INTERNATIONAL ATOMIC ENERGY AGENCY

FOURTEENTH INTERNATIONAL CONFERENCE ON PLASMA PHYSICS AND CONTROLLED NUCLEAR FUSION RESEARCH

Würzburg, Germany, 30 September – 7 October 1992

IAEA-CN-56/D-1-4

3D MHD Study of Helias and Heliotron

T. Hayashi, T. Sato, W. Lotz, P. Merkel, J. Nührenberg,
U. Schwenn and E. Strumberger

(Received – Aug. 21, 1992)

NIFS-168 Sep. 1992

RESEARCH REPORT
NIFS Series

NAGOYA, JAPAN

INTERNATIONAL ATOMIC ENERGY AGENCY

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T.HAYASHI, T.SATO

National Institute for Fusion Science

Furocho, Nagoya 464-01, Japan

W.LOTZ, P.MERKEL, J.NÜHRENBERG,

U.SCHWENN, E.STRUMBERGER

Max-Planck-Institut für Plasmaphysik

IPP-EURATOM Association

D-8046 Garching bei München

Federal Republic of Germany

key words: helical system, helias, heliotron, torsatron, stellarator, three dimensional equilibrium, beta limit, magnetic island, self-healing of magnetic island, divertor, finite pressure effect

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ABSTRACT

Properties of magnetic islands induced by the finite pressure effect are numerically analyzed for three-dimensional magnetohydrostatic equilibria of Helias and $l = 2$ heliotron/torsatron types. For Helias, it is found that an island chain is generated on the 5/6 rational surface, when such a surface appears in the plasma region of a finite-β equilibrium. The island chain, however, is not so dangerous as to destroy the plasma confinement even if it appears in a vanishingly small shear region. Moreover, it is definitely confirmed that the finite pressure effect sometimes exhibits a surprisingly good aspect, namely, that the vacuum islands are removed as β increases, which can be called 'self-healing' of islands. This property can be explained by the numerically discovered fact that the phases of islands induced by the finite pressure effect are always locked i.e. do not change regardless of β. The way islands appear at finite-β for heliotron/torsatron is significantly different from that for Helias. However, we find the self-healing of islands can also occur for the heliotron configuration. This phenomenon can partly explain the reason why the fragility of surfaces decreases when they are shifted inward by control of the external vertical field B_v, though the configuration develops a magnetic hill. Furthermore, we analyze the diversion properties of the magnetic field outside the last closed magnetic surface for finite-β equilibria, and find that divertor concepts which have been developed from the diversion properties of the corresponding vacuum fields can be maintained for finite-β equilibria for both configurations.

1.Introduction

Whether or not a three-dimensional (3D) magnetohydrostatic finite-β equilibrium can keep clearly nested magnetic surfaces is a long-pending question, but its physics has not yet fully been understood. Properties of magnetic islands induced by a finite pressure effect in typical helical systems, such as Helias proposed for W7-X and $l = 2$ heliotron/torsatron proposed for LHD, are quantitatively studied by a numerical method, namely the 3D equilibrium code HINT [1,2], which does not a priori demand the existence of regularly nested magnetic surfaces. The equilibrium calculation is made for the half-pitch period of the configuration, keeping the stellarator symmetry.

In the process of equilibrium calculations, we find a remarkable property of magnetic islands induced by the finite pressure effect; the islands, in some cases, show the property of 'self-healing', i.e. the islands tend to shrink as β increases.

