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Validation of HF coil location by field mapping on CTH

Field mapping is typically performed on stellarators to confirm the existence of closed nested flux surfaces. Qualitative agreement is often obtained between the simulation and measured vacuum flux surfaces before the device is used in further plasma experiments. In this study, field mapping results on the Compact Toroidal Hybrid (CTH) are quantitatively compared to simulation results and through a fitting procedure the simulation coil model is modified to achieve a better agreement between the experimental and calculated results.

Description of the CTH facility

CTH [1,2] at Auburn University is a 5 field period, low-aspect-ratio torsatron with a major radius of $R_0 = 0.75$ m and a minor radius $a_{\text{vessel}} = 0.29$ m. The CTH device is designed to investigate the MHD stability of current-carrying compact stellarator plasmas.

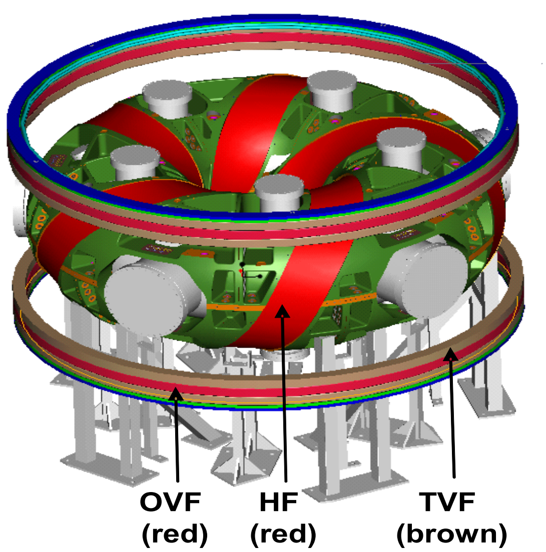

Fig. 1. The CTH device.

The CTH facility is shown in Fig. 1. The 96-turn helical field (HF) coil consists of a single $\ell = 2$, $m = 5$ coil. The HF coil was designed to have stellarator symmetry. The helical path followed by the center of the HF coil is expressed by radial and toroidal winding laws which are both functions of the poloidal angle, θ:

$$r_c(\theta) = ax_0 + ax_1\cos(\theta) + ax_2\cos(2\theta) + \ldots$$
$$+ \mathrm{bx}_1\sin(\theta) + bx_2\sin(2\theta) + \ldots \qquad (1)$$
$$\varphi(\theta) = \frac{2}{5}\theta + af_0 + af_1\cos(\theta) + ax_2\cos(2\theta) + \ldots$$
$$+ bf_1\sin(\theta) + bf_2\sin(2\theta) + \ldots . \qquad (2)$$

Here, r_c is the minor radius of the coil center and φ is its toroidal location. The values of the coefficients (ax, bx, af, bf) of the designed HF coil winding law are listed in Table 1.

The HF coil was constructed by winding the flexible conductor into a helical trough surrounding the vacuum vessel (see Fig. 1), thus defining the toroidal portion of the winding law. The HF trough dimensions were machined to tolerances of ±0.5 mm. Additional uncertainties in the toroidal winding law of Eq. (2) are estimated up to ±1 mm

In this issue . . .

due to compression of the flexible conductor inside the trough.

The radial position of the coil was expected to exhibit greater deviations from the design because the outer radius of the HF coil is not constrained by the winding frame. Measurements of the radial build of the HF coil were made during the construction process to determine deviations from the radial winding law of Eq. (1). The deviations generally show similar behavior from one field period to the next. These measurements were averaged and used to develop a new field period–symmetric HF winding law with the coefficients listed in the second column of Table 1. The measured coil winding law shows a small deviation from up-down symmetry of the design coil.

HF coil coefficients	Designed	Measured	Optimized
ax_1 (m)	0.385	0.3836	0.3826
ax_2 (m)	0	0.0000	0.0012
ax_3 (m)	0	0.0005	-0.0011
ax_4 (m)	0	0.0001	0.0009
bx_2 (m)	0	-0.0007	-0.0009
bx_3 (m)	0	0.0002	0.0002
bx^4 (m)	0	-0.0001	0.0004
af_1 (radians)	0	0.0000	0.0002
af_2 (radians)	0	0.0000	0.0005
af_3 (radians)	0	0.0000	0.0002
af_4 (radians)	0	0.0000	0.0013
bf_2 (radians)	-0.252	-0.2520	-0.2521
bf_3 (radians)	0.052	0.0520	0.0530
bf_4 (radians)	-0.024	-0.0240	-0.0243

Table 1. HF coil winding law coefficients for the designed, physically measured (before optimization), and optimized (after optimization) coil model.

