J. Plasma Fusion Res. SERIES, Vol. 5 (2002) 500–504

Equilibrium Calculation of Tohoku University Heliac

HARADA Koumei, KITAJIMA Sumio, HASHIZUME Hidetoshi and SUZUKI Yasuhiro[1]
Tohoku University, Sendai 980-8579, Japan
[1] Graduate School of Energy Science, Kyoto University

(Received: 11 December 2001 / Accepted: 2 December 2002)

Abstract

Numerical analysis of equilibrium states in the heliac configuration is performed by using VMEC code. In the heliac configuration, it is possible to produce flux surfaces with the magnetic well under vacuum condition. Mercier instability is stabilized in a wide region of the plasma column in the deep well configuration. On the other hand, the local stability is limited only around a magnetic axis in the hill configuration. In the Mercier criterion, the well term has favorable effect on the local stability, while the geodesic curvature has negative effect.

Keywords:

heliac, plasma, VMEC, equilibrium, stability, beta

1. Introduction

In the heliac configuration [1,2], many kinds of magnetic configurations can be obtained easily by changing in the ratio of coil currents. The heliac configuration can produce flux surfaces with a moderate shear and a magnetic well under the vacuum condition. There is possibility to achieve high beta plasma confinement in the heliac configuration, which is really required for future fusion reactors. For the high β plasma confinement, it is important to know how the magnetic surface quantities, such as rotational transform and well depth, change with increase in β. One of the analysis code of the MHD equilibrium solution is VMEC code [3,4] which assumes the nested flux surfaces.

The magnetic surfaces of Tohoku University Heliac [5] (TU-Heliac) are produced by three sets of simple circular coils, thirty two toroidal field coils, a center conductor coil and two vertical field coils, which means no needs of complicated helical coils. The difficulty in constructing the magnetic coils in the heliac can be solved by realizing the demountable magnetic coil proposed in the ref. [6]. In this paper, both rotational transform and well depth are evaluated under the finite beta and vacuum conditions using VMEC code, and then the local stability is also investigated based on the Mercier criterion [7]. This study is the first step for suitable design of the high β D-^{3}He plasma confinement reactor by the heliac configuration.

2. Parameters for Magnetic Configuration

In the TU-Heliac, the parameters characterizing the magnetic field configurations are a ratio of center conductor coil current to toroidal coil current (I_c / RH_0) and a ratio of vertical coil current to center conductor coil current (B_v / I_c). The I_c, R and H_0 are center conductor coil current, major radius and toroidal magnetic field, respectively. RH_0 is a quantity proportional to toroidal coil current, and B_v is a vertical magnetic field. By changing I_c / RH_0 we can control a magnetic surface configuration which is equivalent to controlling the rotational transform and shear. In the same way, B_v / I_c affects radial shift of the surfaces relating to magnetic well.

Figures 1(a) and 1(b) show the magnetic well depth

Corresponding author's e-mail: koumei.harada@qse.tohoku.ac.jp

and rotational transform under the vacuum condition, respectively. In these calculations, the value of I_c / RH_0 is selected to be 0.40. Since the period of magnetic field is 4 in the TU-Heliac, this configuration contains rational surface of $n/m = 8/5$ (n: toroidal mode number, m: poroidal mode number) which is located in the core plasma region. As shown in Fig. 1(a), the well depth increases with decrease in B_v / I_c. On the other hand, B_v / I_c does not affect the rotational transform profiles, as shown in Fig. 1(b).

3. Results

The equilibriums of the TU-Heliac are calculated by using VMEC code. Two typical configurations are chosen from conditions in Fig. 1. In the vacuum condition, one has the deep well ($I_c / RH_0 = 0.40$ and $B_v / I_c = 2.0$), and the other has the high hill ($I_c / RH_0 = 0.40$ and $B_v / I_c = 5.0$).

