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 losses of alpha particles are minimized and the heat flux on the first walls is reduced. The latest design has a fairly large major radius $R_c \sim 17$ m of the helical coils in order to satisfy this condition. It has been found, as an alternative design, that equivalent clearances are obtained with $R_c = 15$ m by employing a lower helical pitch parameter and splitting the helical coils in the poloidal cross-section at the outboard side. Furthermore, splitting the helical coils provides another modified configuration at $R_c \sim 17$ 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 be constructed by prefabricating half-pitch segments using high-temperature superconductors; the segments are then to be assembled on site with joints.

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

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1. Introduction

Based on the steadfast 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 on both physics and engineering issues [2, 3]. 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 a major radius of 14-18 m with a 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, the parameter 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 [4]. 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 $\gamma = 1.15$.

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, a "helical x-point diverter (HXD)" was proposed [5]. However, this choice gives an extremely high heat flux on the limiter-like structures. Moreover, the confinement of alpha particles deteriorates by cutting the magnetic field lines in the ergodic region where alpha particles are still confined [6].

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 currently improved design, "FFHR-2m2," gives $R_c = 17.33$ m and $a_c = 4.02$ m with $\gamma = 1.20$, which assures a blanket space of 0.95 m at the inboard side. 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 [7]. The new configurations are named "FFHR-2S," and two options "Type-I" and "Type-II" are discussed in this paper.

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

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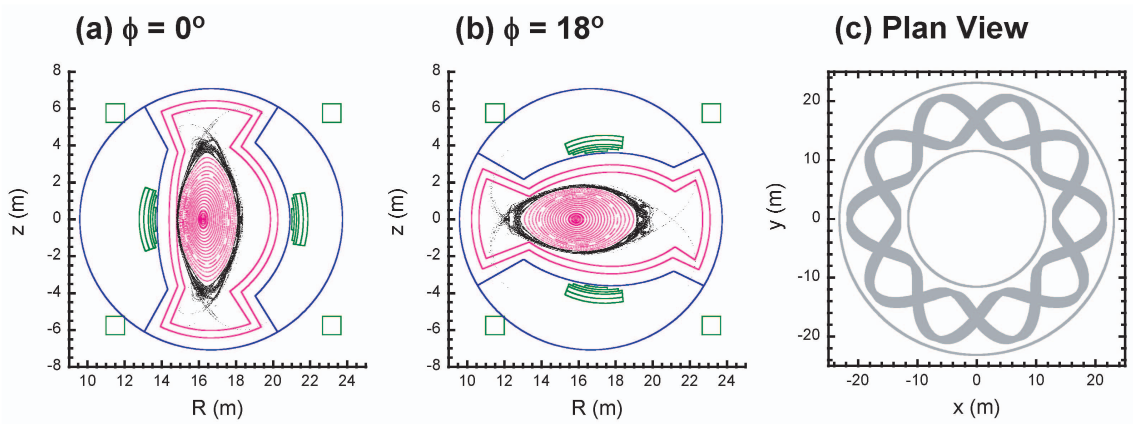

Fig. 1 Vacuum magnetic surfaces at (a) the toroidal angle $\phi = 0°$ and (b) $\phi = 18°$ of FFHR-2m2 (Type-A) with $R_c = 17.33$ m, $a_c = 4.02$ m and $\gamma = 1.2$. The magnetic axis is shifted inward at $R_p = 16.0$ m. (c) Plan view of the coils.