Also shown in Fig. 1 are the outer vertical field (OVF) and trim vertical field (TVF) coils needed to produce the vertical field necessary for confinement equilibrium. The HF and OVF coils are electrically connected in series. The current in the TVF coil is independently controlled for radial positioning of the plasma. For clarity, the 10 toroidal field coils, shaping vertical field coil set, and ohmic heating coil system are not shown in Fig. 1 so that the HF coil can be more clearly viewed.

Vacuum field mapping

Vacuum field mapping experiments were performed on CTH to confirm the existence of closed nested flux surfaces and to compare the shape and rotational transform of the observed surfaces with calculation. The field mapping results presented in this note focus only on the HF, OVF, and TVF coils.

Field mapping measurements were performed with techniques similar to those used on previous devices [3,4]. A movable electron beam source is used in conjunction with a screen or movable wand coated in zinc-oxide viewed by a digital camera capable of long exposure photographs. Points of interest in the resulting Poincaré puncture plot photograph undergo a calibrated transformation to coordinates in real space using LabView Vision Software® [5]. The measured surfaces are then compared to those predicted by a field line following code [6], with the goal of quantifying the discrepancies between the actual coils of CTH and the simulation coil model used in the calculation, or other sources of error such as ambient magnetic fields. While images can be made of the full cross section of flux surfaces, the analysis in this article makes use of the location and rotational transform of the magnetic axis because it is a fixed point, and it can be determined both experimentally and through simulation.

Multiple field mapping experiments were performed with DC power supplies at $I_{HF/OVF}$ = 300 A (B_0 = 450 G). This is approximately 7% of the normal operating field used in plasma experiments. In these studies, the TVF current I_{TVF} was varied from 9% to 17% of the HF current (B_0 = 20 G–38 G). The magnetic axis position and rotational transform were measured at two toroidal locations, φ = 36° and φ = 252°. The experimental magnetic axis positions from one such TVF current scan are shown in Fig. 2. As expected, the increased vertical field produced by increasing I_{TVF} shifts the magnetic axis radially inward by up to 0.15 m. The vertical position of the axis is found to shift upward, above the midplane by 0.022 m as the I_{TVF} is increased, indicating that in this regime the magnetic field structure has an up-down asymmetry.

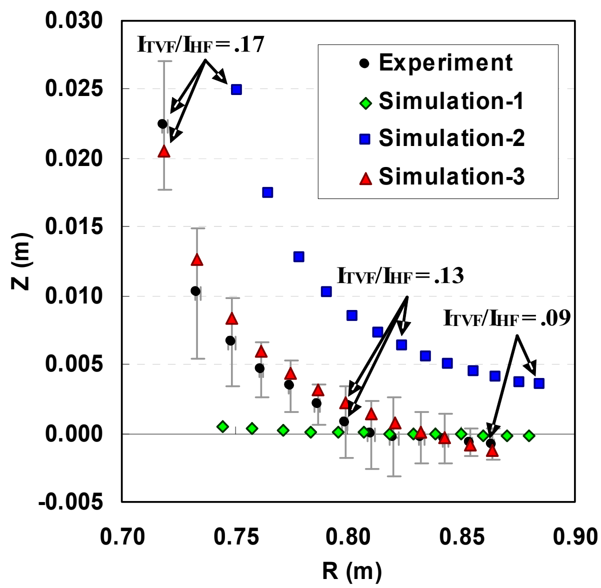

Fig. 2. Magnetic axis locations in (*R*, *Z*) for a TVF current scan. The results of Simulation-1 are computed with a model of the coils based on the original design and the expected ambient magnetic field of the laboratory. The results of Simulation-2 are computed with a physically measured model of the coils (before optimization). The results of Simulation-3 are computed with an optimized model of the coils based on the fitting results.

Simulation Results

The location of the magnetic axis is calculated using a field line following code and compared with the experimental field mapping results. With the original HF coil winding law, the calculated magnetic axis remains near the midplane regardless of changes in the value of I_{TVF} (Simulation-1).

