Exhaust and Impurity Control Experiments in the JET Pumped Divertor

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ABSTRACT

The first results of divertor studies in the JET Pumped Divertor are discussed. Plasmas using either the horizontal or vertical plates of the target have been investigated and sweeping of the divertor plasma strike points has been used to increase the wetted area of the target during high power experiments. As a result of careful alignment, the surface of the target has not exceeded 800°C while total plasma input energies of up to 140MJ have been used. Experiments with the divertor cryopump have shown that the most efficient pumping is obtained when the outer strike point is adjacent to the pump. However, pumping efficiency falls by only a factor of 2 as the strike point is moved up to 20cm from the optimum position. Measurements of the SOL and divertor parameters in discharges diverted onto the horizontal or vertical target plates have confirmed certain features predicted by numerical models. Steady-state H-modes with duration of up to 20s and confinement enhancement factors close to twice L-mode scaling have been obtained and have been extended to high density. The approach to detachment, obtained so far only in ohmic and L-mode plasmas, has been studied experimentally and numerically.

1. INTRODUCTION

Following a major upgrade JET now operates with a Pumped Divertor [1] which combines high power handling capability, flexibility of plasma configuration and a cryopump operating at liquid helium temperature. This has equipped JET to address the central problems of the ITER divertor: efficient dissipation of heat exhaust with minimal erosion, control of particle fluxes, including helium, and effective impurity screening. In experiments to date, X-point plasmas with currents of up to 4MA have been established and an extensive characterization of the properties of diverted plasmas has been performed in L and H-modes, with an emphasis on diagnosing plasmas in steady-state conditions. The power handling capability of the target has been demonstrated at total powers of up to 26MW and in steady-state H-modes lasting up to 20s.

Close co-ordination of experimental and theoretical studies of divertor plasmas, to provide validation of numerical codes used in predictive modelling and to guide the evolution of the experimental programme, is a key feature of the JET divertor programme. Here initial comparisons between experimental observations of discharges using horizontal and vertical target plates and the results of simulations are discussed.

2. THE JET PUMPED DIVERTOR

The main features of the new divertor configuration are shown in Fig. 1. Four internal coils allow a wide range of configurations to be established at currents of up to 6MA. Divertor connection length and X-point height can be varied independently. In addition, the divertor strike points can be swept at frequencies above 4Hz and at amplitudes of 10cm to increase the wetted area for heat exhaust. The divertor target consists of narrow, water-cooled inconel beams on which CFC tiles are mounted. Tiles are machined and carefully aligned to eliminate edge exposure. Slots between the support beams allow neutrals to recirculate and to reach the divertor cryopump [2].

Diagnostics have also been extensively upgraded with many new systems being introduced, particularly for SOL and divertor studies. Principal diagnostics used in these studies include an array of single and triple Langmuir probes, which provide both divertor target and upstream (SOL) plasma parameters; IR and CCD cameras providing observations of target heating and recycling as well as impurity influxes; poloidally resolving visible spectroscopy and bolometry yielding measurements of deuterium and impurity radiation; and ionization gauges, distributed below the divertor target and at the entrance to the cryopump, which determine neutral densities in the divertor.

3. POWER HANDLING STUDIES

Divertor experiments in the original JET device were constrained by the occurrence of the carbon bloom at high power, often as a result of localized heating on exposed tile edges [3]. Considerable care has, therefore, been taken in design and installation of the target tiles to eliminate the exposure of edges. In addition, X-point sweeping distributes the loss power over a larger surface area, reducing the heating rate of the target. In combination with the giant ELM's, which are now a feature of JET H-modes and which distribute power over a wide area of the divertor, sweeping is very effective in establishing essentially steady-state surface temperatures on the target. This is illustrated in Fig. 2, which shows the peak temperature in the outer strike point during a pulse with a total power of 12MW. The target temperature gradually rose over the first 2s of the (unswept) heating phase, reaching ~800C. Following the initiation of sweeping at 16s, as indicated by the 4Hz oscillation in the current of one of the divertor coils, the peak tile temperature fell and oscillated slightly about a steady-state value of ~600C. The sweeping has no deleterious effects on either the ELM behaviour or the plasma energy confinement. In long steady-state H-modes of up to 20s duration, 140MJ has been delivered to the plasma, with >100MJ deposited on the divertor target. The vertical targets have also proved robust in this respect, having sustained 80MJ of injected energy of which 50MJ was deposited on the target.

Asymmetries in the power deposition on inner and outer targets, as observed in previous JET experiments [4], could adversely affect gas target divertor regimes. Therefore, a series of experiments was performed with the ∇B ion drift towards and away from the target to investigate its influence on such asymmetries. In these discharges, the direction of the plasma current was also reversed to maintain a constant magnetic helicity, as required by the inclination of the target tiles, and this necessitated the use of counter-NBI.

