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Flow generation and intermittent transport in the scrape-off-layer of the Tore Supra tokamak

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ABSTRACT

Results on transport in the scrape-off-layer from a set of ohmic discharges in Tore Supra are discussed. The particle balance in the SOL is described trough a steady-state model that utilizes profile measurements from reciprocating-probes. Experimental evidence of the non-uniformity in the poloïdal distribution of particle outflux is found, with the highest outflux being concentrated in a narrow sector at the outboard midplane. High and intermittent fluctuations originating from the same outboard midplane sector are interpreted as the signature of the transport mechanisms that result in the time-averaged equilibrium. The radial convection of subsonic structures is assumed as the dominant transport process.

1. Introduction

Ion flows in the scrape-off-layer (SOL) are both the cause and the symptom of plasma edge phenomena. Parallel flows are a consequence of outflux distribution across the last closed flux surface (LCFS), and are believed to influence the L–H mode transition [1] by inward momentum transport to the plasma edge. These flows are also linked to the growth of material deposits on divertor plates and limiters, impurity transport, neutral recycling, etc. Therefore, understanding transport mechanisms in the plasma boundary is of great interest.

Anomalous transport is well known to take place in the scrape-off-layer (SOL) of divertor or limiter tokamak plasmas; particularly intermittent behaviours of fluctuations makes Fick's formulation of transport unlikely to describe the SOL physics [2]. Indeed, experimental evidence collected on a variety of magnetically confined plasma devices agrees well with a picture of transport dominated by intermittent convection of macroscopic structures. In spite of many theoretical efforts to model this phenomenon, the generation mechanism is not well understood. A good candidate could be the interchange instability, forced by flux [3], whose simulations are in good qualitative agreement with experiments. In this work, based on Tore Supra (TS) experimental data, we show that intermittency can be generated at the outboard midplane, where the outflux across the last closed flux surface is expected to be strongly enhanced.

This paper is organised as follows: Section 2 presents a set of TS discharges. Section 3 introduces a physical model for transport equilibrium in the SOL and its application to TS data. The results are discussed in Section 4.

2. Experimental setup

Tore Supra is a circular cross section tokamak (major radius $R = 2.4$ m and minor radius $a = 0.72$ m) equipped with a set of movable limiters defining the LCFS: the bottom Toroïdal Pump Limiter (TPL) is the main one. Poloïdal limiters placed on the high field side (HFS) or on the low field side (LFS) are also available. The plasma current and toroïdal magnetic field are oriented in the clockwise direction viewed from above. Two fast reciprocating Langmuir probes in Mach configuration [4], separated toroidally by 120°, enter the plasma from the top. The probes sample open field lines at points far away from the strike points. The heads are composed of metallic pines holding behind a cylindrical CFC shield with circular openings of 4 mm diameter. The head diameter is 4 cm. One of the probes measures I–U characteristics for local density and temperature deconvolution at a rate of 1 kHz. The second one is biased at −100 V and measures ion saturation currents for the e-side (directly connected to HFS) and the i-side (directly connected to LFS) of the probe head. Acquisitions at a rate of 1 kHz are done along the profile and fast acquisitions at a rate of 1 MHz are triggered on a 16 ms window when the probe reaches its maximum depth into the SOL.

The measurements described in the following are performed on steady-state ohmic plasmas ($I_p = 0.58$ MA, $B_t = 3.5$ T, $\langle n_e \rangle \sim 2.5 \times 10^{19}$ m^{-3}, $a = 0.65$ m). Two limiter configurations are used, with different locations of their contact point: the first one is limited on the HFS (TS35246), and the second on the LFS (TS35249) (Fig. 1). Because toroidally discrete limiters are used, the

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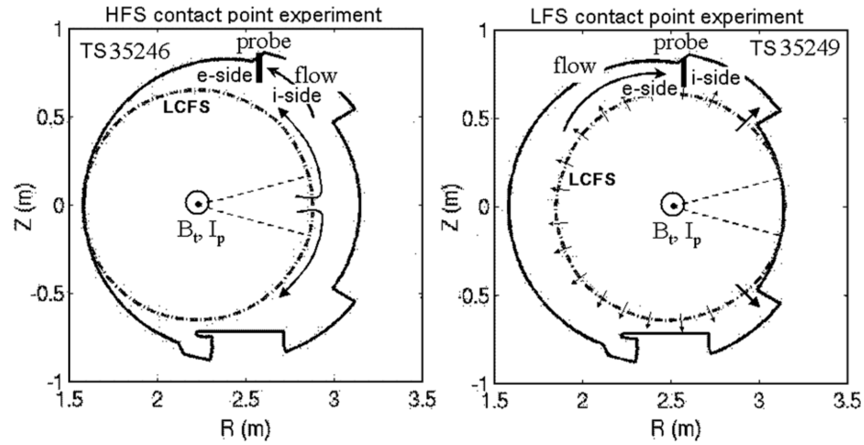

