Turbulent structures shape in 3D global simulations of edge plasma turbulence with divertor geometry

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1 Objectives of the work and simulations setup

The TOKAM3X code allows to simulate tokamak plasma edge turbulence in divertor geometry [1], including both open and closed flux surfaces. We focus here on the effects of divertor geometry on edge turbulent structures shape, performing global flux-driven simulations. Turbulent structures are generated self-consistently in the edge region, as a result of the interchange mechanism, and propagate radially, until they are dissipated in the Scrape-Off Layer (SOL) under the action of the boundary conditions at the sheath. With this first-principle approach, we evaluate the deformation of turbulent structures in the 3D space. The physical model solved by TOKAM3X is described in [1]. It is a drift-reduced, electrostatic turbulence model, and it is used at present in its isothermal version, without the description of neutral dynamics. The parameters of the model are set as in [2]. A COMPASS-like diverted geometry is used: a poloidal cross section showing density fluctuations at a specific time step is represented in figure 1a. The actual value of the poloidal field can be rescaled in order to obtain a realistic safety factor, whose profile is represented in figure 1b.
Here the safety factor is calculated as in Wesson[3], Chapter 3. For open flux surfaces, only the main SOL is retained in this calculation, while divertor legs are excluded. The X-point represents a mathematical singularity, which is numerically avoided by mesh construction.

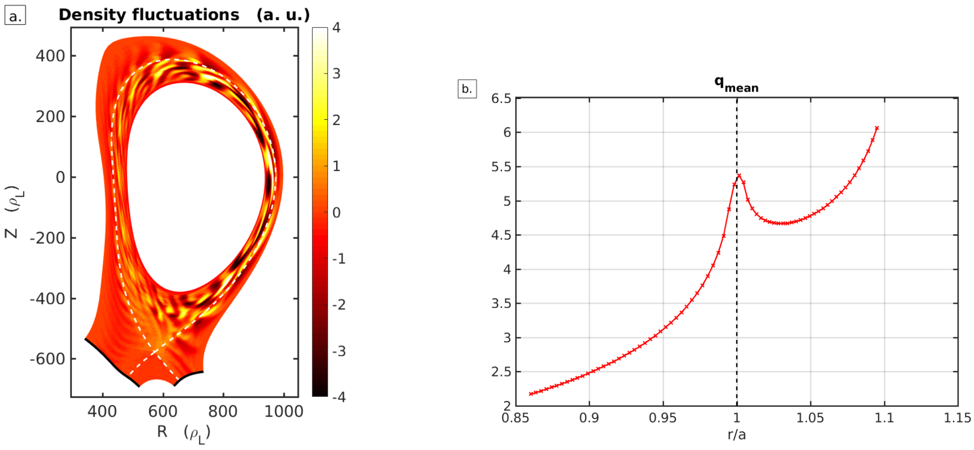

Figure 1: a)Snapshot of density fluctuation amplitude at a specific time step. b)Radial profile of the safety factor in the reference COMPASS-like simulation.

2 Turbulent structures shape in the poloidal plane

Turbulent transport is highly dependent on the competing actions of perpendicular and parallel transport. Calculating the parallel auto-correlation length for a typical density fluctuation at a certain time, we obtain a value of $10^4\rho_L$. This value is, as expected, much larger than the size in the poloidal plane of the same structure at the midplane, which is of the order of $10\rho_L$, confirming thus the plausibility of the flute assumption made by the 2D codes. This parallel correlation length corresponds roughly to the distance covered along a field line in a poloidal half-turn. This element can be explained by the ballooning nature of interchange turbulence, which enhances the fluctuation amplitude at the LFS midplane.

We expect so, at a first order, the homogeneity of turbulent structures in parallel direction. This means, in turn, to admit that the local fluctuation amplitude is constant over a flux tube. The flux tube centred on a flux surface changes its radial extension according to the local value of the flux expansion, which is directly related to the poloidal field. If we take the LFS midplane as reference position, we can define the flux expansion as $f_x(\psi,\theta) = \frac{|\vec{\nabla}\psi_{mp}(\psi)|}{|\vec{\nabla}\psi(\psi,\theta)|}$. Because of the null divergence of the magnetic field, the cross-section of the flux tube is conserved along the parallel direction. The extension in the poloidal direction must thus vary with an inverse proportionality with respect to the flux expansion (the poloidal direction will be here and in the following analysis used instead of the binormal direction). It is therefore logical to expect the wave number in the poloidal direction, to be proportional to the local flux expansion. The flux tube cross-section is also inversely proportional to the magnitude of the magnetic field. Considering the approximate inverse proportionality of the magnetic field on the major radius, we expect for a mode perfectly aligned on a flux tube:

$$k_\theta\,(\psi,\theta) = k_\theta^{mp}(\psi)\frac{f_x(\psi,\theta)R^{mp}(\psi,\theta)}{R(\psi,\theta)} \tag{1}$$

