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Radiation distribution and neutral-particle loss during detachment in JET

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1. Introduction

Detached operation close to the density limit (DL) is a preferred mode of operation in reactors because it allows the reduction of the power load on the divertor targets by radiating a significant part of the power in the divertor volume. Previously, it has been found that in JET high-density plasmas the power carried by neutral particles can be a significant fraction of the total loss power [1,2]. It is important to understand the physical processes in the divertor that give rise to the electromagnetic radiation and to the power loss by neutral particles that are produced by charge-exchange (CX) processes.

The radiation profiles and neutral-particle loss have been studied previously in JET for impurity seeded H-mode DL discharges [1]. Because of ELMs it is difficult to study H-mode discharges by code simulations, and measurements can be difficult to interpret [1]. Therefore, we focus here on L-mode plasmas close to the density limit and try to relate the results to H-mode plasmas.

2. Measurements and simulations

The main analysis tools are bolometer tomography [1,3] and EDGE2D/NIMBUS code simulations [4]. Figure 1(a) shows the radiation profile predicted by EDGE2D/NIMBUS for a detached L-mode discharge with vertical targets in the MkIIA divertor, close to the density limit. The radiation close to the X point consists mainly of carbon line radiation. If one calculates what the JET bolometers would measure if this were the actual emission profile and makes a tomographic reconstruction of these values, one obtains Fig. 1(b). This shows that the coverage of the JET bolometer system [1] is insufficient to resolve the details of the emission profile. Figure 1(b) agrees well with the tomographic reconstruction of the actual bolometer measurements [Fig. 1(c)]. Furthermore, comparing individual simulated and actual bolometer measurements, good quantitative agreement is found. The agreement with other diagnostics (probes and visible spectrometers) is also good. However, although the bolometer data is matched well, the spectral emission of the CII and CIII charge states is not reproduced well in the simulations.

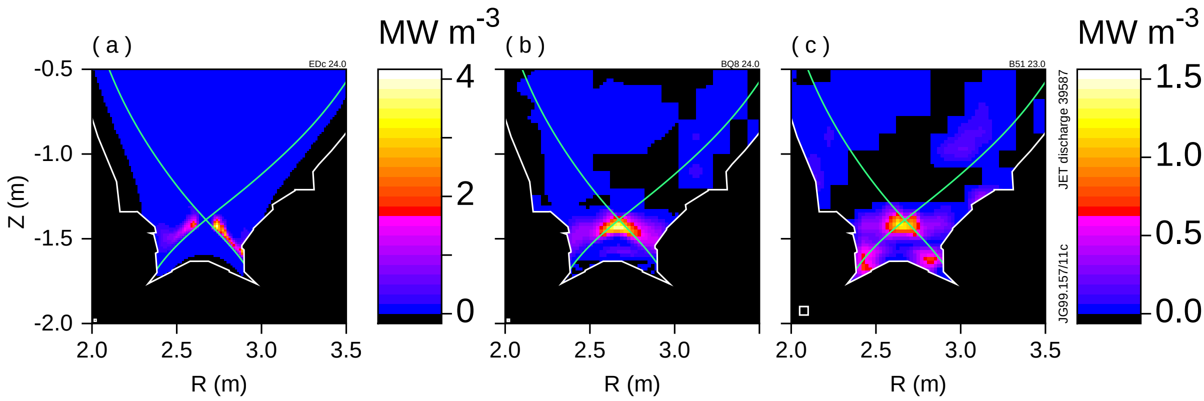

Figure 1 *(a) Emission profile predicted by EDGE2D/NIMBUS, (b) tomographic reconstruction of simulated bolometer data from the EDGE2D/NIMBUS results, and (c) tomographic reconstruction of experimental bolometer data. The plasma under consideration is an L-mode discharge with vertical targets in the MkIIA divertor, close to the density limit. The white box in the lower left corner of each picture indicates the grid size used in the divertor.*

