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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.

(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

37 study the energetic ion confinement [1]. In deuterium operations, confinement of 1 MeV

38 tritons created by d(d,p)t reactions is intensively studied as a simulation study of alpha

39 particle confinement because the Larmor radius and the precession frequency are the

40 same as those of DT born 3.5 MeV alpha particles [2]. In addition, the velocity

41 distribution of tritons is isotropic as alpha particles.

42 In tokamaks, study of 1 MeV triton confinement by experiments and numerical

43 simulations has been intensively performed in the deuterium experiment [3-8]. In

44 stellarator and heliotron, the study of the confinement property of alpha particles was

45 performed using the orbit simulation in a fusion-reactor-relevant machine, of which the

46 plasma volume is 1000 m^3 and the magnetic field strength is 5 T [9, 10]. The birth profile

47 of alpha particles is proportional to n^2T^2, where n and T represent fuel ion density and

48 fuel ion temperature, respectively. Therefore, the loss fraction of alpha particles born in

49 the core region of the plasma was discussed because the alpha particles mainly born in

50 the core region. It was reported that most of the alpha particles are confined during the

51 collisional damping time [10]. The triton burnup experiment was initiated in the first

52 campaign of deuterium operations in March 2017 on the Large Helical Device (LHD)

53 [11]. This is the first triton burnup experiment in stellarators/helical devices. The triton

54 burnup experiments are performed in neutral-beam heated deuterium plasmas. In these

3

55 experiments, neutrons and 1 MeV tritons are mainly created by beam-thermal DD

56 reactions. 1 MeV tritons created by DD reaction can undergo secondary DT reaction with

57 the bulk deuteron while they slowed down. The triton burnup ratio defined by the total

58 DT neutron amount per discharge divided by the total DD neutron amount per discharge

59 is surveyed [12]. The scintillating fiber (Sci-Fi) detector using a discriminating method

60 with absolutely calibrated by the neutron activation system is applied for DT neutron

61 measurement and the neutron flux monitor is utilized for DD neutron measurement. It

62 was reported that the triton burnup ratio significantly increases in the inward shifted

63 configuration. In order to understand the significant increase of triton burnup ratio with

64 the inward shift of the magnetic axis position, it is important to know the triton

65 confinement properties in each magnetic configuration. When we considered a classical

66 confinement of tritons, the loss of tritons could be caused due to the collisionless issue

67 which is a result of the lost orbit, the collisional issue which the particle reaches the loss

68 cone due to the collision, and the charge exchange with neutral gas. In these experiments,

69 typical electron temperature T_e of 3 keV and typical electron density n_e of 2×10^{19} m^{-3},

70 therefore, it needs more than 2 seconds for 1 MeV triton to decrease its energy to 100 keV

71 [13]. Here, the triton energy of around 100 keV is considered because the DT cross section

72 has a peak around this energy. The typical charge exchange loss time of tritons is

73   evaluated to be 40 ms. Here, neutral density of 10^{15} m^{-3} at $r/a < 0.6$ [14] is used because

74   tritons mainly exist in the interior region of the plasma. The charge exchange cross section

75   of 10^{-20} m^2 at the triton energy of around 100 keV [15] is used. Therefore, the loss of

76   tritons which occurred in a short period of time, t of less than 1 ms, is mainly due to the

77   collisionless issue. In particular, because the Larmor radius of 1 MeV triton evaluated by

78   energy ~10 cm is comparable to the minor radius of the LHD ~60 cm, the first orbit loss

79   could be a considerably large fraction in considering the confinement of 1 MeV tritons.

80   In this paper, the first-orbit loss fraction of 1 MeV tritons is evaluated as a first step by

81   means of the Lorentz orbit code in order to understand the magnetic configuration effect

82   on the triton burnup ratio.

83

84   **2. Setup for first orbit loss calculation**

85   The Lorentz orbit following code developed by National Institute for Fusion Science

86   (LORBIT) [16] is used to evaluate the first-orbit loss fraction of 1 MeV tritons. The code

87   solves the equation of motion $m \, d\bm{v}/dt = q(\bm{E}+\bm{v}\times\bm{b})$ without including collisions. Here, m,

88   v, q, E, and b represent the mass of charged particle, the velocity of charged particle,

89   charge of the charged particle, the electric field, and the magnetic field, respectively. In

90   this calculation, we used the magnetic field in a vacuum and assumed no electric field.

