EUROFUSION WP14ER-PR(16) 16363

N Fedorczak et al.

Width of turbulent SOL channels in tokamak plasmas

Preprint of Paper to be submitted for publication in
22nd International Conference on Plasma Surface Interactions
in Controlled Fusion Devices (22nd PSI)

Width of turbulent SOL channels in tokamak plasmas

N. Fedorczak[a,*], N. Nace[a], A. Gallo[a], C. Baudouin[a], H. Bufferand[a], G. Ciraolo[a], Th. Eich[b], Ph. Ghendrih[a], J.P. Gunn[a], P. Tamain[a]

[a] *CEA, IRFM, F-13108 Saint-Paul-Lez-Durance, France*
[b] *MPI fr Plasmaphysik, EURATOM Association, Boltzmannstrasse 2, 85748 Garching, Germany*

Abstract

The relation between turbulent transport and scrape off layer width is investigated in the case of toroidally limited circular plasmas. A broad range of experimental observations collected in the Tore Supra scrape off layer are detailed and compared to turbulent interchange models. In particular, it is shown that blob velocities agree reasonably well with analytical expressions derived for isolated density blobs immersed in a background. It is also shown that, although SOL density width can be expressed in a form proportional to the blob velocity, it needs to be weighted by an intermittent parameter more difficult to assess. Because this parameter as well as blob sizes and amplitudes need to be guessed, this expression is of moderate interest for SOL width predictions. On the other hand, a numerical scaling of the SOL density width built from 2D turbulent simulations is found to describe well both the amplitude and parametric dependence of density width of Tore Supra SOL plasmas. The main dependence is roughly inversely proportional to the poloidal magnetic field, as found for for the heat load decay length in H-mode diverted conditions. It may suggest that SOL width in H-mode could also be described with an interchange turbulence model, at the condition than shear flow be correctly accounted for.

---

1. Introduction

Prediction of scrape off layer (SOL) properties in future tokamak reactors is a fundamental step to prepare and design several aspects of their operation. Heat load amplitudes on every plasma facing components (PFCs) composing the first wall depend on mainly three aspects: amount of kinetic power lost across the separatrix, geometry of both magnetic configuration and wall components, and the width of the SOL heat channel. In contrast with power and geometry, the SOL width is very transport dependent, and therefore difficult to control and even assess. Recent extrapolations from current tokamak measurements [1] suggest that ITER SOL width could fall in the range of neoclassical orbit width (1mm or one poloidal Larmor radius), which is in principle the shortest width physically allowed and therefore the most restricting. To achieve high power throughput, active and complex mitigation strategies like divertor detachment by impurity injection will be needed [2], at a cost on both operation control and performances. But heat load is not the only important facet of SOL. The SOL density profile controls the efficiency of electromagnetic waves coupling systems like lower hybrid current drive or ion cyclotron resonance heating. A minimum plasma density is required at the system interface with the plasma chamber in order to allow efficient wave propagation to the confined plasma volume, which then constrains the plasma to wall distance depending SOL density width. Heat load comes again as a limit on these heating systems, but also impurity production enhanced by the waves interacting with SOL particles [3]. Additionally, SOL density fluctuations can interact with propagating waves, resulting in wave spectra alteration [4], intermittent acceleration of particle beams in a broad SOL volume [5], etc. More generally fluctuations of large amplitudes, as commonly observed in SOL plasmas, will tend to complexify plasma interaction with electromagnetic waves, wall components or neutrals in the divertor [6]. In this contribution, an attempt is made to clarify the predictability of the SOL state in relatively simple plasma scenarios already well documented [7]: toroidally limited L-mode discharges performed in Tore Supra tokamak, in which conditions plasma filaments (blobs) dominate the transport of particle in the SOL [8]. Motivations are twofold: circular geometries in L-mode are often associated to relatively large SOL widths, thus allowing more precise and more diversified diagnostic measurements. For instance, reciprocating probes consisting in arrays of small collectors -to study turbulence- can be more safely used than in diverted configurations where SOL are thinner and heat flows more intense. Also, lower gradients characterizing these SOL regimes mean that shear flows are weak with respect to turbulence intensity, which simplify the physical system to model. Second, circular geometry simplifies theoretical models. In facts, the possible influence of a magnetic X-point on edge turbulent transport is still under investi-

