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Study of first orbit losses of 1 MeV tritons using the Lorentz orbit code in the LHD

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Abstract

Shot-integrated measurement of the triton burnup ratio has been performed in the Large Helical Device (LHD). It was reported that the triton burnup ratio, defined as total DT neutron yield divided by total DD neutron yield, increases significantly in inward shifted configurations. To understand the magnetic configuration dependence of the triton burnup ratio, the first orbit loss fraction of 1 MeV tritons is evaluated by means of the Lorentz orbit code for various magnetic configurations. The first orbit loss of 1 MeV tritons is seen at *t* of less than 10^{-5} s and loss points of the triton are concentrated on the side of the helical coil case where the magnetic field is relatively weak. The significant decrease of the first-orbit loss fraction by 15% is obtained with the inward shift of the magnetic axis position from 3.90 m to 3.55 m. It is found that the decrease of first-orbit loss is due to the reduction of the first orbit loss of transition and helically trapped tritons.

Keywords: large helical device, tritons, energetic ion, first orbit loss, Lorentz orbit code

(Some figure may appear in colour only in the online journal)

1. Introduction

One of the key issues for sustaining fusion reactions in a burning plasma is how DT fusion born alpha particles are sufficiently confined. For understanding the alpha particle confinement property in a burning plasma, it is valuable to understand the confinement of energetic particles in existing torus fusion devices. Instead of alpha particles, neutral beam injection and the ion cyclotron range of frequency heating have been employed to study the energetic ion confinement [1]. In deuterium operations, confinement of 1 MeV tritons created by d(d,p)t reactions is intensively studied as a simulation study of alpha particle confinement because the Larmor radius and the precession frequency are the same as those of DT born 3.5 MeV alpha particles [2]. In addition, the velocity distribution of tritons is isotropic as alpha particles.

In tokamaks, study of 1 MeV triton confinement by experiments and numerical simulations has been intensively performed in the deuterium experiment [3-8]. In stellarator and heliotron, the study of the confinement property of alpha particles was performed using the orbit simulation in a fusion-reactor-relevant machine, of which the plasma volume is 1000 m^3 and the magnetic field strength is 5 T [9, 10]. The birth profile of alpha particles is proportional to n^2T^2, where n and T represent fuel ion density and fuel ion temperature, respectively. Therefore, the loss fraction of alpha particles born in the core region of the plasma was discussed because the alpha particles mainly born in the core region. It was reported that most of the alpha particles are confined during the collisional damping time [10]. The triton burnup experiment was initiated in the first campaign of deuterium operations in March 2017 on the Large Helical Device (LHD) [11]. This is the first triton burnup experiment in stellarators/helical devices. The triton burnup experiments are performed in neutral-beam heated deuterium plasmas. In these experiments, neutrons and 1 MeV tritons are mainly created by beam-thermal DD reactions. 1 MeV tritons created by DD reaction can undergo secondary DT reaction with the bulk deuteron while they slowed down. The triton burnup ratio defined by the total DT neutron amount per discharge divided by the total DD neutron amount per discharge is surveyed [12]. The scintillating fiber (Sci-Fi) detector using a discriminating method with absolutely calibrated by the neutron activation system is applied for DT neutron measurement and the neutron flux monitor is utilized for DD neutron measurement. It was reported that the triton burnup ratio significantly increases in the inward shifted configuration. In order to understand the significant increase of triton burnup ratio with the inward shift of the magnetic axis position, it is important to know the triton confinement properties in each magnetic configuration. When we considered a classical confinement of tritons, the loss of tritons could be caused due to the collisionless issue which is a result of the lost orbit, the collisional issue which the particle reaches the loss cone due to the collision, and the charge exchange with neutral gas. In these experiments, typical electron temperature T_e of 3 keV and typical electron density n_e of 2×10^{19} m^{-3}, therefore, it needs more than 2 seconds for 1 MeV triton to decrease its energy to 100 keV [13]. Here, the triton energy of around 100 keV is considered because the DT cross section has a peak around this energy. The typical charge exchange loss time of tritons is evaluated to be 40 ms. Here, neutral density of 10^{15} m^{-3} at $r/a < 0.6$ [14] is used because tritons mainly exist in the interior region of the plasma. The charge exchange cross section of 10^{-20} m^2 at the triton energy of around 100 keV [15] is used. Therefore, the loss of tritons which occurred in a short period of time, t of less than 1 ms, is mainly due to the collisionless issue. In particular, because the Larmor radius of 1 MeV triton evaluated by energy ~10 cm is comparable to the minor radius of the LHD ~60 cm, the first orbit loss could be a considerably large fraction in considering the confinement of 1 MeV tritons. In this paper, the first-orbit loss fraction of 1 MeV tritons is evaluated as a first step by means of the Lorentz orbit code in order to understand the magnetic configuration effect on the triton burnup ratio.

