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Design studies on split-type helical coils for FFHR-2S

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Configuration optimization is being carried out for the LHD-type fusion energy reactor FFHR. One of the present issues is to find a sufficient clearance between the ergodic layers of the magnetic field lines and the blankets so that direct loss of alpha particles is minimized and the heat flux on the first wall is reduced. It has been newly found that by having the combination of splitting the helical coils in the poloidal cross-section and adopting a small pitch parameter for the winding law of the helical coils, a large gap is clearly obtained. Here, splitting of the helical coils means that they have higher current density at the inboard side of the torus and lower at the outboard side, which contributes in enhancing the helical symmetry. A small value of the pitch parameter such as 1 is adopted in the configuration named FFHR-2S, and the plasma volume is almost the same as that with the original design of FFHR-2m1 that has the pitch parameter of 1.15. Various physical parameters of the vacuum magnetic surfaces are investigated with the new configuration, such as the rotational transform, specific volume and the drift orbits of helically trapped particles.

Keywords: FFHR, LHD, heliotron, split-type helical coils, forbidden zone, ergodic layers, blanket space, configuration optimization

1. Inroduction

Based on the successful progress of fusion relevant plasma experiments performed for 10 years in the Large Helical Device (LHD) [1], the conceptual design studies on the LHD-type fusion energy reactor (FFHR) are being conducted both on physics and engineering issues, and the recent design activities are summarized in [2]. For FFHR, a heliotron magnetic configuration similar to that of LHD will be employed so that the confined plasma is current free and the steady-state operation is realized. Though the further optimization of the configuration is still being carried out, the basic parameters give the toroidal magnetic field of 6 T with a major radius in the range 14-18 m in order to generate 3 GW fusion power. By having the machine size approximately four times bigger than that of LHD, the stored magnetic energy of the superconducting coil system is in the range 120-150 GJ.

In these studies, the coil 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 adopted for the present LHD. This choice is made for the purpose of reducing the electromagnetic hoop-force on the helical coils while ensuring larger blanket space between the core plasma and the helical coils [3]. The latest standard configuration, named FFHR-2m1, has $\gamma = 1.15$ with $m = 10$, $l = 2$, $a_c = 3.22$ m and $R_c = 14$ m.

The vacuum magnetic surfaces of FFHR-2m1 is shown in Fig. 1(a). One of the most difficult issues with this configuration is found in the still observed interferences between the ergodic layers of the magnetic field lines and the blankets (thickness: ~1.1 m) especially at the inboard side of the torus. In order to reduce the heat flux on the blankets, the concept of "helical x-point divertor (HXD)" was proposed [4]. However, this choice gives a high heat flux on the limiter-like structures, and moreover, a recent study shows that the confinement of alpha particles is deteriorated. Since the alpha particles are lost finally along the magnetic field lines in the ergodic regions, the loss rate is substantially reduced if the ergodic layers are not cut by metallic materials.

In this connection, we are seeking for another approach of ensuring much clearer blanket space by modifying the coil configuration while keeping the major radius below 16-17 m. As was found in the previous study [5], the symmetry of magnetic surfaces around the magnetic axis is significantly improved, without shifting the magnetic axis inward, by increasing the current density at the inboard side of the helical coils while decreasing at the outboard side. Modulation of the current density can be practically realized by splitting the helical coils in the poloidal cross-section. Using this feature by splitting the helical coils, we found a new configuration that assures sufficient clearance between the ergodic layers and the blankets. For the new configuration, various physics properties of the magnetic field are investigated and the initial results of the parameter surveys are introduced in this paper.

