Heat Flux Reduction by Helical Divertor Coils in the Heliotron Fusion Energy Reactor

N. Yanagi 1), A. Sagara 1), T. Goto 1), S. Masuzaki 1), T. Mito 1), G. Bansal 2), Y. Suzuki 1), Y. Nagayama 1), K. Nishimura 1), S. Imagawa 1) and O. Mitarai 3)

1) National Institute for Fusion Science, 322-6 Oroshi-cho, Toki, Gifu 509-5292, Japan
2) Institute for Plasma Research, Bhat, Gandhinagar, Gujarat 382-428 India
3) Tokai University, 9-1-1 Toroku, Kumamoto 862-8652, Japan

E-mail contact of main author: yanagi@LHD.nifs.ac.jp

Abstract. In order to best utilize the built-in helical divertors in the heliotron-type fusion energy reactor, we propose a new divertor sweeping scheme which could effectively reduce the divertor heat flux and mitigate the erosion of divertor plates. The concept employs a small set of helical coils, which we call the "helical divertor coils". It is found that the divertor legs can be moved effectively by modulating the amplitude of the current in the helical divertor coils by ±2 % of the amplitude in the main helical coils. Despite the movement of divertor legs, the magnetic surfaces show almost no change with this scheme. The width of strike points is enlarged to ~800 mm and a fast sweeping reduces the heat flux < 1 MW/m^2 on time average having the total power flow of ~600 MW to the divertor regions with a 3 GW fusion power. Erosion of divertor plates would also be mitigated and the replacement cycle could be significantly prolonged. Regarding the engineering design of the helical divertor coils, we propose that these coils be fabricated using YBCO high-temperature superconductors. The coils could be constructed with prefabricated segments and jointed on site.

1. Introduction

Based on the progress of high-density and high-temperature plasma experiments in the Large Helical Device (LHD) [1], conceptual design studies on the heliotron-type fusion energy reactor FFHR are being conducted on both physics and engineering issues [2]. In the design of FFHR, the divertor is one of the biggest issues as in the design of tokamak reactors. It is expected that the heat flux through the divertor legs in FFHR will reach up to 10 MW/m^2, and therefore, realization of a detached plasma should be considered as a key issue to mitigate the engineering requirement on divertor tiles [3]. As an alternative method, in tokamaks, enlargement of magnetic flux tubes in divertor layers is proposed such as the "Super-X divertor" concept [4].

Another method to alleviate the heat flux on divertors is to make a temporal sweeping of strike points, which has been proposed for tokamaks, and for example, implemented in JET [5]. In heliotron configurations, two methods of divertor sweeping were previously proposed for LHD. One is to change the poloidal coil currents, or resultantly, the magnetic axis position. This scheme has been effectively applied to support the steady-state experiments in LHD, and the world record of 1.6 GJ injection energy was successfully attained [6]. Though this scheme has been proven to be effective for LHD with still limited power, it could not give a sufficient sweeping capability for reactors with high power such as FFHR unless the magnetic axis is shifted over a substantial distance. In this case, the magnetic configuration, and resultantly the plasma volume, is seriously altered and the fusion output power changes substantially. The other scheme for divertor sweeping is to change the minor radius of the current center in the helical coils [7]. However, this scheme is effective only when the current center is significantly changed, and then it also alters the confining magnetic configuration and plasma volume. At the same time, the engineering concerns with these two schemes are the generation of AC losses in the poloidal coils as well as in the helical coils. The changes of electromagnetic loads both in these coils are also of serious concerns.

In order to overcome the difficulties observed in these divertor sweeping schemes and to best utilize the built-in helical divertors in FFHR, in this paper, we propose a new sweeping scheme which could effectively reduce the divertor heat flux and mitigate the erosion of divertor plates without altering the fusion power.