2. Setup for first orbit loss calculation

The Lorentz orbit following code developed by National Institute for Fusion Science (LORBIT) [16] is used to evaluate the first-orbit loss fraction of 1 MeV tritons. The code solves the equation of motion $m\,\mathrm{d}\boldsymbol{v}/\mathrm{d}t = q(\boldsymbol{E}+\boldsymbol{v}\times\boldsymbol{b})$ without including collisions. Here, m, v, q, E, and b represent the mass of charged particle, the velocity of charged particle, charge of the charged particle, the electric field, and the magnetic field, respectively. In this calculation, we used the magnetic field in a vacuum and assumed no electric field.

Note that the effect of the electric field on the 1 MeV triton orbit will be negligibly small because of the high energy of tritons. We used a random number generator to choose the radial position, the poloidal angle, the toroidal angle, the velocity component parallel to the magnetic field and the velocity component perpendicular to the magnetic field. Note that the normalized minor radius of the birth position of 1 MeV triton is chosen to be less than 0.2 because most tritons are mainly born in the core region of the plasma. Here, we choose the simple birth profile of 1 MeV triton in order to exclude plasma parameter effects to show the magnetic configuration effect on 1 MeV triton confinement clearly. The initial velocity of the tritons is uniformly distributed in the velocity space with the Monte Carlo method. In this calculation, we judged that a triton is lost when the triton reaches the vacuum vessel (VV). Figure 1 shows the poloidal cross section of VV, the last closed flux surface (LCFS), and birth positions of tritons in the magnetic axis R_{ax} of 3.55 m, 3.60 m, 3.75 m, and 3.90 m in the vertically elongated poloidal cross section. Note that the other in-vessel components are not included because the LHD has no limiter and no ICRF antenna is installed in these experiments. The divertor plate is placed far away from the plasma, the effect of divertor plates on the first orbit loss ratio of tritons will be very limited or negligible.

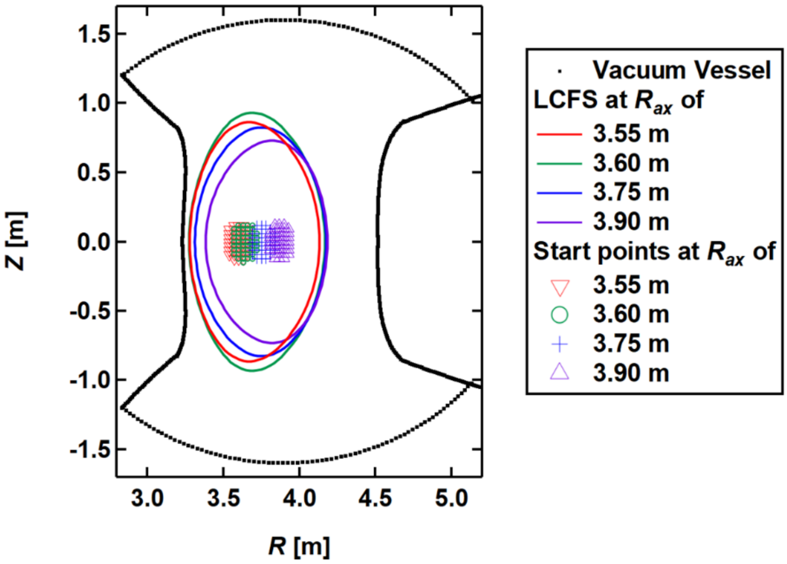

Figure 1. The poloidal cross section of the vacuum vessel of the LHD, the LCFS of R_{ax} of 3.60 m, 3.75 m, and 3.90 m at the vertical elongated poloidal cross section. Triton birth positions located at a normalized minor radius of less than 0.2.

