



# Charge and current transport in open field lines turbulence: Influence of plasma-surface boundary conditions

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## ABSTRACT

We investigate the impact of both parallel and transverse boundary conditions on the current and charge transport in open field line systems using the TOKAM2D code, which solves a minimal model for interchange turbulence. Various limit test cases are discussed and analyzed. In the parallel direction, the sheath conductivity is found to play an essential role in the stabilization of large-scale potential structures, leading to the formation of transport channel or transport barrier respectively for an insulating end wall or a wall with an enhanced sheath conductivity. On another hand, the addition of transverse boundary conditions intrinsically changes the transport characteristics, influencing both radial profiles and probability density functions. It underlines that in some cases a detailed description of the plasma-wall interaction process is required to get a proper description of the current loop pattern that determines electrostatic turbulent transport.

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## 1. Introduction

The presence of a physical object in the Scrape-of-Layer (SOL) of a tokamak is crucial in the edge plasma physics. Magnetic field lines are intercepted by a solid surface, which then act as a perfect particle sink. Moreover, in these open field line systems, transverse transport mainly results from a plasma turbulence governed by self-sustained electromagnetic fields generated by electric polarization or electric currents [1]. At low enough plasma pressure, the electrostatic turbulence results from the competition between the drive due to the transverse diamagnetic current (vertical charge separation) and damping by parallel currents. The polarization current allows to close the current loops by controlling the transverse transport of the electrostatic potential. This mechanism is known as interchange turbulence and is thought to dominate perpendicular transport in the SOL of tokamaks.

Charge transport through current loops thus appears as a major element of plasma confinement in open field line systems. Modeling and understanding these properties then require an appropriate description of the electric current flowing between the plasma and the wall elements. In the parallel direction, one can consider that the sheath physics provide a reliable description backed up by solid theoretical considerations [2,3]. In the transverse direction, the physics of the plasma-wall boundary is more

complex to handle, since no equivalent of the Bohm criterion has been derived.

In this paper, we study how the circulation of current can impact the transport characteristics through the parallel and transverse boundary conditions modification. The paper is organized as follows: in Section 1 we describe the physical model used for the SOL interchange turbulence. Then we analyze the effect of changing parallel and transverse boundary conditions respectively in Sections 2 and 3. Finally, discussion of the results and their implications for SOL cross-field transport are found in Section 4.

## 2. TOKAM2D, a minimal model for SOL interchange turbulence

In the last two decades, 2D models have been developed in order to capture and understand most of the essential characteristics of SOL turbulence observed in experiments. As a common point, most of them rely on an interchange model [4–7]. The following work relies on the TOKAM2D model which solves the current balance equation  $\vec{\nabla} \cdot \vec{j} = 0$  in conjunction with the continuity equation  $d_t n = S$  to determine the evolution of the electrostatic potential and density fields [8]. The perpendicular turbulent transport is described in term of drifts (electric, diamagnetic and polarization) and is driven by an incoming particle flux instead of a density gradient, which give rise to an avalanche-like dynamics characterized by profile relaxation and strong outwards bursts of density [8]. The parallel boundary conditions, derived from the Bohm criterion, appear through source terms after the integration of the equations along the parallel direction on the basis of the flute hypothesis,

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which ensures the reduction of the model to two dimensions. Assuming the plasma is isothermal with  $T_i \ll T_e$ , the system is then reduced to [8]:

$$\partial_t N + [\phi, N] = -\sigma_N N e^{A-\phi} + D \nabla_{\perp}^2 N + S_N \quad (1)$$

$$\partial_t \nabla_{\perp}^2 \phi + [\phi, \nabla_{\perp}^2 \phi] = \sigma_{\phi} (1 - e^{A-\phi}) - g \partial_y \log(N) + \nu \nabla_{\perp}^4 \phi \quad (2)$$

with two fields, the normalized density  $N = n_e/n_0$  and the normalized electric potential  $\phi = eU/T_e$ , taken with the wall potential as reference,  $U$  being the electric potential,  $e$  the electric charge and  $T_e$  the electron temperature. Note that  $n_0$  is an arbitrary reference density (the system is independent of the value of  $n_0$ ). Time is normalized to the inverse of  $\omega_c = eB_0/m_i$  the ion cyclotron frequency while space is normalized to the Larmor radius  $\rho_L = c_s/\omega_c$  where  $c_s = \sqrt{T_e/m_i}$  is the acoustic velocity. The Poisson brackets derive from the electric drift flux divergence and are defined by  $[\phi, f] = \vec{b} \cdot (\nabla \phi \times \nabla f)$ , with  $\vec{b}$  the unit vector in the direction of the magnetic field.  $\sigma_N$  and  $\sigma_{\phi}$  characterize the sheath losses ( $\sigma_N$  for density and  $\sigma_{\phi}$  for current) in order to control the parallel fluxes. The divergence of the diamagnetic current, driving the interchange instability, is found to be proportional to a curvature coefficient  $g$ . The floating potential  $A = 0.5 \cdot \log(m_i/(2\pi m_e))$  corresponds to the equilibrium potential canceling out the sheath current.  $S_N$  (the source term mimicking an incoming particle flux from the plasma core) is a Gaussian centered on the first third of the domain, and is defined by  $S_N = S_0 \cdot e^{-\frac{(x-x_0)^2}{L_s^2}}$ . Finally,  $D$  and  $\nu$  are normalized to the Bohm coefficient  $D_B = T_e/eB_0$ , and account for transport processes which are not included in the model such as collisional transport. Their main effect is to stabilize the simulations by the damping of small scales.