2. Helical divertor coils for FFHR

The new concept employs a small set of helical coils, which we call the “helical divertor coils”, at both sides of the main helical coils. Figure 1 shows a plan view of the coil system of the presently designed heliotron reactor, FFHR-2m2, including the helical divertor coils. It is noted that the winding path of a helical divertor coil is defined as that of a split-type helical coil [8]. Figure 2 shows the vacuum magnetic surfaces of FFHR-2m2. We note that the magnetic axis is shifted inward in order to obtain good particle confinement like the standard configuration of LHD. The major and minor radii of the main helical coils are 16.74 m and 4.02 m, respectively. One of the remarkable features of the heliotron configuration is that clear divertor legs (that reach the divertor plates in Fig. 2) appear out of the confining region and their structures are not seriously affected by plasma beta or toroidal plasma current. It is also strongly emphasized that the divertor plates are effectively shielded by breeder blankets from the direct irradiation of neutrons emitted from the core plasma.

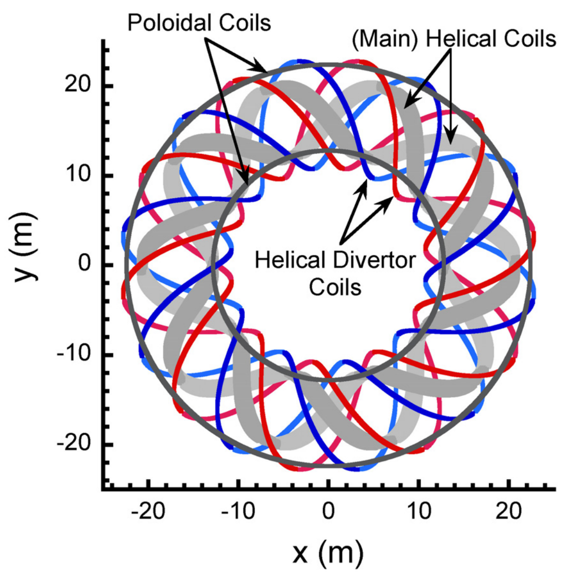

FIG. 1. Plan view of the coil system of FFHR-2m2 including the helical divertor coils.

