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Global simulations of turbulence, transport and shear suppression across edge and SOL of diverted tokamaks

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GRILLIX [1,2] has emerged as a solution for affordable 3D turbulence simulations on transport time scales and in complex (advanced) diverted geometry – providing a framework in which most relevant physical processes for transport in tokamaks can be included and studied. We present computationally demanding global simulations across wide experimental parameter spaces on transport (many ms) time scales, particularly for the TCV and ASDEX Upgrade tokamaks, both in single null as well as in advanced divertor geometries.

Apart from paving the way for predictive computations for future tokamak reactors, these simulations provide new insights for fundamental physical mechanisms. We find and characterize non-linear interactions between equilibrium compressional (neoclassical), turbulent zonal and sheath driven SOL flows, that can lead to turbulence suppression through vortex shearing [3,4,5]. This process also depends on the geometry-dependent magnetic shear [6]. The interface between open and closed field line regions, the separatrix, is particularly interesting: X-points affect magnetic shear, Reynolds stress and blob propagation. We find drift and Alfvén waves to be crucial for the non-linear turbulence cascade, including zonal flow generation and the GAM oscillation. The major transport driving instability, however, is characterized as ballooning driven in present simulations, partly because ions are hotter than electrons – and it is only slightly affected by zonal flows.

The goal is to achieve confinement improvement through turbulence suppression that is compatible with power exhaust in fusion reactors. To this end, novel numerical techniques – particularly the flux-coordinate independent (FCI) field-aligned approach [7,8] - allow unprecedented flexibility for the optimization of magnetic geometry, for studying the impact of shaping of conventional single null diverted geometries or advanced divertors on turbulent transport. Likewise, a state-of-the-art global multi-fluid model describes the evolution of equilibrium profiles together with turbulent fluxes, allowing to incorporate both wave physics on μs scale and transport physics on millisecond scale in a global framework.

To capture a wider range of waves, instabilities and transport channels, the physical model is continuously extended. For instance, we find electromagnetic induction to play a crucial role in regulating the current dynamics. At low plasma beta (L-mode), electromagnetic transport plays a less important role though. The self-consistent inclusion of small-scale instabilities into global transport however also requires strong advances in HPC software design and performance improvements.

Ultimately, the code is able to predict turbulent fluxes, including their suppression in the pedestal, as well as the resulting equilibrium profiles, electric field and fall-off lengths like the SOL width. We show first validation results and describe steps towards predictive ITER and DEMO simulations.

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