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Evidence for a poloidally localized enhancement of radial transport in the scrape-off layer of the Tore Supra tokamak

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Abstract

Near-sonic parallel flows are systematically observed in the far scrape-off layer (SOL) of the limiter tokamak Tore Supra, as in many L-mode X-point divertor tokamak plasmas. The poloidal variation of the parallel flow has been 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 transport concentrated in a 30° sector near the outboard midplane. If the plasma contact point is placed on the inboard limiters, then the SOL expands to fill all the space between the plasma and the outboard limiters, with density decay lengths between 10 and 20 cm. On the other hand, if the contact point lies on the outboard limiters, the localized plasma outflux is scraped off and the SOL is very thin with decay lengths around 2–3 cm. The outboard radial transport would have to be about two orders of magnitude stronger than inboard to explain these results.

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Keywords: Cross-field transport; Edge plasma; Plasma flow; Tore Supra

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1. Introduction

Ion flow in the scrape-off layer (SOL) is both the cause and the symptom of many tokamak edge

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phenomena. Neutral recycling and impurity transport are intricately linked to edge flow patterns. SOL flows are believed to play a role in the asymmetric formation of carbon deposits in divertors [1], and they may influence the H-mode threshold [2]. It became evident a long time ago that radial cross-field transport from the core into the SOL is anomalous and poloidally asymmetric, necessarily being strongest on the outboard side in order to explain certain experimental observations, such as large flows directed towards the inboard side (e.g. [3]). Many calculations using 2D fluid codes can reproduce the general qualitative behaviour of the flow patterns by including 'ballooning type' transport coefficient asymmetries ($\sim 1/R$) or arbitrary unphysical forces [4,5], but most do not give high enough magnitudes of the flow. The correct implementation of drifts in fluid codes is especially challenging, and recent work shows that they can play an important role in the overall SOL flow distribution [6]. The persistent disparity between modelling and experiment has led some to postulate that Mach probes might not work correctly [7]. The reader can find a comprehensive review of the present state of SOL flow research in [8].

Until now most SOL measurements were 'passive' in the sense that flows and poloidal asymmetries might be observed, and anomalous ballooning type transport invoked to explain them, but little effort has been made to act upon the plasma in order to study the nature of the transport. Some of the most convincing recent results come from Alcator C-Mod where changing the X-point geometry from single to double null clearly demonstrates that a large fraction of the core-to-SOL particle flux is localized on the outboard side [9]. In this paper, we present complementary measurements made in the Tore Supra tokamak that give striking new information both about the poloidal localization of the anomalous transport and its strength. By moving the contact point of a small plasma 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 indicate that the anomalous core-to-SOL outflux is poloidally localized in a 30° sector near the outboard midplane.

To maximize performance most tokamaks run large plasmas occupying as much of the vacuum chamber volume as possible. The SOL is often choked off by various limiters, as evidenced by the radial cascade of discretely varying decay lengths. By making unusually small plasmas, we allow the SOL to expand naturally, thus gaining significant new information about the strength of the anomalous transport. Our measurements indicate that the inboard/outboard transport asymmetry is much stronger than usually supposed. 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 is not blocked by an object. For example, in an experiment with a very small plasma ($a = 50$ cm) placed on the inboard modular bumper limiters, plasma was detected 30 cm away from the last closed flux surface (LCFS) at the edge of the vertical port in which the probe is housed. However, when the contact point lies on outboard modular limiters separated by short toroidal connection lengths, the SOL width is only 2–3 cm, and a thick vacuum region separates the plasma from the wall.

2. Normalized parallel coordinate

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 [10]. The equations of conservation of mass and momentum are

$$\frac{\mathrm{d}}{\mathrm{d}x_\parallel} nV_\parallel = S, \quad \frac{\mathrm{d}}{\mathrm{d}x_\parallel} n(V_\parallel^2 + c_\mathrm{s}^2) = 0, \tag{1}$$

where $x_\parallel$ is the parallel coordinate, n is the ion density, $V_\parallel$ is the parallel flow speed, and the sound speed is $c_\mathrm{s}^2 = k(T_\mathrm{e} + T_\mathrm{i})/m_\mathrm{i}$. We seek the solution on the domain $-L/2 \leqslant x_\parallel \leqslant L/2$, where L corresponds to the connection length of a magnetic field line in the SOL. We define a dimensionless distance as:

$$s_\parallel = \frac{1}{\langle S \rangle L} \int_{-L/2}^{x_\parallel} \mathrm{d}x_\parallel S \quad \text{with } \langle S \rangle = \frac{1}{L} \int_{-L/2}^{L/2} \mathrm{d}x_\parallel S \tag{2}$$

