Modular Coil Winding Form Design, Analysis, Specification

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for the NCSX Team

NCSX Final Design Review

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PPPL

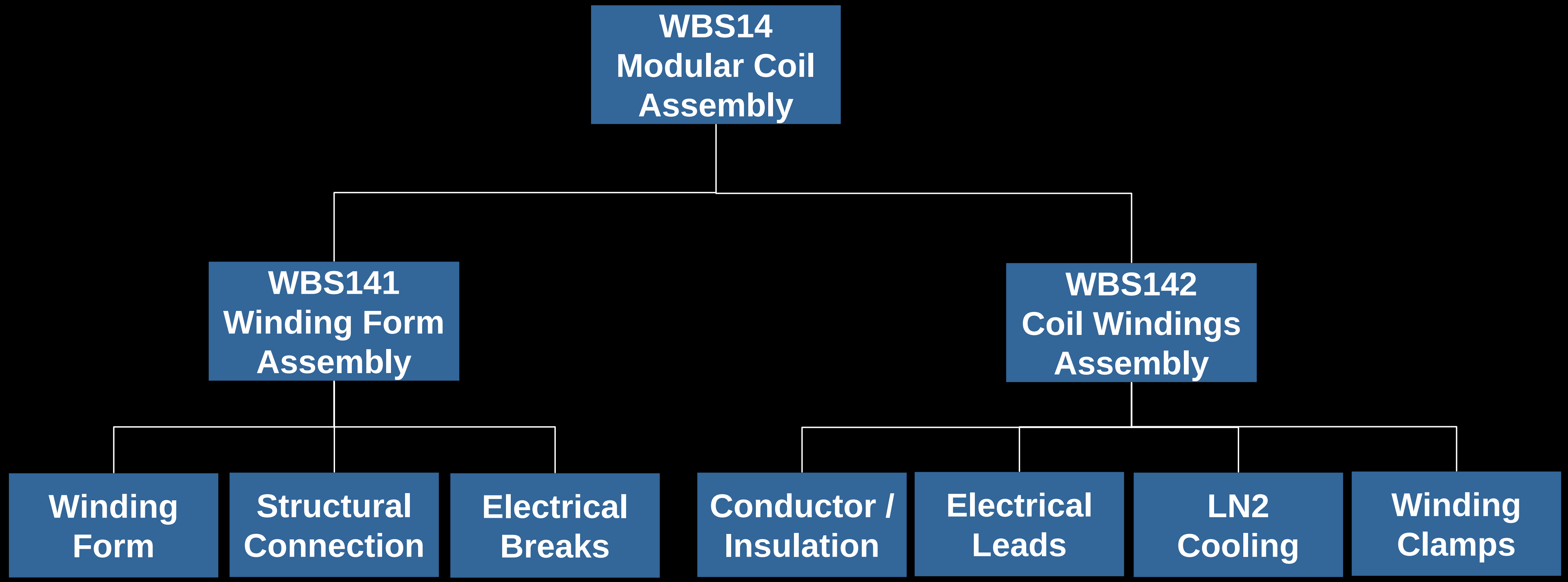
Presentation Outline

- 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



Functional Requirements

The winding forms provide an accurate means of positioning the conductor during the winding and vacuum-pressure impregnation (VPI) process

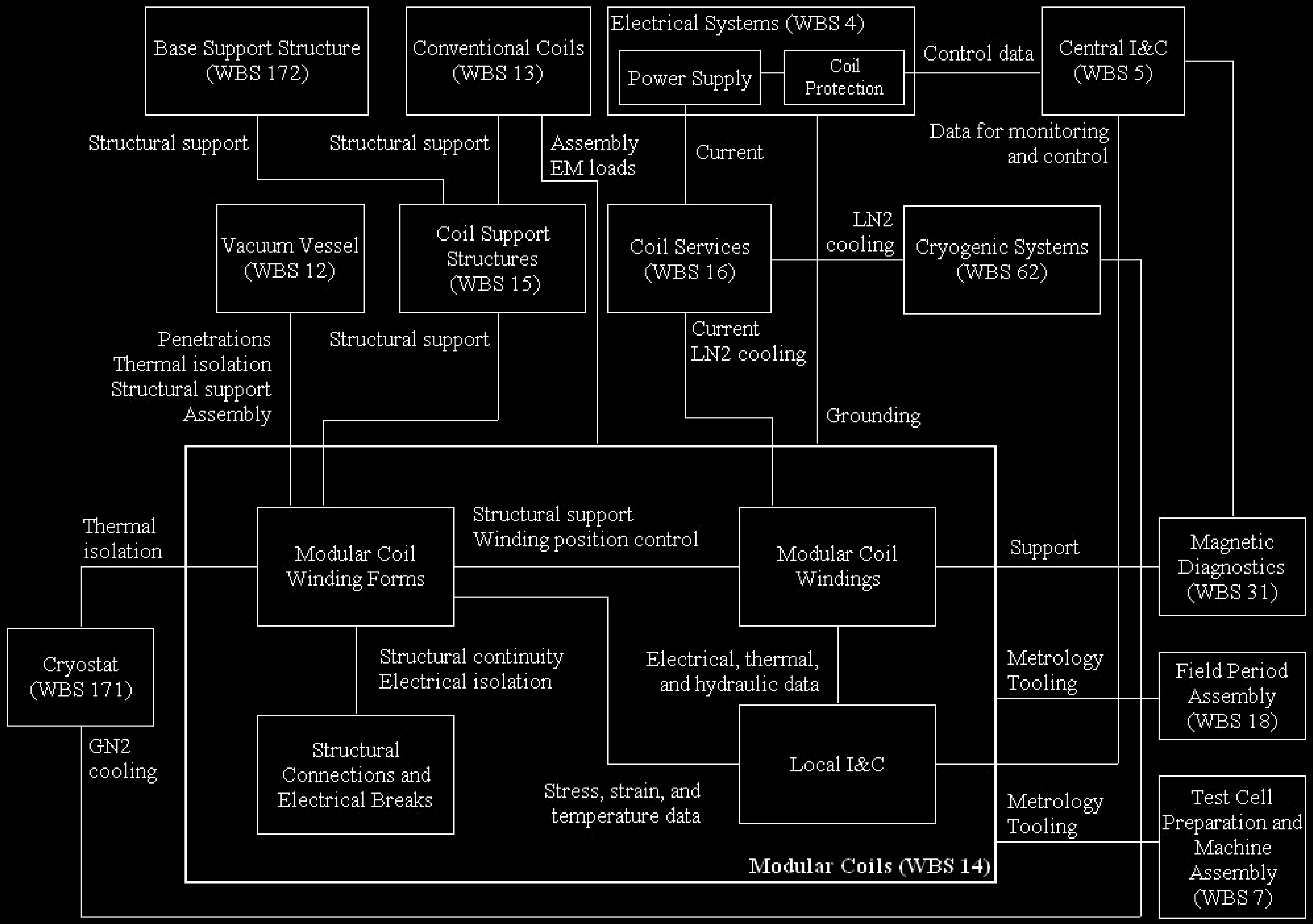
- Machined surfaces within 0.020-in (0.5-mm) of CAD profile
- Segmented for assembly and to meet electrical requirements
- Provide access for NBI, ICRH, diagnostics, personnel
- Support vacuum vessel, interface with PF/TF coil structure

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

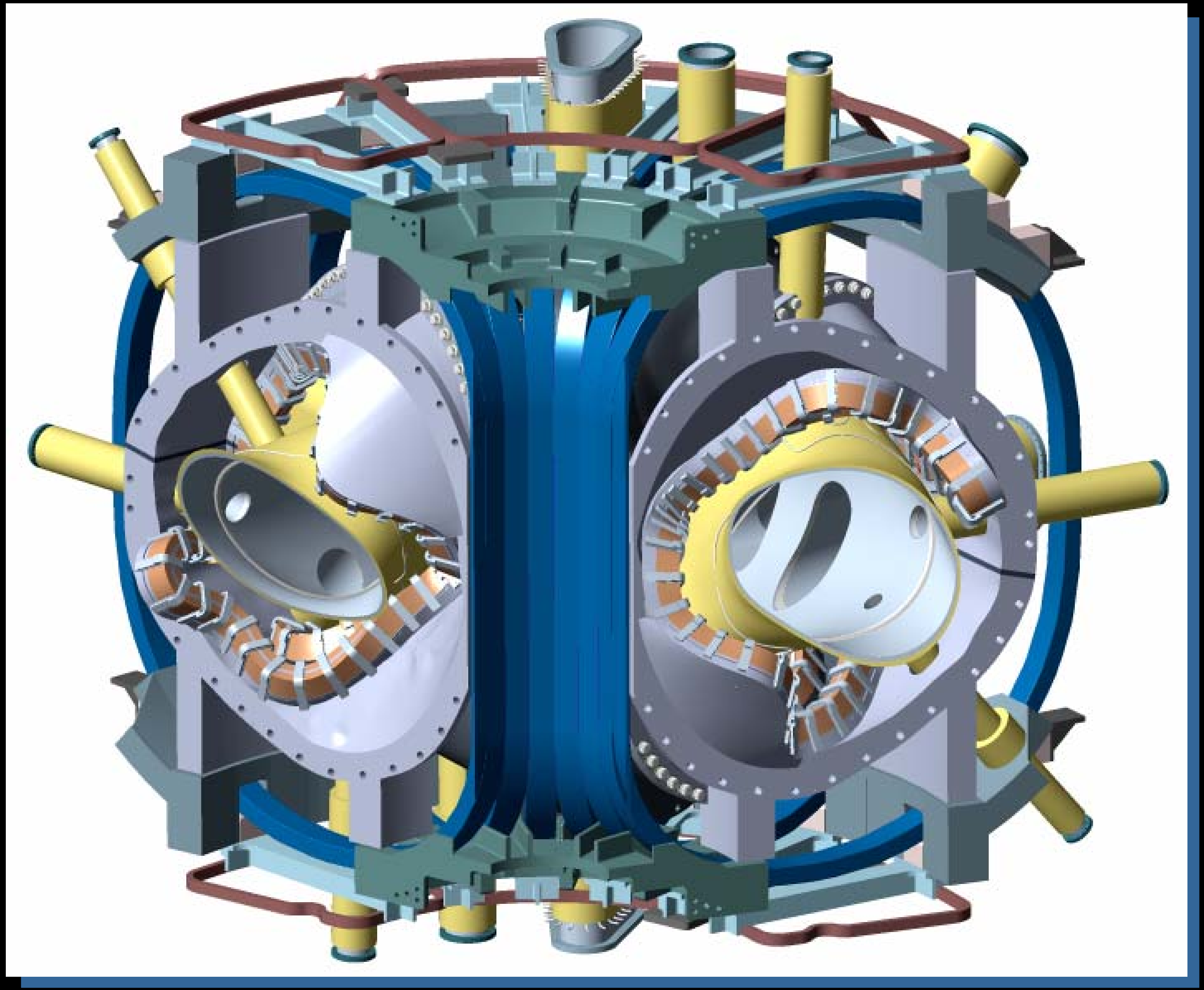
Design for 150 cool-down cycles, 130,000 pulses over >10 years of operation

Interface Requirements



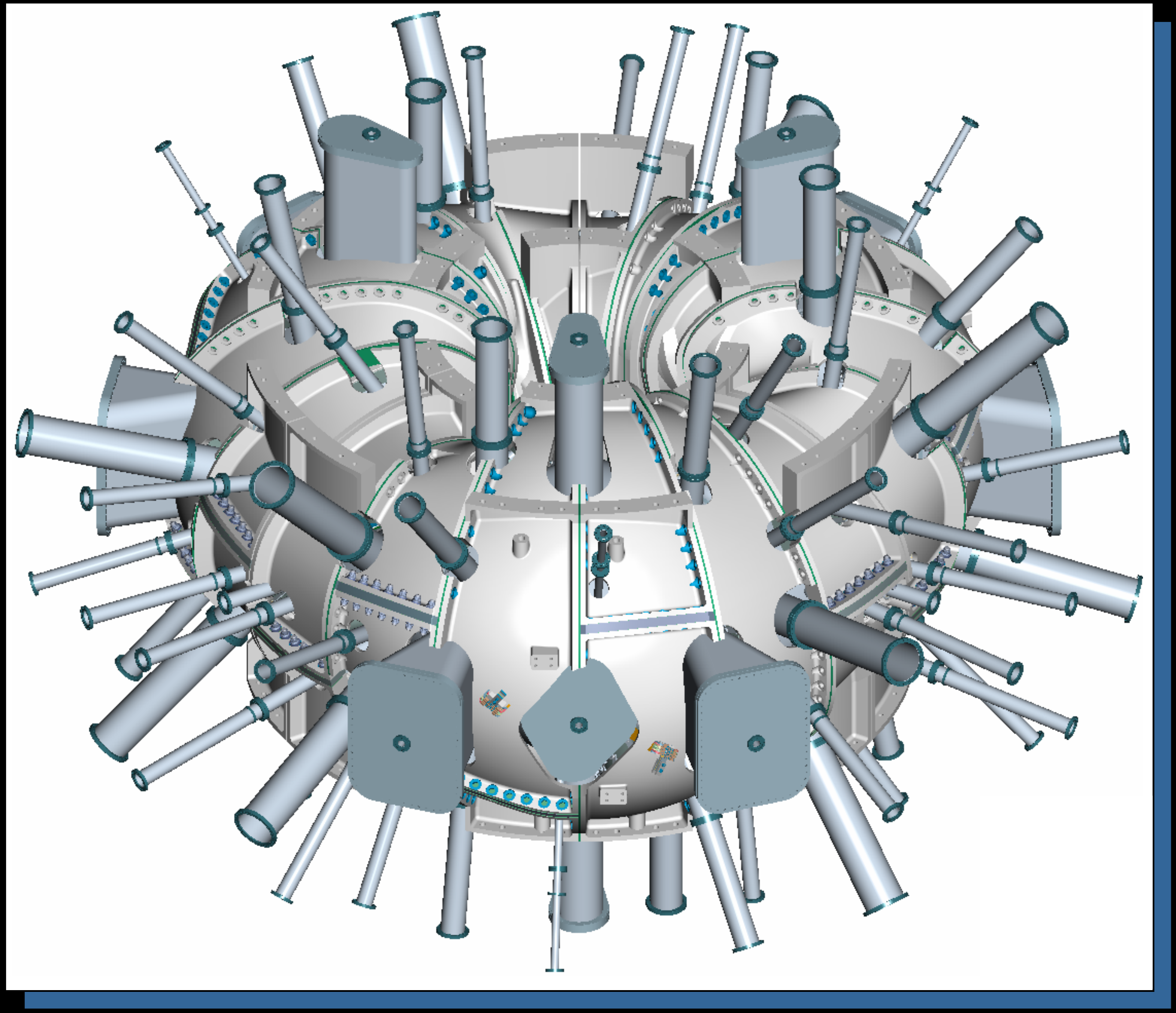
Structural Support Interface

- 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)

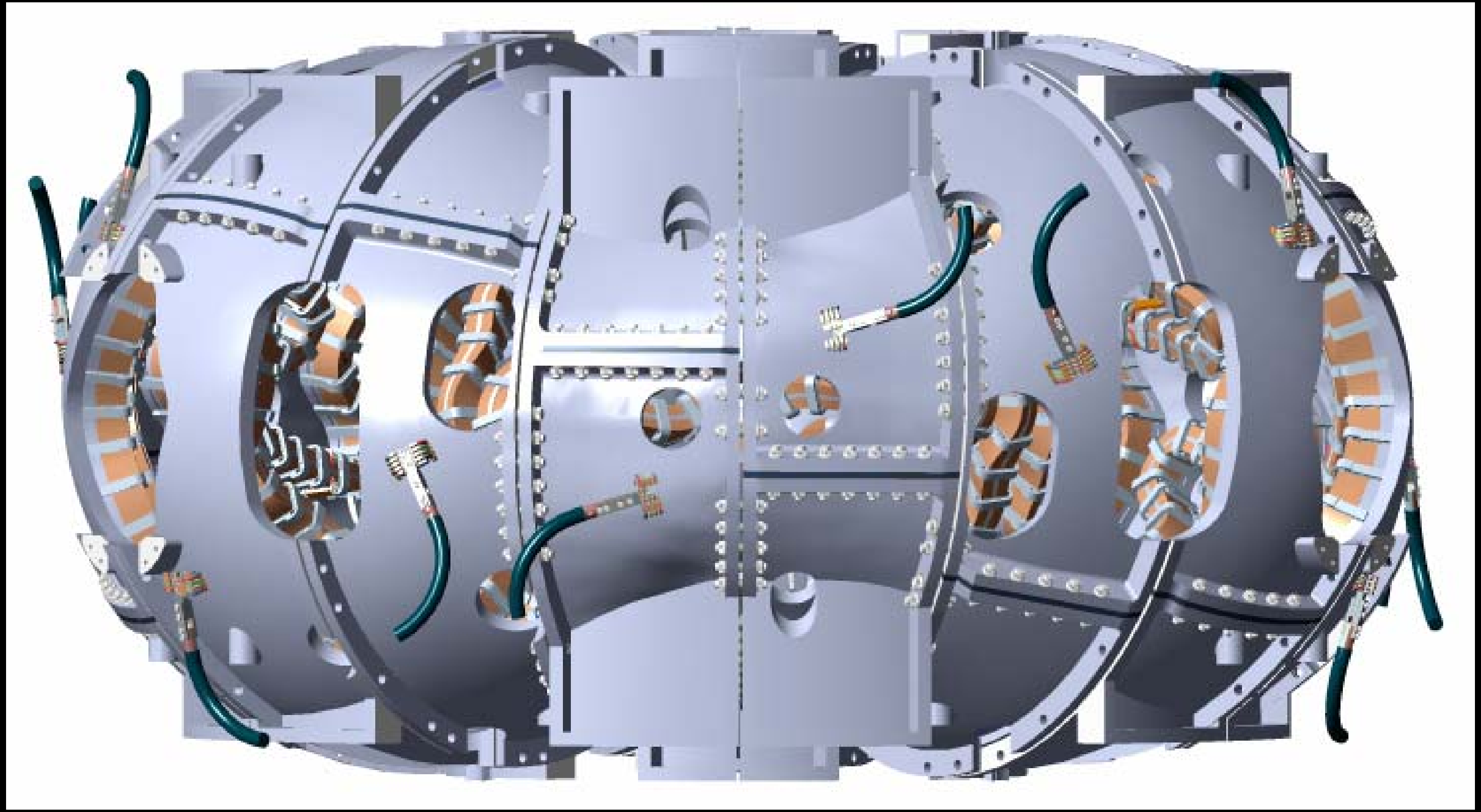


Vacuum Vessel Interface

- 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

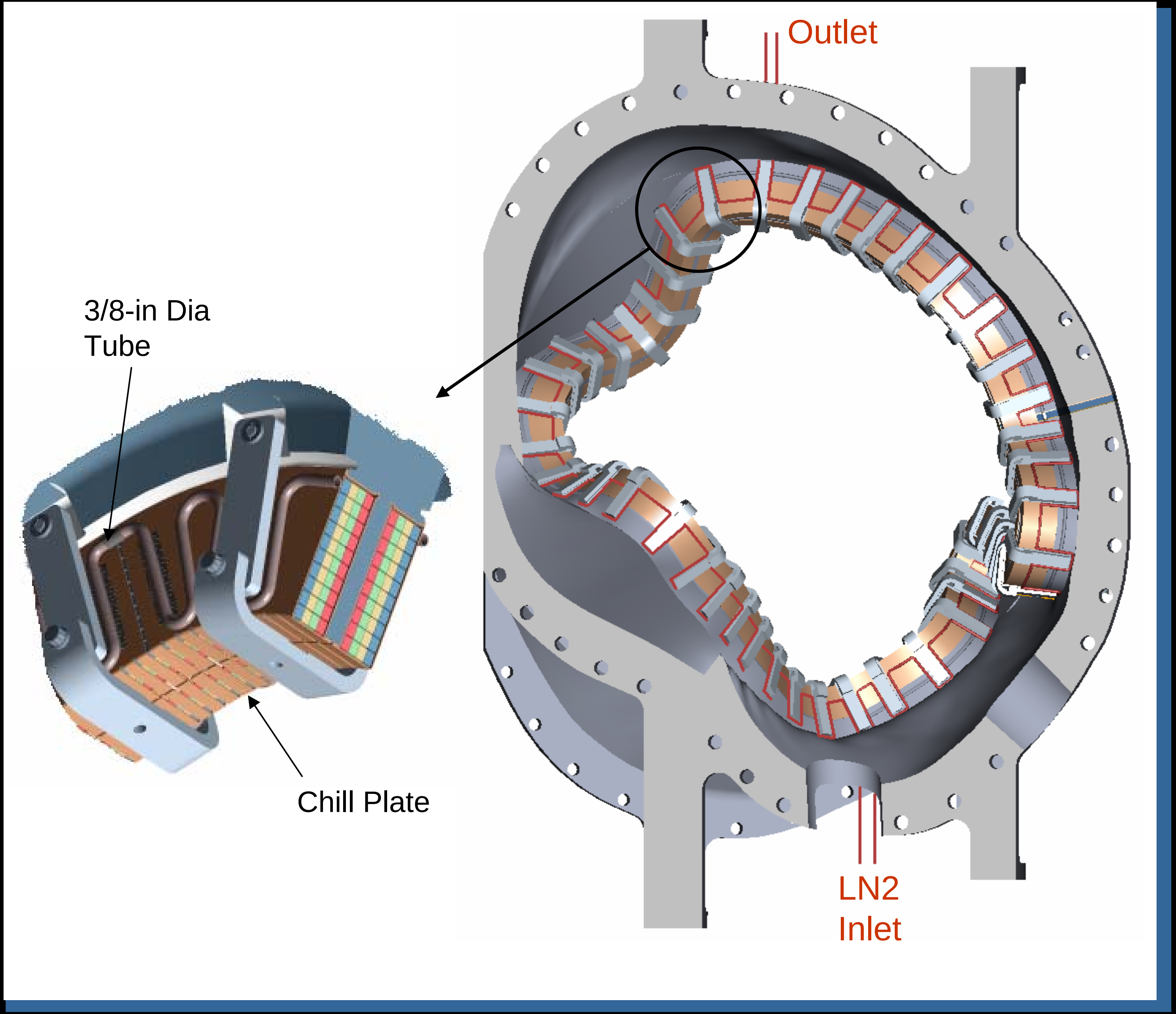


Up / Down Symmetry of Leads

- 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.

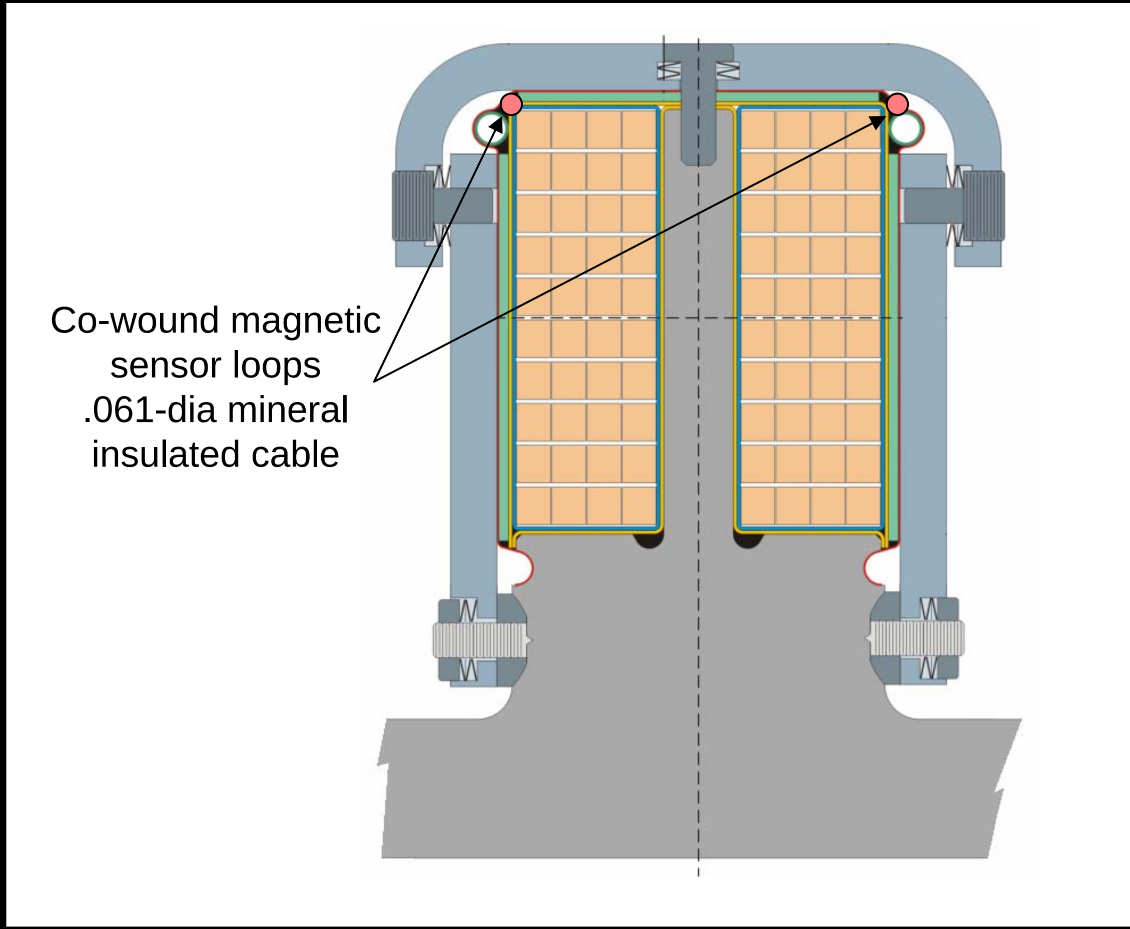
Cryostat and Cooling Interface

- 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.



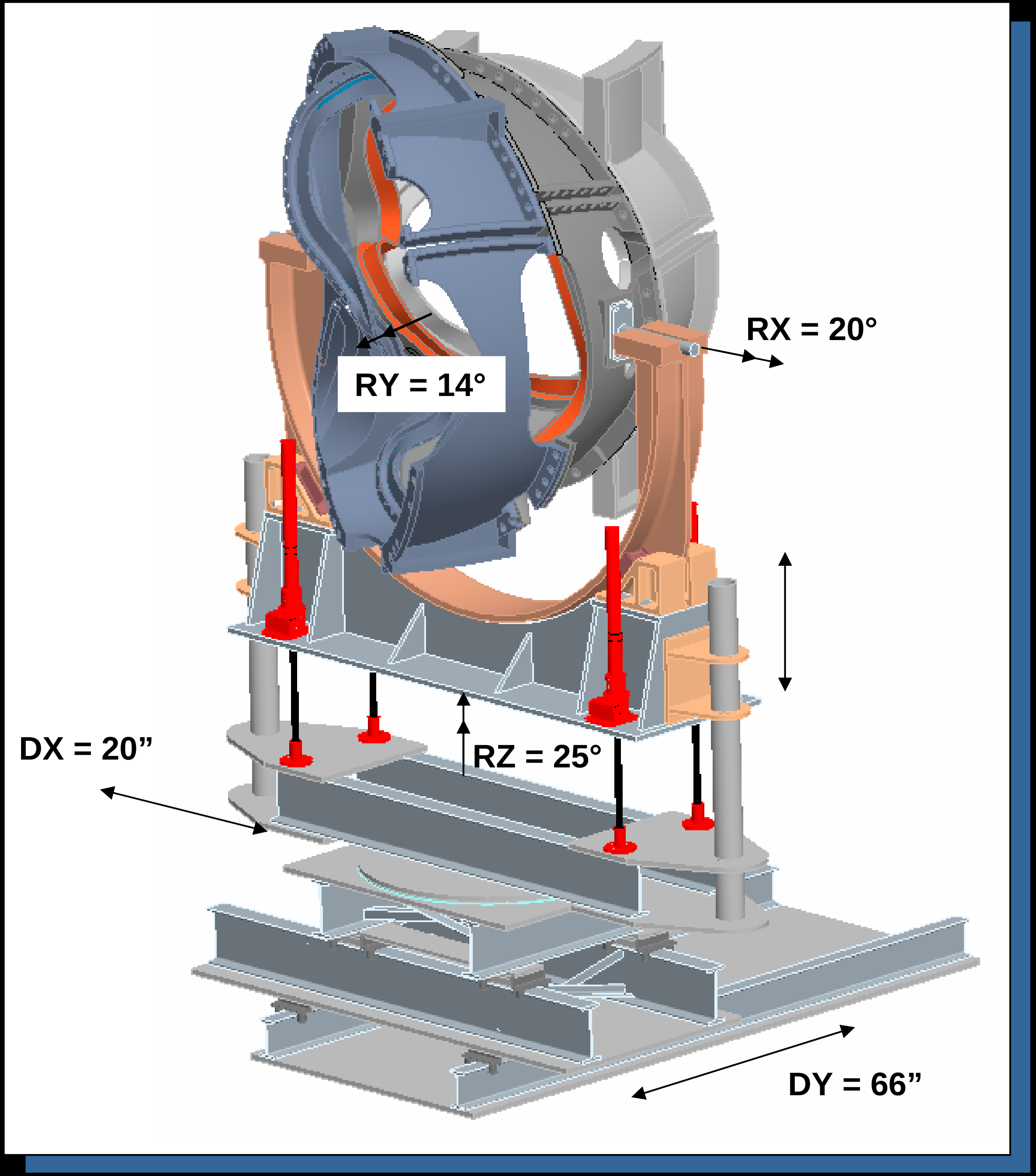
Instrumentation Interface

- 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.



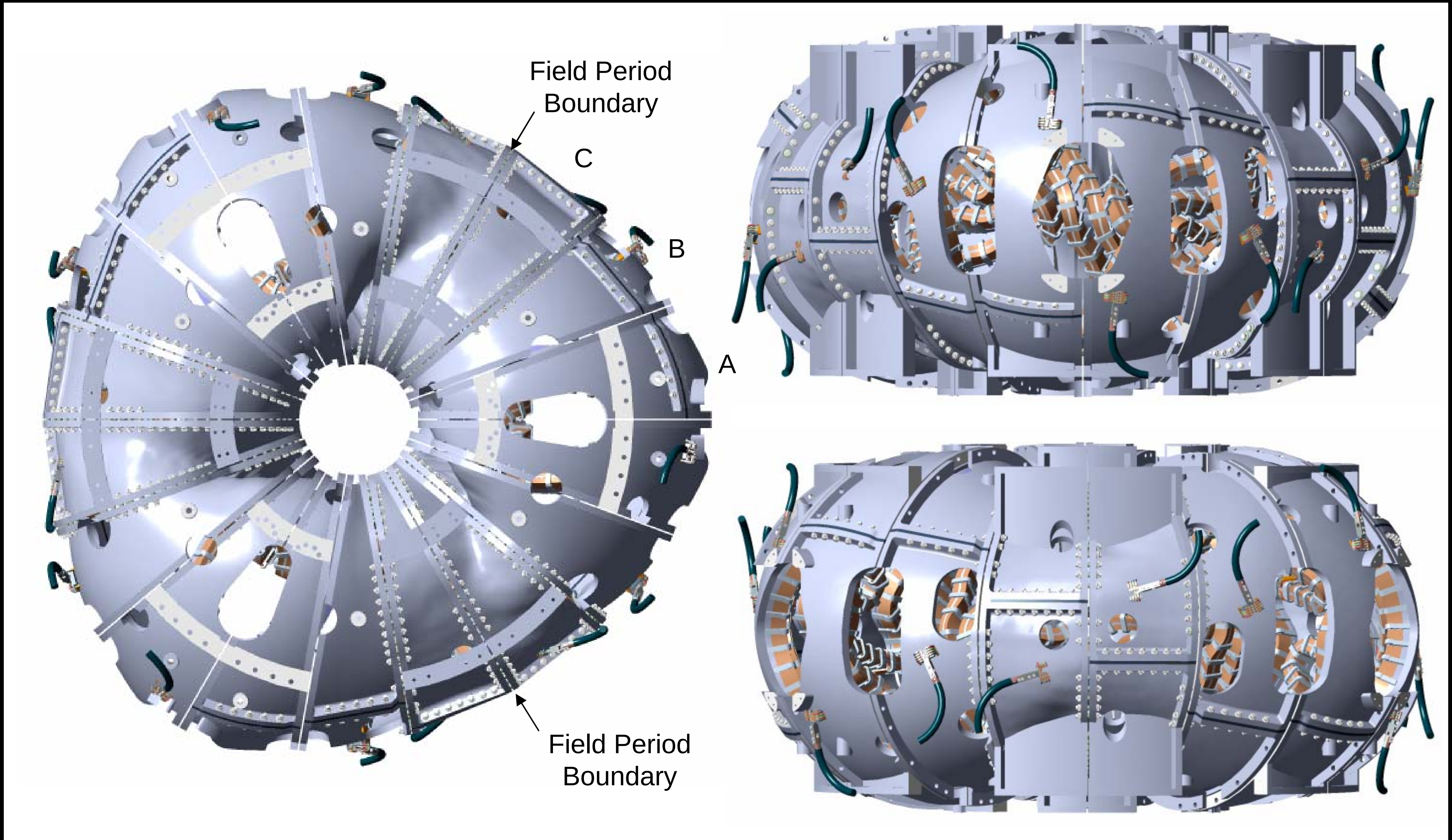
Field Period Assembly Interface

- Tooling required for field period assembly interfaces with the modular coils at specified lift points.
- Monuments are required to facilitate position measurements.

