Challenges in Designing the Modular Coils for the National Compact Stellarator Experiment (NCSX)

D. Williamson\textsuperscript{a}, A. Brooks\textsuperscript{b}, T. Brown\textsuperscript{b}, J. Chrzanowski\textsuperscript{b}, M. Cole\textsuperscript{a}, H-M. Fan\textsuperscript{b}, K. Freudenberg\textsuperscript{a}, P. Fogarty\textsuperscript{a}, T. Hargrove\textsuperscript{c}, P. Heitzenroeder\textsuperscript{b}, G. Lovett\textsuperscript{d}, B. Nelson\textsuperscript{a}, S. Raftopolous\textsuperscript{b}, W. Reiersen\textsuperscript{b}, B. Stratton\textsuperscript{b}, D. Strickler\textsuperscript{a}

\textsuperscript{a} Oak Ridge National Laboratory, PO Box 2008, Oak Ridge, TN 37831-6169
\textsuperscript{b} Princeton Plasma Physics Laboratory, PO Box 451, Princeton, NJ 08502
\textsuperscript{c} DevTech, 118 Colonial Dr, Scottsboro, AL 35768
\textsuperscript{d} MK-Technologies, PO Box 30197, Knoxville, TN 37930

Abstract—The National Compact Stellarator Experiment (NCSX) is a quasi-axisymmetric plasma experiment that combines the high beta and good confinement of an advanced tokamak with the low current, disruption-free characteristics of a stellarator. The experiment is based on a three field-period plasma configuration with an average major radius of 1.4 m, a minor radius of 0.3 m, and a toroidal magnetic field on axis of up to 2-T. The modular coils are one set in a complex assembly of four coil systems that surround the highly shaped plasma. There are six each of three coil types in the assembly, for a total of 18 modular coils. The coils are constructed by winding copper cable onto a cast stainless steel winding form that has been machined to high accuracy, so that the current center of the winding pack is within +/-1.5 mm of its theoretical position. The modular coils operate at a temperature of 80 K and are subjected to rapid heating and stress during a pulse. The final coil design has presented many challenges with its requirements for winding accuracy, good thermal performance, a robust supporting structure, and ease of assembly and maintenance.

Keywords—Stellarator, modular coil, electromagnetic, design

I. INTRODUCTION

The National Compact Stellarator Experiment (NCSX) is based on a three field-period plasma configuration with an average major radius of 1.4 m, a minor radius of 0.3 m, and a toroidal field on axis of up to 2 T. The facility includes four coil systems that surround the highly shaped plasma. The modular coil set is closest to the plasma, and its main functions are to: (1) provide a specified magnetic field configuration, (2) provide access for tangential neutral beams, radio frequency (RF) heating, and diagnostics, and (3) provide a robust structure that minimizes coil deflection and non-symmetric field errors [1]. Due to stellarator symmetry, only three different coil shapes are needed to make up the complete set of 18 coils. The coils are connected electrically in three circuits according to type, and as such can produce alternate magnetic configurations by independently varying the current for each type. Fig. 1 shows the general arrangement of the stellarator core and Fig. 2 shows the modular coil subassembly.

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II. COIL GEOMETRY

The geometry of the modular coil set has been developed through a physics optimization process that emphasizes both plasma properties and geometric constraints, such as coil-to-coil spacing (a key factor in determining current density) and minimum bend radius. In the optimization code, COILOPT [2], the coils are constrained to lie on a winding surface that is represented by a Fourier series in poloidal and toroidal coordinates. The coil set is represented by approximately one hundred independent parameters. Optimization targets the surface magnetic field error, while measures of plasma-coil separation and coil-coil spacing are used to control current density. The final design limits sharp bends to >10 cm at the conductor surface while maximizing the available conductor space. Fig. 3 illustrates the compact design of the windings and lists the basic parameters of the coil set.

The modular coils are wound onto stainless steel castings which are then bolted together to form a structural shell. As shown in Fig. 4, the winding cavity is a “tee” structure that is located on the inside of the shell. During operation, electromagnetic forces push the windings outward against the shell and laterally toward the “tee”, so that only intermittent clamps are required for structural support.