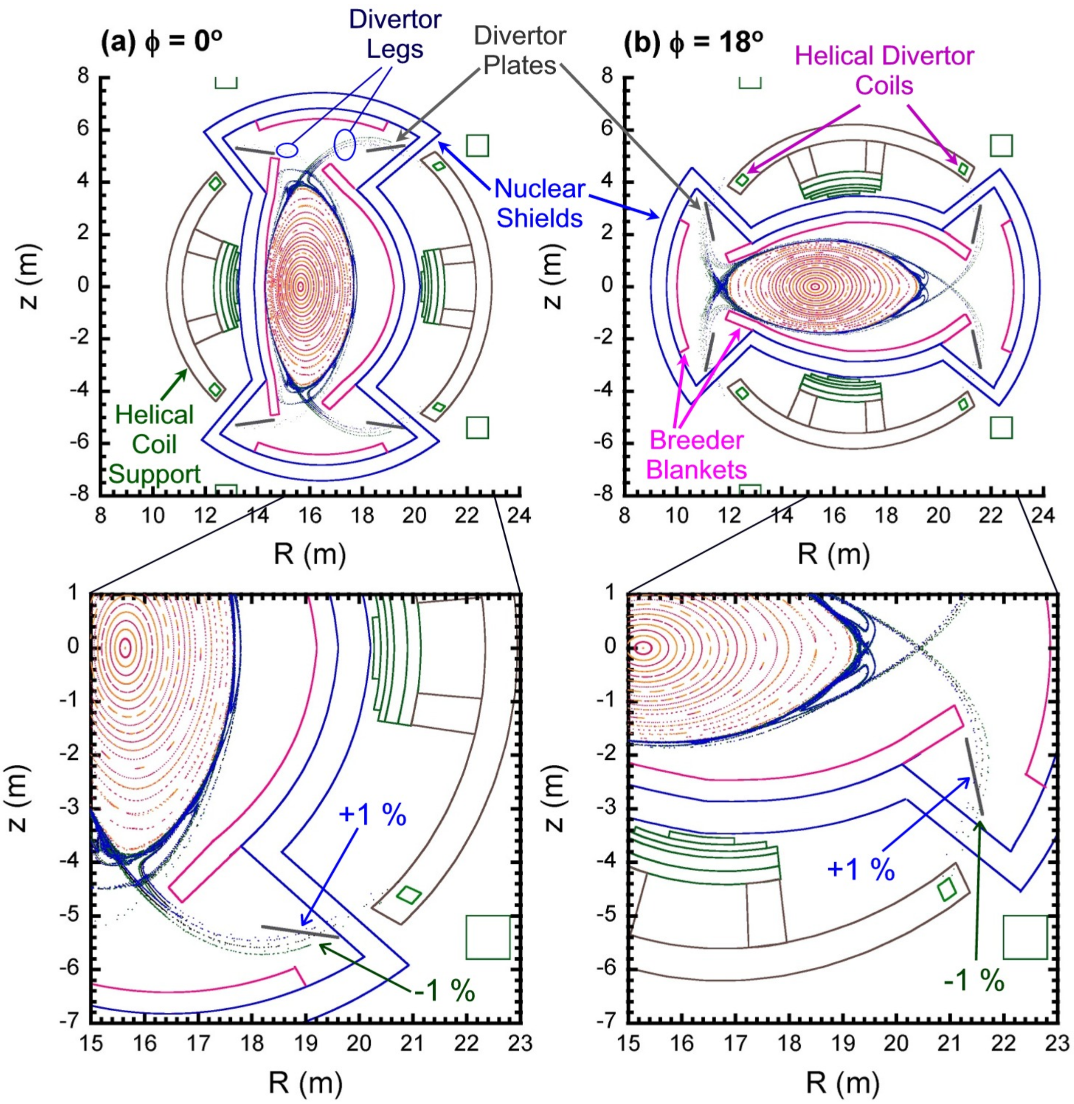

FIG. 2. Vacuum magnetic surfaces and divertor legs of FFHR-2m2 at two toroidal cross-sections of (a) ϕ = 0° and (b) 18°, including the field changes provided by the helical divertor coils.

In Fig. 2, the field changes provided by the helical divertor coils are also included, and it is found that the divertor legs can be moved effectively by modulating the amplitude of the current in the helical divertor coils by ±1 % of the amplitude in the main helical coils. As shown in Fig. 2, inclining the divertor plates against the divertor legs enlarges the width of strike points to ~800 mm. Since the total length of four divertor legs is ~900 m along the torus, the wetted area would be ~700 m^2. If a fast sweeping is realized, the effective heat flux would then be < 1 MW/m^2 on time average having the total power flow of ~600 MW to the divertor regions with a 3 GW fusion power. Erosion of divertor plates would also be mitigated even with slow sweeping and the replacement cycle could be significantly prolonged. It should be emphasized that despite the movement of divertor legs, the magnetic surfaces show almost no change with this scheme. This is similar to the situation realized in JET [5].