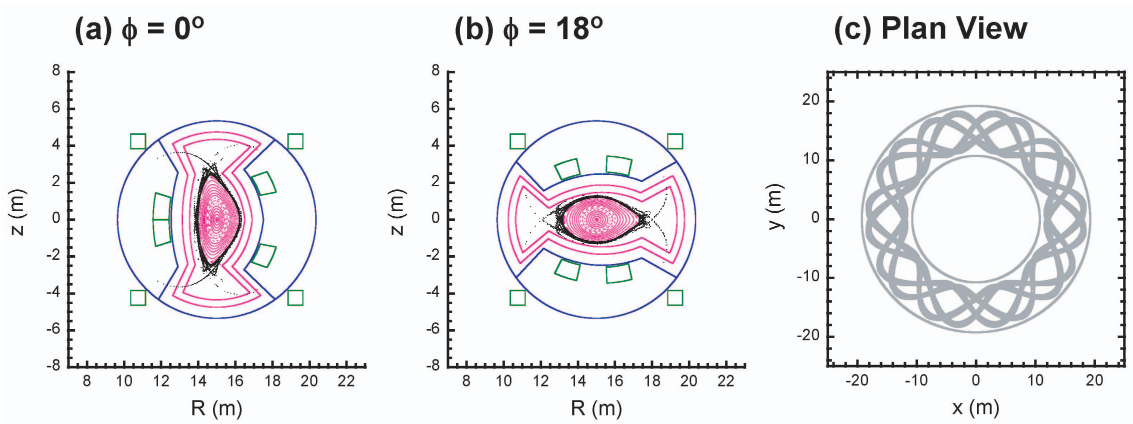

Fig. 2 Vacuum magnetic surfaces at (a) the toroidal angle $\phi = 0°$ and (b) $\phi = 18°$ of FFHR-2S Type-I with $R_c = 15.0$ m, $a_c = 3.0$ m and $\gamma = 1.0$. The magnetic axis is at the center of the helical coils ($R_p = 15.0$ m). (c) Plan view of the coils.

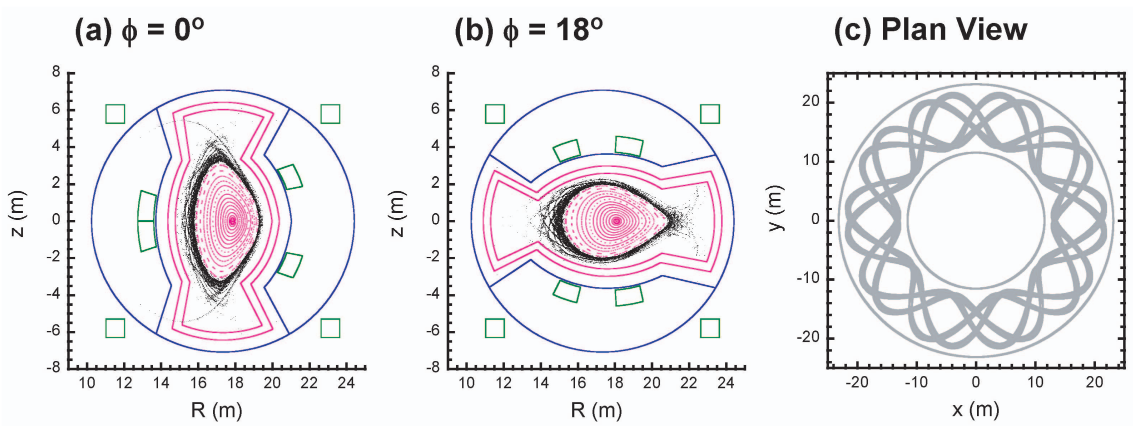

Fig. 3 Vacuum magnetic surfaces at (a) the toroidal angle $\phi = 0°$ and (b) $\phi = 18°$ of FFHR-2S Type II with $R_c = 17.33$ m, $a_c = 4.02$ m and $\gamma = 1.2$. The magnetic axis is shifted outward at $R_p = 18.0$ m. (c) Plan view of the coils.

The feasibility of the HTS option is briefly discussed in this paper.

2. Proposal of Split-Type Helical Coils

The vacuum magnetic surfaces of the FFHR-2m2 configuration are shown in Fig. 1, and it is seen that the magnetic axis is shifted inward (located at $R_p = 16.0$ m) in order to have good particle confinement. It is noted that the magnetic surfaces have good symmetry with the inward shifted configuration. On the other hand, it was previously found that the symmetry of magnetic surfaces would be significantly improved, without shifting the magnetic axis inward, by increasing the current density of the helical coils at the inboard side of the torus while decreasing at the outboard side [8–10]. This situation can be practically realized by splitting the helical coils in the poloidal cross-section at the outboard side.

Here, we newly found that drastically large nested magnetic surfaces (or the plasma volume) can be obtained by the symmetry improvement using split-type helical coils even if the original configuration (non-split 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 $\gamma = 1.0$ [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 [11]. 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 as a result of the symmetry improvement. This configuration is named "FFHR-2S Type-I." Owing to the smaller major radius, our designs indicate the toroidal magnetic field to be 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 a "superdense core (SDC)" at outward shifted configurations [12]. 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 be obtained even with outward shifted configurations by splitting the helical coils. Figure 3 shows an example of the vacuum magnetic surfaces using 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 [10].

