Links Between Wide Scrape-Off Layers, Large Parallel Flows, and Bursty Transport in Tokamaks

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Abstract. Near-sonic parallel flows are systematically observed in the far scrape-off layer (SOL) on top of the limiter tokamak Tore Supra, as in many X-point divertor tokamaks when operated in the L-mode confinement regime. The poloidal variation of the parallel flow was measured by moving the contact point of a small circular plasma onto limiters at different poloidal angles. The resulting variations of flow are consistent with the existence of a poloidally localized enhancement of radial core-to-SOL transport concentrated near the outboard midplane. It seems to be possible to block the flow from this localized source using modular limiters. For example, with modular limiters placed near the plasma on the outboard midplane, the edge plasma thickness on top of the torus is around 2 cm and a thick vacuum layer separates the plasma from the first wall. In astounding contrast, when the limiters are removed, the thickness can increase up to a factor of 10 and plasma is observed to entirely fill all the available volume between the last-closed flux surface and the wall. Similar effects are not observed using the inboard bumper limiters. In general, we have identified a single simple condition that must be satisfied if plasma is to be observed far from the last closed flux surface: the magnetic field lines connected to the probe have to pass unobstructed across the outboard midplane. In another experiment the plasma contact point was placed on the bottom toroidal limiter. The outboard modular limiters were initially in contact with the plasma and then retracted shot-by-shot. The width of the SOL increased dramatically, the parallel flow increased to Mach 0.5 from a nearly stagnant state, and at the same time we began detecting large intermittent bursts of ion saturation current deeper in the SOL. The existence of bursts is correlated with the existence of the wide SOL and the large parallel flows. This triple correlation lends credence to the hypothesis that the SOL is fed by long range bursty transport events that are preferentially created near the outboard midplane. The effective particle source due to this enhanced transport is responsible for the large flows that we observe.

1. Introduction

Mach probe measurements of parallel ion flow in the scrape-off layer (SOL) of the Tore Supra tokamak [1] demonstrate the universality of many phenomena that have been observed in X-point divertor tokamaks [2] when operated in the L-mode confinement regime. Tore Supra [3] is a large tokamak with a plasma of circular cross section (major radius R=2.4 m and minor radius a=0.72 m) lying on a toroidal pump limiter (TPL). The maximum plasma current and toroidal magnetic field are respectively I_p<2.0 MA and B_ϕ<4 T; both are oriented in the negative toroidal direction. The ion B×∇B drift is directed downward towards the TPL. As in the JET tokamak [4], surprisingly large values of parallel Mach number are measured midway between the two strike zones, where one would expect to find nearly stagnant plasma if the particle source were poloidally uniform. Using a simple fluid model, we postulated that the observed flow is mainly due to a particle source that is poloidally localized on the outboard side of the torus [5]. We will present results of a novel experiment that provides direct evidence of this poloidal nonuniformity. By moving the plasma contact point around the poloidal section, it is possible to modify the edge flows. Asymmetric flows are observed in cases that should be symmetric from simple geometrical considerations. The results of the experiment are consistent with the predictions of the simple model if one assumes that the core-to-SOL outflux, which provides a significant fraction of the particle source on open flux surfaces, is poloidally localized near the outboard midplane.

The parallel flow indicates the location of the source, but the measurements of the density profiles also provide new information about its nature. Plasma that is transported into the SOL in the immediate vicinity of the outboard midplane seems to be able to travel a significant radial distance if its parallel motion does not lead it to neutralize on an object. For example, when the plasma contact point lies on modular bumper limiters on the inboard midplane, leaving a large volume on the low field side, the SOL density profiles are nearly flat and plasma is detected everywhere between the last closed flux surface (LCFS) and the edge of the vertical port in which the probe is housed. For example, in an exotic experiment with a very small plasma placed on the inboard bumper, plasma was detected up to 30 cm away from the last closed flux surface! However, when the contact point lies on the outboard midplane on modular limiters separated by short toroidal connection lengths, the SOL width is only 2 to 3 cm, and a thick vacuum region separates the plasma from the wall. The observations suggest that the wide SOL arises when field lines with long connection lengths are permitted to pass unobstructed across the outboard midplane. This condition appears to favour the existence of an enhanced radial transport that cannot occur anywhere else around the poloidal circumference. This behaviour is similar to what is observed in Alcator C-Mod in double-null divertor operation [6].

