Particle transport induced by energetic geodesic acoustic modes

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Energetic particles naturally exist in tokamaks due to either fusion reactions or external heating such as ICRH or NBI. These energetic particles need to be well-confined in order to transfer their energy to thermal particles and achieve this way a regime with self-sustained fusion reactions. However, energetic particles excite modes that tend to de-confine the particles themselves. This is the reason why energetic particle mode excitation and saturation need to be understood and controlled. In this presentation we focus on a special class of energetic particle modes, called energetic geodesic acoustic modes (EGAMs) [1, 2]. Because these modes are axisymmetric, they have been usually believed to play little role on the transport in a tokamak. Nevertheless, it was observed experimentally [1] and numerically [3] that particles can be de-confined in the presence of EGAMs. We explain in this presentation the underlying mechanisms of the role of EGAMs on transport and show they can actually have an impact, both directly on the trajectories of particles [4] and indirectly on the turbulent transport [5, 6, 7]. For this purpose, we use full-*f* gyro-kinetic simulations with the state-of-the-art multi-species GYSELA code [8]. We will explain how the EGAMs can be linearly excited in GYSELA [5, 9] and will show quantitative agreement between theoretical predictions [10] and numerical results [4, 11, 12]. Also, the nonlinear saturation of EGAMs will be analysed [9], with the observation of islands in phase space [4]. By means of a recently developed test-particle tracking code [4], it is shown that these islands can induce transport of counter-passing energetic particles that become trapped and eventually de-confined, in agreement with previous observations [3]. We show that this phenomenon relies upon a complex interaction between the chaotic EGAM separatrix and the X-point of the trapping cone characteristic of toroidal devices, differing from the standard and generally accepted understanding *à la Chirikov*, and leading to losses modulated at the EGAM frequency [4]. The nature of the transport (sub- or super-diffusive) in phase space from counter-passing to trapped trajectories is analysed using statistical methods [13], showing a transition from ballistic to anomalous transport when the EGAM interacts with the trapping cone. Finally, comparisons with the full-f gyro-kinetic code ORB5 [14] will be presented, both in linear and nonlinear regimes, in a self-consistent way.

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