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Breakdown of adiabatic invariance of fast ions in spherical tokamaks

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The trajectories of collisionless charged particles in static magnetic fields are Hamiltonian flows, hence may be understood using tools of Hamiltonian dynamics. In the presence of three independent constants of the motion, it is known that a trajectory is regular. A low-energy particle in an axis-symmetric device possesses two exact constants of motion: the total energy and the momentum along the direction of symmetry; and a third one, adiabatic invariant in reality: the magnetic moment μ. Thus, its trajectory is regular. By increasing the particle energy up to values such that its Larmor radius becomes no longer negligible with respect to ambient scales, one may reach a scenario where μ is no longer conserved. Accordingly, the trajectory may become chaotic.

In this work we present a study of the dynamics of fast particles in an axis-symmetric magnetic geometry patterned after that of the NSTX Spherical Tokamak. Trajectories are computed from full Hamilton's equations of motion, not of the guiding center ones. Thus, no a-priori hypothesis is done about the conservation of the magnetic moment μ, which is instead computed and monitored at the post-processing stage. We find—consistently with earlier studies [1,2] — that, within a sizable domain of the machine, μ encompasses three regimes (see fig. 1): an adiabatic one, where μ is roughly constant with superposed small periodic oscillation at the Larmor frequency, and which is characteristic of the lower end of the energy range; a superadiabatic one, where μ still conserves a constant mean value, but large-scale oscillations at the bounce frequency are superposed; finally, a genuinely chaotic regime (fig. 2), where μ experiences sudden irregular jumps between widely differing mean values. These two latter regimes are characteristic of the energy range of beam ions for NSTX scenario, or alpha particle in fusion-scale devices, with appropriately rescaled fields. The boundary between these two regimes is not sharp: we find instances of trajectories which appear superadiabatic even over times very long with respect to bounce frequency, yet ultimately turn into non-adiabatic.

An analysis of the details of the trajectories shows that the breakup of adiabaticity occurs when an orbit with a large enough velocity crosses a region of low magnetic field amplitude and with a large variation of the orientation of the field.

We highlight also an interesting crosstalk between the different degrees of freedom: even when μ is not conserved and chaotic orbits are present, the conservation of the toroidal momentum sets strong constraints about the volume available to the particles, and their radial diffusion stays bounded. An example is shown in Fig. (2).

Our findings have both practical and physical consequences. First, when μ has large oscillations (not necessarily chaotic jumps), the use of guiding-center or gyrokinetic calculations for such orbits is questionable. Second, the capability of these particle to excite Alfvènic instabilities decreases, since the velocity of the particle fluctuates with respect to the phase-velocity of the Alfvèn wave, which imposes a fluctuating sign to the energy exchanges with this wave. Signatures of this effect might have already been evidenced in experiments [3].

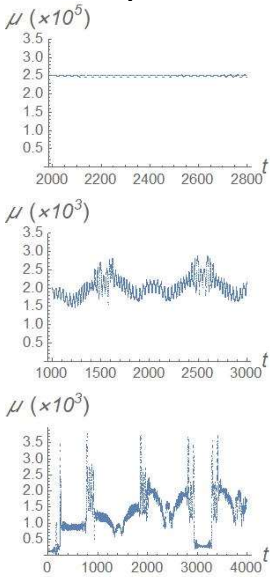

Figure 1. From top to bottom: time trace of μ for a low-energy adiabatic trajectory; a superadiabatic one (notice the fast oscillations, at the Larmor time scale, and the lowest modulation); and a chaotic one for high-energy particles.

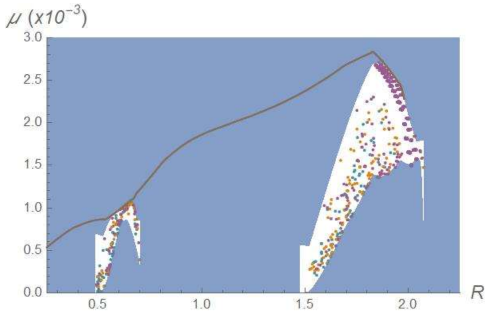

Figure 2. Poincaré plot in the plane (R, μ) for different trajectories, each labelled by a different color; *R* is the major radius. All the trajectories have the same value of the kinetic energy and toroidal momentum. The shaded area is the region forbidden to the particle by dynamical constraints. The brown curve is the maximum value potentially achievable by μ.

References

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