Electrostatic transport in L-mode scrape-off layer plasmas of Tore Supra tokamak. II. Transport by fluctuations

N. Fedorczak, J. P. Gunn, J.-Y. Pascal, Ph. Ghendrih, G. van Oost et al.

Citation: [Phys. Plasmas](#) **19**, 072314 (2012); doi: 10.1063/1.4739059

View online: <http://dx.doi.org/10.1063/1.4739059>

View Table of Contents: <http://pop.aip.org/resource/1/PHPAEN/v19/i7>

Published by the [American Institute of Physics](#).

Additional information on Phys. Plasmas

Journal Homepage: <http://pop.aip.org/>

Journal Information: http://pop.aip.org/about/about_the_journal

Top downloads: http://pop.aip.org/features/most_downloaded

Information for Authors: <http://pop.aip.org/authors>

ADVERTISEMENT

AIPAdvances

Special Topic Section:
PHYSICS OF CANCER

Why cancer? Why physics? [View Articles Now](#)

Electrostatic transport in L-mode scrape-off layer plasmas of Tore Supra tokamak. II. Transport by fluctuations

N. Fedorczak,^{1,a)} J. P. Gunn,² J.-Y. Pascal,² Ph. Ghendrih,² G. van Oost,³
P. Monier-Garbet,² and G. R. Tynan¹

¹Center for Energy Research, University of California San Diego, La Jolla, California 92093, USA

²Commissariat à l'Energie Atomique et aux Energies Alternatives, Institut de Recherche pour la Fusion Magnétique Contrôlée, F-13108 Saint-Paul-Lez-Durance, France

³Department of Applied Physics, Ghent University, St. Pietersnieuwstraat 41, B-9000 Gent, Belgium

(Received 24 April 2012; accepted 13 June 2012; published online 25 July 2012)

The turbulent transport of particles is investigated using rake probes at the top of the scrape-off layer (SOL) of circular ohmically heated L-mode plasmas in the Tore Supra tokamak [G. Giruzzi *et al.*, Nucl. Fusion **49**, 104010 (2009)]. Both radial and poloidal non-linear fluxes are estimated by means of two reciprocating arrays separated toroidally by 120°. The time average of the radial (poloidal) flux is positive (negative) through the whole SOL profile. The respective effective transport velocity are about $\langle v_r \rangle_t \approx 30 \text{ m s}^{-1}$ and $\langle v_\theta \rangle_t \approx -60 \text{ m s}^{-1}$ close to the last closed flux surface. Both components present a standard deviation about 10 times higher than their respective mean amplitude, and time-distributions highly skewed toward values of the same sign as their mean values. The existence of a nonlinear poloidal flux is associated with the local tilt of filament eddies due to electric and magnetic shear. At the last closed flux surface, where plasma filaments experience their early life, the orientation of the velocity field is consistent with structure dynamics which originate from the outboard midplane and spread along field lines toward the rest of the poloidal section. The localized tilt of the eddy structures corresponds to the effect of the magnetic shear. Further into the SOL, the orientation of the velocity field evolves along radius in agreement with a simple model of propagating filaments progressively tilted by an electric shear. The combined effects of electric and magnetic shear on the eddy tilting have potentially a crucial impact on the existence of a Reynolds stress $\langle v_r v_\theta \rangle_t$ component, which is strongly poloidally asymmetric at the edge of tokamak plasmas. © 2012 American Institute of Physics. [<http://dx.doi.org/10.1063/1.4739059>]

I. INTRODUCTION

A large body of experimental evidence suggests that turbulent transport at the boundary of tokamak plasmas is dominated by the cross-field convection of coherent plasma structures having enhanced density and temperature with respect to the time-averaged background.^{1,2} These structures, commonly known as blobs, are mostly aligned with magnetic field lines, with short transversal scales compared to the plasma minor radius. They can propagate from the outer edge of the confined region to the far scrape-off layer (SOL) over distances larger than their transversal size. This phenomenon, often referred to as avalanches or nonlocal transport, is responsible for a large fraction of radial losses of particle and energy at the edge of tokamak plasmas. In fact, these coherent structures are observed in all magnetized plasma configurations, including tokamaks (limiter and divertor configurations), stellarators, reversed field pinches, simple magnetized tori (Refs. 3–9 and references therein) and have been studied intensively to understand their origin, dynamics, and role in edge transport processes. This processes include: (1) radial transport of particle and energy, (2) generation of quasi-sonic parallel flows in the SOL, and (3) radial transport

of transversal momentum, a potential important player in the onset of intrinsic rotation at the plasma edge.

An important feature in tokamak SOL plasmas is the local enhancement of the fluctuation induced radial transport in the low field side (LFS) region. In a separate publication, the particle balance in Tore supra SOL plasmas was investigated in detail, and concluded that the radial particle flux in the SOL is centered at the outboard midplane and presents a Gaussian poloidal half width of about $\Delta\theta \approx 50^\circ$ at the last closed flux surface (LCFS). At the top of the plasma, the radial convection of density fluctuations gives a mean radial flux in quantitative agreement with the mapping produced from the particle balance. This strong poloidal asymmetry is a well known property of the radial flux at the plasma edge, observed in a variety of tokamaks either indirectly by its consequence on parallel flows,^{10–14} or directly by the measurement of the fluctuation induced radial flux at different poloidal locations.¹⁵ The turbulent flux is strong at the outboard midplane^{16,17} and very weak at the inboard midplane¹⁸ (high field side or HFS), the same statement arising from fast imaging.^{10,19–21} For this reason, it is not possible to directly match the local turbulent radial flux with the density profile,^{16,22} which contrasts with the common assumption of flute modes (zeros parallel wave number) often associated with SOL fluctuations²³ or supported by isolated experimental findings.²⁴

^{a)}Author to whom correspondence should be addressed. Electronic mail: nfedorczak@ucsd.edu.

