Quasi Steady State Advanced Tokamak Scenarios in JET

C D Challis, B Balet, V P Bhatnagar, J C M de Haas, L-G I Eriksson, M Gadeberg,
C Gormezano, C W Gowers, J A How, G T A Huysmans, S Ishida*, W O K Kerner,
M J Loughlin, F G Rimini, G J Sadler, A C C Sips, A Tanga, B J D Tubbing and D J Ward
JET Joint Undertaking, Abingdon, Oxon, OX14 3EA, United Kingdom
* JAERI, Naka Fusion Research Establishment, Ibaraki-ken, Japan 311-01

Introduction

It is thought that a steady state tokamak reactor will need a substantial fraction of the plasma current to be provided by the neoclassical bootstrap effect. To achieve this requires that the poloidal β be significantly greater than unity which, in turn, requires good energy confinement without the use of very high plasma currents. It is likely that such a plasma would also have to achieve $\beta_N \geq 3$ ($\beta_N = \beta_T aB_T/I_p$ in %mT/MA) if very high toroidal fields are to be avoided. Experiments have been performed in JET with the demanding aim of simultaneously achieving these conditions, high β_p, high confinement and high β_N, in steady state. The investigation of the characteristics of plasmas in this domain, the so-called 'Advanced Tokamak Scenario', is necessary to assess the prospects for steady state reactor concepts.

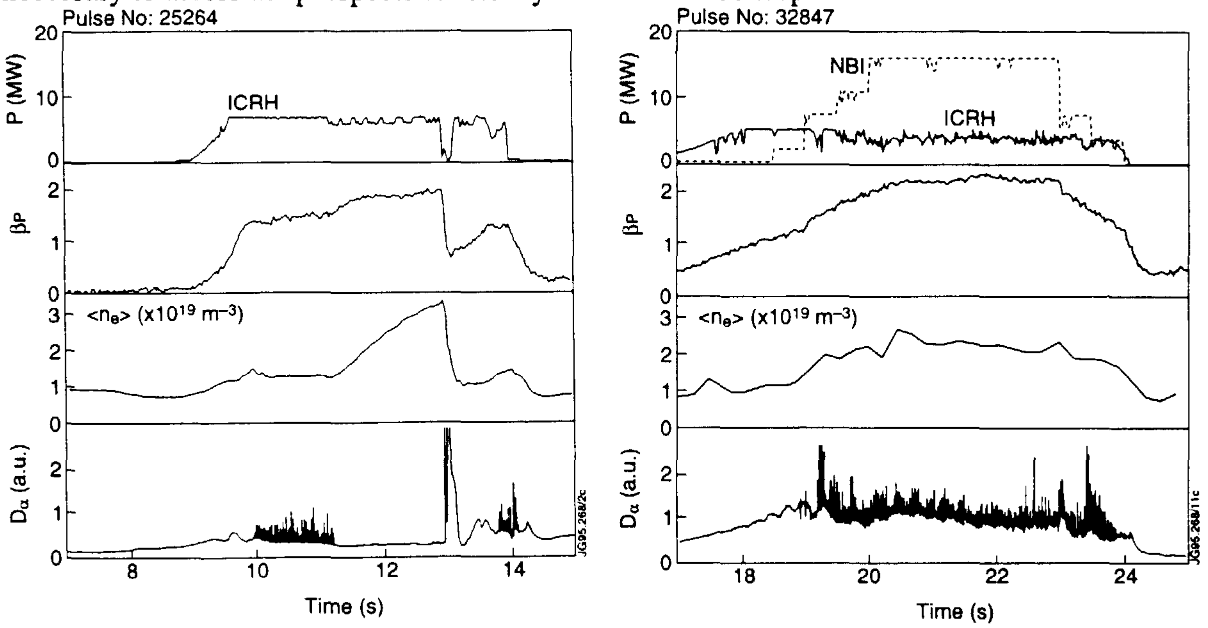

Fig 1: Comparison of two 1MA/2.8T pulses #25264(1991) and #32847(1994)

