Diamagnetic effect on the energetic ion losses in a ripple tokamak

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1. Introduction

The finite number of the toroidal field coils (TFCs) breaks the symmetry of the tokamak. The non-axisymmetric field from TFCs is called the toroidal ripple field. Due to the ripple field, the amount of energetic ion losses is increased in a tokamak plasma. Especially, the losses of the fusion alpha particles induce some significant issues such as the deterioration of the heating efficiency of plasma and the localized heat loads on the vessel. In order to confine energetic ions successfully, the magnetic field structures have to be investigated.

The plasma itself changes the magnetic field structures. These effects are called the finite beta effects. They have been thoroughly researched to analyze the effects on the energetic ion losses in a low beta plasma [1][2]. Since the finite beta effects are not as strong in a low beta plasma, the toroidal field due to the poloidal plasma current is sometimes ignored. This toroidal field reduce the field strength $|B|$, it is called the diamagnetic effect. The diamagnetic effect significantly changes the curvature of the $|B|$ contour in a high beta plasma [3]. Since the reflection point of the trapped particle follows the $|B|$ contour, the diamagnetic effect significantly changes the energetic ion losses.

In this study, the toroidal field due to the plasma current is obtained by resolving the MHD equilibrium equation in a D-shape ripple tokamak. In order to analyze the diamagnetic effect on the energetic ion losses, 5 models of the 3D field structures are created by changing the toroidal field due to the plasma current. And then we investigate how the diamagnetic effect changes the energetic ion losses by calculating the orbits of the fusion alpha particles for each case.

2. MHD equilibrium calculation

First, the two dimensional MHD equilibrium field is calculated by the VMEC code which uses the inverse spectral method. The pressure and safety factor profile are shown in Fig.1 (a) and (b). To achieve the high safety factor value, the reversed shear profile is used in this study. Figure 1(c) shows the color map of the vacuum ripple ratio δ, which is defined by

$$\delta = \frac{\boldsymbol{B}_{\max} - \boldsymbol{B}_{\max}}{\boldsymbol{B}_{\max} + \boldsymbol{B}_{\max}}, \quad (1)$$

where B_{max} and B_{min} are the maximum and minimum field strength along the toroidal angle on the fixed R and Z position. The 18 toroidal field coils are set on the toroidal angle is

$$\phi = \frac{2\pi(\boldsymbol{i}-1)}{18} \qquad (\boldsymbol{i} = 1, 2, 3\ldots18). \quad (2)$$

The maximum vacuum ripple ratio is less than 0.01. This value almost equals to that value for the ITER operation. By superimposing the vacuum ripple component on the 2D MHD equilibrium field, the approximated 3D field structure can be created in this study.

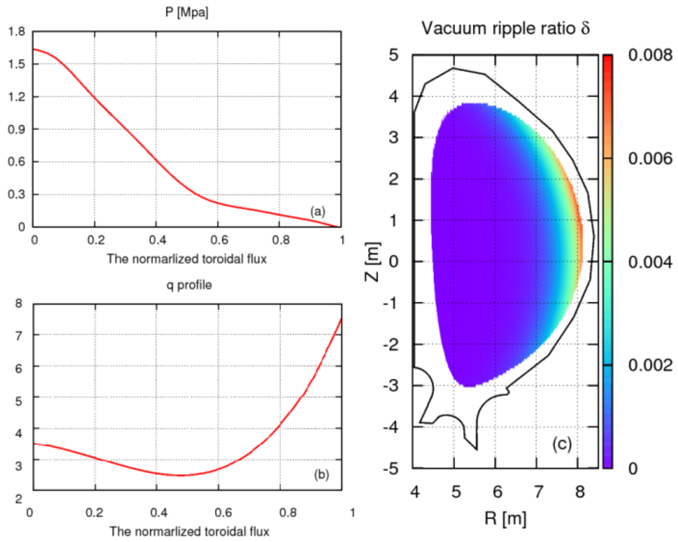

Fig.1 (a) The pressure profile, (b) the safety factor profile and (c) the vacuum ripple ratio