In the LHD, there are four types of orbits depending on the pitch angle: co-passing transit, counter-passing transit, transition, and helically trapped orbits. The orbits of co-passing transit and counter-passing transit ions are similar to those in tokamaks, whereas helically trapped ions are trapped in a helical ripple created by a pair of twisted helical coils. The pitch angles of transition ions correspond to values between those of passing ions and those and helically trapped ions. The orbit of the transition particle is unstable and the confinement of transition ions is expected to be not good [17]. Typical 1 MeV triton orbits in R_{ax}/B_t of 3.60 m/2.75 T are shown in figure 2. In figure 2, initial pitch angles of co-passing transit, counter-passing transit, transition, and helically trapped tritons are 30 degrees, 150 degrees, 80 degrees, and 89 degrees, respectively. Here, the start point is set to be (R, Z, ϕ) of (3.61 m, −0.05 m, 0 degree) and orbit following time is set to be 10^{-5} s. In this case, co-passing transit, counter-passing transit, and helically trapped tritons are confined, whereas the transition triton is lost.

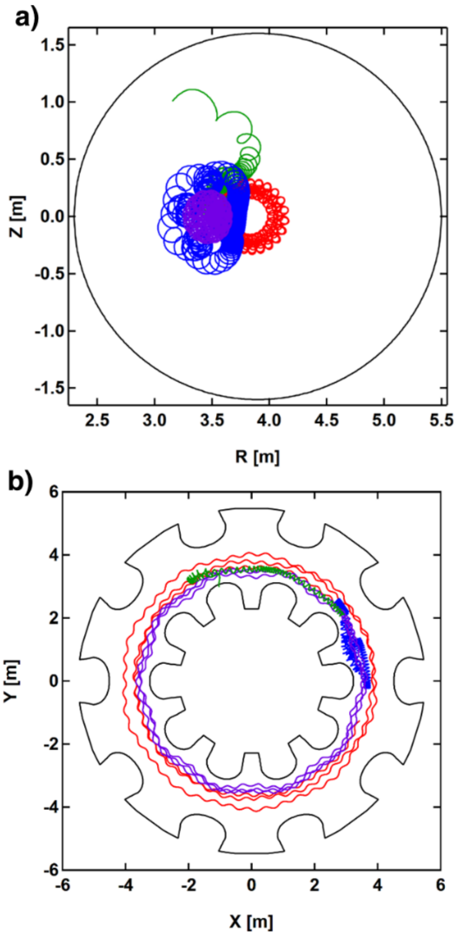

Figure 2. Typical orbit of 1 MeV tritons having the pitch angle of co-passing transit (red), transition (green), helically trapped (blue), and counter-passing transit (purple) region a) as projected into the (R, Z) plane and b) as seen from above.

3. First orbit loss calculation

An orbit following calculation for a relatively long time, around collision time of 1 MeV tritons, i.e., 1 ms is performed to see the time evolution of the loss fraction of tritons (figure 3). Here, we launched 5×10^5 particles. It is found that the loss fraction becomes lower with the inward shift of the magnetic axis position in the normal toroidal magnetic field strength (B_t > 2.5 T). The loss fraction of tritons rapidly increased with t of from 2×10^{-6} to 10^{-5} s, then became almost flat, and then increased again with time at B_t > 2.5 T. The loss of tritons which occurred at t less than 10^{-5} s corresponds to the first-orbit loss, whereas t greater than 10^{-5} s corresponds to a loss due to collisionless diffusion. Here, the collisionless diffusion occurs due to the trapping and detrapping of tritons by the magnetic field ripple. The time trend of the loss fraction is similar to the time trend obtained by the five dimensional drift kinetic equation solver based on the Boozer coordinates, Global NEoclasscal Transport code (GNET) [18]. Note that the plateau region appears because it may require time for tritons to reach the VV with the collisionless diffusion. On the other hand, the loss fraction almost monotonically increases in the half field condition (B_t = 1.375 T). There is almost no plateau region, because the collisionless diffusion of the tritons is considerably larger due to the lower magnetic field. Figure 4(a) shows the three dimensional plot of loss points at the toroidal field direction of counter clockwise (CCW) from the overhead view at R_{ax}/B_t of 3.60 m/2.75 T. Here, the orbit following time is set to be 10^{-5} s. In this plot, loss points are accumulated in one period of the LHD. The toroidal and poloidal angle distribution of lost tritons on the VV is shown in figure 4(b). Here, toroidal and poloidal locations of helical coils are indicated in the figure 4(b). Tritons reach between the helical coils where magnetic field strength is relatively low, as expected. We found that tritons reach one side of the helical coil case and the loss points are changed due to the inverted direction of toroidal magnetic field.

