Modular Coil Winding Form Design, Analysis, Specification

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for the NCSX Team

NCSX Final Design Review
May 19-20, 2004
PPPL

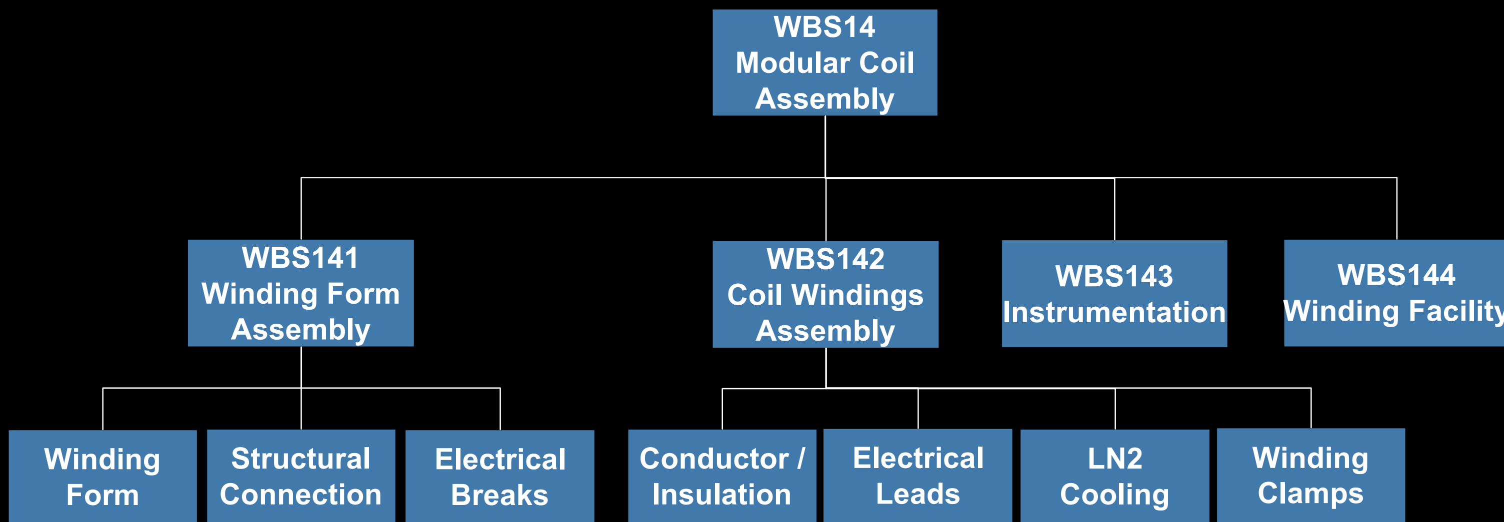
Presentation Outline

- Requirements and Design Description
  - Overview of modular coil assembly; winding form details
- Design Analysis
  - EM loads, linear / nonlinear structural analysis
- Winding Form Specification
  - Requirements, models and drawings, verification

- Procurement Plans (P. Heitzenroeder)

WBS and Scope

- Modular coil system is composed of two major subassemblies plus winding facility
- Coil 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

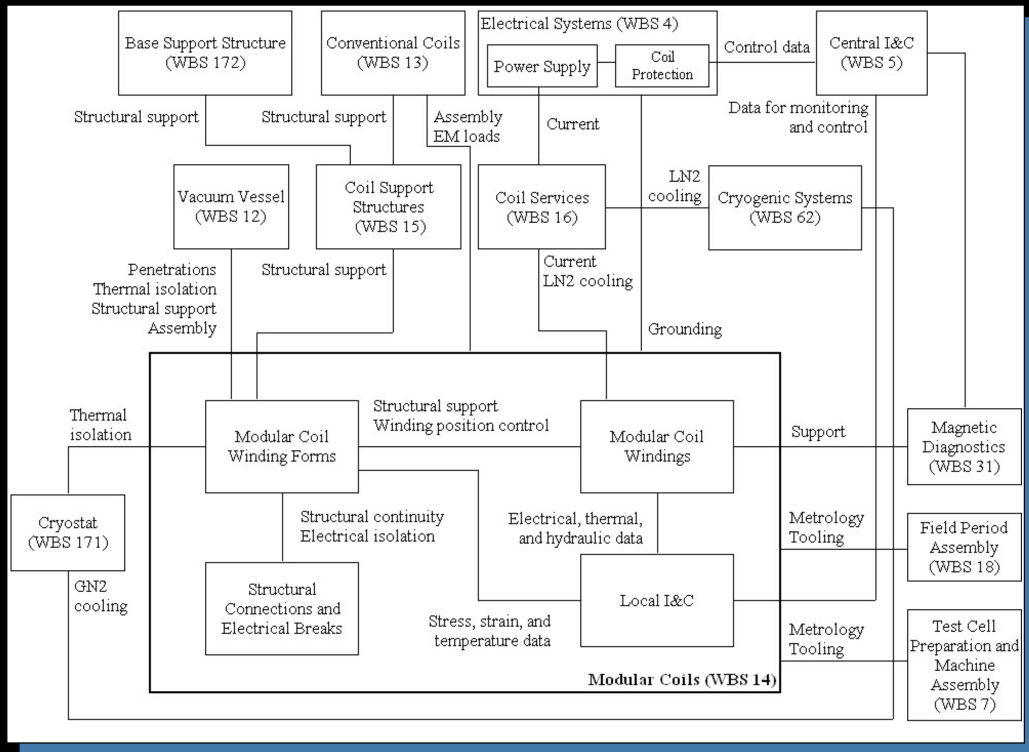
The coil windings provide the basic quasi-axisymmetric field configuration

