Development of Advanced Tokamak Scenarios based on High Bootstrap Currents in JET

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ABSTRACT

High bootstrap current experiments with the bootstrap fraction ($I_{bootstrap}/I_{plasma}$) up to 0.7 at 1 MA and 0.5 at 1.5 MA were previously achieved in JET in plasmas with high q(a), high triangularity and high confinement (H≥3). During initial operation with the new JET pumped divertor, the domain of parameters has been extended to cover reactor relevant domains such as low q(a) and high β_n; up to $\beta_n = 3$. High beta poloidal plasmas (necessary for the achievement of high bootstrap fractions) with β_p up to 1 for 2MA plasmas and with β_p up to 2 for 1MA plasmas have been achieved. $\beta_p = 1.5$ and $\beta_n = 3$ have been obtained simultaneously over several seconds at $q_{95} = 4.5$. The confinement of these plasmas is lower than in the previous campaign but these discharges display "quasi steady state" characteristics. In order to improve the confinement of these discharges, several parameters have been varied such as plasma volume, triangularity and β_p itself showing no significant benefit. Configurations using non-inductive current drive to produce stable, higher confinement plasmas are being developed. A "deep" shear reversal configuration has been established and initial data are presented.

1. INTRODUCTION

A large proportion of the plasma current in a steady state reactor [1] will probably have to be provided by the neoclassical bootstrap effect. This "advanced tokamak" scenario results in challenging requirements for both plasma confinement and stability. In previous JET experiments [2] a bootstrap fraction of 0.7 has been obtained in plasmas with high confinement compared to the usual L-mode and H-mode scalings. However, these discharges, although sustained for ≈2 seconds, were not stable and collapsed with a large ELM. The cause of the collapse has not yet been unambiguously identified. Theory predicts that high bootstrap fraction discharges will tend to be prone to a large number of MHD instabilities on the current diffusion time scale, the more dangerous being the infernal modes due to the hollow current profile and the external kink modes due to the large current density in the plasma periphery. It is also predicted that several of these instabilities can be avoided if the current profile and/or pressure profiles are optimised. JET is developing "advanced tokamak" scenarios aiming at achieving high β_p plasmas in reactor relevant conditions in quasi steady state conditions using JET high power heating systems and using current profile control techniques to produce MHD stable configurations and possibly to improve confinement.

2. HIGH BETA EXPERIMENTS

The new JET pumped divertor configuration has several features which are noticeably different from the old JET configuration as discussed in [3]. For instance, the plasma volume and q(a) are lower for similar plasma current and magnetic field. During initial JET experiments in the new configuration, the recycling appears to be high and long ELM free periods with high confinement (VH-mode) have not yet been achieved, but the power handling capability of the divertor tiles is higher.

2.1 Beta poloidal values

The performance of the new JET configuration has some consequences on the magnitude of the current bootstrap which depends directly upon the confinement for a given power. Higher power is necessary to obtain a similar β_p as achieved previously, 26MW to achieve $\beta_p = 2.1$ at 1MA and 23MW for $\beta_p = 1.45$ at 1.5MA instead of the previously required 10MW in ELM-free condition. In the new configuration, the high β_p discharges are no longer transient and reach "quasi steady state" conditions as shown in fig.1: with a combined power of 20MW (ICRH plus NBI) for several seconds, β_p stays at a value of 0.8 at $I_p = 2$MA while the confinement time is 0.9 times the JET-DIIID H-mode scaling.

2.2 Confinement

Some ELM free discharges lasting more than one second have been achieved in double null configuration as shown in fig.2. These discharges have a higher β_p than single null discharges, but the ELM-free period is much reduced when power exceeds 15MW and the benefit of this type of configuration seems to be eroded by the re-occurrence of ELMs. It is also to be noted in fig.2 that the lower confinement normally observed in reversed ∇B configuration for counter NBI injection is partially restored when combined ICRH NBI heating is used in this configuration.

Other attempts to try to increase the confinement of these high β_p discharges have been made. For instance, the volume and the aspect ratio of the plasma have been varied respectively from $80m^3$ to $55m^3$ and from 3.7 to 3.1. The ELM free phase disappears with small volume plasmas, but during the ELMy phase, the confinement is observed to be similar, with H factor between 1.8 and 2, for both configurations as shown in fig.3. This is quite remarkable given the large change in the plasma configuration.

It should also be noted, as shown in fig.4, that the confinement does not increase with β_p for ELMy plasmas although some parameters such as ℓ_i, T_e, collisionality, etc. were also changed.

