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Divertor configuration studies on JET

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Abstract

In the 1994/1995 JET experimental campaign, with the MkI divertor, a systematic study of the influence of X-point height, flux expansion and target orientation on the plasma performance was executed. Various plasma configurations were tested under a number of different conditions, including Ohmic density limits, L-mode with 3 MW of NBI, H-mode at 10 MW of NBI and divertor seeding with nitrogen at 10 MW of NBI. The behaviour of the main plasma for the various configurations was quite similar, although there were small differences, for example in impurity control and fuelling efficiency. The paper describes the details of the experiment and presents the results, comparing the findings to the results of simulations using the EDGE2 D plasma boundary code.

Keywords: JET; Divertor plasma; Density limit; Detached plasma; Radiation asymmetry; MARFE

1. Introduction

During the 1994/95 experimental campaign JET, with the MkI divertor installed, has operated on horizontal and vertical target plates and with various combinations of X-point height and parallel connection length. The different divertor configurations have lead to various differences in the plasma and divertor performance. The target orientation affected, as was predicted, the detailed profiles at the target, but made little difference to any more global parameters such as confinement, the density limit, or even the density of detachment. The variation of the X-point height, or the associated variation in wall clearance, did, however, have more impact on global parameters. Radiation stability in the divertor was significantly altered, as was the ELM behaviour in H-mode, and the central impurity levels with nitrogen seeding. The paper begins with a review of the observed differences in the plasma performance between operation with the strike point on the horizontal and vertical targets in both Ohmic and NBI heated discharges. The paper then presents the results obtained with horizontal target plasmas of differing magnetic geometry. In these cases Ohmic density ramps, NBI heated H-modes and nitrogen seeded plasmas were investigated.

2. A comparison of horizontal and vertical target plates [1,2]

2.1. Plasma configurations

Although a large number of different plasma configurations have been used in JET, for this study we concentrated on three configurations. Initially two configurations were developed at 2 MA plasma current, one on the vertical target and one on the horizontal targets, Fig. 1a, b, to be compatible with the reciprocating probe, positioned at the top of the vessel. Based on previous experience and the observation of a low density limit in the horizontal target configuration, a large wall clearance, horizontal target configuration was developed, Fig. 1c. This configuration could not be reached by the reciprocating probe.

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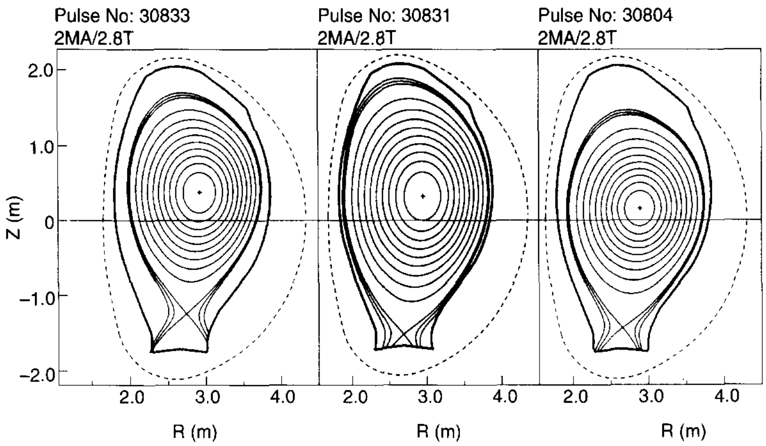

Fig. 1. The three plasma configurations used in the comparison between horizontal and vertical target operation. (a) and (b) are the vertical and horizontal target configurations compatible with the reciprocating probe, while (c) is a high wall clearance horizontal target configuration.

2.2. Ohmic density ramp

The two high clearance configurations were ramped in density using deuterium gas fuelling in the divertor region. The rate of rise of the density for the vertical target configuration was almost double that of the horizontal target configuration for the same puff rate, but both reached the density limit at a line integrated density of about 1.5×10^{20} m^{-2} and about 80% radiated power fraction. The low clearance horizontal target discharge reached the density limit at only 60% radiated fraction. As the density was increased both configurations showed a 'roll-over' in the ion-saturation current to the target Langmuir probes occurring at the same line integrated density [3], Fig. 2, this was in contradiction to the predictions made using EDGE2 D [4] which showed the vertical target discharge to detach at much lower densities.

