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Journal of Nuclear Materials 290–293 (2001) 896–899

journal of nuclear materials

www.elsevier.nl/locate/jnucmat

Narrow power deposition profiles on the JET divertor target

J. Lingertat *, M. Laux, R. Monk

Max-Planck-Institut für Plasmaphysik, Euratom Association, Teilinstitut Greifswald, Wendelstein Str. 49A, D-17491 Greifswald, Germany

Abstract

One of the key unresolved issues in the design of a future fusion reactor is the power handling capability of the divertor target plates. Earlier we reported on the existence of narrow power deposition profiles in JET, obtained mainly from Langmuir probe measurements. We repeated these measurements in the MkI, MkII and MkIIGB divertor configurations with an upgraded probe system, which allowed us to study the profile shape in more detail.

The main results of this study are: In NB heated discharges the electron temperature and power flux at the outer target show a distinct peak of ~5 mm half-width near the separatrix strike point. The corresponding profiles on the inner target do not show a similar feature. The height of the narrow peak increases with NB heating power and decreases with deuterium and impurity gas puffing. Ion orbit losses are suggested as a possible explanation of the observed profile shape. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: JET; Power flux; Fast ions; Langmuir probe; Divertor

1. Introduction

In this paper we examine the nature of narrow power deposition profiles which are regularly observed on the divertor target plates during neutral beam heated plasma discharges in JET. This phenomenon is highly undesirable, since it reduces the maximum power exhaust capability of a given divertor configuration. Earlier [1–3] we reported on the existence of narrow power deposition profiles in JET, obtained mainly from Langmuir probe measurements with limited spatial resolution. We repeated these measurements in the MkI, MkII and MkII GB divertor configurations with an upgraded probe system and by applying the technique of strike point sweeping, which allowed us to study the profile shape in more detail.

The crucial question, how the observed narrow power deposition profiles extrapolate to a next-step device like ITER, can only be answered satisfactorily after identification of the physics mechanism. In [3] the narrow peak of power flux and the simultaneously observed current flow between divertor plasma and target were assumed to be caused by radial gradients of electron and ion temperature. This model qualitatively reproduced the experimentally observed current flow profiles. However, fitting the observed narrow power deposition profile required rather large values for the ratio T_i/T_e or artificially small values for the ration λ_i/λ_e (fall-off lengths of ion and electron temperature, respectively). Another tentative approach, discussed in this paper, assumes ion losses to be responsible for the observed profile shape.

2. Experiments and results

The divertor target plates in JET are equipped with an array of Langmuir probes [4]. Each probe consists of three probe tips which alternatively can be used in single or triple mode of operation. Fig. 1 shows a poloidal cross-section of the MkI divertor together with the location of the probes. To obtain probe measurements with high spatial resolution the two strike points are periodically swept with constant velocity (~1 mm/ms) over some of the probe tips. Typically, the sweep

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* Corresponding author. Tel.: +49-1235 465 51.

E-mail address: johann.lingertat@ipp.mpg.de (J. Lingertat).

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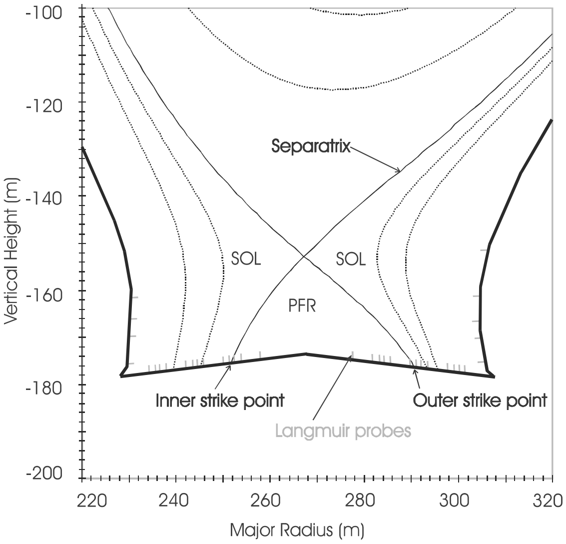

Fig. 1. Poloidal cross-section of the MkI divertor in JET showing the location of Langmuir probes together with a typical plasma equillibrium.