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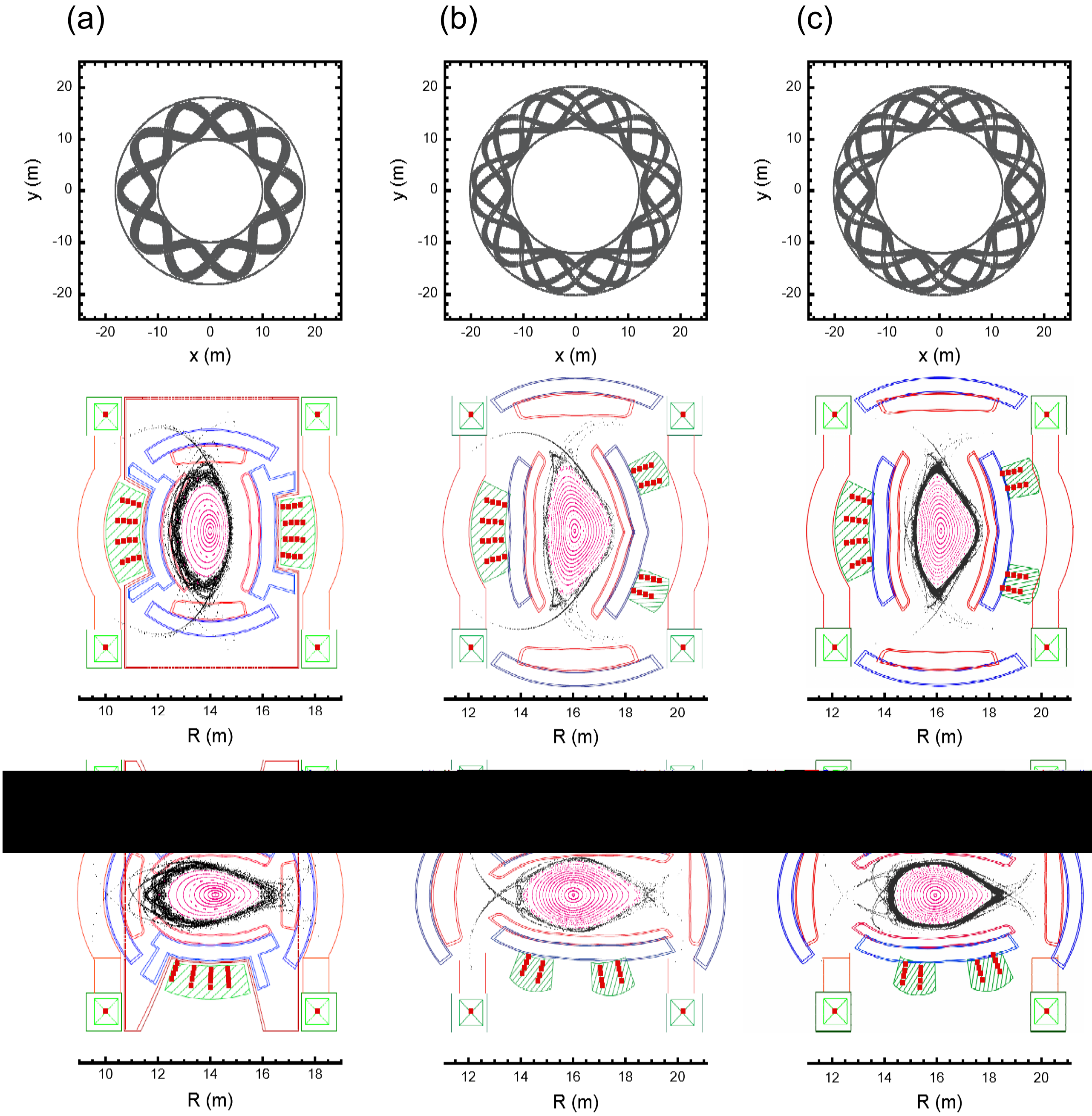

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Fig.1 Plan views of the coils and magnetic surfaces at two cross-sections for (a) FFHR-2m1, (b) FFHR-2S (γ = 1.0, α = +0.1) and (c) FFHR-2S (γ = 1.0, α = -0.1). The coil currents are assumed by 16 filaments in one helical coil. For splitting a helical coil, the half portion of the coil is assumed by 8 filaments.

2. Vacuum magnetic surfaces of FFHR-2S and their properties

Using the remarkable properties of improving the helical symmetry by splitting the helical coils in the poloidal cross-sections, new magnetic configurations were surveyed. However, it was found that the ergodic layers could not be easily removed from the blanket area at the inboard side by simply splitting the helical coils while maintaining the original pitch parameter of γ = 1.15. In order to overcome this difficulty, we newly found that a drastically larger gap is obtained by reducing the pitch parameter to be as low as γ = 1.0 together with splitting of the helical coils. Figure 1(b) and (c) show examples of the vacuum magnetic surfaces with γ = 1.0 configurations. Two examples are shown with the pitch modulation parameter α of +0.1 and –0.1. The major radius is 16.1 m for both cases by keeping the minor radius of the helical coils to be 3.22 m, the same as that for FFHR-2m1. As is seen in these figures, the outermost ergodic layers are clearly displaced from the blankets. Here, the shapes and the positions of the blankets are adjusted in these figures in order to avoid any interference.