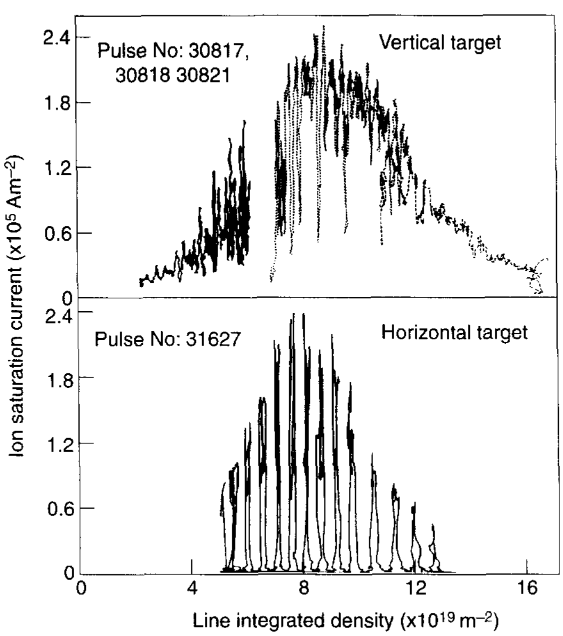

Fig. 2. The ion-saturation current to the target probes for an Ohmic density ramp for the high clearance horizontal and vertical target configurations plotted versus the line integrated density. The strike points were swept over the probe at 4 Hz in both cases.

The differences in the target profiles were small, with a slightly more peaked ion-saturation current profile for the vertical target at low density and both configurations showing detachment at the separatrix first as the density was increased, Fig. 3. Inverted electron temperature profiles were observed for both configurations at densities beyond the 'roll-over' and at lower densities for the vertical target discharges, however the simple interpretation of these measurements becomes questionable under such conditions [5].

2.3. Discharges with additional heating

The L-mode behaviour was very similar to the Ohmic plasmas with more peaked ion-flow profiles at the target for the vertical configuration and detachment at a similar density in both configurations. In both L and H-mode no effect is seen on the radiation profiles in the divertor or on the main plasma performance [6,7]. ELM behaviour in the H-mode is little affected by the target orientation, which is reflected in the energy confinement.

3. An investigation into the effects of X-point height and parallel connection length

3.1. Plasma configurations

The four close divertor field coils of JET enable the X-point height and parallel connection length to be inde-

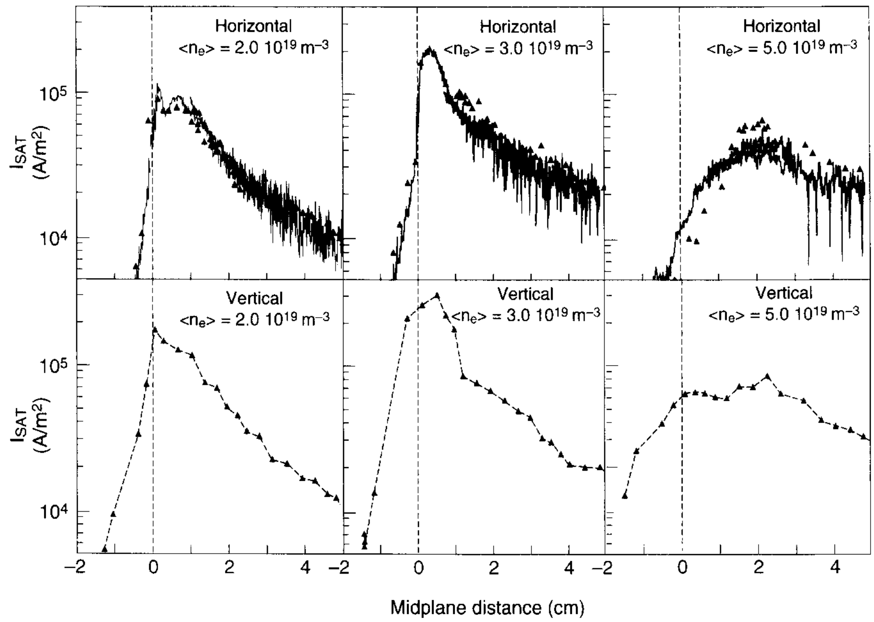

Fig. 3. The ion saturation current profile at the target for a horizontal and vertical target configuration. The profiles are shown at three densities, prior to, at and after the roll-over in the peak ion saturation current.

pendently varied. The flux expansion, however, is dependant upon these two variables and causes some problems in maintaining a similar wall clearance. Three configurations were developed to investigate the effects of X-point height and parallel connection length on plasma performance, they are shown in Fig. 4. Type I has an X-point 30 cm above the horizontal target and parallel connection lengths of 7.5 m and 6 m on the inner and outer divertor legs, respectively. Type II is an attempt to maintain the connection lengths of I, but at half the X-point height, this was partially successful with 7.5 m and 4.5 m for the inner and outer legs, respectively. Type III was a less successful attempt to increase the parallel connection length with a 30 cm X-point height. Due to the distance to the outer coil it was difficult to increase the outer connection length, and only 7.3 m was achieved, compared to 13.4 m for the inner leg. The high flux expansion required to achieve configurations II and III brought both plasmas close to the wall at the low field entrance to the divertor.

