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SIGNIFICANCE OF THE RADIAL ELECTRIC FIELD TO DIVERTOR LOAD ASYMMETRIES

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ABSTRACT

JET divertor load measurements using embedded thermocouples have indicated a large target asymmetry and non-uniformities in the loads and that, under H-mode conditions, the load is dominated by the ion component. ASCOT simulations of the ion contribution to JET divertor loads are consistent with the presence of a large outward radial electric field E_r in the Scrape-Off-Layer (SOL) next to the separatrix. Such a field would provide an explanation for observed features of the divertor loads in JET. The required field for reversing the load asymmetry is within the range of the estimated SOL E_r in JET, but reproducing the experimental heat deposition profiles requires higher field values.

PACS: 52.55.Rk *Key words*: divertor, load distribution, radial electric field, monte carlo, ascot

1. INTRODUCTION

How to extend the lifetime of the divertor targets is a key question in the design and operation of ITER. A good understanding of the various mechanisms affecting the particle and energy load distribution on divertor targets is clearly important for the optimisation of divertor design and of scrape-off layer parameters. The radial electric field E_r (both in the core plasma and in the SOL), the direction of the gradient drift proportional to $B \times \nabla B$, the pedestal density and temperature as well as the poloidally asymmetric plasma density, neutral density and temperature profiles in the SOL can all have an effect on the distribution of particle and heat fluxes at the divertor targets [1, 2, 3].

In JET, measurements of the heat loads to the divertor targets indicate that the heat load displays a narrow (few mm) peak close to the separatrix. Such a ‘hotspot’ structure can lead to the need of a premature disposal of the divertor targets. Furthermore there is a strong asymmetry between the inner and outer targets and the ions seem to dominate the load at least in H-mode conditions [3]. Because such asymmetry in heat deposition is hard to conceive within the fluid approach, these observations call for a detailed study of the kinetic behaviour of the ion component in the vicinity of the separatrix. In this work, the H-mode divertor load distributions in JET and ASDEX Upgrade are simulated with the orbit-following Monte Carlo code ASCOT [4] using experimental density, temperature and magnetic background, wall and divertor geometry together with OSM2/EIRENE SOL density and temperature data obtained from JET. The SOL radial electric field emerges as an important factor in determining the heat load asymmetry between the inner and outer divertor targets as well as the observed peaking of the load profile near the separatrix.

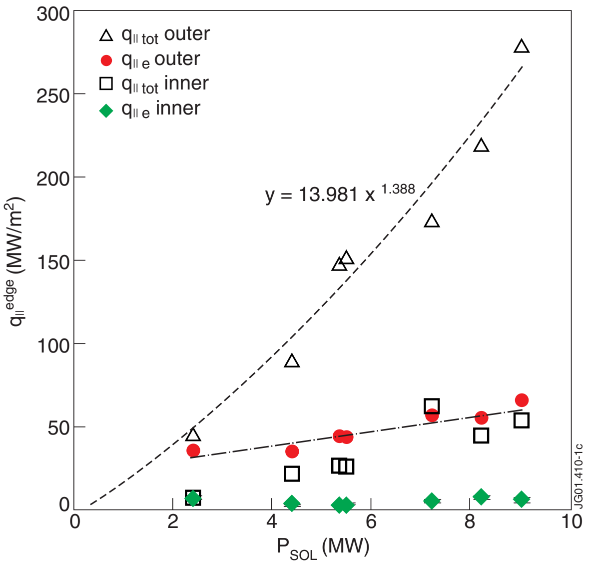

Fig.1: Parallel peak power flux on the targets vs. power entering the SOL. The peak heat flux to the targets can be obtained by dividing $q_{\parallel}$ by a geometrical factor of 13.

2. DEPOSITION PROFILES OBSERVED ON JET DIVERTOR TARGETS.

The embedded thermocouples indicate a large inner/outer target load asymmetry under H-mode conditions in JET [3]. Figure 1 shows the peak heat flow to inner and outer targets as a function of the power through SOL. On the average the magnitude of the integral power asymmetry is of the order of 1:3, but in terms of the peak heat flux the asymmetry can be much higher. The deposition profile can be determined both with shot-by-shot method and by sweeping the X-point [5]. The shape of the profile is different for the inner and the outer target, see Fig.2.