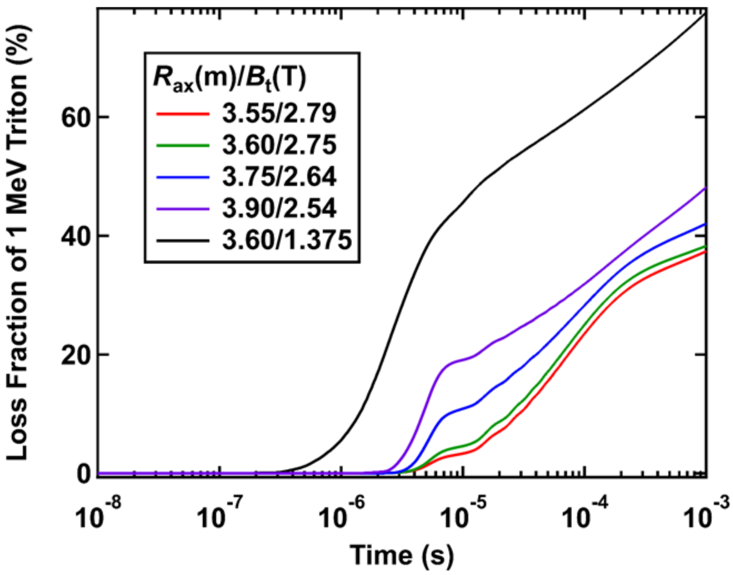

Figure 3. Time evolution of the triton loss fraction. The loss fraction becomes larger with the increase of R_{ax} in the normal B_t region ($B_t > 2.5$ T). Significant increase of loss fraction is obtained in B_t of 1.375 T compared with B_t of 2.75 T in R_{ax} of 3.60 m.

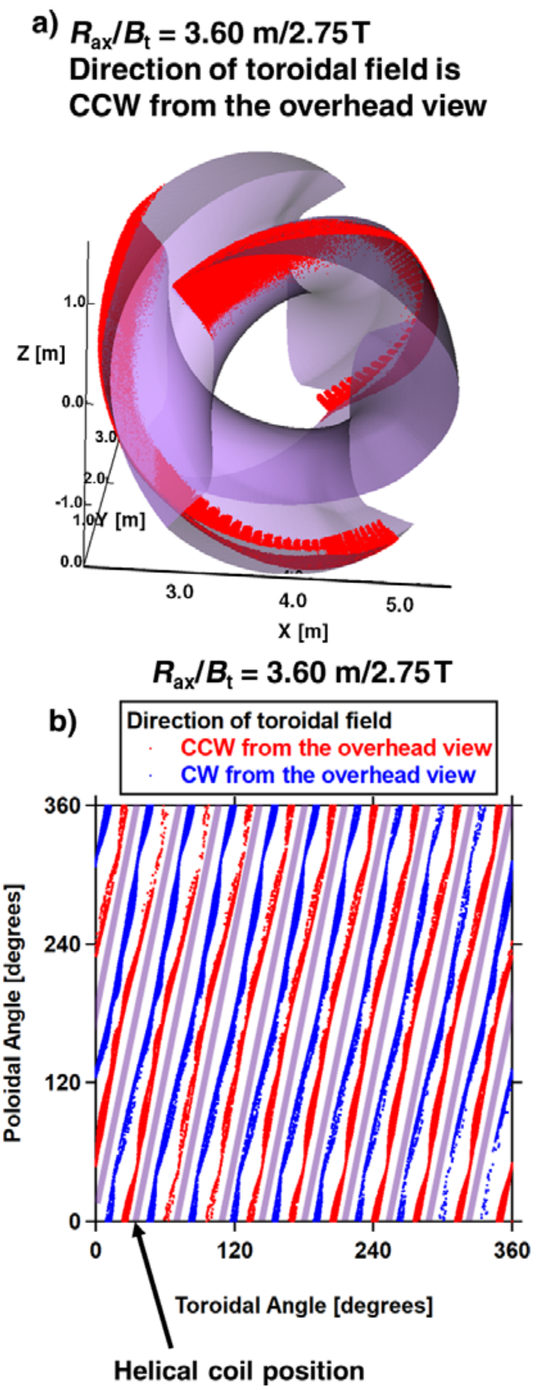

Figure 4. Strike points of 1 MeV tritons with three dimensional plot (a) and toroidal and poloidal distribution (b). Loss points are located in a relatively narrow region and changed with the reversal of toroidal magnetic field direction.

