RECENT RESULTS FROM DIVERTOR AND SOL STUDIES AT JET

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Abstract

Recent progress in the study of divertor and scrape-off layer plasma (SOL) phenomena in JET is reviewed. Up to the present time, three pumped divertors (Mark I, Mark IIA/AP and Mark IIGB) have been installed and exploited under reactor relevant conditions. With increased divertor closure, it is found that the particle exhaust rate has increased and neutral compression factors of >100 are obtained with the Mark IIGB divertor. Helium enrichment factors of >0.2 are measured under a wide range of conditions and satisfy the minimum requirements for ITER. Fast infra-red camera measurements show broad deposition profiles during type I ELMs and energy densities of ~0.12MJm^{-2}. During the recent D-T experiments, the codeposition of tritium on cold shadowed surfaces in the inner divertor has been identified as an important form of long-term tritium retention. This has serious implications for the divertor design and tritium inventory in a next-step tokamak. Core plasma purity has not improved with enhanced divertor closure or decreased main chamber neutral pressure. Studies of the chemical sputtering yield have shown a dependence on surface temperature and hydrogen isotope. This accounts for the observation of increased impurity production and lower disruptive density limits in Mark II (at 500K) compared to Mark I (at 300K). Significant progress has been made in the study of divertor detachment, and volume recombination has been spectroscopically identified. With increasing isotope mass, detachment and the disruptive density limit occur at lower main plasma density as predicted by the EDGE2D/NIMBUS codes. Using differential gas fuelling in the Mark IIGB divertor, it has been possible to modify the in-out asymmetry of the divertor plasma for the first time.

1. INTRODUCTION

Over the last five years, JET has pursued a coherent programme to investigate the influence of divertor geometry on plasma performance under reactor relevant conditions. The four single-null pumped divertor configurations are outlined as follows :

- Mark I (1994-1995) : Open divertor configuration which allows a flexible magnetic geometry.
- Mark IIA (1996-1997) : Moderately closed divertor with enhanced power handling.
- Mark IIAP (1997-1998) : Modified Mark IIA divertor with plugged neutral leakage paths.
- Mark IIGB (1998-1999) : Highly closed ITER specific “Gas Box” geometry with septum.

With each successive configuration the width of the divertor entrance has decreased. Under high recycling conditions, this is anticipated to enhance the “closure” (i.e. the fraction of recycling neutrals ionised within the divertor region). This has several advantages with respect to (a) increased divertor neutral pressure and particle exhaust, (b) easier access to radiative/detached regimes thus reducing the divertor power loading, and (c) lower main chamber neutral pressure which may reduce wall sputtering and, more speculatively, improve the confinement quality. However, there may be drawbacks from the interaction of ELMs with the narrow divertor entrance and poorer impurity retention due to reduced parallel flows. Furthermore, due to the chemical sputtering of carbon, target plate erosion may not be reduced and this has important implications for the divertor lifetime and tritium retention.

In this paper we present an overview of recent progress in the study of divertor and SOL physics at JET. Emphasis is placed upon the effect of the divertor configuration on core and edge plasma phenomena. We also present new results from the recently installed Mark IIGB divertor, which are compared with observations from its Mark I, Mark IIA and Mark IIAP predecessors.

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[1] see Appendix to IAEA-CN-69/OV1/2, The JET Team (presented by M.L. Watkins)

2. POWER AND PARTICLE EXHAUST

Effective particle exhaust in next-step tokamaks is necessary to control the plasma density and remove helium ash. One of the most significant effects of increasing the divertor closure in JET has been to increase the exhaust rate for deuterium and recycled impurities [1]. The pumping speed is proportional to the neutral pressure in the volume below the target (subdivertor) and is plotted in fig. 1 as a function of the main plasma density for L-mode discharges. The improvement in pumping with divertor closure can be clearly seen, the new Mark IIGB divertor having a two-fold enhancement over Mark IIAP. Similar, albeit weaker, trends are observed during steady-state ELMy H-mode discharges. This is probably due to the presence of ELMs which cause recycling outside the divertor chamber and/or variations in the proportionality between the separatrix and line averaged density [2] which complicate such comparisons. No difference in the divertor pressure was observed between Mark IIA and Mark IIAP and has been omitted from the plot for clarity. In all cases, the subdivertor neutral pressure is relatively insensitive to the strike point position and a factor of two variation can only be obtained with excursions of 10-20cm from the pumping slot (plenum). The weak dependence of the pumping speed on the strike zone position and factor of two to three enhancement from Mark I to Mark IIA/AP was predicted by EDGE2D/NIMBUS [3] simulations and is a result of multiply scattered neutrals [4].

