High Current operation with the new JET divertor

R Sartori, S Ali-Arshad, E Bertolini, T Bonicelli, M Bures, J P Christiansen, P Chuilon,
H De Esch, N Deliyanakis, G Fishpool, O N Jarvis, T T C Jones, R Konig, K Lawson(1),
P J Lomas, A C Maas, F B Marcus, M F Nave(2), G Sannazzaro, B Schunke, P Smeulders,
A Taroni, P R Thomas, K Thomsen
JET Joint Undertaking, Abingdon, OX14 3EA, Oxfordshire, UK
(1) UKAEA, Culham Laboratory, Abingdon, OX14 3DB, UK
(2)Associacao EURATOM/IST, Lisbon, Portugal

Introduction In 1991, 4 and 5 MA H-modes were obtained in marginally diverted double null configuration /1/. The H-modes were ELM free and they were limited by strong rise of density and radiation. The plasma purity was decreasing with increasing plasma current. The degradation in ELM free H-mode confinement with plasma current, observed in particular at 5 MA, was attributed to the reduction in shear due to the X-point position being outside the target plates. The JET pumped divertor was designed to overcome these limitations and permit operation up to 6 MA in a clear X-point magnetic configuration. This capability was exploited in experiments to obtain more extensive H-mode confinement data at high plasma current and up to the maximum achievable combined heating power. Safe operation of high current plasmas was proven and H-modes were demonstrated up to 6 MA.
The high plasma current, low q regime is an important issue for future devices such as ITER.

The confinement experiment: 3 to 5 MA The H-mode data presented are of intermediate/high density regime (target density 3-5 10^{19} m^{-3}), at constant I_p/B_T ($q_{95} \approx 2.3$-3). In addition to study of ELM free and repetitive giant ELM regimes, some effort was invested to improve ICRH coupling. The data presented therefore include discharges where strong gas puff was applied in an attempt to obtain H-mode with grassy ELMs, and although this regime was not obtained, the frequency of ELMs increased with increasing gas puff (and the ELM free duration decreased). The maximum additional heating power achieved was 28 MW (20 MW NBI and 8 MW H-minority ICRH); the total power was limited because it proved difficult to maintain ICRH coupling resistance above 2 Ω in a properly diverted H-mode discharge. The new JET configuration shows naturally ELMy H-modes. The duration of the ELM free H-mode is increased by increasing the shear (and triangularity) of the magnetic configuration /4/. The achievable shear is limited at high plasma current by machine safety. The moderate shear magnetic configuration used up to 6 MA is shown in Fig.1. At plasma current $\geq$4 MA ELM free periods $\geq$0.5s were obtained with power step down. The ELM free length, the frequency of the ELMs and the stored energy evolution in the ELMy H-mode which follows the ELM free phase can be different even in similar discharges. Most of the discharges are still evolving towards steady state at the final power step down. H-modes with low frequency ELMs ($\approx$ 2 Hz) tend to completely recover the ELM free confinement. The use of CFC or Be as divertor target material has little effect on confinement quality. With Be, the discharge needs sweeping of the strike zones (not used with CFC) to avoid melting. Melting of the target is observed especially associated with the fast stored energy loss caused by a giant ELM event. This melting is localised to the edges of the tile castellation and does not degrade the power handling of the target and the performance of subsequent discharges. Both the ELM free and ELMy data contains discharges with long sawtooth free periods, which were not uncommon despite the low q_{95} of those discharges. In some discharges with ICRH heating, especially at the highest powers, fishbone activity was observed.

6 MA The recent operation at 6 MA has completed the MarkI design operation window. Operation at the machine limits required the reassessment of the forces on machine components both during normal operation and in the event of a disruption. Of particular concern were the forces during disruptions: the predicted mechanical vessel force as a result of loss of vertical position control early in the current quench of a disruption was of 600/700 tonnes. The 6 MA start-up uses a limiter aperture expansion scenario up to the X-point formation when q(a) of the limiter discharge is still above 3. The following X-point ramp (at a rate of 0.5 MA/s) reaches the final q_{95} (≈ 2.1) at low l_i. Low power additional heating from the X-point formation provides fuelling and avoids locked modes The flat top duration was limited to $\approx$600 ms, but only by TF cooldown time. Flux swing analysis suggests a 4-6 s flat top would be possible. ELMy H-modes were obtained at 6 MA with 9-12 and 18 MW of Neutral Beams power. Time traces for the highest power 6 MA discharge are shown in Fig. 2; the confinement results will be discussed in the following section. The extensive 5 MA programme and the demonstration of 6 MA have increased our confidence in routine operation at high current: we have had only few (<10%) 5 MA disruptions in the whole campaign. The disruption amelioration techniques successfully reduced the plasma current $\leq$4.4 MA at the time of the current quench and reduced the vertical destabilising force so that the few high current disruptions have been relatively gentle (the measured vessel forces were $\leq$350 tonnes).

