Nonlinear collision effect on alpha particle confinement

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Abstract

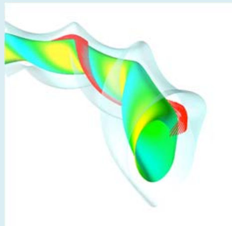
Confinement of α-particles is investigated including the collisions with various plasma species such as electron, deuterium, tritium, and high-energy α-particle itself in a heliotron fusion reactor, which is based on the LHD configurations. GNET (Global NEoclassical Transport) code is being improved to take into account the nonlinear collision effect on the α-particle confinement. The code is benchmarking with the linear operator in the shifted Maxwellian plasma.

Introduction

Helical device

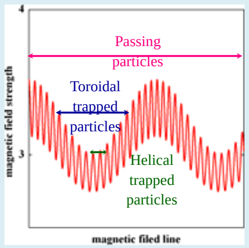
- **The magnetic field is generated mainly by the coil current.**
  - **Permits a steady state plasma.**
  - **No plasma disruption caused by the plasma current.**
- **The magnetic configuration is inherently three-dimensional (3D).**
  - **The plasma behavior is more complex than in tokamaks.**

✦ **Several physics and technical problems remain to be studied and solved, such as the behavior and confinement of high energy α particles in helical plasma.**



α particle in helical plasma

- **Helical trapped particles**
  : trapped in the helical ripple
- **Toroidal trapped particles**
  : trapped in the toroidal ripple
- **Passing particles**
  : not trapped in either the helical or toroidal ripples
- **Transition particles**
  : transition between being trapped particles and passing particles



➡ **These trapped motions cause complex orbits of trapped particles and enhance radial diffusion of energetic particles.**

Simulation model

GNET code

We solve the drift kinetic equation in the 5D phase-space with pitch angle and energy scattering using the GNET code (Global Neoclassical Transport code) [4].

The drift kinetic equation

$$\frac{\partial f_\alpha}{\partial t} + (\mathbf{v}_{/\!/} + \mathbf{v}_D)\cdot\nabla f_\alpha + \dot{\mathbf{v}}\cdot\nabla_{\mathbf{v}} f_\alpha = C^{coll}(f_\alpha) + L^{particle}(f_\alpha) + S_\alpha$$

- f_α : distribution function of α particles
- $v_{/\!/}$: velocity parallel to magnetic field line
- v_D : drift velocity
- C^{coll} : Coulomb collision operator (linear and nonlinear)
- $L^{particle}$: particle loss term (LCFS)
- S_α : particle source generated by fusion reaction

The steady state distribution of α particle is evaluated.
The GNET code uses a Monte Carlo technique to calculate the distribution function of a set of test particles.

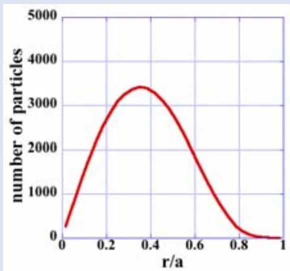
α particle source (S_α)

Fusion reaction rate

$$S_\alpha = n_D n_T \langle \sigma v \rangle = n_D n_T \iint f_D(v_D)\, f_T(v_T)\, \sigma_T(E)\, |v_D - v_T|\, dv_D dv_T$$

- σ : total reaction cross-section
- E : relative energy
- n_e : radial profile of plasma density
- T_e : plasma temperature

$$n_e(\rho)\ [10^{20}\mathrm{m}^{-3}] = 1.9(1-\rho^8) + 0.1$$
$$T_e(\rho)\ [\mathrm{keV}] = 9.5(1-\rho^2) + 0.5$$



- ρ : normalized minor radius
- 0 : the value at the magnetic axis
- 1 : the value at the last closed flux surface (LCFS)

Based on the fusion reaction rate, we get an initial radial profile of α particles.

