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Study of radial diffusion of energetic ion by high-m magnetic perturbations using DCOM

DCOMコードを用いた高m磁場摂動による高エネルギー粒子の径方向拡散

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Radial diffusion of energetic ions is studied using DCOM code. Effect of magnetic perturbations which have relatively high poloidal mode number ($m = 200$) is studied. To evaluate the diffusion of energetic ions, the time evolution of the second cumulant C_2 is estimated. After short ballistic phase, the diffusion phase is observed. Local diffusion coefficient, D, is estimated and dependence of D on the strength of magnetic perturbation, s, and on the particle energy, E, are investigated. We found that $D \propto s^2E^{1/2}$ for the lower particle energy case ($E \lesssim$10keV) and $D \propto sE^{3/2}$ for the higher energy case ($E \gtrsim$100keV).

1 Introduction

A good confinement of energetic particles is required in magnetic confinement fusion reactors. Because α-particle energy is used to sustain high-temperature fusion plasma, the loss of energetic α-particles may cause serious damage to the first wall of a fusion reactor.Recently confinement experiments of energetic ions at ASDEX-U and DIII-D suggest the existence of anomalous diffusion of off-axis injected beam particles[1, 2], and the measured beam current profile does not agree with that predicted from classical theory. It has suggested that the microscopic electromagnetic fluctuations caused by background plasma turbulence may cause anomalous particle diffusion. However, it has long been considered that microscopic electromagnetic fluctuations do not affect the diffusion of energetic particles.

We use DCOM (Diffusion COefficient evaluation by Monte-carlo method) code[3], which can calculate radial diffusion of particles by the Monte Carlo method, to study the effect of microscopic electromagnetic fluctuations on radial diffusion of energetic particles. In a tokamak configuration, we follow the trajectory of the test ions, α particle, in the presence of magnetic fluctuations and calculate the second cumulant C_2. In addition we estimate the diffusion coefficient D from the obtained C_2 and investigate the dependence of the diffusion coefficient on the particle

2 Simulation model

We assume that the magnetic field has the following form with equilibrium magnetic field B and magnetic perturbation δB

$$B_t = B + \delta B \tag{1}$$

$$\delta B = \nabla \times bB \tag{2}$$

In the DCOM, the drift motion equations of the guiding centers in the above magnetic field[4, 5] are integrated by the six-order Runge-Kutta method.

We represent the magnetic perturbation b in Eq. (2) using a Fourier series as

$$b(\psi,\theta,\zeta) = \sum_{m,n} b_{mn}(\psi)\cos(m\theta - n\zeta + \zeta_{mn}) \tag{3}$$

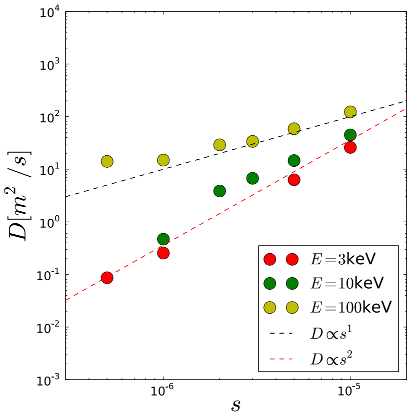
$$b_{mn}(\psi)/a = s_{mn}\exp\left(-\frac{(\psi-\psi_{mn})^2}{\Delta\psi^2}\right) \tag{4}$$

where ψ, θ and ζ are magnetic surface function, oloidal angle and toroidal angle respectively, ζ_{mn} is phase, a is minor radius, s_{mn} is strength of magnetic perturbation, ψ_{mn} is center of magnetic perturbation, and $\Delta\psi$ is width of magnetic perturbation.