Quasi Steady State

Improved power handling has been achieved in the new JET pumped divertor configuration and has allowed long pulse high power heating of ELMy (Edge Localised Mode) H mode plasmas which reach quasi steady conditions with respect to density and plasma stored energy. Figure 1 shows the comparison between a recent high β_p plasma (#32847) and a discharge obtained before the installation of the JET pumped divertor (#25264). Stationary conditions have been achieved in pulse 32847, whereas in pulse 25264 the density rises in the ELM free H mode until a collapse of the plasma stored energy occurs during which the density falls. The cause of this collapse has not been unambiguously identified [1], but similar values of β_p have now been achieved without either the density rise or the collapse phenomena. However, significantly higher additional heating power is required to reach the same value of β_p in the ELMy regime. This, together with the more modest plasma density in these plasmas, results in a significant fraction (≈ 30%) of the plasma stored energy being due to fast particles. The fraction of the plasma current driven by the bootstrap effect is estimated (using only the thermal pressure) to be ≈50% in the ELMy regime compared with about 70% in the ELM free experiments.

High β_p Plasmas

Figure 2 shows the achieved values of β_p plotted against q_{95}. The plasma currents were in the range $I_p \approx 1.0$-1.75MA. Approximate lines of constant β_N are shown for the JET pumped divertor configuration. A notional 'Advanced Tokamak Domain', typical of reactor concepts such as SSTR [2], is indicated. The optimum value of q_{95} depends mainly on the achievable β_N. Plasmas have been obtained approaching the overall conditions required for a steady state reactor although the bootstrap current in these plasmas is probably insufficient to provide the necessary fraction of the plasma current required for a true 'Advanced Tokamak' (>70%).

