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The New Helical Plasma Device at IAE, Kyoto University

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Abstract

Studies of the confinement optimization of heliotron such as Heliotron E have led to the concept of "helical-axis heliotron" which is characterized by reduced neoclassical transport and enhanced beta limit with small bootstrap current. Based on these novel theoretical results, the $L=1$ helical-axis heliotron experiment is being planned at the Institute of Advanced Energy, Kyoto University, with a goal of demonstrating the capability of this confinement line. The related physics and engineering design issues are discussed.

Keywords:

advanced helical system, helical-axis heliotron, bumpy field, plasma-energy complex system, advanced fusion material

1. Introduction

As the post Heliotron-E device, a new plasma device is proposed at IAE in order to carry out the research for the advanced helical system and the development for the advanced fusion materials. A high degree of flexibility of plasma operation for the studies of plasma-material interactions as well as the magnetic configuration studies is required for the device design. In addition, the design must meet the following purposes of the Institute project: (i) to find out the universal principles underlying magnetic plasma confinement from the viewpoint of a complex physical system and to achieve necessary improvements in energy transport, (ii) to find out the methodological approaches for understanding the synergetics of energy conversion in the areas of plasma and material science and to improve the relevant energy conversion efficiencies, and (iii) to find out new kinds of experimental manipulation and testing for material synthesis by using composite particle beams and to explore the techniques for fabricating the advanced fusion materials. The system is planned to be a combination of the new plasma device and the material processing device. This paper reviews the physics and engineering design issues of the plasma device.

2. Physics Design

2.1 Critical issues for heliotron development

A goal of the new helical plasma device is to study

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some of the critical issues relating to the feasibility of heliotron line as an attractive steady-state reactor. From this viewpoint, the new device aims at (1) the improved high-energy particle confinement, (2) the higher beta capability (MHD stability), and (3) the advanced particle and power handling (divertor). However, it is not so easy to settle these critical issues simultaneously in the planar-axis helical system. In an effort to enhance the performance of the planar-axis heliotron, the Heliotron-E experiments faced a difficulty in the full compatibility of good high-energy particle confinement with MHD stability[1].

2.2 Design criteria for helical-axis heliotron

The helical-axis heliotron is intended to clear away the constraint of planar axis, thus creating the vacuum magnetic well in the whole confinement region by using an advanced three-dimensional magnetic axis[2]. To ensure the compatibility of good particle confinement with MHD stability, its configuration provides a new scheme for drift optimization using a near-straight magnetic axis at the field strength minimum in which the deeply trapped particles remain close to the magnetic surface due to their minimized grad B and curvature drifts. Thus, the design criteria are based on the different principle from that of the quasi-symmetry device in which the purity of symmetry in the configuration is requested by using modular coils. Furthermore, the device assembly using a continuous helical coil secures an advantage of a large access to the plasma on the outside, top, and bottom for the divertor physics and materials-handling studies.

2.3 A new parameter for physics design

The design parameters of the proposed device are as follows: the major plasma radius of 1.2 m, the average plasma radius of 0.15 ~ 0.20 m, and the field strength on magnetic axis of 1 ~ 1.5 T, with heating systems such as 0.5 MW-ECH, 1.5 MW-NBI, and 2.5 MW-ICRF. Schematic of the device is shown in Fig. 1. The device provides a new configuration parameter, *i.e.* the bumpiness (ϵ_b) in the magnetic field spectrum, where the magnetic field $B(r, \theta, \varphi)$ is modeled as:

$$\frac{B(r, \theta, \varphi)}{B_0} = 1 - \epsilon_b \cos(M\varphi) - \epsilon_t \cos\theta - \epsilon_h \cos(L\theta - M\varphi) \qquad (1)$$

Here r is the plasma radius; θ and φ are the poloidal and toroidal angles; $L=1$ and $M=4$ are the polarity and the pitch number of the helical coil; B_0 the magnetic field on magnetic axis; ϵ_t the toroidicity; ϵ_h the helicity. Figure 2 shows an example of ϵ_b, ϵ_t, and ϵ_h as a function of radius. By the introduction of ϵ_b, the neoclassical ripple transport in the $1/\nu$ regime can be improved down to the plateau level of the equivalent tokamaks under the condition of $\epsilon_b/\epsilon_h < 0$ [3,4]. As shown in Fig. 3, furthermore, the ripple transport for the parameters in Fig. 2 is found to be a factor 3 smaller than that of Heliotron E on the basis of the transport integral S given by K.C. Shaing and S.A. Hokin[5]. Besides the transport improvement, the introduction of ϵ_b can also provide enough flexibility to control the extent and direction of bootstrap current that can be a problem for zero-net-current operation at low collisionality. As for MHD characteristics, the

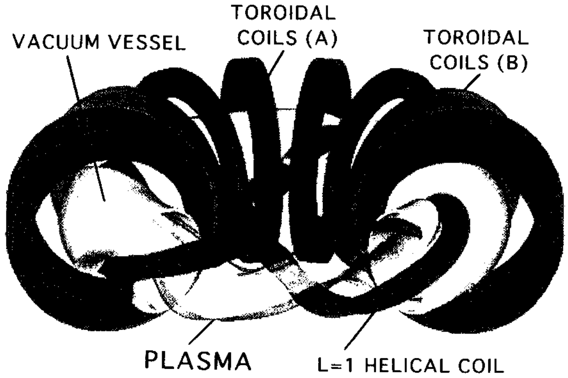

Fig. 1 Schematic of the device.