In Section 2 we describe the intuitive 1D fluid model that we employ to help us interpret the parallel flow measurements. In Section 3 we describe four experiments that were performed in order to test the predictions of the model. Finally in Section 4 we make our concluding remarks.

2. Simple Fluid Model

To interpret our measurements, we employ a convenient normalization of the simple, 1D, isothermal SOL with an arbitrary source of ions S in the convection-dominated, low recycling regime [7]. The equations of conservation of mass and momentum are

$$\frac{d}{dx_{//}} nV_{//} = S, \qquad \frac{d}{dx_{//}} n\left(V_{//}{}^2 + c_s^2\right) = 0 \tag{1)}$$

where $x_{//}$ is the parallel coordinate, n is the ion density, $V_{//}$ is the parallel flow speed, and the sound speed is $c_s{}^2=k(T_e+T_i)/m_i$. We seek the solution on the domain $-L/2 \leq x_{//} \leq L/2$, where L corresponds to the connection length of a magnetic field line in the SOL. The effect of a poloidal electric drift is neglected here because its magnitude is small in Tore Supra [5]. The source term S is a free function that is in general, but not necessarily, independent of n and $V_{//}$. We define a dimensionless distance as

$$s_{//} = \frac{1}{\langle S\rangle L} \int_{-L/2}^{x_{//}} dx_{//}\ S \tag{2)}$$

with

$$\langle S\rangle = \frac{1}{L} \int_{-L/2}^{L/2} dx_{//}\ S \tag{3)}$$

being the average source rate in the SOL. The parallel coordinate is respectively $s_{//}=0$ and $s_{//}=1$ on the ion side and electron side strike points. We define the parallel Mach number $M_{//}=V_{//}/c_s$, and enforcing the Bohm criterion at both boundaries, $M_{//}(s_{//}=0)=-1, \quad M_{//}(s_{//}=1)=+1$, we obtain the solution for the Mach number

$$\frac{M_{//}}{M_{//}^2+1}=s_{//}-\frac{1}{2} \tag{4)}$$

A measurement of the parallel Mach number therefore gives an indication of the position of the probe with respect to the source, which has two origins: ionization of recycled gas near the strike points and the cross-field transport of particles from the core plasma into the SOL. The stagnation point $M_{//}=0$ lies at the center of the source distribution, $s_{//}=0.5$. The link between the source distribution and the local flow speed was verified experimentally by massive injections of gas at different poloidal locations leading to predictable modifications of the Mach number [8].

3. Experiment

In Tore Supra the plasma usually lies on the bottom TPL. The reciprocating Mach probe, located in a top port, is roughly half way between the two strike zones. If half of the recycling occured near each strike zone, and if the poloidal distribution of radial outflux from the core were uniform, one would expect to measure nearly stagnant ion flow. However, large values are always measured, $M_{//}\approx 0.5$. Eq. 4) suggests that the probe is located at $s_{//}=0.1$, that is, 90% of the SOL particle flux originates between the probe and the low field side strike zone. A special experiment was performed in order to test this hypothesis. Ideally one would like to measure the flow at many poloidal locations; the poloidal gradient of the flow profile would yield valuable information about the source distribution. That is not possible in Tore Supra, so instead we made a small plasma of radius a=0.65m and moved its contact point to four locations around the chamber (Fig. 1). The first was on six discrete inboard bumper limiters at the midplane (referred to hereafter as "HFS" contact); the second was the usual bottom configuration on the TPL ("BOT" contact); the third ("LFS" contact) was on a set of six modular limiters on the outboard midplane (three ICRH antennae at toroidal angles 40°, 100°, and 280° respectively, two LH antennae at 320° and 340° respectively, and the antenna protection limiter APL at 140°); in the fourth configuration the plasma contact point was on

