EXPERIMENTAL INVESTIGATION
OF THE MAGNETIC STRUCTURE
IN THE H-1 HELIAC

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ABSTRACT. The results of an experimental study of the magnetic structure in the H-1 heliac are presented. Electron beam magnetic mapping has confirmed the existence of closed nested flux surfaces, in good agreement with a computer model. Measurements over a wide range of helical winding currents demonstrated a variety of attainable magnetic configurations within a rotational transform range of $0.6 \leq \tau_0 \leq 1.8$. The observed islands can be attributed to deduced small errors in the coil alignment in H-1. A magnetic island study and a correction in the model to fit the experimental observations revealed the error sources in the magnetic field.

1. INTRODUCTION

A heliac is a stellarator-type helical axis device in which magnetic structure is formed by a toroidally directed central conductor (to produce a tokamak-like poloidal field) and a set of toroidal field coils whose centres follow a helix around it. Such a configuration is capable of producing nested helical flux surfaces [1]. The addition of an $l = 1$ winding wrapped around the central ring conductor greatly improves control of the rotational transform and shear [2] and makes it possible to avoid unstable configurations. The magnetic configuration of the heliac is characterized by a deep magnetic well, relatively low shear and has a high rotational transform per field period ($0.2 < \tau / N < 0.7$) compared with conventional stellarators. The last two properties can be potentially dangerous for plasma confinement since the higher the rotational transform per period the more low order resonances exist. Magnetic islands due to these resonances can break the flux surfaces [3, 4], especially in a low shear configuration [5].

Magnetic islands can develop on rational magnetic surfaces, (i.e. where the rotational transform has a rational value: $\tau = n/m$) when a perturbation field having toroidal and poloidal mode numbers $n$ and $m$ resonates with the rotational transform. If no error field exists, `natural' or intrinsic resonances (having $n = kN$, $k = 1, 2, 3, \ldots$) are still present. The magnetic field structure inevitably differs from the ideal configuration due to the errors in coil assembly, stray magnetic fields and modelling approximations of the design computations. When the $N$ fold toroidal symmetry of the magnetic field is broken by the errors, new resonances can arise, some of which can destroy the nested flux surfaces.

This paper describes experimental measurements of the vacuum magnetic structure in the H-1 heliac. The purpose of the study is to demonstrate the existence of closed magnetic surfaces and to search for field errors and their sources. Investigation of the potentially fragile configurations (containing low order resonances) is necessary in order to avoid them in plasma experiments or to control their presence. It also helps the error source to be identified by comparing numerical simulations with experimental measurements.

The magnetic field structure is usually mapped using low energy electrons (either from a directed electron beam [6–9, 10, 11] or an emissive filament [12, 13]) injected along the magnetic field lines. The electrons follow and are approximately confined to the magnetic field lines so that one can monitor the intersection of their trajectories in a given poloidal cross-section using a fluorescent detector or a electric probe (magnetic mapping technique). Alternatively, one can analyse the confinement of the electrons by measuring electron current on the walls of the vacuum chamber or a transparent grid (stellarator diode and triode technique).

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In the present work we use a directed electron beam and fluorescent target to monitor the field line intersection within a poloidal cross-section of the magnetic surface. In addition, an electron current collector is used to detect the position of the magnetic axis and/or of magnetic surfaces in the toroidal field period other than that occupied by the fluorescent target. The directed electron beam technique also makes measurements of the rotational transform possible.

The H-1 coil arrangement and details of the diagnostic technique are discussed in Section 2. The results of the magnetic mapping are presented in Section 3, including a detailed study of the standard magnetic configuration and magnetic islands. Section 4 gives the conclusions.

2. COIL ARRANGEMENT AND DIAGNOSTIC METHODS

H-1 is a medium sized heliac [14], that has the following parameters: major radius \( R_0 = 1.0 \) m, mean minor radius \( a \sim 0.2 \) m, number of field periods \( N = 3 \) and a wide range of rotational transform at the magnetic axis: \( 0.6 \leq \alpha \leq 2.0 \).