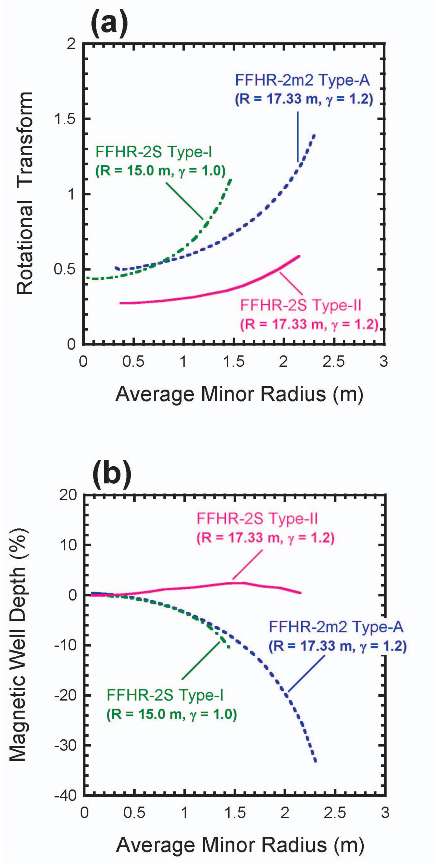

Fig. 4 Radial profiles of (a) rotational transform and (b) magnetic well depth for FFHR-2m2, FFHR-2S Type-I and Type-II.

Figure 4 shows the radial profiles of rotational transform and magnetic well depth for three configurations: FFHR-2m2, FFHR-2S Type-I and Type-II. As shown in Fig. 4, magnetic well is observed 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 configuration than those of the other two. For all these configurations, magnetic field properties concerning the neoclassical ripple transport and drift orbits of alpha particles will be clarified in our future studies and further optimization will be pursued. Moreover, plasma beta should also be included in these studies and MHD stabilities will be investigated.

We here note that split-type helical coils are useful not only for configuration optimization but also for engineering purposes, such as for injecting pellets and/or RF waves from the high-field side through the gaps of helical coils at the outboard side. It is proposed that ICRF heating has good accessibility in case of FFHR-2S configurations [13].

3. Proposal of Segmented-Type Fabrication of Helical Coils

From the engineering viewpoint, we admit that the three-dimensional winding process of helical coils of a huge size as FFHR would become even more complicated by incorporating splitting. In order to overcome this difficulty, we propose a "segmented-type" fabrication of helical coils [14]. The concept is illustrated in Fig. 5(a). We employ a number of joints for conductors between half-pitch segments of the helical coils. The segments are fabricated in factories, transferred to the site, assembled and jointed. Then, there is no need to construct a huge winding machine with a ~40 m diameter. This may drastically ease the construction of helical coils not only for the split type of Figs. 2(c) and 3(c) (with 40 segments) but also for the conventional non-split type of Fig. 1(c) (with 20 segments). We also expect that this option would shorten the construction period, and moreover, each segment can be cold tested separately if required.

Here we also note that this idea would become more plausible if we employ high-temperature superconductors (HTS), since joule heating at the joint sections could be accepted more easily with elevated temperature operations compared to the case with low-temperature superconductors (LTS). We presently consider that the so-called "second-generation" HTS wires, i.e., "REBCO coated-conductors" will be available for large-scale applications in the near future according to the recent development of wire production technology [15]. Here, RE stands for rare earth metal, and Y-Ba-Cu-O (YBCO) [16] and/or Gd-Ba-Cu-O (GdBCO) [17] are promising materials. Figure 5(b) shows an example of the HTS conductor design, which has a nominal current of 100 kA at a maximum magnetic field of 13 T, and an operating temperature in the range of 20-30 K using an indirect-cooling scheme.

It should be reminded that this conductor selection is regarded as the third option in our present engineering design for the FFHR superconducting magnet system. Here, the first option is to employ force-cooled coils wound with cable-in-conduit conductors (CICC) made of LTS cables, such as Nb_3Sn or Nb_3Al. This is regarded as an extension of the ITER technology [18]. The second option is to incorporate solid-type LTS (Nb_3Sn or Nb_3Al) conductors with an aluminum-alloy jacket, with the windings indirectly cooled using cooling panels [19]. For both the first and second options, long-length LTS conductors will be fabricated, transferred to the site, heat treated if necessary and wound using a winding machine. Each option has its advantages and disadvantages, and the details will be discussed elsewhere. For every option, the present design requires about 400 turns of windings in one helical coil with a conductor current of about 100 kA.