2.Formation of magnetic islands at finite-β in Helias

The magnetic surfaces of the W7-X configuration are designed in such a way that the rational surfaces, $\iota = 1, \frac{5}{6}$, can be avoided. It is however of interest to study the finite-β behaviour of the $n=5/m=6$ island chain to assess whether this would be dangerous or not. For this study a vacuum field situation was selected in which at finite-β this island chain occurs. The rotational transform at the magnetic axis, ι_0, for the vacuum field is set slightly greater than $\frac{5}{6}$. One characteristic in the finite-β behaviour of the ι profile for Helias is that ι_0 decreases as β increases; in the case of $l = 2$ heliotron/torsatron configuration, ι_0 usually increases as a function of beta. Because of this behaviour, the $\frac{5}{6}$ rational surface can come into the plasma region; first it appears near the magnetic axis, and moves outward as beta increases. Thus, the $\frac{5}{6}$ island chain can appear when the $\frac{5}{6}$ surface resides at about half the plasma radius which is the position of vanishingly small shear. In this case the plasma β at the magnetic axis is $\beta_0 = 7.2\%$. As is shown in Fig.1, our results indicate that even this situation is not so dangerous as to destroy the plasma confinement. Most of the plasma region is covered by clearly nested surfaces. This is of course a consequence of the optimization of the configuration [3]. Corresponding to the formation of islands in the magnetic field structure as is shown in Fig.1 (a), the island structure is formed also in the pressure profile, as is shown in Fig.1 (b), where the pressure is almost flattened inside the $\frac{5}{6}$ island. We note that in the HINT code the pressure is automatically computed inside islands as a result of the incorporated calculation step which makes the pressure uniform along each field line. Coincidence of magnetic and pressure islands, which is for the first time demonstrated explicitly here in computational stellarator equilibria, proves validity of the code. Interestingly, local instabilities (Mercier and resistive interchange) are stabilized around the rational surface due to this flattening, the size of the islands being just large enough to bring about this stabilization.

When β is further increased, the $\frac{5}{6}$ island chain comes to the boundary region. Although

β is increased, the size of the island does not change so much, presumably due to the increased shear in the boundary region.

3. 'Self-healing' of magnetic islands in Helias

So far we have analyzed finite-β effects on equilibria from the point of view of formation of islands. Computational experience indicates that the phase induced by finite-β is independent of the value of β. Taking advantage of this property, we can have situations in which the finite-β effect acts rather to suppress islands which have existed in a vacuum field, if the phase of the vacuum field island is opposite to that of the β-induced ones. This process is confirmed in equilibrium calculations. A vacuum field is shown in Fig.2 (a), where a chain of magnetic islands is formed externally by controlling external currents, on the $\iota = \frac{5}{6}$ rational surface existing in the region of closed surfaces. Shown in Fig.2 (b) is the corresponding finite-β equilibrium with $\beta_0 = 9\%$. It is clearly observed that the $\frac{5}{6}$ island chain, which existed in the vacuum field, almost completely disappears, and a nice magnetic surface recovers by the effect of 'self-healing', though the $\iota = \frac{5}{6}$ surface still exists in the plasma region. Thus a high beta equilibrium keeping beautiful surfaces can be realized by making use of this feature.

When β is further increased, as is shown in Fig.2 (c) for $\beta_0 = 12\%$, the position of the $\iota = \frac{5}{6}$ surface moves further toward the boundary of the plasma, and the $\frac{5}{6}$ island chain appears again. Note, however, that the phase of the reappeared $\frac{5}{6}$ island chain is opposite to that of the vacuum one.

Based on the fact that islands may exhibit the property of self-healing described here, the physical equilibrium mechanism of formation of islands at rational surfaces in finite-pressure equilibria appears to be such that they are governed by resonant magnetic fields generated by the global effects of the plasma current density, mainly of the Pfirsch-Schlüter current, integrated over the whole plasma volume. We note that part of the reduction of the island size as β increases, shown in Fig.2 (b), may be attributed to the increase in the shear in the boundary region. However, the mere shear effect cannot explain the whole process shown here, since it does not explain the inversion in the phase of islands shown in Fig.2 (c). It appears natural to consider that the global plasma current effect, which determines the magnitude and the phase of the resonant field, mostly rules the island behaviour.

