Simulation Study of Triton Confinement and Nuclear Reaction in the Deuterium Plasma Experiment at LHD

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Abstract:
Deuterium plasma experiments are planned in Large Helical Device (LHD). During deuterium plasma discharges, 1 MeV tritons are produced by D-D fusion reactions between deuterium beams and deuterium thermal plasmas. The motions of these energetic tritons are complicated because of their large finite orbit effect and the three-dimensional magnetic field configuration of LHD. The confinement of energetic tritons is investigated by the Global NEoclassical Transport (GNET) code, which can solve the five-dimensional drift kinetic equation using Monte Carlo methods. We evaluate the velocity space distribution and particle loss fraction of the energetic tritons. The loss of the tritons is attributed to two processes: prompt orbit loss and diffusive loss. The loss fraction of energetic tritons increases to 30% on a short time scale of approximately \(10^{-5}\) s by prompt orbit loss and then gradually increases to 90% on a slow-down time scale of approximately \(10^{-1}\) s by diffusive loss for the assumed plasma parameters. The prompt loss fraction is also almost independent of the plasma density and largely depends on the magnetic configuration. Furthermore, the amount of neutrons generated by D-T fusion reactions between tritons and deuterium thermal ions is estimated.

1 Introduction

Energetic tritons of 1 MeV are produced by D(d,p)T fusion reactions during D-D discharges, and the secondary D-T fusion reactions between tritons and deuterium plasmas produce 14 MeV neutrons. The confinement and slowing down of energetic tritons can be experimentally investigated by measuring the production rate of 14 MeV neutrons. These experiments have been performed in JT-60U \(^1\) known as triton burn-up experiments.

In the Large Helical Device (LHD), experiments using deuterium plasmas are planned to clarify the isotope effect on energy confinement or turbulent transport and to understand energetic ion confinement. Plasma confinement is expected to improve by use of deuterium plasmas. In the deuterium experiments, 1 MeV tritons are produced by fusion reactions between deuterium Neutral Beam Injection (NBI) beams and deuterium
thermal ions. Understanding the behavior of energetic tritons would make it possible to experimentally study energetic particle confinement in future reactors.

In helical systems such as LHD, however, motions of the energetic tritons are complicated since magnetic field configurations are inherently three dimensional. In addition, energetic tritons have large orbits that can easily become complicated. These complicated motions may lead to a significant loss of energetic tritons.

In this study, we investigate the confinement of energetic tritons for the LHD deuterium plasma using the Global NEoclassical Transport (GNET) code, in which the drift kinetic equation of energetic particles is solved in five-dimensional phase space. The velocity distributions of energetic tritons are calculated over a range of minor radii, and we present the characteristics of the triton distribution in velocity space. Next, we calculate the energy and particle loss fractions of tritons and investigate their dependence on plasma parameters. Finally, we evaluate T(d,α)n nuclear reaction rates using the obtained velocity distribution of tritons and simulate triton burn-up in the LHD deuterium plasmas.

2 Simulation Model

We apply the GNET code\cite{2,3}, in which finite drift orbits and complex motions of trapped particles are included, to solve the drift kinetic equation using Monte Carlo methods. The drift kinetic equation for tritons in five-dimensional phase space is described as follows:

\[ \frac{\partial f_T}{\partial t} + (v_\parallel + v_{dr}) \cdot \frac{\partial f_T}{\partial x} + v \cdot \frac{\partial f_T}{\partial v} = C_{\text{coll}}(f_T) + L_{\text{particle}}(f_T) + S_T, \]

where \( f_T \) is the distribution function of tritons, \( v_\parallel \) is velocity parallel to the field line, \( v_{dr} \) is the drift velocity, \( C_{\text{coll}}(f_T) \) is a linear Coulomb collision operator, \( L_{\text{particle}}(f_T) \) is the particle loss term from the last closed flux surface (LCFS), and \( S_T \) is the source term of the tritons.