In parallel with obtaining high divertor neutral pressures and pumping speeds, it is desirable to minimise the main chamber neutral pressure. The motivation for this is to prevent sputtering by charge-exchange neutrals and possibly improve the H-mode confinement quality. For this purpose, the compression may be used as a figure of merit and is defined here as the ratio of the subdivertor pressure to the pressure measured at the outer midplane of the main chamber. This is plotted in Fig. 2 as a function of the main plasma density for L-mode discharges. One can see that the compression has increased with closure and we now obtain factors in excess of 100 with the Mark IIGB divertor. These observations are also reproduced in ELMy H-mode discharges. Unfortunately, no calibrated main chamber pressure measurements are available for the Mark I divertor. The characteristic roll-over of the compression that is seen in Fig. 2 at main plasma densities of 2.4-2.8x10^{19}m^{-3} is associated with the onset of detachment, during which the mean free path of the neutrals increases and escape from the divertor. In going from Mark IIA to Mark IIAP, the actual geometry remained unchanged but leakage paths (by which neutrals could directly pass between the divertor and main chamber) were blocked. The increased compression of Mark IIAP was almost entirely due to a reduction in main chamber pressure. However, no improvement in the confinement quality or plasma purity of ELMy H-modes was seen [5]. In the case of the Mark IIGB divertor, the enhanced compression is achieved by an increased divertor pressure at similar main chamber pressure.

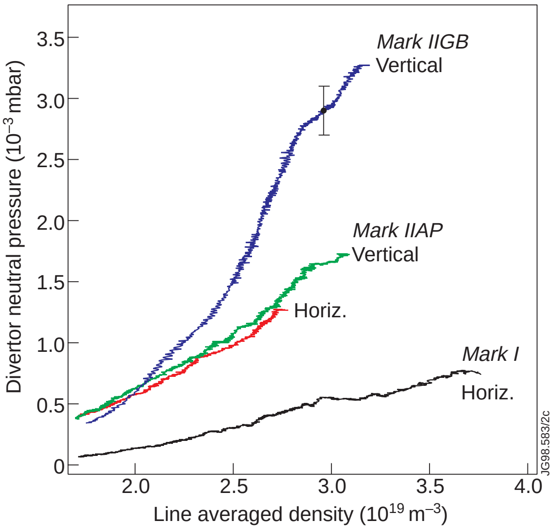

Fig. 1 : Divertor neutral pressures (and thus pumping speeds) for L-mode discharges in the Mark I, Mark IIAP and Mark IIGB divertors.

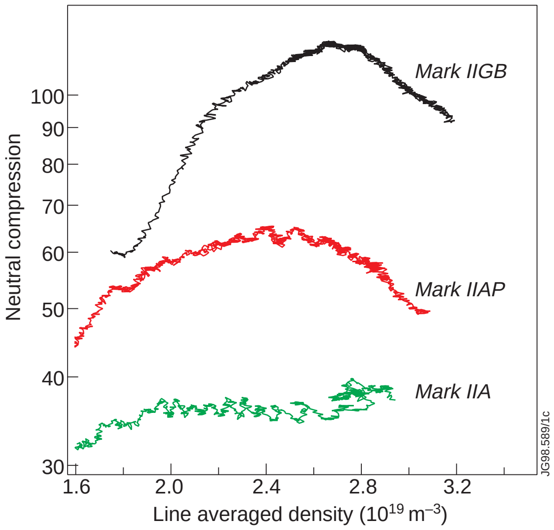

Fig. 2 : Comparison of the divertor neutral compression for L-mode discharges in the Mark IIA, Mark IIAP and Mark IIGB divertors.

