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physics in JET pure He and D  
discharges**

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**Divertor detachment during pure  
Helium plasmas in JET**

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## Comparing scrape-off layer and divertor physics in JET pure He and D discharges

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### Abstract

Though Helium plasmas are one option for the low activation phase of ITER, little effort has thus far been devoted to studying them in a large, diverted tokamak. A recent campaign on JET has therefore sought to address some of the important questions related to helium operation (He concentrations near 90%) in single null configurations, particularly with regard to edge and divertor physics. This contribution compiles a selection of results from these experiments, in which, in each case, discharges have been chosen to match as closely as possible previous, well characterised D plasmas in both L and ELMing H-modes. These matched pulses are used to draw conclusions regarding the principle source and location of carbon production in D plasmas, to compare and contrast the mechanisms of the density limit and the detachment process in D and He, to investigate the nature of cross-field power transport in the SOL and to gain insight into the process by which ELM energy is transported to the divertor targets.

## 1. Introduction

Operation in helium is considered as one option for the low activation phase of ITER. To date, however, with the exception of a short campaign on the DIII-D facility [1], pure helium plasmas have constituted a negligible fraction of discharges executed in large diverted tokamaks. In a graphite containing machine (as presently foreseen for ITER [2]), the absence of carbon chemistry in a pure He plasma is expected to significantly modify the source of impurity production. The recycling nature of He compared with D and the significant differences in He atomic physics might be expected to strongly influence global particle balance, SOL transport, divertor physics, density limits and perhaps ELM transport in the edge plasma. With these key issues in mind, together with the important aspects related to the L-H transition threshold and energy confinement, an extended series of pure He experiments has recently been performed on JET. This contribution compiles some of the more important edge and divertor physics observations resulting from this campaign. Companion papers providing more detail may be found within these proceedings and are appropriately referenced in the text.

## 2. Experiment and diagnostics

A total of over 100 JET pure He discharges have been dedicated to the study of edge physics issues, following a programme closely matching previous pulses in D for comparative purposes. A large majority of experiments are conducted in one of two single null lower equilibria with high or low wall clearance (Fig.1) frequently used at JET (all with the  $B \times \nabla B$  drift direction towards the X-point). All have been performed in the Mark IIIGB divertor configuration with wall temperature at 200°C (some comparison D pulses were at higher  $T_{\text{wall}} = 320^\circ\text{C}$ ). Divertor targets are in graphite, in common with poloidal armour on the central column. The possibility at JET for conversion of the D neutral beam injection (NBI) sources to  $\text{He}^4$  has allowed both L-mode and ELMing H-mode plasmas to be compared with  $P_{\text{NBI}}$  available up to 12 MW. With

the exception of a handful of very high power discharges, NBI was the sole additional heating source used in these experiments. Argon frosting on the NBI cryopanel was required between He pulses for reliable beam operation, but the use of helium as working gas precluded efficient divertor cryopumping (unlike in companion D pulses). An early important result from these He discharges was the discovery of an L-H transition threshold power ~50% higher in He than D and an energy confinement in H-mode ~0.75 that of an equivalent D discharge [3]. The lower NBI power available with pure He beams, the lack of density control and the higher H-mode threshold prevented Type I ELMing H-mode He pulses at  $I_p$ ,  $B_T$  combinations typical of D discharges (2.5MA, 2.5T).

Essential visible spectroscopic diagnostics from the point of view of this paper are wide-angle views of the inner and outer divertor regions looking from the top of the machine and a horizontal line of sight (LOS) viewing the inner wall at the plasma midplane (recycling fluxes, intensity of CIII line emission). In addition to the standard foil bolometry, data from tangentially viewing divertor CCD cameras equipped with interference filters ( $D_\alpha$ , HeI, HeII) and a poloidally scanning VUV spectrometer are also available. Target Langmuir probes, IR thermography and tile embedded thermocouples provide divertor plate parameters, with a reciprocating Langmuir probe and lithium beam used to obtain profiles in the main SOL plasma. Total pressures in the subdivertor and main chamber are monitored using penning gauges.

### **3. D-He changeover**

The switch from D to He and back was performed in a low clearance discharge using ICRH power ramps to monitor the development of the L-H transition threshold as the working gas was exchanged. Helium concentrations, monitored both by the ratios of He and  $D_2$  partial pressures in the subdivertor (accounting for the enhanced cryopumping of  $D_2$ ) and edge spectroscopy, show the ratio He/(D+He) reaching 80-85% during in the ohmic phase of the first changeover

discharge, decreasing later to ~50% with ~7.0 MW of ICRH [4]. The effect of heating on the ratio was reduced to negligible levels after 8-9 repeated discharges. Throughout the campaign, the ratio was typically in the range 90-95%.

#### 4. Impurity production

##### 4.1 General observations

Emission from the molecular species CD and C<sub>2</sub> in the outer divertor fell to undetectable levels after just the first two He fuelled discharges of the changeover. In the inner divertor, a large decrease in the first discharge was followed by a slower decrease with further pulses, attributed to erosion of saturated C films providing a hydrocarbon source. (The inner divertor in JET is known to be colder, more dense, detached at anything but low density and a region of net redeposition in D. In contrast, the outer target is an area of net erosion [5].) Operation in pure helium helps to illustrate this further using the response of the target surface temperature,  $T_{\text{surf}}$ , to NBI power steps, examples of which, for matched D and He discharges are compared in Fig.2. Measured using IR thermography, at the outer target in D plasmas,  $T_{\text{surf}} \propto \sqrt{t}$  in response to each power step as expected. Such behaviour is not observed at the inner target in D, where the response more closely matches the power staircase waveform. Moreover, tile calorimetry shows conclusively that most of the power is deposited in the outer divertor, even though  $T_{\text{surf}}^{\text{inner}} > T_{\text{surf}}^{\text{outer}}$  from thermography. In He plasmas,  $T_{\text{surf}} \propto \sqrt{t}$  at both targets and  $T_{\text{surf}}^{\text{outer}} > T_{\text{surf}}^{\text{inner}}$ , in accordance with calorimetric power balance. The different temperature responses to incident power for D compared to He is an indication of a surface modification during D operation. This modification can be modelled as a reduced thermal conductivity at the surface and is thought to be due to redeposited material. A detailed interpretation of these IR measurements is the subject of a companion paper [6].

Conclusions regarding the general behaviour of C sources in JET can be drawn by

comparison of matched D and He discharges, one L-mode example of which is shown in Fig.3. These are two low clearance equilibria for which, during the period of NBI heating, the total input power (Fig.3(b)) is similar in both He and D, albeit it for a 20% higher D plasma density (Fig.3(a)). This is due to a strong D<sub>2</sub> puff into the outer divertor during this time for the D discharge (Fig.3(j) - a second D<sub>2</sub> puff follows later into the inner divertor). The incremental Z<sub>eff</sub> (Z<sub>eff</sub> - 1 for D and Z<sub>eff</sub> - 2 for He) in Fig.3(d) demonstrate the cleanliness with respect to core carbon content of these He discharges (XUV and VUV core spectroscopy show the light impurities, C and O, to be reduced generally by about a factor 10 in L-mode He plasmas). This is correlated with a reduction of a factor 3 in the intensity of inner midplane CIII (465 nm) emission (Fig.3(e)), whilst inner and outer divertor CIII signals are of similar magnitude in D and He during the beam heating phase for this pair of discharges (Fig.3.(f,g)).

The midplane and subdivertor pressures in Fig.3(h,i) vary strongly in the D plasma owing to the intense gas puffs, but at ~19.8s into each discharge (marked by the dashed line), there is a point where  $\bar{n}_e$  in both cases is identical. Although this is not a steady state situation, at this time outer midplane pressures are approximately equal in He and D, whilst the ratio of D and He subdivertor pressures is ~6. Such a large difference in compression ratios would appear to rule out the existence of strong bypass leaks from divertor to main chamber in JET. Since the penning gauge is sensitive primarily to molecules in D and atoms in He, for similar pressure in He and D, one expects the original neutral flux to have been a factor 2 higher in D.

At t = 18 s in each of these discharges, Fig.4 compares SOL profiles, mapped to the outer midplane, of  $n_e$ , T<sub>e</sub> and parallel flow Mach No., combining data from a reciprocating Langmuir probe (RCP) and lithium beam, both located at the top of the machine on the low field side. Some edge LIDAR data are also included. The similarity between D and He profiles is remarkable, with differences between the diagnostic signals for the same discharge easily

accounted for within the alignment precision of the various systems. The high values of parallel flow (Fig.4(c)) seen in D for forward field direction are apparently present also in He plasmas, as is the peaked structure often seen in D plasmas [7].