The coil configuration of the H-1 heliac shown in Fig. 1 consists of 36 toroidal field (TF) coils of radius \( a_T = 0.383 \) m with their centres located on the three period toroidal helix around the poloidal field (PF) coil (central ring conductor).

The \( l = 1 \) helical winding (HW) that provides additional control of the rotational transform and shear encircles the central ring three times in phase with the TF coils. Two sets of vertical field coils, inner (IVF) and outer (OVF) (located outside the vacuum tank), control the variation of the vertical magnetic field with major radius.

Configuration studies are performed with a steady state magnetic field at the axis of \( B_0 \leq 0.16 \) T. Whenever possible the coils were connected in series, though a shunt was used for adjustment of the current in the helical winding. The value of the vertical magnetic field is changed by varying the number of connected turns in the outer vertical coils. We use the ratios \( H = (Iw)_{\text{HW}}/(Iw)_{\text{PF}} \) to characterize the current scan in the helical control winding and \( V = (Iw)_{\text{OVF}}/(Iw)_{\text{PF}} \) for the vertical field characterization (where \( I \) is the current and \( w \) is the number of turns in the corresponding coil). For the standard magnetic configuration \( H = 0 \) (no current in the helical winding) and \( V = 0.22 \) (8 turns in the OVF coil).

Figure 2 shows a plan view of the experimental apparatus. The electron gun used for the H-1 field mapping can be positioned anywhere in a poloidal cross-section (fixed toroidal angle). The gun consists of a thoriated tungsten filament inside a stainless steel cylinder (6 mm diameter) with an exit aperture of 0.7 mm.

The electron beam detection system combines the ideas of two well known methods, namely, the fluorescent rod technique [7, 9, 10] and the fluorescent mesh technique [6, 8, 11, 15, 16]. The steerable fluorescent rod array used in H-1 [17] consists of 21 phosphor coated wires (0.3 mm diameter) mounted on a bean shaped frame. The frame is mounted on the helical winding on a Teflon bearing that allows the fluorescent target to pivot around the central ring conductor within the angle range \( \pm 15^\circ \).

The target is driven by a stepping motor located outside the vacuum tank through a bellows so that, when scanned, the wires collectively can cover the entire poloidal cross-section of the torus. The interception of the electron beam by the target causes the wires to fluoresce at typically 10 to 20 positions for a fixed target location. As the array is scanned over an electron drift surface, an image consisting of up to 200 interceptions (punctures) is formed. The images are recorded with a Reticon CCD camera for further processing and geometrical transformation to correct perspective distortion in the optics.

To monitor the position of the magnetic surfaces at different toroidal locations (especially important in the presence of symmetry breaking field errors), an electron current collector (4 mm diameter copper disc isolated from ground) is inserted in a poloidal cross-section displaced one field period (120\(^\circ\) toroidally) from both the fluorescent target and the electron gun. Measurement of the electron current on this collector as a function of its position establishes location of the magnetic axis and the shift of the magnetic surfaces in each of the three field periods: at the electron gun (240\(^\circ\)), the fluorescent target (120\(^\circ\)) and the electron current collector (0\(^\circ\)).

The electron beam is attenuated as it travels around the torus. The attenuation rate depends mainly on the background pressure in the vacuum tank and on the transparency of the experimental apparatus. The pressure is kept typically at \( 4 \times 10^{-7} \) torr during mapping of the magnetic surfaces and the electron gun filament is biased negatively at 300 V with respect to the grounded gun anode and grounded H-1 coil shielding. As the pressure increases, excitation and ionization of the background gas by the electron beam makes the path of the electrons visible. The brightest tracks (up to ten transits around the torus) are observed with helium pressure \((0.7-2) \times 10^{-4} \) torr. In this pressure range attenuation of the electron beam is sufficiently great to allow unambiguously the toroidal transit number \( n \) for each visible track to be determined by its relative brightness. Superimposing the images of the visible tracks on the...
FIG. 1. Coil arrangement of the H-1 heliac.