The structural shell is segmented poloidally and toroidally to reduce the effect of eddy currents. The toroidal segmentation results in a nested configuration, with protruding “wings” which extend beyond the radial flanges and underneath the adjacent coil (Fig. 5). In order to permit some flexibility in positioning the coils during final assembly, gaps of >12 mm were designed between coil mating surfaces. The gaps will be filled by customized metal shims at the bolted connections and epoxy-filled shims between “wing” surfaces.

The structural shell also includes many openings for the vacuum vessel ports. This geometry was developed using an integrated CAD model of the stellarator core assembly.

III. WINDING ACCURACY

A critical element of the winding process involves locating and maintaining the theoretical current center. For design purposes, the winding center positional tolerance of ±1.5 mm has been divided equally between 1) coil fabrication, 2) field period assembly (6 coils), and 3) final machine assembly (18 coils). In-process techniques, using a multi-link coordinate measuring machine (CMM) and other mechanical measuring tools, have been developed to monitor the location of the current center, and shims will be used to make minor corrections during winding. Thus far, winding trials have shown that the allocated coil fabrication tolerance can be achieved.

In order to gage the severity of winding errors in the final coil assembly, analyses have been performed to determine the effect of random fabrication errors on the plasma magnetic field. Error types that were considered include 1) a Fourier
representation in which the local tolerance varies with coil-plasma spacing, 2) a short wavelet type displacement in orthogonal directions to the winding center, and 3) a broad displacement over a significant length of the coil. In each case, the magnitude of the fabrication error is >1.5 mm. Typical results indicate that while errors that are located within 30 cm of the plasma (typically the inboard region) have a significant effect on flux quality, errors in other regions are more benign, and may approach 3 mm, or twice the specified coil tolerance.

IV. THERMAL ANALYSIS

The modular coils are cooled between pulses by conduction to a series of thin, copper plates on the exterior of the winding pack. Analysis of several configurations has resulted in the design shown in Fig. 6, where the winding pack is surrounded by a “cladding” layer, adjacent to the tee, and chill plates that are attached to cooling tubes. The cladding and chill plates are segmented in order to minimize eddy currents and facilitate fabrication using flat developments.

Finite element analysis indicates that, during a high-field pulse, the temperature of the windings increases to 145 K over several pulses, while the winding form temperature increases only slightly. The nominal cool-down time between pulses is 15 min. Fig. 7 and 8 illustrate the thermal performance at maximum current.

Figure 6. Winding pack cooling configuration

Figure 7. Temperature distribution after 10th cool-down cycle

Figure 8. Temperature history for high-field operating scenario

V. STRUCTURAL ANALYSIS

Electromagnetic loads have been calculated for the reference operating scenarios and for several fault conditions that may occur due to short circuit, reverse current, etc. The maximum loads occur during a high-field pulse, as illustrated by Fig. 9. Running loads of up to 1.2 MN/m act in the direction of the supporting structure, except in very localized areas. A series of clamps provides ~100 lb of centering preload to prevent gaps between the windings and shell in the highly loaded inboard region.

Linear and non-linear structural analysis has been performed frequently throughout the design process. Using material properties derived from tests of cast stainless steel and composite copper/epoxy beams, the analysis has been refined to include thermal cool-down and pulse heating effects, electromagnetic loads, and clamp forces on a very accurate
representation of the as-cast winding form. The results indicate that the windings track the shell deflection in most places, and that coil deflection is small enough not to affect plasma performance. Fig. 10 and 11 illustrate the typical displacement and stress response of winding form and windings.

VI. COIL ASSEMBLY

The modular coils will be combined into three-coil sectors and then installed over a segment of the vacuum vessel to form a six-coil, field period assembly. Other components of the field period assembly include the TF coils, coil structure, and external trim coils.

At assembly, the modular coils are positioned relative to one another using a set of three spherical seats in the flange of one winding form and three adjustable alignment balls in the flange of the other. The position of the coils is determined by the optimization code, STELLOPT [3], which can determine the effect of rigid body manipulations of the as-built coil on specific resonances of the vacuum magnetic field. Once the optimum position has been established, shims and bolting will maintain alignment. In this way, field errors due to tolerance buildup can be minimized.

VII. SUMMARY

Engineering and physics optimization has helped the NCSX modular coil design to meet all of the requirements for winding accuracy, good thermal performance, a robust supporting structure, and ease of assembly and maintenance. At this time, the modular coil winding forms are in production and coil fabrication is set to begin in October, 2005.

REFERENCES