Fig.5 compares a further two pairs of illustrative matched high clearance discharges, the first for an L-mode density ramp (density limits will be discussed further in Section 5 - see Fig.7 for another pair of matched density limit pulses, this time in a low clearance configuration) and the second for a pair of Type I ELMI H-mode discharges at low  $I_p$  and  $B_T$  (1.0MA/1.0T). In comparison with the “larger” equilibria (Fig.1(a)), higher wall clearance in L-mode leads to still lower main chamber and inner divertor carbon levels (the latter more than a further factor of 2 lower) than in equivalent D discharges. At low to medium  $\bar{n}_e$ , the outer divertor carbon emission is again comparable in He and D, but with rising density, carbon emission in the He plasma falls to undetectable levels everywhere. Before the onset of divertor detachment (section 5), at the same value of  $\bar{n}_e$ , subdivertor and midplane pressures behave similarly to those in the shot pair of Fig. 3. In the Type I ELMI H-mode (RHS of Fig.5), CIII intensities are comparable at all locations in both D and He and midplane pressures are again similar (though these are averaged values over the ELMs).

#### *4.2 Discussion*

Qualitatively, the observations described above for L-mode diverted plasmas are consistent with a picture in which carbon chemical sputtering accounts for a large fraction of the impurity source in D plasmas, particularly at medium to high densities. Quantitative conclusions regarding the regional (inner/outer divertor, main chamber walls) dependence of the source strength are more problematic, due principally to the difficulty in deriving absolute fluxes from the spectroscopic lines of sight (LOS), particularly in the divertor, where strong (unmeasured) variations in the local  $n_e$  and  $T_e$  translate to considerable variations in the photon efficiencies



(S/XB) and hence in the derived carbon source rates. The fact that in He at high density, CIII emission decreases to low values everywhere, whilst in D it remains constant or even increases in the main chamber (as evident in the density limit discharges of Figs.5,7), points strongly to a chemically sputtered source, since ion energies at the target plates under these conditions are below the threshold for physical sputtering (in D and He) even at the hotter, more attached outer target.

In the absence of more extensive diagnostic coverage, code simulations offer the only real chance of quantifying both the source strength at any particular location and its efficiency in contaminating the discharge (screening). Such simulations are now in progress for these helium plasmas, using both the two edge codes currently in use at JET (EDGE2D-Nimbus and SOLPS5 (B2.5-Eirene)) and the US fluid plasma code, UEDGE. The latter has been applied in particular to examine the differences in divertor carbon source rates in D and He by obtaining the best match to experimental target and upstream plasma conditions and then computing averaged S/XB's along the LOS of a poloidally scanning VUV spectrometer observing CIV emission at 31.2 nm and a CCD camera measuring the intensity of the CII visible line at 658 nm. Both are vertically viewing and both offer good poloidal coverage of the divertor region.

For matched high clearance, baseline reference L-mode cases with  $\bar{n}_e = 3.6 \times 10^{19} \text{ m}^{-3}$  and  $I_p = 2.4 \text{ MA}$ ,  $B_T = 2.4 \text{ T}$  and  $P_{\text{NBI}} \sim 3 \text{ MW}$ , comparison of experiment and code indicate that in the He pulse there is reduction in the inner divertor  $C^+$  source by a factor 4, a reduction of the  $C^{3+}$  source by a factor of 12 throughout the divertor and a comparable  $C^+$  source at the outer target in both D and He. This comparison suggests that the outer divertor C source is not a major factor in determining that of the higher ionisation states which eventually lead to core contamination. Similar analysis for higher power or density shows that the dominant source for divertor C production in He is ion physical sputtering, that the latter is also present in D at the

attached outer target (but perhaps does not contribute significantly to core contamination) and that chemical sputtering at the inner divertor is a major contributor. A detailed discussion of the results can be found in a separate paper to these proceedings [8].

Concerning main chamber sources, some preliminary B2.5-Eirene results compiled in Fig.6 concerning the poloidal distribution of ion ( $D^+$  and  $He^{2+}$ ) and neutral ( $D^0$  and  $He^0$ ) perpendicular outfluxes are of interest. Dividing the ordinate by the electronic charge gives a number of particles in each of 96 equal angle bins covering the  $360^\circ$  of one poloidal section. The data are generated from a standalone Eirene run based on a converged SOLPS5.0 plasma solution and have not yet been converted to fluxes at the wall surfaces. Particle balance has been verified so that neutral influx to the code is balanced by the sum of the ion and neutral outfluxes presented in Fig.6. The simulations are appropriate to the low clearance discharges of Fig.3, albeit at code separatrix density of  $n_{e,sep} = 8 \times 10^{18} m^{-3}$ , about a factor of two higher than indicated in the experimental profile data of Fig.4.

Ion outfluxes in the main chamber behave as expected, with  $\Gamma^{He^{2+}} \sim 0.5\Gamma^{D^+}$  and are comparable to the neutral outfluxes everywhere except at the inner midplane location, where,  $\Gamma^{D^0}$  is more than a factor 100 greater than any other ion or neutral loss. Elsewhere,  $\Gamma^{D^0} \approx 3.5\Gamma^{He^0}$ , consistent with reduced charge exchange reaction rates in He compared with D at the energies characteristic of the SOL. This accumulation of neutrals in D at the inner wall, due probably to leakage from the colder, more dense inner divertor and the flux surface geometry (Fig. 1a), would appear to explain why midplane horizontal spectroscopic ionisation fluxes (from HeI and  $D_\alpha$  emission) in the discharge pair of Fig.3 differ by a factor of  $\sim 50$  (even in the absence of strong gas puffing in D), whilst the outer midplane penning gauge pressures in He and D are similar - the horizontal spectroscopic LOS is dominated in D by emission from the inner wall.

Taken together, these results imply that in He L-mode, ion sputtering at the main chamber walls (particularly the inner wall which represents the largest graphite surface area) is the principle source of main chamber carbon production. This is further supported by the observation (see above) of still further reduced CIII emission (compared with D) in the inner divertor and at the midplane in moving from low to high wall clearance - the reduced plasma-wall distance likely increases the He ion physical sputtering source of carbon near the inside top of the vacuum vessel (Fig.1). In D, since chemical sputtering yields at the fluxes and energies characteristic of the far SOL exceed the maximum of the D physical sputtering yield [9] carbon chemical sputtering by neutrals almost certainly dominates the source, particularly at high density where main chamber C emission is observed to increase in D (Figs.5,7) and ion energies at the wall are likely below the threshold for physical sputtering.

### **5. Detachment and density limits**

Just as the absence of carbon chemistry in He discharges can be used to imply chemical sputtering as the main source of impurity production in L-mode D plasmas (section 4), the differing atomic physics and recycling properties of He and D may be invoked as the principal factors in explaining the higher density limit observed in He compared with equivalent D discharges. The details are presented in an accompanying paper [10], where it is demonstrated that the enhanced density limit in He (up to a factor 2.8 higher than in D depending on wall clearance), is, in part, a consequence of reduced ionisation rate coefficients (longer mean-free paths for He neutrals in the cold divertor plasma at high density) and significantly lower charge exchange and elastic collision rates in He. This combination leads to an increased neutral penetration depth (enhanced neutral leakage from the divertor) such that, although an X-point MARFE forms at similar densities in both D and He, in the He plasma the density can be increased continuously until the radiative power fraction reaches 100%. In deuterium,

increasing density beyond the X-point MARFE leads to the formation of an inner wall MARFE and a rapid (in density) approach to 100% radiation [11]. The effect on the density limit of reduced carbon impurity levels in the He plasma compared with D is not known quantitatively. For JET deuterium discharges [11] modelling has shown that the critical density for the onset of the inner wall MARFE is reduced by ~20% when carbon radiation is accounted for, but a similar exercise has not yet been performed for He plasmas.

In H-mode, it appears that the D and He density limits (defined as the density at the H-L-mode back-transition) are very similar [10]. It is arguable, however, that the increased L-H transition threshold and significantly different recycling properties of He make comparison with equivalent D pulses somewhat unfair.

The increased He neutral penetration in comparison with D also produces significant differences in the divertor detachment behaviour of He plasmas. Detachment in D is well documented in JET [12] and elsewhere [13] and is compared with the observations in He in Fig.7. Both the density and radiated power fraction (Fig.7 (a,b)) are well matched temporally in these two low clearance discharges - the higher density limit in He is evident (as it was in Fig.5 for the high clearance L-mode density limit discharges #53080 and #54030). The CIII signals (Fig.7 (d-f)) indicate the same trends as discussed in Section 4: rising with  $\bar{n}_e$  in the main chamber in the D pulse, becoming negligible in He, reaching constant values in the divertor at high density in D and falling to zero in He. Subject to the uncertainty in interpretation due to changing photon efficiencies, these observations indicate a strong role for carbon chemical sputtering in the divertor D with increasing  $\bar{n}_e$ . This conclusion is supported by the strike point  $T_e$  measurements in Fig.7(i), in which, for the inner target,  $T_e$  is too low ( $< 10$  eV) in both D and He for physical sputtering to be a serious contributor to the observed C source. At the outer target,  $T_e$  is high enough for the yield due to physical sputtering to contribute significantly to

carbon production in both He and D at low densities, but cannot at higher  $\bar{n}_e$ , resulting in the gradual decrease of the CIII intensity to low levels in He. The divertor source remaining at high density in D must therefore be attributed practically solely to chemical sputtering.