being the average source rate in the SOL. The parallel coordinate $s_\parallel$ equals the fraction of the field-line integrated source that lies between the ion side (i-side) strike zone and a given point along the field line. It is, respectively, $s_\parallel = 0$ and $s_\parallel = 1$ on the i-side and electron side (e-side) strike points of the principal limiter that defines the last closed flux surface (LCFS). We define the parallel Mach number $M_\parallel = V_\parallel / c_\mathrm{s}$, and enforcing the Bohm criterion at both strike zones, $M_{\|}(s_{\|}=0)=-1$, $M_{\|}(s_{\|}=1)=+1$, we obtain the solution for the Mach number:

$$\frac{M_{\|}}{M_{\|}^2+1}=s_{\|}-\frac{1}{2}. \tag{3}$$

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 barycenter 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 [11].

3. Three novel experiments

Tore Supra [12] is a large tokamak with a plasma of circular cross-section (major radius $R=2.4$ m and minor radius $a=0.72$ m) whose last closed flux surface is defined by the intersection with the bottom toroidal pump limiter (TPL). The maximum plasma current and toroidal magnetic field are, respectively, $I_p<2.0$ MA and $B_\phi<4$ T; both are oriented in the negative toroidal direction, i.e. clockwise viewed from above. The ion $B\times\nabla B$ drift is directed downward towards the TPL, upon which the plasma contact point is usually placed. The reciprocating Mach probe is located in a top port roughly half way between the i-side and e-side 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 at the probe location. However, large values are always measured, independent of the core plasma parameters or additional heating scenario, $M_{\|}\approx-0.5$, suggesting (Eq. (3)) that the probe is located at $s_{\|}=0.1$. That is, 90% of the SOL particle flux originates between the probe and the e-side strike zone.

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 $a=0.65$ m 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 was displaced upwards so that its contact point was on 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 far 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. 2(a). If the core-to-SOL outflux were poloidally uniform one would

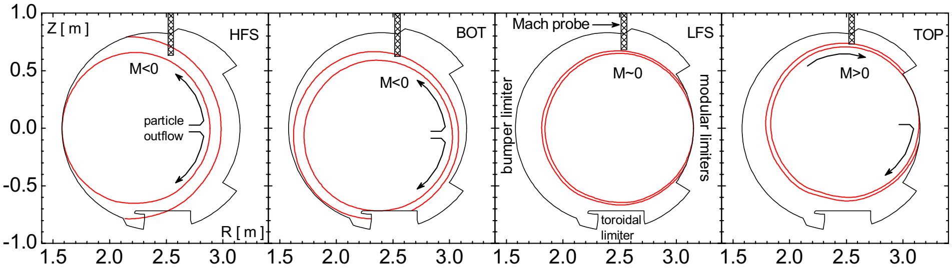

Fig. 1. From left to right these four panels show the magnetic configurations used in the experiment. Both the LCFS and the flux surface on which $1/e$ of the LCFS density was measured in each case are drawn. The main paths of the particle outflux from the core, as we postulate based on the simple model, 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.

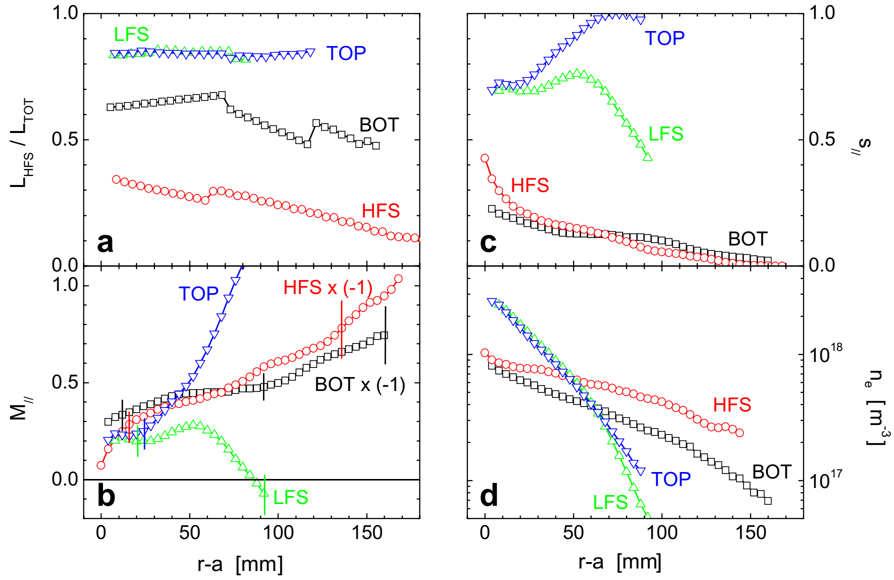

Fig. 2. (a) Connection length between the probe and the i-side strike zone divided by the total connection length between the two strike zones (HFS, circles; BOT, squares; LFS, up triangles; TOP, down triangles). The ratio is calculated using the reconstructed magnetic equilibrium, and is plotted as 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. A few typical error bars are indicated by vertical lines. (c) Dimensionless parallel distance from the simple model, Eq. (3). This quantity is the fraction of the total field-line-averaged source that lies between the probe and the i-side strike zone. (d) Measured electron density in each configuration.