Figure 2 shows finite β effect on the deep well configration. Remarkable change of the well depth can be obtained by increasing the β value. The well depth increases with increase in β. On the other hand, the rotational transform does not change when β is less than 3.5 % as shown in Fig. 2(a). The magnetic shear increases monotonically with increase in minor radius, while it changes to negative value around the magnetic axis when $\beta = 3.5$ %. Figure 2(c) shows the stable region evaluated from the Mercier criterion, where the local stabilities are evaluated on the each magnetic flux surfaces. The stable region expands with increase in β, and reaches maximum when $\beta_0 \cong 2$ [%], and then it shrinks with increase in β. Figure 2(d) shows profiles of terms for Mercier criterion. Stable state is achieved

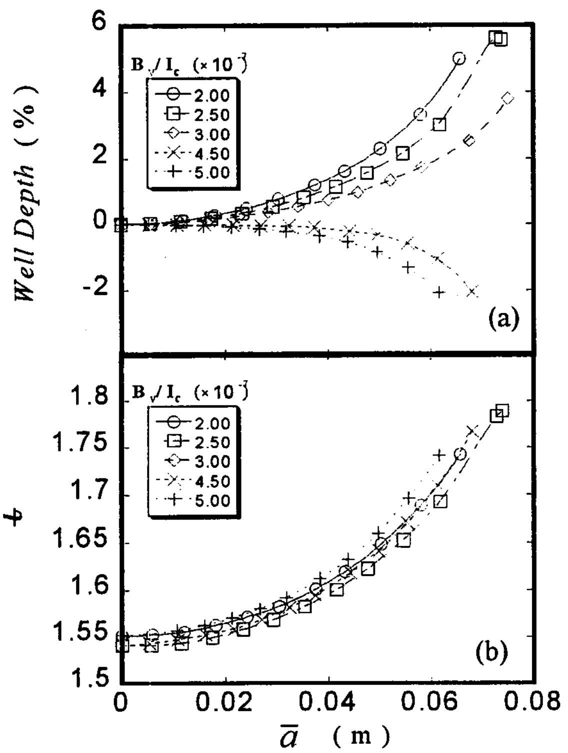

Fig. 1 The radial profile of (a) the magnetic well depth and (b) the rotational transform under vacuum condition. Horizontal axis represents mean plasma radius, and B_v / I_c is chosen as a parameter in both figures.

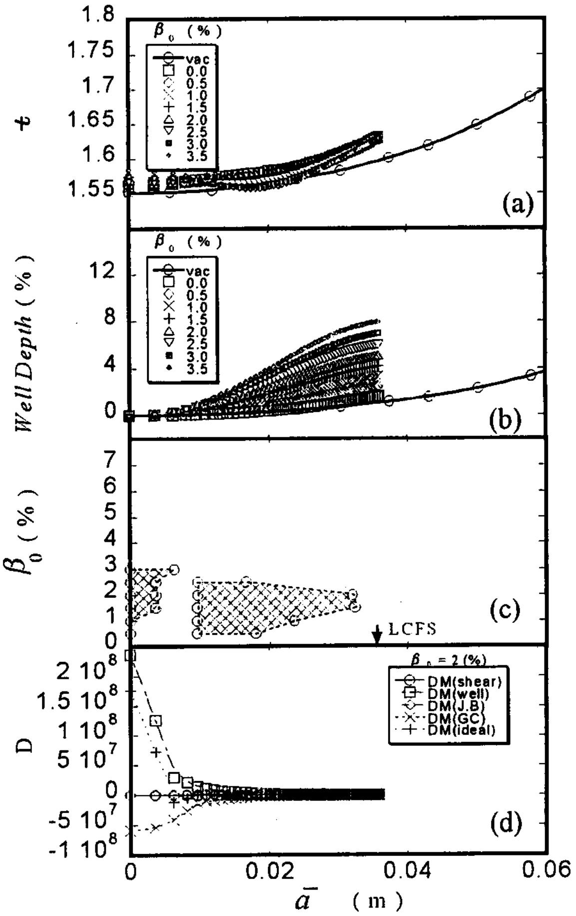

Fig. 2 The finite β effect on the well configuration. (a) the rotational transform, (b) the well depth, (c) Mercier stable region (mesh region) and (d) indexes for Mercier criterion. LCFS means Last Closed Flux Surface. Local stability is achieved when DM(ideal) (= DM(shear) + DM(well) + DM(J.B) + DM(GC)) > 0. DM(shear), DM(well), DM(J.B) and DM(GC) are related to magnetic shear, well depth, parallel current with magnetic field and geodesic curvature, respectively.