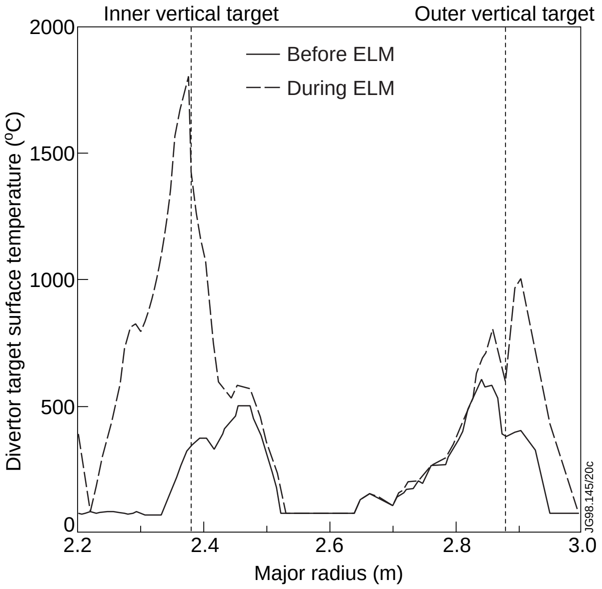

Fig.3 : Variation of the divertor surface temperature before and during an ELM.

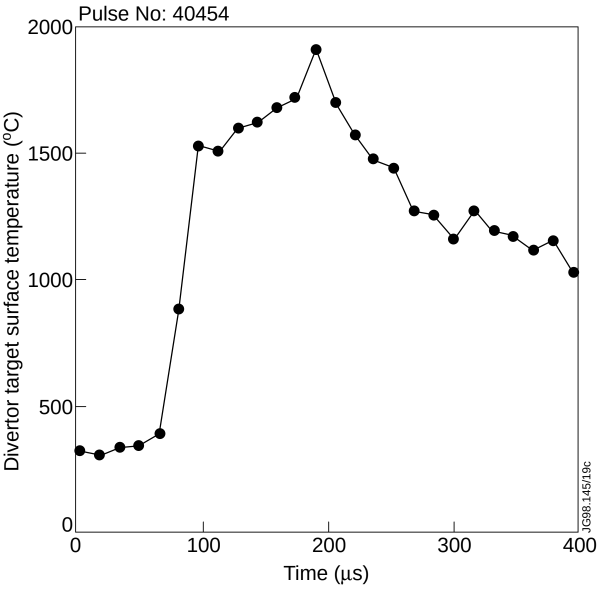

Fig.4 : Temporal evolution of the peak divertor target temperature during an ELM event.

In general, it would appear that the main chamber pressure (in the absence of external fuelling) is sufficiently low for all the JET pumped divertor configurations to not adversely influence the confinement quality or plasma purity.

Helium enrichment studies have been performed under L- and ELMy H-mode conditions in the Mark IIAP divertor [6]. These experiments were carried out by injecting helium into the discharge and deriving the enrichment (η) from the ratio of the partial pressure in the subdivertor volume to the core plasma concentration. In each case, the enrichment was measured with the divertor strike zones in three distinct positions : Horizontal target (H), Corner (C) and Vertical target (V). Under L-mode conditions the enrichment has values in the range of η=0.2-0.6 and depends upon the strike zone position with the ratio 0.5 (H):1(C):0.35(V). The enrichment is also observed to consistently decrease with increasing main plasma density. In ELMy H-mode discharges, the enrichment is observed to be less sensitive to the main plasma density with values in the range η= 0.2-0.5 compared with the ITER requirement of >0.2 [7].

Currently, one of the most critical issues for ITER is the peak divertor power loading during ELM events. For the first time on JET, it has been possible to evaluate the power flux during ELMs using a fast (13µs) infra-red camera system [8]. Broad profiles of the divertor surface temperature distribution are measured after each Type I ELM (Fig. 3) which is attributed to simultaneous broadening and displacement of the strike points. In most cases, the peak power deposition occurs at the inner divertor and has a typical duration of 120±20µs (Fig. 4). To account for the presence of surface layers with unknown thermal properties (section 3), an energy based calculation is used to infer energy densities of ~0.12MJm^{-2} which are consistent with the stored energy loss from the plasma [8]. In order to scale these results to ITER, it is assumed that the deposited energy is a fixed proportion of the plasma stored energy, the interaction area scales with the major radius and that the time duration of the ELM is independent of the machine size [1]. Using the typical example described above, the energy deposition per ELM in ITER would be ~8MJm^{-2} which, for a time duration of 100µs, is considerably higher than the acceptable threshold of 0.4 MJm^{-2} for strong evaporation of the target [7]. Furthermore, these energy losses are significantly higher during the low frequency ELMs associated with highly shaped discharges [9]. In summary, these results highlight the incompatibility of the Type I ELMy H-mode regime with the current ITER operating requirements. Promising results have, however, been obtained using shallow pellet injection in JET to increase the ELM frequency and consequently reduce the peak power deposition [10].

