The New Phase of JET and Prospects for Future Operation

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The Joint European Torus (JET) [Fusion Technol. **11**, 1 (1987)] restarted operations in its new Pumped Divertor configuration. The main elements of the new configuration are four divertor coils, an inertially cooled divertor structure, and an internal cryogenic vacuum pump. Two major differences were observed with respect to the 'old' JET. First, the heat load capability of the divertor is dramatically improved. Second, in the High confinement mode (H-mode) the occurrence of Edge Localised Modes (elms), is more prevalent. Quasi steady-state elmy H-modes are now obtained in a wide variety of conditions. In the 1994 experimental campaign maximum plasma currents of 4MA have been obtained. Steady-state H-mode operation has been obtained for a duration of 20s. Detached divertor operation was established in ohmic and L-mode plasmas, but not yet in H-mode. In low current discharges a poloidal beta $\beta_P = 2.6$ has been obtained in transient. The high β_P regime has been extended to long pulse elmy H-mode. Preliminary experiments have not shown an effect of magnetic shear reversal on the confinement. Using the new internal saddle coils, powered by high frequency amplifiers, Toroidal Alfven Eigen-modes (TAE) were excited. The first direct measurements of the damping of TAE modes were carried out.

I. INTRODUCTION

In February 1994, after a 22 month shutdown for installation of the new 'Pumped Divertor', the Joint European Torus (JET)[1] has entered a new phase. The main elements of the pumped divertor configuration[2] are four divertor coils, wound inside the vacuum vessel, an internal cryogenic vacuum pump, and an inertially cooled divertor target structure.

The key objective of the new phase of JET is to demonstrate effective control of impurities by divertor action, both in 'steady-state' and in 'transient peak performance' regimes. The new installation serves this objective: the internal coils allow formation of diverted magnetic equilibria up to high plasma currents (design current is 6MA), the cryogenic pump allows the removal of particles, and the target structure is designed for a high heat load capability, in particular when X-point sweeping is applied.

The initial months of operation in the new configuration[3,4] revealed two important differences with the past. First, the new target structure has a strongly improved heat load capability. Carbon influxes (or blooms), resulting from local overheating of target tiles, were a common feature in past high power experiments. They have not been observed in the new configuration. Second, in the High confinement (H)-mode operation, a significant change in the behaviour of Edge Localised Modes (elms) was observed. In the past operation of JET in the H-mode - at low and medium densities - was characterised by long elm-free periods. At present elms appear soon after the transition from L to H-mode. Due to these elements the focus of the achievements of the past months has been on the 'quasi steady-state', elmy H-mode regime[5].

The elmy H-mode regime is at present considered the most credible candidate for operation of the International Thermonuclear Experimental Reactor (ITER)[6]. However, to be credible the regime needs to be compatible with a comprehensive set of requirements: acceptable confinement, sufficient helium ash removal, compatibility with detached divertor operation, etc. A demonstration of this viability is still lacking. Further development of the regime, integrated with detached divertor operation, and leading to a demonstration of its compatibility with reactor requirements, is a priority of the JET project.

The peak transient performance - achieved in the past with the Hot-ion H-mode and Very High confinement (VH)-mode - , has not yet been reproduced. The maximum Deuterium-Deuterium (D-D) neutron rate achieved so far in 1994 ($2.3\ 10^{16}$) is about half of that achieved in the past ($4.3\ 10^{16}$). A variety of factors is found to play a role; the shorter elm-free periods, the generally higher levels of operating density and recycling, and effects of plasma geometry which affect confinement and edge stability. A recovery, or preferably an improvement in the peak performance levels over the past is desirable before execution of further Deuterium-Tritium experiments. Hence, optimisation of the transient peak performance remains a priority issue[7].

Significant work has been done in the area of tokamak concept improvement[8]. This covers the general exploration of methods to affect confinement and stability by modifying the current density profile. The most important results are the extension of the regime of high bootstrap current to a quasi steady-state and to lower safety factors, and an initial experiment on the effects of shear reversal on the transport.

In section 2 the new configuration and the many upgraded and new systems are presented. In section 3 the differences in machine behaviour between the past and present, and their effects on confinement and performance are highlighted. In section 4 the work on long pulse elmy H-mode, on divertor detachment and on cryopump effects is discussed. In section 5 the work in the general area of tokamak concept improvement is shown. In section 6 the first experiments on external excitation of Toroidal Alfven Eigen-modes is presented. In section 7 a preview of the further JET programme is given, and in section 8 the main conclusions of the paper are summarised.

