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Structure of the Edge Magnetic Field of the $\ell=1$ Helical-Axis Heliotron

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Abstract

The structure of the edge magnetic field of the $\ell=1$ Helical-Axis Heliotron, which is designed at the Institute of Advanced Energy, is numerically analyzed. In contrast to the Heliotron E case, the edge magnetic field structure of this low shear device is strongly affected by "natural-islands" such as $n/m=4/5$, $4/6$, $4/7$ or $4/8$ near the outermost magnetic surface. By changing the vertical field strength, we observe "wall-limiter", "island-divertor" and "local divertor" configurations.

Keywords:

advanced helical system, helical-axis heliotron, plasma edge control, magnetic island, divertor

1. Introduction

The design study of an $\ell=1$ helical-axis heliotron device is undertaken at Institute of Advanced Energy, Kyoto University [1] as one way to survey an advanced helical magnetic configuration for fusion plasma confinement.

One of the essentially required conditions for a plasma confinement device is capability of practical particle/heat handling (divertor). The most suitable divertor configuration for a confinement device strongly depends on the field structure in the edge region. The ideas of the divertor configuration proposed for the helical system up to now can be divided into two categories. One is the "helical divertor" where the flux bundles diverted from the core edge to the wall are used as divertor fields like the poloidal divertor in tokamaks. The second is the "island divertor" proposed for W7-X [2]. In this case, a chain structure of "natural" islands is used. The "local island divertor" proposed as one option of the divertor study in LHD [3] can be considered as a kind of "island divertor" with a low mode large island. It can be expected more advantage of "clean edge" by using a low mode resonance [4]. Several experiments for these ideas have been performed in several helical devices, independently [5-7]. Besides the necessity of experiments with full divertor function for each idea, the basic study is still required to clear up the characteristics of each divertor configuration.

Since one of the main objectives of the $\ell=1$ Helical-Axis Heliotron device is to study the configuration effect on the plasma confinement, the characteristics of the magnetic surface can be widely varied by the combination of coil-sets. The edge field structure can also have a wide variation. This will give us a good opportunity to study the effect of different edge structure on divertor function and core plasma confinement.

2. Device Parameter

The details of the design parameters of the $\ell=1$ Helical-Axis Heliotron device are reported in [1]. In

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short, the nominal major radius is 1.2 m, the minor radius of the highly modulated $\ell=1/M=4$ helical coil is 0.2 m and the averaged minor radius of the outermost magnetic surface is changed in the range of 0.1–0.2 m. The rotational transform with low shear is also variable in the range of 0.4–0.7. The coil system of this device is composed of one helical field coil (HFC), two toroidal field coil sets (TFC-A, TFC-B) and three pairs of poloidal field coils (VF, AV and IV). By changing the current ratio for these coils, the field configuration can be controlled in a wide range. The property of core plasma physics in this device is discussed in [8].

3. Characteristics of Edge Magnetic Fields

In this paper, the change of the field structure caused by β^*-scan is mainly studied, where $\beta^* = B_v/B_{t,HFC}$, the ratio of the vertical field strength to the toroidal field strength by HFC. The changes of the rotational transform, ι, and the averaged plasma radius, $<a>$, are plotted in Fig. 1 as a function of β^*, where only B_{AV} is scanned under a fixed condition of B_{VF}, B_{IV}, $B_{TFC\text{-}A}$, $B_{TFC\text{-}B}$ and B_{HFC}. As shown in the figure, the plasma radius becomes small near the resonance condition, $n/m=4/6$, $4/7$. Near the resonance of $n/m=4/8$, however, the moderate shear prevents reducing $<a>$ in this particular β^*-scan case.

The edge field lines are numerically traced without finite β-effect and plasma current effect. In general, the edge island affects the shape of the outermost magnetic surface (OMS). Figures 2(a)-2(b) show puncture-plots at a poloidal cross-section ($\phi=45°$) for two cases with different rotational transform. In Fig. 2(c), the Heliotron E case is plotted as a reference.