91   Note that the effect of the electric field on the 1 MeV triton orbit will be negligibly small

92   because of the high energy of tritons. We used a random number generator to choose the

93   radial position, the poloidal angle, the toroidal angle, the velocity component parallel to

94   the magnetic field and the velocity component perpendicular to the magnetic field. Note

95   that the normalized minor radius of the birth position of 1 MeV triton is chosen to be less

96   than 0.2 because most tritons are mainly born in the core region of the plasma. Here, we

97   choose the simple birth profile of 1 MeV triton in order to exclude plasma parameter

98   effects to show the magnetic configuration effect on 1 MeV triton confinement clearly.

99   The initial velocity of the tritons is uniformly distributed in the velocity space with the

100   Monte Carlo method. In this calculation, we judged that a triton is lost when the triton

101   reaches the vacuum vessel (VV). Figure 1 shows the poloidal cross section of VV, the last

102   closed flux surface (LCFS), and birth positions of tritons in the magnetic axis R_{ax} of 3.55

103   m, 3.60 m, 3.75 m, and 3.90 m in the vertically elongated poloidal cross section. Note

104   that the other in-vessel components are not included because the LHD has no limiter and

105   no ICRF antenna is installed in these experiments. The divertor plate is placed far away

106   from the plasma, the effect of divertor plates on the first orbit loss ratio of tritons will be
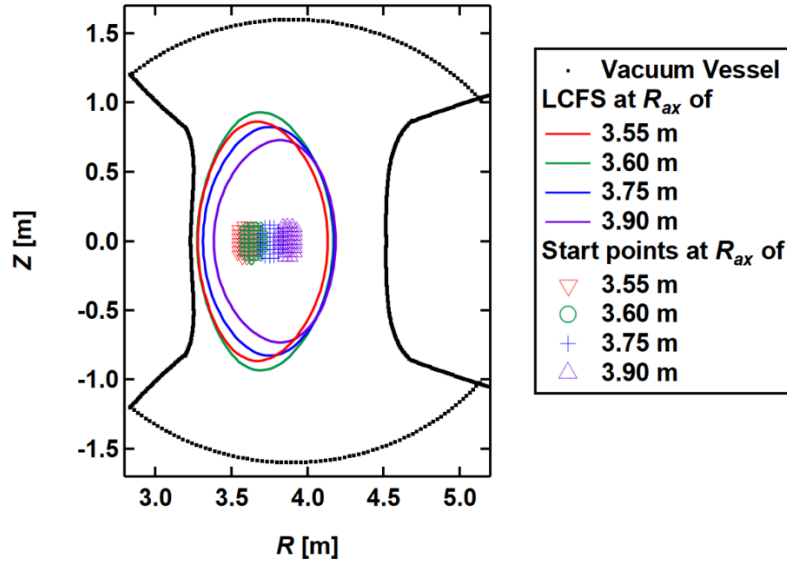
107   very limited or negligible.

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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-

121   passing transit, counter-passing transit, transition, and helically trapped tritons are 30

122   degrees, 150 degrees, 80 degrees, and 89 degrees, respectively. Here, the start point is set

123   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.

124   In this case, co-passing transit, counter-passing transit, and helically trapped tritons are

125   confined, whereas the transition triton is lost.
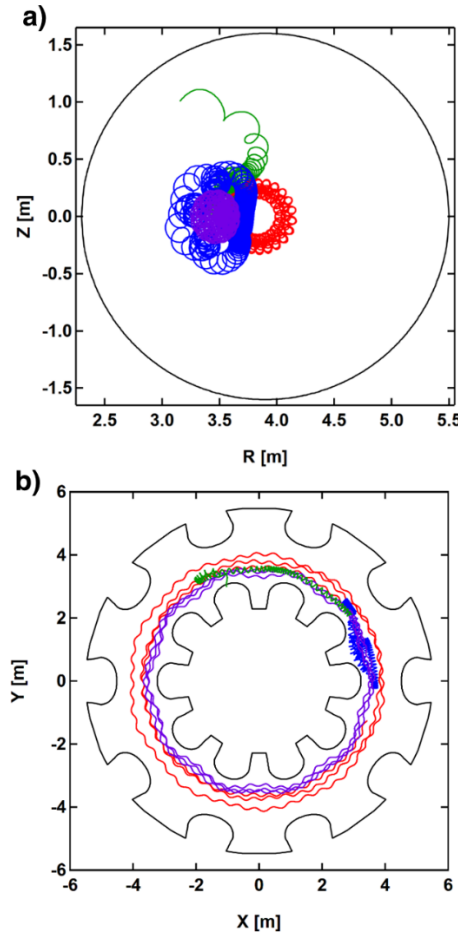
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127   Figure 2. Typical orbit of 1 MeV tritons having the pitch angle of co-passing transit (red),

128   transition (green), helically trapped (blue), and counter-passing transit (purple) region a)

129   as projected into the (R, Z) plane and b) as seen from above.