II. THE NEW CONFIGURATION

A. The pumped divertor

The new pumped divertor configuration of JET is shown in figure 1. There are four internal divertor coils. On these, the water-cooled support structure for the target tiles is mounted. The divertor target consists of Carbon Fibre Composite (CFC) tiles, with typical dimensions 35 x 80, depth 50mm. The fibres of the CFC are aligned perpendicular to the plasma facing surface, so as to have a high heat conductivity into the tile. Cooling of the tiles is by conduction and radiation to the structure, on a 'between shots' timescale.

The divertor cryopump has a pumping speed for deuterium of $170m^3s^{-1}$. Conductance from the scrape-off layer to the pump is via the slots between the divertor tiles. The pump is designed to pump Helium using the Argon frost technique.

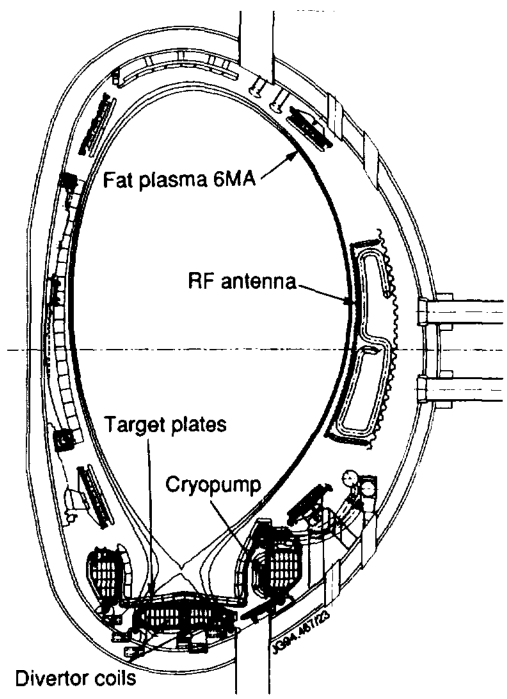


Fig.1 Poloidal cross-section of the JET pumped divertor configuration.

B. The additional Heating Systems

The Neutral Beam Injection (NBI) system has undergone minor modifications. The capability is about 20MW (in Deuterium), with half the injectors operating at 80keV and the other half at 140keV.

The Ion Cyclotron Resonance Heating (ICRH) system has been strongly modified, mainly in view of developing the Fast Wave Current Drive capability. There are four antennas containing four current-carrying straps each. The phase of each of the straps is controlled and adjustable, so that a directional Fast Wave can be launched. The design power capability is 20MW. At present, up to 12MW has been coupled to H-mode plasmas, and H-mode with ICRH alone has been achieved. The performance has been limited by technical problems. First, there have been several problems with the new low-power electronics. Second, a minor modification to cross-over straps inside the antennas is required.

The Lower Hybrid (LH) system has been upgraded to the full capability of 10MW installed power. Up to 6MW has been coupled to the plasma.

C. Other systems

Eight internal saddle coils were installed inside the vacuum vessel. These coils have a triple objective. First, to perform experiments on the stabilisation of the $n=1$, $m=2$ tearing mode. Second, to reduce error fields which can narrow the operational domain. Third, to study the active excitation and the damping of Toroidal Alfven Eigen-modes.

A new Fast Radial Field Amplifier for vertical position control has been installed. A new fully digital plasma current and shape control system now allows feedback control of selected geometrical entities, such as plasma to vessel distances, X-point position, and separatrix strike points on the target.

In addition to these 'active' systems, a large number of new diagnostics has been installed, in particular aimed at improving the measurement capability in the divertor.

III. PERFORMANCE OVERVIEW

A. Divertor heat load capability

The power handling capability of the new divertor is strongly improved with respect to the past. In discharges without X-point sweeping, and with 14MW of NBI power at medium density, tile surface temperatures of about 1000°C are reached about 4s after switch-on of the NBI, that is at an input energy of about 55MJ. This contrasts with the 10 to 15MJ input energy quoted in the past for obtaining peak tile surface temperatures in excess of 1200°C. Several elements are involved in this improvement: the shaping of tiles to avoid exposure of edges; the small installation tolerances, the orientation of the CFC fibres, and perhaps the spreading of power by the elms.