- 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

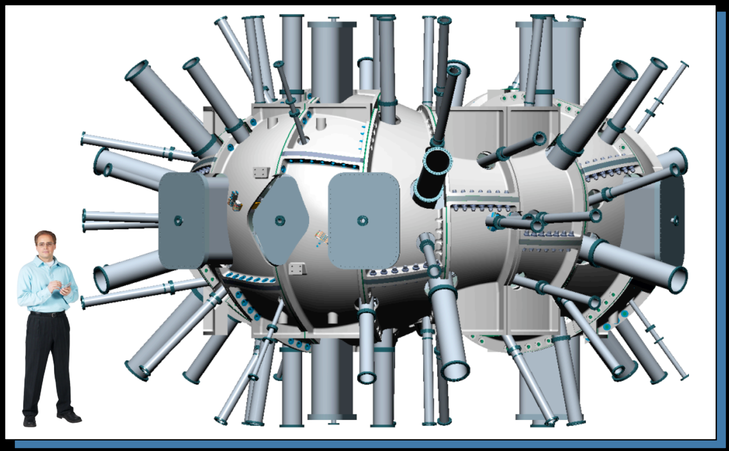
Interface Requirements

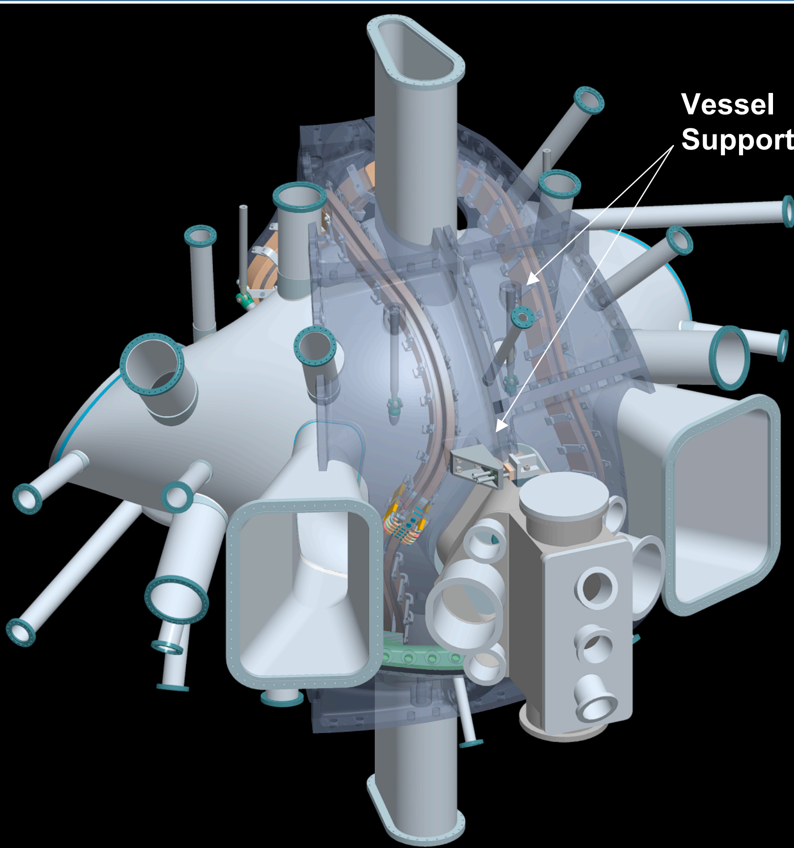
- Primary interfaces:
  - Vacuum Vessel
  - Support Structure
  - Coil Services
  - Assembly / Metrology



Vacuum Vessel Interface

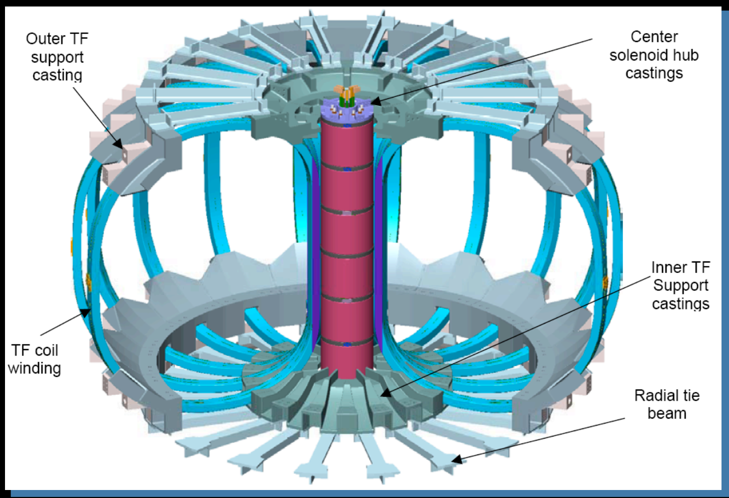
- The modular coil system supports vertical and lateral loads from the vacuum vessel:
  - Gravity load = 21,000-lb
  - EM loads due to 320-kA plasma disruption
- Openings in the modular coil structure have a 2-in metal-to-metal clearance with ports to accommodate thermal growth and fabrication / assembly tolerance.

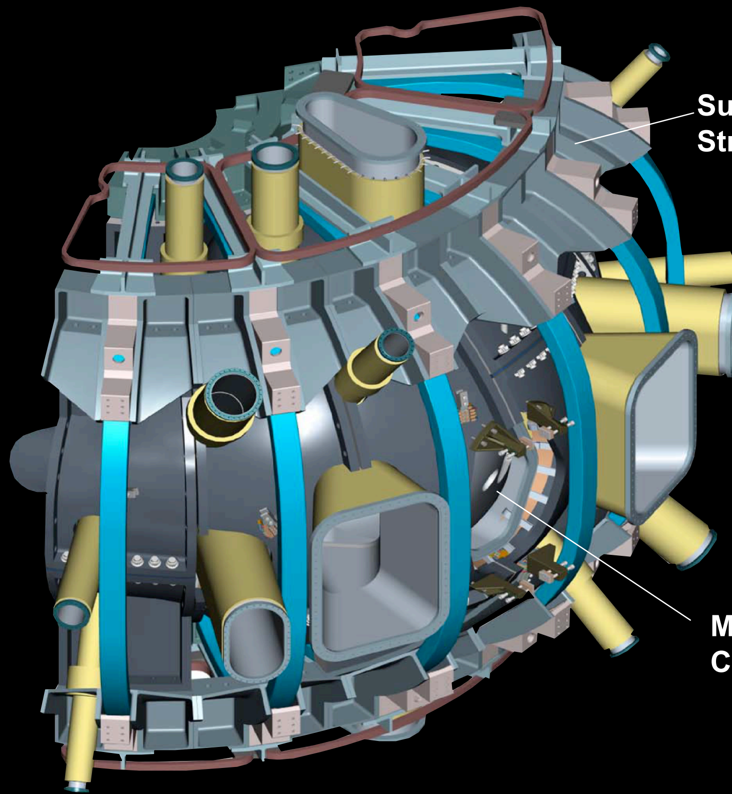




Structural Support Interface

- The modular coils interface with the support structure at inboard and outboard rings ~50-in off midplane
- Interface transmits gravity and EM loads through base structure to ground (MC+VV = 64-ton)
- Same operating temperature (77K)