The results are illustrated in Fig. 3, in which the ratio of peak temperature on the outer target to that on the inner target (after approximately 4s of additional heating) is plotted as a function of q_{95}. In L-mode plasmas with the ∇B ion drift towards the target it was found that tile heating on the outer target was dominant, but that the degree of asymmetry decreased with increasing q_{95}. With the toroidal field direction reversed, tile heating on the outer target was still dominant, but the degree of asymmetry increased with increasing q_{95}. It was also observed that asymmetries in the D_α emission from the divertor and in the radiation, which were dominated by emission from the inner divertor leg with the ∇B ion drift towards the target, were reversed when the toroidal field was reversed. Thus, it appears the toroidal field reversal mainly affected the density distribution between the two divertor legs [5], a conclusion supported by Langmuir probe data. However, asymmetries in the power flow to the target cannot be simply explained by asymmetries in radiation from the divertor legs and further analysis is in progress to develop a detailed understanding of these experiments.

A power balance analysis of these L-mode plasmas showed that the loss power was completely accounted for by bulk and divertor radiation, convection and conduction to the divertor target and a significant (~20%) component of atomic recombination at the target. Power accountability in H-mode plasmas is not yet as well documented as ELM's complicate the analysis.

4. EXPLOITATION OF THE DIVERTOR CRYOPUMP

With a measured speed of ~$170m^3s^{-1}$, the divertor cryopump allows greater control over the plasma density and modification of the particle flows in the divertor and SOL, leading to the possibility of improved impurity control. In addition, the use of argon frosting will permit the study of helium exhaust in reactor-relevant regimes. Initial experiments with the cryopump have investigated the dependence of the pumping efficiency on X-point geometry and the quantitative balance between gas input rate and particle removal rate. The latter is calculated from the measured pressure in front of the pump and its calculated proportionality with particle removal in D gas tests.

Fig. 4 shows the results of an experiment in which the outer strike point of the plasma was moved across the horizontal target and up the vertical plate while the pressure in front of the cryopump was monitored with an ionization gauge. During this scan the plasma density was held constant by gas-puffing. The particle removal rate rose to a maximum of $8\times10^{21}Ds^{-1}$ as the strike point reached the corner of the divertor target, adjacent to a toroidal slot in front of the pump, then fell as the strike point rose up the side-plate. However, the variation in particle removal rate was only a factor of 2 as the strike point scanned over virtually the entire usable surface area of the target, indicating that the radial slots between the target support beams provide an adequate conductance to the cryopump. Moreover, the ratio of removal rate to fuelling rate was found to be independent of the fuelling location.

The low sensitivity of the particle removal rate to strike point position contrasts with the experience in DIII-D [6] and is of great significance to the JET divertor programme, since it permits exploitation of the wide range of configurations for which the divertor was conceived. In addition, it demonstrates the feasibility of using strike point sweeping to redistribute exhaust power while exploiting the benefits of the particle control provided by the pump. This conclusion is supported by observations of density behaviour in steady-state H-modes, which showed a significant reduction in edge plasma density when the cryopump was active, even when the strike point was distant from the cryopump slot.

A quantitative fuelling balance has been performed for a variety of JET plasmas, ranging from ohmic to long steady-state H-modes without gas fuelling and high density L and H-modes. The total gas input in these discharges ranged from 500 to 8000mbl. In the majority of cases, there was a balance to better than 10% between the total gas input and that removed by the pump.

5. INVESTIGATION OF SOL AND DIVERTOR PARAMETERS

A detailed comparison is underway of SOL and divertor parameters in various regimes and plasma configurations in order to develop a greater understanding of the behaviour of the plasma edge, particularly in regimes of interest to ITER such as the gas target divertor, and to benchmark codes used to model divertor behaviour [7]. In particular, it has been predicted that, in plasmas with strike points on the divertor sideplates, the probability of escape for recycling neutrals should be substantially reduced [8], possibly facilitating access to the detached divertor regime. Such plasmas have been established and their edge parameters compared with equivalent plasmas on the horizontal target. Fig. 5 shows equilibria for a pair of discharges at 2MA/2.8T. These cases had similar densities, input and radiated powers, and similar impurity content. Electron temperatures and densities were derived from single and triple Langmuir probe measurements in the divertor target and compared with numerical predictions of the EDGE2D code [9] which are based on the measured input power, radiated power and a SOL inventory adjusted to match measured divertor densities.

A comparison between the experimentally determined electron temperature and density profiles and the results of modelling for an attached divertor plasma is shown in Fig. 6. One notable result is that even at central plasma densities as low as $4\times10^{19}m^{-3}$ and input powers of 4MW, divertor densities in the region of $1\times10^{20}m^{-3}$ are observed, indicating that the divertor is in a very high recycling regime. This contrasts strongly with observations made in the old JET configuration [10] and suggests that, in spite of its relatively open geometry, the pumped divertor configuration is closed to a far higher degree than the previous JET divertor. The main features of the density profiles predicted by the code are in reasonable agreement with those obtained experimentally. In addition, there is a striking agreement between the code prediction of an inverted temperature profile on the side-plate configuration and that actually observed, suggesting that the behaviour of recycled neutrals is accurately predicted by the code.