3. LONG TERM TRITIUM RETENTION

The JET Deuterium Tritium Experiment (DTE1) provided a unique opportunity to study hydrogenic isotope recycling and retention in an ITER relevant divertor configuration. Due to the safety implications, long-term tritium retention has emerged as a potentially serious constraint to continuous reactor operation and will strongly influence the choice of divertor and first-wall materials [11]. By monitoring the tritium inventory, it was possible to identify two forms of retained tritium: (a) a dynamic inventory which is consistent with existing wall implantation models [12,13] and, (b) a continually growing long-term inventory of unknown origin. The evolution of the long-term inventory is shown in Fig. 5 and is inferred from the difference between the actual inventory and that predicted by a diffusion based model [12]. Conventional detritiation methods were found to be ineffective and by the end of the campaign 6g of tritium (out of 35g injected) remained in the vessel [14]. To model the long-term tritium inventory, one has to assume that a fixed fraction of the divertor ion fluence (1.7%) or gas input (14%) is retained.

Since the long-term retention of tritium was not observed during the 1991 JET Preliminary Tritium Experiment (PTE), it was suspected that the presence of the pumped divertor was responsible. Earlier surface analysis of Mark IIA divertor target tiles had shown the presence of films and flakes of up to 40μm in thickness which are saturated with deuterium (D/C ratio of >0.4) [15]. These deposits are present on the inner divertor pump louvres which are shadowed from a direct line of sight with the plasma and have a low (~40^{o}C) ambient temperature. It is clear that these cold shadowed regions introduce a sink from which carbon cannot be re-eroded or sublimated. Such regions were not present during the PTE which had a completely open divertor configuration at high ambient temperature. Remote video inspection of the divertor target after the DTE1 experiments revealed the presence of similar deposits and it is evident that these contain a significant proportion of the retained tritium. This has important implications for the design of divertor targets in next step tokamaks such as ITER.

One possible source of the carbon flakes observed on the louvres is sputtering from the inner divertor target. Assuming that the carbon atoms are emitted from the target with a cosine distribution, ~20% of the particles are expected to enter the pumping slot. However, their arrival at the louvres implies a mean-free path of the order of several centimeters. Given the estimated total carbon content of the flakes from samples analysed prior to the DTE1 experiments (~$2x10^{25}$) and the ion fluence to the inner divertor (~$2.5x10^{26}$) this also implies an effective sputtering yield of 40%. Such values are very high compared to the typical yields of 1-4% observed in JET (section 4) and suggests that conventional ion induced sputtering is not responsible. Possible mechanisms to enhance the yield include neutral particle impact and main chamber sputtering [16]. However, the absence of deposition on the outer divertor louvres cannot be easily explained. Dedicated experiments and modelling are underway to understand the physics of the codeposition process and investigate the effect of different operating regimes (i.e. ELMy versus non-ELMy).

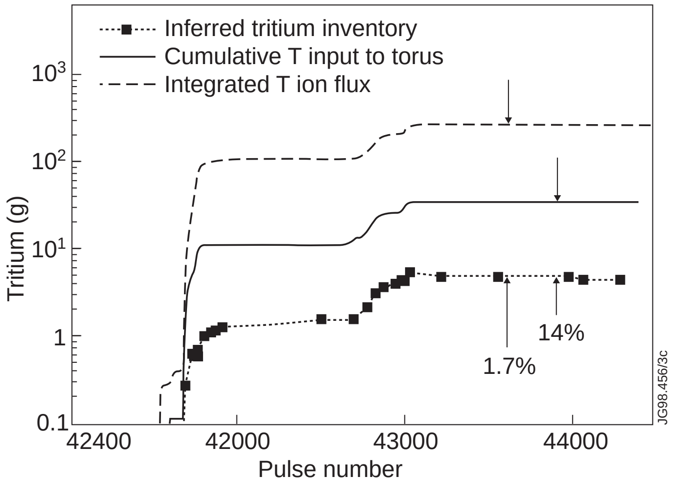

Fig. 5 : Inferred long term tritium inventory from the difference between the actual and predicted values.

