Effects of triangularities in LHD-type planar-axis stellarators

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Progresses in plasma parameters and performances have been made continuously in LHD experiments, which is the largest superconducting helical device. The magnetic configuration of LHD is a planar-axis stellarator, which has a simple ring-type (two dimensional) magnetic axis of the torus. On the other hand, newer designs of stellarators have magnetic axies of three-dimensional (3-D) shape, which is called non-planar type magnetic axis. A present major control knob of magnetic field configuration of LHD is the vertical field control, with which the major radius of magnetic axis position (R_{ax}) is varied. This simple control creates a large change in the MHD stability and plasma confinement in LHD.

In this paper, we analyze the 3-D magnetic configuration of LHD based on the boundary shape of the torus. For analyzing the boundary shape, we use the Fourier decomposition of the 3-D torus boundary used in the VMEC equilibrium solver [1], which is expressed as following formulas:

$$R(\theta, \phi) = \Sigma\, r(m, n)*\cos(m\theta - n\phi)$$

$$Z(\theta, \phi) = \Sigma\, z(m, n)*\sin(m\theta - n\phi)$$

Fourier coefficients $r(m, n)$ and $z(m, n)$ are sufficient to define the boundary shape of the torus and, when the plasma pressure and the plasma current profiles are given, we can calculate three dimensional equilibria. So the difference in the stability and confinement characteristics for LHD magnetic configurations with different magnetic axis positions should be expressed by these coefficients. Physical meanings of basic coefficients are clear from the expressions of Fourier series: (1) components with n = 0 express toroidally averaged geometric shape, (2) a major radius is expressed by $r(0, 0)$, (3) minor radius of toroidally averaged cross section is given by $r(1, 0)$ and $z(1, 0)$, (4) ellipticity (elongation) of toroidally averaged cross section is expressed by $r(1, 0)/\, z(1, 0)$, (5) components with n!=0 express various 3-D shaping factors. Among them, $r(1, 1)$ and $z(1, 1)$ are responsible to the basic helical structure of stellarator magnetic surfaces.

Three LHD vacuum configurations with R_{ax} = 3.6 m, 3.75 m, 3.9 m are taken in the analysis. These three configurations clearly show variations of confinement properties of LHD with the vertical field control. R_{ax} = 3.6 m configuration has good drift orbits of deeply trapped particles, resulting in a small neoclassical diffusion. The magnetic well (in a vacuum configuration) exists only in R_{ax} = 3.9 m configuration among these three configurations. R_{ax} =3.75 m configuration has a very basic characteristics with neutral or intermediate confinement properties.