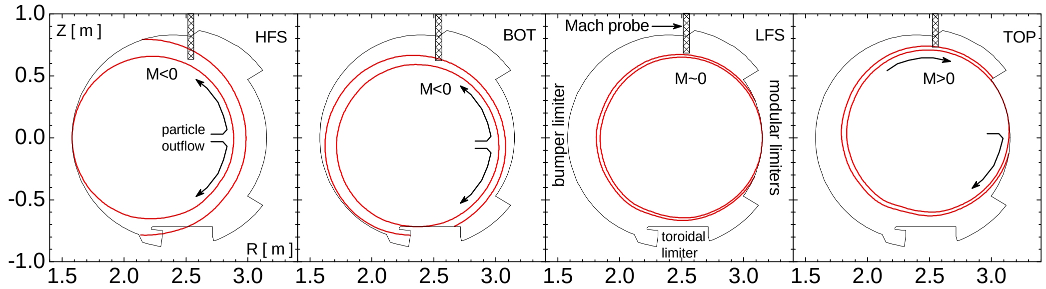

Fig. 1. From left to right these four panels show the magnetic configurations used in the experiment. Both the LCFS and the flux surface on which 1/e of the LCFS density was measured in each case are drawn. The postulated paths of the particle outflux from the core are indicated by arrows. The sign of the parallel flow is defined to be positive when its poloidal projection is directed in the positive poloidal direction (clockwise in the R-Z plane). At the probe location positive flow is directed from the high field side towards the low field side.

top of the outboard modular limiters at a poloidal angle approximately 30° above the midplane ("TOP" contact). Because the HFS, LFS, and TOP contact points are made on discrete limiters , we ran the experiment at high edge safety factor q=6. That way all field lines in the SOL strike some object before crossing the midplane, so we can assume that the modular limiters act effectively like a continuous toroidal limiter.

The location of the probe relative to the four contact points is illustrated in Fig. 2a. If the core-to-SOL outflux were poloidally uniform one would expect to measure large negative flow (for HFS contact), roughly zero flow (BOT), or large positive flow (LFS and TOP). The measurements of parallel Mach number in Fig. 2b largely confirm the prediction of the model in the far SOL if one assumes that the outflux is mostly ejected across the outboard midplane, as indicated by arrows in Fig. 1. In contrast to the significant difference in connection schemes between HFS and BOT, the flow is more or less the same. The invariance of the flow implies that the parallel flux on top of the torus is fed from the low field side. The difference between LFS and TOP is astounding. The connection schemes are identical; the probe is very close to the low field side strike zone in both cases. However, moving the plasma slightly above the outboard midplane from LFS to TOP appears sufficient to allow the outflux to escape towards the bottom, flow all the way around the poloidal circumference, past the probe on top, and finally neutralize on one of the modular limiters. This singular behaviour is further illustrated in Fig. 2c where the dimensionless parallel distance $s_{//}$ derived from the Mach number is shown. The curves would be very similar to those in Fig. 2a if the source distribution were poloidally uniform.