Electrical Interface

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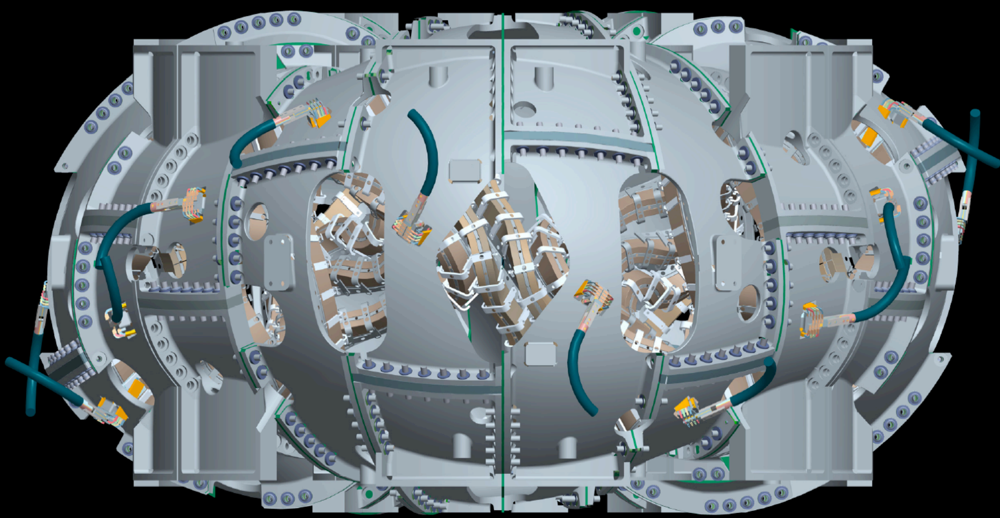
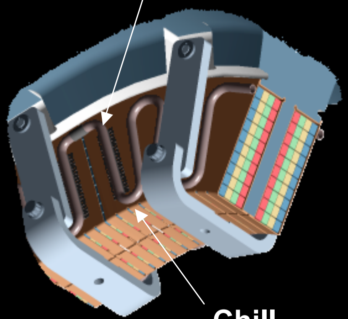


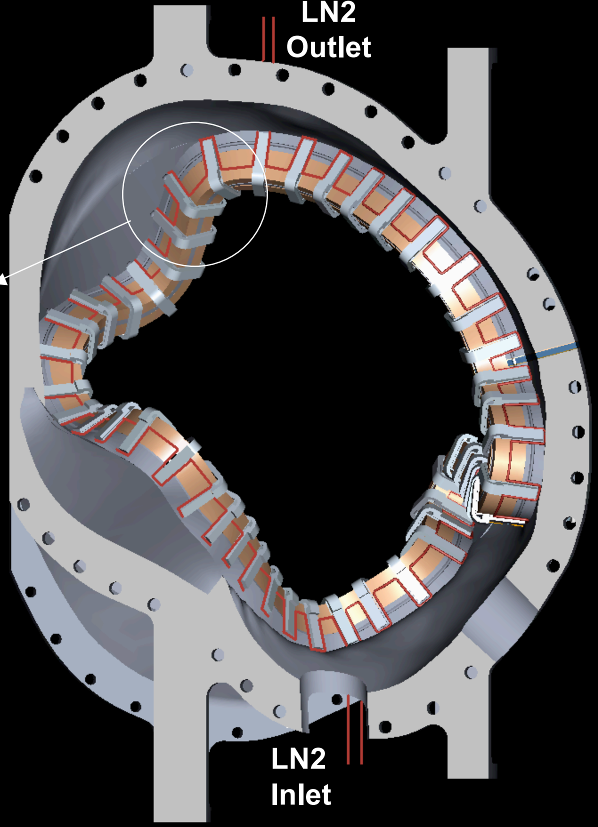
Up / Down Symmetry of Leads

- 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 buswork inside the cryostat.
- Electrical ground wires are to be routed from 12 individually isolated coils and 3 field joint pairs to the cryostat exterior.

Cryostat and Cooling Interface

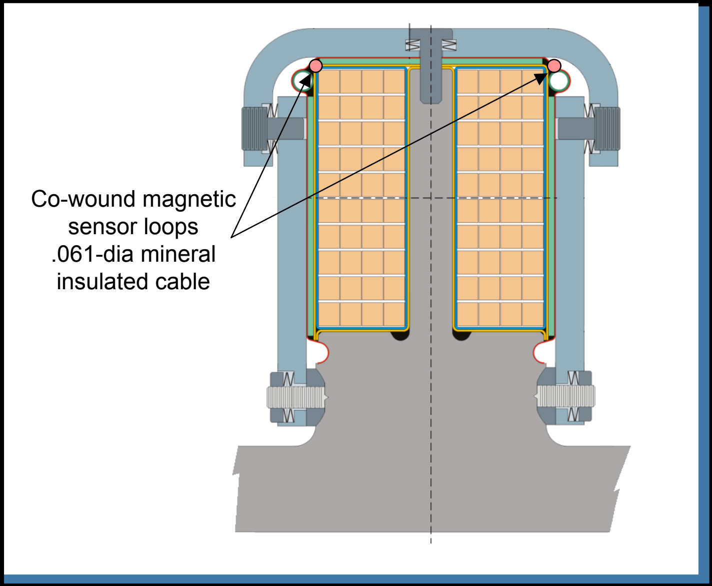
- The modular coils have LN2 coolant connections at the top and bottom of each winding form (4 lines per coil)
- Total flow requirement is 16 GPM
- The cryostat does not interface with the modular coils directly.