4. 'Self-healing' of magnetic islands in $l = 2$ heliotron/torsatron

We observe the nature of self-healing of islands not only in Helias but also in the $l = 2$ heliotron/torsatron configuration, which is characterized by medium to high shear. As is shown in Fig.3 (a) for typical vacuum surfaces of an $M = 10$ heliotron, the boundary region of the vacuum field is ergodic due to the loss of symmetry; in this case, two island chains, $n = 10/m = 8$ and $n = 10/m = 7$, are clearly visible near the outermost closed surface. It is a general property for vacuum fields of a wide range of $l = 2$ heliotron/torsatron configurations that the appearing islands are in phase at the outside of the torus when they are induced on several rational surfaces simultaneously [4]; here, both island chains have the x-point at the outside of the $\phi = \frac{\pi}{10}$ (horizontally elongated) poloidal cross section.

Because of the high shear nature, the way the islands appear at finite-β for heliotron/torsatron is significantly different from that for Helias; for heliotron, in general, the boundary region is ergodized due to overlapping of multiple island chains with smaller sizes and the boundary ergodized region gradually expands as β increases. However, we find the self-healing of islands can occur also for the heliotron configuration. Shown in Fig.3 (b) are magnetic surfaces for finite-β, $\beta_0 = 4.5\%$. When we observe the fine structure of boundary islands, it is visible that the $n = 10/m = 8$ island chain shrinks significantly, and the phase of the $n = 10/m = 7$ gets inverted. When the $n = 10/m = 7$ island chain disappears at slightly lower β, the minor radius of the outermost closed surface expands compared with that of the vacuum field. These island behaviours indicate that the finite pressure effect acts to generate resonant fields with a global structure with respect to the phase. In fact, when β further increases, island chains, all having the o-point at the outside of $\phi = \frac{\pi}{10}$, grow at several rational surfaces simultaneously, and eventually the boundary region is ergodized. In this way, the development of the expansion of the boundary ergodic region is delayed as β increases, because of the opposite nature in the phase of island chains between the vacuum field and the finite-β field for this case. This opposite nature in the phase typically appears when surfaces are shifted inward by control of the external vertical field B_v. This can partly explain the reason why fragility of surfaces at finite-β decreases as surfaces are shifted inward, although the configuration develops a magnetic hill.[1]

5. Divertor field structure in finite-β equilibria

One property of magnetic fields of helical systems is that divertor structures can be realized without installing any additional coils. We analyze the diversion properties of the magnetic field outside the last closed magnetic surface for finite-β equilibria, and investigate whether or not divertor concepts which have been developed from the diversion properties of the corresponding vacuum fields can be maintained for finite-β equilibria of heliotron and Helias, which has not been analyzed so far. For $l = 2$ heliotron/torsatron, the structure of magnetic surfaces near the plasma boundary for finite-β equilibria can be considerably different from that of the vacuum field with respect to the value of rotational transform or the extent of ergodic region. However, the position of the divertor field remains almost the same, which suggests that the same divertor plate can be used even in equilibria with quite high β. It should be noted that the 'width' of the divertor structure broadens when β increases. Therefore, one has to be careful in designing the divertor geometry, such as the baffle plate. For Helias, it is found that the finite-β equilibrium shows the same diversion properties as the vacuum field. Since the positions of the helical edges [5] are almost the same, the helical 'troughs' defined for the vacuum magnetic field work as well in the case of the finite-β equilibrium.

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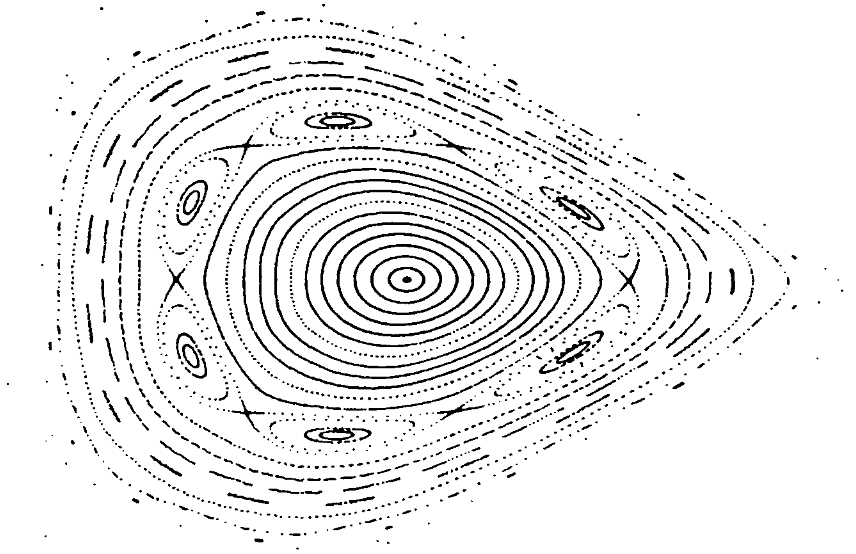
Figure Captions