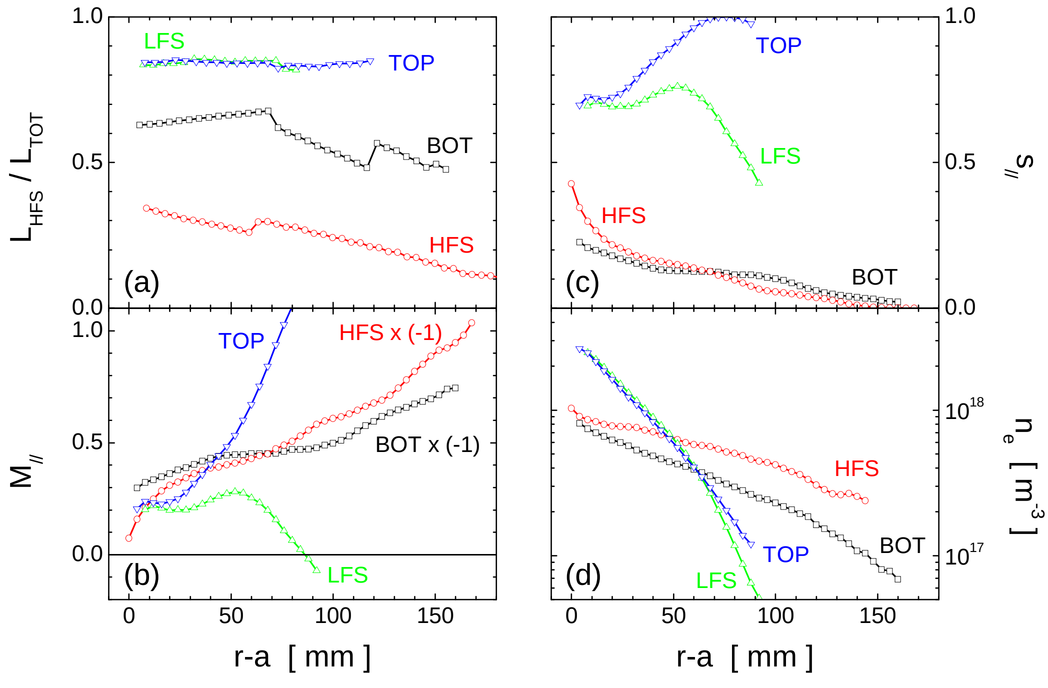

Fig. 2. (a) Connection length between the probe and the inboard strike zone divided by the total connection length between the two strike zones (HFS - circles; BOT - squares; LFS - up triangles; TOP - down triangles). The ratio is calculated using the reconstructed magnetic equilibrium, and is plotted as a function of the radial distance from the LCFS. (b) Parallel Mach number profiles measured for each configuration. Those for BOT and HFS contact are inverted for the sake of comparison. (c) Dimensionless parallel distance from the simple model, Eq. (4). (d) Measured electron density in each configuration.

Further information about the nature of the localized source is obtained from the density measurements, as shown in Fig. 2d. In the HFS and BOT configurations, when a large clearance exists between the LCFS and the modular limiters, plasma can be detected all the way to the edge of the vertical port in which the probe is housed. In the LFS and TOP configurations the density profiles are steep and a thick vacuum region separates the plasma from the wall. In Fig. 1 the flux surface corresponding to the first density decay length is plotted along with the LCFS in order to emphasize the significant difference between the density profiles. It is especially interesting to compare HFS and LFS. Apart from geometrical effects due to toroidicity, the two configurations are symmetric. However, in HFS the flow is large and the density decay length is around λ_n=120 mm, whereas in LFS the flow is small and λ_n=30 mm. One is led to speculate that the net radial transport is much stronger near the midplane than at other poloidal angles. In LFS, the plasma is transported across the LCFS into a region of very short connection length, only a few metres, and the particles flow along field lines to neutralize immediately on the side of one of the modular limiters; the parallel transport time is so short that the plasma does not have sufficient time to undergo any significant radial transport. On the other hand, in HFS contact, the parallel transport is unhindered, allowing the plasma to expand out to the wall before leaving the midplane region. In general, in order to have strong radial transport producing a fat SOL, it appears to be necessary to have long field lines passing unobstructed through the outboard midplane.

