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Towards the prediction and quantification of energetic particle transport and losses in fusion plasmas

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Energetic particles (EP) are ubiquitous in fusion plasmas and need to be well-confined in order to transfer their energy to thermal particles and thus achieve self-sustained fusion reactions. However, a fusion plasma is a complex system where micro- and macro-instabilities develop. These instabilities can dramatically reduce the EP confinement and therefore limit the performance of future fusion devices such as ITER. This is the reason why understanding and controlling EP transport in the presence of different instabilities is of prime importance on the route towards steady-state scenarios. Here we focus on the analysis, understanding and quantification of the EP transport and losses induced by electro-magnetic modes. To simplify the analysis, we study the impact of single-helicity modes on the EP transport and losses. Single-helicity electro-magnetic modes are characterized by one poloidal (m) and one toroidal (n) mode numbers. Although such modes have been usually believed not to result in any chaotic transport, significant losses of EP have been observed, both experimentally and numerically. The purpose of this work is to shed light on these observations and provide a reduce model to understand and predict the transport and losses of EP. For this purpose, we use an analytical gyro-kinetic model describing the impact of the EP on electro-magnetic modes. This model is combined with a recently developed 5D Guiding-Centre Tracking (GCT) code to obtain a reduced model for the self-consistent interaction between EP and electro-magnetic modes. The transport and losses are quantified and compared to analytical predictions based on quasi-linear theory.
The emphasis is put on two paradigmatic single-helicity modes: (a) the energetic geodesic acoustic modes (EGAMs) [1-4], excited by EP and exhibiting mainly an electrostatic component, and (b) the tearing modes (TMs), excited by the radial gradient of the parallel current and characterized by a magnetic component.
Because EGAMs are not only single-helicity but also axi-symmetric modes, they have been assumed in the past to play little role in transport. However, experiments in DIII-D provided puzzling evidence that particles can be de-confined in the presence of EGAMs [1]. Using GCT and a potential obtained from full-f gyro-kinetic simulations we elucidate the underlying mechanism and show that even if the EGAM is axisymmetric and non-turbulent, a chaotic channel from the inner region to the edge of the tokamak is created (FIG. 1) leading to losses of counter-passing EP [5]. We provide for the first time evidence that EP dynamics is governed by trapping-induced super-diffusion, leading to asymmetric transport and a net toroidal torque.
The analysis is extended to the TMs, known to induce EP losses [6-9], which is extensively analysed here by means of GCT in the context of alpha particle transport in ITER-like scenarios. As for EGAMs, counter-passing particles are predominantly lost (FIG. 2), whose impact on ITER plasma confinement and tokamak performance is assessed. For this purpose, a reduced model has been developed based on the evolution of the thermal and EP populations in the presence of single-helicity modes using a transport coefficient calculated from the previous numerical simulations. We present parametric analyses for EP transport and losses in ITER-like scenarios.
The theoretical explanation of the observed transport is as follows. EP are characterized by large orbit widths. In the presence of one single (m,n) mode, the large orbit width generates multiple resonances in phase-space, parametrized by a generalized mode number n_2. If these resonances overlap, transport can occur. As an example, we plot in FIG. 3 some of the resonances created by a single helicity (m,n) mode. The plotted resonances are represented by the blue, red and green curves, ranging from smaller to higher mode numbers n_2. On the same figure, the boundary between the trapping and passing particles is given by a dashed-dotted line. An example of passing EP trajectory is given by the magenta curve. Such an EP is initially confined and exhibits a perturbed motion in the presence of the resonances, approaching the edge of the tokamak where it is lost. The width of the island corresponding to each of the resonances is calculated analytically and a criterion for the overlap is derived. This criterion is used to quantify the radial transport of EP in the presence of single-helicity modes, which will be compared to predictions obtained using the reduced model based on GCT and gyro-kinetic theory.

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