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Effect of nonlinear collisions on the α-particle confinement in helical plasmas
ヘリカルプラズマにおける非線形衝突の α 粒子閉じ込めへの影響

Yoshitada Masaoka, Sadayoshi Murakami
政岡義唯, 村上定義

Department of Nuclear Engineering, Kyoto University, Sakyo-ku, Kyoto 606-8501, JAPAN
京都大学工学研究科原子核工学専攻 〒606-8501　京都市左京区吉田本町

Confinement of α-particles is investigated including the collisions with various plasma species such as electron, deuterium, tritium, and high-energy α-particle itself in a heliotron fusion reactor based on the LHD configurations. GNET code (Global NEoclassical Transport) is improved to take into account the nonlinear collision effect on the α-particle confinement. The real and velocity space distributions are analyzed and the energy and particle loss rate changing the background plasma parameters are evaluated.

1 Introduction

Confinement of energetic particles is one of the important issues in the fusion reactor research. Energetic α-particles are produced by D-T fusion reactions and the energy of α-particle is indispensable to sustain a high temperature fusion plasma. Also the lost energetic α-particles might damage the first wall. Therefore, it is important to confine the energetic particles until the energy slow-down to thermal energy. Particularly, in helical systems, energetic particle trajectory is complicated in a three dimensional magnetic configuration. Thus the confinement of energetic particles is one of the critical issues in designing a helical reactor. Additionally, collisions between the energetic particles could enhance the pitch angle scattering[1] and would deteriorate the confinement. Thus the analysis including the both complicated orbit and nonlinear collision effects are necessary to make clear the energetic particle confinement in LHD plasmas.

2 Simulation Model

In this study, we assumed a heriotron type fusion reactor extending the LHD magnetic configuration [2]. This reactor is based on the NeoClassical transport optimized (NC) configuration which is the inward shifted magnetic configuration optimized the neoclassical transport based on $R_{ax} = 3.53$m in LHD [3]. R_{ax} is the magnetic axis position in the major radius. This reactor configuration has the plasma volume of 1000m^3 and the magnetic strength of 5T at the plasma center.

In order to analyze a stationary distribution of α particles including the nonlinear collision effects, we solve the drift kinetic equation for α particles in five dimension phase space using the GNET (Global NEoclassical Transport) code [4]. This code uses a Monte Carlo technique to calculate the distribution function following test particles. The drift kinetic equation is described as follow ;

$$\frac{\partial f_\alpha}{\partial t} + (\vec{v}_\parallel + \vec{v}_D) \cdot \nabla f_\alpha + \dot{\vec{v}} \cdot \nabla_V f_\alpha = C(f_\alpha) + L(f_\alpha) + S_\alpha \tag{1}$$

where f_α is the distribution function of α particles, $\vec{v}_\parallel$ and $\vec{v}_D$ are the velocity parallel to magnetic line and the drift velocity respectively. L is the loss term form the last closed flux surface and S_α is the source term of the α particles generated by fusion reaction.The source term S_α is evaluated by using fusion reaction rate.

C is the Coulomb collision operator including the linear collision effects $C^{linear}$and the nonlinear collision effect C^{nl}. C^{linear} includes the operator of the pitch angle scattering and the energy scattering with background ions and electrons. These operators have been evaluated by Boozer and Kou-Petravic [5] and are described as follow ;

$$\lambda_n = \lambda_{n-1}(1-\nu_d\tau) \pm \left[\left(1-\lambda_{n-1}^2\right)\nu_d\tau\right]^{1/2} \quad (2)$$

$$E_n = E_{n-1} - (2\nu\tau)\left[E_{n-1}\left(\frac{3}{2}+\frac{E_{n-1}}{\nu}\frac{d\nu}{dE_{n-1}}\right)\right] \pm 2\left\{E_T E_{n-1}(\nu\tau)\right\}^{1/2} \quad (3)$$

where $\lambda = v_{\|}/v$. v and $v_{\|}$ are the particle velocity and the velocity parallel to magnetic line. ν_d is the deflection collision frequency. τ is length of a time step. n and $n-1$ are numbers of time step, and The symbol $\pm$ means the sign is to be chosen randomly. E_n, E_T are the energy at time step n and thermal energy respectively. The subscript k, l are the components of Einstein convention.

We can write the nonlinear collision operator C^{nl} with Rosenbluth potentials [6] as

$$C_{\|}^{nl} = \Lambda_c\left\{\frac{\partial^2\phi(\vec{v})}{\partial v_{\|}^2}+\frac{\partial\phi(\vec{v})}{\partial v_{\|}}\frac{\partial}{\partial v_{\|}}\right\}f(\vec{v}) \quad (4)$$

$$C_{\perp}^{nl} = 2\Lambda\left\{\frac{\partial^2\phi(\vec{v})}{\partial v_{\perp}^2}+\frac{\partial\psi(\vec{v})}{\partial v_{\perp}}\frac{\partial}{\partial v_{\perp}} - \frac{\partial^2\psi(\vec{v})}{\partial v_{\perp}^2}\frac{\partial^2}{\partial v_{\perp}^2}\right\}f(\vec{v}), \quad (5)$$

where $\Lambda_c = \ln\Lambda(e_\alpha e_b/m_\alpha\epsilon_0)^2$. Λ is the the Coulomb logarithm. e_α and e_b are charges of test α-particles and of background ions and electrons, especially. m_α is the mass of test α-particles and ϵ_0 is permittivity of free space. ϕ and ψ are Rosenbluth potentials. $v_{\|}$ and $v_{\perp}$ are the velocities parallel and perpendicular to magnetic filed lines. In this paper, we assumed that the background plasma consists of electrons, deuterium, tritium, and α particles. Electron temperature T_e and density n_e profiles are taken to be

$$T_e(\rho)[\text{keV}] = 9.5(1-\rho^2)+0.5, \quad (6)$$

$$n_e(\rho)[10^{20}\text{m}^{-3}] = 1.9(1-\rho^8)+0.1, \quad (7)$$

where ρ is normalized minor radius.

3 Benchmark

We run the GNET code until the test α particles are thermalized varying the background plasma parameters and applying the linear and/or nonlinear collision operator. We estimate α particle confinement with four cases of the background plasma conditions : Case 1 : electrons and deuterium (1.0), Case 2 : electrons , deuterium (0.5), and tritium (0.5), Case 3 : electrons, deuterium (0.45), tritium (0.45), and α particles (using linear collision operator) (0.1), Case 4 :, deuterium (0.45), tritium (0.45), α particles (using nonlinear collision operator) (0.1), where the number of parentheses are the ratio of ion charge density.

We found that an increase of mass density of background plasma leads to degradation of the confinement efficiency of the α particle because of enhancement of the pitch angle effect. Assuming the Maxwellian background plasma is distribution, for each collision operator, we can not see a clear difference the α particle confinement are almost same. This indicate the validity of our nonlinear collision operator.

4 Summary

We have investigated α particle confinement in a helical type fusion reactor with varying the background plasma parameter and the collision operator, keeping the charge neutrality. The validity of our nonlinear collision operator is verifyed. We will use this collision operator in order to estimate α-α particle collision effect with non-maxwellian distribution.

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