Modular Coil Winding Form
Design, Analysis, Specification

D. Williamson
for the NCSX Team

NCSX Final Design Review
May 19-20, 2004
PPPL
Presentation Outline

- Requirements and Design Description
  - Overview of modular coil assembly; winding form details
- Design Analysis and R&D
  - Properties testing, nonlinear deflection / stress, plans
- Winding Form Specification
  - Requirements, models and drawings, inspection
- Procurement Plans (P. Heitzenroeder)
WBS and Scope

- Modular coil system is comprised of two major subassemblies
- Winding forms to be fabricated Sep-2004 through Apr-2006
- Windings and assembly to be fabricated in-house, Jan-2005 through Sep-2006
The winding forms provide an accurate means of positioning the conductor during the winding and vacuum-pressure impregnation (VPI) process
- Machined surfaces within 0.020-in (0.5-mm) of CAD profile
- Segmented for assembly and to meet electrical requirements
- Provide access for NBI, ICRH, diagnostics, personnel
- Support vacuum vessel, interface with PF/TF coil structure

The coil windings provide the basic quasi-axisymmetric field configuration
- Field up to 2-T for 1-s with 15-min rep rate
- Winding center accurate to +/- 0.060-in (1.5-mm)
- Independent control of each coil type for flexibility
- Feedback for coil protection system

Design for 150 cool-down cycles, 130,000 pulses over >10 years of operation
The modular coil system and coil support structure shall provide matching interfaces for the purpose of transmitting gravity and electromagnetic loads.

Components have the same operating temperature (80K).
Vacuum Vessel Interface

- The modular coil system supports vertical and lateral loads from the vacuum vessel and is thermally insulated to minimize the heat leak during bakeout and operation.
- Openings in the winding form have 2-in clearance with ports accommodate thermal growth and fabrication and assembly tolerance.
Electrical Interface

- Power systems is responsible for providing the necessary current and voltage to the modular coils, for providing coil protection circuitry, and for maintaining an electrical ground to all components.

- The modular coils have specified interface locations for the connection to the electrical busswork inside the cryostat.

- Electrical ground wires shall be routed from 12 individually isolated coils and 3 field joint pairs to the cryostat exterior.
The modular coils shall provide cooling inlet and outlet connections to the LN2 manifold at specified locations.

The cryostat does not interface with the modular coils directly, but maintains a defined gap for the circulating nitrogen gas environment.
• Central I&C takes output from the modular coil sensors (strain gauges, RTDs, thermocouples) and processes it for use in the facility control logic.

• Diagnostic magnetic field sensor loops shall be co-wound with the coil winding packs.
• Tooling required for field period assembly interfaces with the modular coils at specified lift points.

• Monuments are required to facilitate position measurements.
Design Description

- Integral shell composed of 18 modular coil assemblies
- Three field periods, 6 coils per period, 3 coil types
- Shell thickness = 1.5-in, can vary to meet stress requirements
- Total weight = 125,000-lb
- Each modular coil:
  - 1,900-ft of conductor
  - 48 coil clamps
  - 200 fasteners
Coil Configuration

- Three field periods with 6 coils per period, for a total of 18 coils

- Shape developed through a physics optimization process that emphasizes plasma properties, geometry constraints, and current density limitations

- Coilset # m50_e04
- Coil lengths = 291, 283, 263-in
- Min coil-coil dist = 6.1-7.6 in, Max dist = 27-36 in
- Min coil-plas dist = 8.1-9.0 in, Max dist = 20-28 in
- Max coil current = 818, 831, 730-kA
- Min bend radius at winding pack outer surface is 2.5-in, 2.7-in, and 3.1-in for coils A, B, and C
Coil “twist” has been developed through an iterative process.

Resulting cross-section is normal to winding surface along most of coil length, but varies inboard to accommodate adjacent coils.

Some regions require taper in base of tee to avoid interference.