Fig. 1. Plasma poloidal cross sections. The 30° sector straddling the outboard midplane indicated by the dashed lines represents the location of the region of enhanced outflux. Arrows cross the LCFS represent the main outflux. The ion-side (i-side) and electron side (e-side) of the probe are shown, connected to the LFS and HFS, respectively.

experiments were run at high edge safety factor $q = 6$ to get quasi axisymmetric conditions. During plasma stationary phase, the probes plunge to the LCFS, and both give the same saturation currents along their profiles, within the error bars; meaning we can assume toroïdal symmetry.

3. SOL model and data analysis

Unperturbed and time-averaged quantities at the probe location are first evaluated from the saturation currents measured on the two sides of the probe; typically $n.c_s$ and $M_\parallel$, where n is the local density, $c_s^2 = k_B(T_e + T_i)/m_i$ is the ion sound speed and $M_\parallel$ the parallel Mach number. The time-averaged plasma-probe interaction is described using a 1D steady-state model introduced in [4]. The radial outflux in the SOL, needed to build the equilibrium, is evaluated using a 2D steady-state model in (x, r) space. The coordinate x is along field line, oriented in the counter clockwise direction, and r is the radial coordinate perpendicular to flux surfaces. We assume isothermal field lines, in a convection-dominated, low recycling regime [5]. The mass and momentum conservation equations are:

$$\partial_x(nV_x) = -\partial_r(\Gamma_r) \equiv S, \quad \partial_x(n[V_x^2 + c_s^2]) = 0, \tag{1}$$

where V_x is the parallel flow speed and Γ_r is the radial flux of particles. The particle source from ionisation of recycled gas at the strike zones is neglected with respect to the cross field transport along the field line. We look at the solution in the domain $-L/2 \leqslant x \leqslant L/2$, where L is to the total connection length of the magnetic field line at the probe location. We define an effective source along the field line:

$$\langle S \rangle_x = \frac{1}{L}\int_{-L/2}^{L/2} S\,dx \equiv -\partial_r \Gamma_r^{\text{eff}}. \tag{2}$$

We define the Mach number $M_\parallel = V_x/c_s$, and enforcing the Bohm criterion at the both strike zones, $M_\parallel(x = -L/2) = -1$, $M_\parallel(x = L/2) = +1$, we solve Eq. (1) for the effective source function of density and Mach number at the probe location:

$$\partial_r \Gamma_r^{\text{eff}} = -\frac{(M_\parallel^2 + 1)\cdot nc_s}{L}. \tag{3}$$

Thus, the radial profile of the radial outflux in the SOL, averaged along field lines, is calculated from the probe measurements of the radial profiles of nc_s and the parallel Mach number, and from the local connection length, evaluated from the magnetic equilibrium reconstruction.

In the following, models are applied to the two data sets from the experiments described above. Assuming constant pressure along the field lines (Eq. (1)), the flow is oriented from the main source location. When the plasma is limited on the HFS, a negative flow at the top means that the source is mainly located at the LFS (Figs. 1 and 2). On the other hand, when the plasma is limited on the LFS, the flow at the top is observed to reverse, consistent with the main source being located at the HFS and bottom part of the plasma section. Moreover, the effective outflux at the LCFS, evalu-