Eqs. (1) and (2) are solved in 2D slab geometry:  $x = r/\rho_L$  with  $r$  the minor radius and  $y = r\theta/\rho_L$  with  $\theta$  the poloidal angle. The initial version of the TOKAM2D code was developed by using bi-periodical transverse boundary conditions. For the following study, an upgraded version of the code was developed to include and assess the impact of non-periodical transverse boundary conditions. In both cases, the source region (of width  $L_s$ ) separates the domain between an unstable gradient region (unfavorable gradient with respect to the interchange instability) located on the right hand side of the source along the  $x$ -axis and a stable gradient region located on the left hand side.

In this paper, we focus mainly on the impact of boundary conditions for charge fluxes. We will in particular analyze their impact in terms of charge transport by the three currents involved in the charge balance Eq. (2), i.e. the parallel current, the diamagnetic current and the polarization current, whose divergence are the following:

$$\vec{\nabla} \cdot (\vec{j}_{\parallel}) = \sigma_{\phi} (1 - e^{A-\phi}) \quad \vec{\nabla} \cdot (\vec{j}_{dia}) = -g \partial_y \log(N)$$

$$\vec{\nabla} \cdot (\vec{j}_{pol}) = -\partial_t \nabla_{\perp}^2 \phi - [\phi, \nabla_{\perp}^2 \phi] + \nu \nabla_{\perp}^4 \phi$$

Note first of all that the sum of the current divergences involved in the model is equal to zero by construction, and that the diffusive current term is taken into account as a component of the polarization current divergence. However, its contribution is negligible compared to the other terms (of the order of 1%).

Unless explicitly stated, the simulations studied in this paper were run with the following set of parameters:  $g = 6 \cdot 10^{-4}$ ,  $\sigma_N = \sigma_{\phi} = 10^{-5}$ ,  $D = \nu = 10^{-3}$  with a simulation box of size  $L_x = L_y = 256\rho_L$  discretized by  $N_x = N_y = 256$  grid points. Except in Section 3, where the sheath conductivities  $\sigma_N$  and  $\sigma_{\phi}$  are locally modified in a stripe in the middle of the unstable region, the model parameters are taken uniform in the whole domain.

### 3. Impact of sheath current boundary condition on turbulent transport

As previously mentioned, the current flow parallel to the magnetic field is governed by sheath physics and the Bohm criterion. The electron outflow is then given by  $-\sigma_N N e^{A-\phi}$  and the charge outflows follows  $\sigma_{\phi} (1 - e^{A-\phi})$ . This boundary condition on current regulates the electrostatic potential and damps electrostatic fluctuations, by dragging back the plasma potential to the floating potential. It has already been proved that a local polarization of the wall (mimicking a Langmuir probe) can influence the plasma density through its impact on the charge balance [9] while recent experiments on linear devices demonstrated that changes in the electrical conductivity of the wall at the end of field lines [10] impact the global transport. Such experiments can be studied with the TOKAM2D code through the control of the parallel charge fluxes. This can be made by zeroing (insulating the wall) or enhancing the sheath conductivity ( $\sigma_{\phi}$ ) on a radially localized stripe around  $x = \frac{3}{4}L_x$ . Simulations are run under periodic transverse boundary conditions.

#### 3.1. Insulating wall

In the insulated area the parallel current is totally canceled ( $\sigma_{\phi} = 0$ ) and we drop the potential dependence of the density loss term:  $\sigma_N N e^{A-\phi} \rightarrow \sigma_N N$ . The gradient of the mean density radial profile (presented in Fig. 1) is locally impacted around the location of the stripe by the parallel boundary condition; it slightly steepens in the near region before flattening which results from an enhancement of the radial transport due to the formation of vortices around large potential structures. These structures grow up as expected from the dispersion relation resulting from the linear study (which predicts the stabilization of large-scale potential fluctuations by the sheath conductivity [8]), until reaching a size of the order of the insulated stripe width. Fig. 2 clearly shows this increase of large modes, with an amplification of the  $k_y < 0.1 \cdot \rho_L^{-1}$  wave vectors a decade higher than in the reference case, corresponding to the typical size of these structures. They also have a resilient behavior with a longer lifetime and a slower motion, as one can observe in Fig. 3 where an increase of low frequencies is evidenced inside the insulating stripe. In Fig. 4 we see that long-lived

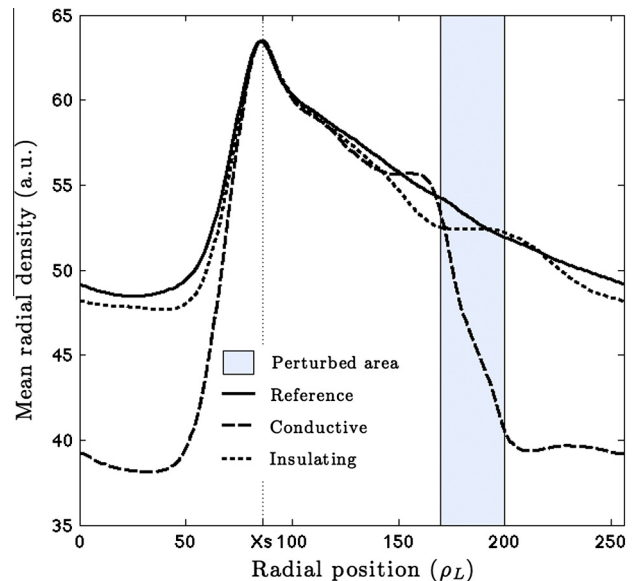


Fig. 1. Comparison of mean radial profile of SOL density.  $\nabla \bar{n}$  is locally impacted around the location of the stripe where the sheath conductivity was changed.

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