In Fig.7(g), the wide angle  $D_\alpha$  emission from the inner divertor rises rapidly with  $\bar{n}_e$  despite the decreasing integrated ion flux to the target plates (Fig.7(h)) - the classic signature of total detachment at the inner target [12]. In contrast, the outer target ion flux in D rises with density, as does the  $D_\alpha$  emission, indicating that the attached, high recycling state is maintained in the hotter outer divertor (Fig.7(i)) right up to the density limit. In He, detachment begins at much higher upstream densities and is similar to that in D only in the sense that the inner target appears to detach first. What is different is the decrease in power flux, especially at the inner target, (Fig.7(j), measured by IR thermography), long before the particle flux.

Although Figs.7(h,j) compare a peak power flux with an integrated target ion flux, the same is also true at the strike point - the ion flux detaches long after the power flux. Such behaviour was also observed during similar experiments on DIII-D [14] and is in contrast to the general picture in D whereby ion-neutral frictional processes [13] at low divertor  $T_e$  and eventually recombination [15] reduce the target ion flux. In He, the increased mean-free-path for neutral ionisation allows He neutrals to progressively escape the divertor volume to regions beyond the X-point, where intense line radiation (mostly from  $He^+$ ), leads to a pressure collapse in the SOL plasma. Increasing the power into the same discharge can prevent particle detachment in both inner and outer divertors right up to the density limit.

The rapid movement and spatial localisation of the radiation front with increasing  $\bar{n}_e$  in the colder inner divertor are reflected respectively in the HeI line intensity of Fig7.(g) and the bolometric inversions of Fig.8(b), which should be contrasted with the distribution of radiation in the D case (Fig.8(a)). Similar trends are also seen in the reconstructed emission from 2D

tangential CCD camera observations of the divertor and X-point HeI,II line emission. Equally, the plateau value of midplane pressure and collapse in the subdivertor pressure in He as the radiation moves to the X-point should be compared with the monotonic increase of both up to the density limit in D (Fig.7(k)). One may also note that to obtain consistency in the reconstruction of the total radiation using in-divertor and ex-divertor bolometer lines of sight [16], a neutral contribution of up to 20% of the power measured by divertor bolometers must be assumed for D plasmas, whilst no such contribution is required for equivalent He discharges.

Most of these experimentally observed features can be reproduced by simulations, first performed for DIII-D with the B2-Eirene code by Loarte [17]. For JET, modelling has been performed with both the EDGE2D-Nimbus package and with the B2.5-Eirene code, with results from the latter being presented in a companion paper [18].

## **6. L and H-mode scrape-off layer transport**

The technique of divertor target strike point sweeping across tile mounted Langmuir probes and embedded thermocouples to obtain peak parallel field power flux densities and deposited power profiles (from which power scrape-off widths,  $\lambda_q$  can be derived) in both L and ELMing H-mode D discharges has been pioneered at JET and is well documented in the literature [19,20]. In the absence of strong D<sub>2</sub> puffing and under high power conditions, a narrow feature appears in the power profile which is being interpreted as due to inter-ELM ion orbit losses from the pedestal region. More details of the complex numerical modelling demonstrating this phenomena can be found in a separate contribution to these proceedings [21].

During the He campaign, a series of strike point swept, high clearance pulses have permitted a number of additions to the D database, notably the inclusion of a previously unavailable A(Z) dependence and some parameter variation in  $q_{95}$  and  $B_T$ . Unfortunately, the lower NBI powers available and the increased (compared to D) L-H transition power, restricts the new He data to

Type III ELMing H-modes at lower  $I_p/B_T$  combinations, typically 1.5MA/1.5T, in comparison with the standard combination for shots populating the D database (2.5MA/2.4T). Fig.9 compiles a selection of the D and He data (restricted for clarity to constant  $q_{95} = 2.6$ ) for the variation with  $P_{SOL}$  of  $q$  and  $\lambda_q$  at the outer target (where most of  $P_{SOL}$  is deposited in both D and He (see Fig.2)). Data points denoted by the label TC are obtained from thermocouple analysis, representing the total (ion and electron) deposited power, whilst LP refers to the result of applying standard sheath theory to compute the parallel (electron) power flux from target probe measurements of  $T_e$  and particle flux.

As described elsewhere [20], the D points demonstrate clearly that in high power H-modes, ions dominate the energy balance ( $q(TC) \gg q(LP)$ ). For He, there appears to be a much stronger coupling between ions and electrons up to the maximum  $P_{SOL}$  achievable in these experiments. This could be due both to the increased ion-electron collisionality in He and a lower fraction of hot ions (due to lower pedestal temperatures in the He Type III ELMing H-modes). In general, there is tendency for  $\lambda_q^{He} > \lambda_q^D$ , particularly in H-mode. Regression analysis performed on the TC  $\lambda_q$  data [22] with respect to the variables  $Z$ ,  $B_T$ ,  $P_{SOL}$  and  $n_{e,sep}$  yields:  $\lambda_q^{fit} \sim Z^{0.92} B_T^{-1.03} P_{SOL}^{-0.29} n_e^{-0.14}$ , showing a strong charge and magnetic field scaling, a weak density dependence and preserving the negative power exponent previously derived in analysing D data alone [20]. Assuming that ion convection dominates the parallel mass transport, this parametric dependence, when compared with a large number of candidate models describing cross-field energy transport, is closest to that which would be expected on the basis of a classical scaling for  $\chi_{\perp}$ .

## 6. ELM durations

Although the Type I ELMing H-mode regime is foreseen as the reference scenario for inductive operation of ITER [2], the large divertor target power loads and intolerable erosion

that can result when extrapolations are made to next step devices is a cause for serious concern. Understanding the mechanism by which the heat and particles expelled by the ELM arrive at the target plates is thus of great importance. Previous analysis of the ELM power pulse duration using IR thermography on the JET and ASDEX-U divertor targets indicated a correlation of this time with the parallel loss time for ions to flow from the upstream (outer midplane) location of the ELM event along field lines to the divertor [23]. This characteristic time was taken as  $\tau_{\parallel} = 2\pi R q_{95} / c_s (1 + \sqrt{3/2} v^*)$  with  $c_s$  the sound speed (evaluated for  $T_i$  and  $T_e$ ) at the top of the pedestal and  $v^* = \pi R q_{95} / \lambda$  with  $\lambda$  the mean-free-path for ion-ion collisions. New data from the JET pure helium experiments indicate that the key element determining the transmission of energy to the targets is simply the arrival time of the ion pressure wave front, given by  $\tau_{\parallel} = 2\pi R q_{95} / c_s$ . This is shown in Fig. 10, where,  $\tau_{\text{IR}}$ , defined as the rise time of  $T_{\text{surf}}$  due to the ELM, is plotted as a function of  $\tau_{\parallel}$  from JET and ASDEX-U deuterium Type I ELMing H-modes and in which two new JET He points have been added [24]. These  $\tau_{\text{IR}}$  helium points are from discharges with an  $I_p$ ,  $B_T$  combination of 2MA, 2T, somewhat lower than the values typical of the JET deuterium H-modes and represent an average over just a handful of Type I ELMs obtained in a short time interval immediately after the L-H transition with  $\sim 12$  MW of He NBI power and just before a transition to Type III ELMs. On the basis of Fig. 10, the ELM power duration on ITER ( $\tau_{\parallel} \sim 220 \mu\text{s}$ ), would be expected to be in the range  $\sim 500 \mu\text{s}$ .

## 7. Conclusions

A recent JET campaign of pure He plasmas with He neutral beam injection has provided a wealth of data which, in addition to providing valuable information with which to judge the merits of He as an option for fueling the discharges of the ITER low activation phase, offer interesting new insights into D operation. The combination of spectroscopic observations from and code simulations of these plasmas indicates strongly that carbon contamination of



the discharge in L-mode D plasmas in JET is dominated by chemical sputtering (due to ionic and neutral fluxes) at the inner wall and at the inner divertor. In He, where carbon chemistry is absent, ion physical sputtering dominates, but is at such a low level compared with the combination of chemical and physical processes in D that  $Z_{\text{eff}}$  in L-mode diverted discharges is close to that expected in a pure He plasma.

Divertor detachment is very different in He, being driven by the escape of recycling neutrals from the divertor volume to the X-point region where the resulting intense radiation from ionisation of He neutrals and  $\text{He}^+$  ions starves the divertor of power and leads, eventually to particle flux detachment. This, together with the lower charge exchange rates in He, is the principle reason for L-mode density limits a factor of 2-3 higher in He compared with equivalent D plasmas. The increased atomic number in He permits the addition of a further parameter in the regression analysis of SOL power scrape-off widths, already the subject of detailed study at JET in D plasmas. First results indicate that classical cross-field transport comes closest to describing the radial heat flux in the JET scrape-off layer. Although data are sparse, results from these He plasmas point strongly to the validity of a picture in which the ELM energy released in the main SOL propagates parallel to the field lines down to the divertor targets with speed governed only by that of an ion pressure wave travelling at sonic speed appropriate to the upstream pedestal  $T_e$ ,  $T_i$ .