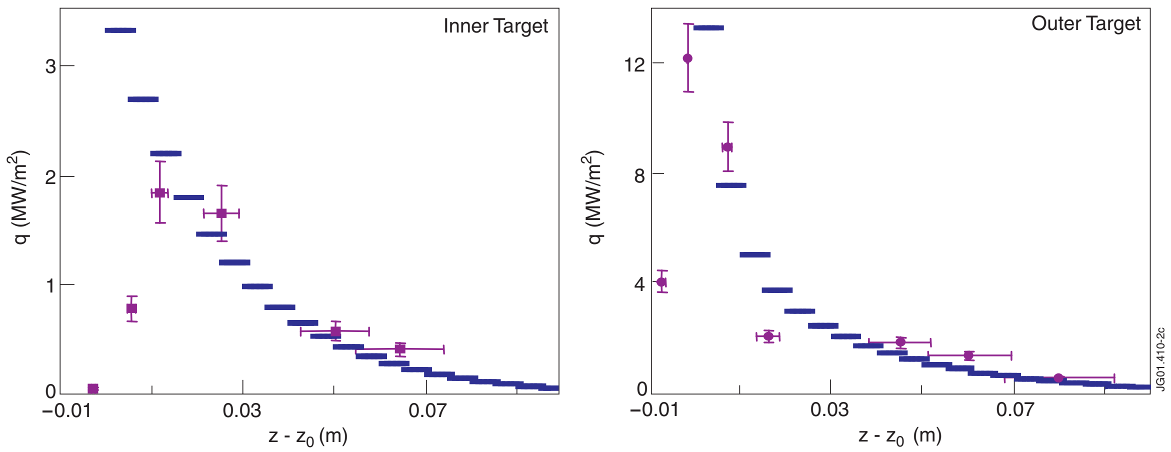

Fig.2: Comparison of shot-by-shot (with error bars) and swept measurements of the divertor heat deposition profiles in JET. On the horizontal axis is the vertical distance from the separatrix.

The width of the heat deposition profile is found to decrease with input power, and the structure of the profile appears to require a double exponential: there seems to be a very narrow (few millimeters) layer adjacent to the separatrix in which the heat load is significantly higher than further out. This 'hot spot' structure can be very detrimental to the divertor targets, and thus this kind of features should be eliminated under normal operation. From Fig.1 it is also seen that, in H-mode conditions,the total power deposited to the targets is much higher than the estimated electron power (from the Langmuir probes), thus indicating that most of the target load is provided either by ions or supra-thermal electrons.

Conventionally, the fluid approach has been considered sufficient when modelling SOL dynamics. However, the observed target load asymmetries as well as the peaked structure of the load profiles cannot easily be explained by conventional edge fluid models [3]. Because the radial profiles of the heat and particle loads on the divertor targets exhibit very narrow structures close to the separatrix (recall Fig.2), and the ion component dominates the loads, it is natural to consider kinetic effects due to ions as a possible explanation. In the kinetic approach, ions originating from the bulk plasma and traversing the separatrix on wide orbits could provide a mechanism responsible for the narrow peak observed on the targets and explain why the ions dominate the heat load in this region. Indeed, this mechanism was already addressed by Chankin et al. by considering collisionless orbits of hot ions originating from the plasma bulk [6].

It should be kept in mind that kinetic effects will strongly depend on the direction of the toroidal magnetic field B_T : in the normal magnetic configuration the ∇B drift is towards the divertor targets, and in the reversed B_T configuration the ∇B drift is away from the divertor targets. This reversal will thus have a profound effect on the orbits of charged particles and may affect the divertor target loads considerably. Thus, the experimental reversal of the direction of B_T can provide an important test for the validity of the kinetic hypothesis. Following the ideas of Chankin et al., we consider collisionless ion orbits that originate right inside the separatrix on the outer horizontal midplane (see Fig.3).

