**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.

**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

\[
\frac{\partial f_\alpha}{\partial t} + (\mathbf{v}_{\parallel} + \mathbf{v}_D + \mathbf{v}_D^* \cdot \nabla) f_\alpha = C^{\text{coll}}(f_\alpha)+L^{\text{lossy}}(f_\alpha)+S_\alpha
\]

\(f_\alpha\): distribution function of α particles
\(v_{\parallel}\): velocity parallel to magnetic field line
\(v_D\): drift velocity
\(C^{\text{coll}}\): Coulomb collision operator (linear and nonlinear)
\(L^{\text{particle}}\): particle loss term (LCFS)
\(S_\alpha\): 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 (\(S_\alpha\))**

Fusion reaction rate

\[S_\alpha = n_D n_T \left( \int f_D v_D f_T v_T \sigma(E) dv_D dv_T \right) v_D - v_T \]

\(\sigma\): total reaction cross-section
\(E\): relative energy
\(n_D\): radial profile of plasma density
\(n_T\): plasma temperature

\(\rho\): normalized minor radius
\(\theta\): the value at the magnetic axis
\(l\): 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 : \(C^{\alpha/b}_{\text{nonlinear}}\)**

We can write the \(C^{\alpha/b}_{\text{nonlinear}}\) with Rosenbluth potentials[6],

\[
C^{\alpha/b}_{\text{nonlinear}} = -\frac{\sigma_{\alpha/b}}{4\pi} \nabla \cdot \nabla \phi_{\alpha/b}(\mathbf{v})
\]

\[
D = -\frac{\mu_b}{4\pi} m_a \nabla \phi_b(\mathbf{v})
\]

\[
F = -\frac{\mu_b}{4\pi} \frac{n_b}{n_a} m_a \nabla \phi_b(\mathbf{v})
\]

\[
\Gamma_{\alpha/b} = \frac{n_b q_a q_b^2 \ln \Lambda_{\alpha/b}}{4\pi \varepsilon_0 m_a^2}
\]

\(D\): diffusion tensor
\(F\): average force tensor
\(n\): density of plasma
\(m\): mass of particle species
\(\varepsilon_0\): electrical constant
\(a\): test particle species
\(b\): background particle species

† Rosenbluth potentials \(\phi, \psi\)

\[
\phi_a(v, \theta) = \sum_{l=0}^{\infty} \sum_{b=0}^{a} \frac{n_a + n_b}{m_b} \phi_a^{(l)}(v) P_l(\cos \theta)
\]

\[
\psi_a(v, \theta) = \sum_{l=0}^{\infty} \sum_{b=0}^{a} \psi_a^{(l)}(v) P_l(\cos \theta)
\]

\[
\phi_a^{(l)}(v) = \frac{1}{2l+1} \left[ \int v^{2l+1} f_a^{(l)}(v') dv' + \int v^{2l+1} f_a^{(l)}(v') dv' \right]
\]

\[
\psi_a^{(l)}(v) = \frac{1}{2(l+1)^2 - 1} \left[ \int v^{2l+2} f_a^{(l)}(v') dv' + \int v^{2l+2} f_a^{(l)}(v') dv' \right]
\]

† Legendre Polynomial Expansion

\[
f_a(v, \theta) = \sum_{l=0}^{\infty} f_a^{(l)}(v) P_l(\cos \theta)
\]

\[
f_a^{(l)}(v) = \frac{1}{2l+1} \int f_a(v, \theta) P_l(\cos \theta) \sin \theta d\theta
\]

\(P_l(\mu) = 1\)

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

**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 trapped particles and passing particles

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

<table>
<thead>
<tr>
<th>Energy</th>
<th>Collision frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_e kV</td>
<td>n_i 1.0 x 10^{20} m^{-3}</td>
</tr>
<tr>
<td>T_i kV</td>
<td>n_i 2.0 x 10^{20} m^{-3}</td>
</tr>
<tr>
<td>NBI(1MW/m^2 200keV)</td>
<td>n_i 1.0 x 10^{20} m^{-3}</td>
</tr>
</tbody>
</table>

Objective

- Assuming LHD type reactor as a typical helical reactor, we investigate the helical fusion reactor in a view point of the \( \alpha \)-particle confinement.
- We include the collisional effects (the energy and pitch angle scattering) and evaluated the distribution function of \( \alpha \)-particles.
- We analyze including the both complicated orbit and nonlinear collision effects in order to make clear the \( \alpha \)-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 : 1000 m^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 \( C^{nonlinear} \).

\[
C^{coll}(f) = C^{linear}(f) + C^{nonlinear}(f)
\]

The linear collision operator : \( C^{linear} \)

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

Pitch angle :

\[
\lambda_n = \lambda_{n-1} - \sum_i \left( \frac{\nu_d r^2}{2} \left[ 1 - \lambda^2_{n-1} \right] \nu^2 r^2 \right)^{1/2}
\]

Energy :

\[
E_n = E_{n-1} - \sum_i \left( \frac{2 \nu_d r^2}{2} \left[ F_{n-1} \left( \frac{3}{2} + \frac{E_{n-1}}{2} \frac{d\nu^2}{dE_{n-1}} \right) \right] \right)
\]

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We improve the GNET code to take into account the nonlinear collision effect on the \( \alpha \)-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.

Reference


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Summary

We will benchmark the nonlinear collision operator using the same background distributions.