In He the L-H transition power threshold is found to be higher than in D by about a factor 1.5, with energy confinement  $\sim 75\%$  of that in D. For the ITER low activation phase, helium is therefore preferable to hydrogen from the point of view of threshold power (at the expense of confinement), but the JET results presented here indicate that He operation would not provide an adequate test of critical divertor physics issues for the next step. In particular, if ITER is to employ graphite armour in the divertor during the early phase of operation, He plasmas would

not provide an adequate comparative (to D) test of target erosion (and fuel retention). Likewise, divertor detachment and pumping in He are so different that a campaign in hydrogen would appear to be more attractive with respect preparing for the later D-T operation phase.

### **Acknowledgements**

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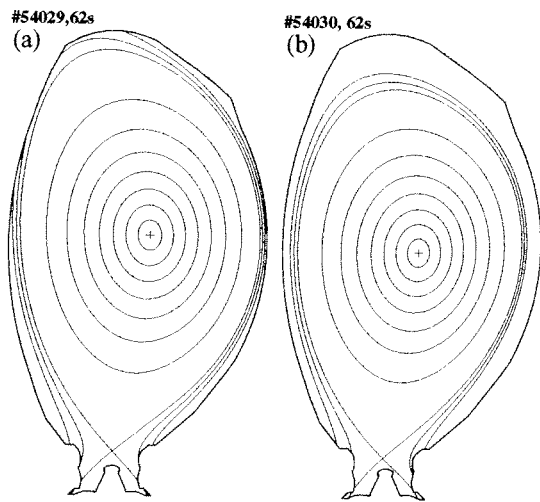


Fig. 1. Low (a) and high (b) wall clearance equilibria used for the majority experiments described in this paper.

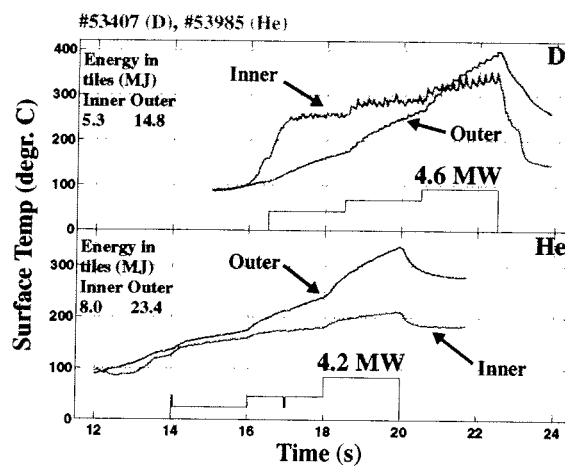


Fig. 2. Response of peak surface temperature on inner and outer divertor targets to NBI power steps during D (#53407) and He (#53985) plasmas. The discharges are matched, L-mode, high wall clearance discharges with  $I_p = 2.4$  MA,  $B_T = 2.4$  T. The total energy deposited on the inner and outer divertor vertical tiles at the end of the shot from thermocouple analysis is also given.

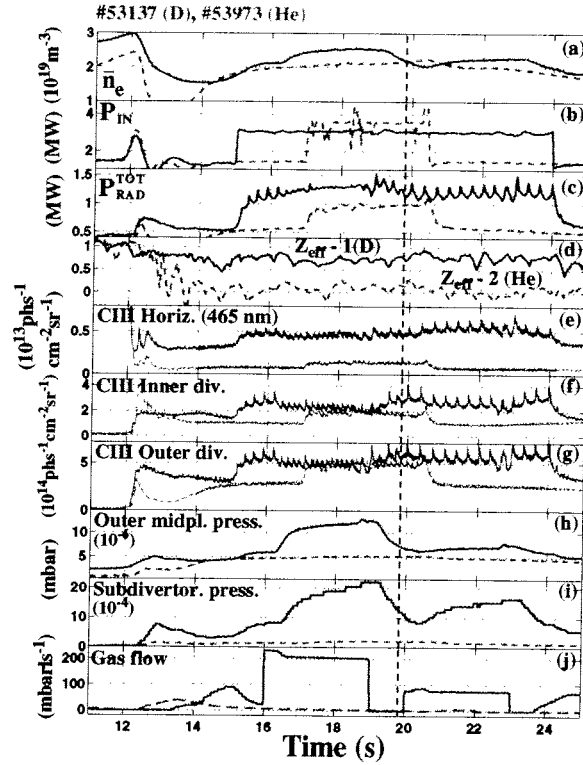


Fig. 3. Comparison of matched L-mode D and He shots at  $I_p = 2.4$  MA,  $B_T = 2.5$  T: full blue lines D (#53137), dashed red lines He (#53973). These are low wall clearance discharges. The dashed vertical line at 19.8s shows how when the plasma density is very similar and the D gas fueling is low, midplane pressures are almost the same but subdivertor pressures are about a factor 6 lower in He compared with D.

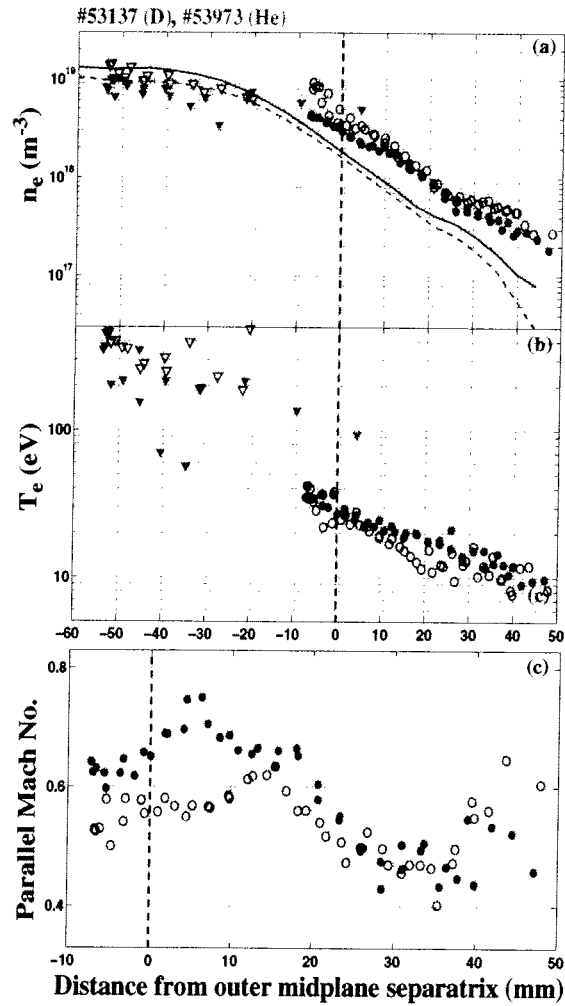


Fig. 4. Comparison of edge  $n_e$ ,  $T_e$  (a,b) and Mach No. profiles (c) at  $t = 18\text{s}$  for the matched He and D shots in Fig. 3 showing the remarkably similar edge conditions for two very different plasma species. Open symbols (D), closed symbols (He), circles (RCP), triangles (Edge LIDAR), lines (Li beam): full (D), dashed (He). The slightly higher density in the D case is due to the higher  $\bar{n}_e$  (Fig. 3(a)) at the chosen measurement time.

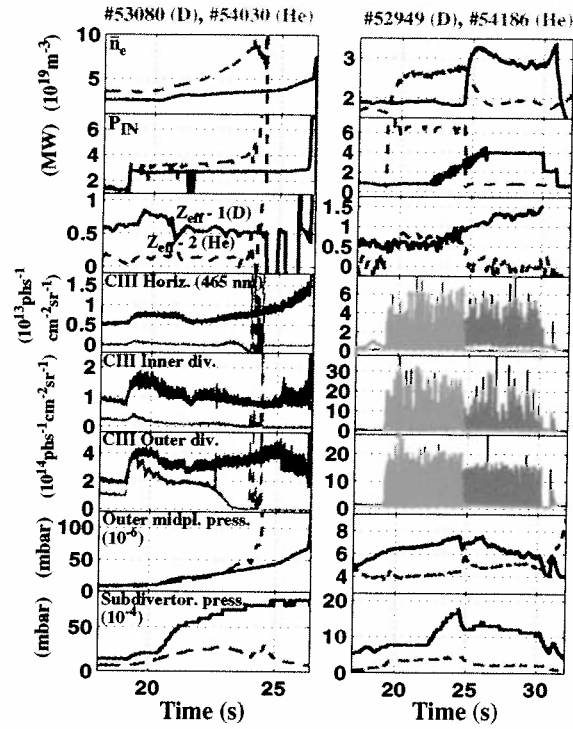


Fig. 5. Comparison of matched L-mode D and He density limit shots at  $I_p = 2.4$  MA,  $B_T = 2.5$  T (left) and matched low clearance Type I ELMing H-mode discharges at  $I_p = 1.0$  MA,  $B_T = 1.0$  T (right). Full blue lines D, dashed red lines He. Both shot pairs are low wall clearance discharges. In the density limit discharges, gas puffing is in both cases into the outer divertor.