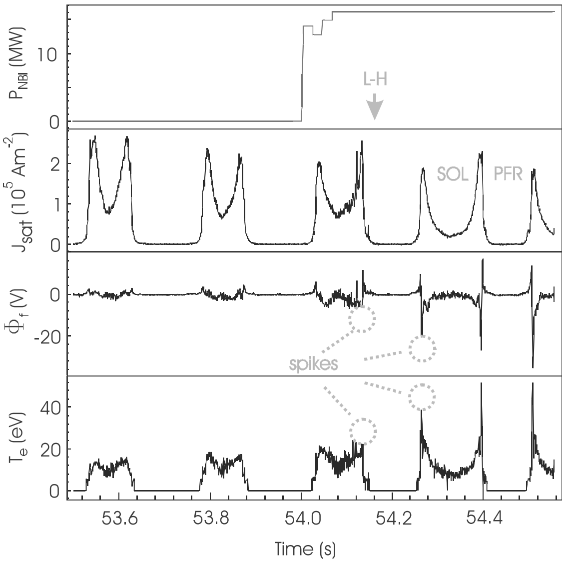

Fig. 2. Overview of typical triple probe results obtained by strike point sweeping (#32745, outer divertor, $\langle n_e \rangle = 7 \times 10^{19}\ \mathrm{m}^{-3}$).

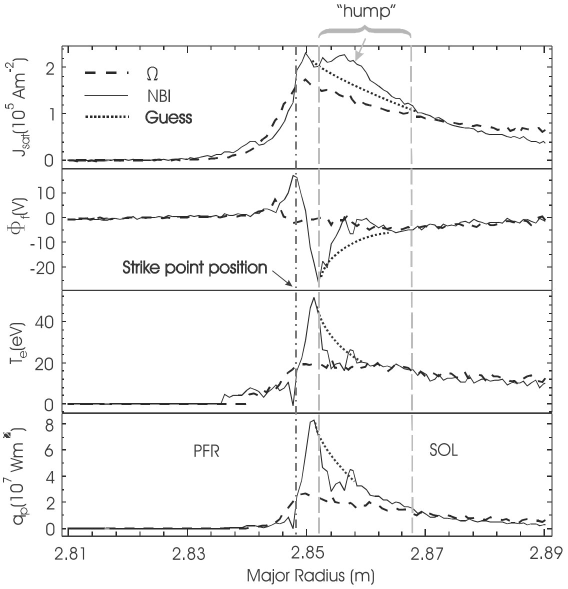

Fig. 3. Profiles of ion saturation current J_{sat}, floating voltage Φ_f, electron temperature T_e and parallel power flux q_p near the outer strike point (#32745). The dashed lines show the profiles during the ohmic heating phase, the solid lines during the NB heating phase. The dotted lines are guessed profiles, assuming the 'hump' in J_{sat} is caused by fast ions on loss orbits.

frequency is 4–5 Hz and the amplitude 10–15 cm. Under those conditions the obtainable spatial resolution in the radial direction is determined by the probe diameter of 2.4 mm. By operating individual probes in the swept target region in single and triple mode, simultaneous results from both modes of operation are obtained.

Fig. 2 shows typical results from a triple probe using the strike point sweeping technique. The probe is located in the outer divertor target. The discharge starts with an ohmic phase. At 54 s the neutral beam injection (NBI) is switched on (~16 MW) and at ~54.16 s the discharge goes into H-mode. The probe is crossed during the time interval shown in Fig. 2 by the outer strike point 9 times, as visible by the occurrence of peaks in the ion saturation current J_{sat}. The first four crossings take place during the ohmic phase of the discharge, the next two during the L-mode phase and the last three during the H-mode phase. During the sweep the probe is exposed to the private flux region (PFR) and scrape-off layer (SOL).

With the onset of NBI the floating voltage (Φ_f) and the electron temperature (T_e) develop sharp peaks (spikes), which are located near the strike point. The occurrence of the sharp T_e peak before the L → H transition is barely visible in Fig. 2. However, discharges with NBI power below the H-mode threshold clearly show the existence of the sharp T_e peak in L-mode.

Fig. 3 shows a detailed view of J_{sat}, Φ_f, T_e and q_p profiles obtained from Fig. 2 by substituting for one sweep period time by major radius and overlaying profiles from the ohmic and the NBI-phases. The ohmic and NBI profiles of all four parameters in Fig. 3 agree quite well in a region which is 4–10 mm away from the strike point position. The strike point position has been arbitrarily set to ~2.85 m, which is within the accuracy (±2 cm) of JET equilibrium codes [5].