The nonlinear collision operator : $C_\alpha^{nonlinear}$

We can write the $C^{nonlinear}$ with Rosenbluth potentials[6],

$$C^{a/b} = -\overleftrightarrow{D}^{a/b}\nabla f_a(\boldsymbol{v}) + \overleftrightarrow{F}^{a/b} f_a(\boldsymbol{v})$$

$$\overleftrightarrow{D}^{a/b} = -\frac{4\pi\Gamma^{a/b}}{n_b}\nabla\nabla\psi_b(\boldsymbol{v})$$

$$\overleftrightarrow{F}^{a/b} = -\frac{4\pi\Gamma^{a/b}}{n_b}\frac{m_a}{m_b}\nabla\phi_b(\boldsymbol{v})$$

$$\Gamma^{a/b} = \frac{n_b q_a^2 q_b^2 \ln\Lambda^{a/b}}{4\pi\epsilon_0^2 m_a^2}$$

- ***D*** **: diffusion tensor**
- ***F*** **: average force tensor**
- ***n*** **: density of plasma**
- ***m*** **: mass of particle species**
- ε_0 **: *electrical* constant**
- **a : test particle species**
- **b : background particle species**

➢ **Rosenbluth potentials ϕ, ψ**

$$\phi_a(v,\theta) = \sum_{l=0}^{\infty}\sum_b \frac{m_a + m_b}{m_b}\phi_b^{(l)}(v)P_l(\cos\theta)$$

$$\psi_a(v,\theta) = \sum_{l=0}^{\infty}\sum_b \psi_b^{(l)}(v)P_l(\cos\theta)$$

$$\phi_b^{(l)}(v) = -\frac{1}{2l+1}\left[\int_0^v \frac{v'^{l+2}}{v^{l+1}} f_b^{(l)}(v')dv' + \int_v^\infty \frac{v^l}{v'^{l-1}} f_b^{(l)}(v')dv'\right]$$

$$\psi_b^{(l)}(v) = \frac{1}{2(4l^2-1)}\left[\int_0^v \frac{v'^{l+2}}{v^{l-1}}\left(1 - \frac{\left(l-\frac{1}{2}\right)v'^2}{\left(l+\frac{3}{2}\right)v^2}\right) f_b^{(l)}(v')dv' + \int_v^\infty \frac{v^l}{v'^{l-3}}\left(1 - \frac{\left(l-\frac{1}{2}\right)v^2}{\left(l+\frac{3}{2}\right)v'^2}\right) f_b^{(l)}(v')dv'\right]$$

➢ **Legendre Polynomial Expansion**

$$f(v,\theta) = \sum_{l=0}^{\infty} f^{(l)}(v)P_l(\cos\theta)$$

$$f^{(l)}(v) = \frac{2l+1}{2}\int_0^\pi f(v,\theta)P_l(\cos\theta)\sin\theta d\theta$$

$$P_0(\mu) = 1$$

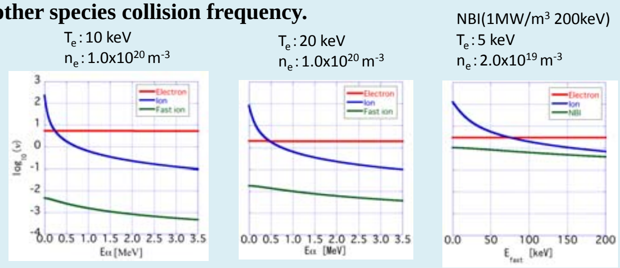
$$(l+1)P_{l+1}(\mu) = (2l+1)\mu P_l(\mu) - lP_{l-1}(\mu)$$

Nonlinear collision effect

- The relative velocity between high-energy particles sometimes becomes very small.
- Although the amount of high-energy particles are much less than thermal ions, it is considered that the nonlinear collision by each fast ion has usually larger effect than that by other background ions [1].
- This collision effect may lead to deteriorate the high-energy particle confinement, because of increasing a pitch angle scattering.

Collision frequency

We compare with the beam-beam collision frequency and the beam-other species collision frequency.



Objective

•Assuming **LHD type reactor** as a typical helical reactor, we investigate the helical fusion reactor **in a view point of the α-particle confinement.**

⬩We include the collisional effects (**the energy and pitch angle scattering**) and evaluated **the distribution function** of α-particles.

⬩We analyze including the both complicated orbit and nonlinear collision effects in order to make clear the α-particle confinement in heliotorons.

•The assumed fusion reactor

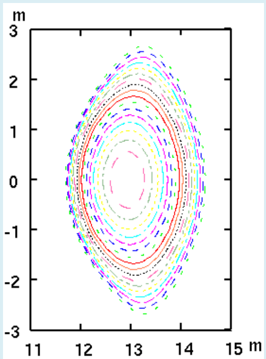
⬩The helical type of fusion reactor extending the LHD magnetic configuration. (R_{ax} is about 3.55 times larger than that of the LHD.)