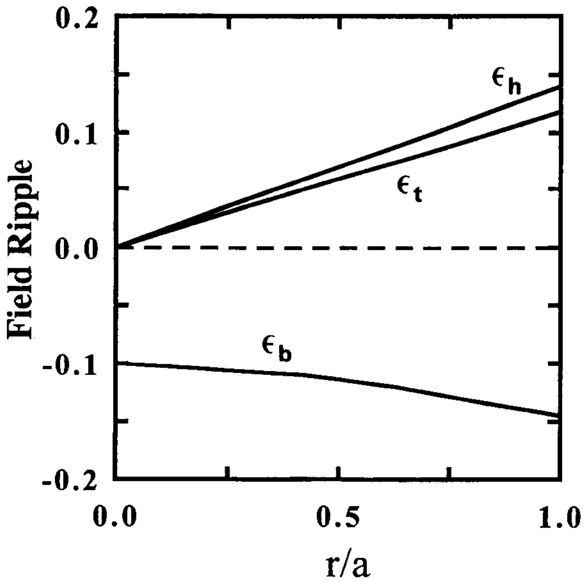

Fig. 2 Field ripples, ϵ_b, ϵ_t, and ϵ_h, for a vacuum magnetic field of $L=1$ helical-axis heliotron.

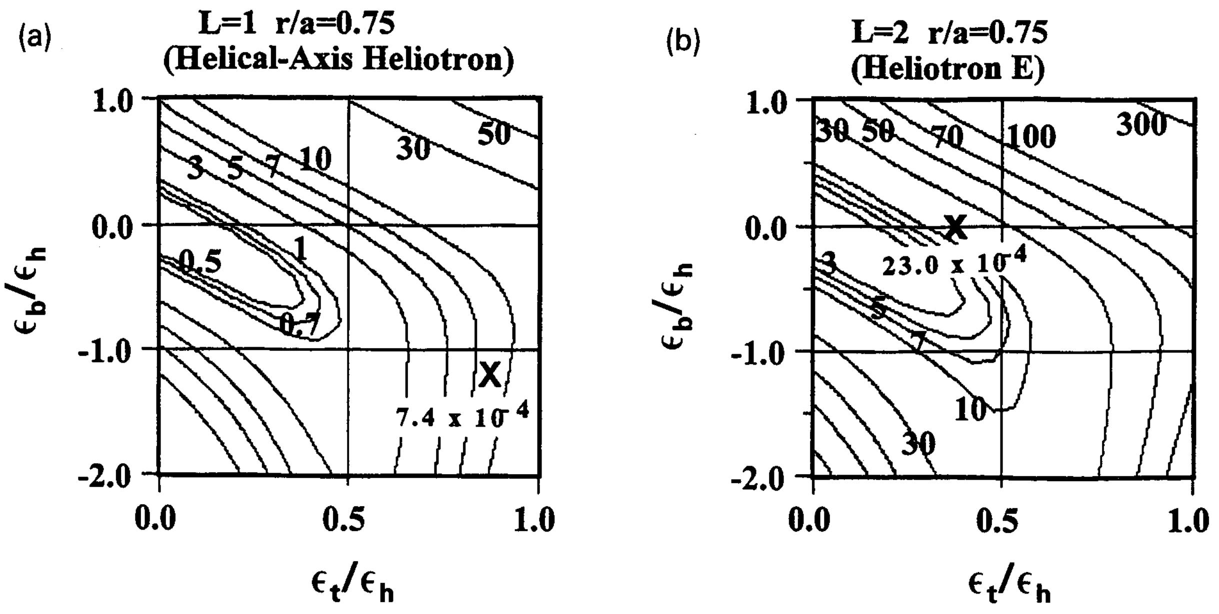

Fig. 3 Comparison of the contour plot of the transport integral S, given in Ref.[5], between (a) L = 1 helical-axis heliotron and (b) Heliotron E. The mark (x) shows each operation point, 7.4×10^{-4} for (a) and 23.0×10^{-4} for (b), at the reference plasma radius of $r/a = 3/4$.

equilibrium beta limit of 4 % is determined by the Shafranov shift owing to the relatively large Pfirsch-Schlüter current. It is also found that, due to the enhancement of magnetic well through the Shafranov shift, the MHD interchange instabilities (Mercier modes) can be stabilized up to the equilibrium beta limit. This value is a factor 2 higher than the stability beta limit of Heliotron E. On the other hand, the energetic orbit confinement is improved with an increase in beta. As for the divertor, the edge whisker field lines, *e.g.*, due to the $n=4/m=5$ islands, diverge from the outermost surface, affording a possibility of utilizing these field lines as the natural divertor[6].

