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

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(Received 26 November 2014 / Accepted 25 February 2015)

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.

Keywords: LHD, deuterium experiment, triton, energetic particle, GNET

DOI: 10.1585/pfr.10.3403050

1. Introduction

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. It is important to understand the isotope effect for designing future fusion reactors.

During the D-D discharges, 1 MeV tritons are produced by fusion reactions between deuterium Neutral Beam Injection (NBI) beams and deuterium thermal ions. The kinetic properties of 1 MeV tritons are expected to be similar to those of alpha particles produced by D-T reactions in a fusion reactor. Therefore, understanding the behavior of energetic tritons would make it possible to experimentally verify alpha particle confinement in D-T plasmas, which is of great importance for sustaining high temperature burning plasmas. 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 [1]. It is necessary to simulate triton burn-up and predict the signals of the neutron measurement systems in the deuterium experiments on LHD.

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.

2. Simulation Model

We apply the GNET code [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:

$$\frac{\partial f_{\mathrm{T}}}{\partial t} + (\mathbf{v}_{\parallel} + \mathbf{v}_{\mathrm{dr}}) \cdot \frac{\partial f_{\mathrm{T}}}{\partial \mathbf{x}} + \dot{\mathbf{v}} \cdot \frac{\partial f_{\mathrm{T}}}{\partial \mathbf{v}} = C^{\mathrm{coll}}(f_{\mathrm{T}}) + L^{\mathrm{particle}}(f_{\mathrm{T}}) + S_{\mathrm{T}}, \quad (1)$$

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*) This article is based on the presentation at the 24th International Toki Conference (ITC24).

where f_T is the distribution function of tritons, $\mathbf{v}_{\|}$ is velocity parallel to the field line, $\mathbf{v}_{dr}$ is the drift velocity, $C^{coll}(f_T)$ is a linear Coulomb collision operator, $L^{particle}(f_T)$ is the particle loss term from the last closed flux surface (LCFS), and S_T is the source term of the tritons.

To evaluate the source profile of tritons for the GNET code, we use the FIT3D-DD code, which can calculate the D(d,p)T fusion reaction rates between deuterium beams and thermal deuterium ions. The cross section for the D(d,p)T reaction is given as follows [4]:

$$\sigma_{DD}(E) = \frac{\left[\left(1.220 - 4.36\times 10^{-4}E\right)^2 + 1\right]^{-1} \times 372}{E\left[\exp\left(46.097E^{-\frac{1}{2}}\right) - 1\right]}, \quad (2)$$

where E is the deuteron kinetic energy for the relative velocity between the Maxwell plasma and the fast beam-ion.

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 $n_e(0) = 0.8, 2.0$, and $3.5 \times 10^{19}\,\mathrm{m}^{-3}$; edge electron density $n_e(a) = 0.1 \times 10^{19}\,\mathrm{m}^{-3}$; 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

$$T_e(r) = (T_e(0) - T_e(a))\left[1 - \left(\frac{r}{a}\right)^2\right] + T_e(a), \quad (3)$$

$$n_e(r) = (n_e(0) - n_e(a))\left[1 - \left(\frac{r}{a}\right)^8\right] + n_e(a). \quad (4)$$

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.

To evaluate the D-D fusion reaction rate, we use the FIT3D-DD code, which is an extension of FIT3D, to calculate the D-D fusion reaction rate in helical plasmas. In Fig. 1, the radial profiles of the evaluated triton production rate due to D-D fusion reactions in the three density cases are shown. Each of the production rates peaks at approximately $r/a = 0.4$ because of the peak position of the NBI beam ions. It is found that the triton production rate does not simply depend on the density 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 $n_e(0) = 2.0 \times 10^{19}\,\mathrm{m}^{-3}$.

