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 $B_T \leq 2.25T$, $I_P \leq 1.6MA$ and $q_{95}=5$, 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, $q_{95} = 4.7$), and power (electron heating ICRH and LHCD in addition to NBI) to reach $T_e/T_i$, $\rho^*$ and $v^*$ 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\textsubscript{ADD}) had weak positive or negative magnetic shear with 1.8$<q_{\text{min}}<2.9$. 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 (<7.5x10^{21} e/s D_2+10\% H_2), in plasmas with \( \bar{n}_e = 4-4.8 \times 10^{19} \text{m}^{-3} \), tolerable LH and ICRF wave coupling is obtained in plasmas with good edge confinement (H_{IPB98(y,2)} \approx 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_{II} = 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 (>10x\tau_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 \( \beta_N >2.7 \), P_{ADD} \geq 26MW is needed. Fig. 1 shows a shot with average \( \beta_N = 2.7 \), H_{IPB98(y,2)} = 1.2. The fusion performance factor \( \beta_N H_{98}/q_9 \approx 2.1 \), \( v/n_{\text{ITER}} \approx 4.5 \), nearer ITER values than lower B_T experiments (Fig. 2). The Greenwald fraction (f_{GLD}) is 0.6-0.65 and \( <T_e>/<T_i> = 0.9-0.95 \). Importantly, their thermal energy fraction (f_{TH}) is high, up to 78%.

These plasmas are characterised by a good edge confinement, i.e. compatible with H_{IPB98(y,2)} \sim 1 without improved core confinement. Only those with in addition a weak internal transport barrier (ITB) (according to the empirical criterion \( \rho^{*}_{Ti} > 0.014 \) [7]) reach H_{IPB98(y,2)} > 1.15 (Fig.3) and \( \beta_N > 2.6 \). Only cases with high \( \rho^{*}_{Ti} \) 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...
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 $\beta_N$, 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 $q_{\text{min}} > 2$, $q = 2$ 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 $\rho > 0.6$ 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 $N//$, $n_{e,\text{PED}} > n_{e,\text{access}}$ 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 ($H_{IPB98(y,2)} = 1.1, \quad \beta_N$)

Figure 4.a) Current profiles at 6.2s and b) $q$ profile evolution for 77895 calculated with CRONOS [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 \( j_{\text{Ohmic}} \), and not enough off-axis CD (note that CRONOS possibly overestimate \( j_{LH} \)). As a result, core q is driven down, with \( q_{\text{min}} \) 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 simultaneously ITER SS scenario dimensionless parameters \( \beta_N, H_{PB98(y,2)}, f_{\text{thermal}} \) and \( f_{\text{GDL}} \) and \( \langle T_e \rangle /\langle T_i \rangle \) (Fig. 5). ITER \( \nu^* \) and \( f_{\text{GDL}} \) can not be matched simultaneously in JET, and preference was given to the latter in these experiments. To get nearer \( \rho^* \) and \( \nu^* \) ITER values at high \( \beta_N \) 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].

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