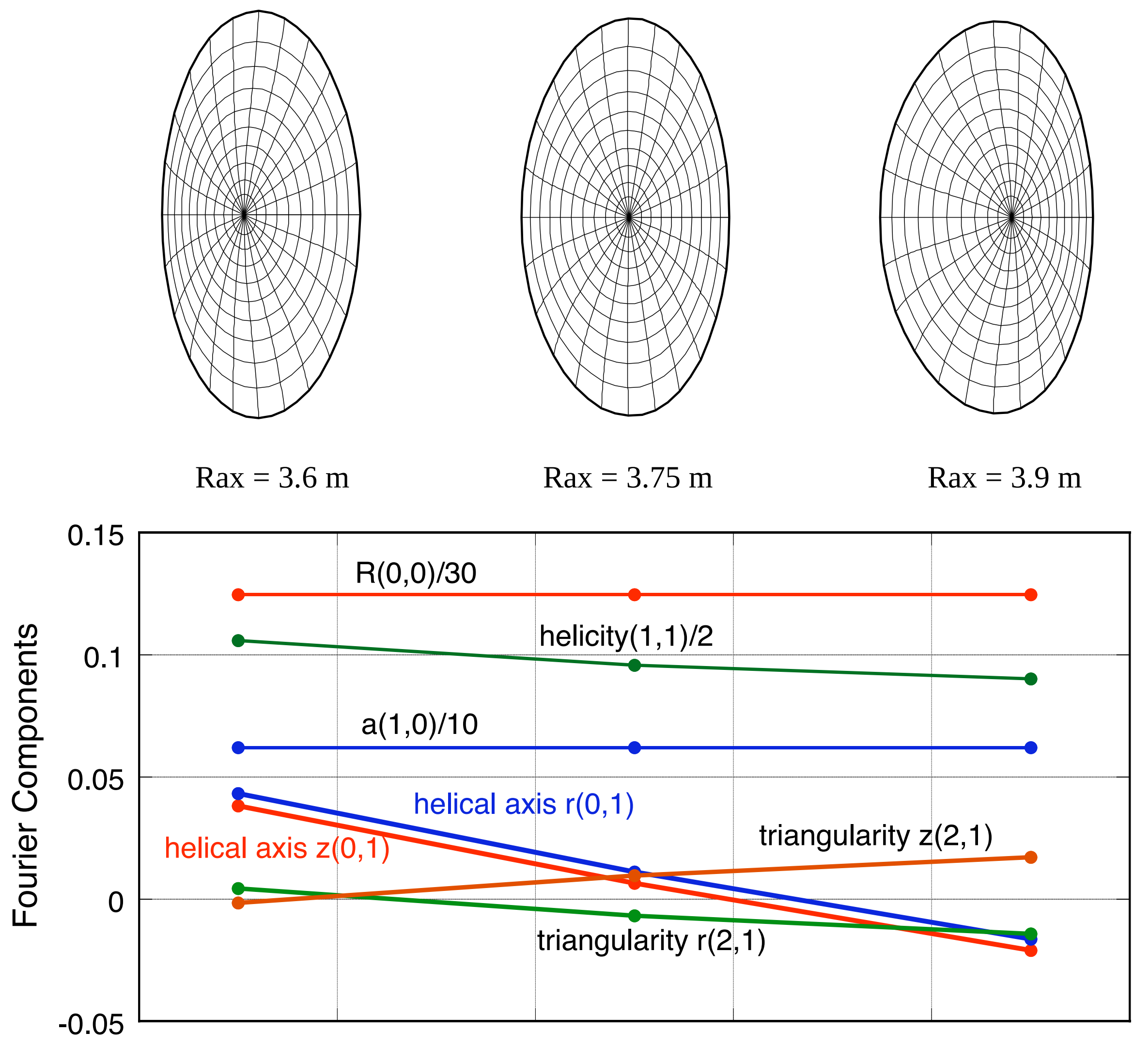

Fig. 1 Vertically elongated cross sections of LHD vacuum configurations. Original configurations are modified to have the same major radii and aspect ratios. Small Fourier components are eliminated to elucidate the functions of major basic components. In lower figure, relative variations of basic Fourier components are shown. Amplitues of some components are reduced for displaying in one windows.

Before comparing coefficients of Fourier modes for each configuration, we modify three configurations to be similar in toroidal averaging sense. This process is introduced for the purpose to extract effects of different shaping of three configurations on confinement properties as purely as possible by making the major radius, aspect ratio and the averaged elongation unified for three configurations. We replace $r(0, 0)$, $r(1, 0)$ and $z(1, 0)$ of R_{ax} = 3.6 m and R_{ax} = 3.9 m configurations with those of R_{ax} = 3.75 m configuration (intermediate one).

Figure 1 shows vacuum magnetic surfaces of three configurations expressed by only 9 Fourier components which dominantly determine confinement properties of these configurations. Amplitudes of other components are small and it was confirmed that their inclusion give negligible effects on the confinement properties. As is described above, the major and minor radii are unified. The helicity and minor radius <a> are averaged values of r and z components. It is shown that the configuration control in LHD with the vertical field, which is very important and beneficial in the experiments, are produced by the variations of only two kinds of small components: helical axis modes and triangularity control.

It was reported [2] that the vertical field control of the LHD magnetic field configuration is given by the additon of small helical axis structure to the planar-axis stellarator con-