During the NBI phase the maximum ion saturation current increases. In addition, it shows a 'hump' which can be regarded as a current J_{add} flowing on top of J_{sat}. The dotted line in Fig. 3 is a schematic and rough guess on how the profile might look like without the additional current contribution. In the region of the 'current hump' Φ_f and T_e appear to be suppressed. The result of that suppression is a narrowing of the negative peak in Φ_f and the positive peak in T_e. Again the dotted lines are rough guesses of how the profile shapes might look like without distortion.

From Fig. 3 it is obvious that the sharp peaking of the parallel power flux q_p is related to the T_e peak. The half-width of the power flux peak is ~4 mm. Integrating the power flux profile over the half-width shows that ~30% of the total power flow in the narrow layer. The fall-off length of the guessed profile is ~8 mm. Taking the flux expansion into account the latter value transforms to ~3 mm at outer midplane.

The triple probe results are qualitatively supported by single probe measurements. Independent from probe techniques, the existence of narrow power deposition profiles in JET has been recently confirmed by calorimetric measurements [6].

On the inner divertor plate, profiles of J_{sat}, Φ_f and T_e were measured by Langmuir probes located in this area. They do not show any narrow features or structure. Only the floating voltage deviates from the standard case, in that its value stays positive over the whole region of the inner divertor plate. This feature is well known and usually associated with an thermoelectric current flowing from the outer (high T_e) to the inner (low T_e) target plate [7]. The positive peak of the floating voltage on the outer target plate (Fig. 3) is again an indication of an electric current, this time circulating between different parts of the outer target plate and probably driven by strong radial gradients of electron and ion pressure near the plate [3].

3. Discussion

The observed profile structure in the outer strike zone has not been reproduced by plasma edge codes like EDGE2D, even with the inclusion of drift terms and non-ambipolar transport. One well-known phenomenon, the loss of fast ions from the closed flux surface region due to the existence of loss orbits [8], is generally not included in those codes. It was used in the past to explain anomalies of power deposition patterns (third strike zone) observed on the JET divertor target [9–11]. Thereby the deposition pattern of lost ions on the divertor target plate was calculated with the particle following code ORBIT [12]. This code calculates and displays the trajectory of an ion, which is launched from the closed flux surface region at a distance δx from the separatrix, using the real magnetic geometry. Important input variables of the code are the ion energy E_{ion} and the ratio of parallel v_p to total velocity $v(\alpha = \arcsin\{v_p/v\})$. A typical result is shown in Fig. 4, where a deuterium ion with 5 keV was launched from a position 5 mm inside the separatrix at outer midplane and with $\alpha = 45°$. Clearly, the ion crosses the separatrix near the x-point region and hits the target plate outside the strike point. By systematically varying the input parameters a loss region can be constructed [13] and the deposition pattern on the target plates studied.

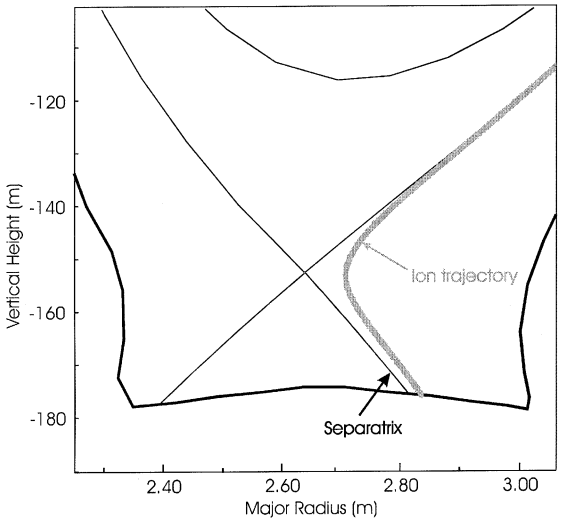

Fig. 4. Calculated poloidal plane trajectory of a 5 keV deuterium ion, launched 5 mm inside the separatrix at outer midplane with $\alpha = 45°$.

We used the ORBIT code to calculate the deposition pattern for typical discharges where we observed narrow power flux profiles. Radial electric field (see [13]) and ripple effects were not included. The main results are: the majority of the loss ions are deposited on the outer target plate near, however outside, the strike point. The radial width of the deposition zone increases with increasing ion energy. The maximum possible ion energy, 80 or 140 keV is defined by the injection energy of neutral beam particles. The deposition width for such energies would be $\geqslant$ 10 cm. For energies of a few keV, which are present in the tail of the Maxwellian distribution of the thermal ion component, the deposition width is in the range of 1–2 cm. It is worth to mention, that at such energies and at typical plasma edge densities, the ions are collisionless.