FIG. 2. Plan view of the electron beam mapping experiment.
point images produced by the fluorescent target allows the
toroidal transit numbers corresponding to the poloidal
punctures on the target image to be identified. In this way
the rotational transform \((t = n/m)\) can be determined with
an accuracy of 1.5\% (eight transits used).

3. RESULTS OF MAGNETIC MAPPING

3.1. Standard magnetic configuration

Computed flux surfaces in the standard magnetic
configuration of H-1 \((H = 0, V = 0.222)\) are shown in
Fig. 3(a). The computed surface of greatest radius is
limited by the stainless steel jacket of the helical winding.
In experiments, the outermost closed magnetic surface is
defined by a diagnostic limiter, namely the target frame

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\text{FIG. 3. Flux surfaces, (a) computed and (b) measured at } \phi = 120^\circ
\text{ for the standard configuration of the H-1 heliac; (c) probe measure-
ments at } \phi = 0^\circ. \text{ The electron gun is positioned at } R = 1.25 \text{ m (open }
\text{squares) and } R = 1.34 \text{ m (solid circles).}
\]

The number of detectable toroidal transits for the outer
surfaces is typically 150–200. This decreases as the
electron gun moves in the direction of the magnetic axis
owing to the decrease in relative transparency of the
experimental apparatus (the larger fraction of the surface
outline is blocked by the electron gun itself at smaller
minor radii).

Measurements of the electron current using the current
collector located toroidally at \(\phi = 0^\circ\) are presented in
Fig. 3(c) for two positions of the electron gun
\((\phi = 240^\circ)\): \(R = 1.345 \text{ m} (\text{solid circles})\) and \(R = 1.25 \text{ m}
(open squares). When the electron gun is placed close to
the outermost surface and the collector moves inward

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\text{FIG. 4. Measured (squares) and computed (solid line) rotational}
\text{transform versus distance from the magnetic axis for the standard}
\text{magnetic configuration.}
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The rotational transform for the standard configuration is determined as described in Section 2. To limit the number of detectable poloidal punctures on the magnetic surface to 15-20, the surface images for these measurements are obtained at a helium pressure $P \sim 10^{-5}$ torr.

A rational surface $m/n = 8/7$ observed for a gun position of $R = 1.315$ m is used for calibration of $\iota$. Figure 4 presents measured and computed profiles of the rotational transform. The discrepancy between the results is 1%. The standard configuration is characterized by $1.1 < \iota < 1.2$ and relatively low positive shear. Introduction of the diagnostic limiter restricts flux surfaces so that $\iota$ does not reach the value of $\iota = 1.2$ and experimental surfaces do not exhibit the $n = 6, m = 5$ island chain clearly visible in the computed configuration in Fig. 3(a).

The rotational transform measurements for the configurations with non-zero current in the helical winding give a larger relative discrepancy between experiment and computations: about 2.5% at $H = 0.095$. Inaccuracies in the computer model of the helical winding (its shape, location or swing radius), manufacturing and positioning of the HW and in HW current measurements could contribute to this discrepancy.

Most of the results presented in this paper were obtained for an electron beam energy of 300-400 eV and a magnetic field at the magnetic axis $B_0 = 0.15$ T. It is important to consider whether the shift of the observed electron drift surfaces with respect to the true magnetic surfaces is significant in H-1, as has been reported for some stellarator type machines [7, 11].

Figure 5 shows two surfaces observed in the standard magnetic configuration. The position of the electron gun is the same for both surfaces. Surface 1 corresponds to an electron energy of $U_e = 250$ eV and the magnetic field $B_0 = 0.154$ T. Surface 2 was measured at $U_e = 600$ eV and $B_0 = 0.0385$ T. The largest relative shift of the drift surfaces for these two cases is about 3 mm with a higher energy surface lying inside the lower energy one. An estimate of the displacement of the drift magnetic axis with respect to the magnetic axis [18] $\Delta = -(\pm v_{st}/\Omega_e)$ (where $\Omega_e$ is the electron cyclotron frequency and $v_{st}$ is the electron velocity in the direction of the magnetic field; the electron velocity perpendicular to the magnetic field does not exceed $0.1v_{st}$ so that its contribution to $\Delta$ is negligibly small) gives corresponding shifts for the surfaces 1 and 2 of 0.3 and 2 mm. Estimated relative shift of the two surfaces is 1.7 mm, which is a factor of 2 smaller than the maximum experimentally observed deviation. We also measured the relative shift of the drift surfaces by reversing the direction of the magnetic field. For the electron energy and magnetic field used in these experiments (300 eV, 0.154 T) the shift of the drift surfaces was found to be less than 2 mm, i.e. within the spatial resolution of the experimental method.