Global confinement results In Fig.3 the diamagnetic stored energy versus plasma loss power is plotted for the constant I_p/B_T ELM free H-mode data of 1994/95. The new data labelled in the plot as 5 MA include both 5MA/3.4T discharges with NBI heating and 4.7MA/3.1T discharges with combined (NBI+ICRH) heating. In the plot the 5 MA and the best of the 4 MA data from the previous JET experimental campaign are also shown. The interpretation of the data in Fig.3 should take into account that W_{dia} errors increase with I_p^2, that most of the new data, although selected from discharges with ELM free period $\geq$0.5s, are of a quite transient nature and that fast ion correction are not included. The data are compared with the ITER93 H-mode scaling for thermal energy confinement time. The new data show a trend of increasing stored energy with plasma current confirmed by the general agreement, for all plasma currents, between the energy confinement time and the predictions of the ITER93 ELM free H-mode scaling. No significant difference is observed between old and new data. The interpretation of the old data, which suggested a confinement scaling with I_p less than linear at 5 MA, was probably a consequence of the limited dataset available at the time. An alternative explanation of the similarity of old and new 5 MA data might be that the confinement degradation due to poor configuration in the old data /1/ was compensated by the larger plasma volume (in the new JET the volume available to the plasma is reduced by 20% with the introduction of the divertor coils and cryopump inside the vacuum vessel). A deviation from the $P^{1/3}$ prediction of the ITER93 ELM free H-mode scaling is observed at low loss power. At high loss power there is a notable degradation for the discharges with strong gas puff. The departure from the $P^{1/3}$ dependence of the data without gas puff appears significant but a further extension of the loss power range of the data would be required for this to be confirmed above any uncertainty in the data. Figure 4 gives the plot of diamagnetic stored energy versus loss power for ELMy H-mode discharges (Fig.5 shows the time traces for two such discharges). A clearer picture emerge from the data (which contains also the 6 MA results) showing that the confinement improves with plasma current. The data are in good agreement with the prediction of 0.85*ITER93 H-mode scaling. The gas puff data suggests further degradation worse than $P^{1/3}$, but again more experimental data would be needed to clarify whether this is due only to the change in regime.

Fusion performances Some of the best fusion performances discharges are shown in the $n_d(0)\tau_E T_i(0)$ versus T_i plot in Fig.6. Most discharges falls in the region of T_e=T_i; some have more "hot-ion like" behaviour (in particular when large part of the gas fuelling was substituted with neutral beams). Q_{DT} of ≈ 0.5 are achieved transiently both in ELM free and ELMy discharges and Q_{DT} of ≈ 0.25 is achieved in ELMy H-modes approaching steady state. The results are encouraging and show improvement with respect to old JET probably due to the lower dilution achieved with a proper diverted configuration. The optimisation for fusion performance would include fuelling, recycling and density control.

Conclusions In the recently ended experimental campaign the JET database on high current low q discharges has been extended both in current and in range of loss power. The 6 MA operation has demonstrated the combination of highest current and lowest q H-mode.

The data is consistent with a linear scaling of confinement with plasma current, as expected from scaling laws. A definitive conclusion on the high power behaviour is rendered difficult by uncertainty in the magnetics data and by variation in the H-mode character. Further analysis is in progress to include the corrections due to the fast ion contribution, beam shinethrough, orbit losses and full kinetic analysis. The future development will include the extension of the data to higher power and the optimisation to achieve higher stored energy. Steady conditions in fusion performances will be explored by extending the ELMy regime and by the use of power step down. The improved control of density and recycling in the more closed new JET MarkII divertor could represent a step towards better performances.

/1/ T T C Jones et al, 19th EPS Conference on Controlled Fusion and Plasma Physics, Europhys.Conf.Abstracts,Vol I,1992,p 1.

