Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Journal of Nuclear Materials 337–339 (2005) 342–346
journal of nuclear materials
www.elsevier.com/locate/jnucmat

Control of long range turbulent transport with biasing in the tokamak scrape-off-layer

C.F. Figarella [a,*], Ph. Ghendrih [a], Y. Sarazin [a], G. Attuel [a], S. Benkadda [b], P. Beyer [b], G. Falchetto [a], E. Fleurence [a], X. Garbet [a], V. Grandgirard [a]

[a] *Association Euratom-CEA, CEA/DSM/DRFC/SIPP CEA Cadarache, 13108 St-Paul-Lez-Durance, France*
[b] *LPIIM, DSC, UMR 6633 CNRS-Université de Provence, Case 321, 13397 Marseille cedex 20, France*

Abstract

Cross-field transport in the SOL influences tokamak performance in particular regarding the divertor efficiency. Recent experiment evidence emphasizes non-exponential and/or flat SOL profiles that suggest a large perpendicular transport. A 2D fluid model based on the interchange instability to simulate the SOL turbulence was found to exhibits intermittent dynamics of the particle flux. We propose a control method that prevents long range transport events from reaching the far SOL: It consists in biasing the far SOL leading to a transport barrier which stops the propagation of these intermittent events. The best trade off is to localize the biased toroidal ring around the baffles. We show that such a control is achievable providing the strength of the barrier is strong enough. The investigation of the minimal biasing power required to achieve the control as well as its experimental estimate is performed.

PACS: 52.35.Ra; 52.55.F; 52.25.Fi; 52.25.Gj; 52.65.Kj
Keywords: Edge modelling; Edge plasmas; Fluctuations and turbulence; Intermittent transport

1. Introduction

Cross-field transport in the scrape-off-layer (SOL) influences the tokamak performances via the divertor efficiency. The magnetic divertor configuration, which will be used in the next step fusion device ITER-FEAT, minimizes the plasma wall interaction, provides heat and particle exhaust, provides ash removing and shields the main plasma from impurity contamination [1]. Once the plasma crosses the separatrix, it penetrates the SOL, region of open field lines which ends onto the divertor plates, and flows along theses magnetic field lines to the divertor where it neutralizes. Moreover the next step fusion device will use tight divertor baffle configuration which lead to the best performances. Such configuration permits: an increase of the gas pressure in the divertor chamber, an increase of the screening of impurities from the plasma core, a low neutral density in the main chamber, a lower power threshold for the H mode [2]. In the standard view of diffusive transport, the SOL profiles are exponential with short decay lengths, from 1 to 3 cm [1]. However recent experiments [3–6] show that these profiles can be non-exponential and flat in the far SOL suggesting a large perpendicular transport. This long range transport is characterized by intermittent events [11] which propagate ballistically with large velocities as well in experiments [4,7–10] as in

* Corresponding author. Tel./fax: +33 442256110/+33 442254990.
E-mail addresses: charles.figarella@cea.fr (C.F. Figarella), philippe.ghendrih@cea.fr (Ph. Ghendrih).

0022-3115/$ - see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.jnucmat.2004.10.069

numerical simulations [12,15]. The consequences can be harmful for the tokamak performances:

- The cross-field plasma flow can overcome the one along the fields lines to the divertor, this phenomenon is known as the *main chamber recycling* regime [4]. In that case the divertor volume receive only part of the total flux from the main chamber and the neutral density in the main chamber is high,
- in the case where the events propagates in the far SOL, they can damage the first wall components with the production of chemical erosion, an increase of the wall particle content and an increase of the wall tritium inventory.

Even if the main operating regime for ITER will be the ELMy H-mode, and the fact that related work of LaBombard et al. [4] is in L-mode, there is still a debate whether the main chamber recycling regime will persist in H-mode. In order to prevent the plasma-wall interaction, one can use a biased probe to stabilize the turbulence and locally create a transport barrier [16,17,19]. Indeed recent numerical work has shown that an intermittent event hardly cross a transport barrier [18]. A preliminary [12] work on controlling long range turbulent transport with biasing the far SOL showed that the transport barriers can stop these events. The implementation of a biased ring in the far SOL (for example on the divertor baffle) permits to lower the power supplies required to sustain these barriers. Such idea, originally proposed in reference [12] is investigated in detail in this paper. The concept of the toroidal ring located around the baffles is not simulated here, we extrapolate the biasing probe to this toroidal ring. One should note that it is a steady state *probe* biasing contrary to the *divertor* biasing, the latter allowing one to control the plasma flow in the SOL, an increase of the density and thus the power deposition onto the divertor plates (For a review on the divertor biasing see [20]). The steepening of the electron density profile due to divertor biasing action was observed in the paper of Shoji et al. [21]. The proposed biasing method can also be beneficial to suppress heat flux to the main chamber wall components due to ELMs provided an increase of the biasing voltage.

