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Lorentz Alpha Orbit Calculation in Search of Position Suitable for Escaping Alpha Particle Diagnostics in ITER

Mitsutaka ISOBE[1)], Dan FUNAKI[2)], Mamiko SASAO[2)]

1) National Institute for Fusion Science, 322-6 Oroshi-cho, Toki-shi, 509-5292, Japan

2) Tohoku University, Aoba-ku, Sendai-shi, 980-8579, Japan

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The Lorentz orbit code is developed to understand escaping alpha particle orbits and to contribute to the design of an escaping alpha particle probe in ITER. The code follows the full gyromotion of an alpha particle in ITER equilibrium, considering the toroidal field magnetic field ripple produced by the finite number of toroidal field coils as well as full three-dimensional first wall panels placed at the outboard side of the torus. It is shown that alpha particles that exist in the peripheral region and have banana orbits intersect the first wall placed at the outboard side on the lower plane.

Keywords: Alpha particle, Orbit, ITER, Magnetic field ripple, First wall

1. Introduction

Issues related to alpha particles are of great concern in deuterium (D)-tritium (T) burning plasma experiments. Actually, in the International Thermonuclear Experimental Reactor (ITER), D-T produced 3.5 MeV alpha particles are super-Alfvénic and can potentially destabilize fast-particle-driven magnetohydrodynamic (MHD) instabilities such as the toroidicity-induced Alfvén eigenmode (TAE) [1,2]. As a result of the TAE excitation, the anomalous loss of alphas may occur, causing a reduction of nuclear fusion power and damage to the first wall (FW). Also, the energetic-particle-mode (EPM) [3] may be excited due to the presence of a substantial amount of energetic alphas, inducing the redistribution and/or loss of alphas. To reveal such alpha-related physics, diagnostics for confined and escaping alphas are required [4]. As for escaping alpha particle diagnostics, a probe based on a magnetic spectrometer concept has been proposed [4,5]. This is often called the lost fast-ion probe (LIP) and has been widely employed in the Tokamak Fusion Test Reactor (TFTR) [6,7], the Compact Helical System (CHS) [8], the Wendelstein 7-AS [9] and other toroidal devices [10-12]. In ITER, because the LIP has to be placed on the surface or interior of the FW to protect the probe head against the severe heat load, the LIP should be designed carefully, based on a great number of calculations on escaping alpha particle orbits. With regard to alpha particle orbit/transport calculation, the OFMC [13] and ASCOT [14] codes are famous and often used. Those codes are superior for the study of the confinement properties and/or the loss mechanism of alphas. However, it should be noted that those codes compute guiding center orbits of energetic ions. In ITER, because the Larmor radius of a 3.5 MeV alpha particle is not negligible, about 5 cm, the Lorentz alpha particle orbit code needs to find a position suitable for detecting **lost** alphas, treating the finite Larmor radius of the alpha particle. Also, in order to design the probe in detail, the orbit calculation with the treatment of full gyromotion is necessary. In this work, we have developed a Lorentz alpha particle orbit code suitable for designing a LIP for ITER.

author's e-mail: isobe@nifs.ac.jp

2. Calculation setup

2.1 Magnetic field with TF ripple

Alpha particle orbits are computed in the ITER equilibrium magnetic field, scenario 2 and scenario 4. Scenario 2 is a standard H-mode plasma (B_T/I_p=5.3 T/15

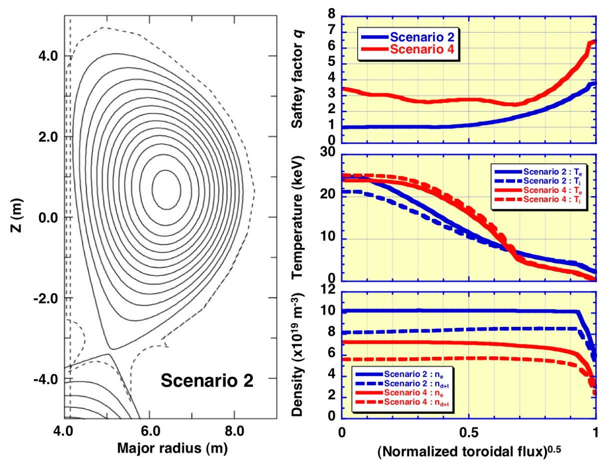

Fig. 1 Magnetic flux surfaces of ITER Scenario 2 (left) and radial profiles of safety factor, temperature and density for Scenario 2 and 4 (right).

