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Proposal of Split and Segmented-type Helical Coils for the Heliotron Fusion Energy Reactor

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Configuration optimization is carried out for the heliotron-type fusion energy reactor FFHR. One of the important issues is to find sufficient clearances between the ergodic region outside the nested magnetic surfaces and blankets at the inboard side of the torus so that direct loss of alpha particles is minimized and the heat flux on the first walls is reduced. Though the primary option is to have a fairly large major radius R_c of the helical coils to be ~17 m in the present design, it has been found that equivalent clearances are obtained with R_c = 15 m by employing a lower helical pitch parameter and by splitting the helical coils in the poloidal cross-section at the outboard side of the torus. On the other hand, splitting the helical coils provides another modified configuration with R_c ~ 17 m that ensures magnetic well formation in the fairly large nested magnetic surfaces with outward shifted configurations. From the engineering viewpoint, we propose that such helical coils can be constructed by prefabricating half-pitch segments using high-temperature superconductors and the segments are to be assembled on site.

Keywords: heliotron, FFHR, configuration optimization, split-type helical coils, high-temperature superconductor, segmented-type helical coils

1. Introduction

Based on the successful progress of fusion relevant plasma experiments in the Large Helical Device (LHD) [1], the conceptual design studies on the heliotron-type fusion energy reactor FFHR are being conducted both on physics and engineering issues [2]. For FFHR, a magnetic configuration similar to that of LHD is employed so that the confined plasma is net current-free with steady-state operations. Though configuration optimization is still being pursued, the present choice gives the major radius of 14-18 m with the toroidal magnetic field of 6-4 T in order to generate ~3 GW of fusion power. The stored magnetic energy of the superconducting coil system should be in the range of 120-150 GJ.

In these studies, the helical pitch parameter γ defined by $(m/l)(a_c/R_c)$ for continuous helical coils (having the toroidal pitch number m, poloidal pole number l, average minor radius a_c and major radius R_c) has been chosen to be lower than 1.25 that was adopted for the present LHD. This choice is made for the purpose of ensuring a sufficient blanket space (thickness > 1 m) between the ergodic region of magnetic field lines (outside the nested magnetic surfaces) and the blankets [3]. At the same time, the lower γ reduces the electromagnetic hoop-forces on the helical coils. The configuration proposed in 2005, "FFHR-2m1", has m = 10, l = 2, R_c = 14 m and a_c = 3.22 m with γ = 1.15.

One of the difficult issues with this configuration is the still observed interferences between the ergodic region and blankets especially at the inboard side of the torus. In order to reduce the heat flux on the blankets, the "helical x-point diverter (HXD)" was proposed [4]. However, this choice gives an extremely high heat flux on the limiter-like structures. Moreover, the confinement of alpha particles is deteriorated by cutting the magnetic field lines in the ergodic region where alpha particles are still confined.

In this respect, two approaches are being considered to secure more sufficient clearances. One is to enlarge the major radius of the helical coils, and the latest design, "FFHR-2m2", gives R_c = 17.33 m and a_c = 4.02 m with γ = 1.20. The vacuum magnetic surfaces of this configuration are shown in Fig. 1, and the blanket space of 0.95 m is secured at the inboard side. As shown in Fig. 1, the magnetic axis is shifted inward (located at R_p = 16.0 m) in order to have good particle confinement.

The other approach is to find optimized magnetic configurations by modifying the winding laws of the helical coils. In this respect, we found that favorable configurations could be obtained by splitting the helical coils in the poloidal cross-section. The new configurations were named "FFHR-2S", and two options of FFHR-2S, namely, "Type-I" and "Type-II" are proposed in this paper.

From the engineering viewpoint, we also propose that such complicated helical coils with the continuous manner and huge size can be constructed by prefabricating half-pitch segments of the windings using high-temperature superconductors (HTS), and the segments are to be assembled on site.