As reported in reference [12], B_t is changed according to the change of R_{ax} because the maximum B_t in each R_{ax} is decided by the maximum helical coil current in each layer. Therefore, to clarify B_t effects on the triton confinement improvement/degradation, an effect of B_t on the first orbit loss of 1 MeV tritons is evaluated at R_{ax} of 3.60 m. In this calculation, 10^7 particles are launched and the orbit following time is set to be 10^{-5} s. The first orbit loss fraction as a function of B_t shown in figure 5(a) indicates that the effect of B_t on the first orbit loss fraction is weak in $B_t > 2.5$ T. The first orbit loss fractions in B_t of 2.55 T, 2.65 T, 2.75 T, and 2.85 T are 6.6%, 5.5%, 4.6%, and 3.8%, respectively. Note that the first orbit loss fraction reaches 46% at the half field strength condition (B_t of 1.375 T). A pitch angle distribution of tritons launched and confined are shown in Figure 5(b). Most of the tritons with the exception of some particles having helically trapped and transition orbits are confined in $B_t > 2.5$ T. Note that the number of losses in the helically trapped region is almost unchanged with the change of the magnetic field strength because the structure of the helical ripple is the same. Hence, the increase of B_t only provides the slight improvement of the triton burnup fraction in $B_t > 2.5$ T. Note that a large fraction of the first orbit loss of tritons in B_t of 1.375 T is consistent with the low triton burnup ratio measured in the experiment [12]. Evaluation of first orbit loss fraction in each configuration is performed. The number of particles and the orbit following time are the same as the previous calculation. Figure 6(a) shows the first orbit loss fraction of tritons as a function of R_{ax}. The loss fraction increases rapidly with outward shift of R_{ax}. In the case of the inward shifted configuration, the first orbit loss fraction is around 5%, whereas the fraction increases around 20% in the outward shifted configuration R_{ax} of 3.90 m. Pitch angle distribution of tritons launched and confined is shown in figure 6(b). The number of confined transition and helically trapped tritons significantly decreased with the outward shift of R_{ax}. The loss of helically trapped and transition tritons becomes larger because the deviation of the orbit from the flux surface becomes larger as the outward shift of R_{ax}. The results indicate that decrease of the first orbit loss of tritons is mainly due to inward shift of R_{ax} which reduces the first orbit loss of transition and helically-trapped 1 MeV tritons. The decrease of first orbit loss of 1 MeV tritons is one of the important factors to induce the significant improvement of the triton burnup ratio as the inward shift of R_{ax} obtained in the experiment.

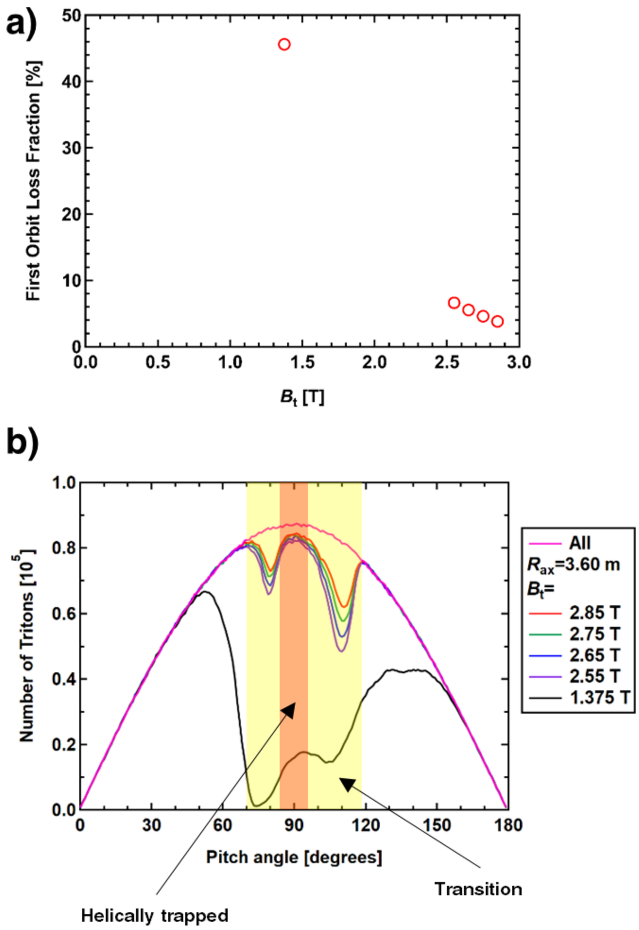

Figure 5. (a) The effect of B_t on 1 MeV triton loss fraction. The loss fraction is slightly changed when B_t is greater than 2.5 T, whereas there is significantly increase at B_t of 1.375 T. (b) Pitch angle distribution of launched 1 MeV tritons (pink) and confined tritons in B_t of 2.85 T (red), 2.75 T (blue), 2.65 T (green), 2.55 T (purple), and 1.375 T (black) at R_{ax} of 3.60 m.