MA) with a monotonic positive magnetic shear due to inductive current, producing fusion power P_{fus} of 400 MW of fusion gain Q=10. Scenario 4 is a steady-state plasma with a weak reversed magnetic shear, producing P_{fus} of 300 MW of Q=5. The magnetic axis position R_{AX} of both equilibria is 6.2 m. Magnetic flux surfaces, profiles of safety factor, and plasma parameters for scenarios 2 and 4 are shown in Figure 1.

The alpha orbit is calculated in a cylindrical coordinates system (R,Z,ϕ). In our code, the magnetic field in ITER is treated as follows.

$$\boldsymbol{B}(R,Z,\phi) = \bar{\boldsymbol{B}}(R,Z) + \tilde{\boldsymbol{B}}(R,Z,\phi)$$

$$\bar{\boldsymbol{B}}(R,Z) = -\frac{1}{R}\frac{\partial\Psi}{\partial Z}\bullet\boldsymbol{e}_R + \frac{1}{R}\frac{\partial\Psi}{\partial R}\bullet\boldsymbol{e}_Z + \frac{R_0 B_{\phi 0}}{R}\bullet\boldsymbol{e}_\phi$$

$$\tilde{\boldsymbol{B}}(R,Z,\phi) = \tilde{\boldsymbol{B}}_R(R,Z)\cos N\phi\bullet\boldsymbol{e}_R$$

The axisymmetric poloidal field components B_R(=-($d\Psi/dZ$)/R) and B_Z(=($d\Psi/dR$)/R) are obtained from the rectangular grid of the value of the poloidal flux function $\Psi(R,Z)$ (4.0 m≤R≤9.7 m, -5.7 m≤Z≤5.7 m, 129 grids for each) by the use of a spline routine for interpolation. The toroidal magnetic field B_ϕ is given as B_ϕ=$B_{\phi 0}R_0/R$. Both plasma current I_p and B_ϕ are oriented to be in the clockwise direction because ITER accepts only this operation. The ion grad-B drift direction is downward in this case. As for the toroidal field (TF) magnetic field ripple coming from the discreteness of TF coils (the number of TF coils N=18), we use a two-dimensional array of ripple amplitude $\delta(R,Z)$(≡(B_{max}-B_{min})/(B_{max}+B_{min})) on the same (R,Z) grid for $\Psi(R,Z)$ and consider modification of the toroidal field only. Because ITER is designed so as to reduce the ripple transport of alphas, $\delta(R,Z)$ is small, less than 1% on the last closed flux surface (LCFS) at the equatorial plane of the torus. The spatial profile of $\delta(R,Z)$ for ITER is available in Ref. 2.

2.2 Full gyromotion following orbit calculation with three-dimensional first wall

Alpha particle orbits with finite Larmor radii are tracked in the ITER equilibrium mentioned above by numerically solving the Lorentz force equation (m_α•$d\boldsymbol{v}/dt$=q•($\boldsymbol{v}\times\boldsymbol{B}$)) using the Runge-Kutta-Verner method. Here, m_α is the mass of the alpha particle, $\boldsymbol{v}$ is the velocity, q is the elementary electric charge and $\boldsymbol{B}$ is the magnetic field. This code is capable of computing an alpha particle orbit both forward and backward in time. The former is used to investigate the spatial distribution of losses of alphas on the FW. On the other hand, the latter is used to find an escaping orbit reaching the possible location for the LIP installation and detailed design of the LIP head.

Figure 2 shows a schematic drawing of ITER FW. As can be seen, the FW of ITER has a non-axisymmetric, three-dimensional shape consisting of a large number of flat panels. Because our interest is primarily on escaping alpha particle orbits in the vicinity of the three-dimensional FW, the shape of the FW should be exactly treated. In our code, we reproduce all FW panels placed at the outboard side in the torus. This is because alphas are expected to be lost at the weak field side, i.e., the outboard side. Each FW panel is expressed as Ax+By+Cz+D=0. Our scheme to check whether or not energetic alphas intersect the FW is,

$$Ax + By + Cz + D\begin{cases}\leq 0 & \text{-> alphas hits the FW}\\ > 0 & \text{-> alphas still confined}\end{cases}$$

Once alphas intersect the FW, the computation is immediately stopped. The results of the guiding center orbit calculation by Konovalov [15] suggest that most escaping alphas intersect FW#16 and 17 through processes of ripple banana diffusion and TF ripple trapping.