The differences in recycling patterns between discharges on the horizontal and vertical targets should lead to a thinner SOL in the latter case. Initial measurements made in L-mode plasmas support this prediction. SOL profiles have been obtained using a reciprocating Langmuir probe near the top of the plasma in equilibria similar to those illustrated in Fig. 5, but with the toroidal field and current directions reversed. Examples of electron density profiles, mapped to the plasma midplane, are shown in Fig. 7. These indicate that, under the same conditions of power and density, the scale length for the density fall off in the vertical plate discharge is approximately half (λ_n=1.6cm) that in the horizontal plate discharge (λ_n=3.1cm).

6. STEADY-STATE REGIMES

Extension of ITER-relevant plasmas to steady-state conditions is a central theme of the JET programme. Two specific regimes have been investigated, steady-state H-modes and detached divertor plasmas. In the new JET configuration, repetitive ELM's occur naturally and this has allowed long pulse, steady-state H-modes to be established. Experiments have been conducted with plasma currents in the range 2-3MA (q_{95}=3.3-2.9) at total input powers of up to 11MW. At the lower current 20s H-modes (Fig. 8) have been produced, while 9s H-modes have been obtained at 3MA. In all cases the H-mode duration was restricted by that of the additional heating. It is particularly significant that, as shown in the figure, the surface temperature of the target does not exceed 550°C. Thus it appears likely that this regime will be limited only by technical constraints, such as bulk heating of the target tiles or limitations of the poloidal and toroidal circuits.

In the 2MA/2.1T case shown in Fig. 8 fuelling was provided by NBI heating only and the cryopump was used. Comparative discharges with and without the cryopump showed that the use of the pump reduced plasma edge density and plasma average density (by ~10%) and improved confinement (by ~15%). A comparison with earlier JET results on steady-state H-modes is also revealing. Long steady-state H-modes were established in the old JET configuration by gas-puffing into otherwise ELM-free plasmas [9]. In those cases $\overline{Z}_{eff}$ fell to ~2, while the plasma density rose after ~10s as the walls saturated. In addition, energy confinement was ~80% of the JET/ DIII-D H-mode scaling and considerable difficulty was experienced with large amplitude mhd activity. In the present experiments, $\overline{Z}_{eff}$ lay in the range 1-1.5 and, as with all significant bulk plasma parameters, was in steady-state throughout. In addition, even in cases in which additional gas-puffing was used to increase the plasma density, there was no evidence of saturation of the pumping. Stored energy in the case shown is equal to that predicted by the JET/ DIII-D H-mode scaling and for all discharges in which the cryopump was used was within 10% of this value.

Maintaining steady-state plasmas in which most of the input power is dissipated by radiation or charge exchange processes in the divertor is a central problem in current fusion research. Previous experiments on JET [12] succeeded in establishing 'detached' L-mode plasmas in which virtually all of the input power was lost by radiation. Maintaining this regime in steady-state in combination with enhanced confinement is a major aim of JET divertor experiments. Results of an initial experiment are shown in Fig. 9. This illustrates the evolution of an L-mode discharge at 2MA/2.8T with 5.5MW of input power in which deuterium puffing was used to access the 'detached' divertor regime. Operationally this phase is defined to occur when the ion saturation current, I_{sat}, to the target falls as the bulk plasma density increases, indicating that the plasma is detaching. This process occurs initially in the vicinity of the separatrix as the plasma approaches the density limit in JET [13]. We have, therefore, implemented a feedback loop in which the ion saturation current from a Langmuir probe close to the separatrix is used to control the gas fuelling rate and, eventually, to bring the plasma into a steady-state condition. This process is shown in the lower panel of the figure, where the reference waveform and a smoothed version of I_{sat} used to control the deuterium puffing rate are compared. As the bulk plasma density and radiated power rise, I_{sat} falls, gradually reaching the level of the reference waveform, at which point the feedback system holds the plasma in steady-state. The physics of these plasmas is discussed in detail in an accompanying paper [7].

7. SUMMARY

Initial operation with the JET Pumped Divertor has established that it provides a flexible and powerful device for the investigation of key issues relevant to the development of the ITER divertor. A wide range of plasma configurations has been developed with X-point connection lengths of up to 10m. Careful alignment of the divertor target has resulted in excellent power handling capability, which is augmented by the beneficial effects of sweeping and ELM's. Further reduction in the power loading of the target is associated with the existence of a high recycling divertor and access to detached divertor regimes. Experiments with the divertor cryopump have shown that it provides effective particle exhaust over much of the divertor target area and there have clearly been beneficial effects on the performance of steady-state H-modes. Comparisons of discharges using the horizontal and vertical targets have confirmed some aspects of divertor models, although much further experimentation is required to exploit the possible benefits of side-plate operation. The new capabilities of the Pumped Divertor have allowed us to establish steady-state plasmas in regimes of interest to ITER, such as ELMy H-modes and detached divertor plasmas and the study of these regimes will be pursued vigorously in the current experimental campaign. A key goal is to establish the viability of combining the improved confinement of the steady-state H-mode with the beneficial effects in power handling and target erosion of the detached divertor.