A study of finite build coil fields indicates twist adjustments are acceptable.
Modular Coil Types

A 89-in 46-in
B 82-in 46-in
C 77-in 46-in

A 106-in
B
C
• Poloidal break is required to prevent persistent eddy currents during operation
• Fabrication approach is to saw-cut casting, insulate and bolt prior to final machining of the tee region
• Tee web connection using double insulated pin or bolt may also be required
Winding Pack Configuration

- **Parameters:**
  - Coil Envelope = 2 x 1.675 x 4.671-in
  - Current / Coil = up to 831-kA-turns
  - Number of Turns = 20 (A, B) and 18 (C)
  - Max Current / Turn = 41.6 –kA
  - Conductor Size = .391 x .35 in (9.9 x 8.9 mm)
  - Cu Current Density = 15.1-kA/cm² (Max)
  - Conductor operating temp. range 85K-130K
  - Operating voltage = 2-kV

- **Layout changed from CDR concept, a double-layer pancake, to 4-in-hand layer wound design**
  - Reduced keystoning due to smaller conductor
  - Low turn to turn voltage
  - Less time estimated to wind
Type-C coil has less current, fewer turns
Conductor Specification

- Copper specification:
  - OFHC Copper, 34-ga Wire
  - 12x5/54/34 cable, 3240 strands
  - Clean mfg process

- Insulation specification:
  - S-2 glass with reactive amino silane finish, .004 in center and .007 at edge, (avg=0.0055-in) thick
  - Four harness satin weave
Winding Pack Assembly

- Two Winding Packs
- Copper Rivets
- Flexible Braided Cable
- Clamp Assembly
- Copper Chill Plates
- Copper Coolant Tubing
- Diagnostic Magnetic Field Sensor Loop
- Bag Re-enforcement
- Modular Coil Tee / Shell
- Copper Chill Plates
- Welded Stud
- VPI Mold Seal
- Ground Insulation
- Four-in-Hand Winding x 10 Turns
- Bag
- Modular Coil Form
Winding Pack Assembly (cont’d)

Winding form with welded studs

Attach cladding, electrically isolated from tee
Winding Pack Assembly (cont’d)

Lay in ground wrap

Wind coil, attach sensor loops
Attach outer chill plates, rivet top and bottom

Attach pre-formed cooling line
Winding Pack Assembly (cont’d)

Attach G11 pads

Form VPI mold and clamp
Form “french toast” over mold, VPI

Remove mold as required
Winding position is continuously monitored and adjusted to avoid tolerance stack-up.

Tolerance issues:
- Machined surfaces of winding form are accurate to +/- 0.010-in (0.5-mm)
- Conductor w/o insulation has a dimensional tolerance of +/- 0.010-in (0.5-mm)
- Geometry requires up to 0.036-in (.91-mm) per layer allowance for conductor keystoning

Current center can be adjusted by use of shims between layers.
Allowance for Twist and Keystoneing

- Keystone measurements made by winding conductor on 5-in dia pipe
- Change in height proportional to width x (width / radius)
- Results vary with conductor strand size, pitch, insulation, etc
- Winding pack dimensions include shim allowance of 0.035-in between each layer radially and 0.014-in laterally
Winding Pack “Swelling” due to Twist

- Winding pack dimensions can be accommodated by radial shims, nominally 0.035-in thick
- Laterally, shims are not sufficient but swelling is symmetric and maintains current center
- Twisted racetrack winding R&D will confirm ability to compensate

<table>
<thead>
<tr>
<th>angle of conductor with plane (deg)</th>
<th>multiplier on conductor dimension</th>
<th>lateral &quot;swelling&quot; of winding pack (in)</th>
<th>radial (height) &quot;swelling&quot; of winding pack (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>1</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>85</td>
<td>1.003819838</td>
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<td>80</td>
<td>1.015426612</td>
<td>0.026</td>
<td>0.071</td>
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<td>75</td>
<td>1.03527618</td>
<td>0.059</td>
<td>0.163</td>
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<tr>
<td>70</td>
<td>1.064177772</td>
<td>0.107</td>
<td>0.297</td>
</tr>
<tr>
<td>65</td>
<td>1.103377919</td>
<td>0.173</td>
<td>0.478</td>
</tr>
</tbody>
</table>

note: width of pack 1.675
height of pack 4.625
Coil Leads

- Leads are located in “straight” outboard regions that minimize field errors
- Continuous conductors extend through shell wall to junction block on exterior surface
- Like conductors from each winding pack are connected in series to maintain current center
- A flexible co-axial cable connects block to power supply buswork outside cryostat
A thin chill plate is located on both sides of each winding pack to remove joule heating between plasma discharges.

