Evidence for Impurity Drift in the Scrape-off Layer of JET

J P Coad, P L Andrew[1], J D Elder[2], S K Erents[3], H Y Guo, C F Maggi, G F Matthews and P C Stangeby[2]

JET Joint Undertaking, Abingdon, Oxon., OX14 3EA, U.K
[1]present address: Dept of Physics, University of Wisconsin, Madison, WI 53706, USA
[2]University of Toronto, Institute for Aerospace Studies, Toronto, M3H 5T6, Canada
[3]UKAEA Fusion, Culham (UKAEA/EURATOM Fusion Assoc.), Abingdon, OX14 4DB, U.K.

1. Introduction

To be able to predict erosion/deposition in future tokamaks, models must provide an accurate match to data from present-day machines. The principal result of the modelling for the divertor geometry is that most eroded material is re-deposited locally, so that there is net erosion close to the strike-point, and net deposition deeper into the Scrape-Off Layer (SOL) [1]. After JET operated with an X-point inside the vessel in 1991-2, using the roof of the torus as an open divertor, it was already clear that this was not the complete picture. Although the greater power flux arrives at the outer divertor, net deposition occurred at the **inner** SOL (extending into the private region), with no evidence of deposition in the outer SOL (except in regions shadowed from the plasma) [2]. A toroidally symmetric divertor was then built at the bottom of the JET vessel using in-vessel divertor coils. The asymmetry in the pattern of deposition was again obvious in the Mk I divertor (Figure 1) [3]. However, the presence of heavy deposition of carbon leading to flaking on the water-cooled louvres beyond the inner corner of the MkII divertor [4,5] raises additional issues, and has necessitated a fresh approach to the modelling of erosion/deposition.
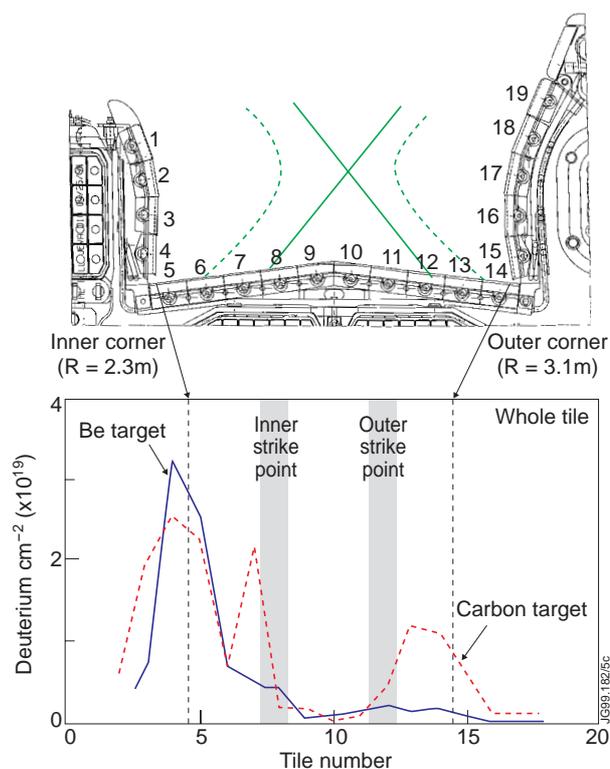

Fig.1: Cross-section of the JET MkI divertor, and a plot of deuterium concentration versus tile number for both the carbon and beryllium tile phases.

2. Modelling to address the Experimental Data

The experimental data from JET that the modelling must address is as follows:

(a) There is no significant impurity deposition in the outer divertor SOL, though there may be some local recycling into shadowed areas close to the strike zone.

(b) Impurity deposition occurs predominantly at the inner divertor leg, deep into the SOL

(c) This deposition is particularly heavy in Mk IIA. Most of the carbon is deposited on the water-cooled louvres, which are several centimetres into the pumping aperture at the corner of the divertor and shadowed from the plasma. The flux at the entrance to this aperture thus must be carbon **neutrals**. The number of carbon atoms deposited is about 4% of the number of ions to the inner target (~1.2 10^{25} carbon atoms in 2000 pulses).

(d) Interaction between the plasma and the main chamber walls (inner and outer) is evident from the appearance and analysis of poloidal limiter tiles. This interaction clearly involves **ions** and not merely charge-exchange neutral (CXN) bombardment. An obvious manifestation of this interaction is that the deposition in the inner divertor SOL for the Be Mk I divertor was carbon-based [3], and also the principal plasma impurity was usually carbon [6].