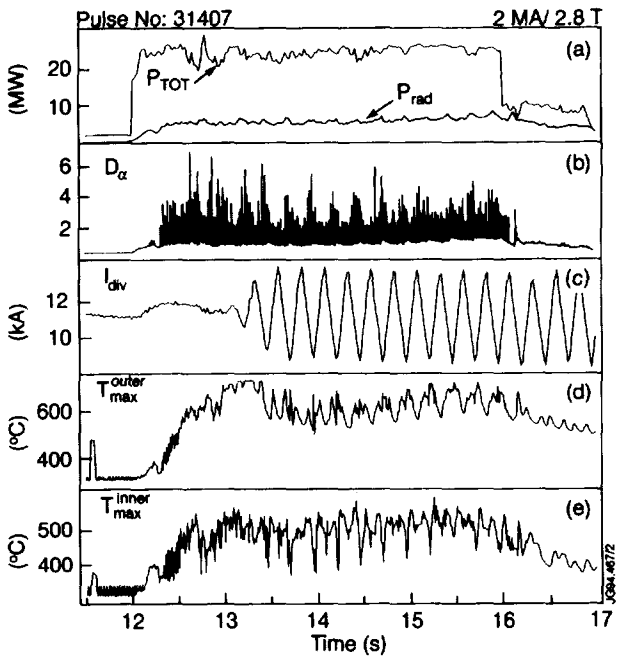


Fig.2 Time evolution of a discharge with 25MW of combined heating power for 4s. X-point sweeping is 100mm, starting at 13s, and is shown here by the current in one divertor coil. The bottom two traces shot maximum target tile surface temperature near outer and inner strike zone respectively.

With X-point sweeping, significantly higher input energies can be used. In figure 2 the time evolution is shown for a discharge with an input power of 24MW for 4s, in which the X-point is swept. The divertor tile surface temperature is seen to saturate at about 600°C. There is no evidence of impurity influxes.

B. Energy confinement scaling

The changes in the geometry of JET have an effect on the predicted energy confinement. Using the ITER89P L-mode scaling, the predicted confinement is lower by about 15% for the present configuration.

In figure 3 the confinement enhancement factors H_{ITER89}, that is the ratio of measured to predicted confinement, are shown for a selection of 1994 discharges in the elm-free phase. The value of H, typically around 2.3, has not changed significantly with respect to the past. However, VH performance[9], which in the past has led to higher enhancement factors, has not yet been reproduced.

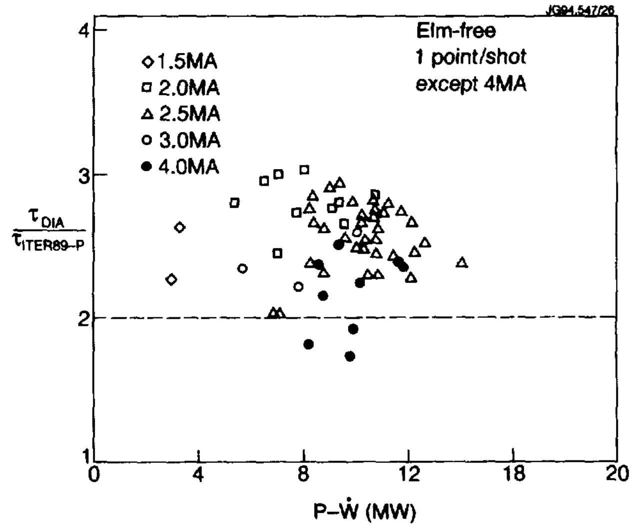


Fig.3 Confinement times, normalised to the ITER-89P scaling law prediction, for a selection of 1994 JET discharges in the elm-free phase.

Elmy H-mode data has now been obtained in a variety of conditions. Figure 4 shows normalised confinement times for a selection of the elmy data. The figure shows that the typical level of the enhancement factor is about $H \approx 1.9$. The reduction in confinement, when operating in steady-state elmy conditions is thus of the order of 20% when compared to 'standard' elm-free H-mode, but is larger when compared to VH mode.

