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External Magnetics Diagnostics for the National Compact Stellarator Experiment

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ABSTRACT

The National Compact Stellarator Experiment (NCSX) will have a complete set of magnetics diagnostics to constrain equilibrium reconstructions and for plasma control. The flux loops laying on the exterior surface of the vacuum vessel and the flux loops co-wound with the field coils must be installed during machine construction because they will later be inaccessible. Designs and installation techniques for these diagnostics are described.

I. INTRODUCTION

The National Compact Stellarator Experiment (NCSX) will explore stellarator physics in quasi-axisymmetric plasmas at low aspect ratio (R/⟨a⟩~4.4) and high β~4%)[1,2]. NCSX is a three-period stellarator with the majority of the rotational transform provided by a set of 18 modular coils. A set of toroidal field, poloidal field, and trim coils will allow access to a wide range of equilibria. The coil arrangement is shown in figure 1. NCSX will have R=1.4 m and B≤2.0 T, with pulse lengths up to one second. 3 MW of neutral beam heating power will be implemented early in the experimental program, providing the plasma heating and bootstrap current drive required for high β operation. Additional neutral beam power and radio-frequency heating may be added later. NCSX is currently under construction and first plasma operation is scheduled for 2009.

NCSX will have a full complement of diagnostics implemented in phases to accommodate the goals of the research plan[3,4]. In particular, NCSX will have an extensive set of external magnetics diagnostics. These include 225 flux loops on the exterior surface of the vacuum vessel, ~200 in-vessel magnetic field probes, 50 flux loops co-wound with all of the independently-powered magnets, 2 Rowgowski coils, and ~36 flux loops to sense eddy currents in the modular coil support shell. Signals from a subset of the co-wound flux loops will be combined to measure the plasma diamagnetism. Data from all of these sensors will be used for plasma control and to constrain magnetic equilibrium reconstructions.

The ex-vessel flux loops must be installed during machine construction because they will ultimately be trapped in the space between the vacuum vessel and the modular coil support shell. This space, shown in Fig. 1, will be inaccessible after machine construction is complete. The co-wound flux loops must be installed during magnet fabrication. Designs have been developed for both of these diagnostics and fabrication of them has started. Modeling to determine the optimum placement and size of the ex-vessel flux loops has been completed. Engineering of both the vacuum vessel and co-wound flux loops is challenging because they must be accurately positioned and they must be reliable in a cryogenic environment for the lifetime of NCSX. This paper presents designs for the ex-vessel flux loops and co-wound flux loops that meet these requirements.

II. VACUUM VESSEL FLUX LOOPS

A. Modeling to Determine Loop Locations

The vacuum vessel flux loops lay on the exterior surface of the vacuum vessel, which conforms approximately to the plasma boundary; thus, they sense the flux that is predominantly due to the component of the magnetic field that is normal to the plasma surface. The signals are expected to be predominantly stellarator symmetric (SS) with toroidal mode numbers of n=3, but imperfections in the coils and machine assembly as well as plasma instabilities will cause non-SS fields with other values of n. Design criteria for the flux loops are: 1) the signals should provide a strong constraint on reconstruction of both SS and non-SS equilibria, 2) the loop signals should be easily detected (determining minimum loop area) and be distinguishable from the total measured signal, 3) the number of loops and their placement should allow good spatial resolution of the modes, and 4) a subset of the loops should be capable of measuring $n \leq 6$ resonant field perturbations.

Modeling was performed to determine the optimum location and size of the loops[5-7]. The vacuum vessel surface was populated with a trial set of 100 flux loops distributed over the entire area of one half period of the vacuum vessel. This is sufficient because the two half periods that compose a single vacuum vessel period are mirror symmetric. The V3POST code[5] was used to calculate the flux through each loop for an ensemble of 2500 free-boundary equilibria generated by the VMEC code[8]. The equilibria span the range of I_p, B_T, and β that can be produced in NCSX and incorporate random combinations of a variety of current and pressure profiles. The loops were assumed to have two turns. The magnetic fields from each equilibrium were calculated at ~1200 points on a single, close fitting, toroidal surface surrounding all of the equilibria. A least-squares regression of the flux loop signals was performed on these field values. The utility of each flux loop in constraining the equilibrium was then determined by singular value decomposition of a signal matrix having dimensions of the number of flux loops times the number of equilibria. Thus, the trial flux loops could be ranked according to the criteria given above to determine which regions of the vacuum vessel are most important for placement of the actual loops. In order to provide maximum sensitivity to non-SS modes, the loops were randomly distributed over the entire vacuum vessel surface, rather than concentrating them on one period or half period. In addition, two groups of closely-spaced loops were chosen to allow detection of resonant field perturbations with $m \leq 11$, and two toroidally-continuous arrays of flux loops on the inboard and outboard midplane aid the identification of the dominant n numbers and symmetry-breaking fields.

