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Characterization of Scrape-Off Layer Transport in JET Limiter Plasmas

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ABSTRACT

The JET scrape-off layer (SOL) has been characterized with a reciprocating probe in inner wall, IW, and outer wall, OW, limited plasmas. Experiments revealed that SOL profiles are substantially broader (by a factor of $\sim 5 - 7.5$ in the power e-folding length) for IW limited than in OW limited plasmas. Results are consistent with the larger radial turbulent transport found for IW limited plasmas. Major differences are observed between IW and OW limited plasmas on the density and electron temperature e-folding lengths, parallel flow, radial turbulent transport as well as on the temporal and spatial characteristics of the fluctuations. Experimental findings on JET suggest that the differences in the SOL characteristics for both configurations are due to a combination of a poloidal asymmetry in radial transport with a reduced cross-field transport across the last closed flux surface associated with the confinement improvement observed for OW limited plasmas.

The dependence of the SOL power e-folding length on the main plasma parameters was also investigated for IW limited plasmas and a modest negative dependence on both the plasma current and the line-averaged density found. Finally, it is shown that the SOL radial transport and the amplitude of the fluctuations increase with plasma current and decrease with line-averaged density for IW limited plasmas.

1. INTRODUCTION

Plasma start-up in ITER will be in limiter configurations, using either the inner or outer beryllium wall as limiting surface [1]. Both the beryllium limiters themselves and the start-up scenario must be therefore carefully tailored to minimize the power loading, keeping the peak power load below the engineering limit. It remains a challenge to understand and control turbulence and the associated cross-field transport. Consequently, there is still considerable uncertainty in the scaling of the e-folding length for power flux density parallel to the magnetic field, λ_q , one of the most important parameters determining this power loading. Therefore, dedicated experiments have been performed in different devices (see e.g. [2-7]) to characterize the limiter scrape-off layer (SOL) plasma and to establish a scaling law for λ_q , as a function of the main plasma parameters. In addition, it is also important to validate physics-based transport models to allow more robust extrapolations from present devices to ITER. Experiments using well diagnosed limiter plasmas with varying input power, density and magnetic connection length present a unique opportunity to investigate the physics mechanisms responsible for cross-field transport by providing high quality data for turbulence modelling. Experiments in JET are particularly relevant as: (i) uses the material combination for the plasma-facing components foreseen for ITER (JET ITER like Wall); and (ii) is the largest tokamak in operation, reaching plasma conditions in limiter discharges similar to those expected for ITER during ramp-up.

Observations from a large number of tokamak experiments suggest that transport in the edge plasma of fusion devices is not a one-dimensional, radial diffusive process [2–15]. Such a view is clearly incomplete and both poloidal asymmetries and intermittent convective transport play an

important role in the edge plasma. The occurrence of strong inhomogeneities in the tokamak SOL plasmas has been the subject of a number of papers [2–11]. Clear indications were found that the turbulence drive is ballooning-like, favoring therefore the outboard region. Furthermore, substantial evidence exists for intermittent convective radial transport in the edge plasma of fusion devices [12–15]. The large amplitude intermittent events can be responsible for large fractions of the cross-field particle and heat transport, leading to nearly flat temperature and density profiles in the far-SOL of many devices. Understanding of the turbulence and the enhanced transport that accompanies it is presently the goal of intense investigation.

Diagnosing the edge plasma, particularly through the use of electrostatic probes, has yielded a lot of information regarding the anomalous level of energy and particle transport. The basic limitations in studying the large poloidal/toroidal extent of the boundary region to get a complete picture are generally circumvented by assuming toroidal/poloidal symmetry. However, poloidal asymmetries in radial transport can be indirectly investigated by performing discharges limited in different contact points around the poloidal section [2–7].

Measurements in tokamaks revealed a substantially broader SOL for plasmas limited in the inner wall, IW, when compared to outer wall, OW, limited plasmas [2–7]. A comprehensive study of the influence on the SOL of different plasma contact points with limiters has been performed on Tore Supra, revealing clear evidence for a poloidally localized enhancement of radial transport near the outer midplane [4–5]. The effect on the SOL of changing the position of the main limiter from the inner to the outer wall was studied previously on JET, although for a significantly different limiter geometry, with λ_q found to be 2.9 times larger for IW limited plasmas [3]. This ratio is larger than the 1.5 factor predicted by the model considered by Harbour and Loarte [3] based on geometric effects. Detailed measurements of SOL profiles for ohmic limiter plasmas have also been performed previously in JET over a wide range of operating conditions but again with a significantly different limiter configuration [16–17]. Data for this experiment showed an inverse dependence of the diffusion coefficient on the average plasma density and plasma current although no fluctuations measurements were performed.

Plasmas limited in the inner and outer wall have recently been performed on JET to characterize the SOL transport and the power decay length [6, 7]. Striking differences on the power e-folding length, parallel flow and turbulent transport were observed for IW and OW limited plasmas suggesting that core-to-SOL outflux is not poloidally symmetric, favouring the low field side. In this paper, we build on the previous JET work summarized above aiming at a better understanding of the distinct plasma behaviour for IW and OW limited plasmas. The SOL plasma is further characterized by comparing the fluctuations properties and plasma confinement for both configurations. It is shown that the existence of a localized region of enhanced radial transport near the outer midplane is not fully consistent with reciprocating probe observations at the plasma top showing a large turbulent transport. JET results suggest that the confinement improvement observed when the plasma is moved to the outer wall also plays a role in explaining the different SOL characteristics detected for IW and OW limited plasmas.