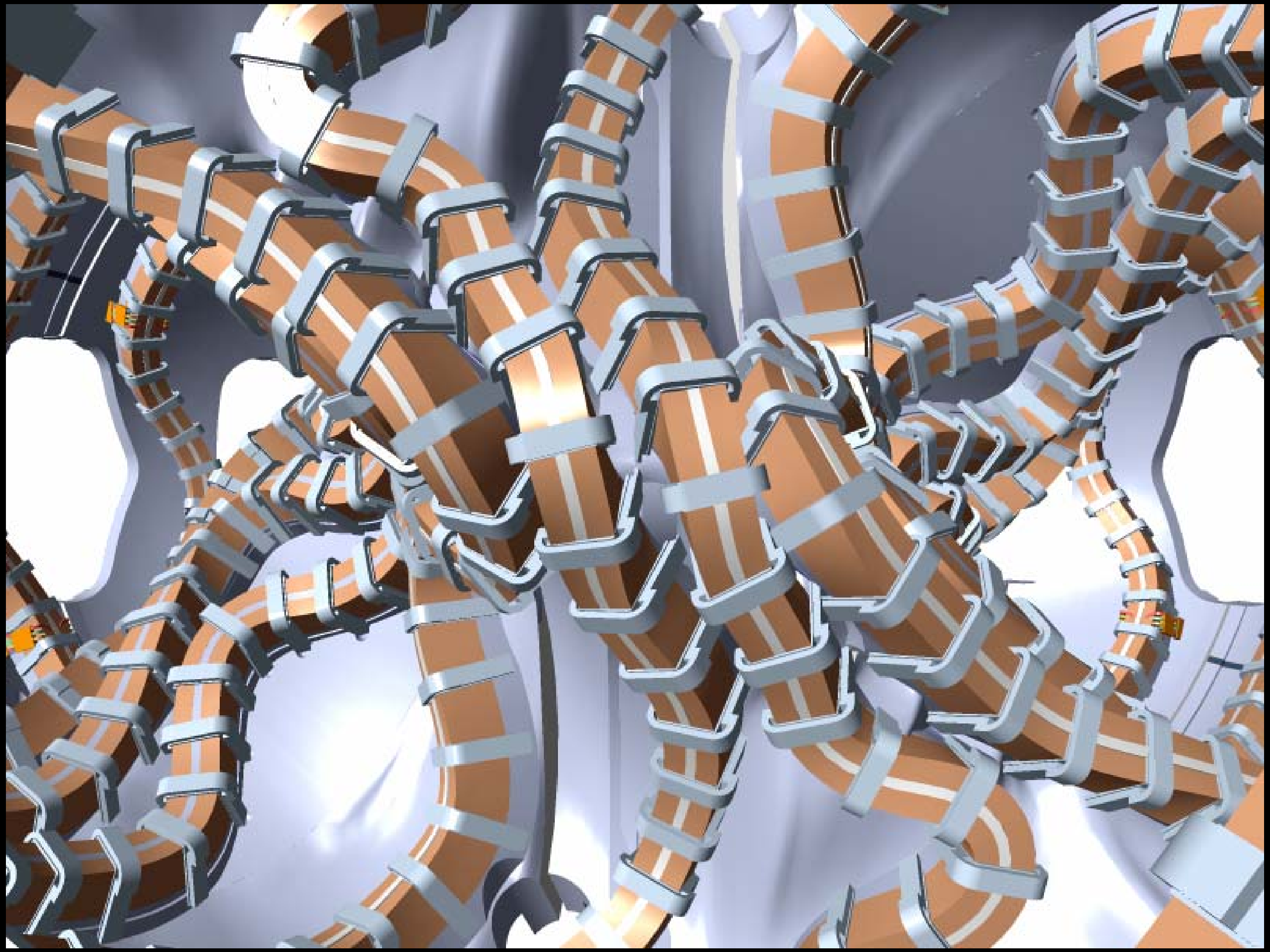


Design Description

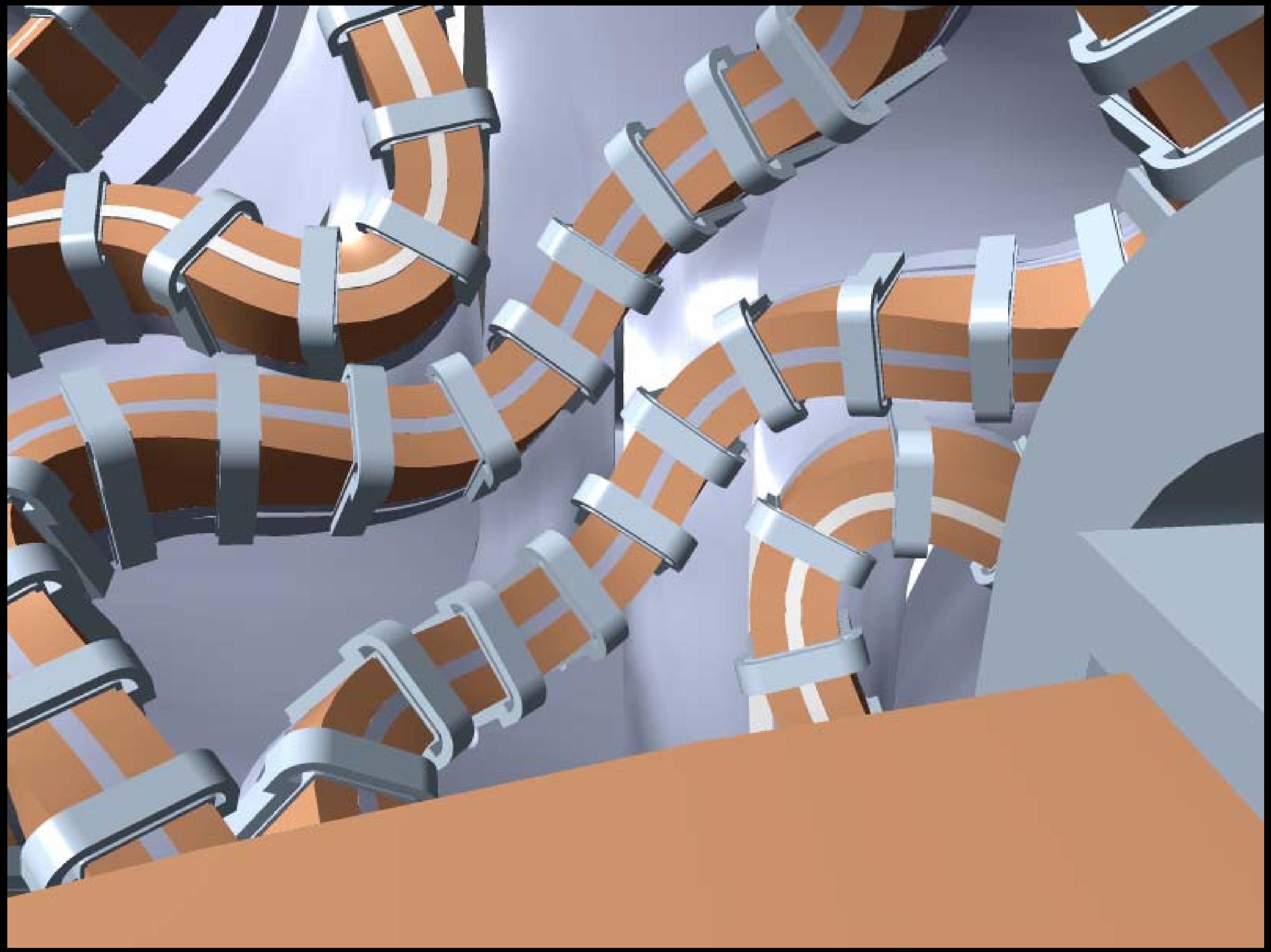
- Integral shell composed of 18 modular coil assemblies
- Three field periods, 6 coils per period, 3 coil types
- Shell thickness = 1.5-in, can vary to meet stress requirements
- Total weight = 125,000-lb
- Each modular coil:
  - 1,900-ft of conductor
  - 48 coil clamps
  - 200 fasteners



