NCSX Engineering Design Document

Design Description
Modular Coils (WBS 14)

NCSX MCWF Final Design Review

May 19-20, 2004

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1 INTRODUCTION

The National Compact Stellarator Experiment (NCSX) is an experimental research facility that is to be constructed at the Department of Energy's Princeton Plasma Physics Laboratory (PPPL). Its mission is to acquire the physics knowledge needed to evaluate compact stellarators as a fusion concept, and to advance the understanding of 3D plasma physics for fusion and basic science.

A primary component of the facility is the stellarator core, an assembly of four magnet systems that surround a highly shaped plasma and vacuum chamber. The coils provide the magnetic field required for plasma shaping and position control, inductive current drive, and error field correction.

This document describes the requirements, design concept, design basis, implementation, cost, and risk associated with the construction of the modular coil subsystem of the stellarator core. The work breakdown structure (WBS) for the modular coil system includes the winding forms (WBS 141), coil windings and assembly (WBS 142), local instrumentation (WBS 143), and the winding facility and fixtures (WBS 144). The winding facility and fixtures (WBS 144) required to wind, pot, and test the modular coils are not part of the experimental systems and are covered in separate documentation.

2 DESIGN REQUIREMENTS AND CONSTRAINTS

2.1 System Definition

The modular coil set consists of three field periods with 6 coils per period, for a total of 18 coils. Due to symmetry, only three different coil shapes are needed to make up the complete assembly. The coils are connected electrically with three circuits in groups of six coils, according to type. Figure 1 shows the general arrangement of the coils and structure.

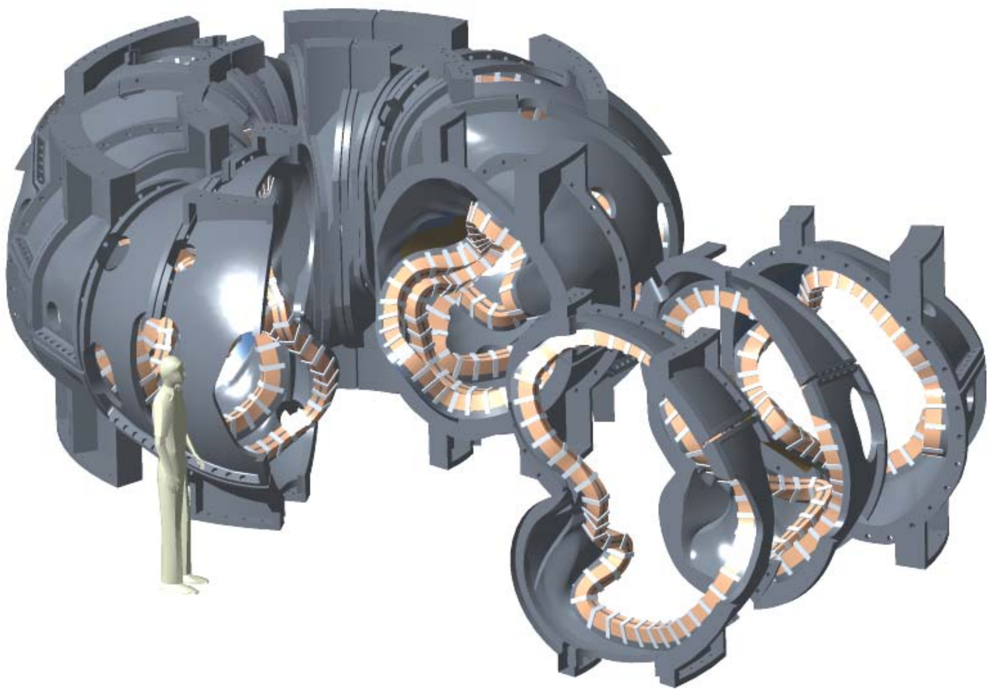

Figure 1 Modular Coil Assembly

2.2 Primary Functions

The function of the modular coil windings is to provide the basic quasi-axisymmetric magnetic configuration for the device. The windings can produce alternate magnetic configurations by varying the current for each coil type independently.

The function of the winding forms is to provide an accurate means of positioning the conductor during the winding and vacuum-pressure impregnation (VPI) process. The winding forms are permanent structures that also provide mechanical support for the windings during coil operation. The complete assembly of winding forms is referred to as the structural shell.

Sensors are required on each coil in order to monitor behavior during operation and provide feedback to the coil protection system. The required data includes voltage, temperature, strain, and flow measurement.

2.3 Configuration Requirements and Essential Features

The winding forms provide the interface between the windings and both internal and external components of the stellarator core. Essential features include 1) accurately machined surfaces for the conductor, 2) a poloidal break to meet electrical (eddy current) requirements, and 3) construction using a low magnetic permeability (<1.02) material. Configuration requirements are 1) to support the vacuum vessel, 2) provide access for tangential NBI, ICRH, vacuum pumping, diagnostics, and personnel, and 3) provide a mechanical interface with the coil support structure.

The most important configuration requirement for the windings is that the final position of the winding center conform to the prescribed geometry within a tolerance of +/- 1.5-mm. Essential features of the windings include 1) compatibility with existing power supplies (determines number of turns), and 2) independent control of each coil type for flexibility.

Configuration requirements for instrumentation include 1) voltage taps at the leads, 2) strain gages along the length of the coil, 3) flow sensors at each inlet/outlet, and 4) multiple Resistance Temperature Detectors (RTDs) for pre- and post-pulse monitoring of conductor average temperature.

2.4 Performance and Operational Requirements

When assembled into a structural shell, the main performance requirement for the winding forms is to support the coil electromagnetic loads with a minimum of deflection. Table 1lists the range of loads that are expected:

Table 1 Maximum Operational Loads on Structural Shell

	Max Radial Load (kip)	Max Vertical Load (kip)	Avg Inboard Pressure (psi)	Avg Outboard Pressure (psi)	Max Coil Radial Load (kip/in)	Max Coil Lateral Load (kip/in)
Segment / Coil A	200	10	220	70	3	6
Segment / Coil B	320	110	280	75	6	7
Segment / Coil C	90	120	170	80	4	6.5

The modular coil windings must be capable of meeting the reference operating scenarios defined in GRD [1]Section 3.2.1.5.3.3 and summarized in Table 2.

[1] NCSX General Requirements Document, NCSX-ASPEC-GRD-00, edited by W. Reiersen, April, 2004.

Table 2 Reference Scenarios and Modular Coil Current

Scenario	Max Current (kA)	Max I^2t (A^2-s)	Max ESW (s)
First Plasma (0.5-T)	225	93 E6	0.76
Field Mapping	225	450 E6	3.6
1.7-T Ohmic	763	1400 E6	1.0
1.7-T High Beta	763	1350 E6	0.97
2.0-T High Beta	818	1530 E6	0.90
1.2-T Long Pulse	538	1300 E6	2.0
320-kA Ohmic	707	1270 E6	1.0

A complete list of performance requirements and design constraints is given in the Modular Coils System Requirements Document[2].

[2] NCSX System Requirements Document for the Modular Coil System (WBS 14), NCSX-BSPEC-14-00

3 DESIGN DESCRIPTION AND PERFORMANCE

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. Improvements to the conceptual design were made in these areas and also to the twist of the coil cross-section in regions where the winding packs are close together. The present design minimizes the number and severity of sharp bends in the conductor while maximizing the available conductor space. A study of the effect of finite-build coils on plasma reconstruction indicates that these small coil adjustments do not significantly affect the magnetic field or plasma properties.

3.1 Winding Forms

The overall dimensions of each winding form type are shown in Figure 2, Figure 3, and Figure 4. Due to the complexity of these shapes, the winding forms will be fabricated as castings, with a tolerance of +/- 0.25-in on all the as-cast features of the part. Machining of only the winding cavity, flanges and other interfaces is then necessary to achieve the desired accuracy. The main design features of the winding forms are 1) the "tee" structure that forms the winding cavity, 2) a poloidal electrical break, and 3) toroidal segmentation that results in a "nested" assembly of the structure.

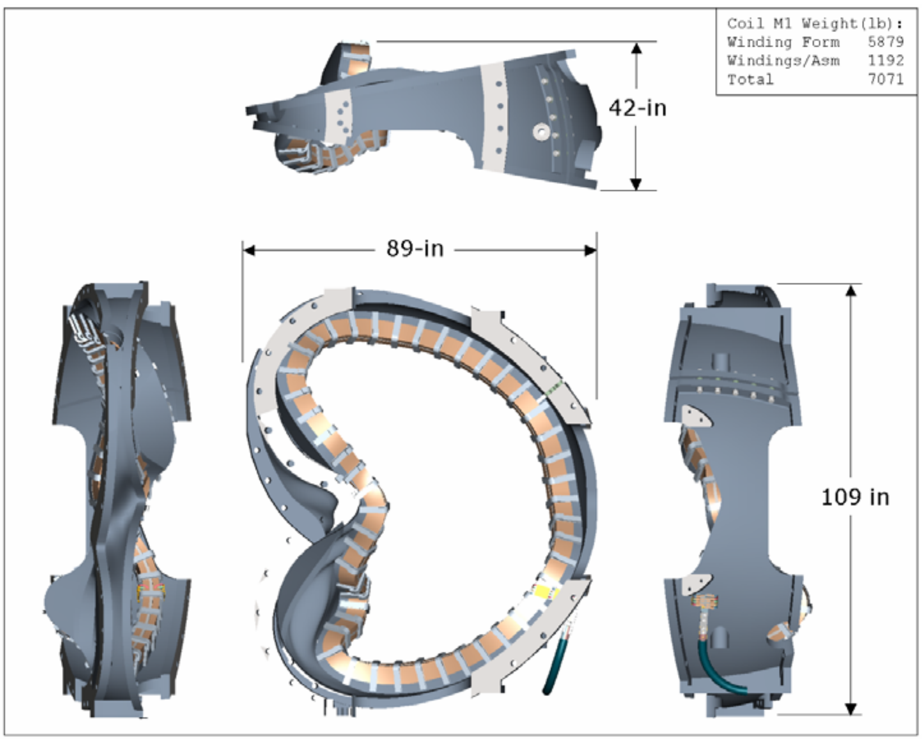

Figure 2 Winding Form Type 1

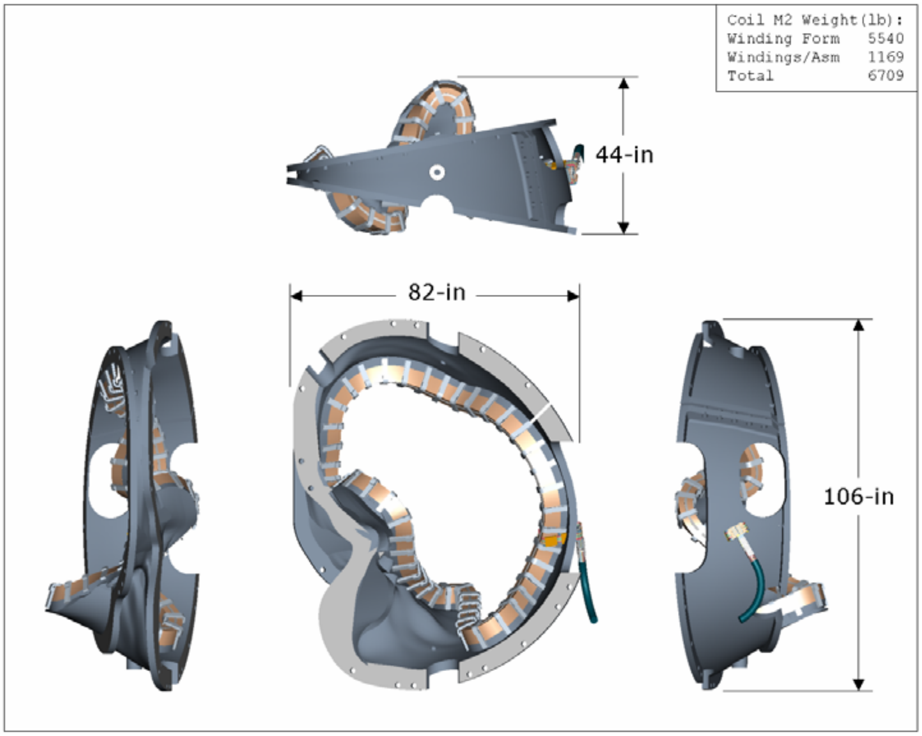

Figure 3 Winding Form Type 2

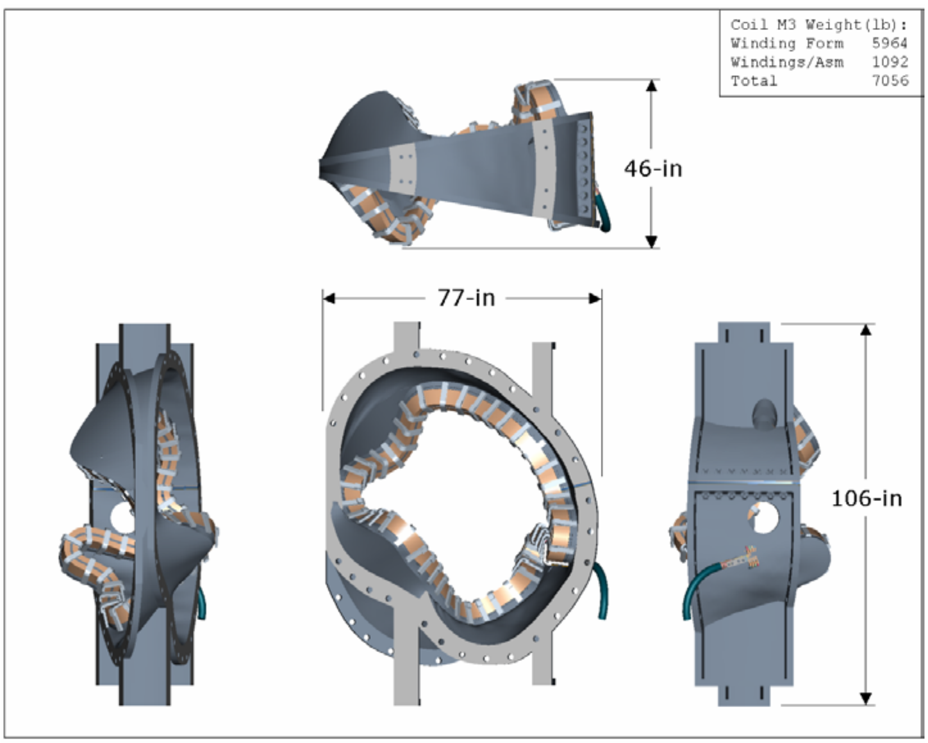

Figure 4 Winding Form Type 3

The first feature, the tee section, is shown in detail in Figure 5. The tee is machined to a profile tolerance of +/- 0.10-in and serves as the reference surface on which to locate the conductor. Along the sides of the tee, there is a continuous groove for the VPI bag mold which encloses the tee, winding packs, and cooling system. Outside of this envelope are spherical seats machined approximately every 3 inches along each side of the "tee" base that serve as locating features and clamp interfaces. Threaded studs are welded into these seats for attaching external winding clamps. The clamps are spaced approximately every other seat, or every 6-in, except in some inboard regions where the assembled coils are too close together for full clamps.