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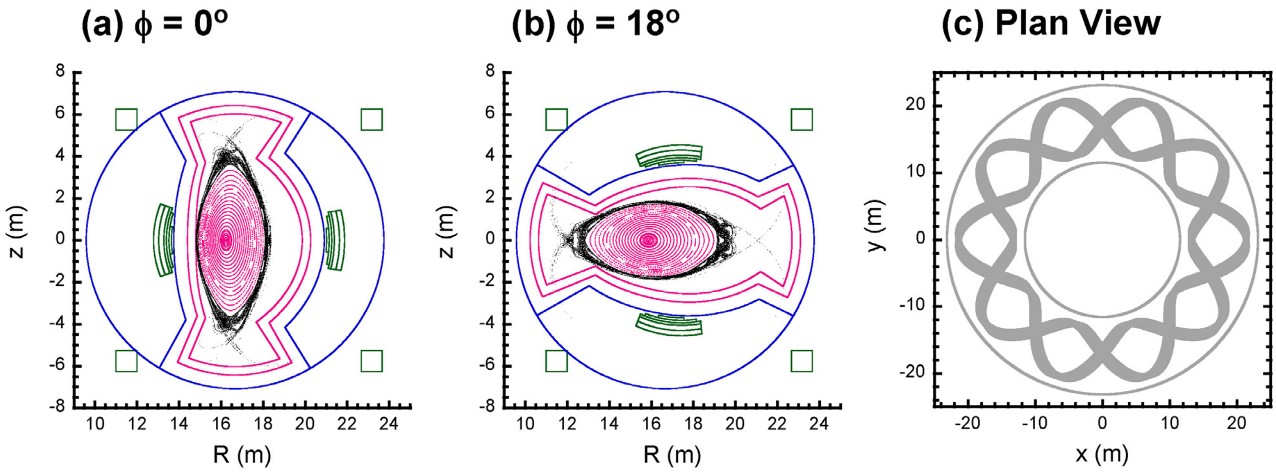

Fig. 1 Vacuum magnetic surfaces at (a) the toroidal angle $\phi = 0°$ and (b) $\phi = 18°$of FFHR-2m2 (Type-A) with $R_c = 17.33$ m, $a_c = 4.02$ m and $\gamma = 1.2$. The magnetic axis is shifted inward at $R_p = 16.0$ m. (c) Plan view of the coils.

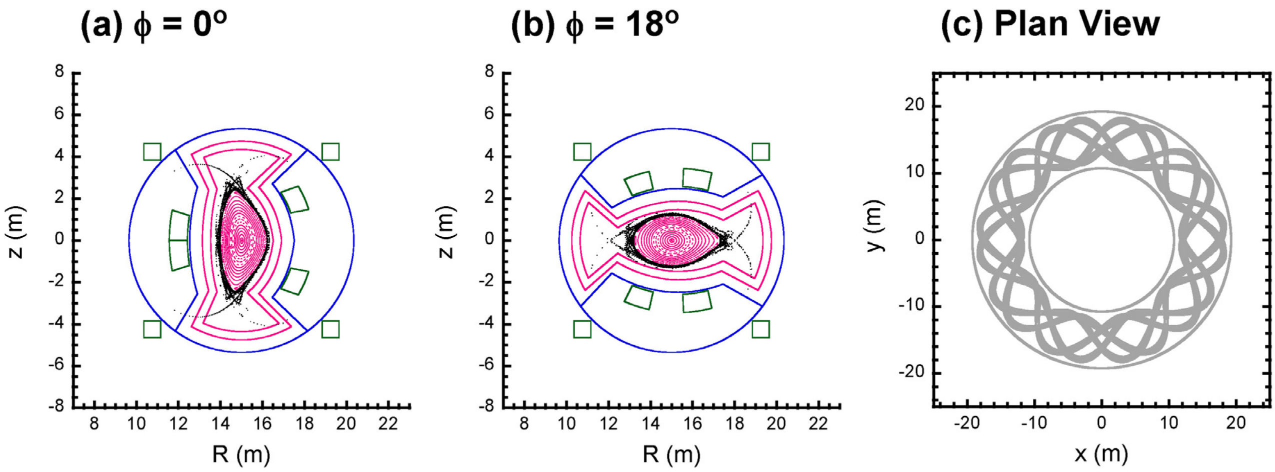

Fig. 2 Vacuum magnetic surfaces at (a) the toroidal angle $\phi = 0°$ and (b) $\phi = 18°$ of FFHR-2S Type-I with $R_c = 15.0$ m, $a_c = 3.0$ m and $\gamma = 1.0$. The magnetic axis is at the center of the helical coils ($R_p = 15.0$ m). (c) Plan view of the coils.