Variations of the SOL thickness can be caused by differences in radial transport for constant connection length, or vice versa. If the radial transport coefficients were poloidally uniform, one would need the connection lengths in HFS configuration to be more than an order of magnitude longer than in LFS, but in fact, the total HFS connection length is nearly twice as short as LFS! Clearly, the difference in the decay lengths can only be explained by a poloidal nonuniformity of the radial transport. This idea is not new, but until now even assuming strong ballooning-type dependencies for the transport coefficients (~1/R or even ~$1/R^2$) does not allow 2D fluid codes to produce such starkly different density profiles. These measurements indicate that the nonuniformity is much stronger than previously guessed.

An experiment was performed on shot #35230 in order to estimate the poloidal extent of the region of enhanced radial transport. The plasma was displaced from the bottom to the top of the modular limiters in 10° steps of poloidal angle (Fig. 3). Despite nearly identical magnetic connections in all cases, the parallel flow exhibits spectacular reversal depending on whether the field lines sampled by the probe are connected to the outboard midplane via the positive or negative poloidal direction. The far-SOL flow was large and negative when the contact point was below the midplane due to the outflux moving upwards from the outboard midplane towards the top of the torus; it was small for the 3rd and 4th intermediate positions, and reversed for the upper positions (Fig. 4). This experiment allows us to estimate that the region of enhanced radial transport is limited to a sector around 30° in poloidal extent roughly centered near the outboard midplane. If we make the crude assumption that the wide decay length in HFS configuration is due to strong diffusive radial transport in a 30° poloidal sector, while that the short decay length in LFS is due to weaker transport over a full poloidal

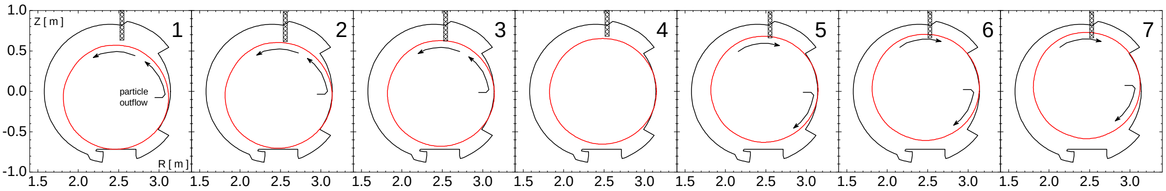

Fig. 3. Magnetic measurement of last closed flux surface as the plasma strike point is displaced upward along the outboard modular limiters. The arrows indicate the direction of flow past the Mach probe assuming that most of the SOL source is concentrated near the outboard midplane.

turn, we find that the ratio of the two effective diffusion coefficients would be around 200.

Further evidence of the poloidal nonuniformity of the SOL particle source comes from a toroidal array of four fixed Langmuir probes that are mounted at the entrance of pumping throats under the TPL on the high field side Fig. 5a. These probes are located 6 cm vertically below the surface of the TPL and at R=2.282 m. Two shots were compared. In both cases the plasma current was ramped slowly from 0.4 to 1.0 MA with toroidal field B_ϕ=2.5 T to vary the edge safety factor, 6.4>q_a>2.5, Fig. 5b. In the first shot (34587) that served as a reference case, all the outboard modular limiters were fully retracted. The parallel ion current density was the same at all four toroidal positions, confirming toroidal symmetry, Fig. 5c. On the second shot (34588) the APL alone was inserted almost to the LCFS. In contrast to the LFS and TOP configurations described above, the APL acts like a modular limiter in this case, rather than a continuous toroidal limiter, because the safety factor is low, and the other limiters remain retracted. The APL casts a narrow magnetic shadow that is seen as a decrease in ion current on the probe to which it is connected. As the safety factor varies, the shadow moves around the TPL and is detected sequentially by each probe. When the probe is not shadowed, it measures practically the same flux as when the APL is retracted.