After a description of the flux driven model which lead to intermittent bursts of density through the SOL, we will analyze the biasing control technique as a way to insulate the main chamber from the large density flux.

2. Interchange instability in the SOL

The model used to describe the SOL turbulence is 2D, fluid, based on the interchange instability [12]. It describes the evolution of the density n and the vorticity $\nabla_\perp^2\phi$ which govern the particle balance for the electrons and the charge conservation, respectively

$$\partial_t n + [\phi, n] = -\sigma n \exp(\Lambda + \mathrm{Vbias} - \phi) + D\nabla_\perp^2 n + S, \tag{1}$$

$$\partial_t \nabla_\perp^2\phi + [\phi, \nabla_\perp^2\phi] = \sigma\{1 - \exp(\Lambda + \mathrm{Vbias} - \phi)\} - g\partial_y \mathrm{Log}(n) + \nu\nabla_\perp^4\phi. \tag{2}$$

The Vbias stands for the biasing potential, described in the next section. Time and space are respectively normalized to $1/\Omega_i$ the ion cyclotron frequency and to ρ_s, the hybrid Larmor radius. The Poisson brackets are defined by $[u,v] = \partial_x u\partial_y v - \partial_y u\partial_x v$ where x and y are the normalized radial $x = (r - a)/\rho_s$ and poloidal $y = a\theta/\rho_s$ coordinates with a the minor radius. The sheath boundary conditions introduce parallel loss term to set the particle flux to the ion saturation current and to ensure a vanishing current density into the wall [1]. The parallel loss term is set by the floating potential Λ and the characteristic time of parallel transport $\sigma = \rho_s/L_\parallel$. $L_\parallel$ being the parallel connection length that controls the loss term σ. In this model the temperature is constant with $T_i \ll T_e$; the radial and temporal dependance of T_e is omitted for simplicity. Their inclusion can lead to an instability [13] which has been studied by Bisai et al. [14]: the results indicate an increase of the growth rate, the elongation of the poloidal structures and an increase of the rotation shear stabilization. The non-constant T_e can also accelerate electrons thus creating some additional currents which will increase the required biasing power unless the biasing is located in the far SOL. Assuming $T_i = 0$ do not affect the global quantitative behaviour of the dynamic. Moreover we used the flute hypothesis in order to reduce the system in 2D, assuming the perturbations constant along magnetic field lines. D is the particles diffusion coefficient and ν the vorticity diffusion coefficient, both are normalized to the Bohm value, i.e., T_e/eB. D and ν govern the damping of the small scales. The curvature is proportional to $g \sim \rho_s/R$ with R the major radius. This curvature is averaged along the field line thus is constant in the vorticity equation. The source term S maintains the system out of equilibrium and simulate the incoming flux from the plasma core. This approach is known as the flux-driven transport, the density gradient is not frozen but can evolve self-consistently with transport [15]. S is localized radially with no poloidal dependence, its radial shape is a gaussian $S = S_0 \exp(-(x/\rho_{\mathrm{source}}^2))$ with a radius of $\rho_{\mathrm{source}} \sim 8.5\rho_s$. Numerical simulations are carried out with a 256×256 mesh, the grid size being ρ_s. The values of the control parameters used in this paper are the following: $g = 5.7 \times 10^{-4}$, $S_0 = 5 \times 10^{-3}$, $\sigma = 2.3 \times 10^{-4}$, $\Lambda = 3.88$, $D = \nu = 10^{-2}$, $\rho_s = 3.4 \times 10^{-4}$, $\rho_{\mathrm{source}} = 8.5$. This system ((1) and (2)) was found to exhibit intermittent transport with a 44% of the cross-field particle flux due to events at more than 4 standard deviations [12]. Moreover a long range turbulent transport was established characterized by a large poloidal extend and steep radial density gradients.