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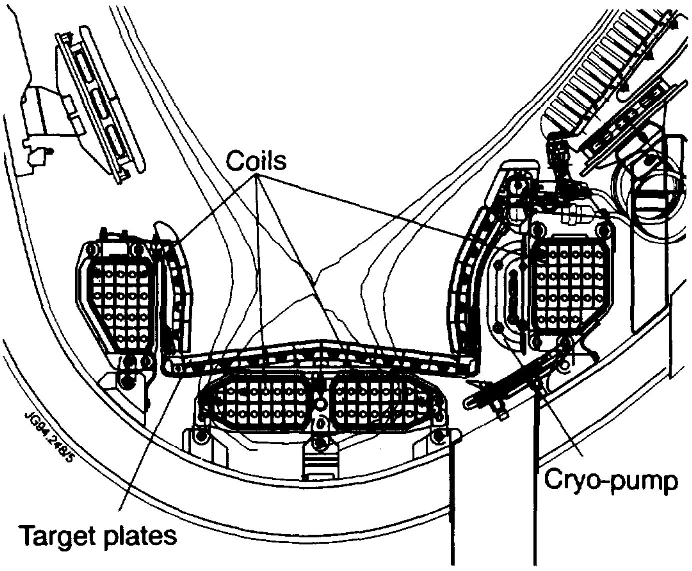

Fig. 1 *Cross-section of the JET Pumped Divertor showing the major components.*

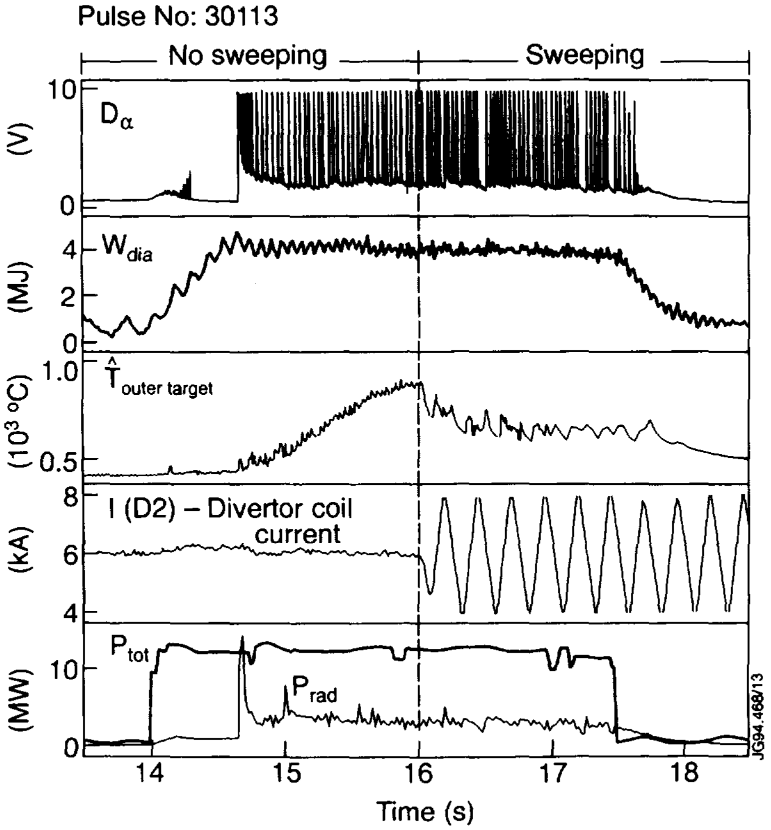

Fig. 2 *An additionally heated pulse in which divertor strike point sweeping was started at 16s. As a result, the peak temperature on the outer target fell from ~800°C and gradually approached a new steady-state value of ~650°C.*