3. Engineering Design

3.1 Helical coil

A continuous helical coil is wound on the torus with the following winding law:

$$\theta = \theta_0 + \frac{M}{L}\phi - \alpha \sin\left(\frac{M}{L}\phi\right) \qquad (2)$$

where $\theta_0(=\pi)$ is the initial constant of the poloidal angle; $\alpha(=-0.4)$ is the pitch modulation of the coil. A highly negative pitch modulation is selected to ensure the criteria of (i) $\epsilon_b/\epsilon_h < 0$ and (ii) edge magnetic well. The specification of the helical coil is that one helical winding, composed of three parallel conductors, carries the maximum current of 120 kA with 8 turns to produce a helical magnetic field on magnetic axis $B_{h\varphi 0}$ of about 0.6 T. To attain the accuracy of the coil position, a helical trough in the vacuum vessel serves as a firm guide for the coil winding.

3.2 Toroidal coils and poloidal coils

To control the bumpiness in the toroidal field, the two types of toroidal coils (A,B) are incorporated; the maximum magnetomotive forces are 600 kAT and 218 kAT, respectively, which excite the toroidal field on magnetic axis B_{t0} of about 1 T. As shown in Fig. 4, the increase in the ratio (α^*) of B_{t0} to $B_{h\varphi 0}$ causes (i) a decrease in the edge rotational transform $\iota(a)/2\pi$, (ii) a growth of the edge magnetic well $\delta_{well}(a)$, and (iii) a reduction of the effective bumpiness $<\epsilon_b>$. The drop of plasma radius, *a*, is governed by the rational values of $\iota(a)/2\pi$ that causes the destruction of the outer magnetic surfaces. It is found that there exists a trade-off between the deep magnetic well and the sufficient degree of bumpiness. However, other options such as the poloidal coil or the ratio of the two toroidal coil magnetomotive forces can also control the bumpiness. The poloidal coils, which are composed of the inner vertical coil (IV) and the auxiliary mid-vertical coil (AV) and the outer vertical coil (V), provide a number of useful multipole field components. The vertical component provides a shift of the plasma position, which changes the magnetic well depth as well as the bumpiness.

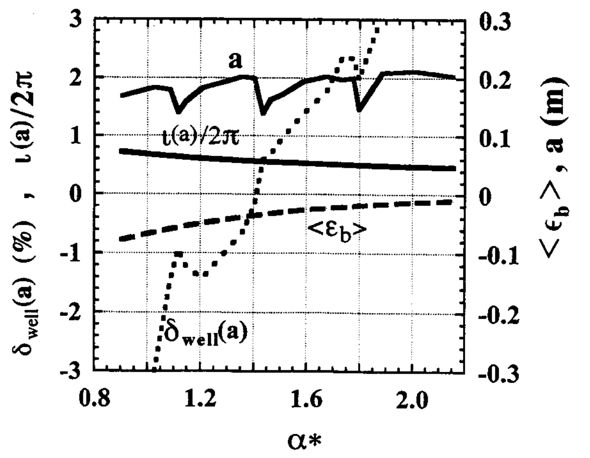

Fig. 4 Plasma radius a(m), edge rotational transform $\iota(a)/2\pi$, edge well depth $\delta_{well}(a)$ (%), effective bumpiness $<\epsilon_b>$ as a function of α^*, where $<\epsilon_b> = (B_{min} - B_{max})/(B_{min} + B_{max})$ and $\alpha^* = B_{t0}/B_{h\varphi0}$.

When beta increases, the use of the poloidal coils is a solution to prevent the breakup of the outer magnetic surfaces. The quadrupole component provides a change of plasma ellipticity, which influences the mod-B structure determining the characteristics of the drift surfaces for trapped particles.

3.3 Vacuum vessel

The vacuum vessel (SUS316) of magnetic permeability <1.1 is constructed from four torus elements for which the welding of one upper and one lower elements provides two half-torus elements. After winding of the helical coil on these half-torus elements, the two elements are joined together with introducing the toroidal coils. The insulated helical trough is NC machined while the minimum thickness of the wall is 20 mm. The vessel has 65 ports for pumping, diagnostics, and heating. The vessel weight is supported on a set of four sliding supports which allow (i) thermal expansion (2.4 mm at 100°C) of the vessel and withstand (ii) earthquakes of 0.3 G.

4. Summary

Design studies for a helical-axis heliotron with a highly modulated $L=1/M=4$ helical coil were generally satisfactory for providing a reliable approach to attack the problem of compatibility between good particle confinement and MHD stability in the helical system. The detailed optimization studies are now under way to increase flexibility of the confinement geometry and of the particle and power handling for use in the materials processing. Construction of the device is also inaugurated.

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