Simulation Study of Energetic Triton Confinement in the D-D Experiment on LHD

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Introduction

Energetic particles in fusion plasmas

- Nuclear fusion reactions
  \[ \text{D} + \text{T} \rightarrow \text{He}^+(3.52 \text{MeV}) + \text{n}(14.06 \text{MeV}) \]
  \[ \text{D} + \text{D} \rightarrow \text{T}(1.01 \text{MeV}) + \text{p}(3.03 \text{MeV}) \]
- Energetic particles give their energy to background ions and electrons through Coulomb collisions and heat the plasma.
- Energetic alpha particles produced by D-T fusion reactions heat the plasma, and the high-temperature plasma can be sustained without any additional power input from outside.
- Loss of energetic alpha particles deteriorates the heating of the plasma. Also, it might severely damage the first wall of the reactor.

Confinement of high-energy alpha particles for a sufficiently long time is of great importance.

Helical fusion reactors

- External coils are applied to induce a toroidal and poloidal magnetic field in order to confine the high-temperature plasma.
- Magnetic field configurations are inherently three-dimensional, and motions of trapped energetic particles are complicated.
  → These motions can lead to a loss of the energetic particles.
- In helical systems, the small modulations generated by the helical coils can be seen in the magnetic field, in addition to the large modulations due to the toroidal modes.

The transition between passing and trapped particle orbits can enhance the radial diffusion of the energetic particles.

LHD D-D experiment

In LHD, experiments using deuterium plasmas are planned to be performed in order to make clear the isotope effect on energy confinement, turbulent transport, and energetic ion confinement.

The plasma confinement improvement is expected by use of deuterium plasmas.

Simulation conditions

- Confinement of tritons in the D-D experiment on LHD is simulated assuming the typical values for the plasma parameters, as shown in the table.
- The ion temperature is assumed to be equal to the electron temperature. The bulk plasma is assumed to be the hydrogen-deuteron mixture plasma with an equal amount.
- Assuming tangential NBI (with energy \( E_b = 180 \text{keV} \)), we evaluate the quantities per 1 MW of heat power.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron temperature at the magnetic axis</td>
<td>( T_e(0) = 3.0 \text{keV} )</td>
</tr>
<tr>
<td>Electron temperature at the outermost surface</td>
<td>( T_e(a) = 0.1 \text{keV} )</td>
</tr>
<tr>
<td>Electron density at the magnetic axis</td>
<td>( n_e(0) = 2.0 \times 10^{19} \text{m}^{-3} )</td>
</tr>
<tr>
<td>Electron density at the outermost surface</td>
<td>( n_e(a) = 0.1 \times 10^{19} \text{m}^{-3} )</td>
</tr>
<tr>
<td>Magnetic field strength</td>
<td>( B_0 = 2.75 \text{T} )</td>
</tr>
<tr>
<td>Magnetic axis major radius</td>
<td>( R_a = 3.60 \text{m} )</td>
</tr>
<tr>
<td>Beta value</td>
<td>( \beta = 0.23 % )</td>
</tr>
</tbody>
</table>

\[ T_e(r) = (T_e(0) - T_e(a)) \left[1 - \left(\frac{r}{a}\right)^2\right] + T_e(a) \]

\[ n_e(r) = (n_e(0) - n_e(a)) \left[1 - \left(\frac{r}{a}\right)^2\right] + n_e(a) \]

Birth profile of tritons

- The radial birth profile of the 1 MeV tritons is evaluated applying the FIT3D-DD code.
- The population of the beam ions depends on their birth and slowing-down processes. Therefore, the triton production rate does not simply depend on the plasma density.

Velocity space distribution (\( r/a = 2.8 \times 10^{-3} \text{m}^{-2} \))

<table>
<thead>
<tr>
<th>Particle loss fraction</th>
<th>Energy loss fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>(I) ( t = 1 \times 10^{-5} \text{s} )</td>
<td>(I) ( t = 0.3 \times 10^{-5} \text{s} )</td>
</tr>
<tr>
<td>Particle loss fraction</td>
<td>30 %</td>
</tr>
<tr>
<td>Energy loss fraction</td>
<td>30 %</td>
</tr>
</tbody>
</table>

Loss of the tritons

- A lot of tritons escape with nearly the initial energy 1 MeV. This is the prompt orbit loss due to the drift motion immediately after their birth.
- In the passing region \( (v_\parallel > v_\perp) \), we can see the tritons which get partially thermalized before reaching the LCFS. This is because the passing particles moving near the LCFS undergo pitch-angle scatterings due to the collisions with the bulk ions.
- In the region with a pitch angle \( \theta \sim 120^\circ \), a large number of lost particles can be seen regardless of their energy. This tendency results from the stochastic diffusion of the transition particles.
> During the D-D discharges, 1 MeV tritons are produced by fusion reactions between deuterium NBI (Neutral Beam Injection) beams and deuterium thermal ions.

