Gyrofluid turbulence computations in the edge and SOL regions of tokamak plasmas using realistic magnetic field geometry

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Introduction: The boundary of tokamak plasmas is characterised by electromagnetic interactions between wavelike and fluidlike motions on space scales down to the ion gyroradius. We use the two moment gyrofluid model GEM3 [1] to investigate electromagnetic turbulence and the associated transport phenomena both in the edge and scrape-off layer (SOL) of such region of the plasma. The combined effect of both the equilibrium magnetic field geometry of a tokamak and the intersection of the flux surfaces by the material plates of a divertor/limiter is analysed. The issue of the spatial resolution of the simulations is also addressed.

Results: The simulations performed in Ref. [2] were done with a model flux tube geometry, with toroidal effects represented through the curvature terms (we call it SLABC here). Nevertheless, in an experiment, not only this, but all the seven geometrical quantities representing the magnetic field configuration [4] have a role on the dynamics [3]. Here, all those are included in the model through the accurate description of the geometry presented in the latter reference. The geometrical configuration used was obtained from the free boundary CLISTE code [5], and corresponds to a typical lower null configuration (X-point) of the magnetic field of the AUG tokamak. The simulations were performed in an electromagnetic ($\hat{\beta} = [(c_\mathrm{s}/L_\perp)/(v_\mathrm{A}/qR)]^2 = 2.0$) collisional drift wave ($C = 0.51\hat{\mu}[\nu_\mathrm{e}/(c_\mathrm{s}/L_\perp)] = 7.65$) regime, consistent with typical edge parameters, with warm ions $\tau_\mathrm{i} = T_\mathrm{i}/T_\mathrm{e} = 1$. Further, the parameters controlling the sound waves and the parallel electron (via inertia) were set to $\hat{\varepsilon} = (qR/L_\perp)^2 = 18350$ and $\hat{\mu} = [(c_\mathrm{s}/L_\perp)/(V_\mathrm{e}/qR)]^2 = 5.0$, respectively. In terms of physical quantities, together with the information taken from the equilibrium magnetic field, these yield roughly $T_\mathrm{i} = T_\mathrm{e} = 70\mathrm{eV}$, $n_\mathrm{i} = n_\mathrm{e} = 3\times 10^{13}\mathrm{cm}^{-3}$, $M_\mathrm{i} = 3670 m_\mathrm{e}$, $B = 2\mathrm{T}$, $R = 165\mathrm{cm}$, $a = 45\mathrm{cm}$, $L_\perp = 3.5\mathrm{cm}$ and $q = 3$. The spatial domain is given by two grid counts: $32\times 128\times 16$ and $64\times 256\times 32$, in xys, which we designate in the remaining text by half (HR) and full resolution (FR) grids, respectively. The domain is given by $L_y = 4L_x = 80\pi\rho_\mathrm{s} = 4L_\perp$ and $L_s = 2\pi$ (normalised). The numerical dissipation in the model [6], needed to address the physical effect of thermal free energy cascade to subgrid scales [7, 8], is obtained through a parallel diffusion $-\nu_\parallel \partial^2/\partial s^2$ and a perpendicular hyperdiffusion $-\nu_\perp \nabla_\perp^4$ added to each $E \times B$ derivative [9].

Closed flux surfaces: The artificial dissipation used was $\nu_\parallel = \nu_\perp = 0.003$ for the HR case. No important qualitative differences were found between the results from the two grids, showing that no relevant spatial scales involved in the dynamical system were under-resolved as a result of the variation in the perpendicular metric components, g^{xx} and g^{yy}. As an illustrative example of such, the parallel structure of both the amplitudes of the electrostatic potential $\tilde{\phi}$, electron density ($\tilde{h}_e = \tilde{n}_e - \tilde{\phi}$) and nonadiabatic pressure fluctuations are plotted on figure 1. A drift wave type turbulence signature, similar to the one obtained with the SLABC geometry [2] is visible in the amplitude spectra, reflecting the electron parallel dynamics as an effective controlling mechanism for $\tilde{\phi}$, which keeps it at a value closer to $\tilde{p}_e$. The observed ballooning (peaking near $s = 0$) is a result of the additional effect of interchange forcing [1, 6]. It is important to stress that the two minima, corresponding to the location where the flux surfaces are the furthest apart radially (minima of g^{xx}), are seen in both resolution cases. This again shows a well spatially resolved system, even at the locations where the grid cells are most severely deformed. The study also revealed that the transport in realistic geometry decreases by one order of magnitude when compared to the SLABC geometry [2], approaching the values observed experimentally, therefore showing the important effect of the geometry on the dynamics.

