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FIFTEENTH INTERNATIONAL CONFERENCE ON PLASMA PHYSICS AND CONTROLLED NUCLEAR FUSION RESEARCH

Seville, Spain, 26 September – 1 October 1994

IAEA-CN-60/D-2-II-4

Behavior of Magnetic Islands in 3D MHD Equilibria of Helical Devices

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Abstract

Magnetic island formation in three-dimensional finite-β equilibria in the H-1 Heliac is studied by using the HINT code. It is found that the size of a dangerous island should increase with β but that a destruction of the equilibrium at low β is avoided because the rotational transform evolves to exclude the rational surface concerned. At higher β there is evidence of near-resonant flux surface deformations which may lead to an equilibrium limit. A reconnected equilibrium at still higher β exhibits a double island structure which is similar to homoclinic phase portraits which have been observed after separatrix reconnection in Hamiltonian systems. Physical mechanism of the island formation in finite-β helical equilibria is investigated to confirm there are cases where the global effect of the Pfirsch-Schlüter currents is important. The earlier theory is extended to elucidate the occurence of the complete self-healing of island when the resistive interchange criterion satisfied.

1. Evolution of magnetic islands in a Heliac

One of the critical issues in obtaining a high-β plasma for helical devices is the formation of magnetic islands induced in nonaxisymmetric finite-β equilibria. This issue has been studied by the 3D equilibrium code HINT, which does not a-priori demand the existence of regular nested magnetic surfaces. It has been discovered numerically that breaking of magnetic surfaces due to the finite-β effect occurs in a practical configuration of a toroidal helical system, such as heliotron/torsatron [1] and Helias [2], and often imposes severer limitation on the equilibrium beta than the Shafranov shift. In addition, unexpectedly good aspect, which can be called "self-healing", has also been discovered.

The island issue is especially the case for the Heliac configuration, which has a small shear and contains a large number of Fourier harmonics in the magnetic field structure. In this paper, properties of magnetic islands induced due to finite pressure effects in a H-1 Heliac configuration [3] are studied using HINT. H-1 fields have a large degree of flexibility due to an $l = 1$ helical trim coil, however, this flexibility does not seem to allow varying the phase of the major, stellarator-symmetric island chains. In this study we examine a configuration which includes the island structure corresponding to the $\iota = 6/5$ resonance ($\iota = 2/5$ per field period) in the vacuum field and assume the existence of stellarator symmetry. A sequence of results from these simulations are shown in Fig. 1 where one cross section of the H-1 flux surfaces is shown at various plasma β's starting with Fig. 1(a) for the vacuum field. The ι profile for the vacuum field is monotonous and the shear is quite small (Fig. 1(b)).

As the increase of β, minimum of ι (vanishing shear) appears at around half the minor radius. As is shown in the following, depending on the value of the minimum ι with respect to 6/5, the most dangerous (low order) rational surface relevant, a variety of topology appears for magnetic islands induced in finite β equilibria. Figure 1(c), at $\beta_0 = 1.5\%$ ($\langle\beta\rangle \approx 0.5\%$), shows that the size of the $\iota = 6/5$ island should increase with plasma pressure to about 1/5 of the plasma radius. If the pressure is increased to $\beta_0 = 2.0\%$, in Fig. 1(d), the plasma appears to experience a form of self-healing, however the corresponding ι profile shows that this is because the 6/5 surface has been excluded from the configuration. It is possible that this exclusion might be due to some self-consistent plasma dynamics and, as such, could be considered as a (new) form of self-healing. In any case, it is a favorable property of the H-1 configuration that reasonably smooth flux surfaces can be obtained at these plasma β's.

As the pressure is increased further the HINT results show that the minimum value of ι remains just above 6/5, however the flux surfaces show marked signs of *near-resonant* deformation (Fig. 1(e)). Figure 1(f) shows the flux surfaces when the equilibrium pressure has increased to $\beta_0 = 4.4\%$. The flux surfaces have reconnected to form a double island structure, indicating that the minimum of ι has decreased down to 6/5. The topology of the island is analogous to the homoclinic phase portraits observed for Hamiltonian dynamical systems after separatrix reconnection [4], but appears to be new in the context of stellarator magnetic fields. The possibility of separatrix reconnection occurring is due to the corresponding Hamiltonian being degenerate, which, in our case, corresponds to $\iota' = 0$ across a finite fraction of the plasma radius.

The behavior of islands shown in Fig. 1(f) suggests an existence of a new type of *self-organizing* process, which is driven by a pressure-driven instability. Based on an equilibrium obtained by HINT, nonlinear simulations are also studied, where a compressible full MHD model is assumed in a 3D geometry. Excitation of strong pressure driven instability with global structure is observed as an increase in β. Interestingly, a tendency is found that the pressure profile spontaneously relaxes to a simple confined structure after a disordered state driven by the instability.

