Contribution ID: **1327** Type: **Regular Poster**

Interaction between magnetic geometry and turbulence in 3D global fluid simulations

Friday 14 May 2021 12:10 (20 minutes)

The description of cross-field transport has long been identified the main limit for the predictive character of mean-field edge plasma codes. The coarse-graining of plasma fluid equations in time and space, by removing the fluctuations from the sought solution, makes it necessary to close the system of equations by an ad-hoc assumption on the nature and level of turbulence-driven transport. Whether turbulence dominates cross-field transport, as it has been shown to be the case in L-mode, or is quenched by an edge transport barrier, as it is the case in H-mode, it is a key ingredient of the physics of transverse transport in the edge plasma and calls for cautious description.

Nevertheless, mean-field codes have for long been and still are the main work-horses for divertor design and edge physics interpretative studies in tokamaks or stellarators. Simulations including self-consistently turbulence have long been restricted to simple small systems (e.g., linear machines, small tokamaks) or reduced idealized geometries (e.g., 2D slab codes), and the complexity of the numerical implementation of turbulence models considerably slowed down the integration of other relevant aspects of edge physics in these models (e.g., neutrals recycling, impurities⋯). However, progress made in the last decade in edge turbulence modelling tools opens the way for going beyond these limits in the near future. In particular, strong effort has been invested in implementing realistic magnetic geometries, including X-points in main edge turbulence codes. We report here about such effort carried out with the TOKAM3X code.

TOKAM3X solves 3D electrostatic drift-fluid model in a flux driven frame. In the last 4 years, 2 versions of the model have been exploited, either isothermal [1] or including self-consistent electron and ion temperatures evolutions through energy balance equations [2]. Special care has been given to designing the code to handle arbitrary axisymmetric magnetic geometries, including arbitrary q-profiles, flux surface shaping, limited as well as singly or multiply diverted configurations. More recently, the code has also been modified to treat non axisymmetric magnetic perturbations as found when using Resonant Magnetic Perturbations (RMPs) or in the presence of ripple. In this presentation we review key findings concerning the influence of these geometrical features on edge turbulence and transport.

We first discuss simulations run in various diverted configurations taken from experiments on COMPASS [3], TCV [4] or WEST [5]. Comparison with circular limited cases shows that the main characteristics of edge turbulent transport remain unchanged and reminiscent of experimental observations: transport is dominated by fluctuation induced ExB convection cells; fluctuations are strongly intermittent in the Scrape-Off Layer (SOL) but much less or even negatively skewed in the closed field lines region; they take the form of strongly elongated filamentary structures mainly localized in the low-field side part of the machine, which contributes to the existence of asymmetric parallel flows; the spontaneous build-up of a radial electric field's well is observed just inside the separatrix leading to the presence of an ExB poloidal velocity shear layer.

Nevertheless, specific interaction of the X-point with transport is observed. In particular, poloidal gradients associated with the presence of a quasi-empty and cold private flux region lead to large amplitude steady-state radial ExB flows around the X-point which are the main contributors to the spreading of particles fluxes into the private flux region [4]. Moreover, filaments are observed to be disconnected from the target in the near SOL while they reconnect in the far SOL, leading to different scalings for their radial velocity in both regions [5]. The magnetic shear as well as the poloidal shear of the ExB radial velocity in the vicinity of the X-point are identified as the main mechanisms leading to this disconnection [6]. Finally, we show that diverted simulations exhibit a mild transport barrier around the separatrix. Comparison with limited cases in which the q profiles has been artificially modified to mimic an X-point-like magnetic shear suggests that the magnetic shear at the separatrix is the main drive for the existence of this barrier [7]. Such conclusion is also supported by the analysis of the interaction between filaments and magnetic shear in simple slab geometry showing that the differential tilting of field lines generates ExB vortices leading to the destruction of filaments [8].

Our studies also demonstrate that the shaping of magnetic flux surfaces is an important player of edge turbulent transport. In all simulations, a poloidal modulation of the turbulent flux as a function of the local flux expansion can be observed: radial fluxes driven by turbulence are at first order proportional to the local flux expansion. This can be simply explained by the flute nature of fluctuations and has a major consequence for mean-field modelling: the diffusion coefficient modelling anomalous transport should not be taken poloidally constant but should be modulated to include, not only the ballooning character of turbulent transport, but also a dependence in local flux expansion. To analyze further the impact of plasma shaping but independently from the presence of an X-point, dedicated simulations have been performed in limited configuration [9]. The elongation is scanned from 1. to 1.7 and the triangularity has been scanned from -0.5 to 0.5. Both are found to impact turbulent transport in different ways. In line with experimentally observed trends, elongation has

a negative impact on turbulent transport. In closed field lines and in the near SOL, increasing the elongation leads to a drop of the fluctuation level of the potential and a reduction of turbulent fluxes. As a consequence, a steepening of gradients and a narrowing of the SOL is found for all plasma fields (density and temperatures). Concerning triangularity, while positive values don't lead to significant changes in turbulent transport, negative triangularity simulations exhibit a steepening of gradients in the near SOL, especially on the electron temperature, associated with an amplification of the poloidal velocity shear layer.
We conclude our review by presenting first results regarding the impact of non-axisymmetric magnetic field perturbations on edge plasma turbulence. Scans of perturbation mode number and amplitude have been performed in circular limited configuration as a start [10]. Some key experimental features of RMP experiments are recovered, in particular a flattening of the radial electric field Er profile due to an increase in closed flux surfaces and a pump-out of the electron density. The latter is found to be strongly dependent on the relative localization of energy and particle sources and can even reverse into a pump-in in some cases. The flattening of Er is driven by a reorganization of poloidal asymmetries which impacts the charge balance of the plasma. Turbulence properties on the other hand are only moderately impacted.

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Session Classification: P7 Posters 7

Track Classification: Magnetic Fusion Theory and Modelling