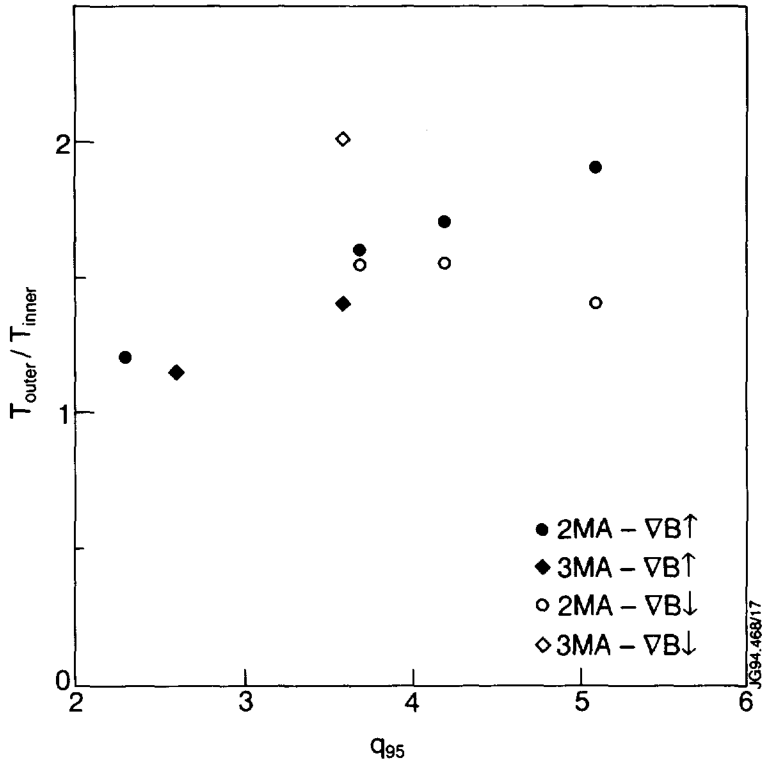

Fig. 3 *Ratio of the measured peak temperature on the outer strike zone to that on the inner strike zone as a function of q_{95} and the direction of the ∇B ion drift for a series of L-mode plasmas.*

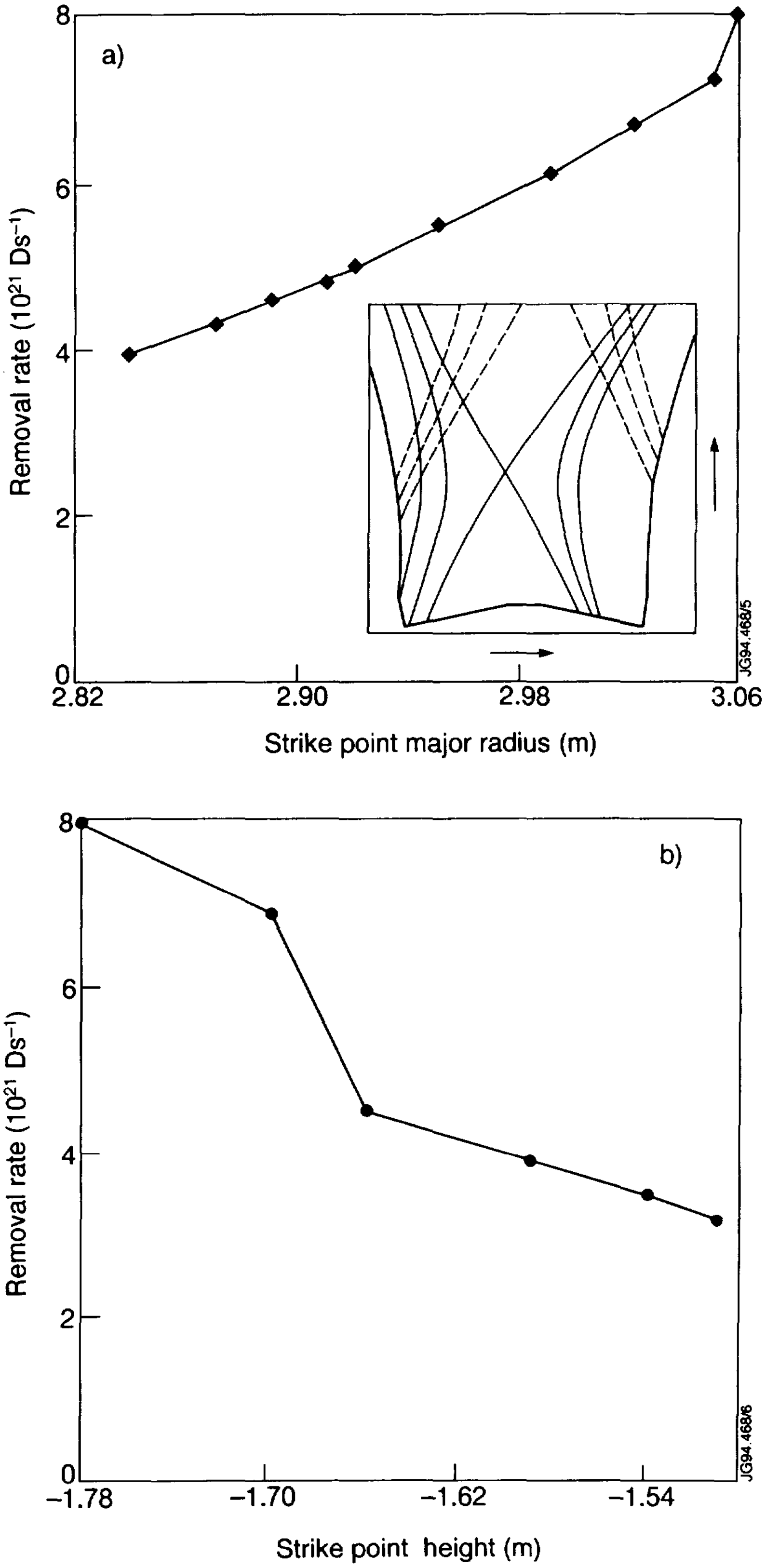

Fig. 4 *The measured particle removal rate as a function of the outer separatrix position for a pulse in which the cryopump was active: a) shows the removal rate as the separatrix moved across the horizontal target plate and b) the removal rate as it moved up the vertical target plate.*