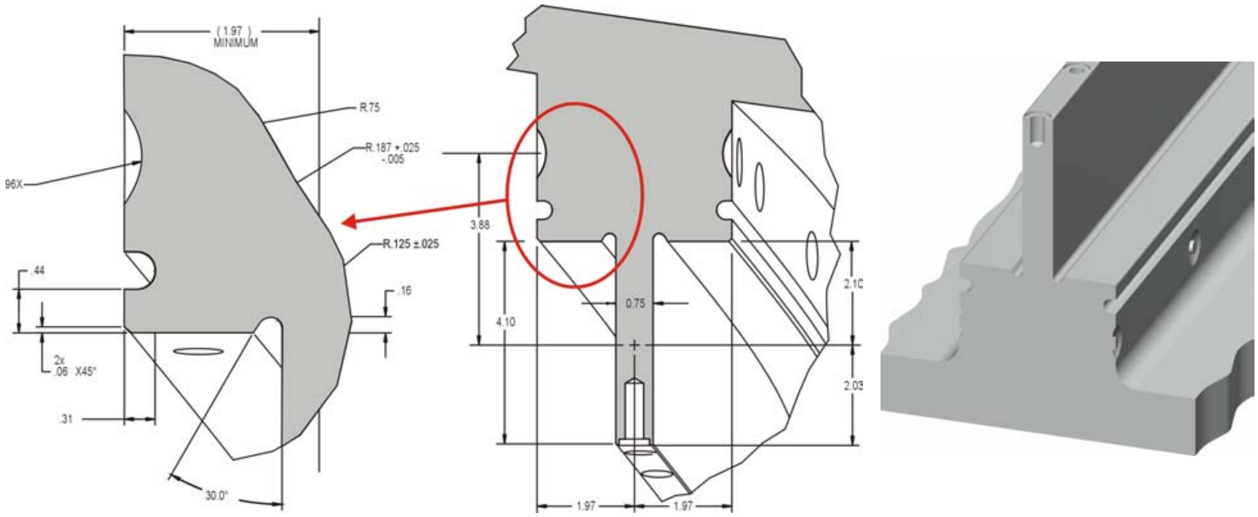

Figure 5 Winding Form Tee Details

The poloidal electrical break is located in the outboard midplane region of each winding form, as shown in Figure 7. The break is accomplished by cutting the casting prior to final machining, then bolting the form together using an insulated metal spacer and bolts. The web of the tee is connected by use of double-insulated studs.

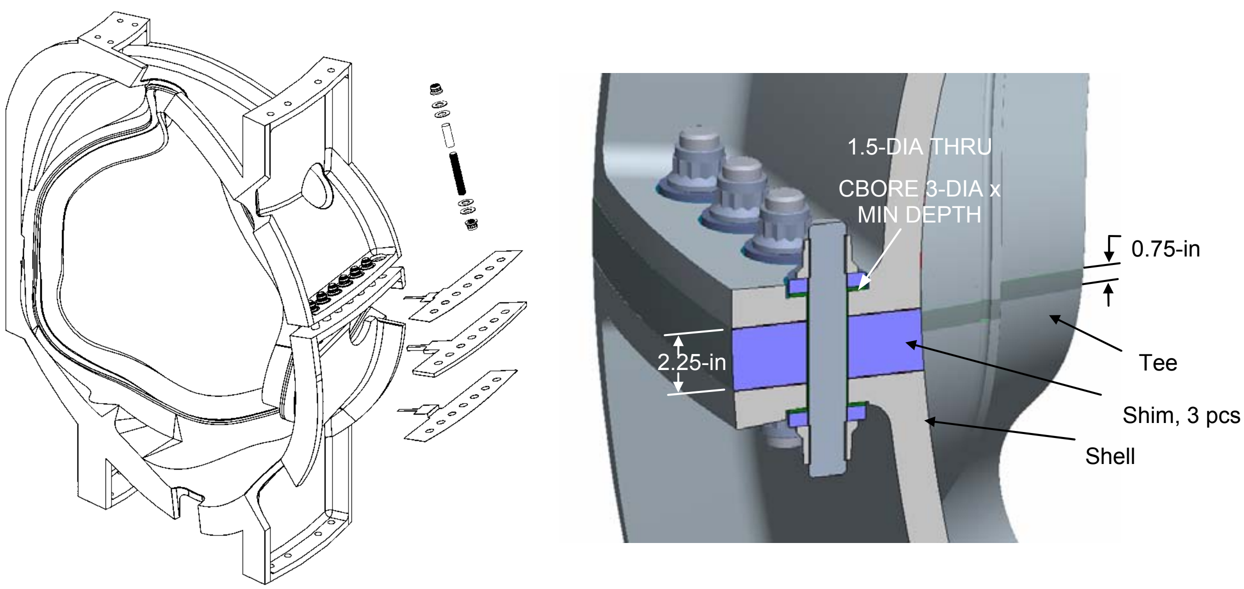

Figure 6 Poloidal Break Details

The toroidal segmentation of the winding forms has received considerable attention in design, owing to the "nested" assembly of coils. After the windings are installed, the winding forms are bolted together to form a monolithic shell structure. Insulating shims and bolts are used at each flanged joint in order to prevent circulation of toroidal currents, except the three joints made at final assembly. The complex shape of the coils results in protrusions (a.k.a. wings), which extend beyond the flanges of the winding form and must fit underneath the adjacent winding form. In order to use the as-cast shape in these areas, the gap between overlapping structures must be at least 0.5-in. This is illustrated by the section view in Figure 7. During final design it was determined that in some wing areas the clearance would be less than 0.5 inches, so in these areas machining or grinding to size may be required on the male features.

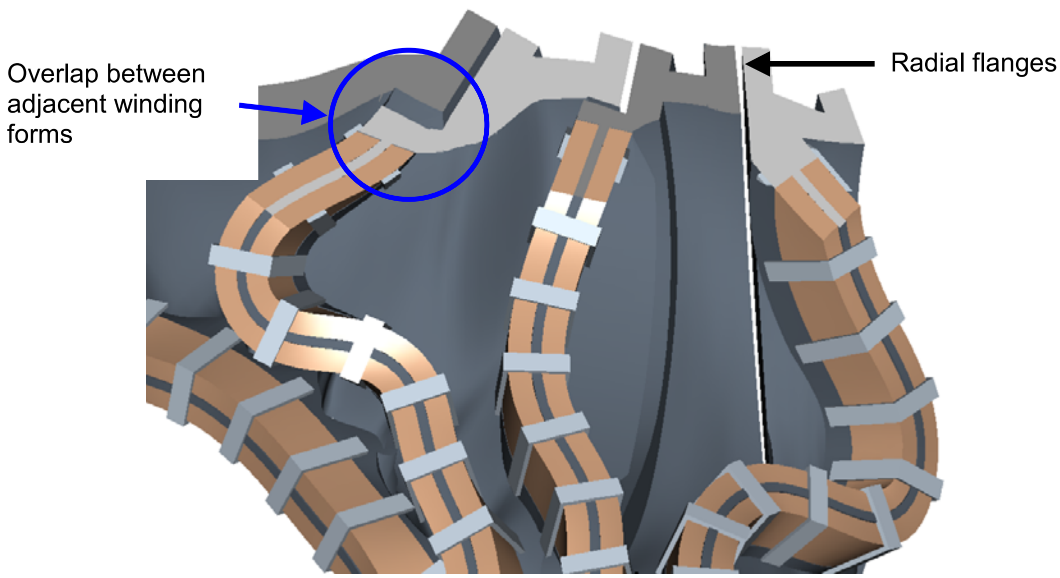

Figure 7 Nesting of Winding Forms

In summary, the winding forms create a robust structure mechanically that provide the best possible coil accuracy. The coils are wound onto machined winding cavities, which are referenced to machined assembly flanges. The accuracy of the winding cavity with respect to the flanges is expected to be very good, within 0.010 inches. The coils are designed to be shimmed at the interface flanges to allow optimally positioning each coil. No other structure is needed for the modular coils, except the interfaces to the gravity supports.

A product specification has been developed for the modular coil winding forms[3] that will be used as the technical basis for the procurement.

3.2 Windings and Assembly

Table 3 summarizes the main modular coil parameters. Important design features are 1) conductor and insulation, 2) winding pack layout, 3) leads, 4) cooling concept, 5) VPI bag mold, and 6) winding clamps.

[3] NCSX Product Specification for the Modular Coil Winding Forms, NCSX-CSPEC-141-03-00

Table 3 Modular Coil Parameters

Coil #	A'		A		B		C		C'
Coil Length (in)			290.5		283.2		263.0		
Min Coil-Coil Dist (in)		7.56		6.31		6.09		6.85	
Max Coil-Coil Dist (in)		35.0		36.4		30.7		26.6	
Min Radius of Curvature (in)			4.15		4.41		4.16		
Min Coil-Plasma Dist (in)			8.79		8.09		8.98		
Max Coil-Plasma Dist (in)			28.5		22.6		20.2		

The conductor is fabricated using a flexible copper cable with 3420 strands of bare AWG 34 (0.0063-in diameter) wire. The primary advantages of the flexible cable design are ease of winding and low cost. The primary disadvantage is the loss of copper area compared to a solid conductor. In the present design, the cable is compacted into a rectangular shape, 0.35 x 0.391-in, with a packing fraction of about 78%. A typical compacted conductor is illustrated in Figure 8. A packing fraction of 75% can be assured, although 80% is theoretically possible. Due to helical twisting of the cable strands, the length of the strands is about 12% greater than the conductor length. The conductor is insulated with a half-lapped layer of 0.004-in woven glass tape.

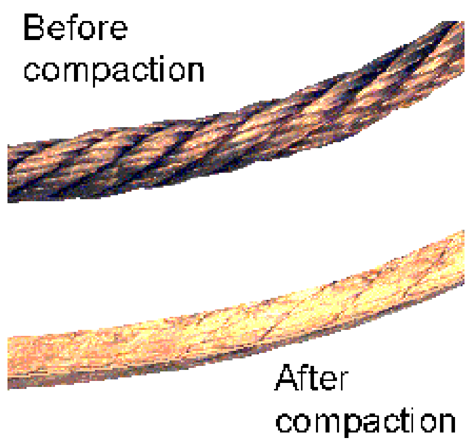

Figure 8 Compacted Cable Conductor

The winding pack layout has evolved from a double-layer pancake in the conceptual design to a four-in-hand, single layer pancake, as shown in Figure 9 and Figure 10. The main benefits of the design change are 1) reduced keystoning due to smaller conductor size, 2) reduced turn-to-turn voltage, and 3) reduced time estimated to wind the conductor. As shown in the figure, each winding pack is 10 layers in height for coil types A and B and 9 layers for coil type C, with a 0.030 to 0.036-in per layer allowance for conductor keystoning. A thin chill plate is located on both sides of each winding pack to remove the joule heating in the coil between plasma discharges. The chill plate consists of a .040 inch thick sheet of copper that is cut into the flat developed shape of the winding and then formed to match the winding pack contour. The forming is simplified by cutting the long edge of the plate into multiple strips to avoid the necessity of stretching the copper. The chill plate on the outer side is cooled by running liquid nitrogen through a tube connected to the outer surface, while the chill plate on the structure side of the winding is cooled by conduction to the outside chill plate. The nitrogen will enter the chill plate circuits near the bottom of each coil and exit near the top of each coil. The chill plates are electrically isolated from each other and the winding form structure to avoid circulating eddy currents.

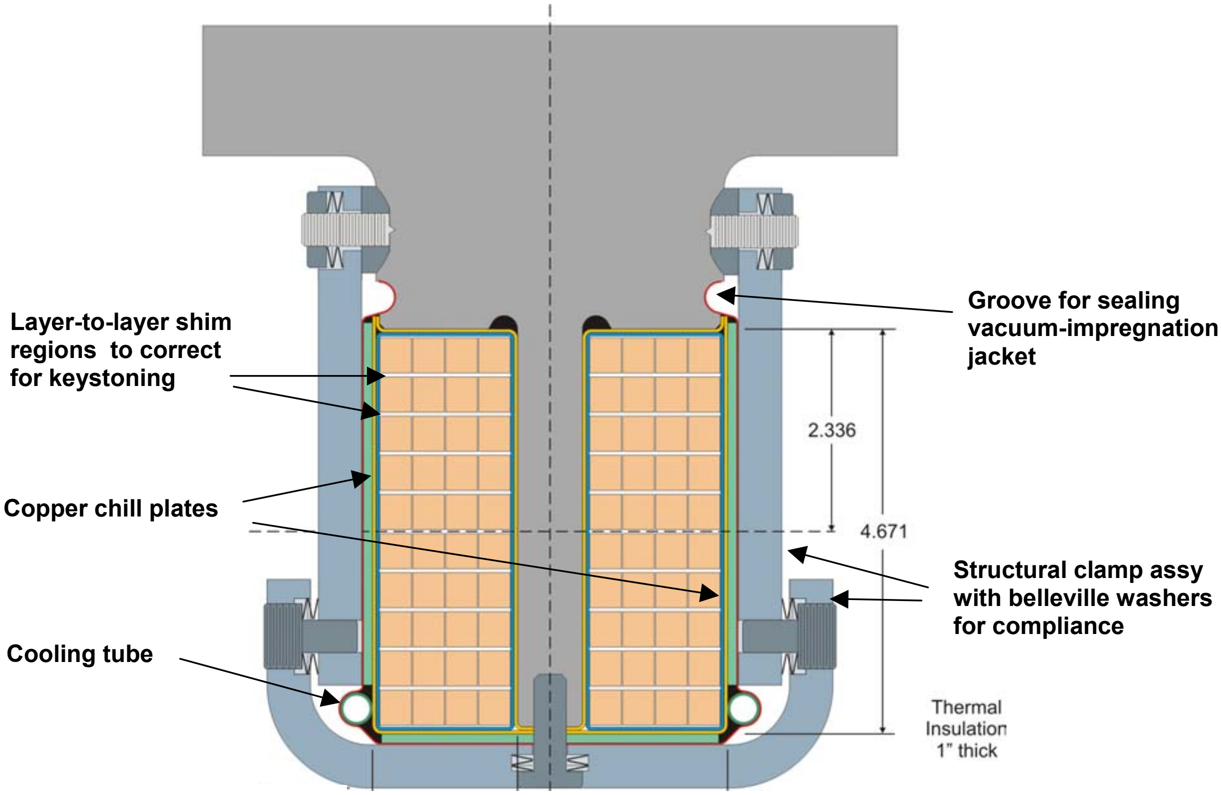

Figure 9 Winding Pack Layout

Figure 11 shows some details of the modular coil crossover region and current feeds. The four-in-hand windings enter the winding pack at the top of the "tee" and exit at the bottom, or plasma side of the winding. The turns are in parallel within a row of conductor, and the turns are not of equal length nor inductance, so like turns in each of the two winding packs for each coil are connected in series. That is, the current in the turns closest to the "tee" web are equal, the current in the next column of turns is equal and so forth. This ensures that the current center remains in the center of the pair of two winding packs, even though the current in the individual parallel turns is not equal. The details of the crossover connections outside the shell, shown in Figure 11, illustrate how the turns are interconnected.

