Effects of small helical axis components in planar-axis stellarator configurations of LHD and CHS

Shoichi Okamura
National Institute for Fusion Science
Oroshi 322-6, Toki, Gifu, Japan

Magnetic confinement research using stellarator-type devices has a large attractiveness with its intrinsic ability of steady-state operation. We have several different active approaches (different type of devices) in the world. For establishing a reliable roadmap of its development to the economical fusion reactor system, a selection of research path is necessary. Types of stellarator configurations are basically divided into two categories: planar axis stellarators and non-planar axis ones. LHD and CHS devices in Japan, both of which have heliotron-type configurations, are in the former group and TJ-II (in Spain), Wendelstein 7-X (under construction in Germany), HSX (in U.S.) and Heliotron J (in Japan) are in the latter group. In terms of Fourier mode of configuration, the essential difference between them is the inclusion of the helical axis component for the latter case. However, even in so-called planar-axis stellarators, the helical axis component exists and it plays an important role in the control of magnetic configuration in experiments.

Let us define the Fourier mode components describing the boundary shape of three dimensional stellarator configurations. When we take a cylindrical coordinate system (R, Z, Φ), two dimensional cross section of the boundary shape of a torus at a given toroidal angle Φ is described by two variables R(θ, ϕ) and Z(θ, ϕ) with two angle parameters on the boundary surface. We decompose them into the Fourier modes as followings.

$$R(\theta, \phi) = \Sigma\, rbc(m, n)*\cos(m\theta-n\phi)$$
$$Z(\theta, \phi) = \Sigma\, zbs(m, n)*\sin(m\theta-n\phi)$$

Fourier coefficients *rbc* and *zbs* 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 using the equilibrium solver, e.g., VMEC code [1]. In this paper, we try to extract as small number of Fourier coefficients for the LHD and CHS magnetic configurations and analyze them to find the relations between the Fourier coefficients and the magnetic surface properties. Since the LHD and CHS devices are in the same group of the heliotron type stellarator with a similar number of toroidal period (10 for LHD and 8 for CHS), it was confirmed that the essential physics is the same for two devices. Because of the limited space of the paper, we show here the discussions only for CHS device. Some discussions for LHD are already published in a separate paper [2].

Figure 1 shows a comparison of the mode amplitude distribution for two representative configurations of CHS device. These are vacuum configurations with no plasma pressure. In LHD and CHS, the basic confinement characteristics are determined by the selection of the position of the magnetic axis (in the major radius). We use a non-dimensional parameter R_0 defined as the ratio of the magnetic axis position and the major radius of the poloidal center of the helical coils ($R_0 = R_{ax}/R_h$). The configuration with $R_0 = 0.92$ is the standard one, which was most frequently used in the experiments because of the good global confinement characteristics, and the configuration with $R_0 = 0.99$ is the outward shifted configuration. Largest difference between them is that the outward shifted configuration has the magnetic well in the core region and the standard one does not.

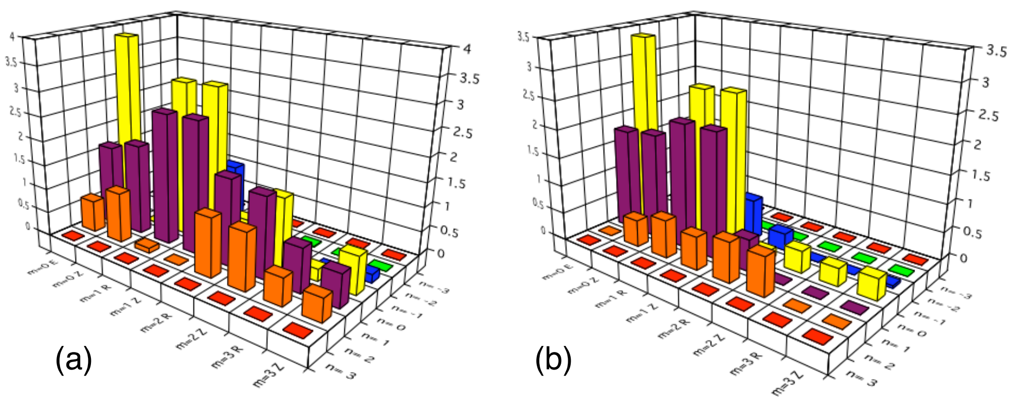

Fig. 1 Fourier mode coefficients of boundary shapes of CHS vacuum configurations. Amplitudes are shown in the logarithmic scale. (a) standard configuration R_0=0.92 and (b) outward shifted configuration R_0=0.99.