Interior View of Structure

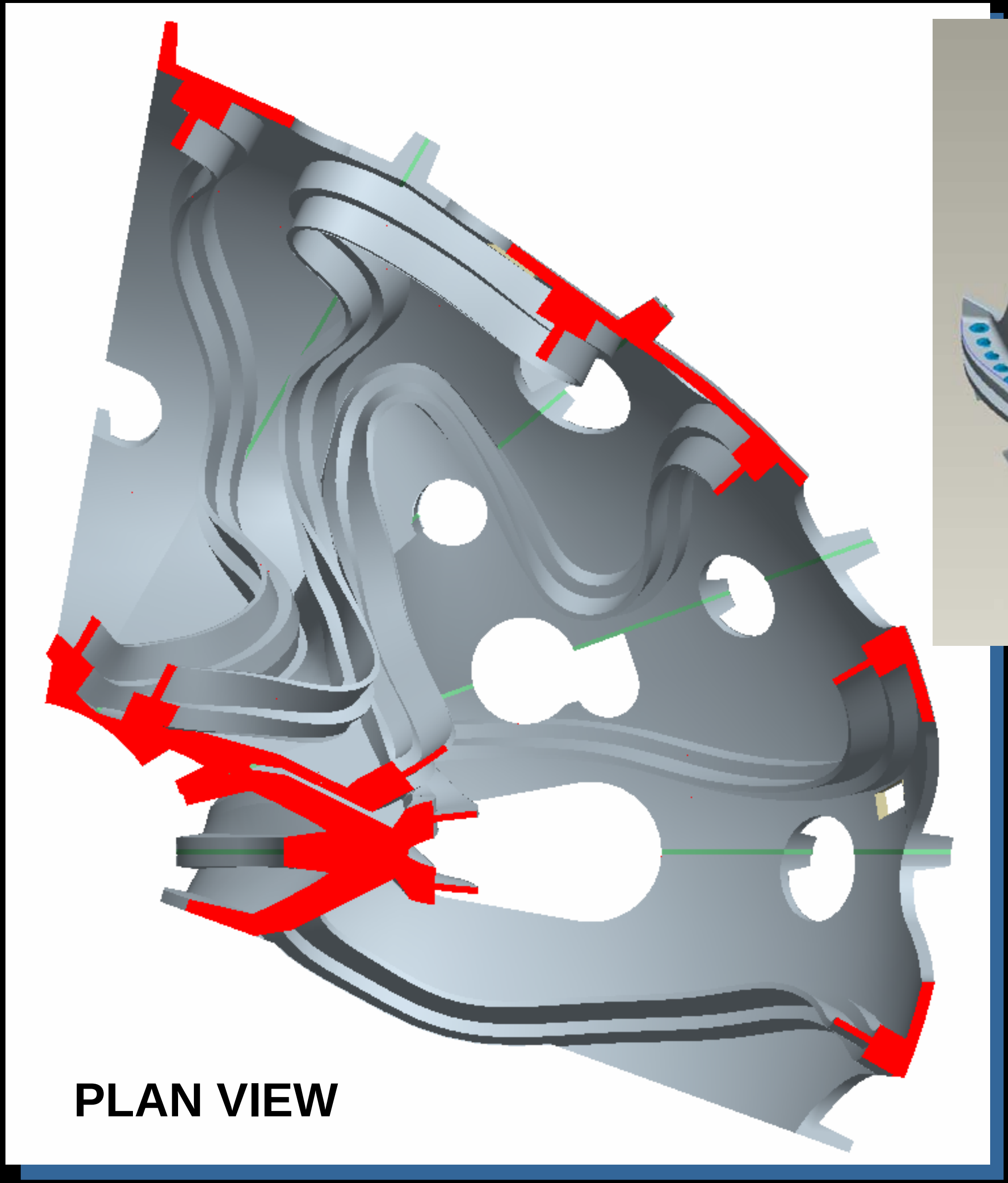


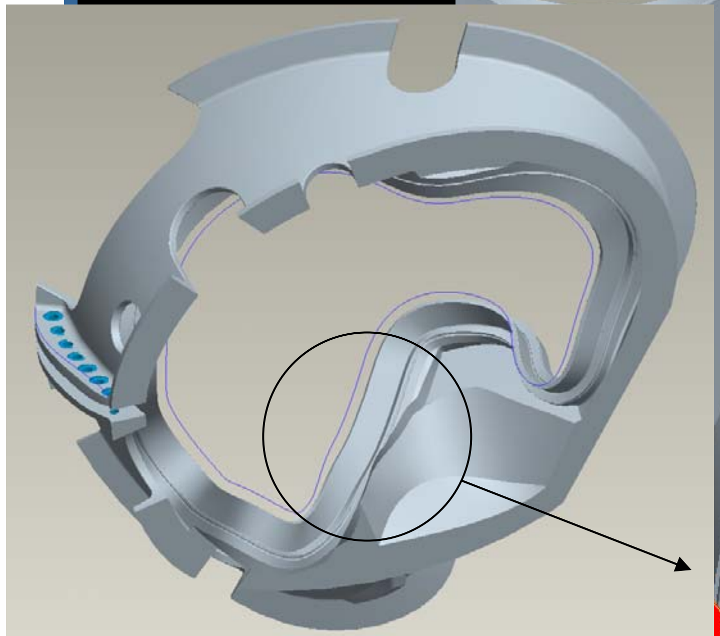
Wide Angle View at Coil Type A-A

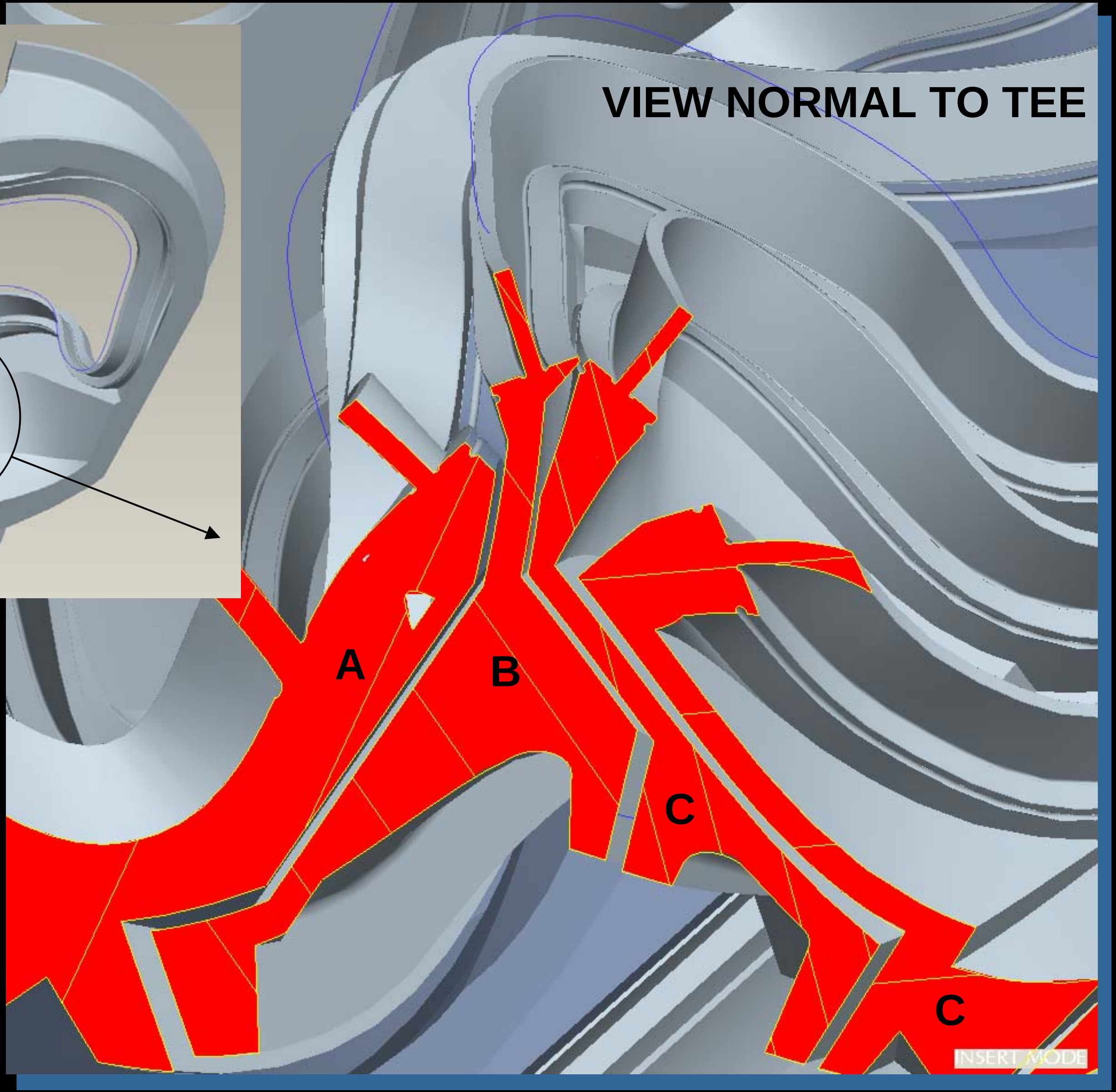


Wide Angle View at Coil Type C-C

Section Views of Assembly

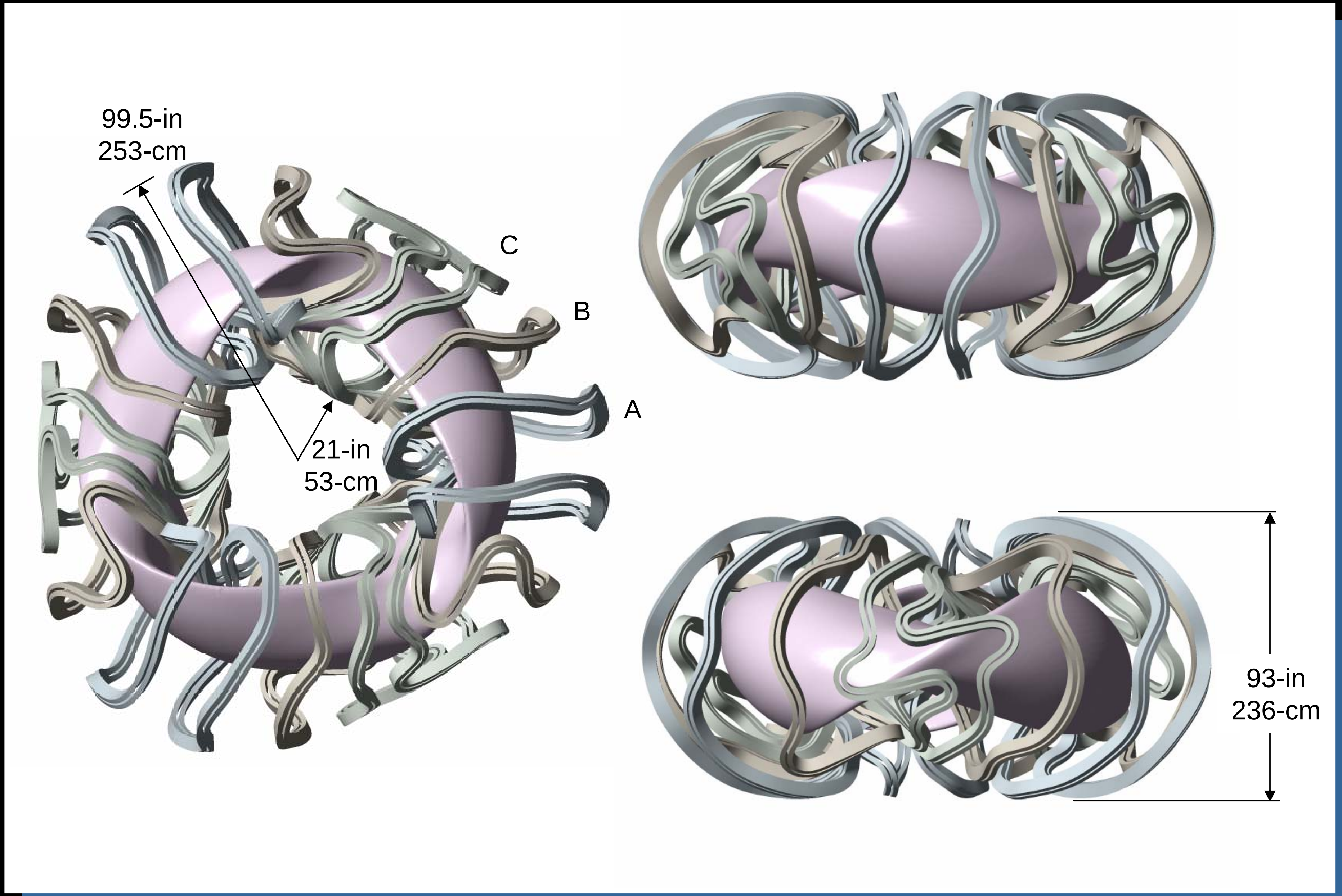






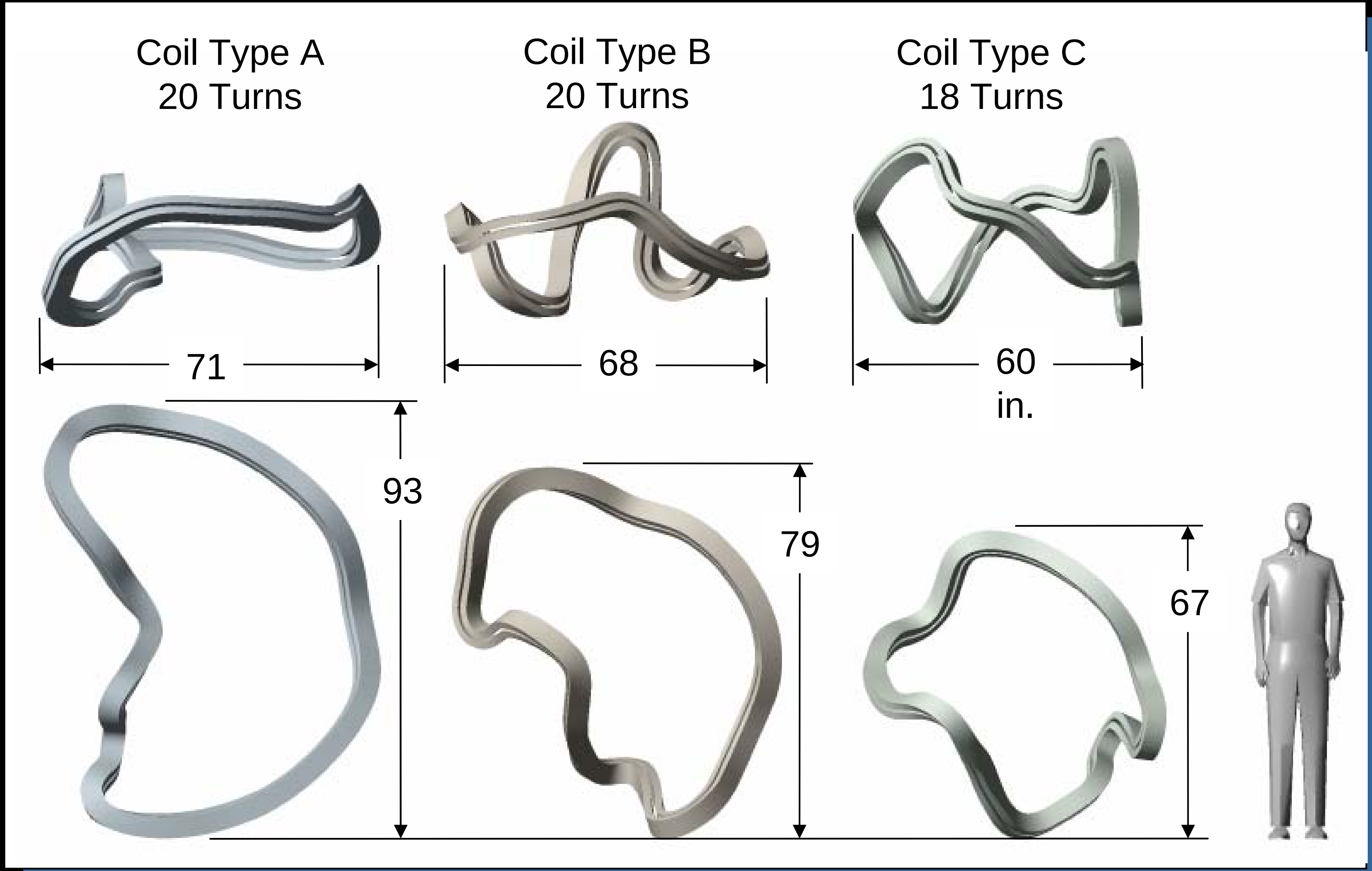
Coil Configuration

- 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



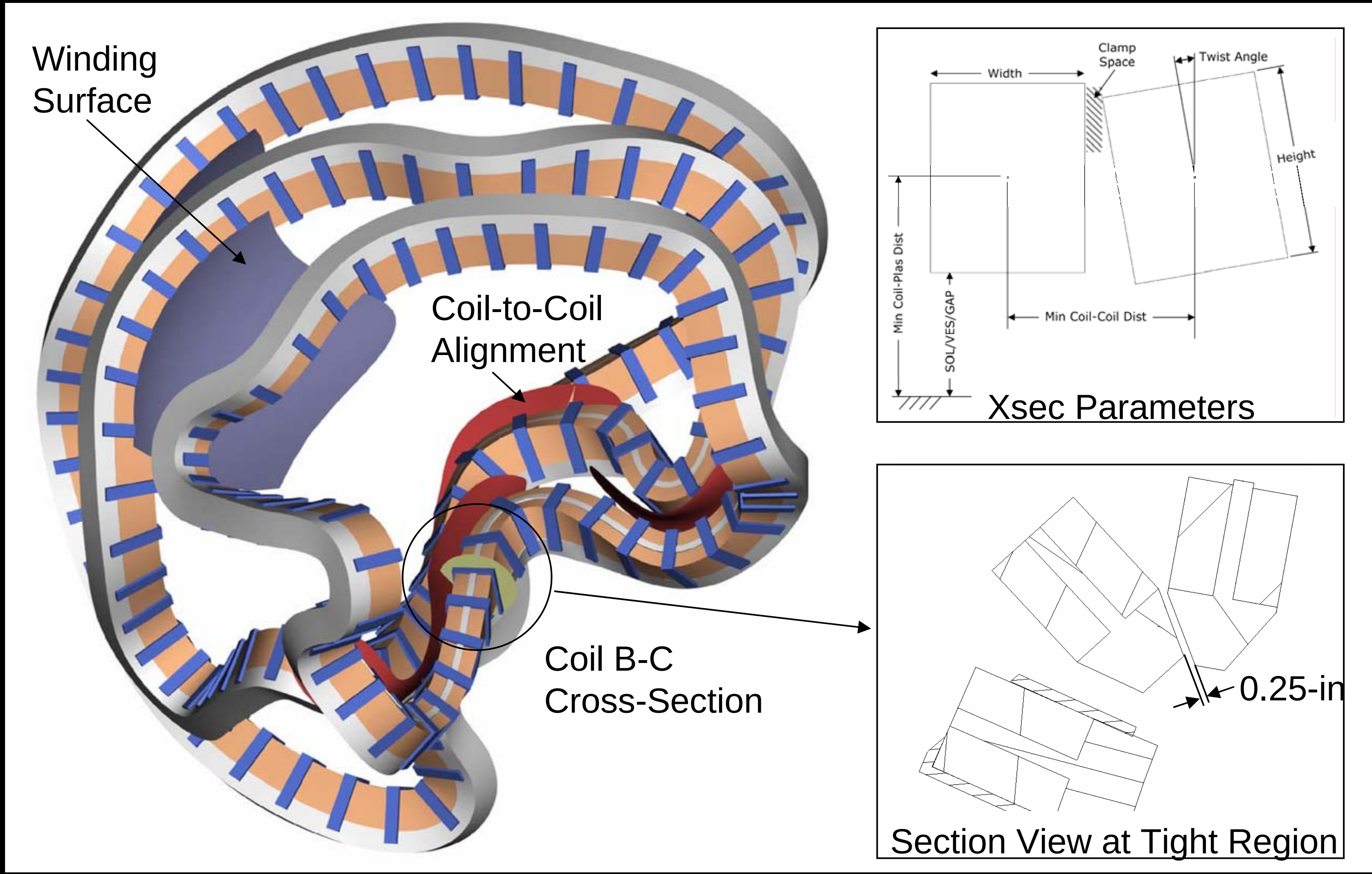
Coil Geometry

- 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

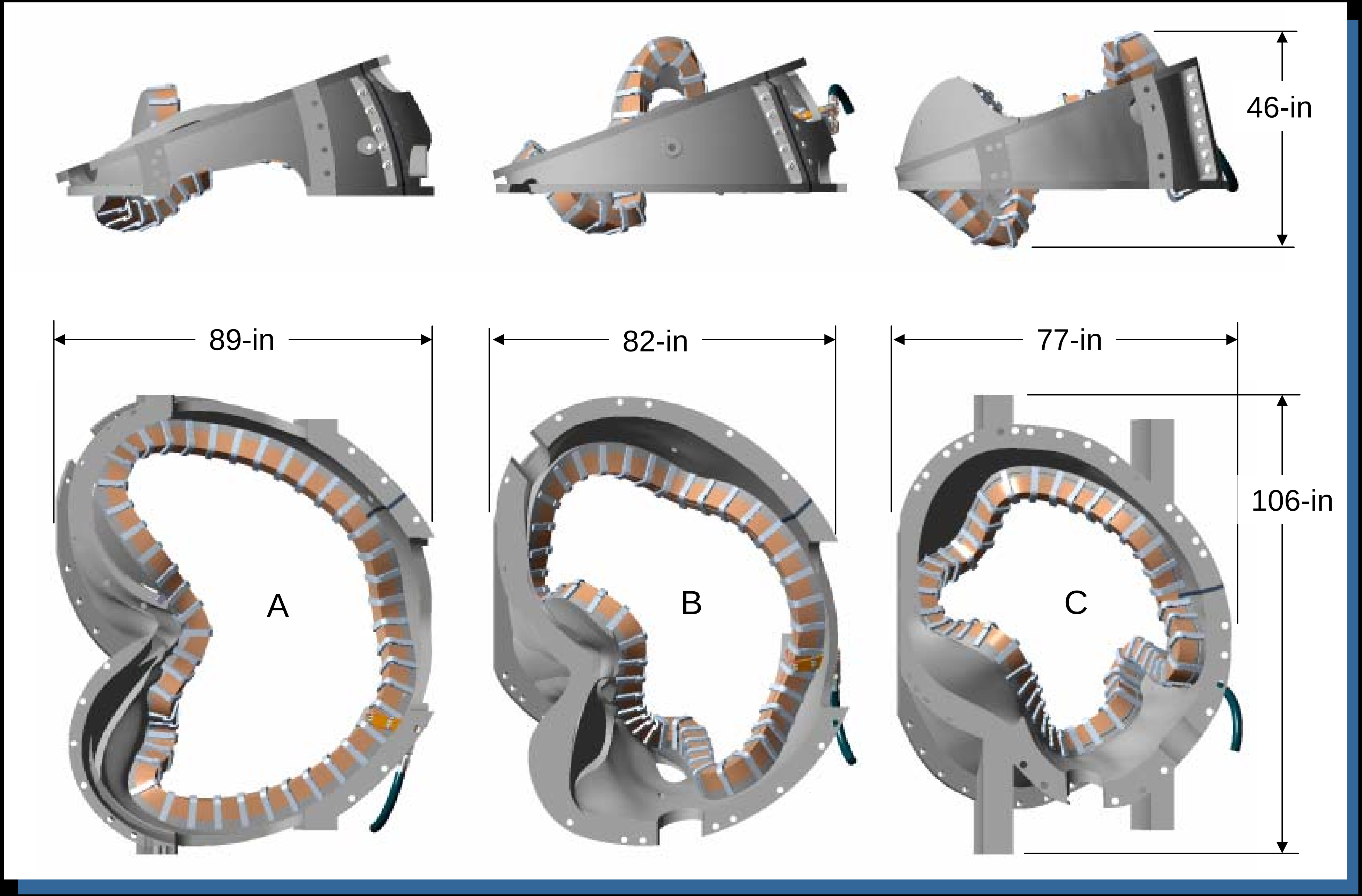


Cross-Section Development

- 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

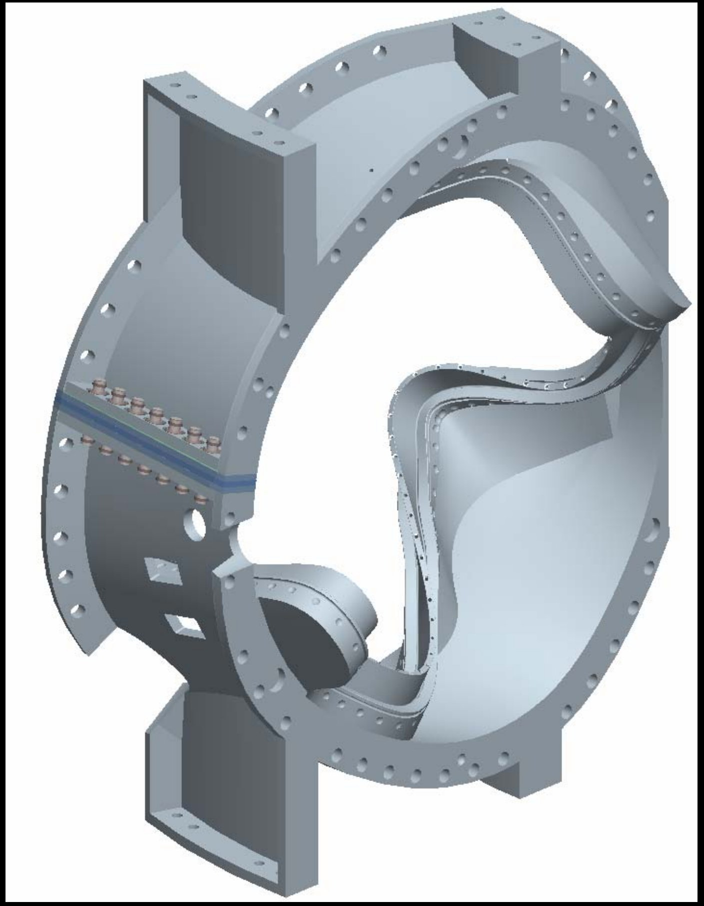


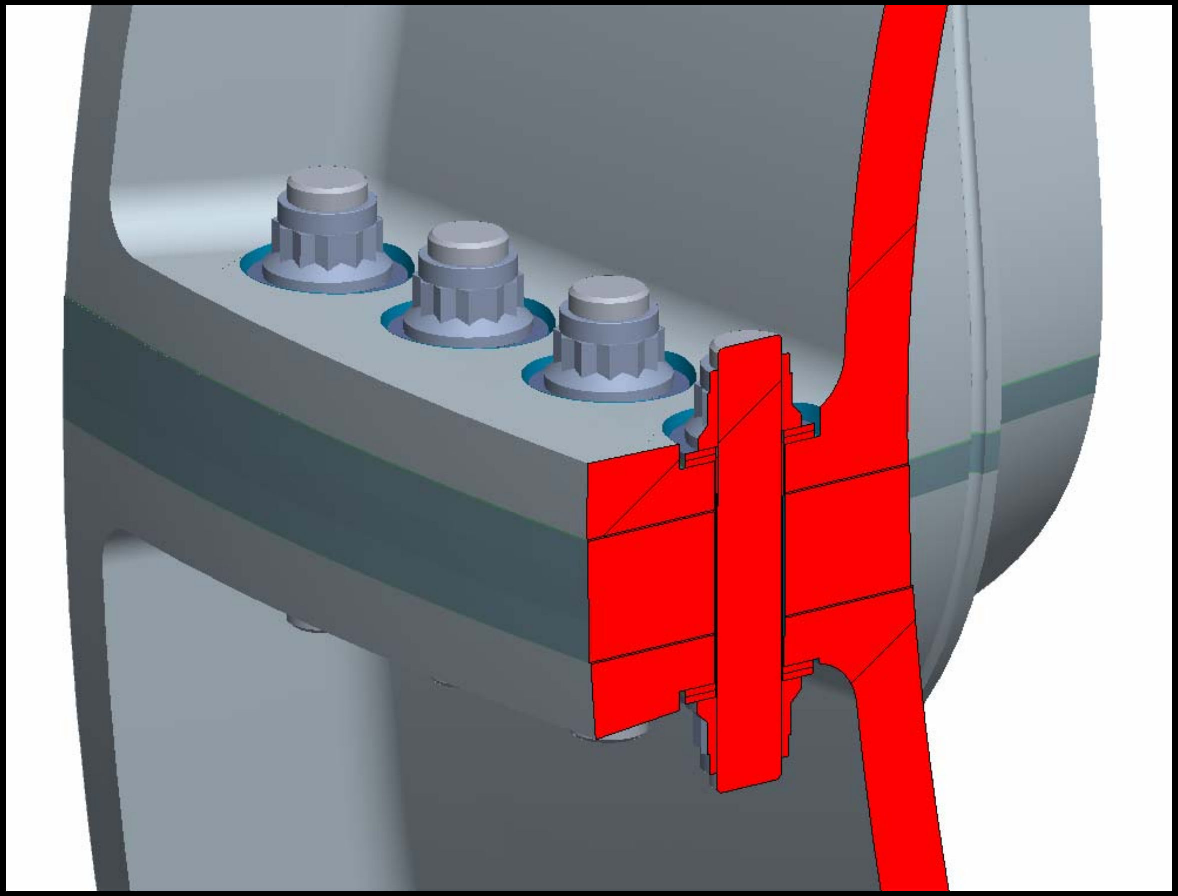
Modular Coil Types



Poloidal Break

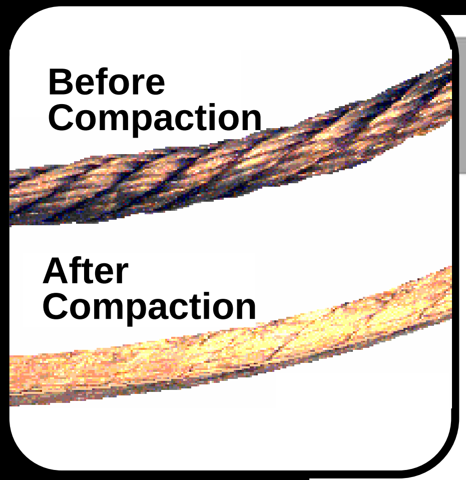
- Poloidal break is required to prevent persistent eddy currents during operation
- Fabrication approach is to saw-cut casting, insulate and bolt prior to final machining of the tee region
- Tee web connection using double insulated pin or bolt may also be required

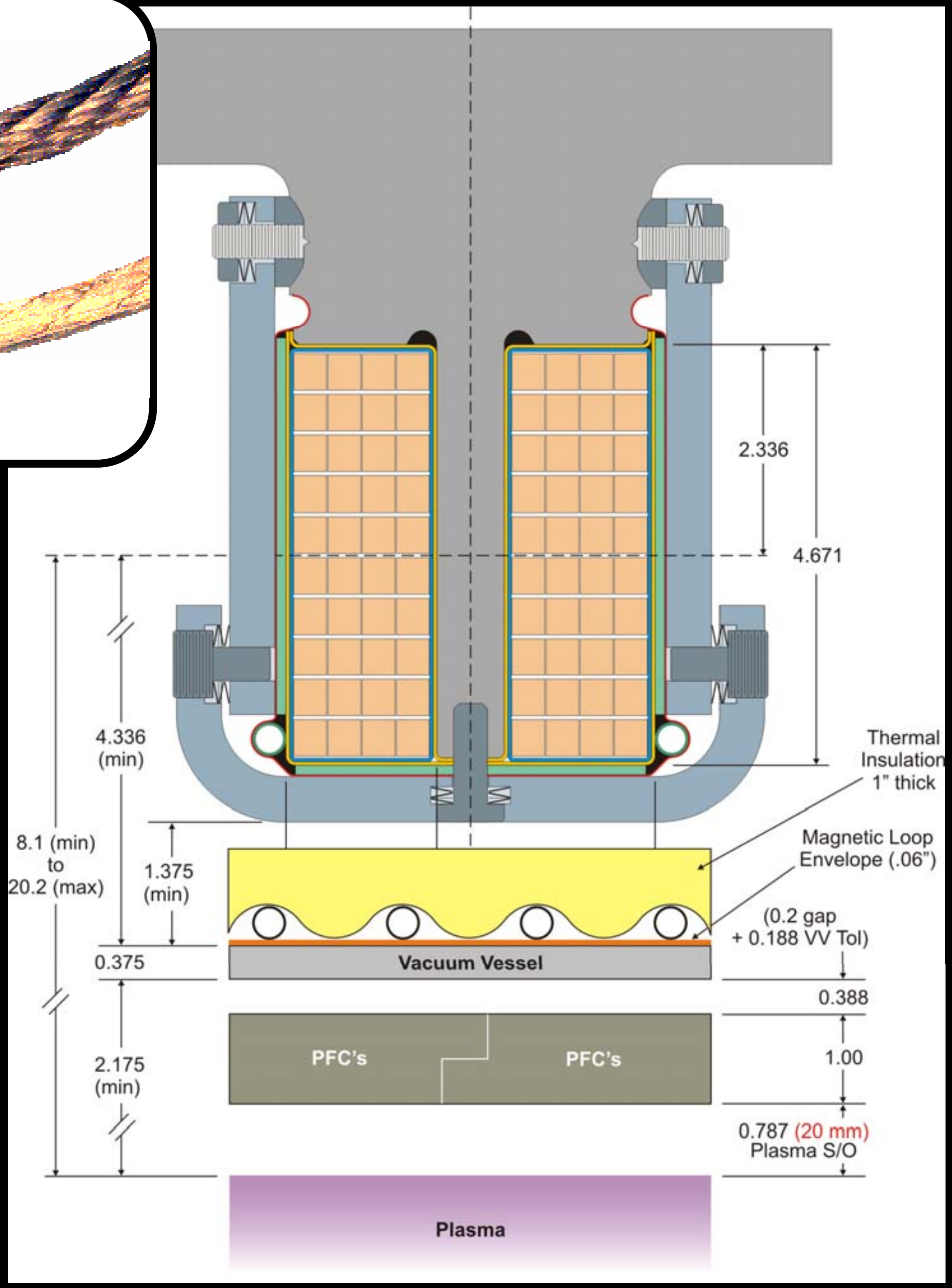




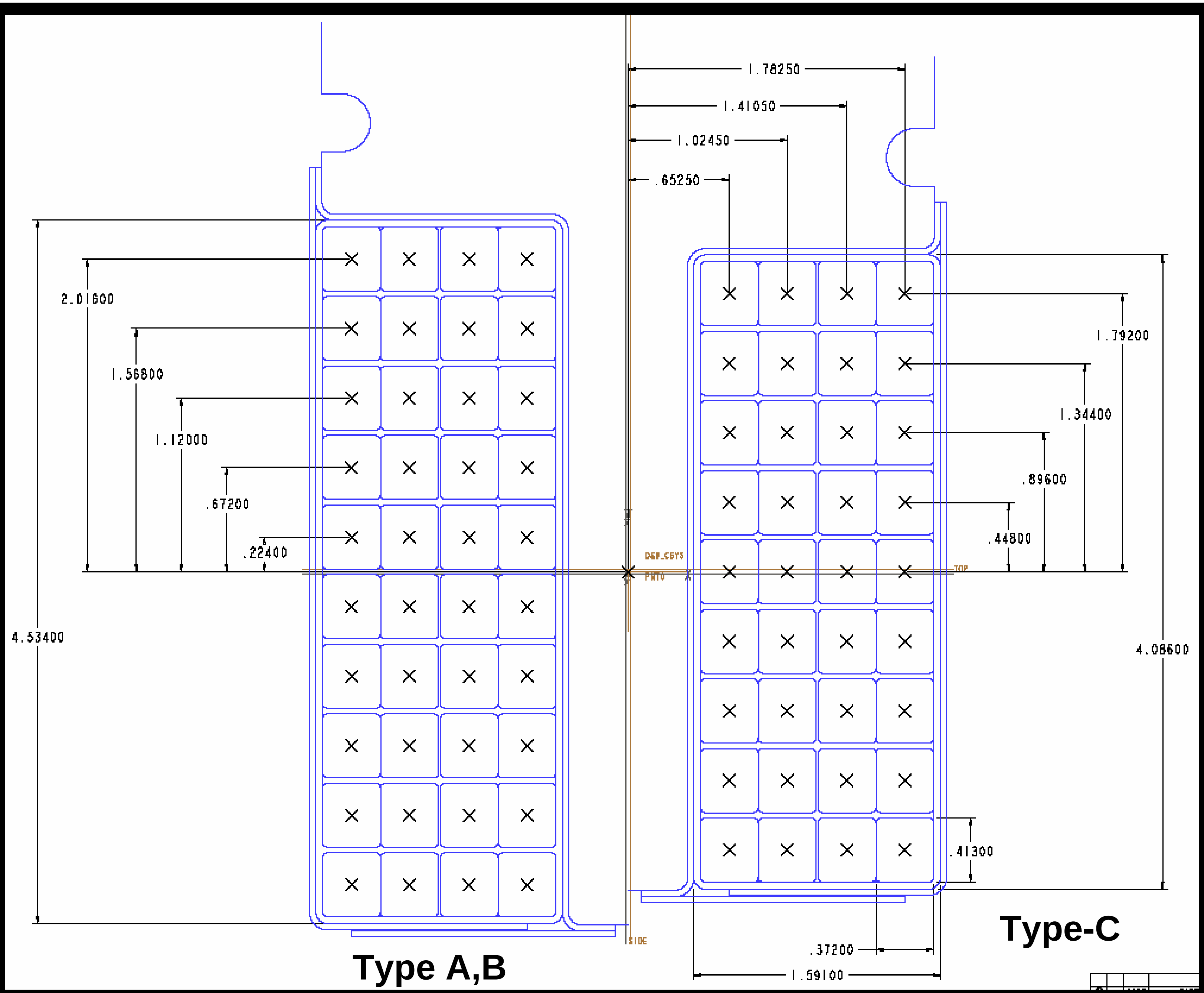
Winding Pack Configuration

- 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

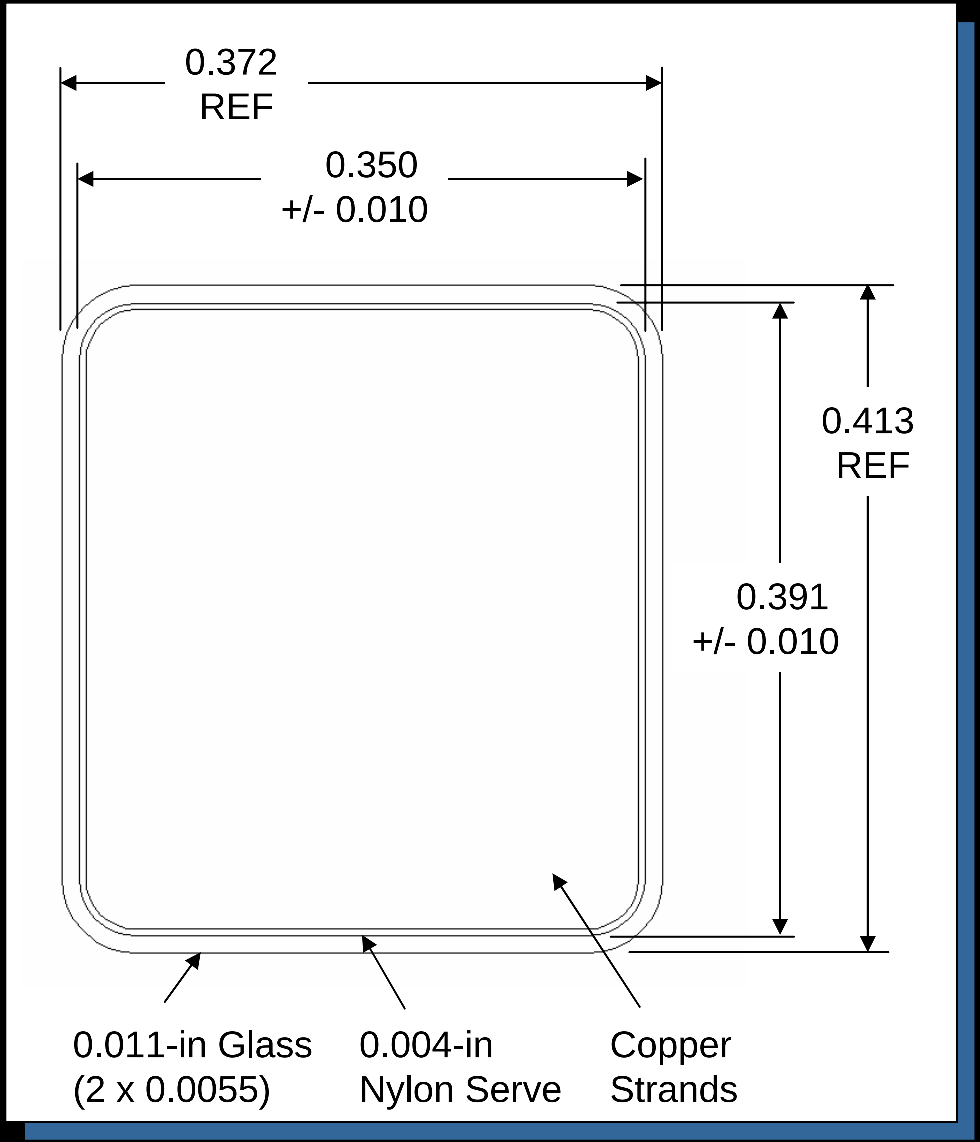




Type-C coil has less current, fewer turns

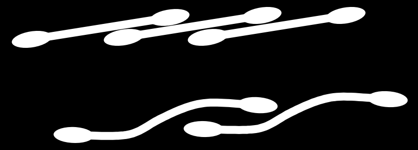


Conductor Specification

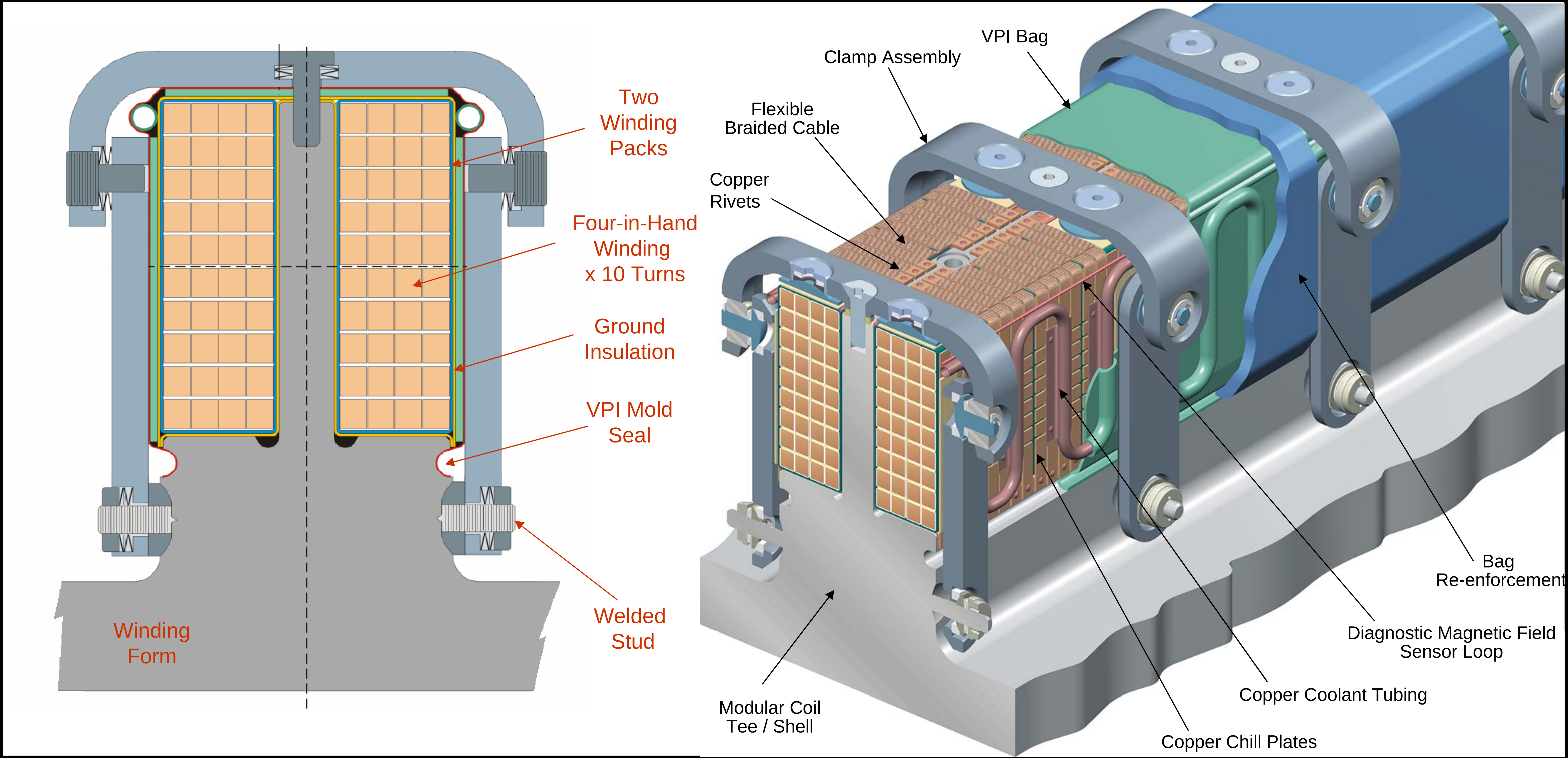


- **Copper specification-**
- **OFHC Copper, 34-ga Wire**
- **12x5/54/34 cable, 3240 strands**
- **Clean mfg process**

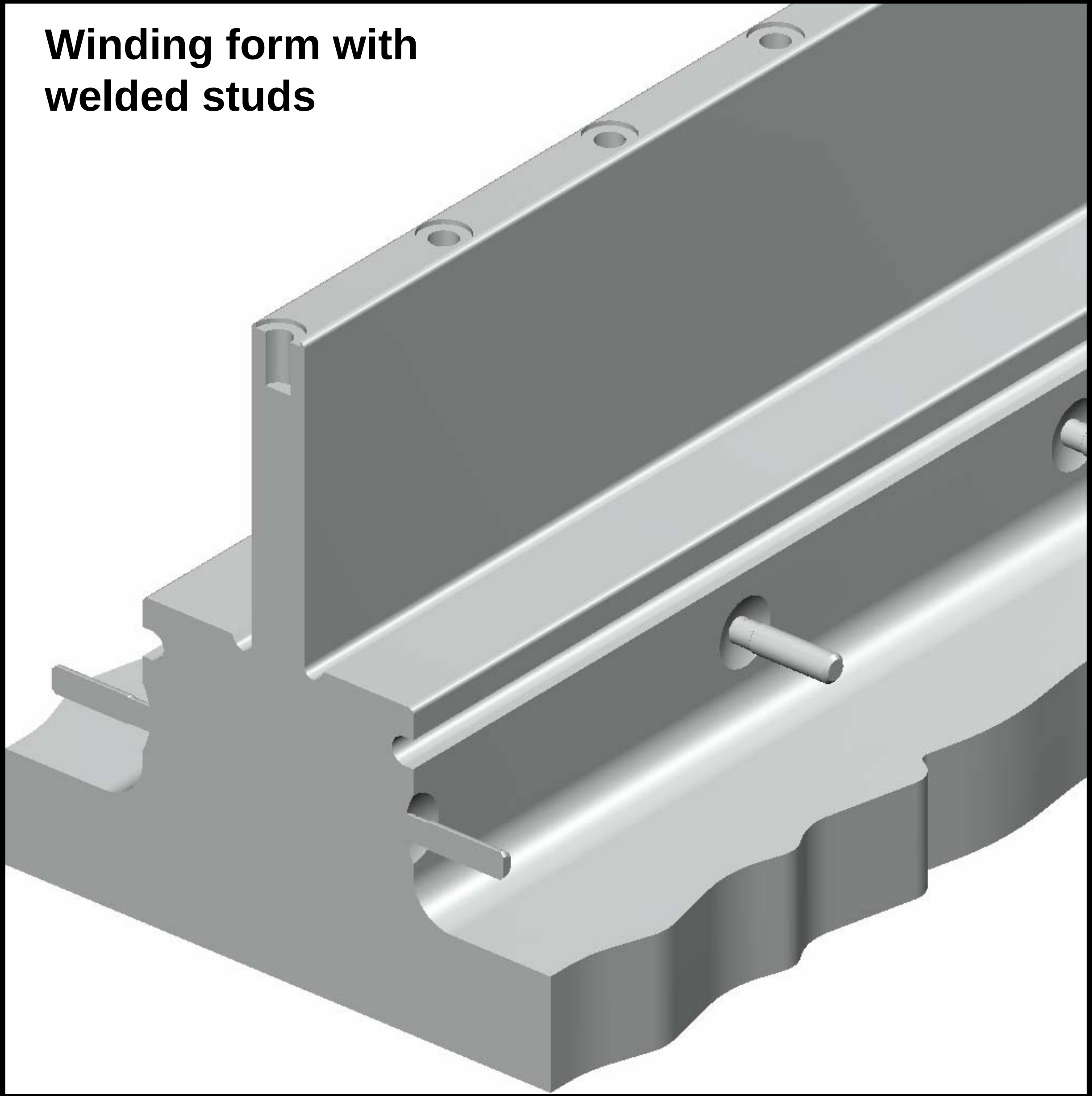
- **Insulation specification-**
- **S-2 glass with reactive amino silane finish, .004 in center and .007 at edge, (avg=0.0055-in) thick**
- **Four harness satin weave**

