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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. Broad SOL profiles are observed for IW limited plasmas with power e-folding length substantially larger (by a factor of ~5–7.5) than in OW limited plasmas. The properties of the fluctuations in the SOL parameters indicate larger turbulent transport for IW limited plasmas. The striking differences observed between IW and OW limited plasmas on the power e-folding length, parallel flow, turbulent transport as well as the characteristics of the fluctuations support the existence of a poloidally localized region of enhanced radial transport near the outboard midplane. 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.

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 actively cooled beryllium limiters themselves and the start-up scenario must be therefore carefully tailored to minimize the power loading. Unfortunately, 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 and are being performed in different devices (see e.g. [2-5]) 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.

Measurements in tokamaks revealed a substantially broader SOL for plasmas limited in the Inner Wall, (IW), when compared to Outer Wall, (OW), limited plasmas [2-5]. 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 [2-3]. The effect on the SOL of changing the position of the main limiter from the inner to the outer wall was also 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 [5]. This ratio is larger than the 1.5 factor predicted by the model considered by Harbour and Loarte [5] based on geometric effects.

In this contribution, SOL transport in IW and OW limited plasmas are characterized by comparing not only the power e-folding length but also the parallel flow, effective diffusion coefficient and turbulent particle transport. Furthermore, the dependence of λ_q on the plasma current and line-averaged density is investigated for inner wall limited plasmas.

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 new probe head recently installed on JET, schematically illustrated in figure 1, consists of 9 cylindrical pins with a diameter of 1.5mm and an exposed length of 3mm, although only 6 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 4mm) measure the floating potential, V_f, making possible the determination of the turbulent particle flux (estimated using $\Gamma_{E\times B} = \langle \tilde{n}\tilde{E}_q \rangle / B_,$ where $\tilde{n}$ and $\tilde{E}_q$ are the density and the poloidal electric field fluctuations, respectively). Density and plasma potential fluctuations are evaluated from I_{sat} and V_f, respectively, neglecting electron temperature fluctuations. The remaining 3 pins used are located 5 mm radially further out, with pins 4 and 5 operated in I_{sat} mode used to measure the parallel flow, while pin 7, operated in swept mode, is dedicated to estimate the electron temperature, T_e, 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 (1MHz). Parallel flow Mach numbers are calculated using Hutchinson's formula $M_{//} = 0.4ln(I_{sat}^{u}/I_{sat}^{d})$ [6]. 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 [7].

Experiments have been performed in near full bore JET IW and OW limited plasmas for different values of plasma current and line-averaged density. 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. The main plasma parameters were not significantly different during the two phases of the discharge, apart from the line-averaged density that is 20–40% higher in OW limited plasmas, resulting in a larger radiated power and consequently a ~20–40% lower power into the SOL in this configuration. 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 2.5MA) and for line-averaged densities ranging from 3.8 to 8.5×10^{19} m^{-3} at constant magnetic field, $B_T = 2.4$ T, and elongation, $\kappa = 1.4$. 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 [8]. This conclusion is corroborated by the SOL density profiles that show a single-exponential behaviour.

3. COMPARISON BETWEEN IW AND OW LIMITED PLASMAS

Using the density and temperature e-folding lengths, λ_n and λ_T, estimated from the reciprocating probe data and assuming $T_e = T_i$ (T_i measurements are not available) and sheath-limited conditions, $q_{//}$ µ $nT_e^{3/2}$ µ $I_{sat}T_e$, the power decay length can be calculated using $1/\lambda_q = 1/\lambda_{Isat} + 1/\lambda_{Te}$. Limiter plasmas in JET are generally in the sheath-limited regime as the electron temperature measured by the probes embedded in the limiter tiles is similar to that measured by the reciprocating probe near the top of the plasma. 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 1MHz). 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, we have experimentally observed that $\lambda_{Te} \sim 2 - 6 \times \lambda_{Isat}$ and therefore the λ_{Te} error has a modest impact in the λ_q determination.

Inner and outer wall limited plasmas are compared in figure 2, showing the I_{sat} and T_e 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. 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 (λ_{Isat} ~5–8cm, λ_{Te} ~12–20cm), 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, ~10cm. The position of the outer wall 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. 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 I_{sat} and T_e profiles assuming an exponential decay, is substantially larger for OW limited plasmas, in agreement with the scaling $q_{//}^{LCFS} \mu \lambda_q^{-1}$ expected from the conservation of the power into the SOL and observed in previous experiments [3,4]