2.3 Beta normalised values

β_n values of 3 have been obtained together with β_p values of 1.5 and H = 2 (see note*) for $I_p = 1$MA B_T - 1.4T plasmas as shown in fig.5. For discharges with $I_p = 1.5$MA and $B_T = 1$T, high β_n values are also achieved but a degradation is observed at high power compared to plasmas at 1.4T. A stability analysis has shown that at 1.4T the plasma is completely stable to ballooning modes. If the same pressure profiles were achieved at 1T, the plasma would then have become unstable. In practice the pressure gradients are reduced in the 1T plasma so that the analysis again indicates stability against ballooning modes. It is therefore possible that the lower achieved β_n at high power is linked to the effect of ballooning modes on the pressure profile.

3. SHEAR REVERSAL EXPERIMENTS

It is probable that very high bootstrap experiments need some form of plasma profile control to remain mhd stable. Extrapolation of previous high bootstrap current plasmas in JET to steady state using the TRANSP code has shown that steady state would be reached in 20 to 30sec. but that the resulting current profile would be unstable to ballooning modes. Other analyses [4] have shown that "deep" shear reversal with high central q values and q minimum above 2.5 have to be achieved to prevent instabilities due to infernal modes. Simulations [5] have shown the possibility of producing such configurations at JET.

In JET, an attempt has been made to obtain such a "deep" shear reversal configuration by injecting LHCD and ICRF early in the discharge to "freeze" the current profile at the required shape. An X-point plasma is produced and ICRH and LHCD are used together during the ramp-up phase to maintain the broad profiles with the high q(o) which normally occur during this phase. The time history of such a plasma is shown in fig.6. The ramp up rate of the current is 0.75MA/sec. LHCD and ICRF are injected less than 1 second after the breakdown when the plasma current is only 300 kA The temperature goes up to 6 keV during this phase. In the absence of specific diagnostics, the q profiles are deduced from magnetic reconstruction. Analysis has shown that shear reversal is produced at 42s and persists in the current flat top with q(o) values from 4 and 5 and minimum q values of about 3. ℓ_i remains very low, at about 0.5, and confinement time is about 0.8 times the JET-DIIID H-mode scaling. But the stored energy is larger than the stored energy observed in discharges with similar power and current and ℓ_i in the range 0.7-0.8. Further experiments are required to assess the benefit of these profiles.

4. CONCLUSIONS

The previous JET high bootstrap current experiments were performed within a limited parameter range: medium power (10 MW of ICRF), relatively low β_n values (1.5), high q(a) (~10) and high triangularity. The new JET configuration allows a significant enlargement of the parameter domain: variation of q(a), and triangularity, combined ICRF and Neutral Beam Heating. This is shown in fig. 7 where β_p is plotted versus q_{95}. The achieved parameters are now much closer to the advanced scenario domain. For instance, β_p of 1.5 together with $\beta_n = 3$ and H = 2 have been achieved in quasi steady state. High β_p plasmas obtained during the initial operation in the JET pumped divertor configuration have a lower confinement than during the previous campaign when only transient conditions were achieved. Confinement does not increase with β_p in ELMy plasmas. Deep shear reversal configurations have been established. Further experiments are required to assess the benefit of these configurations and to exploit the JET non inductive current drive capabilities. With the heating systems installed on JET, a target domain with $\beta_p \geq 2$, $\beta_n \sim 3$ and $H \geq 2$ appears to be achievable at 1MA. The confinement has to be slightly improved to enter this domain at $I_p = 1.5$MA, and significantly improved for larger plasma currents. Current profile control will mainly be used to improve the confinement.

* H factor refers to ITER 89-P L-mode scaling law.

