Vacuum Configurations of D Shape Heliotron[*]

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The effects of the deformation of the flux surfaces into a "D shape" on vacuum heliotron configurations are examined numerically. In this study, one poloidal coil on the mid plane just inside the helical coils is assumed to be installed so that the current in the coil can deform the surface shape. Such deformation gives the advantage that the clearance between the helical coil and the outermost surface can be enlarged, which is crucial for the divertor action in heliotrons. The effects of the deformation on other vacuum properties are also discussed, such as rotational transform, magnetic well, and $|B|_{min}$ contour. We also focus on such effects on downsized configurations.

1. Introduction

The stellarators have the great advantage that no net toroidal current is needed for the generation of the confinement field, while a large toroidal current is necessary in tokamaks. This advantage allows us to operate continuous discharges without any current-drive facilities and without any disruptions. In addition, the heliotrons in the stellarator category have the further splendid feature that the helical divertor field lines are provided intrinsically. These field lines are able to be generated only with the continuous coils in the heliotrons. However, such field lines are not generated with the modular coils utilized in other types of stellarators. In order to obtain good divertor performance in the heliotrons, we must maintain the clearance for the divertor field lines between the helical coils and the outermost surface.

Considering the construction cost of the future reactor, downsizing the system is attractive. Furthermore, the superconducting coils are necessary for the long term operation. Since the current density of the superconducting coils cannot be increased easily, the width of the cross section of the helical coils for obtaining a similar amplitude of the magnetic field cannot be reduced even in the smaller-sized system. Therefore, the relative width of the coils becomes large as the system size becomes small. In this case, the helical coils approach the outermost surface. The clearance between the helical coils and the outermost surface, in particular in the inward side of the surface, shrinks, which is necessary for the divertor action. Thus, we consider keeping or enlarging the clearance by deforming the shape of the outermost surface into a "D shape." This de-

formation reduces the inward convex structure of the flux surfaces and therefore can enlarge the divertor clearance. In the present study, we seek to achieve such a D shape by incorporating one additional poloidal field coil just inside the helical coils. We also examine the effects of the deformation on the properties in the vacuum configurations such as rotational transform, magnetic well, and contours of $|B|_{min}$.

Concerning the D shape deformation of heliotron plasmas, Matsumoto *et al.* [1] analyzed the effects on the vacuum LHD (Large Helical Device) configuration [2] and the finite beta equilibria. In their analysis, they applied an analytic hexapole field on the original vacuum configuration to add the triangularity on the surface shape. However, they did not show the actual control method for the deformation, nor did they examine the deformation effects on the divertor clearance. Thus, we focus on the actual coil installation and the compatibility between the flux surface properties and the divertor clearance enlargement in this paper.

2. Calculation of Vacuum LHD Configurations with D Shape Coil

The vacuum magnetic configurations are obtained with the KMAG code [3]. This code calculates the magnetic field based on the Biot-Savart's law from the current flowing in the finite size coils in the cylindrical coordinates (R, ϕ, Z). The current density is assumed constant in each coil. In order to examine the effects of the D shape deformation, we consider the situation with a single poloidal field coil installed on the mid plane just inside the helical coils, which we call "D shape coil," as shown in Fig. 1 schematically.

Here, the effects of the D shape coil current on the

LHD configuration are examined. The LHD coil system consists of one pair of helical coils and three pairs of poloidal field coils or vertical field coils. Figure 2 shows the puncture plots of the field lines in the poloidal cross sections without the D shape coil current. In this case, the major radius R_{cnt} and the pitch parameter $\gamma_c \equiv (M/\ell)(a_c/R_{cnt})$ of the helical coils are employed as $R_{cnt} = 3.9$ m and $\gamma_c = 1.254$. Here M, ℓ, and a_c are the number of the toroidal field period, the pole number, and the minor radius of the helical coils, respectively, The numbers of $M = 10$ and $\ell = 2$ are fixed in the LHD configuration. In the calculation for the case of Fig. 2, the current density in the helical coils $j_H = 37.5$ A/mm^2 is used and the toroidal field at the coil center is obtained as $B_T = 2.77$ T. Note that the properties such as magnetic field line configuration, rotational transform, specific volume, and $|B|_{min}$ contours do not depend on the magnetic field strength, and therefore, do not depend on the current itself in each coil. These properties depend only on the current ratio between the coils.