The resulting final set of flux loops positioned on the vacuum vessel is shown in figure 2. There are a total of 225 loops, with 20 of them not shown on Fig. 2. These are

16 loops forming one continuous poloidal array on one of the vacuum vessel spacers (which connect the vessel segments) and two loops on the two symmetry points (θ=0° and θ=180°) on the other two spacers. Also not shown on Fig. 2 are four toroidal loops that will sense the loop voltage.

B. Loop Design and Implementation

Implementation of the vacuum vessel flux loops poses several engineering challenges: 1) the loops must be very reliable because they can not be repaired or replaced once NCSX is complete, 2) they must be able to tolerate temperatures up to 350º C during vacuum vessel baking, 3) the loops must be accurately positioned during installation, and 4) their installed locations must be accurately measured to ensure that the data can be used for equilibrium reconstruction.

To satisfy these requirements, the loops are made of mineral-insulated coaxial cable[9]. This cable consists of a solid outer sheath and a single-strand center wire with magnesium oxide powder insulation. Inconel was chosen for the sheath and wire to match the coefficient of thermal expansion of the Inconel vacuum vessel on which the loops are mounted. The cable diameter is 0.059 inches (1.5 mm). The loops consist of two turns and are held to the vacuum vessel by straps made of thin stainless steel shim stock that is spot welded to the vessel on both sides of the loop.

The loop leads are twisted to avoid pickup of spurious signals. They are routed along the vacuum vessel surface to termination boxes located on the outside of the cryostat at the ends of the large vertical ports shown in Fig. 2. In these boxes, the mineral insulated cable is terminated to connectors to make the transition to conventional twisted-pair cable for the run to the racks housing the integrators and digitizers. The bottom side of the box rests on flanges that penetrate the cryostat. A silicon rubber seal is used to seal the bottom of the box from the cryostat, which contains cold nitrogen gas.

To ensure that the loops have the correct shapes and are accurately located on the vacuum vessel, the cable is wound onto templates that are temporarily mounted on the vacuum vessel. The templates are water-jet cut from 0.043 inch (1.1 mm) thick copper sheet using CAD files developed directly from the results of the modeling. There are generally four notches on the edges of each template which are aligned with points pre-marked on the vacuum vessel surface using a coordinate measuring machine (CMM). The CMM uses CAD coordinates for each alignment point that are developed from the modeling. The thin copper is annealed and bends easily to conform to the vacuum vessel surface but is stiff enough to hold its shape. Once positioned, it is held in place with temporary shim-stock tabs that are spot welded to the vessel. The two turns of cable are wound around the template and the shim stock clamps that hold the cable onto the vessel surface are installed before removing the template. The leads are then twisted and routed to the termination boxes. They are also held in place with stainless steel shim stock clamps. The templates will be positioned within ±4 mm of the design loop locations, except for the templates for the loops at the symmetry points, which will be positioned within ±0.5 mm. The as-built vessel surface imposes a positioning constraint; thus, the loop position tolerances are relative to the best achievable location on the as-built vessel surface. The larger position tolerance for most of the loops allows some latitude in positioning them to avoid interference with adjacent loops and the mounting pads for the vessel heating/cooling tubes, which are also mounted on the vessel surface. Once the template is removed, the as-installed path of each loop is measured within ±0.25 mm using the CMM. These data are required for later use of the data in equilibrium reconstructions. This installation technique has been successfully tested on a prototype section of the vacuum vessel.

III. CO-WOUND FLUX LOOPS

The co-wound flux loops sense a flux that is predominantly produced by the coils on which they are mounted. To minimize contributions from other sources of flux, the flux loops should be mounted on the plasma-facing side of the coil. To provide redundancy against failure, two co-wound loops are installed on each modular coil. The engineering requirements for the modular coil co-wound flux loops are similar to those for the vacuum vessel flux loops, except that the loops will need to tolerate liquid nitrogen temperature (-196º C), rather than temperatures up to 350º C.