---

[*] Corresponding author
N. Fedorczak, Cadarache center, Building 508, F-13108 Saint Paul Lez Durance
Email address: `nicolas.fedorczak@cea.fr` (N. Fedorczak)

gation [?]. Recent experiments also suggest that the SOL width is sensitive to divertor geometry, which questions the basic understanding that only main SOL transport matters [9]. Reasons why SOL profiles are generally thinner in diverted than in limited configurations are possibly related to the influence of magnetic expansion and magnetic shear on turbulence and large scale flows, but mechanisms are still unclear. First, proving that transport in circular geometry can be understood is a necessary step before extending to more complex situations.

In a first section, the experimental setup in Tore Supra is briefly described. Then, an analyses is made on the link between blob dynamics and SOL profile, based on experimental observations. It is shown that the SOL width is proportional to the blob velocity weighted by an intermittency parameter. In the third section, comparison with theoretical transport model is made. First, blob velocities measured in Tore Supra SOL are found to agree with an analytic blob model. Then, variations of density SOL width over a large range of plasma parameters are compared to a scaling built from 2D turbulent simulations. Model predictions agree with experimental SOL width, both in amplitude and trend.

2. Experimental characterization of profiles and turbulence

The following discussion on SOL width and turbulence will be illustrated by measurements performed in the Tore Supra (TS) tokamak during Ohmic limited phases, by means of 2 reciprocating probe systems located at the plasma top [10]. One is equipped with a Mach head with tunnel collectors allowing calibrated measurement of parallel flows , electron density and temperature (using IV characteristics) across SOL profiles. The second is equipped with a poloidal rake of small collectors measuring floating potential and saturation current (J_{SAT}) at a rate of 1MHz across the full SOL profile [11]. On these fluctuating time traces, the choice is made to define blob events as local maxima of J_{SAT} exceeded the local mean value ($J_b > \langle J \rangle_{loc}$). Normalized blob amplitude will be defined as $n_b/\bar{n} \equiv J_b/\langle J \rangle_{loc}$. For every of these time points, a radial drift velocity V_b (referred to as blob velocity) is estimated from the spatial difference of floating potential measured by probes surrounding saturated collectors. Then, statistical averages are made upon collection of blobs belonging to the same spatial location: averaged blob amplitudes, velocity and duty cycles, as illustrated in Fig1c)d)e). Additionally, the turbulent radial flux transport coefficient will also be estimated by averaging directly the product of saturation current and poloidal electric field fluctuations, as detailed in [11]. Finally, the mean flow profiles measured by the Mach probe will be used to estimate the local radial particle flux responsible for the onset of parallel flows, using a Tailoring flow model as detailed in [8].

Finally, SOL width analyses will focus on a database of about 100 reciprocations performed with the Mach probe to study the SOL properties in ITER-like start-up phase [7]: ohmic plasmas limited at the high field side. Slow ramp of plasma current are performed over approximately 10 seconds at constant toroidal magnetic field allowing about 7 probe reciprocations per shot, up to the separatrix, during slowly varying plasma conditions. Gas fueling was adjusted shot to shot to decouple plasma density and plasma current variations. Detachment or MARFE phases are removed from the dataset. Conditions are summarized in Fig.3c.