Additionally, the dependence of SOL quantities (such as density, electron temperature, parallel heat flux, power decay length, radial turbulent transport and fluctuations properties) on the plasma current and line-averaged density is investigated for inner wall limited plasmas. Finally, the SOL characteristics in limiter and divertor configuration are compared.

2. DESCRIPTION OF THE EXPERIMENT

The principal diagnostic used in this work is a multi-pin probe head mounted onto a fast reciprocating system driven into the top, low field side of the plasma cross-section. The probe head presently installed on JET, schematically illustrated in figure 1, consists of 9 cylindrical pins with a diameter of 1.5 mm and an exposed length of 3 mm, although only 7 pins are used in the present work. Within the three pins at the inner-most radial position, one (pin 3) measures the ion saturation current, I_{sat}, and the other two pins (1 and 2, poloidally separated by 4 mm) measure the floating potential, V_f, making possible the determination of the turbulent particle flux (estimated using $\Gamma_{F\times B} = \langle \widetilde{n}\widetilde{E}_{\theta} \rangle / B$ where \tilde{n} and \tilde{E}_{θ} are the density and the poloidal electric field fluctuations, respectively). Density and plasma potential fluctuations are evaluated from Isat and Vf, respectively, neglecting electron temperature fluctuations. The remaining 4 pins used are located 5 mm radially further out, with pins 4 and 5 operated in Isat mode used to measure the parallel flow, pin 6 measures the floating potential, while pin 7, operated in swept mode, is dedicated to estimate the electron temperature, Te, from the standard voltage/current characteristic swept at 100 Hz. This probe allows therefore the simultaneous measurement of I_{sat}, V_f, parallel Mach flow and the turbulence driven particle flux with high temporal resolution (1 MHz). Parallel flow Mach numbers are calculated using Hutchinson's formula $M_{//}=0.4ln(I_{sat}^{u}/I_{sat}^{d})$ [18]. Edge plasma density and temperature profiles from the reciprocating probe have been compared with the results of the Li beam and high-resolution Thomson scattering diagnostics and a good agreement obtained taken into account the typical inaccuracies of the EFIT equilibrium [19].

Experiments have been performed in near full bore JET IW and OW limited plasmas for different values of plasma current, I_p , and line-averaged density, <n>. Discharges were first limited at the IW and then, by means of a small radial movement of the plasma, the OW limited phase of the discharge was established. Parameters such as plasma current and toroidal magnetic field are not significantly different during the two phases of the discharge. However, other parameters such as the line-averaged density, radiated power and the stored energy are typically 20 – 40% higher in OW limited plasmas as discussed in section 3.3. Plasma current and line-averaged density were varied independently from shot to shot in a series of Ohmic discharges. Probe data is available for two values of plasma current ($I_p = 1.5$ and 2.5 MA) and for line-averaged densities ranging from 3.8 to 8.5×10^{19} m⁻³ (corresponding to a greenwald fraction between 0.2 and 0.5) at constant magnetic field, $B_T = 2.4$ T, and elongation, $\kappa = 1.4$. For comparison, diverted discharges were also included with similar main plasma parameters (magnetic field, plasma current and line-averaged density).

The new JET ITER Like Wall features 12 poloidal limiters with a large poloidal plasma-wetted area in the outer wall and 10 limiters in the inner wall, acting therefore as an effective toroidally continuous limiter [20]. This conclusion is corroborated by the SOL density profiles that show a single-exponential behaviour.

3. COMPARISON BETWEEN IW AND OW LIMITED PLASMAS

3.1 SOL PROFILES

Radial profiles of the floating potential, electron temperature and ion saturation current are simultaneously measured across the JET SOL by the reciprocating probe. Using the density and temperature e-folding lengths, λ_n and λ_T , and assuming $T_e = T_i$ (T_i measurements are not available) and sheath-limited conditions, $q_{//} \propto nT_e^{3/2} \propto I_{sat}T_e$, the power decay length can be calculated using $1/\lambda_q = 1/\lambda_{Isat} + 1/\lambda_{Te}$. Small uncertainties are associated with the λ_{Isat} estimate because profiles have a clear exponential decay and a large number of data points are recorded (derived from pin operated in I_{sat} mode with signals acquired at 1 MHz). In contrast, λ_{Te} measurements have larger uncertainties due to the significant error bars in the T_e determination (up to 20%) and the reduced number of experimental data points. Fortunately, it is experimentally observed that $\lambda_{Te} \sim 2 - 6 \times \lambda_{Isat}$, reducing therefore the impact of the λ_{Te} uncertainties in the λ_q determination.