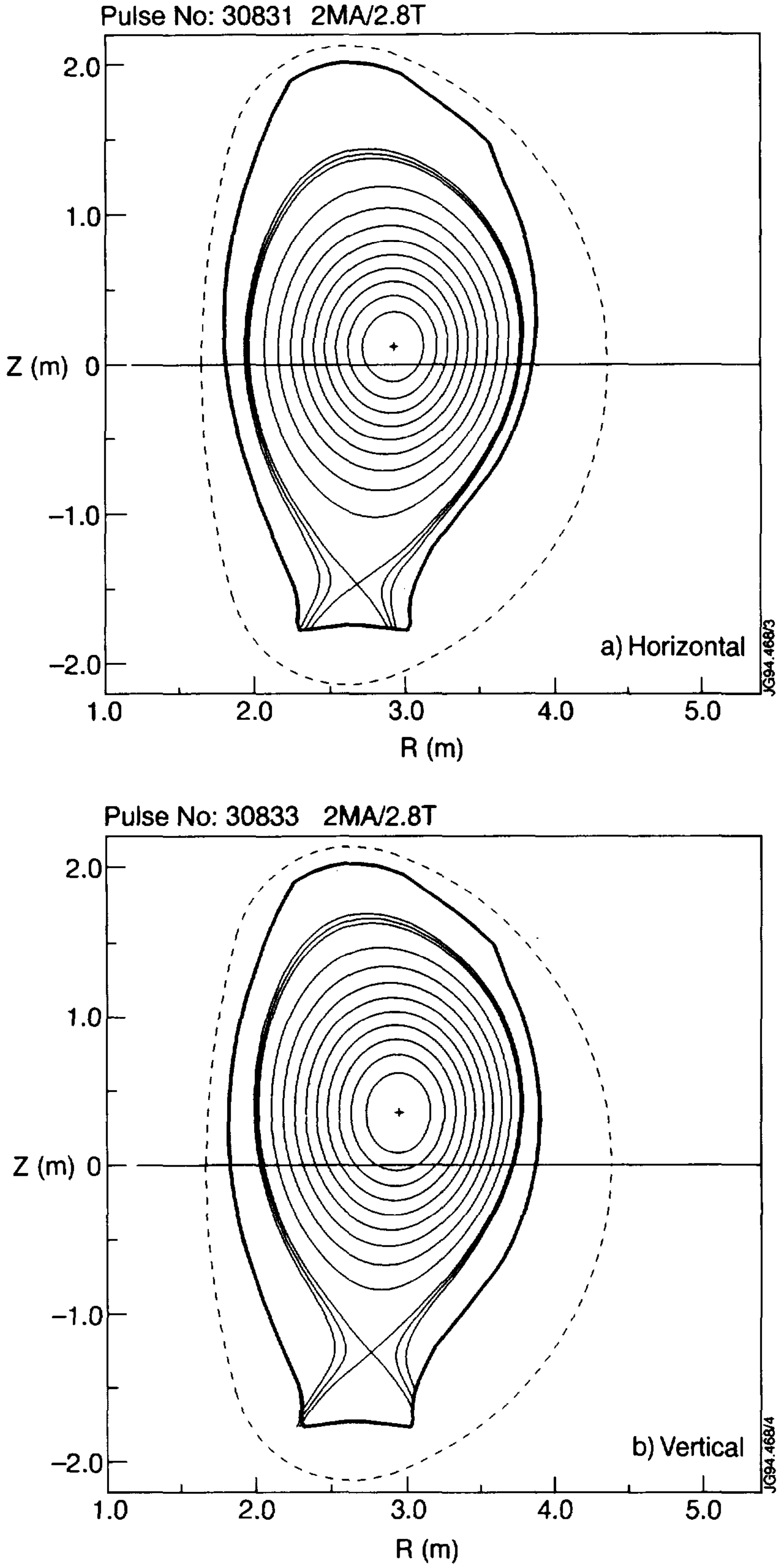

Fig. 5 *a) a horizontal target plate equilibrium. b) a vertical target plate equilibrium.*