Chill plate is cut in flat patterns from 0.040-in thick copper and formed around winding pack.

Chill plate is segmented and electrically isolated from winding form.

Outer plate is cooled by liquid nitrogen in tube bonded to surface.

Nitrogen enters the chill plate circuit at the bottom and exits near the top of each coil.
• VPI mold composed of epoxy impregnated felt and silicon rubber tape
• Located between winding pack and clamps, sealed by base groove
• Bleed holes at “top” position
Winding Pack Clamps

- Winding packs are clamped by discrete bracket assemblies, spaced approximately every 6-inches.
- Clamp is attached by studs at base of tee and tapped holes in web of tee, shimmed to fit winding pack.
- Spring washers provide compliance, allow clamp to preload winding pack to structure.
Instrumentation

- Preliminary list of temperature, voltage, strain, and flow sensors has been developed
- Gages will have “back-to-back” elements that reduce EM noise during operation
- Diagnostic magnetic field sensor loops will also be co-wound with the modular coils

<table>
<thead>
<tr>
<th>Modular Coil Instrumentation</th>
<th>Total Number</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Tap</td>
<td>36</td>
<td>2 per coil</td>
</tr>
<tr>
<td>Strain Gages</td>
<td>72</td>
<td>4 per coil</td>
</tr>
<tr>
<td>Flow Sensor</td>
<td>36</td>
<td>2 per coil</td>
</tr>
<tr>
<td>RTD / Thermocouples</td>
<td>72</td>
<td>4 per coil</td>
</tr>
</tbody>
</table>

Co-wound magnetic sensor loops .061-dia mineral insulated cable
Coil services include buswork and cooling lines inside the cryostat

**Buswork:**
- commercial, anti-kick cables modified for cryogenic use
- gas feed for cooling
- all coils (modular, PF, TF, Trim) will use the same cable design
- prototype cable to be tested during racetrack coil testing

**Cooling lines:**
- consists of manifolds and lines inside cryostat
- assume stainless steel manifolds with pigtails to each circuit
- pigtails made from teflon hose, ala C-Mod experiment at MIT
- assume each cooling circuit has valve and pressure gage for balancing
Preliminary design analysis has been completed for
- Coil and lead field errors
- Eddy currents in modular coil structure
- Thermal and thermo-hydraulic response
- Electromagnetic field and forces
- Stress due to thermal and electromagnetic loads

Structural analysis models:
- Global deflection and stress in the winding forms
- Nonlinear behavior of the windings due to thermal and EM loads
- Deflection and stress in the clamps

Detailed analysis, checking to be completed during final design
Preliminary analysis has validated several modular coil design features:

- Eddy current analysis for electrical segmentation, poloidal break design
- Transient thermal analysis for coil cooling line configuration
- Field error analysis to determine required winding form tolerance

Structural analysis, however, has proved to be complicated due to complex geometry and lack of material property data

Analysis to-date involves mostly global and some detailed models, with varying degrees of realism
## Coil Electrical Parameters