3.2. *Ohmic density ramp*

All three configurations were ramped in density, until the plasma collapsed due to radiation, by deuterium fuelling in the divertor. The fuelling rates were identical in each case and increased as a function of time to ensure reaching the density limit. The rate of rise of the density for the low X-point configuration was much greater than for the high X-point configurations, but the finally achieved density was quite similar, Fig. 5. The radiation behaviour showed differences between the high and low X-point discharges. In the low X-point discharge the radiation

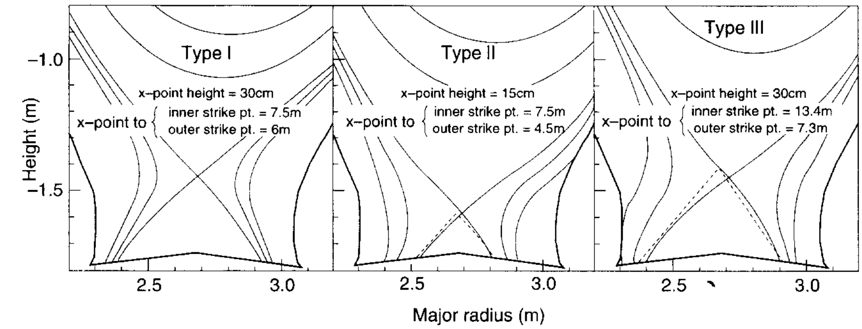

Fig. 4. The divertor geometry for the three plasma configurations used to investigate the affect of X-point height and parallel connection length on plasma performance.

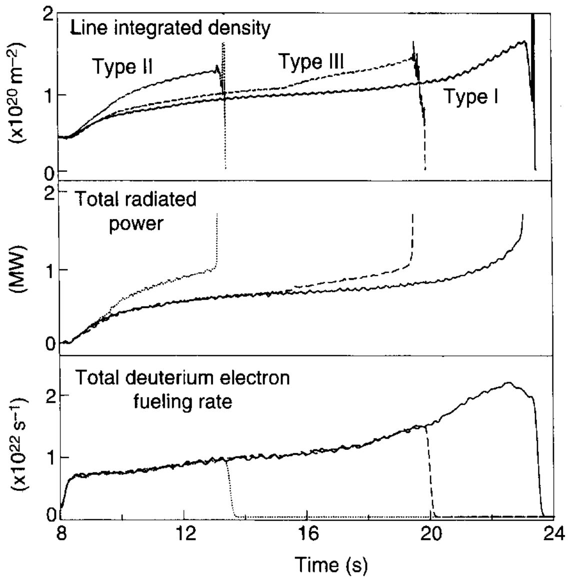

Fig. 5. Some of the main plasma parameters for density ramps of Ohmic plasmas of configurations type I, II and III.

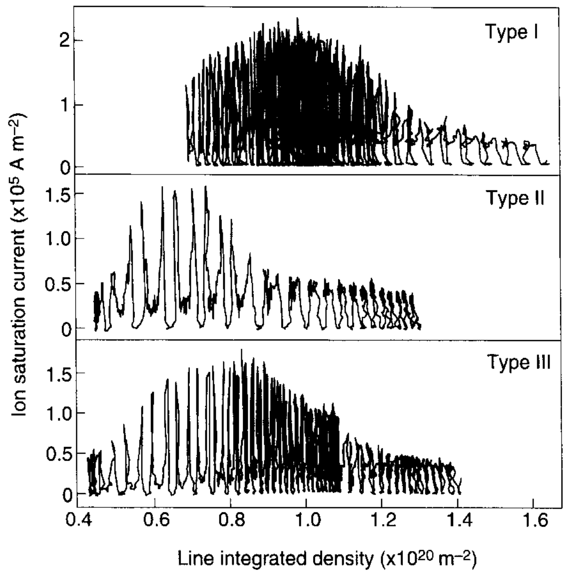

Fig. 7. The ion-saturation current to the target probes for an Ohmic density ramp for the three configurations, type I, II and III, plotted versus the line integrated density. The strike points were swept over the probe at 4 Hz in all cases.

which started at the target plate moved towards the X-point and became centred inside of the separatrix above 60% radiation, where it remained stable until close to 100% radiated fraction was achieved, Fig. 6. In both of the high X-point configurations the radiation remained in the SOL up to in excess of 80% radiated fraction and then disrupted immediately after the radiation centre crossed the separatrix. In all cases the radiation was initially most intense in the outer divertor leg and for the high flux expansion cases there was a tendency for the radiation to be just outside of the divertor on the low field side, this is where due to local flux expansion the plasma is closest to the wall.