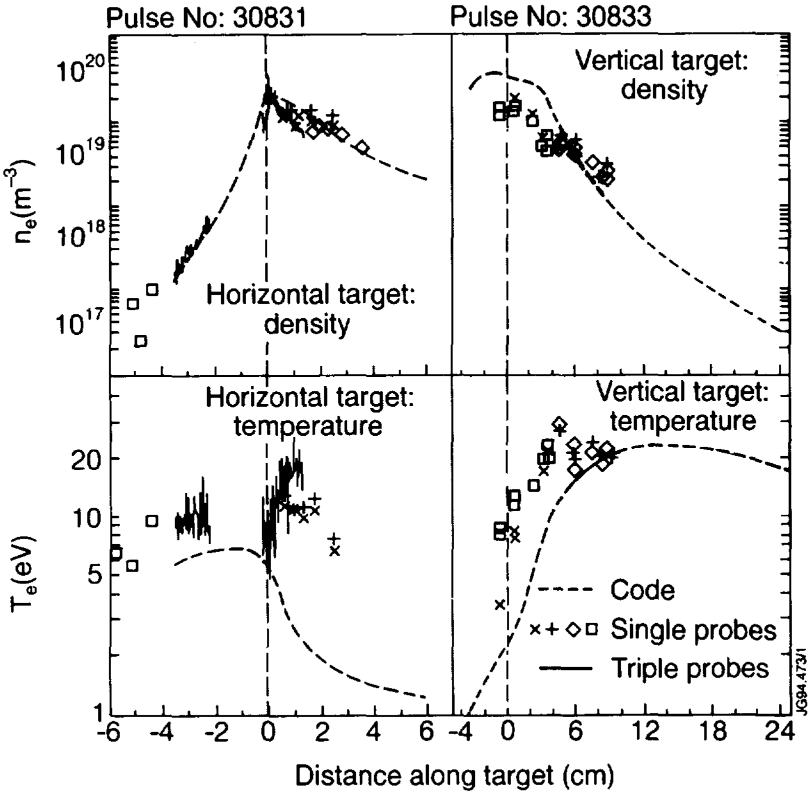

Fig. 6 *A comparison between measured and modelled electron density and temperature profiles at the divertor target for plasmas on the horizontal target, and on the vertical target. The profiles are plotted as a function of radial distance along the target.*

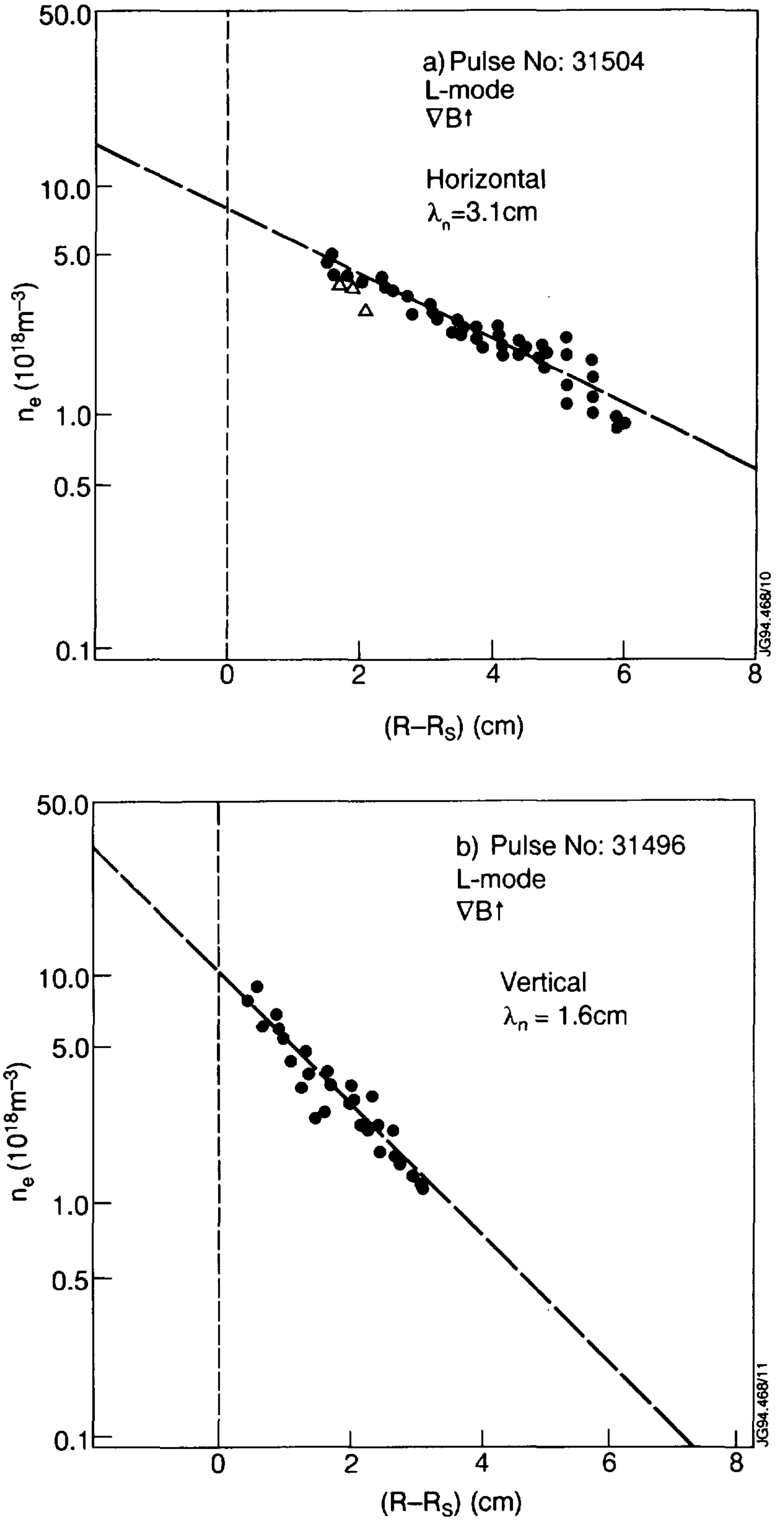

Fig. 7 A comparison of density fall off lengths for plasmas on the horizontal target, a), and on the vertical target b), mapped to the plasma midplane and plotted as a function of radial distance from the separatrix, R-R_S.