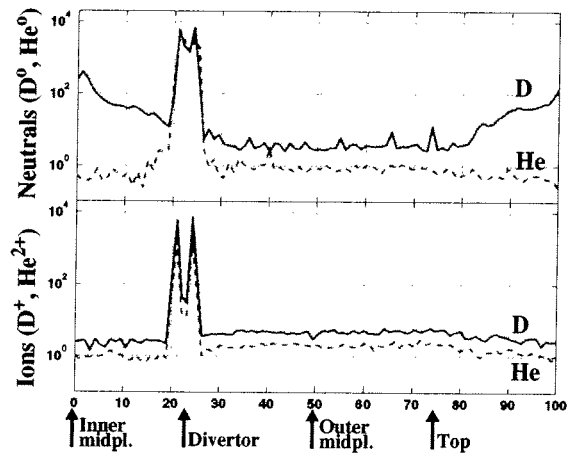


Fig. 6. Simulated poloidal distributions of perpendicular neutral and ion outfluxes for D (blue full lines) and He (red dashed lines) from SOLPS5 runs on a low clearance equilibrium with  $n_{e,sep} = 8 \times 10^{18} \text{m}^{-3}$ ,  $P_{SOL} \sim 3 \text{ MW}$  and  $D_{\perp} = 0.2 \text{ m}^2 \text{s}^{-1}$ ,  $\chi_{\perp} = 1.0 \text{ m}^2 \text{s}^{-1}$ . The dominant contribution from the divertor is evident in both ion and neutral outfluxes.

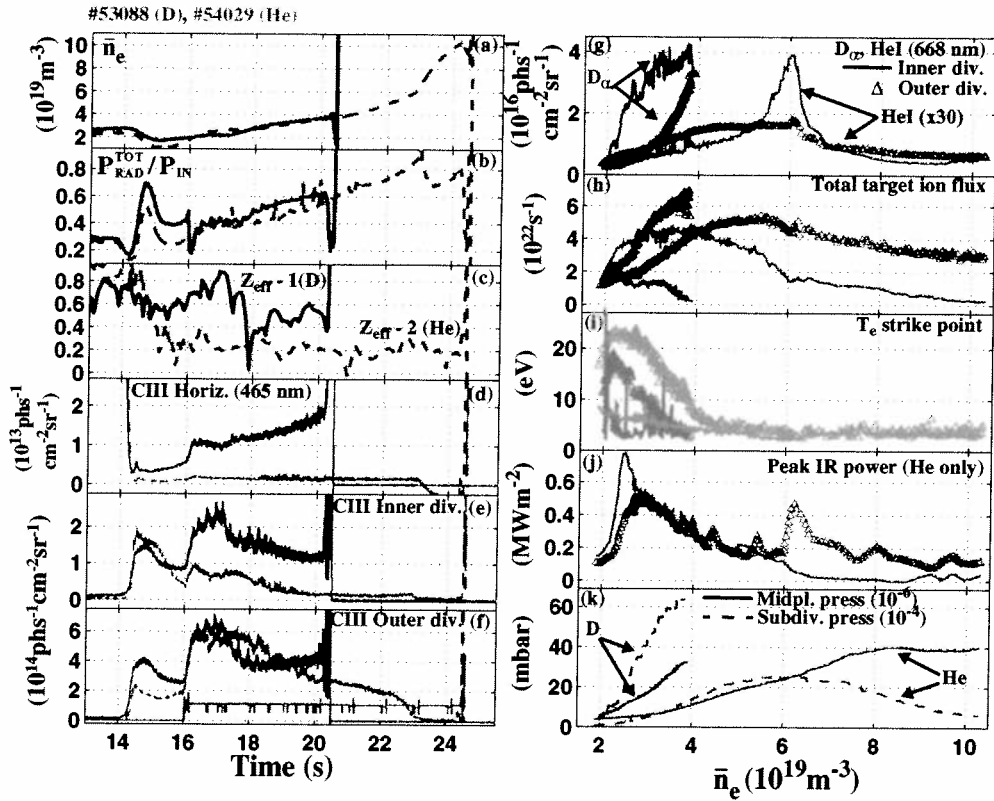


Fig. 7. Comparison of matched D (blue) and He (red) density limit discharges at  $I_p = 2.0 \text{ MA}$ ,  $B_T = 2.4 \text{ T}$ . The configuration has low wall clearance, as in the matched pair of Fig. 3. Note that IR data are available only for the He discharge. The step in CIII fluxes at 16s indicates the switch-on of  $\sim 1.1 \text{ MW}$  of NBI power which is maintained in each case until disruption (see the power traces at the foot of panel (f)). Note that the plots on the RHS are given as a function of density and that the symbols represent outer target quantities and the full lines the inner target in each case.

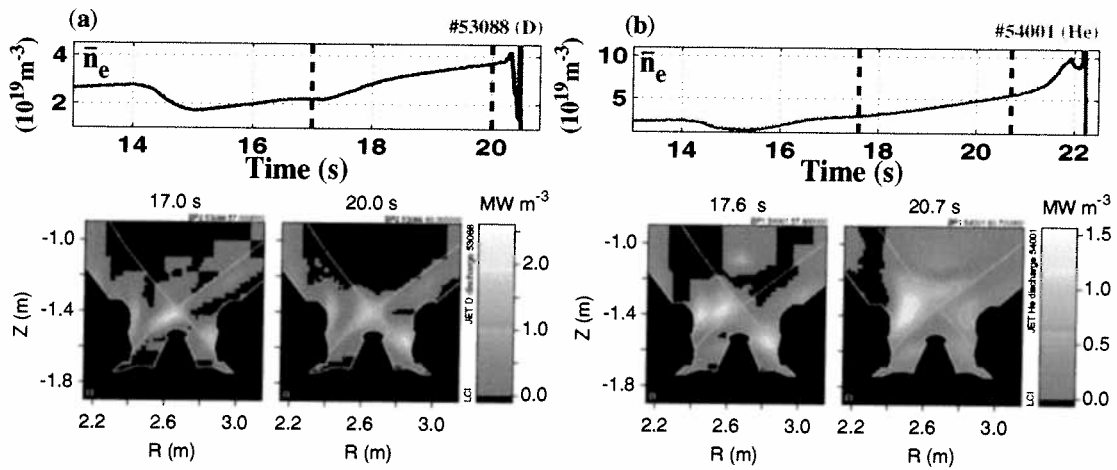


Fig. 8. Illustrating the differences in divertor total radiation distributions in the nearly matched shot pair (a) #53088 (D) and (b) #54001 (He). The vertical dashed lines in the time traces of density indicate the times at which the bolometric inversions have been performed. Note that in both cases, the reconstructions correspond to plasma densities below the onset of the inner wall MARFE in D and the fully developed X-point MARFE in He [10].

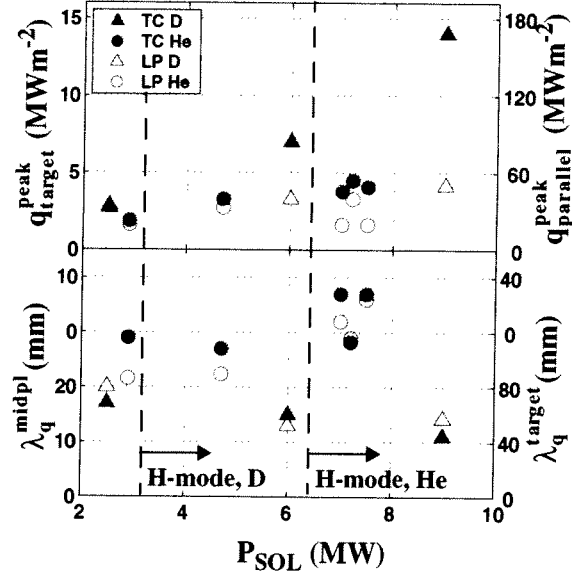


Fig. 9. Dependence of peak target heat fluxes and outer midplane power scrape-off lengths at the outer target as a function of power reaching the SOL for NBI heated L and H-mode D and He plasmas in identical high clearance equilibria. LP and TC refer to quantities measured with divertor Langmuir probes and tile thermocouples respectively. Note that although  $q_{95} = 2.6$  for all points, the He H-mode points are for lower  $I_p$  and  $B_T$  (1.5 T/1.5 MA) than for the He L-mode points and all D points. The strong  $\lambda_q \propto B_T^{-1}$  scaling which results is clear (see text).