Plasma volume : 1000m^3

Magnetic field : 5T

Magnetic configuration

(R_{ax} : the magnetic axis position in vacuum): NC , which is the neoclassical transport optimized configuration, based on R_{ax}=3.53m of LHD [3].



Coulomb collision ($C^{coll}(f)$)

C is the Coulomb collision operator including the linear collision effect C^{linear} and the nonlinear collision effect $C^{nonlinear}$.

$$C^{\rm coll}(f_\alpha) = C_e^{linear}(f_\alpha) + C_D^{linear}(f_\alpha) + C_T^{linear}(f_\alpha) + C_\alpha^{linear}(f_\alpha) + C_\alpha^{nonlinear}(f_\alpha)$$

The linear collision operator : C_i^{linear}

The operator of the pitch angle and energy scattering with background ions and electrons[5].

Pitch angle :

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

Energy :

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

i : background ions(D, T, α) and electrons

ν_d : the deflection collision frequency

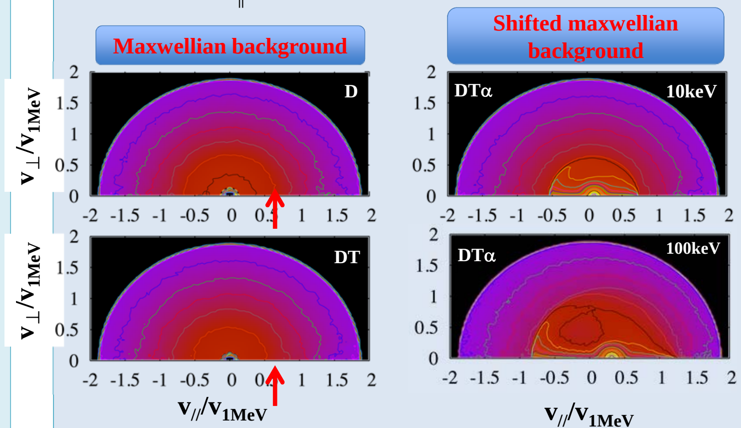
τ : the length of a time step

n, n-1 : numbers of time step

± : the signs to be chosen randomly

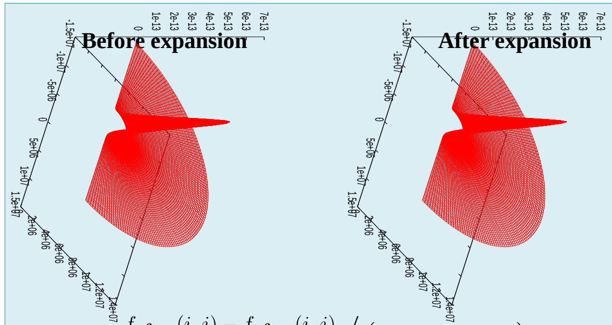
E_n, E_T : the test particle energy at time step and thermal energy

$\lambda = v_{||}/v$



We evaluate the velocity space distribution of α particle in the case with the linear collision operator (no orbit calculation).

- An increase of mass density of back ground plasma leads to improvement of slowing down.
- A shifted maxwellian background (10keV, 100keV) shifts the velocity space distributions.
- We will benchmark the nonlinear collision operator using the same background distributions.



$$Err = \sum \frac{f_{\rm after}(i,j) - f_{\rm after}(i,j)}{f_{\rm before}(i,j)} \bigg/ \left(N_{\rm igrid} \times N_{\rm jgrid}\right) = 3.61 \times 10^{-3}$$

Solving this collision operator at each time step, it take a lot of time in the simulation.

Therefore, before the simulation run, we build a database which give us the α-particle velocity changes as a function of α-particle velocity.

- We evaluate the Rosenbluth potential at the grid point in the velocity space.
- Using these Rosenbluth potentials, we build collision operator database.

Summary

We improve the GNET code to take into account the nonlinear collision effect on the α-particle confinement.

- We have extended the linear collision operator to estimate the effect of multi species plasma (deuterium, tritium, and alpha particle).
- We have studied the nonlinear collision operator and obtained its diffusion equation.
- The code is still need improvements.

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Acknowledgments

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