3. Turbulence stabilization with biasing

In the SOL, electric currents determine the turbulent activity. One can distinguish between the curvature driven current proportional to the density gradient $j_\perp \sim gn/L_y$ which is destabilizing and the parallel current $j_\parallel \sim n\sigma(1 - \exp(\Lambda + \text{Vbias} - \phi))$ which is stabilizing. Here L_y is the characteristic length of the poloidal gradient of the density field. A way to modify the cross-field transport is to act on this parallel current via the biasing potential Vbias [12] which is numerically simulated by a gaussian radial shape with a radial extend of $10\rho_s$ with no poloidal dependance. Its implementation is in the far SOL in order to require the minimum power to sustain the biasing voltage. Fig. 1 represents the simulation domain with radials profiles of the density source (dashed) localized around the separatrix and the biasing voltage (solid) located in the far SOL. The choice of a gaussian shape for the biasing profile is motivated by the experimental biasing potential observed for example in reference [16].

When simulating the system ((1) and (2)) with the parameters $g = 5.7 \times 10^{-4}$, $S_0 = 5 \times 10^{-3}$, $\sigma = 2.3 \times 10^{-4}$, $\Lambda = 3.88$, $D = \nu = 10^{-2}$, $\rho_s = 3.4 \times 10^{-4}$, $\rho_{\text{source}} = 8.5$, Vbias = −5, it appears, as expected, a transport barrier with a steepening of the gradients at the location of the biasing potential (see Fig. 2, solid line). Such barrier can be strong enough to quench the turbulence and prevent the density blobs from reaching the wall depending on the strength of the biasing potential. In contrast the circles stand for the case without barrier, i.e., Vbias = 0; its profile is exponential. Profiles are averaged in time and over the poloidal direction.

Since the strength of the barrier depends on the amplitude of the biasing potential, we introduce the notion of the minimal power required to have an efficient control with a minimum power involved. Let us define the power required to bias, $P = \int \mathrm{d}s\,\text{Vbias}\, j_\parallel$ which should be minimal for practical reasons. The aim is to create a barrier strong enough to stop the intermittent events with the minimal biasing power. The scan of P as a function of Vbias is shown in Fig. 3. Such figure indicates which biasing voltage one should choose in order to reduce the biasing power of a given fraction of the initial one: a power reduction of 45% corresponds to a Vbias of −1. Since the potential is normalized to the electronic temperature $T_e = 100\,\text{eV}$, a normalized biasing potential of −1 corresponds to −100 V in real units.

A rough estimate of the biasing power with ITER parameters with a toroidal probe of 1 cm large, a normalized biasing potential of −0.5 corresponding to −50 V, an averaged density of $10^{-19}\,\text{m}^{-3}$, a parallel current of 20 kA, a $T_e = 100\,\text{eV}$, gives $P < 1\,\text{MW}$. Such value of biasing power can be achieved with the current power supplies.

A qualitative way to characterize the effect of the biasing on the turbulence is to consider the ratio of the poloidally and time averaged turbulent flux after and before the barrier, respectively. An illustration is presented on Fig. 4. This flux ratio gives an indication about the relative avalanches's activity which crosses the barrier: this activity increases with the decrease of absolute value

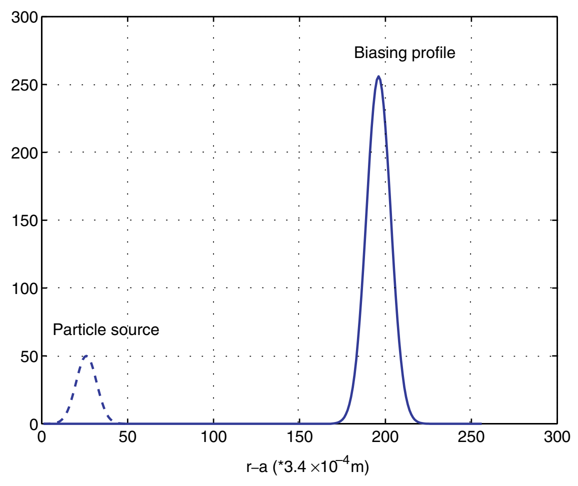

Fig. 1. Radial profile of the source (dashed) and biasing potential (solid), the simulation box is of $8\,\text{cm}^2$.

