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LHD-type fusion reactor magnetic configuration with helical coils winding along geodesic line of a torus
円環の測地線に沿って巻くヘリカルコイルによる LHD 型核融合炉磁場配位

Tsuguhiro WATANABE
渡辺二太

National Institute for Fusion Science,322-6 Oroshi-cho, Toki 509-5292, Japan
核融合科学研究所 〒 *509-5292* 土岐市下石町 *322-6*

A new concept, the geodesic winding helical coil system, to satisfy the requirement of the wide blanket space and the large plasma volume is proposed for the LHD-type fusion reactor. The position of the magnetic axis shift close to the center of the two helical coils. The magnetic well is formed in the core region, and the high magnetic shear is present in the peripheral region. The D-shaped to the bean-shaped cross-section of the last closed magnetic surface is produced at vertically elongated cross-section. Direct loss of 3.52MeV alpha particles is reduced by the adoption of a "winding frame" with oval shaped cross-section.

1. Introduction

LHD-type magnetic configuration ($\ell = 2$ Heliotron configuration) is produced by continuous helical and vertical coil systems. LHD experiments have achieved an average beta value of 5 % without beta collapse.

The LHD helical coils are wound as $\theta = p\phi + \alpha_c \sin p\phi$ on a torus with circular cross section ($R_c = 3.9$m, $a_c = 0.975$m), where p is the helical pitch number ($\equiv m/\ell = 5$). The coil pitch parameter $\gamma \equiv (m/\ell)/(R_c/a_c) = 1.25$. The small pitch modulation of $\alpha_c = 0.1$ was determined by considering the the gap distance between the first wall and the last closed magnetic surface (LCFS) and the confinement properties of the high energetic particles [1]. High helical symmetry of magnetic surface with elliptic cross-section, and good confinement of high energetic particles of standard LHD configurations have been numerically confirmed [2]. High performance of energetic particle confinement was experimentally proved by a high energy ion tail which extended up to 1.6MeV during the long-pulse ICRF heating operation of LHD [3].

In the LHD-type fusion reactor (FFHR) design studies, the balance blanket space and plasma volume become an important issue. Kozaki have pointed out that the γ dependence of magnetic structure is essential in LHD-type reactors, which is critically sensitive not only for optimizing plasma volume but also for selecting the optimum blanket conditions[4]. Sufficient blanket space is necessary for adequate tritium breeding and for shielding the magnet. For this purpose, the small γ configuration is preferable, but this leads to the reduction the plasma volume.

For the compatibility of the sufficient blanket space and the large plasma volume, we have studied the possibility of the D-shaped cross-section of the LCFS. For this purpose, we have analyzed numerically the magnetic configuration produced by the helical coils winding along a geodesic line of a torus, which we call the torus as "winding frame" for the helical coils. The effective value of the coil pitch parameter γ of the geodesic line is reduced(increased) inboard(outboard) side of the torus. Therefore, the enough space between the first wall and the LFCS is reserved, and the position of the magnetic axis shift close to the center of the two helical coils, and the volume of the LCFS increased and magnetic well is created. However, when the cross-section of the "winding frame" is a circle, the geodesic line is very close to the pitch modulation curve with $\alpha_c \simeq 0.532$, ($R_c = 3.9$m, $a_c = 0.955$m). Helical field produced by large positive pitch modulation winding law has very poor confinement performance for the high energetic particles. To recover the confinement performance for the high energetic particles, we have developed a magnetic configuration with helical coils winding along geodesic line of a "winding frame" with oval type cross-section.

In Sec. 2, we describe the helical winding along the geodesic line on a toroidal oval. Characteristics of the magnetic lines of force produced by the helical coil system is summarized. In Sec. 3, we discuss our results.

2. Helical winding along the geodesic line on a toroidal oval

To achieve an excellent alpha-particle confinement, we mitigate the variation of magnetic field intensity distribution in horizontally elongated cross-section ($\phi = 0$) by introducing a "winding frame" with oval shaped cross-section as shown in Fig.1(a), given by constant major radius R_c and variable minor radius $a(\chi)$. The orbit of the helical coil center $\boldsymbol{r}_c$ is given

$$\boldsymbol{r}_c(\phi) \quad = \quad \{R_c \cos p\phi + a(\chi)\cos(\chi - p\phi)\}\, \boldsymbol{i}$$

$$+ \quad \{-R_c \sin p\phi + a(\chi)\sin(\chi - p\phi)\}\, \boldsymbol{j}\,, \qquad (1)$$

using helical rotating helical coordinate system [2]. The orbit length L of the helical coil center $\boldsymbol{r}_c$ is given

$$L = \int_{\pi/2p}^{\pi/2p+2\pi/p} \sqrt{\left(\frac{\mathrm{d}\boldsymbol{r}_c}{\mathrm{d}\phi}\right)^2}\mathrm{d}\phi\,, \qquad (2)$$

the Euler equation for the geodesic line is reduced to

$$0 = -\frac{\mathrm{d}}{\mathrm{d}\phi}\left[\frac{\{a(\chi)^2 + a'(\chi)^2\}\frac{\mathrm{d}\chi}{\mathrm{d}\phi}}{d}\right] + \frac{R_c + a(\chi)\cos\chi}{d}\left\{a'(\chi)\cos\chi - a(\chi)\sin\chi\right\} + \frac{a'(\chi)\{a(\chi) + a''(\chi)\}}{d}\left(\frac{\mathrm{d}\chi}{\mathrm{d}\phi}\right)^2 \qquad (3)$$

$$d = \sqrt{\{a(\chi)^2 + a'(\chi)^2\}\left(\frac{\mathrm{d}\chi}{\mathrm{d}\phi}\right)^2 + \{R_c + a(\chi)\cos\chi\}^2} \qquad (4)$$

In the present paper we have adopted the following functional form for the variable minor radius,

$$a(\chi) = a_0\left(1 + a_2\sin^2\chi + a_4\sin^4\right)\,, \qquad (5)$$

with parameters shown in Table.1, with scale corresponding to the LHD.

