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MHH2 Experimental Design Studies

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Abstract

Three methods of constructing a MHH2 quasi-axisymmetric experiment are explored: modular coils, conducting shell, and saddle coils. The conducting shell and saddle coils make use of existing tokamak toroidal field coils. The evolution of the flux surface shape is difficult to control with the shell. Saddle coils must be well separated from the plasma to generate good magnetic surfaces, but may be attractive for MHH2-like configurations.

Keywords:

quasi-axisymmetric stellarator, modular coils, conducting shell, saddle coils

1. Introduction

Three methods of constructing a quasi-axisymmetric stellarator physics experiment are being developed and analyzed to determine their flexibility and relative cost: modular coils, a conducting shell, and saddle coils. The magnetic configuration used for these studies is the MHH2, a two field period, low aspect ratio stellarator. The designs are being studied in consultation with Paul Garabedian who developed this concept [1]. A parallel effort is under way to further optimize the magnetic configuration [2].

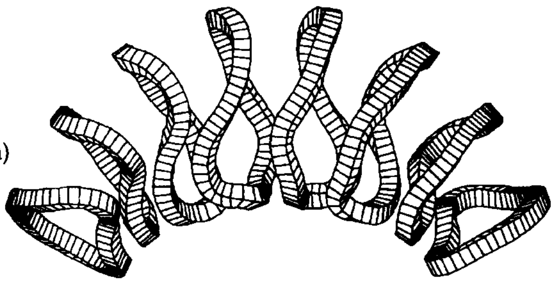
2. Modular Coil Design

The design studies started with the modular coil design since it was the embodiment of the MHH2 first worked out by Garabedian and the design was, therefore, in a mature state. A top and side view of half of the coils is shown in Fig. 1.

This design is advantageous because it has only 16 coils which, though shaped three dimensionally, are not linked so that they can be changed out like a tokamak TF coil. The distance to the plasma edge from the coils is substantial which allows good experimental access and scaling the configuration to a reactor allowing a blanket between the coils and the plasma.

A point design was developed at a major radius of

(a)



(b)

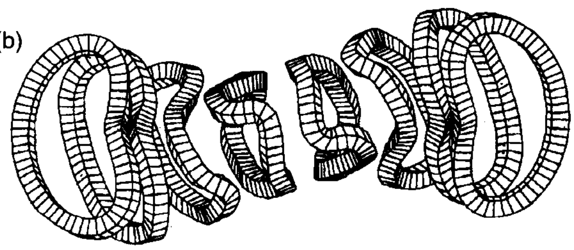


Fig. 1 Modular coils for MHH2 (a) top view (b) side view.

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3.5 meters and engineering analyses were performed. The design concept has the modular coils supported by cases which are tied together by an inter-case shell structure. The case and half the inter-case structure on each side of it form a monolithic module tentatively planned to be a casting. This structure would also act as the winding mandrel for the coil. There would be four such unique modules. Four of these modules would make up a quadrant of the device. All four quadrants would be identical, just flipped relative to each other to form the whole MHH2 device.

The force pattern on the MHH2 repeats every field period so a structural NASTRAN model was generated for half the device. A series of runs were made with the electromagnetic, gravity, and thermal loads imposed for a field level of 2.5 Tesla and an equivalent square wave, ESW, of 6 seconds. The case and inter-case structure thicknesses were adjusted to give acceptable stress levels in these structures and the coils.

Using this design as a reference, following basic scaling relations, and holding the coil current density constant, the modular coil design can be scaled over a range of sizes. Figure 2 shows a plot of this parameter space. The horizontal scale is the major radius of the device. The left-hand vertical scale is the field strength on the magnetic axis achievable with a coil current density that allows an ESW pulse of 6 seconds. The right-hand scale is the width of the neutral beam access at the scaled major radius. In the right-hand margin are the widths of the available neutral beams from PBX-M and TFTR. Noted on the bottom of the plot are the radii at and above which these two beam line sets would fit a modular MHH2. Also plotted is the field level and

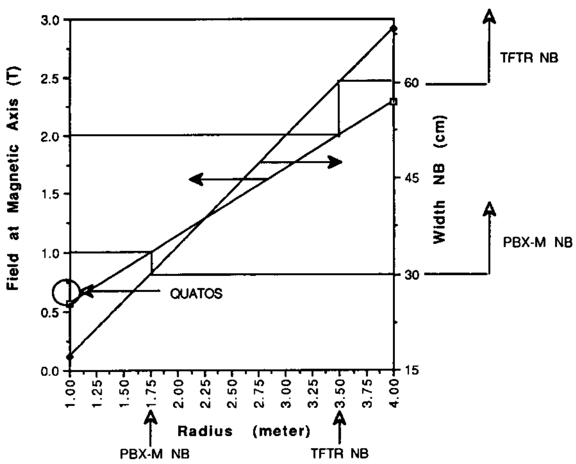

Fig. 2 Scaling of the modular coil design for MHH2.

major radius of QUATOS, the MHH2 device proposed by Auburn University, which fits the scaling.