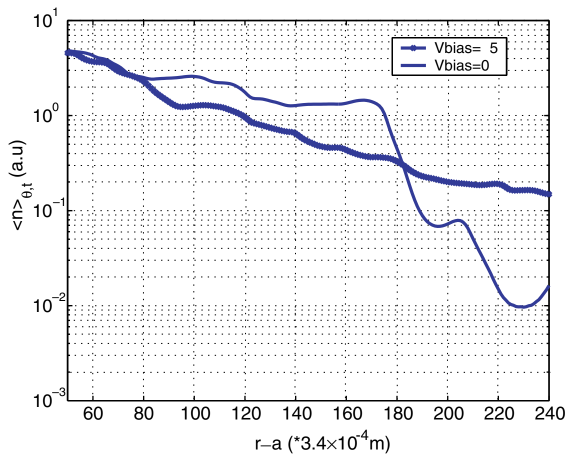

Fig. 2. Radial density profile averaged in (θ, t) for Vbias = −5 (circles) and Vbias = 0 (solid line).

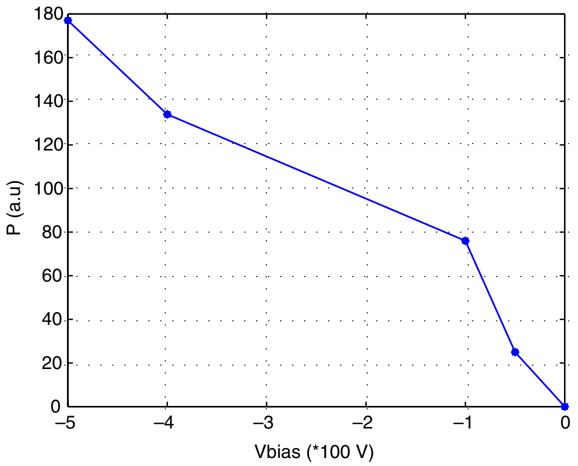

Fig. 3. Scan of the biasing power P as a function of Vbias.

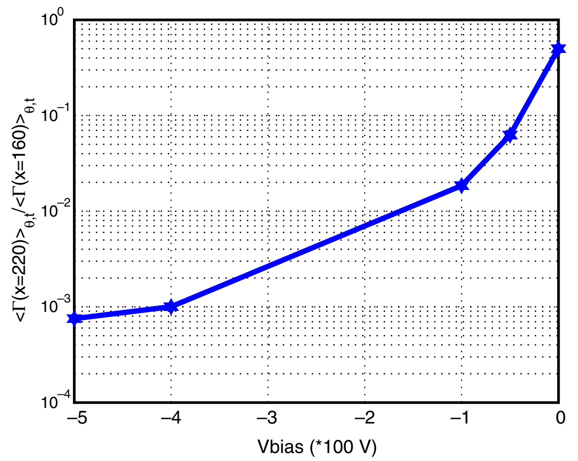

Fig. 4. Scan of the flux ratio before/after the barrier as a function of Vbias.

of the the biasing potential. A Vbias = −1 value reduces the initial level of avalanches of more than an order of magnitude.

The statistical properties of the turbulent transport can be illustrated with the probability distribution function (PDF). We represent on the Figs. 5 and 6 the normalized flux PDF averaged in θ at two given radial position, before ($x = 160$) and after ($x = 220$) the barrier, respectively, for different values of the biasing potential. Before the barrier (Fig. 5) the pdf have the same structure, mainly asymmetric resulting of the intermittency and of the same order, i.e., with a maximum flux located around 0.1. Before the barrier the pdf is not sensitive to the biasing potential. After the barrier there is a strong difference compared with the previous case: first the magnitude of the flux decreases from 40% (Vbias = −1) up to two orders of magnitude (Vbias = −4 and −5),

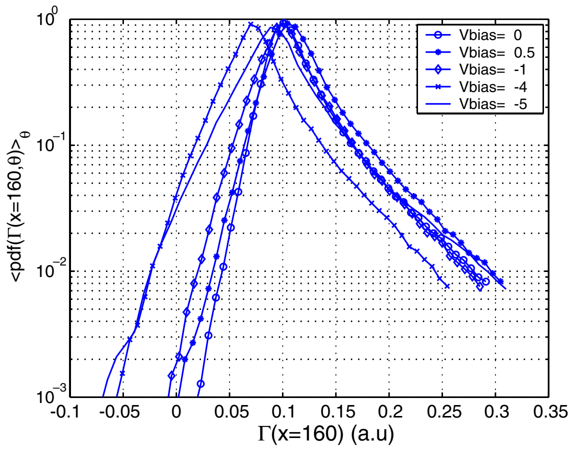

Fig. 5. Flux PDF averaged before ($x = 160$) the barrier.