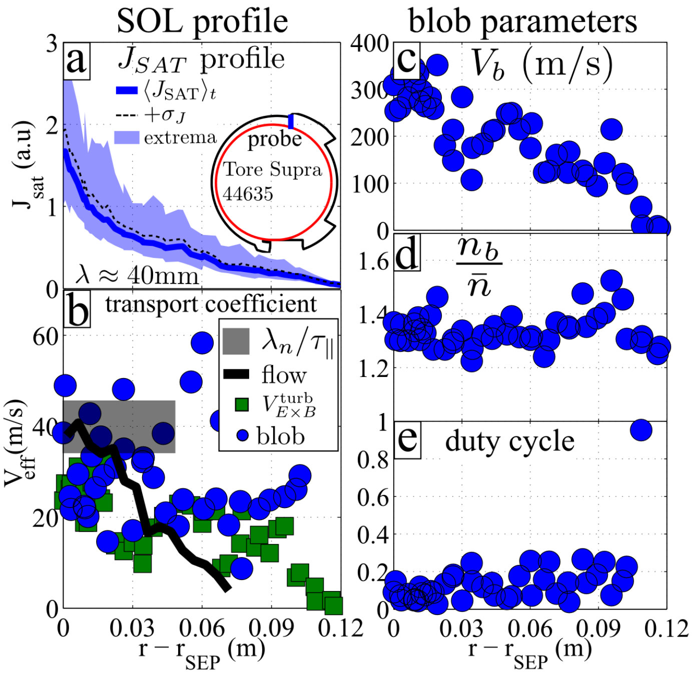


Figure 1: SOL properties in Tore Supra 44635 discharge. a) Saturation current profile from turbulence RCP: mean profile (thick curve) and min-max envelope (blue area). The radial decay length of the profile is mentioned. b) Transport coefficient built from the profile decay length (dark area), mean flow analyses (thick black curve), turbulence estimate (green squares), or estimated from blob averaged parameters (blue dots). c) averaged blob velocity in the radial direction, d) normalized blob amplitude e) blob duty cycle across the SOL profile.

3. On the link between SOL width and blob dynamics

As illustrated in Fig1a, the SOL density profile exhibits a wide dynamical envelope characterized by local maxima 2 to 3 times larger than local minima. On the other hand, the fluctuation level, defined as the standard deviation of the fluctuations, do not exceed 15% of the time average, denoting what is often called large intermittence. It involves, as it is commonly considered, local density filaments or blobs, evolving in 3D: in the periphery of the outer midplane, curvature polarization generates potential vortices vertically around density blobs that drift them outward in average. These blobs are also immersed in poloidal flows of larger scales while extending along magnetic field lines. In low confinement regimes of limited configurations, the radial convection of matter and energy associated with their outward motion participates to the onset of SOL width, in balance with poloidal losses (including parallel) toward targets and target recycling (considered small in limited configuration). In simple transport theory, an average density width λ_n would be expressed by equality of transport times: $\tau_\parallel = \tau_\theta$, or $\lambda_r = v_r L_\theta / v_\theta$, where v_r and v_θ are the radial and poloidal transport coefficients respectively and L_θ the typical poloidal extent of the SOL. In general, parallel particle flows are in the range of Bhom values from around the midplane to the targets ($M_\parallel \leq 1$), which gives roughly fractions to one millisecond for τ_θ ($L_\parallel \approx 60$m and $v_\parallel \approx 60$km/s for TS case). Then, SOL density width of a few centimeters ($\lambda_n \approx 4$cm TS case) would correspond to radial transport coefficients in the range of $v_r \approx 40$m/s, as shown in Fig1b. Interestingly, the SOL width estimated from the radial speed of individual filaments (about 300m/s close to separatrix of TS, Fig1c) would be about 10 times the measured value. This obviously questions some recently proposed statistical approach of SOL profile, which directly links SOL density width to blob velocity [12]. To compile with averaged widths, which is a physical consequence of particle flux balance, blobs need to be included within such a balance model.

Considering filaments of density n_b, transversal dimension δ_b, velocity V_b, and local duty cycle $f_b\tau_b$ (where f_b is the blob occurrence frequency and τ_b the local transit time over its own size), the time averaged particle flux resulting from blob propagation is $\langle\Gamma_r\rangle_t^{blob} = f_b\tau_b n_b v_b$. Now, the particle flux can also be expressed from the time averaged density $\bar{n}$ and an effective transport coefficient $\langle\Gamma_r\rangle_t \equiv \bar{n} V_{eff}$ such that $V_{eff} = n_b/\bar{n} f_b \tau_b V_b$, which is referred to as blob transport coefficient in Fig1b. For duty cycles in the range of about 10% (Fig1e) and normalized blob amplitudes in the range of 1.3 (Fig1d), V_{eff}^{blob} effectively falls in the range of several tens of meter per seconds, or a fraction of the filament speed. The local turbulent particle flux estimated from the non linear average of potential and density fluctuations (done without blob identification) agrees in ordering with the later, which is not totally surprising since they refer to the same fluctuations, but treated differently. Finally, a third estimate of the local particle flux (at probe location) - obtained from a Tayloring model of parallel flows - also falls in the range of turbulent values. These estimates of transport coefficients measured at the top poloidal position of the plasma are in relatively good agreement, at least close to the separatrix, to the coefficient required to explain the SOL width ($\approx$ 40m/s). Considering that the radial particule flux is strongly inhomogenous around the poloidal section of the plasma [8], this agreement could be fortious. In facts, it rather shows that the poloidal average of the radial transport - that sets the global SOL width - coincides with the local transport amplitude at the top probe position.