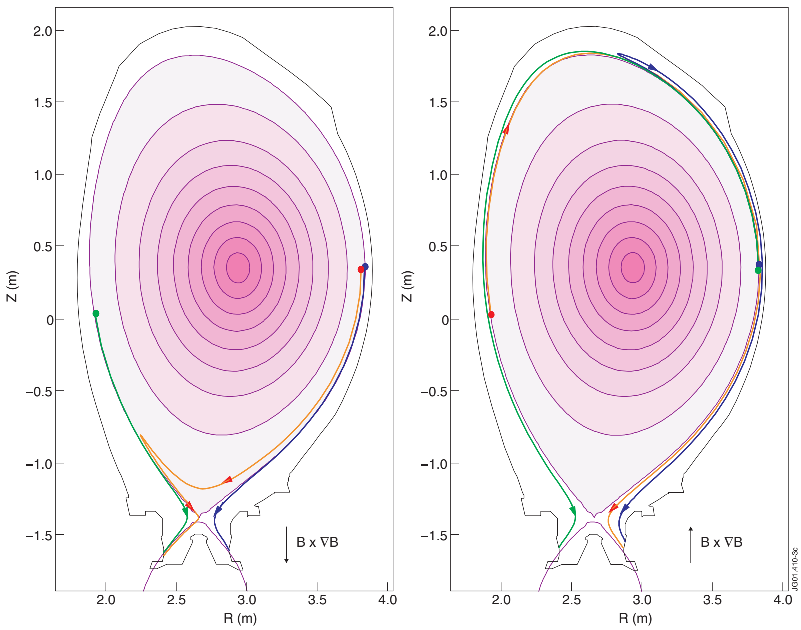

Fig. 3: Collisionless divertor orbit topologies in normal and reversed magnetic field configuration.

It then appears reasonable to expect an inboard-outboard asymmetry favoring the inner divertor target for the normal configuration (∇B drift towards the divertor targets). This is because all trapped orbits with turning points on the high field side end up at the inner target, while only a very selected group of orbits can reach the outer target. (The situation is reversed if the particles have very high energy: for $E > 4.5$ keV all the particles end up at the outer target [6]). Also, the orbits intersecting the inner target are on the average much longer than those leading to the outer target and, thus, the flux to the inner target is much more prone to collisional broadening than the flux to the outer target. Consequently, the deposition profiles to the inner target are expected to be higher and not to exhibit thin structures. For the reversed configuration (∇B drift away from the X-point) the asymmetry is reversed now favoring the outer target. Thus, even though this mechanism appears to naturally account for the measured shape of the deposition profiles, it produces target asymmetries opposite to what has been observed experimentally.

It is not, however, sufficient to consider only one location in the poloidal plane when estimating the fluxes to different targets. In reality, ions are born on loss orbits uniformly in the poloidal plane. When other points of origin are included in the investigation of collisionless orbits, the target load asymmetry is further enhanced. Consider, for example, the point in Fig.3 at the separatrix near the inner horizontal midplane. In the normal configuration in the absence of collisions, all the divertor orbits from this location will end up on the inner target. Because no orbits lead from the high field side to the outer target, and even from the low field side only a fraction of the ions entering the SOL end up at the outer target (many of the banana orbits are too short to reach the divertor targets), the total asymmetry is clearly opposite to the one observed experimentally: the asymmetry ought to be in favor of the inner target. Correspondingly, under the reversed configuration the divertor loads are given by the following orbit topologies: the outer target now receives all the ions that enter the SOL on the left hemisphere and, in addition, ions on sufficiently long banana orbits originating from the right hemisphere. Meanwhile the inner target is reached only by passing orbits entering the SOL from the low field side. Thus the particle load to the outer target should now greatly exceed the load to the inner target. Also another difference arises for the reversed field configuration:under these conditions the average length of the orbit segment connecting a point from the separatrix to the divertor target is much longer than under the normal configuration. Consequently, the collisional effects are expected to be much more important in the reversed configuration than in the normal one, thus eroding the kinetic features in the deposition profile even on the outer target.

3. MONTE CARLO SIMULATIONS

The guiding centre orbit-following Monte Carlo code ASCOT was utilized in a scan of various parameters that may have a role in causing the observed features in JET divertor loads. First, in simple simulations searching for divertor target asymmetry trends caused by varying one parameter, ion ensembles of 1000 deuterons representing edge plasma ions in JET configuration (H-mode discharge #49511) were launched from $\rho = 0.95$, deep enough to prevent direct orbit losses from the launch location. Each particle was followed for 0.1s or until it hit a divertor target. The particles suffered Coulomb collisions from a fixed background plasma. The edge density in this simulation was $2{:}4 \cdot 10^{19}\ m^{-3}$ for electrons and ions, and the temperature was 830 eV for electrons and about 580 eV for ions. The results of a basic case in the normal and reversed magnetic field configuration indicate an asymmetry in the load distribution. Under normal configuration the heat load to the inner target is much higher than to the outer target with an out/in load ratio of about 1:2. In the reversed magnetic configuration, the out/in load ratio is reversed to about 8:1 in favour of the outer target. Unfortunately, while these asymmetries agree well with the analysis of the collisionless orbits shown in Fig.3, they are in striking disagreement with the experimental observations (Figs.1 and 2). It is therefore necessary to find the physical mechanism that is missing from the simulations and responsible for reversing the asymmetries.