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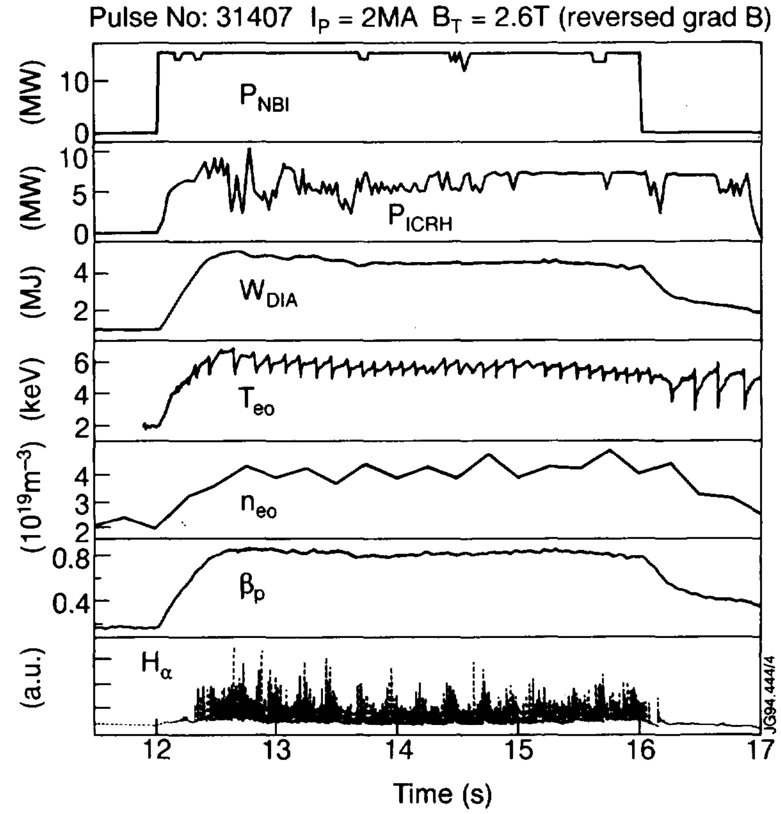

