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The effect of divertor geometry on divertor and core plasma performance in JET

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Abstract

JET has completed a series of experiments in the Mk I and Mk IIA divertors on the effects of increased geometrical closure and target orientation. The potential benefits from closure were expected to be enhanced volumetric energy loss in the divertor (detachment), increased divertor neutral pressure for better pumping and He exhaust, and reduced main chamber neutral pressure for reduced sputtering. The expected effects on neutral pressures were observed. In ohmic and L-modes this led to detachment at lower upstream density and reduced density limits, in qualitative agreement with code calculations. The pumping speed was increased by about a factor of three. Z_{eff} did not reduce, despite the reduced main chamber neutral pressure. In ELMy H-modes the effects of closure were less distinct, which may have been due in part to ELMs striking the upper surfaces of the divertor and main chamber limiting surfaces. The density limit and confinement quality were unaffected by changes in divertor geometry. Increasing triangularity increased the density limit, but also raised Z_{eff}. Confinement was degraded by either deuterium puffing or nitrogen puffing. Detachment occurred at the inner target between ELMs, but not at the outer target until confinement was strongly degraded. Vertical target ELMy H-modes have thinner SOL's and lower midplane separatrix densities than those run on horizontal targets in Mk IIA. Given the JET observations on the lack of sensitivity of core plasma ELMy H-mode performance to divertor geometry, it appears appropriate to review the possibility of simpler, lower cost divertor options than the deep divertor design currently proposed for ITER.

Keywords: JET; Divertor; Geometry effects; H-mode preformance

1. Introduction

This paper summarizes a series of experiments carried out at JET to study the effects of divertor geometry on the performance of the divertor plasma, the edge plasma, comprising the scrape-off layer (SOL) and edge pedestal region, and the core plasma. The experiments began in mid-1994 following a major shutdown of the JET device to install the four internal divertor coils, the cryopump, and the Mark I divertor structure, shown in Fig. 1(a). The divertor coil system allows large variations in X-point height, so that both horizontal and vertical targets can be tested, and in magnetic flux expansion. Following completion of the Mark I campaign in mid 1995, the Mark II divertor substructure was installed, together with the Mark IIA tile carriers and tiles, shown in Fig. 1(b). In October 1996, the bypass leakage conductance between the divertor sub-volume and the

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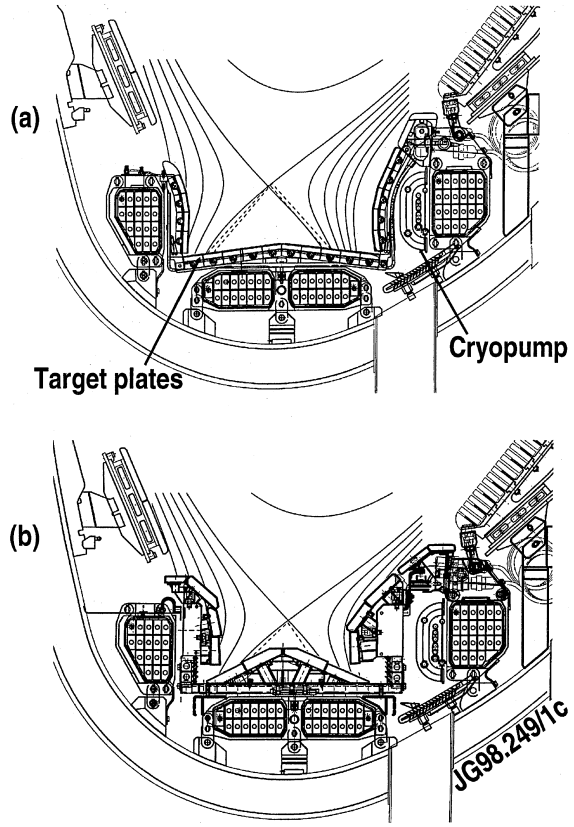

Fig. 1. Poloidal cross sections of Mk I and Mk IIA, showing poloidal flux surfaces for typical ELMy H-mode equilibria (1 cm midplane spacing).

main chamber was reduced by 75%, with the subsequent divertor phase referred to as Mark IIAP (plugged). Where no distinction is made between Mk IIA and Mk IIAP in this paper, the text refers to both. More details on the results summarized here are given in Refs. [1–3].