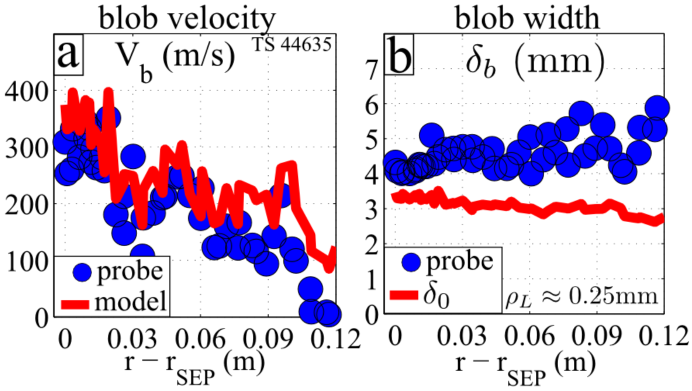


Figure 2: a) Blob velocity estimated experiment (blue dots) along the SOL profile, compared to analytical blob model (red curve). b) Blob width measured along the SOL profile compared to the model scale length δ_0 separating inertial and sheath limited blob regimes.

4. Comparison with interchange models

The above mentioned transport properties from Tore Supra SOL are in qualitative agreement with interchange mechanisms: over dense blobs propagating outward, transport enhanced around the outer midplane precisely where curvature driven polarization is destabilizing. In order to match these observations with quantitative numbers, 3D simulations of SOL dynamics are in principle needed [13], precisely because of the parallel dynamics entering poloidal asymmetries of turbulence. On the other hand, the simple circular geometry of Tore Supra SOL could benefit to an attempt to compare simplified models with experimental results. For a large class of models of interchange SOL transport are 2D (radial poloidal), the parallel dynamics is simplified into control parameters. TOKAM2D is such code [14], with the simplification of isothermal plasma. The set of equation consists of:

$$\begin{array}{rcl} \partial_t n &=& -\{\phi, N\} + D\Delta n - \sigma_\parallel n e^{\Lambda-\phi} + S_n \\ \partial_t \omega &=& -\{\phi, \omega\} + \nu\Delta\omega + \sigma_\parallel\left(1 - e^{\Lambda-\phi}\right) - g\frac{\partial_y n}{n} \end{array} \qquad (1)$$