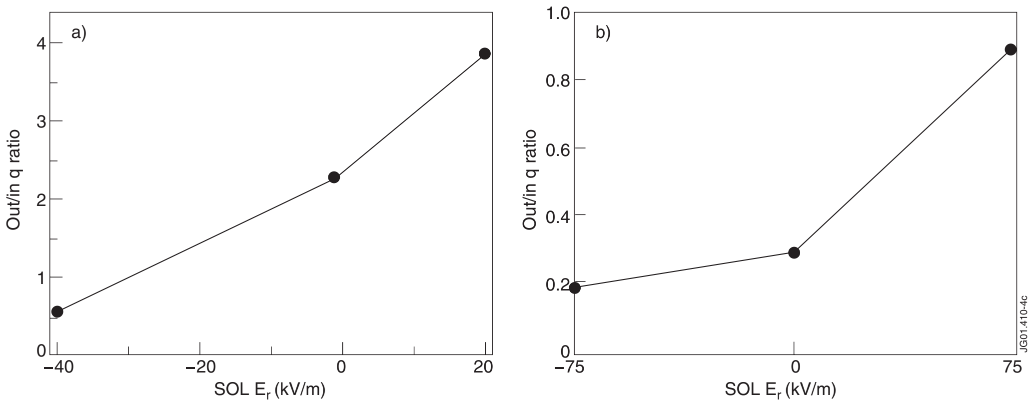

Fig. 4: Total load asymmetry between targets vs. SOL radial electric field (a) in ASDEX Upgrade, and (b) in JET (ASCOT simulation).

An obvious mechanism that could not only reverse the in-out asymmetry but also even strengthen the kinetic nature of the deposition profile is the radial electric field in the SOL. A positive E_r (pointing radially outwards) provides the ions with a poloidal drift velocity that would favor the outer divertor target. Figure 4(a) shows a picture of such a study made for ASDEX Upgrade. It is found that E_r of the order of +20 kV/m would be sufficient to produce the measured asymmetry and preserve the observed narrow structures in the deposition profile. When the magnetic field direction was reversed, the asymmetry was also reversed, and the narrow peak in the distribution disappeared in agreement with the expectations.

The same simulations were repeated in JET configuration. Looking at total heat loads on the targets, the ratio of outer and inner target loads (Fig. 4(b)) suggested that the SOL E_r has an effect on the asymmetry, but a significant change towards experimental results requires a large E_r. The Langmuir probe measurements have indicated a fairly uniform value of about 30–60 kV/m in the SOL. In ASCOT simulations of JET, the *peak* heat load asymmetry was observed to reverse alreadyat about +40 kV/m, so the effect of SOL *Er* deserves a more detailed analysis.

To study the divertor particle and heat loads quantitatively, it is necessary to simulate the neoclassical steady state situation in which any radial currents are balanced by an ambipolar radial electric field. ASCOT calculates the neoclassical ambipolar radial electric field inside the plasma from the test ion fluxes using the polarisation equation [4]. This method provides a steady-state density profile together with divertor particle and heat loads consistent with such profile.

Detailed simulations with 420 000 particles and self-consistent calculation of the edge radial electric field E_r inside the plasma were made to obtain particle and energy deposition profiles on the targets. The SOL E_r was assumed constant in the narrow region outside the separatrix which is relevant to ions escaping from the plasma. The results are shown in Fig.5 as a function of R - R_{sep}, which is the distance [mm] of the strike point magnetic surface from the separatrix along the outer midplane. A narrow peak in the particle deposition profile to the outer target was observed.