The studies were directed in particular at attempting to reduce the heat loads and erosion at the targets while maintaining good core plasma performance, in support of ITER or any large next step tokamak. For this reason, the Mark I → Mark IIA → Mark IIAP series was one of increasing geometrical closure, intended to increase the retention of neutral deuterium and neutral impurities in the divertor in the regime of high density, detached divertor operation. The direct benefits of increased closure to neutrals were expected to be increased neutral pressure in the divertor/subdivertor and decreased neutral pressure in the main chamber.

This in turn was expected to result in

- earlier onset of detachment, leading to reduced target power loads for given SOL power and density,
- improved particle exhaust rate for density and impurity control,
- reduced Z_{eff} from intrinsic impurities, as a result of reduced neutral particle sputtering in the main chamber,
- and, possibly, improved confinement in ELMy H-modes, based on correlation of confinement quality with main chamber neutral pressure as reported in several tokamaks (although causality had never been established).

At the same time, there were concerns about making the divertor too closed. First, the reduced SOL flow into the divertor resulting from the lack of long range internal recycling could impair the flushing of impurities and He ash from the main chamber. In addition, it was realized that the ELMs might cause problems, although the distance that ELM particle and energy flows extend beyond the separatrix into the SOL was not well characterized at the time the divertors were designed. There was also hope that properly designed sidewalls and entrance baffles might induce sufficient flow patterns in the divertor itself to cause retention of recycling impurities, introduced to enhance radiation, within the divertor (e.g. below the X-point), although such solutions were not found in the 2-D simulations made during the design phase. It should be pointed out that closure to neutrals does not, in itself, cause impurities to remain in the divertor, since impurity ions will tend to be driven towards the main chamber by the ion thermal gradient force [4,5].

In the remainder of this paper we discuss first the observations in Ohmic and L-mode plasmas, for which no ELMs are present. We then report on studies of steady state ELMy H-modes, which are the ITER preferred operating scenario, followed by a section specifically on the merits of vertical targets, as chosen by ITER, relative to horizontal or "dome" targets in Mark IIA. We next address the question of whether or not the performance of a deep divertor, in the particular context of application to an ITER-like device, justifies its cost in space and money relative to a more open, shallow divertor, before turning to the conclusions.

2. Ohmic and L-mode plasmas

In the case of Ohmic and L-mode plasmas, whose SOL width in general is small enough to fit comfortably within both Mk I and Mk IIA, most of the changes expected from increasing closure, given in Section 1, were observed. The pumping rate was increased by a factor of two to three [6]. For a given upstream density, both D_a and CIII signals in the divertor increased significantly [7]. The photon yield, CIII/D_a, also increased, an unexpected result. While the relationship between the photon yield and sputtering yield ($\Gamma_{\mathrm{CIII}}/\Gamma_D$) depends on plasma temperature and density as well as material properties, detailed analysis [3,8] suggests that the dominant effect here is increased chemical sputtering resulting from higher average target temperatures in Mk IIA than in Mk I, which are related to the divertor cooling system design.

For given power input, detachment occurs at lower density in Mk IIA than in Mk I, as predicted. Fig. 2 shows the degree of detachment, (DOD), as a function of line-averaged density for three pulses, where DOD is defined as the ratio of the target ion saturation current which would be expected in a conventional high-recycling divertor plasma to that actually measured [9]. The upper half shows the DOD for the inner divertor target, and the lower half for the outer. The low flux expansion Mk I discharge begins to detach at the highest density, followed by a flux expanded (hence more closed) Mk I discharge. The lowest density for onset of detachment was found in Mk IIA, and the detachment proceeded more rapidly once it began. As the density increases for this discharge, a "knee" is formed, corresponding to formation of an X-point MARFE, followed by a more rapid increase in the DOD until disruption occurs, indicated by the end of the data. The lowest density limit in Ohmic discharges was found in the most closed configurations. This is characteristic of a MARFE-induced density limit, and is entirely different from the density limit in ELMy H-modes discussed in Section 3.

