Turbulent regimes in the tokamak scrape-off layer

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The plasma dynamics in the tokamak Scrape-off Layer (SOL) is of fundamental importance to determine the performance of a tokamak. It can be described as the interplay of plasma source from the core, perpendicular transport, and losses at the limiter plates. In the electrostatic limit, the instabilities thought to play the most important role in the SOL are ballooning modes (BMs), with the inertial and resistive branches (IBM and RBM), and drift waves (DWs), with inertial and resistive branches (IDW and RDW) [1, 2, 3, 4, 5, 6, 7]. BMs are curvature driven instabilities, characterized by a non-adiabatic plasma response: they are destabilized in presence of finite resistivity, electron mass or plasma β. DWs are caused by a pressure gradient and are destabilized by either finite electron mass or resistivity. Both the instabilities are active in the plasma SOL, but the knowledge of the conditions under which one or the other is active is still lacking. The goal of this study is to identify the SOL turbulent regimes, determining the driving instability as a function of the SOL operational parameters, such as resistivity, ν, eletron to ion mass ratio, m_e/m_i, safety factor, q, and magnetic shear, $\hat{s}$.

Our study of plasma turbulence in the SOL is based on the two-fluid, electrostatic, non-linear, drift-reduced Braginskii equations [8]. The fluid approach is justified by the high plasma collisionality in the SOL. For the sake of simplicity we consider $T_i \ll T_e$, since the fundamental properties of the dominant SOL instabilities, BMs and DWs, can be captured within a cold-ion model. We consider $s-\alpha$ circular geometry with a toroidal limiter positioned on the high field side equatorial midplane of the device. We also assume $\varepsilon = a/R \to 0$ (a is the tokamak minor radius and R is the major radius). The model is completed by a set of boundary conditions described in Ref. [9]. We focus on the mechanism leading to the saturation of the linear modes. It has been demonstrated [10] that, for typical SOL parameters, the saturation is provided by the *gradient removal* mechanism, i.e., the saturation of the linearly unstable mode due to non-linear flattening of the driving plasma gradients. The gradient removal theory provides an estimate of the plasma pressure gradient as a function of the SOL operational parameters. Saturation occurs when the radial gradient of the perturbed density becomes comparable to the radial gradient of the background density, i.e. $k_r\tilde{n} \sim \bar{n}/L_n$, where L_n is the radial length of the background density, and k_r denotes the typical radial wavevector of the instability. (The tilde indicates fluctuating quantities, while the over bar denotes equilibrium quantities, e.g. $n = \bar{n} + \tilde{n}$). In the following, we assume $L_n \sim L_p \sim L_T$. The time and poloidal averaged turbulent $\mathbf{E} \times \mathbf{B}$ radial particle flux can be estimated as $\Gamma_r = R\langle \overline{\tilde{n}\partial_y \tilde{\phi}} \rangle_y \sim Rk_y\tilde{\phi}\tilde{n}$, where k_y is the poloidal wavenumber of the mode dominating transport. Since the electric potential fluctuation can be evaluated from the leading order terms in the density equation, $\partial_t n \simeq -R[\phi, n]$, as $\tilde{\phi} \sim \gamma\tilde{n}L_n/(\bar{n}Rk_y)$, where γ is the linear growth rate of the mode that dominates the turbulent dynamics, we obtain an estimate for the radial flux, $\Gamma_r \sim \gamma\bar{n}/\left(k_r^2 L_n\right)$. For both DWs and BMs, we can assume $k_r \sim \sqrt{k_y/L_n}$, following non-local linear theory methods outlined in Refs. [11] and [12]. In order to obtain an estimate of L_n, we write a balance between the radial particle flux and the parallel losses at the limiter plates, i.e. $\partial_r\Gamma_r \sim \Gamma_r/L_n \sim \bar{n}c_s/q$, as the plasma flux to the limiter can be neglected compared to the parallel one. Substituting the expressions for Γ_r into the particle balance, we obtain:

$$L_n \sim \frac{q}{c_s}\left(\frac{\gamma}{k_y}\right)_{\max}, \quad (1)$$

where the ratio of the linear growth rate to the poloidal wavenumber has to be maximized over the unstable modes present in the system. In order to predict L_n according to Eq. (1), we evaluate the linear growth rate γ by using a linearized set of Braginskii equations [13]. Once L_n is calculated, we can predict which of the four main instabilities is driving the SOL dynamics. This is achieved by evaluating the growth rate of IBM, RBM, IDW, and RDW separately, as a function of the SOL operational parameters, at the k_y and R/L_n given by Eq. (1) [13]. The turbulent regime is defined according to the instability among those four that has the highest γ/k_y value. In Fig. 1 different colors are used to represent the non-linear turbulent regimes obtained at $q = 4$. The transitions between each couple of instabilities can be estimated by comparing their respective γ/k_y as a function of the SOL parameters (for more details see Ref. [13]). The estimates of the transitions are indicated in Fig. 1 by red symbols.

