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Abstract

The National Compact Stellarator Experiment (NCSX) is a quasi-axisymmetric facility that combines the high beta and good confinement features 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. At this time, the project has completed construction of several prototype components which validate the fabrication and inspection processes that are planned for the production coils. In addition, some advanced techniques for error-field compensation and assembly simulation using computer-aided design (CAD) have been developed.

1. Modular Coil System

The function of the NCSX modular coil system is 1) to provide specified quasi-axisymmetric magnetic field configurations, 2) to provide access for tangential neutral beam injection (NBI), radio frequency (RF) heating, and diagnostics, and 3) to provide a robust mechanical structure that minimizes non-symmetric field errors. The coil set consists of three field periods with six coils per period, for a total of 18 coils. Due to stellarator symmetry, only three different coil shapes are needed to make up the complete coil set. 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 coils and structure.

2. Coil Optimization

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 determining the current density) and minimum bend radius. In the optimization code, COILOPT[1], 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 effectively minimizes the number and severity of sharp bends in the windings while maximizing the available conductor space. Table 1 lists the basic engineering parameters for the selected coil design.

3. Windings and Structure

The modular coils are wound onto stainless steel castings that are then bolted together to form a structural shell. As shown in Fig. 2, the winding cavity is a “tee” structure that is located on and integral with the plasma side 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. Nonlinear finite element analysis indicates that, under maximum electromagnetic and thermal load, the windings experience a symmetric displacement of ~1 mm relative to the structural shell.

Fig. 3 shows some details of the modular coil leads, which are located in the outboard region to minimize field errors. The four-in-hand conductor enters the winding pack at the outward base of the “tee” and exits toward the plasma, where it is then routed back through the structural shell. Like conductors from each winding pack are connected in series to maintain the current center. A flexible co-axial cable connects the terminal block of each coil to power supply buswork outside of the cryostat.

The toroidal segmentation of the winding forms has received considerable attention during the design phase, owing to the “nested” configuration of the coils. As shown in Fig. 4, the complex shape of the coils results in protruding “wings”, which extend beyond the radial flanges and underneath the adjacent coil. In order to permit some flexibility in positioning the coils during assembly, assembly gaps of >12 mm exist between coil mating surfaces, which will be filled by custom metal shims at the bolted connections and epoxy-filled shims between “wing” surfaces. Linear finite element analysis has shown that deflection and stress in the structural shell is minimal with this configuration.

4. Coil Fabrication

The modular coils will be wound at Princeton Plasma Physics Laboratory (PPPL), using techniques perfected during recent research and development (R&D) activities. Winding operations include 1) preparing the casting, 2) installing inner copper sheet and ground wrap, 3) winding the conductor, 4) installing outer copper chill plates and cooling, 5) preparing the mold for epoxy vacuum-pressure impregnation (VPI), 6) potting the coil, and 7) inspecting and testing the coil at operating temperature (80 K).

A critical element of the winding process involves locating and maintaining the theoretical current center. 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.

In order to gage the severity of winding errors, an analysis has been performed to determine the effect of random fabrication errors on plasma magnetic field islands. 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. A typical result of the analysis is the graph of island size versus coil-plasma separation for a broad winding center displacement (Fig. 5). The graph indicates that while errors greater than 1.5 mm in regions of the coil that are 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. .

5. 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 [2], 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.

The field period assembly fixture, which is required to position a three-coil sector over the vacuum vessel, has been designed by a unique analysis method. Beginning with CAD models of the modular coils and vacuum vessel in the assembled position, a code was developed to compute the inverse kinematics of the assembly fixture while maximizing the clearance distance between components. The resulting fixture design is illustrated in Fig. 6.

6. Conclusion

Engineering and physics optimization has helped the NCSX modular coil design to systematically progress from physics targets to filamentary models to prototype components. At this time, the winding forms are ready for procurement, and the windings and assembly designs are nearly complete. It is anticipated that coil production will begin in January, 2005 and continue for approximately 18 months.

Acknowledgement

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References

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[2] D. Spong, S. Hirshman, et al, Nucl. Fusion 41 (2001) 711

[3] W. Reiersen, Modular Coils (WBS14) System Design Description, NCSX FDR, May 2004.