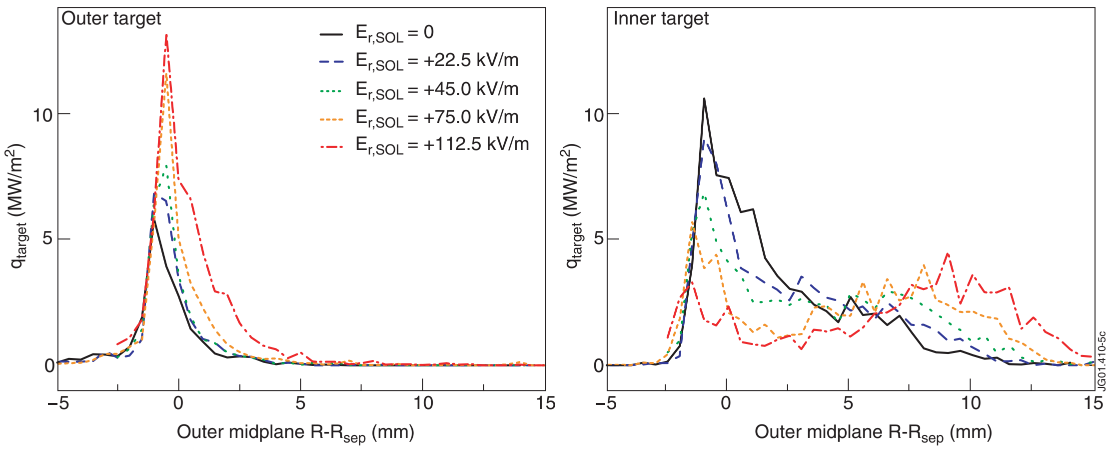

Fig.5. ASCOT simulation of the effect of SOL E_r *on the heat load profiles of the outer and inner target vs. the strike point magnetic surface distance from the separatrix along the outer midplane.*

With increasing SOL E_r, the peak heat flux at the outer target grows while the peak heat flux to the inner target diminishes and the heat load is spread more evenly towards higher R - R_{sep} (upwards on the target). This phenomenon is explained by the $\mathbf{E}_r \times \mathbf{B}$ drift in the SOL. Because this drift is pointing poloidally towards the outer target, ions in the SOL that are moving towards the inner target have a smaller poloidal velocity, and thus the $\mathbf{B} \times \nabla B$ drift has more time to displace them towards outer magnetic surfaces in the lower hemisphere. On the outer target,the opposite effect takes place and the heat flux peak does not get significantly wider when it grows with increasing SOL E_r. At large positive SOL E_r of the order of +75 kV/m, the profiles as well as the target peak load asymmetry (shown in Fig.6) agree with measurements.

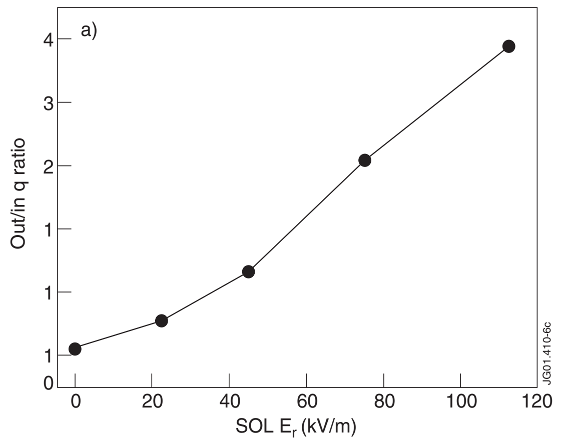

Fig.6. Effect of SOL E_r *on the peak heat load asymmetry between the outer and inner target.*

4. THE SOL RADIAL ELECTRIC FIELD IN THE VICINITY OF THE SEPARATRIX

The Monte Carlo simulations presented above strongly imply that a positive radial electric field in SOL would provide the divertor loads all the characteristics observed experimentally: the correct in-out asymmetry, a large ion contribution to the heat load, and the narrow structure in the deposition profile right next to the separatrix. The electric field values required for the reversal of the asymmetry are in the range experimentally inferred in JET SOL, but matching the measured deposition profiles requires high E_r values of about +75 kV/m. However, it should be realized that the high field values are needed only in a very narrow radial layer (of the order of millimetres) right next to the separatrix.