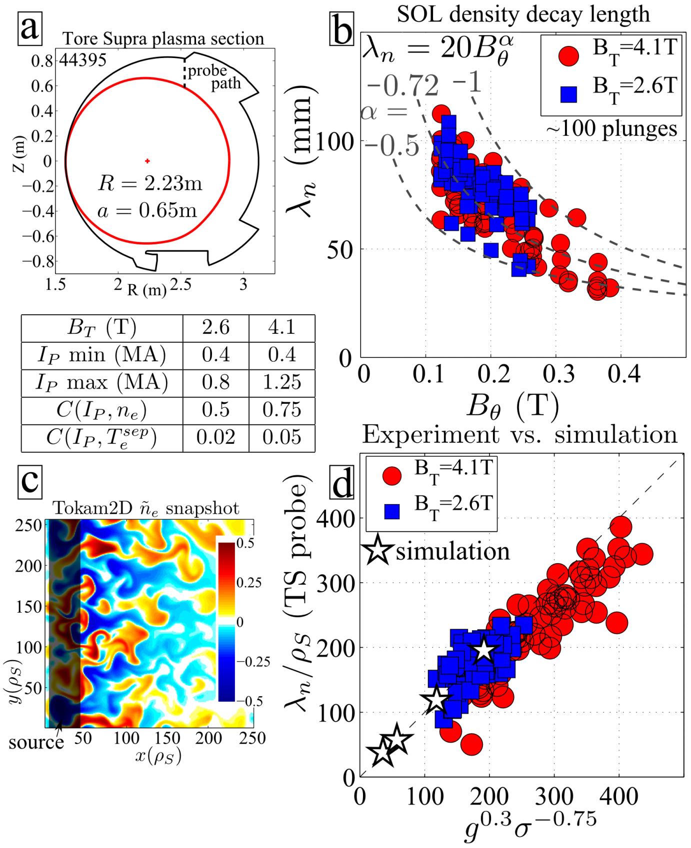
, where t is normalized to $\omega_i^{-1} = \left(\frac{ZeB}{m_i}\right)^{-1}$, space is normalized to $\rho_L = \frac{c_S}{\omega_i} = \sqrt{\frac{m_i T_e}{B^2 Ze}}$ where m_i is the ion mass in kg, T_e is the electron temperature in eV, Z is the ion charge number, e is the unitary charge in C, B is the magnetic field strength in T, g is the curvature term $g = \frac{\alpha_g \rho_L}{R}$ where R is the plasma major radius in m, Λ is the sheath potential drop, again normalized to T_e, $\sigma_\parallel = \frac{\alpha_\sigma \rho_L}{q_{cyl} R}$ is the parallel loss rate with q_{cyl} the cylindrical safety factor, $\omega = \Delta\phi$ is the plasma vorticity. D and ν are diffusion and viscosity coefficients normalized to the Bohm value ($\rho_L^2 \omega_i$), usually small ($< 10^{-2}$). The system is driven by a particle source S_n localized in the radial direction. Plasma density

n is normalized to arbitrary value and plasma potential is normalized to T_e. The direction y corresponds to the poloidal direction oriented along the electron diamagnetic direction, assumed normal to the magnetic field and x is the direction along the minor radius, directed outward. The Poisson bracket reads $\{A,B\} \equiv \partial_x A \partial_y B - \partial_y A \partial_x B$. Note that both g and $\sigma_\parallel$ are defined up to a multiplication factor that can be adjusted to account for a varying degree of poloidal asymmetries. In the following, unitary values are adopted, to account for the outer midplane enhancement of the transport: $\alpha_g = 1$ suggests an effective polarization rate in-between midplane extrema ($\alpha_g = -2$ at high field side and $\alpha_g = 2$ at low field side), and $\alpha_\sigma = 1$ suggests a parallel loss rate larger than over the entire field line.

Before presenting a comparison of experimental SOL widths with the scaling given by such model, a rough proof of principle is proposed. Considering isolated blob over immersed in a background density, a blob drift velocity can be analytically derived from the vorticity equation by balancing source and sink terms, each written using blob parameters. As detailed in [15], the blob velocity reads:

$$V_b^m = \frac{1}{2}\sigma_\parallel \delta_b^3 \left(\sqrt{1+\left(\frac{\delta_0}{\delta_b}\right)^5}-1\right)c_S$$

, where $\delta_0 = \sqrt[5]{\frac{4g\delta n_b}{\bar{n}\sigma_\parallel^2}}$ is a model scale length (whose value is shown in Fig2b), and $\delta n_b = n_b - \bar{n}$ is the blob density perturbation above background. As seen in Fig2a, this analytical expression agrees reasonably well with the blob velocity measured in TS SOL. Coincidentally or not, the blob size is also found to be relatively close to the model scale length, which normally sets the transition between regimes of propagation. The agreement suggests that blob dynamics in TS SOL can be described by such simple blob model, which would encourage to derive an analytical expression for the SOL width based on blob velocity. That said, such an approach would require to make several important guesses concerning blob size (what fraction of δ_0), blob amplitude $\delta n_b/\bar{n}$ and blob duty cycle $f_b\tau_b$, which would certainly lead to poor predictability. On the other hand, it might simply help to give a qualitative explanation for the influence of the main control parameters. Assuming that blob size is a fixed fraction of the model scale length $\delta_b \propto \delta_0$, the blob velocity simply reads $V_b \propto \sigma_\parallel^{-0.2} g^{0.6} c_S$, which leads to a SOL width scaling : $\lambda_n \propto \sigma^{-1.2} g^{0.6} \rho_L$.