Inner and outer wall limited plasmas are compared in figure 2, showing the Isat and Te profiles for both configurations. Profiles are plotted as a function of the distance to the last closed flux surface, LCFS, mapped onto the outer midplane, OMP. The uncertainty of the probe locations with respect to the LCFS is on the order of 1 cm due mainly to uncertainties in the EFIT reconstruction. In general, I_{sat} profiles exhibit a well defined exponential decay with radius over two orders of magnitude for both configurations. Broad SOL profiles are observed for IW limited plasmas ($\lambda_{Isat} \sim 5 - 8 \text{ cm}$, λ_{Te} ~12 – 20 cm), with λ_q substantially larger (by a factor of ~5 – 7.5) than in OW limited plasmas. Radial e-folding distances are estimated at the outer midplane assuming an exponential profile. In contrast to the observed in OW limited plasmas, for discharges limited in the IW the plasma extends all the way up to the outboard limiter despite the high discharge clearance, ~10 cm. The position of the outer wall poloidal limiters is clearly visible in IW limited plasmas, with steeper profiles observed for $r - r_{LCFS} > \sim 10$ cm corresponding to the decrease of the connection length, L_c , in the limiter shadow. T_e profiles are broader than I_{sat} profiles typically by a factor of 2 – 3 for IW limited plasmas and by a factor of 4 - 6 for OW limited plasmas. The parallel heat flux at the LCFS, derived extrapolating the measured SOL Isat and Te profiles assuming an exponential decay, is substantially larger for OW limited plasmas, in agreement with the scaling $q_{1/2}^{LCFS} \propto \lambda_{\alpha}^{-1}$ expected from the conservation of the power into the SOL and observed in previous experiments [2,4,5]. As suggested before [4, 5], an inner wall plasma start-up in ITER would be advantageous due to the broader SOL power thickness and consequent lower peak heat load on the limiters.

The ratio of λ_q between IW and OW limited plasmas reported here is larger than that observed on Tore Supra (where the ratio is around 3 – 4 [4–5]) and in previous JET experiments (ratio of 2.9 [3]). As suggested by Gunn et al. [4], the dramatic change in the SOL profiles between the two phases of the discharge supports the existence of an enhanced radial transport near the outer midplane, implying a shorter effective connection length, $L_{c,eff}$, for OW limited discharges. Note that the magnetic connection length is roughly the same (within 10%) for the two configurations. Assuming that core-to-SOL outflux occurs in a narrow region around the OMP, particles reaching the SOL have to travel significantly different distances to reach the limiters for IW and OW limited plasmas. The distance along the field from the plasma source to the limiter (effective connection length) is therefore much shorter for OW limited plasmas. As a consequence, the SOL characteristic time ($L_{c,eff}/c_s$, where c_s is the ion sound speed) for OW limited plasmas should be smaller, and particles and energy rapidly lost by parallel transport to the limiters result in narrower profiles. In contrast, for IW limited plasmas the effective connection length, and consequently the transit time in the SOL, are larger and therefore broader profiles should be observed associated with a large parallel flow at the probe location.

The parallel Mach number measured near the top of the plasma is compared in figure 3 for IW and OW limited plasmas and again significant differences are found. A large parallel flow ($M_{//} \sim 0.5$) is observed for IW limited plasmas that is roughly constant across the entire SOL. For OW limited plasmas, the flow is modest ($|M_{//}| < 0.2$) showing, however, a significant radial variation near the LCFS that may be related with the strong radial electric gradients observed at that location (see section 3.3). The differences in Mach number between IW and OW limited pulses give further evidence that the core to SOL outflux is poloidally localized near the outboard midplane, as suggested in [4].

3.2 CHARACTERIZATION OF THE FLUCTUATIONS

The fluctuations in I_{sat} and V_f have been characterized in order to better understand the differences in the SOL transport for the two configurations under consideration. I_{sat} and V_f are measured with a high temporal resolution permitting the detailed study of the SOL fluctuations. A typical temporal evolution of the V_f and I_{sat} fluctuation is shown in figure 4 for the two configurations, revealing a major difference in the amplitude and characteristics of the fluctuations. Figure 5 shows the radial profile of the standard deviation and skewness for V_f and I_{sat} fluctuations. As illustrated, the amplitude of the fluctuations is significantly larger for IW limited plasma, with the exception of the I_{sat} fluctuations near the LCFS. Note however that in this region the mean I_{sat} value is significantly larger for OW limited plasmas and consequently the I_{sat} fluctuations level is smaller for this configuration across the whole profile. Clear differences are also observed in the skewness that is roughly zero for OW limited plasmas and around one for IW limited plasmas. Large amplitude, intermittentlike fluctuations are observed for IW limited plasmas that lead to a significant convective transport resulting in the broad profile observed. In contrast, OW limited plasmas are characterized by low amplitude fluctuations with near Gaussian distribution. This result may also be explained by the different effective connection length expected for the two configurations. As a consequence of the short $L_{c,eff}$ for OW limited plasmas, the convective structures (or filaments) crossing the LCFS from the core plasma should be rapidly drained out in the SOL by parallel transport reducing the amplitude of the intermittent-like fluctuations.