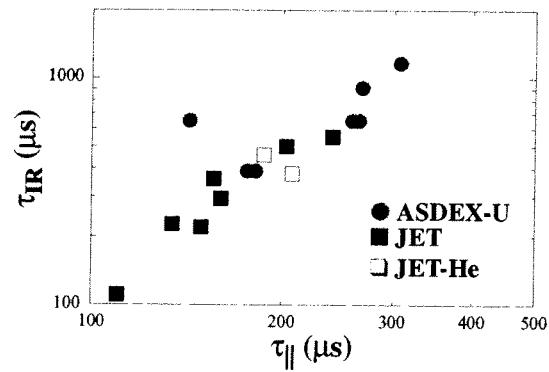


Fig. 10. The variation of ELM target power deposition times measured by thermography with time for parallel propagation of the SOL pressure wave travelling at sound speed from the upstream location of the ELM event to the outer targets in JET and ASDEX-U. The new JET helium points are the blue squares.



## Divertor detachment during pure Helium plasmas in JET

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### Abstract

A campaign of pure helium discharges in the JET tokamak equipped with the MarkIIIGB divertor has been performed. This paper describes some of the experimental observations of divertor detachment obtained in L-mode density ramp He discharges and presents a selection of results from the application of B2.5-Eirene code modelling to a JET He plasma. Detachment is very different from that observed in equivalent D discharges. Particle fluxes remain attached up to higher densities and, with decreasing input power, particle detachment occurs earlier in density. However, in contrast to comparable D plasmas, the low measured target  $T_e$  at all but the lowest  $n_e$  in helium leads to an earlier decrease in power flux. Simulations show that detachment is caused by the escape of He neutrals from the target vicinity where, together with the  $\text{He}^+$  ions they radiate along the separatrix and above the X-point area, starving regions downstream of power.

### 1. Introduction

A number of intimately linked key factors determine the onset and nature of tokamak divertor detachment, some related to magnetic and divertor geometry (parallel field connection lengths, degree of neutral baffling, etc.) and many to details of distributed power loss in the divertor volume (momentum losses due to charge exchange and impurity and main plasma species line radiation). These volumetric losses are in turn governed by the material of first wall surfaces and the choice of fuelling gas. By exchanging deuterium for helium in a machine containing significant quantities of graphite whilst retaining the important geometrical parameters, the effect on the character of detachment of a significant change in both the

principal atomic physics processes and the nature of the carbon impurity source can be studied. Helium plasma discharges with He neutral beam injection (NBI) and operating conditions matched to previous D discharges have been performed during a recent JET campaign in the MarkIIIGB divertor configuration [1]. This paper concentrates on some of the key experimental observations of divertor detachment obtained in He L-mode density ramp discharges and presents a selection of results from B2.5-Eirene code modelling of these pulses.

## 2. Experiment

The discharges discussed here have  $I_p = 2.5\text{MA}$ ,  $B_t = 2.4\text{T}$ , with strike points on the vertical divertor targets and are each characterized by a density ramp to the density limit with varying levels of He NBI power up to 5MW. The mean purity level of the He plasma discharges is around 90%, measured both by visible spectroscopy in the plasma edge and by monitoring partial pressures in the subdivertor volume. As shown in Fig. 1, these pulses have low wall clearance in the main chamber (similar density limit pulses in high wall clearance configurations are described in a separate contribution to these proceedings [2]).

Fig. 2 compiles the density dependence of key strike point experimental data from both target Langmuir probes and IR thermography for the inner (Fig. 2 (a - c)) and outer (Fig. 2 (d - f)) targets. With the exception of the peak IR power (for which no data is available in D), the data are from three He discharges with varying  $P_{\text{NBI}}$  and a single D pulse for reference matched most closely to the He discharge #54001, corresponding to the mid-range power in the heating scan. Note the considerably higher density limit in He compared with D [2]. Fig. 2 shows clearly how the observed detachment in He is very different from that in D. At the inner divertor, particle (Fig. 2 (a)) and energy (Fig. 2 (c)) detachment occurs immediately in D. This is a common observation in JET discharges with the  $B \times \nabla B$  drift direction towards the X-point. [3].

In equivalent He plasmas, inner target ion fluxes begin to decrease at much higher densities, with the onset of detachment coincident with the formation of a strong X-point MARFE. This MARFE occurs earlier in density as input power is decreased. In common with D plasmas,  $T_e$  at the inner target in He appears to be collapsed at all densities for the limited power scan described here (Fig. 2 (c)). Note also the low peak powers (Fig. 2 (b)), only just above the experimental sensitivity of the IR camera - although particles still arrive at the target, the energy flux is low, even at the maximum  $P_{\text{NBI}}$  of 5MW.

At the outer target, particle flux detachment in He occurs at marginally higher  $\bar{n}_e$  (Fig. 2 (d))



in comparison with the inner target and is again sensitive to the degree of input power. In D for the reference case in fig. 2, the outer target remains attached almost until the density limit, where the formation of an X-point and then rapidly an inner wall MARFE occurs [2]. The outer target electron temperatures (Fig. 2 (f)) demonstrate clearly the effect of increasing input power, decreasing in He, as in D, to values of  $\sim 5\text{eV}$  as  $\bar{n}_e$  increases. Unlike in D however, when  $T_e$  falls in the He plasma, the particle flux does not (as also observed in the inner divertor). In D, strong momentum loss is followed by recombination which ultimately decreases the particle flux [4]. Note that the known problems of Langmuir probe interpretation at low  $T_e$  prevent any knowledge of the true value of  $T_e$  at high  $\bar{n}_e$  [5]. In He, for densities below the detachment threshold, the peak IR power at the outer target (Fig. 2 (e)) falls in synchrony with  $T_e$ , despite the increasing ion flux (Fig. 2 (d)).

Fig. 3 illustrates the behaviour for a single discharge of the total radiation (from bolometry) in the divertor region as  $\bar{n}_e$  rises. Initially located at both the inner and outer strike zones at low  $\bar{n}_e$ , the total radiation increasingly concentrates at the inner leg and then finally above the X-point during the MARFE phase. Likewise, the HeI emission (HeI, 706nm, from tomographic reconstruction of tangential CCD camera images [6]) begins at the outer and switches to the inner leg at high  $\bar{n}_e$ . At high density in He, CIII emission in the divertor and main chamber is observed to extremely low levels. This is unlike the case in D, in which this emission remains constant or even increases with increasing  $\bar{n}_e$  [1, 2]. This is attributed to the absence of chemical sputtering in He (and the decrease of ion energy below the threshold for physical sputtering at high  $\bar{n}_e$ ) and implies that the radiated power (Fig. 3b) in He plasmas is due almost exclusively to that from  $\text{He}^0$  and  $\text{He}^+$  at elevated densities.

### 3. Simulations

The SOLPS5 (B2.5-Eirene) code has recently been fully installed at JET and is now being routinely used for the simulation of D plasmas [7]. However, modelling the complex high density detached cases has only just begun and the results are insufficiently mature to be included here. In helium, the absence of hydrocarbon chemistry and molecular species renders the situation somewhat less complex. The basic findings reported in this paper have much in common with those found in an earlier attempt at He plasma modelling [8] for DIII-D discharges with the older, SOLPS4 version of the code. The latter has also been used to simulate a single reference JET He plasma case and the results found to be in good agreement with those

of SOLPS5 reported below.

The simulations are conducted on a grid (Fig. 1b) extending from  $\rho = -4\text{cm}$  to  $\rho = 3\text{cm}$  relative to the outer midplane separatrix - chosen so as to be compatible with concurrent EDGE2D-NIMBUS and UEDGE [9] modelling of similar discharges. Radial transport coefficients  $D_{\perp} = 0.2 \text{ m}^2\text{s}^{-1}$ ,  $\chi_{\perp} = 1.0 \text{ m}^2\text{s}^{-1}$  are used in these first simulations - sensitivity studies to variations in these coefficients are underway.

Ion sputtering occurs only at the divertor targets in SOLPS5, whilst neutral interaction with divertor and main chamber walls is included in the model. Physical sputtering is implemented according to the Roth-Bodansky formula [10] with chemical sputtering (for the D minority) fixed at 1%. Concerning the percentage of D in these code runs, sensitivity tests have been performed for constant  $n_e$  and input power,  $P_{\text{SOL}}$  at the inner boundary of the simulation grid by varying the ratio of density due to  $\text{D}^+$  and  $\text{He}^{2+}$  ions corresponding to D concentrations up to 40%. No significant change in the target profiles was observed throughout this concentration scan, in contrast to the findings for SOLPS5 simulations with horizontal target geometry [7]. This apparent sensitivity in the code to divertor geometry is the subject of ongoing study. For the results presented here, the D concentration was fixed at values below 8%.