Figure 3 shows an example of the puncture plots with the D shape coil current. Here the D shape coil is assumed to be located at $R_D = 2.6$ m. The current flowing in the coil is adjusted so that $I_D/I_H = 0.370$ in this case. Here I_D and I_H are the D shape coil current and the current in each helical coil, respectively. It is seen that the current
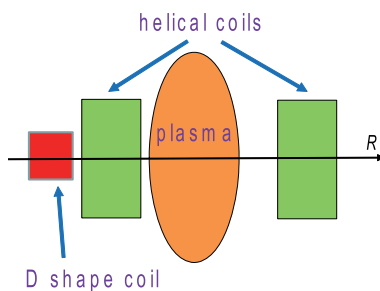

Fig. 1   Schematic image of the D shape coil and the helical coils.

effectively deforms the flux surfaces into the D shape. The position of the inner edge of the outermost surface on the mid plane is $R_{in} = 3.27$ m for $I_D/I_H = 0$ and $R_{in} = 3.52$ m for $I_D/I_H = 0.370$. Therefore, the clearance between the inward helical coil and the outermost surface that is needed for drawing out the divertor field lines is enlarged due to the deformation. Here, in the evaluation of R_{in}, we utilize the starting position of the field line tracing. The starting position is shifted on the mid plane inwardly from the magnetic axis every 0.015 m. The field line is traced for 400 toroidal field periods from the starting position and whether the field line is bounded around the magnetic axis or not is examined. Then, we define R_{in} as the most inward starting position from which the field line is bounded.

On the other hand, the horizontal position of the magnetic axis is shifted outward by the current as shown in Fig. 4. This outward axis shift is similar to the shift obtained by the control of the current in the vertical field coils. The outward axis shift enhances the magnetic well as shown in Fig. 5, where the profiles of the specific volume are plotted as the functions of the average minor radius $\langle r \rangle$. The well enhancement is favorable for the stability against the pressure driven modes. However, the axis shift reduces the particle confinement. Figure 6 shows the contours of the $|B|_{min}$ which indicate a simple index of the orbit of the deeply trapped particles. The confinement region of such particles shrinks in this D shape case. Figure 7 shows the change in the rotational transform profile. As I_D/I_H increases, the rotational transform decreases up to $I_D/I_H = 0.074$ slightly and increases in the range beyond the value. This tendency is similar to the outward shift case by vertical field control [4].

3. D Shape LHD Configurations under Fixed Axis Position Constraint
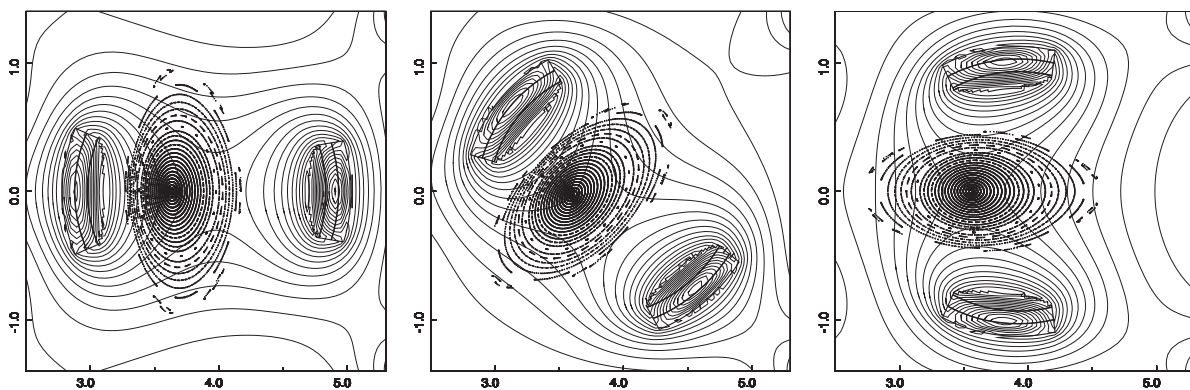
Regarding good particle confinement, we consider the