/2/ G M Fishpool, P S Haynes,Nuclear Fusion, Vol.34,(1994),p109

/3/T T C Jones et all, these Proceedings

/4/ T Hender et all, these Proceedings

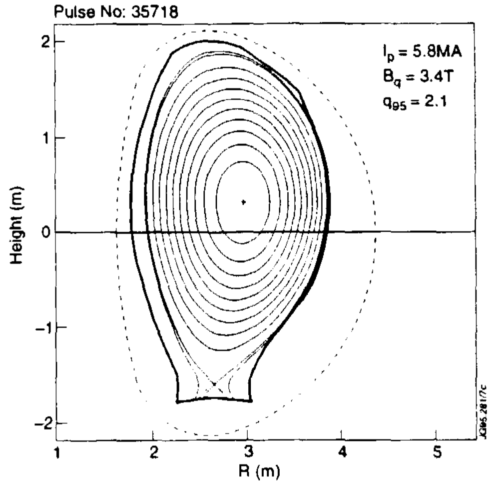

Figure 1: Magnetic equilibrium of a 6 MA discharge

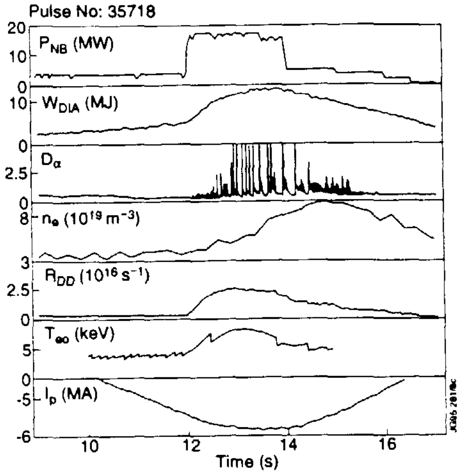

Figure 2: 6 MA H-mode at high power

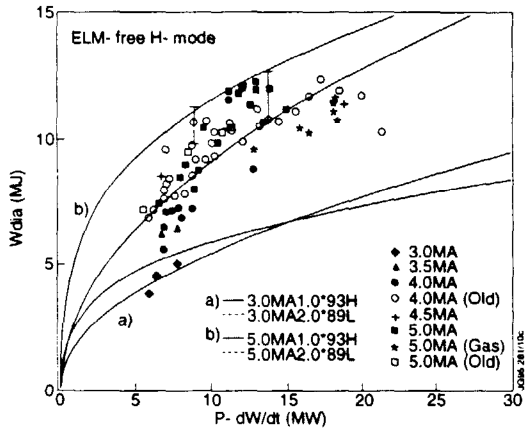

Figure 3: Diamagnetic stored energy versus loss Power. The lines represent the Power dependence predicted by the ITER93 ELM free H-mode and 2*ITER89P L-mode scalings.

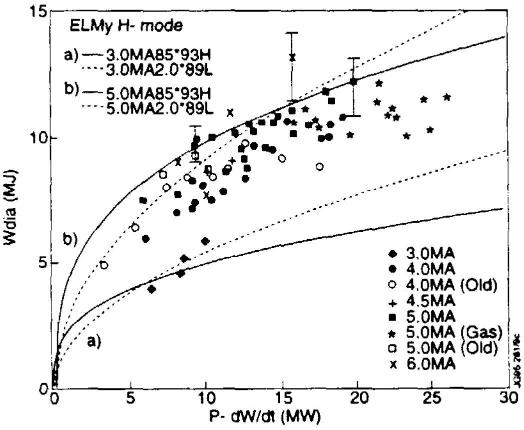

Figure 4: Diamagnetic stored energy versus loss Power. The lines represent the Power dependence predicted by 0.85* ITER93 ELM free H-mode and 2*ITER89P L-mode scalings.

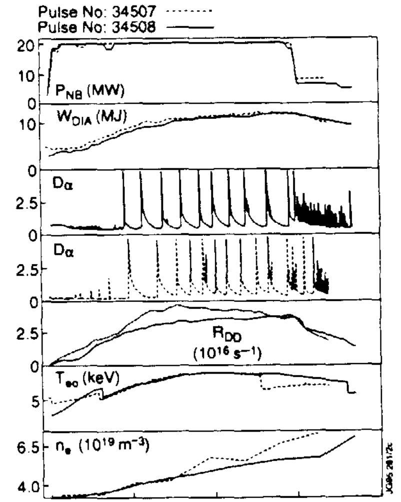

Figure 5: 5 MA/3.4T ELMy H-modes

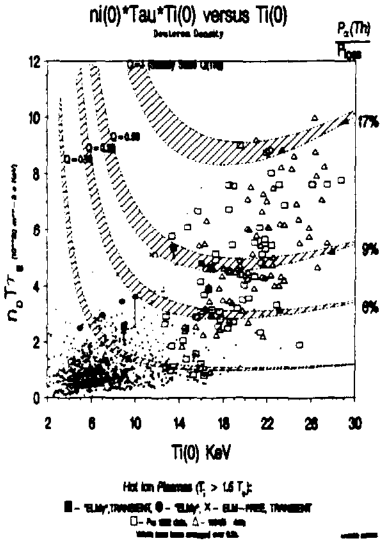

Figure 6: Plot of $n_d(0)\tau_E T_i(0)$ versus T_i