For fixed  $P_{\text{SOL}} = 3.8\text{MW}$ , comparable to discharge #54001 of Fig. 2, fig. 4 compiles code output and target probe measurements, the latter averaged over 0.6s intervals, at four different times in the density ramp for  $n_e$ ,  $T_e$  and ion particle flux profiles across the outer and inner targets mapped to the outer midplane. Code output is plotted for 4 upstream separatrix densities in an attempt to simulate the experimental density ramp. The probe data are color coded, with each color referring to a time slice in the density ramp, corresponding to the four times highlighted by the vertical lines in fig. 3(a). Agreement is in general reasonable given that transport coefficients have been fixed for code optimization and code comparison rather than providing the best match to upstream profiles. There is however a persistent tendency in the code to underestimate  $T_e$  in the strike point and private flux regions at all but the lowest densities.

This does not appear to be the case for comparable UEDGE and EDGE2D simulations in which  $T_e$  is well matched at the outer target, though none of the codes (drifts are not included) can match the inner/outer target asymmetries seen in experiment. Further SOLPS5 simulations are planned (variation of transport coefficients,  $P_{\text{SOL}}$  etc.) in order to further investigate this interesting discrepancy.

In Fig. 5 the variation with  $n_e^{ib}$  (inner boundary density) of total ion and power flux to the targets shows that the general experimental observation (Fig. 2) in helium plasmas of power flux detachment occurring before particle loss is reproduced by the code. The simulations also demonstrate a clear tendency for lower total power flux to the inner target compared with the outer.

In the context of this study, the principle differences between He and D are the increased mean-free-path for neutral ionisation ( $\lambda_{mfp}^{He} \sim 6\lambda_{mfp}^D$  at 10 eV) and the reduced CX reaction rates (factor of 3-4 at 10 eV). What happens is simply that neutral He recycled at the targets penetrates further upstream before being ionized than would be the case for D neutrals. Fig. 6 illustrates this effect from the point of view of the code. With increasing  $\bar{n}_e$ , the ionisation fronts for  $He^0$  and  $He^+$  move progressively further away from the targets to produce a strong radiating zone dominated by HeII line radiation, starving the divertor of power until pressure collapse prevents further ionisation and the target flux falls.

The main carbon sputtering mechanisms in these simulations are physical sputtering due to  $He^+$  and  $He^{2+}$  ion impact, although D and  $D^+$  contribute to the total sputtered flux at levels up to 30% due to the observed (in the simulations) accumulation of  $D^+$  ions in the divertor region. At high densities, this contribution can amount to 25% of the total electron density in the target region. With increasing  $n_e^{ib}$ , the total carbon content in the simulations decreases by a factor of  $\sim 2$  (the C ion fluxes always remaining negligible compared to the He ion fluxes at the targets), and the radiative losses due to CIII and CIV, reaching their maximum only at the lowest simulated densities, are always low (2% to 25%) compared to these losses from HeII.

#### 4. Discussion and Conclusions

In helium, divertor detachment begins at much higher upstream densities than in deuterium and is similar to that in D at most in the sense that the inner target detaches first. For varying input power, only at the highest densities and at high input power is particle detachment observed at both targets. Particle detachment occurs close to the density limit whilst power detachment is observed to occur at much lower densities. From comparison of simulations and experimental data it is clear that the power detachment is a consequence of He atoms escaping further upstream compared to the case for D neutrals, followed by power loss, mostly due to  $He^+$  line radiation. At the highest densities a large enough fraction of the power entering the

SOL is lost through line emission that there is insufficient energy for ionisation of the recycled neutrals, thereby leading to a collapse in particle flux to the targets. This is very different to the situation in D plasmas where a complex interdependence between CX reactions, radiative cooling due to high carbon concentrations, recombination and ionisation processes lead to the observed power and particle detachments. In He, recombination processes play no role during detachment since insufficient momentum is removed by ion-neutral friction to allow residence times for  $\text{He}^+$  in the divertor region to be sufficiently high for recombination to be effective as a sink of charged particles. Due to the few simple atomic key processes involved in the detachment of He plasmas (and the absence of molecular species) they are an ideal subject for benchmarking SOL codes. It is not yet clear why, for example, with vertical targets in the MarkIIIGB divertor, B2.5-Eirene produces very low electron temperatures in the strike point and private flux regions compared to higher values simulated by UEDGE and EDGE2D-NIMBUS and measured by target Langmuir probes. Comparisons with SOLPS5 simulations for matched JET deuterium discharges are underway.

### Acknowledgement

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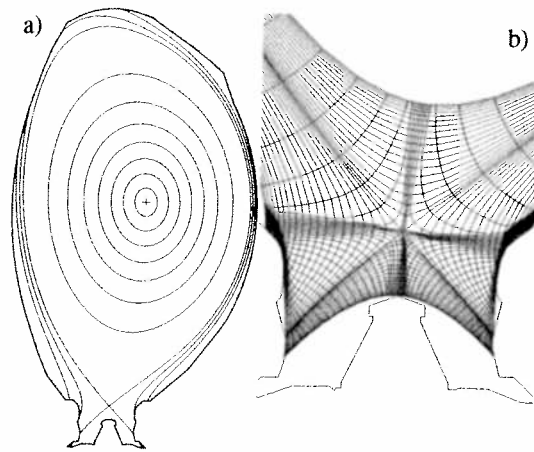


Fig. 1. a) JET low clearance equilibrium referred to in this paper and the simulation grid (b) in the divertor region.

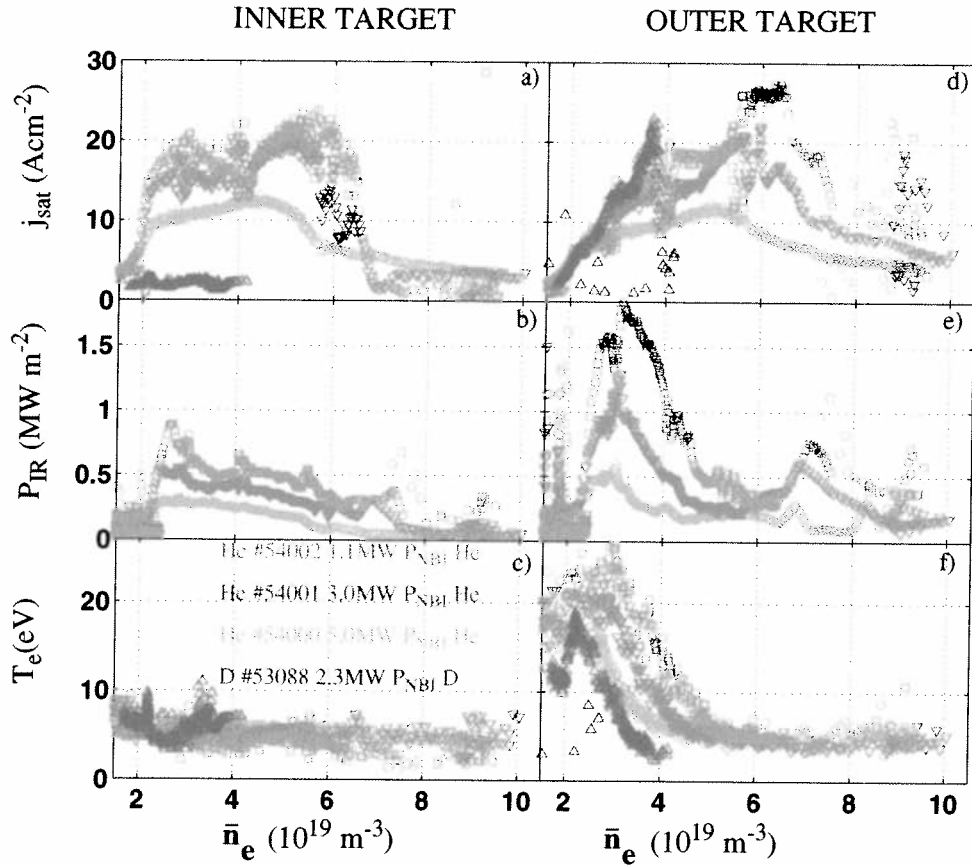


Fig. 2. Experimental measurements of the plasma density dependence of ion particle flux (a, d), peak surface heat flux (b, e) and electron temperature (c, f) at the inner (left) and outer (right) divertor targets. Data are shown for three He discharges and a single comparable D pulse, with the exception of  $P_{\text{IR}}$ , for which no measurements are available, in D.