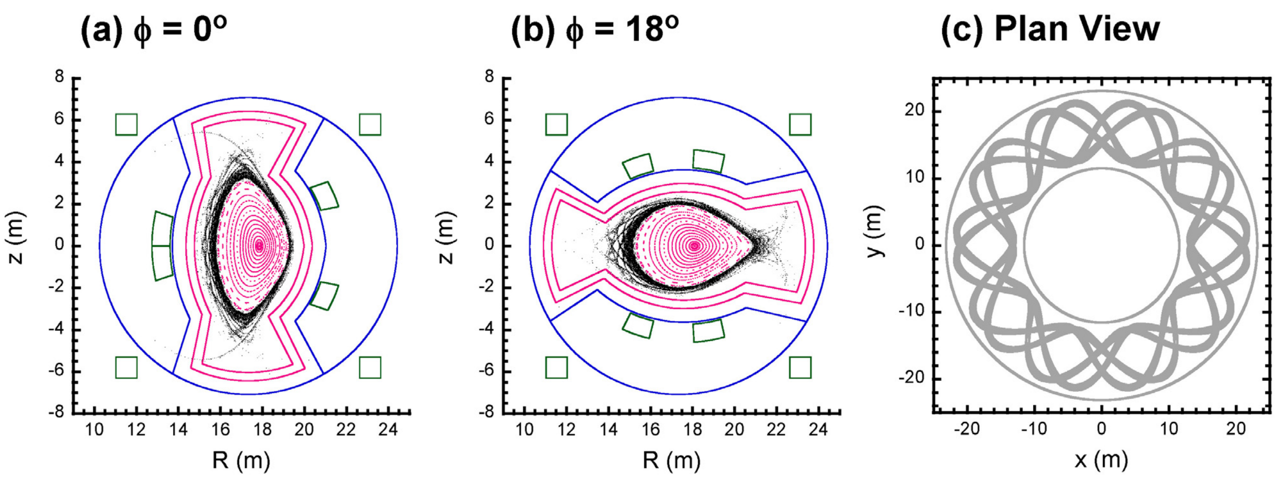

Fig. 3 Vacuum magnetic surfaces at (a) the toroidal angle $\phi = 0°$ and (b) $\phi = 18°$of FFHR-2S Type II with $R_c = 17.33$ m, $a_c = 4.02$ m and $\gamma = 1.2$. The magnetic axis is shifted outward at $R_p = 18.0$ m. (c) Plan view of the coils.

2. Proposal of split-type helical coils

It was previously found that the symmetry of magnetic surfaces is significantly improved by increasing the current density of the helical coils at the inboard side of the torus while decreasing at the outboard side [5, 6]. This situation can be practically realized by splitting the helical coils in the poloidal cross-section at the outboard side. It should be reminded, on the other hand, that good symmetry of magnetic surfaces is usually obtained by shifting the magnetic axis inward with conventional heliotron magnetic configurations, like that of LHD.

Here, we newly found that drastically large nested magnetic surfaces (or the plasma volume) can be obtained by the symmetry improvement with split-type helical coils even if the original configuration (without splitting the helical coils) possesses a fairly large ergodic region outside the relatively small nested magnetic surfaces. In this respect, we first found that sufficient clearances are obtained even with a smaller major radius of R_c = 15.0 m (than that of the standard configuration of FFHR-2m2 with R_c = 17.33 m) by splitting the helical coils and at the same time by reducing the helical pitch parameter to be as low as γ = 1.0 [7]. The vacuum magnetic surfaces of this configuration are shown in Fig. 2. The magnetic axis is located at the center of the helical coils and the blanket space of ~1 m is secured at the inboard side. Here we should note that such a low helical pitch parameter has never been examined so far, as it is well known that one is almost in the so-called forbidden-zone for generating magnetic surfaces with a l = 2 heliotron configuration [8]. We understand that the low helical pitch parameter is effective for compacting the separatrix while the splitting of helical coils at the outboard side ensures larger nested magnetic surfaces by the symmetry improvement. This configuration is named "FFHR-2S Type-I". Owing to the smaller major radius, we design that the toroidal magnetic field is as high as 6 T, while it is 4.84 T for FFHR-2m2.

We then found that split-type helical coils could provide another configuration based on the same concept of symmetry improvement. The FFHR-2m2 has the inward shifted magnetic surfaces, which ensures good particle confinement properties. On the other hand, it has been recently found in the LHD plasma experiments that high electron density is achieved with the "superdense core (SDC)" at outward shifted configurations [9]. However, one of the problems with this configuration is that the nested magnetic surfaces become considerably smaller than those at inward shifted cases. Here, we propose that fairly large nested magnetic surfaces can be obtained even with outward shifted configurations as we split the helical coils. Figure 3 shows an example of the vacuum magnetic surfaces with this concept, which is named "FFHR-2S Type-II". The basic parameters of this configuration are the same as those for FFHR-2m2 except for the split-type helical coils, and the magnetic axis is located at R_p = 18.0 m where the toroidal magnetic field is 4.3 T. Though the original configuration gives ~35% reduction of the average minor radius at R_p = 18.0 m compared to that at R_p = 16.0 m, it is only ~7% with FFHR-2S Type-II. Here, it should be noted that a similar idea had been previously proposed in [6].

Figure 4 shows the radial profiles of rotational transform and magnetic well depth for three configurations: FFHR-2m2, FFHR-2S Type-I and FFHR-2S Type-II. As shown in Fig. 4, magnetic well is formed within the entire magnetic surfaces of FFHR-2S Type-II. On the other hand, the rotational transform as well as shear are lower with this case than those of other configurations. For all these configurations, the field properties including the plasma beta should be investigated in our future studies.

We here note that split-type helical coils are useful not only for configuration optimization but also for some other purposes, such as injecting pellets and/or RF waves from the high field side through the gaps of helical coils at the outboard side. It is proposed in [10] that ICRF heating has good accessibility in case of FFHR-2S configurations.