Scaled to the minimum major radius that allows use of the PBX-M neutral beams, the modular coil design would fit into the PBX-M test cell but would not into the existing PBX-M vacuum vessel. The field level would be 1 Tesla for room temperature copper coils. Seeking to minimize the cost and difficulty of a MHH2 experiment and desiring a higher field level, it seemed like other approaches should be considered.

3. Conducting Shell Design

At this point in the study, it was suggested[3] that an existing Tokamak could be converted to a MHH2 stellarator through the introduction of a shaped conducting shell into its vacuum vessel. The eddy currents induced in this shell by the rise of the toroidal field, TF, would establish the desired helical magnetic topology. For such a design, the conducting shell would be near the last closed flux surface, providing a fixed boundary equilibrium. The advantages of this design are that fabricating and installing the shell would be much less expensive than fabricating the modular coils and that the magnetic configuration could be more easily changed by changing out the shell.

Since PBX-M has a large vacuum vessel and a history of new configurations being fabricated within the vessel, a study was undertaken to see if the conducting

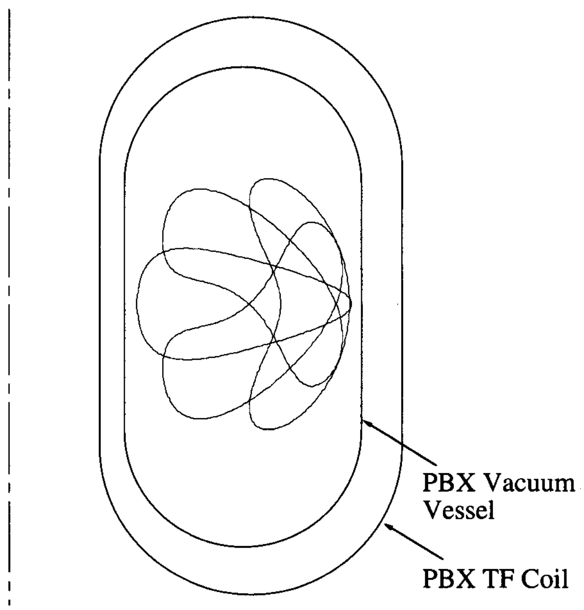

Fig. 3 Cross section showing a number of toroidal cuts of the conducting shell in the PBX-M vacuum vessel.

shell would be feasible at that scale. Figure 3 shows a cross section of PBX-M superimposed on various poloidal cross sections of a MHH2 shell that was developed by P.R. Garabedian to fit within the PBX-M vacuum vessel.

Diagnostic access through a conducting shell was a concern. It was feared that penetrations would perturb the configuration. Therefore, a SPARK model of this shell was developed to solve for the eddy currents induced by the TF to see if shell penetrations would be possible. Figure 4(a) shows a top view of the shell with the eddy current patterns. An interesting result is that the eddy currents flow predominantly on the inboard three quarters of the shell. Almost no current flows near the outboard midplane. The conducting shell design was modified to take advantage of this fact and a uniform gap 30.5 cm high was cut out of the outboard midplane of the shell with minimal effect on the basic magnetics, as shown in Fig. 4(b). This cut allowed the shell design to accommodate the complete set of PBX-M midplane diagnostics and allowed clear access for the PBX-M neutral beams.