In the complex magnetic geometry of a tokamak where the magnetic field line helicity varies along the minor radius (magnetic shear), the ballooning of the fluctuations has another important consequence on the local shape of the filaments. The dynamical drive of a single blob arises at the outboard midplane due to curvature driven polarization, and parallel dynamics spread this polarization to the rest of the field line along magnetic flux tubes. Consequently, the local dynamics of blobs at a given poloidal position on a flux surface are determined by both the geometry of the magnetic flux tube from the unstable region to this position and the dynamics at the unstable region. In particular, the magnetic shear—besides the electric shear—will tilt the blob shape and convection velocity field, as documented in Ref. 25 by fast imaging of the lower X-point SOL region. Here, we document and quantify these effects by means of Langmuir probe arrays at the top of ohmically heated plasmas of Tore Supra. We show that blobs in this region present a velocity field determined by the joint action of magnetic and electric shear.

In a first part of this contribution, the experimental setup is described: plasma geometry, parameters, and Langmuir probes diagnostics. Then, the statistical properties of the non-linear radial and poloidal particle flux at the plasma top are detailed: The statistics of the radial flux is positively skewed and presents a net positive mean value, due to a phase shift between density and poloidal electric field centered on zero. The poloidal flux shows a negatively skewed distribution and a net negative mean value (directed from the plasma top to the outboard midplane), with a similar phase shift between density and electric field. The orientation of the mean flux in the transversal (r, θ) plan is consistent with the magnetic and electric shear tilting, at least close to the LCFS. A discussion is proposed on the existence of Reynolds stress components $\langle v_r v_\theta \rangle$ and $\langle v_r v_\parallel \rangle$, respectively, linked to transversal blobs tilting and parallel flows mixing across the LCFS. These terms potentially play significant roles in the onset of edge plasma rotation.

II. EXPERIMENTAL ARRANGEMENT

Tore Supra is a large tokamak (major radius $R \approx 2.3$ m) operating with circular plasmas (minor radius $a \approx 0.7$ m) mainly limited with a toroidally symmetric bottom limiter (TPL).³² The LCFS is normally defined on its contact (see Fig. 1). However in this paper, the plasma is also limited by the bottom part of low field side limiters (see Fig. 1) and present a smaller minor radius ($a = 0.65$ m). The plasma is ohmically heated ($P_\Omega = 1$ MW), with a magnetic field B_T 3.4 T at the plasma center and $B \times \nabla B$ directed downward, toroidal plasma current $I_P = 1$ MW directed along B_T , line averaged density $\bar{n}_e \approx 4 \times 10^{19} \text{ m}^{-3}$, and radiated power fraction $f_{\text{RAD}} \approx 0.45$. Two reciprocating Langmuir probes are located at the top of the vessel ($\theta \approx 80^\circ$), separated toroidally by 120° . Along the paper, analysis will refer to data collected by a poloidal and a radial probe array, each on a movable system. Arrays are composed of thin 1.2 mm in diameter pins distributed every 3 mm and alternatively in floating and saturation mode (biased at $V_{\text{BIAS}} = -200\text{V}$).

FIG. 1. Poloidal cross section of Tore Supra plasma, which LCFS is delimited both on the bottom by the TPL and below the outboard midplane by the set of 2nd limiters.

The acquisition is done at a rate of 1 MHz with an anti-aliasing cut-off frequency of 250 kHz. The poloidal rake pins protrude from the boron nitride probe head and thus are out of the main probe body's wake. This configuration helps to reduce the potential impact of the turbulence created by the probe head (4 cm diameter) on the measurement.²⁶ The radial rake probe is composed of two radial arrays of four pins installed back to back on the probe body with respect to the magnetic field orientation. For low density ohmically heated plasmas, the two probe heads can penetrate the SOL plasma up to the LCFS. In the following, the poloidal direction is positively oriented along the cross product of the magnetic field unit vector by the local radial unit vector (see Fig. 1).

III. DISCUSSION ON THE INTERPRETATION OF RAKE PROBE DATA

The particle flux carried by fluctuations is by definition the cross product of the local density by the electric field fluctuations (time averaged values have been subtracted):

$$\tilde{\Gamma} \equiv \frac{\tilde{n}\tilde{E}}{B^2} \times B. \quad (1)$$

To cover the wide range of fluctuation frequencies at the edge of a Tokamak, it is necessary to acquire probe data with a sufficient time resolution that does not allow—at least with standard diagnostics—to perform I - V characteristics and resolve the plasma density and plasma potential from the collected currents. The assumption is always done that the saturation current reflects the density fluctuations and the floating potential reflects the plasma potential fluctuations. This is equivalent to neglect the temperature fluctuations, although some dedicated experiments have proven that this is not fully relevant.²⁷ Another issue comes from the uncertainty about the effective collection area of tiny pins, which can have a potentially strong impact on the value of the current per surface unit collected in saturation modes. Finally, the electric field which is estimated by a spatial finite difference of potential can be under-sampled if the pins separation

width is larger than the typical potential eddy size. All these issues can lead to potentially strong mis-interpretations about the particle flux.