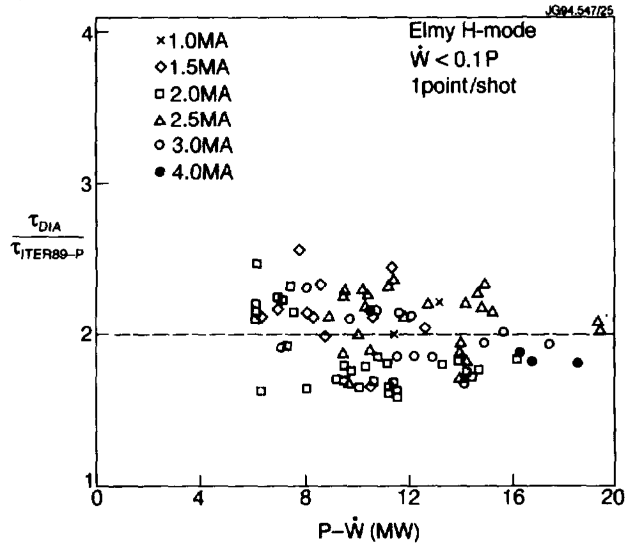


Fig.4 Confinement times, normalised to the ITER-89P scaling law prediction, for a selection of 1994 JET discharges in the elmy phase.

C. Operation at high plasma current

The maximum plasma current achieved so far is 4MA[7]. In figure 5 an overview is shown for a 4MA discharge with 15MW of additional heating. The safety factor q_{95} of this discharge is 2.8 at 3.4T. The maximum stored energy is about 9MJ. The fusion triple product $n_D\ T_{i0}\ \tau_E$ is about 4.9 10^{20} m^{-3} keV s during the transient elm-free phase, and drops to about 2.5 10^{20} m^{-3} keV s during the quasi steady elmy phase.

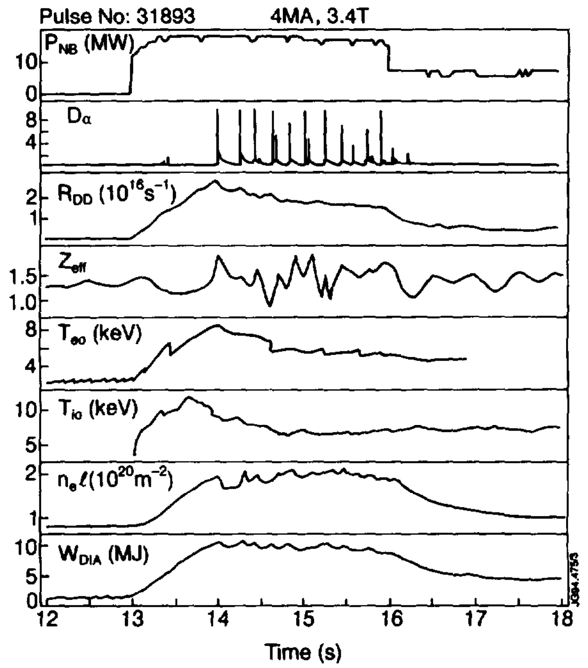


Fig.5 Traces for a 4MA discharge, showing both the elm-free phase (13.4 - 14s) and the elmy phase.

D. Performance optimisation

Short elm-free periods limit the peak fusion performance. Therefore, a large part of the work on performance optimisation has concentrated on attempts to increase the duration of the elm-free period. Two aspects have been addressed. First, the condition of the machine and the differences in operating temperature, hydrogenic inventory and target design with respect to the past. Second, the effects of the magnetic configuration.

Several experiments were carried out to address the possible effect of the target. As a result of these, it appears now unlikely that details of target design, target temperature or target outgassing are the cause of the increased elminess.

The D-D neutron rate, for discharges with similar parameters, has been significantly improved by the use of the divertor cryopump. With the cryopump, the NBI particle source is dominant over the recycling particle source. Then, the peaked density profiles, for which NBI penetration is favourable, are established.

IV. DIVERTOR REGIMES AND CRYOPUMP

A. Long pulse elmy H-mode

The high heat load capability of the divertor has allowed quasi steady-state elmy H-modes of 20s duration to be obtained[5]. In figure 6 traces are shown of one of these discharges with about 7MW NBI input power. During the H-mode, plasma fuelling was by NBI alone. The divertor cryopump was used for control of the density. With the crypump, no saturation effect of the pumping was experienced. This contrasts with old results on long pulse elmy H-mode, where the wall pumping saturated after about 10s, and where no true steady-state could be achieved as regards fuelling.