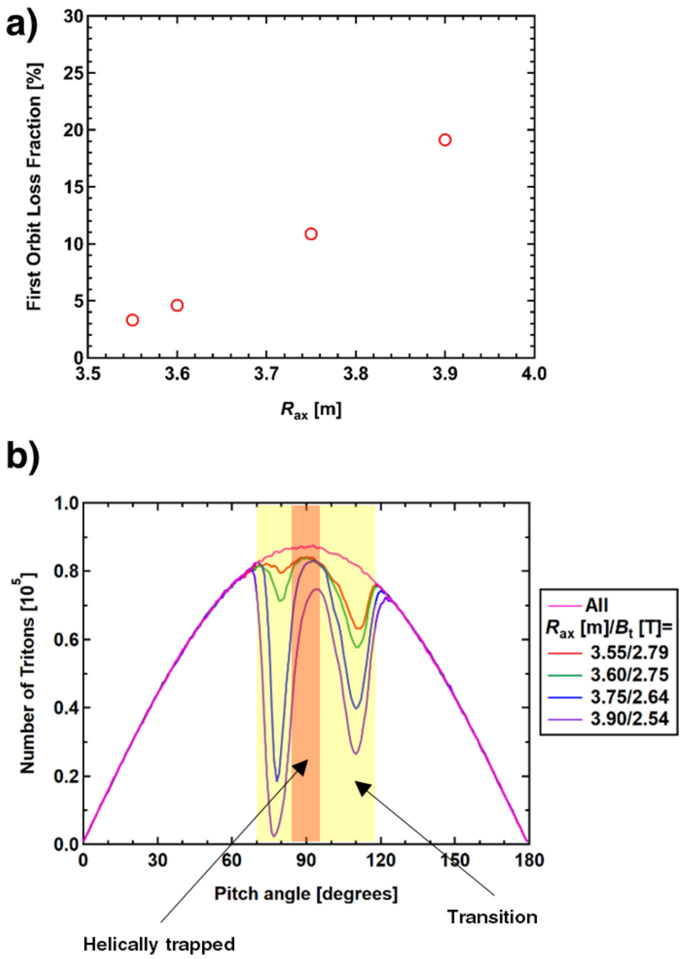

Figure 6. (a) The effect of R_{ax} on 1 MeV triton loss fraction. The loss fraction significantly increases with the outward shift of R_{ax}. (b) Pitch angle distribution of launched 1 MeV triton (pink) and confined tritons in B_t(T)/R_{ax}(m) of 3.55/2.79 (red), 3.60/2.75 (green), 3.75/2.64 (blue), and 3.90/2.54 (purple). Confinement of tritons having transition orbit is significantly degraded with outward shift of R_{ax}.

4. Summary

The study of the magnetic configuration effect on the first orbit loss of 1 MeV tritons is performed using Lorentz orbit calculation code LORBIT. First orbit loss mainly appears *t* of less than 10^{-5} s. Those losses mainly occur in transition region and in helically trapped region. Toroidal and poloidal distribution of loss points of tritons shows that the loss points are accumulated in one side of the helical coil case. Most of the tritons are confined in the normal toroidal magnetic field strength (B_t > 2.5 T) condition in R_{ax} of 3.6 m. It is shown that the effect of B_t on first orbit loss is weak. In the half toroidal magnetic field strength condition (B_t = 1.375 T), most of the tritons are lost and the result is consistent with the low triton burnup ratio obtained in experiments. The first orbit loss fraction is evaluated in the magnetic configurations where triton burnup experiments were performed. The loss fraction of tritons drops from 20% to 5% with the inward shift of R_{ax}. It is found that the first orbit loss fraction of transition and helically trapped 1 MeV tritons is significantly decreased with the inward shift of R_{ax}.

Acknowledgments

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