Fig. 2   Puncture plots of the field lines in the LHD configuration with $R_{ax} = 3.6$m and $\gamma_c = 1.254$ with no D shape coil current at the poloidal cross sections of $\phi = 0$ (left), $\pi/(2M)$ (center), and π/M (right). Solid lines show the contours of the amplitude of the magnetic field. The helical coils are also plotted. The numbers along the horizontal and the vertical axes denote the measure of R and Z coordinates in meters, respectively.
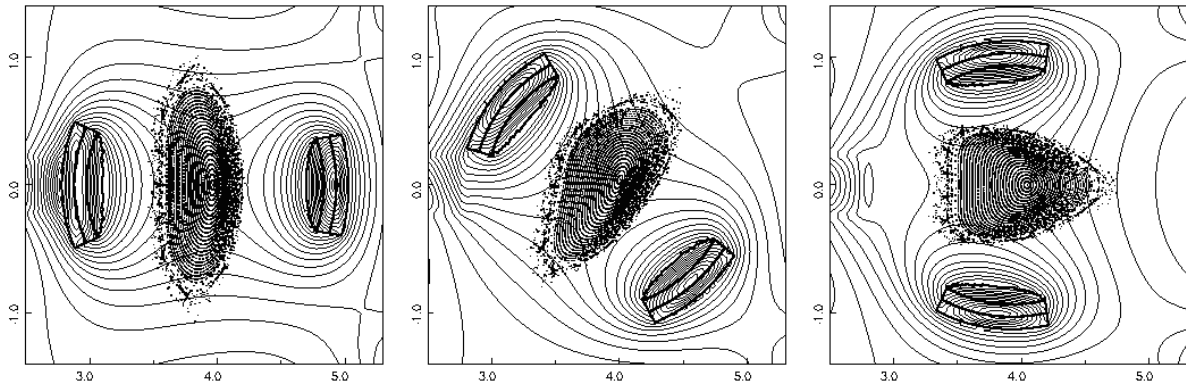
Fig. 3   Puncture plots of the field lines in the same LHD configuration as in Fig. 1 with $I_D/I_H = 0.370$ at the poloidal cross sections of $\phi = 0$ (left), $\pi/(2\,M)$ (center), and π/M (right).
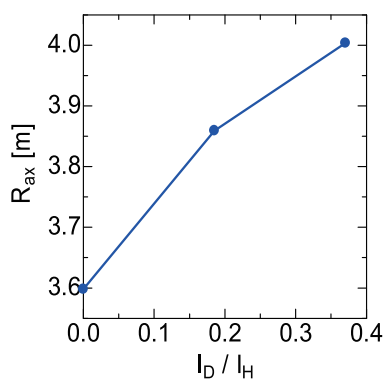

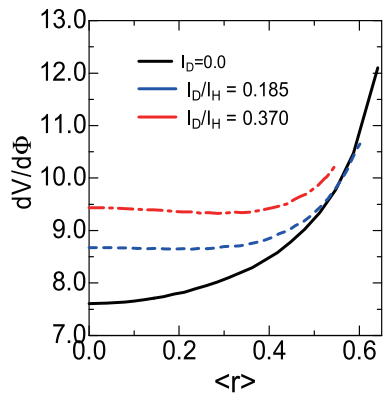Fig. 4   Dependence of the magnetic axis position on the D shape coil current.

Fig. 5   Profiles of the specific volume for $I_D/I_H =$ 0, 0.185, and 0.370 in the LHD configuration.
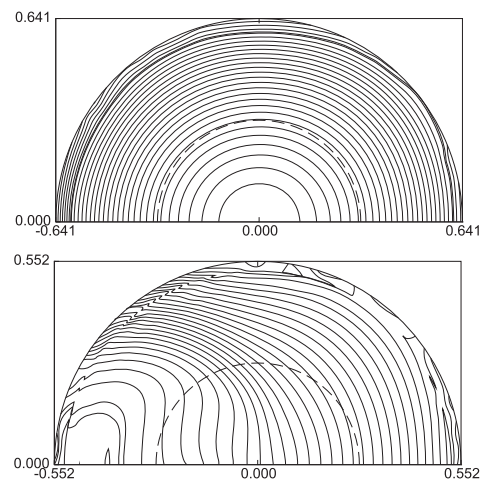