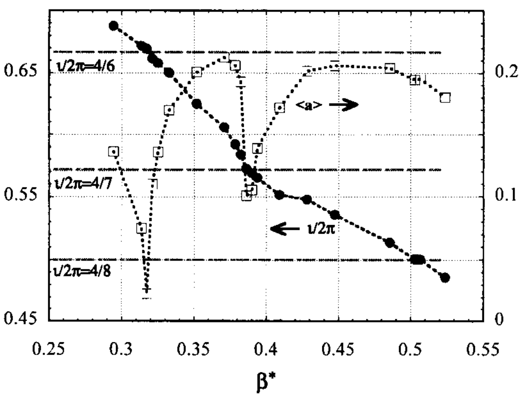

Fig. 1 β^*-dependence of χ and $<a>$. ($B_{IV}=0$, $B_{v,VF}/B_{t,HFC}=0.409$, $(B_{t,TFC\text{-}A}+B_{t,TFC\text{-}B})/B_{t,HFC}=1.5097$)

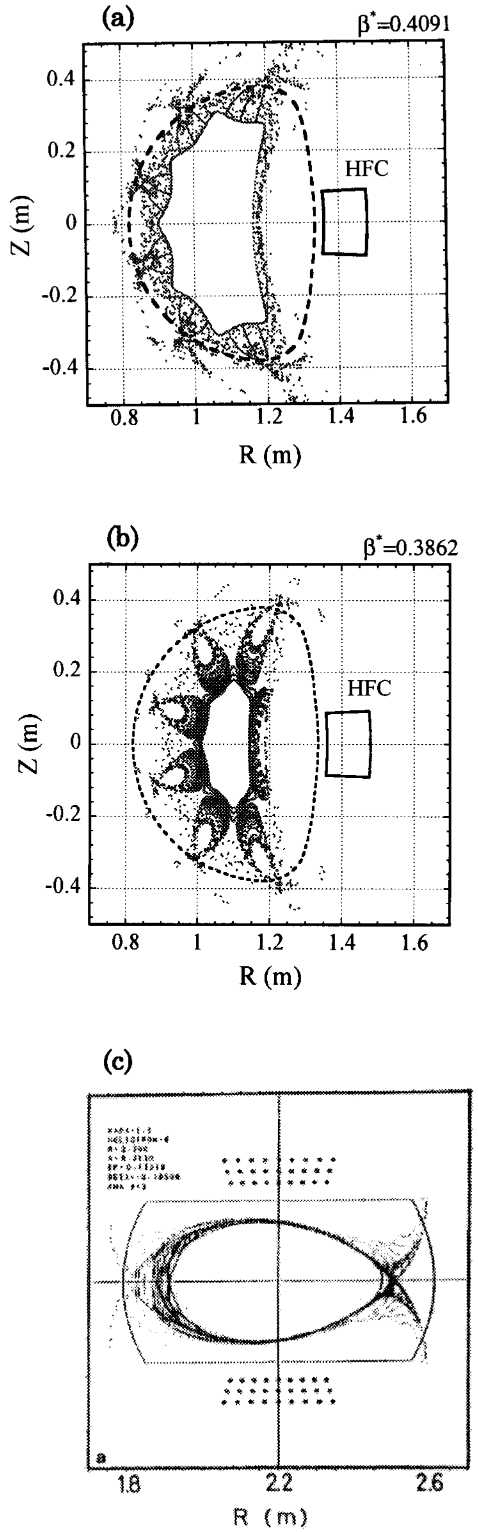

Fig. 2 Puncture-plots of the field lines at one poloidal cross-section for three different configurations.
(a) $\beta^*=0.409$, $\iota=0.5514$, (b) $\beta^*=0.386$, $\iota=0.5723$, (c) Puncture-plot for Heliotron E.

Figure 2(a) shows an off-resonance case with $\beta^* = 0.4091$ and the edge $\iota = 0.5514$. The outermost surface seems to be surrounded by rather "ergodic" region like the Heliotron E case. The effective edge structure is affected by the position of plasma-facing materials including the wall surface. The current design of the wall shape (inner surface) is shown as a dashed-line in the figure. The connection length to the wall of the edge field line, Lc, sharply drops just outside of OMS as shown in Fig. 3(a), where is plotted for field lines starting along the major radius, R, at $\phi = 0°$ and 45°. This short Lc seems to reduce the "degree of ergodicity." The footprints of the field lines on the wall surface are shown in Fig. 4(a). The footprints seem to be localized in two restricted areas in one helical-pitch. This is convenient for particle control ("local divertor", where particle collectors are set in the ergodic region surrounding the plasma edge.). This configuration, however, does not show so-called "X-point like structure", which is observed in Heliotron E (see Fig.2(c)).