GNET is also applied to evaluate the source profile of the tritons solving the drift kinetic equation for NBI beam ions. Using the distribution functions of NBI deuterons obtained by GNET, we calculate the D(d,p)T fusion reaction rates between deuterium beams and thermal deuterium ions. The averaged reaction rate of the D(d,p)T reaction can be expressed as follows:

\[ \langle \sigma_{DD} v \rangle = \int \int f_D^{\text{beam}}(v_D^{\text{beam}}) f_D^{\text{th}}(v_D^{\text{th}}) \sigma_{DD}(E_{DD}) |v_D^{\text{beam}} - v_D^{\text{th}}| dv_D^{\text{beam}} dv_D^{\text{th}}, \]

where \( f_D \) and \( v_D \) represent distribution function and velocity of deuterons. The suffix beam and th mean the NBI fast ion and Maxwellian thermal ion respectively. The cross section \( \sigma_{DD} \) is given as follows\cite{4}:

\[ \sigma_{DD}(E_{DD}) = \left[ (1.220 - 4.36 \times 10^{-4} E_{DD})^2 + 1 \right]^{-1} \times 372 \frac{1}{E_{DD} \left[ \exp \left( 46.097 E_{DD}^{1/3} \right) - 1 \right]}, \]
where $E_{dd}$ is the deuteron kinetic energy for the relative velocity between the Maxwell plasma and the deuteron beam-ion.

Using the distribution functions of tritons obtained by GNET, we calculate the $T(d,\alpha)n$ fusion reaction rates between energetic tritons and thermal deuterium ions. Similarly, the average of reactivity for the $T(d,\alpha)n$ reaction can be expressed as follows:

$$
\langle \sigma_{DT}v \rangle = \int \int f_{\text{th}}^{(v_{th})} \sigma_{DT}(E_{DT})|v_{D}^{th} - v_T| dv_{D}^{th} dv_T,
$$

where $v_T$ is velocity of energetic tritons. The cross section for the reaction is given as follows\[4\]:

$$
\sigma_{DT}(E_{DT}) = \frac{409 + \left(1.076 - 1.368 \times 10^{-10} E_{DT}\right)^2 + 1}{E_{DT} \left[ \exp \left(49.95 E_{DT}^{\frac{1}{2}}\right) - 1 \right]^{-1} \times 50200},
$$

where $E_{DT}$ is the deuteron kinetic energy for the relative velocity between the Maxwell deuterium plasma and the fast triton.

3 Results

Confinement of tritons in the D-D experiment on LHD is simulated assuming typical values for the plasma parameters: core electron temperature $T_e(0) = 3.0$ keV; edge electron temperature $T_e(a) = 0.1$ keV; core ion temperature $T_i(0) = 3.0$ keV; edge ion temperature $T_i(a) = 0.1$ keV; core electron density $n_e(0) = 0.8, 2.0, \text{ and } 3.5 \times 10^{19} \text{ m}^{-3}$; edge electron density $n_e(a) = 0.1 \times 10^{19} \text{ m}^{-3}$; magnetic field strength $B_0 = 2.75$ T; magnetic axis major radius $R_{ax} = 3.60$ m; and beta value $\beta = 0.23\%$. The radial profiles of plasma temperature and density are given by

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

$$
n_e(r) = (n_e(0) - n_e(a)) \left[1 - \left(\frac{r}{a}\right)^8\right] + n_e(a).
$$

The bulk plasma is assumed to be a hydrogen-deuterium mixed plasma with equal amounts of each species.

Five NBI heating systems are installed in the LHD: three tangential injection beams ($E_b = 180$ keV) and two perpendicular beams ($E_b = 40$ keV). The injection energy is much higher for the tangential injection beams, and the fusion reactions between the tangential injection beams and the thermal ions are dominant in the LHD deuterium plasma experiments. Assuming tangential NBI with energy $E_b = 180$ keV, we evaluate the quantities per megawatt of heat power.

We evaluate the D-D fusion reaction rate applying the velocity distribution of deuteron beams obtained by the GNET code. In Fig. the radial profiles of the evaluated triton
production rate due to D-D fusion reactions in various density and magnetic configuration cases are shown. It is found that the triton production rate does not simply depend on the density or the position of the magnetic axis because the population of energetic beam ions depends on the beam ion birth and slowing-down process. Hence, interestingly, the highest production rate occurs at \( n_e(0) = 2.0 \times 10^{19} \text{ m}^{-3} \). The total production rate of tritons per 1 MW of heat power is approximately \( 3 \times 10^{14} \text{ s}^{-1} \) regardless of the plasma density or the magnetic configurations.

We apply the calculated source term to the GNET code and evaluate the triton distribution in velocity and real spaces. First, we calculate at the typical case of density \( n_e(0) = 2.0 \times 10^{19} \text{ m}^{-3} \) and magnetic configuration \( R_{\text{ax}} = 3.60 \text{ m} \). The velocity distributions at minor radii \( r/a = 0.2, 0.5, \) and 0.9 and the total are presented in Fig. 2. Here \( v_\parallel \) and \( v_\perp \) represent the parallel and perpendicular velocity components relative to the magnetic field direction, and they are normalized by the velocity of 1 MeV tritons \( v_{1\text{MeV}} \).

