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THE CONDUCTING SHELL STELLARATOR: A SIMPLE MEANS FOR PRODUCING COMPLICATED FIELDS

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One of the main characteristics of stellarators , both helical [1] and modular [2], is that their coil sets must take difficult shapes in order to produce the complicated stellarator magnetic fields. The complex coil shapes make fabrication difficult and costly compared to say the toroidal field, TF, coil set of a tokamak. The conducting shell stellarator, CSS, configuration described in this report shows that complicated stellarator fields can be produced by inducing eddy currents in a conducting shell from a simple TF coil set (a field that varies like 1/R). This technique is applicable not only to a pulsed system at room or cryogenic temperatures, but can be implemented for a superconducting TF with a superconducting shell in a stellarator reactor. The CSS has the added benefit that within this device the metalic shell which can be made up of discrete plates can be changed out and replaced with new plates to create a different stellarator configuration within the same TF coil set. The work of creating the complicated magnetics is done by the passive conductor reshaping the simple TF field.

I. BACKGROUND

There is renewed interest in stellarators in recent years because of the problems in tokamaks with disruptions and with the cost of driving current for steady state. Another developement which has caused this new interest is that techniques have been develeoped to optimize the stellarator configuration to make it have symmetries in magnetic coordinates and to have optimums for various parameters. Furthermore, stellarator designs have been developed with lower aspect ratios and modular coils which improve the prospect for smaller, maintainable stellarator reactors.

The stellarators in operation now or being designed are either based on helical or modular coil systems. Figures 1 and 2 show these two types of coils respectively. As can be seen by inspection, the modular coil system is simpler to fabricate, install, and maintain than the helical coil system and this is the way most of the new stellarators will be built.

However, it can also be noted that the configuration is not very flexible. The coils are expensive and would have to be replaced to implement a substantial configuration change.

The conducting shell stellarator, CSS, described in the following sections was developed to reduce the complexity of the coil system for a stellarator and to allow greater flexibility for experimental operation over a variety of configurations by changing out only passive structures while leaving the basic coils in place.

II. DESCRIPTION OF CSS CONCEPT

The conducting shell stellarator , CSS, is somewhat analogous to the early conducting shell tokamaks.

In the early tokamaks, the rising plasma current induced eddy currents in the shell which prevented any poloidal field from passing through the shell so that the shell became a magnetic surface defining the outer shape of the plasma and establishing the tokamak equilibrium configuration.

In the CSS, the rising field from a toroidal field , TF, coil set induces eddy currents in a shell that is geometrically shaped to have the form of the desired outermost stellarator surface. The shell prevents any field from passing through its surface so that it becomes the outer most, 3D magnetic surface establishing the stellarator configuration.

The early tokamak shell had to be broken electrically toroidally so that the ohmic heating coil flux could induce the toroidal plasma current and broken poloidally so that the toroidal field could reach the plasma.

The CSS shell only has to be broken poloidally so that the toroidal field can reach the plasma. However, it can be broken toroidally for convenience of assembly or disassembly.

In early tokamaks, the conducting shells were copper at room temperature so they had relatively short time constants. The tokamak shells could have been cooled to cryogenic temperatures to increase the shell time constant substantially but tokamak development moved towards active coils to replace the shell as a means of extending the experiment time. If the tokamak shell was a superconducting shell and the plasma current was maintained by non-inductive methods, the result would be a steady state tokamak.

In the same way, the CSS shell can be designed to have various time constants to fit the needs of each experiment. If the experiment need to only establish the configuration for a fraction of a second, room temperature copper may be sufficient. If the experiment requires times that are of the order of 5 to 10 seconds, copper at liquid nitrogen temperature would be a good choice. For steady state experiments the shell can be NbTi or Nb_3Sn with a comparable superconducting TF.

III. COMPUTER MODEL OF ONE EMBODIMENT OF CSS

In order to test the CSS concept, a computer model was developed to simulate a superconducting shell within an axisymmetric toroidal field which varies inversely with major radius: $B_{TF} = Bo\ Ro\ /R$.