In a series of trace-neon-puffed pulses, it was found that the neon decay time was shorter in Mk IIA than in Mk I, by a factor of three to four, consistent with the increased effective pumping speed [10]. As has been reported by ASDEX-Upgrade [11], the neon exhaust rate increases with neutral pressure in the divertor.

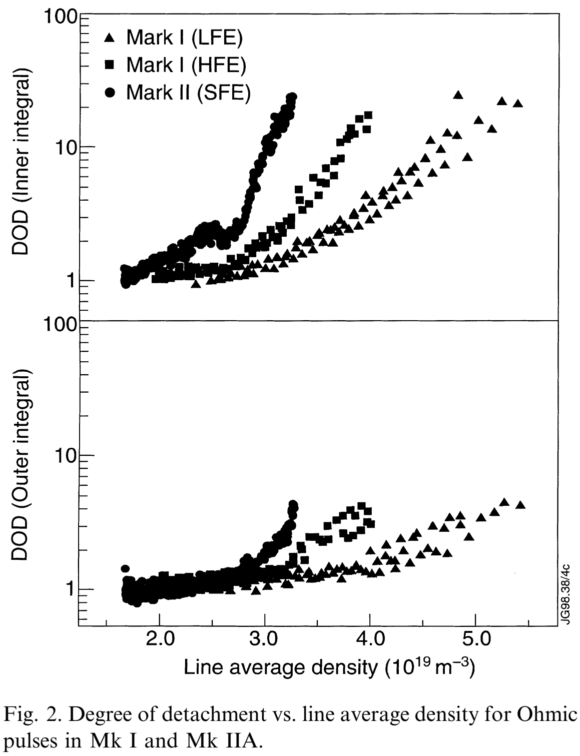

Fig. 2. Degree of detachment vs. line average density for Ohmic pulses in Mk I and Mk IIA.

It had been hoped that Z_{eff} would be reduced due to lower main chamber sputtering, but this was not the case. Several factors are involved. First, as indicated above, the divertor sources of carbon in Mk IIA were higher than in Mk I for given upstream conditions. The fact that Z_{eff} did not increase suggests that target produced impurities are in general well-shielded.

Secondly, although the upstream neutral pressures were reduced as the closure was improved Mk IIA $\rightarrow$ Mk IIAP, the fraction of the inner wall covered by carbon tiles was also increased, which tended to offset the effect of reduced neutral pressure. Thus it remains possible that a closed divertor may reduce intrinsic impurity content, at least in non-ELMing discharges.

All of the effects seen here are at least in qualitative agreement with 2D simulations of the edge plasma [12–14].

3. Effect of geometry on the performance of steady state ELMy H-modes

In general, differences in the performance of the divertor, SOL, and main plasmas caused by varying the divertor closure (either by variation of the flux expansion or the divertor structure) were much less evident in ELMy H-mode plasmas than in Ohmic or L-mode plasmas. There are two reasons why this may have occurred:

1. Mark IIA is narrower than Mk I, and the ELMs can deposit significant amounts of particles and energy on the upper parts of the divertor or on limiting surfaces in the main chamber, thus diluting the effects of closure [1]. The displacement of the strike zones during an ELM diminishes as the ELM amplitude decreases [15]. Fig. 1 shows reconstructed equilibria for typical ELMy-mode discharges in Mk I and Mk IIA. The poloidal flux surfaces shown have a spacing of 1 cm in the outer midplane. While the SOL fits well within both divertors in between ELMs, this is not the case during ELMs. *If this is the principal reason for the insensitivity of the results to divertor geometry, it might be altered by having a wider, deeper divertor, such as in the ITER design, where the* 5 cm *midplane flux surfaces intersect the targets deep in the divertor.*

