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Theoretical and numerical analyses of trapping and precession drift of fast ion
高速イオンの捕捉と歳差ドリフトに関する理論・数値解析

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Trapped fast ion motion in magnetic confinement devices is investigated theoretically and numerically. Using a particle simulation code based on the drift model, precession drifts of trapped fast ions in a helical system are simulated, where the precession drift orbit shows a circular, helical shape around a magnetic axis. Poloidal precession drifts of the trapped fast ions are in the direction of the ion diamagnetic drift. Simulation results of the precession drift directions are benchmarked with an analytic theory.

1. Introduction

In the magnetic confinement fusion devices, such as tokamaks and helical systems, fast (or energetic) ions are produced by external heating and/or thermonuclear fusion. To maintain high temperature plasmas, fast ions must efficiently heat background plasmas. However, fast ion losses can become anomalously large, when fast-ion-driven magnetohydrodynamic (MHD) instabilities are excited. Concerning passing fast ions, the fast-ion-driven Alfven eigenmodes are well known [1]. The fishbone mode in tokamaks is known to be driven by trapped fast ions [2]. In tokamaks, the resistive wall mode driven fast ions has been observed [3,4]. In helical systems, the fishbone-like mode has been observed [5], although a physical mechanism is not clarified yet. In order to study wave-particle interaction among fast ions and MHD waves, it is necessary to understand fundamental behavior of a single fast ion. In this study, we focus on trapped fast ions in helical systems.

2. Simulation Model

We introduce a so-called drift model [6,7], where gyro-motion of particle is averaged so that the model only involves guiding center velocities of the particles. In the drift model, the guiding center velocity is given by

$$\mathbf{v}_{gc} = v_{//}\mathbf{b} + \mathbf{v}_E + \mathbf{v}_m , \tag{1}$$

with

$$m\left(dv_{//}/dt\right) = \mathbf{b}\cdot\left(e\mathbf{E} - \mu\nabla B\right), \tag{2}$$

where $v_{//}$ is the velocity parallel to the magnetic field, $\mathbf{b}$ is the unit vector of the magnetic field, $\mathbf{v}_E$ is the ExB drift velocity, and $\mathbf{v}_m$ is the magnetic drift including the ∇B and inertia drifts, m is the ion mass, e is the ion charge, μ is the magnetic moment, and $\mathbf{E}$ is the electric field. The drift model gives good approximations of particle motion as long as μ is well conserved along particle orbits. In addition, in the low β limit, Eqs. (1) and (2) can be derived from more sophisticated model [7], which ensures the conservation of μ.

A simulation code, which solves the model in three-dimensional Cartesian coordinate, is developed. A time evolution of the particle motion is solved by the fourth-order Runge-Kutta method, and the Lagrange interpolation is used to specify the field data at the particle position from discretized field data. The particle motion in mirror devices and tokamaks by the drift model is benchmarked with that by an exact Newton equation.

3. Simulation Result

The helical system is characterized by twisting magnetic fields by external coils, where a dominant component of the magnetic field $\mathbf{B}$ is given by those in currentless and vacuum limits. Relations $\nabla\cdot\mathbf{B}=0$ and $\nabla\times\mathbf{B}=0$ give $\mathbf{B}=\nabla\Phi$ and $\nabla^2\Phi=0$, where Φ is the magnetic scalar potential. In the large aspect ratio limit of torus, the equation for Φ is reduced to that in cylindrical coordinates (r,θ,z), where r is the minor radial position, θ is the poloidal angle, and z is the toroidal position. Assuming that the helical systems have the pole number l and the pitch number M, we consider that Φ has a form

$$\Phi = -\left(B_0 R_0 / M\right) \varepsilon_h \sin\left(l\theta - Mz/R_0\right), \qquad (3)$$

where B_0 is the magnetic field amplitude at the magnetic axis, R_0 is the major radius, ε_h is the relative magnitude of the helical component of the magnetic field. Components of the magnetic field in the cylindrical coordinates are given by $B_r = d\Phi/dr$, $B_\theta = (1/r)(\partial\Phi/\partial\theta)$, $B_z = B_0 + (\partial\Phi/\partial z)$, respectively.

In the following, typical parameters in the LHD are considered: $\varepsilon_h = 0.45(r/a)^2$, $B_0 = 2.0[T]$, $R_0 = 3.6[m]$, $a = 0.7[m]$, $l = 2$, and $M = 10$. In these parameters, we have $\iota = 0.6$ at the center, and $\iota = 1.8$ at the last closed surface, where, ι is the rotational transform normalized by 2π.

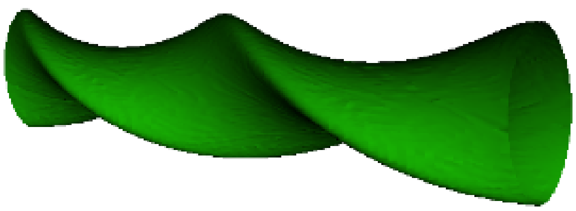

Fig.1. Isosurface plot of the magnetic flux surface

Figure 1 shows the typical magnetic flux surface, where two toroidal ripples are plotted. In simulations of trapped fast ion motion using Eqs. (1)-(3), we consider the following initial conditions: $\rho_i = 1.0[\mathrm{cm}]$, $|v_{//}/v_\perp| = 0.1$, where ρ_i is the Larmor radius, $v_\perp$ is the perpendicular velocity.

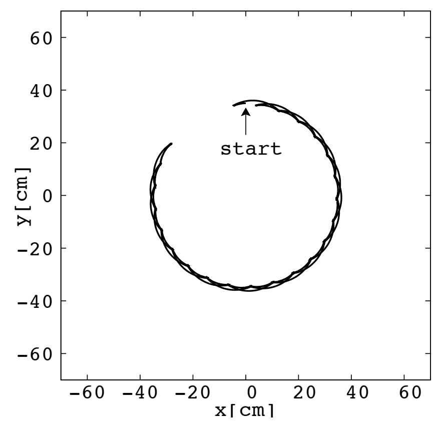

Fig.2. Poloidal projection of trapped fast ion motion

Figure 2 shows the poloidal projection of trapped fast ion motion. The fast ions are trapped by the rippled toroidal magnetic fields, where the toroial magnetic field is in the positive direction z is Cartesian coordinates. During the bounce motion, centers of trapped fast ions drift in both the poloidal and toroidal directions, which are called precession drifts. The precession drift is due to the magnetic drift approximated by

$$\mathbf{v}_m = \left(c\mu/eB\right)\mathbf{b} \times \nabla B, \qquad (4)$$

for trapped fast ions. Equations (1) and (3) show that the trapped fast ions are located around $l\theta - Mz/R_0 = \pi + 2k\pi$ for arbitrary integer k. Then, the poloidal precession drift frequency is approximated by

$$\omega_\theta = -\left(c\mu/e\right)\left(d\varepsilon_h/dr\right). \qquad (5)$$

This indicates the poloidal precession drift is in the clockwise direction in the x-y plane (ion diamagnetic drift direction), which is consistent with the result in Fig. 2. The toroidal precession drift frequency is given such that $\omega_z = \left(l/M\right)\omega_\theta$.

4. Discussion

An evolution of trapped fast ions' distribution function is described by a so-called bounce-averaged drift-kinetic equation, which involves the precession drift frequency and eliminates the rapid bounce motion [8]. Considering the bounce-averaged drift-kinetic equation, the fishbone-like mode in helical systems could be analyzed.

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