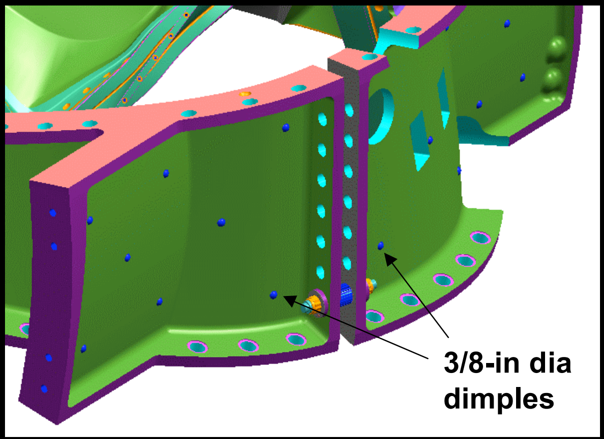
Instrumentation Interface

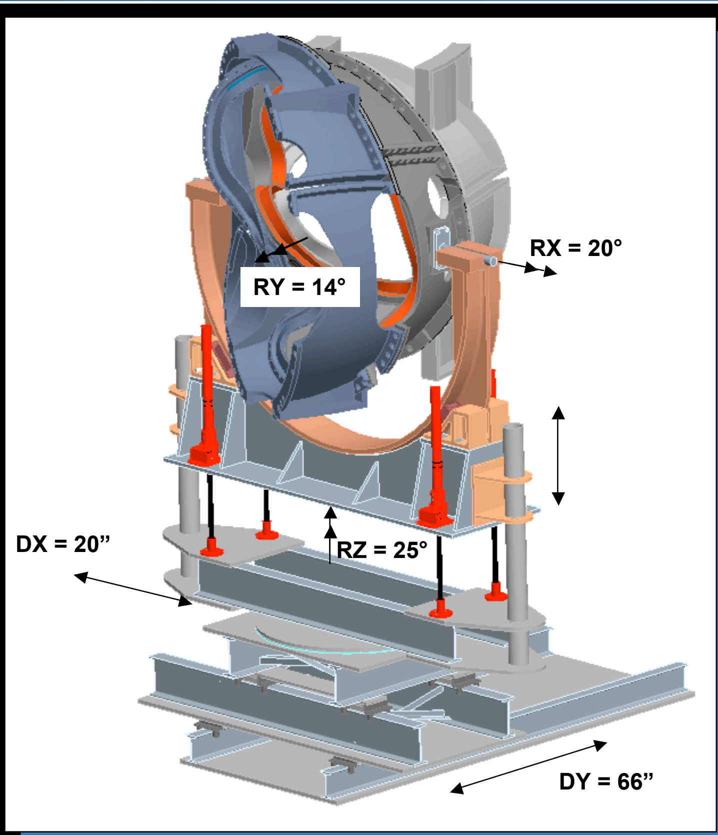
- Central I&C takes output from the modular coil sensors (strain gauges, RTDs, thermocouples) and processes it for use in coil protection logic.
- Instrumentation layout is not expected to impact the MCWF, except for thermocouple holes in thick sections which will be added.
- Magnetic field sensor loops shall be co-wound with the coil winding packs as shown and exit through the poloidal break.



Metrology and Assembly Interface

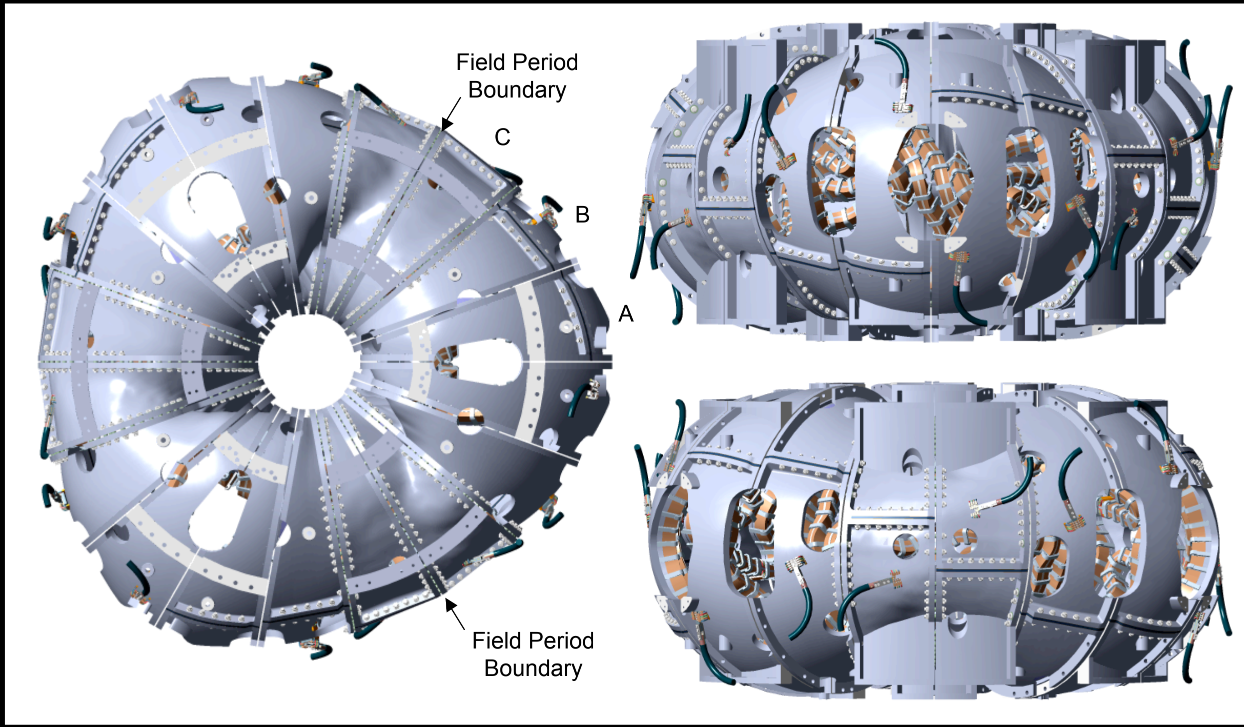
- Monuments that are developed for casting and machining process will also be used for inspection, fabrication, and assembly of the coils.
- Tooling required for field period assembly will interface with the half field-period modular coil assembly at the inboard and outboard midplane.





Design Description

- Integral shell composed of 18 modular coil assemblies
- Three field periods, 6 coils per period, 3 coil types
- Shell thickness = 1.375-in
- Total weight = 108,000-lb
- Each modular coil:
  - 1,900-ft of conductor
  - 48 coil clamps
  - 200 fasteners