4. INTRINSIC IMPURITY BEHAVIOUR

Detailed studies of the intrinsic impurity behaviour have been carried out for the Mark I, Mark IIA and Mark IIAP divertors [17]. The plasma purity (Z_{eff}) of steady-state ELMy H-mode discharges is shown in Fig. 6 for all the JET divertor configurations including the Mark I with beryllium (Be) divertor target. The impurity content is surprisingly independent of the divertor configuration and main plasma density. Only in the case of the Mark I beryllium target is there a clear reduction of the core Z_{eff} which highlights the role of the divertor impurity source. Similar trends are obtained from core charge exchange spectroscopy, which indicate that carbon is the dominant impurity with concentrations in the range of 1-4% [1]. Contrary to expectations, the Z_{eff} in the Mark IIAP divertor did not reduce with respect to Mark IIA despite the decrease in main chamber neutral pressure. However, this comparison is somewhat complicated by a simultaneous increase in the carbon coverage of the inner wall. First results from the Mark IIGB divertor (Fig. 6) indicate that the Z_{eff} is comparable to the previous divertor configurations. In accordance with expectations, increased divertor closure acts only on neutrals and does not appear to improve the screening of ionised impurities from the core plasma.

Over a wide range of plasma conditions it was found that the impurity production from the divertor target increased in the Mark IIA/AP divertor with respect to Mark I [18]. This is attributed to an increased chemical sputtering yield from ~2% to 4% [19]. An important difference between the two divertor configurations is the divertor tile temperature of ~500K in Mark IIA/AP compared to ~300K in Mark I. To investigate the role of the target temperature, dedicated experiments were carried out in which the Mark IIAP divertor temperature was reduced from 500K to 330K. In the discharges at low wall temperature, the core carbon concentration was reduced by ~40% and the L-mode density limit increased by ~20%. An example of the outer divertor chemical yields at three target temperatures is shown in Fig. 7. These yields are inferred from a combination of CD band emission and probe measurements which are calibrated from methane injection experiments [19]. It is evident that for impact energies of <60eV the chemical yield is reduced at the lower target temperature. An additional observation is that the chemical yield appears to be reduced at high fluxes (i.e. $>2x10^{22}m^{-2}s^{-1}$) and is a function of the target temperature with a dependence of $\Gamma^{-0.4}$ at 500K and $\Gamma^{-1.25}$ at 300K [18]. It should, however, be stressed that these flux dependencies depend upon the assumptions used to infer the methane production rate from the spectroscopic measurements. In addition, these results imply that any such flux dependence may be negligible at the relatively high divertor surface temperature (~1500K) [11] of ITER.

In order to study isotope effects over the widest range, a period of operation in hydrogen was carried out after the DTE1 experiments. A clear isotope dependence of the chemical sputtering yield was observed with a yield roughly proportional to mass [19]. These results indicate that the chemical yield is influenced by thermal reaction processes which are enhanced by radiation damage [20].

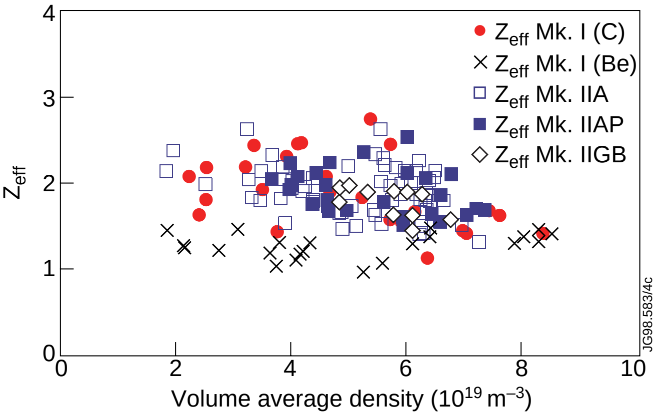

Fig. 6 : Core plasma Z_{eff} for ELMy H-modes in the various JET divertor configurations.

