high confinement than the input power per se, though disentangling the role of these two parameters is not trivial. In a first analysis, a dependence of the kind $H_{98y2} \propto \beta_N^{0.63}$ is found to best fit data for Ip > 1.8 MA and $1.1 < \beta_N < 2.4$ (fig. 1). The indication that best performance is obtained at high beta (and/or power) is also theoretically justified and reproduced in modeling activity as a virtuous core-edge feedback that reduces micro-turbulence and MHD effects [7]. A comparison between hybrid (tailored q-profile) and baseline (relaxed q-profile) run at same 'engineering' parameters such as density, current, field and power does not show any major difference in confinement, beta, neutrons and MHD stability [8]. This observation, together with the task of maximizing the equivalent fusion performance for future DT experiments, motivated the removal of the current overshoot introduced in the past to shape the q-profile [9, 10]. In fact, the no-overshoot start-up avoids low q transient phases and fast current ramps when pushing to high performance that require maximum current and field in the flattop. JET experience shows that a H factor in excess of 1 can be achieved also without the overshoot though this issue needs further optimization. A main heating timing scan, performed to optimize the q-profile, points as well to the same conclusion: figure 2 shows the case of two discharges where the main heating start differs by 1.5 s showing only small differences in performance. The early heating features less radiation losses and a higher ELM frequency.

When moving to lower q_{95}, the threshold for NTM onset decreases as well [11]. A comparison with baseline plasmas shows that the hybrid behavior is not more stable than baseline's when operating in the same β_N and q_{95} range (fig. 3). In the last campaigns, a substantial effort was devoted to push the hybrid to high absolute performance i.e. to high current and field: the strategy was to increase the current first at q_{95}~4 (I=2.5 MA; B=2.9 T) and then lower q_{95} at constant field. This study was performed at low trinagularity (δ~0.25) to take advantage of the lower operating density that maximizes the fusion performance at constant pressure. With these parameters, a new ILW neutron yield record has been established of $2.3x10^{16}$ n/s at β_N= 2.1 and H_{98y2}= 1.1. In spite of a limited amount of available power, it was possible to achieve a good peak performance, while obtaining stationarity was far more difficult. As seen in figure 3, these plasmas were heavily affected by impurity accumulation. A gas scan performed at 2.5 MA, 2.9 T and 23-26 MW of additional power, revealed a strong sensitivity of ELM frequency to small changes of gas rate not seen at lower current and power: this made it difficult to find a good compromise between impurity control and performance degradation. Figure 4 shows the two extremes of a five shot scan in which the gas rate was gradually increased: a 40% gas reduction is seen to cause a dramatic effect on performance and impurity behavior. An approach to q_{95}=3 operation performed at constant field (2.9 T) and increasing current not only confirmed that, at lower q_{95}, MHD instabilities onset have a lower β_N threshold but also that more gas is needed to keep the same ELM frequency for impurity control: this counteracts the expected confinement improvement due to the higher current. Further investigation will be needed to optimize q_{95} for best fusion performance within the power limits envisaged for the JET DT campaign. In view of this, a modeling activity to predict the DT performance is being carried out including extrapolations to higher current and power. In the coming campaigns a substantial experimental time will be devoted to hybrid studies to focus on various aspects of scenario integration and optimize the target for DT experiments.

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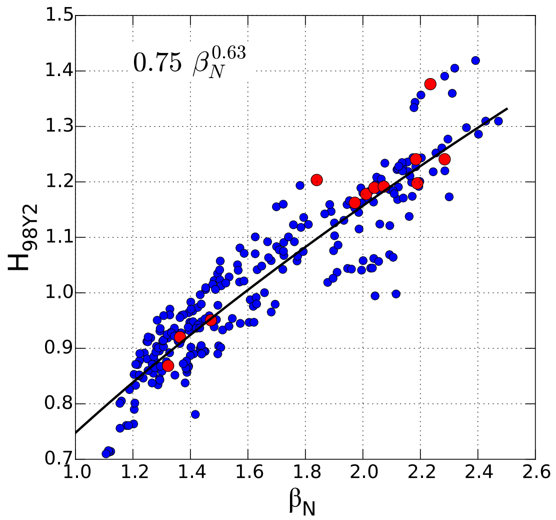

Figure 1: H98y2 versus β_N for Hybrid with I_p> 1.8 MA. Red symbols refer to plasmas with constant ϱ* (5.0-5.1 x10^{-3}).