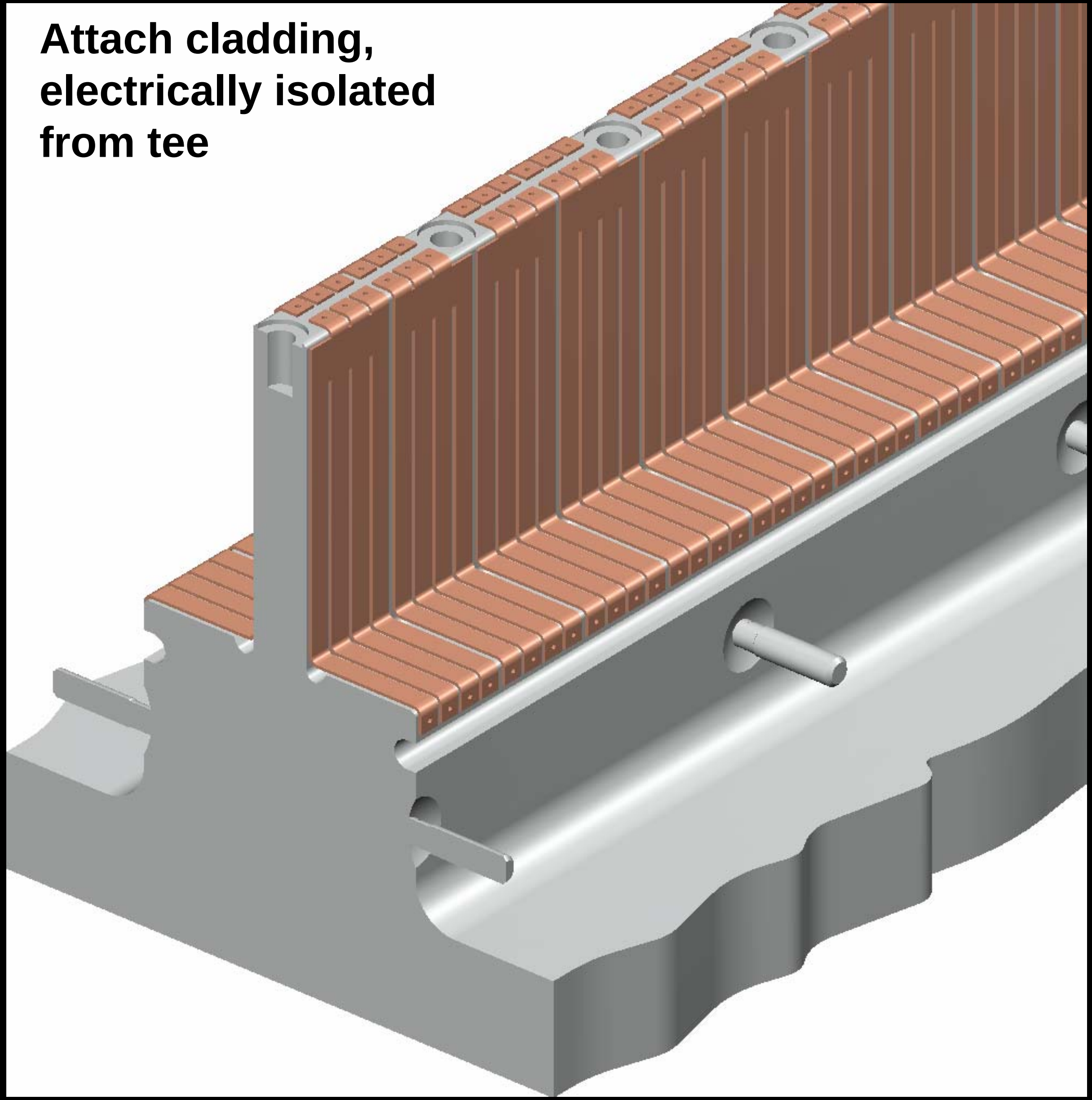


Winding Pack Assembly

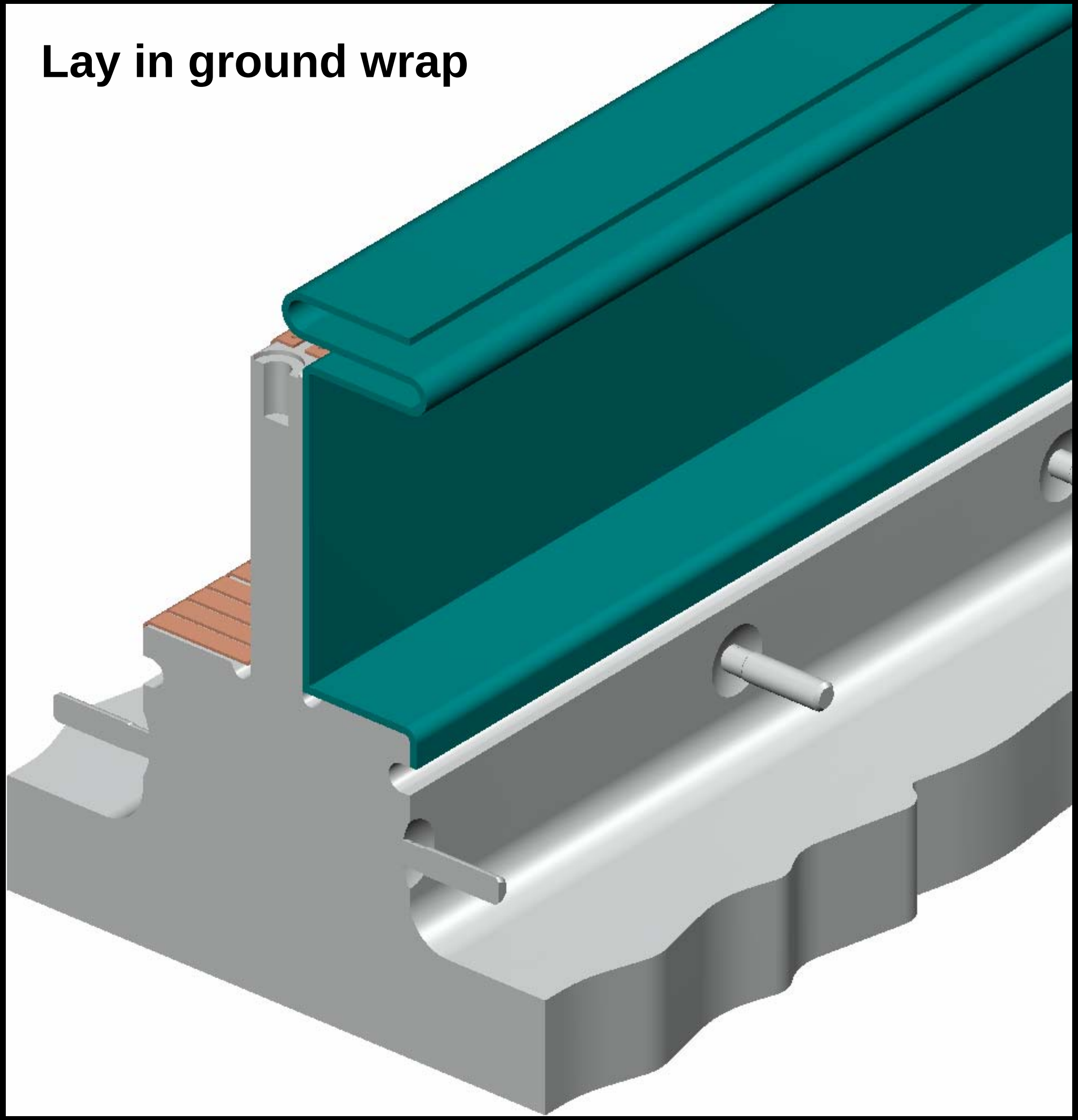


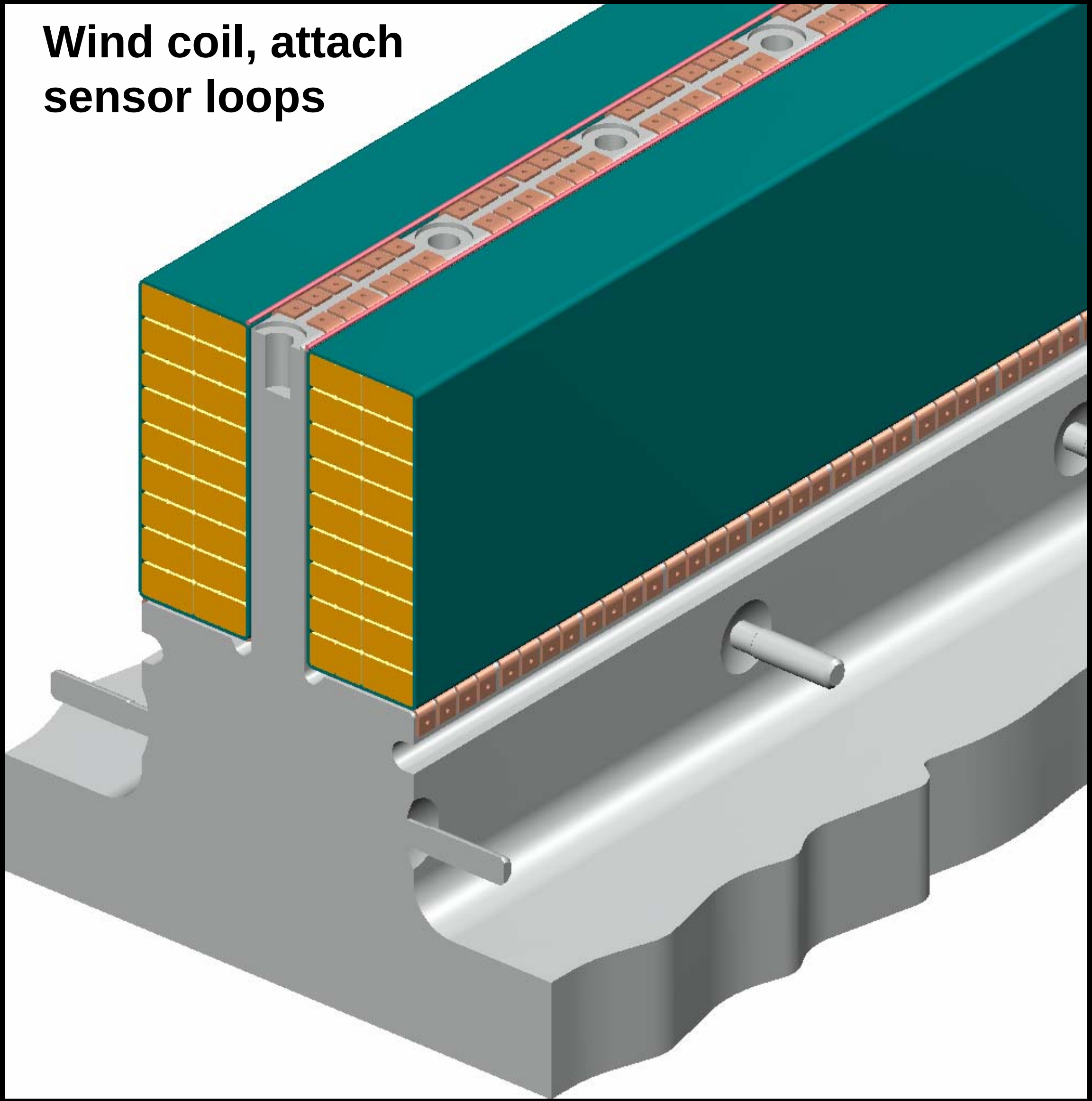
Winding Pack Assembly (cont'd)



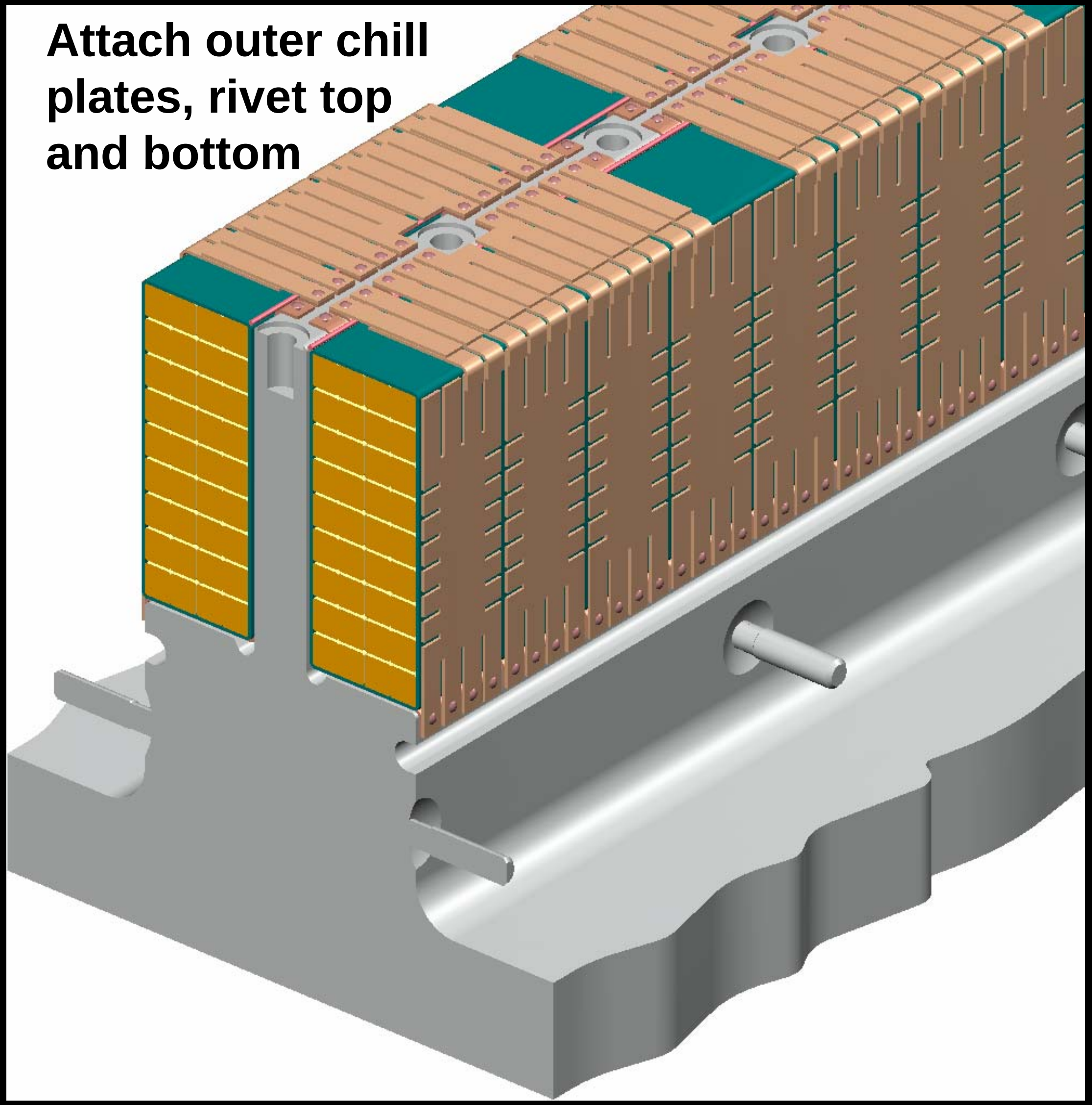


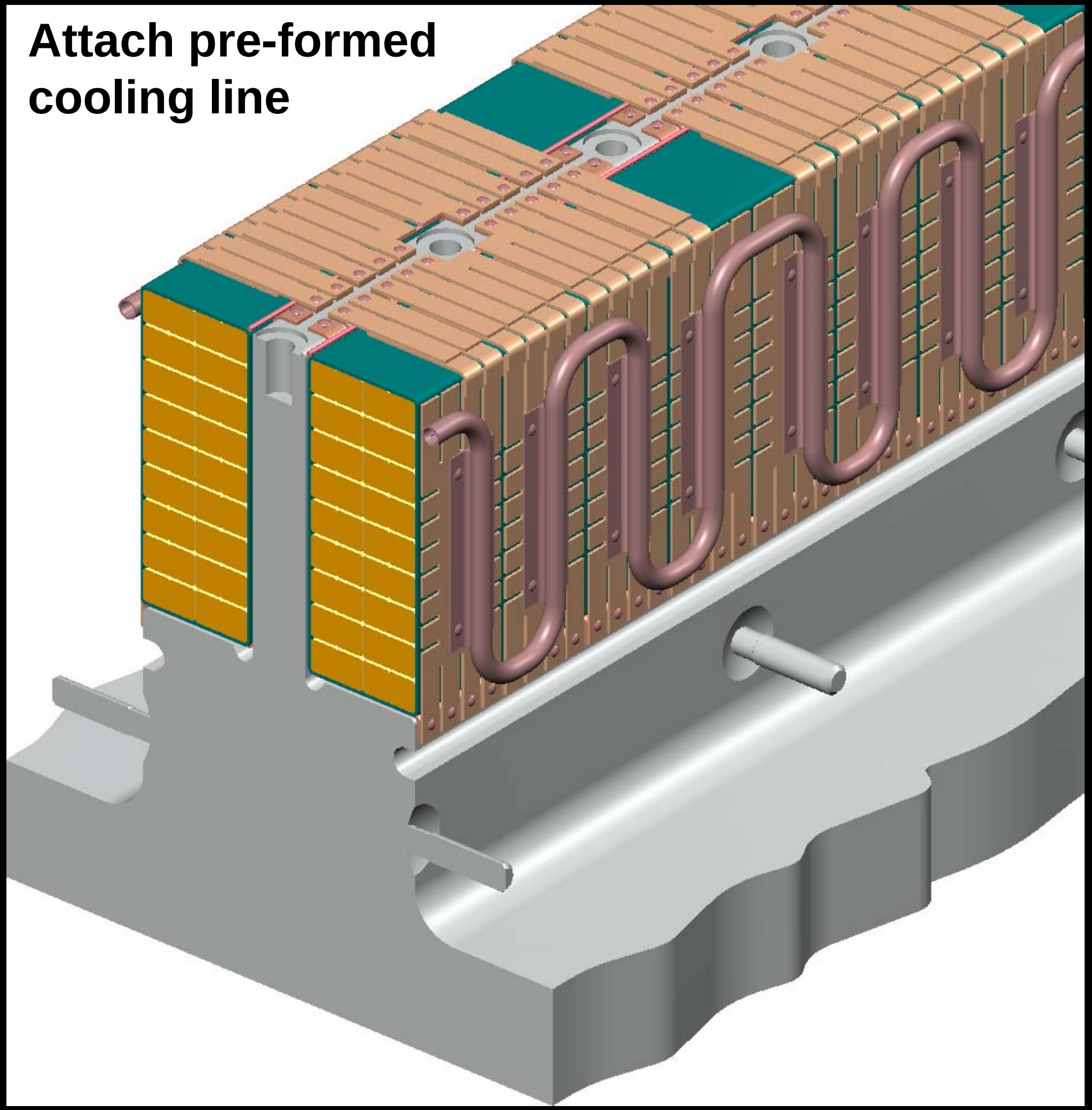
Winding Pack Assembly (cont’d)



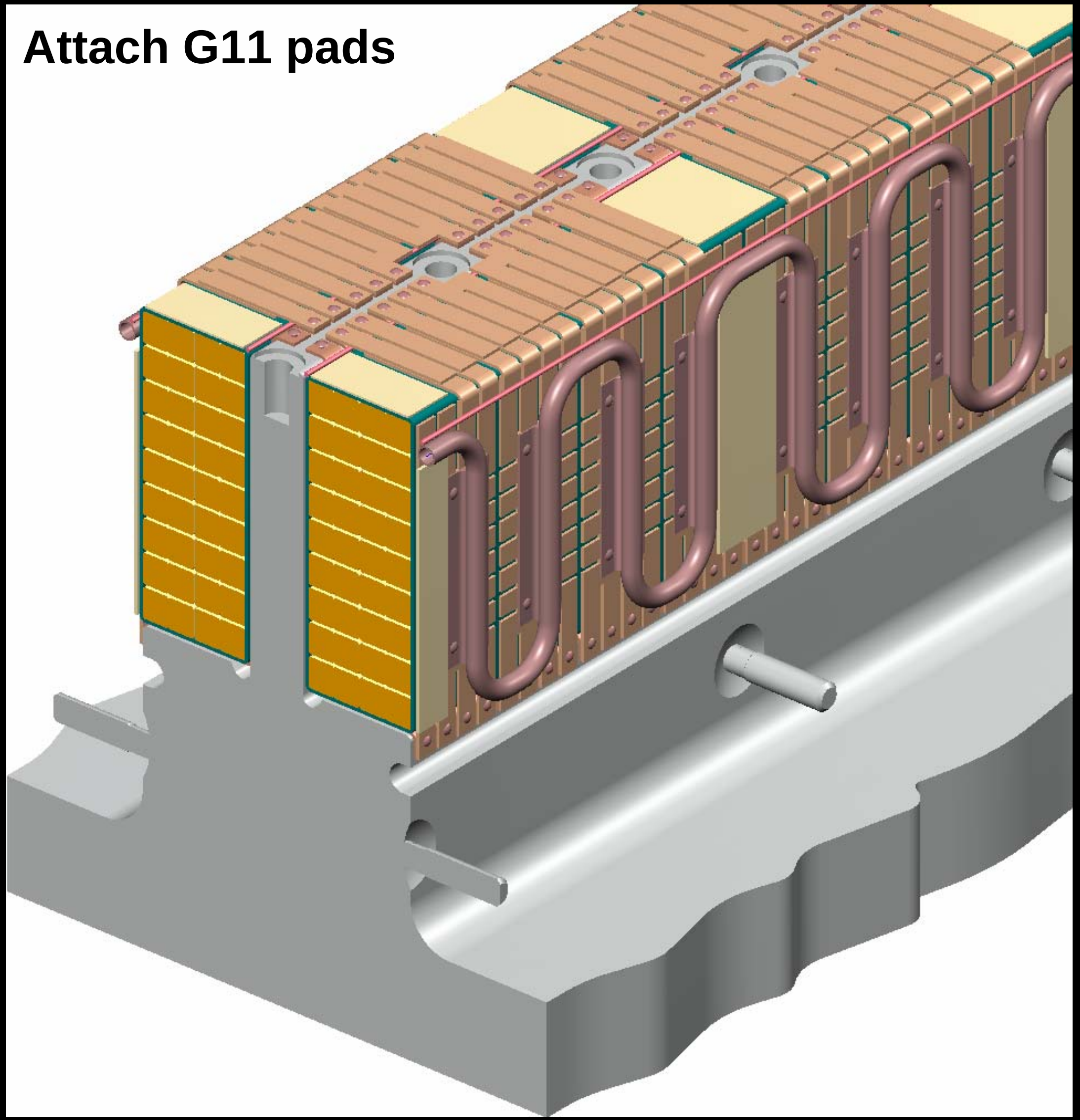


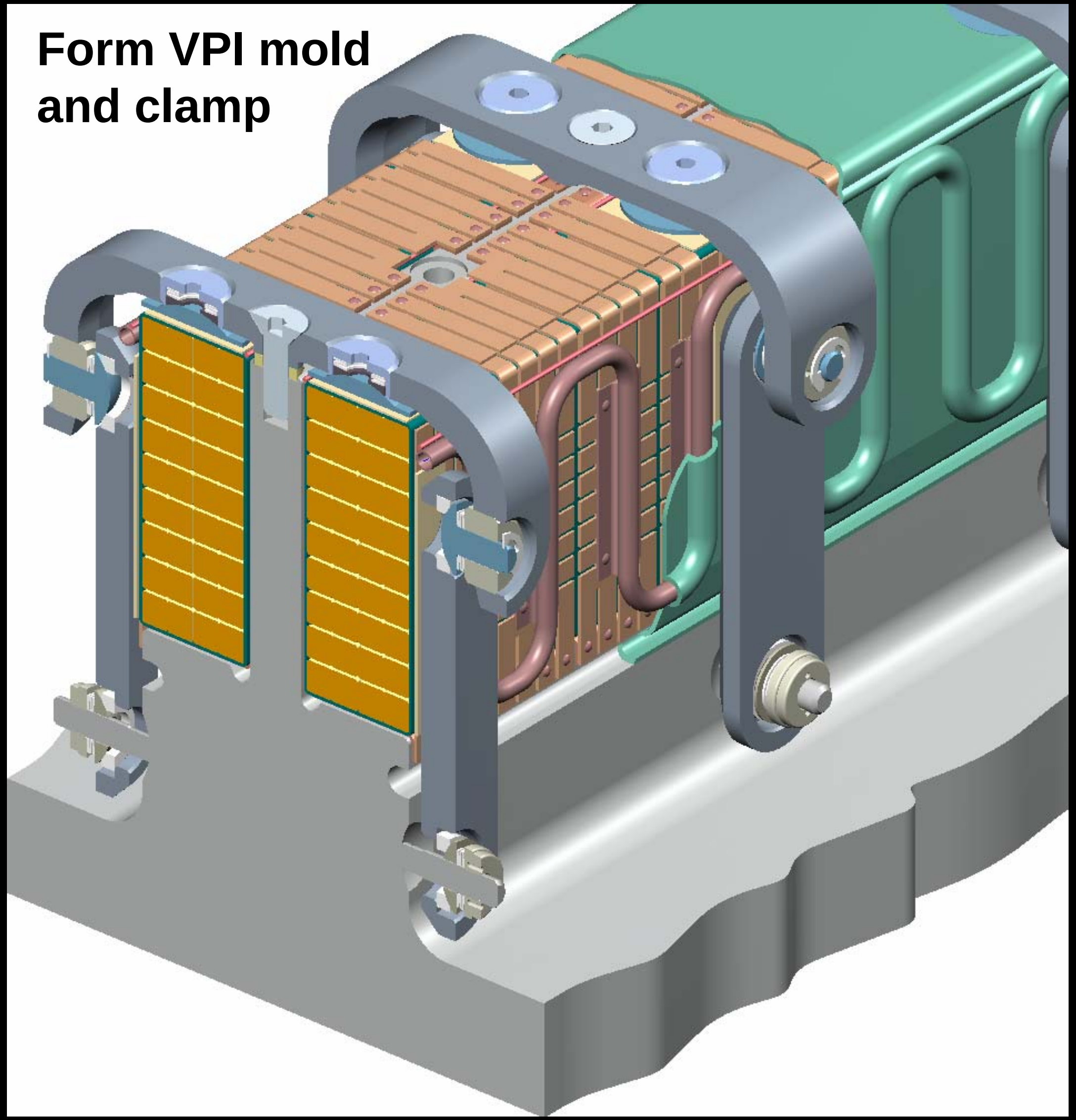
Winding Pack Assembly (cont'd)



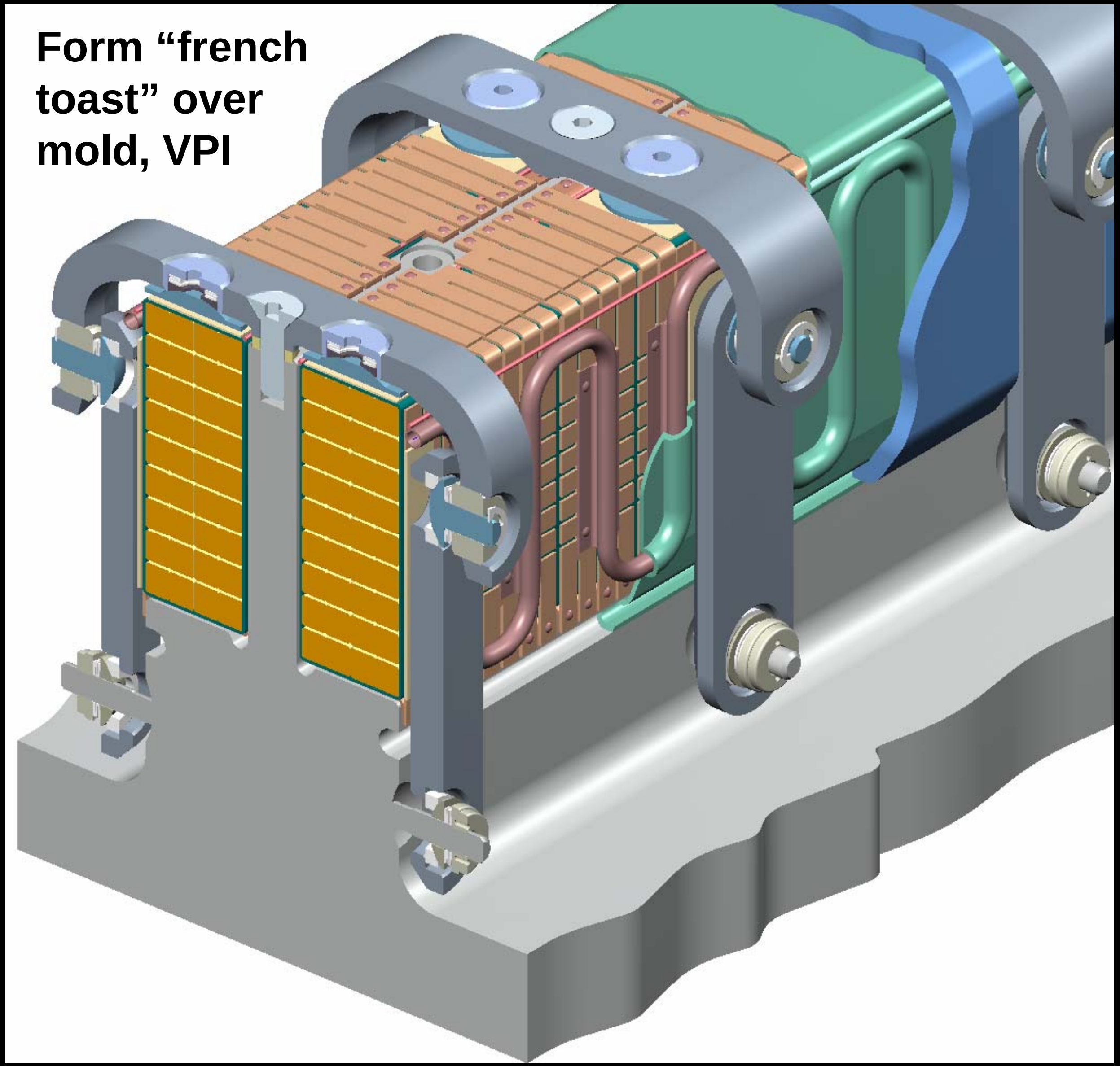


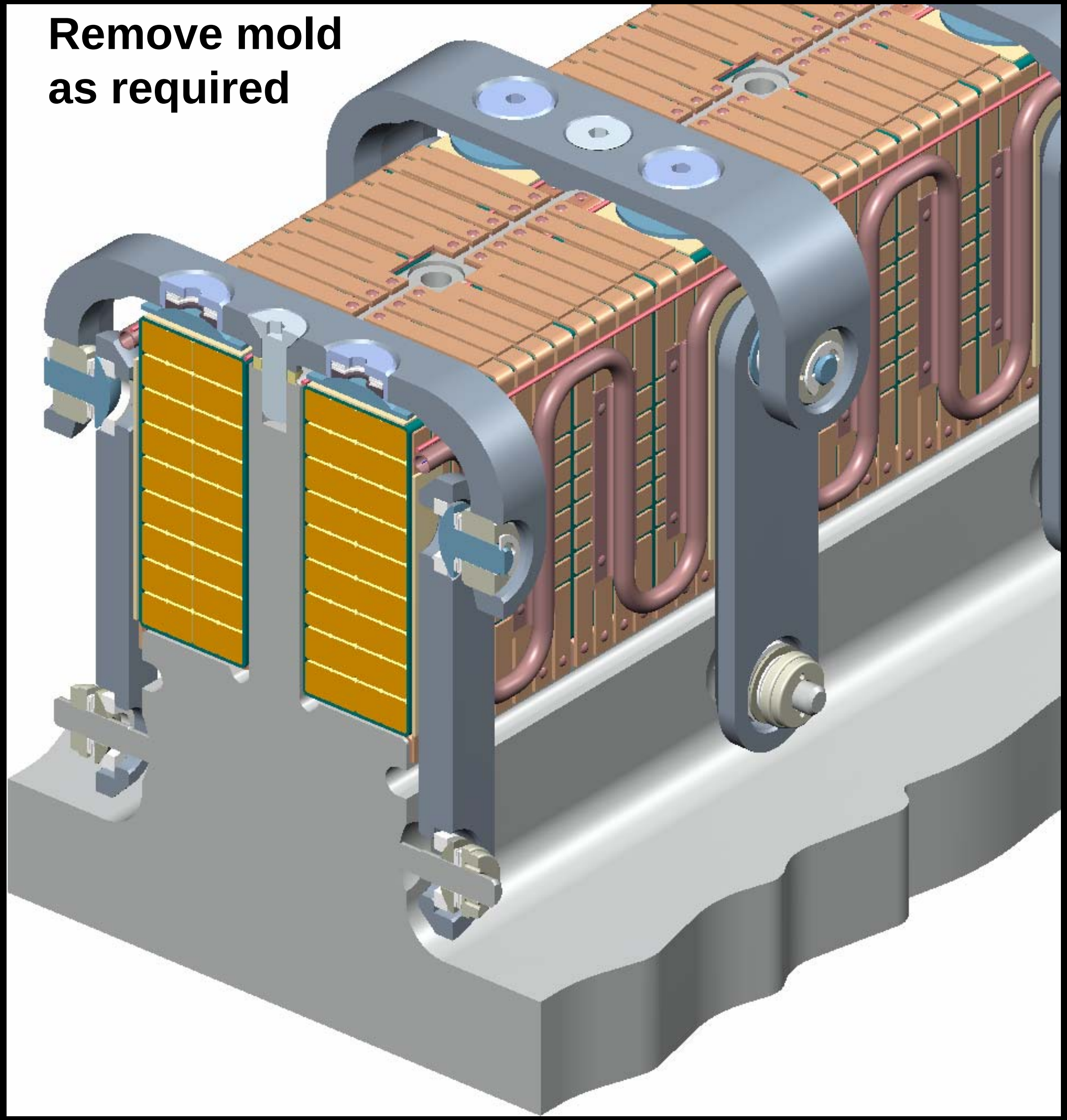
Winding Pack Assembly (cont'd)





Winding Pack Assembly (cont'd)



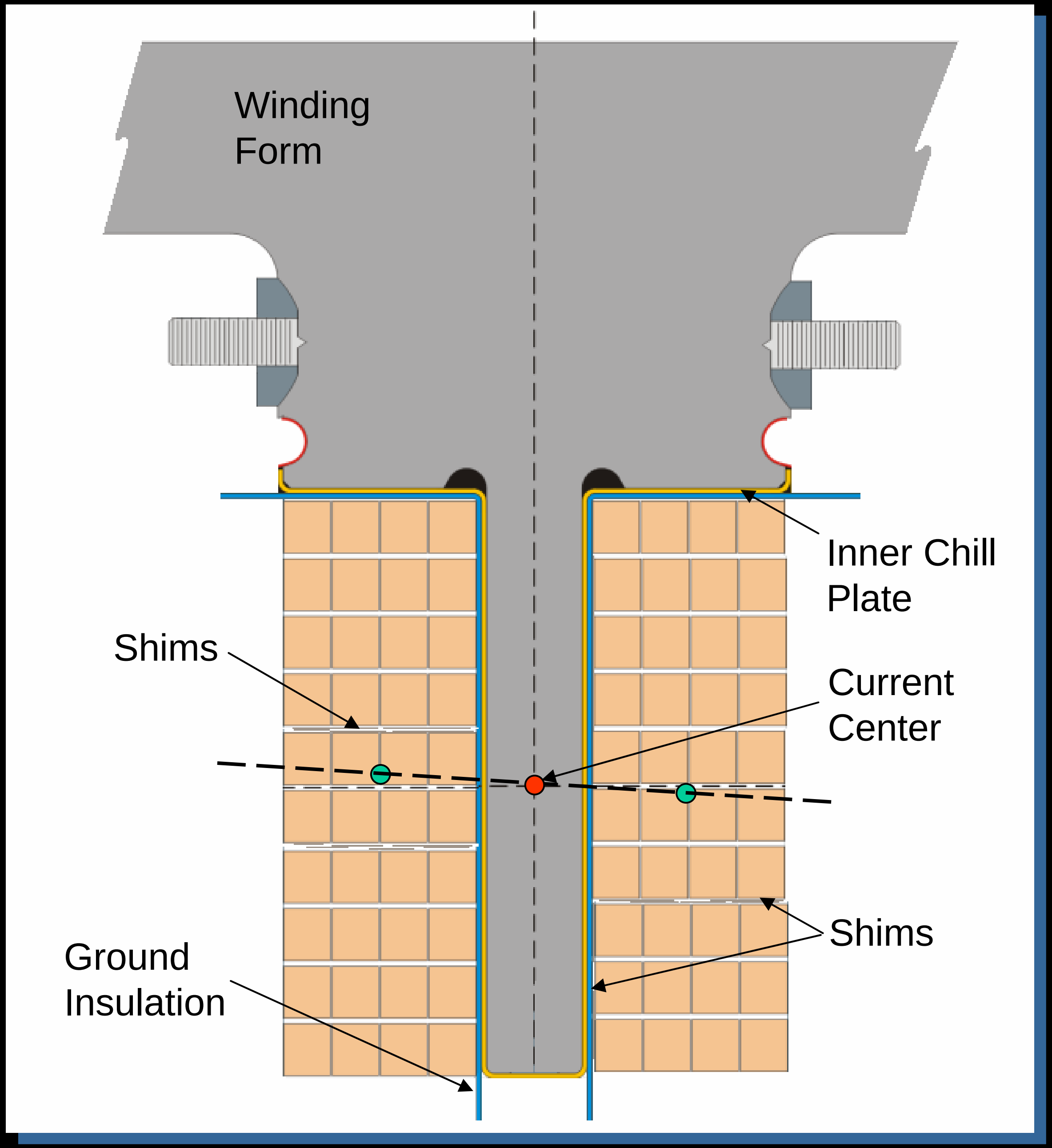


Winding Accuracy

- Winding position is continuously monitored and adjusted to avoid tolerance stack-up