when DM (ideal) > 0, where DM (ideal) = DM (shear) + DM (well) + DM (J.B) + DM (GC). DM (shear), DM(well), DM(J.B) and DM(GC) are related to magnetic shear, well depth, parallel current with magnetic field and geodesic curvature, respectively. Figure 2(d) indicates that the magnetic well is effective for stability, but the geodesic curvature has negative effect on the stability. Because absolute value of DM (shear) is smaller compared with DM (well) and DM (GC), the magnetic shear does not affect the stability from the view point of the Mercier criterion in the heliac configuration.

Figure 3 shows results in the high hill configuration. The magnetic well is produced in the finite β configuration even though the magnetic hill has been generated under the vacuum condition. Local stability exists only around the magnetic axis as shown in Fig. 3(c). Items of Mercier criterion in Fig. 3(d) show the same tendency as those in the well configuration shown in Fig. 2(d). The magnetic well contributes to the

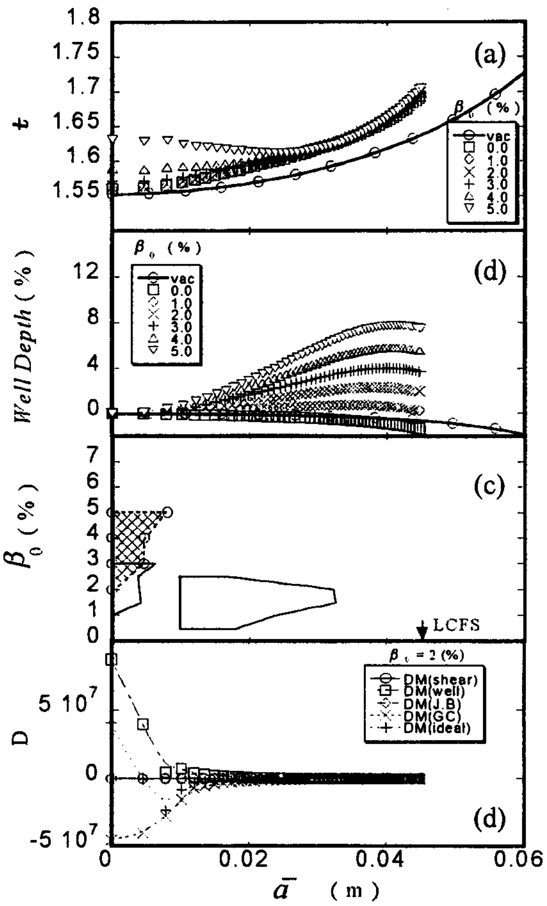

Fig. 3 The finite β effect on the hill configuration. (a) the rotational transform, (b) the well depth, (c) Mercier stable region (mesh region) and (d) indexes for Mercier criterion. LCFS means Last Closed Flux Surface. Local stability is achieved when DM(ideal) (= DM(shear) + DM(well) + DM(J.B) + DM(GC)) > 0. DM(shear), DM(well), DM(J.B) and DM(GC) are related to magnetic shear, well depth, parallel current with magnetic field and geodesic curvature, respectively.
Solid line region in figure (c) is stable region shown in Fig. 2 (c).