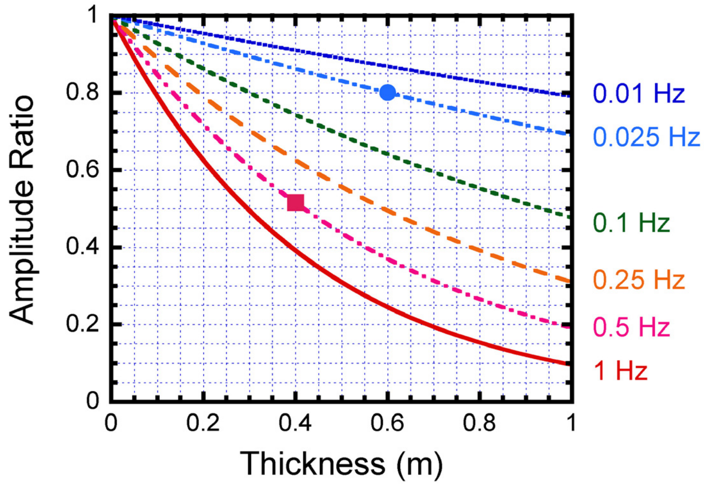

FIG. 3. Amplitude ratio of magnetic field strength reduced by the skin effect in stainless-steel as a function of thickness with various frequencies.

3. Required current change in the helical divertor coils

For employing the divertor sweeping, it is essential to determine the necessary frequency, or the repetition time of sweeping. We here consider two cases of frequency for operating the helical divertor coils: 0.5 Hz and 0.025 Hz, which have the repetition period of 2 s and 40 s, respectively. We note that a big problem is the reduction of the alternating magnetic field strength due to the skin effect in the nuclear shield located near the helical divertor coils. As is well known, the amplitude ratio η is given for the reduction of magnetic field with a thickness d of metal as

$$\eta = \exp\left(-d/\delta\right)$$

where the skin depth is expressed by

$$\delta = \sqrt{\omega\mu/2\rho}$$

and ω is the angular frequency, μ is the magnetic permeability and ρ is the resistivity of the metal. If the resistivity of stainless-steel is used, the amplitude ratio is shown in Fig. 3 as a function of thickness. For example, if we use a 0.4 m thick shield and employ a 0.5 Hz frequency of sweeping, the skin effect reduces the magnetic field to be half. This means that making a ±1 % amplitude of field change in Fig. 2 requires a ±2% amplitude in the current of the helical divertor coils. On the contrary, for 0.025 Hz frequency, the nuclear shield of 0.6 m thickness still maintains 80% amplitude of the field change. This seems beneficial for the engineering design of the helical divertor coils. However, the slow frequency may induce a large temperature change in divertor tiles, and thus, the thermal fatigue should become a serious problem, which is examined in the following section. On the other hand, another choice is to employ quasi steady-state sweeping only for the purpose of mitigating the erosion of divertor plates. In this case, the thickness of the nuclear shields is not a problem.

4. Temperature distribution in divertor tiles

In order to analyze the temperature rise of the divertor tiles under a temporal sweeping of divertor strike points, we hereby estimate the evolution of temperature distribution by analytically solving the one-dimensional heat diffusion equation. We consider a slab geometry of thickness L along the coordinate z, and then the temperature evolution $T(z,t)$ is governed by the following heat diffusion equation as a function of time t:

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(k \frac{\partial T}{\partial z} \right),$$

where ρ is density, k is thermal conductivity, C_p is specific heat. If we assume that k is uniform over a concerning temperature region, the diffusion equation is simplified to be

$$\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial z^2}, \tag{1}$$

where $\kappa = k/\rho C_p$ is the heat diffusivity. In the present problem, two boundary conditions are given: one is that a constant heat flux q_0 is applied to the surface at $z = 0$ from $t = 0$ to t_0, which is expressed as

$$-k \left. \frac{\partial T}{\partial z} \right|_{z=0} = q_0 \left\{ 1 - H(t - t_0) \right\},$$

where $H(t\text{-}t_0)$ is a Heaviside function defined as

$$H(t - t_0) = \begin{cases} 0 & (t < t_0) \\ 1 & (t \ge t_0) \end{cases}.$$

The other boundary condition is that the temperature at the other end $z = L$ is kept constant, such as by water cooling, so that

$$T(z = L) = T_0.$$

The initial condition is given that the base temperature is uniform over the whole region:

$$T = T_0.$$

Then, Eq. (1) can be analytically solved using the Laplace transformation technique, such as applied for solving the magnetic/current diffusion problem in a pure aluminum conductor [9]. The solution is expressed as