Fig. 6   Contours of $|B|_{min}$ for $I_D/I_H =$ 0 (top) and 0.370 (bottom) in the toroidally averaged flux surface of the LHD configuration. The thick solid line indicates the boundary of the $|B|_{min}$ contour closed in the outermost surface. The dashed line shows the position of the flux surface with a half average radius. The numbers along the horizontal and the vertical axes denote the measure of R and Z coordinates in meters, respectively.
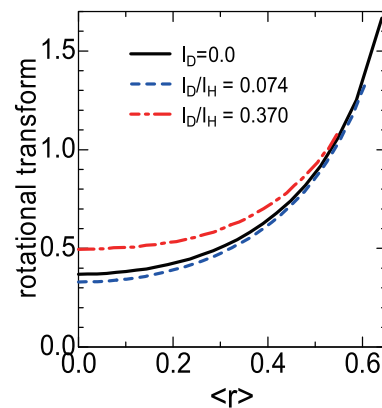

Fig. 7   Profiles of the rotational transform for $I_D/I_H =$ 0, 0.074, and 0.370 in the LHD configuration.
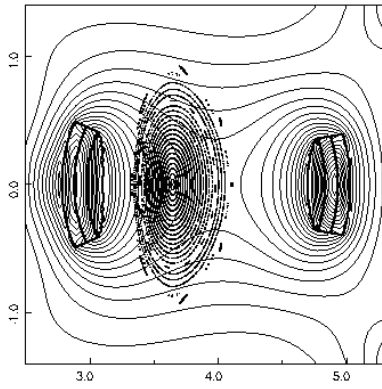
D shape deformation under the constraint in which the magnetic axis position is fixed. For this purpose, the axis position with no D shape coil current, $R_{ax}(I_D = 0)$, should be shifted inwardly under the control of the vertical field coil currents. Here, the vertical field coil currents are adjusted so that the magnetic axis is located at $R_{ax} = 3.6\,\mathrm{m}$ combined with the D shape coil current. Figure 8 shows the puncture plots at the $\phi = 0$ cross section in the case

Fig. 8 Puncture plots of the field lines in the same LHD configuration as in Fig. 1 with $R_{ax} = 3.6$m and $I_D/I_H = 0.1622$ at the poloidal cross section of $\phi = 0$.
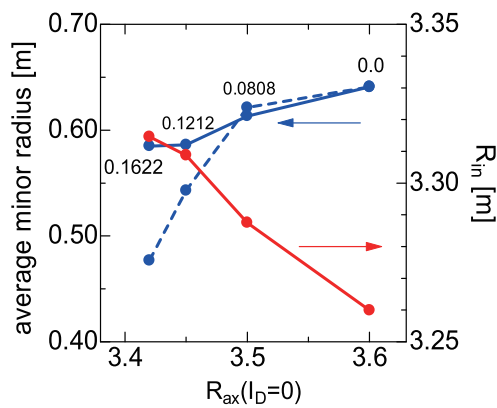

Fig. 9 Dependence of the average minor radius and the inward edge position on $R_{ax}(I_D = 0)$ in the LHD configuration. Blue solid line and red solid line show the average minor radius and the inward edge position, R_{in}, respectively, in the increase of the D shape coil current with $R_{ax} = 3.6$m. Blue dashed line shows the average minor radius with no D shape coil current. Each number indicates the value of I_D/I_H corresponding to $R_{ax}(I_D = 0)$.

Fig. 10 Profiles of the specific volume for I_D/I_H =0, 0.0808, and 0.1622 in the LHD configuration with $R_{ax} = 3.6$m.

Fig. 11 Contours of $|B_{min}|$ for I_D/I_H =0.1622 in the LHD configuration with $R_{ax} = 3.6$m plotted in the same way as in Fig.6.

Fig. 12 Profiles of the rotational transform for I_D/I_H =0, 0.0808, and 0.1622 in the LHD configuration with $R_{ax} = 3.6$ m.

of $R_{ax}(I_D = 0) = 3.42$ m and $I_D/I_H = 0.1622$. Compared to Fig. 2, the divertor clearance is also enlarged even under this constraint. The divertor clearance improves, that is R_{in} increases, with the smaller $R_{ax}(I_D = 0)$ and the larger I_D/I_H as shown in Fig. 9. Figure 9 also shows that the minor radius is reduced in the increase of the divertor clearance. This is considered to be due to not only the enhancement of the D shape deformation but also the inward shift by the poloidal field control, because the reduction of the minor radius in the case without the D shape coil current is larger than in the case with the current.

