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Gyrokinetic simulations in stellarators using different computational domains

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Gyrokinetics is the appropriate theoretical framework to study turbulence in magnetized plasmas. It takes advantage of scale separation between turbulence and background quantities (such as magnetic geometry and plasma profiles), and provides a reduction of phase-space dimensionality, which allows an important saving of computational resources. In tokamaks, the theoretical analysis and the numerical simulation of micro-instabilities and turbulence are largely facilitated by its axisymmetry, which makes all the field lines in a flux surface equivalent, so that simulations can be carried out in a reduced spatial domain called flux tube: a volume extending several Larmor radii around a magnetic field line. Thanks to axisymmetry, the result of a calculation in a flux tube is independent of the chosen magnetic field line. Periodic boundary conditions in the parallel direction (standard twist-and-shift formulation [1]) is commonly used.
The lack of axisymmetry in stellarators introduces complexity at several levels. First, the twist-and-shift approximation is questionable [2] as equilibrium quantities affecting micro-instabilities, such as magnetic field line curvature, magnetic shear and the fraction of trapped particles, have a three-dimensional dependence. As a consequence of this dependence, different flux-tubes over a given flux surface are in general not equivalent to each other [3]. A common practice when using flux-tube codes in stellarators is to simulate the most unstable flux tube, which allows to quantify the upper bound of the instability. However, the turbulence saturation level can be largely affected by the interaction between small-scale fluctuations and zonal flows, and the long time behavior of the latter (which, in stellarators, shows distinct features as compared to tokamaks [4, 5, 6]) depends on the magnetic geometry of the whole flux surface. Different saturation mechanisms can dominate in different devices depending on the magnetic geometry [7]. In addition, the radial electric field might play a role in stellarators, affecting the linear stability [8] and the turbulence saturation in a more involved manner than in tokamaks, through its influence on zonal flows [9]. For all these reasons, the standard flux-tube approximation appears insufficient for stellarators.
In this contribution, we address the question of which is the minimum computational domain appropriate for the simulation of plasma turbulence in stellarators and study to what extent simplified setups, such as the flux tube approximation, can be used in these devices. For this purpose, we compare gyrokinetic simulations in different stellarator configurations using different computational domains and codes. The codes used are EUTERPE [10], stella [11], GENE [12], and GENE3D[13] (the radially global version of GENE for stellarators), which cover different computational domains and implement different numerical methods. stella is a flux-tube continuum code. Both a flux tube and a full-flux-surface version of GENE are available for stellarators. EUTERPE and GENE3D are both radially global, although with different numerical schemes; EUTERPE is a PIC code while GEN3D is continuum. The comparison of calculations with such different codes requires carefully defining a compatible setup. Global and local codes provide different insights into the physical problem and the comparison is not always straightforward.
Several stellarator configurations, LHD, W7-X, NCSX have been considered. The same physical problem has been simulated with several codes covering different domains and the results have been compared. Two physical problems are studied as a starting point: the linear relaxation of zonal potential perturbations and the linear evolution of electrostatic instabilities. Both problems are treated in simulations with adiabatic electrons, which allows relatively cheap computations. However, the spectra of unstable modes are found to be significantly wider than in tokamaks and, consequently, the simulations more expensive, particularly in some configurations. The comparison of non-linear simulations in different computational domains is also underway.
It has been found that the residual zonal flow level obtained with a flux-tube calculation can significantly differ from the result obtained in a global simulation, the local results converging to the full flux surface or global ones when the length of the flux tube is increased up to several poloidal turns [14]. The number of poloidal turns required for convergence to full-flux-surface (or global) results depends on the magnetic geometry. With respect to the linear stability, the agreement between calculations of the growth rate of the most unstable modes in different domains is found to be good in general, provided that the flux tubes are sufficiently extended as to provide converged results. The comparison of real frequencies usually shows poorer agreement.

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