Due to the harsh plasma conditions corresponding to the strong in-out asymmetries, there exist no reliable measurements of the radial electric field in this region because the Langmuir probes cannot penetrate to such an environment. In the region within a few mm of the separatrix there exists a mechanism that could provide very high E_r values: the fast electrons supplied by the plasma bulk comprise a hot flux to the divertor targets thus creating a sheath potential that produces a stream of cold electrons upstream from the divertor targets. The magnitude of the sheath potential ϕ_{sh} is approximately given by [7]

$$\phi_{sh} = -2.8 \cdot k_B T_e / e, \qquad (1)$$

where k_B is the Boltzmann constant, T_e is the electron temperature, and e is the elementary charge. This potential repels the electrons from and accelerates ions towards the divertor target. If the temperature varies from field line to field line, a radial potential difference is created thus constituting a radial electric field,

$$E_r = \frac{\phi_{sh}(r_1) - \phi_{sh}(r_2)}{\Delta r} \qquad (2)$$

where $\Delta r = r_1 - r_2$, and $r1$ and $r2$ correspond to different field lines at given poloidal angle. Indeed, the sheath potential and the associated radial electric field have already been invoked to explain pressure asymmetries in SOL [8].

Usually it is assumed that the electron temperature in the SOL is of the order of 50 eV and varies exponentially with a fairly large decay length, of the order of centimeters. However, in high performance discharges in which the edge temperature can be of the order of 1 keV, this is not necessarily a good assumption. It does not seem unreasonable to assume that, in the vicinity of the separatrix, the ion temperature can decay very rapidly. With this in mind, in this narrow layer an exponential decay length of the order of millimeters for the electron temperature as well would already suffice in amply providing the radial electric field values needed to explain the experimental observations. Unfortunately, it is more difficult to accept a very strong decay for the electrons, because the electron transport in the SOL is assumed strongly turbulent, leading to the long decay lengths. However, the extracted diffusivities in the SOL have indicated that the H-mode transport barrier can extend beyond the pedestal region to the SOL [5]. Under such conditions one can conceive a situation where the parallel transport of electrons is much faster than the radial transport, and the decay length could be as short as a couple of millimeters.

It should be mentioned that the sheath potential is by no means the only possible source for a positive E_r in SOL. For instance, a recent 2-D transport study [9] gives significant E_r values in the vicinity of the separatrix and indicates that, in this region, the radial electric field is determined by subtle details of pressure, parallel velocity and parallel heat flux distribution.

5. CONCLUSIONS

We have investigated the effect of an SOL radial electric field on the heat and particle loads on divertor targets. Because measurements on JET divertor targets have indicated that, in H-mode conditions, the ion contribution dominates the target loads, we have used the orbit-following Monte Carlo code ASCOT to evaluate the ionic flow from plasma bulk to the divertor targets in both JET and ASDEX Upgrade configurations.

Considering collisionless orbits from the plasma periphery it was determined that under normal conditions (∇B drift towards the targets) the in-out asymmetry ought to favor the inner target. This was also verified by ASCOT simulations. However, imposing an outward E_r in SOL appears to reproduce the correct asymmetry as well as a narrow peak in the deposition profile next to the separatrix. The critical field value at which the peak load asymmetry is reversed is about +40 kV/m in JET, and the best quantitative match to the thermocouple data on the outer divertor target was obtained at about +55 kV/m [5]. The sheath potential was suggested as a possible source of a high radial electric field of about +75 kV/m required near the separatrix in the SOL to reproduce the experimentally measured
deposition profiles.

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REFERENCES

[1] P.C. Stangeby *et al.*, Nuclear Fusion 36 (1996) 839.

[2] A.V. Chankin *et al.*, Contributions to Plasma Physics 40 (2000) 288.

[3] G.F. Matthews *et al.*, Journal of Nuclear Materials 290-293 (2001) 668.

[4] J.A. Heikkinen *et al.*, Physics of Plasmas 8 (2001) 2824; J.A. Heikkinen *et al.*, to appear in Journal of Computational Physics. Czech. J. Phys. 51 (2001) A 9 Taina Kurki-Suonio et al.: Significance of the radial electric field to divertor load asymmetries . . .

[5] W. Fundamenski *et al.*, ”Power Exhaust in JET MkIIGB ELMy H-modes”, 28th EPS Conf. on Controlled Fusion and Plasma Physics, Funchal, Madeira, 18–22 June 2001. To appear in the Proceedings.

[6] A.V. Chankin *et al.*, Nuclear Fusion 33 (1993) 1459.

[7] J. Wesson, *Tokamaks*, Clarendon Press, Oxford, 1987.

[8] A.V. Chankin *et al.*, Nuclear Fusion 41 (2001) 421.

[9] V.A. Rozhansky *et al.*, Nuclear Fusion 41 (2001) 387.

[10] A Czech. J. Phys. 51 (2001)