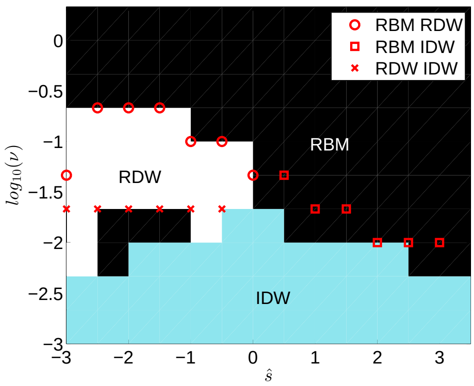

Figure 1: *Turbulent regimes for $q = 4$; different colors identify different regimes: RBM (black), IDW (light blue), and RDW (white). The red symbols indicate the estimate of the transition between regimes.*

In order to support the validity of our methodology to determine the SOL turbulent regimes, we carried out a number of non-linear simulations using the GBS code, described in Ref. [8]. The code has been initially conceived for simulating plasma turbulence in basic plasma physics devices, and it has been further developed in order to describe the SOL turbulence. Since in the SOL fluctuations are comparable to background quantities, the code solves the Braginskii

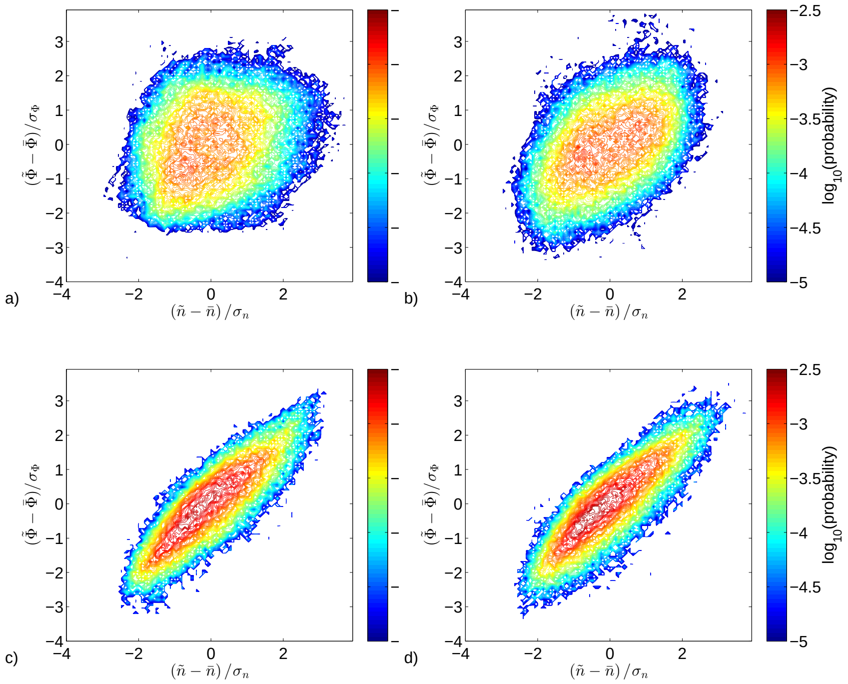

Figure 2: *Cross coherence between $\tilde{\phi}$ and $\tilde{n}$ for the RBM (a), IBM (b), RDW (c), and IDW (d).*

equations, with boundary conditions described in Ref. [9], without separation of background and fluctuation quantities. Therefore, the background pressure gradient is not fixed a priori and it results from the self-consistent evolution of the plasma profiles. Among the available simulations, we focus on the results of four simulations that belong to the four predicted instability regimes: RBM, IBM, RDW and IDW.

We analyze the relation between the potential and density fluctuations, according to the methods proposed in [3] and [7]: the phase shift probability and the cross coherence analysis. Herein, as an example, we report on the latter. For BMs the n and ϕ fluctuations are not correlated, while for DWs their amplitudes are clearly correlated. The cross coherence is computed at a fixed radial position. The ϕ and n fluctuations are considered as a function of the poloidal and toroidal directions, and time, and normalized to their standard deviation. We then evaluate the probability of finding both fluctuations at a certain ordered pair of amplitudes and we display it in Fig. 2. The cross coherence in Figs. 2a, for RBM, and 2b, for IBM, does not show correlation between ϕ and n, while the cross coherence in Figs. 2c, for the RDW, and 2d, for the IDW, show a high correlation between ϕ and n fluctuations. This additional analysis supports our predictions of the turbulent regime of the non-linear simulations.

In the present study we have identified the non-linear SOL turbulent regimes as a function of the SOL operational parameters (q, ν, $\hat{s}$, and m_i/m_e) depending on the instability responsible for the non-linear transport. The instabilities playing a major role in the tokamak SOL are believed to be the resistive and inertial branches of BMs and DWs. The SOL plasma dynamics has been described by the electrostatic drift-reduced Braginskii equations with cold ions, in the infinite aspect ratio limit with a toroidal limiter at the equatorial high-field midplane. We have assumed that the linear instabilities are saturated by the gradient removal mechanism, i.e. when the plasma pressure gradient is non-linearly flattened by the growth of the unstable modes. This has allowed us to predict the time-averaged plasma gradient length, which is proportional to γ/k_y, where γ is the linear growth rate and k_y the poloidal wavenumber of the instability that dominates the non-linear dynamics.

In order to verify the validity of our methodology, we have performed a set of four non-linear simulations each belonging to a different instability regime. The simulations have been carried out with GBS, a global, non-linear code that solves the drift-reduced Braginskii equations. For each set of SOL parameters of the non-linear simulations, we have predicted the instability regime, according to the gradient removal hypothesis. The predictions and the results of the non-linear simulations show good agreement.

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