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SUPPRESSION OF MAGNETIC SURFACE BREAKING BY SIMPLE EXTRA COILS IN A FINITE BETA EQUILIBRIUM OF HELICAL SYSTEM

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ABSTRACT.

A simple method is proposed to suppress actively the breaking of magnetic surfaces which occurs in $l = 2$ Heliotron/Torsatron equilibria, by which fairly high beta equilibria with clearly nested magnetic surfaces can be realized without changing other physical properties such as the rotational transform profile and the well depth.

Keywords: Heliotron, Torsatron, correction coil, finite beta helical equilibrium

It is well known that the outer region of magnetic surfaces is ergodic in vacuum fields of toroidal helical systems, which is attributed to loss of symmetry. Furthermore, by using a newly developed three dimensional equilibrium code HINT [1], it has recently been discovered that the outer ergodic region expands and the plasma region shrinks when the plasma beta is increased in actual configurations of toroidal helical systems. Such breaking of magnetic surfaces due to the finite pressure effect often imposes severer limitation on the equilibrium beta than the Shafranov shift [2].

Thus, it is required to find out an ingenious method to suppress the breaking of magnetic surfaces due to the finite beta effect in order to obtain a high beta equilibrium. Behavior of the appearance of magnetic islands has been studied by the HINT code for finite beta equilibria of $l = 2$ Heliotron/Torsatron configurations. The results suggests that one practical way to control the breaking is to make use of an axisymmetric external poloidal field, especially the vertical component B_v [2]. In fact, by slightly shifting inwardly the radial position of the vacuum magnetic axis by use of B_v, we can obtain a high beta equilibrium, such as $\bar{\beta} \geq 5\%$, keeping clearly nested surfaces as well as the Shafranov shift limit even for a rather low aspect ratio (the pitch period number $M = 10$) Heliotron/Torsatron configuration. One problem for this way, however, is that the physical properties of the configuration, such as the rotational transform profile $\iota(r)$ and the magnetic well profile $U(r)$, are significantly modified as the external poloidal field is changed to suppress the formation of magnetic islands. As a result of the inward shift by the control of B_v, the shear increases in the ι profile, which is favorable to the stability, but the well depth significantly reduces, which is not. Thus, we have to be cautious about other physical effects, such as the stability and the particle orbit loss, when we control the breaking by use of the axisymmetric external field.

In this paper, we propose an ingenious way to suppress the magnetic surface breaking by use of a set of simple extra coils, which is free from the problem mentioned above.

Islands which appear on a rational surface either in a vacuum field or in a finite beta field of a $l = 2$ Heliotron/Torsatron configuration have the following empirical properties for a wide range of variation of examined configurations;

1) the island size is noticeably larger on the outer side of the torus, than on the inner side,

2) islands appear in phase at the outside of the torus when islands are induced on several rational surfaces simultaneously.

The first property indicates that the island size can be controlled by an external field with the toroidal period number $n = M$ which has a relatively simple structure in a real space and is applied on the outer side of the torus.

The second property suggests a possibility for all islands to be suppressed simultaneously by properly choosing the radial profile of the amplitude of the simple external field.

By taking advantage of these properties, we can come up with a set of simple extra coils enough to suppress induced islands as is shown in Fig.1. It consists of M coils, each of which has the figure eight shape, set at the toroidal directions where the poloidal cross section of magnetic surfaces is up-down symmetric and horizontally elongated. The direction of the coil current is shown in the figure.

This method is studied by using the Cary-Hanson technique [3] to measure the island size, by which the amount of the extra coil current and the size of the coil are optimized. Figure 2(a) shows an example of induced islands which appear in a finite beta equilibrium ($\bar{\beta} \sim 4\%$) of a $M = 10/l = 2$ heliotron configuration. As is shown in Fig.2(b), these islands are clearly suppressed by adding the extra coil (Table I), so that clear magnetic surfaces are recovered in the outer ergodic region as is seen in Fig.2(a). It is interesting to note that the required extra coil current is only about 3% of the helical coil current. One important advantage of this method is that the physical properties, such as the well depth and the ι profile, are very slightly changed when the extra coil field is imposed, as is shown in Fig.3.