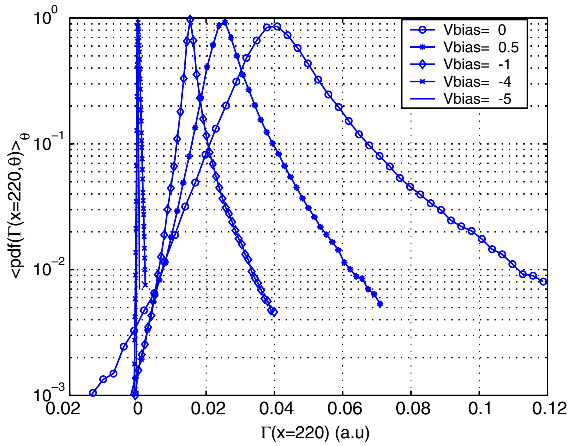

Fig. 6. Flux PDF averaged after ($x = 220$) the barrier.

second the pdf are more asymmetric and broader with decreasing Vbias. The general asymmetry of the pdf in the SOL were observed experimentally in recent works [7,8,10].

4. Conclusion

To summarize, we have studied the long range turbulent transport in the SOL which exhibits intermittent behavior. These intermittent events can propagate in the far SOL beyond the e-folding length and thus can reduce the divertor performances. A way to control this long range transport is to bias the far SOL. Biasing will lead to the formation of a transport barrier which quench the turbulence and may prevent these events from crossing it. We have shown that such control is achievable numerically provided the strength of the barrier, characterized by the biasing voltage, is strong enough. If main chamber recycling persists in H-mode (which has still to be proven), an implementation of a ring probe toroidally located in the vicinity of the baffles could be a good trade off.

References

[1] P. Stangeby, The Plasma Boundary of Magnetic Fusion Devices, IOP, Bristol, 2000.
[2] S.M. Kaye et al., J. Nucl. Mater. 121 (1984) 115.
[3] J.A. Boedo et al., Rev. Sci. Instrum. 69 (1998) 2603.
[4] B. LaBombard et al., Nucl. Fusion 40 (2000) 2041.
[5] M.R. Wade et al., J. Nucl. Mater. 266–269 (1999) 44.
[6] J. Neuhauser et al., Plasma Phys. Control. Fusion 44 (2002) 855.
[7] D.L. Rudakov et al., Plasma Phys. Control. Fusion 44 (2002) 717.
[8] J.A. Boedo et al., Phys. Plasmas 8 (2001) 4826.
[9] J.A. Boedo et al., Phys. Plasmas 10 (2003) 1670.
[10] G.Y. Antar et al., Phys. Plasmas 8 (2001) 1612.
[11] M. Endler et al., Nucl. Fusion 35 (1995) 1307.
[12] Ph. Ghendrih et al., Nucl. Fusion 43 (2003) 1013.
[13] H.L. Berk et al., Nucl. Fusion 33 (1993) 263.
[14] N. Bisai et al., Phys. Plasmas 11 (2004) 4018.
[15] Y. Sarazin, Ph. Ghendrih, Phys. Plasmas 5 (1998) 4214.
[16] J.A. Boedo et al., Phys. Rev. Lett. 84 (2000) 2630.
[17] R.J. Taylor et al., Phys. Rev. Lett. 63 (1989) 2365.
[18] S. Benkadda et al., Nucl. Fusion 41 (2001) 995.
[19] C.F. Figarella et al., Phys. Rev. Lett. 90 (2003) 015002.
[20] G.M. Staebler, J. Nucl. Mater. 220–222 (1995) 158.
[21] T. Shoji et al., Proceedings of 14th International Conference on Wurzburg 1992, vol. 1, IAEA Vienne, 1993, p. 323.