In order to verify if turbulent structures follow the flux tube shape, we calculate the local poloidal wave number of the fluctuations of the density logarithm. In order to do this, we identify the local maxima and minima in the poloidal waveform at a specific time step and radial position, calculating then the local poloidal wave number as $k_\theta^{TK3X} = \frac{2\pi}{2(\theta^{max}-\theta^{min})}$, where the superscripts max and min indicate two consecutive local maximum and minimum values. In figure 2 we show the comparison between the local value of the calculated poloidal wave number, and the theoretical prediction (1).

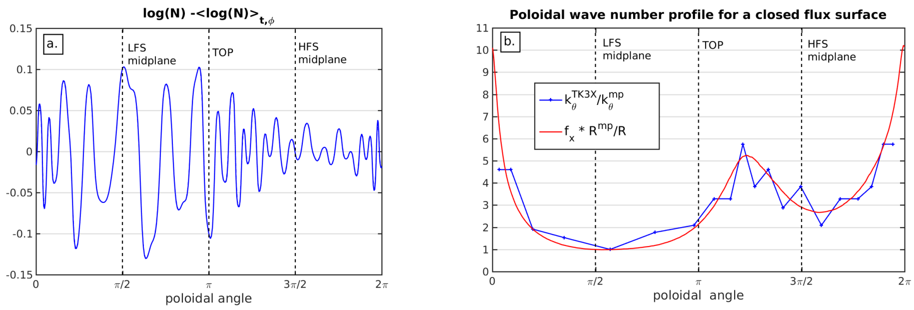

Figure 2: a): Poloidal profile of the density logarithm fluctuation , for a flux surface radially located at $r/a \simeq 0.95$ at a specific time. b) Poloidal profile of the locally calculated poloidal wave number, normalized to the LFS midplane value (localized at $\pi/2$). This profile is compared with the one theoretically predicted.

One can notice that the code results coincide well with the theoretical prediction based on the flux tube shape. The peak values on the curves correspond to the points where the flux expansion is bigger, namely the top of the machine, and the bottom, corresponding to the point poloidally closer to the X-point. Here the effect of flux expansion is extreme, and structures get very elongated in radial direction and thin in the poloidal one. This has already been shown mathematically[4], assuming an analytical function describing the magnetic field, and numerically (see [5]) using seeded blobs in flux-tube geometry. Some experimental analysis carried out with the fast imaging visible camera on MAST (see [6]) confirm this trend. Here, at a normalized radius of $\simeq 0.95$, we see an amplification of the wave number by more than a factor 5 at the X-point with respect to the LFS midplane.

The elongation of the structures according to the flux expansion has potentially strong consequences on their amplitude, since their linear growth rate can be modified by their own local shape. At a position correspondent to the X-point, the typical wavelength in poloidal direction can fall up to few ρ_L. From a linear analysis of the system, which can be found in [7], we know that, with the parameters characterizing these simulations, the growth rate of the interchange turbulence is lower for bigger wave numbers. This geometrical feature related to the flux expansion can also affect the poloidal wave number spectra analysis. When performing a Fourier analysis on the modes on a certain flux surface, the poloidal curvilinear coordinate must be scaled according to the factor appearing in (1), otherwise multiple artefact modes would appear. Finally, the variable structures shape along the poloidal direction leads to the spatial variation of the $E \times B$ fluxes in the radial direction. Recalling (1):

$$\left|u_E^{\psi}\right| \simeq \left|\frac{k_\theta \Phi}{B}\right| \simeq f_x k_\theta^{mp} \Phi \tag{2}$$

Equation (2) shows that the velocity in the ψ direction varies locally proportionally to the flux expansion. Therefore, when measuring a radial flux, the latter must always be scaled according to the flux expansion, in order to have a coherent picture of the transport across the flux surfaces, independently from the spacing among them.

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