<table>
<thead>
<tr>
<th>Calculated quantity</th>
<th>Flat Racetrack</th>
<th>Twisted Racetrack</th>
<th>Prototype (Coil type C)</th>
<th>Production Coil type A</th>
<th>Production Coil type B</th>
<th>Production Coil type C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of elec turns per winding pack</td>
<td>14</td>
<td>9</td>
<td>9</td>
<td>10</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>Number of electrical turns per coil</td>
<td>28</td>
<td>18</td>
<td>18</td>
<td>20</td>
<td>20</td>
<td>18</td>
</tr>
<tr>
<td>Number of physical turns per electrical turn</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
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<tr>
<td>Conductor width, with serve</td>
<td>in 0.625</td>
<td>0.350</td>
<td>0.350</td>
<td>0.350</td>
<td>0.350</td>
<td>0.350</td>
</tr>
<tr>
<td>Conductor height, with serve</td>
<td>in 0.500</td>
<td>0.391</td>
<td>0.391</td>
<td>0.391</td>
<td>0.391</td>
<td>0.391</td>
</tr>
<tr>
<td>Packing fraction</td>
<td>0.78</td>
<td>0.78</td>
<td>0.78</td>
<td>0.78</td>
<td>0.78</td>
<td>0.78</td>
</tr>
<tr>
<td>Winding resistance at RT</td>
<td>ohms 1.36E-02</td>
<td>7.20E-02</td>
<td>1.50E-02</td>
<td>1.84E-02</td>
<td>1.80E-02</td>
<td>1.60E-02</td>
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<tr>
<td>Winding resistance at 120K</td>
<td>ohms 1.72E-03</td>
<td>2.11E-02</td>
<td>5.13E-02</td>
<td>6.30E-02</td>
<td>6.16E-02</td>
<td>5.13E-02</td>
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<tr>
<td>Winding resistance at 80K</td>
<td>ohms 7.35E-04</td>
<td>1.08E-02</td>
<td>6.62E-03</td>
<td>8.17E-03</td>
<td>7.97E-03</td>
<td>6.62E-03</td>
</tr>
<tr>
<td>Inductance - windings only</td>
<td>Henries 6.63E-04</td>
<td>7.91E-03</td>
<td>7.90E-03</td>
<td>1.24E-02</td>
<td>9.23E-03</td>
<td>7.90E-03</td>
</tr>
<tr>
<td>Time constant - windings only, RT</td>
<td>seconds 4.86E-02</td>
<td>1.10E-01</td>
<td>5.26E-01</td>
<td>6.71E-01</td>
<td>5.12E-01</td>
<td>5.26E-01</td>
</tr>
<tr>
<td>Time constant - windings only, 120K</td>
<td>seconds 3.74E-01</td>
<td>3.75E-01</td>
<td>1.54E-01</td>
<td>1.97E-01</td>
<td>1.50E-01</td>
<td>1.54E-01</td>
</tr>
<tr>
<td>Time constant - windings only, 80K</td>
<td>seconds 8.46E-01</td>
<td>7.32E-01</td>
<td>1.19E+00</td>
<td>1.52E+00</td>
<td>1.16E+00</td>
<td>1.19E+00</td>
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<tr>
<td>Max operating current per elec. turn</td>
<td>Amps N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>40969</td>
<td>41561</td>
<td>40596</td>
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<tr>
<td>Maximum test current</td>
<td>Amps N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>40969</td>
<td>41561</td>
<td>40596</td>
</tr>
</tbody>
</table>
Transient conduction/convection model has been updated for four-in-hand winding
2D transient analysis of cooling after adiabatic heating to 130-K during pulse
Initial temp = 85-K, cooling by conduction to trace-cooled copper chill plates, some convection
Analysis shows cooldown in 15-min, equilibrium after ~10 cycles
Temperature During Cooldown

3 minutes

7 minutes

15 minutes
Temperature After 15-min

Same Scale as above cases at 15 mins

Automatic Scale at 15 mins
Temperature After 10 Cycles

Temperature profile at this node

Temperature profile at this node
Electromagnetic Loads Analysis

- Two independent calculations have been performed using ANSYS, MAGFOR codes
- Seven reference scenarios examined at time step with maximum modular coil current
- Scan of all possible coil currents for a more severe fault load condition is in progress