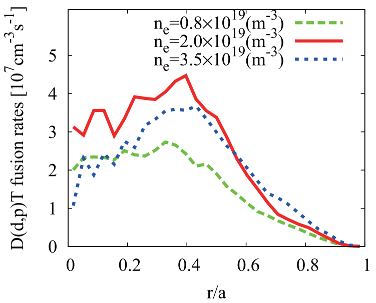


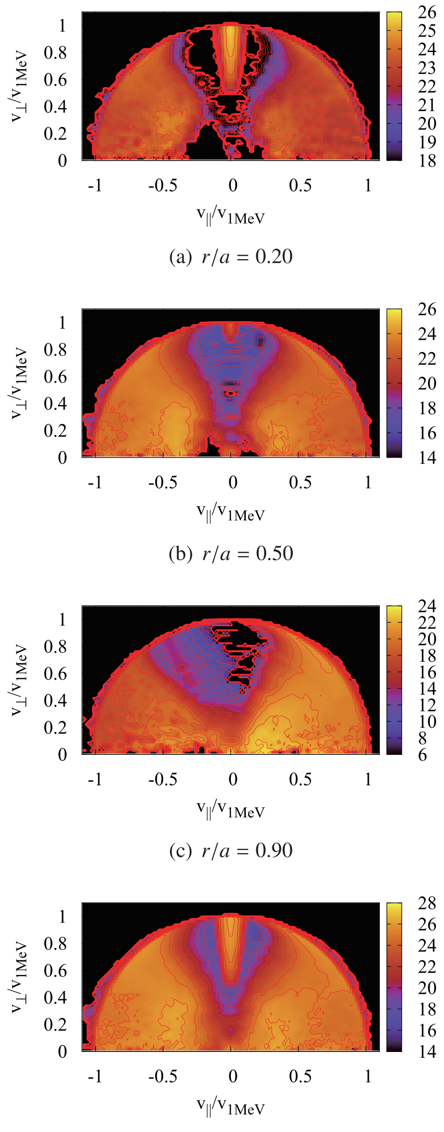
Fig. 1 Radial birth profile of tritons calculated by the FIT3D-DD code.

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 density case $n_e(0) = 2.0 \times 10^{19}\,\mathrm{m}^{-3}$. The velocity distributions at minor radii $r/a = 0.2, 0.5$, and 0.9 and the total are presented in Fig. 2. Here $v_{\|}$ 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 $v_{1\,\mathrm{MeV}}$.

In Fig. 2 (a), a relatively large number of tritons are seen in the region where $|v_{\perp}| \gg |v_{\|}|$. These are the deeply helically trapped particles, whose orbits are stable along helical ripples. However, the distribution is reduced in the neighboring region ($|v_{\perp}| > |v_{\|}|$). 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 Figs. 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 ∇B is leftward parallel to the page. Starting at time $t = 0$ s at minor radius $r/a = 0.5$ and poloidal angle $\theta = 90°$, a triton with $v_{\|} > 0$ moves poloidally in a counterclockwise orbit. The stable motion of deeply trapped particles and the stochastic behavior of the transition particles are seen in Figs. 3 (a) and (b), respectively. Due to the poloidal drift motion, the orbit of the passing particles with $v_{\|} > 0$ is shifted outward, while that with $v_{\|} < 0$ 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



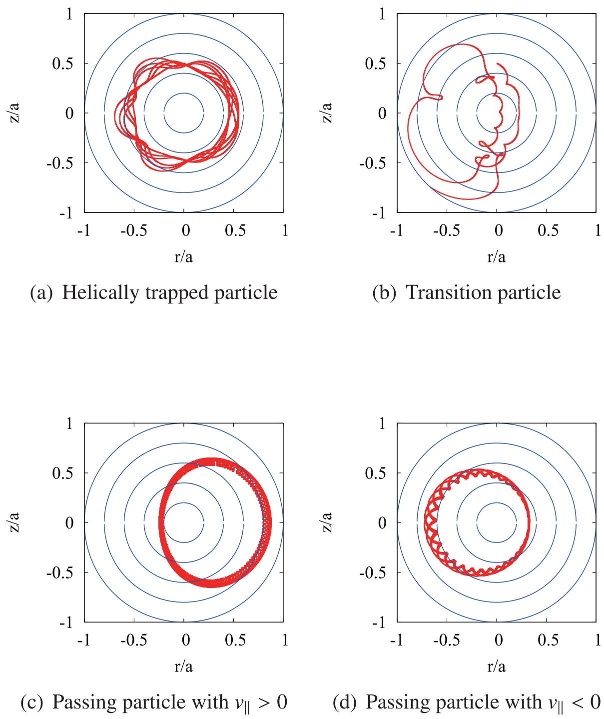
(a) r/a = 0.20

(b) r/a = 0.50

(c) r/a = 0.90

(d) total

Fig. 2 Contours of the velocity distribution function of tritons at different normalized minor radii: (a) r/a = 0.20 (near the magnetic axis), (b) r/a = 0.50, (c) r/a = 0.90 (near the LCFS), and (d) total.