According to this picture, it is expected that filaments reaching the SOL near the OMP will then "fill" the SOL by parallel transport. An asymmetry is therefore expected in the amplitude of the fluctuations for parallel Mach probe signals, with larger fluctuations anticipated for pins facing the LFS. The amplitude of the I_{sat} fluctuations for both Mach tips is shown in figure 6, confirming that the standard deviation of the fluctuations is larger for pins facing the LFS for IW limited plasmas. No significant differences are observed for OW limited plasmas.

The frequency spectra of the V_f and I_{sat} fluctuations are also significantly different for the two configurations (see figure 7). Contrary to the observed for OW limited plasmas, fluctuations in IW limited plasmas are dominated by frequencies below 40 kHz, as a consequence of its intermittent character. The difference in spectra is reflected in the auto-correlation of the fluctuations that is again noticeably different for the two configurations (see figure 8). The auto-correlation time for V_f fluctuations is about 3 µs for OW limited plasmas while for IW limited plasmas is around 50 µs. Similar values are observed for I_{sat} fluctuations.

The cross-field turbulent particle flux is routinely estimated from I_{sat} and V_f signals. In figure 9, the radial profiles of I_{sat} , $\Gamma_{E\times B}$ and the effective radial velocity are compared for IW and OW limited plasmas. The effective radial velocity is defined here in terms of the local E×B radial particle flux and the local (time averaged) density: $v_r = \Gamma_{E\times B}/\bar{n}$. As illustrate, a large turbulent transport is observed for IW limited plasmas across the entire SOL and the effective radial velocity is 4 to 10 times larger than the observed for OW limited plasmas.

The large turbulent transport observed for IW limited plasmas results from the existence of large amplitude, intermittent-like fluctuations that lead to a significant convective transport. In summary, the striking differences in the power e-folding lengths, parallel flows, turbulent transport as well as the characteristics of the I_{sat} and V_f fluctuations observed for IW and OW limited plasmas appear to be in agreement with the assumption of an enhancement of radial transport near the outer midplane.

Experiments on Tore Supra moving the plasma to different contact points demonstrated that crossfiled transport across the LCFS occurs at a very narrow poloidal region of about 30° around the OMP, explaining the observation of a broader SOL by a factor of 3–4 when the plasma is limited in the IW [4]. As the asymmetry between IW and OW limited plasmas is larger on JET one would expect an even narrower region of enhanced radial transport. Consequently, the radial transport across the LCFS to the SOL should be modest at the probe location (near the plasma top) in opposition to our observations. As shown in figure 9, a large radial particle flux is observed across the whole SOL up to the LCFS for plasmas limited in the inner wall, with no clear reduction seen when approaching the LCFS. Probe measurements for OW limited plasmas indicate that transport is modest all the way from the SOL to the LCFS, hinting that particle transport is significantly different in the region just inside the LCFS for both configurations. Assuming that radial transport is only localized near the OMP, large amplitude fluctuations would not be expected to exist at the plasma top close to the LCFS. The parallel travel time $(\tau_{//})$ from the OMP to the plasma top is about $\tau_{//} = L_{//}/c_s \sim 10/5 \times 10^4 \sim 200 \ \mu s$. During this time filaments travel radially a minimum of 2 cm, assuming a modest radial velocity of 100 m/s. This estimate is conservative as the peak radial velocity during filaments is in the order of 500 m/s. The amplitude of the intermittent fluctuations at the probe location should therefore be small near the LCFS peaking at least 2 cm further out in the SOL that is in contradiction with the experimental observations.

Another piece of evidence that transport is not reduced near the LCFS at the probe location comes from the radial correlation of the potential fluctuations. Figure 10 presents the radial correlation for floating potential signals measured by pins radially separated by 5 mm. As illustrated, for IW limited plasmas the radial correlation is around 0.9 across most of the SOL, implying that large structures exist up to the LCFS. Assuming an exponential decay of the correlation with the distance between pins, the radial correlation length of the potential fluctuation is estimated to be around 4 cm for IW limited plasmas and about 0.5 cm for plasma limited in the outer wall. Turbulent structures have therefore dimensions in the order of a few centimetres up to the LCFS for IW limited plasmas. We conclude that although there are clear evidences for a poloidally asymmetric radial transport, probe measurements are not consistent with a narrow region of enhanced radial transport located around OMP as observed on Tore Supra.

3.3 PLASMA CONFINEMENT

The temporal evolution of the main plasma parameters during a typical discharge is shown in figure 11. It is clearly seen that when the plasma is moved from the inner to the outer limiter both the stored energy and the line-averaged density increase and the D_{α} radiation falls, suggesting an improvement in plasma confinement. These modifications cannot be explained simply by geometric effects resulting from the plasma radial movement as the different lines of sight (line-integrated densities at core and edge, D_{α} monitors with vertical and horizontal views) show a similar behaviour. The improvement in particle confinement suggested by the increase in the line-averaged density for OW limited plasmas is consistent with the reduced particle transport across the LCFS described in the previous section.

The improvement in confinement is confirmed by the density and electron temperature radial profiles. As illustrated in figure 12, both the high resolution Thomson scattering (HRTS, solid line) and reflectometry (symbols) diagnostics show that the density increases strongly when the plasma is moved to the outer wall. As a consequence of the reduction in the electron temperature observed at the plasma core the electron pressure is only enhanced in the outer plasma region ($\rho > 0.5$).