130

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

9

148   dimensional plot of loss points at the toroidal field direction of counter clockwise (CCW)

149   from the overhead view at R_{ax}/B_t of 3.60 m/2.75 T. Here, the orbit following time is set to

150   be 10^{-5} s. In this plot, loss points are accumulated in one period of the LHD. The toroidal

151   and poloidal angle distribution of lost tritons on the VV is shown in figure 4(b). Here,

152   toroidal and poloidal locations of helical coils are indicated in the figure 4(b). Tritons

153   reach between the helical coils where magnetic field strength is relatively low, as expected.

154   We found that tritons reach one side of the helical coil case and the loss points are changed

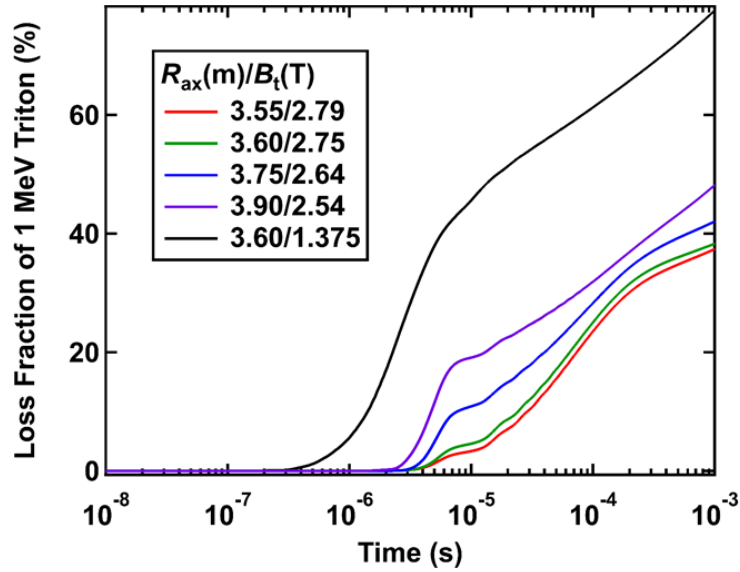155   due to the inverted direction of toroidal magnetic field.

156

157   Figure 3. Time evolution of the triton loss fraction. The loss fraction becomes larger with

158   the increase of R_{ax} in the normal B_t region ($B_t > 2.5$ T). Significant increase of loss fraction

159   is obtained in B_t of 1.375 T compared with B_t of 2.75 T in R_{ax} of 3.60 m.

160

a) R_{ax}/B_t = 3.60 m/2.75 T
Direction of toroidal field is
CCW from the overhead view

R_{ax}/B_t = 3.60 m/2.75 T

b)

Direction of toroidal field
· CCW from the overhead view
· CW from the overhead view

Helical coil position
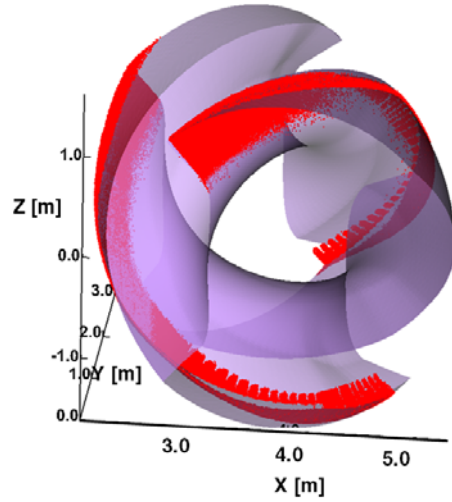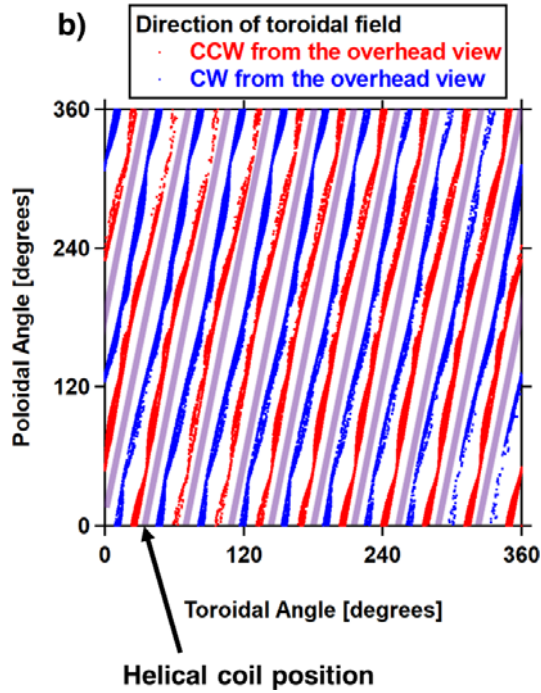
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162   Figure 4. Strike points of 1 MeV tritons with three dimensional plot (a) and toroidal and