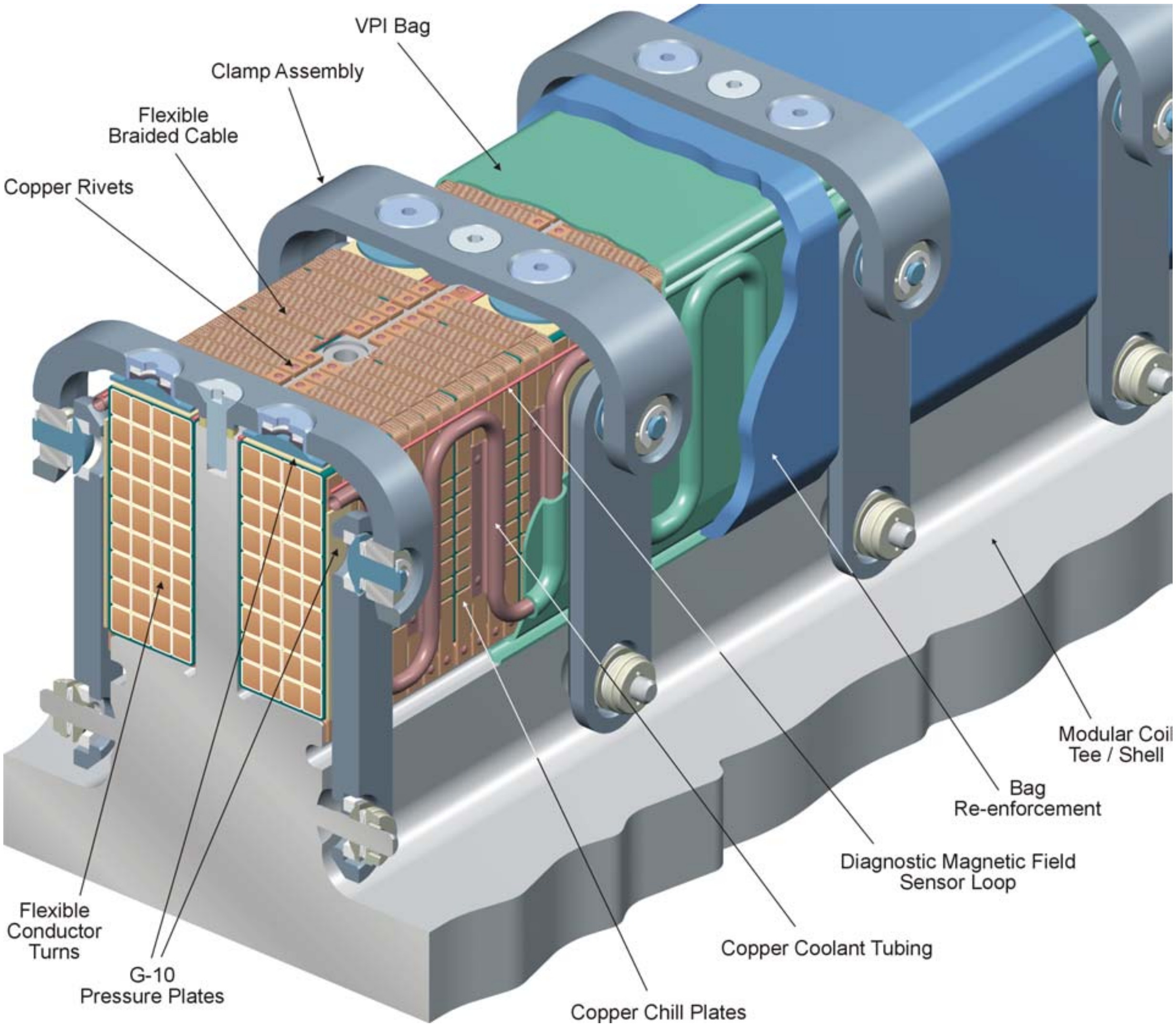

Figure 10 Cutaway view of winding packs on winding form

The current feeds for the modular coils consist of commercial, "kickless" cables, which have been modified to operate at liquid nitrogen temperatures by substituting reinforced Teflon for the insulation. The cables consist of 6 conductors, 3 of each polarity alternating and twisted together and contained within a common jacket. They are cooled by conduction and by bleeding nitrogen gas through the interspace of the jacket.

The winding packs are clamped in place by discrete bracket assemblies, or clamps, also illustrated in Figure 9 and Figure 10, which preload the winding packs against the structure. The predominant electromagnetic loads are towards the web structure. Outward loads do exist in tight bend areas, and the clamps help react the loads in these regions. The clamps also help control the position of the winding packs relative to the winding form during cooldown from room temperature to liquid nitrogen temperature, when the winding packs shrink about .04% more than the winding form. This is discussed in more detail in Section 0.

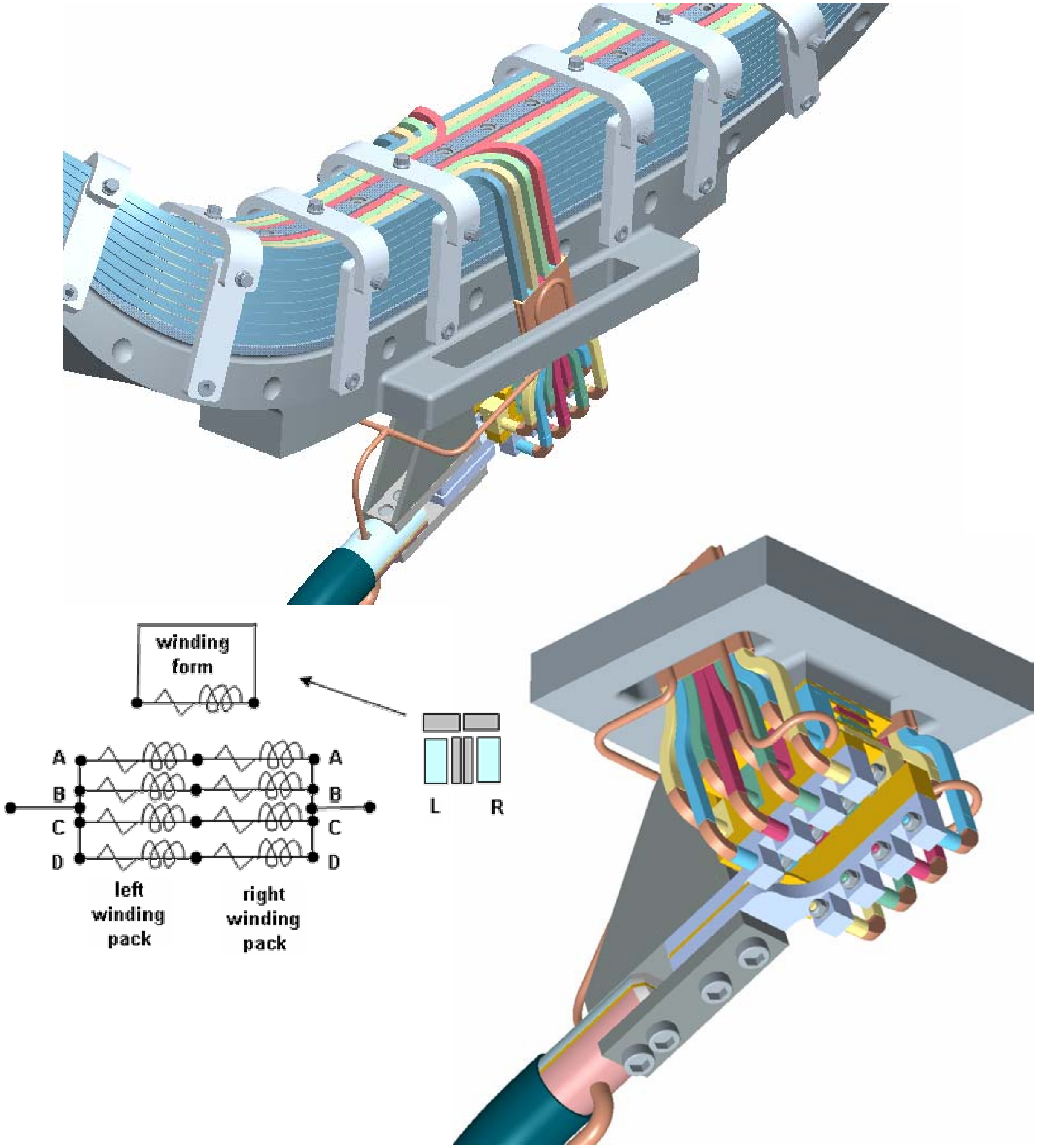

Figure 11 Modular Coil Lead arrangement

3.3 Local I&C

Table 4 lists the preliminary number and location of sensors, which are necessary to monitor behavior during operation and provide feedback to the coil protection system. The gages will have “back-to-back” elements that cancel transient electromagnetic fields to first order to reduce noise during operation.

Table 4 Modular Coil Instrumentation

Instrumentation	Total Number	Comment
Voltage Tap	36	2 per coil
Strain Gages	72	4 per coil
Flow Sensor	36	2 per coil
RTD / Thermocouples	72	4 per coil

4 DESIGN BASIS

The modular coil design is based on design criteria, preliminary analysis, R&D activities, and input from manufacturing development teams.

4.1 Design Criteria

The modular coils have been designed according to the NCSX Structural Design Criteria[4], which is based on the ASME Boiler and Pressure Vessel Code, Section VIII, Division 2. This document provides guidance on general structural criteria, cryogenic applications, and high temperature / high heat flux environments. It represents the consensus of experts in fusion and plasma science through meetings held in 1990-92 and has recently been updated to include a section on cable conductor.

4.2 Design Analysis

The design has been analyzed for coil and lead field errors, eddy currents in the structural shell, thermal and thermo-hydraulic response, electromagnetic (EM) forces, and stress due to thermal and EM loads. Design basis analyses will be documented and formally checked prior to release of those components for fabrication.

4.2.1 Coil and Lead Field Errors

Previous analyses have shown that the modular coil assembly must be very accurate to produce flux surfaces of sufficient quality. The Conceptual Design Report documented a study of the effect of small perturbations of the modular coils in the vertical and toroidal directions. The study found that coil displacements of 10-mm produced magnetic islands of a size that exceeded 10% of the total toroidal flux in the plasma but that these errors could be readily corrected by external trim coils.

Since then, additional studies have been performed to determine the effect of individual coil winding tolerances on island formation. An analysis was performed in which random errors in the position of a coil winding center were introduced. Three types of error were considered: 1) a Fourier representation in which the local tolerance varies with coil-to-plasma separation, 2) a short wavelet type displacement in orthogonal directions to the winding center, and 3) a broad displacement of the winding center over a significant length of the coil. A typical result of the analysis is the graph of island size versus coil-to-plasma separation distance for a broad winding center displacement (Figure 12). The graph indicates that while errors in the regions of the coil within 30 cm of the plasma (typically the inboard region) have a significant impact on flux quality, errors in the regions of the coil more than 30 cm away from the plasma are more tolerable.

Subsequent studies have looked at the effect of modifying the position of a deformed coil to reduce islands. The VACOPT code [5] has been implemented as part of the Stellarator Optimization (STELLOPT) code [6]. This code allows targeting of specific resonances in the vacuum field. The effect of rigid body manipulations of the modular coils can then be examined and the position of each as-built coil can be optimized. The current version of the code only works for stellarator symmetric errors, which would result from systematic fabrication errors or winding distortions due to structural deformations. Upgrading of the code to optimize non-stellarator symmetric errors is planned. An example of the effectiveness in reducing targeted islands by optimally positioning coils is shown in Figure 13. Note the substantial reduction in size of the m=7 islands.

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[4] NCSX Structural and Cryogenic Design Criteria, NCSX-CRIT-CRYO-00

[5] D. Strickler, "Control and Optimization of the Vacuum Field", May, 2004.

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

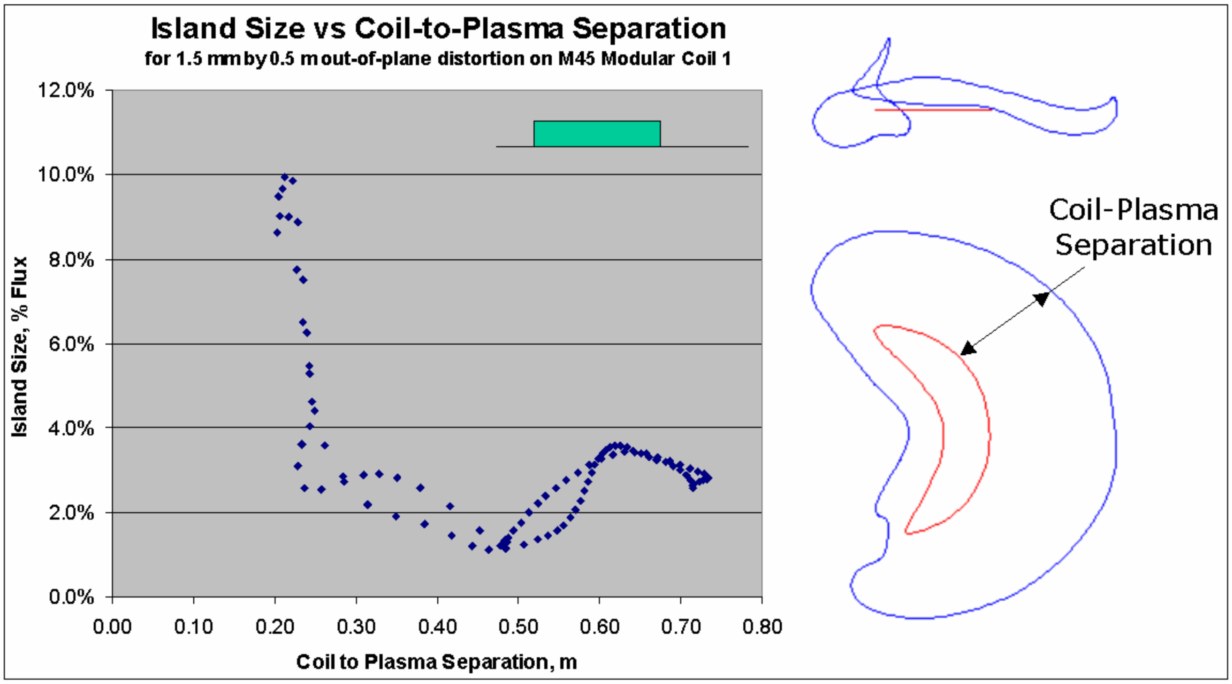

Figure 12 Field Error due to Winding Center Displacement

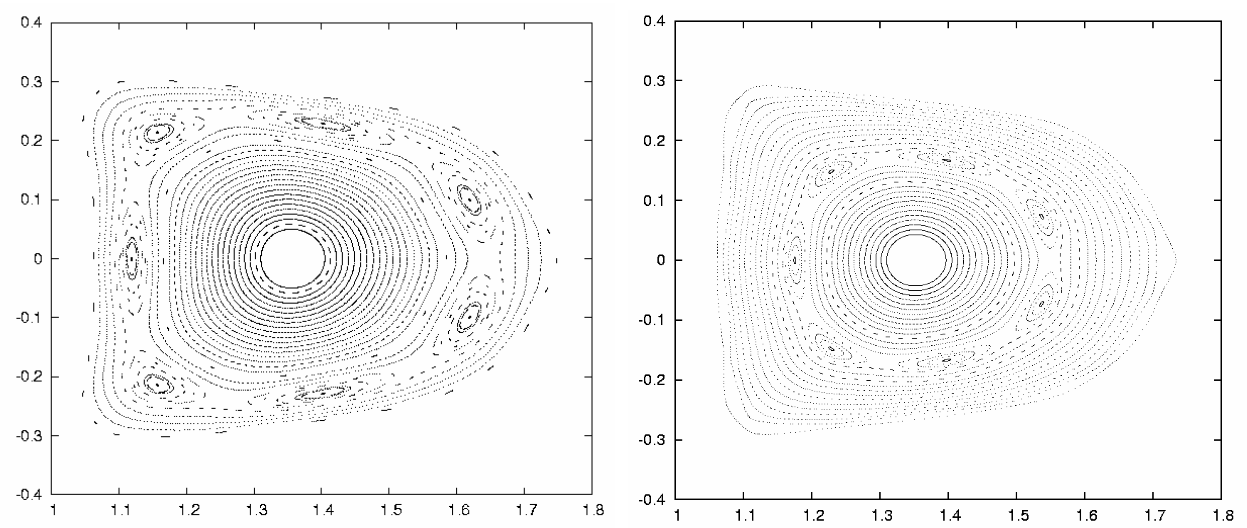

Figure 13 Example of Island Reduction by Optimizing Position of As-Built Modular Coils

This optimization technique will be used during assembly of the individual coils into field periods, and of the field periods into the full assembly of the machine. The coils are positioned relative to each other using a set of three spherical seats cut into the flange of one winding form and a set of three adjustable alignment balls in the mating flange of the adjacent winding form. The optimal position of one winding form is determined with the VACOPT / STELLOPT code based on measurements of the as-built winding center trajectories. The alignment ball positions are adjusted to match the spherical seats in the adjacent coil such that when the balls and seats are registered, the two coils are in the optimum position relative to each other. The shims are then cut to match the resultant gap between the coils and the coils are bolted together. In this way the tolerance buildup among coils during field period assembly and final assembly is minimized.