2. The edge plasma/SOL region, which is believed to play a key role in core plasma performance, is strongly affected by ELM physics, which are relatively poorly understood, and less so by the divertor geomety. *If this is the principal factor, then the divertor geometry may have little effect on ELMy H-mode physics, even for deep, well baffled divertors.*

Despite the problems with ELMs mentioned above, the ratio of neutral pressure in the subdivertor volume to that in the inner and outer midplanes (time-averaged through the ELMs) increased from Mk I to Mk IIA, and again in Mk IIAP when the leaks were plugged (Fig. 3). The second increase was due principally to reduced main chamber neutral pressure. Studies of directly comparable discharges in Mk IIA and Mk II AP, however, showed that the confinement quality (e.g. as measured by H_{97}) did not improve (Fig. 4). These two pulses had identical field, current, input power, and gas fuelling rates. They produced identical densities and divertor neutral pressures, but the Mk IIAP pulse had lower neutral pressure at both inner and outer midplane. Nevertheless, the confinement quality was the same for both. Examination of the full steady state H-mode Mk IIA-Mk IIAP database suggests that the confinement is more closely linked to the SOL density and divertor neutral pressure than to the midplane neutral pressure [1].

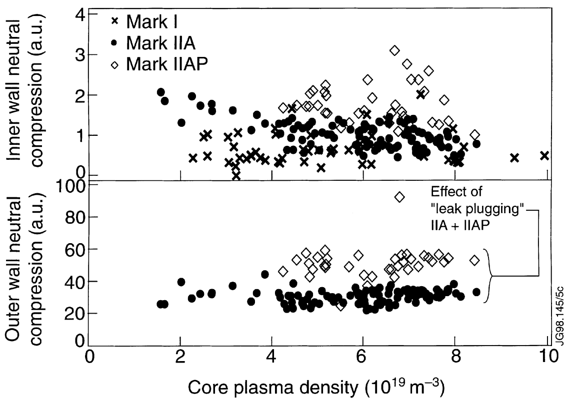

Fig. 3. Neutral compression ratio at the inner target (arbitrary units) and outer target, ELMy H-modes.

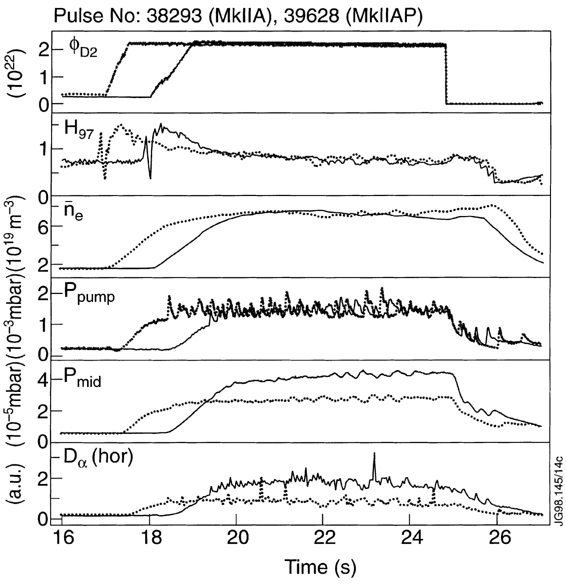

Fig. 4. Comparison of two ELMy H-mode pulses in Mk IIA and Mk IIAP showing non-dependence of confinement on midplane neutral pressure.

Fig. 5 shows the measured ELM-averaged Z_{eff} from intrinsic impurities for non-seeded ELMy H-modes in Mk I and Mk IIA. For CFC targets there is almost no difference, presumably for reasons similar to those discussed in Section 2. The cleanest plasmas were obtained with Be targets in Mark I. More details on the behaviour of intrinsic impurities in JET are given in [3]. The maximum radiated power fraction which could be achieved by addition of nitrogen or neon to the H-mode discharges appeared to decrease systematically in going from Mk I → Mk IIA → Mk IIAP, from roughly 80–75–65%, as shown in Fig. 6. There is some indication that the reduced photon radiation fraction is offset by an increase in neutral particle losses in the divertor, although this effect has not been made quantified [16].