In Fig. 2(a), a relatively large number of tritons are seen in the region where \( |v_\perp| \gg |v_\parallel| \). These are the deeply helically trapped particles, whose orbits are stable along helical ripples. However, the distribution is reduced in the neighboring region \( (|v_\perp| > |v_\parallel|) \). Particles in this region make a transition between passing and trapped particle orbits and behave as stochastic particles. The stochastic behavior of the transition particles would enhance the radial diffusion of energetic particles. In Fig. 2(b) and (c), we see a small or negligible distribution of deeply trapped particles. This is because helically trapped particles drift to the region close to the plasma edge in those radial positions and are easily lost by orbit loss.

In Fig. 3, typical orbits of the energetic tritons in the poloidal cross section at various pitch angles are shown. The direction of the magnetic field is upward orthogonal to the page, and the direction of \( \nabla B \) is leftward parallel to the page. Starting at time \( t = 0 \text{ s} \) at minor radius \( r/a = 0.5 \) and poloidal angle \( \theta = 90^\circ \), a triton with \( v_\parallel > 0 \) moves poloidally in a counterclockwise orbit. The stable motion of deeply trapped particles and the stochastic behavior of the transition particles are seen in Fig. 3(a) and (b), respectively. Due to the
poloidal drift motion, the orbit of the passing particles with \( v_\parallel > 0 \) is shifted outward, while that with \( v_\parallel < 0 \) is shifted inward. This is the reason for the asymmetry of the velocity distributions at \( r/a = 0.2 \) (Fig. 3(c)) and at \( r/a = 0.9 \) (Fig. 3(d)).

The lost triton distribution in velocity space is presented in Fig. 4. In the GNET code, a particle is considered to be lost when it has reached the LCFS. The particle loss mechanism in fusion plasmas is classified into two major categories: prompt orbit loss and diffusive loss. A lot of tritons escape with almost all of their initial energy of 1 MeV. This is prompt orbit loss due to drift motion immediately after their birth. In the passing region, we can notice the tritons that get partially thermalized before reaching the LCFS. This occurs because the passing particles moving near the LCFS undergo pitch-angle scatterings due to collisions with bulk ions. In the region with pitch angle \( p \sim 120^\circ \), a large number of lost particles can be seen independent of their energy. This tendency results from stochastic diffusion of the transition energetic tritons, as mentioned above.

The temporal history of particle and energy loss fraction is presented in Fig. 5. Prompt orbit loss normally occurs before a particle has completed its first orbit in the poloidal direction, i.e., before \( t \sim 10^{-5} \) s. In this calculation, 30% of the tritons generated escape as a result of prompt orbit loss, and then diffusive loss becomes dominant. The total particle loss fraction, which is the sum of the prompt orbit and diffusive loss fractions, reaches 96% at \( t = 0.3 \) s with the energy loss fraction at 92%. Particle and energy loss fractions obtained in this calculation can be more or less overestimated because re-entering particles are not considered in the GNET code. The energy loss fraction is a little lower than the particle loss fraction. This suggests that a triton loses some of its energy due to collisions with the bulk plasma before reaching the LCFS.
FIG. 3: Typical orbits of (a) helically trapped particle (θ_p = 92°), (b) transition particle (θ_p = 110°), (c) passing particle with v_∥ > 0 (θ_p = 10°), and (d) passing particle with v_∥ < 0 (θ_p = 170°).

FIG. 4: Contours of the velocity distribution function of tritons that escaped from the plasma.
We investigate the dependence of particle loss fraction on the plasma parameters. In Fig. 5(a), a comparison of the particle loss fractions for the three cases, $n_e(0) = 0.8, 2.0,$ and $3.5 \times 10^{19} \text{m}^{-3}$, is presented for fixed ion and electron temperatures, $T_i(0) = T_e(0) = 3.0 \text{keV}$. In the case of $n_e(0) = 0.8 \times 10^{19} \text{m}^{-3}$, the prompt orbit loss fraction is 30% and the total loss fraction increases to 98% at $t = 0.3 \text{s}$. When $n_e(0) = 3.5 \times 10^{19} \text{m}^{-3}$, 30% of all the tritons are lost from the confinement domain due to prompt orbit loss, and in total 92% have entered the loss region by time $t = 0.3 \text{s}$. Changes in the plasma density have little effect on prompt orbit loss. For $n_e(0) = 3.5 \times 10^{19} \text{m}^{-3}$, however, the diffusive loss fraction is approximately 6% lower than that for the case $n_e(0) = 0.8 \times 10^{19} \text{m}^{-3}$. The slowing-down time of energetic tritons due to collisions with background plasmas depends inversely on plasma density. Hence, the slowing-down time is shorter for the higher density case and the diffusive loss of tritons is reduced.