Fig.1 Magnetic surfaces (a) and pressure contours (b) of a finite-β Helias equilibrium selected for code validation: coincidence of magnetic and pressure islands, which is demonstrated here in computational stellarator equilibria for the first time.

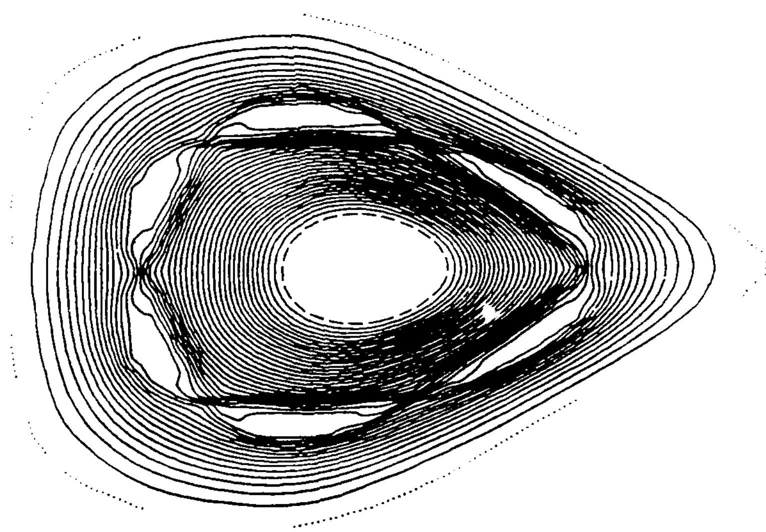
Fig.2 'Self-healing' process of magnetic islands in a Helias equilibrium. (a) Vacuum magnetic surfaces which have a 5/6 island chain. (b) Magnetic surfaces of a finite pressure equilibrium with $\beta_0 = 9\%$. The magnetic islands disappear and nice surfaces recover due to finite pressure effects, which is an opposite tendency compared to that found usually. (c) Magnetic surfaces of a higher β equilibrium with $\beta_0 = 12\%$. The island chain appears again, but with the inverted phase.

Fig.3 'Self-healing' process of magnetic islands in a $l = 2$ heliotron/torsatron equilibrium. (a) Vacuum magnetic surfaces which have $n = 10/m = 7$ and $n = 10/m = 8$ island chains in the boundary region. (b) Magnetic surfaces of a finite pressure equilibrium with $\beta_0 = 4.5\%$. The $n=10/m=8$ island chain almost disappears, and the phase of the $n=10/m=7$ gets inverted.