The edge radial electric field measured by the reciprocating probe presents another evidence for the confinement modification when the plasma is moved to the outer wall. As shown in figure 13, floating potential profiles exhibit significant differences between the two configurations with flat profiles observed for IW limited plasma resulting in a modest radial electric field (around 0.5 kV/m)

that is consistent with the existence of large turbulent structures. On the contrary, for OW limited plasmas a large radial electric field exists near the LCFS (around of 5 kV/m) that in agreement with the small size of the turbulent structures and the modest radial transport observed for this configuration. The improvement in confinement observed when the plasma is moved to the outer limiters is therefore consistent with the edge potential profiles and the associated $E_r \times B$ flow shear rate that is significantly different for the two configurations.

The large radial electric field observed around the LCFS for OW limited plasmas, associated with low turbulence levels indicates that the radial transport is reduced in the confined region for this configuration. Results suggest therefore that the differences in radial transport for the two configurations are not limited to the SOL but extend into the confined region. The difference in cross-field transport across the LCFS presents therefore an alternative justification for the distinct SOL properties observed for the two configurations, not requiring the existence of a rather narrow region of enhance transport near the OMP.

It is important to understand why plasma confinement is enhanced when the plasma is in contact with the outer wall and if the differences in the SOL transport between the two configurations under consideration are a cause or a consequence of the improved confinement. A possible mechanism could be that an originally small poloidal asymmetry in radial transport favouring the outboard plasma region leads to steeper SOL profiles when the plasma in limited at the OW (due to the faster SOL losses for this configuration) resulting in a larger radial electric field that leads to a further reduction in radial transport, to even steeper profiles and finally would result in the large asymmetry observed. In summary, experimental findings on JET suggest that the differences in the SOL characteristics for both configurations are possibly due to a combination of a poloidal asymmetry in radial transport with a reduced cross-field transport across the LCFS associated with the confinement improvement observed for OW limited plasmas.

Recent simulations support the observation that IW and OW limited plasmas are dominated by different turbulent regimes [21]. The effect of the limiter position on the SOL width has recently been investigated via global, three-dimensional turbulence simulations [21]. It is suggested that the smaller SOL width for IW limited plasmas can be explained by the different turbulent regimes present in the two configurations. Transport in the IW limited configuration is dominated by ballooning modes, while in the OW limited configuration transport is dominated by drift-waves. This is due to the location of the limiter, which has a stabilizing effect on the ballooning modes when its location coincides with the position of their maximum drive.

4. DEPENDENCE OF THE SOL QUANTITIES ON THE MAIN PLASMA PARAMETERS

The dependence of SOL quantities on the plasma current and line-averaged density has been investigated for inner wall limited plasmas. Probe data is available for two values of plasma current ($I_p = 1.5$ and 2.5 MA) and for line-averaged densities ranging from 3.8 to $8.5 \times 10^{19} \text{ m}^{-3}$.

The dependence on the plasma current is investigated using data from a series of discharges with a line-averaged density of $\sim 3.8 \times 10^{19} \text{ m}^{-3}$, while the dependence on the line-averaged density was investigated at I_p = 2.5 MA. Figure 14 presents the density, electron temperature and heat flux at the LCFS position (extrapolated from measured SOL profiles assuming an exponential decay) as a function of the main plasma density and plasma current. It is found that the LCFS density, electron temperature and parallel heat flux increase with plasma current, with q_{1/2} scaling roughly linearly with I_p, in agreement with the linear increase in the power to the SOL. Furthermore, the LCFS parameters are observed to depend weakly on the line-averaged density. As expected, when the line-averaged density increases the density at the LCFS also increases and the electron temperature is reduced, resulting in an approximately constant heat flux apart from the highest density values. This is in agreement with the power into the SOL remaining approximately constant with the discharge density as both the Ohmic heating and the radiative losses do not change significantly with line-averaged density in the range considered.

The scaling of the SOL power e-folding length with the plasma current and line-averaged density was estimated, with the results summarized in figure 15. As illustrated in figure 15a, λ_q has a negative power dependence on the plasma current. This effect is, at least partially, due to the change of the SOL connection length that has an inverse dependence in the plasma current. Profiles become broader as the connection length increases due to the fact that the parallel losses are reduced since particles have to travel larger distances to reach the limiters. This observation has been well reproduced by a recent numerical study [22]. Figure 15b shows the λ_q dependence on the line-averaged density for $I_p = 2.5$ MA. We observe that λ_q depends on the density for $\langle n \rangle$ lower than 5×10^{19} m⁻³, with no clear dependence observed above that value. The small dependence of λ_q on $\langle n \rangle$ may be related to the fact that the SOL plasma parameters show a modest variation with the line-averaged density (see figure 14). The resulting λ_q scaling on the plasma current and line-averaged density for the existing dataset is presented in figure 15c. The SOL power e-folding length for JET IW limited plasmas follows $\lambda_q \propto I_p^{-0.23} < n^{-0.16}$. A similar trend was observed on Tore Supra [4–5], though, with a stronger dependence on the plasma current, $\lambda_q^{TS} \propto I_p^{-0.8}$.