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 [2-3]) and in previous JET experiments (ratio of 2.9 [5]). As suggested by Gunn et al. [2], 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. As a consequence of the shorter $L_{c,eff}$, 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. 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 [2]. Fluctuation in I_{sat} and V_f are routinely measured with the JET probe system allowing for the estimate of the cross-field turbulent particle flux. In figure 4, the radial profiles of I_{sat}, $\Gamma_{E\times B}$ and cross-field diffusion coefficient are compared for IW and OW limited plasmas. As effective diffusion coefficient, $D_{\perp,eff}$, is estimated using the Fick's law $\Gamma_{E\times B} = D_{\perp,eff}\nabla n$. Note however that, in the SOL convective transport is in general important leading to the overestimation of $D_{\perp}$. A large turbulent transport is observed for IW limited plasmas across the entire SOL and values of $D_{\perp,eff}$ in the range 3–6m^2/s obtained, up to two orders of magnitude larger than the observed for OW limited plasmas.

The fluctuations in I_{sat} and V_f have also been characterized in order to better understand the differences in the SOL transport for the two configurations under consideration. Figure 5 shows the radial profile of the standard deviation and skewness of the floating potential fluctuations (similar results are observed for I_{sat} fluctuations). As illustrated, the amplitude of the fluctuations is significantly larger for IW limited plasma. Clear differences are also observed in the skewness that is roughly zero for OW limited plasmas and around one for IW limited plasmas. The large turbulent transport observed for IW limited plasmas results therefore from the existence of large amplitude, intermittent-like fluctuations that lead to a significant convective transport. In contrast, OW limited plasmas are characterized by low amplitude fluctuations with near Gaussian distribution and consequently the turbulent transport is modest (see figure 4). 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. 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 are in agreement with the assumption of an enhancement of radial transport near the outer midplane.

4. DEPENDENCE OF λ_Q ON THE MAIN PLASMA PARAMETERS

The scaling of the SOL power e-folding length with the plasma current and line-averaged density was investigated for IW limited plasmas, with the results summarized in figure 6. Figure 6a presents data from a series of discharges with plasma current of 1.5 and 2.5MA for a line-averaged density of $\sim 3.8\times10^{19}$ m^{-3}. Note that the parallel heat flux at the LCFS is observed to increase roughly linearly with I_p, in agreement with the linear increase in the power to the SOL. As illustrated in figure 6a, λ_q has a negative power dependence on the plasma current. This dependence is in agreement with the simple SOL model [9], predicting a dependence of the SOL width on $L_c^{1/2}$, with L_c having an inverse dependence on I_p. Figure 6b shows the λ_q dependence on the line-averaged density for I_p = 2.5MA. We observe that λ_q depends on the density for $n < 5\times10^{19}$ m^{-3}, with no clear dependence observed above that value. The small dependence of λ_q on the density may be related to the fact that the SOL plasma parameters show a modest variation with the line-averaged density. The SOL density at the LCFS increases and the electron temperature decreases as the line-averaged density rises, resulting in an approximately constant heat flux. This is in agreement with the power into the SOL remaining approximately constant with density in the range considered. The resulting λ_q scaling on the plasma current and line-averaged density for the existing dataset is presented in figure 6c. The SOL power e-folding length for JET IW limited plasmas follows $\lambda_q \mu I_p^{-0.23} n^{-0.16}$. A similar trend was observed on Tore Supra [2-3], though, with a stronger dependence on the plasma current, $\lambda_q^{TS} \mu I_p^{-0.8}$.

SUMMARY

The JET scrape-off layer has been characterized with a reciprocating probe. A large variety of plasma parameters are estimated with the new probe head allowing for an unprecedented characterization of the SOL in IW and OW limited plasmas. Broad SOL profiles are observed for IW limited plasmas (λ_{Isat} ~5–8cm, λ_{Te} ~12–20cm) with λ_q substantially larger (by a factor of ~5 – 7.5) than in OW limited plasmas. Similar measurements have also been made in diverted discharges and many common features were 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.

The properties of the fluctuations in the SOL parameters indicate larger turbulent transport for IW 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, supports the existence of a poloidally localized region of enhanced radial transport near the outboard midplane. The dependence of the SOL e-folding length on the main plasma parameters was also investigated and a modest negative dependence on both the plasma current and the line-averaged density found.