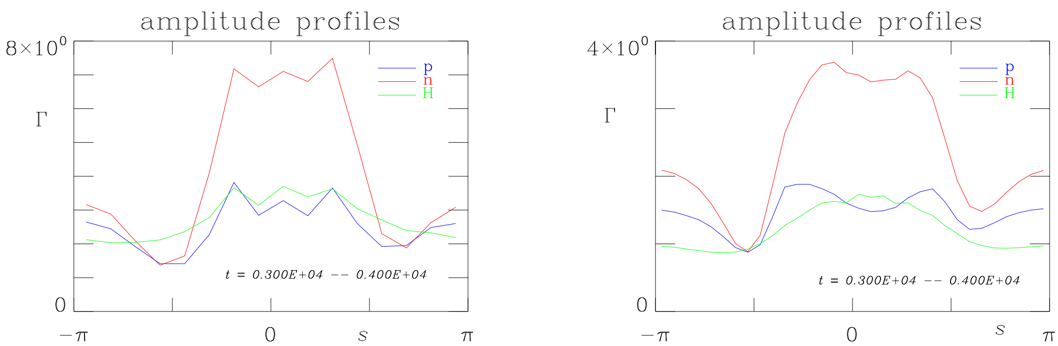

Figure 1: Envelopes of the squared amplitudes $k_y \neq 0$ part of $\tilde{\phi}$ ('p' – blue), $\tilde{n}_e$ ('n' – red) and $\tilde{h}_e$ ('H' – green) vs. the parallel coordinate s, averaged over x, y and $3000 < t < 4000$, for both HR (left) and FR (right) cases. The latter evidences higher degree of smoothness due to higher number of grid points.

Open flux surfaces: scrape-off layer (SOL): A magnetic field on a tokamak is doubly periodic and sheared. This leads to the so called field line connection which ensures a finite parallel response for every degree of freedom for closed flux surfaces [10]. By contrast, in the SOL, the field lines end on plates, breaking such a constraint and allowing the existence of convective cell modes. The SOL conditions were modelled as described in Ref. [2], but using the AUG geometry. The limiter was placed at the lower position of the flux surface, which corresponds to applying the Debye boundary conditions at $s = -\pi/2$ and $s = 3\pi/2$. An artificial dissipation given by the coefficients $\nu_\parallel = \nu_\perp = 0.002$ was used, for the HR grid. Contrary to what happened before, this study evidenced changes in the fluctuations mode structure between the HR and FR simulations. The flute mode that was observed to dominate the dynamics in the SLABC model [2], was not nearly as strong in the HR simulation made here. However, it appeared again when the grid count was doubled, in the FR simulation, showing a clear change in the mode structure between both simulations. This is indicative of resolution issues related to the extreme variations observed in g^{xx} and g^{yy}. The fact that the AUG geometry, that posed no resolution problems for the closed flux surfaces simulation, is verified to do so in the SOL is not unexpected since now other modes, like the flute mode, are allowed to exist. This means that interchange dynamics can dominate the system, for which case the convergence of the simulations is much harder due to the broader drive spectra evidenced by such kind of dynamics [11, caps. 6 and 10]. The results suggest that the high Reynolds limit was not reached, meaning that not enough space scale separation was available in the domain between the large scales and the dissipation range, for the nonlinearities to operate freely. Due to computation time cost, further increasing the resolution of the simulations is no practical solution. Some simulations with a reference flux surface located outside the magnetic separatrix in the same AUG configuration were also performed, but the preliminary results obtained pointed in the same direction as the ones discussed here.