The specific volume itself is enhanced by the D shape deformation as shown in Fig. 10. However, the magnetic well corresponding to the derivative of the specific volume is almost unchanged. This is attributed to the fact that the magnetic axis position is fixed in the change of the D shape coil current. The confinement region of the trapped par-
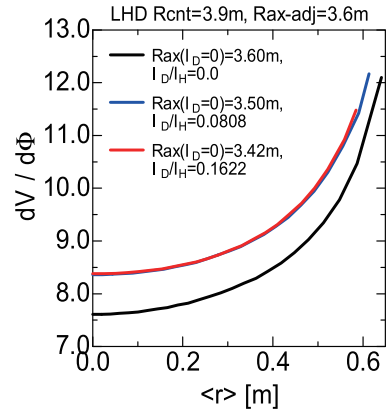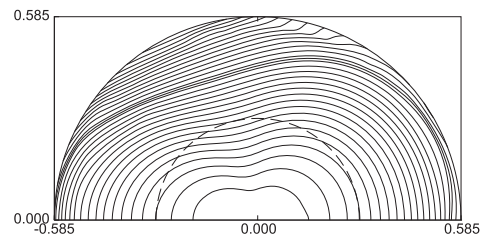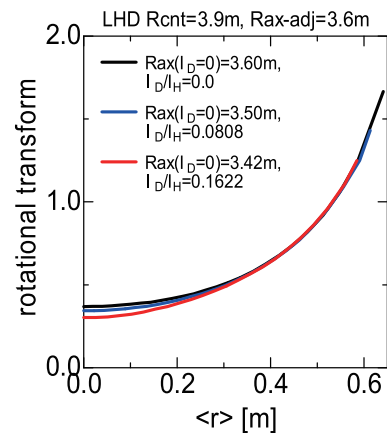
ticle is reduced in the vertical direction by the D shape deformation as shown in Fig. 11, which is different from the reduction in the horizontal direction in the case of the outward shift of the magnetic axis. The D shape deformation slightly decreases the rotational transform in the region near the magnetic axis when the axis position is fixed, as shown in Fig. 12.

4. Downsized D Shape Configurations

Now we consider downsizing the LHD configuration. First, we examine the configuration downsized into the 2/3

size. The major radius of the helical coils is reduced to $R_{cnt} = 2.6$ m, while the width of each coil is assumed to be the same as that in the LHD. The same γ_c as in the original size is employed and the magnetic axis is fixed as $R_{ax} = 2.4$ m. Other coil positions shrink proportionally. Figure 13 shows the puncture plots of the magnetic field lines at the $\phi = 0$ cross section. In the case of $I_D = 0$, the divertor clearance is smaller than that in the original size. Figure 14 shows that R_{in} becomes larger and the divertor clearance is enlarged when the D shape coil current is applied and increased with the magnetic axis position fixed. However, the larger I_D/I_H is needed to obtain the same amount of the enlargement increment compared to the case of the original size as shown in Fig. 14. This figure also shows that the minor radius is reduced as the D shape coil current increases. The specific volume is almost unchanged as shown in Fig. 15. These tendencies are similar to those of the original size case. The rotational transform is also decreased near the magnetic axis as shown in Fig. 16. The reduction is more remarkable than that in the original size.

Next, we examine the configuration downsized into the 1/2 size in the same manner. The major radius of the helical coils is reduced to $R_{cnt} = 1.95$ m and the magnetic axis is fixed as $R_{ax} = 1.8$ m. The puncture plots at the $\phi = 0$ cross section are shown in Fig. 17. In the case

Fig. 14 Dependence of the average minor radius and the inward edge position on $R_{ax}(I_D = 0)$ in the 2/3 size of the LHD configuration. Blue solid line and red solid line show the average minor radius and the inward edge position, R_{in}, respectively, in the increase of the D shape coil current with $R_{ax} = 2.4$ m. Blue dashed line shows the average minor radius with no D shape coil current. Each number indicates the value of I_D/I_H corresponding to $R_{ax}(I_D = 0)$.

