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Development of a steady-state scenario in JET with dimensionless parameters approaching ITER target values

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Introduction

One of ITER goals is to achieve Q=5 in steady-state (SS). To do so requires high performance plasmas, with $\beta_N \approx 3$, $H_{IPB98(y,2)} \approx 1.5$. NBI-only experiments have been performed in JET at $B_T \leq 2.25$T, $I_P \leq 1.6$MA and $q_{95} \approx 5$, to study the plasma stability and confinement at $\beta_N \geq 3$ with various q-profiles [1]. The focus of this paper concerns experiments done at higher B_T, I_P (2.65T, 1.8MA, $q_{95} \approx 4.7$), and power (electron heating ICRH and LHCD in addition to NBI) to reach T_e/T_i, ρ^* and ν^* nearer to ITER values for SS operation, and provide a scenario to study transport, current drive (CD) and operational issues to be resolved for ITER.

Operational scenario

The high triangularity (average $\delta = 0.41$) configuration developed in previous experiments [2] was used, but with the outer strike-point moved from the pump throat to a tile capable of bearing higher power loads, although this degrades the pumping. The target q (at the start of high P_{ADD}) had weak positive or negative magnetic shear with $1.8 < q_{min} < 2.9$. To use and study the full capability of heating & CD mix in JET, these experiments rely on optimising the edge for good RF coupling while maintaining good core and edge confinement. With a small amount of gas dosing ($<7.5\times10^{21}$e/s D_2+10%H_2, in plasmas with $\overline{n_e} = 4\text{-}4.8\times10^{19}m^{-3}$), tolerable LH and ICRF wave coupling is obtained in plasmas with good edge confinement ($H_{IPB98(y,2)}$ ~1) and type I ELMs. The new ICRF ELM resilient systems [3] made it possible to couple up to 8 MW of P_{ICRF}. Up to 3 MW of P_{LH} ($N_{//}$ = 1.84 or 2.1) was coupled.

Performances and limitations

With P_{NBI} = 20-23.8MW, P_{ICRH} = 4-8MW, P_{LH} = 2-3MW, the following steady (>10xτ_E) and peak performances were obtained: $H_{IPB98(y,2)} \approx 1.2$ (up to 1.37), $\beta_N \approx 2.7$ (up to 3.1). To access β_N >2.7, P_{ADD} >26MW is needed. Fig. 1 shows a shot with average β_N = 2.7, $H_{IPB98(y,2)}$ = 1.2. The fusion performance factor $\beta_N H_{89}/q_{95}^2 \approx 0.25$ (0.3 needed for Q=5 in ITER). These plasmas have $\rho^*/\rho^*_{ITER} \approx 2.1$, $\nu^*/\nu^*_{ITER} \approx 4.5$, nearer ITER values than lower B_T experiments (Fig. 2). The Greenwald fraction (f_{GLD}) is 0.6-0.65 and $\langle T_e\rangle/\langle T_i\rangle$ = 0.9-0.95. Importantly, their thermal energy fraction (f_{TH}) is high, up to 78%.