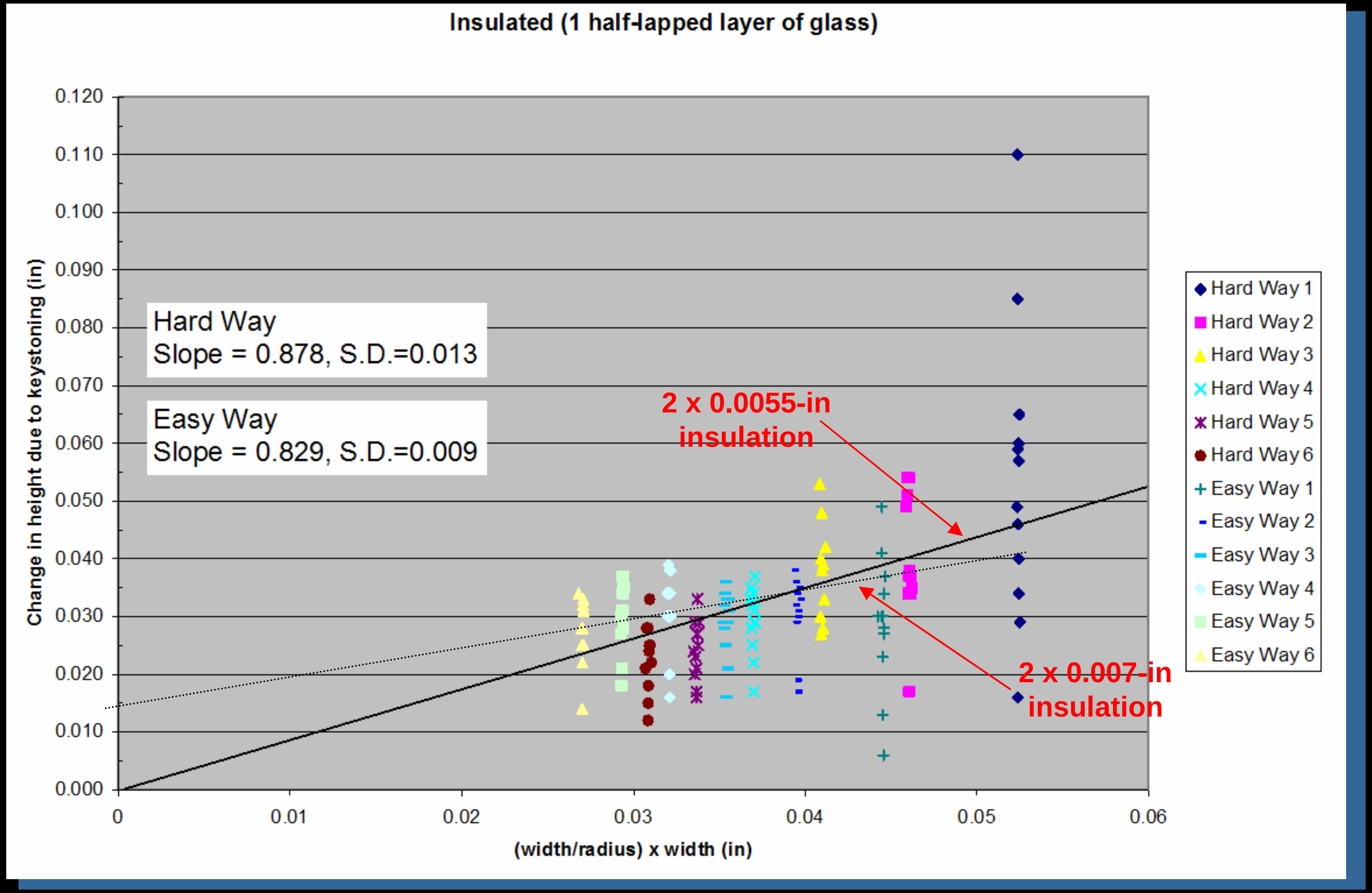
- Tolerance issues:
  - Machined surfaces of winding form are accurate to +/- 0.010-in (0.5-mm)
  - Conductor w/o insulation has a dimensional tolerance of +/- 0.010-in (0.5-mm)
  - Geometry requires up to 0.036-in (.91-mm) per layer allowance for conductor keystoning

- Current center can be adjusted by use of shims between layers



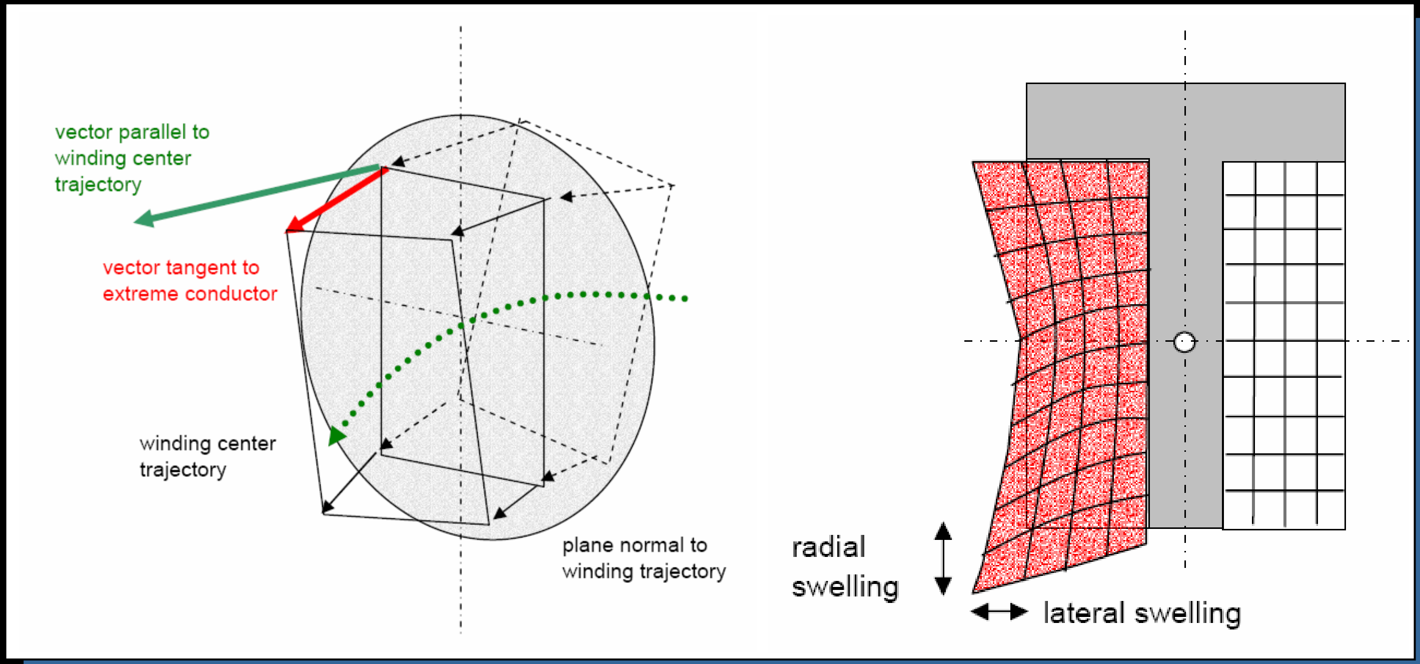
Allowance for Twist and Keystoning

- 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

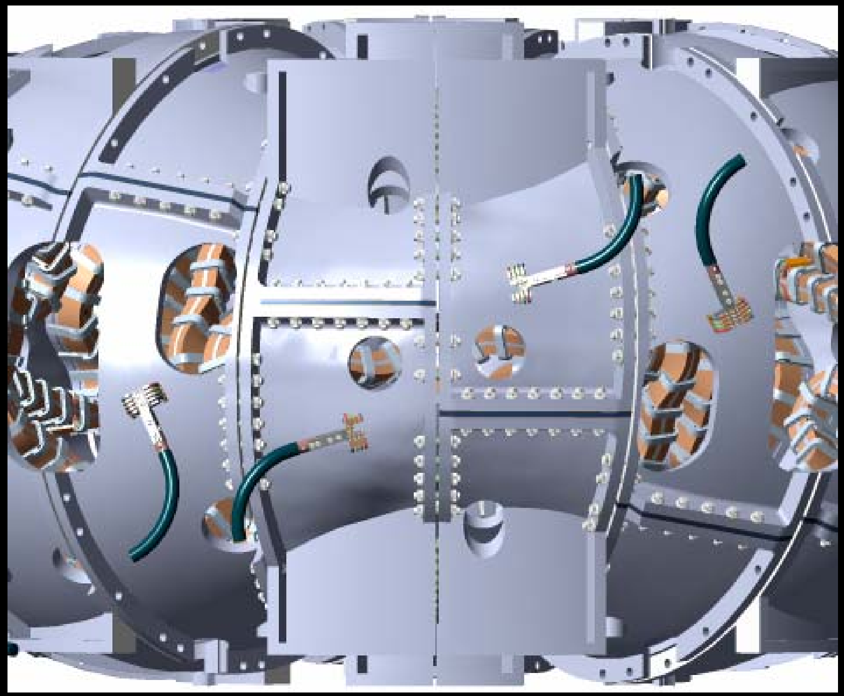
- Winding pack dimensions can be accommodated by radial shims, nominally 0.035-in thick
- Laterally, shims are not sufficient but swelling is symmetric and maintains current center
- Twisted racetrack winding R&D will confirm ability to compensate

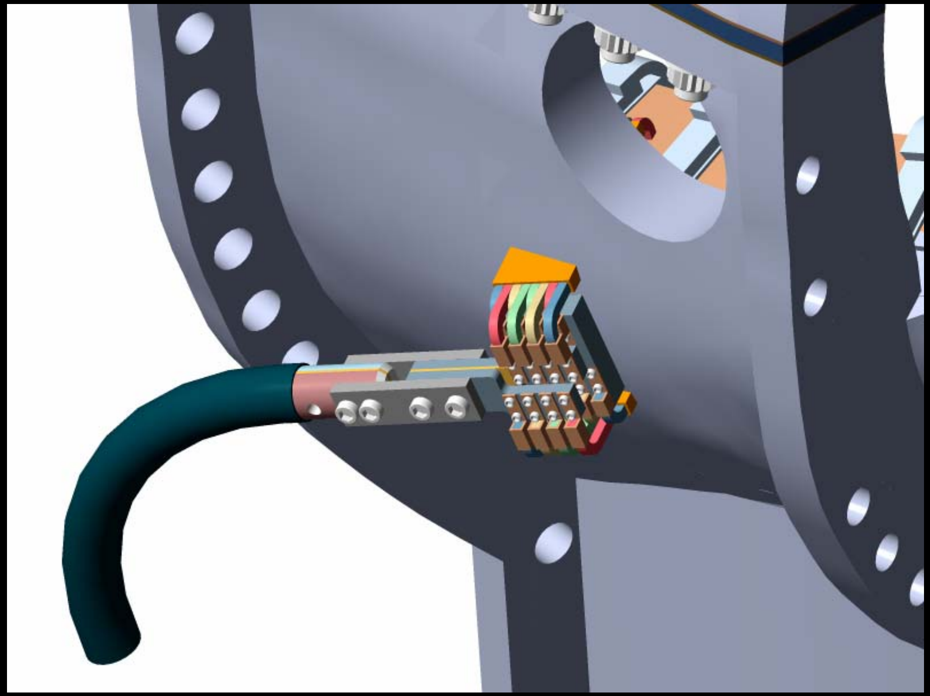


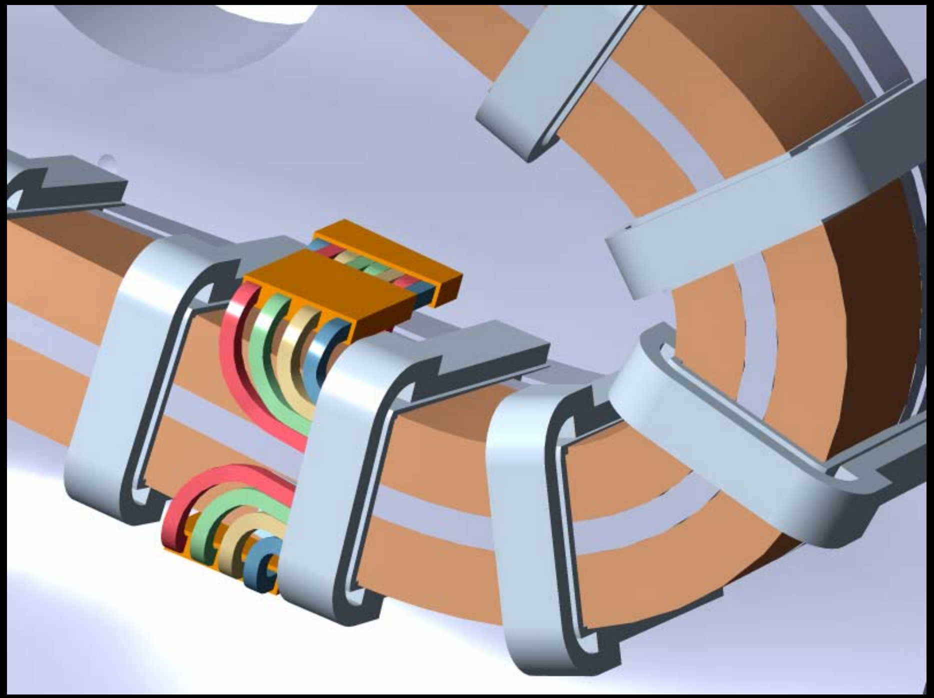
angle of conductor with plane (deg)	multiplier on conductor dimension	lateral "swelling" of winding pack (in)	radial (height) "swelling" of winding pack (in)
90	1	0.000	0.000
85	1.003819838	0.006	0.018
80	1.015426612	0.026	0.071
75	1.03527618	0.059	0.163
70	1.064177772	0.107	0.297
65	1.103377919	0.173	0.478
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

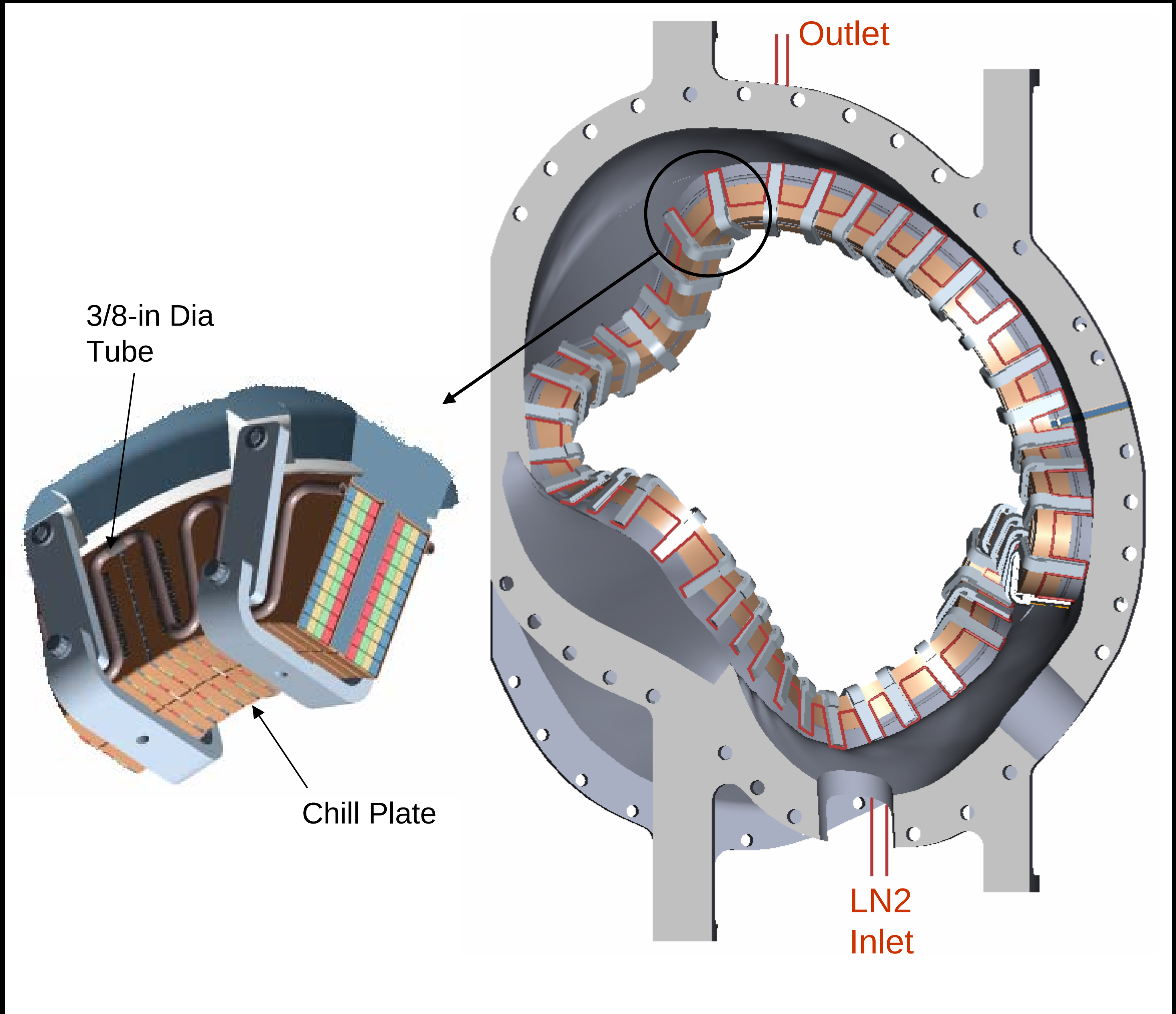

Up / Down Symmetry of Leads


Cable Connection at Shell Exterior


Plasma Side of Winding Pack

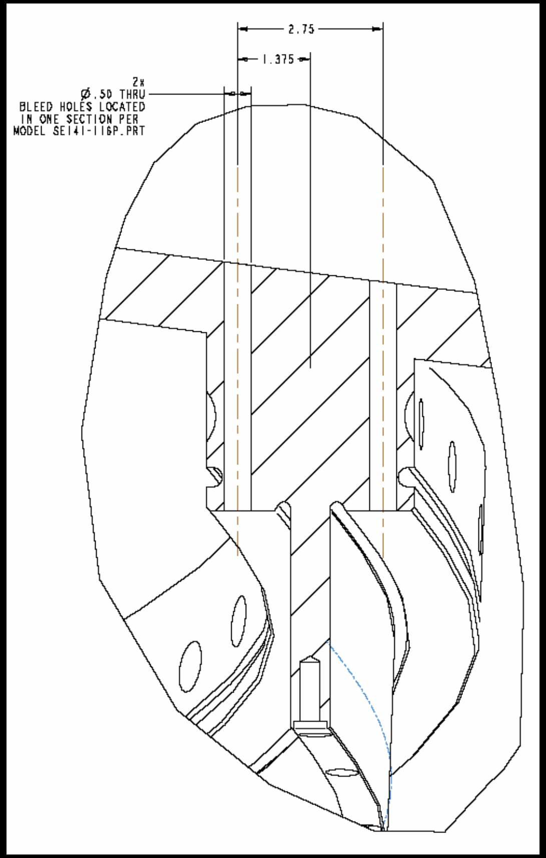
Coil Cooling

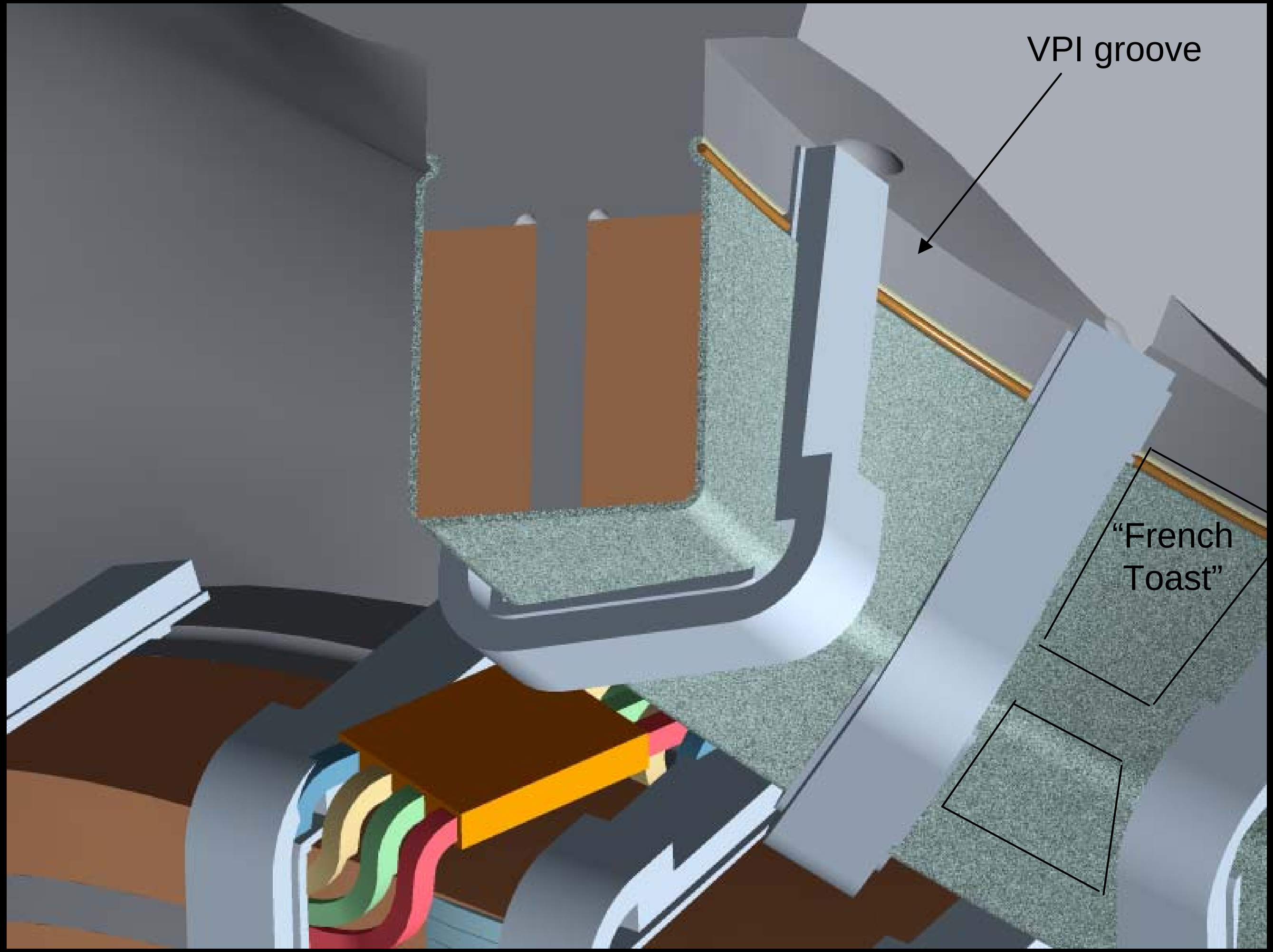
- **A thin chill plate is located on both sides of each winding pack to remove joule heating between plasma discharges**
- **Chill plate is cut in flat patterns from 0.040-in thick copper and formed around winding pack**
- **Chill plate is segmented and electrically isolated from winding form**
- **Outer 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 Bag Mold

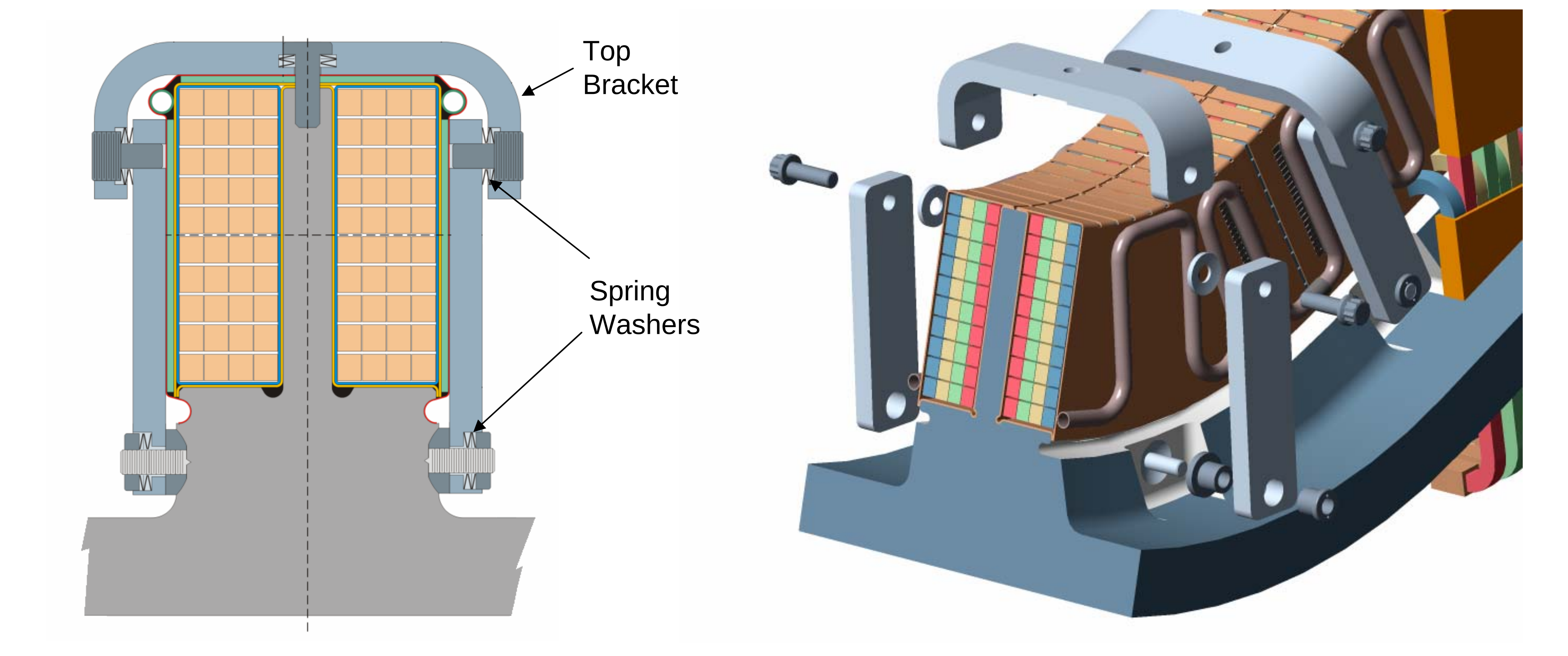
- VPI mold composed of epoxy impregnated felt and silicon rubber tape
- Located between winding pack and clamps, sealed by base groove
- Bleed holes at “top” position