Modular Coil Types

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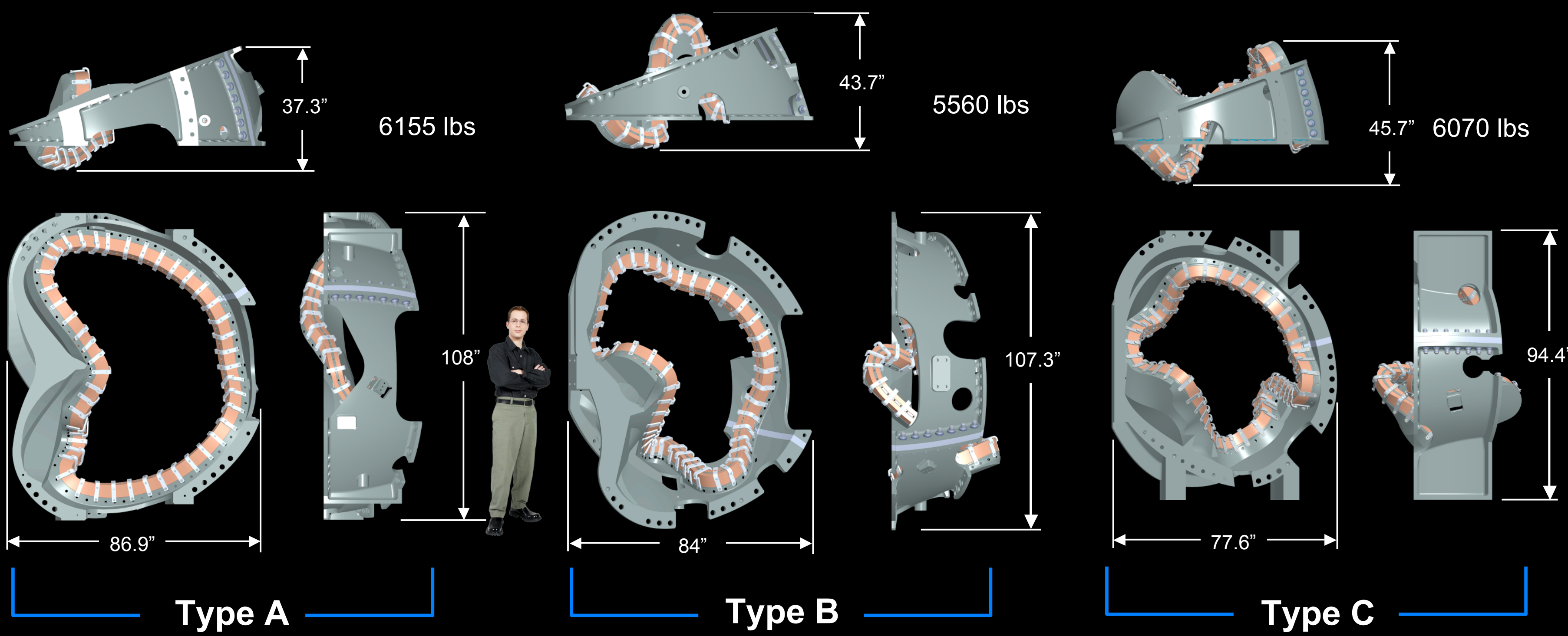
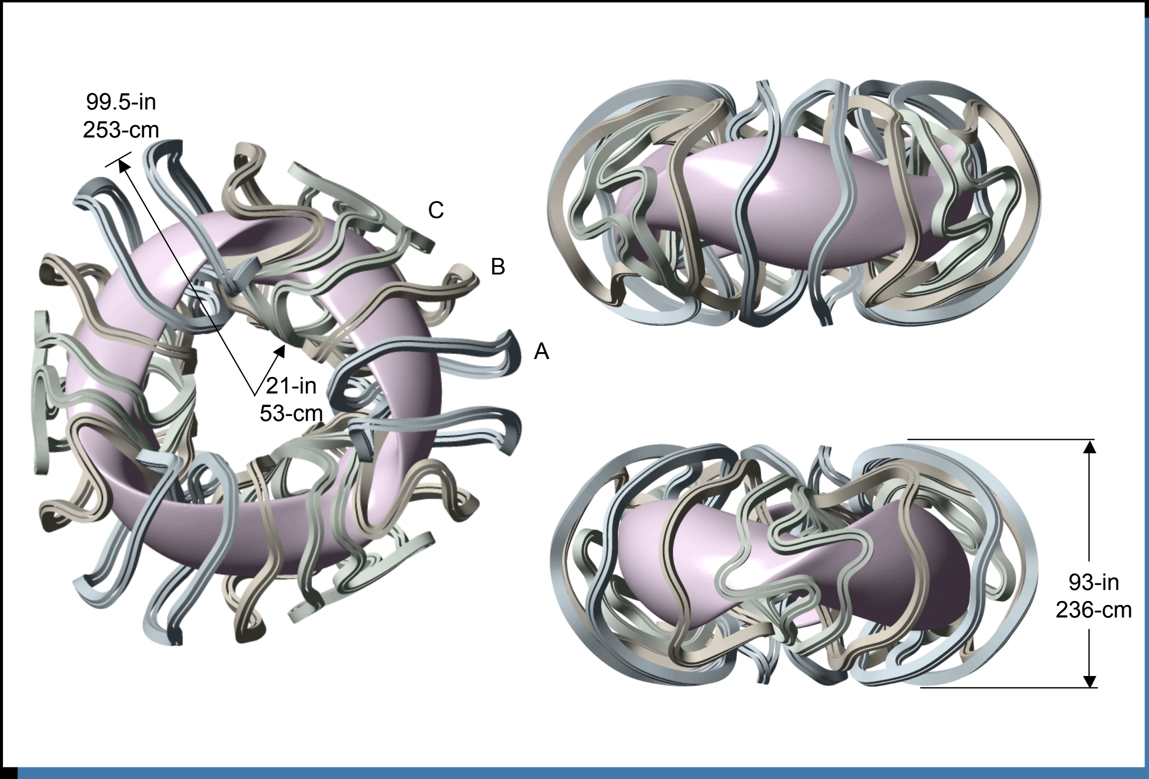


Coil Configuration

- 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

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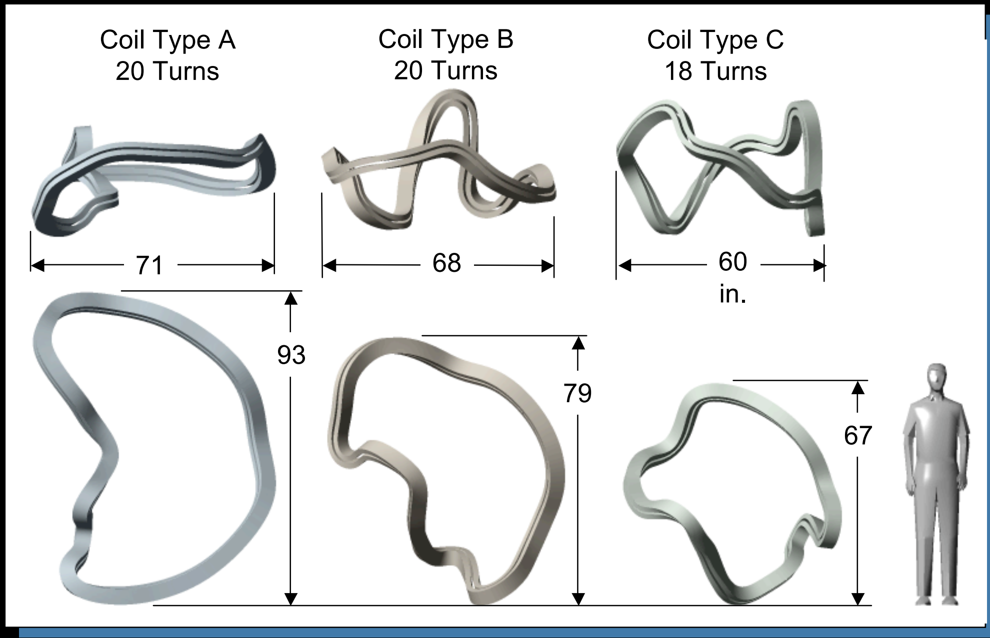
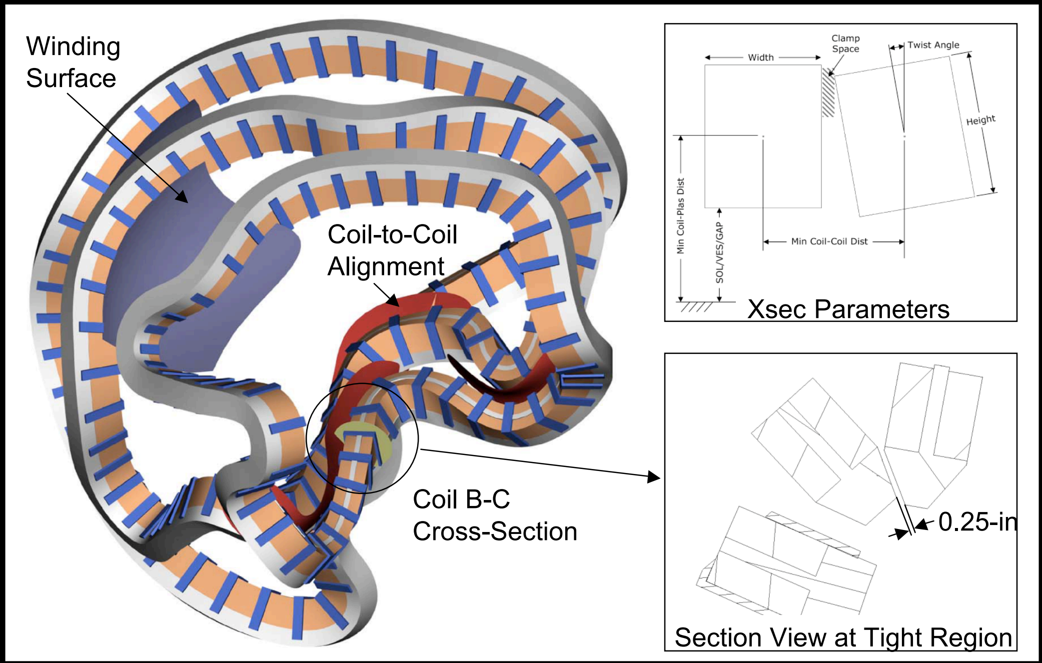
- Coil lengths = 291, 283, 263-in
- Min coil-coil dist = 6.1-7.6 in, Max dist = 27-36 in
- Min coil-plas dist = 8.1-9.0 in, Max dist = 20-28 in
- Max coil current = 818, 831, 730-kA
- Min bend radius at winding pack outer surface is 2.5-in, 2.7-in, and 3.1-in for coils A, B, and C



