NATIONAL COMPACT STELLARATOR EXPERIMENT VACUUM VESSEL EXTERNAL FLUX LOOPS DESIGN AND INSTALLATION

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Abstract— The National Compact Stellarator Experiment (NCSX) will have an extensive set of external magnetic diagnostics. These include flux loops on the exterior surface of the vacuum vessel. Data from these sensors will be integrated with other magnetic sensors and used for plasma control and to constrain magnetic equilibrium reconstructions. NCSX is currently under construction at the Princeton Plasma Physics Laboratory (PPPL). The ex-vessel flux loops must be installed during machine construction since they will ultimately be trapped in the space between the vacuum vessel and the modular coil support shell. Detailed designs have been completed, locator templates have been fabricated and approximately one third of the 225 total loops have been installed as of mid February 2007. Modeling was performed by PPPL to determine the optimum size, placement and number of turns. Engineering of the flux loops was challenging as they must be accurately positioned, optimized geometry maintained and they must be robust and reliable in a bake and cryogenic environment for the lifetime of NCSX. Designs for the ex-vessel flux loops that meet these requirements are presented.

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I. INTRODUCTION

The National Compact Stellarator Experiment (NCSX) is a three period stellarator which will explore stellarator physics in quasiaxisymmetric plasmas with the use of a full complement of diagnostics implemented in phases to accommodate the goals of the research plan. In particular, NCSX will have an extensive set of external magnetic diagnostics including the 225 flux loops which is the subject of this paper.

These flux loops must be robust and installed during the machine construction since there will be no reasonable access to them after machine assembly is complete and in fact they will be trapped in the space between the vacuum vessel and the modular coil support shell.

The installation is ongoing and the following information is a summary as of 6/14/07.

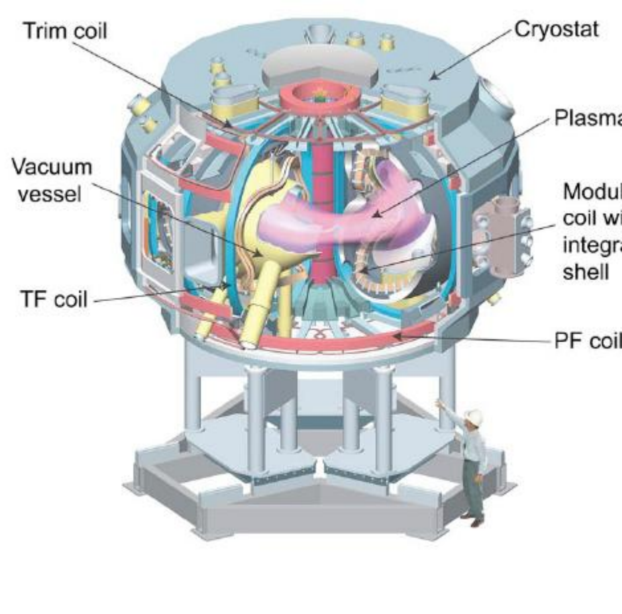

Figure 1. NATIONAL COMPACT STELLARATOR EXPERIMENT (NCSX)

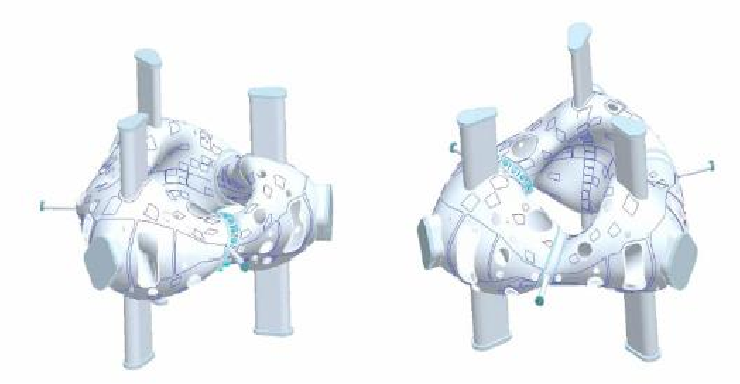

Figure 2. NCSX VACUUM VESSEL
Distribution of Flux Loops

II. FLUX LOOPS

The flux loops are in the process of being installed on the surface of the NCSX vacuum vessel, thereby approximately conforming to the plasma boundary. They are to sense the flux predominantly due to the component of magnetic fields normal to the plasma surface.

The signals are expected to be stellarator symmetric (SS) with toroidal mode numbers of n=3, but imperfections in the coils, vessel fabrication, machine assembly as well as plasma instabilities will cause non SS fields with other values of n.

The design criteria are:

1. Signals should provide a strong constraint on reconstruction of both SS and non SS equilibria.
2. Loop signals should be easily detected (minimize loop area)
3. Good resolution of modes
4. A subset should be capable of measuring $n \leq 6$ resonant field perturbations

Physics modeling[2] using the VMEC code determined the optimum location and size of the loops. In order to provide the maximum sensitivity to non SS modes, the loops were randomly distributed over the three field periods rather than concentrating them on one or one and a half. Note that all the areas if concentrated would completely populate a half field period. In addition, two groups of closely spaced loops were chosen to allow detection of resonant filed perturbations with $m \leq 11$ and two toroidally continuous arrays on both the inside and outside midplane aid the identification of the dominant n numbers and symmetry breaking fields.