Here we should note that such a low pitch parameter of γ = 1.0 has never been examined so far, as it has been well known that one is already in the so-called forbidden-zone for generating magnetic surfaces with a *l* = 2 heliotron configuration [6]. We understand that the low pitch parameter is effective for making the ergodic layers compact, while the splitting of helical coils ensure larger closed magnetic surfaces. Figure 2 shows the distance between the helical coils and the ergodic layers. The magnetic configuration of FFHR-2m1 has an interference with the blankets unless it is with a much larger major radius. For FFHR-2S, much wider space is assured with a smaller major radius. Here it is assumed that the distance between the helical coils and vacuum vessel is constant at 110 mm, which is the same as that for LHD.

The basic physical quantities of the vacuum magnetic surfaces are evaluated, such as the rotational transform and specific volume as a function of the average minor radius. The radial variation of the rotational transform is shown in Fig. 3(a). Even with the lower pitch parameter, a larger plasma minor radius is expected for FFHR-2S. At the same time, a larger shear of the rotational transform is expected, which is good for MHD stability. On the contrary, the specific volume shows that a magnetic hill is formed all over the magnetic surfaces. It is expected that magnetic well is introduced by the plasma beta and this should be calculated in our future study. It should also be stressed, on the other hand, that by having a smaller pitch parameter, the helical coils experience less electromagnetic forces, which is one of the fundamental benefits of the FFHR concept [3].

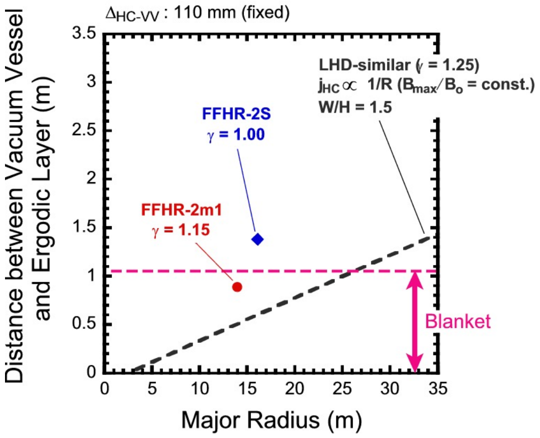

Fig.2 Distance between the vacuum vessel and the ergodic layers of magnetic field lines for FFHR-2m1 and FFHR-2s.

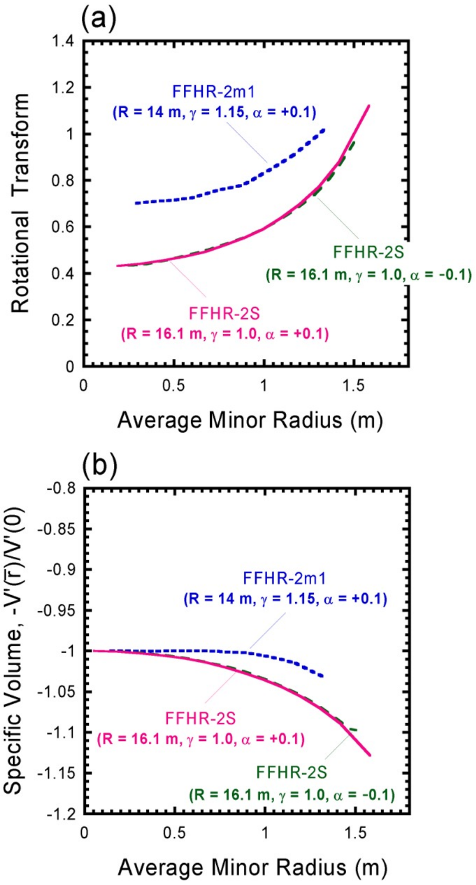

Fig.3 (a) Rotational transform and (b) specific volume for FFHR-2m1 and FFHR-2S with α = +0.1 and –0.1 as a function of the average minor radius.

3. Drift orbits of helically trapped particles

One of the important properties of magnetic configuration for helical devices is the particle orbits especially in terms of the direct loss of particles trapped in helical mirrors. Another advantage of the new configuration of FFHR-2S is found with its particle orbits for the pitch modulation parameter α of –0.1. A comparison of the orbits of perpendicularly injected deuterons is given for FFHR-2m1 and FFHR-2S in Fig. 4. As is always observed for conventional heliotron configurations such as LHD, the drift orbits of the helically trapped particles are shifted inward compared to the magnetic surfaces (with the magnetic axis at the center of the helical coils) as is seen in Fig. 4(a) for FFHR-2m1. The drift orbits for FFHR-2S has a similar tendency for the particles starting from the core region, however, the confinement of particles are better up to the plasma periphery, as is seen in Fig. 4(b).

