Three-dimensional effects on MHD equilibrium in tokamaks

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1. Introduction

In most of situations, tokamak equilibria are analyzed as two-dimensional (2D) systems with the axisymmetry. The nature of this symmetry gives many advantages for its analysis. However, as realistic tokamaks have discreteness of the toroidal field coils, this discreteness yields the toroidal field ripples (TF ripples) and, strictly speaking, realistic tokamaks could not be axisymmetric configurations. In previous work[1)], we pointed out the significance of three-dimensional (3D) effects, which are effects of plasma equilibrium currents along rippled field lines.

On the other hand, in recent tokamak experiments, it is noted that stochastic filed lines reduce strong heat load driven by the edge localize mode (ELM) on the divertor plate. Stochastic field lines are produced by the external helical perturbation and it is called the Dynamic Ergodic Divertor (DED). From the viewpoint of high-β stellarator equilibrium, 3D effects on the stochastic field are very important because finite-β perturbed field produces further stochasticity in the peripheral region. However, in present analysis of DED, 2D MHD equilibrium superimposed vacuum helical perturbed field was still used. In order to consider effects of DED to ELM, considerations of finite-β MHD equilibrium and the impact of 3D effects are critical and urgent issue.

In this study, the fully 3D MHD equilibrium of non-axisymmetric tokamak is solved numerically and equilibrium responses are studied. For this study, we use a 3D MHD equilibrium code VMEC[2)], which is widely used to analyze the 3D equilibrium of helical system plasmas. Since VMEC uses the flux coordinate system, it can not treat magnetic island and stochastic field in the computational domain. Thus, as first step, we study the equilibrium response to the toroidal field (TF) ripple. Special attention is the equilibrium response on the test blanket module (TBM).

2. Vacuum field in the ITER

At first, we discuss the vacuum field in the ITER. The TF ripple in the ITER is usually around 1% and the ripple is already very small. However, the ripple loss of alpha particles is not negligible for the heat load on the first all. To reduce the TF ripple furthermore, the ferritic steel is installed in the inside of the first wall. Install the ferritic steel, the ripple is reduced less than 1%. On the other hand, to breed the tritium, installing the test blanket module (TBM) is planning. Since the TBM will be shielded, the ripple is superposed with low-*n*.

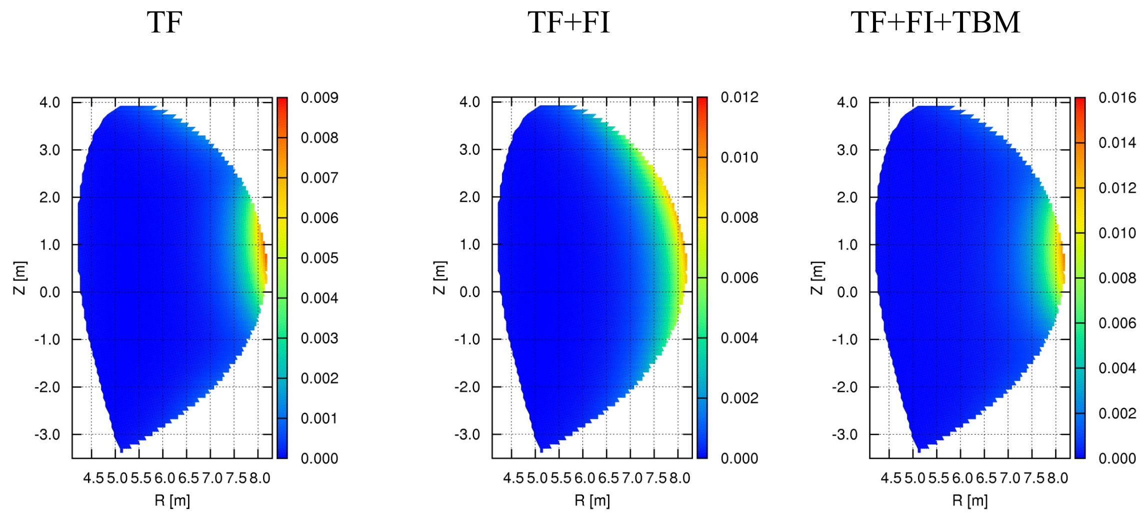

Figure 1 Contour plots of the TF ripple for the vacuum are shown for three cases; the field by only TF coils, superposed the ferritic insert and superposed ferritic insert with the TBM.