A second area of concern for field errors involves the modular coil leads and the turn-to-turn crossovers. A study of the double-layer pancake winding used in the conceptual design[7] showed that field errors can be minimized by:

- Arranging the joggles from layer to layer so that the pattern of turn to turn joggles on one pie form an "X" shape with the pattern of joggles on the adjacent pie.
- Making sure the lateral crossover from pie to pie occurs in opposite directions on the two winding packs within a coil. This reverses the field errors from the lateral current paths and cancels them to first order.
- Minimizing the errors at the lead entrance by immediately tying the leads together into a coaxial arrangement.

Such design rules have been considered for the present four-in-hand design, but the resulting configuration still has larger current loops than the earlier concept.

An analysis of the effect of multiple-in-hand options was performed using the VACISLD code[8]. Estimates of island size were computed for the leads of one, two, and three-in-hand winding configurations at different positions on each coil. A typical result is shown in Figure 14, where island size is shown to vary strongly with poloidal location. The results of the study indicate that field errors from multiple-in-hand leads are relatively low, and that the location of the leads can be optimized. The error in the multiple in-hand configurations is highest for two in hand and decreases for 3 and 4-in-hand because the 2-in-hand configuration has the largest conductor size. The larger conductor has a corresponding larger bend radius, which results in larger error producing current loops. The actual lead location is very close to the 90% poloidal length region shown in Figure 14, so the error fields will not be an issue.

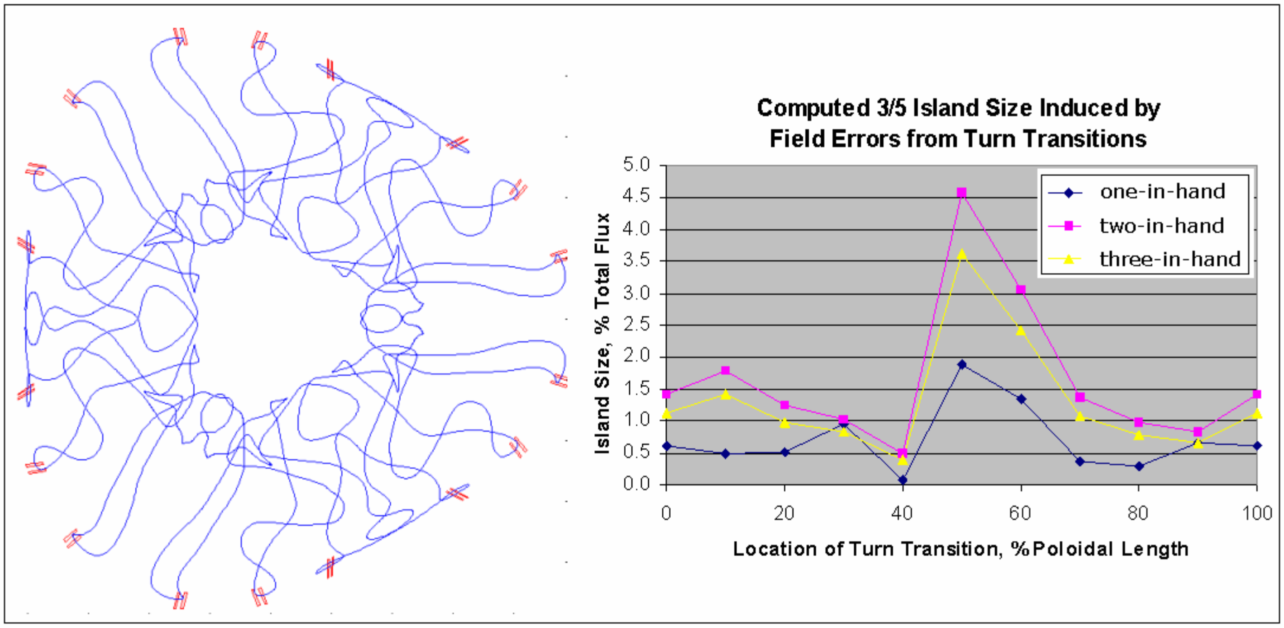

Figure 14 Predicted Island Sizes from Field Errors due to Leads

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[7] A. Brooks, A. V. Georgiyevskiy, W.U.Reiersen, V.A.Rudakov, "Current Feeds And Connection Part Perturbation Study On Magnetic Configuration Of NCSX Stellarator (M45 coils c01r00)", April 2002

[8] Private Communication, Art Brooks, December, 2002

4.2.2 Eddy Currents

An analysis of the eddy currents induced in the structural shell due to varying modular coil currents has been performed using the SPARK code[9]. Figure 15 shows the finite element mesh of the shell and tee. Design details that were investigated include 1) toroidal and poloidal electrical breaks at the flanges and outboard midplane, and 2) segmentation of the copper chill plates attached to the winding packs.

Figure 15 also shows a typical eddy current pattern on the shell structure. The results indicate that the longest time constant without a poloidal break is >50-ms, a value that would likely cause field errors and flux penetration issues for the design. However, by incorporating a poloidal break and electrically insulating the toroidal flange joints (except at the field assembly joint which occurs in three places), the time constant is reduced to below the required 20-ms. The analysis also indicated that the widths of the winding pack chill plates should be kept below 2-in to keep the time constant of those loops below 20-ms.

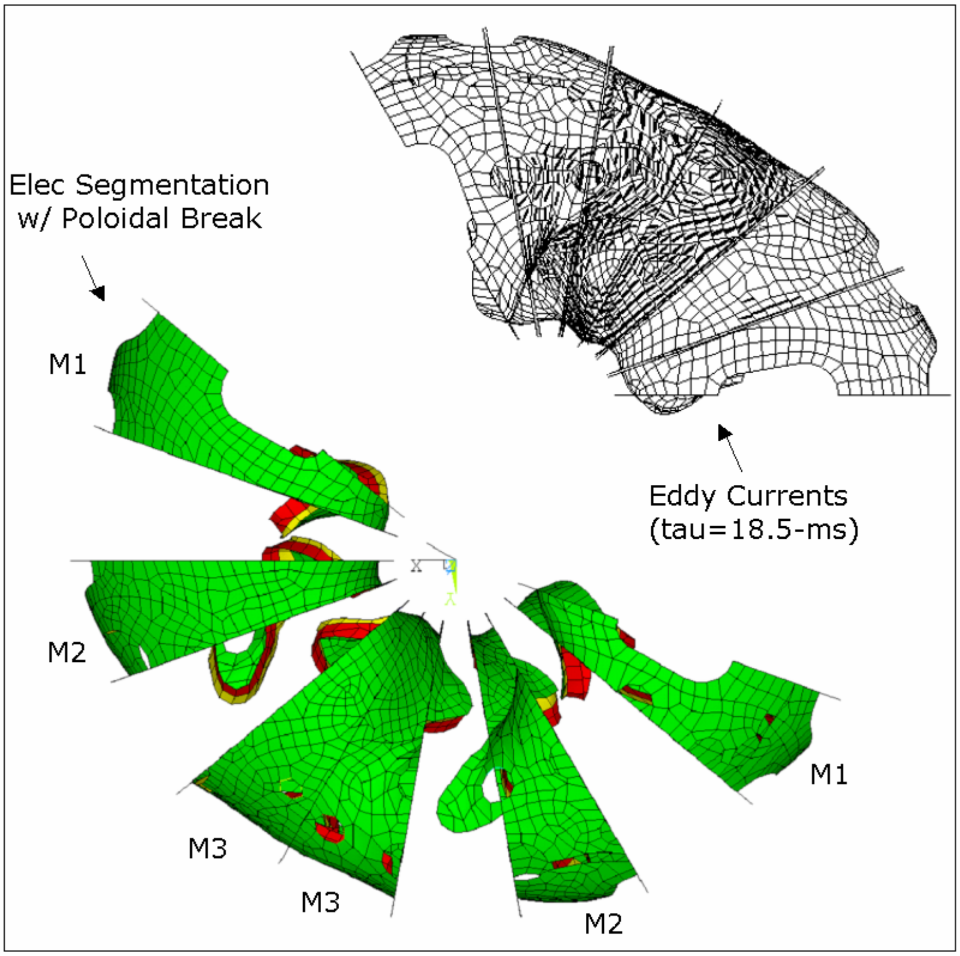

Figure 15 Eddy Currents in Structural Shell

[9] SPARK D. Weissenburger, "SPARK Version 1.1 Reference Manual", Princeton Plasma Physics Lab Report No. PPPL-2494 (1988)

4.2.3 Thermo-hydraulic analysis

An analysis of several chill plate configurations was performed using the ANSYS code[10]. Figure 16 shows the finite element model for a case that is very close to the present design. It models the heat conduction through a 2x9 winding pack to inner and outer chill plates, which are cooled by discrete copper clamps. The present design, in contrast, is cooled directly by the outer chill plate and uses thinner turn insulation, which should compensate for the lack of direct contact between the chill plates and interior turns of the 4x10 configuration.

A transient analysis was performed using temperature dependent material properties. Of the standard operating scenarios, the worst case is the initial ohmic operation at 1.7T, which has a current density of 15 kA/cm^2 in the copper and an ESW of almost 1.4 s. For a starting temperature of 85 K, the temperature rises 45-K during the pulse, which has been adopted as an administrative limit. Figure 16 shows the temperature distribution during the first cooling cycles, and Figure 17 shows the cyclic behavior for multiple cooling cycles. After ten cycles, the starting temperature has stabilized at about 86-K with a coolant temperature of 80-K.

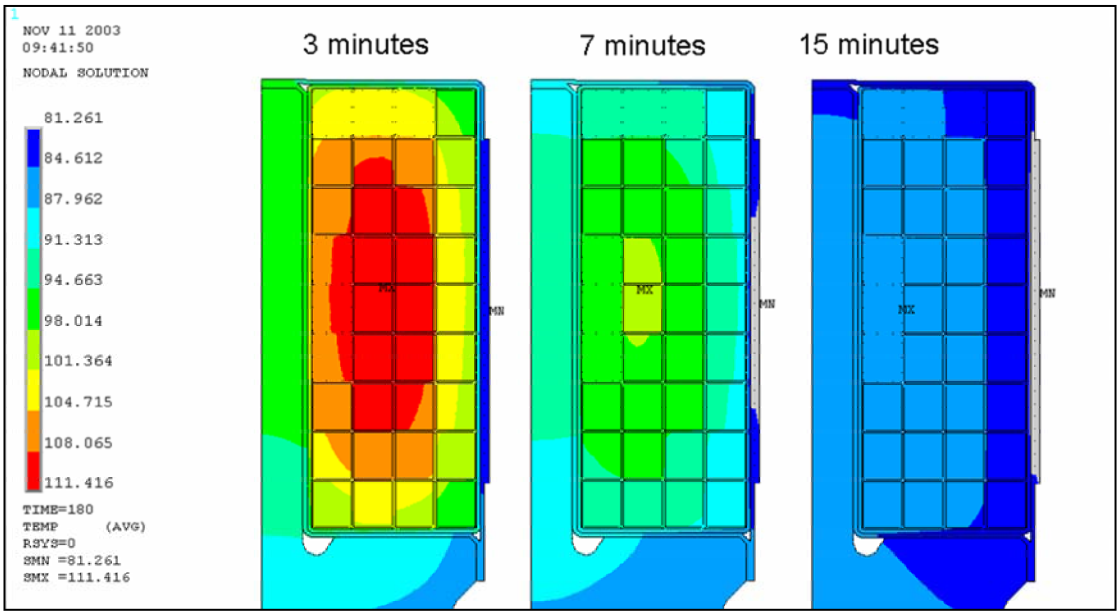

Figure 16 Winding Pack Temperature Distribution during Cooldown

[10] HM Fan, "NCSX Modular Coil Cooling", May 19, 2003.

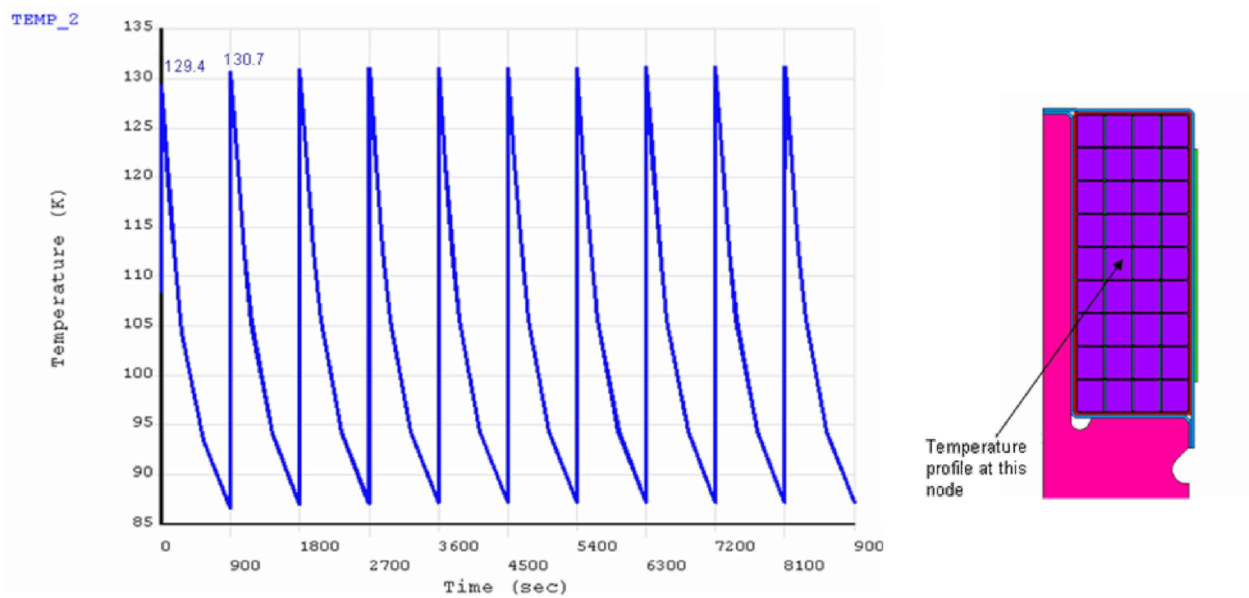

Figure 17 Cooldown of hottest part of winding pack over 10 cycles

A thermo-hydraulic analysis was performed for all three coil systems (PF, TF, and Modular). The present design calls for forced flow LN2 cooling of all coil systems with a prescribed inlet temperature of 80 K at 200 psi. The prescribed equivalent square wave (ESW) used was 1.2-3.5 sec. at the maximum rated current for each coil system. The duty cycle (cool-down period) was specified as 15 minutes (900 sec.). A summary of the results is shown in Table 5. The total LN2 flow requirements for the main coil systems for the modular coils will be 16 GPM. The cool-down of the M1 modular coil is illustrated in Figure 18. The modular coil stops ratcheting after about 4 pulses. The bulk coolant temperature rise is very small, only a few degrees Kelvin.