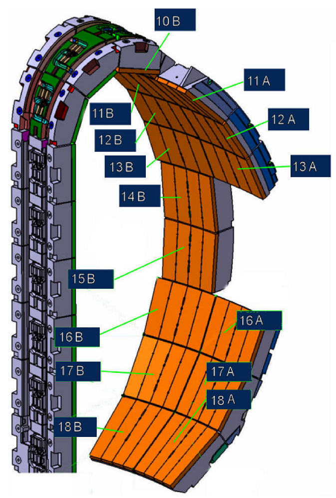

Fig. 2 Computer-assisted drawing of the first wall of ITER.

3. Guiding center orbit of alpha particle

For reference, typical guiding center banana orbits of alphas in the ITER equilibrium field, Scenario 4, are shown in Figure 3(a) for different pitch angles (χ=arcos($v_{//}/v$)). In this calculation, alphas are launched ~ 5 cm away from the lower end of FW#16 and are computed backward in time. An enlargement of the figure is also shown in Figure 3(b) to look into the situation on the gap between the FW and alpha particle orbits. After counter-going alpha particles with relatively high pitch angles experience the reflection at the lower plane of the higher field side, they switch to co-going orbits and come up along the FW. As can be seen in Fig. 3(b), there is no sufficient clearance between the alpha particle orbits and the FW panels. It looks as if the alphas may intersect FW#17 before they reach the location that we set as a destination because of the large Larmor radius (~5 cm) of the energetic alphas. Judging from Fig. 3(b), it can be said that it is difficult to decide on a suitable place for detecting lost alpha particles from guiding center orbit calculation. Also, we need information on the phases of the alphas' gyromotion in the vicinity of the FW in order to design the LIP in detail. Complete information on the gyromotion following orbit calculation is therefore required.

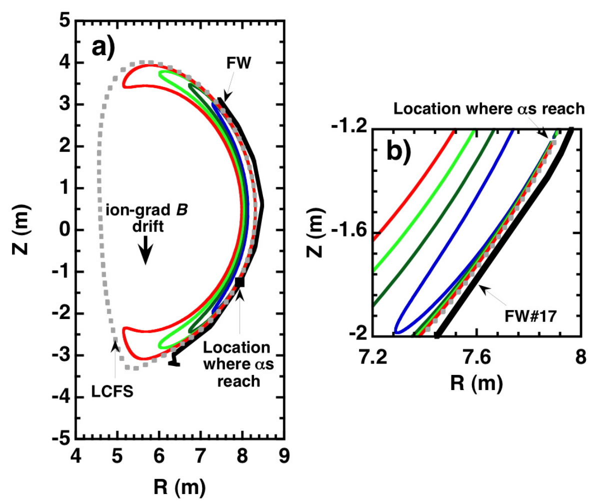

Fig. 3a) Guiding center banana orbits of alpha particles in the ITER equilibrium, Scenario 4 for various pitch angles: b) enlarged figure of 3a) to look into alpha particle orbits close to the FW. Orbits are tracked in the collisionless condition. The ion-grad *B* drift is directed downward.