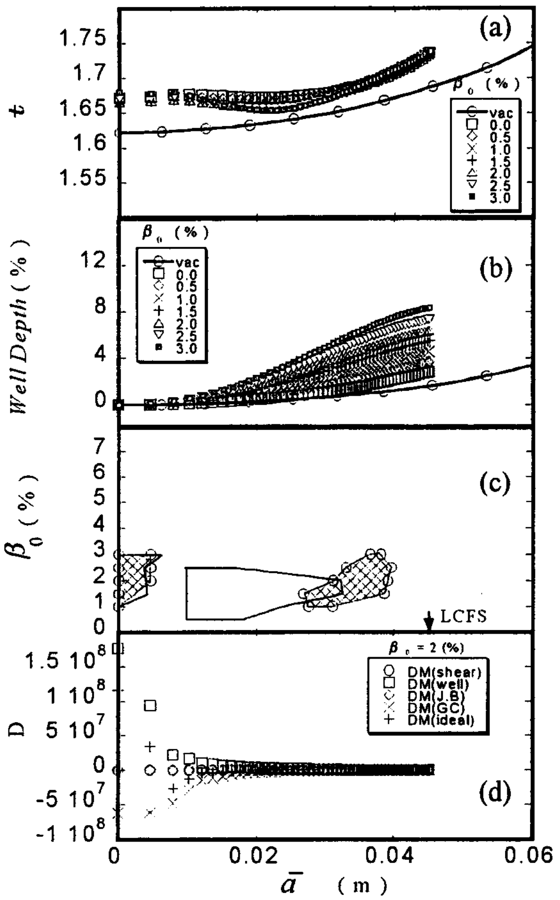

Fig. 4 The finite β effect on the well configuration without 8/5 rational surface. (a) the rotational transform, (b) the well depth, (c) Mercier stable region (mesh region) and (d) indexes for Mercier criterion. LCFS means Last Closed Flux Surface. Local stability is achieved when DM(ideal) (= DM(shear) + DM(well) + DM(J.B) + DM(GC)) > 0. DM(shear), DM(well), DM(J.B) and DM(GC) are related to magnetic shear, well depth, parallel current with magnetic field and geodesic curvature, respectively.
Solid line region in figure (c) is stable region shown in Fig. 2 (c).

stability, on the other hand the geodesic curvature does not improve local stability, which is the same as the well configuration.

The equilibrium of the configuration which does not contain the 8/5 rational surface is calculated. In Figures 2 and 3, sufficient convergence of the calculation is not obtained when the rotational transform is about 1.6, and thus the 8/5 rational surface might have effect on the convergence of the calculation. Results of the stability calculation are shown in Figures 4 and 5,

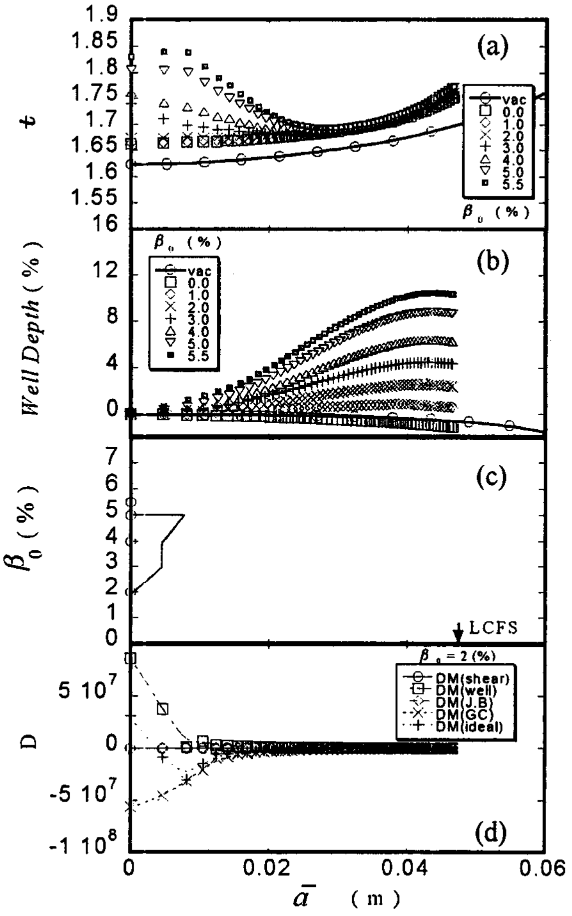

Fig. 5 The finite β effect on the hill configuration without 8/5 rational surface. (a) the rotational transform, (b) the well depth, (c) Mercier stable region (mesh region) and (d) indexes for Mercier criterion. LCFS means Last Closed Flux Surface. Local stability is achieved when DM(ideal) (= DM(shear) + DM(well) + DM(J.B) + DM(GC)) > 0. DM(shear), DM(well), DM(J.B) and DM(GC) are related to magnetic shear, well depth, parallel current with magnetic field and geodesic curvature, respectively.
Solid line region in figure (c) is stable region shown in Fig. 3 (c).

