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Full-torus MHD equilibrium study of a low-shear helical-axis heliotron

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Abstract. The magnetohydrodynamic equilibrium of a helical-axis heliotron with large-vacuum magnetic islands is investigated. Since the helical-axis heliotron is an $L=1/M=4$ low-magnetic-shear configuration, there is the sensitivity to the perturbed field. By assuming the external trim coil, low-order magnetic islands with $n/m=1/2$ can be generated. The effect and change of low-order ($n/m=1/2$) vacuum islands to the finite β equilibrium are investigated. For a finite β equilibrium, $n/m=1/2$ islands disappear but $n/m=4/8$ islands appear by the pressure-induced field. For another case, $n/m=1/2$ islands disappear and other resonances are suppressed. This property depends on the phase of islands.

1. Introduction

A subject of the advanced stellarator is to explore the optimization concept. In order to combine stability to the Magnetohydrodynamic (MHD) activity and good particle confinement, the spatial magnetic axis and the low magnetic shear are adopted in many cases. Since the low-shear configuration has sensitivity to the resonance of the rational surface, the large magnetic island is generated by the perturbed field because of the low magnetic shear. In many configurations, dangerous low-order resonances (typically, 1/1, 1/2, 1/3, 1/4, ...) are avoided in the optimization process. However, if an unexpected error field exists, it has the possibility to generate an unexpected large island. The unexpected field is the error field by the unit of the power supply for an example.

In this study, the effect of the low-order perturbed field to Heliotron J plasmas is studied as a low-magnetic-shear configuration. The Heliotron J device is an $L=1/M=4$ helical-axis heliotron (HAH) configuration, which has large flexibility [1]. The main parameters are $R=1.2\,\mathrm{m}$, $a_\mathrm{p}\sim 0.1$–$0.2\,\mathrm{m}$, $B<1.5\,\mathrm{T}$ and $\tau\sim 0.4$–0.8. In previous studies, it was pointed out that the finite-β equilibrium of the standard configuration has pressure-induced islands by the resonance 4/7 [2, 3]. However, the toroidal mode number of the resonance was only the multiple number of the toroidal field period M and more dangerous resonances; $n/m=2/4$ and 1/2 did not appear.

Magnetic islands with $n/m=1/2$ are generated by the external trim coil. The properties of $n/m=1/2$ islands are studied by the full-torus MHD equilibrium calculation. The equilibrium calculation is performed by the HINT code [2, 4]. HINT

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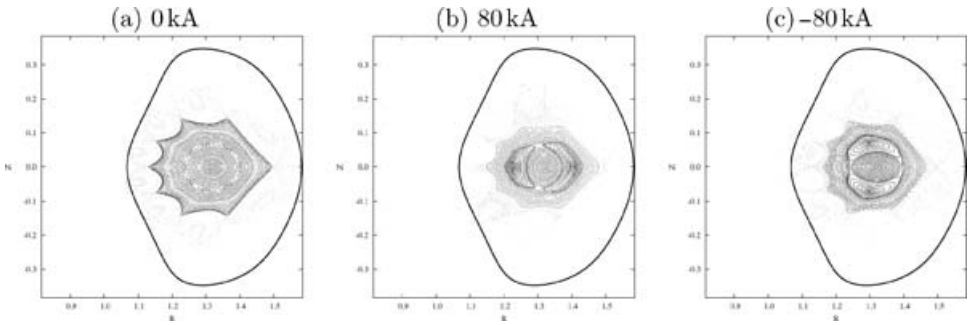


Figure 1. Poincaré plots of magnetic field lines are shown for the three cases. All figures are plotted at $\phi = 0$. Bold lines indicate the wall of the vacuum vessel. The coil current of the trim coil is also shown.

is a three-dimensional equilibrium calculation code based on the relaxation method. Since HINT uses the Eulerian coordinate, it does not assume the nested flux surface. Details of the numerical scheme of the code are given in [2, 4]. In the standard calculation of HINT, only the half period of the field is calculated because of the stellarator symmetry. This assumption is suitable in many helical configurations. However, in this study, the full-torus calculation is required to study $n/m = 1/2$ islands. Since the full-torus calculation consumes a large amount of computational time, the code is parallelized using MPI (Message Passing Interface) [5]. By this modification, the computational time is improved.

In Sec. 2, three island formations of heliotron plasmas and MHD equilibria of those configurations are shown. In Sec. 3, we summarize this study.

2. Island formation of a low-shear helical axis heliotron

As mentioned above, typical configurations of Heliotron J plasmas do not have large vacuum and pressure-induced magnetic islands. However, there is a possibilitiy of the generation of large magnetic islands because Heliotron J is a low-magnetic-shear configuration. In order to study the finite β effect on the low-order vacuum magnetic island, we consider three configurations with (a) $n/m = 4/8$ natural islands, (b) and (c) $n/m = 1/2$ low-order islands. Figure 1 shows three vacuum configurations in this study. Poincaré maps of magnetic field lines are plotted at $\phi = 0$. Bold lines in the figures indicate the wall of the vacuum vessel. In Fig. 1(a), an island chain by $n/m = 4/8$ natural resonance appears. On the other hand, in figs.1(b) and (c), large magnetic islands with $n/m = 1/2$ appear by the external perturbed field and the phase of islands is different in both cases. The external perturbed field is the quadrupole field and it is generated by two pairs of trim coils. The phase of islands can be changed by controling the current of the trim coil. Figure 2 shows radial profiles of the rotational transform as a function of the major radius R at $\phi = 0$. Although the external perturbed field is superimposed, profiles and positions of the magnetic axis are hardly changed.