Table 5 Thermo-Hydraulic Analysis of Coils

	ESW	I (kA)	ΔT peak (deg-K)	Tmax (deg-K)	ΔP (psi)	flow/coil (GPM)	total flow (GPM)
M1	1.2	24	36.1	117.4	10	0.88	5.2
M2	1.2	24	36.2	117.2	10	0.90	5.4
M3	1.2	24	36.4	116.5	10	0.94	5.6
Total							16.2

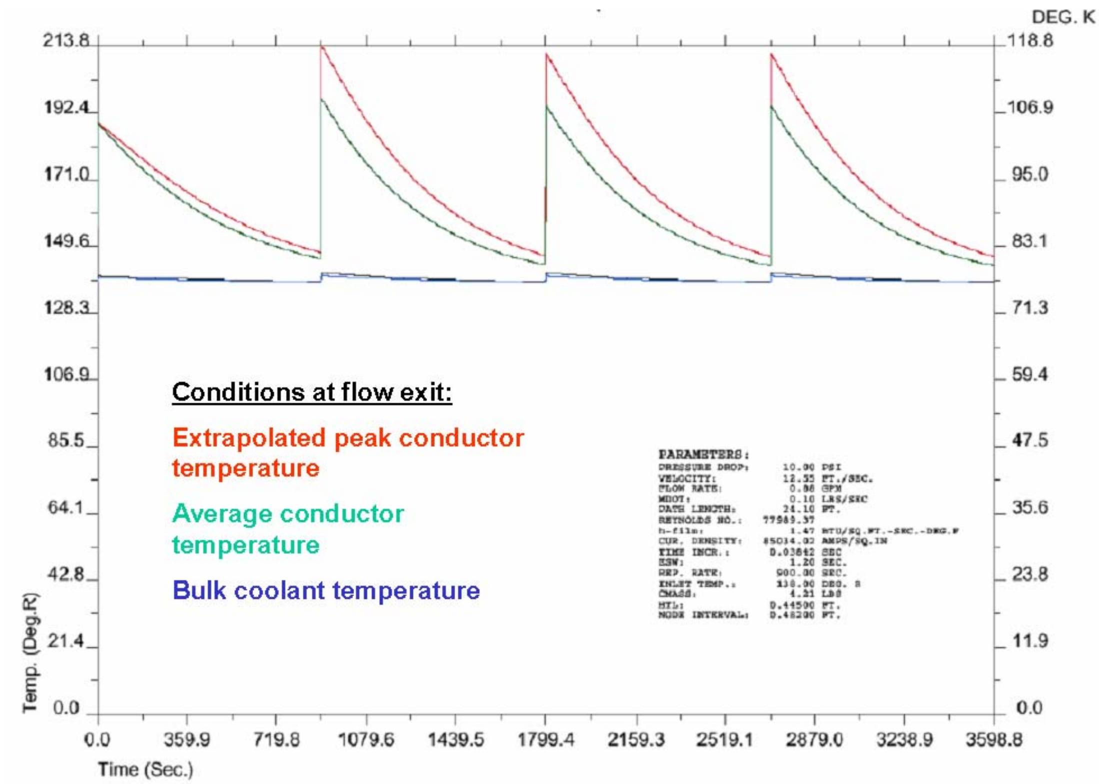

Figure 18 Modular Coil Cooldown

4.2.4 Electromagnetic Loads

Calculations to determine the fields and forces acting on all of the stellarator core magnets have been completed for seven reference operating scenarios. Table 6 summarizes the coil currents for all coils at a time step when the modular coils are at their maximum positive or negative value. The worst case for determining forces in the modular coils appears to be the 2T high beta scenario at time=0.197-s.

Table 6 Electromagnetic Analysis Load Cases

Circuit	Coil Set	0.5-T 1st Plasma (kAT)	Field Mapping (kAT)	1.7-T Ohmic (kAT)	1.7-T High Beta (kAT)	2-T High Beta (kAT)	1.2-T Long Pulse (kAT)	320-kA Ohmic (kAT)
1	TF	13	13	43	45	53	30	26
2	PF1	673	0	1479	1120	1340	1191	1632
---	PF2	673	0	1479	1120	1340	1191	1632
3	PF3	673	0	1286	998	1208	980	1082
4	PF4	749	734	374	416	287	313	1191
5	PF5	0	0	204	209	82	148	128
6	PF6	32	13	104	101	115	72	73
7	M1	224	224	763	763	818	539	695
8	M2	209	209	710	710	831	501	707
9	M3	188	188	638	638	731	451	621
	Plasma	35	0	120	178	210	126	321

Two independent field calculations have been performed, one with the ANSYS code[11] and the other with MAGFOR[12]. A comparison of magnetic flux density at 2-T (Figure 19) indicates that the models are in good agreement, with only a 4% difference in peak field due primarily to mesh and integration differences.

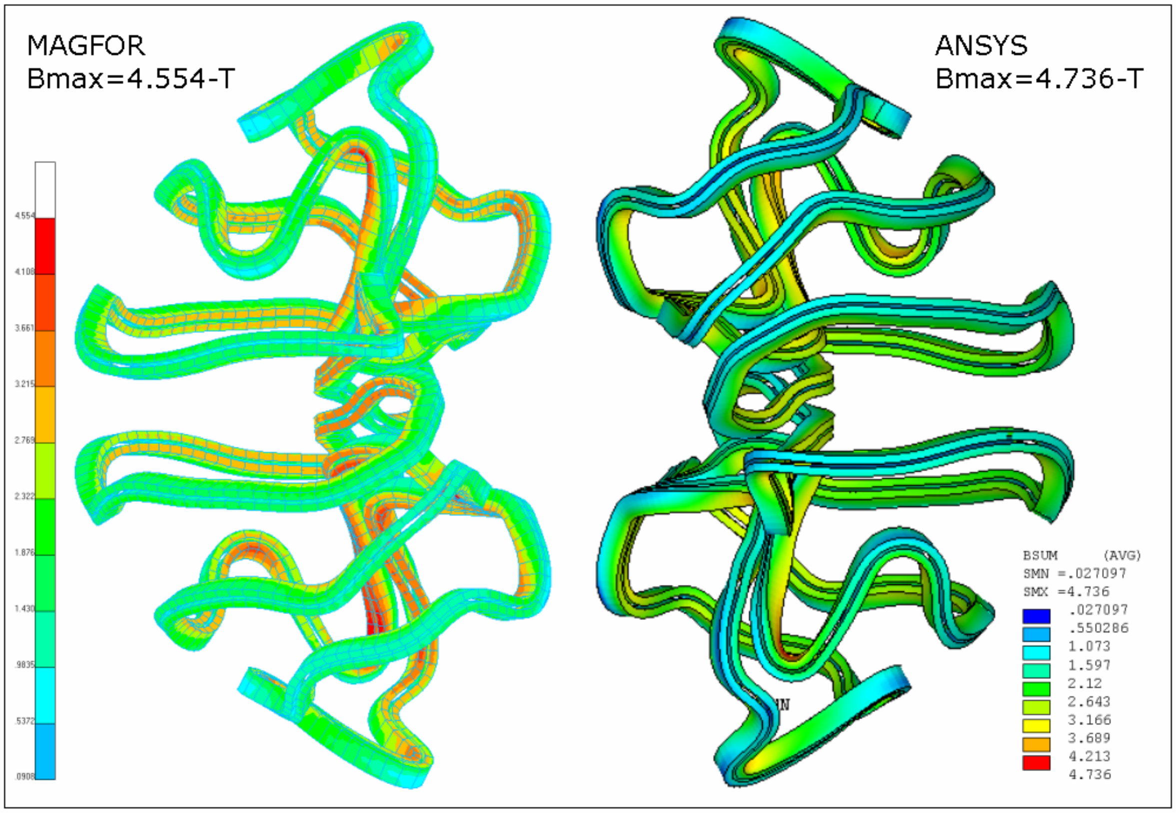

Figure 19 Magnetic Field at Coil Windings

The force distribution for the modular coils is illustrated for the 2-T case in Figure 20. As shown, the net radial centering force per coil varies from 86 to 317 kips, while the vertical force is much smaller. Table 7 lists the net forces and maximum running loads for each of the cases studied.

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[11] ANSYS Inc, 275 Technology Drive, Canonsburg, PA 15317

[12] W.D. Cain, "MAGFOR: A Magnetics Code to Calculate Field and Forces in Twisted Helical Coils of Constant Cross-Section", 10th IEEE/NPSS Symposium on Fusion Engineering, 1983

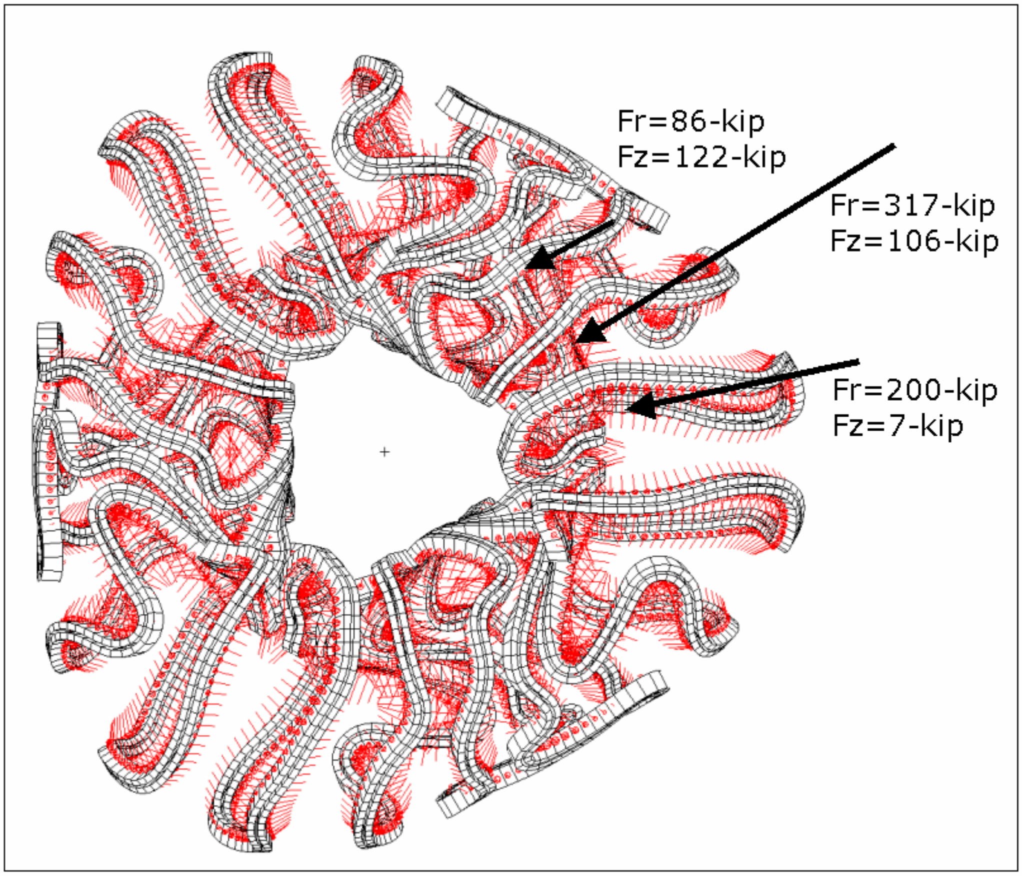

Figure 20 Force Distribution on Modular Coils at 2T

Table 7 Net EM Force on Modular Coils

Coil	Field/Force Component	0.5-T 1st Plasma	Field Mapping	1.7-T Ohmic	1.7-T High Beta	2-T High Beta	1.2-T L. Pulse	320-kA Ohmic
Type A	Max Field at Coil (T)	1.2	0.2	4.2	4.2	4.9	2.9	4.2
	Net Radial Load (kip)	13	1	152	152	200	76	147
	Net Vert Load (kip)	0.5	0	9	9	7	5	7
Type B	Net Radial Load (kip)	20	1	228	228	317	113	230
	Net Vert Load (kip)	7	0	84	84	106	42	79
Type C	Net Radial Load (kip)	5	0	57	57	86	29	62
	Net Vert Load (kip)	8	0	95	95	122	47	89

In order to better understand the forces on the modular coils, they have been resolved into local coordinates in the radial and lateral direction relative to the winding form structure. The lateral forces are in the direction normal to the surface of the supporting "web" structure and the radial forces are those directed outward against the shell. Figure 21 plots these force components as a function of coil perimeter for the M2 coil. Table 8 lists the maximum component forces for each case.

What is also illustrated in the figure is the very local problem of the winding pack force being away from the web. This occurs primarily in regions of sharp lateral curvature, and is due to the local peak fields. For the condition shown, there is a local force peaking at 3000 lbs/in acting over a distance of about 8 inches. The force will be reacted partially by the coil clamps and partially by the winding acting as a beam in this region. For the present spacing of clamps, at least two clamps will act to restrain this region.