Studies for other beta values with the same configuration indicate that the location and the size of the extra coils need not be changed to suppress islands when beta is increased. The only thing that should be controlled depending on the beta value is the amount of the extra coil current. When the shape of magnetic surfaces does not change as beta is increased, the required extra coil current should be proportional to beta. In practice, however, in our experience the coil current is changed as β^{α}, where α is less than 1 because of nonlinear deformation of the shape of magnetic surfaces.

In Fig.1 we showed that the extra coils are placed at the horizontally elongated poloidal cross sections. These locations may not be favorable from the engineering viewpoint, since the extra coils would be an obstacle for facilities, such as neutral beam injection or diagnosis. However, this problem can be resolved in two ways by considering the variation of the location or the shape of extra coils. The first way is to place the extra coils at the vertically, instead of horizontally, elongated poloidal cross sections. The other way is that the figure eight shape coil is divided into two simple circular coils, and are placed apart from each other. In both cases we confirmed that the similar effect on the suppression of islands can be obtained.

According to the calculation of the HINT code, the way islands appear for the Helias configuration [4] is quite different from that for the Heliotron configuration. Namely, while the number of the related dangerous rational surfaces is smaller, the size of islands is much bigger once they appear and the difference of the size between the outer side and the inner side of torus is not so significant. However, we confirmed that the extra coil method proposed in this paper can also be applied for the Helias configuration, by taking advantage of the property of the bigger size of each island.

Thus, this method can provide an efficient and powerful way to remedy magnetic islands for any reasonable beta value and simultaneously can improve the equilibrium beta limit.

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FIGURE CAPTIONS

Fig.1 Schematic view of the proposed extra coils, which consist of M coils and are placed just outside the torus.

Fig.2 Magnetic surfaces of $l = 2$ heliotron configuration (a) before and (b) after the suppression of magnetic islands by use of the proposed simple extra coils. The extra coil is placed just outside the right boundary (the outer side of the torus) of the outermost rectangular in (b).

Fig.3 The rotational transform profile and the magnetic well profile (a) before and (b) after the suppression of magnetic islands by use of the proposed simple extra coils. The plasma minor radius increases in (b) because of the recovery of outer magnetic surfaces. Note that the change in the profile is very slight.

TABLE I. SIZES OF HELICAL AND EXTRA COILS

Helical Coil	
major radius	4 (m)
minor radius	0.97 (m)
M	10
Extra Coil	
width	0.3 (m)
height	$\pm$ 0.6 (m)
distance	0.87 (m)

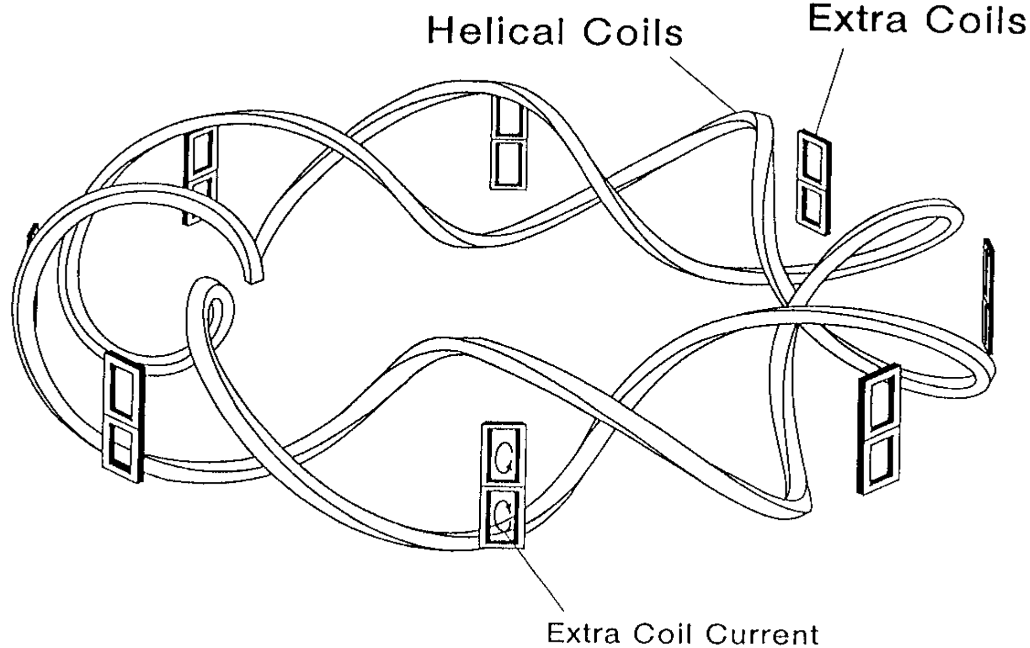

Fig.1

(a)

