Core Plasma Design of a Heliotron Reactor

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abstract

The design of a core plasma with the LHD-type heliotron configuration has been advanced. Recent design study of a LHD-type heliotron reactor has shown that the increase in the reactor size is a possible solution to obtain a sufficient blanket space. This increase in the reactor size enables a flexible selection of a plasma configuration. Then a commercial plant design with the plasma configuration that has a similar shape to that of LHD high-beta plasma discharge was carried out. The design point survey with a system design code showed that there exists the design window that satisfies engineering constraints with the physics condition which can be extrapolated from the present achievements of the LHD experiments. Finite-beta equilibrium calculations by VMEC code showed that almost the same shape of the last closed flux surface as that in the vacuum equilibrium can be obtained by applying an appropriate additional vertical field.

Keywords: heliotron, reactor design, system design code, finite-beta equilibrium analysis

1. Introduction

Helical system without plasma current inherently has a suitable property for a commercial plant. It has easiness in steady-state operation because it is free from any operational obstacle caused by a plasma current. It also needs no current drive power, resulting in low circulating power and high plant energy efficiency. Among helical system, the heliotron configuration with 2 helical coils has many experimental data provided by the Large Helical Device (LHD) in National Institute for Fusion Science (NIFS). Then it is important to investigate a possible design option based on this configuration.

One of the most critical problems in the design of LHD-type heliotron reactors is the simultaneous achievement of the substantial plasma volume that enables a good confinement property and the sufficient space for the blanket and neutron shielding for superconducting coils. A LHD-type heliotron has two key design parameters. One is helical pitch parameter, $\gamma=ma_c/(lR_c)$, where m, l, a_c and R_c are toroidal pitch number, poloidal pitch number, minor radius and major radius of helical coil, respectively. The other is magnetic axis position R_{ax}, which can be adjusted through the vertical field strength generated by poloidal coils.

In the past design of LHD-type heliotron reactors, FFHR-2 and FFHR-2m1 [1], γ=1.15 and outward-shifted magnetic axis position (R_{ax}/R_c=3.75/3.9) were adopted to get as large space for the blanket as possible with a compact reactor size (R_c~10m). On the other hand, relatively good particle confinement is expected with the inward-shifted magnetic axis position (R_{ax}/R_c~3.6/3.9). This fact is also supported by the LHD experiments [2]. In LHD experiment, high-beta discharge (volume-averaged beta value over 5% with diamagnetic measurements) has been achieved also with the inward-shifted configuration and γ=1.2 [3]. Therefore, a reactor design with inward-shifted configuration and γ=1.2 is more feasible.

Recent study has clarified that the stored magnetic energy of superconducting coil system and the total plant capital cost does not so much increase with the increase in the reactor size when the required confinement improvement factor is kept constant [4]. Then increase in the reactor size becomes one possible solution to obtain a sufficient blanket space. This increase of reactor size also leads to the reduction of neutron and heat load of plasma facing components.

Therefore in this study a reactor design with the plasma configuration with inward-shifted magnetic axis position and γ=1.2 was investigated. The reactor design with such a new configuration is quite important from the viewpoint of increasing not only feasibility but also flexibility of the design.

2. Design point survey by a system design code

It can be easily understood that there is some trade-offs of the engineering and physics constraints. For example, the increase in magnetic field strength leads to the relaxation for the physics requirement (beta value, confinement improvement, etc.) but it increases the stored magnetic energy and decreases the blanket space if the current density of helical coils is fixed.

It was discovered that not only the geometry of helical coils but also the property (location and current) of poloidal (vertical field) coils has a considerable influence over the equilibrium magnetic surface structure including a ergodic layer. Then the property of poloidal coils has been examined in detail to increase the volume enclosed by the last closed flux surface (LCFS) and to avoid interference between plasma and the surrounding engineering components (Fig. 1). A system design code has also been developed for heliotron reactors, which can deal with a wide design space. Here plasma geometric shape is assumed to be kept to have a similar shape to that given in Figure 1.

