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**See appendix of the paper by J.Pamela "Overview of recent JET results",*

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INTRODUCTION

Detached operation close to the density limit is a preferred mode of operation in ITER because it allows the reduction of the power load and the average energy of particles on the divertor targets by radiating a significant part of the power in the divertor volume. 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. Details of the radiation and neutral-particle loss have been studied in the past by bolometer tomography in the JET MkI [1] and MkIIA divertors [2,3]. This study is now extended to the JET MkIIGB divertor with improved tools: high-resolution bolometer tomography by plasma sweeps and CCD-camera tomography.

1. INCREASED BOLOMETER RESOLUTION BY X-POINT SWEEP

Assuming rigid (vertical) movement and no change to plasma conditions, the resolution of bolometer tomography can be increased by introducing virtual lines of sight as the result of the movement [1,4,5]. Although the resolution is only improved in the direction of the sweep and the coverage of projection space [6] is only slightly affected, the improvement in resolution can be significant. Figure 1 shows results from a simulation (with a realistic noise level), which clearly demonstrate the improvement that theoretically can be achieved with the sweep technique under ideal conditions. However, in reality the plasma conditions and hence radiation profile will change slightly during the sweep (e.g. the openness of the divertor changes and the plasma is in contact with previously less-exposed parts of the divertor tiles). Furthermore, it is extremely important to know the viewing geometry [5,6] and viewing direction very accurately. With a reasonable sweep amplitude, for instance 12 cm which roughly corresponds to the separation between bolometer lines of sight in the divertor, the sweep method gives reliable results. Figure 2 shows that in the experimental situation the sweep method enhances the radiating peaks, whereas for different sweep heights the insufficient number of lines of sight in tomographic reconstructions without sweep leads to ambiguous reconstructions. All reconstructions in this paper were carried out by a constrained-optimization method with non-negativity constraint [2].

2. CCD CAMERA TOMOGRAPHY

CCD camera tomography of JET plasmas can be done successfully and reliably for the D_{α} and a C_{III} spectral line (see Ref.8). The view of the camera is toroidal, so one has to assume toroidal symmetry. The same constrained-optimization tomography method with non-negativity constraint is used as for bolometry. There are significant difficulties that have to be overcome in CCD-camera tomography: 1) background light (e.g. reflections), 2) poor resolution in the Z direction due to the near-vertical view, and 3) some features are due to non-toroidally-symmetric radiation. The sweep for enhanced bolometer resolution provides an opportunity to test the reliability of the CCD-camera reconstructions. Figure 3 shows that most radiating features move with the sweep and that hence those features are reliable. Figure 3(a) also indicates the reconstruction

grid used; the results obtained with the present grid and a twice finer grid are similar, which indicates that the present grid is sufficient to represent the features that can be resolved by tomography.

3. RADIATION AND NEUTRALS IN HIGH-DENSITY L-MODE DISCHARGES

Although H-mode discharges are most ITER-relevant, L-mode discharges are easier to analyse because:

- 1) ELMs do not cause difficulties in interpreting bolometer measurements and in matching the plasma with code simulations, and
- 2) there is a large database of high-density L-mode discharges in the various JET divertors.

In the main discharge discussed here ($I_p = 2.0\text{MA}$, $B_T = 2.4\text{T}$, $P_{\text{NBI}} = 1.9\text{MW}$), four subsequent sweeps of the plasma during a gas-puff ramp (in the inner divertor) were used to probe the plasma at four densities, from about 50% to 90% of the density limit (Fig.4). For this density range the plasma is detached at the inner target and attached at the outer target. The bolometer and C_{III} reconstructions at these sweeps are shown in Fig.5. The features in the radiation profiles are reliable, but there remains some uncertainty concerning radiation close to upper divertor plates (cf. Fig.3). The reliable features in both types of reconstructions are very similar. However, it is not yet clear which ionization stages of carbon contribute most to the total radiation in the regions where the C_{III} and total-radiation profiles are different. Interestingly, at first the peaking close to the X point goes up, but then decreases with increasing density although the integrated radiation in the divertor continues upwards (Figs.5 and 6).

Bolometers measure both electromagnetic radiation and the power flux from neutral particles. By considering the discrepancy between ex- and in-divertor bolometers in the tomography algorithm, an estimate of the CX-neutral contribution can be obtained at the location of the divertor bolometers. This method has been demonstrated to be successful in the JET MkIIA divertor [2,3]. Unfortunately, in the MkIIGB divertor there are fewer divertor bolometers and it is difficult to obtain similarly reliable estimates of the neutral contribution (consistent non-negative reconstructions could be obtained without needing to assume any neutral contribution). However, like in unswept plasmas in the MkIIA divertor, by taking into account the additional information from sweeps in MkIIGB, consistent reconstructions without negative values could only be obtained by including a certain level of excess power in divertor bolometers, which we attribute to power deposition by neutrals.