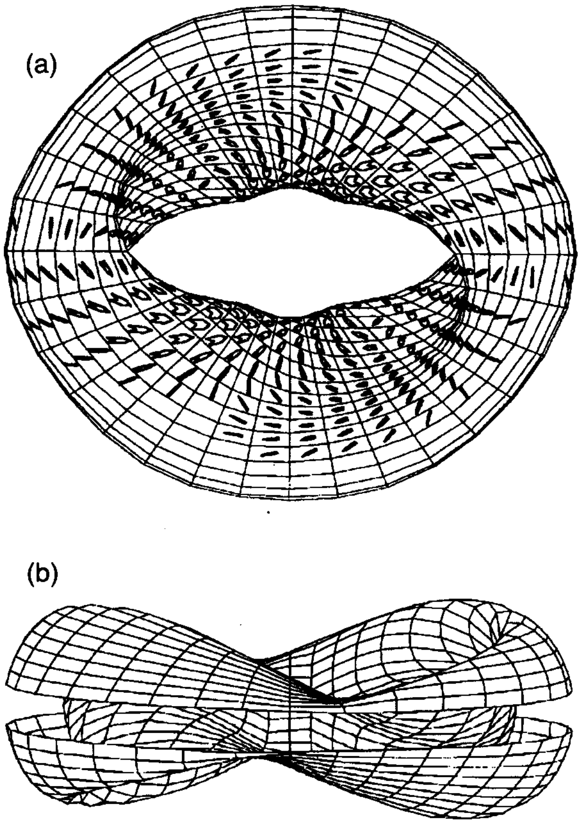

Fig. 4 Conducting shell for MHH2 (a) Showing the eddy current pattern induced by the PBX-M TF, (b) Side view with a 30.5 cm. cut at outboard midplane.

For the conducting shell, the problem is the resistive decay of the currents in the shell. As pointed out by Boozer[4], the effect on the magnetic field in the plasma region enclosed by the shell is mathematically equivalent to the effective radial location of the shell increasing with time,

$$r_{\rm eff} = a \exp\,[2\eta\, t/\mu_{\rm o}\Delta a] \tag{1}$$

with a the actual shell radius, η the resistivity of the shell, t the rise time of the TF, $\mu_{\rm o}$ the permeability of free space, and Δ the shell thickness. For the shell to be effective, its thickness ought to be equal to or less than the skin depth δ given by,

$$\delta = [\eta/\mu_{\rm o}\,\pi f]^{1/2} \tag{2}$$

with f the frequency of the varying field. If we make the approximation that the rise time is a quarter of a sine wave ($f = 1/4t$) and the thickness is equal to the skin depth then

$$t = \Delta^2 \mu_{\rm o}\pi/4\eta\,, \tag{3}$$

and

$$r_{\rm eff}/a = \exp\,[\Delta\pi/2a]\,. \tag{4}$$

Thus, the ratio of the effective radius to the actual radius at the end of the rise time is only a function of the geometry if the thickness equals the skin depth. If we take as an objective to have $r_{\rm eff}/a = 1.2$ in order to maintain control of the flux surface shape then we can force this condition by making $\Delta/a = 0.116$. The problem comes when we look at the resulting rise time required using Eq.(4). For the PBX-M geometric scale with a shell made of 3.5 cm thick copper cooled to liquid Nitrogen temperature, the TF rise time would have to be 0.52 seconds which is probably not practical. This would also be the approximate time scale of flux surface rigidity, which would be too short.

4. Saddle Coil Design

One way to get around the limitations of the resistive decay is to replace the conducting shell eddy current pattern with driven saddle coils which have the shape of the eddy current contours. Such discrete coils have the advantage that the current can be maintained for whatever time is desired. A view of the saddle coils, comparable to the Fig. 4 view of the continuous shell that they are derived from, is shown in Fig. 5.

As noted by Boozer [4], discrete saddle coils have the disadvantage that they destroy the magnetic

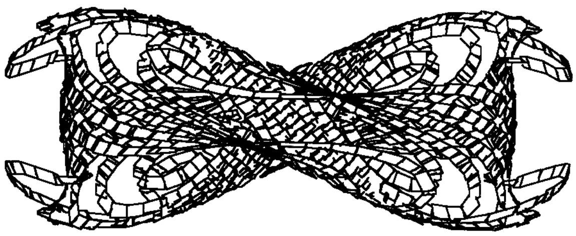

Fig. 5 Side view of equivalent saddle coils.

surfaces near them. Under reasonable assumptions, he estimated that the last good magnetic surface would be at approximately 70% of the radius of the surface on which the coils are located. Field line tracking through these saddle coils confirms this estimate. Further work is required to develop an attractive saddle coil design well separated from the plasma. This may be possible for MHH2-like configurations which allow substantial coil-plasma separation with modular coils.

5. Conclusions and Future Work

Our work to date indicates that a modular coil design for the MHH2 utilizing the TFTR and/or the PBX-M supporting systems and neutral beams is feasible. It would involve fabricating a new coil system as well as a new external vacuum vessel. Though this would certainly not be as expensive as building a whole new device and supporting facility, we want to investigate all approaches that may offer a more cost effective approach to implementing the MHH2. The conducting shell and saddle coil designs offer the ability to reuse existing tokamak coils for a stellarator experiment. We will continue to develop such options including cost estimate comparisons. The conducting shell appears limited to short pulses lengths. A saddle coil design remote from the plasma edge may be attractive.

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