B_T (T)	2.6	4.1
I_P min (MA)	0.4	0.4
I_P max (MA)	0.8	1.25
$C(I_P, n_e)$	0.5	0.75
$C(I_P, T_e^{sep})$	0.02	0.05

Figure 3: a) Cross section of the Tore Supra plasma used for ITER start-up database. The table summarizes the main plasma parameters: magnetic field, plasma current, correlation coefficient between density and current, separatrix temperature and current. b) Dependence of the SOL density decay length with poloidal magnetic field. c) Comparison of the normalized SOL decay length with the numerical scaling.

Comparison between the full TOKAM2D model (Eq1) and experimental evidences is now extended to a large dataset built on Tore Supra for the ITER startup preparation [7]. It consists in about 100 reciprocations with the Tunnel Mach probe, spanning different magnetic field, plasma current and density values during ohmic discharges. Plasma shape and plasma parameters are summarized in Fig3a. As shown by Gunn [7] the SOL heat decay length was found to vary primarily with the plasma ohmic power. Alternatively, the density decay length is also found to vary primarily with the plasma current (Fig3b), with no or weak dependence with the toroidal magnetic field. Comparison with theory is made through numerical simulations performed at different parallel loss and polarization rates to render variation of magnetic field and plasma current: $\sigma_\parallel \in \left[1\cdot10^{-4}, 5\cdot10^{-4}\right]$ and $g \in \left[8\cdot10^{-4}, 40\cdot10^{-4}\right]$. Once saturated turbulent regime is reached (pictured in Fig3c), the time averaged SOL density decay length is measured and a regression is applied on the dataset to extract the dependence with the two control parameters. As illustrated in Fig3d, the following expression is found

$\lambda_n = \sigma_\parallel^{-0.75} g^{0.3} \rho_L$. Note that the dependences built from the blob velocity is not so far from this numerical scaling, in the sens that sign and relative weight of the two exponents are matched.
Comparison between the numerical scaling and experimental data set of Tore Supra is shown in Fig3c, which reveals a quantitative agreement both in amplitude and trend. Note that the asymmetry factors α_g and α_σ are maintained to unity, which could be better adjust to increase the agreement. But this no the purpose of this comparison: it shows that a simplified turbulent transport model can explain the trend found for the SOL width across a large set of conditions.

5. Conclusions

Scrape off layer properties have been investigated in specific tokamak conditions: toroidally limited L-mode plasmas performed in Tore Supra Tokamak. Mean flows across SOL width were measured with a calibrated Mach probe system, and fluctuations of potential and density were collected with a poloidal array of small collectors. At the top of the plasma section where these reciprocating probe systems operate, the radial particle flux is found to be dominated by the $E \times B$ convection of density fluctuations: the amplitude of this turbulent transport is in agreement with the width of the mean density profile. Now, this radial transport is generally conceived as a result of isolated density blobs propagating radially outward. The averaged velocity of the blobs measured in Tore Supra is in the range of $V_b \approx 300$m/s, thus an order of magnitude larger than the transport coefficient needed to construct a SOL width of a few centimeters ($V_{eff} \approx 40$m/s). In facts, the role of blobs in the onset of radial transport needs to be weighted by their duty-cycle, of about 10%. Consequences are twofold: even if an analytical model of blob velocity can be derived and checked against experimental measurements, the SOL width cannot be predicted from such model. As shown in the case of Tore Supra data, the scaling found for the width of the density profile agrees at most qualitatively with the blob model. On the other hand, a good quantitative agreement is found against full turbulence simulations performed with an isothermal 2D code. The SOL width given by the numerical scaling can also be written as $\lambda_n \propto q_{cyl}^{0.75} B_T^{-0.55} R^{0.45} T_{sep}^{0.23}$. Interestingly, the exponents controlling the dependence of λ with safety factor, toroidal magnetic field and major radius exhibit relative weights and signs that are in relative agreement with what can be estimated for H-mode heat load decay length [1]. Strikingly, magnetic topologies, confinement regimes and therefore SOL width amplitudes are different, but it could suggest that transport phenomena may not be uncorrelated: In H-modes with steeper gradients, the poloidal flow shearing rate would probably need to be included in the vorticity balance of the blob, which would certainly modify the velocity amplitude. But more importantly, the H-mode transport barrier also acts as a filter for propagating blobs, therefore reducing their intermittency and duty cycles [16].