163   poloidal distribution (b). Loss points are located in a relatively narrow region and

164   changed with the reversal of toroidal magnetic field direction.

165

166   As reported in reference [12], B_t is changed according to the change of R_{ax} because the

167   maximum B_t in each R_{ax} is decided by the maximum helical coil current in each layer.

168   Therefore, to clarify B_t effects on the triton confinement improvement/degradation, an

169   effect of B_t on the first orbit loss of 1 MeV tritons is evaluated at R_{ax} of 3.60 m. In this

170   calculation, 10^7 particles are launched and the orbit following time is set to be 10^{-5} s. The

171   first orbit loss fraction as a function of B_t shown in figure 5(a) indicates that the effect of

172   B_t on the first orbit loss fraction is weak in $B_t > 2.5$ T. The first orbit loss fractions in B_t

173   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

174   that the first orbit loss fraction reaches 46% at the half field strength condition (B_t of 1.375

175   T). A pitch angle distribution of tritons launched and confined are shown in Figure 5(b).

176   Most of the tritons with the exception of some particles having helically trapped and

177   transition orbits are confined in $B_t > 2.5$ T. Note that the number of losses in the helically

178   trapped region is almost unchanged with the change of the magnetic field strength because

179   the structure of the helical ripple is the same. Hence, the increase of B_t only provides the

180   slight improvement of the triton burnup fraction in $B_t > 2.5$ T. Note that a large fraction

181   of the first orbit loss of tritons in B_t of 1.375 T is consistent with the low triton burnup

182   ratio measured in the experiment [12]. Evaluation of first orbit loss fraction in each

183   configuration is performed. The number of particles and the orbit following time are the

184   same as the previous calculation. Figure 6(a) shows the first orbit loss fraction of tritons

185   as a function of R_{ax}. The loss fraction increases rapidly with outward shift of R_{ax}. In the

186   case of the inward shifted configuration, the first orbit loss fraction is around 5%, whereas

187   the fraction increases around 20% in the outward shifted configuration R_{ax} of 3.90 m.

188   Pitch angle distribution of tritons launched and confined is shown in figure 6(b). The

189   number of confined transition and helically trapped tritons significantly decreased with

190   the outward shift of R_{ax}. The loss of helically trapped and transition tritons becomes larger

191   because the deviation of the orbit from the flux surface becomes larger as the outward

192   shift of R_{ax}. The results indicate that decrease of the first orbit loss of tritons is mainly due

193   to inward shift of R_{ax} which reduces the first orbit loss of transition and helically-trapped

194   1 MeV tritons. The decrease of first orbit loss of 1 MeV tritons is one of the important

195   factors to induce the significant improvement of the triton burnup ratio as the inward shift