Using the technique described above, we have studied field topologies for a wide range of rotational transforms ($\iota(0) = 0.7$ to $\iota(0) = 1.8$) and vertical fields ($V = 0.11-0.33$).

3.2. Magnetic islands

Two types of magnetic islands are observed in H-1: those inherent to the configuration due to the threefold toroidal symmetry and others that can occur as a result of the breaking of this symmetry. An example of a low order intrinsic island is shown in Fig. 6. An increase in the vertical field from $H = 0.22$ (Fig. 6(a)) to $H = 0.33$ (Fig. 6(b)) leads to an increase in rotational transform from $\iota_0 = 1.45$ to $\iota_0 = 1.5$ as shown in Figs 6(c) and (d). A resonance of the rotational transform $\iota = 1.5$ with the $n = 3, m = 2$ field component when the magnetic shear

along the major radius two peaks appear in the radial profile of the collector current $I_p$ corresponding to its intersections with the magnetic surface. When the electron gun is located very close to the magnetic axis only one peak is observed with the collector.

The rotational transform along the major radius two peaks appear in the radial profile of the collector current $I_p$, corresponding to its intersections with the magnetic surface. When the electron gun is located very close to the magnetic axis only one peak is observed with the collector.
is very low (Fig. 6(d)) leads to the bifurcation of the magnetic surfaces to form an O-X-O island structure.

The highest order magnetic islands are found in the configuration containing an \( t = 1.8 \) surface — the highest \( t \) attainable in the present experimental arrangement with \( H = 0.32, V = 0.222 \) (Fig. 7(a)). These islands can also be identified as intrinsic, due to the \( n = 9, m = 5 \) field harmonic.

An example of an island chain that appears as a result of alignment errors is shown in Fig. 7(b). In this configuration \( (H = 0.0418, V = 0.222) \) the computer model predicts no islands unless a symmetry breaking error is introduced. The error leads to the development of the \( n = 5, m = 4 \) magnetic islands about the \( t = 1.25 \) magnetic surface. The island width is about 0.028 m at the tip of the bean. As the current in the helical winding increases the island structure moves inside and the island width decreases.

An \( m = 1 \) island is observed in a magnetic configuration that includes an extended region where the rotational transform \( t \) is 1, as shown in Figs 8(c) and (d). The development of the magnetic structure can be seen in the course of the helical current scan from \( H = 0 \) to \( H = -0.095 \) (negative \( H \) corresponds to the direction of current in the helical winding opposite to that in the central ring conductor) when the rotational transform at the magnetic axis changes from \( t_0 = 1.15 \) (Fig. 8(a)) to \( t_0 = 0.9 \) (Fig. 8(f)). Initially a small O point develops.
FIG. 7. Measured magnetic islands: (a) the \( n = 9, m = 5 \) island at the \( \iota = 1.8 \) surface and (b) the \( n = 5, m = 4 \) island at the \( \iota = 1.25 \) surface.

