Turbulence, zonal flows, and global modes in burning plasmas: code development and simulations

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Fusion-born alpha particles are expected to significantly affect the plasma dynamics in coming experiments such as ITER or BEST whereas DEMO will operate close to ignition with auxiliary power employed only for control. This makes understanding the burning plasma physics through theory and modeling an urgent task especially since a significant rate of alpha particle generation is difficult to attain in present experiments. In the presentation, we will describe analytical models, numerical codes, and their applications developed within the EUROfusion E-TASC project (TSVV Task 10) dedicated to burning plasma physics. The toolset includes nonlinear global gyrokinetic codes, hybrid fluid-kinetic applications, and integrated modeling. The applications range from turbulence, Alfvén modes, and energetic particles to nonlinear emergent structures, equilibria, and transport. Novel physics results will be shown, which include global gyrokinetic simulations of chirping Alfvénic waves in tokamak plasmas, electromagnetic micro-instabilities, turbulence and MHD modes in tokamak and stellarator plasmas, beat-wave-driven zonal flows in JET and their effect on turbulence, and nonlinear generation of Alfvénic modes by the ambient turbulence in Wendelstein 7-X.

First, we describe effects of the bulk-plasma beta on the turbulent transport in tokamaks. Increasing beta can stabilize Ion Temperature Gradient (ITG) modes and suppress turbulent transport. However, when the values of the bulk-plasma beta reach a threshold, the Kinetic Ballooning Mode (KBM) branch is destabilized, which may lead to a sharp increase in the heat and particle fluxes. We address this topic both in tokamak and stellarator plasmas. We find electromagnetic instabilities other than KBMs, such as Alfvénic ion temperature gradient driven modes (AITGs) in tokamak plasmas or short-wavelength "passing-electron" instabilities in Wendelstein 7-X. Some of these instabilities may result in turbulent regimes benign compared to the usual KBM regime. We employ global nonlinear gyrokinetic codes ORB5 [1] and EUTERPE [2] for nonlinear simulations of these instabilities.

The effect of the energetic-particle beta can also be quite complex and include both turbulence stabilization mechanisms, e.g. via dilution of the thermal ions or resonant interaction with the ITGs, as well as destabilization of low-frequency Alfvén Eigenmodes, such as the beta-induced Alfvén Eigenmode (BAE), which may negatively affect the plasma performance. Another important topic is the cross-coupling of turbulence and global modes via the beat-wave-driven generation of zonal flows by Toroidal Alfvén Eigenmodes (TAEs) or fishbones. We present simulations with the ORB5 code addressing the effects of the energetic particles on the turbulence and zonal flows [3]. In addition, there is a possibility of a direct excitation of the Alfvénic wave, which we find [4] numerically in Wendelstein 7-X plasma using the global gyrokinetic EUTERPE code. These results agree well with experimental observations.

Finally, the possibility of an interaction between turbulence and nonlinear MHD perturbations is investigated in both tokamak and stellarator geometries using ORB5 and EUTERPE. In tokamak geometry, gyrokinetic simulations of nonlinear tearing instabilities are performed. Nonlinear growth of a magnetic island leads to a self-induced turbulence around the island structure and, in some cases, to perturbed zonal currents and modifications of the safety factors [5]. Both effects can result in an “island healing” reducing the strength of the tearing instability in the nonlinear regime. In contrast, ambient turbulence may lead to island generation even in the regimes which otherwise, in the absence of the turbulence, are stable with respect to the tearing instability. This happens via the nonlinear coalescence of small-scale high-mode-number island chains generated by the nonlinear perturbations with the tearing parity. We show ORB5 simulations demonstrating this process. In stellarators, nonlinear MHD-unstable regimes are considered using the global gyrokinetic code EUTERPE. For low-shear helical-axis stellarators, linear MHD stability calculations and full-torus electromagnetic gyrokinetic simulations in their linear phase result in similar spatial and temporal structures of unstable globally extended perturbations [6]. In the non-linear phase shown in Figure 1, these perturbations entail deformations of the magnetic surfaces, growing magnetic islands rotating in the electron-diamagnetic direction, eventually leading to the ergodization of a large part of the magnetic field.

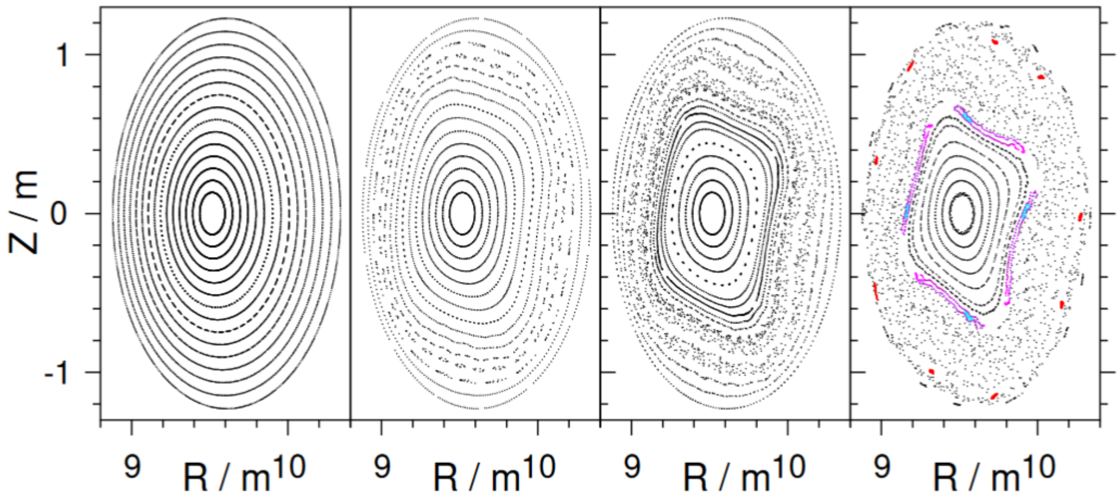

Figure 1: : Field-line tracing for the gyrokinetic perturbed magnetic field in a helical-axis stellarator with turning-ellipse cross-sections shown at different (increasing) times for the toroidal angle ϕ = 0°. Global nonlinear gyrokinetic simulations using the EUTERPE code [2].

References

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