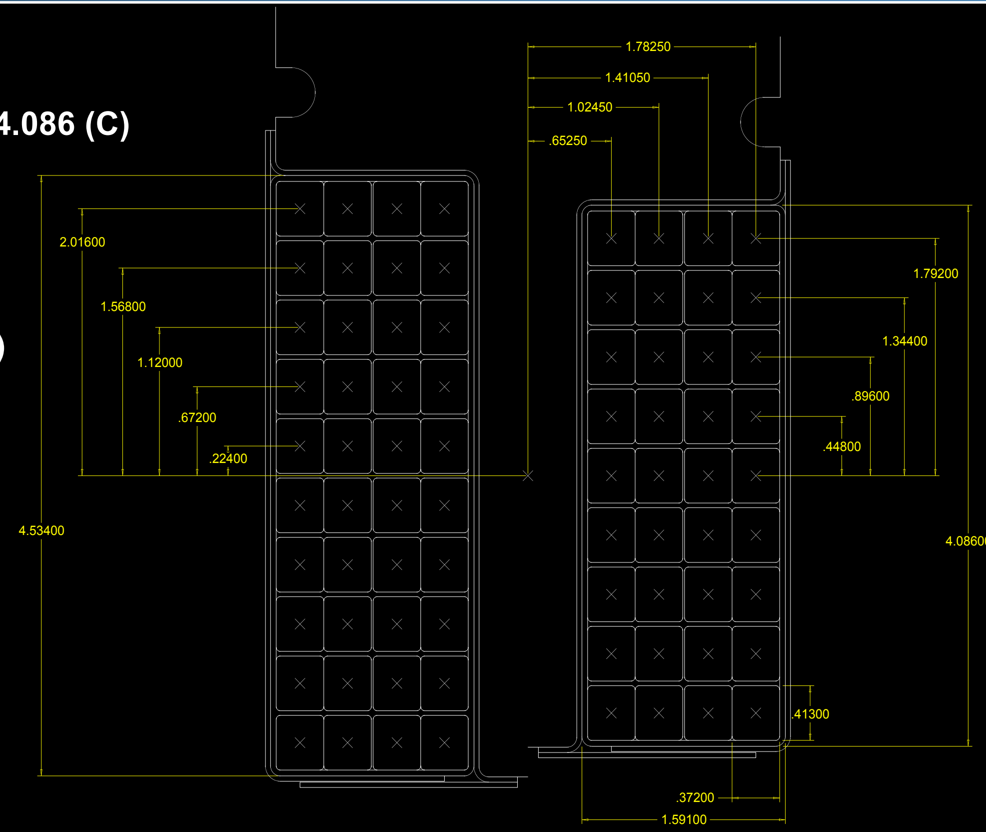
Cross-Section Development

- 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
- Multifilament field studies show that finite build coils produce desired magnetic field



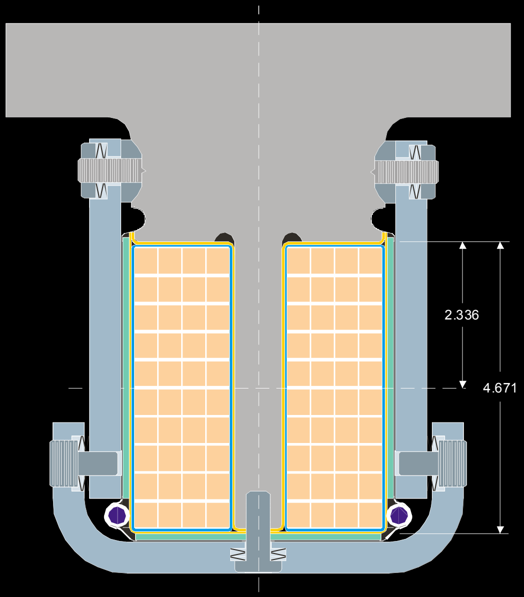
Coil Winding Pack Configuration

- Parameters:
  - Winding pack dims = 1.591 x 4.534 (A, B) or 4.086 (C)
  - 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