Table Captions

Table 1 Modular Coil Parameters

Figure Captions

Fig. 1 Modular Coils General Arrangement

Fig. 2 Modular Coil Winding Pack

Fig. 3 Modular Coil Leads Arrangement

Fig. 4 Modular Coil Assembly Clearance

Fig. 5 Field Error due to Winding Center Displacement

Fig. 6 Field Period Assembly Fixture

Table 1 Modular Coil Parameters

No. of coils	18 (3 x 6)
Winding length	6.6 to 7.4 m per turn
Number of turns /coil	36
Gross cross section	2 x 40 mm x 120 mm
Current per coil*	Up to 828 kA-turns
Max. current density in Cu*	~ 14 kA/cm^2
Temperature operating range	From 85 to 125 K

* at nominal 1.7 T operating conditions

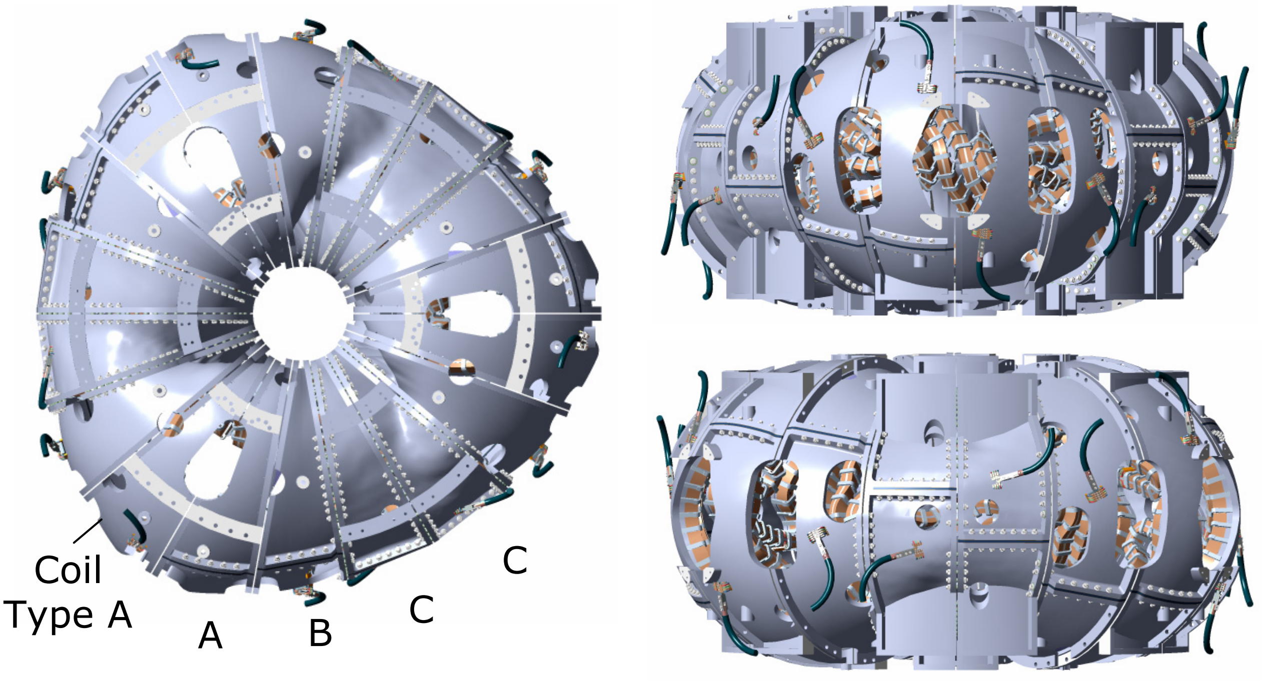
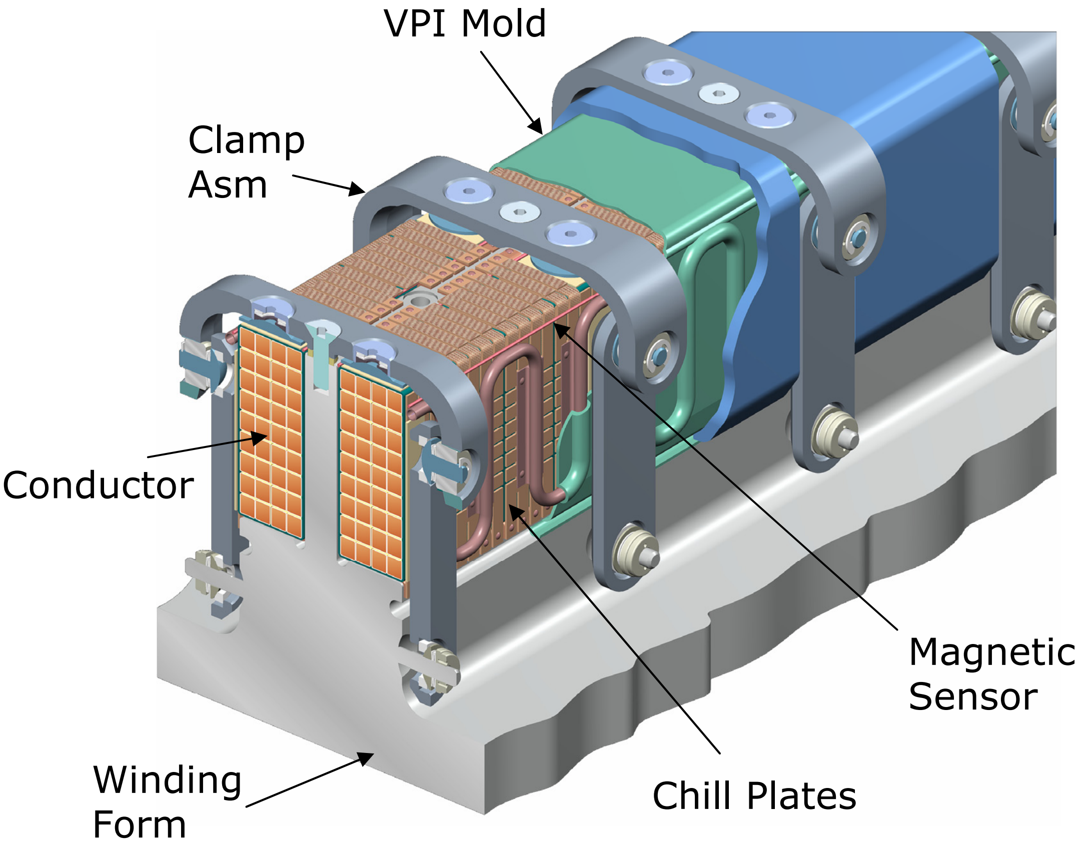