Figure 2 (a) shows the vacuum and equilibrium toroidal field B_t along R direction. The vacuum toroidal field is approximately proportional to $1/R$, therefore, the vacuum toroidal field has not same value along the R direction. By the diamagnetic effect, the vacuum toroidal field is reduced at the outer torus and the curvature of the field strength $|B|$ contour becomes higher. In order to analyze the diamagnetic effect on the energetic ion losses, 5 models of the 3D field structures are created by changing the toroidal field strength from the poloidal plasma current. In this study, 5 field models are called J0, J1, J2, J3 and J4, in which the diamagnetic effect on the toroidal field is multiplied by 0, 1, 2, 3 and 4, respectively. Figure 2(b) shows the field strength $|B|$ along the R direction at (Z,φ)=(0.5m,0) for each field model. By changing the diamagnetic effect, the field strength is reduced at outer torus and the $|B|$ contour is changed. Figure 3 show the $|B|$ contour at φ=0 for each field model. With increasing the diamagnetic effect, the curvature of this contour becomes higher and the closed contour region is extended. In the next section, we will discuss how the changes of |*B*| contour affect on the energetic ion losses.

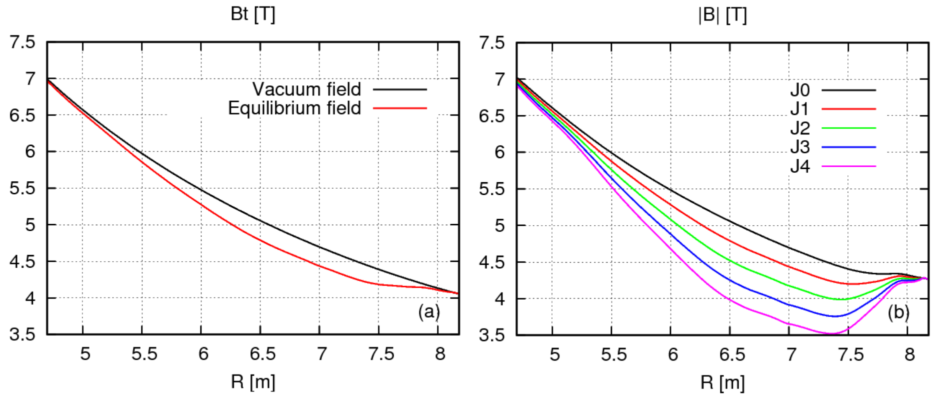

Fig.2 (a) The vacuum and equilibrium toroidal field strength and (b) the field strength |*B*| for each field model along the *R* direction at (Z,φ)=(0.5m,0)

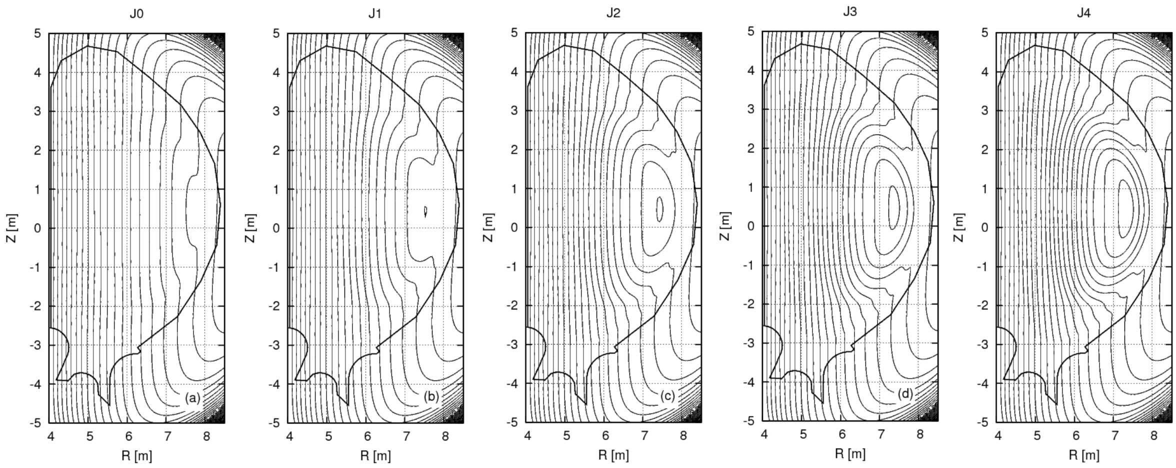

Fig.3 The contour of the field strength |B| at φ=0 for each field model

3 Diamagnetic effect on the energetic ion losses

Changes of the |*B*| contour strongly affect on the energetic ion orbits. Since the magnetic momentum