The loss dependence on the position of the magnetic axis is presented in Fig. 5(b). When $R_{ax} = 3.50 \text{m}$, the prompt orbit loss fraction is 25% and the total loss fraction

![FIG. 5: Temporal history of (a) particle loss fraction and (b) energy loss fraction.](image)

![FIG. 6: Dependence of particle loss fraction on (a) plasma density ($n_e(0) = 0.8, 2.0,$ and $3.5 \times 10^{19} \text{m}^{-3}$) and (b) magnetic configurations ($R_{ax} = 3.50, 3.60,$ and $3.75 \text{m}$).](image)
is 89% at $t = 0.3 \text{s}$ In the magnetic configuration $R_{\text{ax}} = 3.75 \text{m}$, which is the standard configuration in LHD, the prompt orbit loss rate is as high as 45%. When the magnetic axis is shifted outward, the particle orbit greatly deviates from the flux surface and the prompt orbit loss fraction increases.

We evaluate the secondary D-T reaction rate applying the obtained distribution functions of tritons. In Fig. 7, the radial profiles of the evaluated production rate of 14 MeV neutrons in various density and magnetic configuration cases are shown. The fusion rates peak at approximately $r/a = 0.2$ because of the presence of well-confined trapped particles. In these radial positions, energetic particles deeply trapped in helical ripples exist as seen in Fig. 2(a). It is found that those trapped tritons significantly contribute to fusion reactions with background deuterons. In the magnetic configuration $R_{\text{ax}} = 3.50 \text{m}$, however, the distribution has a flat peak near $r/a = 0.2$ because there are few trapped tritons in the radial position.

We calculate the total production rates of 14 MeV neutrons integrated over the plasma volume. The value is $6.5 \times 10^{10} \text{s}^{-1}$ for the typical plasma parameters; $n_e(0) = 2.0 \times 10^{19} \text{m}^{-3}$ and $R_{\text{ax}} = 3.60 \text{m}$. Figure 8(a) indicates the dependences of the neutron emission rates on the plasma density. The production rate increases with the plasma density because the fusion rate is proportional to the density of target deuterons. In Fig. 8(b), a comparison of the D-T neutron emission rates for the three configurations is presented. When the magnetic axis is shifted outward, the loss of energetic tritons increases as shown in Fig. 6(b). Therefore, the production rate is the lowest for the magnetic configuration $R_{\text{ax}} = 3.75 \text{m}$.

4 Conclusion

We have investigated the confinement of tritons in the LHD plasma during the D-D experiment using GNET, the five-dimensional drift kinetic equation solver. The triton production rate has been evaluated by using the distribution function of NBI deuterons

![Graphs](attachment:fig7.png)

**FIG. 7:** Radial birth profile of neutrons with different (a) plasma density ($n_e(0) = 0.8, 2.0, \text{ and } 3.5 \times 10^{19} \text{m}^{-3}$) and (b) magnetic configurations ($R_{\text{ax}} = 3.50, 3.60, \text{ and } 3.75 \text{m}$).
and the dependency of the production rate on the plasma parameters has been calculated. We have evaluated the velocity distribution of the tritons and analyzed the loss mechanisms of energetic tritons. Prompt orbit loss begins immediately after the birth of tritons, and later the diffusive loss, which is caused by stochastic behavior of the transition particles and pitch-angle scatterings of the passing particles, is the primary cause of continuing particle loss. Furthermore, we have calculated the particle and energy loss fractions and investigated the dependence on plasma parameters. Finally, we have simulated triton burn-up and estimated the amount of 14 MeV neutrons produced by D-T fusion reactions between tritons and deuterium plasmas.

In the deuterium experiment plasma, beam-beam reactions, in which both reacting ions are injected NBI deuterons, would also occur as well as beam-thermal reactions. Therefore, it is necessary to estimate the contribution of beam-beam fusion reactions for more precise prediction of triton burn-up ratios and neutron production rates.

References