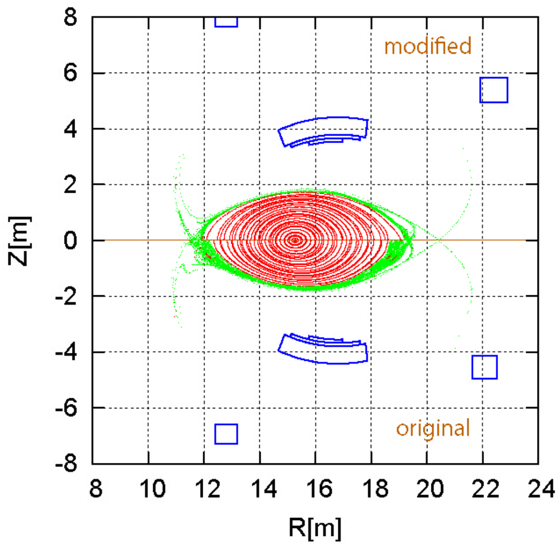

Fig. 1: comparison of magnetic surface structure with original (lower) / modified (upper) poloidal coil position.

Figure 2 shows the relation between the stored magnetic energy W_{mag} and the required confinement improvement factor to the present LHD experiments H^{LHD} (0.93 times of ISS04v3 scaling $H^{ISS04v3}$[5]). In Fig.2 design points that have fusion output around 3GW are plotted with different color by the magnitude of neutron wall loading Γ_{nw}. The hatched region shows the design window that has the same volume-averaged beta value $\langle\beta\rangle$. As you can see, $\langle\beta\rangle$>5.5% is required to confine W_{mag}<160GJ. The required confinement improvement factor depends on the neutron wall loading Γ_{nw}. If Γ_{nw}<1.5MW/m^2 is imposed, the required confinement improvement factor to LHD H^{LHD}~1.3.

Figure 3 shows the relation between blanket space Δ and the required confinement improvement factor for the design points with Γ_{nw} <1.5MW/m^2 and $\langle\beta\rangle$ =5.5%. The curves in the figure show the contour of W_{mag}. You can see that there is a trade-off of stored magnetic energy W_{mag} and blanket space Δ, but there still exists quite narrow window that satisfies W_{mag} <160GJ and blanket space Δ ~1m simultaneously.

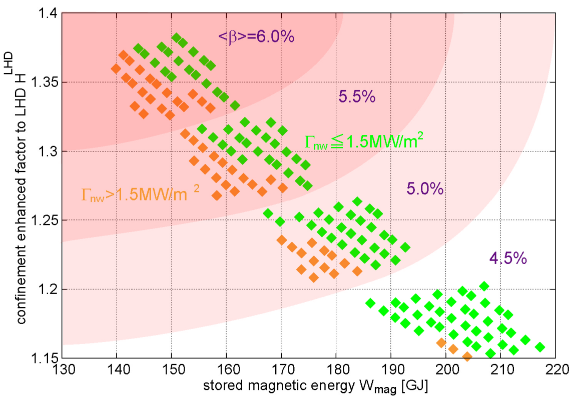

Fig. 2: Stored magnetic energy vs. the required confinement improvement factor of the design points that have fusion output ~3GW.

Here we selected the design point plotted with star symbol in the figure 3. The main design parameters are shown in Table I.

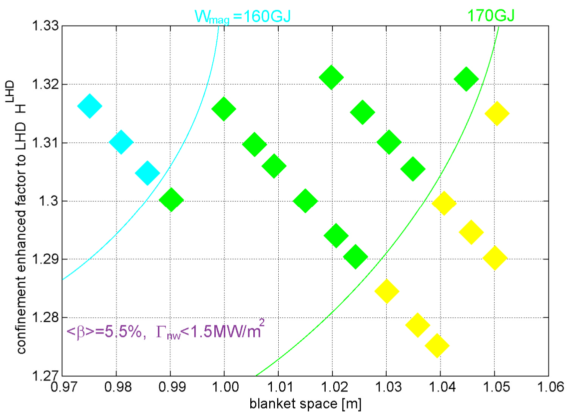

Fig. 3: Space for the blanket vs. the required confinement improvement factor of the design point of which volume-averaged beta value is 5.5%.