The level of neutrals found (Fig. 6) is similar to that found for MkIIA [3]. Figure 6 also shows that the neutral power flux first increases with density and then decreases. Although the error bars on the neutral power flux are large [3], the variation with density is so large that there is no room for doubts. Although the neutral level decreases for high densities, interestingly, the D_α emissivity continues to rise. The decrease of the neutral power flux may be due to an increased distance between the CX-neutral producing region and the target and/or improved shielding by plasma in front of the target with increasing density, which still has to be verified by code simulations. The same quantities have been investigated in a discharge with different fuelling location (outer divertor) (Fig.6). Although different fuelling locations have different efficiencies, the radiation profiles are

very similar. However, although the trends are the same, the neutral flux is quite different for different fuelling locations (there are indications that the peak neutral flux is on the side of fuelling). A high-resolution radiation profile from a sweep in a high-density H-mode plasma (radiation averaged over ELMs) have also been obtained; qualitatively this profile is very similar to the profiles obtained in L-mode. B2-EIRENE SIMULATIONS B2-Eirene [7] simulations have been carried out for a similar L-mode plasma. Although the match to diagnostics has not yet been optimized, the features in the total radiation profile are similar (cf. Fig. 5). In the past, good agreement has been found between code simulations and the neutral power loss derived from the bolometer measurements [2,3]. Such a detailed comparison still needs to be conducted for the present discharges. Unfortunately, the neutral level derived from bolometer tomography only gives estimates at the locations and directions of the bolometer lines of sight; the total power lost by neutrals can only be obtained from code predictions of the neutral power deposition on the entire vessel wall and divertor tiles.

CONCLUSIONS.

High-resolution bolometer tomography and CCD-camera tomography are successful to give improved insight into divertor radiation. However, due to many experimental complications the improvements in resolution are less than what one would expect from simulations. During a density rise close to the density limit, the radiation peaking close to X point goes down just before divertor MARFE formation. The measured power carried by neutrals to the wall follows a similar pattern.

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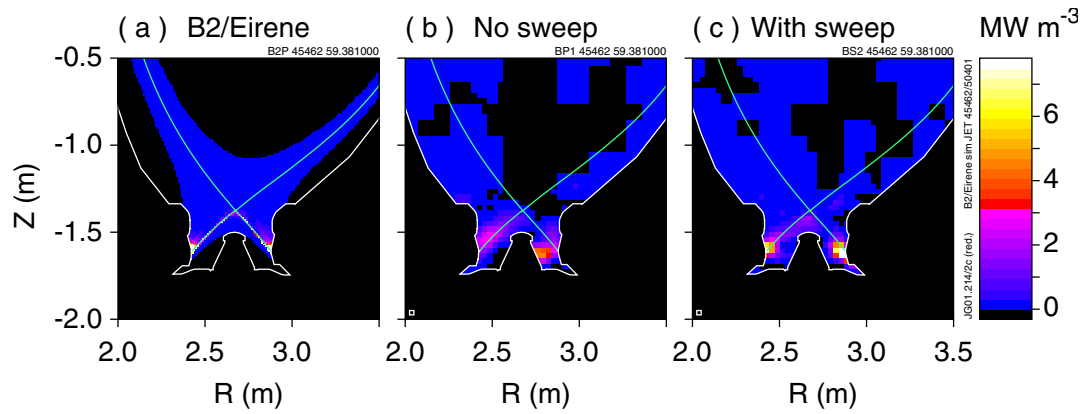


Figure 1: (a) B2-Eirene [7] predicted emission profile used as phantom, (b) reconstruction without sweep, (c) reconstruction with