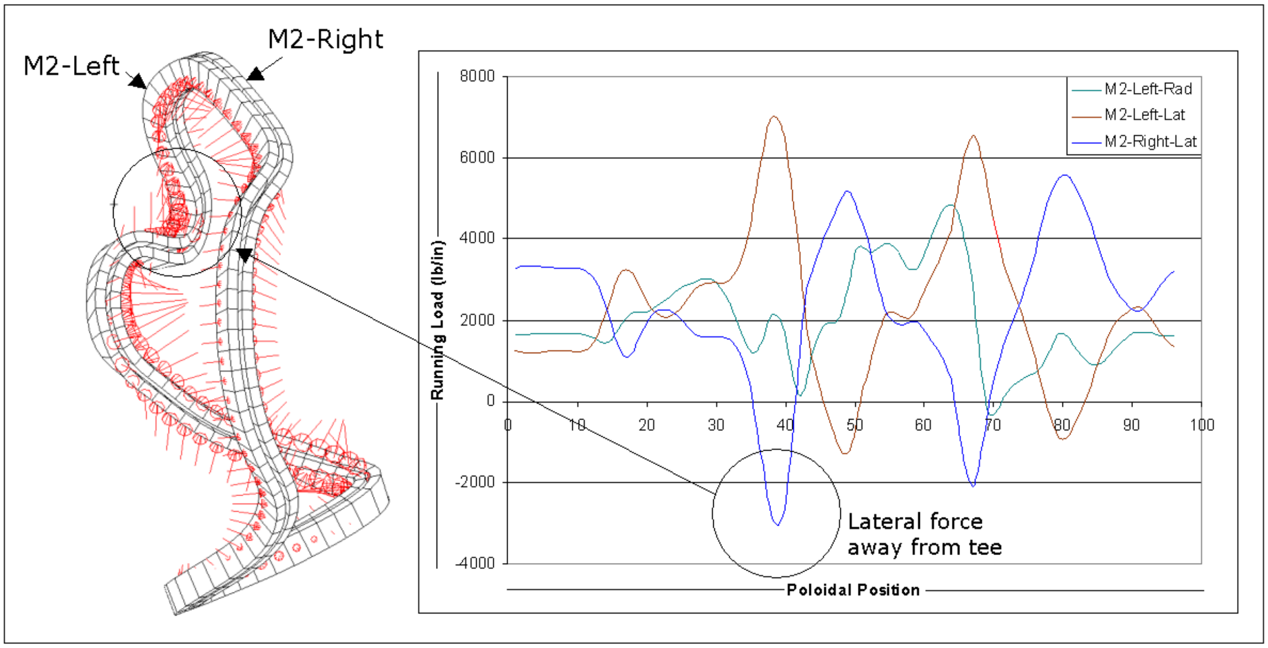

Figure 21 Component Forces for Coil M2 (2T case)

Table 8 Maximum Running Load on Modular Coils

Coil	Field/Force Component	0.5-T 1st Plasma	Field Mapping	1.7-T Ohmic	1.7-T High Beta	2-T High Beta	1.2-T L. Pulse	320-kA Ohmic
M1	Rad Load (lb/in)	200	8	2272	2279	2869	1134	2053
	Lat Load (lb/in)	434	17	4995	4997	5831	2490	4163
M2	Rad Load (lb/in)	351	14	4077	4076	5591	2031	4050
	Lat Load (lb/in)	430	17	4982	4983	6982	2483	5059
M3	Rad Load (lb/in)	233	9	2698	2698	3540	1344	2615
	Lat Load (lb/in)	418	17	4830	4830	6405	2407	4552

4.2.5 Stress due to Electromagnetic Loads

To be provided

4.2.6 Stress due to Thermal Loads

To be provided

4.2.7 Stress due to Combined Loads

To be provided

4.3 R&D Activities

4.3.1 Winding R&D

4.3.1.1 Material Properties

The primary element for analysis is the modular coil set. The material properties for the composite cable conductor are the most critical to understand and a significant test program is underway to characterize the properties of the baseline design conductor[13]. Numerous conductor bundles have been fabricated for use in determining the tension, compression, flexural and shear strengths of the copper conductor matrix at CTD[14] and PPPL. The preliminary results of the testing are shown in Table 9. The tests indicate relatively high strength in tension and compression, with a 30% increase in strength between room temperature and LN2 temperature. Typical thermal expansion data is plotted in Figure 22

Table 9 Cable conductor material property preliminary test results

Test Performed	PPPL Test Result - Ksi
Flexural modulus, bare conductor, at room temp	9700
Flexural modulus, bare conductor, at LN2 temp	11300
Longitudinal shear yield strength at room temp	3.7
Longitudinal shear ultimate strength at room temp	4.6
Longitudinal compressive modulus at room temp	9100
Longitudinal compressive modulus at LN2 temp	
Longitudinal compressive strength at room temp	
Longitudinal compressive strength at LN2	
Longitudinal tensile modulus at room temp	8300
Longitudinal tensile modulus at LN2 temp	
Longitudinal tensile strength at room temp	>20
Longitudinal tensile strength at LN2 temp	

[13] T. Kozub, S. Jurczynski,,and J. H. Chrzanowski, "Cable Conductor Material Properties", May, 2004.

[14] Composite Technology Development, Inc., Littleton, Colorado

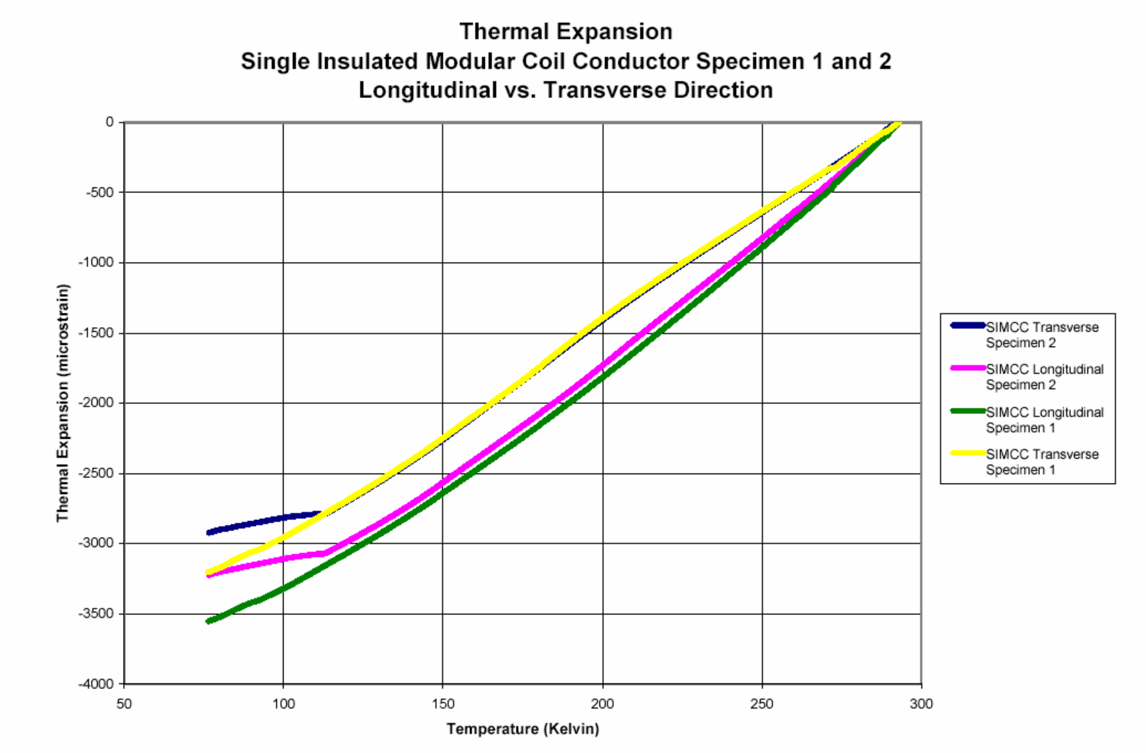

Figure 22Thermal expansion data for a single modular coil conductor specimen

4.3.1.2 VPI Process Development

The NCSX engineering team has developed processes for winding and vacuum pressure impregnation (VPI) of the modular coils at PPPL[15]. Initial preparations for the R&D facility in the TFTR test cell basement have been completed. Additional copper conductor and several short coil forms have been procured for VPI trials. The trial forms have a tee-shaped cross section and are contoured in various patterns representative of the actual NCSX winding form design. The VPI process uses self-fusing silicon tape followed by a wet wrap of the winding pack to form a pressure boundary. The molding process has been tested on single turn and 4-turn straight samples and on samples with the actual coil cross section. A fully insulated 36 turn coil cross-section was assembled and successfully vacuum impregnated. Preliminary inspections indicate a good penetration and wicking of epoxy through the outer ground wrap and turn insulations. Section cuts were made through the bundle, and preliminary reviews show that the copper rope conductor appears well impregnated. The bag mold method was quite successful with no indications of any leaks at the seams or around the sprues (epoxy flow channels). The epoxy for this tee section was fed through machined holes into the tee or tail section of the mold. The epoxy flowed as expected through the areas of least resistance, in some cases bypassing sequentially located sprues. A dry area did occur above the uppermost sprue where a possible air pocket may have been trapped. The sprue was located approximately 2.5 inches from the dry area. The final coil impregnations will require an exit sprue at the highest point on the coil to avoid this problem. Overall the impregnation results were very good. The bag mold method and the epoxy delivery system worked well.

A small oven has been used for the VPI processing to date, but a large autoclave, or vacuum oven, has now been procured and installed and will be used for the prototype and production coils.

[15] J. Chrzanowski, Peer Review of Modular Coil VPI, Jan 2003

4.3.1.3 Keystoning

Numerous keystoning tests have been completed to quantify the problem of bending the conductor around tight radii. The effect is to make the cross section trapezoidal and spoil the dimensional build of the coil. The solution is to provide a shim space between layers of conductor that allows the build to be recovered at every turn, eliminating the stack-up around tight corners. The penalty is a loss of copper fraction in the winding. The tests prove that the conductor cross section must be significantly smaller than the bend radius to keep the shim thickness small[16]. The practical significance of the effect of keystoning on the selection of the winding pack design is shown in Table 10. As shown, the current density is degraded significantly for the conventional, one-in-hand winding pack design compared to the multiple in hand designs that use smaller conductor. The effect has diminishing returns, however, due to the increase in insulation fraction as the number of turns increases. The four-in-hand design chosen as the baseline is the best compromise of low keystoning, lower current density, and lower field errors in the leads due to tighter allowable bend radius.

Table 10 Effect of Keystoning on Three Winding Pack Configurations

	One-in-hand	Three-in-hand	Four-in-hand
Turns high	7	8	9
Turns wide	2	3	4
Conductor width (in)	0.665	0.445	0.319
Conductor height (in)	0.407	0.400	0.366
Keystoning allowance(in)	0.136	0.061	0.031
Keystoning effect	34%	15%	9%
Rel. current density	1.30	1.16	1.17

4.3.1.4 Demonstration / Test Coils

At least four demonstration / test coils are planned or have been completed as part of the R&D effort. The first coil was a small racetrack coil wound at the University of Tennessee (UT). This coil was successfully vacuum impregnated with epoxy at PPPL and tested at ORNL. The coil operated successfully to 10 kA. The pulse length was adjusted to provide a 40C temperature rise and the coil was cooled back down in a relatively short period of time. The cooling was accomplished with copper chill plates, but was otherwise not prototypical. The coil is illustrated in Figure 23.

The second demonstration coil was a larger, more prototypic racetrack coil wound at PPPL. This coil has two complete winding packs of 14 turns each, copper cladding, a prototypic "tee" shaped winding form, and structural clamps. The coil has been wound and vacuum impregnated with epoxy and will be tested this summer. The coil is shown in Figure 24.

A third demonstration coil is planned that will integrate all the major features of the baseline design, including the most severe regions of twist and curvature, the four-in-hand winding configuration, the chill plates, and the structural clamps. Its shape appears like a "twisted racetrack". The coil will be the first one vacuum pressure impregnated using the large autoclave. This coil is shown in Figure 25. The winding form for this coil will be delivered in May, 2004. Winding will be completed this summer.

A cryogenic coil test facility is being constructed at PPPL that is capable of supplying the DC current and LN2 at the levels required for experimental operation. It will be used to test the demonstration coils as well as the production coils.

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[16] W. Reiersen, "Effect of Keystoning on Winding Pack Design", July 30, 2003.

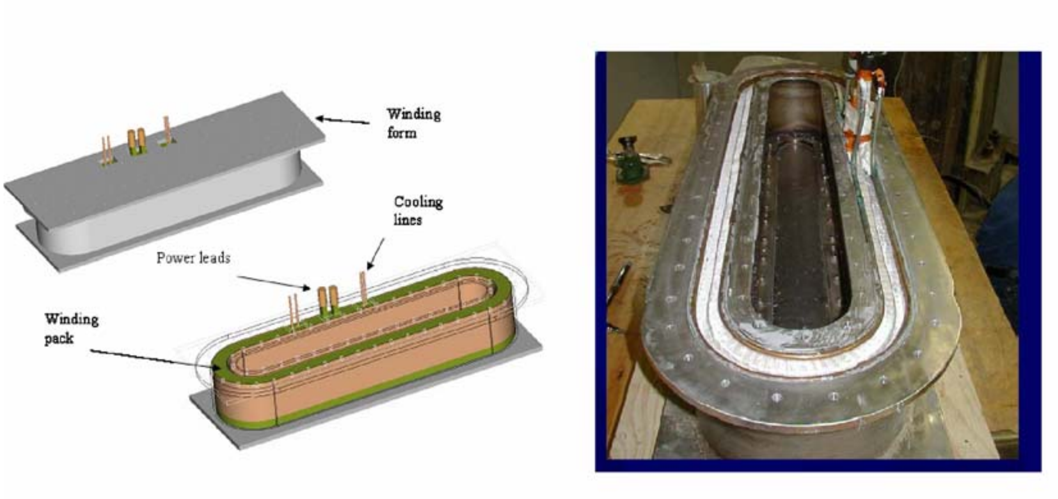

Figure 23 First Racetrack Demonstration Coil, Wound at UT and Vacuum Impregnated at PPPL

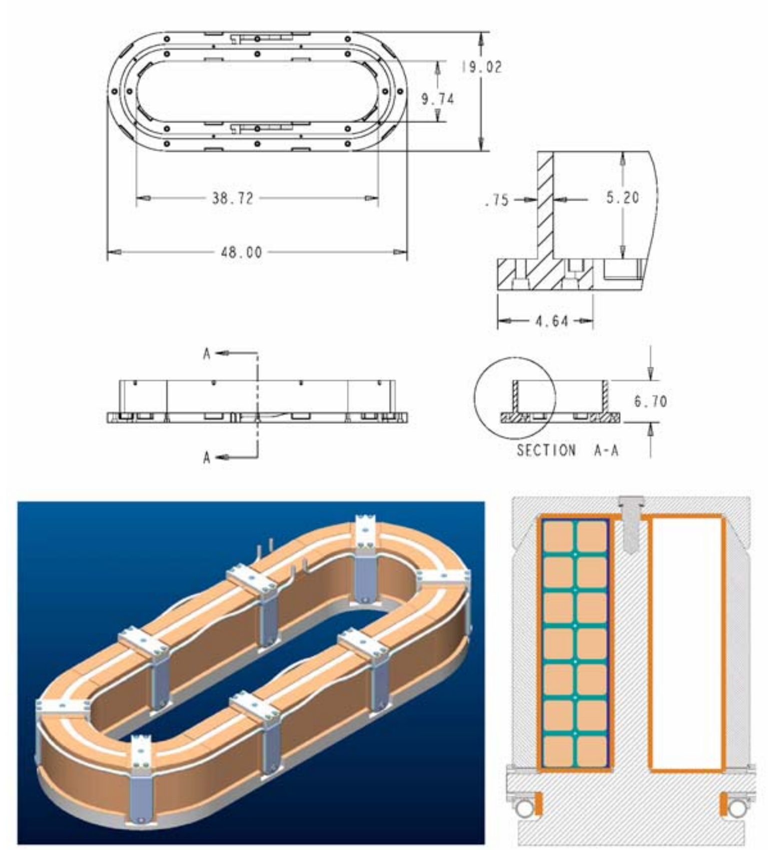

Figure 24 Second Racetrack Demonstration Coil, Wound and Vacuum Impregnated at PPPL