Table I: Selected design parameters

Coil major/minor radius R_c/a_c [m]	17.0 / 4.08
Plasma major/minor radius $R_p/<a_p>$ [m]	15.7 / 2.50
Plasma volume V_p [m^3]	1927
Average toroidal field B_{ax}[T]	5.0
Volume-averaged beta $<\beta>$ [%]	5.5
Confinement improvement factor H^{ISS04}	1.2
Blanket space Δ [m]	0.985
Stored magnetic energy W_{mag} [GJ]	160

The parametric scan by a system code clarifies that design window which satisfies all physics and engineering constraints is quite narrow but still exists with the configuration with inward-shifted magnetic axis and pitch parameter of 1.2, which coincide with the configuration that achieve high-beta discharge in the LHD experiment.

3. Finite-beta equilibrium calculation

As shown in the previous section, the reactor with the sufficient fusion output for a commercial operation can be designed with the core plasma of which volume-averaged beta value ~5.5%. However, the above estimation was carried out with the magnetic surface structure in vacuum equilibrium. Then finite-beta equilibrium calculation was carried out to find such high-beta equilibrium that is consistent with the above estimation.

Magnetic axis position and plasma geometric center position gradually shift outward with the increase of beta value. On the other hand, in heliotron configuration, the position of separatrix is basically determined by a helical pitch parameter. Then plasma volume shrinks with the shift of magnetic axis due to the increase in beta value. On the other hand, vacuum magnetic axis position can be changed by the control of vertical field. Then it is expected that magnetic axis shift and the decrease of plasma volume can be compensated by applying additional vertical field through the adjustment of poloidal coil currents.

In this study, finite equilibrium calculation was carried out by using VMEC code [6] with the following calculation condition.

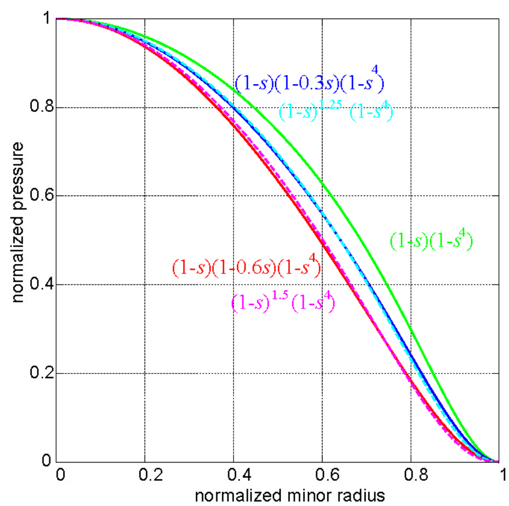

Fig. 4: Pressure profiles used in the finite-beta equilibrium calculation.

Figure 4 shows the pressure profiles used in this calculation. In accordance to the parametric scan by the system design code, 3 profiles were used. One is the parabolic profile; $p(s)=p_0(1-s)(1-s^4)$. The others are more peaked profiles; 1.25 and 1.5 power of parabolic one (actually approximated profiles were used due to the limitation in the input format of the calculation). Boundary condition was fixed as the following manner. Figure 5 shows the edge shape of vacuum magnetic surface of LHD including ergodic layer for 3 different magnetic axis positions in horizontally-elongated cross-section. Here magnetic axis position is controlled by the currents of poloidal coils. As you can see, plasma region enclosed by the LCFS shifts with the shift of magnetic axis position but the position of two separatrix is fixed at almost the same position. Then plasma volume has its maximum around the magnetic axis position at R_{ax}=3.6m. If R_{ax}<3.6m, outer side of LCFS is away from outer separatrix and plasma volume shrinks. On the other hand, inner side of LCFS is away from inner separatrix when R_{ax}>3.6m. Thus it is expected that the LCFS of plasma also moves to the position of that for the magnetic axis position equivalent to 3.6m of LHD with the magnetic axis shift due to the finite-beta effect. Then in this calculation a virtual limiter was set at the outward position of the outermost vacuum surface on the equatorial plane in horizontally-elongated cross- section.