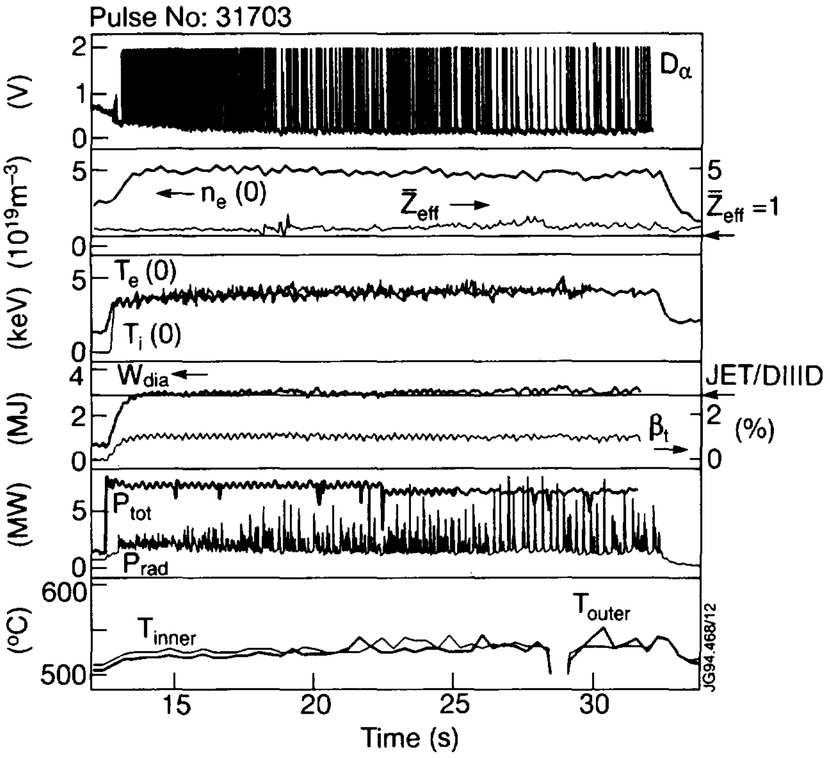

Fig. 8 *A 20s steady-state H-mode at 2MA/ 2.1T.*

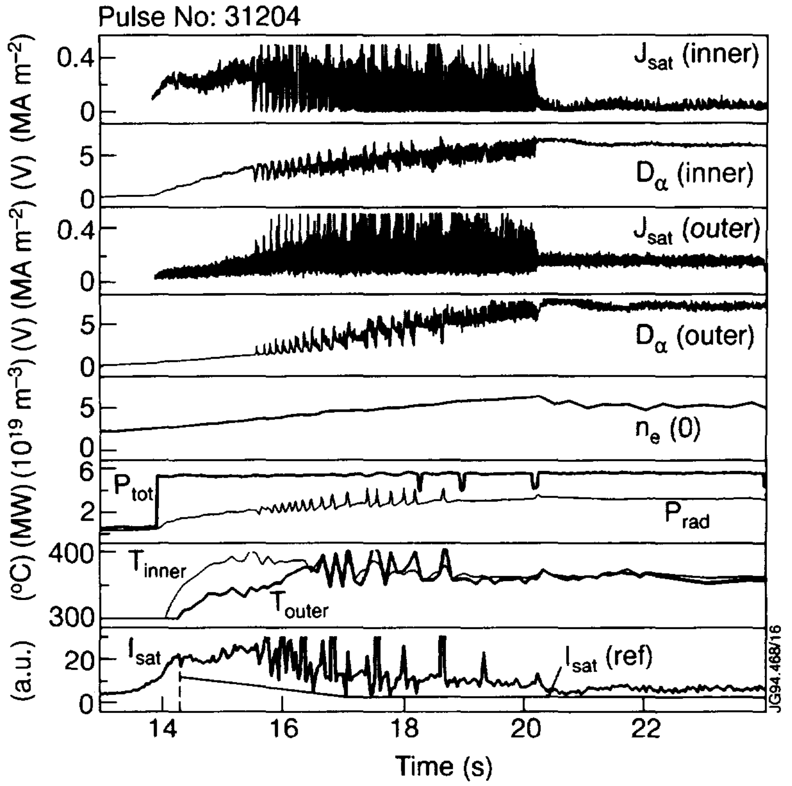

Fig. 9 *A detached L-mode plasma at 2MA/ 2.8T in which the approach to detachment was controlled by reducing the ion saturation current measured by a Langmuir probe close to the inner separatrix almost to zero.*