Figure 3 shows a cross section of a modular coil. The co-wound loops are located near the outside corner of each winding pack in a corner formed where the copper cooling tube joins the copper chill plate structure, as shown in Fig. 3. The loops are made of 0.032 inch (0.8 mm) diameter mineral insulated cable which is insulated with Teflon heat shrink tubing over the portion of the cable that is installed on the coil. This insulation prevents shorting across the slots that are cut in the chill plates to minimize eddy currents. Woven glass fiber tubing is installed over the Teflon tubing. The insulated cable is run along the prescribed route and held in place with silicon RTV adhesive. The path of the as-installed loops is measured using the CMM. The coil is then vacuum epoxy impregnated and the epoxy is cured. This process makes the winding packs and chill plate structure, including the co-wound loops, into a rigid unit, with the epoxy holding the co-wound loops in place. The loop leads are twisted where they leave the chill plate structure and exit the modular coil casting through holes that are near the midplane. The leads will pass through holes in the cryostat and run to boxes where they will be terminated. A similar design will be used for the co-wound loops on the toroidal field coils, poloidal field coils and trim coils.

Acknowledgments

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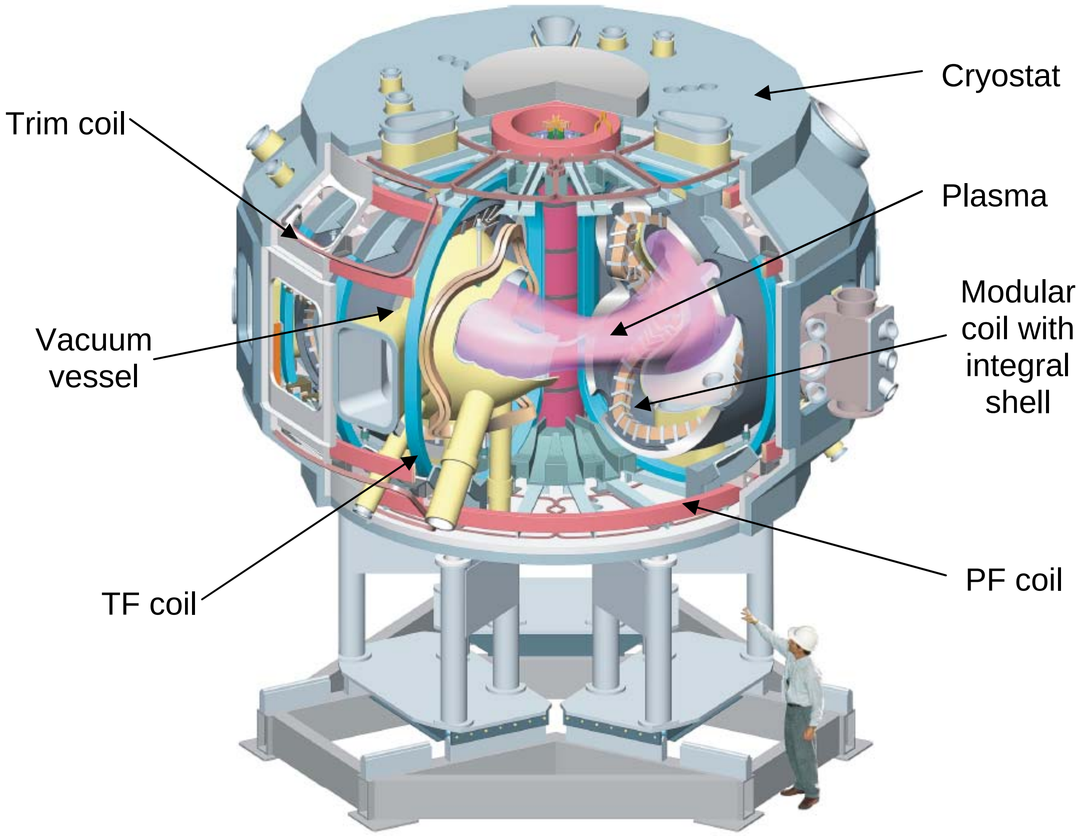

Fig. 1. The National Compact Stellarator Experiment (NCSX).