Since the variation of amplitudes is so large, amplitudes in the figure are plotted in the logarithmic scale and abstract values are used (eliminating sign). Modes of larger amplitude determines basic geometry of a torus boundary shape: *rbc*(0, 0) for a major radius (shown in the figure as a tallest yellow column for m=0R and n=0), *rbc*(1, 0) and *zbs*(1, 0) for the aspect ratio and the toroidally averaged ellipticity (two tall yellow columns for m=1Z and n=0), *rbc*(1, 1) and *zbs*(1, 1) for the basic helical structure of the boundary shape (two tall violet columns).

The vertical field is the control knob for the magnetic axis position control. With the vertical field varied, the major radius and the aspect ratio of the torus are also varied. Because we are interested in the relation between the boundary shapes and the confinement characteristics, we modified the R_0 = 0.99 configuration to be the similar torus to the R_0 = 0.92 configuration in terms of the major radius and the aspect ratio. This was done by replacing the *rbc*(0, 0), *rbc*(1, 0) and *zbs*(1, 0) Fourier components of R_0 = 0.99 with those of R_0 = 0.92 configuration. It was confirmed that the magnetic well still exists in the modified R_0 = 0.99 configuration. It is not the effect of the simple outward shift of the torus that gives the magnetic well in the R_0 = 0.99 configuration.

In order to find which Fourier components are responsible for the creation of the magnetic well, the characteristics of a new artificial configuration with a minimum number of Fourier modes is examined. Figure 2(a) shows the cross section of magnetic surfaces of the configuration with 5 basic Fourier components (5 largest components): *rbc*(0,0), *rbc*(1,0), *zbs*(1,0), *rbc*(1,1) and *zbs*(1,1). The figure at the bottom shows the radial profile of the specific volume ($dV/d\Psi$) for the magnetic well calculation. It is shown that the basic 5 Fourier

