Analysis of the Alpha Particle Orbits in the High Beta Plasma of the Large Helical Device

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We investigate the orbits of the 3.5 MeV alpha particles in the high beta plasma of the Large Helical Device (LHD), in which $B = 6$ T is assumed. For this purpose, we trace the 100 keV proton in the case of $B = 1$ T, the Larmor radius of which is almost the same as the Larmor radius of the alpha particle, by numerically solving the guiding-center equations. As a result, the particle orbit characteristics in the high beta plasma of the LHD are shown in detail. We point out the importance to appropriately trace the re-entering particles in the analyses of the orbits of the high-energy particles, such as the alpha particles, in the high beta plasma. It is found that the lifetime of the alpha particles depends on the lifetime of the chaotic orbit particles almost all of which is lost. The chaotic orbit particles are lost before they heat fuels because the lifetime of the chaotic orbit particles is much shorter than the alpha-electron relaxation time.

Keywords: alpha particle, particle orbit, high beta, re-entering particle, LHD,

1 Introduction

The volume-averaged beta-value $\langle\beta\rangle$ have reached up to 5 % in the recent experiments of the Large Helical Device (LHD)[1]. In a Deuterium (D)-Tritium (T) fusion reactor, alpha particles move in the plasma the beta-value of which is more than 5 %. It is one of the important issues for the realization of a fusion reactor to investigate the confinement of the alpha particles heating the D-T fuels. The magnetic field strength in a future fusion reactor is assumed $B \simeq 6$ T. The Larmor radius of the 3.5 MeV alpha particle in the case of $B = 6$ T is almost the same as that of the 100 keV proton in the case of $B = 1$ T. Therefore, we trace the 100 keV proton in the high beta plasma of the LHD with $B_{\mathrm{ax}} = 1$ T to investigate the alpha particle orbits.

In the high beta plasmas of the LHD, the magnetic configurations changes from the vacuum magnetic field to the followings. The flux surfaces shift to the direction of the major radius due to the Shafranov shift caused by the finite beta effect. Additionally, the volume inside the last closed flux surface (LCFS) in the high beta plasma becomes small since the flux surfaces in the periphery of the high beta plasma are destroyed[2]. In these cases, the number of the re-entering particles[3, 4, 5], which repeatedly pass into and out of the LCFS, could be larger than that in the vacuum magnetic field. Thus, the re-entering particles might play important roles for the plasma heating. But, the re-entering particles have been regarded as the loss particles in the conventional studies on the orbits of the high-energy particles in the high beta plasma of the LHD[6]. We appropriately trace the re-entering particles in the high beta plasma of the LHD.

The numerical model and the initial conditions are given in Section 2. The results of the calculations are summarized in Section 3. Section 4 is devoted to a summary.

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2 Numerical Model

In order to trace the particles, we use the equilibrium magnetic field ($B_{\mathrm{ax}} = 1$ T, $\langle\beta\rangle = 2.7$ % and $R_{\mathrm{ax}} \simeq 3.9$ m) calculated by using the three-dimensional magnetohydrodynamic (MHD) equilibrium code, HINT[7, 8], in which the existence of the nested flux surfaces are not assumed.

We trace the particles by numerically solving the guiding-center equations in the collisionless case. In order to trace the re-entering particles appropriately, the particle loss boundary must set on the vacuum vessel wall, i.e., the particles reaching the vacuum vessel wall are regarded as the loss particles. Therefore, the rotating helical coordinate system[9] is adopted. We use the 6th-order Runge-Kutta formulas[10] and the three-dimensional higher order spline function[11] to accurately trace the complicated orbits of the particles in the plasma periphery.