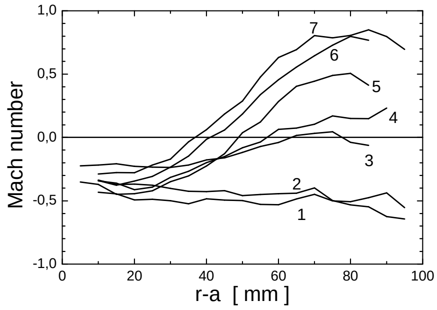

Fig. 4. Measured Mach number profiles on top of the torus for the seven magnetic configurations shown in Fig. 3. Postive flow is directed from inboard to outboard.

The particle flux collected by a given probe is the integral of the source on the field line that the probe intercepts. The insertion of an object somewhere upstream interrupts the flow of particles, thus only the source between the object and the probe can contribute to the

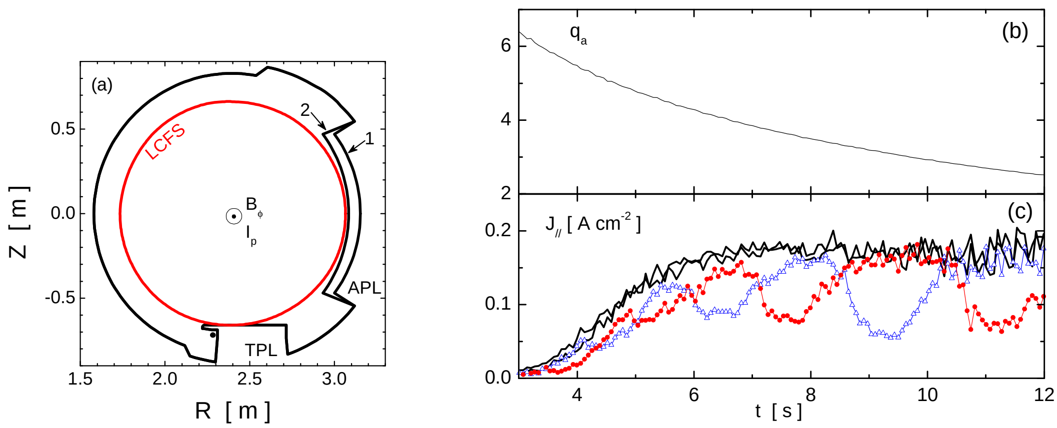

Fig. 5. (a) Poloidal cross section for shots 34587 with the APL retracted (1) and 34588 with the APL inserted (2). The location of the toroidal array of Langmuir probes is indicated by the dot under the TPL. (b) The safety factor on the LCFS versus time for shots 34587 and 34588. (c) The parallel ion current density measured by two fixed Langmuir probes toroidally separated by 180° during both shots. The thick lines were measured on shot 34587 (the values are the same due to toroidal symmetry, so we do not distinguish them). On shot 34588 the movement of the APL's shadow around the toroidal circumference is manifested by the periodic decrease of the ion current measured by the probes at ϕ=82° (open triangles) and ϕ=262° (full circles).

measured ion current. The ratio of the ion current in the shadow to the unperturbed value, which is equivalent to the definition of $s_{//}$ (see Eq. (2)), is observed to decrease to 0.3. This implies that only 30% of the flux is created between the probe and the APL on a field line that is 83% of the total connection length, as reconstructed from magnetic flux loop data. The effect of the shadowing is much stronger than one would estimate from simple geometrical arguments, demonstrating that there must be a strong localization of the source on the low field side of the torus.