From the viewpoint of a commercial reactor design, fusion output should be kept. Then in the following calculations, beta value was determined to keep constant plasma stored energy (~1300MJ). Figure 6 show the equilibrium magnetic surface with the parabolic profile at peak beta value of

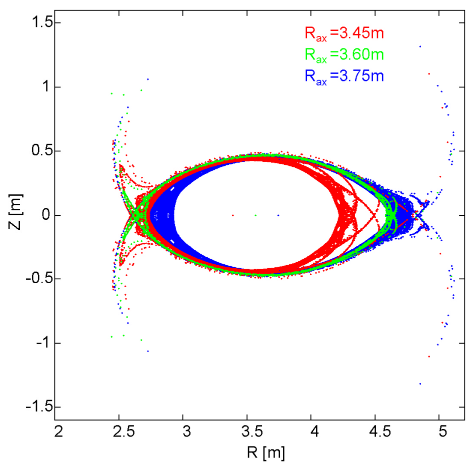

Fig. 5: magnetic surface structure including ergdic layer of LHD with several magnetic

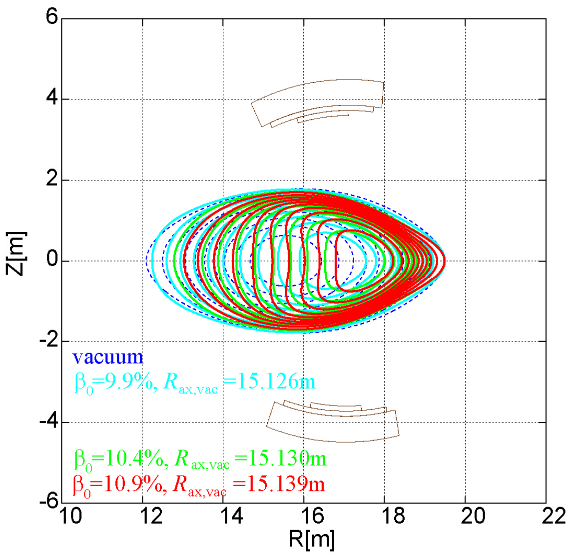

Fig 6: Equilibrium magnetic surface with parabolic pressure profiles.

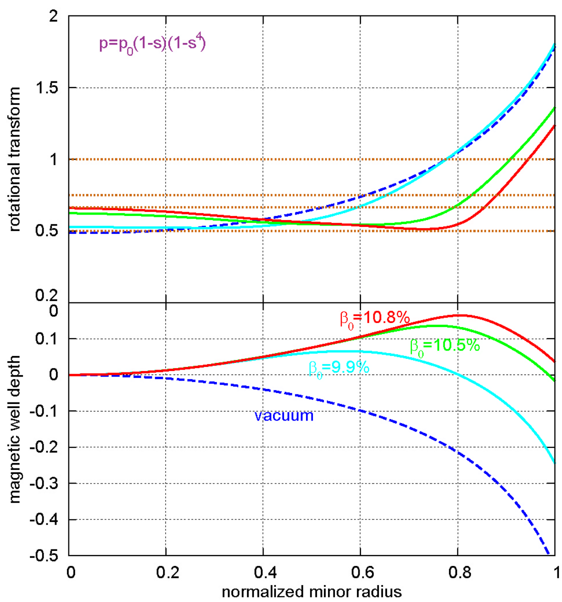

Fig. 7: Radial profiles of rotational transform and magnetic well depth for 3 equilibrium cases in Fig. 6.