4. Lorentz alpha particle orbit

Figure 4 shows typical escaping alpha particle orbits with finite Larmor radii in ITER equilibria, Scenarios 2 and 4 for different strike points. Escaping banana orbits of alphas close to the FW are shown in Figures 4b-1) and 4b-2) for Scenario 2. Alphas are launched from the FW surfaces (4a-1 for FW#16 and 4a-2 for FW#17) and are computed back in time. This scheme provides information on escaping alphas reaching the FW#16 and #17. The energy of alpha particles is set to be birth energy, i.e., 3.5 MeV. The pitch angles of escaping alphas are 62.9° and 74.4° for 4a-1) and 70.2° for 4a-2) at each strike point on the FW surface. As for Scenario 4, the pitch angles of escaping alphas are 70.1° for 4b-1) and 55.2°, 62.2° for 4b-2) at each FW surface. The thicknesses of the drawn trajectories of alpha particles correspond to the gyromotion sizes of the alphas. Compared with the Scenario 2, the banana width of the alpha particle in the Scenario 4 equilibrium is wide because the I_p is lower, and the confinement properties of alphas will be worse. According to the results of Fokker-Planck modeling of alphas in ITER by Yavorskij, the density profile of fusion alphas in Scenario 4 is much wider than that in Scenario 2 [16]. It should be noted that the orbits shown in Figure 4 are final orbits just before alphas reach the FW. Most 3.5 MeV alphas are born in the core domain (r/a<~0.6) [16]. The so-called fat-banana orbit is not seen in ITER equilibria, resulting in prompt, direct loss of alphas from the core domain. Some process, such as ripple banana diffusion, is necessary if alphas are lost. Concerning TF ripple trapping, it was hard to find alphas trapped in the TF ripple. This is supposed to be due to the small value of $\delta(R,Z)$ in ITER.

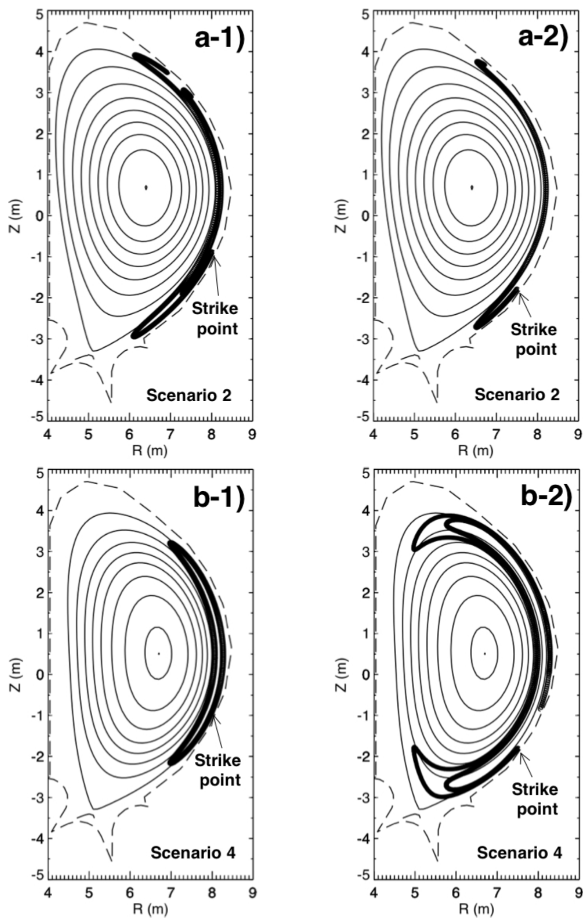

Fig. 4 Typical collisionless banana orbits of escaping alpha particles with full gyromotion in ITER equilibria: a-1) 3.5 MeV alpha particle orbits reaching FW#16 in Scenario 2 for different pitch angles: a-2) orbit reaching FW#17 in Scenario 2: b-1) orbit striking against FW#16 in Scenario 4: b-2) orbits striking against FW#17 in Scenario 4. The ion-grad *B* drift is directed downward.

In summary, the Lorentz orbit code on alpha particles has been developed to contribute to the design of a probe to detect escaping alpha particles in ITER. It has been shown that calculation results from the guiding center orbit code are not very helpful in judging the strike points of escaping alpha particles on the first wall. The Lorentz orbit code is a useful tool for determining where alpha particles are lost, demonstrating classes of escaping orbits and designing a probe to detect escaping alpha particles. It should be noted that alpha particle orbits computed from the Lorentz orbit code are not different macroscopically from those obtained from the guiding center orbit code. Alpha particles existing in the peripheral region will intersect the first wall placed at the outboard side of the torus on the lower plane. Next, in order to find a suitable place for detecting lost alpha particles and to contribute to the design of an optimized detection system, the loss and pitch angle distributions of alphas on the FW will be investigated with attention to the gyromotion phases of escaping alpha particles.

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