The fluctuations in the SOL parameters were also measured and their dependence on the main plasma parameters investigated. Figure 16 presents the radial profile of the ion saturation current, standard deviation of the V_f fluctuations, turbulent radial particle flux and radial effective velocity for the two plasma current values. As illustrated, the turbulent transport and the effective radial velocity increase with plasma current. This augment in radial transport is mainly due to an increase in the amplitude of the V_f and I_{sat} fluctuations. Note that quantities such as the skewness and kurtosis of both V_f and I_{sat} fluctuations are not significantly modified. As referred before, the SOL thickness is expected to decrease with increasing I_p due to the modification in the connection length (filaments have to travel a shorter distance to reach the limiters). The modest λ_q variation with the plasma current observed experimentally is justified by the fact that the radial transport (Γ_{ExB} and v_r) also increases with I_p, compensating partially the effect of a reduction in L_c. It is important to note that

modifications in the plasma current lead to changes not only the connection length but in the power into the SOL and consequently in the SOL parameters as illustrated in figure 14.

The simple SOL model [23] is often used to interpret the SOL measurements in limiter plasmas. However, radial transport for IW limited plasmas is dominated by convection (as shown in section 3.2) and consequently this model based on the Fick's law and the diffusive paradigm is not applicable in JET IW limited plasmas. The simple SOL model can however be adapted for a convective scenario by replacing the Fick's law $\Gamma_{\perp} = -D_{\perp}\nabla n$ by $\Gamma_{\perp} = nv_{\perp}$, where v_{\perp} is the perpendicular velocity. According to this convective simple SOL model the density decay length is given by: $\lambda_n \approx v_{\perp}L_{//}/c_s$. This basic model can be used to interpret JET results using for v_{\perp} the effective radial velocity defined previously. We observed experimentally that when the plasma current is increased from 1.5 to 2.5 MA, $L_{//}$ is reduced proportionally, v_r rises from ~50 to ~80 m/s (see figure 16) and c_s increases by 10% at most (see figure 14). According to the model, it is anticipated that λ_n should be reduced by ~10% when I_p increased from 1.5 to 2.5 MA, in good agreement with our observations.

The dependence of the fluctuations related quantities on the line-average density is presented in figure 17. It is observed that turbulent transport in IW limited plasmas has an inverse dependence on the line-averaged density resulting mainly from a reduction in the amplitude of the potential fluctuations. The amplitude, skewness and kurtosis of the ion saturation current fluctuations are not significantly modified. As shown in figure 15a, no clear dependence of the SOL width on the discharge density was observed for $\langle n \rangle$ above 5×10^{19} m⁻³. Results presented in figure 17 suggest that this behaviour is related with the amplitude of the potential fluctuations that show a minor reduction when $\langle n \rangle$ is increased from 5.4 to 8.4×10^{19} m⁻³. This behaviour is however not observed in the turbulent particle flux and effective radial velocity.

The convective simple SOL model may also be used to interpret the λ_n dependence on the lineaveraged density. It is observed that v_r decreases by a factor of two when <n> rises from 3.8 to 8.4×10^{19} m⁻³ (see figure 17) while c_s is only reduced by 15% (see figure 14). A strong reduction in λ_n with <n> would therefore be anticipated from the model, contrary to our observations. The interpretation of the results clearly requires more sophisticated modelling, including for instance ionization within the SOL that is ignored in the simple model considered.

In summary, the SOL radial transport for JET ohmic IW limited plasmas is observed to increase with plasma current and to decrease with line-averaged density. It is important to note, however, that the SOL parameters depend on the main plasma parameters. As referred before, the SOL electron temperature increases with plasma current and decreases with line-averaged density. Radial transport is therefore proportional to the SOL electron temperature suggesting a Bohm-like diffusion.

A detailed experimental study of SOL transport for ohmic limiter plasmas was previously carried out at JET although with a significantly different limiter geometry and material composition (carbon instead of beryllium) [16–17]. Previous JET results indicated that the power SOL width weakly depends on the plasma density and scale roughly with I_p^{-1} . Although no fluctuation measurements were performed in previous JET experiments, the diffusion coefficient calculated from the density

e-folding length using the simple SOL model was observed to decrease with the line-average density and plasma current, being roughly proportional to the local electron temperature [16–17]. Previous JET results are therefore consistent with observations described in this paper. However, as stated before, the simple SOL model based on the diffusive paradigm is not applicable to the SOL transport, particular in IW limited plasma.

5. COMPARISON OF DIVERTED AND LIMITED PLASMAS

Reciprocating probe data is also available from Ohmic JET discharges in divertor configuration. The SOL profiles in limiter and divertor configuration are compared in figure 18 for discharges with similar main plasma parameters (magnetic field, plasma current and line-averaged density). As illustrated, profiles in divertor configuration are narrower than in IW plasmas (by a factor around 4), and the amplitude of the fluctuations is significantly smaller. It is observed that radial transport, the amplitude of the fluctuations and their skewness in diverted and OW limited plasmas are at similar levels, suggesting that convective transport is largest in IW limited plasma. Significantly different plasma conditions are expected for limiter and divertor plasmas in terms of recycling, impurity influx and even in the magnetic shear that may affect the SOL transport. Consequently, the interpretation of the results clearly requires a detailed modelling of the SOL plasma for the different plasma configurations.

