Orbit-averaged approach to fast-ion transport in stellarators

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Fusion-born alpha particles must be sufficiently well confined so that they have time to transfer their energy to the bulk plasma, heating it and helping sustain fusion reactions. What is more, if alpha particles are lost before transferring most of their energy, the plasma-facing components of the reactor wall can be severely damaged. Since the typical speed of alpha particles is very high, collisions with the bulk plasma are infrequent and thermalization requires alpha particles to be confined for significantly long times. In tokamaks, axisymmetry guarantees good fast-ion confinement over such long time scales. However, in a non-optimized stellarator, collisionless trapped particles are not confined, giving rise to intolerably large fast-ion transport. The optimization of fast-ion confinement is a critical point in the path towards stellarator reactors and, consequently, the development of efficient and accurate fast-ion simulation tools is utterly important for the design of next-generation devices.

In this talk, we will rigorously obtain a fast-ion drift-kinetic equation with reduced phase-space dimensionality that can be the basis for more efficient codes and for a deeper understanding of fast-ion transport in stellarators. This work builds on and extends the analytical techniques introduced in [1] and [2] for the derivation of orbit-averaged equations for thermal species. These equations were implemented in `KNOSOS` [3], that has proven to be accurate and orders of magnitude faster than standard codes for the calculation of neoclassical fluxes in low-collisionality stellarator plasmas. In the talk we will start from the full-orbit kinetic equation for fast ions and will explain under which assumptions one can: (i) gyroaverage the full-orbit kinetic equation and use a drift-kinetic equation for the guiding centers of the fast-ions. This is the typical approach for the evaluation of fast-ion transport; (ii) integrate over the lowest-order orbits of the guiding centers and obtain an orbit-averaged drift-kinetic equation. Along the derivation of the orbit-averaged drift-kinetic equation, we learn that special care must be taken at points where trapped particles transition from one well to another, producing discontinuities in the distribution function or its derivatives. The orbit-averaged equation gives insight into the physics of stellarator fast-ion transport and provides the appropriate theoretical framework to understand, for example, transport due to transitions of trapped particles between different types of wells, usually called stochastic transport [4].

The orbit-averaged drift-kinetic equation for fast ions is radially global, includes collisions, and accounts for passing and trapped particles. It has been implemented in a new Monte Carlo code, `KNOSOS-MC`, which, to our knowledge, is the first orbit-averaged code for fast-ion transport valid for any stellarator magnetic configuration with nested flux surfaces. We will show comparisons of fast-ion losses in Wendelstein 7-X geometry calculated with `KNOSOS-MC` and with `ASCOT` [5], confirming the correctness of our approach. Finally, we will describe specific ways in which these developments can lead to rapid fast-ion transport codes to be integrated into stellarator optimization suites. The theoretical results and numerical tools discussed in this talk can also be applied to fast-ion transport in tokamaks with broken axisymmetry.

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