Figure 1 shows contour plots of the TF ripple. Contours are shown in only the inside of the separatrix. The TF ripple is calculated in a section installed the TBM. For the TF+FI case, the TF ripple is reduced less than 1% but for the TF+FI+TBM case the ripple is increased larger than 1.5%. For the TF+FI case, though the ripple is most reduced, the ripple is increased upper side.

3. 3D MHD equilibrium for the steady-state discharge

In the previous study, the 3D effect for the reversed shear is larger than the normal shear. Since the rotational transform is small for the reversed shear, the Shafranov shift is large. The large shift leads to the change of local pitch of the magnetic field line. In fig.2, the pressure and safety factor profiles are shown for the scenario 4 of the ITER. The steep pressure gradient drives large non-inductive current then the safety factor is reversed in the plasma core. The rotational transform is around 0.3 and magnetic shear is very small in the plasma core.

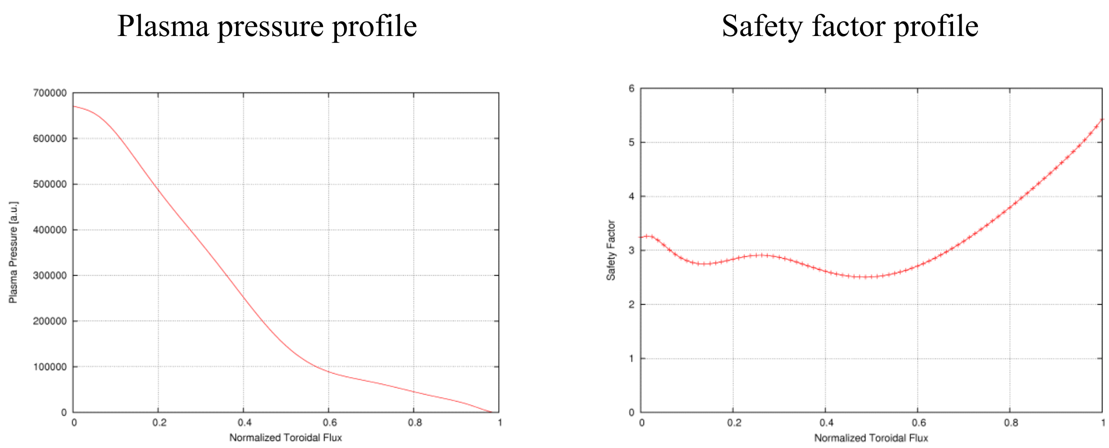

Figure 2 Profiles of the plasma pressure and safety factor for the scenario 4 are shown as the function of the normalized poloidal flux.

Figure 3 shows the magnetic field strength *B* and the position of the last closed flux surface *R* on a *Z=const*. plane along the toroidal angle ϕ. The *B* and *R* are plotted for 3 cases (TF, TF+FI, TF+FI+TBM) corresponding to fig.1. For the TF and TF+FI cases, the *R* changes along the toroidal direction but the change is very small. However, for the TF+FI+TBM case, the *R* changes larger than above 2 cases. Especially, in this study, the TBM is installed to 2 sectors then *R* moves in the inward of the torus under the TBM. The ripple of *R* is about 0.5% in this case.

Figure 4 shows contour maps of the TF ripple for the TF+FI and TF+FI+TBM cases. Comparing the TF ripple for the vacuum field, differences are very small. Figures are plotted in the inside of the last closed flux surface. In the LCFS, the ripple is almost same in both case. Since the TF ripple is calculated by total magnetic field *B*, the plasma response driven by the pressure-induced field $O(\beta)$ is very smaller than the toroidal field. Therefore, the change of the TF ripple is not large.