In Fig. 3, finite β equilibria are shown. Poincaré maps of magnetic field lines are plotted at $\phi = 0$ for comparison. Beta values on the axis are 1% for all cases but volume averaged beta values are (a) 0.63%, (b) 0.38% and (c) 0.35%. The initial pressure distribution is prescribed to $p = p_0(1 - s^4)(1 - s)$ for all cases, where s is

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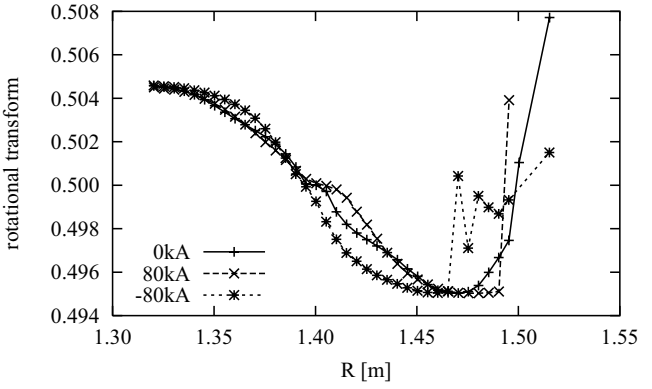


Figure 2. Radial profiles of the rotational transform are shown for the three cases. The profile is plotted as a function of the major radius R at $\phi = 0$.

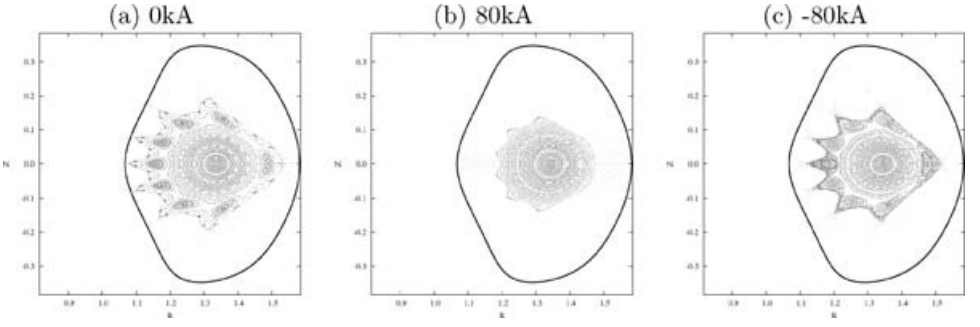


Figure 3. Poincaré plots of finite β field are shown for the three cases. All figures are plotted at $\phi = 0$. Bold lines indicate the wall of the vacuum vessel. The coil current of the trim coil is also shown.

the normalized toroidal flux for the vacuum configuration. In Fig. 3(a), the width of islands is increased by the finite β effect. On the other hand, Poincaré plots for cases (b) and (c) are very different compared with the vacuum field. For case (b), magnetic islands disappear in the finite β field although two large magnetic islands exist for the vacuum field. For case (c), $n/m = 1/2$ islands disappear but $n/m = 4/8$ islands appear by the finite β field. Figure 4 shows radial profiles of the rotational transform corresponding to Fig. 2. Profiles are changed by the Shafranov shift. Although the beta value for case (a) is largest out of the cases, the Shafranov shift is smallest. For case (b), the resonance disappears by the Shafranov shift. On the other hand, for case (c), the resonance 4/8 is locked at the edge region.

Heliotron J configurations have the large effective toroidicity and the large Shafranov shift. Thus, the Pfirsch–Schlüter current is not suppressed. Since the rotational transform is changed by the large Shafranov shift, the resonance surface moves to the edge region and the resonance by the external 'vacuum' perturbed field disappears. From this result, if large magnetic islands exist for the vacuum field, there is a possibility to suppress the magnetic island for the finite β equilibrium. However, the effect of the pressure-induced field is very large in spite of the suppression of the vacuum island. A problem is the generation of magnetic

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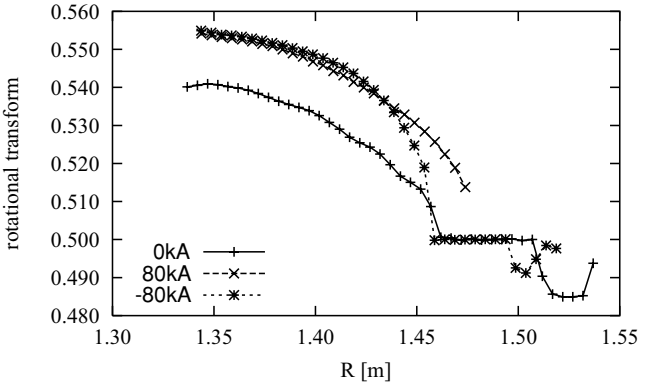


Figure 4. Radial profiles of the rotational transform are shown for finite β equilibria. The profile is plotted as a function of the major radius R at $\phi = 0$.

islands at the edge region. These islands degrade the ramp-up of the plasma β. The difference between two cases is the phase of islands for the vacuum field.

3. Conclusions

MHD equilibria of island formations of Heliotron J plasmas are investigated. Magnetic islands with $n/m = 1/2$ are generated by the external trim coil. Although $n/m = 1/2$ islands exist for the vacuum field, those islands disappear for finite β equilibria. However, in one case, pressure-induced islands appear at the edge region and islands are suppressed in another case.

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