(b)

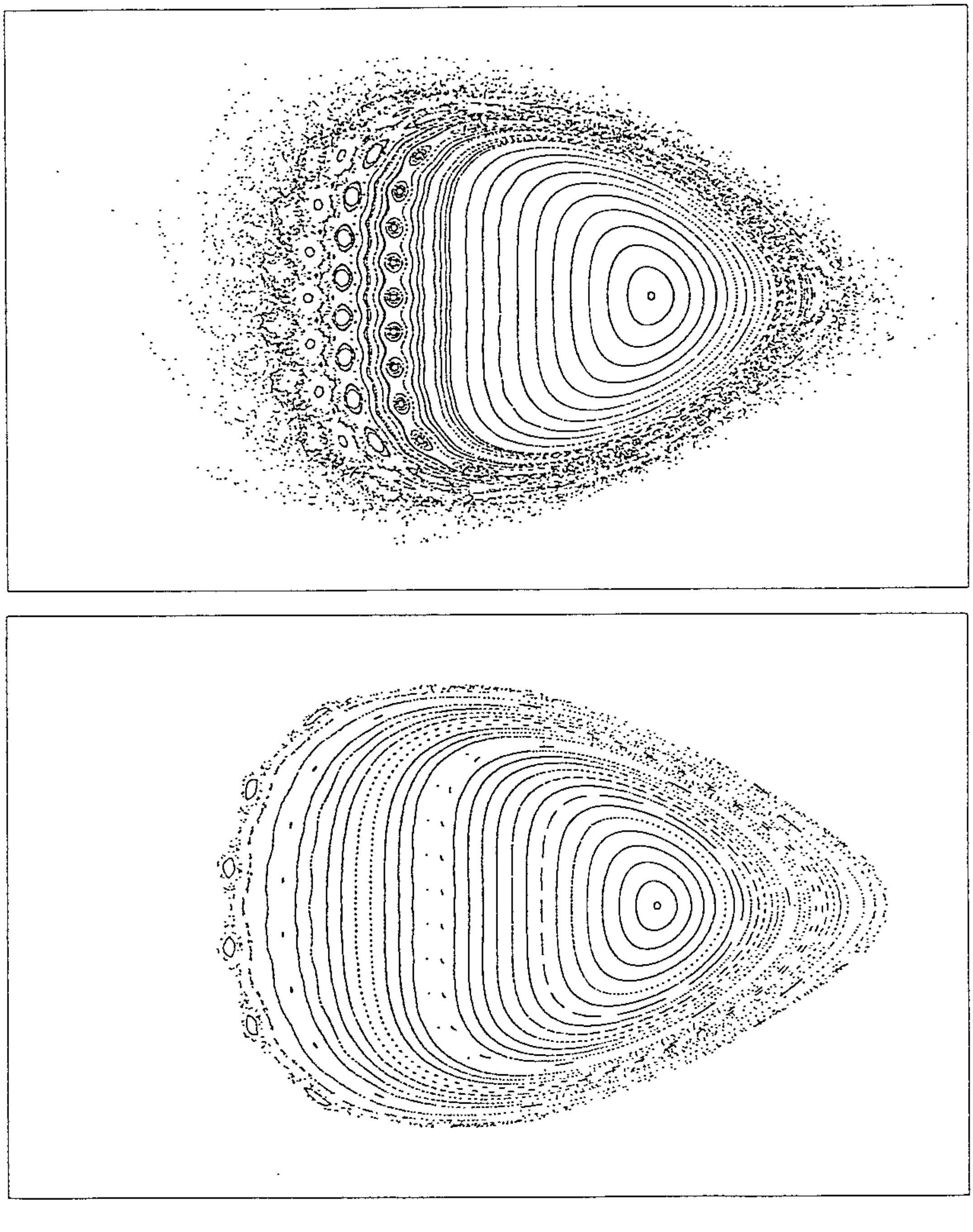

Fig.2

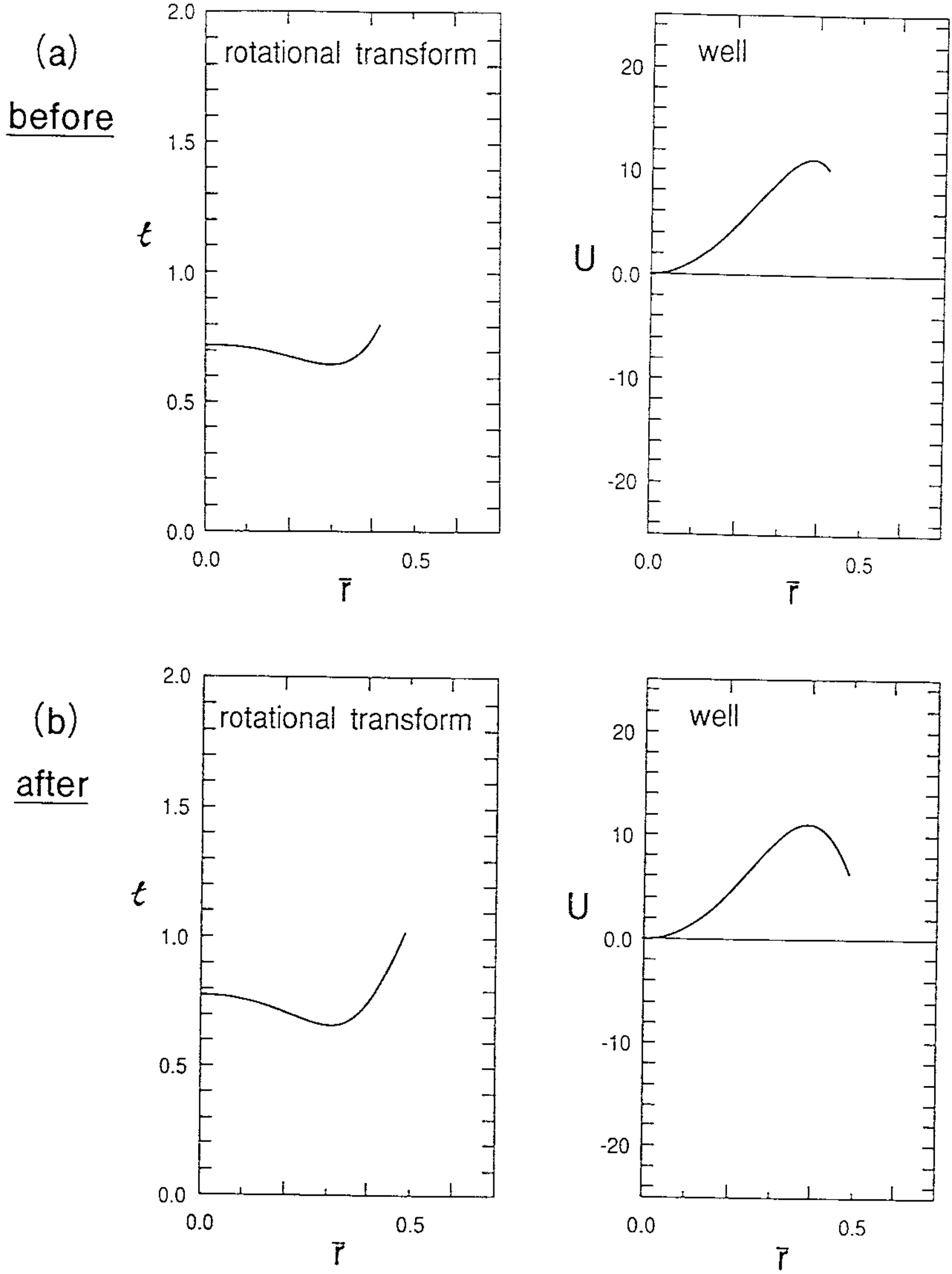
(a)
before
rotational transform
well
2.0
1.5
1.0
0.5
0.0
20
10
0.0
-10
-20
0.0
0.5
U
(b)
after
rotational transform
well

Fig.3

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