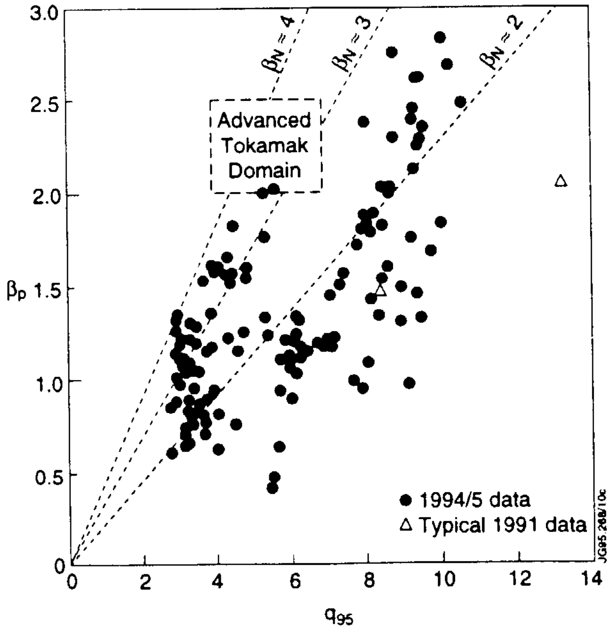

Fig 2: β_p(diamagnetic) plotted against q_{95}

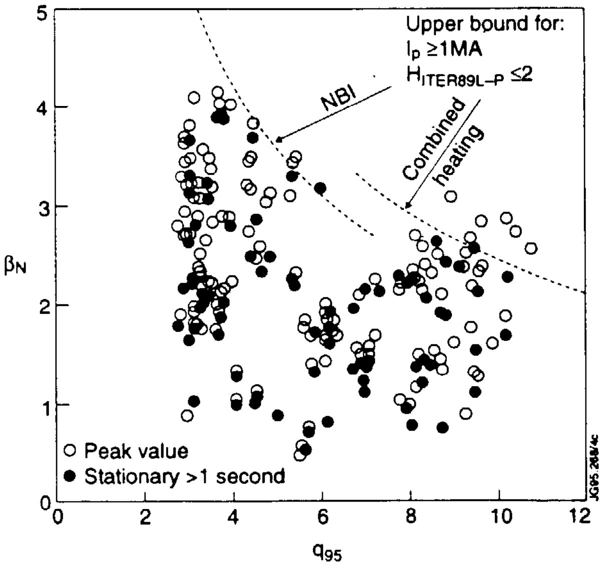

Fig 3: β_N(diamagnetic) plotted against q_{95}

High β_N Plasmas

Figure 3 shows the values of β_N achieved in 1994/5 with $I_p \approx 1.0$-1.75MA. The curves indicate the power limit at $H_{ITER89L\text{-}P}=2$ (typical for this dataset [3]) for plasmas with I_p=1MA in both the high and low q_{95} domains. The ITER89L-P scaling is given in ref [4]. The curves differ in the two regions since at low q_{95} the high values of β_N have been achieved with predominantly neutral beam heating (up to 20MW), whereas combined neutral beam and radio frequency heating up to 28MW has been employed at high q_{95} ($B_T > 2.6T$ at 1MA).

At high values of q_{95} the plasma performance, and hence the value of β_N, has been limited by the plasma confinement and available additional heating power. At $q_{95} < 4$, however, the plasma stored energy can exhibit confinement degradation at high heating power levels which is suggestive that a global β limit may have been reached.

Figure 4 shows the time evolution of a pulse at $q_{95} \approx 3.1$ with a plasma current of 1MA and a toroidal field of 1T where the neutral beam heating power is increased in three steps to 17.5MW. The total plasma stored energy increases at the first two power steps, but at the third step no significant further increase is observed. The maximum value of β_N is about 3.8. The frequency of the ELMs in this discharge increases at the final power step, and this may be the cause of the reduced confinement. The calculated fast ion stored energy for this plasma represents about 40% of the plasma stored energy during the high power heating phase. This results in a more modest value for β_N when only the thermal plasma energy is considered.

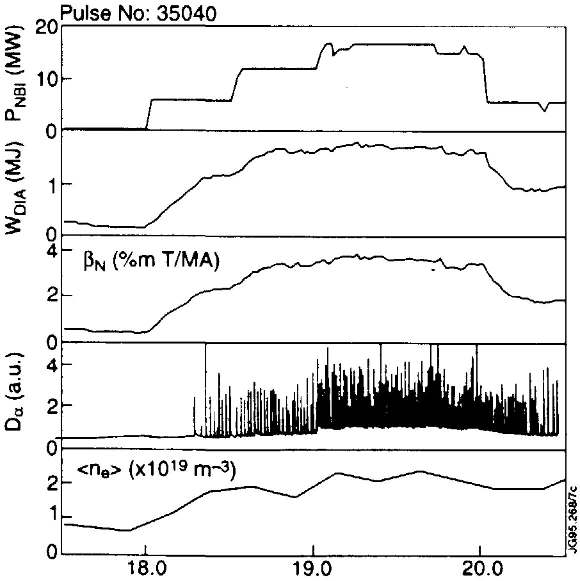

Fig 4: Time evolution of a plasma at 1MA/1T ($q_{95} \approx 3.1$)

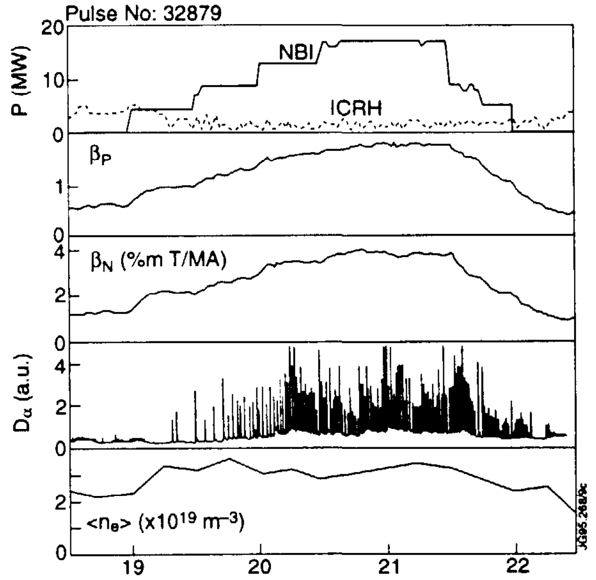

Fig 5: Time evolution of a plasma at 1MA/1.4T ($q_{95} \approx 4.7$)