The issue concerning the effective collection area is addressed by comparing the time averaged profiles of saturation current collected by a rake probe with the same profiles collected by a Tunnel probe, which presents a geometry designed to cancel any sheath expansion around the collector.²⁸ The data collected over a wide range of plasma parameters suggest that the effective collection area of small pines varies by a factor from 0.5 to 3 compared to its geometrical collection area, with a trend that roughly depends on the electron temperature $\frac{A_{\text{eff}}}{A_{\text{geo}}} \propto T_e^{-0.53}$. In fact, the saturation current collected by the small pines has roughly a linear trend with the local plasma density, over at least a decade covering the usual SOL density regimes. Surprisingly, this finding suggests that the variation of the effective collection area somehow compensates the temperature dependence in the saturation current expression. The dispersion is however too large to assume that the saturation current collected by small pines reflects the density with enough accuracy to confound the two quantities. Rather, it is assumed that the saturation current fluctuations collected by small pines reflect the plasma density fluctuations: $\frac{\tilde{I}_{\text{SAT}}}{\bar{I}_{\text{SAT}}} = \frac{\tilde{n}_e}{\bar{n}_e}$, where the bar defines the local time average. This relation means that the probe can reasonably not measure the radial flux directly but rather an effective transport velocity expressed by

$$\tilde{\Gamma} = \frac{\tilde{n}\tilde{E}}{B^2} \times B = \tilde{n} \frac{\tilde{I}_{\text{SAT}}\tilde{E}}{\bar{I}_{\text{SAT}}B^2} \times B \quad \text{with} \quad \tilde{v}^{\text{eff}} = \frac{\tilde{I}_{\text{SAT}}\tilde{E}}{\bar{I}_{\text{SAT}}B^2} \times B. \quad (2)$$

The electric field given by a probe is defined as $\tilde{E} = \frac{\tilde{V}_2 - \tilde{V}_1}{\Delta_{1,2}}$ where $\Delta_{1,2}$ is the separation length between floating tips 1 and 2. If this separation length is larger than the typical blob size, the electric field associated to the density eddy will be mis-sampled. This effect can be characterized by the cross correlation function of the two potential signals of interest. On Fig. 2 is illustrated an example of cross correlation function collected 1 cm from the LCFS for two floating potential signals separated radially by 6 mm. Although the cross correlation level is relatively low (0.2), its time delay behavior is typical of a dipole like structure propagating through the rake.⁹ Indeed, the negative cross-correlation

FIG. 2. Typical cross correlation function between the floating potential signals used to estimate the electric field. The separation width is 6 mm and data are collected 1 cm outside the LCFS.

level at zero time delay means that a hole is measured by one tip whereas the other measures a peak. After about $10 \mu\text{s}$ the cross correlation is positive as if the hole had moved to the second tip or vice versa. This time delay would give a phase velocity of about 600 m s^{-1} , typical of the blob velocities in the SOL. Overall, this hint for the dipolar structure found in the cross-correlation function suggests that the electric field is reasonably well sampled within a plasma structure.

IV. STATISTICAL PROPERTIES OF THE RADIAL AND POLOIDAL PARTICLE FLUX

The statistical property of the radial particle flux in the SOL of Tore Supra is generic of SOL plasma fluctuations: The density fluctuations are more and more intermittent toward the far SOL (Refs. 9 and 29) and the radial particle flux—defined here as the statistics of the effective radial transport velocity, exhibits a net positive value toward the wall (Fig. 3 left) of about 30 m s^{-1} in this particular example. As shown in a complementary publication about Tore Supra SOL particle balance, the level of radial flux carried by these fluctuations is in good agreement with the steady-state particle balance. The statistical distribution of the radial flux—over time—shows a long tail toward positive values, whereas the negative part of the flux has a Gaussian statistics. The positivity of the mean value of the radial flux suggests that density and electric field are on average in phase. That said, there is a large fraction of flux directed inward—negative—which is a collateral effect of a large standard deviation about 10 times higher than the mean value. This can be attributed to density and electric field not exactly in phase. To investigate it in more detail, density and electric time traces are decomposed over time and scales by a continuous wavelet transformation,³⁰ using Morlet-1.5 wavelets. At each time, each scale, the complex phase shift between density and electric field coefficients defines the phase shift at this time and this scale, and a time-histogram is constructed as shown in Fig. 3 right. For all frequencies—time scales—the cross phase fluctuates substantially between $-\pi/2 < \delta\Phi_{n,E} < \pi/2$. For a nonzeros phase shift, the time varying radial flux will present both positive and negative values.

