Magnetic coil design for the improved configuration of LHD

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LHD (Large Helical Device) is a planar-axis stellarator with the super-conducting magnets. The magnetic field configuration is of the Heliotron/Torsatron type with ℓ=2 and N=10. In 15 years of experiments, it has given promising experimental results for the scope of the fusion reactor based on the stellarator concept. Although the magnetic configuration of LHD is the conventional one that is different from the advanced stellarator concept, the inward shifted configuration gives good confinement for high temperature plasmas. However, such favorable features of LHD is lost for the high-beta equilibria because the LHD configuration has a large Shafranov shift. With the shift of magnetic axis due to the P-S current, the configuration becomes similar to the outward shifted configuration of LHD, which has poorer neo-classical confinement than the inward shifted one. It is necessary to investigate a new configuration which has a good confinement as well as the small Shafranov shift for high-beta equilibrium.

We analyzed the confinement properties of magnetic configurations of LHD with different magnetic axis positions based on the Fourier modes of the boundary shape. A clear conclusion was obtained that the magnetic configurations of LHD are composed of a small number of Fourier modes [1]. By re-arranging the combination of Fourier modes, we found a new magnetic configuration LHD-RS1, which gives an improved confinement for high-beta equilibria due to the reduced Shafranov shift [2]. It has a stronger triangularity in the boundary shape of the vertically elongated cross section while the inward shifted one has a small one with an opposite direction of D shaping. The D shape of LHD-RS1 is in the same direction as the outward shifted LHD configuration. In terms of the boundary shape, the new configuration LHD-RS1 is a combination of the inward and outward shifted configuration of LHD. Figure 1 shows the comparison of the vertically elongated cross sections of LHD-RS1 and LHD inward shifted configuration.

We calculated the effective helical ripple ε_{eff} for the evaluation of the neo-classical transport [3]. We compared ε_{eff} of the new configuration and the three LHD configurations (inward shifted, standard and outward shifted ones) for the equilibria of average beta values from zero to 5%. The ε_{eff} at about 1/3 of minor radius are plotted in Fig. 2 as functions of the averaged beta. Because of the large Shafranov shift of LHD configurations, the effective helical ripple rapidly increases with the beta increase for all three LHD configurations. On the other hand, the increase of the effective helical ripple is small for LHD-RS1. The degradation of the confinement from zero beta to 5% beta, which is a nominal value in the LHD-type reactor design, is almost one order smaller than the inward shifted configuration of LHD.

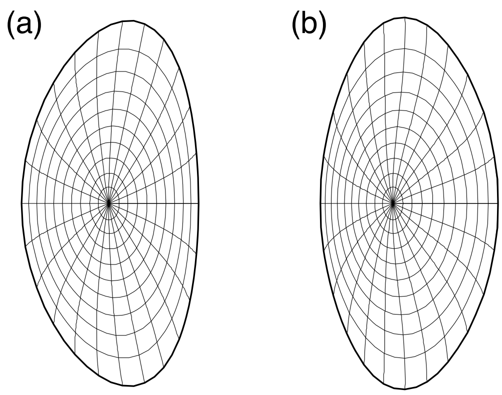

Fig. 1 Comparison of boundary shapes of vertically elongated cross section of (a) LHD-RS1 and (b) LHD inward shifted configuration.

The magnetic coil design for the LHD-RS1 configuration was made using the optimization code COILOPT. Two different concepts of coil design (helical coils and modular coils) were made and both were successful. For the helical coil design, we set 7 free variables for the optimization targets: 4 variables for helical coil shape and 3 variables for the axisymmetric poloidal field. For helical coil design, we use a winding surface of an axisymmetric toroidal shape and a single filament model of helical coil is drawn on the surface. As free variables, we used the major and minor radii (R_c and a_c) of the coil winding toroid with ellipticity ε_c of the poloidal cross section of the toroid. The pitch modulation of helical coil winding is introduced with the formula:

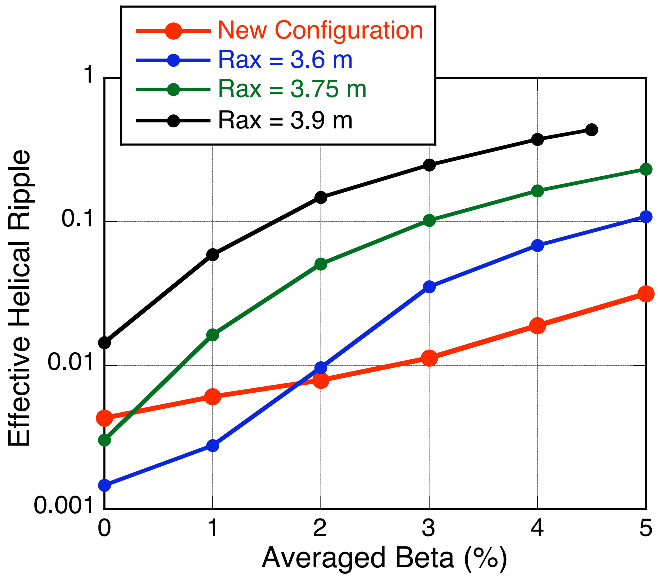

Fig. 2 Variations of effective helical ripple at 1/3 minor radius for new configuration LHD-RS1 and three LHD configurations as functions of averaged beta.

$$\theta = \frac{N}{\ell}\phi + \alpha^{*} sin\left(\frac{N}{\ell}\phi\right),$$

where, θ (ϕ) are poloidal (toroidal) angles of helical coil filament positions, N is the number of toroidal periods (N=10) and ℓ is the number of helical coils (ℓ= 2). α^* is the pitch modulation parameter. For poloidal field, we use terms of the analytic formula for three components: dipole, quadrupole and hexapole terms.

$$B_{vert}: \; B_r = 0, \quad B_z = bv$$

$$B_{quad}: \; B_r = -bq \cdot rz, \quad B_z = bq \cdot \left[z^2 - (r^2 - R_0^2)/2 \right]$$

$$B_{hexa}: \; B_r = -bh \cdot \left[rz(4z^2 - 3(r^2 - R_0^2))/3 \right],$$

$$B_z = bh \cdot z^2 (2z^2 - 6r^2 + 3R_0^2)/3 + bh \cdot (r^2 - R_0^2)^2/4$$

The algorithm of the coil design is as following: the coil shape parameters are chosen such as the local magnetic field created by the coils at the given boundary surfaces are tangential to the surface. In other words, the normal components of the local magnetic field is vanishing on the surface. The COILOPT gave a good solution of the helical coil shape and poloidal field components: R_c= 3.9m, a_c= 1m, ε_c= 0.95, α^*= -0.02, B_{vert} = 0.172 T, B_{quad} = 0.0044 T. We do not need to add the hexapole poloidal field. The cross section of LHD-RS1 helical coil is compared with LHD as shown in Fig. 3 with four cross sections of boundary shape of LHD-RS1. The blue solid line with a small ellipticity is the cross section of the winding surface of helical coil for LHD-RS1 and the dotted line is for LHD. The major radius and the minor radius are the same as LHD. Another difference is the pitch modulation parameter: -0.02 for LHD-RS1 and +0.1 for LHD. These two changes in the helical coil parameters are sufficient for producing the improved configuration of LHD. This coil solution has an additional important product of the larger spacing between the helical coil and the plasma boundary, which

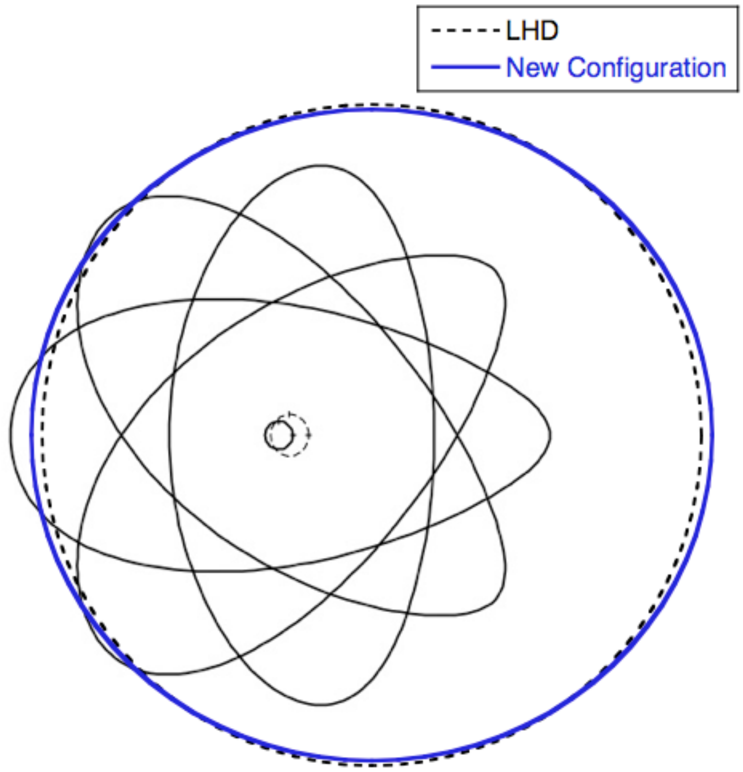

Fig. 3 Cross section of helical coil winding surfaces of LHD-RS1 and LHD. Four cross sections of boundary surface of LHD-RS1 are also shown.

is highly beneficial for the blanket and radiation shield in the fusion reactor design.