The initial conditions are determined as follows. As mentioned in the preceding section, the traced particle is a proton and its initial energy is assumed to be 100 keV. The starting points of protons are set on the horizontally elongated poloidal plane as

$$R = 2.65 + 0.05\mathrm{n_R}\ (\mathrm{n_R} = 0, 1, \cdots, 45)\ \mathrm{m}$$
$$Z = 0\ \mathrm{m}$$

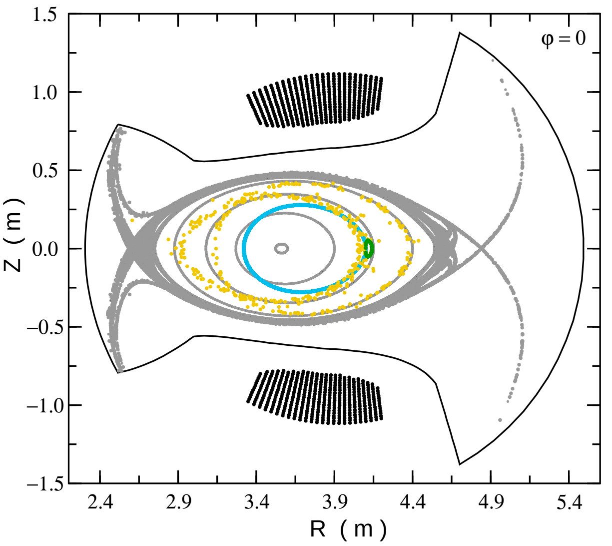

Fig. 1 Poincarè plots of the particles on the horizontally elongated poloidal plane. Typical orbits of the passing (blue), the chaotic orbit (green), and the banana orbit particles (yellow) are shown. These particles are traced from $R = 4.1$ m, $Z = 0$ m in the vacuum magnetic field. The magnetic field lines (gray) are also shown.

$$\phi = 0, \tag{1}$$

where (R, Z, ϕ) are the cylindrical coordinates; R is the major radius, ϕ the toroidal angle. The initial pitch angles (χ_0) are varied from 0.05π to 0.95π with a step size of 0.05π. The protons with such initial conditions are traced for a period of 30 ms.

3 Results

Based on the results of the particle orbits tracing, we classify the particles into the four groups: passing particles, banana orbit particles, chaotic orbit particles[12], and prompt loss particles. Figure 1 is the Poincarè plot of the particles on the horizontally elongated poloidal plane. This shows the typical orbits of these four groups in the vacuum magnetic field, in which $B_{ax} = 1$ T. Both the passing (blue) and the banana orbit particles (green) make the closed drift surfaces. The chaotic orbit particles (yellow) repeatedly transit between the localized orbit and the blocked orbit[13], and make no closed drift surface. Since the prompt loss particles are lost without any poloidal rotations, we cannot make the Poincarè plots of the prompt loss particles. Based on this classification, the orbits of the alpha particles in the high beta plasma of the LHD are studied.

3.1 Orbit characteristics

Figure 2 shows the particle classifications in the case of $B_{ax} = 1$ T, $\langle\beta\rangle = 2.7$ % on the space of the starting points versus the initial pitch angles. Horizontal axis is the major radius of the starting points set on the line of $Z = 0$ m on the horizontally elongated poloidal plane. Vertical axis denotes the initial pitch angles divided by π. The positions of the magnetic axis and the LCFS on the line of $Z = 0$ m on the horizontally elongated poloidal plane are also shown. The red squares denote the loss particles, i.e., the particles reaching the vacuum vessel wall within 30 ms.

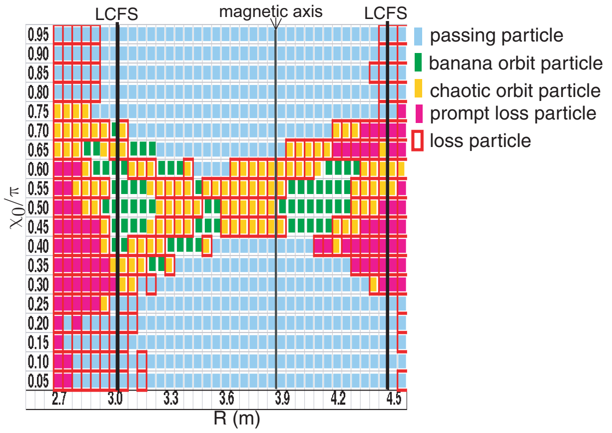

Fig. 2 Particle classifications on the space of the starting points versus the initial pitch angles. Horizontal axis is R of the starting points. Vertical axis denotes the initial pitch angles (χ_0) divided by π. The red squares show the loss particles.