In the cross-phase interval, density and electric field are roughly in phase, meaning that the convection of density peaks is toward the wall, and holes toward the confined region. Only when the phase shift is close to zeros the convection is the most efficient, probably related to the off-Gaussian positive tail of the radial flux distribution. The huge fluctuation amplitude of the radial flux around its mean value suggests that a large statistical fraction of the fluctuations correspond to a back and forth radial motion. Only a small fraction of the fluctuations, the off-Gaussian tail, is responsible for the onset of a positive time averaged radial flux. From the Fig. 3 left, it would correspond to density fluctuations with an effective radial velocity larger than 300 m s^{-1} . Note that the effective velocity is equal to the real drift velocity weighted by the relative fluctuation amplitude, meaning that blobs propagate with a substantially different radial velocity depending on their relative amplitude.

FIG. 3. Fluctuations collected 1 cm outside the LCFS. Left: Probability distribution function of the effective radial velocity, its mean, and root-mean square values. The dashed blue curve is a Gaussian fit of the negative part. Right: Histogram of the phase shift between density and poloidal electric field, at all time scales. The black curve shows the mean value at each time scale.

The poloidal flux investigation is subject to more precautions because the tips do not protrude from the probe head body. As for of Mach probes, a rake of 4 tips is facing the field lines connected to the LFS—noted side B here—and another rake is facing the field lines connected to the HFS—side A. The statistics differ totally on both sides of the probe head, as illustrated in Figs. 4(a) and 4(b). On the side B facing the LFS, the radial electric field fluctuates roughly in phase with the density (Fig. 4(b)), as for the poloidal electric field. The poloidal flux fluctuations exhibits a long off-Gaussian tail toward negative values. The time averaged flux is negative, characterized by an effective poloidal transport velocity of about -60 m s^{-1} outside the LCFS and a standard deviation about 10 times higher. On the other side of the probe, facing the HFS, the phase shift between radial electric field and density is almost random (Fig. 4(b)), and the statistics of poloidal flux is completely Gaussian (Fig. 4(a)). The mean value of the transport velocity measured on this side of the probe is almost zeros (1.3 m s^{-1}) and its fluctuation amplitude is about 4 times lower than on the side B (149 m s^{-1} vs. 640 m s^{-1}).

This radical difference of statistics collected on both sides of the probe finds a natural analogy with standard Mach probe measurements: At the plasma top, the quasi-sonic parallel flows are measured by the difference of pressure between the probe side facing the flow and the probe side in the probe wake. This flow carries particles from the LFS where they crossed the flux surfaces due to the high level of fluctuations here. The blobs convection is indeed due to the self-polarization from magnetic field curvature effects which are destabilizing only at the LFS. The parallel dynamics within a blob spread the local polarization along its magnetic flux tube further away the outboard midplane, allowing the density convection even at the plasma top. Now if a blob reaches the probe head, its HFS tail in the probe wake probably decouples from the favorable region. The fast damping of the polarization due to electrons motion toward the HFS can kill the convection capability and decouples the residual electric field and the density eddy. On the probe side facing the parallel flow, the density eddy is still alimented by the polarization source from the outboard-midplane, thus

FIG. 4. Fluctuations collected 1 cm outside the LCFS by the radial rake probe. (a) Probability distribution function of the effective poloidal velocity, its mean, and root-mean square values for data collected on the side A and B of the probe head. The dashed curves are the respective Gaussian fit of the positive part of each distribution (the Gaussian fit of the side A flux overlaps the PDF). (b) Histogram the phase shift between density and radial electric field, at all time scales for the side A and side B.

sustaining dynamics similar to the initial blob. At the probe surface, the natural parallel losses toward the stabilizing HFS region are replaced by the local sink at the probe body surface, which have equivalent effects. To conclude this discussion, the observations made from the radial rake probe are consistent with the idea that the global blob dynamics are driven by the local dynamics at the outboard midplane.

V. THE TRANSVERSAL TILT OF BLOBS

We now investigate the origin of the intrinsic poloidal blob motion at the plasma top. Note that the SOL mean electric field is directed outward, which corresponds to a negative poloidal flow. That said, the non-linear poloidal particle flux discussed above was calculated by canceling the local mean radial electric field so that was only estimated the cross-correlation between density and electric field fluctuations, which does not include the mean radial electric field. A clue is in the strong similarities of the statistics of the poloidal and radial fluxes. Both poloidal and radial electric fields fluctuate on average in phase with the blob density events so that both components of the electric field should be also on average in phase. In fact, a probe at the plasma top with both poloidal and radial rakes measuring at the same time and same position would resolve this ambiguity. Here, we can only speculate about the transitivity of the correlation information. If this correlation is true, it means that potential eddies are tilted transversally, which is the geometrical picture of the radial/poloidal electric field correlation. A first candidate for the tilting mechanism is the radial shear of the mean radial electric field, which would progressively transfer the initial radial convection of the blob into the poloidal direction. In Tore Supra SOL, the radial electric field is almost fixed by the sheath potential rectification at the end of the field lines: $E_r \approx -3\nabla_r T_e$ directed outward so that the poloidal drift flow is negative—in the ion diamagnetic direction. Since the temperature decays exponentially along the SOL radius, the poloidal flow presents a positive shear that would transfer a positive radial velocity into a positive poloidal velocity. Thus, this is not the dominant ingredient for a positive radial flux correlated with a negative poloidal flux.