The subject of detachment in ELMy H-modes is quite complicated and is discussed in a companion paper by McCracken et al. [17]. Although it was possible to achieve full detachment between ELMs with puffing of D_2, or D_2 plus N_2 or Neon [18], full detachment was always accompanied by high frequency, small amplitude Type III ELMs and low confinement quality, insufficient for ITER's needs. For pulses with Type I ELMs and good confinement, detachment was totally absent at the outer target, and very slight on the inner one. There was no measurable difference in the density for the onset of detachment in H-modes between Mark I and Mark IIA.

When the gas puff is increased from pulse to pulse in an ELMy H-mode gas scan at fixed power, field, cur-

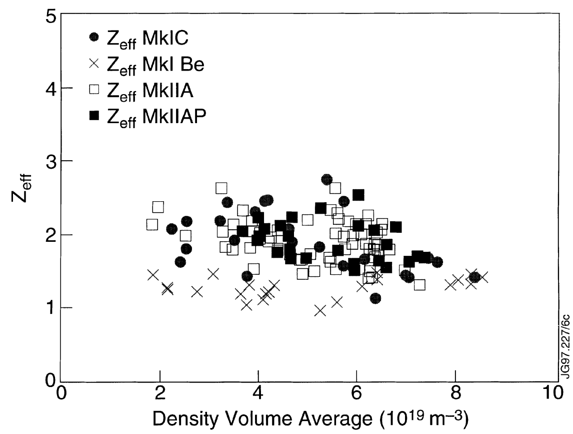

Fig. 5. Z_{eff} vs. density for ELMy H-modes in Mk I and Mk IIA on CFC and Be targets.

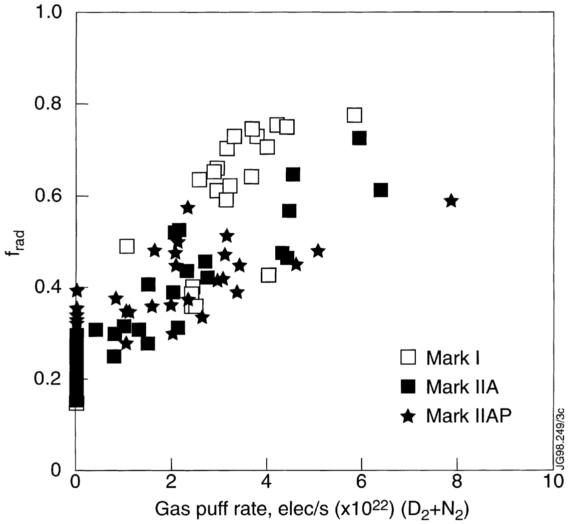

Fig. 6. Radiated power fraction achieved in seeded and non-seeded ELMy H-modes, as function of total gas puffing rate, for Mk I, Mk IIA, and Mk IIAP.

rent, and configuration, the density first increases and then eventually decreases [19]. Simultaneously the ELM frequency increases, the amplitude decreases, and the confinement degrades. The maximum density attained is the same in Mk I (CFC) and Mk IIA within error bars, although Mk I with Be targets reached slightly higher densities. Of more importance for performance, however, is a normalized Lawson product, $(n_e\tau_E/n_{GW}\tau_{E,97})$, where n_{GW} is the Greenwald density limit. Fig. 7 shows this figure of merit plotted against normalized density,