3. X-point sweep experiment to improve resolution

Sweeping the X point is a way to create many more “virtual” lines of sight in the divertor, which makes it possible to reveal more detail about the emission profile than is possible from straightforward tomography [2,5]. In the JET MkIIGB divertor, high-density L-mode plasmas have been moved rigidly down and up by up to 10 cm. To study the peakedness of the radiation profile close to the X point, during the sweep the measurements of three bolometer channels with views close to the X point have been mapped to the angle around a common point where the lines of sight intersect [Fig. 2(a)]. The structure that is revealed by the sweep is very similar to what is predicted by the EDGE2D/NIMBUS simulation of a similar plasma in MkIIA [Fig. 2(b)], which indicates that the vertical localisation in Fig. 1(a) is realistic. The reason for the difference in height of the peak with respect to the X point is not understood. From these experiments it is not possible to confirm the horizontal localisation, nor the split into two peaks on either side of the X point.

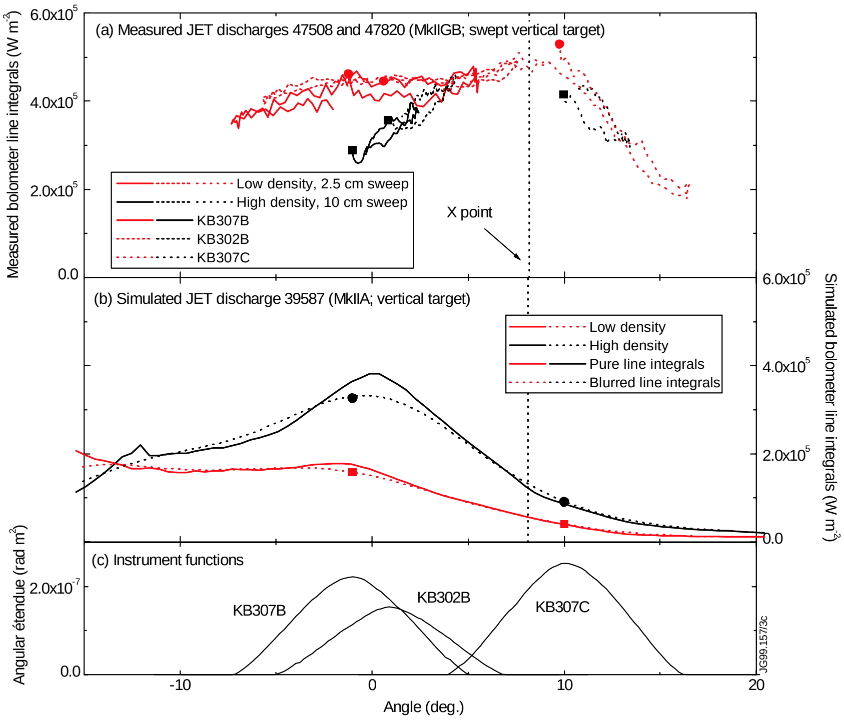

Figure 2 *(a) Experimental and (b) EDGE2D/NIMBUS simulated virtual bolometer line-of-sight data (for three channels KB302B, 307B and 307C), blurred and non-blurred by the instrument function, mapped to angle at two densities [densities not matched in (a) and (b)]. The points indicate the information available without the sweep. (c) Instrument function by which the measurements are blurred.*