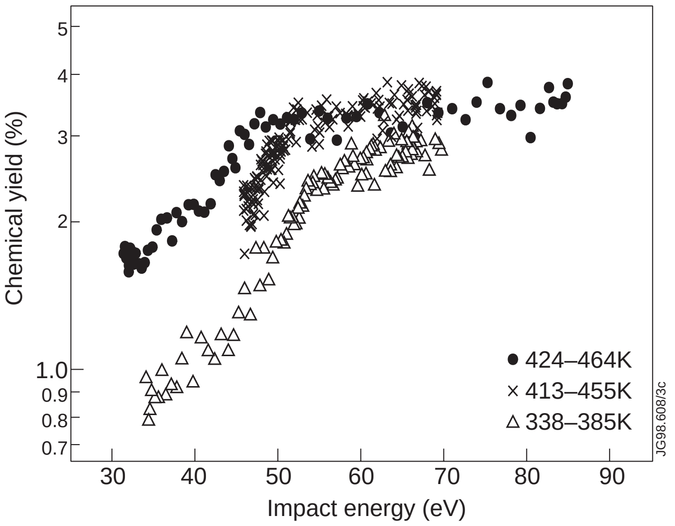

Fig. 7 : Measurements of the outer divertor chemical sputtering yield for different target temperatures in the Mark IIAP divertor.

5. DETACHMENT AND DISRUPTIVE DENSITY LIMITS

Recent spectroscopic studies have highlighted that volume recombination is associated with the detachment process in JET [21]. The ratio of the Balmer series lines D_γ/D_α are used to identify the onset of volume recombination and is correlated with the reduction of the divertor ion flux. While the divertor temperature derived from the Langmuir probes during detachment is ~2eV, the population of the excited states indicates 0.8±0.1eV. With increased divertor closure the onset of volume recombination and divertor detachment is found to occur at lower main plasma density. This is also reflected in the reduction of the L-mode disruptive density limit shown in Fig. 8 (defined at the “maximum density”)[22]. In all divertor configurations, a weak power dependence of approximately $P_{net}^{0.2}$ (where $P_{net}=P_{in}-R_{rad}$) is observed. As discussed in the previous section, it appears that the lower disruptive density limit of Mark IIA/AP compared with Mark I is mostly due to increased divertor impurity production from the divertor as opposed to increased closure. This argument is supported by the observation that similar density limits are observed between the Mark IIA/AP and Mark IIGB divertors Fig. 8) which have different degrees of closure but similar tile temperatures.

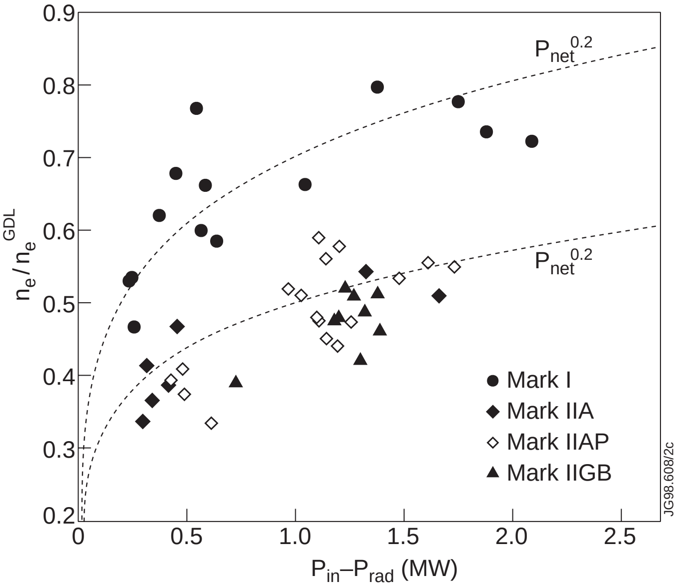

Fig. 8 : Comparison of disruptive density limits as a function of net input power for the various JET divertor configurations.