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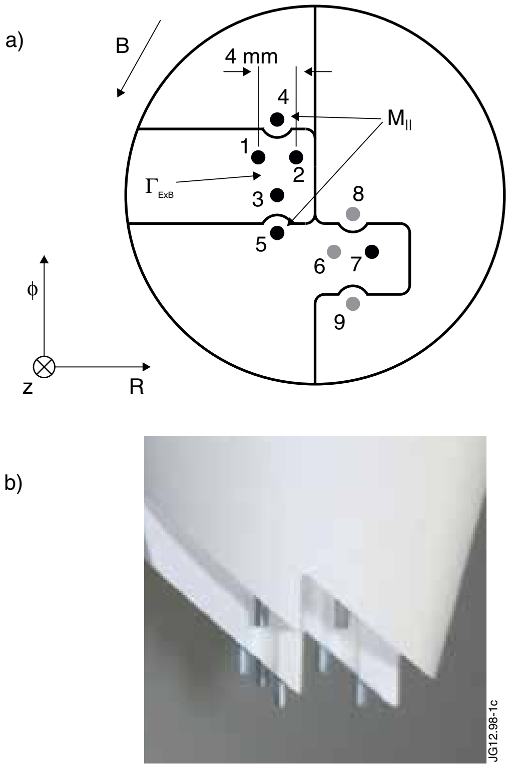


Figure 1: New JET reciprocating probe head: (a) Schematic illustration of the probe front view; (b) Photograph of the probe side view.

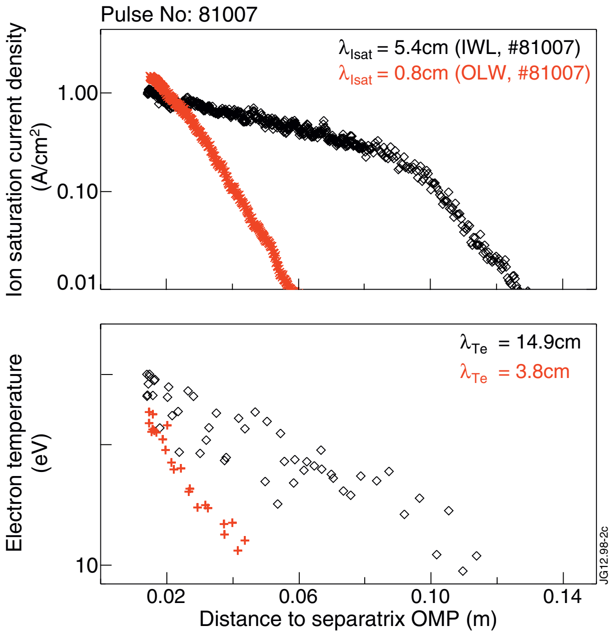


Figure 2: Ion saturation current and electron temperature radial profile for IW and OW limited plasmas (Pulse No: 81007, $I_p = 2.5MA$, $B_T = 2.45T$, $<n> = 6.2\times10^{19}m^{-3}$).

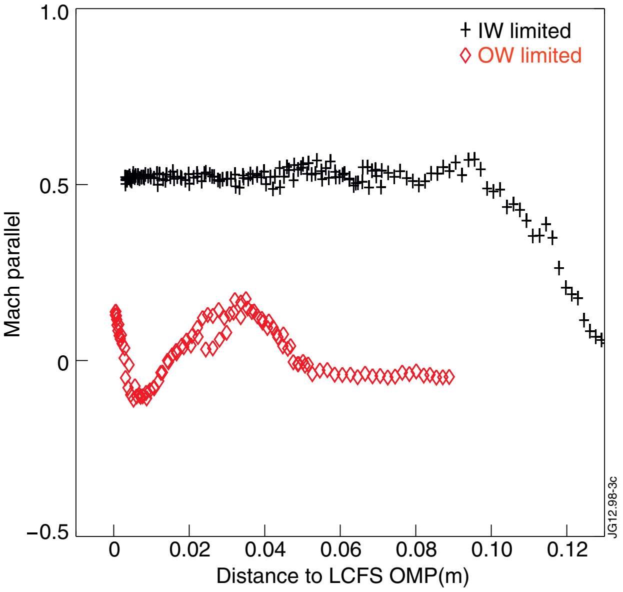
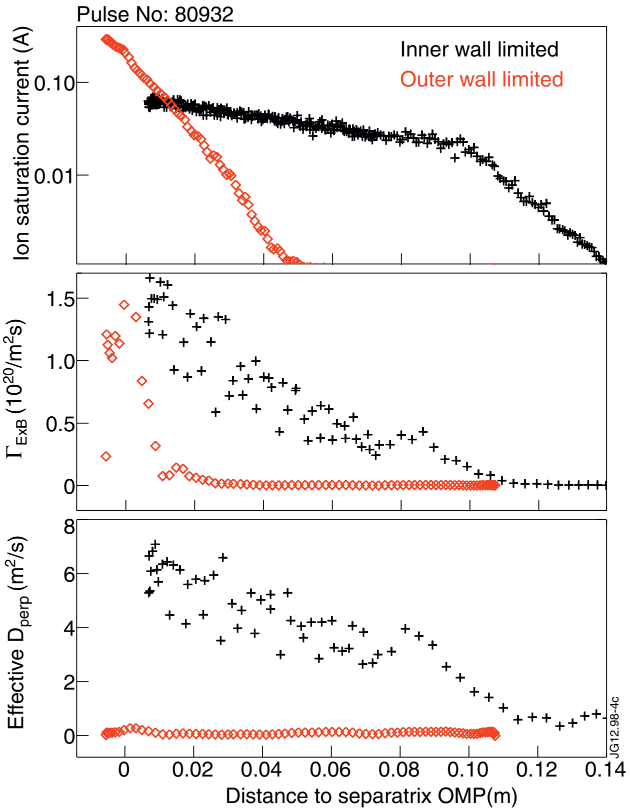