Comparing the code results with the experimental observations we tentatively assume that the 'current hump' of Fig. 3 is caused by lost ions with an energy of a few keV. This additional current density would then have a maximum value of $\sim 5 \times 10^4$ A m^{-2} and the fluence of fast ions at the target would be of the order of magnitude of $2 \times 10^{21}\ \mathrm{s}^{-1}$, which is less than 1% of the total particle flux to the target. The additional ion current would unbalance the ambipolar flow to the floating probe tip and cause the negative value of the floating voltage to drop. This is indeed observed as shown in Fig. 3. The electron temperature, which is derived essentially from the floating voltage, shows a similar drop.

A more quantitative estimate of the expected drop in Φ_f, using the same approach as in [14] with $T_\mathrm{i} \to 0$, but with the addition of a fast ion component with an energy E_fast and assuming a constant plasma potential gives

$$\begin{aligned}\Delta\Phi_\mathrm{f} &= \Phi_\mathrm{f}^\mathrm{fast} - \Phi_\mathrm{f}^\mathrm{thermal} \\ &= \frac{kT_\mathrm{e}}{2\mathrm{e}} \ln\left\{ \frac{1 + r(2\sqrt{(1+r)\eta - r} + r[(1+r)\eta - r])}{1 + r(\eta - 1)/\eta} \right\}\end{aligned} \tag{1}$$

with $r = n_\mathrm{fast}/n_\mathrm{thermal}$, $\eta = 2E_\mathrm{fast}/kT_\mathrm{e}$, $n_\mathrm{fast} =$ density of fast ions, $n_\mathrm{thermal} =$ density of thermal ions. For $E_\mathrm{fast} = 5$ keV, $T_\mathrm{e} = 30$ eV and $r = 0.02$ we find $\Delta\Phi_\mathrm{f} = 9.1$ V, which is of the same order of magnitude as the guessed value in Fig. 3 of 10–15 V. Given the simplifications in deriving $\Delta\Phi_\mathrm{f}$ ($T_\mathrm{i} \to 0$, no secondary electron emission) and the use of guessed values for the undisturbed floating potential, the calculated value is in good agreement with the observed one. This supports the ion loss model, although, it remains speculative without further experimental evidence, like a direct measurement of the ion energy.

Further qualitative support for the ion loss model comes from a preliminary study of parameter dependencies. The narrow T_e peak on the outer target plate decreases with deuterium and impurity gas puffing rate (increasing density, decreasing T_i, increasing collisionality) and increases with heating power (increasing T_i).

As shown qualitatively in Fig. 3, the implementation of the ion loss model into the Langmuir probe data evaluation leads to less narrow Φ_f, T_e and q_p profiles. However, the maximum power flux is not influenced by including J_add and the total power deposited on the outer target plate even increases. This improves the power balance in NB heated JET discharges.

4. Summary and conclusions

Langmuir probe measurements on JET divertor target plates during NB heated discharges show the existence of narrow power deposition profiles near the outer strike point. These profiles have been observed in different divertor configurations. The narrow power flux profile is caused by a strongly peaked electron temperature. The peaking increases with NB power and decreases with increasing deuterium or impurity puffing rates.

These observations are consistent with a model that makes ion orbit losses responsible for the specific form of the observed profile shape. The deposition pattern of the lost ions has been studied with the ORBIT code.

The ion loss model explains three features of the measured profiles: the asymmetry between outer and inner target plates, the radial extent of the distorted profile region and its dependence on the edge T_i and collisionality. In this picture the extreme profile narrowness disappears after including the additional lost ion flow into the Langmuir probe data evaluation. However, the maximum power flux near the outer strike point retains its high value and the total power deposited on the outer target plate increases.

Scaling studies of the power flux and electron temperature fall-off lengths should take the profile distortion properly into account. An estimate of the direct effect of fast ion deposition in ITER (local target sputtering and heating) would require the development of a code which calculates the intensity and the deposition pattern of lost ions for a given magnetic geometry and T_i-profile.

If the lost ion model is correct, the measurement of the ion saturation current profile would allow the determination of the lost ion intensity, an important value in a certain class of L → H transition theories [8,15].

Acknowledgements

The authors gratefully acknowledge support from the Divertor Physics Task Forces and the JET Operation Team.

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