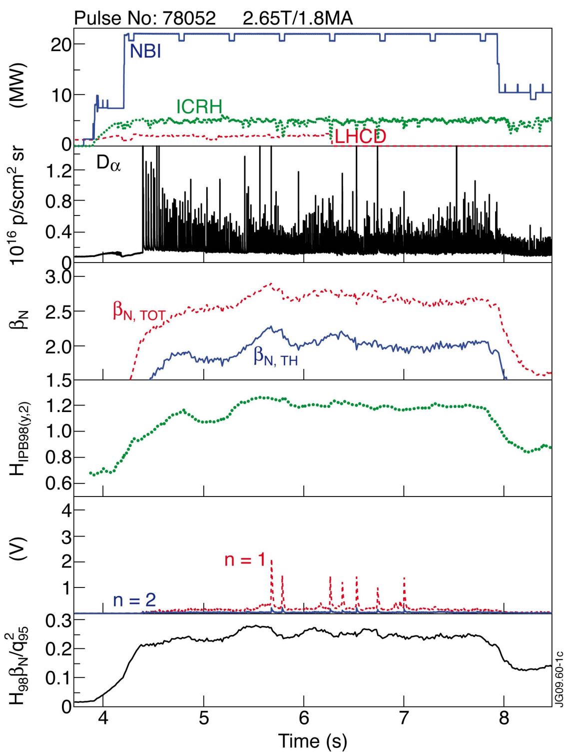

Figure 1. Time evolution of shot 78052

These plasmas are characterised by a good edge confinement, i.e. compatible with $H_{IPB98(y,2)}$ ~ 1 without improved core confinement. Only those with in addition a weak internal transport barrier (ITB) (according to the empirical criterion ρ^*_{Ti} > 0.014 [7]) reach $H_{IPB98(y,2)}$ > 1.15 (Fig.3) and β_N > 2.6. Only cases with high ρ^*_{Ti} also show an electron ITB. The H factor is not as good as in the lower B_T plasmas [1]. To investigate this, 2.65T shots were repeated with same NBI, but without ICRH and LHCD, and with/without gas. During the high performance, the shots have the same edge n_e, T_i, and T_e. Since the NBI-only shots have lower P_{ADD}, this implies that

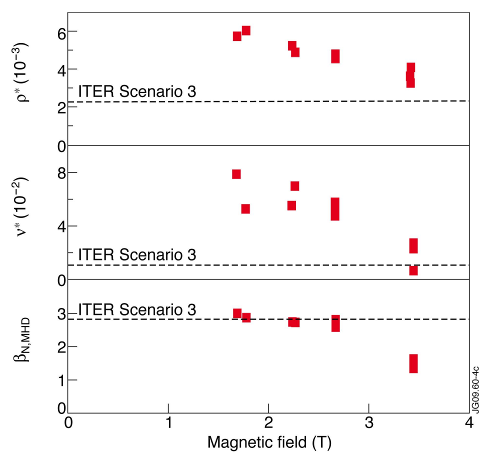

Figure 2. Range of ρ^*, ν^* and β_N achieved in the SS scenario at JET vs B_T. Points at 3.45T correspond to shots from JET ITB experiments reported in [4] and [5], ITER SS scenario 3 is from [6]

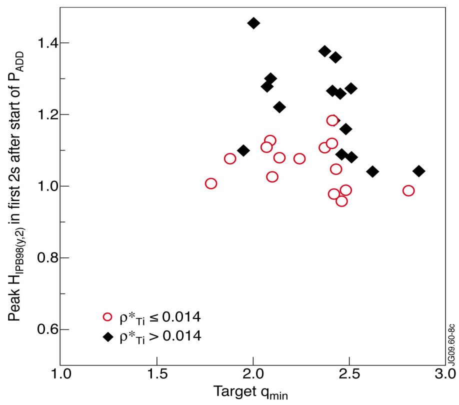

Figure 3. $H_{IPB98(y,2)}$ in first 2s after P_{ADD} start vs target q_{min} for 2.65T shots. q is determined with MSE + Faraday rotation + pressure as in [8]

their edge confinement is better, possibly because of their higher edge rotation. But this does not fully explain the difference, since even the NBI-only shots do not reach the high $H_{IPB98(y,2)}$ observed at lower B_T. Another difference is that the q profile in the highest performance 2.65T shots has higher magnetic shear than the low B_T shots, suggesting that further optimisation of the q profile is required. The I_P overshoot technique described in [9] and used successfully in [1] was applied in the 2.65T shots but did not result in an H factor improvement. At the highest values of β_N, the good performance in most pulses is terminated by pressure driven kink modes, in a few cases leading to disruptions. They correspond to plasmas with the highest core pressure gradient. Also observed is q=2 fishbone activity (as in Fig.1) that erode the performance but do not terminate it. The ITB (and hence high local pressure gradient) location in these shots corresponds within error bars to that of the q = 2 surface, which may also influence the stability. On all pulses there is evidence that q is evolving, so even in shots with target q_{min} > 2, q = 2 appears in the plasma after a few seconds. This suggests that there is not enough non inductive (NI) current. Interpretative modelling of selected pulses was done with TRANSP [10], using n_e, T_e profiles from the High Resolution Thomson Scattering, which provides a good radial resolution of the pedestal. The analysis shows that the bootstrap current fraction (f_{BS}) is 35–44% and NBCD ≈ 20%. P_{LH} modulation analysis as in [11] indicate that in the high performance shots, P_{LH} probably peaks at ρ > 0.6 and hence only a small (<10%) j_{LH} contribution is expected. This is probably because wave accessibility is limited in these plasmas. Based on the Stix-Golant accessibility condition, assuming constant $N_{//}$, $n_{e,PED} > n_{e\_access}$ for waves with $N_{//} \leq 2.1$ at that B_T. CRONOS was used to study the requirements for H&CD in this scenario, based on shot 77895 ($H_{IPB98(y,2)}$ = 1.1, β_N