Clear effects of divertor geometry have been observed from the comparison of horizontal and vertical target operation in Mark IIA/AP [23]. An early onset of detachment is observed at the corner of the inner divertor for horizontal target discharges. This “off-separatrix” detachment was predicted by B2-EIRENE simulations which show that the corner region efficiently traps neutrals and promotes volume recombination [24]. Such effects are not observed for the vertical target where detachment begins at the separatrix. More symmetric detachment between the two divertor legs is observed for operation with the vertical target plates in both the Mark I and MarkIIA/AP divertors. Studies of the detachment and the disruptive density limit have also been carried out in the Mark IIA/AP divertor with pure H, D and T discharges [22]. These are found to scale inversely with the ion mass in vertical target configurations, while no isotope effect is observed for the horizontal target. The isotope effect in the vertical target is reproduced by EDGE2D/NIMBUS numerical simulations [22].

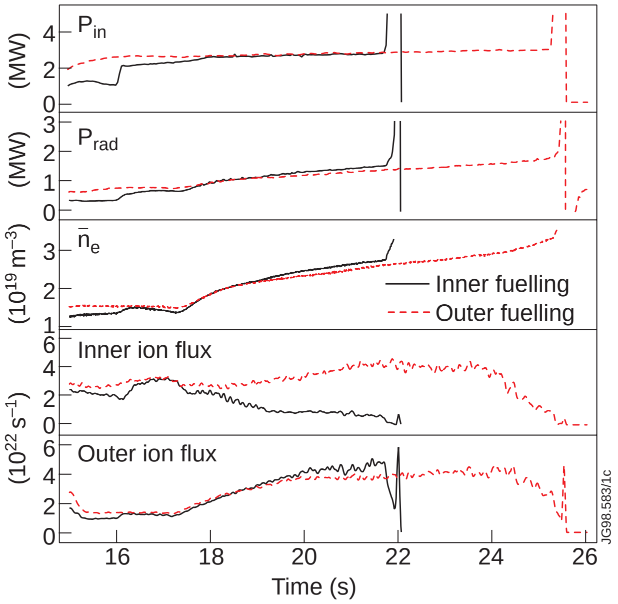

Fig. 9 : Comparison of Mark IIGB discharges in which the differential gas fuelling is used to modify the asymmetry of the divertor plasma parameters.

Using the new Mark IIGB it has been possible to use differential deuterium fuelling to modify the in-out asymmetry of the divertor plasma parameters for the first time in JET. Unlike its predecessors, the Mark IIGB divertor has a septum structure which separates the inner and outer divertor regions. An example of an L-mode discharge is shown in Fig. 9 for which inner divertor fuelling causes an early onset of detachment and the density limit. In contrast, fuelling into the outer divertor produces more symmetric ion fluxes to each divertor. Similar trends are seen in the distribution of energy deposited to each strike zone. These experiments highlight that the disruptive density limit is governed by the onset of complete detachment (i.e. DOD>5) at the inner divertor [22]. Further analysis is in progress to establish the effects of differential gas fuelling in ELMy H-mode discharges.

6. SUMMARY AND CONCLUSIONS

In this paper the recent progress in the study of divertor and scrape-off layer plasma phenomena in JET is reviewed. With increased divertor closure, efficient particle exhaust is obtained and compression factors of >100 are obtained with the new Mark IIGB divertor. During type I ELM events, fast infra-red camera measurements are used to derive energy densities of ~0.12MJ m^{-2} which scale to unacceptably large values for ITER. During the recent D-T experiments, the codeposition of tritium in shadowed regions of the inner divertor has been identified as a mechanism for long-term tritium retention. Conventional ion induced sputtering processes cannot account for the magnitude or the asymmetry of the codeposited films. Studies of the core plasma purity show little dependence on the divertor configuration except with beryllium target plates in Mark I. In accordance with expectations, increased divertor closure does not appear to improve the screening of impurities from the core plasma. Reduction of the wall and divertor temperature have confirmed that the increased impurity production of Mark IIA/AP with respect to Mark I is due to the elevated surface temperature. The reduction of the disruptive density limit from Mark I to Mark IIA/AP/GB is also attributed to the increase in divertor impurity sources rather than the divertor closure. Studies of the chemical sputtering yield have shown a dependence on incident flux and isotope. Spectroscopic measurements have been used to identify volume recombination and is associated with the onset of plasma detachment. With increasing isotope mass, detachment and the disruptive density limit occur at lower main plasma density as predicted by numerical codes. In the Mark IIGB with the septum, differential gas fuelling has been used to modify the in-out asymmetry of the divertor plasma for the first time.

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