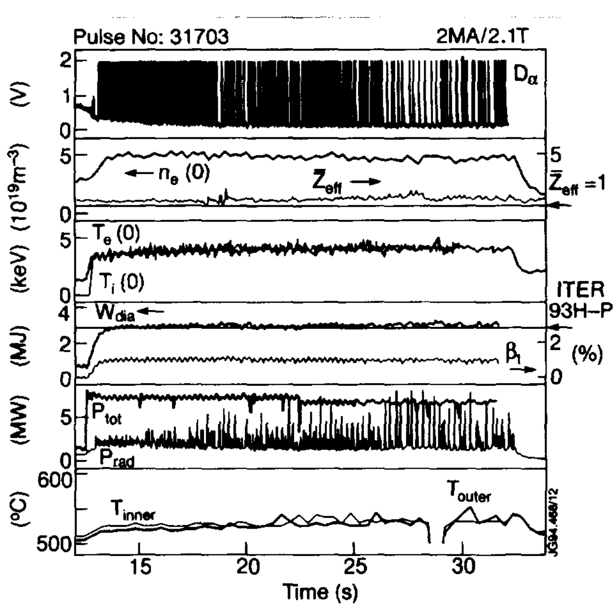


Fig.6 Traces for a steady-state elmy H-mode discharge with a duration of 20s. The bottom trace shows the maximum surface temperature of the divertor target near the inner and outer strike zones respectively.

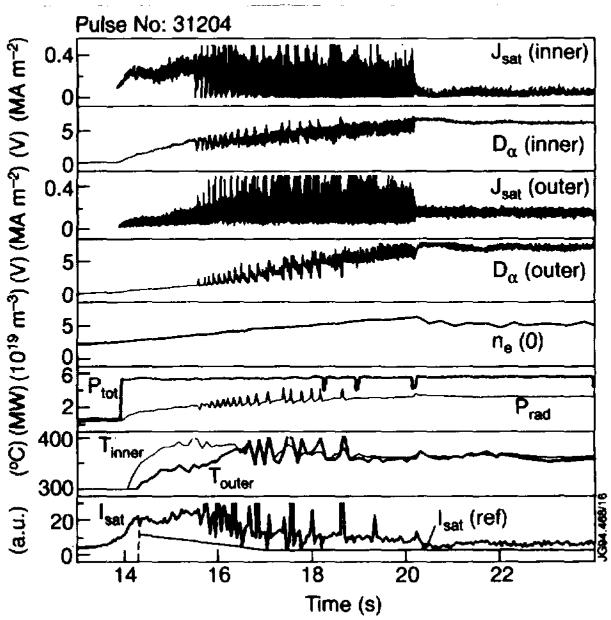


Fig.7 Traces for an L-mode discharge in which divertor detachment is obtained at 20s. In the phase prior to detachment (15 - 20s), a divertor instability is observed.

B. Detached divertor plasmas

In figure 7 traces are shown for a discharge in which detachment is achieved for a Low confinement (L) mode plasma at a power level of 5.5MW[5]. In this scenario, the gas input is controlled by feedback from the ion saturation current of one of the Langmuir probes close to the inner target. We observe the gradual drop of I_{sat} between 16 and 20s, while the density is increasing. A reduction of the pressure at the probe is obtained while the total radiated power is of the order of 50%. Prior to detachment, - 15 to 20s - a divertor instability is observed.

Attempts to achieve similar detachment in H-mode plasma have so far failed. The H-mode returned to L-mode, before detachment was observed.

C. Pumping effects with the cryopump

An experiment was carried out to investigate the dependence of the particle removal rate on the X-point geometry[5]. In this experiment the outer strike zone was moved over the horizontal target plate and up the vertical plate, while the pressure in front of the pump was monitored. The result is shown in figure 8. A maximum particle removal rate of 8.0 10^{21} was reached as the outer strike zone aligned with a toroidal slot in front of the pump. The removal rate is reduced when the strike zone is moved away from this position. The variation is about a factor two, indicating a good conductance to the pump through the radial slots between target tiles for strike zone locations away from the pump.