The second candidate is the magnetic shear. For a structure born at the outboard midplane, as effectively considered for interchange mechanisms, the overall structure geometry of the flux tube is defined at the midplane and then constrained by the flux tube geometry—including the magnetic shear—as illustrated in Fig. 5(a), and discussed in Ref. 31. Translated in term of wave's number, the magnetic shear is responsible for a transfer of poloidal wave number into a radial wave number during the fast parallel extension of the blob from the initial poloidal position θ_0 (referring to the outboard midplane). The detail of the following relation is given in the Appendix:

$$k_r(\theta) = k_r(\theta_0) + k_\theta[\hat{s}(\theta - \theta_0) - V'_E \delta t], \quad (3)$$

which gives the contribution at the position θ of the magnetic shear $\hat{s}$ on a mode defined by a uniform poloidal wave number k_θ and a radial wave number $k_r(\theta_0)$ at the position

FIG. 5. (a) Transversal cross section of a circular plasma cross-section, and of a flux tube presenting a circular shape at the outboard midplane and mapped along the magnetic field (the mapping against the magnetic field direction is not showed). (b) Definition of the tilt angle θ_S (negative here) of a filament. Is also shown the orientation of probes tips that measure radial and poloidal fluxes.

θ_0 . Is also included the contribution from the electric shear $V'_E \equiv \nabla_r \frac{E_r \times B}{B^2}$ that progressively tilts a mode over the time interval δt . In fact, this relation makes sense in the plasma frame, where the poloidal flow has been canceled. We come back on that point later. Applying this wave form to the density fluctuations would effectively yields the tilted shape illustrated on Fig. 5(b). If it is applied to the plasma potential, it effectively describes the fact that the fluctuating velocity orientation is itself tilted along the same axis:

$$\tilde{v}_\theta(\theta) = [-\hat{s}(\theta - \theta_0) + V'_E \delta t] \tilde{v}_r(\theta) \quad (4)$$

for the fluctuating velocity components, assuming there is no initial poloidal velocity at the position θ_0 which is true for the dominant interchange modes— $k_r(\theta_0) = 0$. In the following, this relation is tested with the data collected across the SOL width from the LCFS to the far SOL.

On Fig. 6(a) are plotted the radial profiles of radial and poloidal effective transport velocities measured in the same plasma. The radial flux is positive at all radial positions, and the poloidal flux is negative everywhere. The orientation of the mean transport velocity field, defined by the angle between the local radial vector and the velocity vector (see Fig. 5(b)), is plotted on Fig. 6(b):

$$\theta_S = \text{atan} \frac{\langle v_\theta \rangle_t}{\langle v_r \rangle_t}.$$

Note on Fig. 6(a) that the radial profiles of the fluctuation amplitudes (standard deviation) of both velocity fields follow almost exactly the profiles of mean values, with a factor of ten and a sign difference for the poloidal component. This means that if we define an orientation angle for the fluctuation amplitudes by

$$\theta_S^\sigma = \text{atan} \frac{-\sigma_{v_\theta}}{\sigma_{v_r}},$$

both orientation profiles should coincide, as effectively illustrated on Fig. 6(b). Interestingly, if a linear relation exists between both components of the velocity field fluctuations, as expressed by Eq. (4), the same relation should apply to the mean values and the standard deviations, with respect to a possible sign difference. This is effectively what suggests Fig.

FIG. 6. (a) Radial profile of effective radial and poloidal velocities and their respective standard deviations. (b) Transversal orientation of the mean velocity field or of the fluctuation level along the SOL radius, compared to the tilt angle due to the magnetic shear of an initial circular flux tube propagating radially at the outboard midplane. The opaque region notes where the fluctuating signal is below the noise limit of the diagnostic.

6(b). The orientation angle θ_s increases from about -70° at the LCFS to about -30° at a position 6 cm outside the LCFS.

If we assume that blobs are born somewhere around the LCFS, and they expand along field lines faster than the time needed by the electric shear to tilt them (otherwise, it would refer to a sort of transport barrier), then the local tilt at the top ($\theta = 80^\circ$) of the LCFS ($r - a = 0$) is given by the magnetic shear only (4):

$$\theta_s^0 = \text{atan}(-\hat{s}\theta) = -70^\circ,$$

where the magnetic shear has been taken equal to $\hat{s} = 2$ for the SOL of Tore Supra. A good agreement is found with the tilt measured very close to the LCFS. Note also that the poloidal convection by the mean radial electric field has been neglected here. This flow should rotate the local frame, in which the wave relations (3) and (4) are expressed, by an angular frequency $\omega_\theta = \frac{V_E}{a}$ where a is the plasma minor radius. For typical Tore Supra conditions, the poloidal drift velocity of about 1000 m s^{-1} so that $\omega_\theta \approx 1500 \text{ rad s}^{-1}$. Considering blobs propagating at a speed of 500 m s^{-1} , they take about $100 \mu\text{s}$ to cross the 6 cm width of the SOL. By that time, the blob has been shifted by about 10° by the poloidal flow, which appears as a correction term in the above analysis. On the other hand, the electric shear can significantly participate in the onset of the local tilt of the blob during its transversal motion: The electric shear is positive in Tore Supra SOL so that it tilts the blobs positively as they propagate across the flux surface. This behavior is qualitatively found in the data: The tilt angle increases along the radial direction. In fact if we assume that the blobs propagate with a constant radial velocity v_r^b over a uniform shear V_E' , the progressive tilt reduces to a simple function of the radius:

$$\theta_s(r) = \text{atan}\left(-\hat{s}\theta + \frac{V_E'}{v_r^b}r\right).$$

On Fig. 6(b) is shown a fit of the experimental data obtained with the parameter value $\frac{V_E'}{v_r^b} \approx 40 \text{ m}^{-1}$, which gives $V_E' \approx 2 \times 10^4 \text{ s}^{-1}$ for $v_r^b = 500 \text{ m s}^{-1}$. The shear value would correspond to an electron temperature profile of 20 eV at the LCFS with a radial scale length of 3 cm, which are typical values of electron temperature parameters in SOL of ohmically heated plasmas of Tore Supra. Unfortunately, the use

of two reciprocating rake probes in this experiment did not allow measuring the mean plasma potential and temperature profiles across the SOL using a Tunnel probe.

VI. DISCUSSION AND CONCLUSION

The fluctuations of saturation current and floating potential have been measured in the SOL of Tore Supra plasmas by means of two arrays—a poloidal and a radial—mounted on two different reciprocating probe holders located at the plasma top. These systems allow measurements at a rate of 1 MHz from the far SOL to the LCFS. The radial electric field fluctuates roughly in phase with the density fluctuations, giving rise to a net positive radial flux characterized by a radial transport velocity of about 30 m s^{-1} close to the LCFS. This value agrees with a poloidal reconstruction of the radial flux obtained from a particle balance analysis, as developed in a separate paper. This outward transport arises from the fast convection of density events, called blobs, corresponding to the off-Gaussian tail of the flux statistics. Because the fluctuation amplitude of the flux is 10 times higher than its mean value, a large amount of the radial flux events correspond to an inward particle transport. The radial electric field is measured on sides of the radial rake probe, in a Mach configuration. On the probe side facing the parallel flow from the LFS, radial electric field and density fluctuations are on average in phase, the mean poloidal flux is negative and characterized by a poloidal transport velocity of about -60 m s^{-1} at a radial position 1 cm outside the LCFS. Again the standard deviation of the flux is 10 times higher than the absolute value of the time averaged flux. On the other side of the probe facing the HFS, the electric field fluctuations are decoupled from the density fluctuations, returning almost zero poloidal transport.

The same linear relation is found between the time averaged values of the radial and poloidal fluxes, and their standard deviations. This linear relation would correspond to the tilting of the radial velocity field by the combined effects of the electric field shear and the magnetic shear. The orientation of the transversal flux at the plasma top agrees quantitatively with a model of blobs shaped at the outboard midplane and elongated along magnetically sheared flux tubes. During their radial convection, blobs are progressively tilted by the electric shear, as expected by the progressive change of the orientation across the SOL.

This result is another proof of the strong role played by the outboard midplane region in the dynamic of blobs in the SOL. The polarization of single blobs is driven at the outboard midplane by the diamagnetic current, effect of the destabilizing magnetic field curvature in that region. The parallel dynamics expand the polarization along flux tubes, arising in blob parallel envelope larger than the poloidal extension of the destabilizing curvature region. If a localized material is inserted in the SOL poloidally outside this favorable region, the tail of a blob behind the material with respect to the outboard midplane loses its polarization and stops propagating.

The transversal tilt of the blobs created by the magnetic shear gives a coupling between radial and poloidal velocity fields, as proposed by Eq. (4). In the field of momentum transport, this coupling corresponds to a component of the time averaged Reynolds stress $\langle v_r v_\theta \rangle$ that could potentially participate significantly in the onset of poloidal rotation at the edge. This Reynolds stress component originating from a tilt of the structures would be highly asymmetric on a flux surface as the magnetic shear effect is proportional to the poloidal position. This subject will be discussed in another contribution. Besides, it appears that the radial flux fluctuates with a strong magnitude even across the LCFS. The enhancement of the radial flux at the outboard midplane is supposed to drive quasi-sonic parallel flows toward the field lines strike points.^{11–13} Away from the midplane, the inward particle flux component, illustrated here, could presumably participate in the inward transfer of these averaged parallel flows, and impact the toroidal rotation in the confined region. Again this Reynolds stress $\langle v_r v_\parallel \rangle$ would be highly asymmetric on the separatrix, as a consequence of the asymmetry of the SOL parallel flows. Unfortunately, the probe design in Tore Supra does not allow the investigation of the time fluctuation of the local parallel flows. We can only speculate the existence of a fluctuating transport of mean flow, which may contribute to the rotation at the edge. These are important considerations for experimental investigations of particle and momentum transport at the edge of tokamak plasmas, where measurements should be made away from the outboard midplane in order to resolve probable asymmetries of the fluxes.

ACKNOWLEDGMENTS

This work, supported by the European Communities under the contract of association between EURATOM and CEA, was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission. The authors are grateful to the “Festival de théorie” 2011 organized by the CEA of France, for its source of valuable discussions.

