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Engineering design of helical divertor coils for the heliotron-type fusion energy reactor

ヘリオトロン型核融合炉における熱流束低減用ヘリカルダイバータコイルの工学設計

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To best utilize the built-in helical divertors in the heliotron-type fusion energy reactor, we propose a new divertor sweeping scheme that reduces both the divertor heat flux and erosion of divertor plates. This scheme employs a set of helical divertor coils (HDC) and the current amplitude in the HDC is modulated by a few percent of that of the main helical coils. The strike point width is effectively increased while keeping the core plasma unchanged, and rapid sweeping (~0.5 Hz) reduces the time-averaged heat flux to <1 MW/m^2. The HDC is fabricated using YBCO high-Tc superconductors joined with half-pitch segments.

1. Introduction

As the result of progress in high-density and high-temperature plasma experiments conducted at the Large Helical Device (LHD), conceptual design studies are being carried out for the heliotron-type fusion energy reactor FFHR [1]. A remarkable feature of the heliotron magnetic configuration is that clear divertor legs protrude from the confining region, and their structures are not seriously affected by the plasma beta or the toroidal plasma current. The breeder blankets effectively shield the divertor plates from direct irradiation by neutrons emitted from the core plasma, which assures a significant advantage to solve the engineering problems.

As is the case with tokamak reactor design, the divertor is a serious concern in the engineering design of FFHR. The heat flux through the divertor legs in FFHR is expected to reach up to ~10 MW/m^2. Thus, the realization of detached plasma is considered to be crucial for reducing the engineering requirements on divertor plates. As an alternative method, we have proposed a new strike point sweeping scheme that effectively reduces the time-averaged heat flux and the erosion of divertor plates.

2. Helical Divertor Coils

The new scheme employs a small set of helical coils, which we term helical divertor coils (HDC) on both sides of the main helical coils [2]. Figure 1 shows the vacuum magnetic surfaces of FFHR-2m2 including the field changes provided by the HDC, and the divertor legs show remarkable spreads.

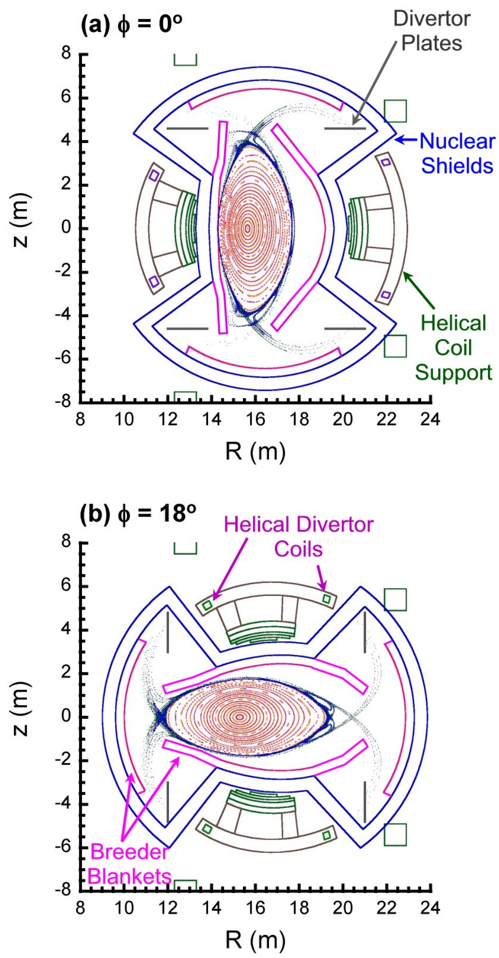

Fig.1. Vacuum magnetic surfaces and divertor legs of FFHR-2m2 for two toroidal cross-sections at (a) $\phi = 0°$ and (b) 18°. The field changes provided by the HDC are included, which spread divertor legs and strike points.