The density at which the ion saturation current at the target rolled-over varied with the configuration. High X-point seemed to give a high density at roll-over, while high flux expansion seemed to reduce it, Fig. 7. Alternatively this is compatible with the proximity of the plasma to the divertor throat.

3.3. Additionally heated discharges

The three configurations were each heated with 10 MW of neutral beam injection for 10 s, the first 5 s were

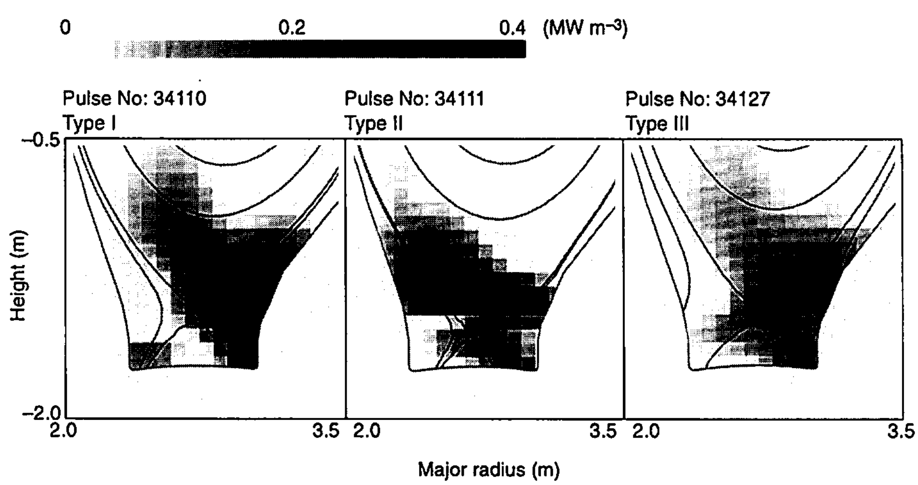

Fig. 6. Tomographic reconstruction of the radiation profiles in the vicinity of the X-point for Ohmic plasmas in each of the three configurations, type I, II and III, at total radiated power fraction of 70%.

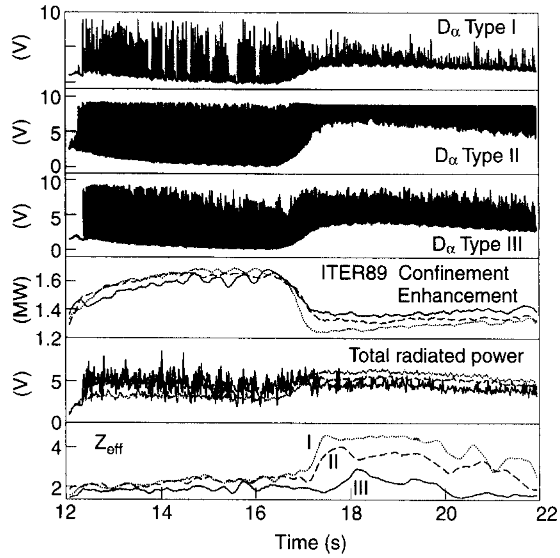

Fig. 8. Some of the main plasma parameters for H-mode plasmas of configurations type I, II and III, with 10 MW of NBI power.

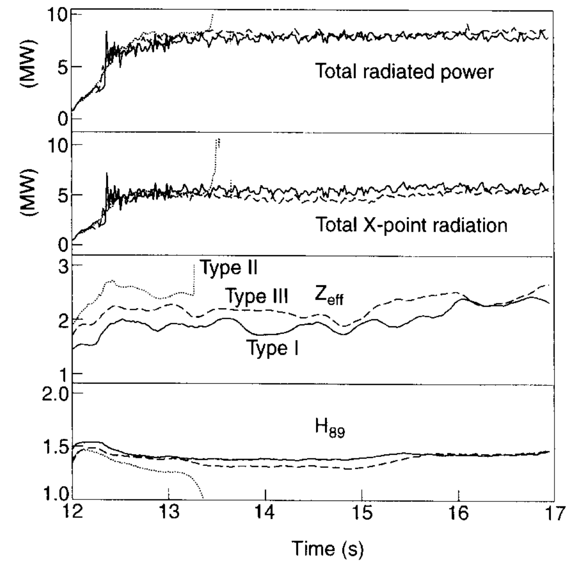

Fig. 9. Some of the main plasma parameters for nitrogen seeded plasmas of configurations type I, II and III, with 10 MW of NBI power.