$$\begin{aligned} T(z,t) = {} & \frac{q_0 L}{k} \left\{ \frac{L-z}{L} - 8 \sum_{n=0}^{\infty} \frac{\sin \frac{L-z}{L} \frac{2n+1}{2} \pi}{(-1)^n (2n+1)^2 \pi^2} \mathrm{e}^{-\frac{(2n+1)^2}{4\tau} \pi^2 t} \right\} \\ & - \frac{q_0 L}{k} \left\{ \frac{L-z}{L} - 8 \sum_{n=0}^{\infty} \frac{\sin \frac{L-z}{L} \frac{2n+1}{2} \pi}{(-1)^n (2n+1)^2 \pi^2} \mathrm{e}^{-\frac{(2n+1)^2}{4\tau} \pi^2 (t-t_0)} \right\} H(t-t_0) + T_0 \end{aligned} . \tag{2}$$

Here τ is given as $\tau = L^2/\kappa$, and the effective time constant of the heat diffusion process is evaluated by the $n = 0$ term in Eq. (2) as $\tau_0 = 4\tau/\pi^2$.

We now assume that Tungsten will be selected for the divertor tiles in FFHR, and the following parameters are used as representative values: ρ = 19250 kg/m3, k = 120 W/m/K, C_p

= 140 J/kg/K. The thickness of the tiles is assumed to be L = 8 mm. Then, the time constant τ_0 is evaluated to be ~0.7 s.

In the 0.5 Hz frequency case, we crudely estimate that the repetition time of the heat flux at an edge region is ~2 s while the irradiation time is ~0.1 s. This is because the total width of the divertor plate is ~800 mm while the effective width of the divertor leg is estimated to be ~80 mm, according to the measured width of ~20 mm in LHD [10]. If the sweeping frequency is 0.025 Hz, the repetition rate is ~40 s and the irradiation time is ~2 s. For both cases, we assume that the heat flux of 10 MW/m^2 is applied at z = 0 surface during the irradiation time. Then, Eq. (2) gives the temperature distributions at specified times, and the results are shown in Fig. 4. For the 0.5 Hz case, the temperature rise at the surface is ~200 K in 0.1 s of irradiation. Then, the cooling lowers the temperature to the initial temperature before the next heat pulse. So the temperature change during the sweeping is ~200 K. On the other hand, a larger temperature change of ~650 K is expected for the 0.025 Hz case. For both cases, we assume that the temperature at z = L is kept constant throughout the process. This could be realized by flowing the cooling water in the direction parallel to the sweeping of strike points. More precise analysis using the finite element method will have to be done to investigate the temperature distribution and thermal stresses in divertor tiles, which will be our future studies.