Almost all the particles with $\chi_0 \simeq 0.5\pi$ are the banana and the chaotic orbit particles. Especially in the particles traced from near magnetic axis, most of the particles with $\chi_0 \simeq 0.5\pi$ are the chaotic orbit particle. Almost all the chaotic orbit particles are lost within 30 ms. The range of the initial pitch angles, with which the particles are the passing particles, are maximum near $R = 3.6$ m. As the starting points are close to the LCFS, the such range of the initial pitch angles becomes narrow. There are no prompt loss particles traced from $3.05 \text{ m} \leq R \leq 4.0$ m. Almost all the starting points of the prompt loss particles exist outside the LCFS. Some particles with $\chi_0 \simeq 0.35\pi$ or $\chi_0 \simeq 0.7\pi$ are also the prompt loss particles.

3.2 Re-entering particle

In order to investigate the effects of the re-entering partices on the confinement of the alpha particle, we evaluate the loss particle ratio. Figure 3 shows the loss particle ratio averaged over pitch angles[12] at each starting points after tracing particles for 30 ms. The black line is the loss particle ratio in the case of re-entering particles appropriately traced. The red line represents the loss particle ratio in the case of the re-entering particles regarded as the loss particles. This case is the same as the conventional study, in which the particle loss boundary is set on the LCFS. The positions of the magnetic axis and the LCFS on the line of $Z = 0$ m on the horizontally elongated poloidal plane are

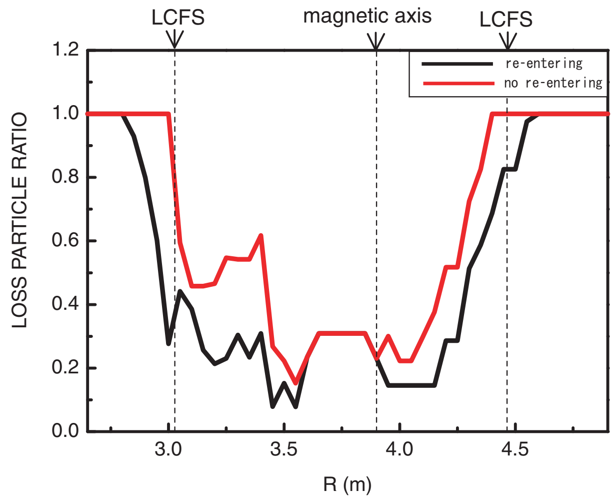

Fig. 3 Loss particle ratio after 30 ms particle tracing. The black line is the loss particle ratio in the case of re-entering particles appropriately traced and the red line the loss particle ratio in the case of the re-entering particles regarded as the loss particles. Horizontal axis is R of the starting points. Vertical axis denotes the loss particle ratio averaged over the pitch angles at each starting points. The positions of the magnetic axis and the LCFS are also shown.

also shown.

The significant difference between the black and the red lines can be seen from Fig. 3. This result implies that many re-entering particles exist in the high beta plasma. Especially, the difference between the black and the red lines is remarkable in the particles traced from $R \simeq 3.3$ m. This means that there exist many re-entering particles in the particles traced from $R \simeq 3.3$ m.

The loss particle ratio are overestimated in the case of the re-entering particles regarded as the loss particles. Thus, it is important to appropriately trace the re-entering particles in the analyses of the orbits of the high-energy particles, such as the alpha particles, in the high beta plasma.

3.3 Confinement of alpha particle

We investigate the confinement of the alpha particles generated by the D-T fusion reaction. As mentioned above, the Larmor radius of the 3.5 MeV alpha particle in the case of $B = 6$ T is almost the same as that of the 100 keV proton in the case of $B = 1$ T. The results of the 100 keV proton in the case of $B = 1$ T could be regarded as that of the 3.5 MeV alpha particle in the case of $B = 6$ T.

