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Self Healing of Magnetic Islands in a Heliac

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Abstract

Studies of sequences of finite pressure equilibria in the H-1NF Heliac using the HINT code have revealed true self-healing of a magnetic island chain. Other phenomena described include a strong dependence of the growth of islands on the plasma pressure profile as well as the possibility of a bifurcation to a double island chain at the minimum width.

Keywords:
magnetic island, helical axis stellarator, self healing, Heliac

1. Background

Low shear, helical axis stellarators can contain internal magnetic islands whose size is comparable to the plasma minor radius – threatening to limit confinement at reactor-relevant pressures. Because of this, simulations of the growth of magnetic islands with plasma pressure were incorporated into design studies for the W7-X stellarator in Germany [1]. The results of these simulations, using the HINT computer code [2], showed that the phase of the pressure-driven island chains appeared to be independent of the phase of the corresponding vacuum island chain. A W7-X configuration having the opposite phase of the finite pressure island chain in its vacuum field was shown to exhibit a "self healing" at a particular value of the plasma pressure before growing again at higher pressures with the conventional phase [3]. Subsequently, analytic treatments have also reproduced the phenomenon of self healing and have predicted that finite pressure island widths are influenced by the presence of current sheets at rational surfaces as well as by the integrated "global effect" of Pfirsch-Schlüter currents [4].

Because of the present world-wide interest in helical axis stellarators as possible fusion reactors, it is important to understand whether the W7-X results also apply to other configurations. As a step in this direction, a study was undertaken of one model configuration of the H-1NF Heliac containing the 6/5 island chain and with a shallow magnetic well [5]. This study was also considered to be a test of the robustness of the HINT computer code due to the greater complexity of the H-1NF configuration compared with the W7-X. The results revealed a "quasi self healing" phenomenon which resulted from a sudden exclusion of the resonant value of the rotational transform from the configuration at some finite pressure. At still higher pressures, the resonant surface reappeared in the plasma and a double island chain with a *homoclinic* geometry developed. The difference between this "quasi self healing" and the earlier results (which was emphasised in Ref. [5]) raises the question whether true self-healing can be found in the H-1NF. This paper describes a modified H-1NF

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configuration, close to that used in the earlier study, which has been shown to have a true self healing property.

2. Configuration Tuning

Previous field line tracing studies of the parameter space of the H-1NF appeared to show a rigidity of the phase of the dominant island chains [5]. Subsequently, the application of a method of tuning the vertical field coil currents in conjunction with a method based on quadratic flux minimising surfaces [6] has discovered an adjacent configuration to that of ref. [5] with approximately the same rotational transform profile. We choose this new configuration for the present study but emphasise that it is an "artificial" H-1NF configuration away from the standard case. The helical tuning windings carry 3.2% of the current of the central coil (and were varied slightly during some of our simulations to fine-tune the rotational transform profile). In the real experiment the 6/5 island-chain competes with the 5/4 island-chain which, not having three-fold symmetry around the torus, cannot be considered without a considerable increase in computer time.

3. Computational Model

The HINT [2] computer code solves scalar pressure MHD equations with (almost) vanishing resistivity by a relaxation procedure which switches between force reduction along the field lines and, alternately, perpendicular to the magnetic flux surfaces. The iterative procedure alternates between a rotating Cartesian coordinate grid and field line tracing to define the flux surface and island geometry. The code is able to robustly compute a sequence of equilibria by stepping up the plasma pressure from a vacuum magnetic configuration. The pressure profile is usually overlaid on the vacuum flux surfaces at the beginning of such a sequence and relaxes as the iteration proceeds. Fixed boundary conditions on a helical box some distance from the plasma boundary are used – which is a particularly good approximation for the H-1NF because of its small Shafranov shift at accessible values of the plasma $<\beta>$ (the ratio of average plasma pressure to magnetic pressure). The HINT code is very well optimised for High Performance architectures with a vectorisation rate in excess of 90% on the Fujitsu VPP300 at the Australian National University.

The results presented in this paper have been obtained using a modified version of HINT which includes a special algorithm which speeds up the calculation for *low shear* systems by up to 40 times. This new algorithm has been benchmarked against the older version of HINT and will be reported in detail elsewhere.