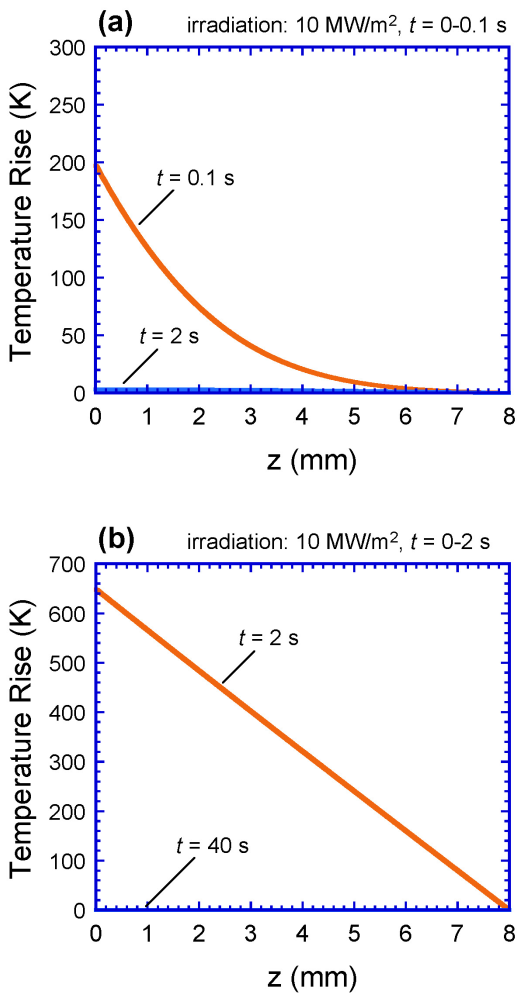

FIG. 4. Temperature distribution of a Tungsten slab solved by the one-dimensional heat diffusion equation. A 10 MW/m^2 of heat flux is applied to z = 0 mm surface at (a) 0-0.1 s and (b) 0-2 s.

5. Engineering design of the helical divertor coils

Regarding the engineering design of the helical divertor coils, we consider that they could be situated in the supporting structures of the main helical coils as shown in Fig. 2. In the present design of FFHR-2m2, the total current in the main helical coil is 37.9 MA, and the ±2% amplitude requires the current in the helical divertor coils of ~±750 kA to realize the divertor sweeping with a 0.5 Hz frequency. The total current of 750 kA would be supplied by 25 turns of 30 kA conductors.

We propose that these coils be fabricated using high-temperature superconductors (HTS) represented by YBCO. It is noted that we have initiated conceptual design studies on applying HTS also to the main helical coils [11, 12], and short sample tests of reduced-scale conductors are being carried out [13, 14]. The helical divertor coils could be constructed with prefabricated segments and jointed on site [8, 12]. The losses in the coils generated at joints and by AC operations are expected to be of no serious concern with elevated temperatures at 60 K or higher. In order to reduce the AC losses, a Roebel-type conductor [14] could be considered as a good candidate. Evaluation of hysteresis losses and the related cooling method will be our future studies.

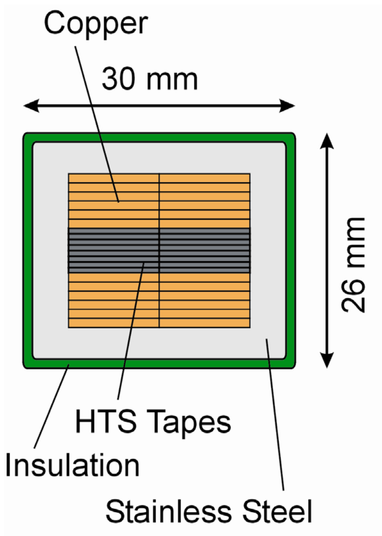

FIG. 5. Design of HTS conductor for the helical divertor coils. At the HTS bundle, transposition could be introduced with a Roebel-type cable.

7. Conclusions

In order to best utilize the built-in helical divertors in FFHR, we propose a new divertor sweeping scheme which could effectively reduce the divertor heat flux and mitigate the erosion of divertor plates. The concept employs a small set of helical coils, which we call “helical divertor coils”. Alternating the currents in these coils within a few percent of amplitude of that in the main helical coils effectively sweeps the strike points on the divertor plates in the poloidal direction. Despite the movement of divertor legs, the magnetic surfaces show almost no change with this scheme. The width of strike points is enlarged to ~800 mm and a fast sweeping reduces the heat flux < 1 MW/m2 on time average having the total power flow of ~600 MW to the divertor regions with a 3 GW fusion power. If a 0.5 Hz frequency of sweeping is employed, the required coil current would be doubled since the skin effect reduces the magnetic field to be half assuming a 0.4 m thick nuclear shielding near the divertor areas. In this case, the temperature rise at the divertor surface is estimated to be ~200 K based on the one-dimensional heat diffusion analysis. Regarding the engineering design of the helical divertor coils, we propose that these coils be fabricated using YBCO high-temperature superconductors. The coils could be constructed with prefabricated segments and jointed on site.

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