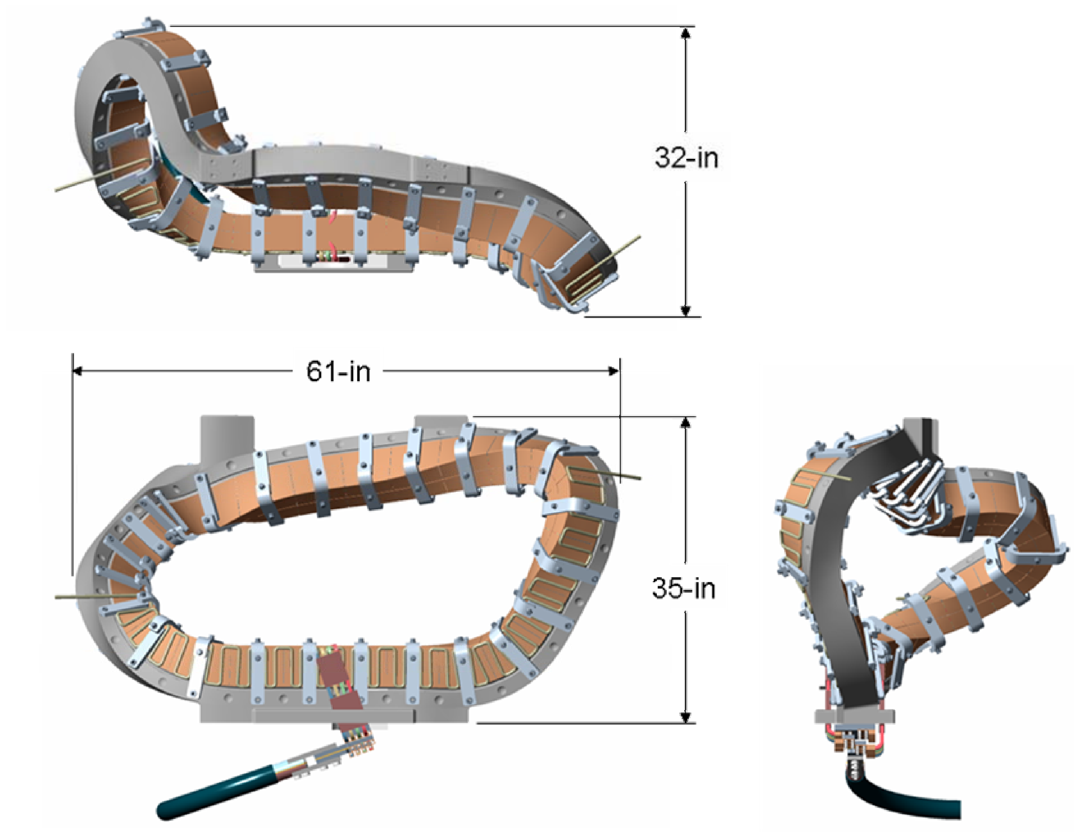

Figure 25 "Twisted Racetrack" Demonstration Coil

Full scale prototype modular coil winding forms will be provided by the suppliers under the current contract. The winding forms will demonstrate that each of the suppliers is qualified to produce the final articles. Upon delivery to PPPL, the winding forms will be used for trial winding exercises. However, we do not plan to complete the windings, vacuum pressure impregnate the coils, and test them at cryogenic temperature.

4.3.1.5 Additional R&D studies

Some other, miscellaneous R&D has been performed to investigate the behavior of the cable conductor.

Cable handling: The cable was tested with respect to general handling characteristics typical of winding processes. The cable is extremely flexible, but repeated bending and manipulation cause it to "unpack".

Cable resistance measurements: The cable resistance was measured and found to be, on average, about 12% higher than one would expect for a straight copper conductor of the same area as contained in 12,240 strands of 36 AWG wire14. This is believed to be due primarily to the twist in the cables before they are compacted and the fact that the wire may have been on the low side of the 36-gage specification (nominal diameter of a single wire = 0.005 inches).

Epoxy fill measurements: Electron beam microscope measurements at 12,000 X magnification show good epoxy fill between the individual copper strands. This provides high confidence that the compacted copper cable to be used by NCSX can be successfully impregnated. A typical result is illustrated in Figure 26

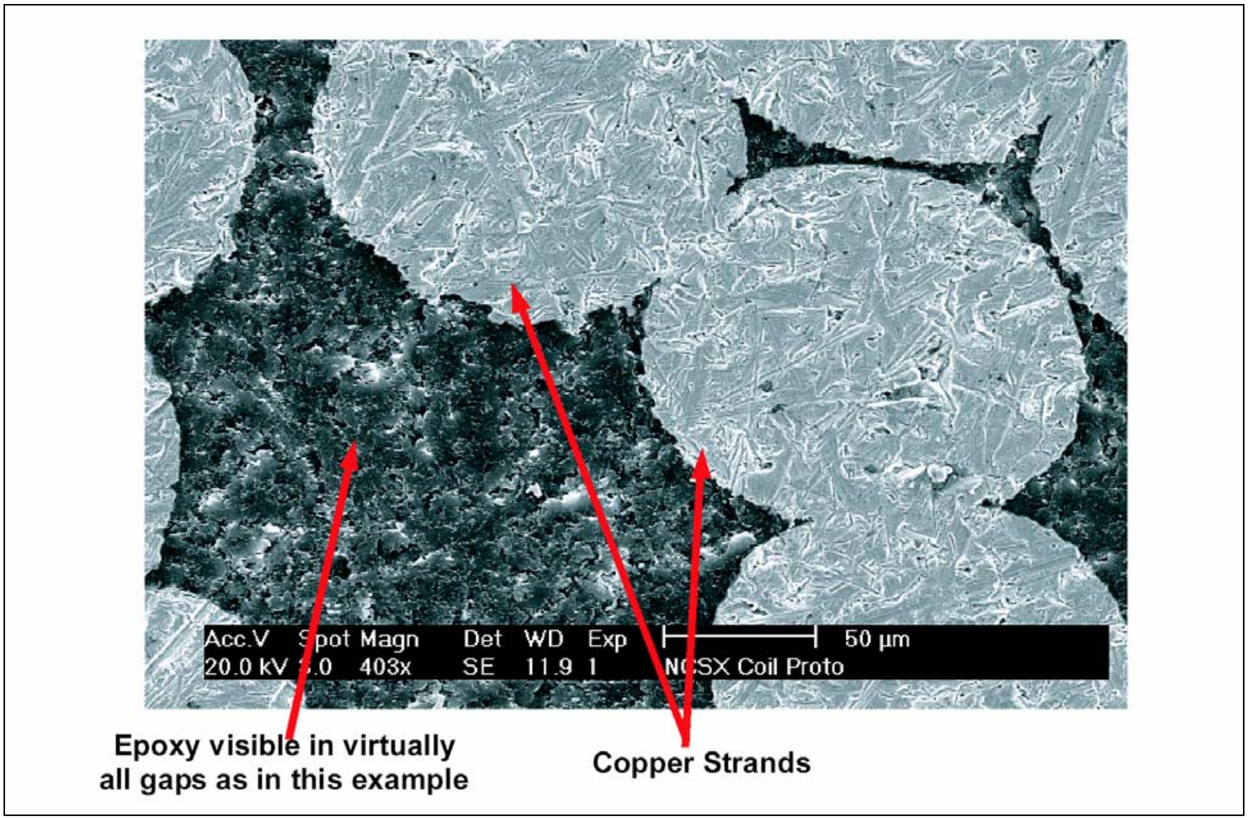

Figure 26 Electron Beam Micrograph of Epoxy Impregnated Cable Conductor

4.3.2 Winding Form Manufacturing Development and Prototype Fabrication

The Project awarded contracts to two industrial teams for manufacturing development of the modular coil winding forms. The purpose of the contracts is to develop the manufacturing processes for the forms through fabrication of full-scale prototypes. The team led by Energy Industries of Ohio includes Metaltek International (Missouri) for casting the forms, Magna Machine Co. (Ohio) for machining the precision surfaces, with buyCASTINGS.com (Ohio), Atlantic Technical Components (New York), C. A. Lawton Co. (Wisconsin), Deformation Control Technology, Inc. (Ohio), Finite Solutions, Inc. (Ohio), Altair Engineering (Ohio), and ARACOR, Inc. (Ohio) providing technology and management services. The team led by J. P. Pattern of Butler, WI, includes Waukesha Foundry, Inc. (Wisconsin) for casting, Remmele Engineering, Inc. (Minnesota) for machining, and TKS Innovation, LLC (Wisconsin) for management services.

The objectives of the manufacturing development and prototype fabrication effort are as follows:

- To develop detailed manufacturing and quality assurance plans for all three types of winding forms;
- To develop cost and schedule information for use in developing project plans.
- To produce a full-scale prototype winding form
- To qualify suppliers for the production phase through this effort.
- To reduce the uncertainties and contingency requirements in the manufacturing costs and schedule.
- To produce fixed price and schedule proposals for production.

This phase is nearing successful completion. Both prototypes will be delivered to PPPL this summer prior to the award of the contract.

5 DESIGN IMPLEMENTATION

5.1 Component Procurement and Fabrication

5.1.1 Modular Coil Winding Form Procurement and Fabrication

Each of the two manufacturing/prototype development teams developed a manufacturing plan for the winding forms. Although they differ in detail, the basic steps are shown in Figure 27 and are described in the text which follows. There are some differences in the sequence of operations and some sequences and details are likely to be refined or changed as a result of the prototype. Since both teams are currently competing for the production subcontract, the detail in the text is limited to "generic" information.

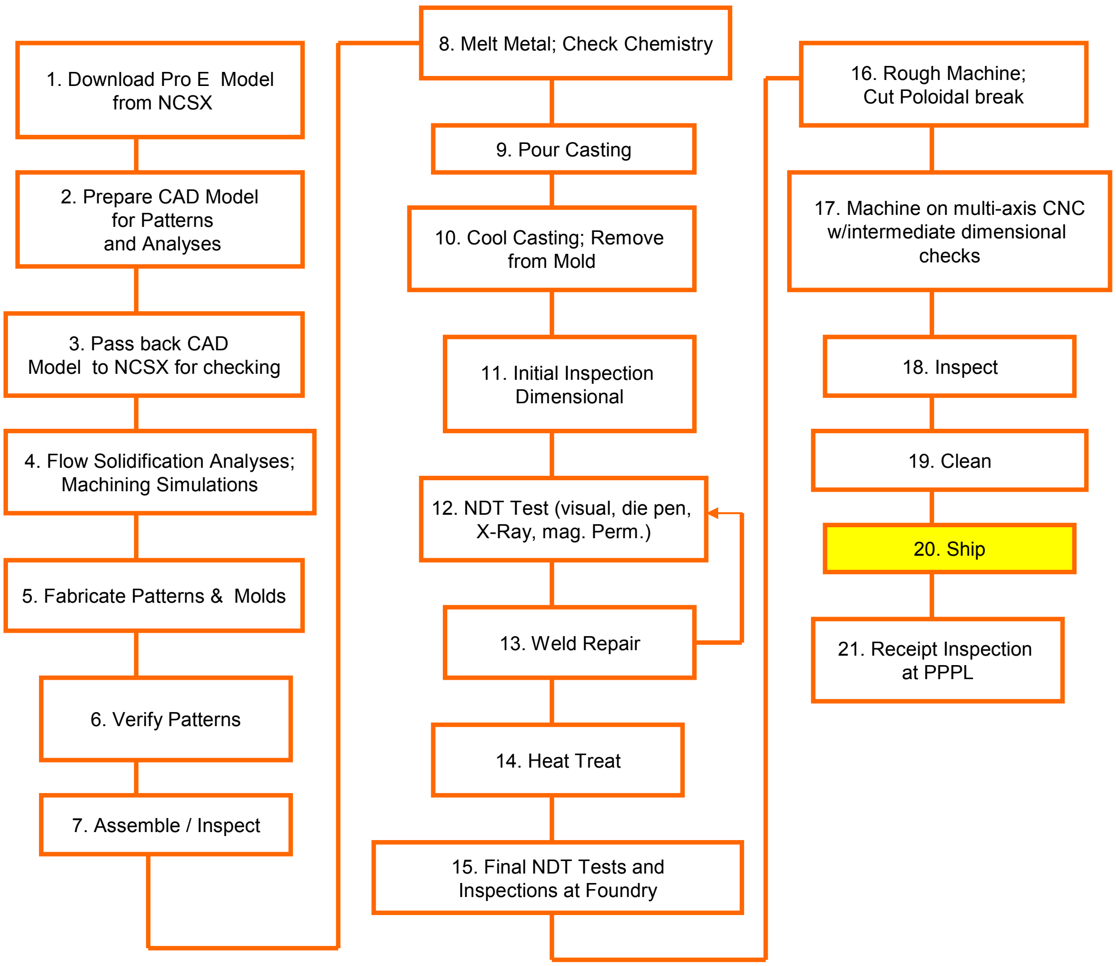

Figure 27 NCSX Modular Coil Winding Form Manufacturing Flow Chart

1. Receive Pro E Model From NCSX: All of the Pro-E models and associated drawings required to manufacture the winding forms will be placed in the manufacturing FTP site; the subcontractors will download the files from there. Write access to this site is limited to Tom Brown (NCSX Des. Integration Mgr.) and Phil Heitzenroeder (Tech. Rep. for this subcontract) who are charged with the responsibility of assuring that the files are properly prepared, checked, promoted, and controlled in accordance with PPPL and NCSX Policy. Subcontractors are not authorized to begin work until Larry Sutton; (Subcontract Procurement Representative for this subcontract) provides them with authorization and notifies them of the availability of the associated approved Specification and Statement of Work, which will also be posted at the NCSX Manufacturing FTP site.

2. Prepare CAD Models for Patterns and Analyses: The subcontractor will refine surfaces, fillets, etc., correct the size of the model for cool-down from casting temperature, and apply "padding" (excess cast material) to assure that the final machine part can be machined from the casting.

3. NCSX -Check Casting CAD Models: The Subcontractor will return the model generated in Step 2 to NCSX, where it will be overlaid onto the original Pro-E model and checked. Changes to surface features, fillets, etc. will also be checked.

4. Flow Solidification Analyses: Machining Simulations: Flow solidification modeling and machining simulations are advances in casting and machining technology that greatly benefit the modular coil winding forms. Flow solidification modeling is an iterative simulation process used to develop details of the mold such the gating (plumbing) and risers (molten metal reservoirs) and casting parameters. Machining simulation programs model the winding form and CAM milling machine and examine such factors as the adequacy of reach and access for the milling head, part placement during machining, machining rates, etc. Both teams were given tasks during the prototype development phase to (1) perform sufficient flow solidification analyses to establish casting feasibility and (2) to review machining requirements and critical machining features such as the "wing" regions to assure compatibility with their machine tools for all three winding form types. (This was done to lessen uncertainties that would most likely otherwise be reflected in higher built-in cost and schedule contingency in their "production" proposals and to give NCSX assurance that the winding forms are, indeed, manufacturable). For the production phase, the subcontractor will make any required additional flow solidification runs required to guide.