(a) Helically trapped particle

(b) Transition particle

(c) Passing particle with $v_\parallel > 0$

(d) Passing particle with $v_\parallel < 0$

Fig. 3 Typical orbits of (a) helically trapped particle (θ_p = 92°), (b) transition particle (θ_p = 110°), (c) passing particle with $v_\parallel > 0$ (θ_p = 10°), and (d) passing particle with $v_\parallel < 0$ (θ_p = 170°).

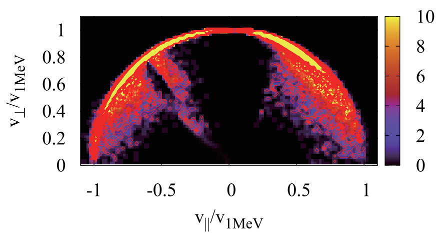
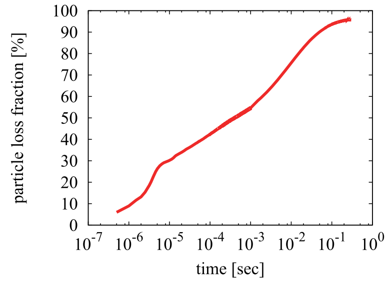


Fig. 4 Contours of the velocity distribution function of tritons that escaped from the plasma.

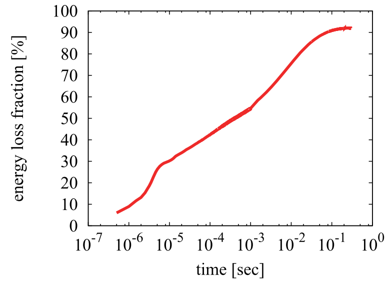
lot of tritons escape with almost all of their initial energy of 1 MeV. This is prompt orbit loss due to drift motion immediately after their birth. In the passing region, we can notice the tritons that get partially thermalized before reaching the LCFS. This occurs because the passing particles moving near the LCFS undergo pitch-angle scatterings due to collisions with bulk ions. In the region with pitch angle $\theta_p \sim 120°$, 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 [5] 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.

We investigate the dependence of particle loss fraction on the plasma parameters. In Fig. 6 (a), a comparison of the particle loss fractions for the three cases, $n_e(0)$ = 0.8, 2.0, and 3.5×10^{19} m^{-3}, is presented for fixed ion and electron temperatures, $T_i(0) = T_e(0)$ = 3.0 keV. In the case of $n_e(0) = 0.8 \times 10^{19}$ m^{-3}, the prompt orbit loss fraction is

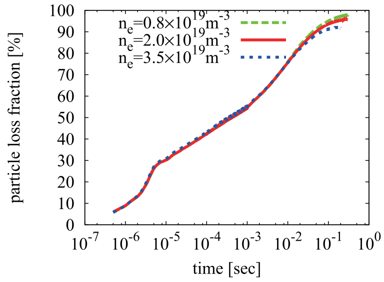


(a) Particle loss fraction

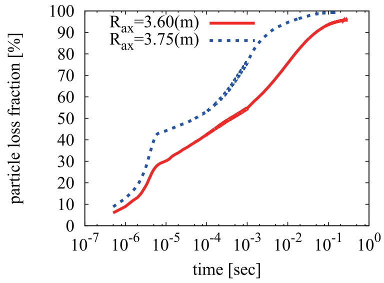


(b) Energy loss fraction

Fig. 5 Temporal history of (a) particle loss fraction and (b) energy loss fraction.



(a) On plasma density



(b) On magnetic configurations

Fig. 6 Dependence of particle loss fraction on (a) plasma density ($n_e(0) = 0.8, 2.0$, and $3.5 \times 10^{19}\ \mathrm{m}^{-3}$) and (b) magnetic configurations ($R_{ax} = 3.60$ and 3.75 m).

30% and the total loss fraction increases to 98% at $t = 0.3$ s. When $n_e(0) = 3.5 \times 10^{19}\ \mathrm{m}^{-3}$, 31% 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 $t = 0.3$ s. Changes in the plasma density have little effect on prompt orbit loss. For $n_e(0) = 3.5 \times 10^{19}\ \mathrm{m}^{-3}$, however, the diffusive loss fraction is approximately 7% lower than that for the case $n_e(0) = 0.8 \times 10^{19}\ \mathrm{m}^{-3}$. 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 position is presented in Fig. 6 (b). In the magnetic configuration $R_{ax} = 3.75$ m, which is the standard configuration in LHD, the prompt orbit loss rate is as high as 44%. When the magnetic axis is shifted outward, the particle orbit greatly deviates from the flux surface and the prompt orbit loss fraction increases.

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 the FIT3D-DD code and the density dependency of the production rate 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.

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