> Confinement and slowing down of the energetic tritons can be experimentally investigated by detecting 14 MeV neutrons generated by D-T reactions between the tritons and deuterium plasmas [1].

**Objective of this study**

> The 1 MeV tritons have similar kinetic properties to those of D-T produced 3.5 MeV alpha particles. Thus, to clarify the behavior of the energetic tritons would make it possible to experimentally verify the alpha particle confinement in D-T plasmas, which is of great importance for sustaining high temperature burning plasmas.

> In this study, we investigate the confinement of energetic tritons by the five-dimensional drift kinetic equation solver GNET assuming the LHD deuterium plasmas and predict the measurement in the upcoming D-D experiment.

> Energetic particle confinement in helical systems can be verified experimentally investigated by detecting 14 MeV neutrons generated by D-T reactions between the tritons and deuterium plasmas [1].

**CNET code [2,3]**

> The drift kinetic equation below is solved in five-dimensional phase space based on Monte Carlo methods in order to obtain the distribution function of the tritons.

> The test particle orbits is followed with high accuracy using the sixth-order Runge-Kutta method.

> In the GNET code, a particle is regarded as lost when it has reached the last closed flux surface (LCFS).

\[
\frac{df}{dt} + (v_{\parallel} + v_{\perp}) \cdot \nabla f + \dot{v} \cdot \nabla f = C_{\text{coll}}(f) + L_{\text{particle}} + S_{T}
\]

\(f\) : the distribution function of the tritons \n\(v_{\parallel}\) : the parallel velocity to the field line \n\(v_{\perp}\) : the perpendicular velocity \n\(C_{\text{coll}}\) : the linear Coulomb collision operator \n\(L_{\text{particle}}\) : the particle loss term \n\(S_{T}\) : the source term of the tritons

**FED-D-D code**

> The heat-deposition profiles of electrons and ions due to NBI are evaluated.

> Using the cross section below [4], we calculate the D(d,p)T fusion reaction rates between deuterium beams and deuterium thermal ions and evaluate the source profile of tritons.

\[
\sigma_{\text{D-D}}(E) = \int \int \int f_{\text{thermal}}(v) f_{\text{beam}}(v_{\text{beam}}) \sigma_{\text{D-D}}(E) \, dv_{\text{beam}} \, dv_{\text{D}} \, dv_{\text{D}}
\]

\(\sigma_{\text{D-D}}\) : the cross section of the D-D reaction \n\(f_{\text{thermal}}\) : the thermal distribution function \n\(f_{\text{beam}}\) : the beam distribution function

**Parameter Dependences**

- The prompt orbit loss fraction does not depend on the plasma density.
- In the case of \(n_e = 3.5 \times 10^{19} \text{m}^{-3}\), the diffusive loss fraction is about 7% lower than that in the case of \(n_e = 0.8 \times 10^{19} \text{m}^{-3}\) because of the shorter slowing-down time.

**On the plasma density**

<table>
<thead>
<tr>
<th>(\ell = 1 \times 10^{-6} \text{s}) (prompt orbit loss)</th>
<th>(\ell = 0.3 \text{s}) (orbit + diffusive loss)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(n_e = 0.8 \times 10^{19} \text{m}^{-3})</td>
<td>30%</td>
</tr>
<tr>
<td>(n_e = 2.0 \times 10^{19} \text{m}^{-3})</td>
<td>30%</td>
</tr>
<tr>
<td>(n_e = 3.5 \times 10^{19} \text{m}^{-3})</td>
<td>31%</td>
</tr>
</tbody>
</table>

> When the magnetic axis is shifted outward, the particle orbit greatly deviates from the flux surface and the prompt orbit loss fraction increases.

**Summary**

> We have evaluated the velocity distribution of the tritons by the GNET code and analyzed the loss mechanisms of the energetic tritons (the prompt orbit loss and the diffusive loss). Furthermore, we have calculated the particle and energy loss fractions and investigated the dependencies on the plasma parameters.

> In the D-D experiment, 14 MeV neutrons are produced by the D-T fusion reactions between tritons and deuterium plasmas. It is necessary to simulate the triton burn-up and predict the signals of the neutron measurement systems in the deuterium experiments of LHD.

**References**