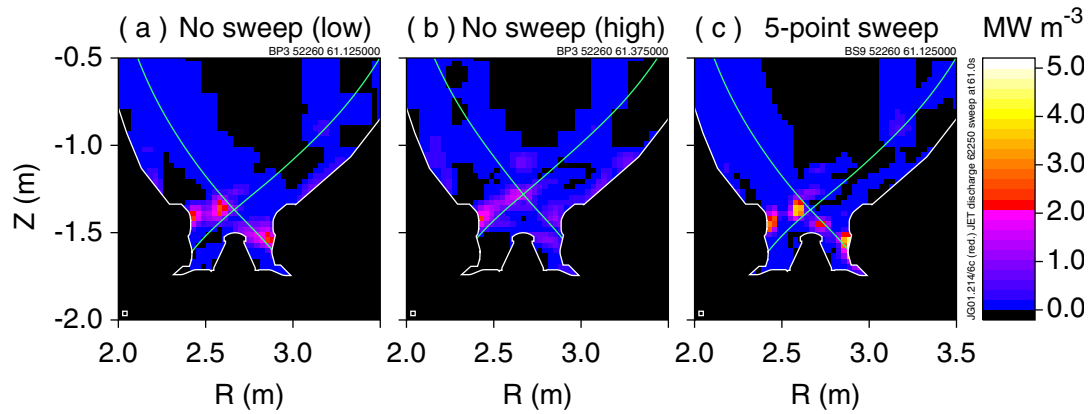


Figure 2: Example of reconstructions from experimental data: (a) at low position of sweep without taking into account sweep, (b) same for high position, (c) taking into account the sweep.

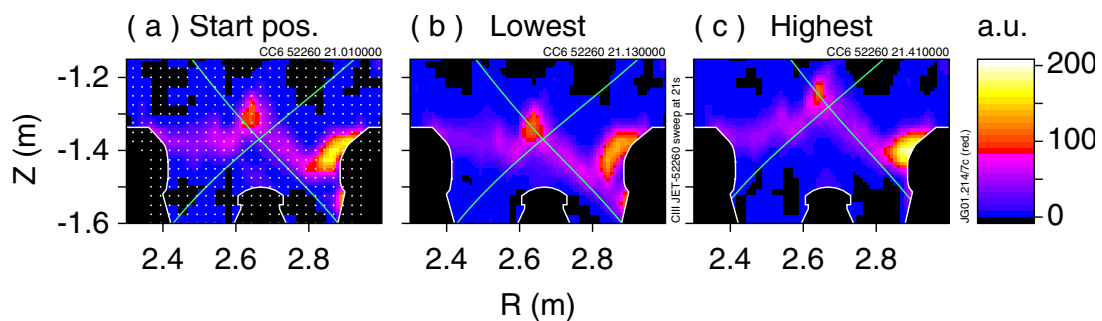


Figure 3: Tomographic reconstructions of CIII light measured by a tangential CCD camera during three phases of the sweep. The dots in (a) indicate the reconstruction grid.

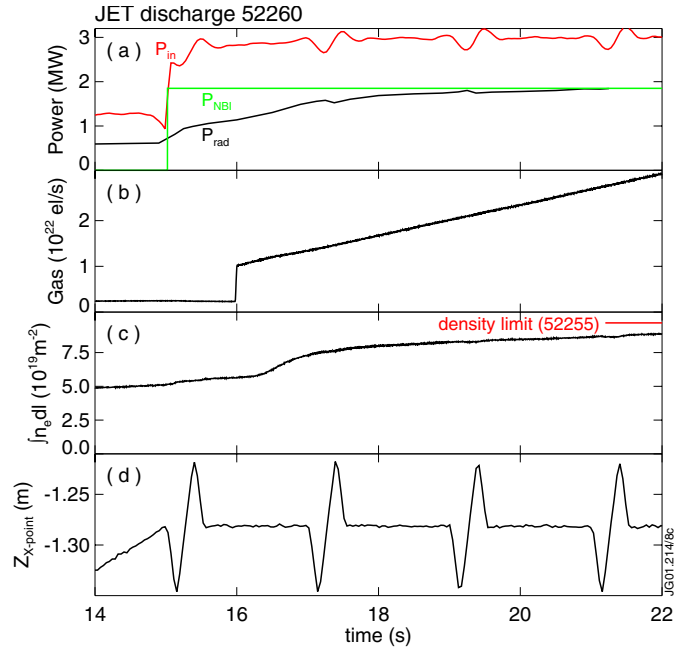


Figure 4: Overview of plasma parameters during a density ramp with inner-divertor fuelling in an L-mode discharge.