Helias



(a) Magnetic Field

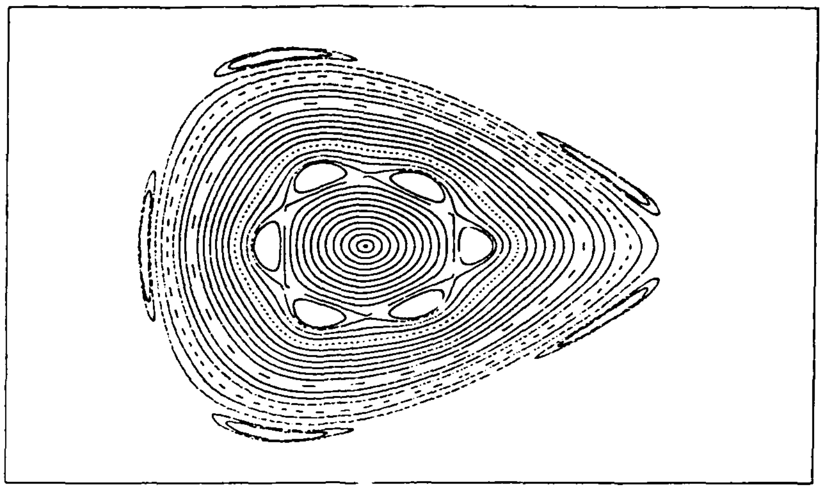


(b) Pressure

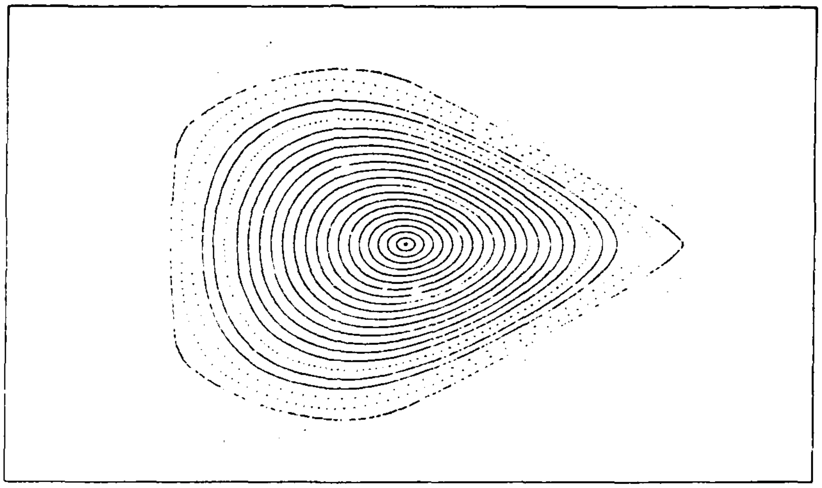
Fig.1

'Self-healing' of magnetic islands

(a) Vacuum Field



(b) $\beta_0 = 9\%$



(c) $\beta_0 = 12\%$