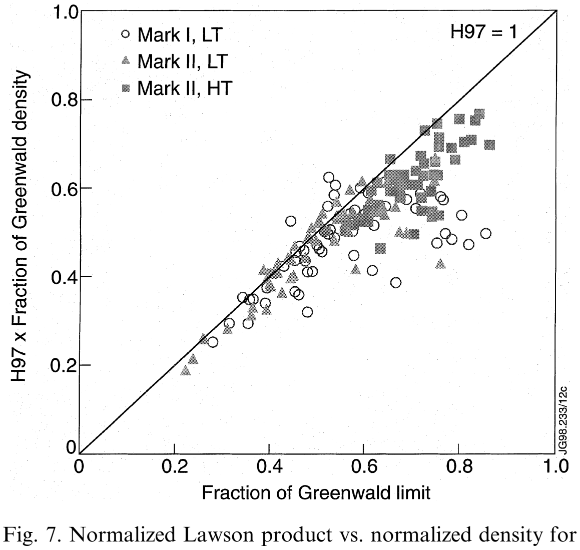

Fig. 7. Normalized Lawson product vs. normalized density for non-seeded ELMy H-modes, differentiated by triangularity and divertor configuration.

n_e/n_{GW}. If there were no confinement degradation with increasing density, all the points would lie on the line labelled $H_{97} = 1$. It can be seen that this trend is followed up to a certain normalized $n\tau$, beyond which saturation begins. This level is the same in Mk I and Mk IIA for a fixed triangularity. As the triangularity was raised (Mk IIA only), this figure of merit improves, but still falls well short of the value required by ITER, which is roughly $H_{97} = 1$ at $n_e = 1.15\ n_{GW}$. However, raising δ reduces the ELM frequency, increases their amplitude, and raises the C content and Z_{eff} of the discharges [3].

It has also been observed that confinement degrades at high radiated power fractions, and the question arises as to whether this degradation was simply a result of the high density edge, or was an additional effect. Fig. 8 again shows $(n_e\tau_E/n_{GW}\tau_{E,97})$ vs. n_e/n_{GW}, this time for low triangularity only pulses in the three divertor configurations. In this figure the solid symbols are seeded pulses with $f_{rad} > 0.5$, while the open symbols are unseeded pulses with less radiation. It can be seen that at any given density, the confinement of the seeded pulses is worse than that of the unseeded ones, although they tend to converge at the highest density levels. Finally, it was reported in [20] that the L → H power threshold is the same, within error bars, for horizontal targets in Mk I, Mk IIA, and Mk IIAP. However, further analysis using an enlarged database suggests that the threshold is significantly lower in Mk IIAP than in Mk I, with Mk IIA in between [1].

In summary, closure to neutrals was improved in going from Mk I to Mk IIA and then further in Mk IIAP, as evidenced by reduced main chamber neutral pressure at both the inner and outer midplanes. Nevertheless, H_{97} did not improve, nor did Z_{eff} (intrinsic) reduce. Detachment between ELMs was similar in all

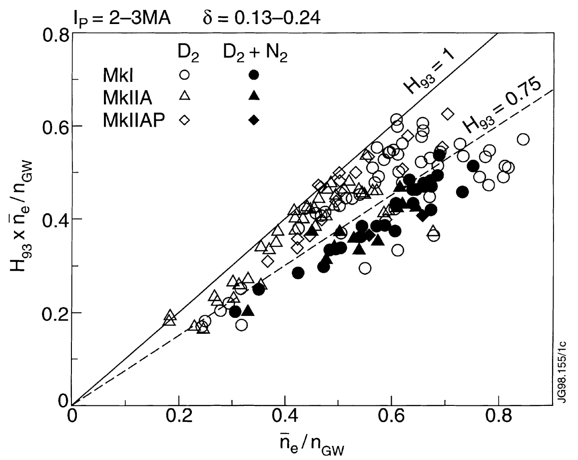

Fig. 8. The same variables as Fig. 7, for low triangularity pulses, seeded (solid symbols) and unseeded (open symbols).

divertor geometries, and only occurred under conditions of strongly degraded confinement. The density limit, n_e τ_E product, and L → H threshold were all unchanged.