The shell shape was picked to be similar to the reference coil shape of the modular stellarator MHH2 [4] to see if a configuration of that family could be established in a CSS.

Figure 3 shows sections through the conducting shell at various toroidal angles, gamma, over one geometric period. The shell has two periods. The form of the shell is shown in Figure 4.

In order to help visualize the configuration, the next few figures show a TF coil set even though the simulation used a 1/R field. Figure 5 shows the shape of one TF coil while Figure 6 shows a projection view of the TF coil set. Figure 7 then combines the TF set and the shell so that the whole CSS configuration can be seen.

The TF field was increased to full value and the eddy currents in the shell did indeed mold the TF field into a MHH2 like magnetic configuration. Figure 8 shows the flux surfaces defined by a poincare plot within the shell at zero gamma. The individual poincare plots for each surface are shown in Figures 9 through 11 with the iota for each surface noted.

Just as with MHH2, the transform is increasing as you move from the outer surface towards the magnetic axis. Figure 12 shows the magnitude of the magnetic field along the magnetic axis for the CSS compared to the magnitude of the driving B_{TF}=Bo Ro/R field. The field along the axis is basically flat as it is in MHH2.

IV. FUTHER WORK NEEDED

The computer model shows that the CSS concept is feasible. However, further work is required to see if a practical embodiment is possible.

A practical experiment will require ports for diagnostics, heating, and pumping. This will require penetrations in the CSS shell. Small ports will probably not be a problem since when one looks at the eddy current distribution on the shell there will no doubt be regions of very low current density where the combined fields are not trying to penetrate the shell. Cutting ports in these locations will not have an impact on the configuration.

However, to make sure of this and to assess if there are low current density regions large enough to accommodate neutral beam access, a more detailed shell model should be constructed and run. It should be noted that the size of a low current region can be designed by introducing a local,external saddle coil which will change the local current density pattern but not the function of the shell.

V. CONCLUSION

The conducting shell stellarator, CSS, configuration described in this report allows complicated stellarator fields to be produced by inducing eddy currents in a passive, conducting shell from a simple TF coil set. This technique is applicable not only to a pulsed system at room or cryogenic temperatures, but can be implemented for a superconducting TF with a superconducting shell in a stellarator reactor.

The CSS has the added benefit that within this device the conducting shell, which can be made up of discrete plates, can be changed out and replaced with new plates to create a different stellarator configuration within the same TF coil set.

The initial work covered in this report shows that a CSS configuration is feasible and the potential benefits warrant the next level of analysis and design.

ACKNOWLEDGEMENT

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FIGURE CAPTIONS

Fig.1 Top view of the helical windings and the last closed flux surface for the CT6 configuration. [1]

Fig.2 Sketch of Wendelstein VII-X basic configuration. The lines on the plasma surface indicate the magnetic field lines and the meridional sections, respectively. [3]

Fig.3 Sections through the conducting shell at various toroidal angles, gamma, over one geometric period. The shell has two periods.

Fig.4 A projection view of one period of the conducting shell.

Fig.5 Shape of a typical toroidal field coil.

Fig.6 A projection view of half a typical toroidal field coil set.

Fig.7 A projection view of the conducting shell inside a typical toroidal field coil set. For visualization of the configuration only since the simulation used B_{TF}=Bo Ro/R.

Fig.8 Poincare plot for the stellarator field resulting from the currents induced in the conducting shell by bringing up the B_{TF}=Bo Ro/R field with the shell assumed to be superconducting.

Fig.9 Poincare plot for the inner surface with the points labeled with the number of passes around the device in the toroidal direction. The normalized iota can be determined from this data and is noted on the plot.

Fig.10 Poincare plot for the middle surface with the points labeled with the number of passes around the device in the toroidal direction. The normalized iota can be determined from this data and is noted on the plot.

Fig.11 Poincare plot for the outer surface with the points labeled with the number of passes around the device in the toroidal direction. The normalized iota can be determined from this data and is noted on the plot.

Fig.12 The magnitude of the magnetic field along the magnetic axis for the CSS compared to the field from the B_{TF}=Bo Ro/R field.