The pulse presented in Fig 4 is representative of a conventional 'ITER-like' configuration ($q_{95} \approx 3.1$, elongation $\approx$ 1.65, triangularity $\approx$ 0.2). In Fig 5 is shown the time evolution of a plasma more representative of the steady state tokamak domain. In this case the plasma current is 1MA and the toroidal field is 1.4T giving $q_{95} \approx 4.7$, and a more shaped equilibrium is used (elongation $\approx$ 1.7, triangularity $\approx$ 0.4). This discharge combines high β_p ($\approx$ 1.8) and high β_N ($\approx$ 3.8) with $H_{ITER89L\text{-}P} \approx 2.2$ in an ELMy H mode plasma with steady density.

The pulse shown in Fig 5 achieves a similar value of β_N to that in Fig 4 despite the higher toroidal field strength and almost identical neutral beam heating power. This is due to the degraded confinement in the lower field discharge at high power. Since the high value of β_N was only just attainable at the highest power in the high field case, it is not known whether there would be degradation of confinement at still higher powers. It should be noted that the fast ion stored energy represents a smaller fraction of the total plasma stored energy in the case shown in Fig 5 ($\approx 30\%$) resulting in a higher achieved thermal β_N.

Long Pulse Experiments

Long pulse heating has been applied to plasmas at high β_p to assess the long timescale effects. Figure 6 shows the time evolution of a plasma with $\beta_p \approx 1.5$ and $\beta_N \approx 3.0$ maintained during a 7 second heating pulse.

Although the timescale for redistribution of the plasma current profile in the plasma core is still longer than the heating pulse length of these discharges, the plasma current density in the plasma periphery should have reached a steady value in 2-3 seconds. Any effects on stability from the edge bootstrap current density in these plasmas should have been seen on the timescale of these experiments.

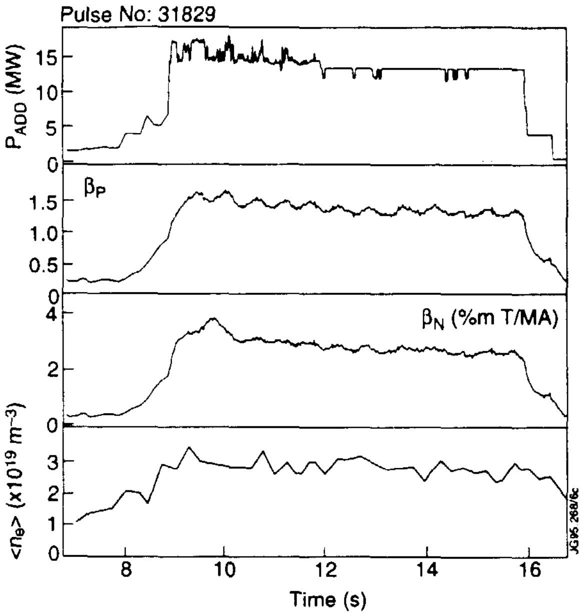

Fig 6: Long pulse plasma at 1MA/1.4T

Conclusion

Quasi steady state conditions approaching those required for a steady state reactor have been achieved in ELMy H mode plasmas for pulse lengths in the range 1–7 seconds. Longer pulse experiments are required to assess the effects of current redistribution in the plasma core.

An apparent global β limit has been observed at $\beta_N \approx 3.8$ with $q_{95} \approx 3.1$. Similar values of β_N were obtained at $q_{95} \approx 4.7$ but it is not possible to establish whether a β limit has yet been reached with the available heating power.

References

[1] C D Challis, et al, Nucl Fusion **33** (1993) 1097.
[2] M Kikuchi, Nucl Fusion **30**(1990) 265.
[3] A C C Sips, et al, this conference.
[4] P N Yushmanov, et al, Nucl Fusion **30** (1990) 1999.