4. Charge-exchange neutral losses

The energy flux carried by CX deuterium atoms to the wall is calculated by the EDGE2D/NIMBUS code. This flux can be compared with local values that are estimated from the divertor-bolometer signals. Bolometers are sensitive to both radiation and particles; the particle contribution can be obtained by comparing the divertor measurements with neutral-shielded measurements through the bulk plasma [1,2]. The values here were obtained from such a comparison integrated into the tomographic reconstruction [1]. An important reconstruction parameter to derive the CX losses is the neutral suppression factor. One can select the bolometer channels to which one expects a contribution from CX losses (the divertor channels); the neutral suppression factor influences the contribution of neutrals that is found by the reconstruction for these channels. If the factor is chosen too low, the emission profile from the tomographic reconstruction is very similar to that obtained without using the divertor channels: the emission profile is very smooth and the excess signal due to actual peaks in the emission profile is attributed to neutrals. If the neutral suppression factor is too high, the tomographic reconstruction does not converge to a positive solution or the emission profile has unrealistic peaks. The largest suppression factor that yields a realistic emission profile is found by trial and error. Simulations with assumed emission profiles and an assumed neutral contribution show that this method is capable of extracting the neutral contribution reliably (within a factor of 1.5). Application of this method to H-mode DL discharges in the past has shown agreement with the neutral level predicted by EDGE2D/NIMBUS [1].

Simulated and measured CX losses in the divertor for the L-mode DL discharge of Fig. 1 are shown in Fig. 3. When comparing the values, a number of complications have to be taken into account. Although internally the EDGE2D/NIMBUS code keeps track of the angle with which neutrals hit the wall, the only relevant quantities that are available as output at present are the flux and energy of particles that hit the wall within a cone normal to the wall with a certain acceptance angle. This cone differs from the cones viewed by the bolometers, which are narrow and generally not normal to the wall. The values in Fig. 3 are averaged over the acceptance angle. By narrowing down the acceptance angle in the simulation, it can be shown that the angular distribution is not uniform [solid and dotted curves in Fig. 3(b)]; it cannot, however, be matched to the non-normal acceptance cones of the bolometers. It is therefore likely that if the acceptance cones of the simulation were matched to those of the bolometers, higher values than the curves in Fig. 3 would be obtained, which brings the overall agreement with the measurements well within a factor of 2. Also the shape of the curve matches that of the measurements, in particular the peak between a divertor distance of 1.1 and 1.2 m. One should also bear in mind that the “measured” CX losses that are found from the tomographic reconstruction depend on the neutral suppression factor. Because the neutral suppression factor was chosen the same for all divertor channels (no independent information is available to justify choosing different values for different channels), one can expect the overall and peak neutral level to be reasonable, but that there can be a variation between neighbouring lines of sight. This can explain the scatter in values at the inner target. Somewhat different values are obtained if a neutral contribution is allowed to the channels that view the X point or not (solid and open circles in Fig. 3), which gives an indication of the range of uncertainty.