Fig. 1 (1/2 pp)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Clamp Asm
Conductor
Magnetic Sensor
Chill Plates
Winding Form

Fig. 2 (1/2 pp)

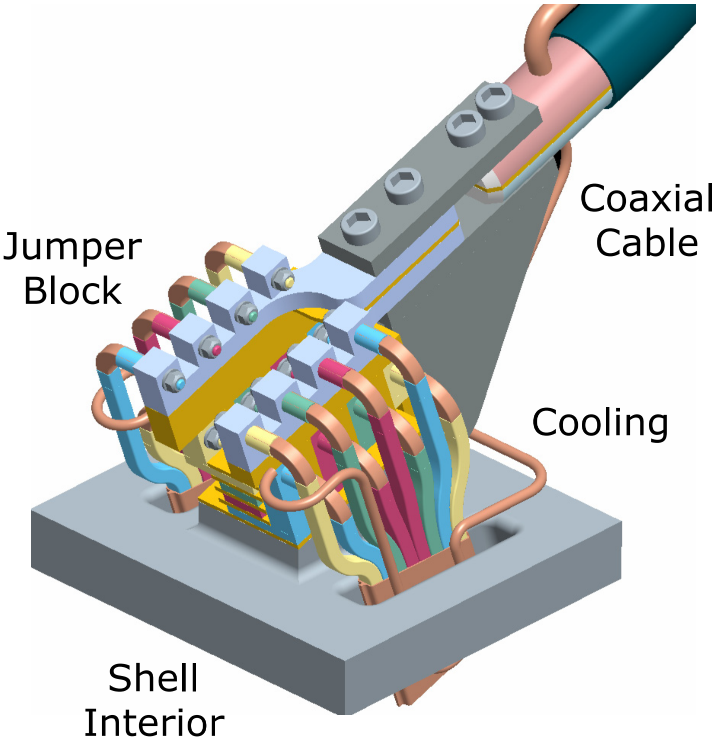

Fig. 3 (1/4 pp)

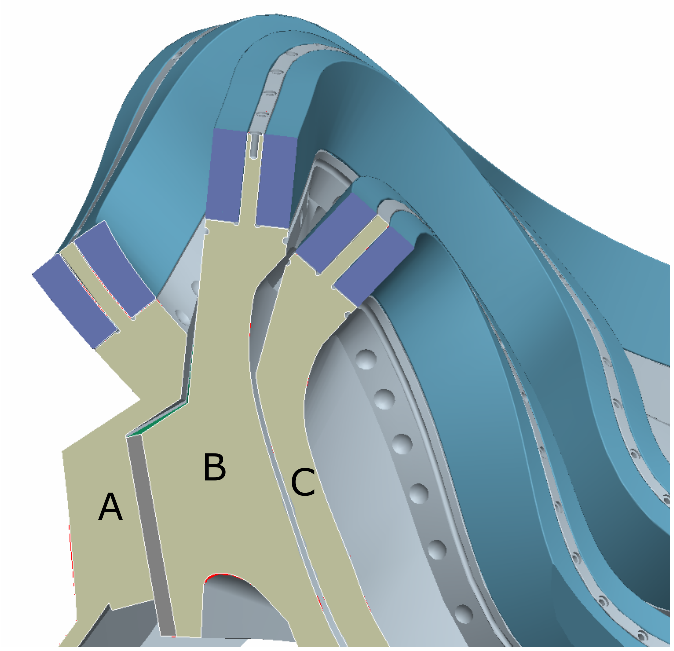

Fig. 4 (1/4 pp)