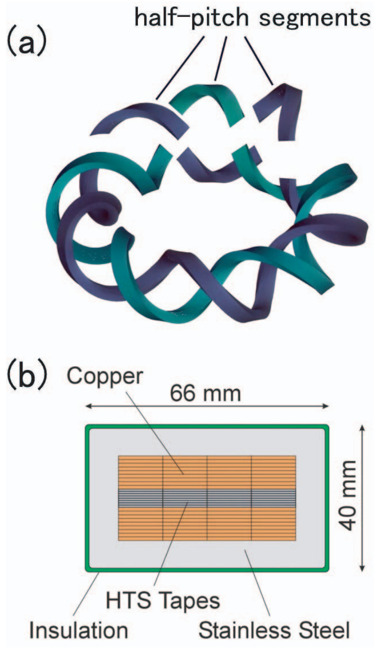

Fig. 5 (a) Illustrative image of segmented-type fabrication of helical coils (shown for the non-split type) and (b) conceptual design of an HTS superconductor with 100 kA current capacity.

In the design of an HTS conductor shown in Fig. 5, HTS wires are supplied in tape forms and are simply stacked together in a rather thin layer of ~6 mm thickness at the center of the conductor. In this case, the bending strain is limited to be 0.05%, which is one order of magnitude smaller than the allowable maximum strain for REBCO tapes. Good mechanical properties are secured also by using a stainless-steel jacket. On the other hand, as the HTS wires are simply stacked without transposition in this proposal, there are some concerns, such as the degradation of cryogenic stability due to the formation of non-uniform current distribution among tapes, enhanced AC losses and generation of error magnetic field by shielding currents. These problems will be discussed in detail elsewhere, but we note that they are of no big concern according to the present analysis.

We should then emphasize that we have successfully carried out the proof-of-principle experiment of HTS conductors using Ag-sheathed Bi-2223 tapes, which showed 10 kA critical current at 8 T and 20 K with a conductor size of 12 mm by 7.5 mm [20]. It was also confirmed that the stability margin is about two orders of magnitude higher than that of low-temperature superconductors (LTS). We also achieved even higher critical current with a similar conductor sample employing YBCO and GdBCO tapes, and the details of this experiment will be reported elsewhere.

At the joint locations between half-pitch segments, the HTS conductors are cut in step-like structures, then overlapped and jointed with superconducting sides facing each other so that low-resistance joint can be formed [14]. Since the HTS conductor has a large temperature margin, the temperature rise at a joint is not a big concern in terms of cryogenic stability. Then, 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 even 3 nΩ is acceptable [14]. In this case, ~15 MW of additional refrigeration power is required for the entire system with ~8000 joints of conductors (~400 turns and 10 segments with 2 helical coils). However, this could be supplied by the surplus refrigeration power with elevated temperature operations compared to the case of LTS coils operated at 4 K [20]. On the other hand, the joint resistance measured with single tapes (~6 nΩ for 50 mm joint length) gives the expected overall joint resistance of a 100 kA conductor to be as low as 6 pΩ with 100 tapes and 500 mm joint length. This requires only ~30 kW of additional refrigeration power for the entire cooling system.

Helical coils assembled in segments may have a further possibility that they can be demountable for maintenance, as was originally proposed with NbTi superconductors [21], and more recently with HTS conductors [22].

4. Summary

Configuration optimization is being carried out as an alternative design 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 at 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 the presently standard design of "FFHR-2m2" with $R_c = 17.33$ m. On the other hand, by splitting the helical coils with the FFHR-2m2 size, 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. From the engineering viewpoint, it is proposed that continuous helical coils with such a complicated structure be assembled by prefabricating half-pitch segments. This method should drastically ease the winding process and shorten the required period. For this purpose, it is feasible to employ high-temperature superconductors (HTS), such as YBCO or GdBCO. The joule heating generated at ~8000 joints is acceptable by the elevated temperature operations and by the expected low joint resistances between HTS tapes.

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