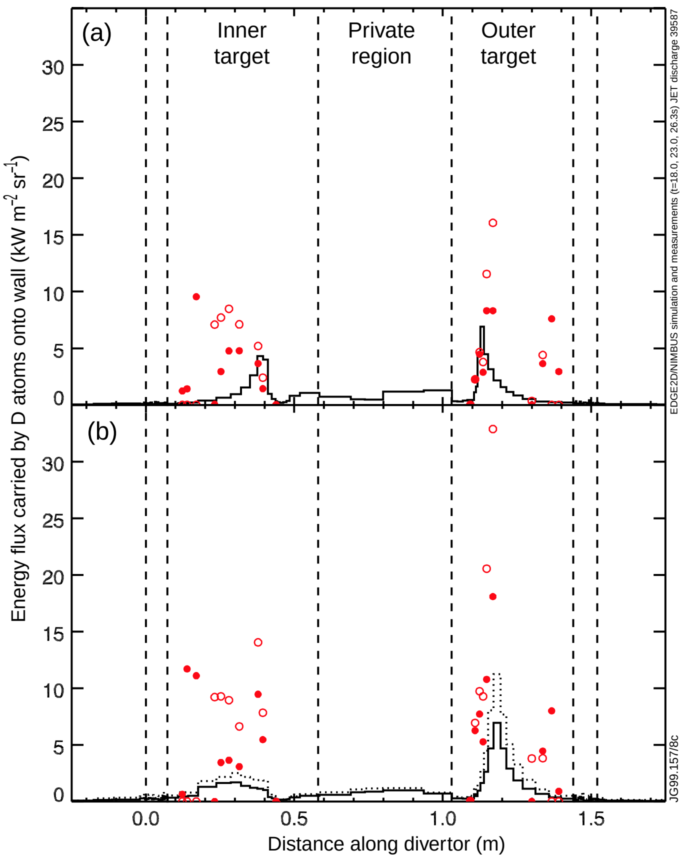

Figure 3 *Energy flux carried by CX neutrals to divertor tiles in (a) low and (b) high density phases of an L-mode DL discharge [(b) corresponds to Fig. 1]. Curves: EDGE2D/NIMBUS simulation (solid and dotted: 90º and 30º acceptance angle, respectively). Points: values derived from bolometer measurements (solid: a neutral contribution allowed for all divertor channels; open: no neutral contribution allowed for channels viewing the X point).*

In the attached L-mode plasma CX neutrals are mainly produced close to the targets. At higher densities (detached plasma) CX neutrals are produced along the separatrix all the way to the X point, with a peak production up to 1/3 of the poloidal distance from the strike point to the X point (5–10 cm). However, most neutrals that reach the wall originate from close to the strike points (their average energy is 5–20 eV), as the neutrals produced at the X point are likely to be ionized before they reach the divertor tiles. This is in contrast with the inference made previously for H-mode discharges [1,2], in which it was thought that the extremely high signals of bolometers viewing the X point were partly due to neutrals from the X point. This is not supported by the code simulations; moreover, impurity and deuterium radiation in simulations of L-mode discharges can account for the high signals of bolometers viewing the X point.

5. Power balance

For a variety of DL plasmas, EDGE2D/NIMBUS simulations show a significant power loss by CX neutrals, in agreement with bolometer measurements. Although no reliable simulations are available for L and H modes in all JET divertors, the following can be concluded from the available simulations. In H-mode DL plasmas in the MkI divertor the neutral loss is small (<5% of the power loss by electromagnetic radiation), whereas in MkIIA plasmas there are strong indications that it is significantly higher (10–20%) [1]. In L-mode DL plasmas in the MkIIA and MkIIGB divertors also a high neutral power loss of 10–25% is found. However, there are indications that it is *not* lower in MkI.

In impurity-seeded H-mode plasmas the maximum-achievable radiated fraction $f_{\rm rad}$ in MkI is higher ($f_{\rm rad} < 80\%$) than in the other divertors (typically $f_{\rm rad} < 65\%$) [1]. At least part of the difference can be explained by the higher neutral losses with increasing divertor closure. In other types of discharges, with lower radiated fractions, the differences between divertors is less clear due to scatter in the data. In the MkIIGB divertor the radiated power and the total deposited power on the divertor tiles, as derived from thermocouple measurements, have been compared. In high-density L and H-mode plasmas it is found that the measured power deposited in the divertor (which includes radiation, ions and neutrals) is very close (within 10%) to the difference between input power and the radiated power deposited on the main vessel wall, as derived from bolometer tomography. Thus, a consistent power balance is found.

6. Conclusions

The radiation profile in high-density discharges in JET usually is very peaked near the X point. The details of the peaking predicted by code simulations cannot be confirmed by bolometer tomography due to the limited resolution of the bolometer system. X-point sweep experiments, however, reveal more information and confirm the vertical peakedness of the radiation profiles.

In several types of plasma in various divertors, high CX-neutral power losses (10–20% of the radiated power) are found from both simulations and measurements. This confirms the initial findings of Refs. 1 and 2. The simulations show that the CX neutrals that deposit the power on the walls are mainly produced near the targets in L-mode DL discharges, and not at the X point as has been inferred previously. Power deposition measurements in the MkIIGB divertor show good agreement with the difference between the input and radiated power.

Acknowledgement

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