4. Comparison of horizontal (dome) and vertical targets in Mk IIA

Because the ITER divertor design incorporates strongly inclined "vertical" targets to produce large wetted area and promote detachment at the separatrix to reduce peak power loading, an extensive comparison of horizontal vs. vertical target performance was carried out. In L-mode studies it was found that vertical target detachment did originate near the separatrix, while for the slot-like operation on the dome ("horizontal targets") it tended to begin away from the separatrix [7], and these findings have been duplicated in 2D edge simulations [12]. In "horizontal" targets in Mark I, which are more orthogonal to the poloidal flux surfaces than those of pulses in Mk IIA on the dome, detachment usually began near the separatrix [9]. There is insufficient data on detachment for H-modes to tell whether the same differences between horizontal, dome, and vertical targets arise.

The normalized n_e τ_E product vs. normalized density for ELMy H-modes appears to be similar, for high triangularity discharges in Mk IIA, for horizontal and vertical targets, and slightly better for horizontal targets for low triangularity, and the degradation of confinement in seeded discharges is likewise similar. With respect to intrinsic impurities, the vertical targets seem to be slightly better at high triangularity, but this difference disappears at low δ.

One of the more conspicuous differences between horizontal and vertical targets arises with respect to midplane separatrix and pedestal densities measured between ELMs [21]. In both cases, the ratio of separatrix density to line-averaged density increases fairly rapidly with increasing gas puff rate at fixed triangularity, for which the ELM frequency also increases monotonically. The ratio of pedestal density to line averaged density remains approximately constant. For the vertical targets, both the separatrix and pedestal density ratios are smaller than in the horizontal target case, as shown in Fig. 9. That is, for a given ELM frequency/gas puff rate, the vertical target produces lower density, thinner SOL's and slightly lower pedestal densities. There is some evidence that the L → H power threshold is somewhat higher for vertical targets than for horizontal, although the database is so far very sparse.

Experiments on He enrichment show that enrichment is slightly lower with vertical targets than horizontal as long as the divertor plasma remains attached, but the differences appear to diminish, in L mode, at high densities [22].

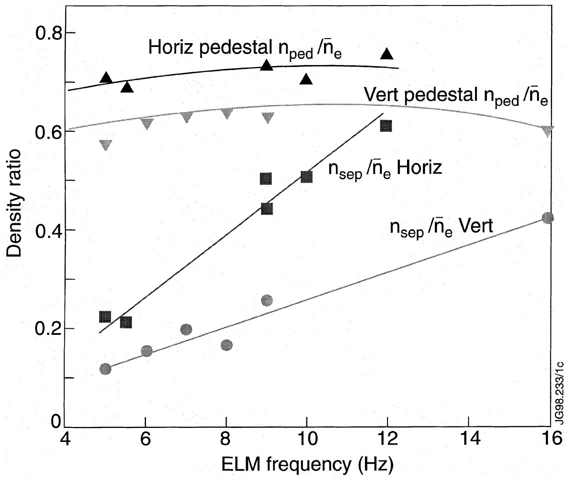

Fig. 9. Variation of midplane separatrix and pedestal density ratios for high triangularity ELMy H-modes on horizontal and vertical targets.

5. Discussion: Is a deep divertor necessary for a next step tokamak?

A deep, well baffled divertor such as the ITER design, where the poloidal distance from X-point to strike point is about 2 m, will probably work effectively, based on studies presented above. However, it requires a considerable amount of space and is a complicated and expensive structure. The question then naturally arises as to whether a less expensive, shallow pumped divertor might work satisfactorily in a Next Step tokamak.

In the ITER power exhaust scheme only 50 MW should reach the targets by direct plasma energy deposition [23]. The sum of α particle power plus auxiliary heating power (driven mode), less bremmstrahlung, will range from 200 to 300 MW, implying a radiated power fraction, relative to power flowing through the edge, of 75–83%. In JET discharges, it is always observed that a MARFE forms at the X-point when f_{rad} exceeds about 55%. If this were to occur in the ITER divertor, nearly all of the divertor volume would effectively be unused, and there seems little reason to retain it.