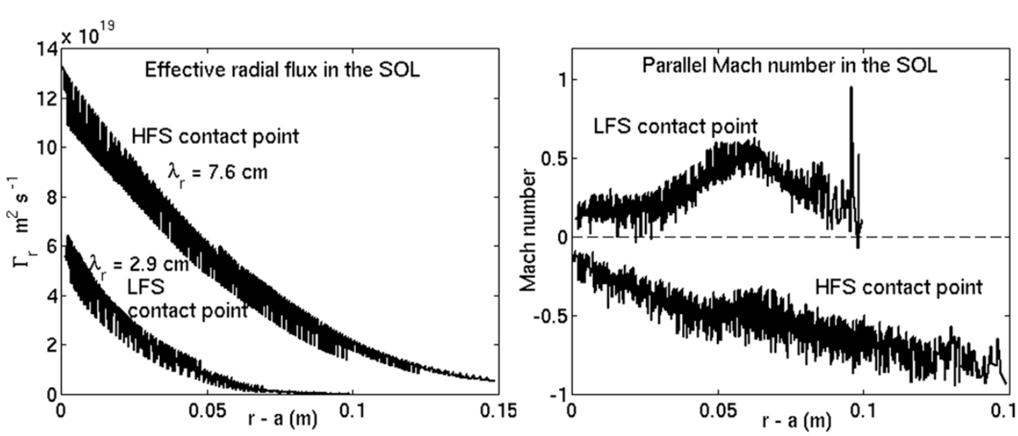

Fig. 2. On the left: effective radial flux along the SOL profile evaluated from Eq. (3). The decay length at the LCFS is indicated. On the right: Mach number profiles.

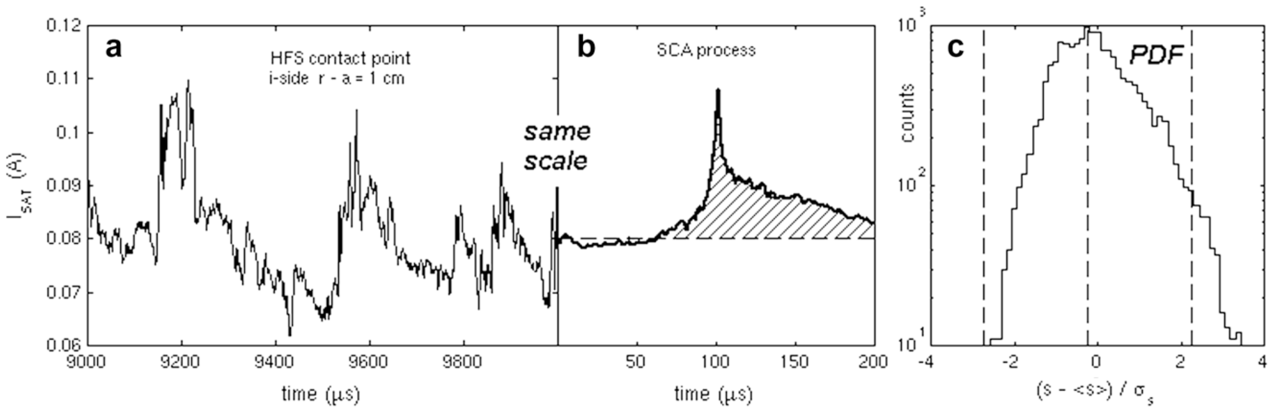

Fig. 3. (a) i-Side ion saturation current fluctuations, for the HFS contact point experiment, 1 cm to the LCFS. (b) SCA process applied to the previous signal. The dashed area represent the event content above the mean value. (c) Probability distribution function (PDF) of the fluctuations. The dash lines are offset (middle) and threshold (left and right) for the SCA process.

ated by integration of Eq. (3), decreases from $12 \times 10^{19}\ \mathrm{m}^2\,\mathrm{s}^{-1}$ to $6.4 \times 10^{19}\ \mathrm{m}^2\,\mathrm{s}^{-1}$ in the latter case (Fig. 2). This is consistent with a higly localised outflux at the LFS, previously discussed in [6]. In this reference, it is shown that in similar experiments, this enhancement seems to be localised in a 30° poloïdal angle around the outboard midplane. Let us consider this section as mostly scraped-off by poloïdal limiters when the plasma is touching the LFS (Fig. 1). Only the outlfux across the rest of the plasma section contibutes to the effective radial outflux, and we call it Γ_r^{HFS}. When the plasma is limited on the HFS, in addition to a fraction of Γ_r^{HFS}, the enhanced source contributes fully to the effective outflux. By simply taking this source to be from the 30° poloïdal sector at the LFS, and evaluating the fraction of the field line in this sector with respect to the total field line length, the magnitude of the enhanced outflux is calculated $\Gamma_r^{\mathrm{HFS}} \approx 77 \times 10^{19}\ \mathrm{m}^2\,\mathrm{s}^{-1}$. Within the uncertainties on the sector size, the ratio $\Gamma_x^{\mathrm{LFS}}/\Gamma_x^{\mathrm{HFS}}$ is $\sim$10. This description is in good qualitative agreement with 3D simulations of the TS plasma edge [7].