Of the 225 loops, 20 are located on the three field period spacers (between vacuum vessel segments). There is a complete (360 °) 16 loop poloidal array on one spacer [with two at the SS points (θ=0° and 180°)] and two each on the other spacers at the SS points (θ=0° and 180°).

Implementation of the flux loops posed a number of engineering challenges:

1. Must be very reliable since they are inaccessible
2. Must survive and operate after subjected to 350°C bake
3. Accurately reproduce the shape determined by modeling
4. Provide electrostatic shielding and maintain to electronics.
5. Limit RF pickup.
6. Generally maintain a radial surface build not exceeding 1/8 inch including the exiting twisted leads.
7. Must be very accurately positioned
8. Installed location must be accurately measure to ensure that the data can be used for equilibrium reconstruction

In support of these requirements the loops are constructed of metal coaxial cable with a compressed MgO powder insulator. The sheath and single conductor material is solid Inconel 600, to match the coefficient of thermal expansion of the Inconel 625 vessel shell. The cable OD is 0.059 inch (1.5 mm).

Each loop consists of two turns and is clamped to the surface of the vacuum vessel with narrow thin strips of 316 SS, 0.005 inch thick with 4 spot welds (two each side). The strips were preformed using a die to obtain a tight fit around the cables with a minimum land extension.

The loop leads are twisted with an average pitch of 5/8 to ¾ inch to avoid pickup of spurious signals. Care was taken to minimize the transition area from loop to exiting leads, and to keep this area essentially constant for each loop. Special tooling was developed during installation to twist the leads for a length of approximately 10 ft. The twisted leads are run along the vacuum vessel surface in a very specific pattern to remain within the radial build tolerance, except for a few exceptions. The leads exit the cryostat region through 2.75 ConFlat flanges located on the large vertical port horse collar. The leads will be strain relieved inside and terminated inside aluminum junction boxes (JB) mounted to the horse collar ConFlat flanges. The JB will be equipped with terminal blocks integrally mounted to circuit boards with RF filtered D subminiature connectors. This permits the transition to conventional twisted shielded copper cable within a minimum distance of the cryostat and yet maintains the electrostatic shield requirement. In addition the JB will have copper foil tape applied to open edges. The bottom side of the JB rests on a mating rotatable ConFlat flange with a silicone rubber seal between. Matching holes in the rotatable flange and JB and a small puncture through the rubber sheet, seals the cryogenic nitrogen gas around the coaxial cables. The twisted leads are clamped to the vacuum vessel surface also using narrow thin strips of 316 SS, 0.005 inch thick that are not preformed. There were a few necessary compromises with the loop physics model definition and placement due to the impact of the pattern of exiting leads and cooling- heating tubing clamp weld studs.

To ensure that the loops were shaped accurately, thin (0.043 inch) 1/8 hard, annealed copper templates were fabricated at PPPL to serve as temporary winding forms. The templates were soft enough to easily conform to the local surface with no spring back, yet hard enough to permit the winding function with no distortion. The 3D physics models were ported into Pro E and flat patterns were developed with a small number of locator points (0.020diameter) inserted on each relevant side. DXF files were subsequently developed, which included indents for the clamping straps, and transferred to the water jet. The templates were machined to an accuracy of better than 0.005 inch. The center of the locator points, CAD coordinates were transferred to the coordinate measurement machine (CMM), Laser Tracker, and in turn transferred to the vacuum vessel segments. The Laser Tracker accuracy is in the range of 0.001 to 0.002 inch. The template locator points were aligned with the matching locator points marked on the vessel, hand formed to conform to the local surface, and temporarily fixed to the vessel surface. Although it was initially planned to use spot welded SS shim stock for the temporary fix, duct tape was easier to use and performed this function well.

After the templates were fixed, the two turns of coaxial cable was applied, preformed straps spot welded, and the first few twists developed by hand. The position of the coil was initially checked at this time with the CMM and if there was no problem the full lead length was twisted and template was removed. The entire length, both turns, was then measured; data archived and transferred to Pro E CAD, then in turn transferred to the physics personnel for evaluation. The physics model was developed in phi-theta space coordinates (toroidal –poloidal).

There were two classes of loop and therefore template position accuracy required. Ones at the SS locations and loops with complement locations which have a positioning accuracy of ± 0.5 mm and the general loops which have a positioning accuracy of ± 4 mm. The general loops need only be reasonably close to ideal but the others are used to check the symmetry of the three field periods and therefore require the more precise location.

At the writing of the paper two field periods are installed and coordinates measured, and the third field period started. None of the vessel spacer loops are installed.

Ref: [1]Brentley Stratton __ Review of Scientific Instruments 77, 10E314 (2006)
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