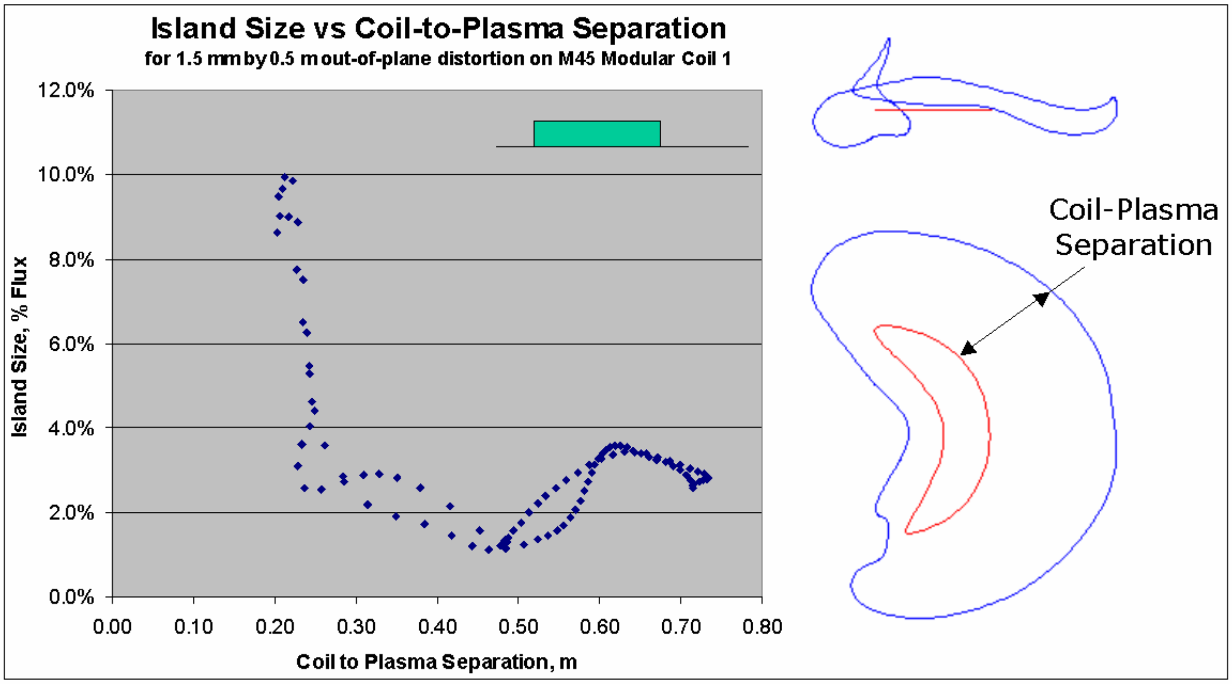
Island Size vs Coil-to-Plasma Separation
for 1.5 mm by 0.5 m out-of-plane distortion on M45 Modular Coil 1
Island Size, % Flux
12.0%
10.0%
8.0%
6.0%
4.0%
2.0%
0.0%
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
Coil to Plasma Separation, m
Coil-Plasma Separation

Fig. 5 (1/2 pp)

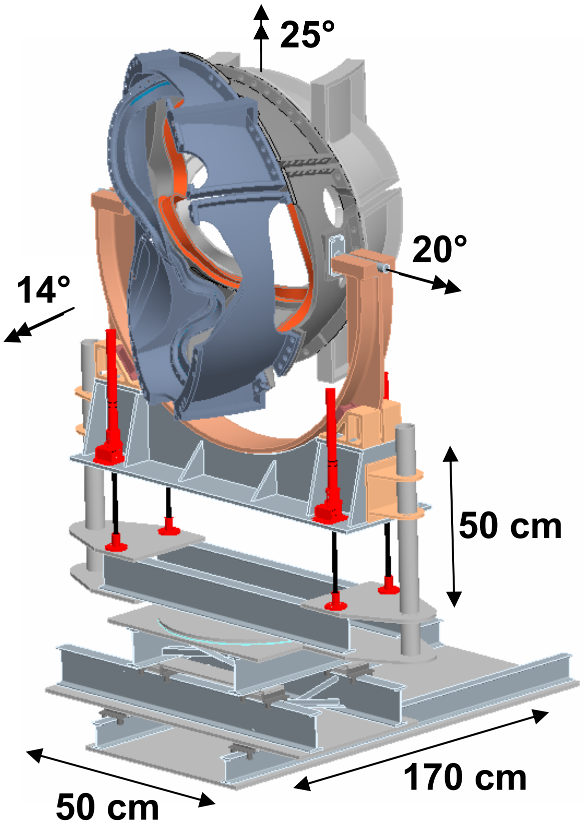

Fig. 6 (1/4 pp)