4. Results

The results presented below relate to two sequen-

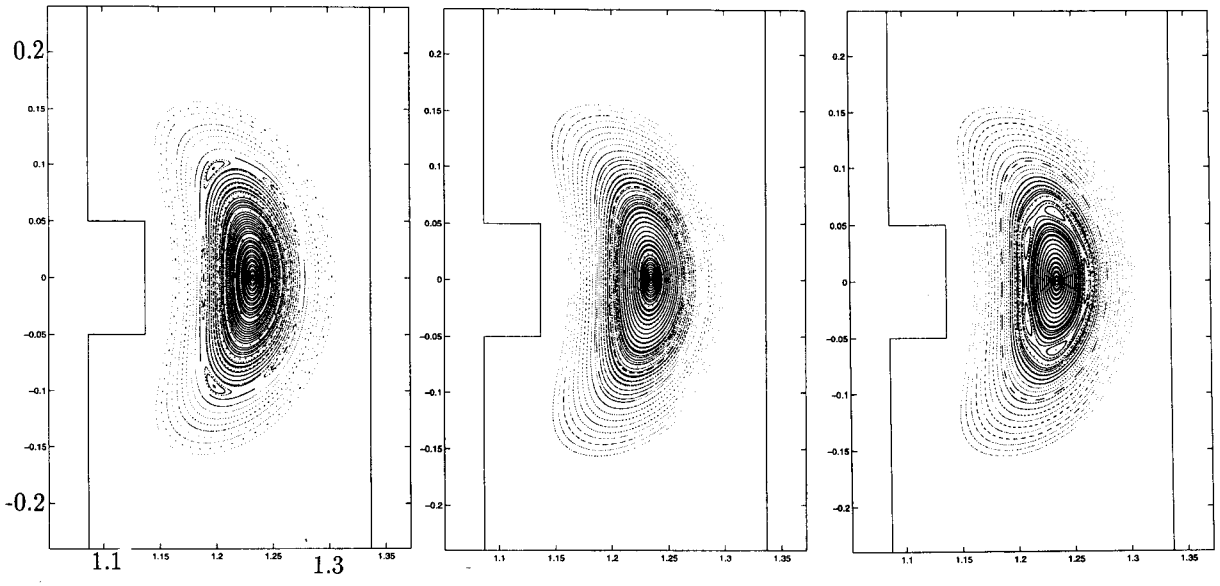

Fig. 1 Flux surface cross-sections from a sequence of equilibria which exhibits self healing as described in the text. From left to right the $<\beta>$ increases from zero to 0.1% to 0.134% with a steep pressure profile inside the island chain. Axis coordinates are in metres from the centre of the device.

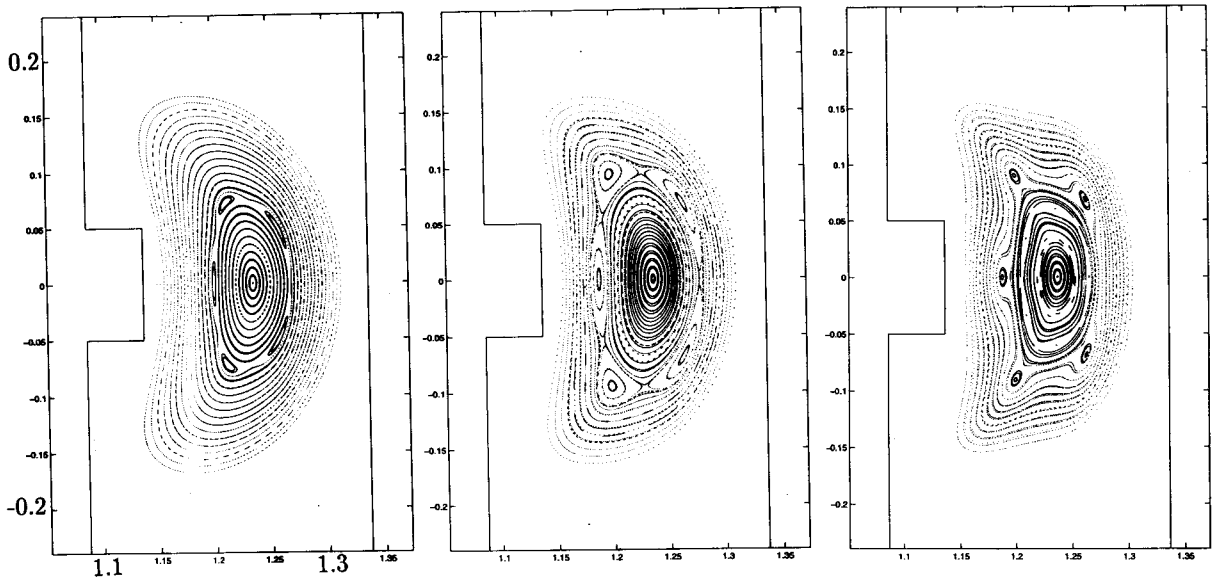

Fig. 2 Flux surface cross-sections from a sequence of equilibria where the 6/5 island chain grows as described in the text. From left to right the $<\beta>$ increases from 0.26% to 0.4% to 0.65% with a broader pressure profile and with additional tuning to control the rotational transform.