To quantitatively estimate particle spreading, we use the second cumulant C_2 defined as $C_2 = \langle (r - \langle r \rangle)^2 \rangle$, where r is the position of particles and $\langle\rangle$ is ensemble average. In a non-uniform magnetic field with magnetic fluctuations, the time evolution of C_2 is classified using correlation time of the particle orbit Δt and characteristic time of the system T_L:

$$C_2(t) \propto \begin{cases} t^2 & : t \le \Delta t \\ t^1 & : \Delta t \le t \le T_L \\ t^0 & : T_L \le t \end{cases} \tag{5}$$

The region in which C_2 is proportional to t^2 is known as the ballistic phase, whereby particle orbits follow



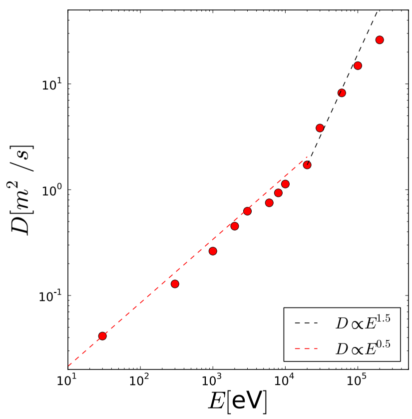


Figure 1: Diffusion coefficients in the presence of magnetic perturbation D at particle energy $E = 3$ keV and $E = 10$ keV is proportional to s^2. On the contrary, D at $E = 100$ keV is proportional to s^1.

Figure 2: Diffusion coefficient versus energy of particles. D is proportional to $E^{1/2}$($\lesssim$10 keV) and to $E^{3/2}$($\gtrsim$10 keV).

a dynamics law and in which C_2 is proportional to t^1, particle spreading is known as the diffusive phase. The diffusion coefficient D is described as

$$D = \frac{1}{2}\frac{dC_2}{dt} \tag{6}$$

The proportion of C_2 to t^0 indicates that particles have reached a steady state.

In this study, test ions are distributed at the radial position $r/a = 0.72$ at $t = 0$, where a is minor radius. We assume a tokamak magnetic configuration: Major radius R is 3.6 m, minor radius a is 0.6 m, and magnetic field at magnetic axis B is 3.0 T. We assume that the magnetic perturbation has 30 high-m Fourier modes, whereby poloidal mode $m = 200$ and toroidal mode $n =$ -118 $\sim$ -147. In addition $\Delta\psi/\psi_a = 0.30$, and $\psi_{mn}/\psi_a = 0.52$; ψ_a is the outermost magnetic surface. In this condition, the center of magnetic perturbation almost corresponds to the radial initial position of the particles. Each ζ_{mn} of Fourier modes is chosen randomly. The strength of magnetic perturbation s_{mn} of all Fourier modes are same: $s_{mn} = s$.

3 Simulation results

In the case of $s = 0$, C_2 increases in proportion to t^2 and then becomes constant. The ballistic phase appears first, followed by the steady state. In the case of $0 < s \leq 1.0 \times 10^{-5}$, the region where C_2 is proportional to t^1 appears, we can confirm that particles diffuse in a radial direction due to magnetic turbulence during the diffusion phase. In the case of larger s ($s = 1.0 \times 10^{-4}$), the diffusive phase does not appear.

Fig. 1 shows the variant of diffusion coefficient D calculated by Eq. (6) due to s. We can see that D is proportional to s^2 when particle energy is 3 keV and 10 keV, and is proportional to s^1 when particle energy increases to 100 keV. These results indicate that the s dependency is influenced by the particle energy and that s dependency is weak in the energetic particle.

In the lower case ($\lesssim$30 keV) with a fixed value $s = 1.0 \times 10^{-6}$, the ballistic and diffusive phases are clear. However, in the intermediate energy case (60 keV$\sim$200 keV), the duration of the diffusive phase is short and the ions reach steady state rapidly. In the higher energy case (200 keV$\sim$3 MeV), the diffusive phase disappears. Fig. 2 shows the variant of D due to particle energy E. D is proportional to $E^{1/2}$ in the lower case ($\lesssim$10 keV): D is constantly proportional to $E^{3/2}$ in the higher region ($\gtrsim$10 keV).

References

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