Finally, the dependence of the SOL fluctuations properties on the line-averaged density is estimated for the divertor configuration. Contrary to the observed in IW limited plasmas, in divertor configuration the radial transport increases with the main plasma density due to a rise of the amplitude of the I_{sat} and V_f fluctuations. The dependence of the SOL radial transport on the main plasma density is in agreement with measurements from others devices. Direct measurement of the cross-field particle transport in different devices [e.g. 24, 25] in ohmic and L-mode discharges indicates that the convective transport due to the filamentary structures strongly increases with plasma collisionality, leading to flatter profiles as observed on JET. This observation is also well reproduced by numerical studies [e.g. 22].

6. SUMMARY

The JET scrape-off layer has been characterized with a reciprocating probe in inner and outer wall OW limited plasmas. A large variety of plasma parameters have been estimated allowing for an unprecedented characterization of the SOL in limiter plasmas. Experiments in JET are particularly relevant due to the similarity with ITER conditions both in terms of the material combination for the plasma-facing components and the ability to reach plasma conditions in limiter discharges similar to those expected for ITER during ramp-up.

JET experiments in limiter configuration revealed that SOL profiles are substantially broader (by a factor of $\sim 5 - 7.5$ in the power e-folding length) for IW limited than in OW limited plasmas. IW limited plasmas are characterized by intermittent-like, large amplitude fluctuations, being therefore

convection dominated, while for OW limited plasmas low amplitude fluctuations with near Gaussian distribution are observed. The striking differences of the power e-folding length, parallel flow, turbulent transport as well as the characteristics of the I_{sat} and V_f fluctuations observed for IW and OW limited plasmas, suggests that core-to-SOL outflux occurs in a narrow region around OMP, consistent with the ballooning character of the turbulent transport. However, this conclusion is not fully consistent with reciprocating probe observations at plasma top showing a large turbulent transport near the LCFS. JET results suggest that the reduction in the cross-field transport across the LCFS associated with the confinement improvement observed for OW limited plasmas also plays a role in explaining the different SOL characteristics detected for IW and OW limited plasmas. It is suggested that the poloidal asymmetry in radial transport leads to a confinement improvement when the plasma is moved from the inner to the outer wall.

The dependence of the SOL e-folding length on the main plasma parameters was also investigated in IW limited plasmas and a modest negative dependence on both the plasma current and the lineaveraged density found: $\lambda_q \propto I_p^{-0.23} n^{-0.16}$. In opposition, the turbulent transport was found to have a stronger dependence on the main plasma parameters. In the range of parameters available, the turbulent particle flux increases by roughly a factor of two with I_p and decreases by a similar value with <n>. Radial transport is therefore proportional to the SOL electron temperature suggesting a Bohm-like diffusion.

Similar measurements have also been made in diverted discharges and many common features found with OW limited plasmas. Profiles in divertor configuration are narrower than in IW plasmas (by a factor around 4) and the amplitude of the fluctuations significantly smaller. Furthermore, radial transport was observed to increase with the discharge density, contrary to the observed for IW limited plasmas.

This paper presents experiments carried on JET using well diagnosed IW and OW limited plasmas with varying input power and line-averaged density that provides high quality data for turbulence modelling. The JET dataset could be used for the validation of plasma turbulence simulations for different SOL configurations. Future work may focus on the quantitative comparison between modelling and experimental measurements in order to contribute to a better understanding of the fundamental mechanisms responsible for cross-field transport.

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Electron Temperature (eV) Ion sat. current dens. (A/cm²) $\lambda_{\text{lsat}} = 0.8$ cm (OLW, Pulse No: 80938) $\lambda_{\text{lsat}} = 5.8 \text{cm} (\text{ILW}, \text{Pulse No: 80938})$ 1.0 SOL Limiter shadow 0.1 0.02 0.04 0.08 0.06 0.10 0.12 0.14 0 $\lambda_{Te} = 13.8 \text{cm}$ $\lambda_{Te} = 3.4 \text{cm}$ 10 0.02 0.04 0.06 0.08 0.12 Ó 0.10 0.14

Figure 1: JET reciprocating probe head: (a) Schematic illustration of the probe front view; (b) Photograph of the probe side view. Pins 1, 2 and 6 are used for fast measurements of the floating potential. Pins 3, 4 and 5 are used for fast measurement of the ion saturation current and for the determination of the parallel Mach number. Pin 7 is operated in swept mode to estimate the electron temperature and density.

Figure 2: Ion saturation current and electron temperature radial profile for IW (black) and OW (red) limited plasmas (Pulse No: 80938, $I_p = 2.5MA$, $B_T = 2.45T$, $\langle n \rangle = 6.4 \times 10^{19} m^{-3}$).

Distance to LCFS @ OMP (m)



Figure 3: Parallel Mach number radial profile for IW (black) and OW (red) limited plasmas (Pulse No: 80933, $I_p = 1.5MA$, $B_T = 2.45T$, $\langle n \rangle = 3.8 \times 10^{19} m^{-3}$).