### Maximum Current / Coil for Reference Scenarios (kA)

<table>
<thead>
<tr>
<th>Circuit</th>
<th>Coil Set</th>
<th>0.5-T</th>
<th>1.7-T</th>
<th>1.7-T</th>
<th>2-T</th>
<th>1.2-T</th>
<th>320-kA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TF</td>
<td>13</td>
<td>43</td>
<td>45</td>
<td>53</td>
<td>30</td>
<td>26</td>
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<tr>
<td>2</td>
<td>PF1</td>
<td>673</td>
<td>0</td>
<td>1479</td>
<td>1120</td>
<td>1340</td>
<td>1191</td>
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<tr>
<td>3</td>
<td>PF2</td>
<td>673</td>
<td>0</td>
<td>1479</td>
<td>1120</td>
<td>1340</td>
<td>1191</td>
</tr>
<tr>
<td>4</td>
<td>PF3</td>
<td>0</td>
<td>204</td>
<td>209</td>
<td>82</td>
<td>148</td>
<td>128</td>
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<tr>
<td>5</td>
<td>PF5</td>
<td>13</td>
<td>104</td>
<td>101</td>
<td>115</td>
<td>72</td>
<td>73</td>
</tr>
<tr>
<td>6</td>
<td>PF6</td>
<td>224</td>
<td>224</td>
<td>763</td>
<td>763</td>
<td>518</td>
<td>539</td>
</tr>
<tr>
<td>7</td>
<td>M1</td>
<td>209</td>
<td>209</td>
<td>710</td>
<td>631</td>
<td>501</td>
<td>707</td>
</tr>
<tr>
<td>8</td>
<td>M2</td>
<td>188</td>
<td>188</td>
<td>638</td>
<td>638</td>
<td>731</td>
<td>451</td>
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<tr>
<td>9</td>
<td>M3</td>
<td>35</td>
<td>0</td>
<td>120</td>
<td>178</td>
<td>210</td>
<td>126</td>
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<tr>
<td>PLAS</td>
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<td>35</td>
<td>0</td>
<td>120</td>
<td>178</td>
<td>210</td>
<td>126</td>
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</tbody>
</table>

May 19-20, 2004

NCSX FDR

D. Williamson
• Maximum magnetic flux density at windings is 4.7-T for 2-T reference scenario
• ANSYS, MAGFOR results differ by ~4% due to mesh and integration differences
- Force distribution indicates large centering force up to 317-kip (1.4-MN) per coil
- Net vertical load up to 122-kip (.5-MN)

<table>
<thead>
<tr>
<th>Net EM Force on Modular Coils</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coil</strong></td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>Max Field at Coil (T)</td>
</tr>
<tr>
<td>M1</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>M2</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>M3</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

Fr=200-kip Fz=7-kip
Fr=317-kip Fz=106-kip
Fr=86-kip Fz=122-kip
• Forces have been resolved into “radial” (away from plasma) and “lateral” (toward tee web) directions
• In general, radial load is toward structure and lateral load is countered by equal force in other wp
• Sharp bends can result in lateral force away from tee; reacted by clamps and beam behavior of coil

<table>
<thead>
<tr>
<th>Coil</th>
<th>Field/Force Component</th>
<th>0.5-T 1st Plasma</th>
<th>Field Mapping</th>
<th>1.7-T High Beta</th>
<th>1.7-T Ohmic</th>
<th>2-T High Beta</th>
<th>1.2-T L. Pulse</th>
<th>320-kA Ohmic</th>
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</thead>
<tbody>
<tr>
<td>M2</td>
<td>Rad Load (lb/in)</td>
<td>200</td>
<td>8</td>
<td>2272</td>
<td>2279</td>
<td>2869</td>
<td>1134</td>
<td>2053</td>
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<tr>
<td></td>
<td>Latt Load (lb/in)</td>
<td>434</td>
<td>17</td>
<td>4995</td>
<td>4997</td>
<td>5831</td>
<td>2490</td>
<td>4163</td>
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<tr>
<td>M2</td>
<td>Rad Load (lb/in)</td>
<td>351</td>
<td>14</td>
<td>4077</td>
<td>4076</td>
<td>5591</td>
<td>2031</td>
<td>4050</td>
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<tr>
<td></td>
<td>Latt Load (lb/in)</td>
<td>430</td>
<td>17</td>
<td>4982</td>
<td>4983</td>
<td>6982</td>
<td>2483</td>
<td>5059</td>
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<tr>
<td>M3</td>
<td>Rad Load (lb/in)</td>
<td>233</td>
<td>9</td>
<td>2698</td>
<td>2698</td>
<td>3540</td>
<td>1344</td>
<td>2615</td>
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<tr>
<td></td>
<td>Latt Load (lb/in)</td>
<td>418</td>
<td>17</td>
<td>4830</td>
<td>4830</td>
<td>6405</td>
<td>2407</td>
<td>4562</td>
</tr>
</tbody>
</table>