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. 2(b) largely confirm the prediction of the model in the far SOL if one assumes that the outflux primarily crossed the LCFS near the outboard midplane, as indicated by arrows in Fig. 1. In contrast to the significant difference in connection schemes between HFS and BOT contact, 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 stark. The connection schemes are identical; the probe is very close to the e-side strike zone in both cases. However, displacing 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. 2(c) where the dimensionless parallel distance $s_{\|}$ derived from the Mach number is shown.

The flow measurements indicate that the radial outflux from the core into the SOL, which provides a large fraction of the effective particle source on open field lines, is concentrated near the outboard midplane. This implies that the radial transport across the LCFS is poloidally non-uniform. In addition, the measured density profiles suggest that the radial transport throughout the SOL also must be non-uniform, as shown in Fig. 2(d). 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. The reader can refer to Fig. 1 where 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 density decay length is around $\lambda_n = 120$ mm, whereas in LFS it is $\lambda_n = 30$ mm. If radial transport in the SOL were poloidally uniform, there would be little difference in the density decay lengths observed between HFS and LFS contact, independent of the poloidal angle at which the outflux from the core is fed into the SOL. In HFS contact, the probe measures high plasma density far from the LCFS, with large parallel flow. The presence of high density far from the LCFS implies that radial transport in the SOL is stronger than for LFS contact. The large parallel flow implies that the plasma that is observed comes from the outboard side. The two observations together imply that radial transport must be strongest near the outboard midplane, across the full width of the SOL. For LFS contact, the plasma that is transported into the SOL near the outboard midplane is deposited in 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. Since we do not have probe measurements of the decay length between the limiters, it is not possible to say whether the enhanced radial transport still occurs there, or if the presence of the limiters somehow suppresses it. Nonetheless it is clear that the short decay length observed on top is due to slower transport at poloidal angles far away from 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 the HFS configuration to be more than an order of magnitude longer than in LFS, but in fact, the total connection length between the two strike zones for HFS contact is nearly twice as short as LFS contact (due to the fact that the field lines strike the inboard limiters quite far above and below the midplane). Clearly, the difference in the decay lengths can only be explained by a poloidal non-uniformity of the radial SOL transport. This idea is not new, but until now even assuming strong ballooning-type dependencies for the transport coefficients ($\sim 1/R$ or even $\sim 1/R^2$) does not allow 2D fluid modelling to produce such starkly different density profiles [16]. These measurements indicate that the non-uniformity 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 ions 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 with HFS contact is due to strong diffusive radial transport in a 30° poloidal sector, while that the short decay length with LFS contact is due to weaker transport over a full poloidal turn (implying that the effective parallel transport length is 12 times longer in the latter case), we find that the ratio of the two effective diffusion coefficients would be around 200, assuming the same rate of parallel transport in both cases.

The parallel flow measurements shown in Figs. 2(b) and 4 tend to low values near the LCFS. The flow measured there is likely some intermediate value between that which occurs on closed magnetic flux surfaces and those deep in the SOL. The radial scale length of the transition (1–3 cm) is determined by viscous coupling and/or the magnetic connection map. For example, in Tore Supra with its 18 superconducting toroidal field coils, the so-called LCFS only touches the TPL at 18 discrete points. In addi-

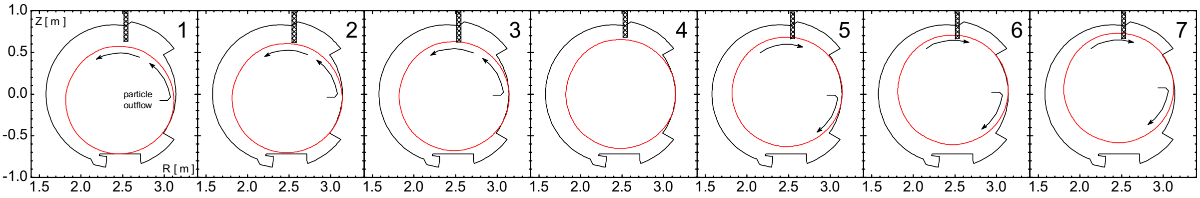

Fig. 3. Magnetic measurement of the LCFS as the plasma strike point is displaced upward along the outboard modular limiters. The arrows indicate the direction of flow past the Mach probe assuming that most of the SOL source is concentrated near the outboard midplane.