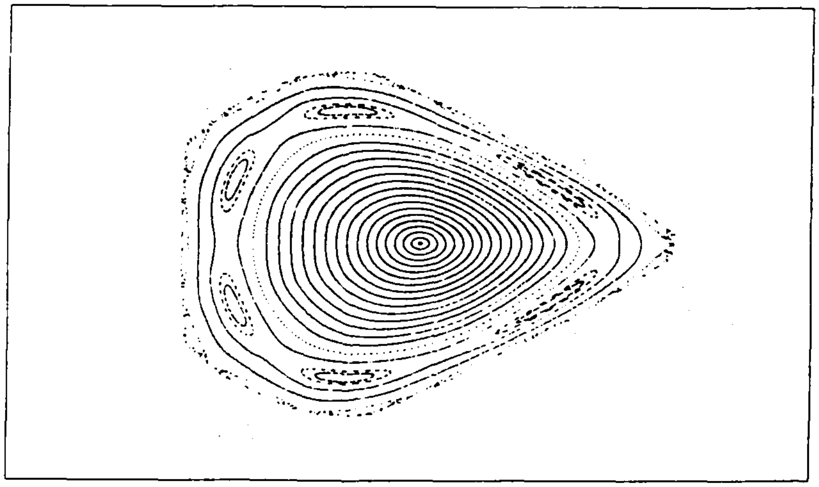
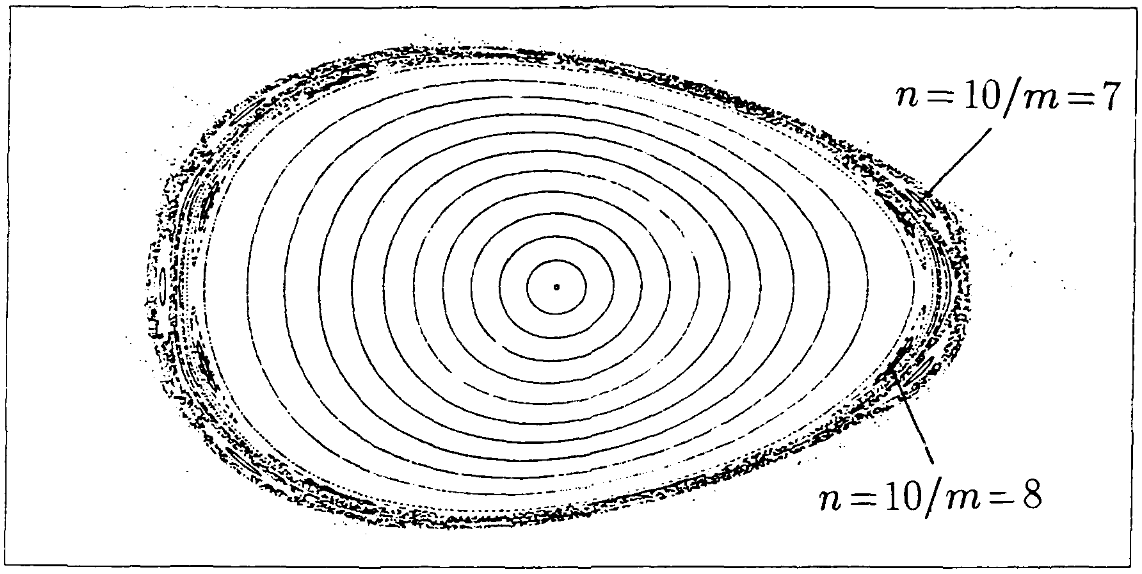
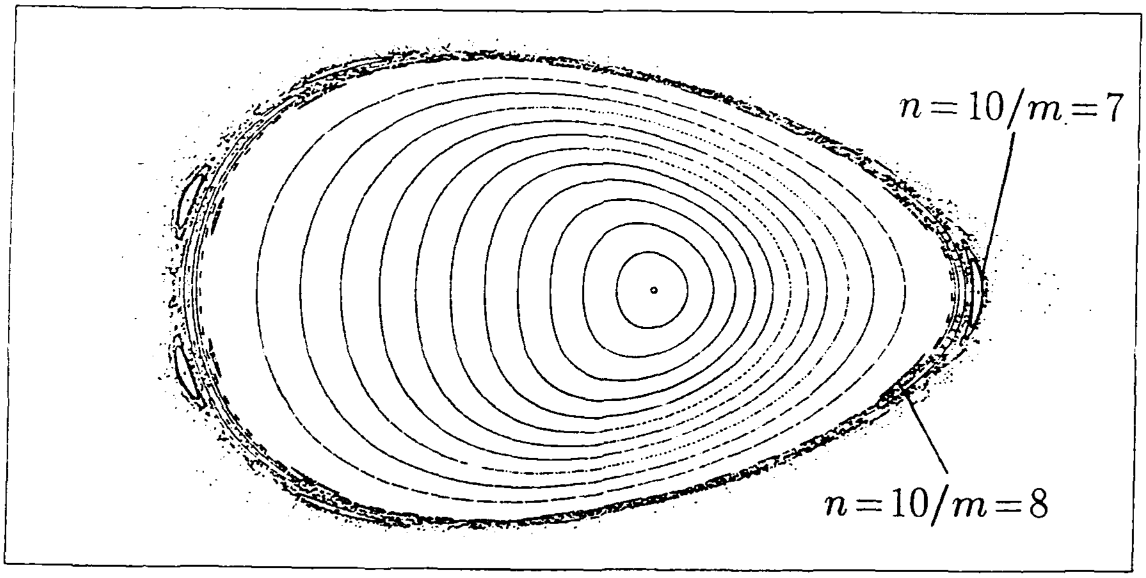


Fig.2

$l = 2$ Heliotron/Torsatron



(a) Vacuum Field



(b) $\beta_0 = 4.5\%$

Fig.3

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