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Finite larmor radius effect in ripple resonance diffusion of alpha particles in tokamaks
トカマクのリップル共鳴拡散における有限ラーマー半径効果

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Finite Larmor radius effects in ripple resonance diffusion of fusion-produced α particles in tokamaks are numerically investigated. An M-shaped energy dependence of diffusion coefficients around ripple resonance conditions, in which the toroidal precession motion of banana particles resonates to the field strength with ripples, was numerically obtained where particle trajectories were evaluated by a guiding center approximation. The M-shaped dependence comes from both island structure and initial distribution of α particles in a $(N\phi, \psi)$ phase space, where N is the number of toroidal field coils, and ϕ and ψ are the toroidal angle and the poloidal flux at the reflection point of a banana particle, respectively. the reflection points of banana particles are strongly affected by finite Larmor radius effects while their toroidal precession, which is the important parameter of the ripple resonance diffusion, is not sensitive to the effects although a Larmor radius of fusion-produced α particles is not negligible compared with their banana width. In this work, both the validity of our model and the finite Larmor radius effect are numerically investigated.

1 Introduction

The confinement of fusion produced α particles is important to maintain burning plasmas in tokamaks. Although α particles are well confined in axisymmetric fields, it has been shown that the loss of α particles due to magnetic field ripple caused by discrete toroidal field (TF) coils is dominant in the diffusion process in actual tokamaks with orbit following Monte Carlo simulations [1, 2]. However the understanding of the loss processes in detail is not sufficient.

Since the radial displacement of a banana orbit by ripples depends on the toroidal phase at the banana tip [3], the cumulated radial displacement becomes resonantly large when the difference in the toroidal angles of successive banana tips is a multiple of the toroidal angle of adjacent TF coils (the ripple resonance). This toroidal distance of successive banana tips is determined by toroidal precession. Yushmanov theoretically analyzed this ripple resonance diffusion by means of the banana-drift kinetic equation without the radial change of the toroidal precession because it is much less than that of the toroidal length of the banana orbit [4]. Since the toroidal precession, however, strongly depends on the radial position in an actual tokamak, we investigate the ripple resonance diffusion in a realistic system with the radial change of the toroidal precession by numerical calculations based on orbit following Monte Carlo simulation.

2 Calculation Model

In this paper, the trajectory of an α particle is numerically evaluated with guiding center equations, in the same way as OFMC code [1, 2]. In an axisymmetric vacuum toroidal field, the guiding center equations conserve the toroidal canonical momentum $P_\phi = mRv_\phi + e\psi$, where R, v_ϕ and ψ are the major radius, the toroidal component of velocity and the poloidal magnetic flux, respectively. The velocities of α particles are also changed by Coulomb collisions with a bulk plasma. Then the velocity of α particles is changed according to both guiding center equations and Coulomb collisions. Diffusion coefficients are evaluated by a rate of change in a variance of the toroidal canonical momentum P_ϕ which corresponds to the poloidal magnetic flux at a banana tip, $e\psi_\mathrm{b} = P_\phi|_{v_\phi=0}$.

3 Numerical Results on Ripple Diffusion

The dependence of the diffusion coefficients on energy, ripple strength and other parameters are calculated with test particles which are launched from the same banana tip position. All α particles with kinetic energy W and magnetic moment μ_m start from banana tips whose poloidal magnetic flux is fixed while toroidal angles are randomly given.

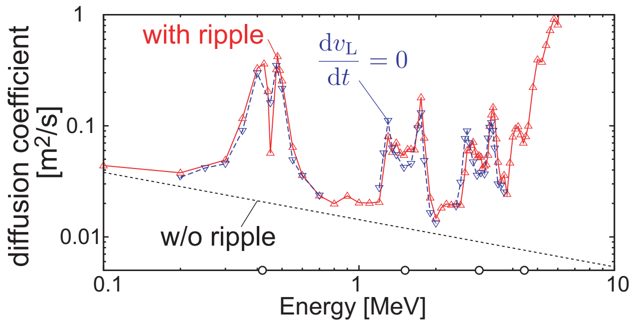

Figure 1: Energy dependence of the diffusion coefficient in rippled field.

Figure 1 (red line) shows the energy dependence of diffusion coefficients in rippled fields. The radial displacement by the ripple depends on the toroidal phase of the banana tip [3]. Generally, this radial displacement is canceled during several bounce since the toroidal phase of every banana tip varies. However, when the toroidal angle difference between its successive banana tips equals a multiple of the toroidal angle between adjacent TF coils, it continues having the same radial displacement at every banana tip and its cumulative radial displacement becomes large resonantly (ripple resonance). This ripple resonance condition depends on the energy of an α particle. In the magnetic configuration used in this paper, ripple resonance energies are 0.4, 1.5, and 2.9 MeV.

The diffusion coefficients do not peak at the resonance energy but make an M-shaped dependence around the resonance energy. Because the ripple resonance of fast ions is a collisionless phenomena, collisionless orbits play an important role in the diffusion process in this energy range.

The difference of the collisionless orbits in rippled fields for a guiding center equation and a full orbit equation is revealed in the banana-tip locations. The difference changes the toroidal precession motion, and cause the difference of the toroidal precession motion. Figure 2 shows the energy dependence of the diffusion coefficient in a rippled field for a guiding center equation and a full equation, respectively.

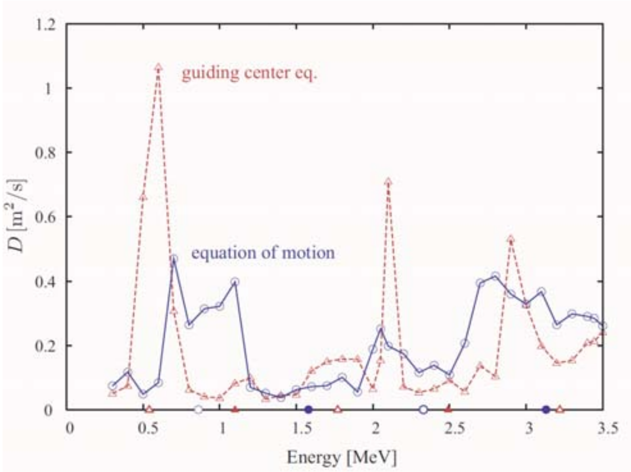

Figure 2: Energy dependence of the diffusion coefficient in a rippled field for a guiding center equation and a full equation. Triangles and circles are a ripple resonant energies for the guiding center equation and a full orbit equation, respectively.

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