Moreover, the radial decay length drops from 7.6 cm to 2.9 cm by changing the contact point from HFS to LFS, when the connection length increases from 60 m to 90 m. Therefore, we expect a change in the flows, turbulence characteristics, and time-averaged profiles at the measurement locations in the SOL when scraping-off the enhanced source.

In the following, fluctuations of saturation currents are analyzed and interpreted as the density fluctuations. They are described as intermittent when front-like structures are present, namely positive coherent events asymmetric in time (Fig. 3(b)), with a time scale in the range of 50 μs. Let us call them blobs. Asymmetry in the probability distribution function of the saturation current amplitudes is another characteristic of this intermittent transport (Fig. 3(c)). A standard conditional averaging (SCA) process is applied to obtain the mean shape and frequency of the blobs [8]. A threshold for including the time signal in the SCA is taken to be 2.5 times the rms level above (below) the average for 'positive' ('negative') structures (see Fig. 3(c)). Their conditionally-averaged time-history (Fig. 3(b)) is found over a 200 μs time window of 1 μs bins, centered at the amplitude maximum. If we assume that the radial flux is a purely blob convection phenomenon, and that probe measurements are the signature of this mechanism, we can simply express: $\Gamma_r^{\mathrm{eff}} = f_{\mathrm{blob}} \langle \int_{\mathrm{blob}} n c_s\, dt \rangle \langle M_{r,\mathrm{blob}} \rangle$, assuming there is no correlation between blob size and velocity. The right hand terms are the blobs frequency, on the order of kHz, the mean integral of $n.c_s$ over a structure, in the order of $10^{18}\ \mathrm{m}^{-2}$ and the mean radial Mach number of blobs respectively. Therefore, from the outflux calculated above, the mean radial velocity of structures is evaluated. Results are summarized in Table 1 and Fig. 3. The fluctuation level is always larger at the probe side connected to the LFS. When the enhanced source is not being scraped-off, i.e. when the plasma is in contact with the HFS, the fluctuations are clearly intermittent, with strong front-like structures on the both sides of the probe (Table 1). The radial Mach number is around 5×10^{-3}, i.e 200 m s^{-1}. This ordering is consistent with velocities evaluated from specific diagnostics on other machines [9,10], and with 2D simulations [3,11]. When the enhanced source is being scraped-off, this fluctuation level is reduced, and the structures are only present on the probe face connected to the LFS (the ion-side). These have a smaller relative amplitude than the ion-side fluctuations when the enhanced source is not being scraped-off. The radial Mach number is around 7×10^{-4}, i.e. 30 ms^{-1}.

Table 1
Fluctuations amplitudes measured by the probe 3 cm from the LCFS, when the plasma touches the HFS (HFS c.p), and the LFS (LFS c.p). The relative amplitudes (rms/<>) of fluctuations are given for the two sides of the probe. The relative sizes of the fronts and their radial Mach numbers are also given.

Fluctuations proprieties		HFS c.p	LFS c.p
$\frac{\mathrm{rms}}{\langle\rangle}$	i-	**15%**	**12%**
	e-	10%	6%
$\frac{\langle I_{\mathrm{ion}}^{\mathrm{front}}\rangle - \langle I_{\mathrm{ion}}\rangle}{\langle I_{\mathrm{ion}}\rangle}$	i-	**40%**	**15%**
	e-	15%	4%
Radial Mach number	i-	0.005	0.0007

4. Discussion and conclusion

Near sonic parallel flows are measured in the SOL of Tore Supra. These flows are consistent with an enhanced outflux approximately localized in a 30° poloïdal sector on the LFS, where the source is $\sim$10 times higher than the averaged outflux from the remainder of the poloïdal circumference. The fluctuations analysis is consistent with the signature of an intermittent convective transport: front-like structures born on the LFS – driven by strong outflux, then elongate along the field lines while propagating toward the far SOL. When the plasma is limited on the HFS, the implied radial fluxes are large, as are the radial decay lengths, and fluctuations are dominant on the probe part facing the flow. On the other hand, when the plasma is in contact with the LFS, the enhanced source is mostly hidden, and profiles are thinner at the probe location. Fluctuations are again dominant on the probe face connected to the LFS. From previous hypothesis, this could require that some of the structures born on the LFS can propagate in the counter flow direction to the probe, despite the LFS limiters. Structures escaping the LFS sector from the bottom part of the plasma section could be magnetically sheared in the HFS region, therefore the e-side measurements, facing the flow, are not intermittent.

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