(e) VUV spectroscopy shows much larger photon fluxes of carbon impurities and neutral D at the lower half of the inner wall. This appears to indicate strong interaction with the inner wall in this area, but it may be due to the large density of neutral particles extending from the inner divertor. Figure 2 shows the phenomenon is not well modelled using the EDGE2D/NIMBUS code

The DIVIMP model has been applied in the Mk IIA configuration for an ELMy H-mode (pulse number 44028). The selected time-slice (60.3 s) is in the middle of a short ELM-free period. Firstly, the pattern of erosion/deposition around the poloidal section was obtained using standard assumptions; the result is shown in Figure 3.
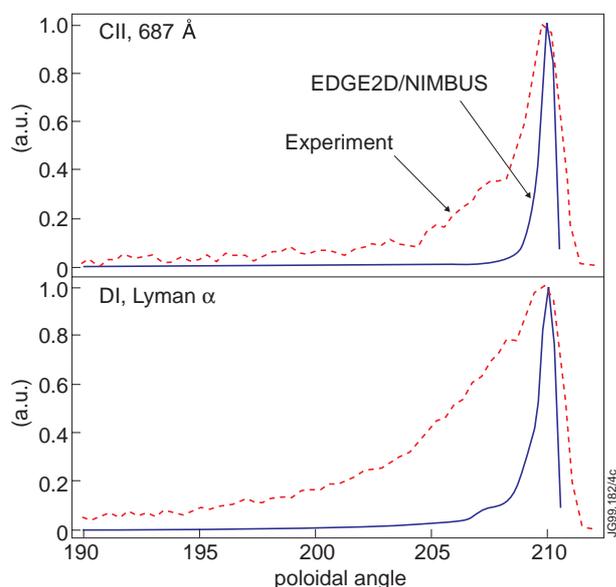

Fig.2: *Spectroscopic observations of C and D photon fluxes from the lower part of the inner wall compared to predictions from the EDGE2D/NIMBUS code*
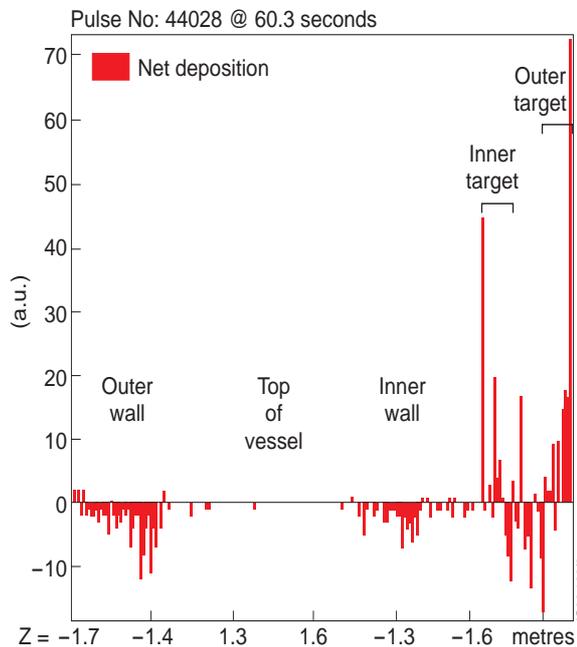

Fig.3: *Net erosion/deposition in the JET MkIIA geometry calculated by DIVIMP for one specific time-slice using standard parameters.*

The match between the model calculations in Figure 3 and the experimental data is poor. In particular, according to the model the flux of neutrals at the aperture to the inner louvres is more than an order of magnitude too low (and in fact most deposition would be at the **outer** corner of the divertor).

The DIVIMP code has many parameters that may be varied, however none of the combinations of values tried could provide agreement with the experimental measurements. It was thus decided to force the model to match the data by introducing extra parameters, and altering some parameters beyond their normal range. A good match to the data could be obtained when the following steps were taken:

(a) Introducing an additional flow in the SOL from outboard to inboard
(b) Enhancing the sputtering at the vessel wall by neutrals (in lieu of adding ion interaction which cannot be done at present in DIVIMP)
(c) Introducing reflection for carbon ions striking the inner divertor target as neutrals.

The result of one such calculation is shown in Figure 4. The flux of neutrals towards the louvres is within a factor of two of the global average for the campaign, deposition/erosion elsewhere in the divertor is modest, and there is some net erosion around the vessel. A comparison between the revised model prediction and the experimental data for the CII emission (visible spectroscopy, looking down into the divertor) is shown in Figure 5. Reasonable agreement is found.
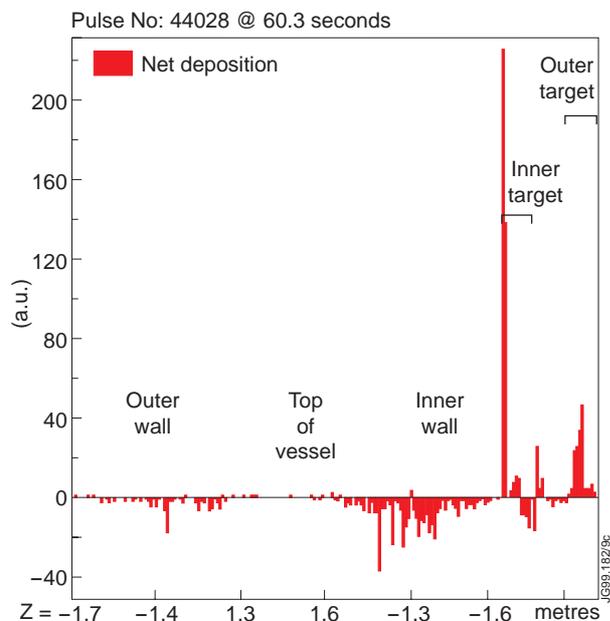