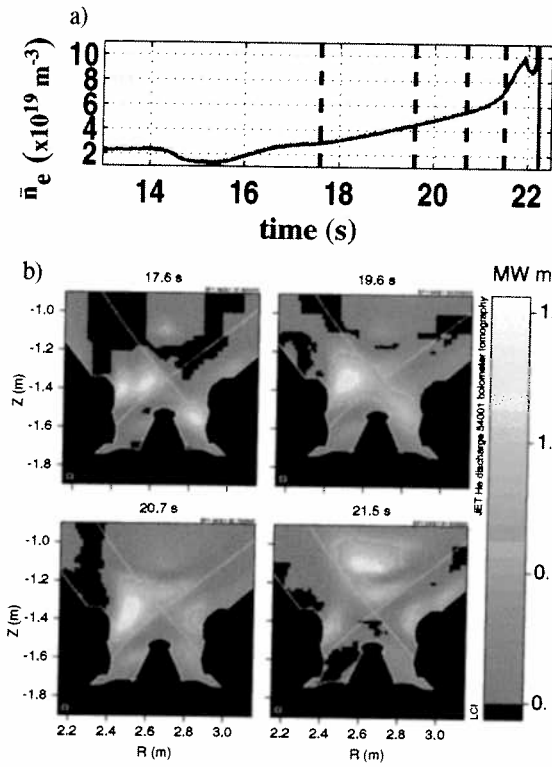


Fig. 3. Density dependence of the 2-D distribution of total radiation in the divertor for He discharge #54001. The bolometric inversions (b) correspond, in the clockwise direction starting from top left, to the times marked by the vertical dashed lines in the density trace (a). Note the intense emission from the inner divertor and the movement of radiation above the X-point at the highest density.



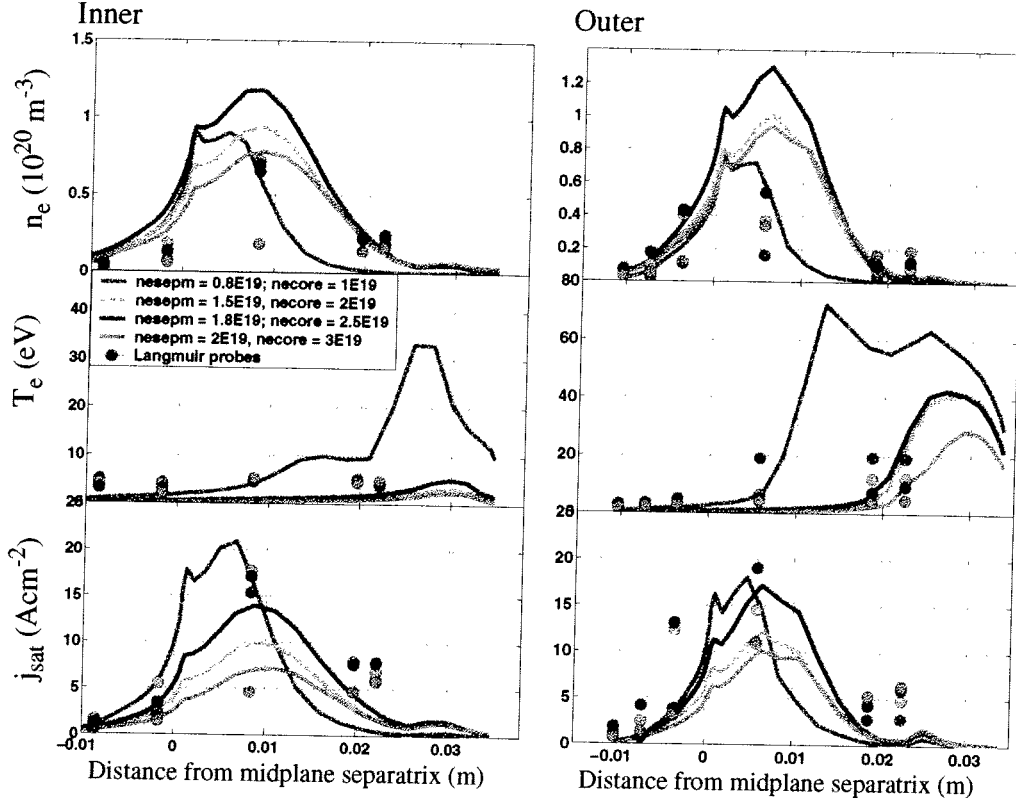


Fig. 4. Comparison of simulated (lines)  $n_e$ ,  $T_e$  and  $j_{\text{sat}}$  with data from Langmuir probes (circles) at four values of  $\bar{n}_e$  in pulse #54001 ( $P_{\text{NBI}} = 3.0\text{MW}$ ). Data are mapped to the outer midplane. “necore” denotes the density at the inner boundary of the grid chosen for the simulations while “nesepm” specifies the electron density at the separatrix at the outer midplane resulting from the simulations. The sequence of colors ●●●● refers to rising density and corresponds to the four times depicted in Fig. 3 in the case of the experimental data points. The experimental points are time averaged over 0.6s. Note that the correspondence between code and experiment for nesepm is only approximate.

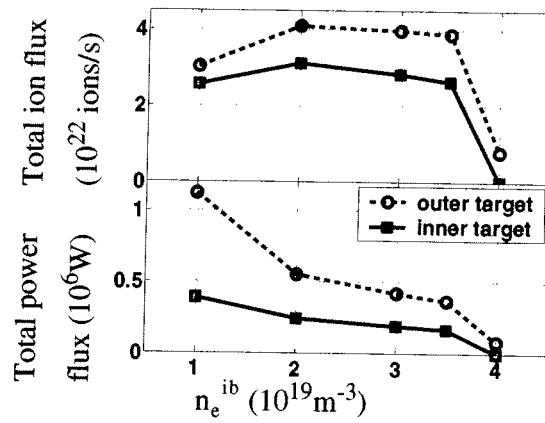


Fig. 5. Simulated total ion and power flux to the inner and outer targets indicating the experimental observation that power flux detachment occurs before particle flux detachment in He plasmas

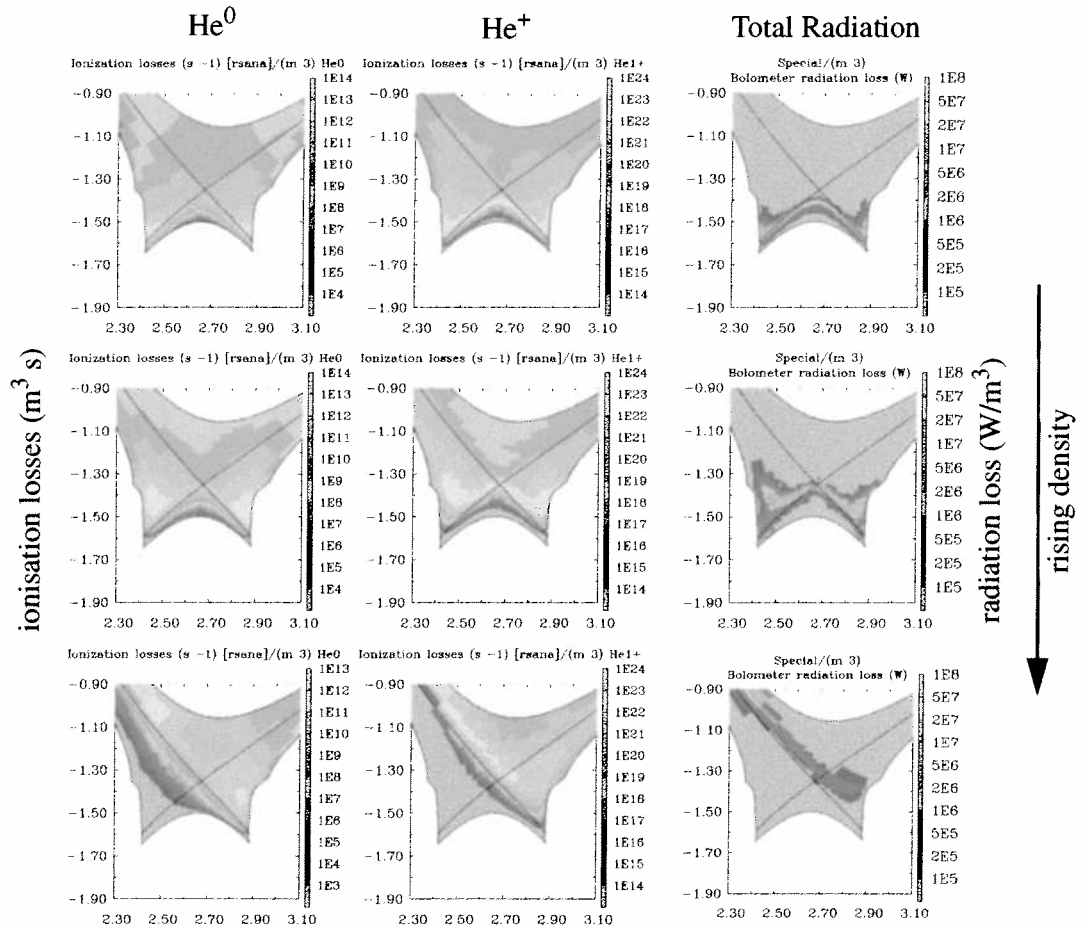


Fig. 6. Simulated ionisation loss rates for  $\text{He}^0$  and  $\text{He}^+$  and total radiation with increasing density based on conditions comparable with discharge #54001 at  $P_{\text{NBI}} = 3.0\text{MW}$ .