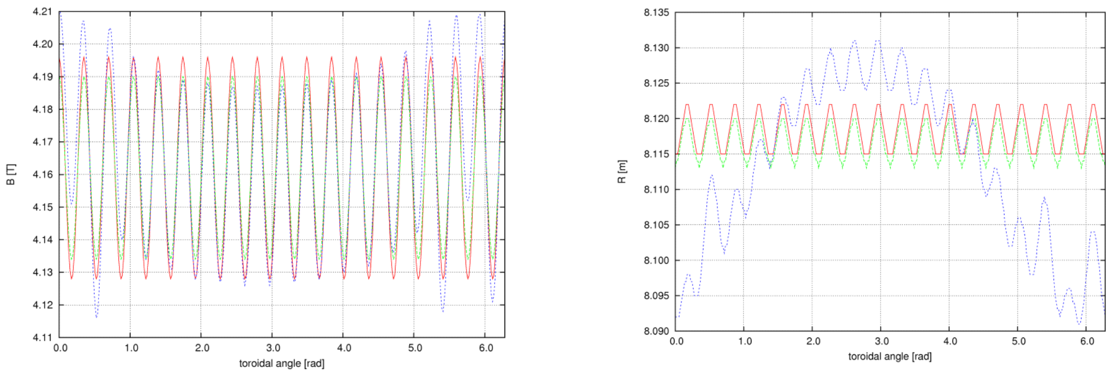

Figure 3 The B and R are plotted for 3 cases (TF, TF+FI, TF+FI+TBM) corresponding to fig.1.

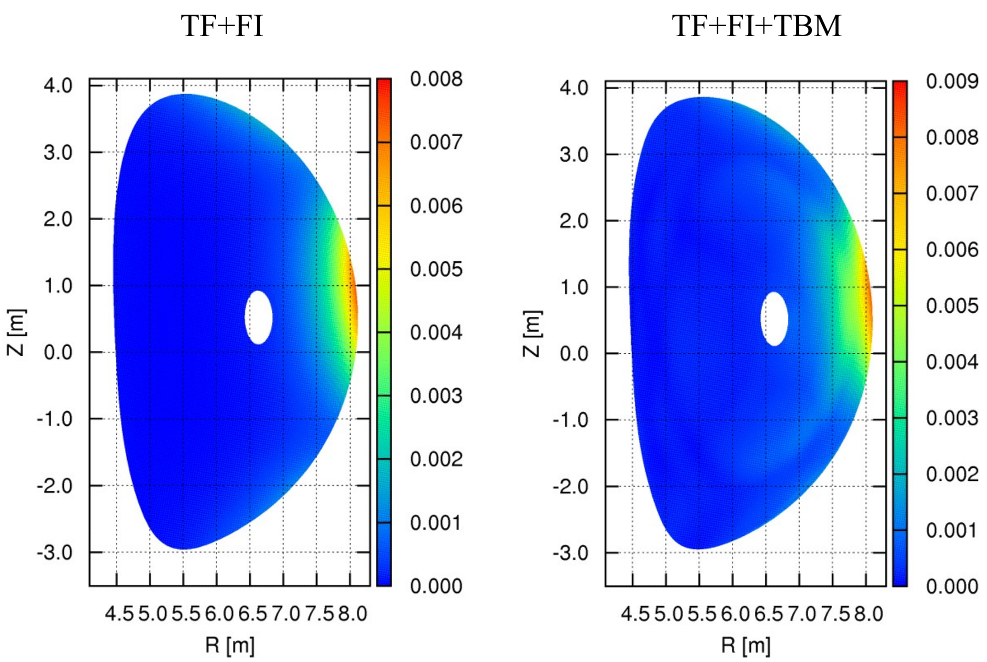

Figure 4 Contour maps of the TF ripple for the scenario 4 are plotted for the TF+FI and TF+FI+TBM case.

The ripple trapped particle is affected by the TF ripple but the transition between trapped and detrapped states is affected by the ripple well along the magnetic field line. This transition leads to the stochastic ripple loss.

4. Summary

We study 3D MHD equilibria for the steady-state scenario of the ITER. Calculating the TF ripple in fully 3D MHD equilibria, the change of the TF ripple by 3D effects are studied. The change of the TF ripple is very small. However, the change of the ripple well be expected for the TF+TBM+FI case. In this case, the confinement of alpha particle is almost same level to the vacuum approximation. However, the energetic particle, whose energy is less than the alpha particle, will be affected the stochastic ripple loss. The study of the degradation of the energetic particle is a future subject.

1) Y. Suzuki, Y. Nakamura and K. Kondo, Nucl. Fusion **43** (2003) 406

2) S.P. Hirshman, W.I.van Rij, and P. Merkel, Comput Phys Comm **43** (1986) 143.