<u>Resolution issues:</u> The previous analysis evidenced resolution problems which are believed to be caused by the variations in the metric components of the flux tube coordinate system used, since those translate in the stretching/compressing of the perpendicular grid cells due to the constraint $g^{xx}g^{yy} \propto B^2$. This has physical relevance since the basic physics of turbulence is isotropic [12] and, specifically in magnetised plasmas, the isotropy occurs in the plane perpendicular to the magnetic field. Hence, modes of comparable scales in both x and y have the dominant nonlinear couplings and because of that, the number spatial modes common to both directions is of key importance. To better understand the previous concepts, the following figure is included, also with the intention to introduce the idea behind a conformal coordinate system, which would constitute the ultimate solution to the problem encountered. As illustrated in the figure 2, which constitutes an extreme example, this implies the complete loss of the isotropy of the original grid cell, with the consequence that no $k_x = k_y$ modes (circles) are allowed. The solution for this problem would be to increase the resolution in the y-direction by a factor of $\sqrt{g^{xx}/g^{yy}} = 4$, in order to recover the possibility of isotropy, for instance one would have again $k_x'^{\max} = k_y'^{\max}$ (note that in our data from AUG we obtain values as big as $\sqrt{g^{xx}/g^{yy}} \sim 7$).

Summary: This study confirmed the effect of the geometry on the dynamics of turbulence in tokamaks. This is especially significant through the local shear, that shows large variations due

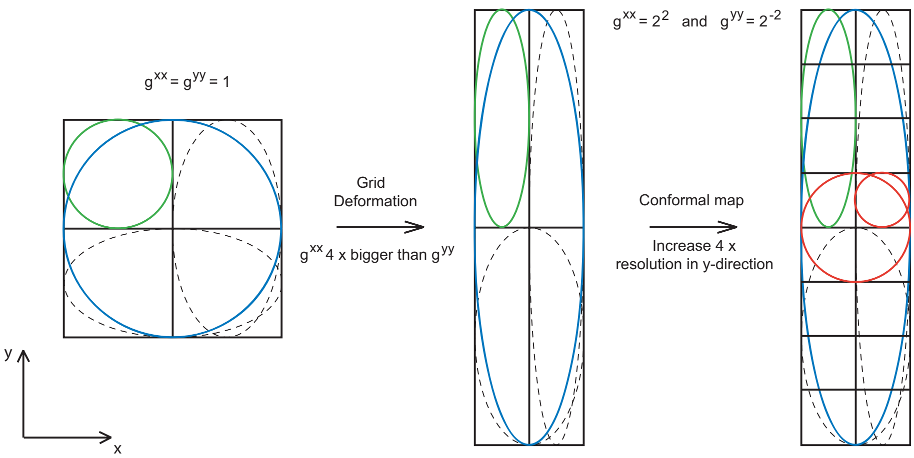

Figure 2: Illustration of the grid deformation cased by variation in perpendicular metric components, and its consequence in terms of preventing the coexistence of isotropic modes in the plane perpendicular to the magnetic field. The ultimate remedy is illustrated in the right-most figure: the conformal map.

to the proximity to the X-point, since it affects directly the polarisation dynamics (the main mechanism behind a fluid drift model [13]). Together with the the parallel coupling of drift dynamics, it forces the perpendicular vortices to twist along the field lines, facilitating the non-linear breaking of such structures [14]. This result stresses the importance of using an exact geometry description of the tokamaks if one intends to get realistic enough turbulence simulations results to aspire experimental comparisons, a statement also applicable to stellarators [15]. However, for open flux surfaces, for which the nonlinear interchange dynamics plays a more important role [2], the results obtained suggest that caution should be taken regarding the resolution of the simulations. The variations of g^{xx} and g^{yy} in a field aligned flux tube model might be strong enough, especially near the separatrix, to prevent the existence of a sufficient number of isotropic modes in the plane perpendicular to the magnetic field for the domain to be representative of the physical dynamical system under study.

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