When the adjusted HF coil model based on the physical measurements made during the coil construction is used in the simulation, the calculated magnetic axis position is observed to shift above the midplane as I_{TVF} is increased (Simulation-2). The results of this calculation are similar to the behavior of the axis seen experimentally, although the calculated data has a radial offset of $\Delta R = 0.02$–0.03 m and a vertical offset of $\Delta Z = 0.005$–0.015 m relative to the experimental data. These discrepancies are well outside the experimental error bars, suggesting that the coil model could be further improved to more accurately describe the results of field mapping.

The discrepancies between the experimental results and those of Simulation-2 are caused not only by inaccurate knowledge of the actual "as-built" HF coil winding law but also by limited knowledge of the background fields present within the vacuum vessel at the time of the experiment. Owing to the presence of ferromagnetic material in the vicinity of CTH (pipes, structural rods in the floor and ceiling, etc.), the background field (the field not due to the currents in the coils) was measured to be significantly different from the expected Earth's field. Measurements made with a hand-held Hall probe in a separate experiment have found that the remnant vertical background field can be as great as 2.5 G. In addition, the background field has been shown to be affected by the currents in the CTH coils and thus can vary depending on the past operational history of CTH. The initial aim of these studies was to use the results of field mapping to accurately model the HF coil winding law along with the other coil positions. With the discovery of a variable background field, extracting information about the coils becomes more difficult and now must include an additional calculation of the background field itself.

A least squares minimization fitting routine [7] has been used to modify the coil parameters in the coil model to minimize the differences between the experimental and computed magnetic axis positions and rotational transforms. Here the term "coil parameters" refers not only to the coefficients in the HF coil winding law [Eqs. (1) and (2)], OVF coil positions, etc., but also to the background field which now must be included in the optimization. In the calculation, the HF coil winding law is assumed to be field period symmetric. The background field is assumed to be uniform throughout the volume of the vacuum vessel with the horizontal and vertical field components to be determined by the fitting routine.

Starting from the physically measured coil positions, the coil optimization procedure was applied to deduce a better coil model. The positions of the magnetic axis computed from the optimized coil model are shown in Fig. 2 (Simulation-3). Comparing the calculated axis positions from before and after optimization, we find the results from the new coil model agree much better with the experimental axis positions than those from the mechanically measured model. The differences in radial position of the axis are reduced to less than 0.001 m, while the differences in vertical position are less than 0.002 m.

The coefficients of the slightly modified HF coil model are given in Table 1. We find that the modifications to the measured HF coil winding law are less than the uncertainties of the coil position measurements. Accurate field mapping measurements thus allow fine adjustments to be made to the HF coil winding law, below the tolerance level achieved using physical measurement techniques. The OVF/TVF coil parameters were left nearly unchanged by the coil optimization. The coil optimization was also used to determine the background field in the laboratory during the experiment. The three components of the earth's field (east, north, up) for Auburn, Alabama, are $\boldsymbol{B} = (0.0, 0.2, -0.4)$ G [8], whereas the background field values computed by the coil optimization are significantly larger at $\boldsymbol{B} = (0.1, 0.7, -2.1)$ G. Overall the new coil model required no unreasonable modifications to successfully simulate the experimental results.

In conclusion, the optimization process was able to account for the observed radial and vertical shift of the experimental magnetic axis by making small modifications to the HF coil winding law and background fields. The optimized HF coil winding law was found to have only slight deviations from both the designed and measured winding laws (although these deviations in fact can break the up-down symmetry of CTH). In addition, the fitting routine identified a characteristic background field vector needed to adequately model the experimental results. The presence of the background field, particularly a time-varying one, limits the ability to make further improvements in the geometrical coil parameter values. To gain further information about the HF/OVF/TVF coils, further field mapping experiments should be performed under conditions where the background field is constant or at least known more accurately.

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Motojima to Receive FPA Distinguished Career Award

Professor Osamu Motojima, Director of the National Institute for Fusion Science (NIFS) in Japan, has been selected by Fusion Power Associates (FPA) Board of Directors to receive its 2008 Distinguished Career Award. The Award will be presented to Professor Motojima at Fusion Power Associates Annual Meeting and Symposium in Livermore, California, December 3–4, 2008.

In selecting Professor Motojima, the FPA Board recognizes his key roles in the design and construction of a series of large stellarator facilities and subsequent experimentation on them, in fostering international cooperation in fusion research, and his leadership of the NIFS.

Fusion Power Associates Distinguished Career Awards have been given annually since 1987 to individuals who have made distinguished lifelong career contributions to fusion development. A list of previous recipients is posted at http://fusionpower.org and click on Awards.

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