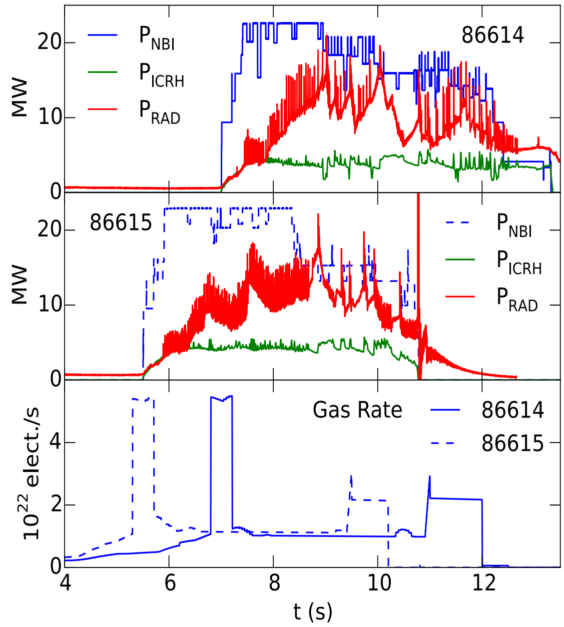

Figure 2. Tailoring q-profiles via main heating timing. Earlier start of NBI power (86615), giving a flatter q profile, produces more frequent ELMs (see spikes on P_{RAD} signal) thus mitigating the impurity accumulation (P_{RAD}) at same gas rate. The performance (β_N, H_{98y2}) remains virtually unchanged.

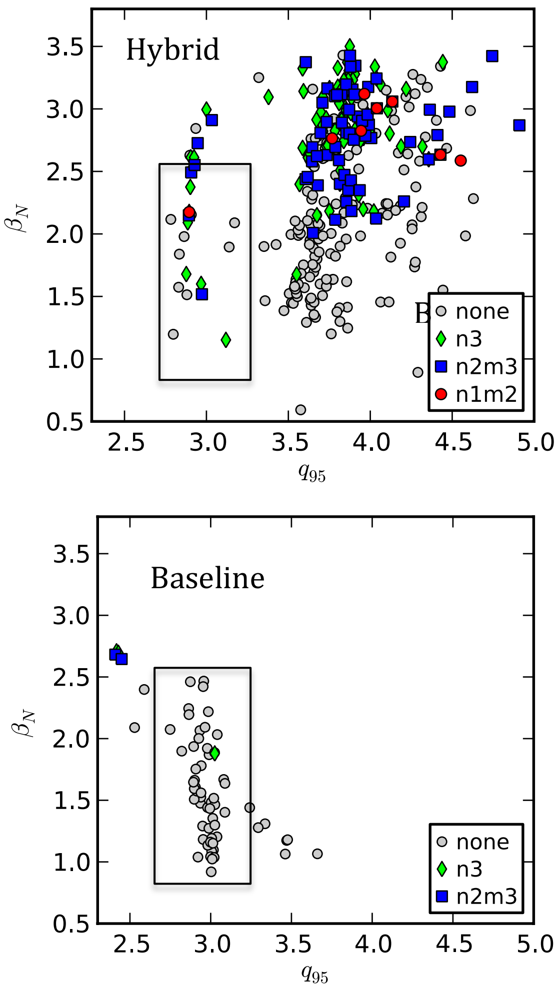

Figure 3: β_N at mode onset versus q_{95}. Rectangles: comparison range.

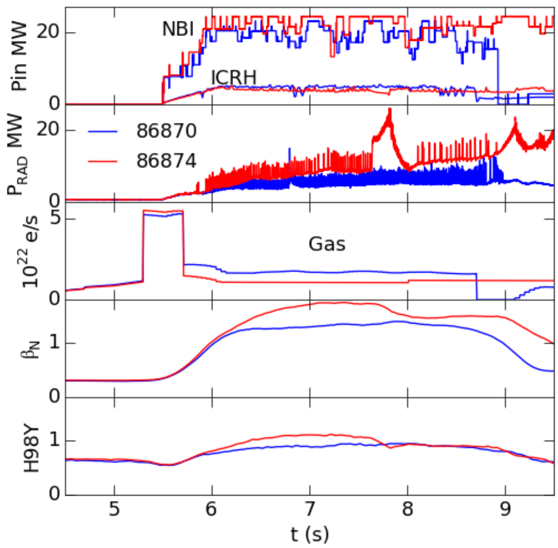

Figure 4. Gas scan at 2.5 MA, 2.9 T, low triangularity, tile 6. Shot 86874 (red) with 40% less gas exhibits a better performance at the cost of more radiation, lower ELM frequency and poorer stability.