In order to exclude the possibility that the observations could be due to complicated changes in magnetic connection schemes rather than fundamental transport characteristics, a special experiment was conducted in order to explicitly and unambiguously determine the role of the outboard limiters. The plasma contact point was placed on the bottom TPL, which was positioned higher than usual, at Z=-0.66 m. The outboard modular limiters were initially in contact with the plasma and then retracted shot-by-shot, maintaining the magnetic equilibrium invariable. The clearance between the LCFS and the outboard limiters was set to δ=0 cm, 1 cm, 2 cm, 4 cm, and finally 8 cm. The width of the SOL increased dramatically (Fig. 6a) as the limiters were retracted. Concurrently, a large parallel flow appeared in the far SOL (Fig. 6b) and at the same locations we began detecting large intermittent bursts of ion saturation current (Fig. 6c). This triple correlation lends credence to the hypothesis that the far SOL is fed by long range bursty transport events that are preferentially created near the outboard midplane. The effective particle source due to this enhanced transport is responsible for the large flow and wide SOL that we observe on top of the torus when there are no parallel losses to outboard limiters.

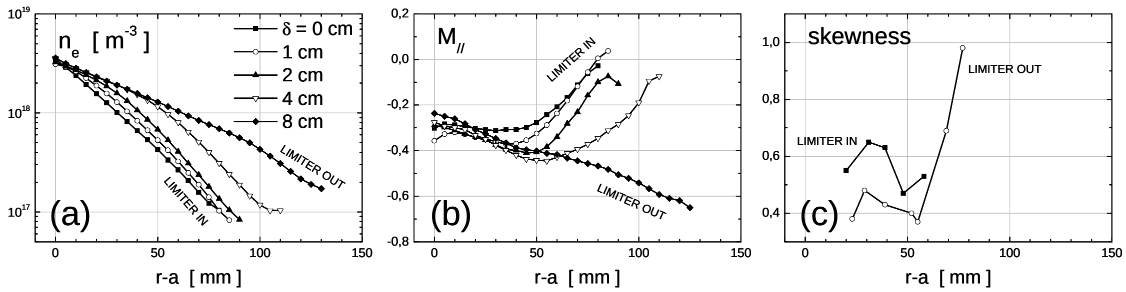

Fig. 6. (a) Radial density profiles measured on top of the torus by the Mach probe for five values of outboard clearance, (b) the corresponding profiles of parallel Mach number, and (c) the skewness of the probability distribution function of ion saturation current flowing to the probe from the low field side.

4. Conclusions

Near sonic parallel flows are systematically observed in the SOL of the limiter tokamak Tore Supra, as in many X-point divertor tokamaks when operated in L-mode. Based on a simple 1D fluid model, we assume that the parallel Mach number directly indicates the fraction of the SOL particle source located between each side of the Mach probe and the two plasma strike zones on the limiter. The poloidal variation of the Mach number of the parallel flow was studied by moving the contact point of a small circular plasma onto limiters at different poloidal angles. The resulting variations of flow are consistent with the existence of an enhanced core-to-SOL outflux, strongly concentrated near the outboard midplane. If no object obstructs the parallel motion of the plasma that gets ejected onto open magnetic flux surfaces, which is the case when the contact point lies on the inboard midplane, the SOL expands to fill all the available volume between the LCFS and the wall. The mechanism that causes this spectacular expansion appears to be favoured by the existence of long field lines that pass unobstructed across the outboard midplane. This is demonstrated by moving the plasma from HFS to LFS contact : the SOL becomes very thin and a thick vacuum region separates the plasma from the wall.

These results, obtained in a limiter tokamak with a circular plasma cross section, seem to be similar to what is observed in X-point divertor tokamaks, perhaps indicating the universality of the phenomenon. A candidate mechanism to explain the enhanced transport is the net outward convection of discrete transport events, or "blobs" [9,10]. In Tore Supra, we have begun to characterize the bursty transport events in these moving plasma experiments. We find that they are initiated in the vicinity of the last closed flux surface and can be detected quite far away in the SOL if the modular limiters are retracted from the outboard midplane [11]. Two-dimensional fluid simulations including anomalous convective transport concentrated on the outboard side are able to reproduce basic features of the measurements in divertor tokamaks [12]. Recent simulations of the Tore Supra experiments using the TECXY code show the same result [13]. Our findings provide significant new information about the strong poloidal localization of the region where blobs are created.

Acknowledgements

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