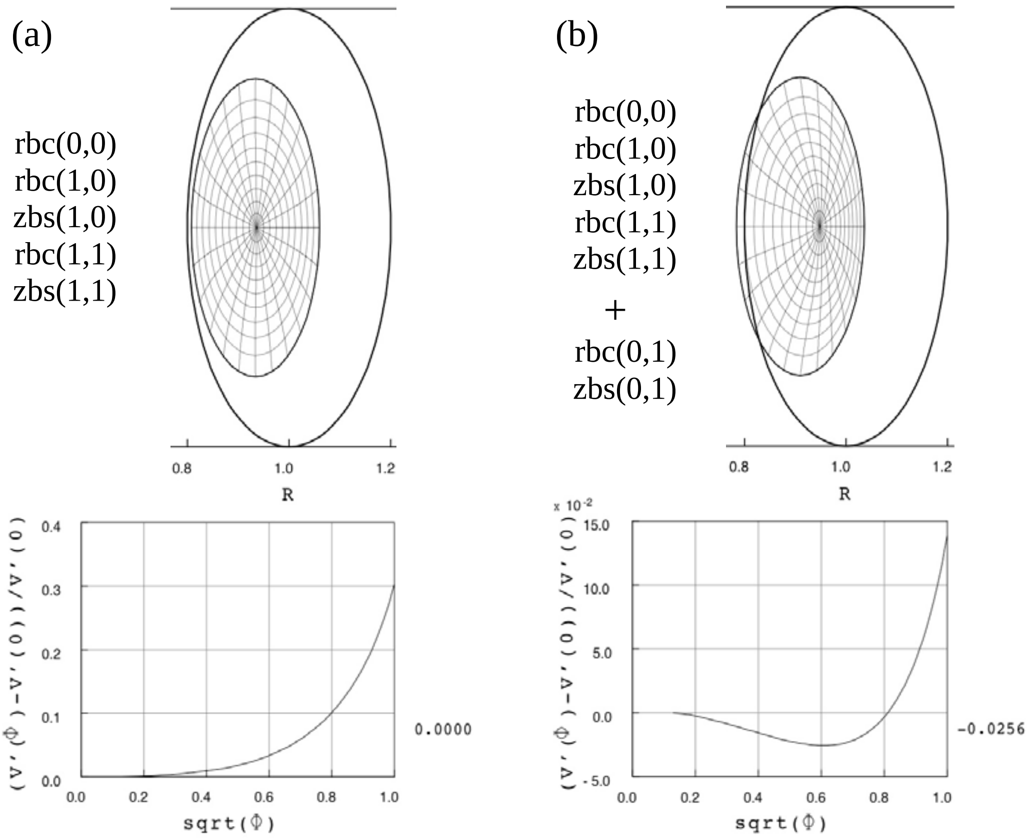

Fig. 2 Comparison of two modified configurations for R_0=0.99 configuration with (a) basic 5 Fourier components and (b) with 5 basic and two helical axis components. Upper figures show cross sections of magnetic surfaces and bottom figures show the radial profiles of specific volume of the surfaces.

components do not give the magnetic well. Figure 5(b) shows the magnetic surfaces and the specific volume for the modified R_0 = 0.99 configuration with 7 components including the helical axis components *rbc*(0,1) and *zbs*(0,1). It is shown that the helical axis structure in CHS configuration is essential to hold the magnetic well. In magnetic surface plots in Fig. 2, a larger ellipse depicts the inner surface of CHS vacuum chamber. The intercrossing of magnetic surface boundary and the vacuum chamber is due to the modification of R_0 = 0.99 configuration to the same major radius and the aspect ratio of R_0 = 0.92 configuration. The apparent position of magnetic surfaces at the inward shifted one (not outward shifted) also comes from the modification of major radius component *rbc*(0,0).

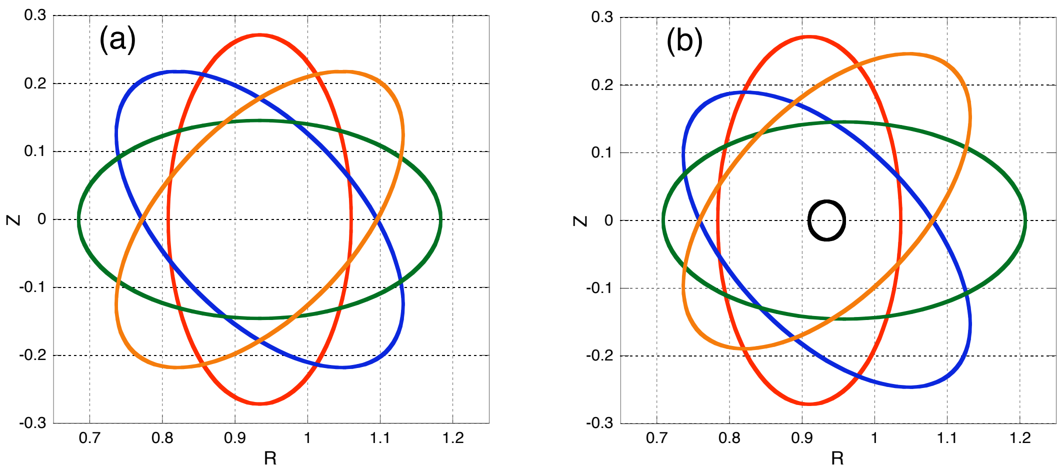

Fig. 3 Cross sections of boundary shape at four different toroidal positions for (a) R_0 = 0.99 configuration with minimum 5 Fourier components and (b) with 7 components including helical axis components. The helical excursion of magnetic surface is also plotted in (b) [a small circle at the center].

In order to evaluate the helical axis component, boundary cross sections at four toroidal positions are plotted in Fig. 3 and compared to the helical excursion of the center of magnetic surfaces. It is generally understood that the helical axis structure of stellarators is favorable to create the magnetic well while the simple straight helical configuration is intrinsically magnetic hill. It should be noted that the toroidal phase of helical structure is important. In Fig. 3(b), the horizontally elongated cross section (green curve) is located relatively rightward shifted to the vertically elongated one (red curve). If it is oppositely located (leftward shifted) with the opposite sign of helical structure Fourier mode, the magnetic well is not created.

References

[1] S. Hirshman, et al., Comput. Phys. Commun. Vol. 43, p.143 (1986)

[2] S. Okamura, Contributions to Plasma Physics, to be published in Vol. 50 (2010)