without gas fuelling, while the last 5 s had identical divertor fuelling at a rate of 3.2×10^{22} atoms per second. All three configurations exhibited ELMs and had confinement enhancement factors of 1.6–1.7 times the ITER89 scaling, during the no fuelling period, Fig. 8. The ELM behaviour, as seen by the target D-alpha oscillations, of the high X-point, low flux expansion case was quite different from the other two cases. In the no fuelling phase no other differences were noticed, but with divertor deuterium fuelling the low X-point case showed a drop in confinement, increased radiated power and an increase in the central impurities. The high flux expansion, high X-point configuration (type III) also showed an increased Z_{eff}, with only the high clearance, high X-point case (type I) showing no increase in impurities.

3.4. Nitrogen seeded discharges

Impurity seeding was performed, with 10 MW of neutral beam injection, by the injection of nitrogen into the divertor volume at a rate of 1.6×10^{21} molecules per second simultaneous with a similar flow of deuterium from the main chamber. While the two high X-point configurations held constant conditions of 80% radiated fraction for five seconds, the low X-point discharge disrupted due to

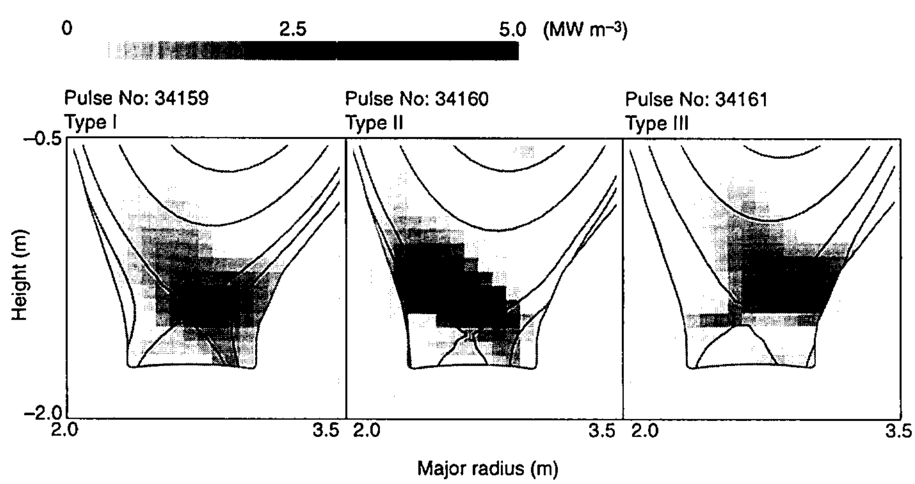

Fig. 10. Tomographic reconstruction of the radiation profiles in the vicinity of the X-point for NBI heated, nitrogen seeded plasmas in each of the three configurations, type I, II and III, at total radiated power fraction of 70%.

radiative collapse after one second. The two high X-point discharges were very similar with 50% radiated fraction from the divertor and an energy enhancement factor of 1.4 with respect to the ITER89 scaling, Fig. 9. The Z_{eff} of the high flux expansion case (type III) was slightly higher. Prior to the radiative collapse the low X-point discharge had a similar split in radiation between the divertor and the core, to the other configurations. However, the divertor radiation was centred inside of the separatrix, Fig. 10, the Z_{eff} was significantly higher and the energy confinement lower.

4. Conclusions

The predicted difference in the density to detachment between horizontal and vertical targets was not observed experimentally on JET, although some of the predicted detailed profile effects were.

Variation of the X-point to target distance and the parallel connection length did show some differences. The differences were mainly in the radiation distribution, both in Ohmic deuterium discharges and additionally heated nitrogen seeded discharges. The high X-point discharges maintained up to in excess of 80% total radiated fraction, with the divertor radiation outside of the separatrix, and showed no stable region with the radiation centered inside of the separatrix. The low X-point discharge had the divertor radiation centered inside of the separatrix for total radiated fractions in excess of 60% and existed stably until close to 100% radiated fraction was achieved. More central impurity contamination was observed when the radiation was centered inside of the separatrix. In addition the type I high X-point discharge exhibited a higher density limit and a higher density of detachment. The cause of the differences between the various configurations is confused by variations in the wall clearance, which we wish to investigate in a further experiment.

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