2. Physical mechanisms of formation and 'self-healing' of magnetic islands

A comparative study is given of some of the computational and analytical results presently available for calculating pressure-induced magnetic islands in 3D equilibria of currentless stellarators. The main goal of this study is to clarify the dominant physical mechanism of island formation, either the 'local' (current sheets) or the 'global' (Pfirsch-Schlüter currents) effects of the plasma current. For this purpose, we examine the behavior of D_R (the criteria for the local resistive interchange mode) and the Jacobian $\sqrt{g}_{mn}$ for results obtained by HINT for the self-healing case of Helias [2].

We find the process can be consistently explained by the 'global' effect by supposing that the self-healing process originates from the property that the pressure-induced islands always have the same phase independent of β ('fixed-phase' property). This property has been discovered numerically; the phase of the pressure-induced islands is determined independent of the phase of the vacuum islands. The field generated by global effects of the Pfirsch-Schlüter current profile integrated over the whole plasma volume appears to have a specific simple global spatial structure. A coupling of this global-structure field with the non-axisymmetric configuration results in the robust 'fixed-phase' property of the pressure-induced islands. Moreover, we analyze the consistency of the equilibrium on the rational magnetic surface 5/6 which exists in the Helias configuration for vanishing island thickness. We find that the plasma deforms itself so that the so-called Hamada condition, that $\int dl/B$ be constant on a rational surface, is satisfied with very good numerical accuracy when the island vanishes completely due to self-healing. The behavior described above for a Helias configuration occurs with the resistive interchange criterion being satisfied. The importance of the global effect is further confirmed by a computation for resistive-interchange unstable equilibria; we observe the similar process of the self-healing.

On the other hand, in order to *elucidate the self-healing process, the earlier* theory [5] is extended to include a small vacuum island which may, in general, have different phases than pressure-induced islands. For a negative (stable) D_R case, the extended theory predicts complete self-healing at a critical value of beta, when the vacuum perturbation and the perturbation caused by the Pfirsch-Schlüter currents are exactly out of phase. Beyond this critical value, the islands reappear but with a flipped phase. This behavior is consistent with the computational results.

An apparent discrepancy remains between computations and analysis for a *positive* D_R case. *It brings forward following* problems to be clarified in the future. It certainly has to be appreciated that for a 3D computation like HINT it is very difficult to achieve the needed accuracy to resolve current sheet investigated by the earlier theories. On the other hand, consistent quantitative estimation of the amplitude as well as the phase of the global effect without assumptions for simplification is possible only by a 3D computation.

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FIGURE CAPTION

Fig. 1 Evolution of magnetic islands and deformation of magnetic surfaces in a Heliac (a) vacuum field, (b) rotational transform profile for vacuum field, (c) $\beta_0 = 1.5\%$, (d) $\beta_0 = 2.0\%$, (e) $\beta_0 = 3.8\%$, (f) $\beta_0 = 4.4\%$.

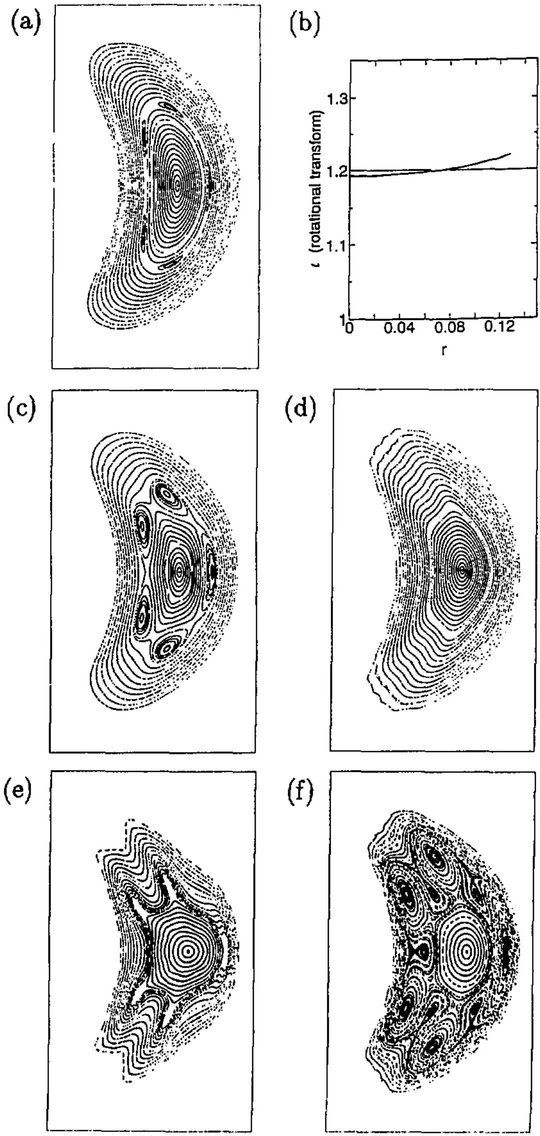

Fig.1

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