Under these conditions of high f_{rad}, confinement quality is poor and probably unsatisfactory for ITER. However, it has been predicted to be possible to operate with more power on the plates in a semi-detached mode and thus avoid the X-point MARFE, and still limit the time-averaged peak heat loads to acceptable values [24,25]. Under this scenario, a shallow divertor would have to perform the same functions as a deep one. The first question is that of wetted target area. A large area can be readily achieved by placing the X-point fairly close to the divertor floor, taking advantage of the large flux expansion near the X-point. The achievable target area depends ultimately only on the chosen angle of incidence of field lines and target, and is usually limited by technical considerations [26]. The question of detachment appears more subtle, but JET did produce detached highly radiating discharges in an open divertor X-point configuration in 1992 [27], and DIII-D has reported similar results [28]. Experiments with low X-point horizontal target detached H-modes in Mk I showed detachment initiating at the separatrix, where it is most effective in reducing peak power loads [9], suggesting such detachment patterns in open divertors are attainable. Under these partial detachment conditions, neutral escape to the main chamber should remain very small due to the very thick SOL near the X-point, and pumping through private flux region ducts should be efficient. The main remaining issues for the shallow divertor concept are thus the escape of neutral deuterium and impurities directly from the PF region into the core plasma through the X-point.

In an effort to compare (geometrically) open and closed divertors quantitatively, we have begun a series of simulations to predict performance on the top (open) target tiles in JET, with the Mark IIA divertor, using equilibria from actual pulses. The simulations were carried out with pure plasmas using the transport model which describes JET ELMy H-mode pulses between ELMs [29], but without pumping, since there is no pump at the top of JET. The wetted target area is somewhat larger for the open divertor case, for this choice of X-point height (limited at the top of JET by the poloidal coil system). In these preliminary simulations the Mk IIA configuration develops slightly higher target-integrated plasma particle flux and detaches slightly on the inner leg, while the open configuration showed less detachment. The Mk IIA case had a higher total leakage of neutrals to the main chamber, but this resulted primarily from bypass leakages, even in the "plugged" case. (Total elimination of bypass leakage in closed divertors is very difficult.) The open divertor configuration produced considerably lower peak power densities and a more symmetric power distribution on the plates. More simulations are underway, to investigate in particular the dynamics of intrinsic and seeded impurities. The work carried out so far, however, is sufficiently promising to justify serious consideration of open divertors as a viable alternative to deep, closed divertors.

6. Conclusions

JET has carried out a series of experiments in Mk I and Mk IIA to assess the influence of divertor geometry on divertor and core plasma performance. Further work on both more closed (Mark IIGB) and more open (Top X-point) configurations is planned for the experimental campaign beginning in Summer of 1998.

In the studies completed so far, it was found that in non-ELMy (Ohmic and L-mode) pulses, the effects of closure were distinct and generally in agreement with theoretical predictions. An exception was the failure of Z_{eff} (intrinsic) to be reduced, which is believed to result from a number of factors discussed in this paper. In quasi-steady ELMy H-modes, the divertor geometry had little effect on global performance parameters such as density limit and confinement quality. Again, the intrinsic impurity level did not reduce. The maximum radiated power fraction which could be achieved in seeded discharges diminished with increasing closure. A specific comparison of vertical and horizontal target operation in Mk IIA showed similar behaviour in most of the global performance parameters. However, the vertical targets resulted in lower pedestal and midplane separatrix densities and thinner SOLs. The L $\rightarrow$ H threshold appears to be higher on the vertical target, but there is insufficient data to establish a firm conclusion.

A geometrically open, shallow pumped divertor would save space and money in a next step tokamak. It is not yet clear whether or not such a divertor would perform as well as a deep divertor, but arguments were presented to suggest that it might, and that this option should therefore be carefully re-assessed in the attempts to scale down ITER.

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