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Nonlinear trapping in wave-particle interactions in tokamaks

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The transport consequences of the nonlinear trapping in wave-particle interactions, including collisions, in tokamaks are investigated for the first time. The perturbed distribution is flattened in the vicinity of the resonance by the nonlinearly trapped particles. Particles trapped or barely circulating diffuse radially as a result of collisions. The transport fluxes, scale as the square root of the perturbed field amplitude, are used to quantify the energy confinement time of the energetic alpha particles in fusion reactors such as ITER. It is found that when the normalized magnitude of the perturbed magnetic field strength is of the order of $\delta B/B$ ˜10^{-4} , the energy loss rate of the energetic alpha particles caused by the nonlinear trapping is comparable to that of the neoclassical theory. This limits the tolerable magnitude of the perturbed fields in a reactor.

Wave-particle interactions are ubiquitous in tokamaks. Fundamentally, they are extensions of the linear Landau damping to toroidal plasmas. The relevant frequencies involved are the mode frequency w, the bounce frequency of the trapped particles w_b, the transit frequency of the circulating particles w_t, and the toroidal drift frequency w_d [1-7]. The transport consequences of the linear collisionless resonances among these frequencies are well known. However, recently, it has been shown that collisions play an important role in connecting various resonant regimes, and that even non-resonant particles can contribute to transport losses [8]. Collisions are also a natural decorrelation mechanism for linear resonances to broaden the perturbed distribution in the vicinity of the resonances even though collision frequency does not appear in the eventual expressions of the transport fluxes.

When the collision frequency ν is smaller than the bounce frequency of the nonlinearly trapped particles, transport consequences of the nonlinear trapping become important. The nonlinear trapping mechanism differs from the nonlinear resonance addressed in [9]. The trapping is not a result of the variation of the perturbed fields along the magnetic field line, i.e., there are no new classes of equilibrium like trapped particles except the bananas. The trapping occurs in the phase space resulting from the coupling of the radial drift motion and the phase of the wave to decorrelate the wave-particle resonance. In terms of the transport terminology, the nonlinear trapping creates superbananas. The transport fluxes depend on the square root of the amplitude of the perturbed field and are proportional to the collision frequency in the superbanana regime. Thus, in fusion reactors, e.g., ITER, where energetic alpha particles are well confined, i.e., their orbit width is much smaller than the plasma minor radius, nonlinear trapping becomes an important transport loss mechanism.

The perturbed particle distribution for the superbananas can be calculated by solving the drift kinetic equation. To facilitate the solution, the equation is cast in a set of independent variables $(p_\zeta, \theta, \zeta_0, E, \mu)$ in Hamada coordinates, where p_ζ is the toroidal component of the canonical momentum, θ is the poloidal angle, $\zeta_0 = q\theta - \zeta$ is the field line label, q is the safety factor, ζ is the toroidal angle, $E = \mathrm{v}^2/2 + e\phi/M$ is the particle energy, v is the particle speed, e is the electric charge, ϕ is the electrostatic potential, M is the mass, $\mu = \mathrm{v}_\perp^2/(2B)$ is the magnetic moment, $\mathrm{v}_\perp$ is the particle speed perpendicular to the magnetic field $\boldsymbol{B}$, and $B = |\boldsymbol{B}|$. The equation is then solved using the Eulerian approach [10]. The purpose of the approach is to remove the poloidal angle dependence in the bounce, transit, and toroidal drift frequencies by choosing a new set of the angle variables. In term of the new set of angle variables, the well-known linear resonance conditions emerge naturally. For trapped particles, the resonance condition is w+lw_b=nw_d, and for circulating particles,it is w+$\sigma[l - nq(p_\zeta)]w_t = nw_d$, where $\sigma = \pm 1$ is the sign of the transit speed, l is the poloidal mode number, and n is the toroidal mode number. One of the salient features of the Eulerian approach is that it is $q(p_\zeta)$ not $q(\chi)$ that appears in the resonance condition for the circulating particles. Here χ is the poloidal flux. By judiciously employing the constants of motion of the nonlinear orbits, and approximating the collision operator by utilizing the localization property of the resonance in the phase space, we obtain the perturbed distribution for a single mode that is in resonance with particles.

The perturbed distribution function for a single mode in the new set of the angle variables is used to calculate the neoclassical toroidal plasma viscosity [11,12] for static magnetic perturbations, and the transport fluxes caused by the electromagnetic waves. The theory can be employed to model transport losses in tokamaks with broken symmetry. In particular, the energy loss rate resulting from the nonlinear trapping can be used to evaluate the impact of the static magnetic perturbations and the electromagnetic waves on the energy confinement time of the energetic alpha particles in fusion reactors, e.g., ITER, by comparing it with that of the standard neoclassical theory. The estimated energetic alpha particle energy loss rate limits the tolerable magnitude of the magnetic perturbations to $\delta B/B$ ˜10^{-4} or smaller to mitigate their impact on the fusion energy gain factor Q in fusion reactors. Here, $\delta B/B$ denotes the typical normalized perturbed magnetic field strength.

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