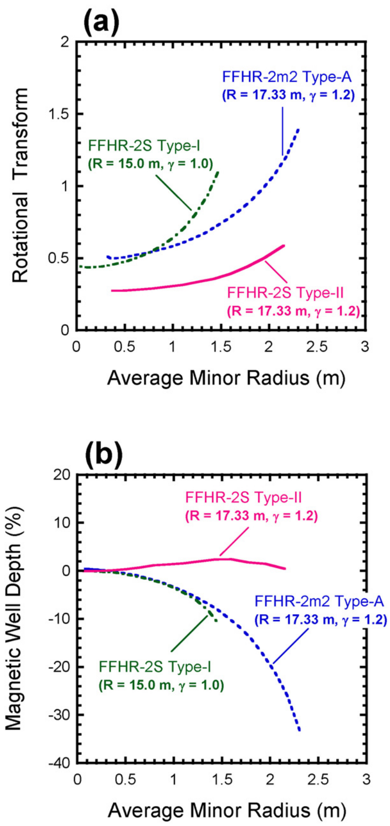

Fig. 4 Radial profiles of (a) rotational transform and (b) magnetic well depth for FFHR-2m2, FFHR-2S Type-I and FFHR-2S Type-II.

3. Proposal of segmented-type helical coils

From the engineering viewpoint for realizing the complicated winding of split-type helical coils with the huge size of FFHR, here we propose "segmented-type" fabrication [11], which could drastically ease the construction process. As shown in Fig. 4 (b), we employ a number of joints between the half-pitch segments which are prefabricated separately. Here we also propose that high-temperature superconductors (HTS) are adopted with indirect-cooling scheme and the surplus refrigeration power operated at 20-30 K is effectively used to remove the joule heating generated by the joints between segments [12]. Our proposal is to employ RE123-based coated-conductors, and Fig. 3(a) shows a conductor design. Here, the HTS tapes are packed without transposition, and the bending strain is limited to be 0.05%. Good mechanical properties are secured also by using a stainless-steel jacket. It should be noted that we have successfully carried out proof-of-principle experiments of HTS conductors with 10-15 kA critical current at 8 T and 20 K [12]. At the joint locations, the HTS conductors are cut in step-like structures, then overlapped and joined with superconducting sides facing each other [11].

Since the HTS conductor has a large temperature margin, the temperature rise at a joint may not be a big concern in terms of the cryogenic stability. For a temperature rise of 5 K, the power density of 990 W/m^3 can be allowed, which means that a joint resistance of 3 nΩ is acceptable [11]. On the other hand, according to the joint resistance measured with single tapes, it is expected that the overall joint resistance of a 100 kA conductor can be as low as 0.06 nΩ, which requires only 300 kW of additional refrigeration power for the entire system. Moreover, helical coils assembled in segments may have a further possibility that they can be demountable for maintenance as was originally proposed in [13] with NbTi superconductors and more recently in [14] with HTS conductors.

4. Summary

Configuration optimization is being carried out for the heliotron-type fusion energy reactor FFHR by splitting the helical coils in the poloidal cross-section at the outboard side of the torus, which is effective in having good symmetry of magnetic surfaces. Together by choosing a low helical pitch parameter of $\gamma = 1.0$, the FFHR-2S Type-I configuration provides a smaller major radius of $R_c = 15$ m to secure sufficient blanket space of ~1 m which is equivalent with that obtained for FFHR-2m2 with $R_c = 17.33$ m. On the other hand, by splitting the helical coils with the FFHR-2m2 design, the FFHR-2S Type-II configuration provides magnetic well formation in the entire region of the fairly large nested magnetic surfaces with outward shifted configurations. It is also proposed that continuous helical coils with such complicated structure can be assembled by prefabricating half-pitch segments using HTS conductors.

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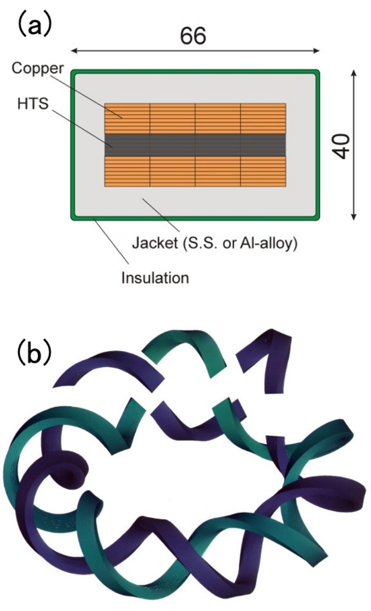

Fig. 5 (a) Conceptual design of an HTS superconductor with 100 kA current capacity and (b) illustrative image of segmented-type helical coils.