APPENDIX: WAVE VECTOR REPRESENTATION OF THE EDDY TILTING

In an eikonal representation of the mode structure, the wave vector is generally defined by the gradient of the complex spatial phase of the mode: $k = \nabla \phi$. Let us consider a

reference flux surface at the radius r_0 , on which are considered the parallel and transversal axes ($\parallel, \perp$) used in the following. In the plasma frame, the transversal drift is taken as zero on that reference flux surface. On a second flux surface radially separated by δr , the transversal flow is $V_E = V'_E \delta r$ where V'_E is the flow shear. Considering A_1 and B_1 at a given parallel position s_1 and aligned along the local radial vector—as pictured on Fig. 7, the local radial wave number is approximated by

$$k_r(s_1, t) = \frac{\phi(B_1, t) - \phi(A_1, t)}{\delta r}.$$

The flux tube geometry of the mode assumes a phase uniform along magnetic field lines. Thus considering two other points A_0 and B_0 on the respective field lines but at the parallel position s_0 , the radial wave number at the position s_1 is also given by

$$k_r(s_1, t) = \frac{\phi(B_0, t) - \phi(A_0, t)}{\delta r}.$$

Written in the $(r, \perp, s, t)$ coordinate system

$$\phi(A_0, t) = \phi(r_0, 0, s_0, t) = \phi(r_0, 0, s_0, 0)$$

since there is no convection and so time variation on the reference flux surface. On the other flux surface

$$\phi(B_0, t) = \phi(r_0 + \delta r, \xi_\perp^0, s_0, t) = \phi(r_0, \xi_\perp^0 - V'_E t \delta r, s_0, 0)$$

where is considered the transversal advection of the phase at the radial position $r_0 + \delta r$ over the time interval t . The transversal displacement $\xi_\perp^0$ between A_0 and B_0 is related to the difference of helicity between the two field lines, or given as a function of the difference of safety factor:

$$\xi_\perp^0 = \frac{s_1 - s_0}{q(r_0)^2} [q(r_0 + \delta r) - q(r_0)] = \delta r (s_1 - s_0) \frac{\hat{s}}{r_0 q(r_0)},$$

where the magnetic shear is $\hat{s} = \frac{r}{q} \partial_r q|_{r_0}$. Now, we consider the parallel position s_0 as a reference of the flux tube, where the phase is defined by the initial wave vector of the ballooning mode $k_{t=0} = (k_r^0, k_\perp)$. The transversal wave number is assumed poloidally uniform under the approximation of weak magnetic flux expansion. We obtain

FIG. 7. Schematic of two field lines lying at two radial positions r_0 and $r_0 + \delta r$. The transversal direction $\perp$ is considered at the position r_0 . The points A_1 and B_1 lie, respectively, at r_0 and $r_0 + \delta r$, at the same transversal and toroidal position. A_0 and B_0 lie, respectively, at r_0 and $r_0 + \delta r$ at the same parallel position but transversally separated by $\xi_\perp^0$ (along axes at r_0).

$$\phi(B_0, t) - \phi(A_0, t) = k_r^0 \delta r + k_\perp [\xi_\perp^0 - V_E' t \delta r]$$

so that the local radial wave vector at the time t and parallel position s_1 is given by

$$k_r(s_1, t) = k_r^0 + k_\perp \left[\hat{s} \frac{s_1 - s_0}{r_0 q(r_0)} - V_E' t \right].$$

The poloidal displacement on a flux surface is related to the parallel one by $\theta - \theta_0 = \frac{s_1 - s_0}{r_0 q(r_0)}$, which gives the following tilting relation for the wave vector from the reference position θ_0 to θ after a time delay δt :

$$k_r(\theta) = k_r(\theta_0) + k_\theta [\hat{s}(\theta - \theta_0) - V_E' \delta t].$$

