Global electromagnetic simulations of turbulence and profile evolution across the tokamak edge and scrape-off layer

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A major endeavour of magnetic confinement fusion research is understanding, controlling and extrapolating turbulent transport. Compared to the plasma core, the edge is of special interest since it can harbour significantly steeper gradients. Turbulence levels in the scrape-off layer (SOL) also largely depend on edge physics, e.g. due to turbulence spreading and filament propagation [1]. Hence, for exhaust studies, a coherent treatment of edge and SOL is required. The interface of the two regions, the separatrix, is particularly interesting and challenging: X-points lead to singularities in field-aligned coordinates, but they also affect blob propagation [2], magnetic shear[3], Reynolds stress [4] and MHD stability [5].

The edge and SOL turbulence code GRILLIX employs the flux-coordinate independent (FCI) approach [6,7], which avoids coordinate singularities while still taking advantage of magnetic field anisotropy to permit toroidally sparse grids. This allows for a flexible and efficient treatment of realistic magnetic geometries, including advanced divertor concepts (ADCs) [8]. The physical model has been extended to the full drift reduced Braginskii set of equations with all global dependencies [9,10]. A semi-implicit solver for the parallel heat conduction allows to reach relevant parameter regimes ($T_\mathrm{e} \gtrsim 500$ eV). Further, this includes electromagnetic induction and flutter, hot ions, sheath boundary conditions and a simple fluid model for neutral gas.

These extensions allow realistic simulations of the edge and SOL at ASDEX Upgrade (AUG) experimental parameters. Since no separation between background and fluctuations is employed, experimentally observed profiles are not prescribed, but self-consistently recovered according to implemented physical mechanisms. For example, parallel heat conductivity, sheath heat transmission and electron ionization cooling result in $T_\mathrm{i} > T_\mathrm{e}$ in the SOL. Rather then resistivity, electromagnetic induction and electron inertia slow down parallel dynamics via shear Alfvén waves. Electromagnetic cross field transport due to field-line flutter, primarily for heat, contributes only at higher pressure (β) though. Turbulence in attached single-null L-mode simulations is ballooning driven. In agreement with experiment, the fluctuation level in the confined region is moderate, $< 4\%$, and rather high in the SOL, $> 15\%$.

The experimentally observed jump in the electric field across the separatrix results from different mechanisms in the closed and open field line regions: towards the plasma core, the electric field mainly balances the ion pressure, while in the SOL, the electric potential follows the electron temperature due to sheath boundary conditions. Poloidal and toroidal rotation and Reynolds stress can also affect the electric field, but at higher temperature these effects are damped by parallel heat conduction and ion viscous stress. The flow shear due to the electric field jump [11], as well as the magnetic shear due to the separatrix [3], can suppress turbulence (and GAMs) in the pedestal.

Besides a dependence of turbulence on β and collisionality, simulations carried out in various geometries (circular, diverted, ADCs) reveal also a strong dependence on machine size and geometry. The importance of implemented and missing physical effects is evaluated through validation against ASDEX Upgrade experiments, which supports extrapolation to larger devices.

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