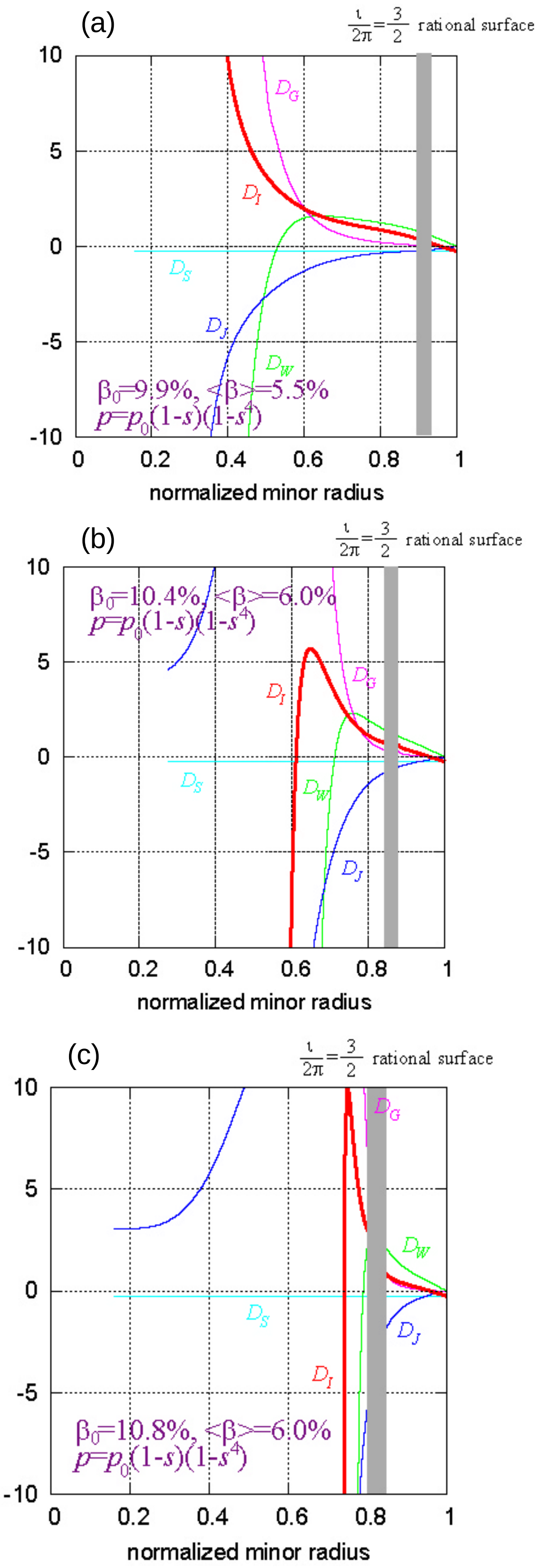

Fig. 8: Radial profiles of Mercier terms for equilibrium cases with parabolic pressure profile with (a)β_0=9.9%, (b)10.4%, (c)10.8%.

9.9% (volume-averaged beta of 5.55%). Here vertical-field that makes inward magnetic axis shift of 0.56m (23% of averaged minor radius) in vacuum configuration was applied. In this condition, almost the same shape of LCFS and the volume enclosed by LCFS as vacuum ones are obtained. By using this equilibrium calculation results, Mercier stability analysis was also carried out. Figure 7 shows the profiles of rotational transform and magnetic well depth. Figure 8 shows the profile of total (D_I) and each term that used in Mercier stability analysis normalized by shear stabilizing term. Here D_I>0 corresponds with a Mercier stable. As you can see this parabolic profile with 9.9% peak beta value is Mercier unstable in the whole region.

In Fig. 6 equilibrium surfaces with slightly smaller additional vertical field are also plotted. The magnetic axis is slightly shifted outward and plasma volume is reduced. But plasma stored energy is still kept around 1300MJ by increasing the peak beta value. Figure 8 and 9 show the rotational transform, magnetic well depth and magnitude of Mercier terms of these configurations. In these cases, core region becomes Mercier stable.