- ¹A. J. Wootton, B. A. Carreras, H. Matsumoto, K. McGuire, W. A. Peebles, Ch. P. Ritz, P. W. Terry, and S. J. Zweben, *Phys. Fluids B* **2**, 2879 (1990).
- ²J. A. Boedo, *J. Nucl. Mater.* **390–391**, 29–37 (2009).
- ³S. J. Zweben, J. A. Boedo, O. Grulke, C. Hidalgo, B. LaBombard, R. J. Maqueda, P. Scarin, and J. L. Terry, *Plasma Phys. Controlled Fusion* **49**, S1–S23 (2007).
- ⁴V. Naulin, *J. Nucl. Mater.* **363–365**, 24–31 (2007).
- ⁵G. Y. Antar, G. Counsell, Y. Yu, B. Labombard, and P. Devynck, *Phys. Plasmas* **10**(2), 419–428 (2003).
- ⁶S. H. Müller, A. Diallo, A. Fasoli, I. Furno, B. Labit, and M. Podest, *Phys. Plasmas* **14**, 110704 (2007).
- ⁷R. Sanchez, B. P. van Milligen, D. E. Newman, and B. A. Carreras, *Phys. Rev. Lett.* **90**(18), 185005 (2003).
- ⁸P. Devynck, P. Ghendrih, and Y. Sarazin, *Phys. Plasmas* **12**, 050702 (2005).
- ⁹P. Devynck, J. Brotankova, P. Peleman, M. Spolaore, H. Figueiredo, M. Hron, G. Kirnev, E. Martinez, J. Stockel, G. Van Oost *et al.*, *Phys. Plasmas* **13**, 102505 (2006).
- ¹⁰N. Fedorczak, J. P. Gunn, Ph. Ghendrih, G. Ciraolo, H. Bufferand, L. Isoardi, P. Tamain, and P. Monier-Garbet, *J. Nucl. Mater.* **415**, 467–470 (2011).
- ¹¹N. Fedorczak, J. P. Gunn, Ph. Ghendrih, P. Monier-Garbet, and A. Pocheau, *J. Nucl. Mater.* **390–391**, 368–371 (2009).
- ¹²J. P. Gunn, C. Boucher, M. Dionne, I. Duran, V. Fuchs, T. Loarer, I. Nanobashvili, R. Panek, J.-Y. Pascal, F. Saint-Laurent *et al.*, *J. Nucl. Mater.* **363–365**, 484–490 (2007).
- ¹³B. LaBombard, J. E. Rice, A. E. Hubbard, J. W. Hughes, M. Greenwald, J. Irby, Y. Lin, B. Lipschultz, E. S. Marmor, C. S. Pitcher *et al.*, *Nucl. Fusion* **44**, 1047–1066 (2004).
- ¹⁴R. A. Pitts, J. Horacek, W. Fundamenski, O. E. Garcia, A. H. Nielsen, M. Wischmeier, V. Naulin, and J. Juul Rasmussen, *J. Nucl. Mater.* **363–365**, 505–510 (2007).
- ¹⁵G. R. Tynan, J. Liberati, P. Pribyl, R. J. Taylor, and B. Wells, *Plasma Phys. Controlled Fusion* **38**, 1301–1305 (1996).
- ¹⁶O. E. Garcia, J. Horacek, R. A. Pitts, A. H. Nielsen, W. Fundamenski, V. Naulin, and J. Juul Rasmussen, *Nucl. Fusion* **47**, 667–676 (2007).
- ¹⁷I. Garcia-Cortes, A. Loarte, R. Balbin, J. Bleuel, A. Chankin, S. J. Davies, M. Endler, S. K. Erents, C. Hidalgo, G. F. Matthews *et al.*, *J. Nucl. Mater.* **290–293**, 604–608 (2001).
- ¹⁸G. S. Kirnev, V. P. Budaev, S. A. Grashin, L. N. Khimchenko, and D. V. Sarytchev, *Nucl. Fusion* **45**, 459 (2005).
- ¹⁹S. J. Zweben, D. P. Stotler, J. L. Terry, B. Labombard, M. Greenwald, M. Muterspaugh, C. S. Pitcher, K. Hallatschek, R. J. Maqueda, B. Rogers *et al.*, *Phys. Plasmas* **9**(5), 1981 (2002).
- ²⁰S. J. Zweben, R. J. Maqueda, D. P. Stotler, A. Keese, J. Boedo, C. E. Bush, S. M. Kaye, B. LeBlanc, J. L. Lowrance, V. J. Mastrocola *et al.*, *Nucl. Fusion* **44**, 134 (2004).
- ²¹J. L. Terry, S. J. Zweben, K. Hallatschek, B. Labombard, R. J. Maqueda, B. Bai, C. J. Boswell, M. Greenwald, D. Kopon, W. M. Nevins *et al.*, *Phys. Plasmas* **10**(5), 1739 (2003).
- ²²M. Endler, *J. Nucl. Mater.* **266–269**, 84–90 (1999).
- ²³Y. Sarazin, Ph. Ghendrih, G. Attuel, C. Clément, X. Garbet, V. Grandgirard, M. Ottaviani, S. Benkadda, P. Beyer, N. Bian *et al.*, *J. Nucl. Mater.* **313–316**, 796–803 (2003).
- ²⁴H. Thomsen, M. Endler, J. Bleuel, A. V. Chankin, S. K. Erents, and G. F. Matthews, *Phys. Plasmas* **9**(4), 1233 (2002).
- ²⁵J. L. Terry, S. J. Zweben, M. V. Umansky, I. Cziegler, O. Grulke, B. LaBombard, and D. P. Stotler, *J. Nucl. Mater.* **390–391**, 339–342 (2009).
- ²⁶B. LaBombard, *Phys. Plasmas* **9**(4), 1300 (2002).
- ²⁷D. L. Rudakov, J. A. Boedo, R. A. Moyer, S. Krasheninnikov, A. W. Leonard, M. A. Mahdavi, G. R. McKee, G. D. Porter, P. C. Stangeby, J. G. Watkins *et al.*, *Plasma Phys. Controlled Fusion* **44**(6), 717 (2002).
- ²⁸J. P. Gunn, J.-Y. Pascal, F. Saint-Laurent, and C. Gil, *Contrib. Plasma Phys.* **51**, 256 (2011).
- ²⁹J. A. Boedo, D. L. Rudakov, R. A. Moyer, G. R. McKee, R. J. Colchin, M. J. Schaffer, P. G. Stangeby, W. P. West, S. L. Allen, T. E. Evans *et al.*, *Phys. Plasmas* **10**(5), 1670 (2003).
- ³⁰M. Farge, K. Schneider, and P. Devynck, *Phys. Plasmas* **13**, 042304 (2006).
- ³¹P. Beyer, S. Benkadda, X. Garbet, and P. H. Diamond, *Phys. Rev. Lett.* **85**, 4892 (2000).
- ³²G. Giruzzi *et al.*, *Nucl. Fusion* **49**, 104010 (2009).