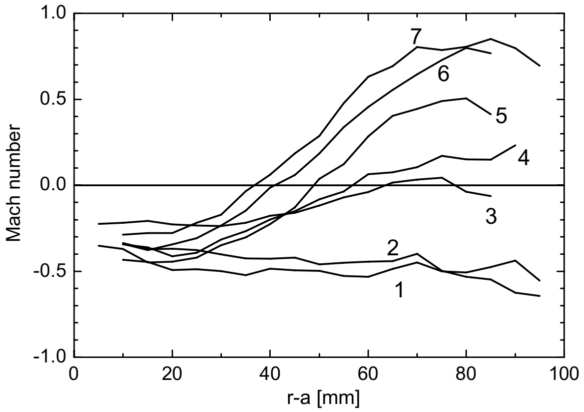

Fig. 4. Measured Mach number profiles on top of the torus for the seven magnetic configurations shown in Fig. 3. Positive flow is directed from inboard to outboard.

tion, the radii of curvature of both inboard and outboard limiters are larger than that of the plasma; a large fraction of the field lines just outside the LCFS make more than one poloidal turn around the torus. These issues need to be examined in the future. Nonetheless, the far SOL flow measurements would appear to be consistent with the simple model of a SOL particle source fed by plasma crossing the LCFS in a region concentrated near the outboard midplane.

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. 5(a), provide additional evidence of the poloidal non-uniformity of the radial transport. These probes are located 6 cm vertically below the surface of the TPL 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 $B_\phi = 2.5$ T to vary the edge safety factor, $6.4 > q_a > 2.5$, Fig. 5(b). 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. 5(c). 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.

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 measured ion current. The ratio

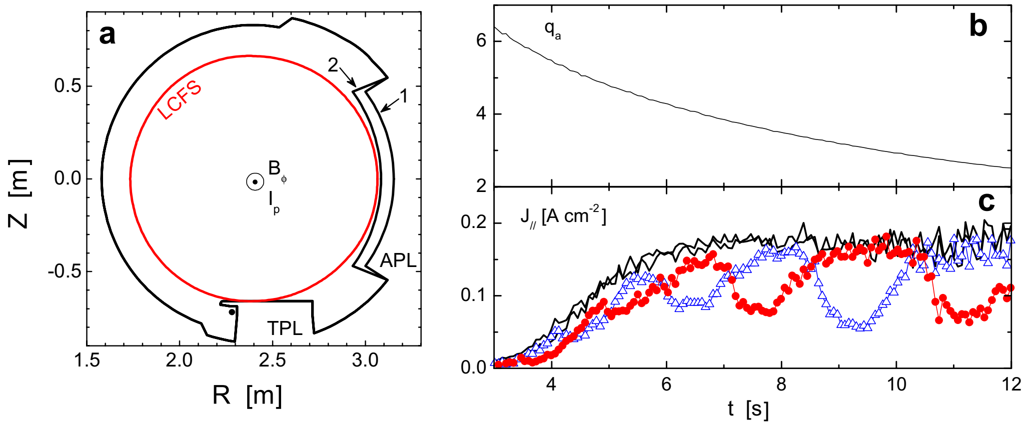

Fig. 5. (a) Poloidal cross-section for shots 34587 with the APL retracted (1) and 34588 with the APL inserted (2). The location of the toroidal array of Langmuir probes is indicated by the dot under the TPL. (b) The safety factor on the LCFS versus time for shots 34587 and 34588. (c) The parallel ion 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 during the I_p ramp is manifested by the periodic decrease of the ion current measured by the probes at $\phi = 82°$ (open triangles) and $\phi = 262°$ (full circles).

of the ion current in the shadow to the unpertubed 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 connection length between the two strike zones on the TPL, 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.

4. Discussion and conclusions

Near sonic parallel flows are systematically observed in the SOL of the limiter tokamak Tore Supra, as in many L-mode X-point divertor tokamak plasmas. 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, especially in the far SOL, are consistent with the existence of an enhanced core-to-SOL transport, strongly concentrated near the outboard midplane. If no object obstructs the parallel motion of the plasma that is transported 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 L-mode X-point divertor tokamak plasmas, perhaps indicating the universality of the phenomenon. A candidate mechanism to explain the enhanced radial ion fluxes in the region of the outer SOL is the net outward convection of discrete transport events, or 'blobs' [13,14]. In Tore Supra, we have begun to characterize the bursty transport events in these variable limiter location 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 [15]. 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 [5]. Recent simulations of the Tore Supra experiments using the TECXY code show the same result [16]. Our findings provide significant new information about the strong poloidal localization of the region where blobs are created.

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