In order to show how the present helical coil solution should reproduce the target configuration, Fig. 4 shows the profiles of the effective helical ripples for the target improved LHD configuration and the configuration created by the helical coils together with three LHD configurations. The helical coil solution has a lower value of the effective helical ripple than the target one.

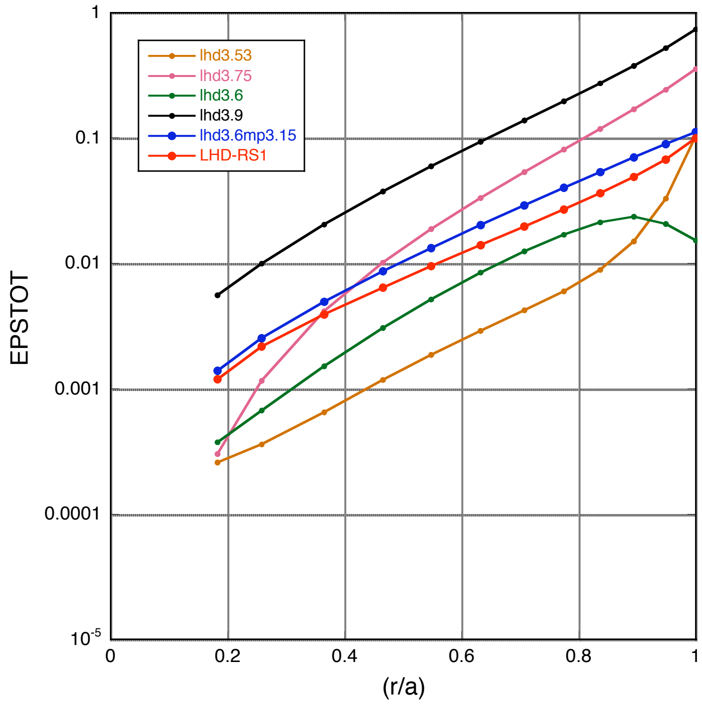

Fig. 4 Profiles of effective helical ripples for target LHD improved configuration, solution of helical coils and three LHD configurations.

Finally we made the modular coil solution for the improved LHD configuration, the shape of which is shown in Fig. 5. Many free variables of COILOPT optimization process are used for the modular coil winding surface shape and the Fourier modes of modular coil shaping shown in Fig. 5. Because the LHD-RS1 configuration is the slight modification of LHD configuration, the modular coil solution shows clearly the helical coil pattern of the current distribution.

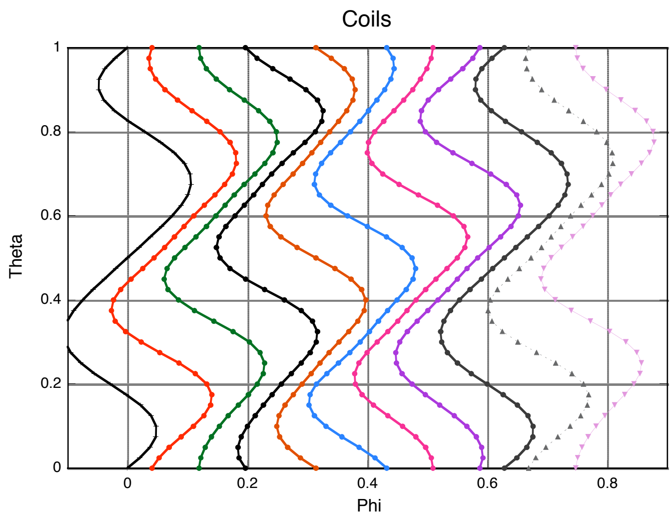

Fig. 5 Coil filament traces of modular coils on the winding surface. 10 modular coils are designed for one toroidal period of LHD-RS1.

References

[1] S. Okamura, Plasma Phys. Control. Fusion **55**, 032002 (2013).
[2] S. Okamura, Plasma and Fusion Research **8**, 2402029 (2013).
[3] V. V. Nemov and S. V. Kasilov, Phys. Plasma **6** (1999) 4622.