Fig. 15 Profiles of the specific volume for $I_D/I_H = 0$, 0.1010, and 0.1825 in the 2/3 size of the LHD configuration with $R_{ax} = 2.4$ m.
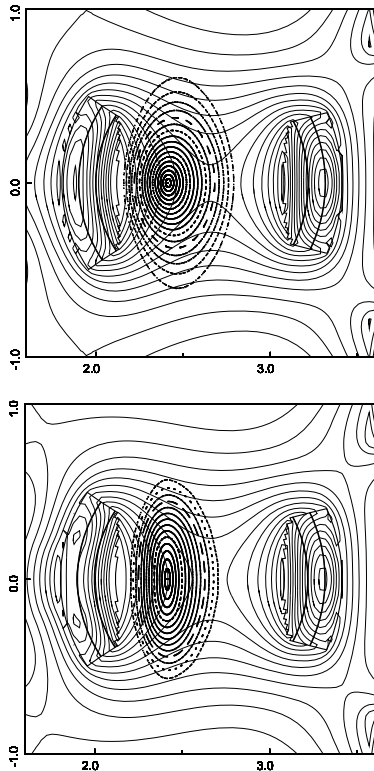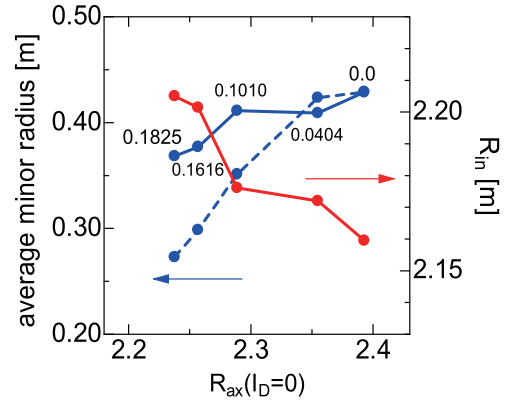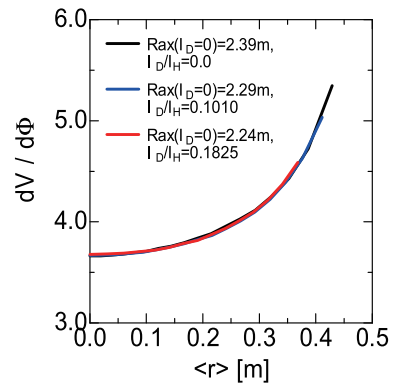

Fig. 13 Puncture plots of the field lines in the 2/3 size of the LHD configuration as in Fig. 1 with $R_{ax} = 2.4$ m and $I_D/I_H = 0$ (top) and 0.1825 (bottom) at the poloidal cross section of $\phi = 0$.
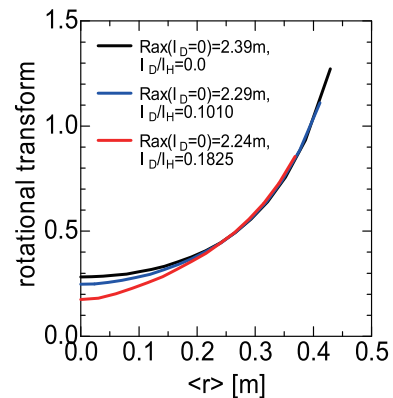

Fig. 16 Profiles of the rotational transform for $I_D/I_H = 0$, 0.1010, and 0.1825 in the 2/3 size of the LHD configuration with $R_{ax} = 2.4$ m.
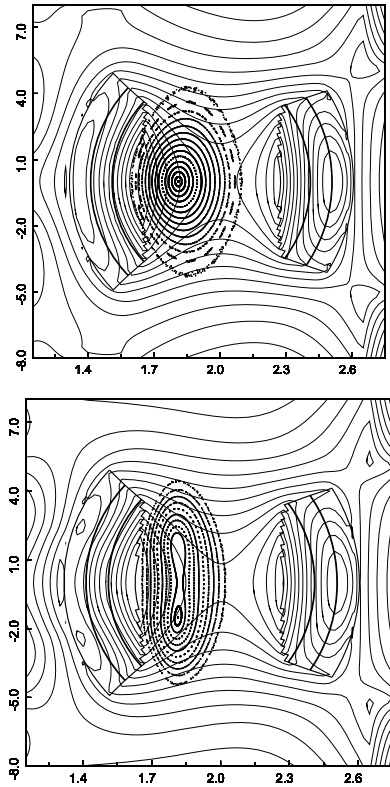
Fig. 17 Puncture plots of the field lines in the 1/2 size of the LHD configuration as in Fig. 1 with $R_{ax} = 1.8$ m and $I_D/I_H = 0$ (top) and 0.2434 (bottom) at the poloidal cross section of $\phi = 0$.