Figure 9 shows the equilibrium surface structures with peaked profiles. As you can

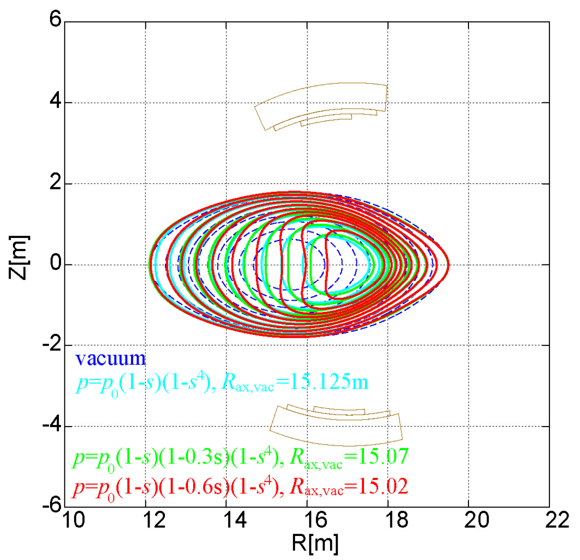

Fig. 9: Equilibrium magnetic surface with 3 different pressure profiles.

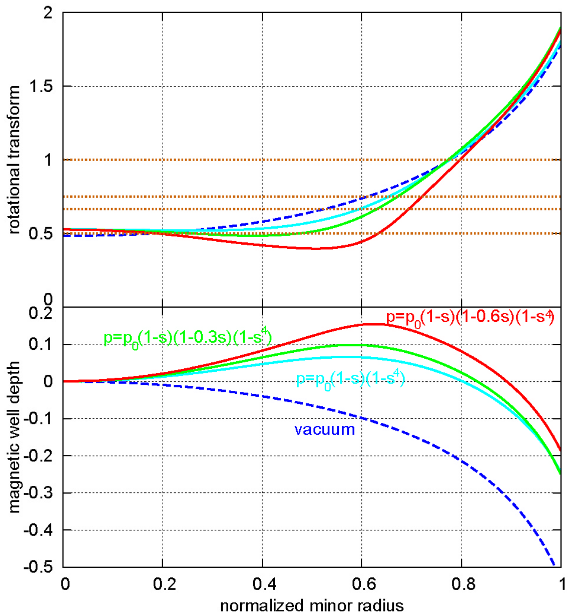

Fig. 10: Radial profiles of rotational transform and magnetic well depth for 3 equilibrium cases in Fig. 9.

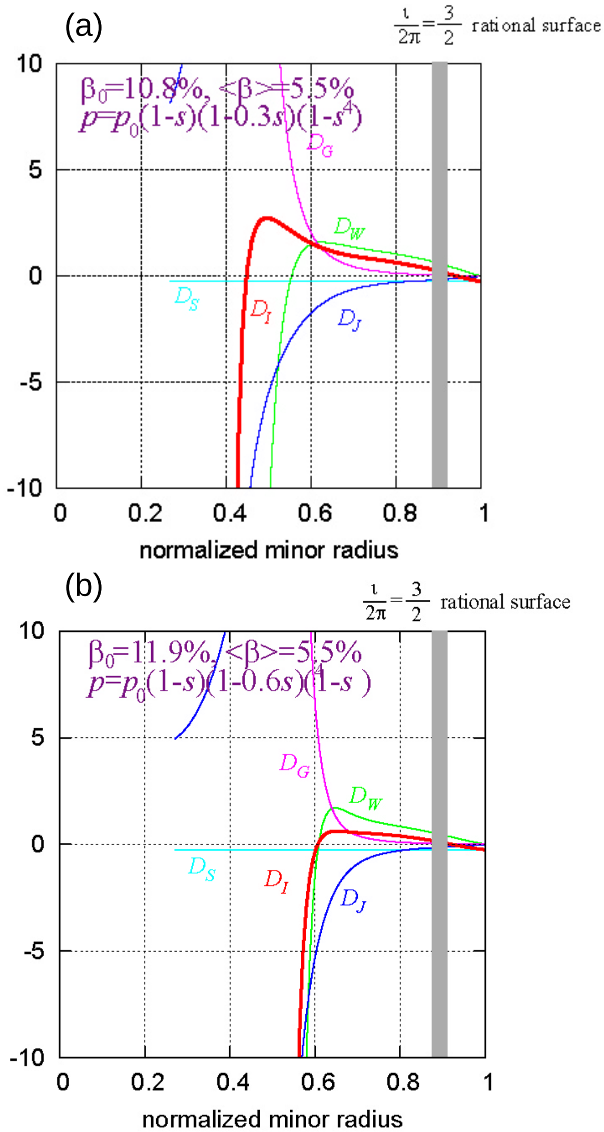

Fig. 11: Radial profiles of Mercier terms for equilibrium cases of pressure profile described as $p=p_0(1\text{-}s)(1\text{-}\alpha s)(1\text{-}s^4)$ with (a) α =0.3, (b) α=0.6