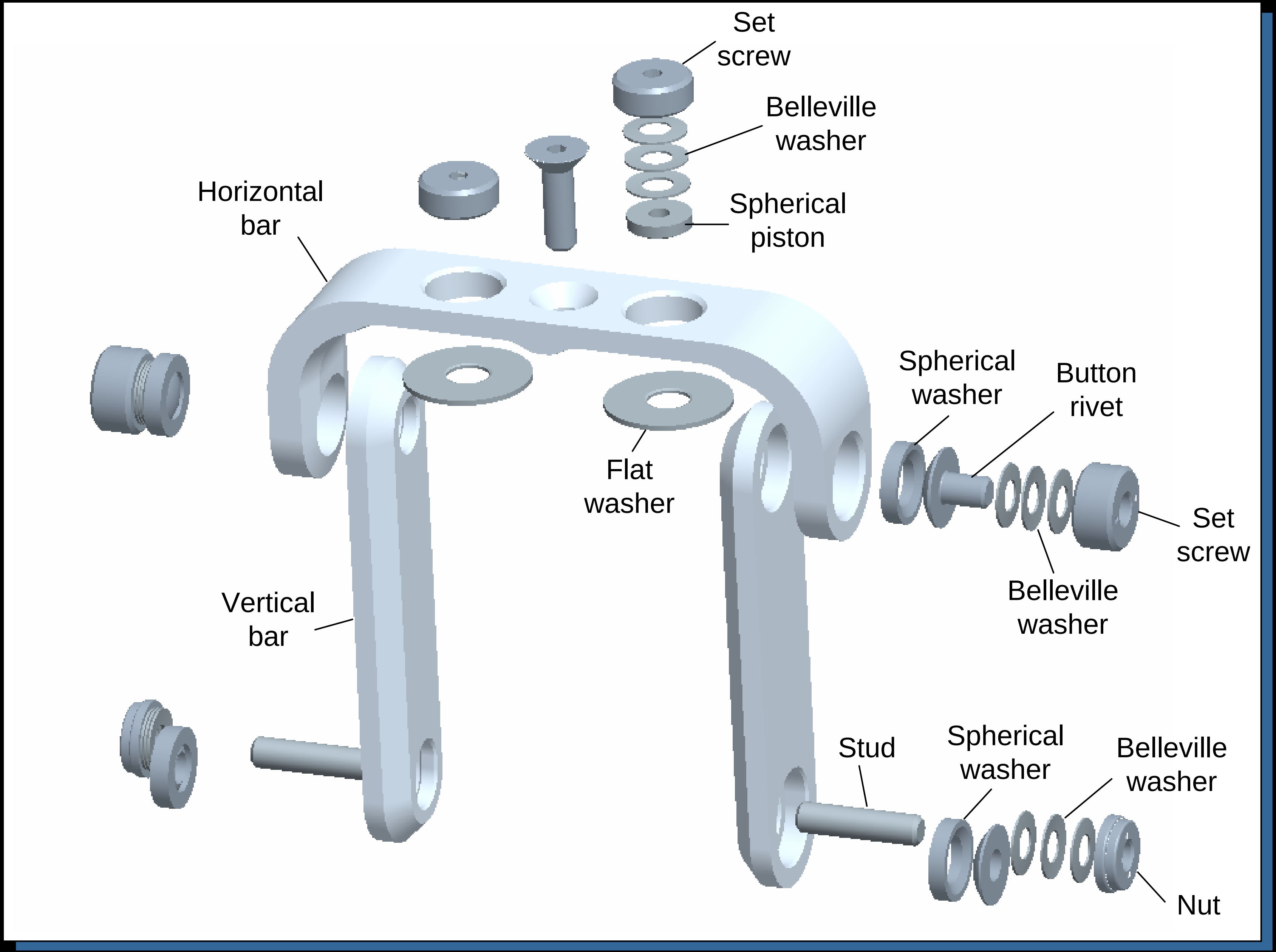


Winding Pack Clamps

- 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



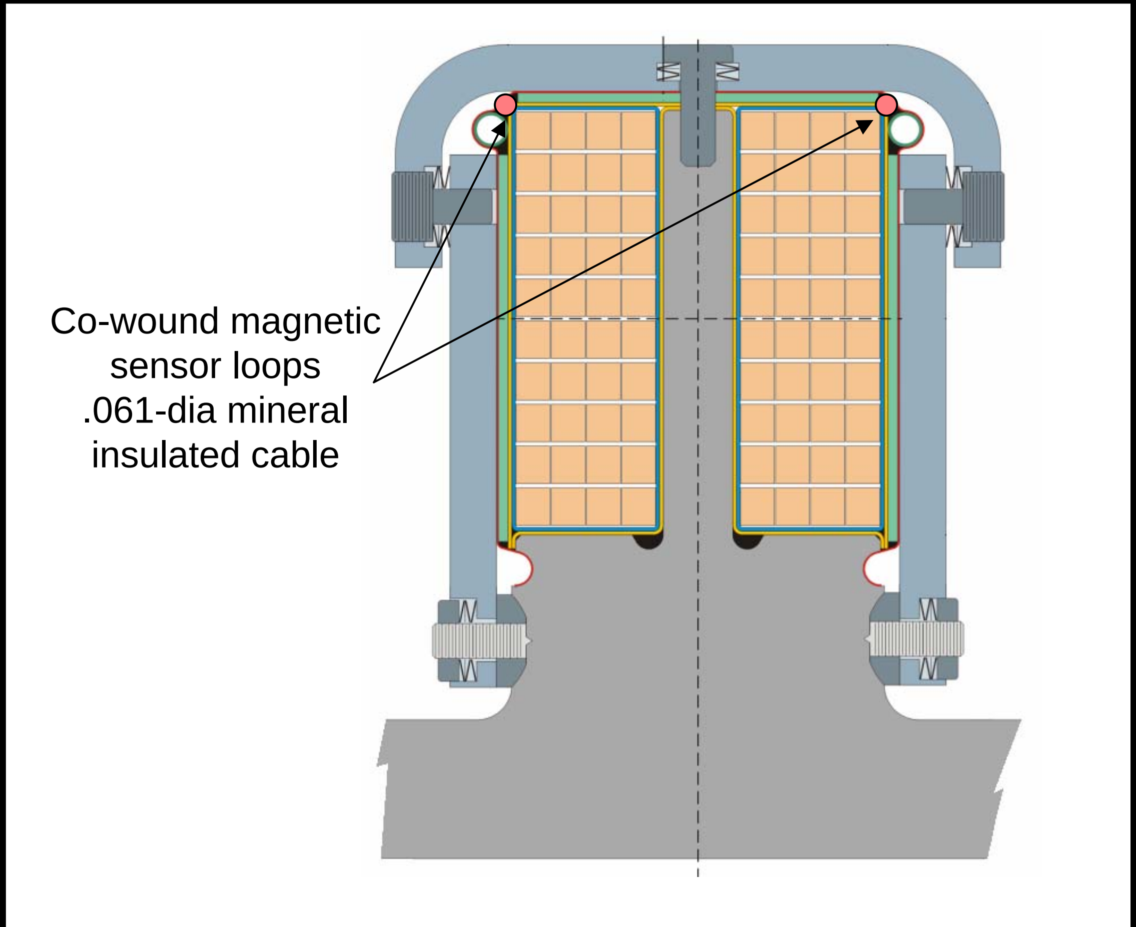
Clamp Exploded View



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

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



Coil Services

- 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

Design Evaluation

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

Design Approach

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

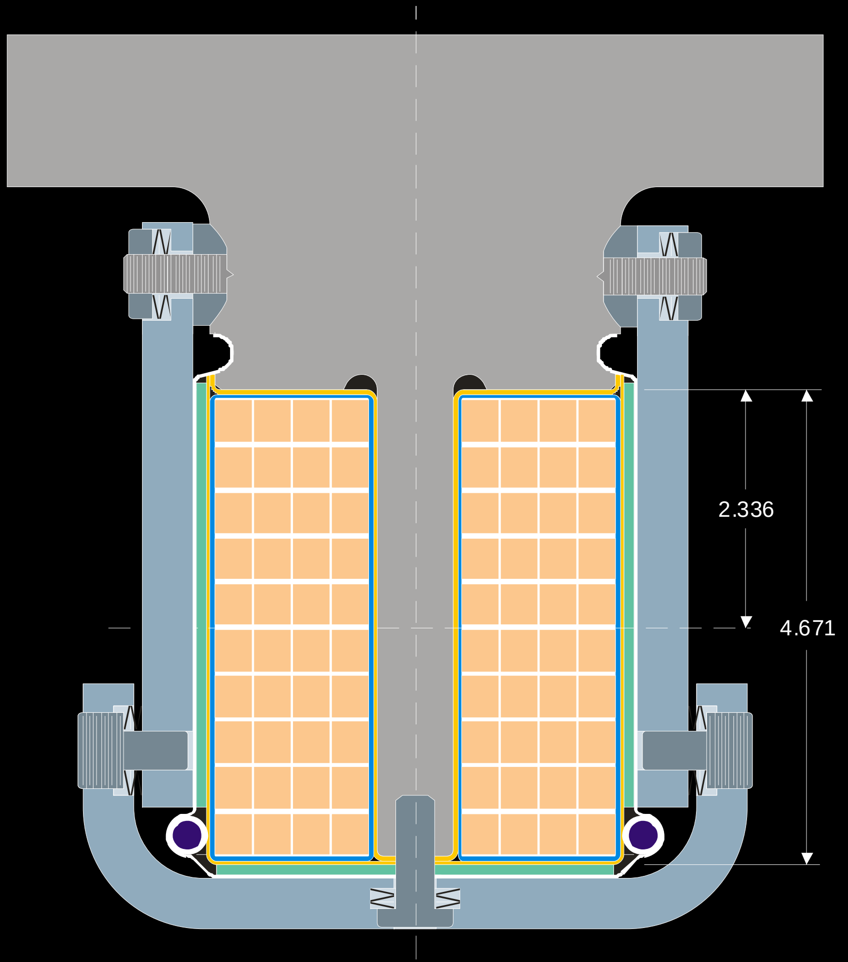
Structural analysis, however, has proved to be complicated due to complex geometry and lack of material property data

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

Issue	Approach	Resources
Normal EM loads	1) Perform 3D magnetostatic analysis of coil sets incl PF/TF/plasma	Fan - ANSYS
	2) Check by independent analysis	Williamson - MAGFOR
Fault Loads	1) Calculate load matrix based on min/zero/max current in each coil circuit	Williamson - MAGFOR
	2) Check worst-case loads by independent analysis	Fan - ANSYS
Winding Pack Behavior	1) Evaluate stress in conductor and insulation due to pulse	Myatt - ANSYS
	2) Check by correlation with tests and simplified modeling	
Clamp Behavoir	1) Evaluate deflection behavior and stress in detailed clamp model	Freudenberg - MECHANICA
	2) Check by correlation with tests and simplified modeling	
Deflection of Coil Assembly	1) Perform 3D global deflection analysis with detailed shell structure but simplified winding/clamp geometry. Evaluate gravity/EM/thermal/fault load conditions.	Fan - ANSYS
	2) Assume fixed winding form, evaluate deflection/stress in winding pack with non-linear contact to structure and more exact clamp behavior.	Freudenberg - MECHANICA
	3) Check to some level by independent analysis.	Myatt - ANSYS
Stress in Structure at Interfaces, Openings	1) As part of 3D global analysis, evaluate stress in bolts and at concentrations.	Fan - ANSYS
	2) Check by independent local analysis	Jun - ANSYS
Seismic Event	1) Part of stellarator core global dynamic analysis.	Titus - ANSYS
Error Field Analysis	1) Evaluate postulated fabrication errors and coil deflection under load to determine best position of coils at assembly.	Brooks, Strickler
Eddy Currents	1) Perform 3D analysis of assembly with electrical breaks, openings, etc	Brooks - SPARK
	2) Check by independent analysis	Strickler, Williamson - EDDYCUFF
Heating, Cool-Down between Pulses	1) Perform 2D/3D transient conduction analysis	Fan - ANSYS
Vessel Bakeout	1) Perform 2D/3D thermal analysis of cross-section in regions of small gap between vessel and coil	Freudenberg - ANSYS
	2) Check by independent analysis	

Coil Electrical Parameters

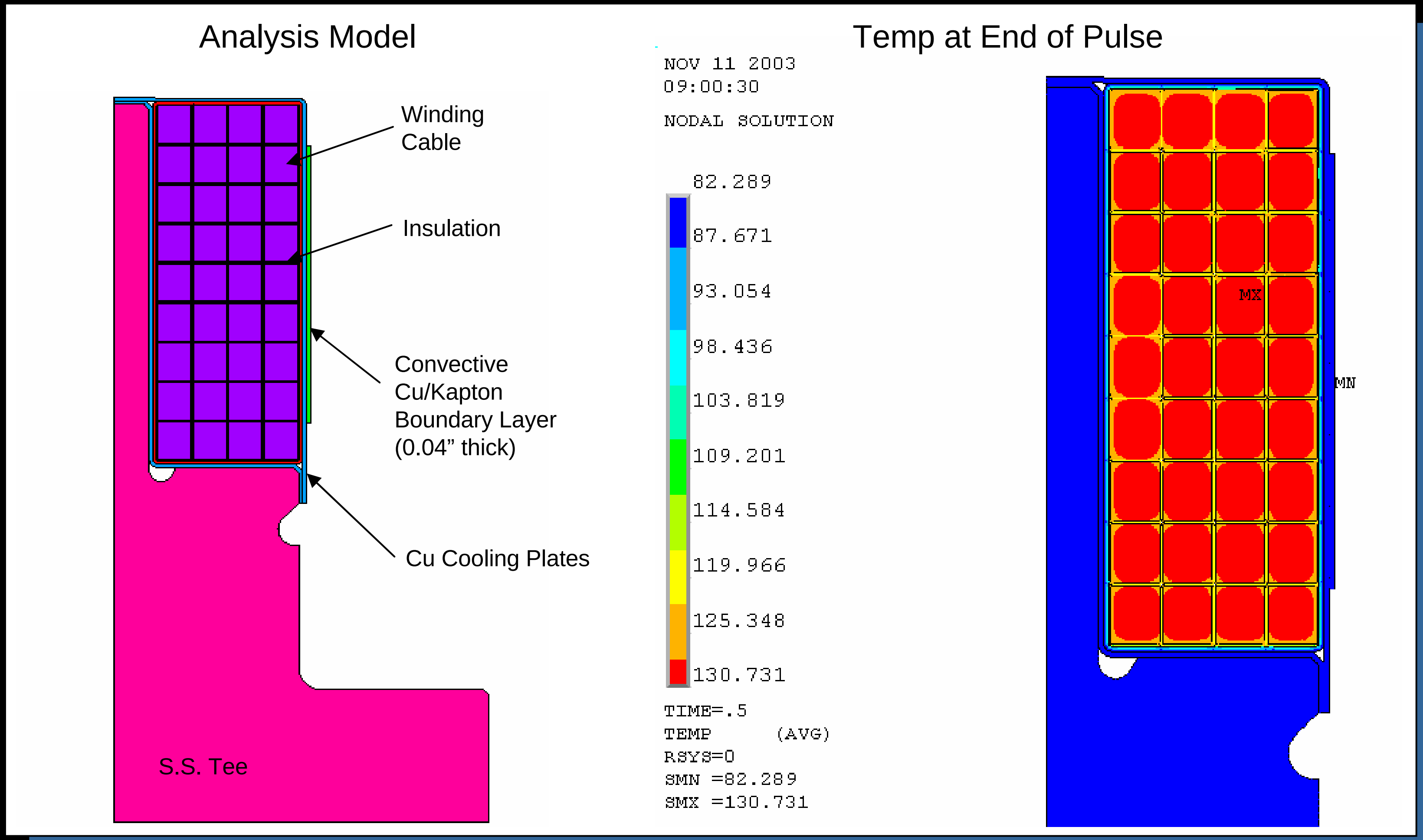
- khhhj



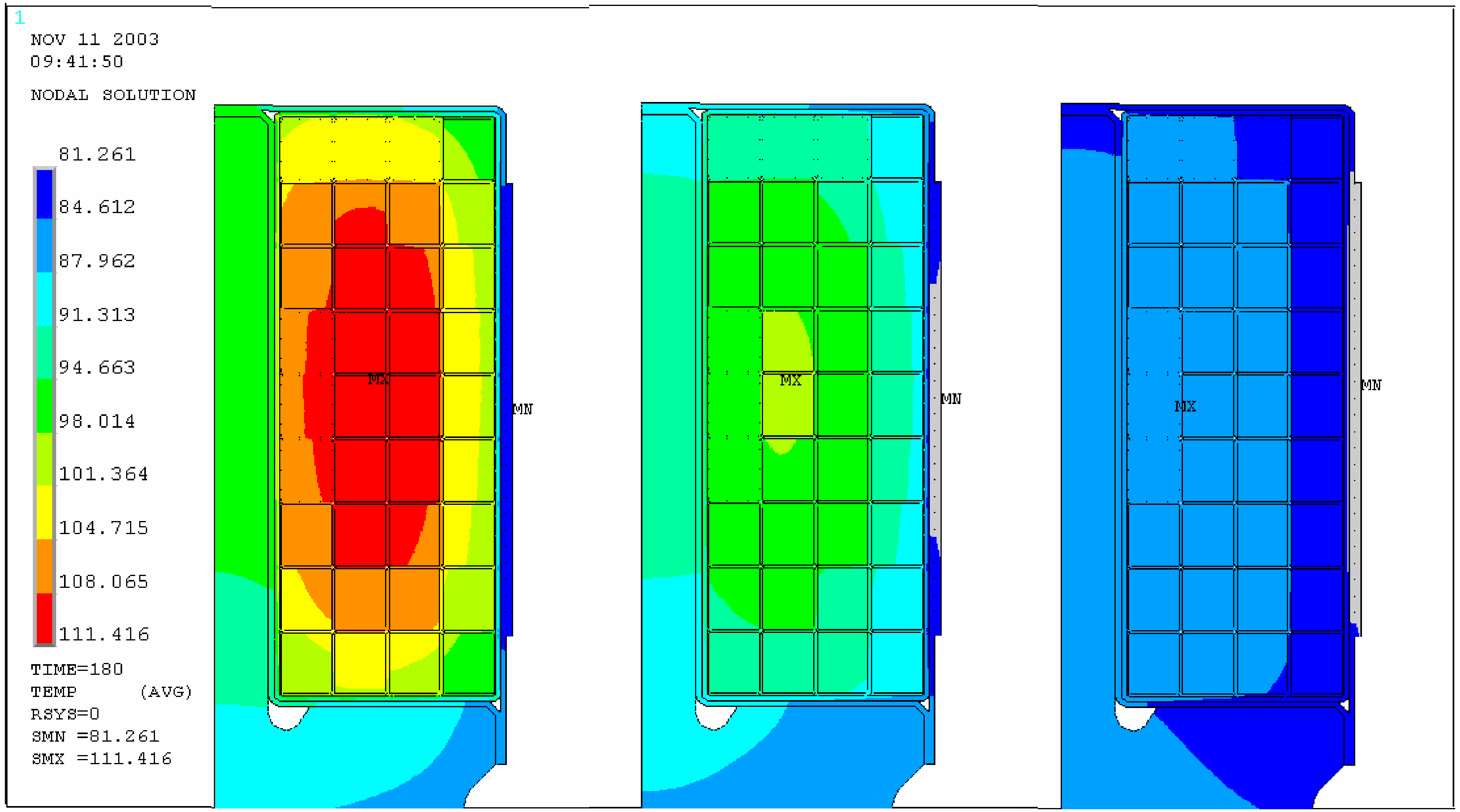
Calculated quantity		Flat Racetrack	Twisted Racetrack	Prototype (Coil type C)	Production Coil type A	Production Coil type B	Production Coil type C
Number of elec turns per winding pack		14	9	9	10	10	9
Number of electrical turns per coil		28	18	18	20	20	18
Number of physical turns per electrical turn		1	4	4	4	4	4
Conductor width, with serve	in	0.625	0.350	0.350	0.350	0.350	0.350
Conductor height, with serve	in	0.500	0.391	0.391	0.391	0.391	0.391
packing fraction		0.78	0.78	0.78	0.78	0.78	0.78
Winding resistance at RT	ohms	1.366E-02	7.201E-02	1.506E-02	1.848E-02	1.802E-02	1.506E-02
Winding resistance at 120K	ohms	1.772E-03	2.111E-02	5.136E-02	6.304E-02	6.146E-02	5.136E-02
Winding resistance at 80K	ohms	7.835E-04	1.081E-02	6.662E-03	8.177E-03	7.972E-03	6.662E-03
Inductance - windings only	Henries	6.63E-04	7.91E-03	7.90E-03	1.240E-02	9.230E-03	7.900E-03
Time constant - windings only, RT	seconds	4.85E-02	1.10E-01	5.25E-01	6.71E-01	5.12E-01	5.25E-01
Time constant - windings only, 120K	seconds	3.74E-01	3.75E-01	1.54E-01	1.97E-01	1.50E-01	1.54E-01
Time constant - windings only, 80K	seconds	8.46E-01	7.32E-01	1.19E+00	1.52E+00	1.16E+00	1.19E+00
Max operating current per elec turn	Amps	N/A	N/A	N/A	40908	41561	40598
Maximum test current	Amps						

Thermal Performance

- 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

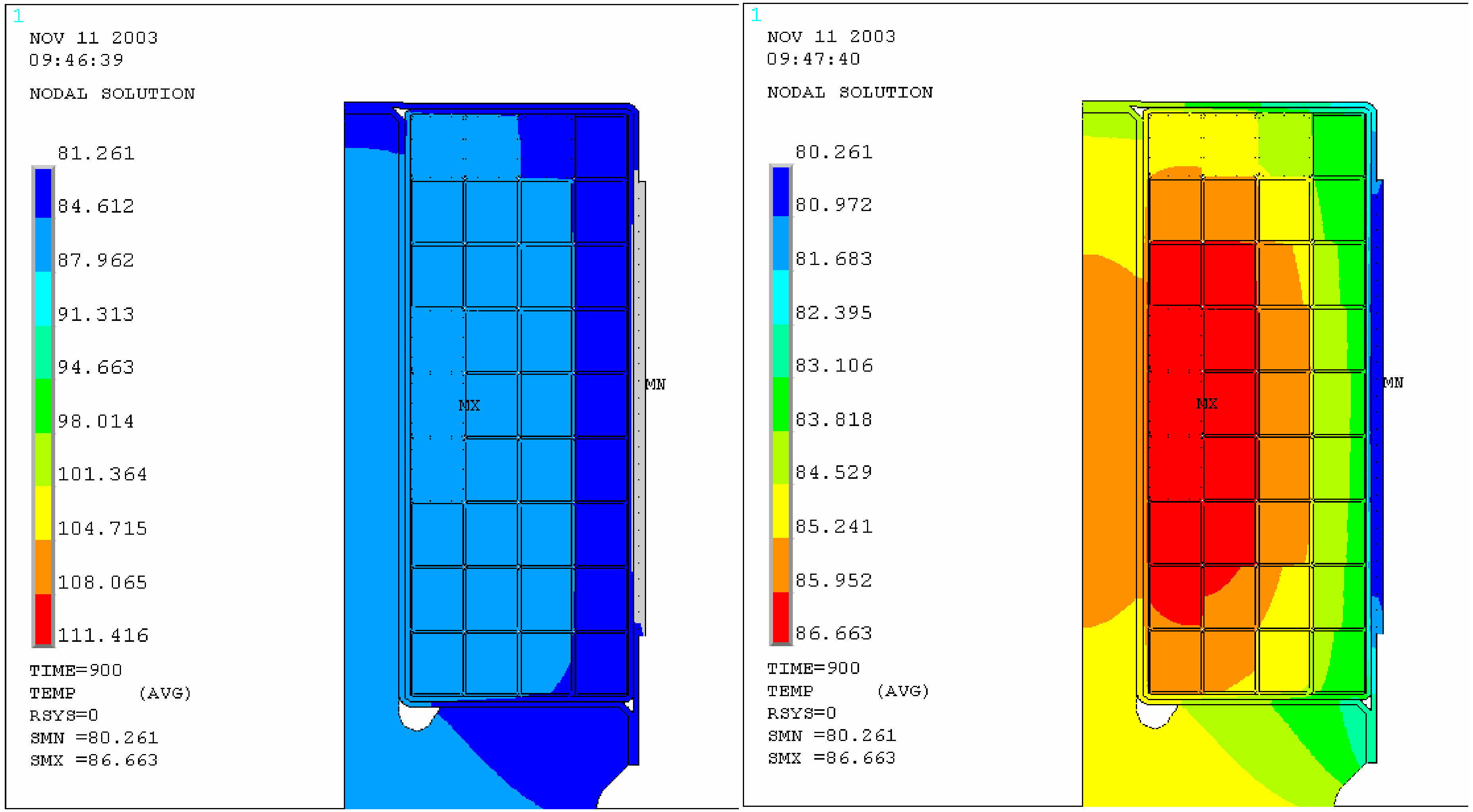


Temperature During Cooldown



3 minutes 7 minutes 15 minutes

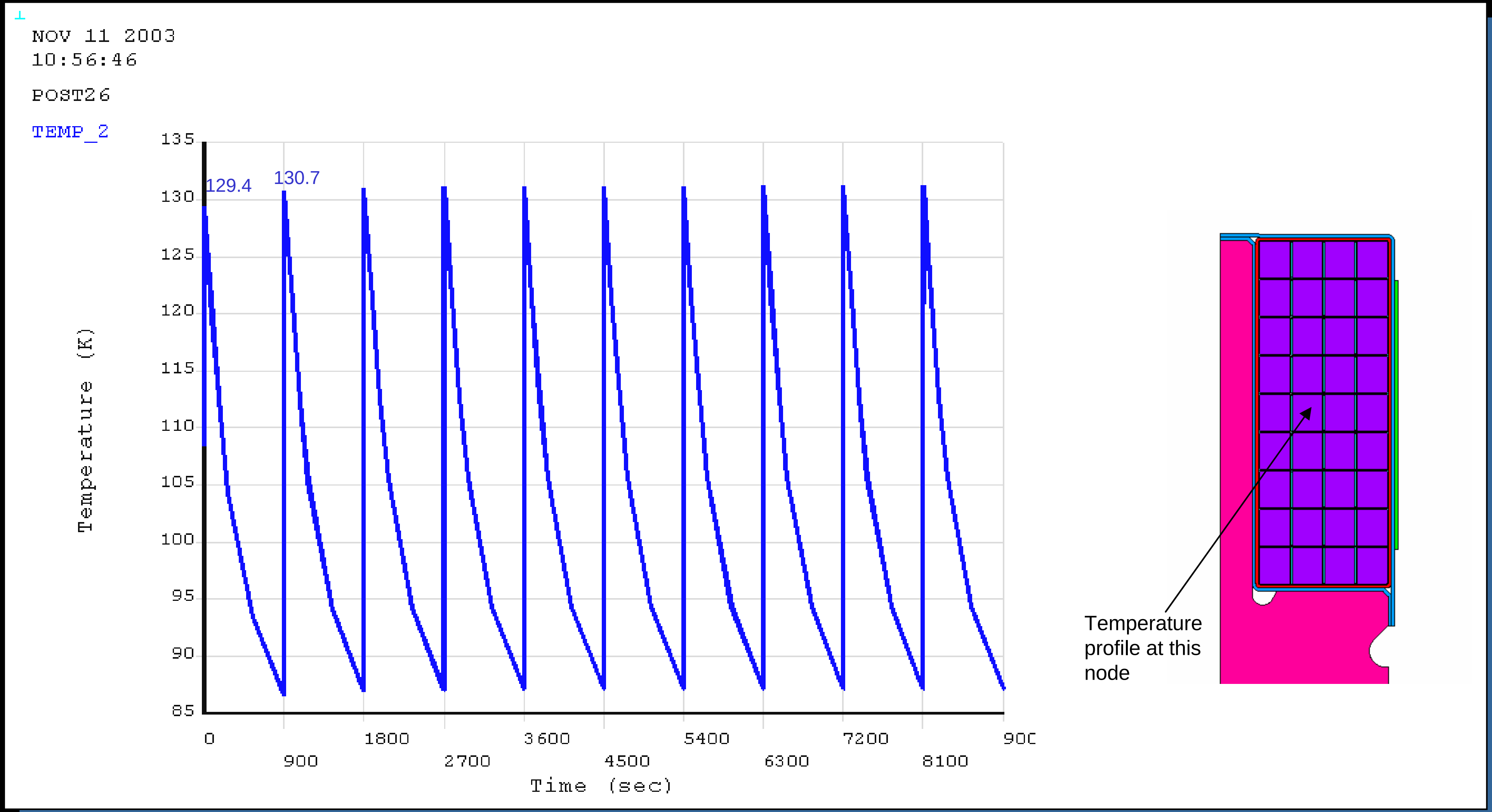
Temperature After 15-min



Same Scale as above cases at 15 mins

Automatic Scale at 15 mins

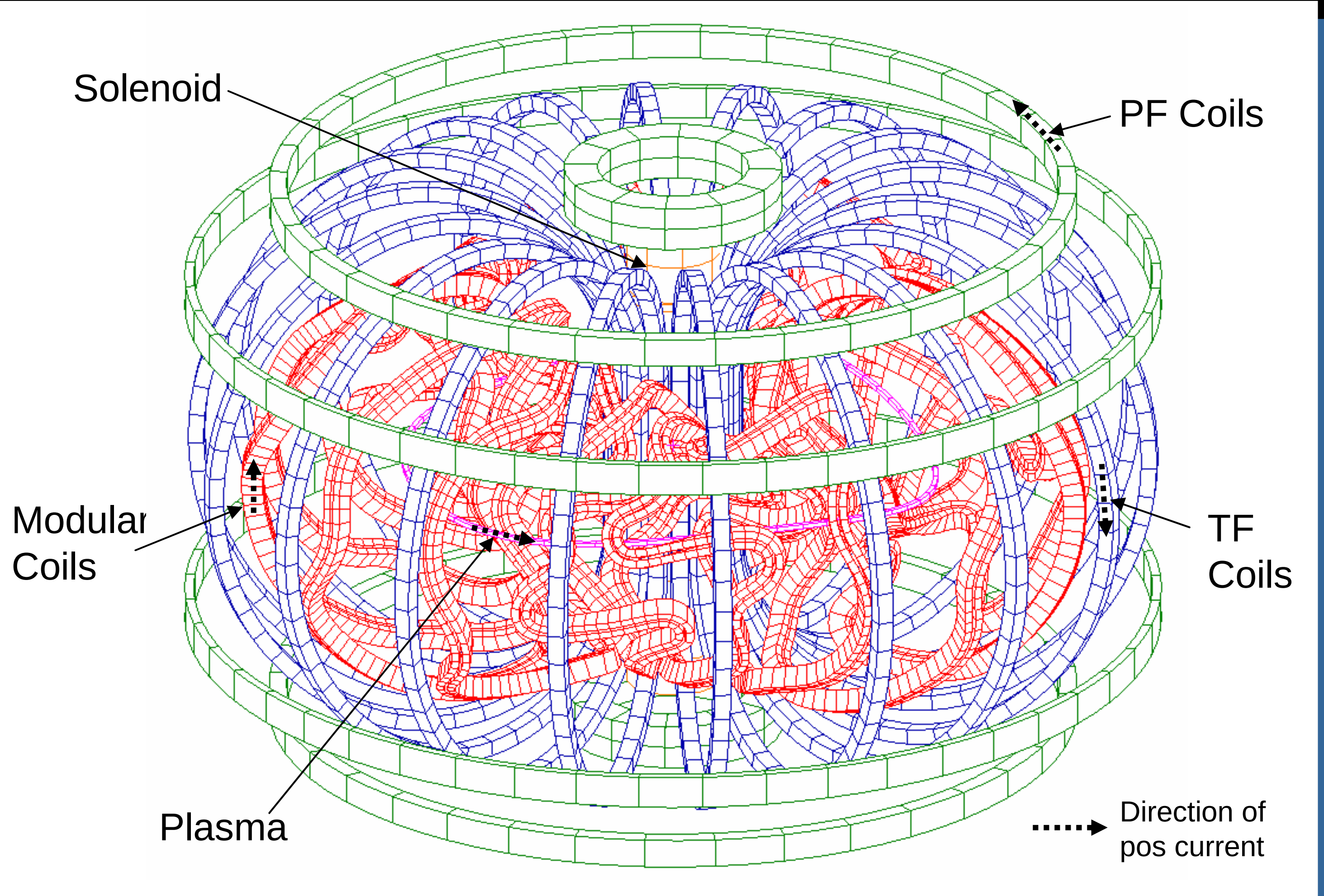
Temperature After 10 Cycles



Electromagnetic Loads Analysis

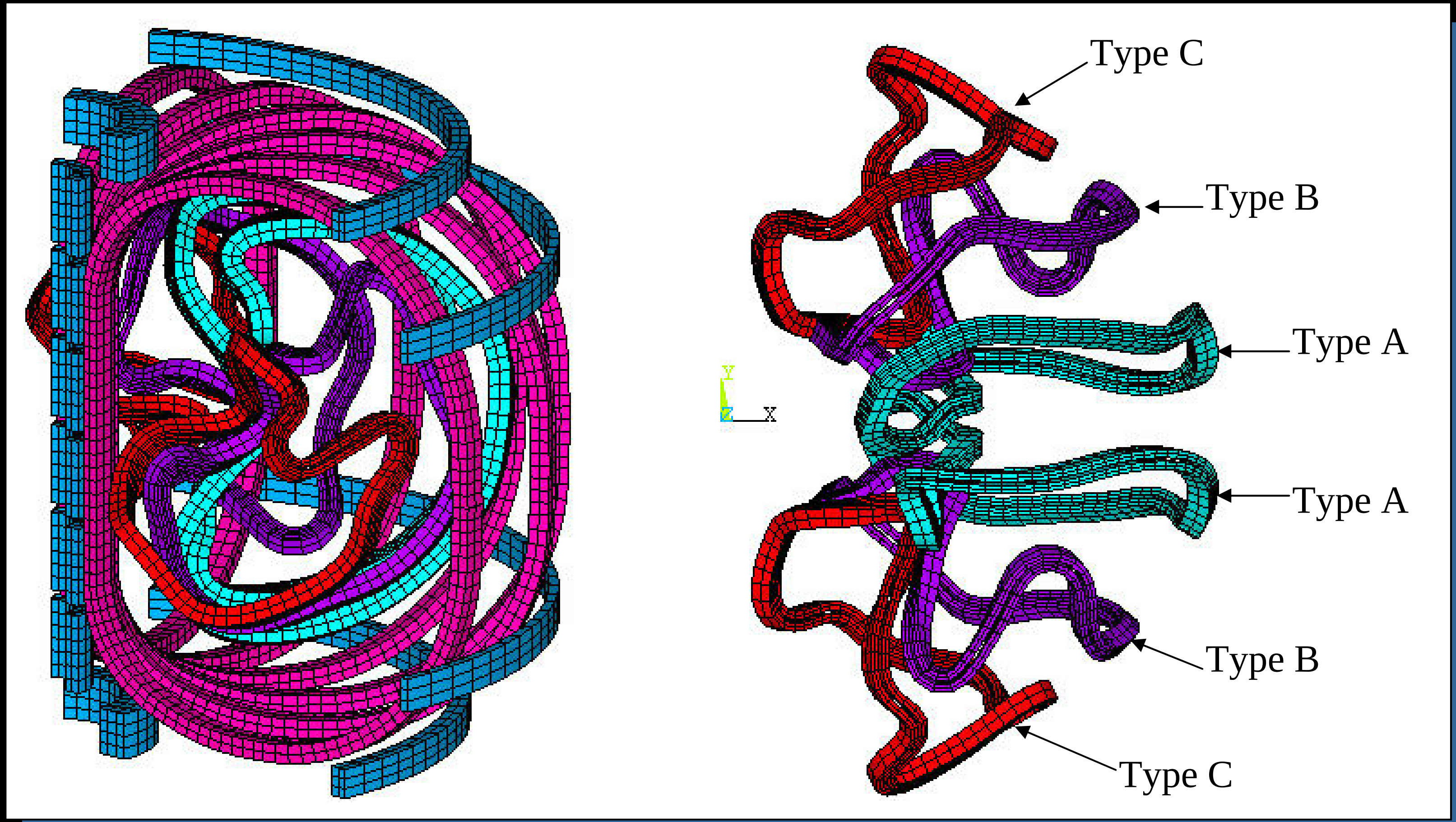
- Two independent calculations have been performed using ANSYS, MAGFOR codes
- Seven reference scenarios examined at time step with maximum modular coil current
- Scan of all possible coil currents for a more severe fault load condition is in progress