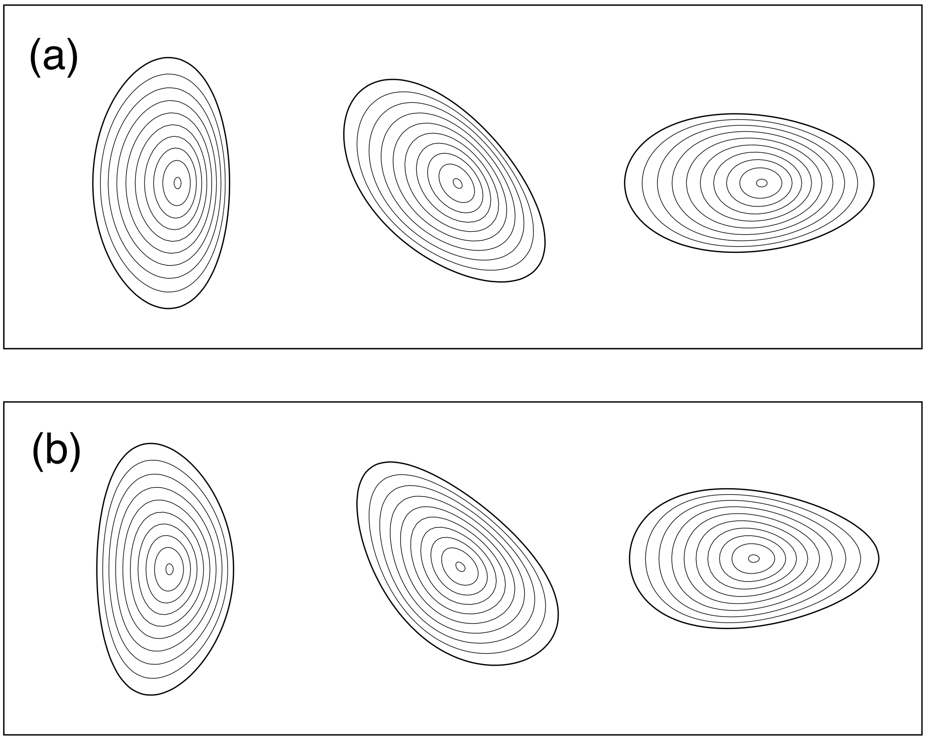

Fig. 2 Magnetic surface cross sections for LHD-type configurations. (a) R_{ax} = 3.9 m configuration with rotating D-shape in addition to helical axis structure, (b) new configuration with axi-symmetric D-shape in addition to helical axis structure.

figuration. Actually for R_{ax} = 3.6 m configuration, this helical axis structure is the essential difference from the R_{ax} = 3.75 m intermediate configuration. On the other hand, for R_{ax} = 3.9 m configuration, the combination of the helical axis structure and the triangularity structure is necessary to produce the magnetic well. In the rest part of this paper, we investigate the effect of triangularity shape in the LHD configurations.

Figure 2(a) shows magnetic surface cross sections at three toroidal angles for R_{ax} = 3.9 m configuration. The triangularity component is included but the direction of D-shape is opposite to the standard tokamak case at the vertically elongated cross section. Because the Fourier mode is (2, 1), the D-shape direction is the same to the tokamak case at the horizontally elongated cross section. In order to confirm the triangularity effect to the stability, an axi-symmetric component of (2, 0) is added artificially in place of (2, 1) component as is shown in (b). In opposition to the anticipation, the magnetic well depth is stongly decreased to 1/5 [although the amplitude of (2, 0) is double of (2, 1)].

Finally the effect of triangularity is compared for tokamak and stellarator configurations using the same Fourier components of cross sections. In Fig. 3, the magnetic well is calculated for tokamak configuration with Ip = 100 kA and q(0) = 5 with opposite triangularities. As is usual case in tokamaks, D-shape configuration in (a) has a deep magnetic well in all confinement region while the opposite D-shape configuration in (b) has a partial magnetic well region with small depth. Stellarator configuration with axi-symmetric triangularity has no magnetic well for either direction of D-shape [(c) and (d)]. It is concluded that the triangularity control (D-shape) in stellarator never work for the MHD stability.

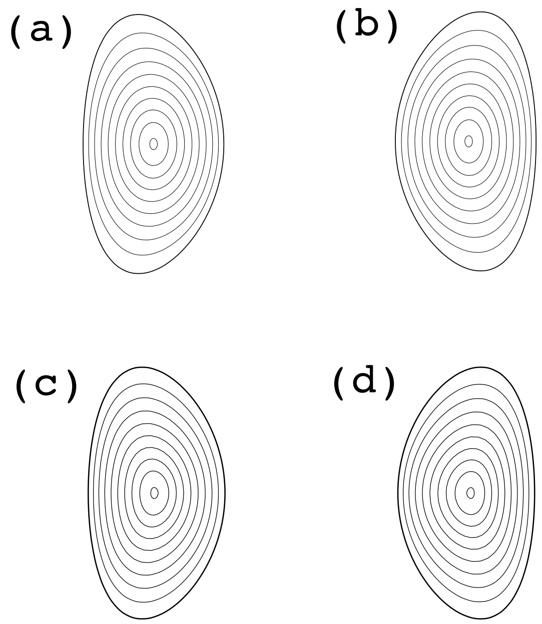

Fig. 3 Cross sections with triangularity, (a), (b) for tokamak case and (c), (d) for stellarator case.

References

[1] S. Hirshman, et al., Comput. Phys. Commun. Vol. 43, p.143 (1986)
[2] S. Okamura, Contributions to Plasma Physics, Vol. 50, p.562 (2010)