In order to clarify the difference about particle orbits, the helical ripples are compared for the two configurations. Figure 5 shows the variation of the magnetic field strength along magnetic field lines. Compared to FFHR-2m1, the helical ripples in FFHR-2S are mitigating the toroidal ripples, which lead to the better confinement of helically trapped particles. Figure 6 shows the variation of the amplitude of the helical ripples as a function of the minor radius. The helical ripple of FFHR-2S is almost the same as that for FFHR-2m1 near the magnetic axis, however, it remains less than half at a larger minor radius. The small helical ripple should contribute in a better confinement of plasma not only in terms of neoclassical transport but also of anomalous one.

4. Conclusions

A new magnetic configuration for the LHD-type fusion energy reactor FFHR is examined by splitting the helical coils in the poloidal cross-section. It was found that by employing a low pitch parameter of γ = 1.0, a large clearance is obtained between the ergodic layers and blankets. This configuration with a negative pitch modulation parameter of α = -0.1 has good properties for the drift orbits of helically trapped particles. The optimization of the coil configuration is being carried out also from the engineering viewpoint.

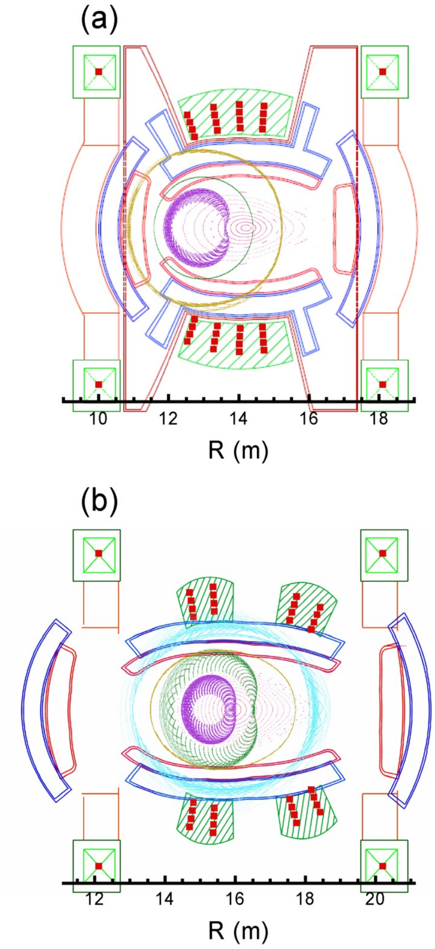

Fig.4 Drift orbits of deuterons for (a) FFHR-2m1 and (b) FFHR-2S. Deuterons with 500 keV energy are injected with a pitch angle of 90 degrees at various locations on the magnetic surfaces.

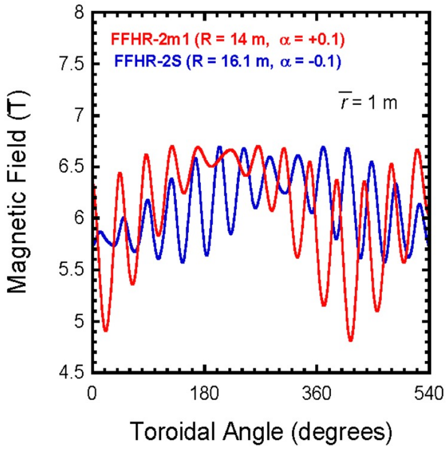

Fig.5 Variation of the magnetic field strength along the field lines for FFHR-2m1 and FFHR-2S (α = -0.1) on the magnetic surfaces having the average minor radius of 1 m for both cases.

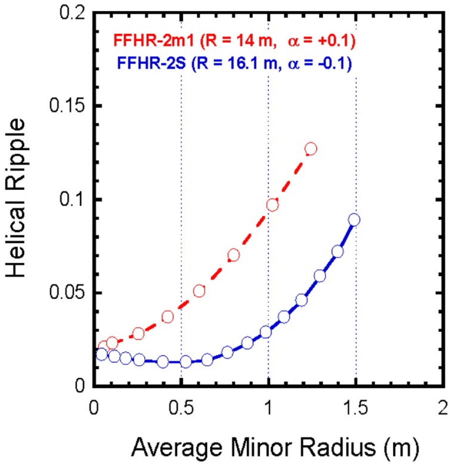

Fig.6 Variation of helical ripples as a function of the average minor radius for FFHR-2m1 and FFHR-2S (α = -0.1).

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