6. Acknowledgment

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the European Union Horizon 2020 research and innovation program under grant agreement number 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

[1] T. Eich, A.W. Leonard, R.A. Pitts, W. Fundamenski, R.J. Goldston, T.K. Gray, A. Herrmann, A. Kirk, A. Kallenbach, O. Kardaun, A.S. Kukushkin, B. LaBombard, R. Maingi, M.A. Makowski, A. Scarabosio, B. Sieglin, J. Terry, A. Thornton, ASDEX Upgrade Team, and JET EFDA Contributors. *Nuclear Fusion*, 53(9):093031, 2013.

[2] M. Bernert, M. Wischmeier, A. Huber, C. Lowry, F. Reimold, S. Brezinsek, R. Dux, T. Eich, A. Kallenbach, B. Lipschultz, C. Maggi, S. Wiesen, JET Contributors, the EUROfusion MST1 team, and the ASDEX Upgrade Team. *Nuclear Materials and Energy*, this conference, 2016.

[3] R. Dux et al. *J. Nucl. Mater.*, 363-365(0):112 – 116, 2007.

[4] J. Decker, Y. Peysson, J.-F Artaud, E. Nilsson, A. Ekedahl, M. Goniche, J. Hillairet, and D. Mazon. *Physics of Plasmas*, 21(9), 2014.

[5] J.P. Gunn, V. Fuchs, V. Petrzilk, A. Ekedahl, N. Fedorczak, M. Goniche, and J. Hillairet. *Nuclear Fusion*, 56(3):036004, 2016.

[6] P. Manz, S. Potzel, F. Reimold, M. Wischmeier, and the ASDEX Upgrade Team. *Nuclear Materials and Energy*, this conference, 2016.

[7] J.P. Gunn, R. Dejarnac, P. Devynck, N. Fedorczak, V. Fuchs, C. Gil, M. Kocan, M. Komm, M. Kubic, T. Lunt, P. Monier-Garbet, J.-Y Pascal, and F. Saint-Laurent. *Journal of Nuclear Materials*, 438, Supplement:S184 – S188, 2013.

[8] N. Fedorczak, J. P. Gunn, J.-Y. Pascal, Ph. Ghendrih, Y. Marandet, and P. Monier-Garbet. *Physics of Plasmas*, 19(7):072313, 2012.

[9] A. Gallo, N. Fedorczak, S. Elmore, B. Labit, C. Theiler, H. Reimerdes, F. Nespoli, R. Maurizio, P. Ghendrih, T. Eich, and the TCV team. *Nuclear Materials and Energy*, this conference, 2016.

[10] J.P., Gunn, J.-Y. Pascal, F. Saint-Laurent, and C. Gil. *Contributions to Plasma Physics*, 51(2-3):256–263, 2011.

[11] N. Fedorczak, J. P. Gunn, J.-Y. Pascal, Ph. Ghendrih, G. van Oost, P. Monier-Garbet, and G. R. Tynan. *Physics of Plasmas*, 19(7):072314, 2012.

[12] O. E. Garcia, M. K. Bae, J.-G. Bak, S.-H. Hong, H.-S. Kim, R. A. Kube, R. A. Pitts, A. Theodorsen, and the KSTAR Project Team. *Nuclear Materials and Energy*, this conference, 2016.

[13] P. Tamain, Ph. Ghendrih, E. Tsitrone, Y. Sarazin, X. Garbet, V. Grandgirard, J. Gunn, E. Serre, G. Ciraolo, and G. Chiavassa. *Journal of Nuclear Materials*, 390-391:347 – 350, 2009.

[14] Y. Sarazin and Ph. Ghendrih. *Physics of Plasmas*, 5(12):4214–4228, 1998.

[15] S.I. KRASHENINNIKOV, D.A. D'IPPOLITO, and J.R. MYRA. *Journal of Plasma Physics*, 74:679–717, 10 2008.

[16] Ph. Ghendrih, G. Ciraolo, Y. Larmande, Y. Sarazin, P. Tamain, P. Beyer, G. Chiavassa, G. Darmet, X. Garbet, and V. Grandgirard. *Journal of Nuclear Materials*, 390-391:425 – 427, 2009.