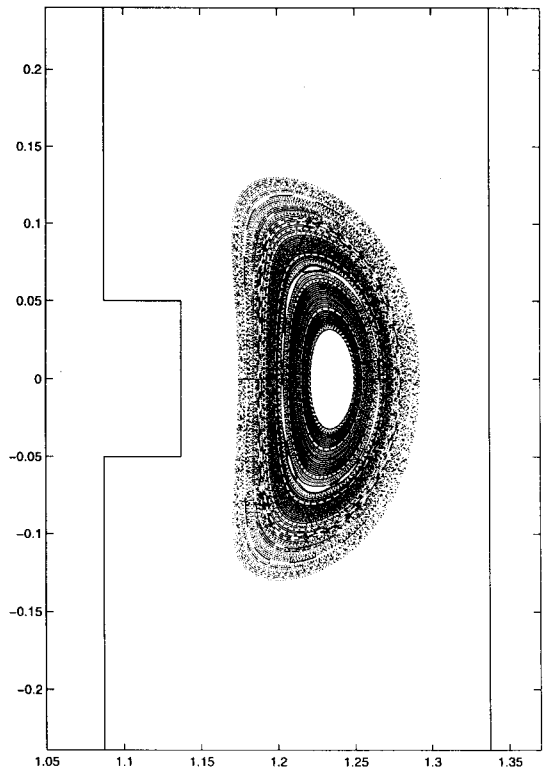

Fig. 3 A double island chain obtained from a self-healed configuration as described in the text. The $<\beta>$ value is 0.2% and the pressure profile is intermediate between the previous two sequences.

ces of H-1NF equilibria. Both start from the same vacuum configuration described above. The 6/5 island surfaces, shown in the left hand side of Figure 1, have an x-point on the mid-plane at the farthest intercept from the central conductor (which is located in the "bite" in the bounding box). This is the opposite phase to the configuration studied in ref. [5]. In the first sequence of equilibria, the plasma $<\beta>$ is increased from the vacuum to $<\beta>=0.134\%$. The initial pressure profile is set to be proportional to $(1-\psi)^5$ where ψ is a normalised flux function ranging from $\psi=0$ at the magnetic axis to $\psi=1$ at the edge of the configuration. This steep pressure profile results in a set of finite $<\beta>$ which results in a concentration of the pressure on the inside of the 6/5 island-chain. The middle of Figure 1 displays what is, to our knowledge, the first proof of true self healing in a Heliac. The vacuum islands reduce in size until this value of $<\beta>=0.1\%$ and then reappear with the opposite phase at higher $<\beta>$ (as shown on the right of Figure 1). The resonant rotational transform is inside the plasma but moves slowly in towards the magnetic axis as the pressure is increased in this sequence.

The second sequence, in Figure 2, shows the same configuration with a broader pressure profile, proportional to $(1-\psi)^2$, which extends through the position of the vacuum 6/5 island-chain. In this case the islands *grow in size* and the rotational transform tends to move

"above" the configuration (so that the islands disappear towards the magnetic axis) in agreement with the results of Ref. [5]. In other words, both this configuration and that in Ref. [5] show that vacuum islands of opposite phases (and with the same pressure profiles) grow as the $<\beta>$ increases. The middle diagram in Figure 2 shows a configuration at $<\beta>=0.4\%$ in which the current in the helical tuning coil in H-1NF has been adjusted to keep the resonant surface inside the plasma (the current was reduced from 3.2% to 3.0% of the central core current). At still higher $<\beta>=0.65\%$ (and with 2.7% helical, on the right side of Figure 2, the rotational transform "buckles" to give two resonant 6/5 surfaces having opposing phases. The merging of these surfaces at still higher $<\beta>$ would give a homoclinic double island chain [5,7].

The final sequence has a pressure profile, proportional to $(1-\psi)^3$, which is intermediate between the previous two cases and uses some careful tuning of the helical tuning coil to produce another example of self healing in which the single island chain *bifurcates* to a double island chain before growing again with the opposite phase. The minimum width configuration, which is shown in Figure 3, has $<\beta>=0.2\%$ and a helical tuning current of 3.16%.

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