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高βリップルトカマクにおけるα粒子のエネルギー損失に関する研究
Research for alpha particle losses in a high beta rippled tokamak

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In a tokamak plasma, the confinement of energetic ions depends on the magnetic field structure. If plasma pressure is finite, diamagnetic current $\boldsymbol{j}_{\mathbf{dia}}$ and Pfirsch-Schlüter current $\boldsymbol{j}_{\mathbf{PS}}$ flow in a plasma to keep the magnetohydrodynamic (MHD) equilibrium. These equilibrium currents generate the poloidal and toroidal magnetic field and alter the field structure. Moreover, if we consider the non-axisymmetry of field structure such as toroidal field (TF) ripples, non-axisymmetric component of the equilibrium current $\boldsymbol{j}_{\mathbf{ripple}}$ can alter TF ripples themselves. When plasma beta becomes high, this change of field structure due to equilibrium currents (i.e., $\boldsymbol{j}_{\mathbf{PS}}$, $\boldsymbol{j}_{\mathbf{dia}}$ and $\boldsymbol{j}_{\mathbf{ripple}}$) might affect the confinement of energetic ions. It is well known that Shafranov shift, which is caused by $\boldsymbol{j}_{\mathbf{PS}}$, changes the birth profile of alpha particles and affects these losses. Therefore, we focus on how $\boldsymbol{j}_{\mathbf{PS}}$ and $\boldsymbol{j}_{\mathbf{ripple}}$ affect the confinement of alpha particles in a high beta plasma.

For this purpose, alpha particle orbits should be followed for the different magnetic field structures with and without the field component due to equilibrium current. We artificially created three cases of the field structure by solving MHD equilibrium equation. In **Case.(i)**, the field component due to whole equilibrium currents (i.e., $\boldsymbol{j}_{\mathbf{PS}}$, $\boldsymbol{j}_{\mathbf{dia}}$ and $\boldsymbol{j}_{\mathbf{ripple}}$) are included. Since the effect of $\boldsymbol{j}_{\mathbf{ripple}}$ is taken into account, it is exactly the three-dimensional (3D) MHD equilibrium field structure and the most accurate one. In **Case.(ii)**, the field component due to $\boldsymbol{j}_{\mathbf{ripple}}$ is artificially subtracted from 3D MHD equilibrium field (i.e., Case.(i)). Since $\boldsymbol{j}_{\mathbf{PS}}$ and $\boldsymbol{j}_{\mathbf{dia}}$ can be calculated by solving two-dimensional (2D) MHD equilibrium equation, it can save the computation time if the effect of $\boldsymbol{j}_{\mathbf{ripple}}$ can be ignored. In **Case.(iii)**, the field component due to $\boldsymbol{j}_{\mathbf{dia}}$ is artificially subtracted from Case.(ii). In terms of equilibrium current, the field structure of each case can be categorized as below.

Case.(i) : $\boldsymbol{j}_{\mathbf{PS}}$, $\boldsymbol{j}_{\mathbf{dia}}$ and $\boldsymbol{j}_{\mathbf{ripple}}$
Case.(ii) : $\boldsymbol{j}_{\mathbf{PS}}$ and $\boldsymbol{j}_{\mathbf{dia}}$
Case.(iii) : $\boldsymbol{j}_{\mathbf{PS}}$

Since the field structures of all three cases include TF ripples generated by the toroidal field coils (TFCs), they have the non-axisymmetric field component.

In this research, the structural design of a reactor is referred to the ITER reactor which has 18 TFCs. Keeping the plasma pressure profile, the safety-factor profile and the shape of plasma boundary, the MHD equilibrium is solved using the VMEC code with changing plasma beta. With the field structures of Case.(i), Case.(ii) and Case.(iii), alpha particle orbits are followed using the F3D-OFMC code. If the particles reach the first wall before the kinetic energy is reduced by the thermal energy due to the Coulomb collision, they are assumed to become lose.

Figure 1 shows the volume averaged beta value <β> dependence on loss power fraction for fusion alpha particles. The loss power fraction is defined by the ratio of the total kinetic energy of all loss particles and the total initial energy of all particles. In a relatively low beta plasma (<β>~2%), the equilibrium currents ($\boldsymbol{j}_{\mathbf{dia}}$ and $\boldsymbol{j}_{\mathbf{ripple}}$) negligibly affected the confinement of alpha particles. While in a high beta plasma (<β>=6%), $\boldsymbol{j}_{\mathbf{dia}}$ significantly increased alpha particle losses. In a high beta plasma, $\boldsymbol{j}_{\mathbf{ripple}}$ also increased these losses, but they are not so effective when it is compared to $\boldsymbol{j}_{\mathbf{dia}}$.

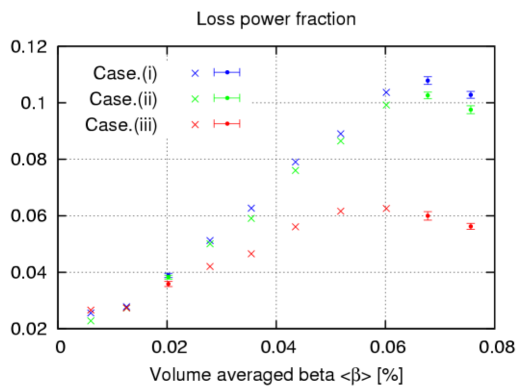

Fig.1 The blue, green and red x-marks respectively show loss power fraction for Case.(i), Case.(ii) and Case.(iii). Points of each color show the average value and the error bars show the standard deviation of loss power fraction