196   of R_{ax} obtained in the experiment.
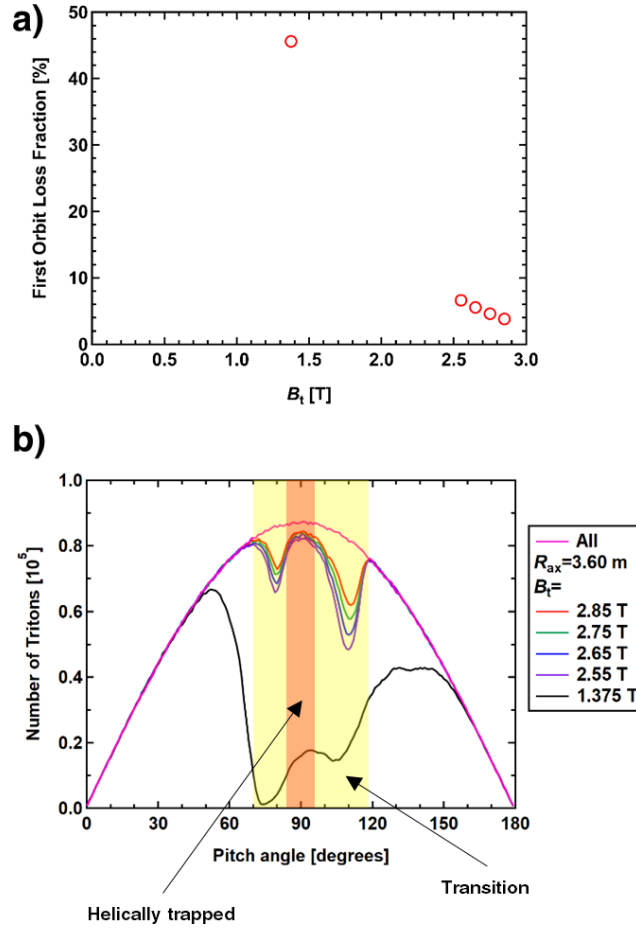
Figure 5. (a) The effect of B_t on 1 MeV triton loss fraction. The loss fraction is slightly

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
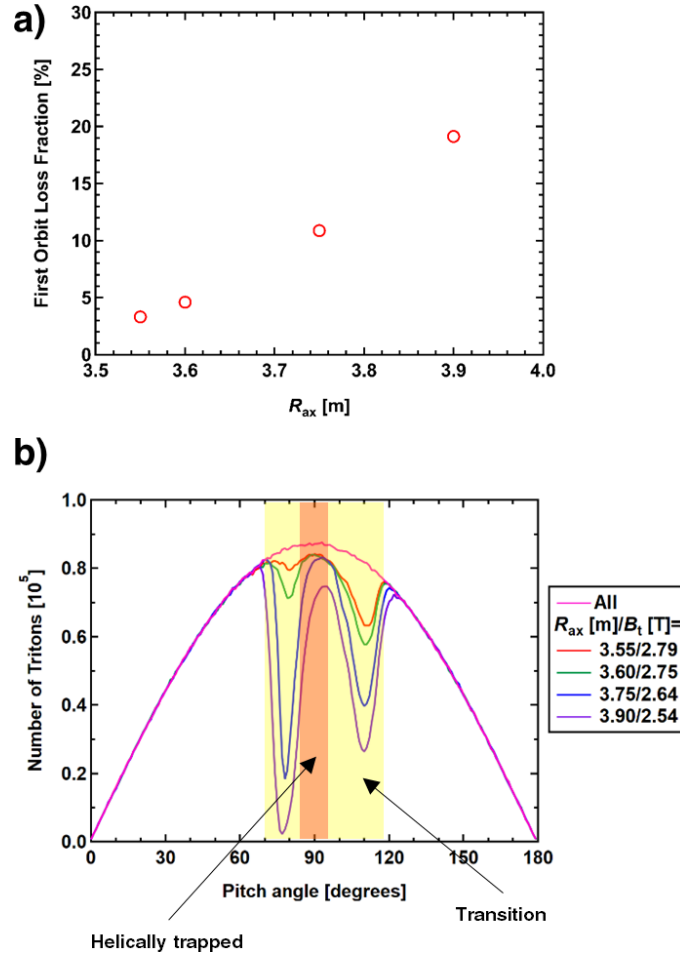
(black) at R_{ax} of 3.60 m.

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

212 performed using Lorentz orbit calculation code LORBIT. First orbit loss mainly appears

213 t of less than 10^{-5} s. Those losses mainly occur in transition region and in helically trapped

214 region. Toroidal and poloidal distribution of loss points of tritons shows that the loss

215 points are accumulated in one side of the helical coil case. Most of the tritons are confined

216 in the normal toroidal magnetic field strength ($B_t > 2.5$ T) condition in R_{ax} of 3.6 m. It is

217 shown that the effect of B_t on first orbit loss is weak. In the half toroidal magnetic field

218 strength condition ($B_t = 1.375$ T), most of the tritons are lost and the result is consistent

219 with the low triton burnup ratio obtained in experiments. The first orbit loss fraction is

220 evaluated in the magnetic configurations where triton burnup experiments were

221 performed. The loss fraction of tritons drops from 20% to 5% with the inward shift of R_{ax}.

222 It is found that the first orbit loss fraction of transition and helically trapped 1 MeV tritons

223 is significantly decreased with the inward shift of R_{ax}.

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