Figure 3: Parallel Mach number radial profile for IW and OW limited plasmas (Pulse No:80933, $I_p = 1.5MA$, $B_T = 2.45T$, $<n> = 3.8\times10^{19}m^{-3}$).



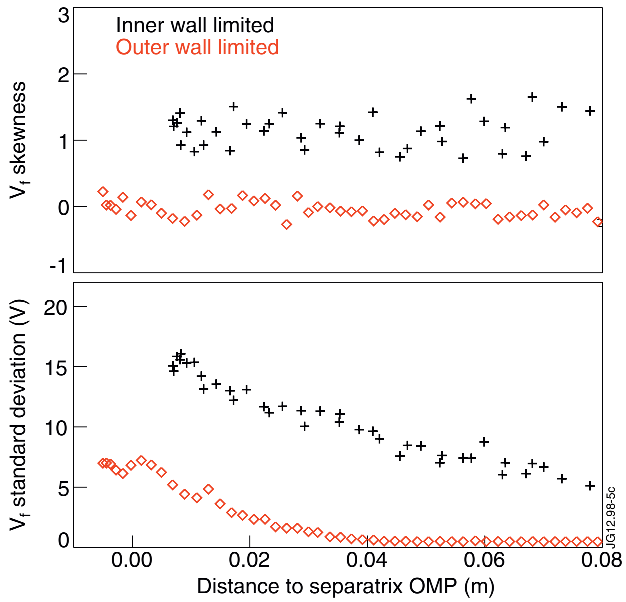


Figure 4: Radial profiles of Isat, GE´B and effective D^ (derived from the Fick's law) for IW and OW limited plasmas (Pulse No:80932, $I_p = 1.5MA$, $B_T = 2.45T$, $<n> = 3.7\times10^{19}m^{-3}$).

Figure 5: Radial profiles of the standard deviation and skewness of the floating potential fluctuations (Pulse No:80932, $I_p = 1.5MA$, $B_T = 2.45T$, $<n> = 3.7\times10^{19}m^{-3}$).

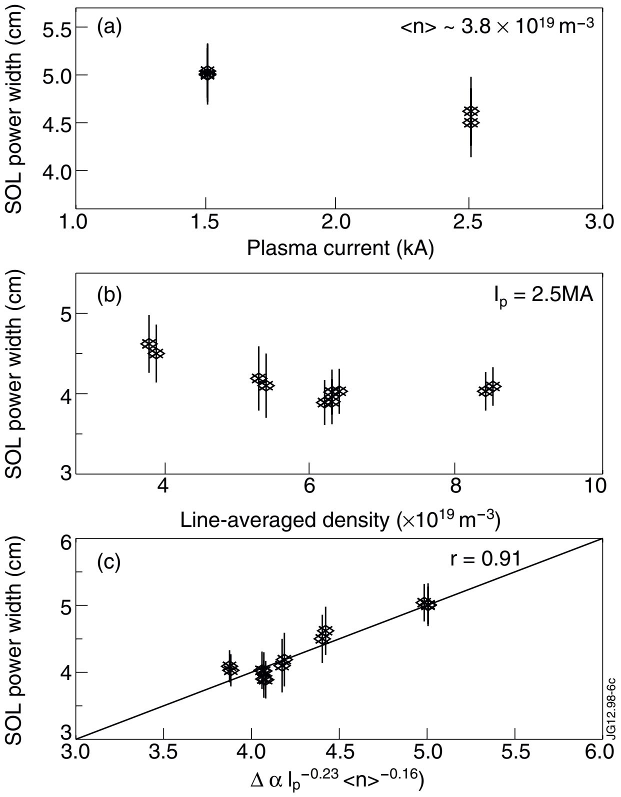


Figure 6: Scaling of the SOL e-folding length with plasma current (a) and line-averaged density (b). λ_q scaling on the plasma current and line-averaged density for the existing dataset is presented in (c).