Lateral force away from tee

Running Load (lb/in)
Global Deflection and Stress

- PDR analysis focused on linear analysis of deflection / stress in the modular coil structure
- Assumption: 2-T EM loads, coil winding is continuously supported by shell structure
- Results indicate max displacement of 0.038-in, peak Von Mises stress of 26-ksi (181-MPa) in steel

\[ E = 30.6 \times 10^6 \text{ psi (structure)} \]
\[ E = 5.3 \times 10^6 \text{ psi (windings)} \]
Global Model (cont’d)

- In final design, analysis has been updated to verify design changes, such as thinner sections to reduce weight, and more diagnostic ports for the vacuum vessel.
- Structural response varies with composite winding stiffness assumption, initial strain in conductor.
- Stress in winding form has safety factor >1.3.
• show analysis of poloidal break, coil-to-coil bolting
• show kevin’s model: assumptions, results
Structural Analysis Summary

- show table of results vs allowables
- plans for follow-on analysis
Winding Form Specification

- Specification NCSX-CSPEC-141-03-00 establishes the manufacturing and acceptance requirements for the winding forms
- Total of 18 winding forms; six each of three types
- Outline of spec:
  - Required characteristics
  - Models and drawings
  - Verification and inspection
Winding Form Characteristics

- Properties of the alloy
  - Chemical composition similar to 316 (CF8M), air-quenched
  - Mechanical properties suitable for cryogenic applications

- Electrical and magnetic requirements
  - Magnetic permeability < 1.02
  - Insulated joint (poloidal break) > 500-kohms at 100-Vdc
### Table 3-3 - Production Winding Form Models and Drawings

<table>
<thead>
<tr>
<th>Level</th>
<th>Next Assembly</th>
<th>Find #</th>
<th>Doc / Part #</th>
<th>Rev</th>
<th>Title / Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SE140-101</td>
<td>2</td>
<td>SE141-101</td>
<td>ASM</td>
<td>Modular Coil Type-A Winding Form Assembly</td>
</tr>
<tr>
<td>1</td>
<td>SE140-102</td>
<td>2</td>
<td>SE141-102</td>
<td>ASM</td>
<td>Modular Coil Type-B Winding Form Assembly</td>
</tr>
<tr>
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Show views of model, exploded assembly
Show views of model, exploded assembly
Show views of model, exploded assembly
Tee Features
Flange Bolting

GDT, hole size and layout, typ bolt asm (not part of procurement)
Tooling Ball Positioner

Show detail of pocket / sph seat in flange, 3d views of positioner
Port Openings

show typical detail
Show detail in winding form, 3d of asm with leads
Vessel Supports

Model view

Drawing view
Wing Shims

Bladder / shim between shell segments

Drawing view
Assembly Tool Mount

Drawing view + dims
Poloidal Break Asm and Parts

Model view
Summarize verification method for
• mechanical, electrical, magnetic properties
• dimensions and tolerances
• defects
Summary – Modular Coil Design

Preliminary design concept meets performance requirements
- Accurately built 18 coil, 3 period modular coil set with integrated structure
- Coils designed for cryogenic and room temperature operation
- Structure is compatible with physics requirements
- Provides access, interface with other stellarator core components

Analysis shows design to be adequate for reference operating scenarios
- Thermal performance meets cooldown requirements
- Deflection and stress in monolithic coil structure is minimal
- Deflection of unsupported coil “wings” is a concern, can be fixed
Summary – Winding Form Design

- Winding forms
  - Winding form specification is complete
  - Winding form models incorporate all anticipated features for coil fabrication and assembly
  - As-machined drawings of winding forms have been completed, being checked
  - Shell assembly Details, Flange shims, hardware, pillow shims are nearly complete

- Winding form design satisfies requirements, can be manufactured and inspected, ready for fabrication