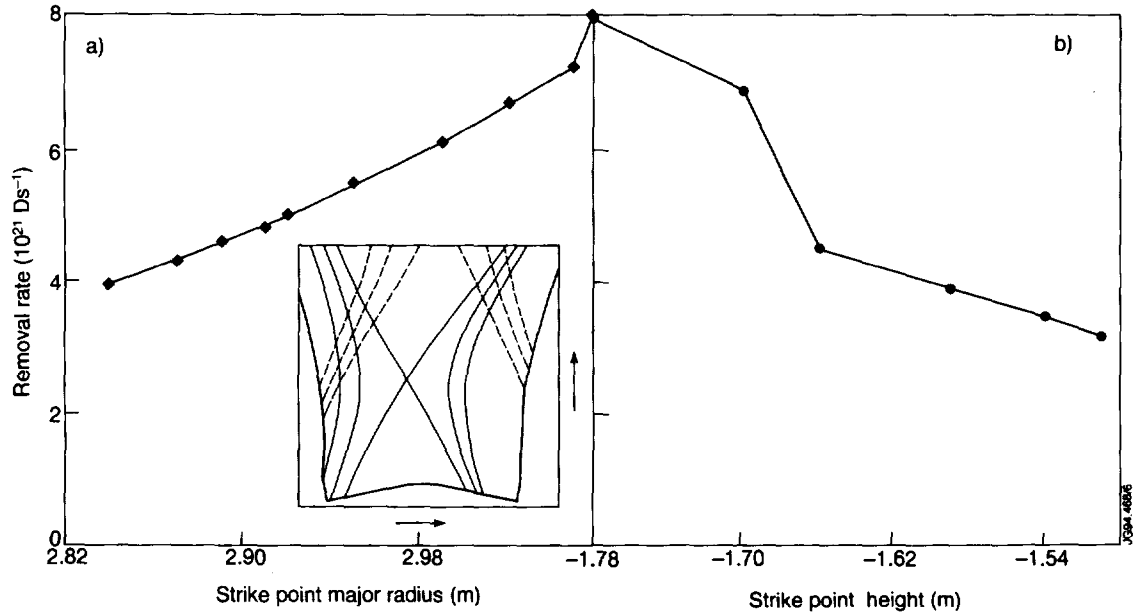


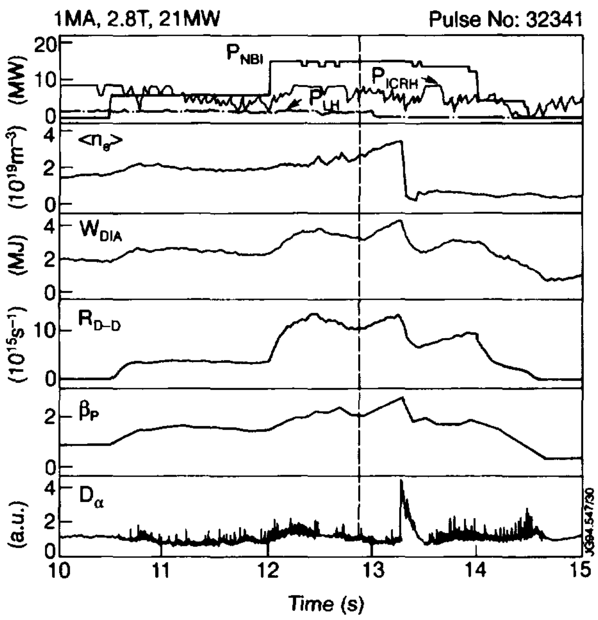
Fig.8 The measured particle removal rate as a function of the outer strike zone position. The removal rate is shown as the outer strike zone is swept across the horizontal target plate (left of the figure), and upwards on the vertical target plate (right of the figure).

V. TOKAMAK CONCEPT IMPROVEMENT

A. The high poloidal beta regime

The present experiments have concentrated on extending the existing results in this regime[10] into quasi steady-state, making use of the frequent elms. Further, on extending it to lower q_{95}, and higher normalised beta β_N. In figure 9 a discharge is shown in which $\beta_P = 2.6$ is obtained in transient in a 1MA, 2.8T, and β_P is maintained above 1.5 for a duration of 3s. In discharges with a toroidal field of 1.4T, a value of $\beta_P = 1.6$, with $\beta_N = 3$, were maintained simultaneously for 7s.

In figure 10 values of the achieved β_P, β_N and q_{95} are shown in relation to the values required for a typical advanced tokamak reactor operating scenario. A distinction is made between transient points and points for which the values are maintained for at least 3s. While the 3s criterion does not define a steady-state as regards current diffusion, it does establish a sufficient energy balance steady-state.