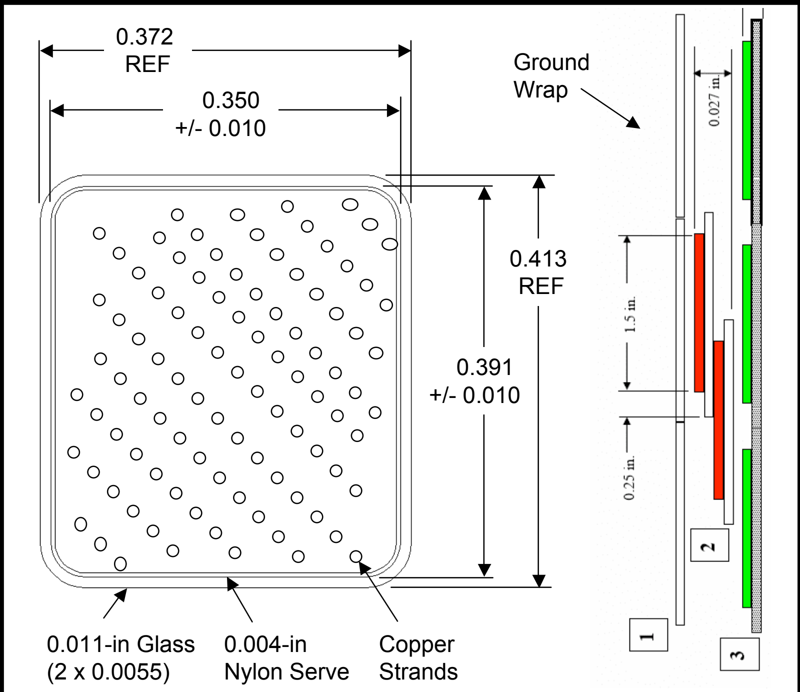
Coil Electrical Parameters

- Twisted racetrack coil, to be completed in August, will be prototypical of production coils



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						

Conductor Specification



- Conductor and turn insulation -
- OFHC Copper, 34-ga Wire
- 12x5/54/34 cable, 3240 strands
- S-2 glass with reactive amino silane finish, .004 in center and .007 at edge, (avg=0.0055-in) thick

- Ground insulation (.0445-in total) –
- Butt-lapped layer of .007-in S2 glass
- Half-lapped layer of composite:
  - 2 wide x .007-in glass +
  - 1.5 wide x .0065 adhesive Kapton
- Butt-lapped layer of same composite:
  - 2 wide x .007-in glass +
  - 1.5 wide x .0035 adhesive Kapton

Coil Winding Sequence

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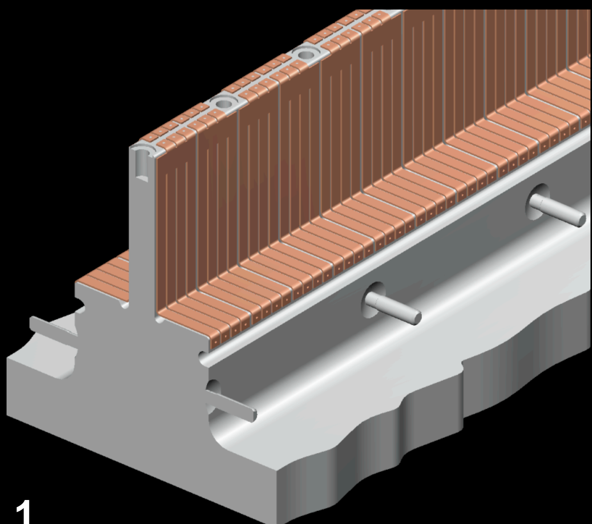
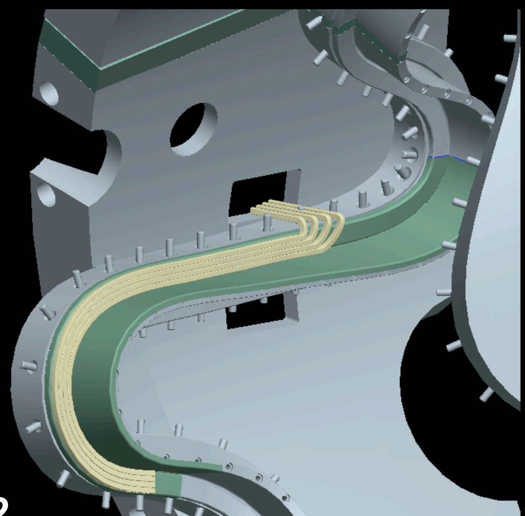


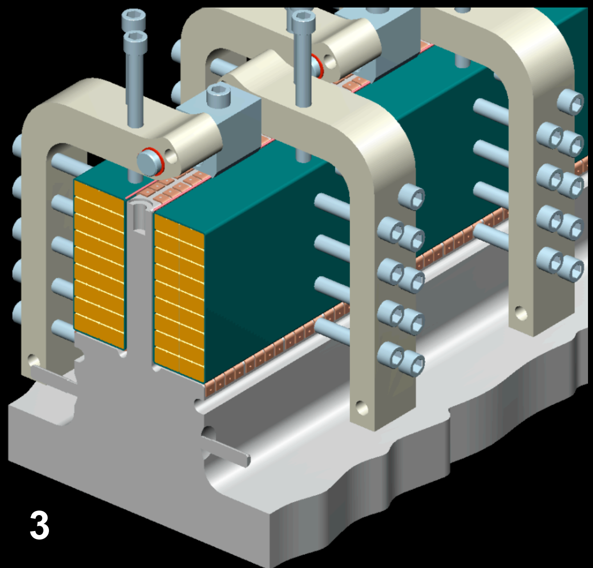
1

- Winding form with welded studs
- Mold release between tee and cladding
- Cladding electrically isolated from tee



2

- Ground insulation and conductor layer
- Winding begins at lead block



3

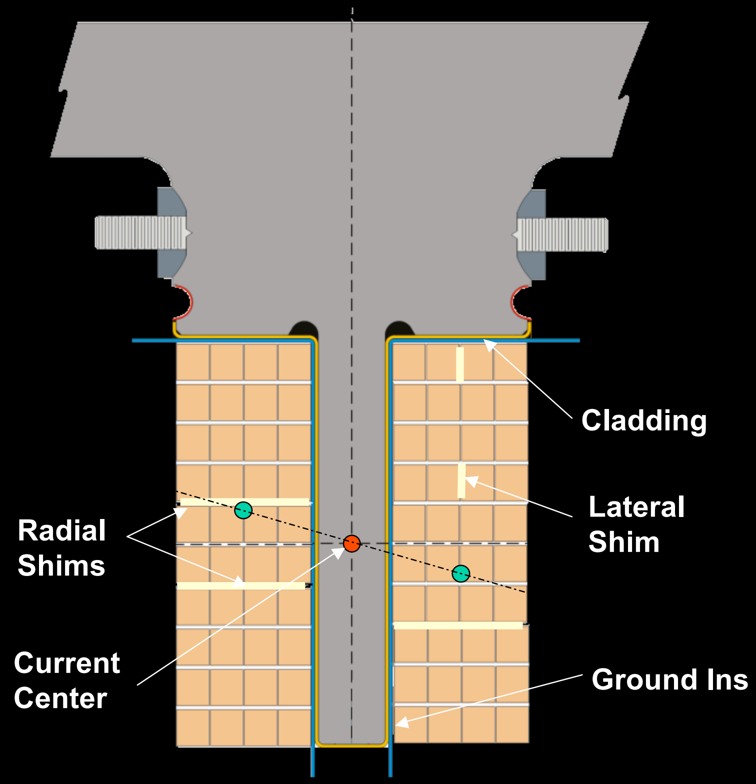
- In-process measure and shim
- Winding clamps hold position