see, the same shape of LCFS as the vacuum one with keeping plasma stored energy can also be obtained by applying appropriate vertical field. The required peak beta value increases with the peaking factor of pressure profile. In these cases, Shafranov shift becomes larger than that in parabolic profile and core region is Mercier stable (see Figs. 10 and 11).

Consequently, from the viewpoint of the existence of equilibrium surface, core plasma design with the sufficient plasma stored energy with the same LCFS volume as the vacuum configuration can be achieved by adjusting vertical field strength. However, there still remain several concerns. Figure 13 shows the vacuum equilibrium field structure with the 5 different vertical fields applied in the finite-beta equilibrium calculation given in this section. You can see both the inner-edge of ergodic layer at vertically-elongated cross-section and the position of divertor leg move with the change in the vertical field. It is expected that such ergodic layer and divertor leg structure have a close shape to that of vacuum equilibrium structure at R_{ax}/R_c =3.6/3.9 when the beta value increase, but it should be confirmed by the further detailed calculation. Calculation result of HINT code, which does not assume the existence of nested surfaces, show that edge magnetic surface structure is distorted by a finite-beta effect and the region with such distortion increases as the increase of beta value [7]. Then effective plasma volume may decrease. As you can see in figures 7 and 10, magnetic axis position has large outward shift compared with the vacuum one. It may enhance the loss of alpha-particle since the deviation between magnetic surface and fast-ion orbit become large. The effect of boot-strap current on the magnetic axis shift

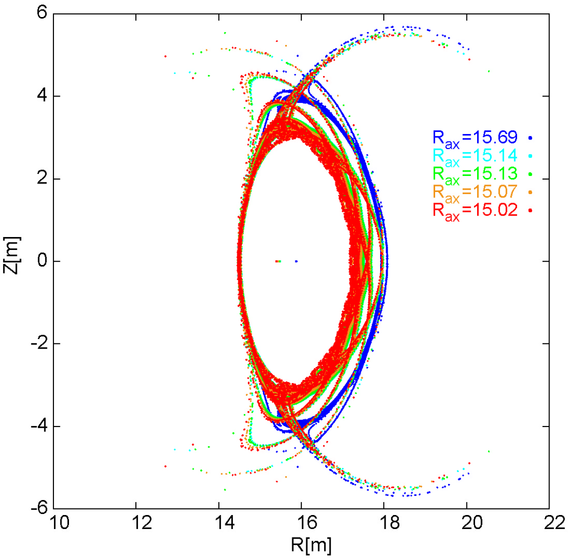

Fig. 13: Equilibrium vacuum magnetic surface structures with several vertical field strengths assumed in the VMEC calculation.

should also be checked. Then the detailed numerical analyses are needed to ensure the design feasibility.

4. Summary

Core plasma design of a LHD-type heliotron reactor was carried out. Parametric scan by the developed system design code showed the existence of design window that satisfies engineering constraints and moderate plasma parameters with the plasma configuration that has a similar shape to that of high-beta discharge in LHD experiment; inward-shifted magnetic axis position and helical pitch parameter of 1.2.

Finite-beta equilibrium calculation by VMEC showed that the existence of equilibrium with the required beta value and almost the same volume enclosed by LCFS as that in vacuum configuration by applying appropriate vertical field with the adjustment of currents of poloidal coils.

Although the further detailed analyses (e.g., boot-strap current, magnetic surface distortion, alpha-particle confinement etc.) are needed to ensure the feasibility of the design, it is important that the possibility of a commercial reactor design with the configuration that has a similar shape to that of LHD high-beta discharge has been shown from the viewpoint of increasing feasibility and flexibility of the heliotron reactor design.

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