Table 1 Parameters of "winding frame" of geodesic winding helical coils(I) and of the LHD helical coils(II).

	p	R_c (m)	a_0 (m)	a_2	a_4	R_{ax} (m)	V_{lcfs} (m^3)
I	5	3.9	0.865	0.4	0.5	3.9	67.0
II	5	3.9	0.975	0.0	0.0	3.6	28.9

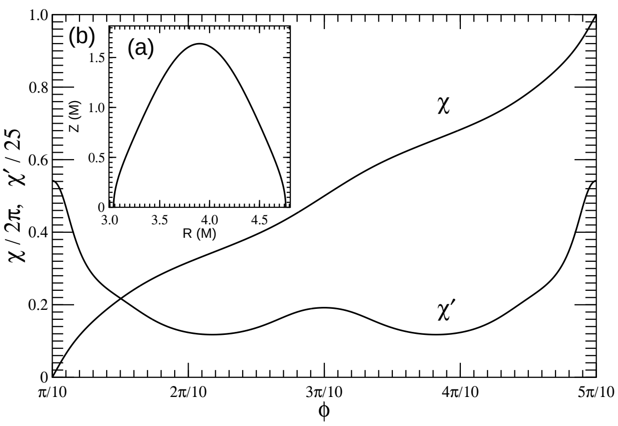

Fig. 1 (a): An example of oval shaped cross-section of a "winding frame" for helical coils. (b): Variation of poloidal angle χ of geodesic line on the "winding frame". One period of toroidal angle ϕ for the helical coils is $2\pi/5$, because of $p = 5$.

Structure of the magnetic surface is shown in Fig.2 and distributions of the rotational transform $\iota/2\pi$ and the specific volume U, produced by helical coils winding along geodesic line of a toroidal oval, is shown in Fig.3.

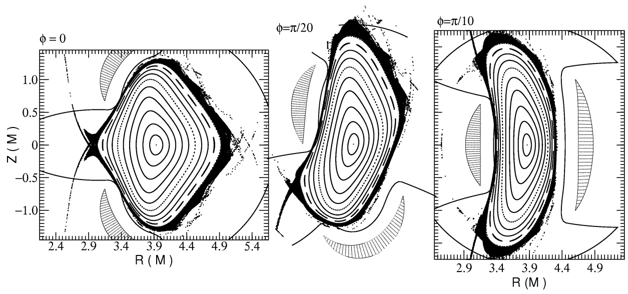

Fig. 2 Magnetic configuration produced by helical coils, winding along geodesic line of a toroidal oval. Poincaré plot of the lines of force at $\phi = 0, \pi/20, \pi/10$ are shown with the cross-section of helical coils and vacuum vessel.

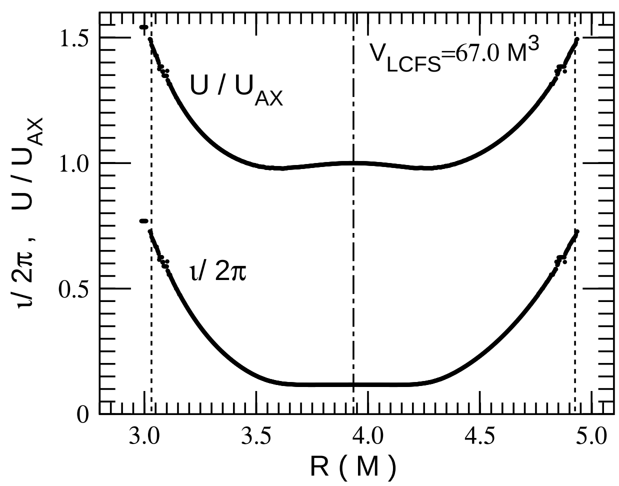

Fig. 3 Distributions of the rotational transform $\iota/2\pi$ and the specific volume U produced by helical coils, winding along geodesic line of a toroidal oval.

3. Discussion

It is shown that the geodesic winding helical coil method satisfies the requirement of the wide blanket space and the large plasma volume. The magnetic well is formed in the core region, and the high magnetic shear is present in the peripheral region. In addition, geodesic winding allows tightening winding of the superconducting wires.

Numerical computations show the 14.0% direct loss rate of 3.52MeV alpha particles, born uniformly in the region of $\rho/\rho_{lcfs} \leq 0.8$, for the case of $R_c = 14$m and $B_{ax} = 6$T. The direct loss rate of alpha particles of standard LHD configuration under the same condition is 0.2%

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References

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