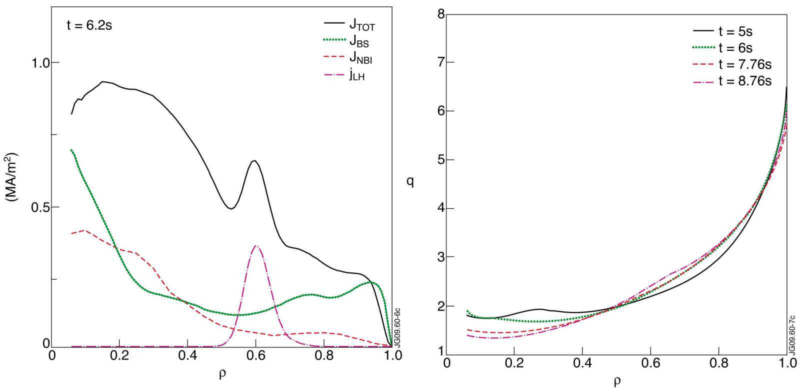

Figure 4.a) Current profiles at 6.2s and b) q profile evolution for 77895

= 2.7 for $22x\tau_E$) [12]. In this shot the good performance is not lost due to plasma instability, but probably because the q profile changes. The analysis shows that the NI currents ($f_{BS} \approx$ 35%, $f_{NB} \approx$ 20%, $f_{LH} \approx$ 10%) are not well aligned (Fig 4-a), i.e. there is too much on axis current (NBI, BS) in addition to j_{Ohmic}, and not enough off-axis CD (note that CRONOS possibly overestimate j_{LH}). As a result, core q is driven down, with q_{min} from 2 to 1.5 in ~4s (Fig. 4-b), and the magnetic shear increases in the region of the ITB.

Conclusion

Good progress has been made towards reaching simultanously ITER SS scenario dimensionless parameters β_N, $H_{IPB98(y,2)}$, $f_{thermal}$ and f_{GDL}, and $\langle T_e\rangle/\langle T_i\rangle$ (Fig. 5). ITER ν^* and f_{GDL} can not be matched simultanously in JET, and preference was given to the latter in these experiments. To get nearer ρ^* and ν^* ITER values at high β_N will require working at higher B_T once JET power upgrade is completed. More off-axis externally driven and BS current are required to make these plasmas SS [12], at $0.4<\rho<0.6$, which is also consistent with the need for 2/1 NTMs avoidance as shown in [1].

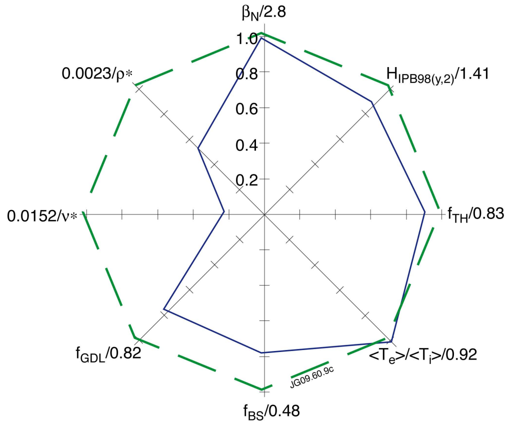

Figure 5. Dimensionless parameters for shot 78052 (red) normalised to ITER SS scenario 3 targets [6]

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