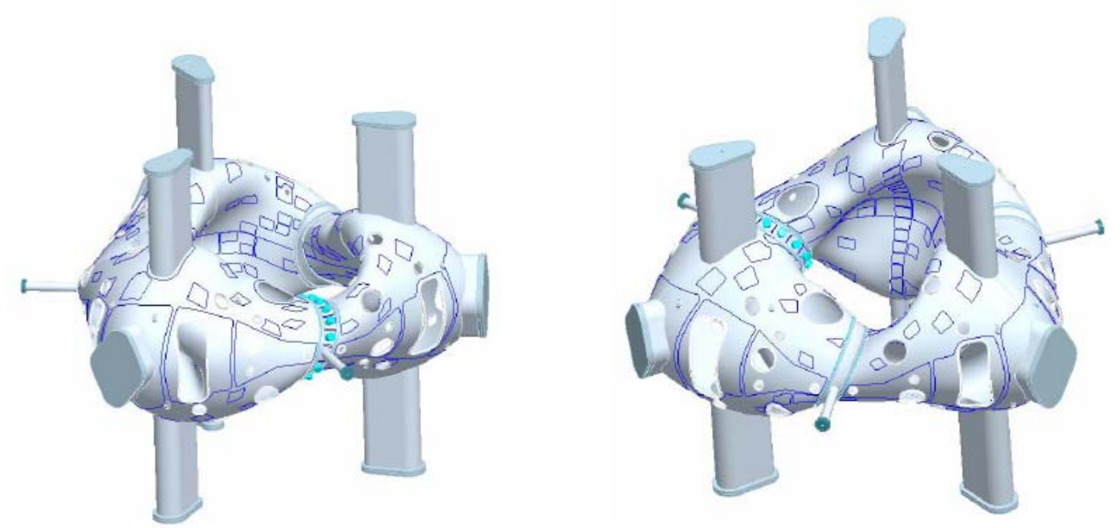

Fig. 2. Two views of the NCSX vacuum vessel showing the final arrangement of the flux loops.

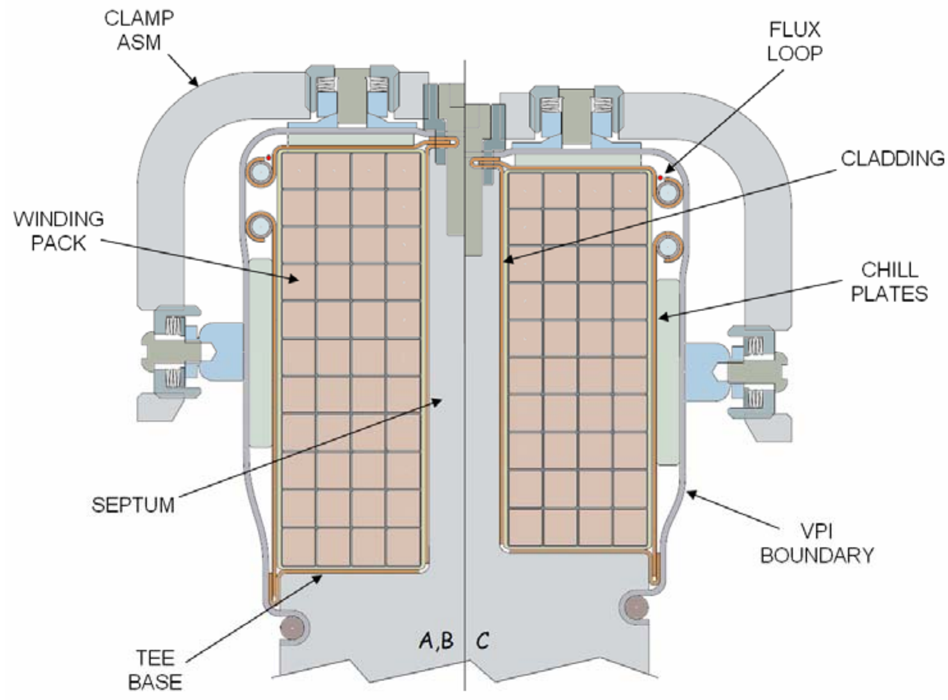

Fig. 3. Cross section of modular coil, showing the winding form, winding packs, and the flux loops.

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