5. Fabricate Patterns and Mold Components: Each team approaches the fabrication of the mold somewhat differently. The basic approach is to fabricate patterns (replicas) of the winding form using multi-axis contour milling machines driven by the CAD model prepared in Step (2). These patterns are then used to fabricate the sand mold by packing sand mixed with an air cure binder around them. The sand bonds into a solid block when the binder cures. The mold is segmented to permit the pattern pieces to be removed, leaving a sand mold with a hollow replica of the winding form. "Gating" (plumbing for molten metal delivery at multiple locations on the part) and "risers (reservoirs which contain sufficient molten metal to provide make-up metal as the part cools and the molten metal contracts). The number and location of the risers are prescribed by the flow solidification analyses performed in (4). Heat sinks and chills are also added, also as prescribed by the flow solidification analyses in step (4).

6. Verify Mold Dimensions: Prior to the pour, the mold dimensions are checked by using either a muti-link measuring system ("Romer" and "Farro" are two manufacturers of such equipment) or a laser tracker system. The data is compared to the model used to generate the part.

7. Assemble and Inspect the Mold: The various molds "blocks" are assembled in a containment structure called a "flask". The dimensions are checked again as the mold is assembled.

8. Melt Alloy; Check Chemistry: Induction furnaces are used to melt and mix the prescribed components of the alloy and to heat the alloy to the prescribed pour temperature. Melt samples are taken and checked in "real time", and adjustments to the chemistry are made as required.

9. Pour Casting: The molten metal is rapidly poured into the mold at several entrance locations simultaneously so it flows into all regions while the metal is hot and flows easily.

10. Cool Casting; Remove from Mold: Because of the large thermal mass and the poor thermal conductivity of the mold, several days is required to cool the part to room temperature. It is desirable to remove as much of the mold as possible during cool-down to avoid thermal stresses which would otherwise occur if the mold was left in place due the differences in the coefficients of thermal expansion between the mold and part.

11. Initial Inspection & Clean Up of Part: An initial inspection is made to determine if the casting was successful – i.e., was the mold completely filled, are defects within acceptable bounds, and are the basic dimensions correct. If the casting passes this first inspection, the risers and gating are cut off, and the casting is generally cleaned up by brushing and grinding.

12. NDT evaluations: A series of non-destructive test (NDT) evaluations made to identify casting defects. (It should be noted that it castings are generally expected to have defects and identifying and repairing of them are considered a normal part of the process.)

1. Visual surface inspection, performed in accordance with ASTM Spec A-703/A703M, Para. 10.1
2. Liquid penetrant inspection to check for surface discontinuities per Supplementary Requirement S6 of ASTM Spec. A703/703M.
3. Radiographic inspection for internal defects per ASTM Spec A-703/A703M using radiographic inspection per Supplementary Requirement S5.
4. Initial permeability tests are made per ASTM Spec A-800/A800M.

13. Weld Repairs: Major repairs (i.e., those which require a cavity for weld preparation exceeding 10% of the actual wall thickness or 1", whichever is less) are welded and documented as defined in Sect. S12 and S20 of ASTM Spec A-703/A703M. Non-conformance reports (NCR's) must be submitted to PPPL for approval of the subcontractor's proposed disposition before proceeding. Repairs and re-performance of the NDT evaluations are repeated until the part is acceptable.

14. Heat Treat: Heat treatment is performed to assure dimensional stability and for materials property control prior to final measurements of mechanical properties and relative magnetic permeability. Records must be prepared and maintained as defined in S21 of ASTM Spec A-703/A703M. Test specimens are heat treated together with the part they represent. The subcontractor is to test these specimens to verify the physical properties for each casting (elastic modulus, yield strength, ultimate strength, elongation, thermal conductivity, electrical resistivity, Charpy V-notch at both room temperature and 77K).

15. Final In-Foundry Tests and Dimensional Inspections: Magnetic permeability tests are performed on a 6" grid with a Severin gauge to assure that the casting complies with the specification. All cast surfaces and features are checked on a 4" x 4" grid on shell sections and 2" x 2" grid on the surfaces that will be machined using either a laser tracker or multi-link measuring systems.

16. Machining: Most of the casting will remain "as cast" the machined regions are the flanges, the "T" regions, and several other interface regions; The castings will be machined on 5 axis CNC milling machines while being held in position by a rigid fixture that permits easy re-positioning of the part as required for reach and access and to "flip" from side to side to minimize distortions due to metal removal. Since the machining was not yet completed when this document was written, the details may change. However, it is likely that the casting will be rough machined; the poloidal break will be cut with the casting restrained by tie rods temporarily welded to the casting to avoid "springing". The insulating break "hardware" (i.e., insulation plate assembly consisting of two G-11 CR plates with a stainless steel mid ground plate to permit electrical testing, and (7) insulated A286 bolts at the flanges) will be installed to restore the structural continuity of the casting. Following this, the temporary tie rods will be removed and the casting will be finish machined to final dimensions and tolerances. Intermediate permeability tests may be performed, at least in the first castings, to assure that work hardening is not causing increases in the permeability.

18. Final Inspection: Final permeability tests and dimensional inspections will be performed which are similar to those performed in Step 15. In this case, the dimensions will be compared to the dimensions of the actual part Pro-E model (not the "padded" model generated in step 2.) The poloidal break will also be electrically tested.

19. Clean: The casting will be degreased/cleaned with a residue free solvent capable of dissolving grease, oils, etc. in preparation for shipping.

20. Shipping: An approved Shipping Release is required before the winding form is shipped. This requires supplier's certification that the winding form and services has been produced under a controlled QA program and are in conformance with procurement requirements. PPPL has to sign off that the Supplier's certification statement has been audited and that nonconformance has been satisfactorily addressed.

21. Receiving Inspection at PPPL: Specific, detailed requirements have not yet been set, but will include dimensional inspection, permeability tests, (both probably performed to a "looser" grid pattern than the used by the manufacturer, but adequate to verify their results), electrical tests of the poloidal break, inspection of surface finish, and cleanliness.

5.1.2 Winding Fabrication

Upon receipt of the winding forms, the modular coils will be wound at PPPL. A coil winding facility is being constructed in the large test cell formerly occupied by TFTR. The winding facility and winding process are described in the NCSX Modular Coil Winding Facility Operations Plan (NCSX-PLAN-WFOP-00). The winding facility features five stations. The first station is where the casting is prepared for winding. Coil winding is can be performed in parallel at the next two stations. At the fourth station, molding and preparations for vacuum pressure impregnation is performed. The fifth station is the autoclave where the coil is vacuum pressure impregnated. Once the coil is removed from the autoclave, it is moved to the basement where the coil test facility is located. Each coil will be cooled to cryogenic temperature and tested.

5.2 Subsystem Assembly, Installation, and Testing

The modular coils will be assembled first into field periods in the D-site pre-assembly area, which is adjacent to the modular coil winding facility. The process for assembly the field periods is described in the NCSX Field Period Assembly Plan (NCSX-PLAN-FPA-00). Completed field periods will be transported to C-site where the NCSX Test Cell is located for final assembly. Final assembly is described in the NCSX Final Assembly Plan (NCSX-PLAN-FAP-01). Pre-operational testing, integrated systems testing, and field line mapping will be performed prior to first plasma. The plan leading from the end of construction to the start of operations is described in the Test and Evaluation Plan (NCSX-PLAN-TEP-00).

6 RELIABILITY, MAINTAINABILITY, AND SAFETY

Several design features have been included to enhance the reliability of the modular coil system or to simplify inspection and repair of obvious trouble spots. The most important active feature is a coil protection system. The Electrical Power Systems (WBS 4) is providing hardwired protection for I^2t, instantaneous and timed overcurrent, and ground faults. Central I&C (WBS 5) will implement additional coil protection based on logic and sensor information provided by the Modular Coil System (WBS 14), which would prevent operation of the coils outside their design envelope. Other, passive features include:

- The modular coil windings are composite structures of copper and epoxy, which could degrade if subjected to large deflections during operation. To prevent overloads that could damage the windings, they are continuously supported against magnetic loads by the stainless steel winding form. Clamps are provided to keep the winding in close contact with the structure.
- The crossovers and leads are located in a relatively straight section of each winding to simplify the crossover geometry and minimize the local forces on this critical area.
- The leads are collected into a coaxial arrangement immediately adjacent to the winding pack to reduce forces further. This arrangement also mechanically connects the two exiting ends of the winding to reduce the possibility of shear failure between the exiting conductor and the winding pack. The coaxial leads are brought all the way outside the shell as hard conductor before transitioning to the flexible coaxial cables that connect the coils to the buswork system.
- All the cooling connections are intended to be accessible with only minor disassembly of external components. This also allows each circuit to be individually tested in the event of a leak.
- Finally, all the coils will use the same flexible, coaxial cable for the leads, which minimizes loads on the coil terminals and standardizes the lead design and analysis.

A formal Failure Mode, Effects, and Criticality Analysis (FMECA) for the Modular Coil System will be documented prior to the subsystem FDR.

7 COST AND SCHEDULE

To be provided at the FDR

8 RISK MANAGEMENT

8.1 Technical risks

The technical risks are listed below, as well as the way in which each has been addressed.

<u>The coils do not have the correct geometry and tolerance</u>

The first risk, that the coils will not have the specified geometry and accuracy, is addressed in the design, R&D, the fabrication process, assembly process, and operation.

Design. The coils are designed around a cast and machined winding form that is very accurate, with the winding surfaces and mounting features integrated into a single unit. The coils are wound directly onto this form and vacuum pressure impregnated with epoxy. The casting is massive (just like the frame of a high precision machine tool) and deflections due to the winding and assembly process should be negligible. Since the windings are not removed from the winding form, the distortions that would normally occur during this operation are avoided.

In addition to the basic design concept, the coil leads and bus interfaces are designed for minimum field errors.

R&D. Significant R&D is planned to demonstrate and test all operations connected with the modular coil fabrication. This includes procurement of two cast and machined winding forms, winding up to 12 partial coil packs and at least one full prototype coil, and performing thermal, and fatigue tests on critical features. This will all occur with sufficient time to incorporate any changes to the design suggested by the R&D.

Fabrication. The coil forms are dimensionally stabilized prior to machining to an accuracy of +/- 0.25 mm anywhere on the winding surface. The forms can be readily and independently inspected by NCSX personnel with conventional laser tracker or multi-link coordinate measuring systems to confirm compliance with specifications.

Once acceptable coil forms are delivered, the coils will be wound at PPPL with total control over all processes by NCSX personnel. The use of the modern 3-D measurement equipment mentioned above will allow the conductor placement to be continuously measured and corrections made throughout the winding process. Once the coils are completed, additional measurements of the as-built geometry can be entered into codes and the relative placement of each coil can be optimized, if necessary, for best control of error fields.

Assembly. Continuous measurements will be made during the assembly process to ensure that the coils are aligned correctly. Each coil will be located to a global reference frame that is continuously updated for the best fit to the coil array.

<u>The coils will fail mechanically</u>

The second risk, that the modular coils will fail mechanically, is mitigated by analysis, conservative design criteria, and by an active coil protection system. Independent groups using different codes and models will perform critical analysis, such as electromagnetic load calculations, stress and deflection calculations, and thermal stress analysis. The stresses will be compared to the ASME code allowables, which provide a safety factor of 1.5 on yield for primary membrane stresses at the operating temperature. The materials chosen for the cast coil form have been demonstrated to have reliably high tensile strength, which adds additional margin. The winding is continuously supported in the cast form, so the winding and coil forms will have approximately the same strain. Since the coil modulus of elasticity is lower than the steel, the winding should have relatively low stresses. The only caveat to this point is the thermal stress, where the coil form restraint adds stress to the winding. Again, a lower stiffness mitigates this problem significantly. Nevertheless, R&D testing will be performed to determine thermal stress limits during the preliminary design phase. Fortunately, the thermal stress problem is mitigated by the shrinkage of the winding pack during cooldown. The slight difference between the thermal contraction of the winding and the winding form, 0.04%, is equivalent to the growth of the winding pack as it heats from 85K to 125K during a pulse.

In addition to designing and analyzing expected loading conditions, the coils will be evaluated for and protected from fault conditions by an active coil protection system. The coil protection system would prevent operation of the coils outside their design envelope. The system would be programmed to monitor the signals from voltage, strain, temperature, and possibly magnetic field sensors on or around the various coil windings and structures as the coils were being energized. If any of the sensor signals were out-of-bounds for the specific current scenario being run, the fault system would crowbar all the power supplies. The system would guard against control errors and physical faults such as shorted buswork.

The coils will fail electrically

There are several mitigating features in the design to guard against electrical failure. The four-in-hand winding scheme results in very low turn-to-turn voltages. Turn-to-ground shorts are protected by overlapped Kapton sheets in the ground insulation. A non-conducting coolant – liquid nitrogen – is used and the coolant tubes are outside the ground wrap, i.e. the conductor is dry.

The modular coil cooling will be inadequate

The fourth risk, that the coils will not cool down in the specified time, will be mitigated by providing two chill plates for each winding. The outside chill plate will be well cooled with tracing, and will be connected to both ends of the inner chill plate. Separation of the chill plates from the winding pack is still a concern, but is mitigated by the over-wrap of the chill plate region for vacuum impregnation.

The coil structure will introduce static or transient field errors

A fifth potential risk, that the modular coil structure will introduce field errors, is mitigated by including insulating breaks at the flanges in the shell structure and by strict adherence to stellarator symmetry.

The cable conductor will not behave as planned

The final technical risk is that the compacted cable conductor will not behave as planned. This problem is mitigated by design and R&D. The design approach, as explained in detail above, is to fully support the windings against electromagnetic forces, nearly eliminating the cyclic bending strain in the conductor that would normally occur in a free standing coil. Extensive R&D is planned and already underway to test one or more small racetrack-shaped coils that can be electrically and thermally cycled. The winding, vacuum impregnation, and restraint conditions would be matched as closely as possible to the planned design. Initial fatigue tests of a small coil indicate full lifetime with no apparent conductor degradation at twice the expected operating strain.

8.2 Cost and schedule risks

The cost and schedule risks associated with the modular coils are also significant, but steps have been and are being taken to reduce those risks substantially. Manufacturing studies were carried out during the conceptual design process to obtain advice from manufacturing engineers on ways to make the design easier or less expensive to fabricate. Four different studies of the modular coils were carried out, and various methods for winding, vacuum impregnation, casting and machining were investigated. Vendors have continued during preliminary and final design with an extensive R&D program. This effort has been carried out concurrently with the modular coil design process such that the results to date have been included in the final design. Two different vendors are fabricating full-scale cast and machined coil forms. At the conclusion of the R&D phase, one (or more) fixed price contracts will be awarded for the production castings. The selection of two vendors for the R&D phase will result in at least two qualified vendors for the production articles, and provides an extra incentive to keep production costs (and bids) low.

This approach also mitigates the schedule risk by starting the R&D process as soon as possible and incorporating any needed design changes as they are uncovered. Two qualified vendors will be available at the end of the R&D process, so schedule pressures could be relieved by adding more capacity. It should be noted that the present schedule for procurement of the winding forms is completely consistent with vendor input, and no specific schedule issue is apparent. The coils will be wound in-house at PPPL, which affords more control over the schedule and resource allocation than would be possible with an outside vendor. Slight in-process changes could be made without ponderous approval cycles.