Fig.1 *Time history of a "quasi" steady state discharge*

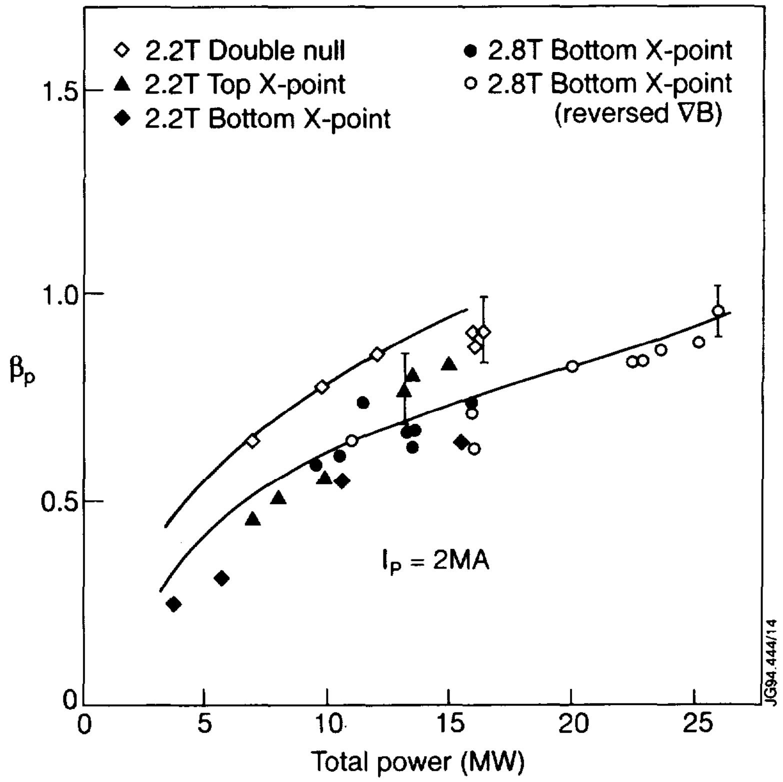

Fig.2 *Beta poloidal dependence with power at I_p = 2MA*

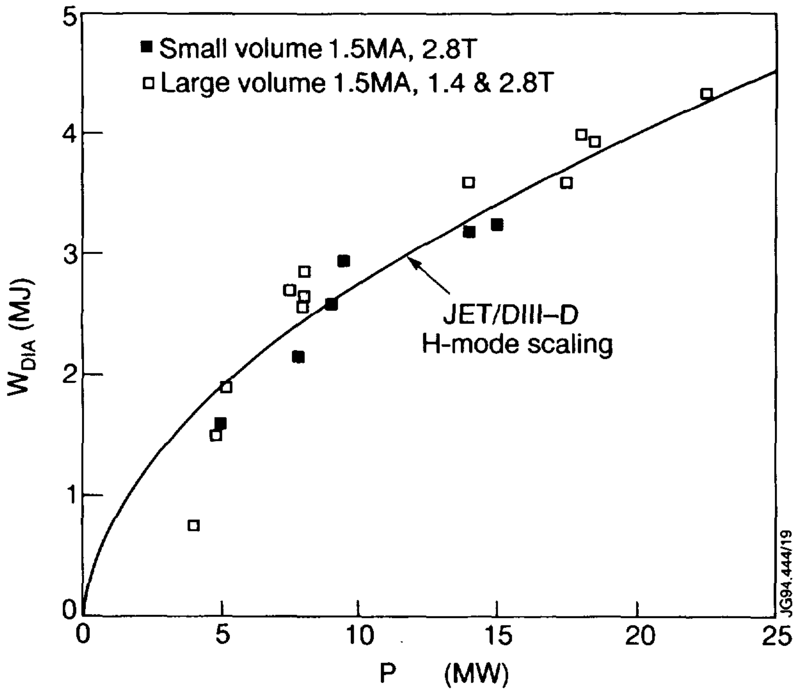

Fig.3 *Stored energy (diamagnetic loop) versus total power for small ($55m^3$) and large volume ($80m^3$) plasmas*

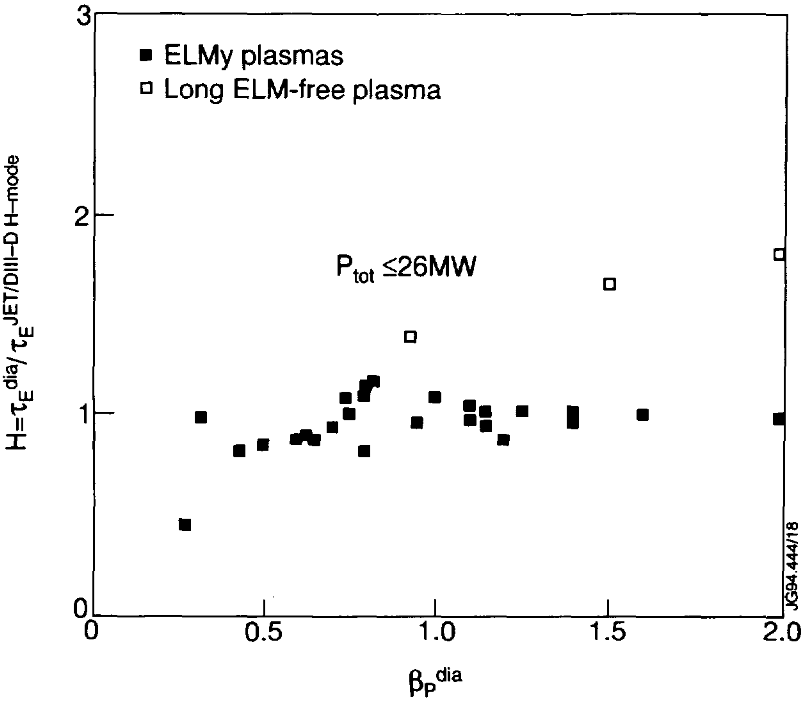

Fig.4 *Confinement time versus β_p. Both data are from diamagnetic loop.*

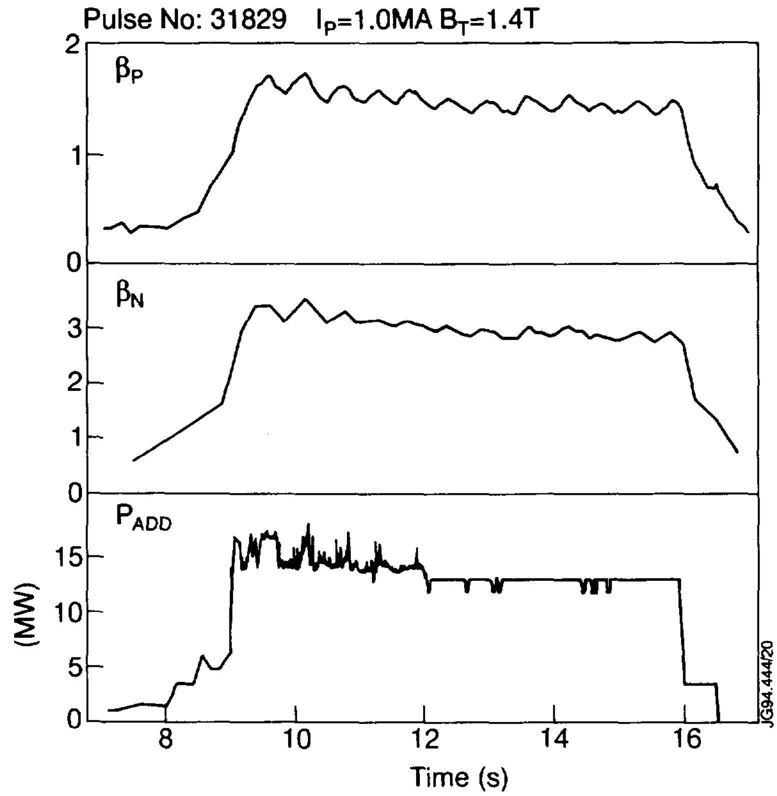

Fig.5 *Time history of a high β_n pulse. Energy confinement time corresponds to JET-DIIID H-mode scaling.*