Fig. 4: Net erosion/redeposition in the JET Mk IIA divertor obtained by DIVIMP after introducing additional flow in the SOL and forcing other variables to give agreement with experiment.
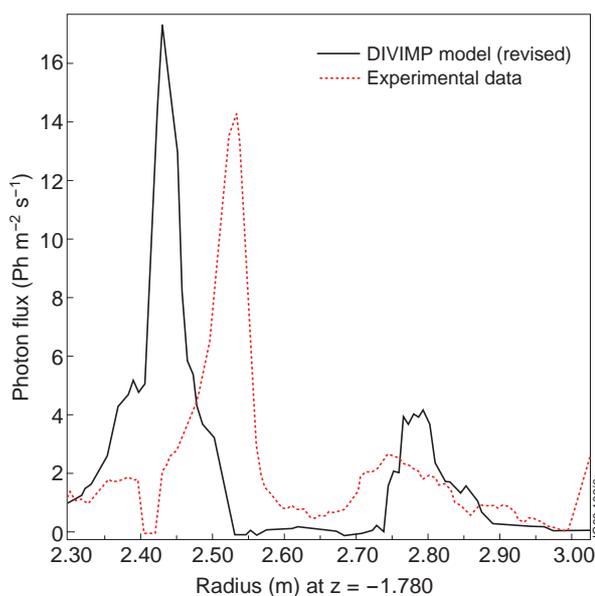
Fig.5: Experimental CII photon flux across the JET MkIIA divertor compared to values calculated by DIVIMP.

The evidence for increased interaction with the main wall was mentioned above. Although initially ad-hoc, the other changes made to DIVIMP are now supported by the following experimental observations:

(a) Measurements of drift velocities for impurities in the SOL have been made with the reciprocating probe located at the top of the vessel [7]. L-mode, H-mode and ohmic pulses all show peak velocities of Mach 0.35 to 0.6 in the SOL in the direction required to sweep impurities to the inner target, as shown in Figure 6.
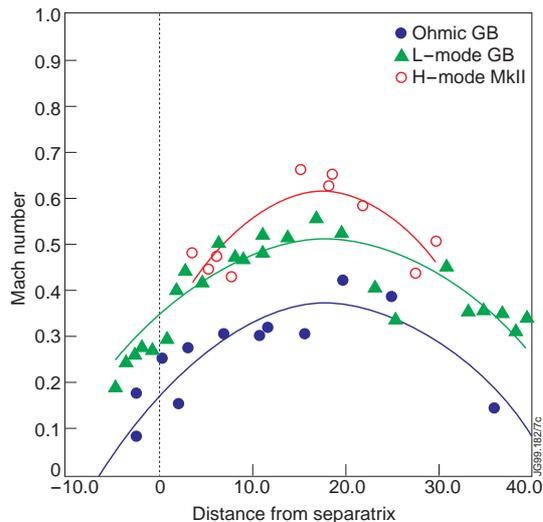
(b) Deposited films exist at the inner divertor. These films may have quite different properties to bulk material [8-10]. More recently, von Keudell et al (in a paper submitted to Nuclear Fusion) have demonstrated high release rates from hydrogen-rich (H/C ~ 0.7) polymer films for C_2H_x at around 550K (close to surface temperatures for MkIIA). This would effectively allow the carbon to recycle.

Fig.6: Flow in the SOL for different types of pulse during Gas Box (GB) and Mk IIA (MkII) operations.

3. Conclusions

DIVIMP modelling of a specific JET discharge has been forced to give agreement with the averaged JET Mk IIA deposition data by introducing several new elements into the model. Taken together, these elements change the magnitude of erosion/deposition in certain areas of the vessel by more than an order of magnitude, as required to match the experimental data. Evidence for each element is seen in JET. Each one implies a physical process that is not included in standard modelling that needs to be explained and quantified. At the same time the empirical DIVIMP solution must be applied to many Mk IIA plasma conditions to show that it is rugged and the **average** deposition agrees with measurements. Erosion/deposition patterns predicted by DIVIMP are sensitive to each of the extra parameters. To demonstrate that these additional processes are correctly simulated, it is important that the effect of varying each parameter can be matched quantitatively, for example:

(a) Different wall/divertor material combinations (e.g. Be/graphite as proposed for ITER, and as employed earlier in JET) can be used to quantify the migration of impurities from the main chamber into the divertor.

(b) Heating/cooling the divertor targets to check the temperature dependence of carbon recycling/ "reflection".

(c) Reversing ∇B reverses the SOL flow [7], so the behaviour of deposition and spectroscopic data on reversing the field direction must be replicated.

Only when a model is shown to correctly reproduce (i.e. quantitatively, not just showing the trends) the erosion/deposition in existing tokamaks, under a range of conditions that test each free parameter, can one have any confidence in using the model to predict behaviour (e.g. tritium retention) in Next Step devices.

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