of $I_D = 0$, the outermost surface is attached to the helical coil and there is no divertor clearance. In the increase of the D shape coil current, the magnetic axis is split at $I_D/I_H = 0.2434$ before the appearance of the clearance. Therefore, it is impossible to obtain the half size of the LHD configuration with finite divertor clearance and a single magnetic axis by means of the D shape coil current.

5. Summary and Discussion

The effects of the D shape deformation of the flux surfaces on vacuum heliotron configurations are analyzed. Here the existence of the coil current installed just inside the helical coils is assumed. The current works well to enlarge the divertor clearance between the helical coil and the outermost surface in the LHD configuration. On the other hand, the current also contributes to the outward shift of the flux surfaces. To maintain the magnetic axis at a fixed position, an additional vertical field is necessary. Even in this case, the divertor clearance is enlarged effectively. However, there is the tendency that the minor radius of the outermost surface and the closed $|B|_{min}$ region are decreased. This tendency is not a favorable feature in the application of the D shape coil current. The rotational transform is slightly decreased. This decrease leads to the enhancement of the Shafranov shift at finite beta. Therefore, this property is favorable for the generation of the magnetic well.

However, this property is not favorable for the particle confinement. The negligible change in vacuum magnetic well is also obtained.

On the other hand, it was found in the previous results by Matsumoto *et al.* [1] that the rotational transform at the axis is unchanged and the magnetic well becomes deep as the triangularity increases. However, both the change in the rotational transform in the present analysis and the change in the magnetic well in the previous analysis are not substantial. Therefore, we consider both results to be consistent. The slight differences in the results would be attributed to the difference in the deformation method and the original circular configuration.

The D shape coil current can work similarly in the LHD configuration downsized to 2/3 size under the assumption that the helical coil width is the same. The larger D shape coil current is needed to acquire the same divertor clearance increment as that in the original size. The decrease of the rotational transform is enhanced compared to that in the original size. On the other hand, in the half size case, it is impossible to obtain a configuration with finite divertor clearance and a single magnetic axis.

In the analysis of the downsized configuration, we assumed the fixed width of the coils. Here we discuss this assumption with respect to the energy confinement of the plasma. The scaling concerning the energy confinement time τ_E for stellarators and heliotrons called ISS04 is given by $\tau_E^{ISS04} = 0.134 a^{2.28} R^{0.64} P^{-0.61} n_e^{-0.54} B^{0.84} \iota_{2/3}^{0.41}$ [5]. Here, a, R, P, n_e, B, and $\iota_{2/3}$ are minor and major radii, absorbed heating power, line-averaged density, magnetic field, and the rotational transform at $r/a = 2/3$, respectively. According to this scaling, when both minor and major radii are downsized to the 2/3 and the 1/2 sizes, the coil currents must be 2.7 and 5.6 times larger than those in the original size configuration to obtain the magnetic field corresponding to the same confinement time, respectively. Therefore, more improvement of the coil current density is required to maintain the ISS04 scaling if we employ the same width of the coils as in the original size configuration. Or a wider width of the coils is necessary if we employ the same current density.

One method for improving the D shape configuration would be the addition of toroidal field coils. The additional toroidal coil currents can increase the rotational transform and may contribute to the enlargement of the divertor clearance. On the other hand, this idea brings another challenging problem to the construction of the superconducting coil system, because there is difficulty in setting the toroidal coils outside the helical coils.

The present study is limited to the vacuum configuration analysis. The effects of the finite beta should be incorporated for the comprehensive understanding of the plasma performance.

Acknowledgments

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