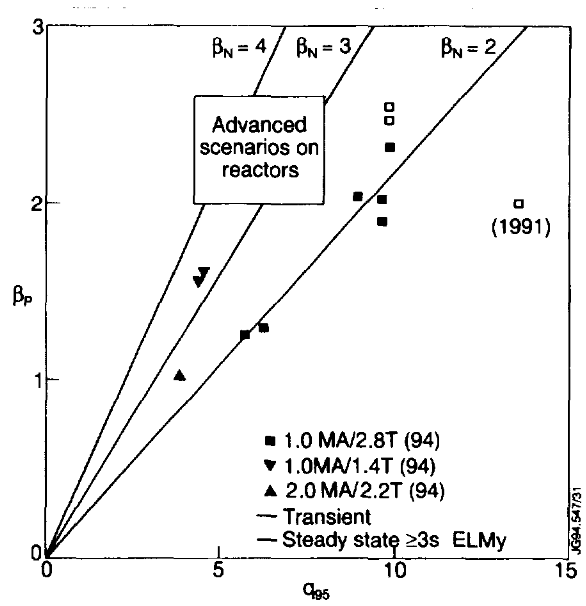


Fig.9 Traces for a discharge with a transient value of βp of 2.6±0.2. With 21MW of combined heating power, an elmy H-mode is established. At 12.8s, there is a sudden transition to a transient phase of improved confinement, which is terminated by a large elm.

Fig.10 The JET data on the high βp regime in a diagram of βp versus q_{95}. Open symbols represent transient data. Closed symbols represent shots which maintain the value of βp for at least 3s.

B. Shear reversal

Configurations with reversed magnetic shear have been produced by additional heating with LH, ICRH and NBI as early as possible in the current rise. This increases the current penetration time. In figure 11 traces are shown for a typical 'shear-reversal' shot. The plasma is initiated by a low voltage breakdown, and plasma current takes off at 0.3s. The X-point configuration is fully formed at 0.9s. NBI heating is started at 2.5s, resulting in an elmy H-mode, which persists throughout the entire discharge phase. The equilibrium code indicates shear reversal between about 2 and 6s. A time sequence of q profiles is shown in figure 12.

During the NBI heated phase it is observed that the energy confinement time and the D-D neutron rate, increase constantly with time while the internal inductance l_i increases. The enhancement factor H_{ITER89} is about 1.1 at 3s at $l_i = 0.5$, and increases to about 1.5 at 9s at $l_i = 0.7$. In a reference shot with a 'normal' $l_i = 0.95$, a the normal H factor for elmy H-mode H = 1.9 is found. These findings are consistent with the observations on several machines that energy confinement time scales with internal inductance, to a power of order unity.

Hence, during the elmy H-mode phase, no evidence of improved confinement due to shear reversal could be found. During the preceding L-mode phase, before 2s, there is some evidence for improved confinement. However, simultaneously, there is evidence for a fast electron population, driven by the LH. This issue needs further analysis.

Although these experiments are not yet conclusive, they do appear to set practical boundary conditions on the types of current density profiles that may lead to reduction of the anomalous transport.

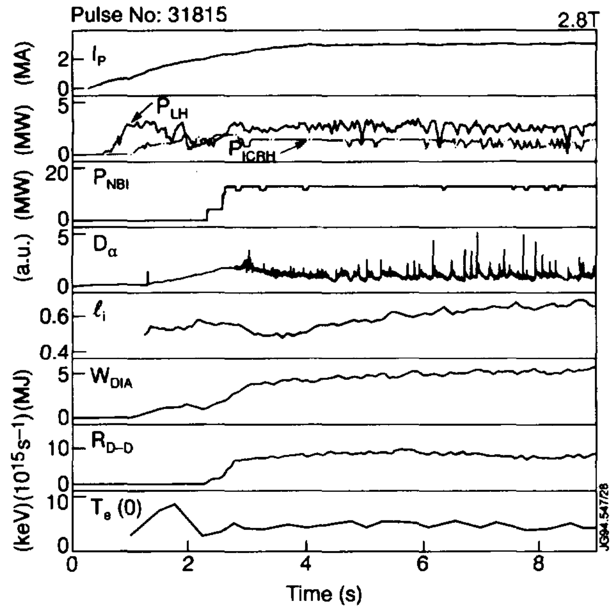


Fig.11 Traces of a shot in which a shear reversed configuration is established. The X-point configuration is established at 0.9s.

