Plasma dynamics simulation in the tokamak scrape-off layer

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One of the greatest uncertainties in the success of ITER and future fusion reactors is related to the turbulent dynamics of the plasma fusion fuel in the scrape-off layer (SOL), the narrow region surrounding the tokamak core where magnetic field lines are open and terminate on the vessel of the device. The plasma behavior in this region governs the overall confinement properties of the device. This is critically important since fusion reactor conditions can be achieved only in sufficiently well confined, high-temperature, and high-density plasmas. SOL plasma phenomena also regulate the impurity dynamics and the level of fusion ashes, which can dilute the fusion fuel, stopping the reactions. Moreover, the SOL dynamics determines the heat load to the tokamak vessel walls – a showstopper for the whole fusion program if the material requirements cannot be met. Also because of the difficulty of diagnostics access, simulations of the plasma dynamics in the SOL region constitutes an invaluable tool for the understanding of the basic plasma physics processes at play. Simulations are also playing an increasing role in the predictions of the plasma dynamics in future fusion reactors.

The simulation of SOL turbulence is particularly challenging. First, transport of density and heat in this region is governed by highly non-linear turbulent processes, occurring on multiple spatiotemporal scales, driven by different energy sources, mainly the inhomogeneity of plasma pressure profiles and confining magnetic field, and with a number of self-regulating mechanisms. Second, the magnetic configuration is particularly complex, as typical coordinate systems used for plasma simulations are found to be singular in the SOL. Third, typical assumptions used in the study of turbulence in the tokamak core (e.g., small turbulent fluctuations) are not valid in the SOL. Finally, sheath physics and neutral dynamics are found to play an important role in the SOL plasma dynamics. yrokinetic and fluid simulations of electromagnetic turbulence in magnetically confined plasmas are reviewed. Gyrokinetic simulation of electromagnetic turbulence in finite beta plasmas is an important task for predicting performance of fusion reactors and a great challenge in computational science due to multiple spatio-temporal scales related to electromagnetic ion and electron dynamics. The simulation becomes further challenging in non-axisymmetric finite beta plasmas, where beta is the normalized plasma pressure. In finite beta plasmas electromagnetic effects are important, and they are, for instance, magnetic field line bending stabilization, anomalous transport due to magnetic perturbation (magnetic flutter), zonal magnetic field production. In the linear analysis, the growth rate of ion-temperature gradient instability (ITG), which is a drift-wave instability, is suppressed by magnetic field line bending as plasma beta increases, while kinetic ballooning mode, which is an MHD instability, is destabilized at high beta. In nonlinear simulations, whereas in low-beta torus plasmas the zonal flow shear acts to regulate ITG driven turbulence, it has been observed that instabilities continue to grow without reaching a physically relevant level of saturation at finite-beta tokamaks. On the other hand, the finite beta turbulence can be saturated by a new saturation mechanism in the presence of three-dimensional magnetic structures, even when the zonal flow is weak. Finally, non-local turbulent transport in electromagnetic turbulence is discussed by means of fluid simulations.