where the magnetic configuration has the well or hill under the vacuum condition, respectively. The rotational transform in Fig. 4 is similar to previously obtained result in Fig. 2. In Fig. 4, converged solutions are not obtained in the case that β_0 is lager than 4.0. Figure 5 shows results for the hill configuration under the vacuum condition without the 8/5 rational surface. There is little stable region in this configuration. From Figs. 4(d) and 5(d), it is found that the magnetic well affects the local stability and geodesic curvature enhances the instability. This behavior is the same as that obtained from Figs. 2 and 3. As a result, equilibrium solutions are not affected by the 8/5 rational surface in the VMEC calculations.

The stability in a large-scale heliac device is evaluated, where the size is 10 times larger than the TU-Heliac one. Major radius and mean plasma radius of the device are 4.8 m and 0.5 m, respectively. Here, the parameters characterizing magnetic configuration are selected to be $I_c / RH_0 = 0.40$ and $B_v / I_c = 2.0$, which correspond to the magnetic configuration with the magnetic well under vacuum condition. As shown in Fig. 6, a stable region exists in the region of $\bar{a} = 0.2$ ~ 0.4 at $\beta_0 = 1.5$ %, which is similar to the TU-Heliac case. On the other hand, the stability is improved around the magnetic axis, because there is a stable region for β_0 = 5 ~ 6 [%] near the axis. Scaling up of the confinement region, therefore, contributes to the high β stability around the axis. However, this different result of simply

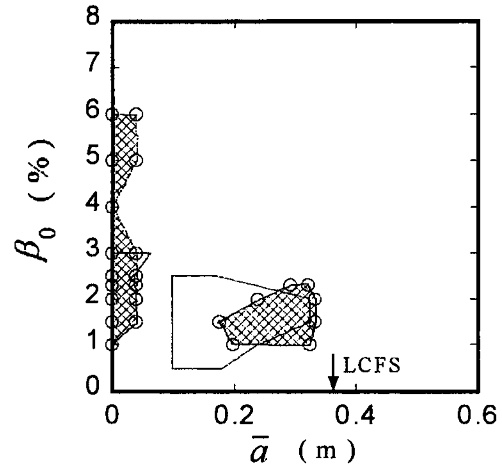

Fig. 6 Mercier stable region (mesh region) in the well configuration of Heliac. The size of Heliac is assumed to be ten times larger than TU-Heliac.
Solid line region is stable region shown in Fig. 2 (c) expanded to 10 times radial size.

scale-up device from TU-Heliac is not acceptable from the viewpoint of ideal MHD model. The reason can be that initial conditions of each calculation, which are obtained after repeated trial and error, are different.

4. Summary

The MHD equilibrium and Mercier stability calculations of the Tohoku University Heliac have been performed by using the VMEC code. There is a wide stable region in the configuration that has the magnetic well under the vacuum condition when β_0 is nearly 2 %. The well term in the Mercier criterion has a favorable effect on the local stability, and the geodesic curvature term enhances instability. There is no effect of rational surface on the equilibrium solution and local stability with the VMEC code.

References

[1] A.H. Boozer *el al., Plasma Physics and Controlled Nuclear Fusion Research (Proc. 9th Int. Conf. Baltimore, 1982)(IAEA, Vienna, 1983)* **3**, 129 (1983).
[2] S. Yoshikawa, Nucl. Fusion **23**, 667 (1983).
[3] S.P. Hirshman *et al.*, Phys. Fluids **26**, 3553 (1983).
[4] S.P. Hirshman *et al.*, Comp. Phys. Comm. **43**, 143–155 (1986).
[5] S. Kitajima *et al.*, Jpn. J. Appl. Phys. **30**, 2606 (1991).
[6] S. Ito, H. Hashizume and S. Kitajima, International Journal of Applied Electromagnetic and Mechanics 13, 14 (2001) (in printing) 'Study on mechanical jointing of high temperature superconductors'.
[7] Mercier C., Nucl. Fusion **1**, 47 (1960).