$$\mu = \frac{\boldsymbol{m}\boldsymbol{v}^2}{2|\boldsymbol{B}|} \tag{3}$$

is conserved, the particles are always trapped on the same |*B*| position. Therefore, if the energetic ions are trapped in the closed |*B*| contour region, they do not become loss. It means that the loss conditions with respect to the trapped position are changed by the diamagnetic effect. The red color in Fig.4 shows the tracing time of alpha particles on the initial point. They are started from inner plasma with non parallel velocity. These figures clearly show that there are two opposite effects due to the diamagnetic effect: the trapped particles in the closed |*B*| contour region do not become loss and the more inner trapped particles become loss. Then, we have to clarify which effect is stronger.

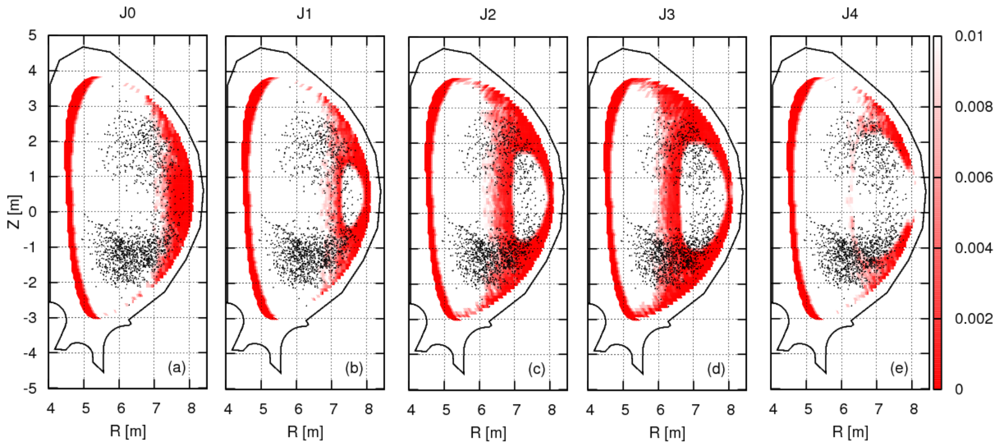

Fig.4 The tracing time [s] for the alpha particles with non-parallel velocity on the initial point (the red color) and the first trapped points (the black dots)

The black dots in Fig.4 show the first trapped points of 10,000 fusion alpha particles. For these birth profiles, the energetic ion orbits are calculated by F3D-OFMC code. Figure 5 shows the loss rate which is defined by the ratio between the total initial energy and the total energy of loss particle which collide to the first wall. The final loss rate for J0, J1, J2, J3 and J4 are 0.050, 0.086, 0.101, 0.104 and 0.089, respectively. It is found that the weak diamagnetic effect increases and strong diamagnetic effect reduces the losses of fusion alpha particles. If we can choose the strong diamagnetic system, such as high pressure, high aspect and high safety factor, the energetic ions can be well confined. In future work, we will investigate the diamagnetic effect on the energetic ion losses by changing the aspect ratio and the safety factor.

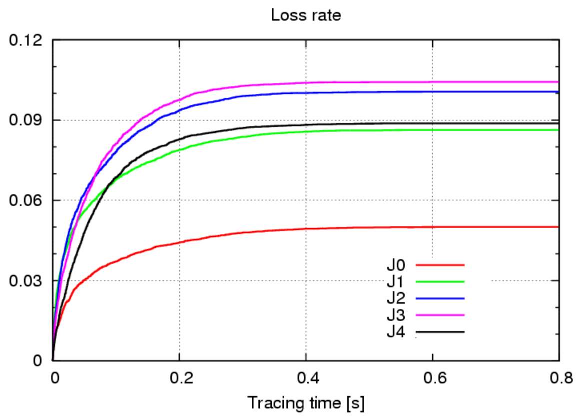

Fig.5 The tracing time dependence of the loss rate for each field model

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