The birth points of the alpha particles produced by the D-T fusion reaction depend on the plasma pressure profile. The number of alpha particles is large in the region of the high plasma pressure, namely, the plasma core. Thus, we focus on the particles traced from the plasma core (3.3 m $\leq R \leq$ 4.2 m). It is seen from Fig. 2 that the prompt loss particles hardly exist in the particles traced from 3.3 m $\leq R \leq$ 4.2 m. Both the passing and the banana orbit particles are confined in the vacuum vessel wall for 30 ms. On the other hand, almost all of the chaotic orbit particles is lost. Therefore, the lifetime of the alpha particles is determined by the lifetime of the chaotic orbit particles.

The lifetime of the chaotic orbit particles is estimated as $\sim 10^{-3}$ s in the present study. In order to compare this lifetime with the collision times, we assume the D-T plasma with the ion temperature $T_{\mathrm{i}} = 10$ keV, the ion density $n_{\mathrm{i}} = 10^{21}$ m^{-3}, the electron temperature $T_{\mathrm{e}} = 10$ keV, and the electron density $n_{\mathrm{e}} = 10^{21}$ m^{-3}. In such plasma, the alpha-ion deflection time $\tau^{\mathrm{d}}_{\alpha-\mathrm{i}} \simeq 0.9$ s and the alpha-electron relaxation time $\tau^{\mathrm{r}}_{\alpha-\mathrm{e}} \simeq 1.6 \times 10^{-2}$ s. The lifetime of the chaotic orbit particles is much shorter than these collision times. Therefore, the chaotic orbit particles are lost before they heat fuels. In addition, the passing and the banana orbit particles confined in our calculations become the chaotic orbit particles by the pitch angle scattering during many toroidal and/or poloidal rotations. Thus, the passing and the banana orbit particles could not sufficiently heat the fuels by the Coulomb collision.

We have analyzed the orbit of the alpha particle in the current LHD (the major radius $R_0 = 3.9$ m, the averaged plasma minor radius $a_{\mathrm{p}} \simeq 0.64$ m[14]). But, the size of the helical reactor, which satisfies the ignition condition, is assumed as $R_0 = 10$ m and $a_{\mathrm{p}} = 2$ m[15]. In such a helical reactor, the region, in which the chaotic orbit particles can move, becomes large. Therefore, the chaotic orbit particle lost in the present study could be confined for a long time enough to heat the fuels.

Instead of the plasma heating by the Coulomb collision, the plasma heating called the alpha-channeling is proposed[16]. In the alpha-channeling, the fuels are heated by the wave in the plasma, which the alpha particle amplifies during the time scale shorter than collision times. If the alpha-channeling is used, the alpha particles could heat the fuels independent of the lifetimes of the alpha particles.

4 Summary

We have investigated the orbits of the 3.5 MeV alpha particles in the high beta plasma of the LHD, in which $B = 6$ T. For this purpose, we have traced the 100 keV proton in the case of $B = 1$ T, the Larmor radius of which is almost the same as the Larmor radius of the alpha particle, by numerically solving the guiding-center equations. The following information has been obtained.

- The passing particles play a large part in the particles traced from the plasma core. On the other hand, most of the particles with $\chi_0 \simeq 0.5\pi$ are the chaotic orbit particles. They are lost within 30 ms.
- It is important to appropriately trace the re-entering particles in the analyses of the orbits of the high-

energy particles, such as the alpha particles, in the high beta plasma.

- The lifetime of the alpha particles depends on the lifetime of the chaotic orbit particles almost all of which is lost.
- The chaotic orbit alpha particles are lost before they heat fuels because the lifetime of the chaotic orbit alpha particles is much shorter than the alpha-electron relaxation time.
- In the future helical reactor, the chaotic orbit alpha particle lost in the present study could be confined for a long time enough to heat the fuels because the size of the future helical reactor will be larger than that of the LHD.
- Through the alpha-channeling, the alpha particles could heat the fuels independent of the lifetimes of the alpha particles.

In the near future, the alpha particles in the higher beta plasma ($\langle\beta\rangle > 5$ %) will be studied. We will investigate the alpha particle orbit by numerically solving the equation of motion because the Larmor radius of the alpha particle is large.

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