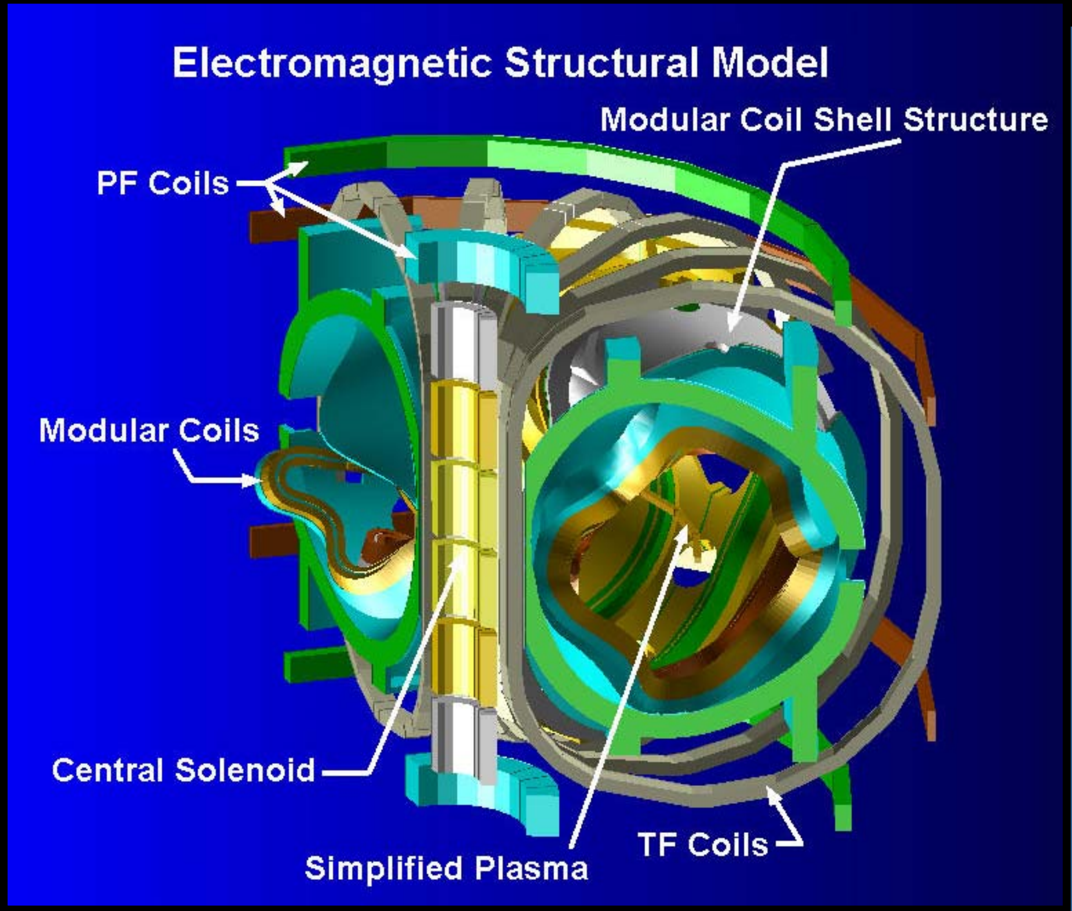
Maximum Current / Coil for Reference Scenarios (kA)								
Circuit	Coil Set	0.5-T 1st Plasma	Field Mapping	1.7-T Ohmic	1.7-T High Beta	2-T High Beta	1.2-T L. Pulse	320-kA Ohmic
1	TF	13	13	43	45	53	30	26
2	PF1	673	0	1479	1120	1340	1191	1632
	PF2	673	0	1479	1120	1340	1191	1632
3	PF3	673	0	1286	998	1208	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
	PLAS	35	0	120	178	210	126	321



MAGFOR Analysis Model

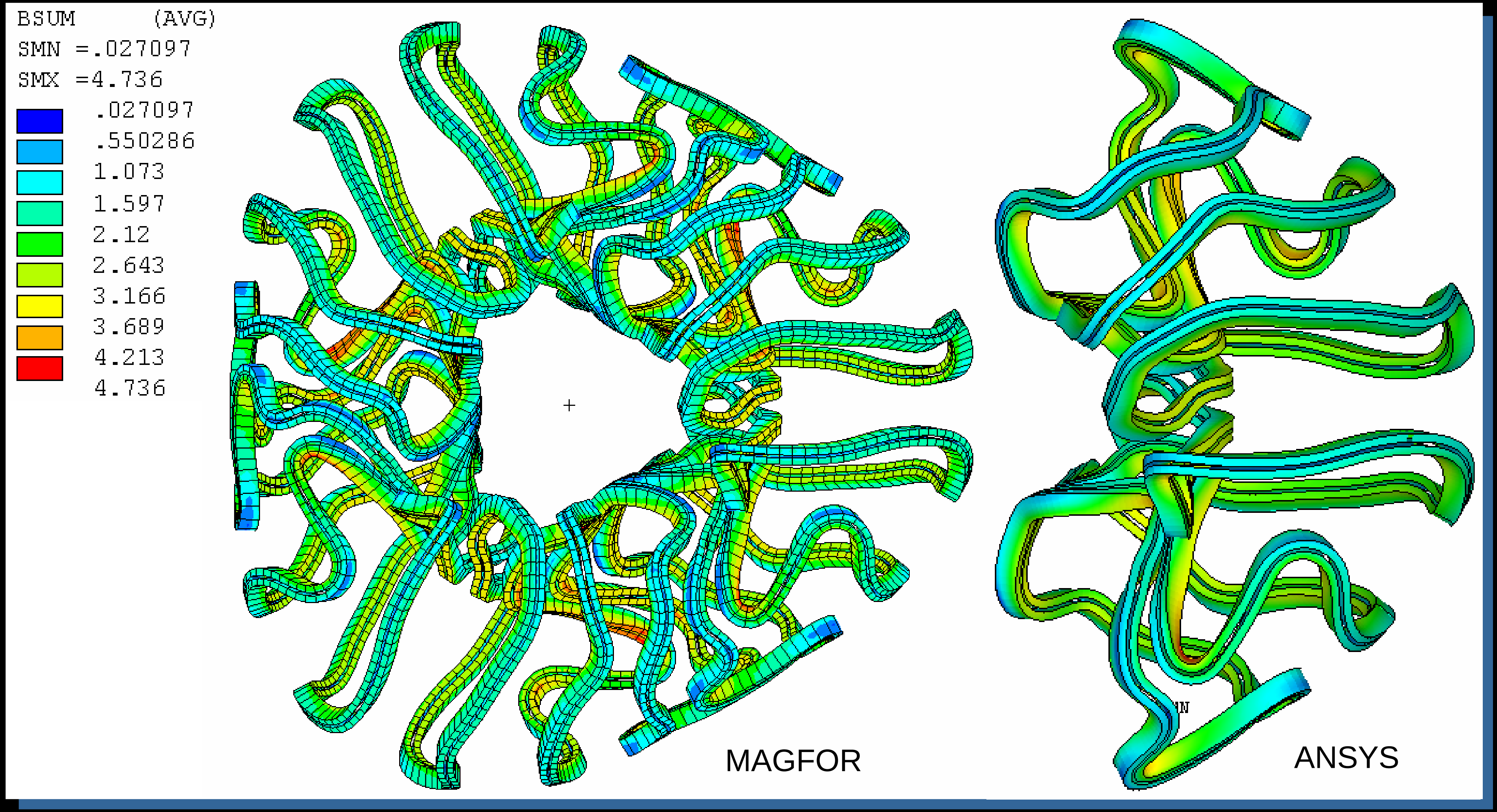
ANSYS EM Models





Magnetic Field Distribution

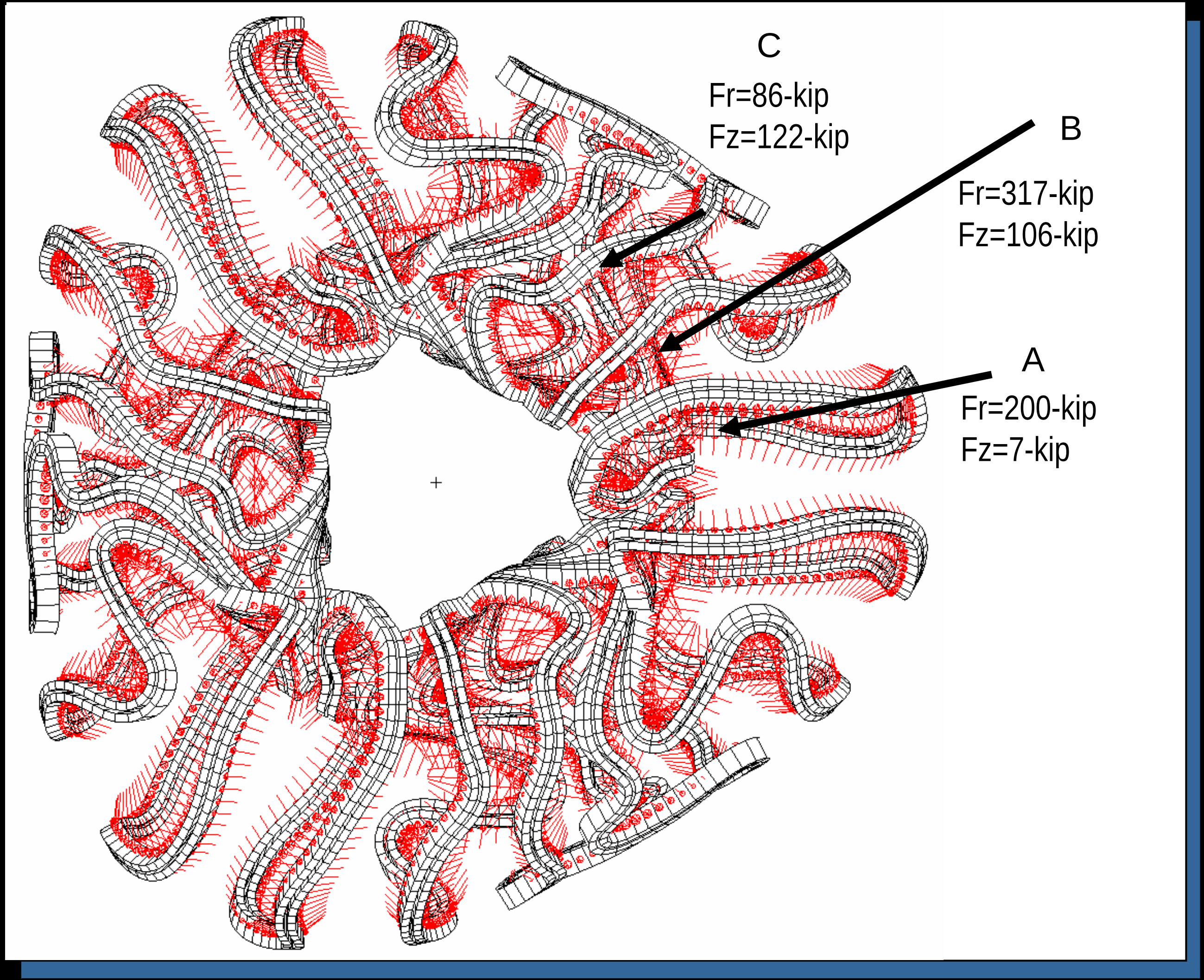
- Maximum magnetic flux density at windings is 4.7-T for 2-T reference scenario
- ANSYS, MAGFOR results differ by ~4% due to mesh and integration differences



Force Distribution

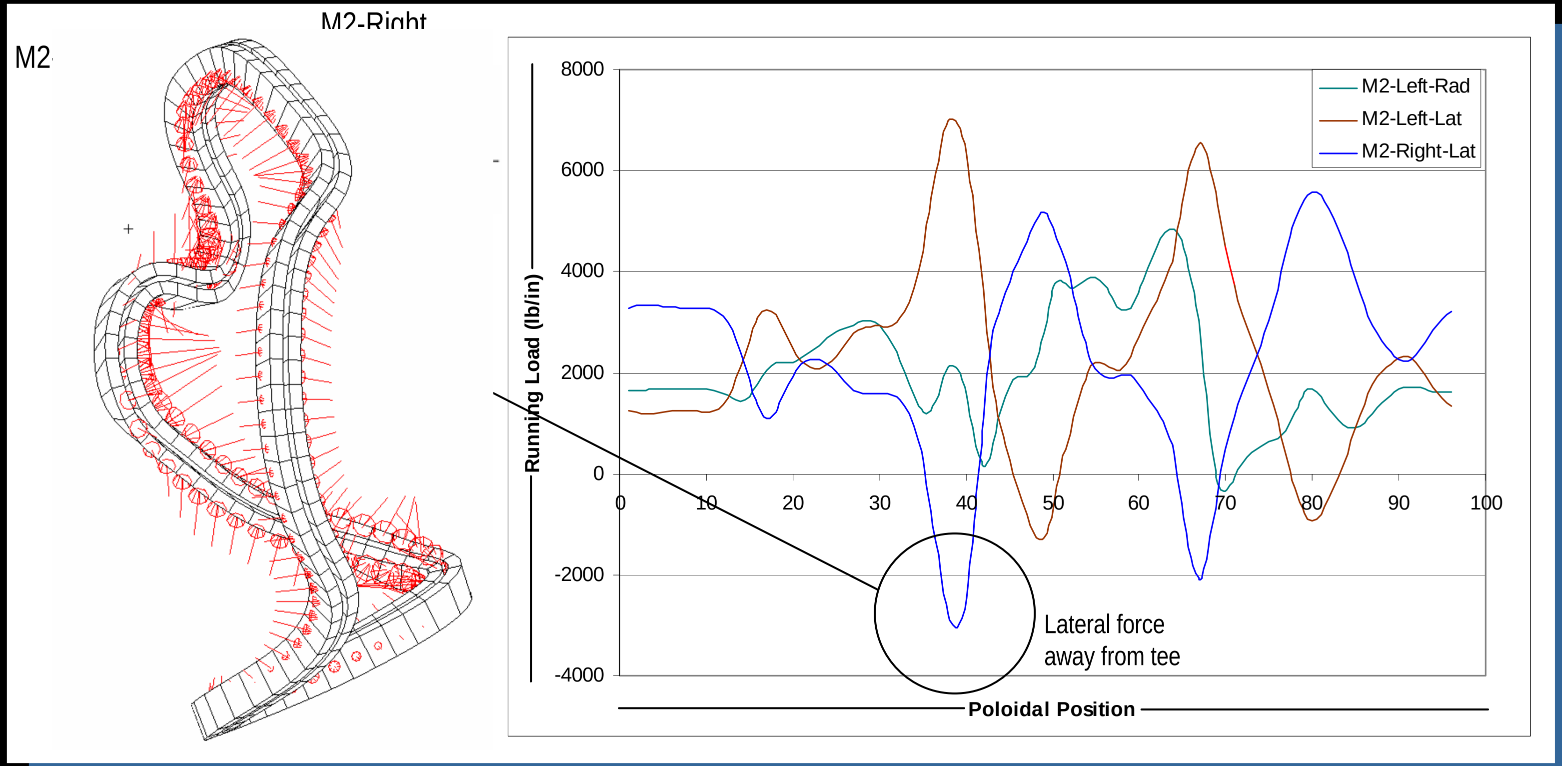
- Force distribution indicates large centering force up to 317-kip (1.4-MN) per coil
- Net vertical load up to 122-kip (.5-MN)

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
	Max Field at Coil (T)	1.2	0.2	4.2	4.2	4.9	2.9	4.2
M1	Net Radial Load (kip)	13	1	152	152	200	76	147
	Net Vert Load (kip)	0.5	0	9	9	7	5	7
M2	Net Radial Load (kip)	20	1	228	228	317	113	230
	Net Vert Load (kip)	7	0	84	84	106	42	79
M3	Net Radial Load (kip)	5	0	57	57	86	29	62
	Net Vert Load (kip)	8	0	95	95	122	47	89



Force Details

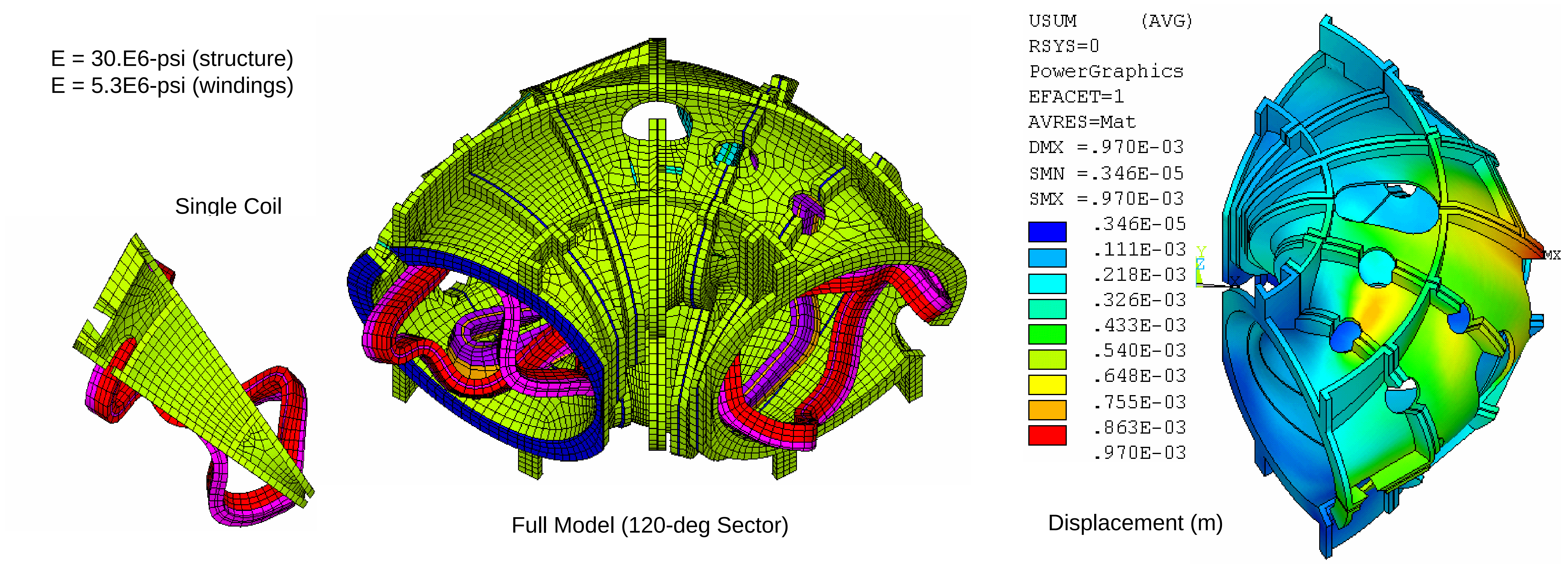
- Forces have been resolved into “radial” (away from plasma) and “lateral” (toward tee web) directions
- In general, radial load is toward structure and lateral load is countered by equal force in other wp
- Sharp bends can result in lateral force away from tee; reacted by clamps and beam behavior of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



Maximum Running Load on Modular Coils (lb/in)								
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

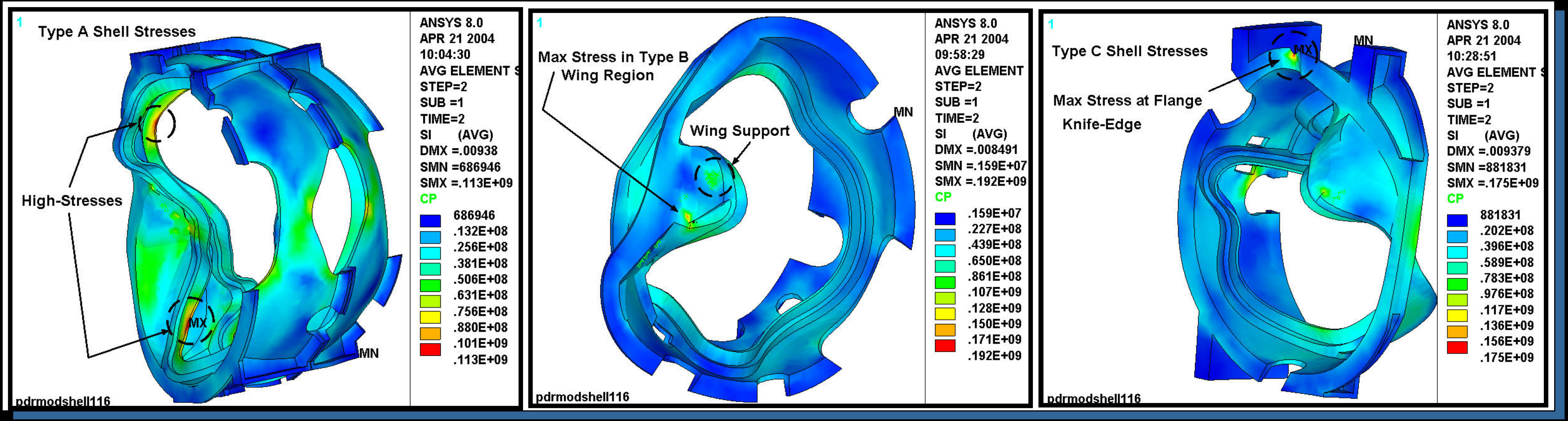
Global Deflection and Stress

- 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



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



Bolted Joints

- show analysis of poloidal break, coil-to-coil bolting

Winding Pack Analysis

- **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**

Models and Drawings

Table 3-3 - Production Winding Form Models and Drawings

Level	Next Assembly	Find #	Doc / Part #	Type	Rev	Title / Description
1	SE140-101	2	SE141-101	ASM	-	Modular Coil Type-A Winding Form Assembly
1	SE140-102	2	SE141-102	ASM	-	Modular Coil Type-B Winding Form Assembly
1	SE140-103	2	SE141-103	ASM	-	Modular Coil Type-C Winding Form Assembly
2	SE141-101	1	SE141-101_SKEL	PRT	-	Type-A Machining Features Layout
2	SE141-101	2	SE141-114	PRT	-	Type-A Winding Form, 316L SS
2	SE141-101	3	SE141-031	PRT	-	Type-A Poloidal Break Lower Insulator, G11CR
2	SE141-101	4	SE141-033	PRT	-	Type-A Poloidal Break Shim, 316L SS
2	SE141-101	5	SE141-035	PRT	-	Type-A Poloidal Break Upper Insulator, G11CR
2	SE141-102	1	SE141-102_SKEL	PRT	-	Type-B Machining Features Layout
2	SE141-102	2	SE141-115	PRT	-	Type-B Winding Form, 316L SS
2	SE141-102	3	SE141-051	PRT	-	Type-B Poloidal Break Lower Insulator, G11CR
2	SE141-102	4	SE141-053	PRT	-	Type-B Poloidal Break Shim, 316L SS
2	SE141-102	5	SE141-055	PRT	-	Type-B Poloidal Break Upper Insulator, G11CR
2	SE141-103	1	SE141-103_SKEL	PRT	-	Type-C Machining Features Layout
2	SE141-103	2	SE141-116	PRT	-	Type-C Winding Form, 316L SS
2	SE141-103	3	SE141-071	PRT	-	Type-C Poloidal Break Lower Insulator, G11CR
2	SE141-103	4	SE141-073	PRT	-	Type-C Poloidal Break Shim, 316L SS
2	SE141-103	5	SE141-075	PRT	-	Type-C Poloidal Break Upper Insulator, G11CR