In Fig. 2(b) case ($\beta^* = 0.3862$, $\iota = 0.5723$), the outermost magnetic surface is bounded by islands of $n/m = 4/7$. Owing to this island structure, OMS is surrounded by the region that has longer connection length as shown in Fig. 3(b). A part of these islands crosses the wall under the current design. The footprints of the field lines are also localized at almost the same areas in the previous case. This field structure is

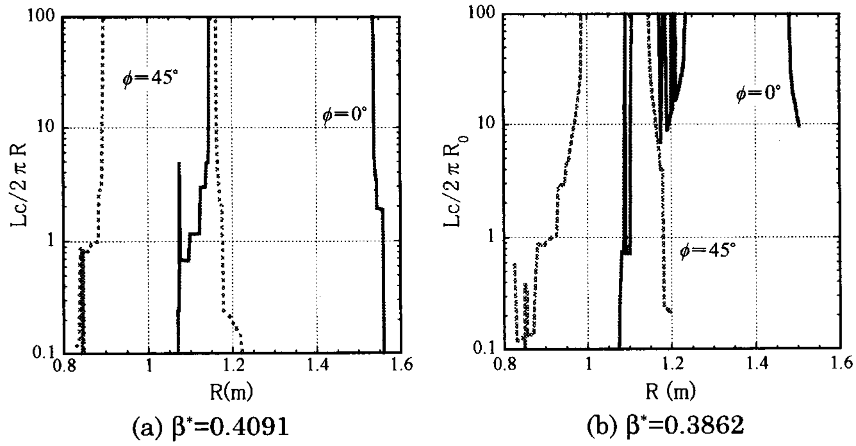

Fig. 3 Connection length to the wall of the currently designed vacuum chamber.
(a) $\beta^* = 0.409$, $\iota = 0.5514$, (b) $\beta^* = 0.386$, $\iota = 0.5723$.

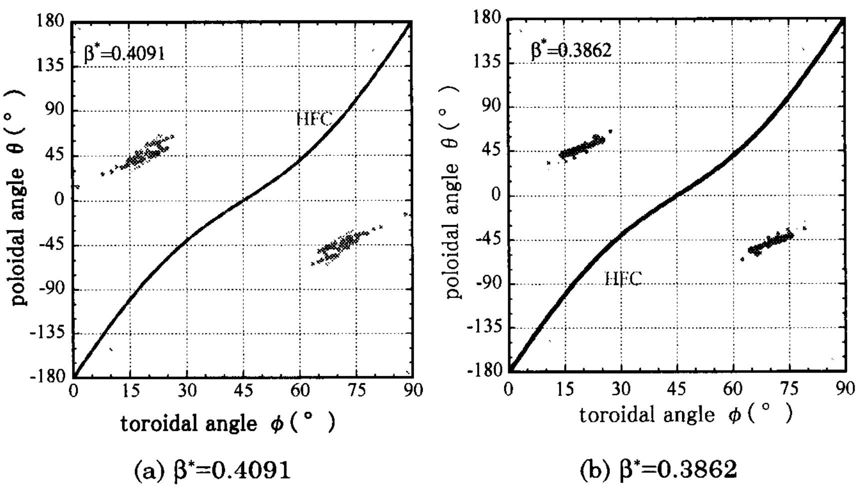

Fig. 4 Footprint of the edge field lines on the wall surface. The solid line is the trace of the helical coil center.
(a) $\beta^* = 0.409$, $\iota = 0.5514$, (b) $\beta^* = 0.386$, $\iota = 0.5723$.

considered as an "island-divertor" configuration. In this particular case, the plasma radius becomes small compared to the Fig. 2(a) case. The size of OMS can increase with keeping similar edge configuration by controlling the combination of $B_{HFC}+B_{VF}$, $B_{TFC\text{-}A}$, $B_{TFC\text{-}B}$, B_{IV} and B_{AV}.

In addition to these configurations, it is possible to make a "wall-limiter" configuration in this device within the limit of the power source of coil systems.

4. Summary

The structure of the edge magnetic field of the $\ell=1$ Helical-Axis Heliotron designed at Institute of Advanced Energy is numerically analyzed.

In contrast to the Heliotron E device, the edge field structure is strongly affected by the change of magnetic field components. By changing the vertical field strength, we have observed "island-divertor", "wall-limiter" and "local divertor" configurations. However, the "helical-divertor" configuration is not observed in this β^*-scan with the current wall design.

In this study, the effect of the vertical field strength is mainly studied. The effects of other coil-current modification on the edge field structure will be reported elsewhere.

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