FIG. 8. Development of the magnetic structure during a scan of the helical winding current. The rotational transform changes from (a) \( \iota = 1.15 \) to (f) \( \iota = 0.9 \) for: (a) \( H = 0 \), (b) \( H = -0.042 \), (c) \( H = -0.048 \), (d) \( H = -0.052 \), (e) \( H = -0.062 \), (f) \( H = -0.095 \). Vertical field parameter \( V = 0.22 \).
into a large \( m = 1 \) island. This structure is toroidally asymmetric: an \( m = 1 \) magnetic island is observed in the \( \phi = 120^\circ \) cross-section at \( z = 0 \) when the electron beam is launched at the toroidal angle \( \phi = 240^\circ \) well above the equatorial plane (\( z_{\text{gun}} \approx +0.04 \) m). The current response from the current collector is monitored at \( \phi = 0^\circ \) when the probe is located below the equatorial plane at \( z_p = -0.04 \) m. This suggests a perturbation in the axis position that is not threefold symmetric, and hence breaking of the toroidal symmetry due to a resonance in the presence of an error field.

4. DISCUSSION AND SUMMARY

A detailed experimental study of the vacuum magnetic field in the H-1 heliac has been performed. The existence of closed, nested surfaces in most of the accessible magnetic configurations has been demonstrated using the electron beam mapping technique. For the standard magnetic configuration, good agreement is found between the computed and measured flux surfaces. The threefold toroidal symmetry for this configuration was carefully tested. Both the magnetic axis position and the radius of the flux surfaces were found to coincide (within the spatial resolution of the diagnostic methods) in all three toroidal field periods. Since the standard magnetic configuration in the H-1 heliac is not subject to low order resonances inside the closed surfaces it is quite insensitive to small coil misalignments.

Computationally observed \( n = 6, m = 5 \) magnetic islands in the standard magnetic configuration that may occur close to the outermost flux surface (Fig. 3(a)) were not observed in the present experiment owing to limiter obstruction in this region.

The observed magnetic islands include those intrinsic to the three period heliac configuration as well as those due to coil positioning errors. The unknown perturbation fields giving rise to the latter can be searched for computationally. Configurations containing low order resonances are the most suitable for this error search since they are extremely sensitive to the presence of even small error fields. The procedure of the error search in H-1 includes:

(a) Experimental mapping of flux surface configurations sensitive to toroidal symmetry breaking error fields;
(b) Introduction into the code of plausible coil displacements that could lead to the observed field perturbations;
(c) Comparison with measured flux surfaces including higher order resonances;
(d) If necessary the field error in the code has to be modified and the procedure repeated.

Such iterative modification of the computer code to fit the experiment starts with the configuration that includes the \( \iota = 1 \) resonance (Fig. 8). The \( m = 1 \) island develops as a result of the resonance of the \( \iota = 1 \) surface with a symmetry breaking field perturbation. Computer modelling of this configuration (\( H = -0.04 \) to \(-0.06, V = 0.222 \)) has given good agreement between measured and computed surfaces when the central ring conductor is shifted upwards by 2 mm and outwards by 1.5 mm. The results of the computations shown in Figs 9(a)–(c) also

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**FIG. 9.** Computed flux surfaces for the configuration as in Fig. 8(c) (\( H = -0.048 \)) in three toroidal field periods: (a) \( \phi = 0^\circ \), (b) \( \phi = 120^\circ \), (c) \( \phi = 240^\circ \).
agree with the experiment on the toroidal asymmetry of this configuration.

This small central ring displacement (which is within the range of mechanical adjustments and can be minimized) is the largest error found. Similarly, the \( n = 5, m = 4 \) island structure (Fig. 7(b)) is not an intrinsic resonance. To fit the width and the phase of this structure to those experimentally observed, known errors due to the PF coil crossover error field were introduced into the model in addition to the central ring displacement.

Examples of intrinsic islands are the \( n = 3, m = 2 \) (Fig. 6(b)) and \( n = 9, m = 5 \) (Fig. 7(a)) islands. Although they exist even in an ideal magnetic field, their width and phase are affected by the field errors. When all the above mentioned field errors (plus a small correction to the nominal helical winding swing radius) are included into the model, good agreement of the code predictions with the experiment is observed for all accessible magnetic configurations.

Thus, a detailed investigation of the magnetic field structure prior to plasma experiments in the H-1 indicates the range of the configurations that can be potentially dangerous to the confinement or can lead to the enhanced transport.

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**REFERENCES**


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