In Fig. 1, the current amplitude in the HDC is modulated by ±2% of that of the main helical coils. The width of the strike points is enhanced to ~800 mm with a total length of the four divertor legs of ~900 m along the torus. Although there is some non-uniform loading of the divertor flux along the torus, the effective wetted area is estimated to be >600 m^2. If a rapid sweeping is realized, the time-averaged heat flux will then be <1 MW/m^2 with a total power flow of ~600 MW to the divertor regions for a fusion power of 3 GW. Note that there is no assumption of increased radiation along the divertor legs. Erosion of divertor plates will be reduced even for slow sweeping allowing the replacement cycle to be significantly lengthened. Despite the movement of the divertor legs, the magnetic surfaces are almost unaffected by this scheme.

3. Engineering Design

For the strike point sweeping, we here consider a sweeping frequency of 0.5 Hz for the HDC. A problem is the reduction in the alternating magnetic field strength due to the skin effect in the nuclear shield near the HDC. We estimate that the amplitude is reduced to half with a 0.4 m-think nuclear shield for 0.5 Hz frequency. Thus, the current amplitude in the HDC should be ±4% of that of the main helical coils.

3.1 *Temperature change of divertor plates*

A concern with divertor strike point sweeping is thermal fatigue of divertor plates. For a sweeping frequency of 0.5 Hz, we crudely model that the mean repetition time of heat pulse application at the reversal points on both ends of the divertor plate to be ~2 s. The irradiation time is modeled to be ~0.1 s for a heat pulse. This is because the total width of the divertor plate is ~800 mm, while the effective width of the strike point is estimated to be ~80 mm, according to the measured width of ~20 mm in LHD [3]. As is shown in Fig. 2, no temperature gradient is observed at the cooled end of a 8-mm plate for a sweeping frequency of 0.5 Hz.

3.2 *Superconducting coils*

The maximum current of the HDC is ±1.5 MA in the present design and this could be supplied by 50 turns of 30 kA conductors. We propose that the HDC be fabricated using high-Tc superconductors (HTS) and be operated at temperature 20 K or higher. As is considered for the main helical coils, the HDC could be fabricated by joining half-pitch conductors with stacks of YBCO tapes [4]. The AC losses are examined and the maximum temperature rise is estimated to be ~10 K for a ±3 T change of magnetic field at 0.5 Hz sweeping frequency, which is still acceptable for HTS.

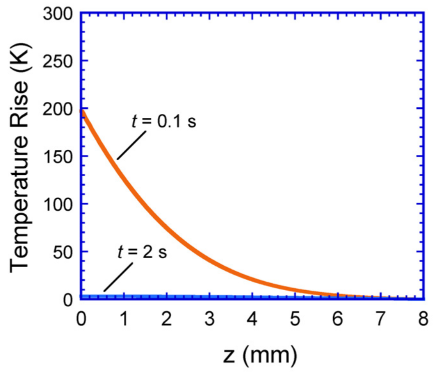

Fig.2. Temperature distribution in a divertor plate made of tungsten by solving the 1-D heat diffusion equation at times of t = 0.1 and 2 s with a heat flux of 10 MW/m^2 applied to the z = 0 mm surface during t = 0-0.1 s.

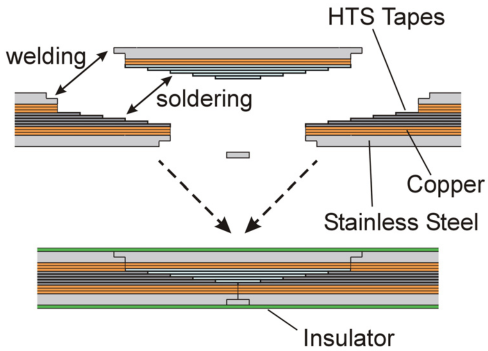

Fig.3. Illustration of the YBCO-HTS conductor joint.

4. Summary

To reduce the divertor heat flux and erosion of divertor plates in FFHR, we are proposing a new divertor sweeping scheme using a set of HDC. Thermal fatigue on divertor plates is expected to be of no serious concern with a rapid sweeping of ~0.5 Hz. The HDC could be fabricated using YBCO-HTS conductors. To solve the problems associated with AC operations, we are also pursuing the configuration modification realized in the steady-state, like the Super-X divertor considered for tokamaks [5].

References

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