Figure 4: Temporal evolution of the V_f and I_{sat} fluctuations for IW (black) and OW (red) limited plasmas at $r-r_{LCFS} \approx 3 \text{ cm}$ (Pulse No: 80932, $I_p = 1.5MA$, $B_T = 2.45T$, $<n>= 3.7 \times 10^{19} \text{ m}^{-3}$).



Figure 5: Radial profiles of the skewness and standard deviation of the V_f and I_{sat} fluctuations for IW (black) and OW (red) limited plasmas (Pulse No: 80932, $I_p = 1.5MA$, $B_T = 2.45T$, $\langle n \rangle = 3.7 \times 10^{19} \text{ m}^{-3}$).





Figure 6: Radial profile of the I_{sat} standard deviation for Mach probe pins facing the LFS (black) and the HFS (red) for IW and OW limited plasmas (Pulse No: 80932, $I_p = 1.5MA$, $B_T = 2.45T$, $\langle n \rangle = 3.7 \times 10^{19} m^{-3}$).

Figure 7: Frequency spectra of the V_f and I_{sat} fluctuations for IW (black) and OW (red) limited plasmas at $r - r_{LCFS} \approx 3 \text{ cm}$ (Pulse No: 80932, $I_p = 1.5MA$, $B_T = 2.45T$, $<n>= 3.7 \times 10^{19} \text{ m}^{-3}$).



Figure 8: Auto-correlation time of the V_f and I_{sat} fluctuations for IW (black) and OW (red) limited plasmas at $r - r_{LCFS} \approx 3$ cm (Pulse No: 80932, $I_p = 1.5MA$, $B_T = 2.45T$, $\langle n \rangle = 3.7 \times 10^{19} \text{ m}^{-3}$).



Figure 9: Radial profiles of I_{sat} , $\Gamma_{E\times B}$ and effective radial velocity for IW and OW limited plasmas (Pulse No: 80933, $I_p = 1.5MA$, $B_T = 2.45T$, $\langle n \rangle = 3.8 \times 10^{19} \text{ m}^{-3}$).



Figure 10: Radial profile of the radial correlation between floating potential signals for IW (black) and OW (red) limited plasmas (Pulse No: 80933, $I_p = 1.5MA$, $B_T = 2.45T$, $\langle n \rangle = 3.8 \times 10^{19} m^{-3}$).



Figure 11: Temporal evolution of the stored energy, power into the SOL, line-averaged density (core and edge lines), D_{α} radiation (vertical and horizontal views) and inner and outer gaps (Pulse No: 81007, $I_p = 2.5MA$, $B_T = 2.45T$). Shadowed regions indicate the time of the probe reciprocations.





Figure 12: Radial profiles of the density, electron temperature and pressure measured by the high resolution Thomson scattering diagnostic (HRTS, solid line) for IW and OW limited plasmas. Also shown is the density radial profile measured by reflectometry (symbols).

Figure 13: Radial profile of the floating potential for IW (black) and OW (red) limited plasmas (Pulse No: 80932, $I_p = 1.5MA$, $B_T = 2.45T$, $\langle n \rangle = 3.7 \times 10^{19} \text{ m}^{-3}$).



Figure 14: Scaling of the density, electron temperature and heat flux at the LCFS position as a function of the main plasma density and plasma current.



Figure 15: Scaling of the SOL e-folding length with plasma current (a) and line-averaged density (b). λ_q scaling on the plasma current and line-averaged density for the existing dataset is presented in (c).





Figure 16: Radial profile of the ion saturation current, standard deviation of the V_f fluctuations, turbulent radial particle flux and radial effective velocity for $I_p = 1.5$ and 2.5MA.

Figure 17: Radial profile of the ion saturation current, standard deviation of the V_f fluctuations, turbulent radial particle flux and radial effective velocity for $\langle n \rangle = 3.8 \times 10^{19} \text{ m}^{-3}$, $5.4 \times 10^{19} \text{ m}^{-3}$ and $8.4 \times 10^{19} \text{ m}^{-3}$ for IW limited plasmas.



Figure 18: Radial profiles of I_{sat} , $\Gamma_{E\times B}$ and skewness and standard deviation of the V_f fluctuations for IW limited (black), OW limited (red) (Pulse No: 80938, $I_p = 2.5MA$, $B_T = 2.45T$, $\langle n \rangle = 6.4 \times 10^{19} \text{ m}^{-3}$) and diverted (blue) plasmas (Pulse No: 80894, $I_p = 2.5MA$, $B_T = 2.45T$, $\langle n \rangle = 6.0 \times 10^{19} \text{ m}^{-3}$).

Figure 19: Radial profile of the ion saturation current, standard deviation of the V_f fluctuations, turbulent radial particle flux and radial effective velocity for diverted plasmas with $\langle n \rangle = 5.3 \times 10^{19} \text{ m}^{-3}$, $8.0 \times 10^{19} \text{ m}^{-3}$ and $9.7 \times 10^{19} \text{ m}^{-3}$ (Pulse No: 81473, $I_p = 2.5MA$, $B_T = 2.5T$).