Type-A Assembly

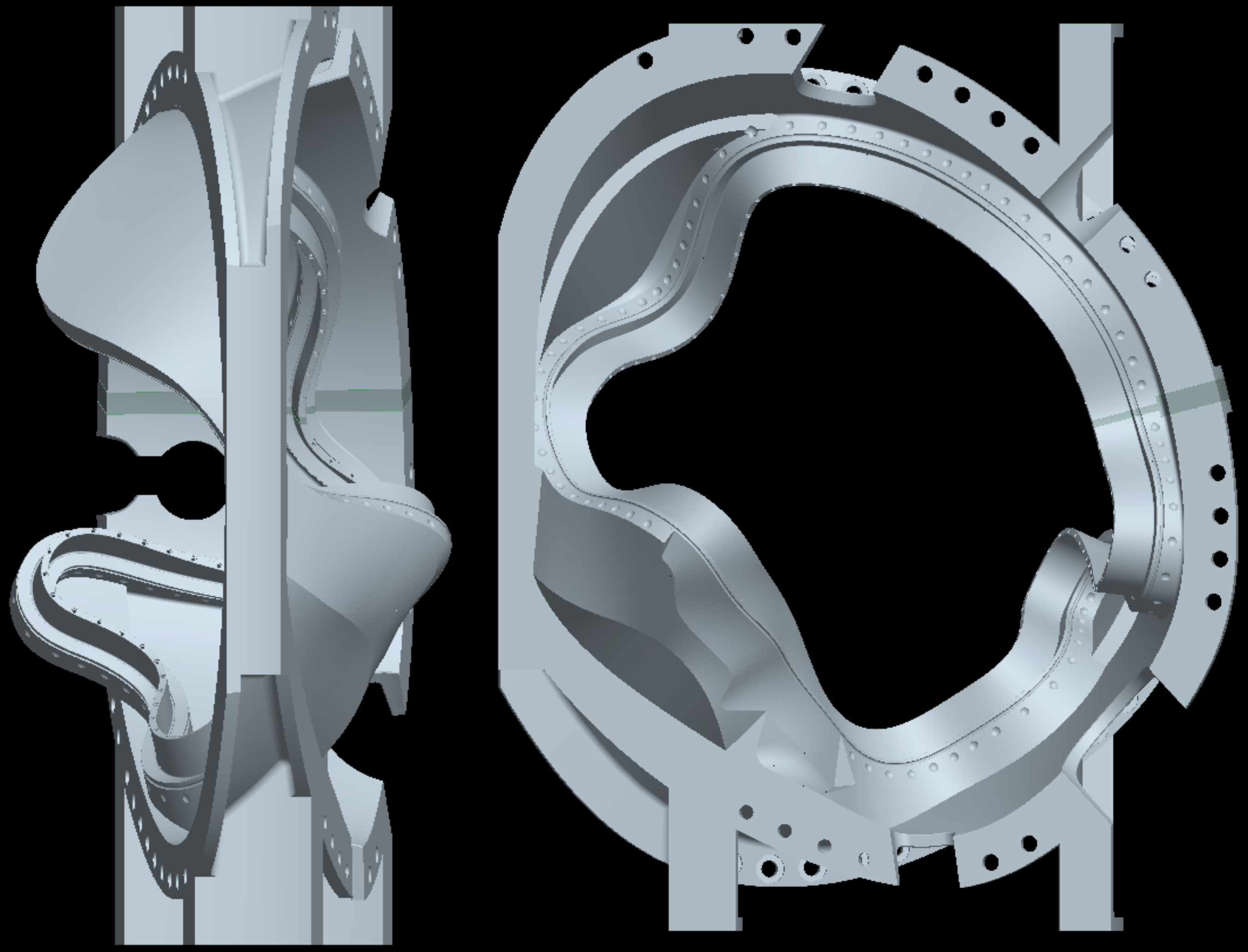
Show views of model, exploded assembly

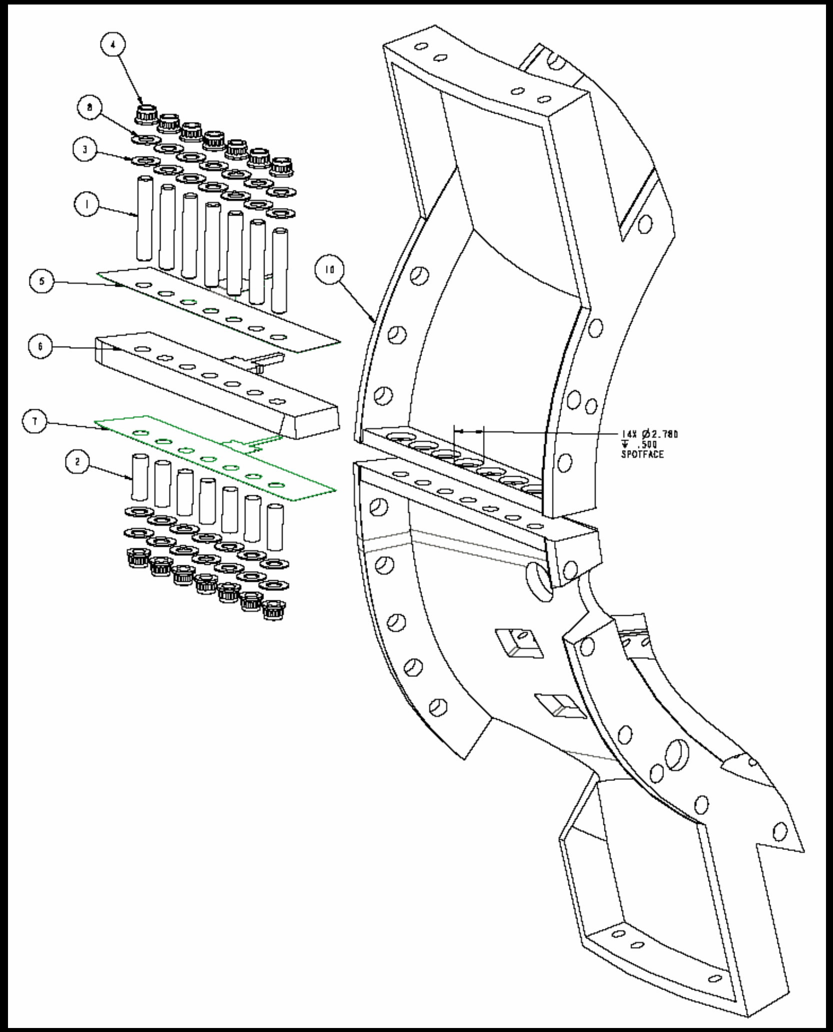
Type-B Assembly

Show views of model, exploded assembly

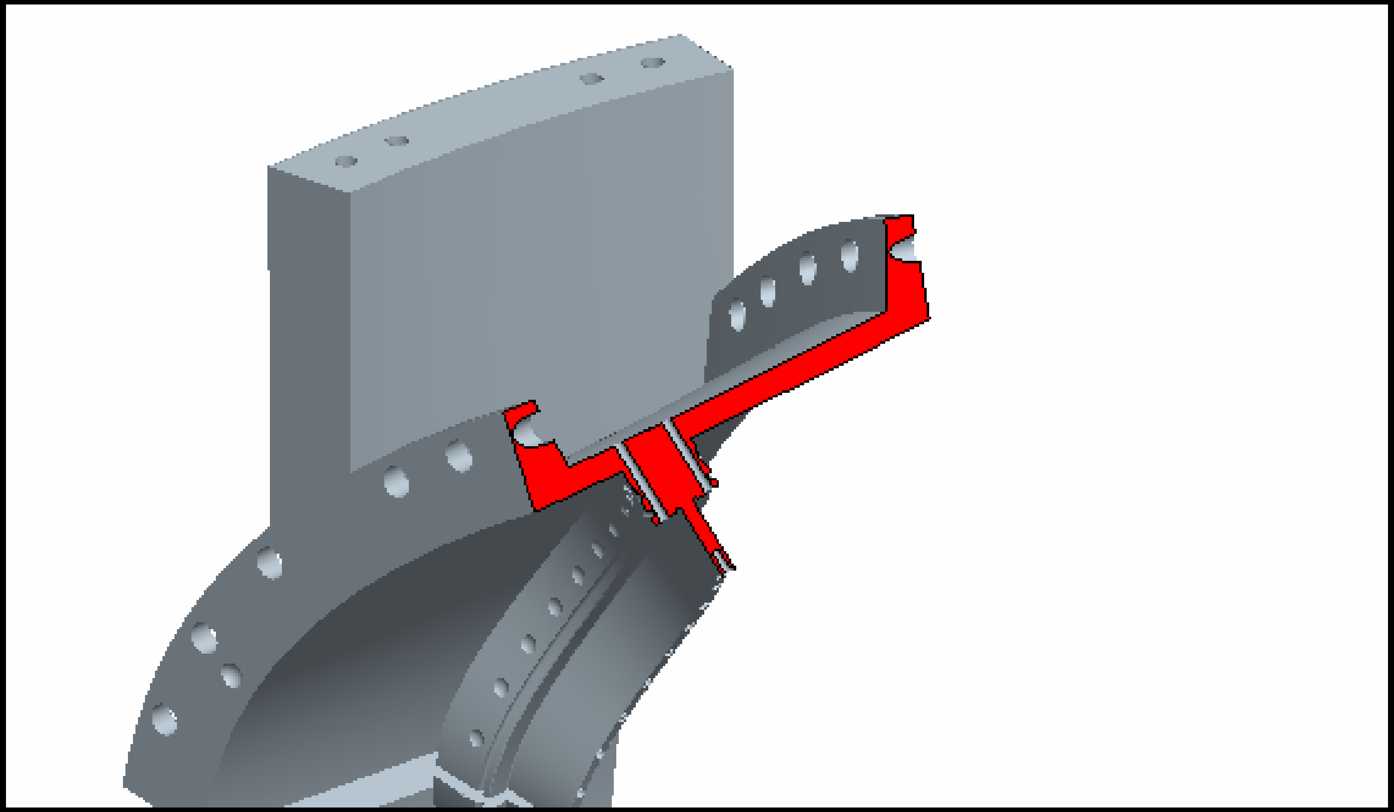
Type-C Assembly

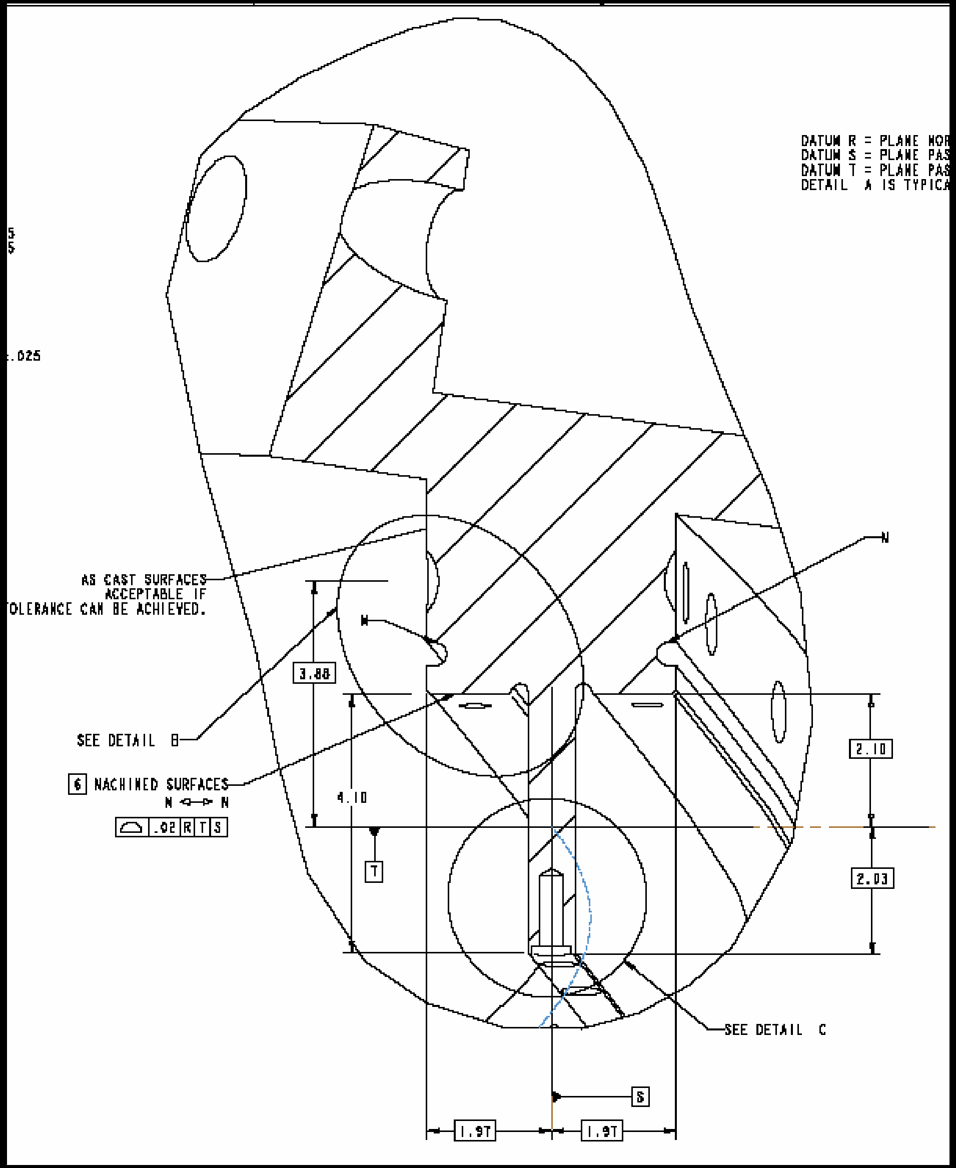
Show views of model, exploded assembly





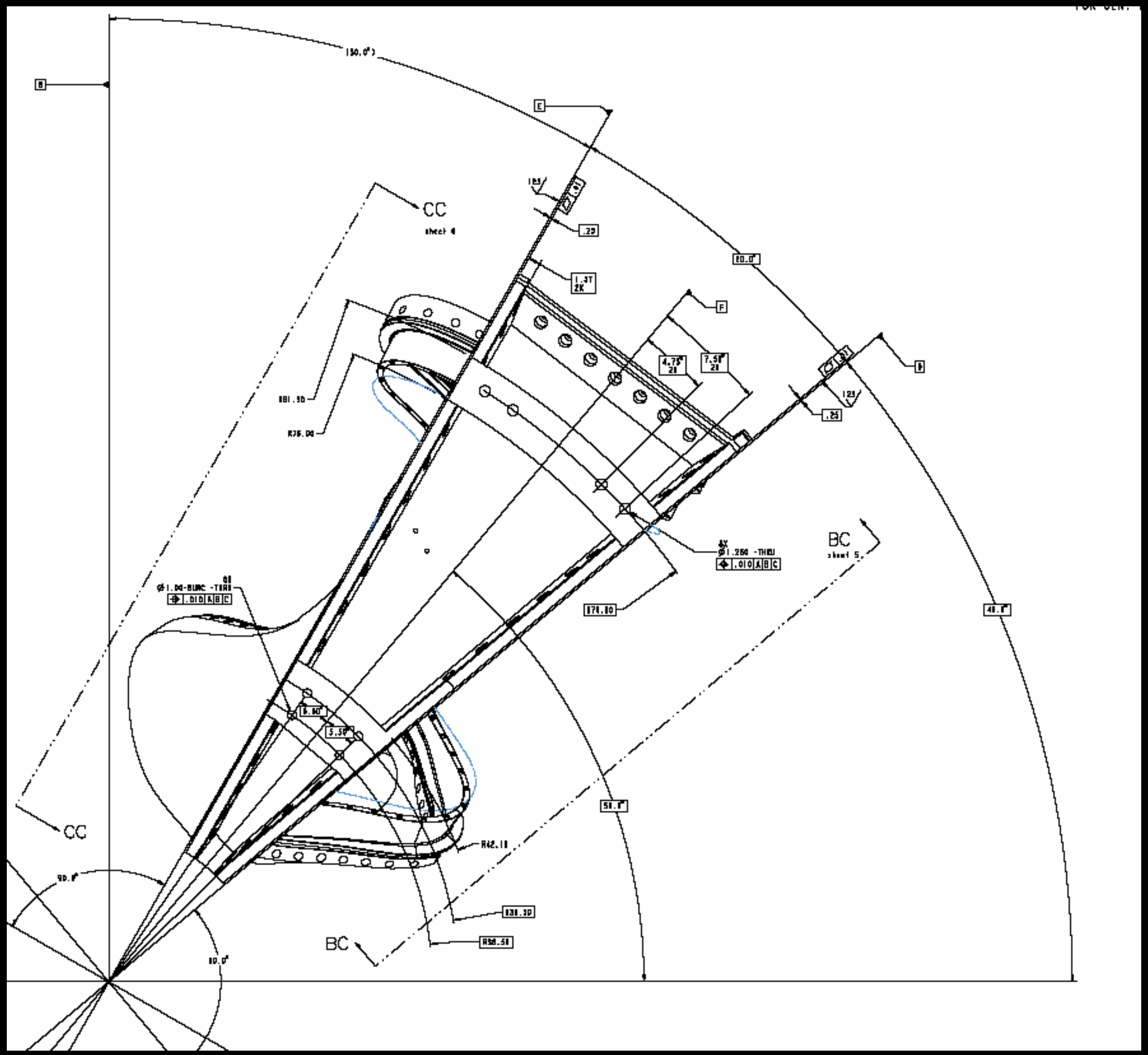
Tee Features

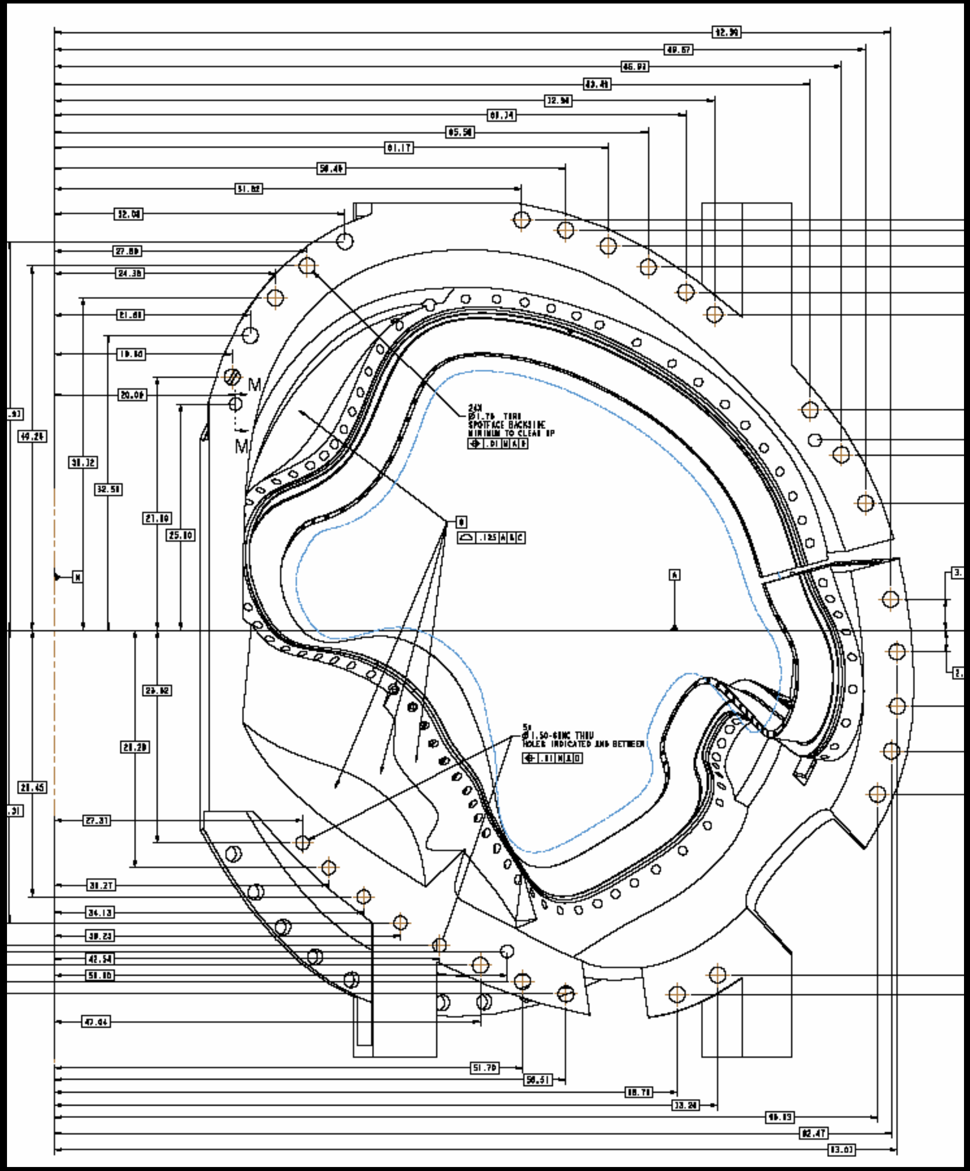




Flange Bolting

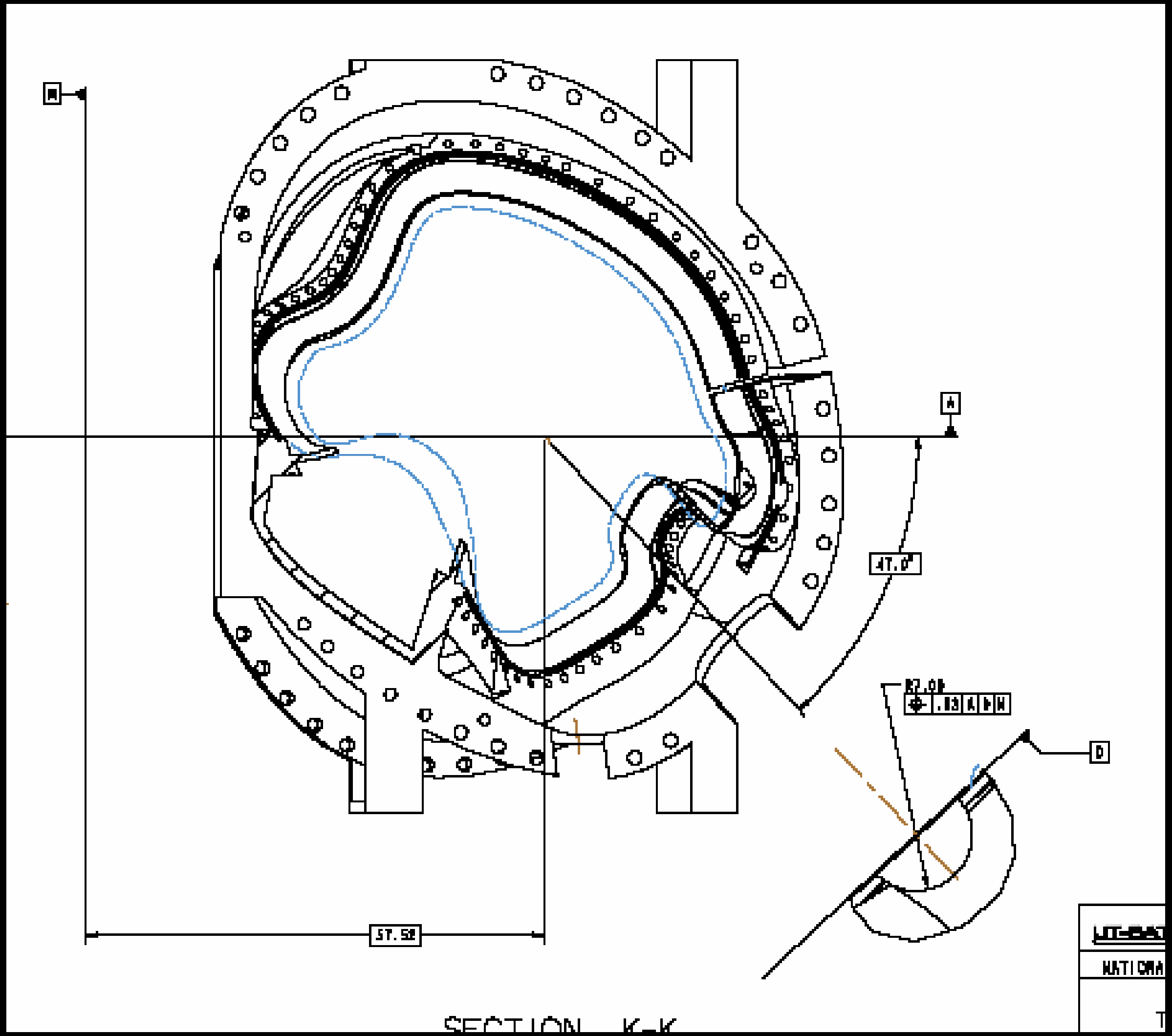
GDT, hole size and layout, typ bolt asm (not part of procurement)





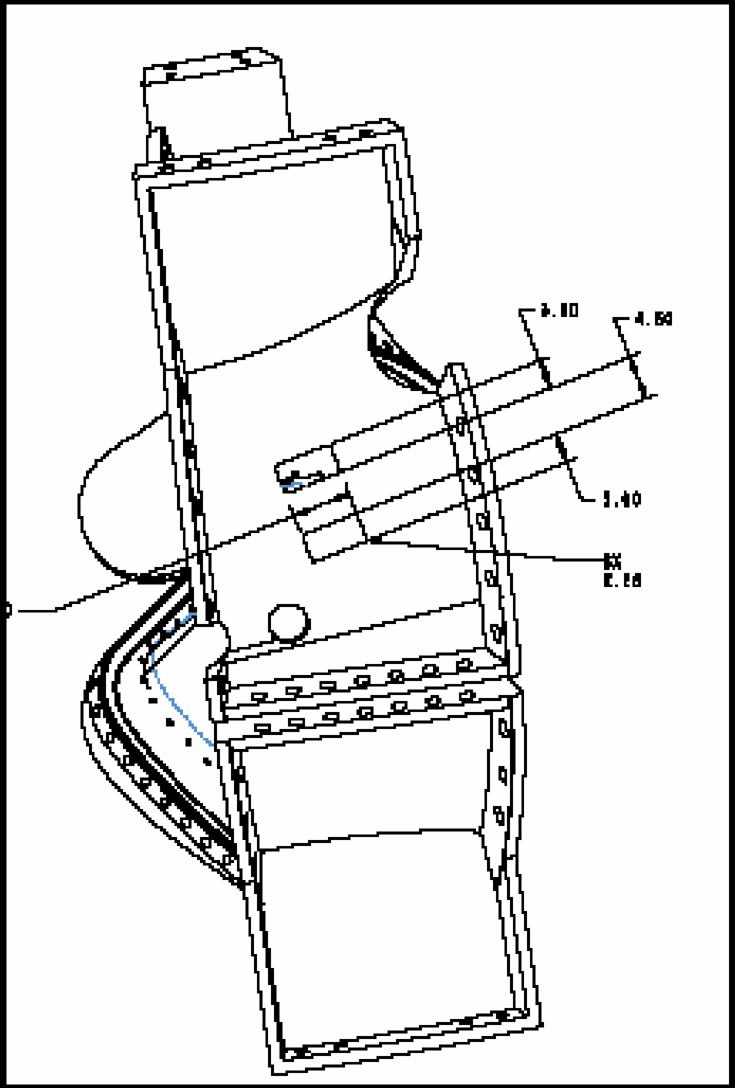
Tooling Ball Positioner

Show detail of pocket / sph seat in flange, 3d views of positioner show typical detail



Electrical Leads

Show detail in winding form, 3d of asm with leads

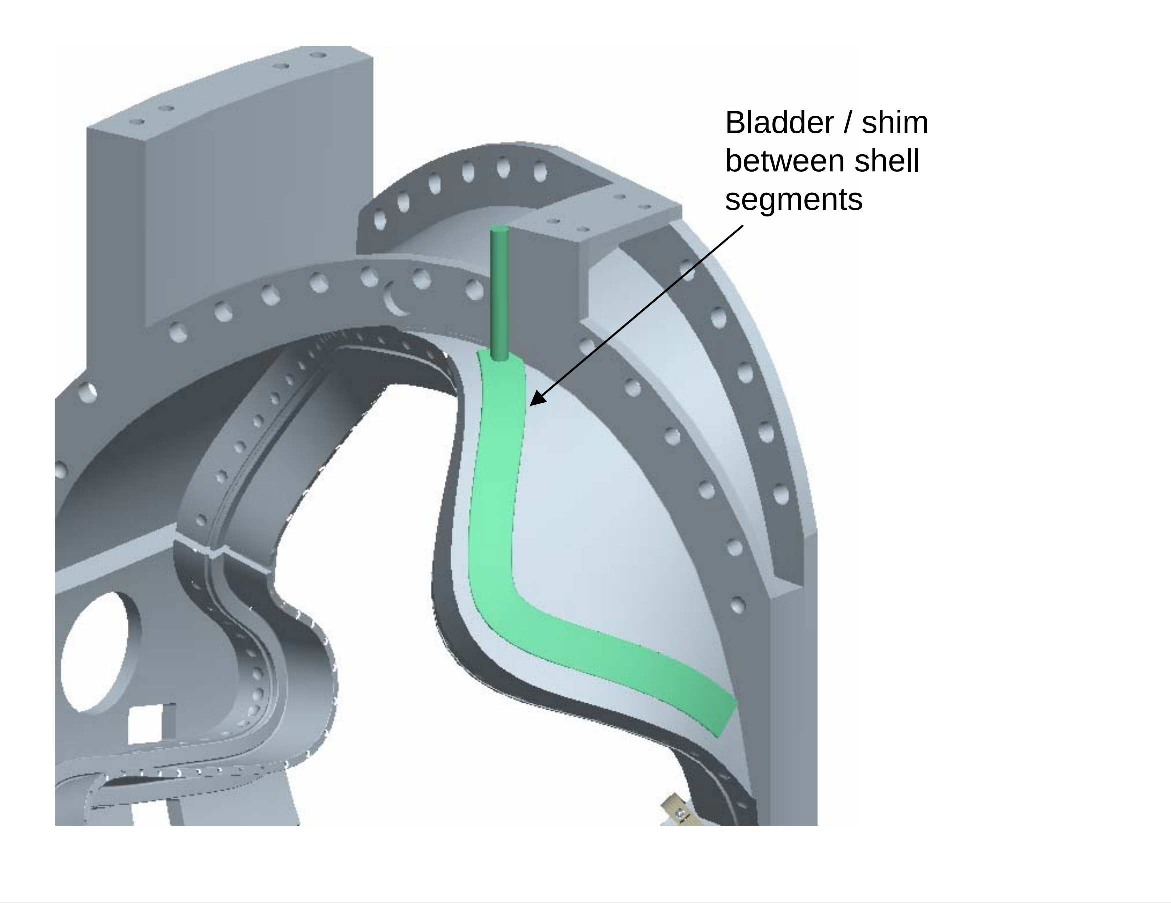


Vessel Supports

Model view

Drawing view

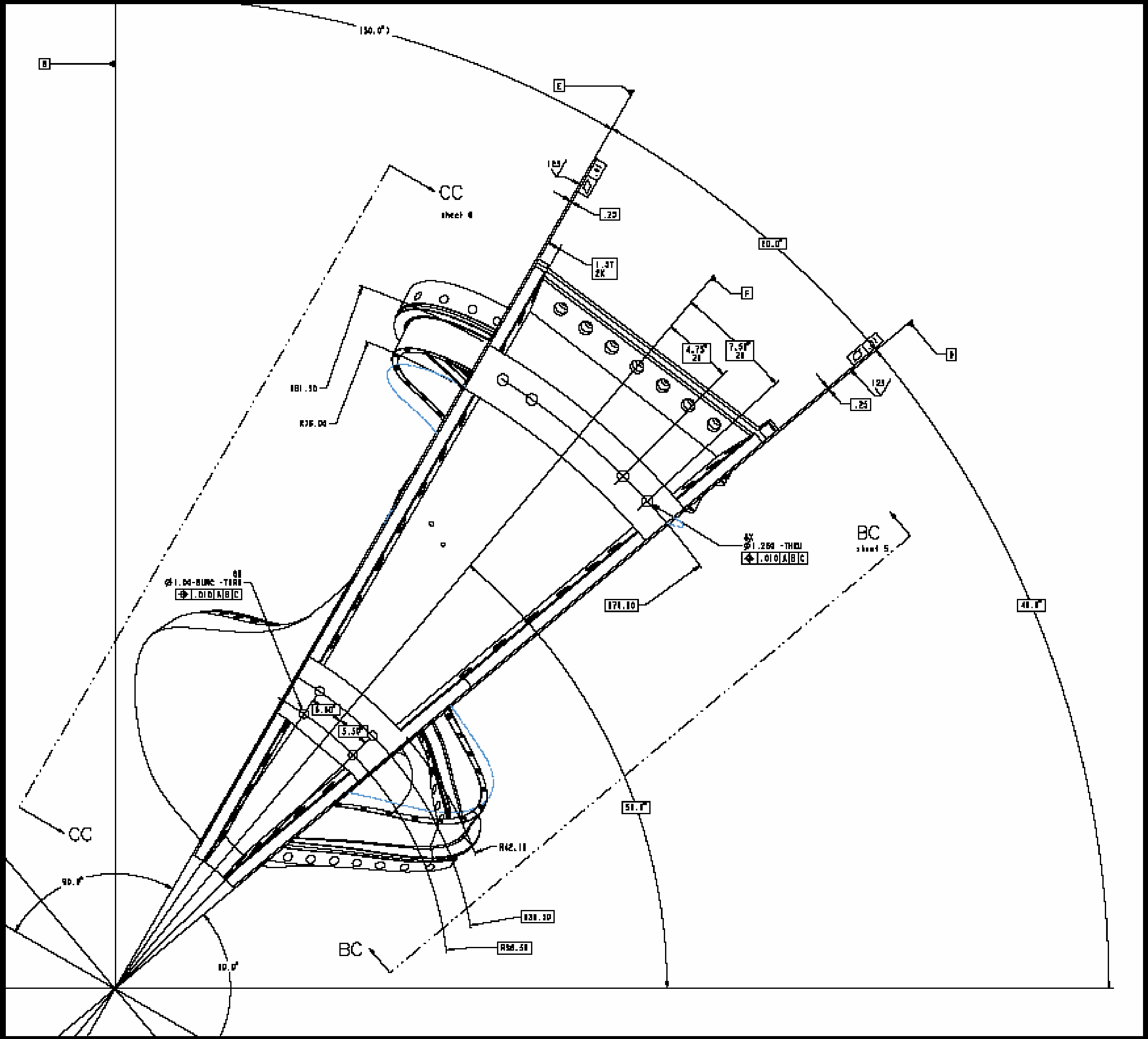
Wing Shims



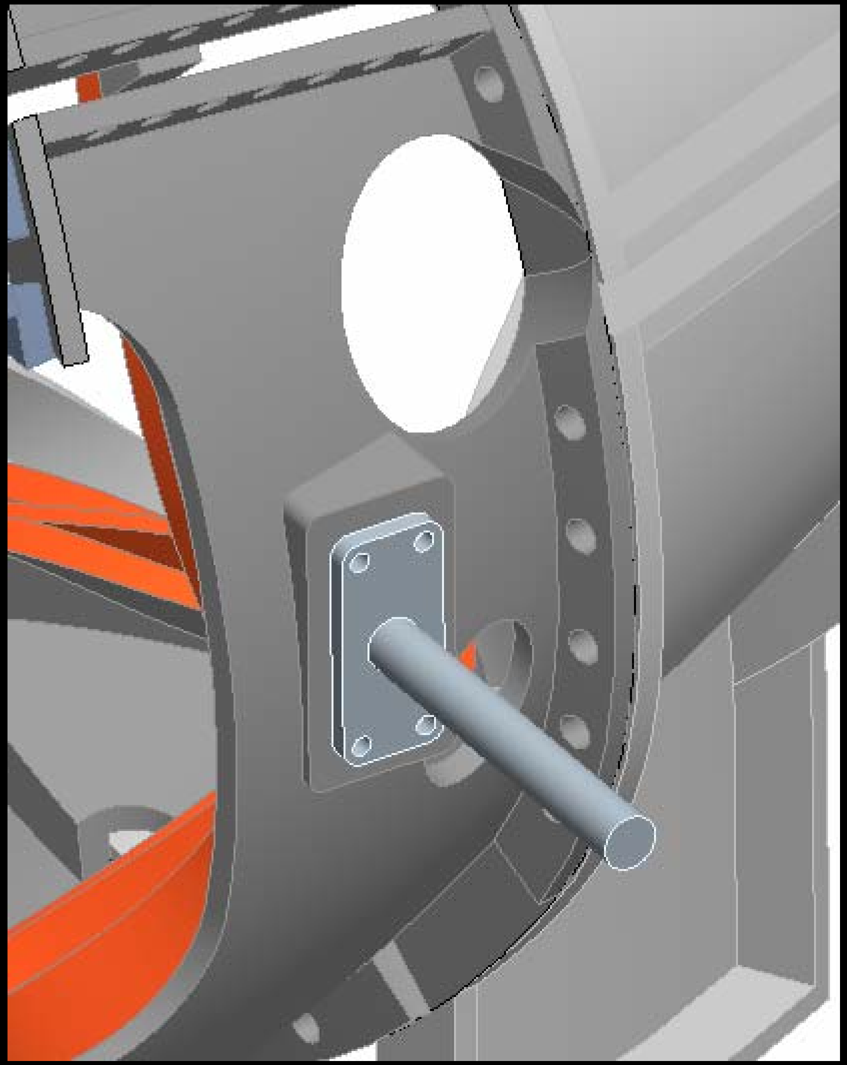
Drawing view

Structural Supports

Model view



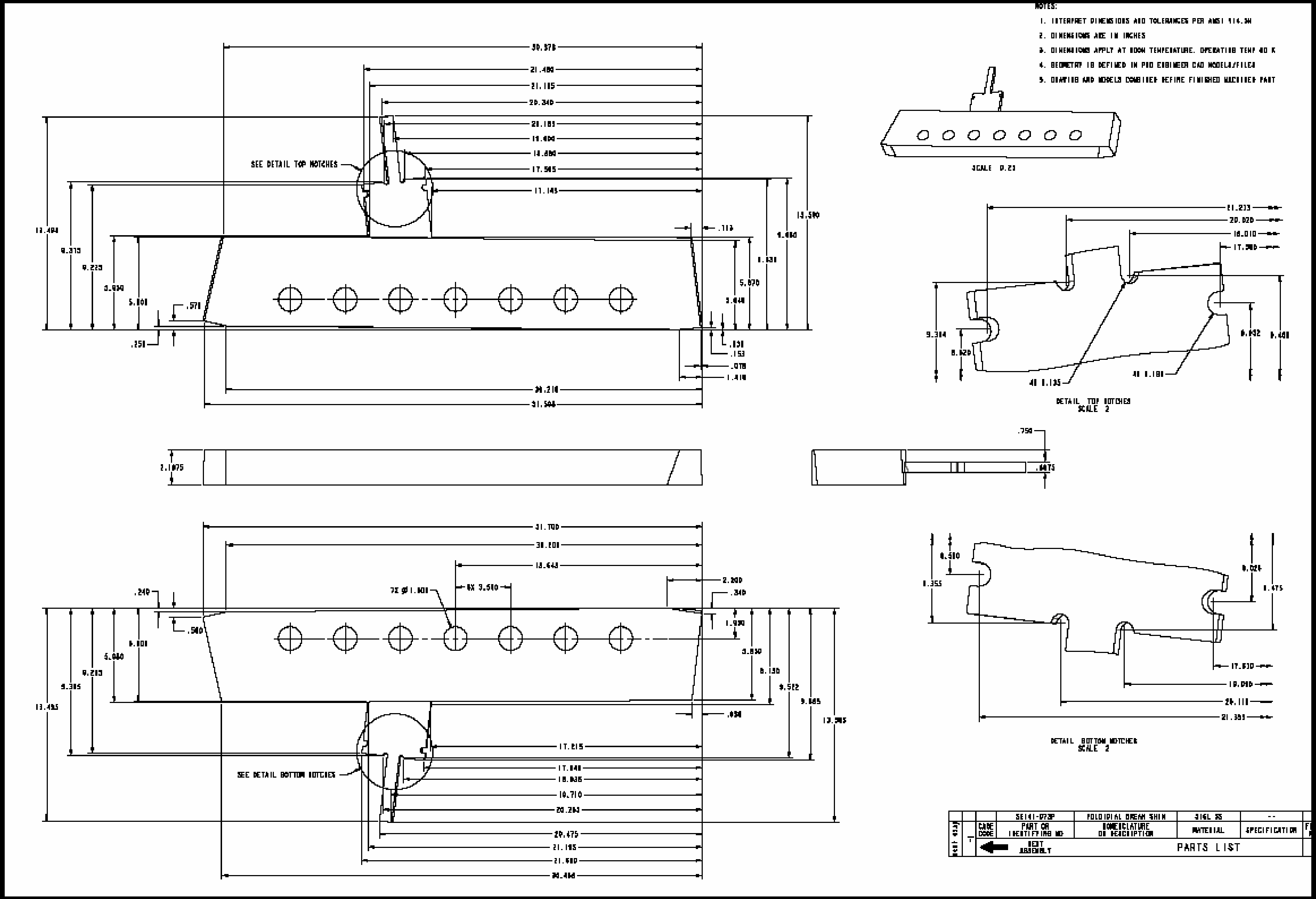
Assembly Tool Mount



Drawing view + dims

Poloidal Break Asm and Parts

Model view



Verification and Inspection

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 manifactured and inspected, ready for fabrication