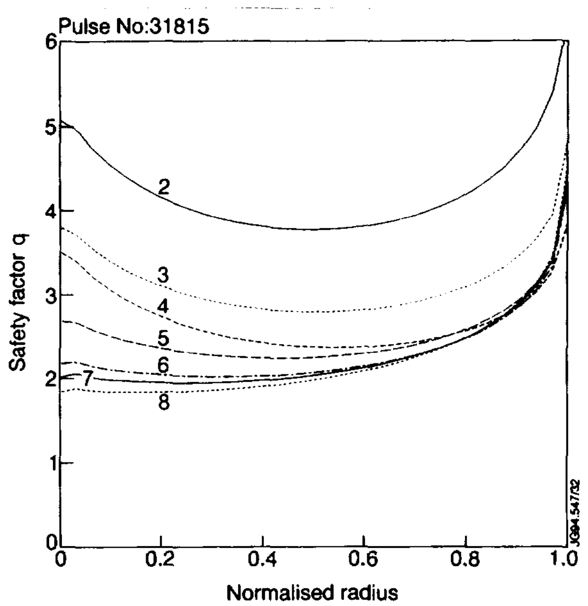


Fig.12 A series of q profiles, reconstructed by the equilibrium code, for the shear reversal shot shown in figure 11.

VI. T.A.E. MODE DAMPING

The first experiments were carried out in which Alfven Eigen-modes were externally excited. This was done with the saddle coils, driven by a high frequency amplifier of 3kW power capability. In ohmic plasmas, resonances have been clearly observed. The Alfven nature of the resonances was verified by executing a scan in toroidal field, and comparing the measured resonance frequency with the calculated TAE frequency. Damping rates of the mode between 0.1 and 0.01 are measured, depending on the density profile. These damping rates are consistent with the predicted presence and absence of continuum damping.

VII. THE FUTURE PROGRAMME

The present JET campaign is scheduled to May 1995. Important elements of the remainder of the campaign are: the extension of X-point operation to 5or 6MA; the further exploration of the detached divertor regime and its compatibility with elmy H-mode operation; a study of Helium transport and pumping using the Argon frosting facility of the cryopump; further studies of effects of current density profile modifications; a number of specific ITER relevant experiments, such as: an experiment on toroidal field ripple; an H-mode threshold experiment and an experiment on the issue of scaling of the transport with gyro-radius. Finally, the present CFC divertor target tiles will be exchanged for a set of Beryllium tiles in order to study the differences between these materials as plasma-facing components.

An extension of the JET programme to the end of 1999 is proposed. A new divertor, called Mark-2, will be introduced in 1995. This will provide a more closed divertor geometry. Mark-2 will feature a large carbon plates as opposed to the present system of many small tiles. The Mark-2 mechanical support structure is designed to accommodate a variety of possible top structures and target plate designs. A period of D-T experiments is planned for the end of 1996. After this, it is planned to construct a strongly ITER relevant 'Gas-Box' divertor, on the same Mark-2 support structure. A final D-T phase is planned for 1999.

VIII. DISCUSSION

The initial operational phase of JET in its pumped divertor configuration has made evident the increased power handling capability of the divertor and the more frequent occurrence of elms. Significant progress has been made in the extension of the H-mode operation to the reactor relevant steady-state elmy H-mode. This regime is now obtained in a variety of conditions, in particular at plasma currents ranging from 1 to 4MA, power levels ranging from a few to 26MW, in the high β_p regime, in discharges with shear reversal, and at high normalised beta. The next milestone in showing the reactor relevance of this regime will be the demonstration of the compatibility of high confinement operation with detached divertor operation, which has not been successful so far. This demonstration may, in fact, require the closed divertor structure planned for the JET extension.

The cryopump allows effective particle removal. The use of it improves vacuum conditions, reduces recycling, allows generally higher performance operation. In the long pulse elmy H-mode regime, the cryopump eliminates the effects of wall saturation that were observed in earlier experiments.

The experiments on optimisation of the JET transient peak fusion performance have not yet resulted in an improvement over the past. Various factors play a role in this; the increased elminess, the change of the plasma geometry, the generally higher operating densities, and the higher recycling. This area will be pursued in the remainder of the campaign.

The regime of high poloidal beta operation has been extended to steady-state, at least as far as the power balance is concerned. Initial experiments on the effects of shear reversal have not yet led to the observation of confinement enhancements, in discharges where the magnetic analysis shows the existence of shear reversal.

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