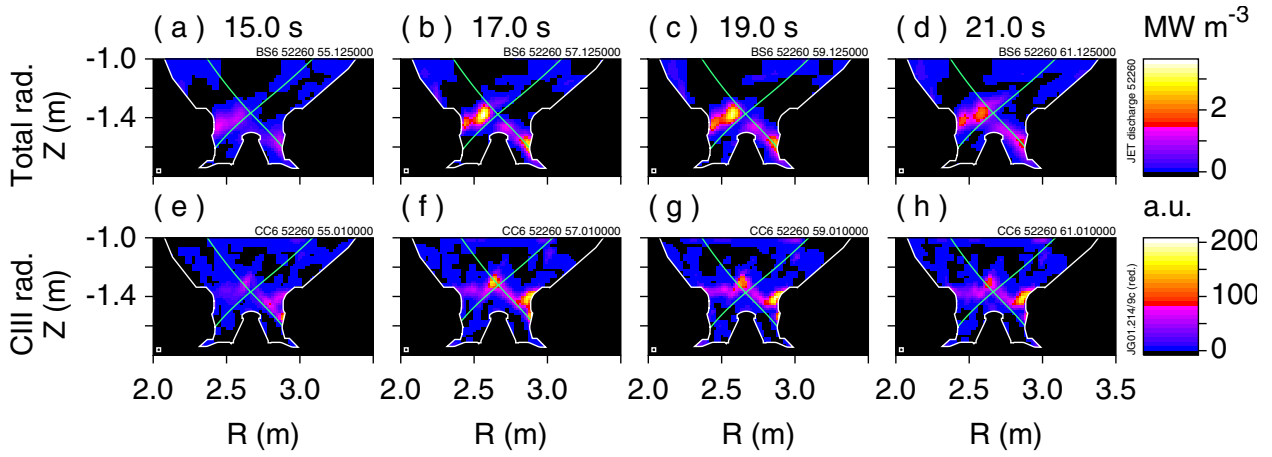


Figure 5: Bolometer reconstructions (taking into account the sweep) and CIII radiation from CCD-camera tomography at four consecutive sweeps in the L-mode discharge of Fig. 4.

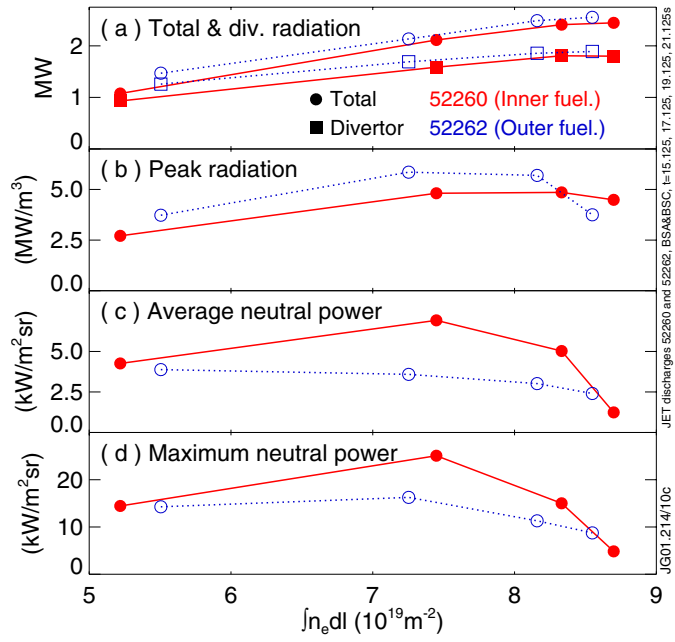


Figure 6: Trends of radiation and neutrals as a function of electron density for two L-mode discharges with different fuelling location

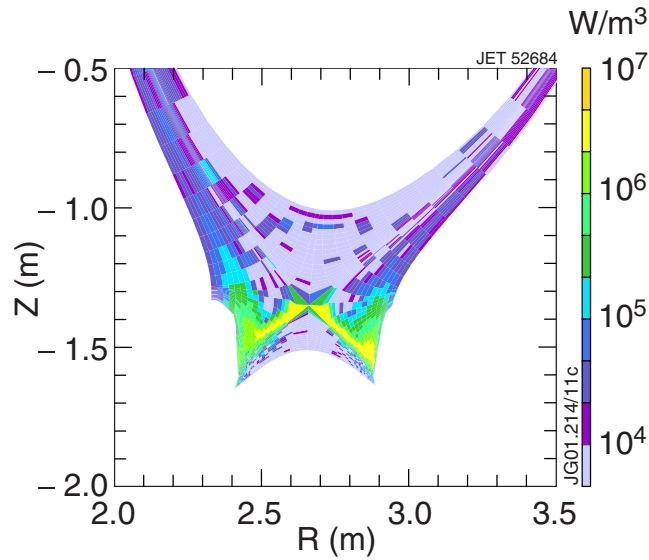


Figure 7: Total radiation pre-dicted by B2-Eirene simulation of a similar L-mode discharge as in Fig. 5.