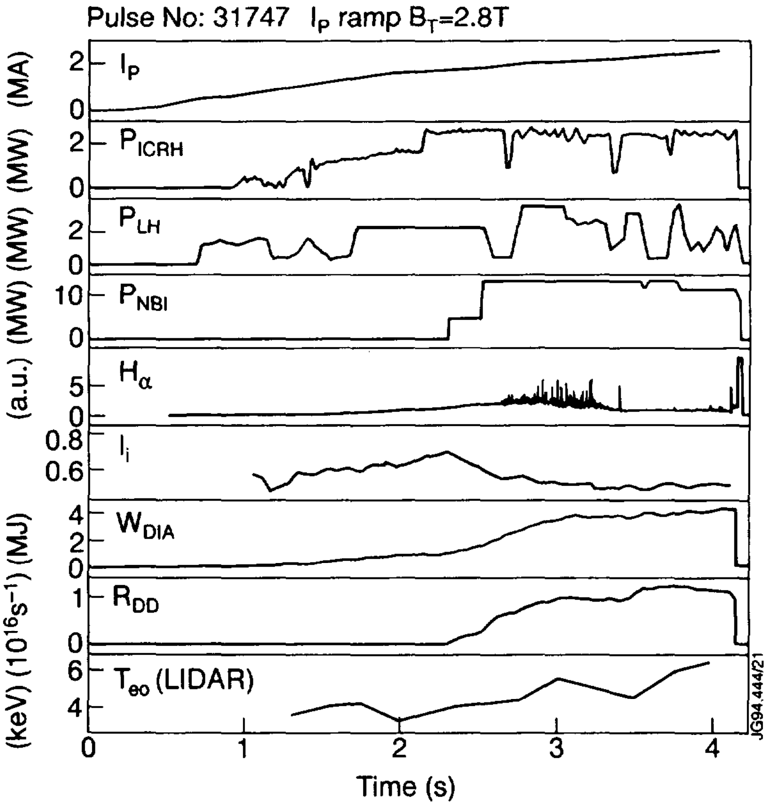

Fig.6 *Time history of a shear reversal configuration plasma discharge.*

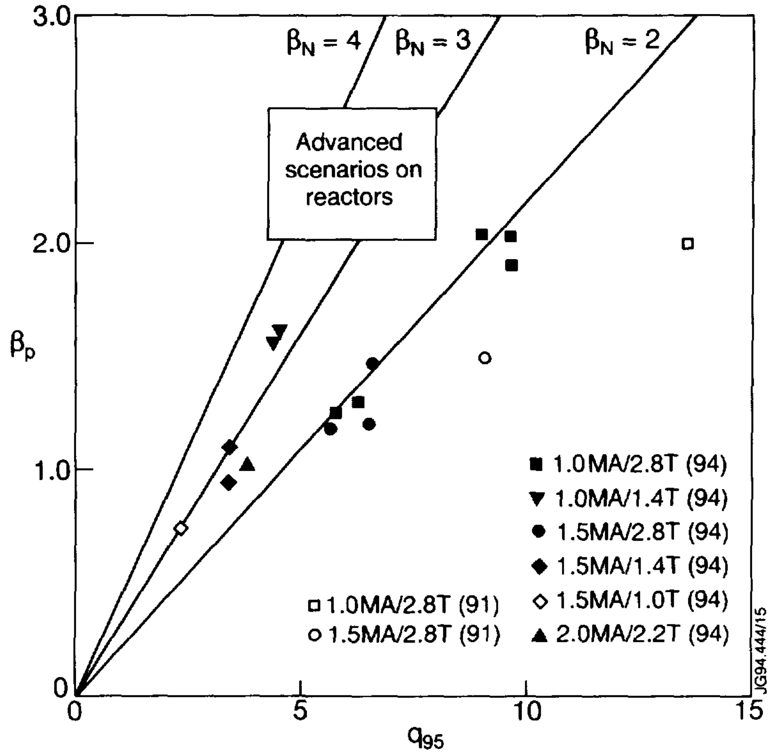

Fig.7 *Beta poloidal versus* q_{95}.