Winding Accuracy

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

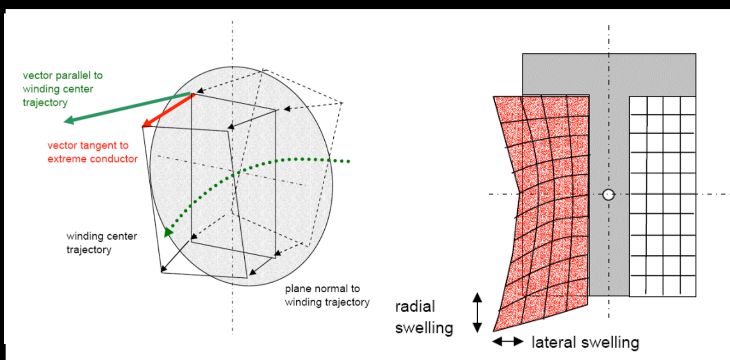
- Tolerance issues:
  - Machined surfaces of winding form are accurate to +/- 0.010-in (0.5-mm)
  - Conductor w/o insulation has a dimensional tolerance of +/- 0.010-in (0.5-mm)
  - Geometry requires up to 0.036-in (.91-mm) per layer allowance for conductor keystoning

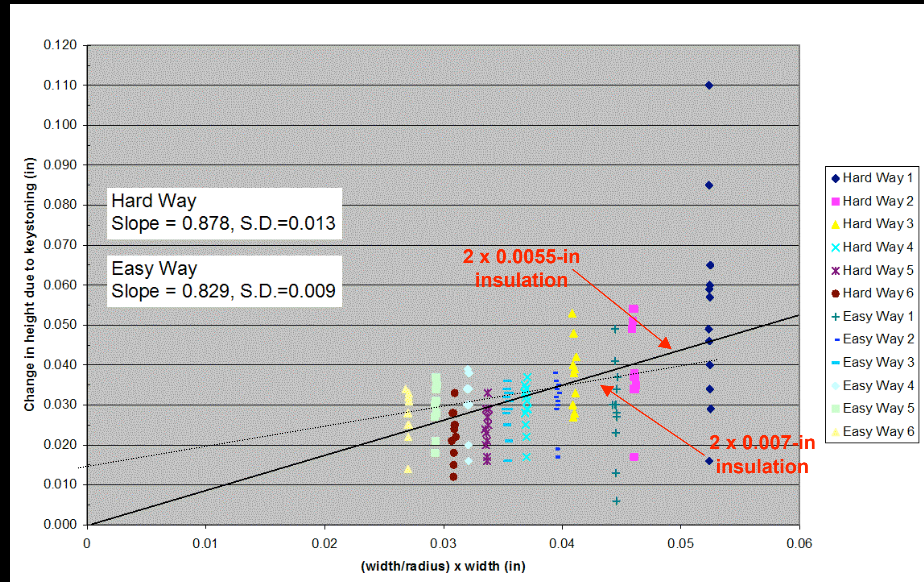
- Current center can be adjusted by use of shims between layers



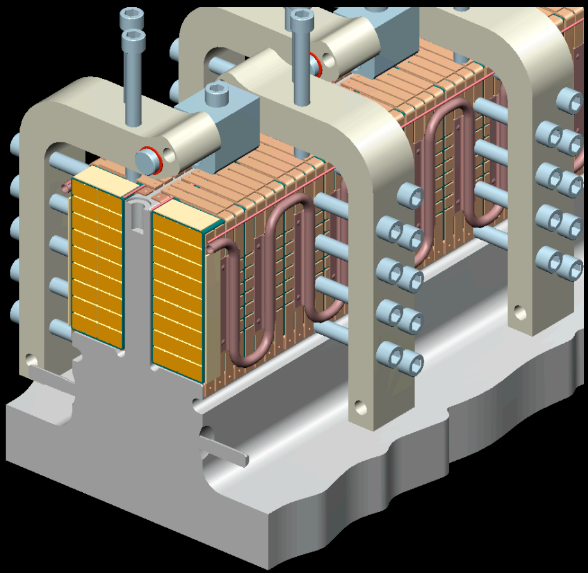
Allowance for Twist and Keystoning

- Keystone measurements made by winding conductor on 5-in dia pipe
- Change in height proportional to width x (width / radius); results vary widely
- Winding pack dimensions include shim allowance of 0.035-in between each layer radially and 0.014-in laterally
- Swelling due to twist also evaluated



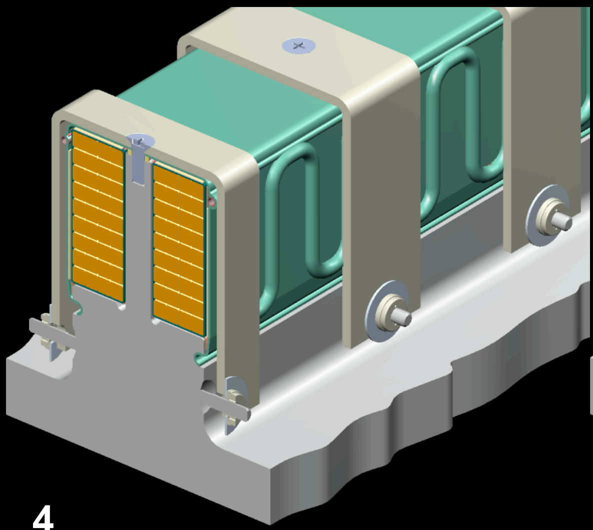


Coil Winding Sequence (cont'd)



3

- Outer chill plates attached to cladding
- Pre-formed cooling line attached
- G10 pads for structural clamps



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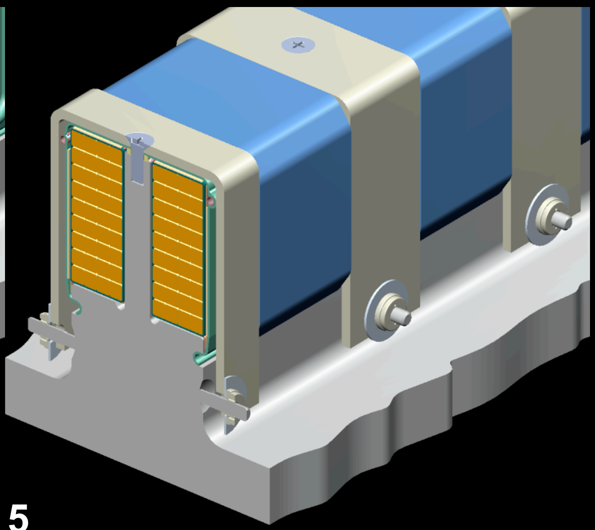
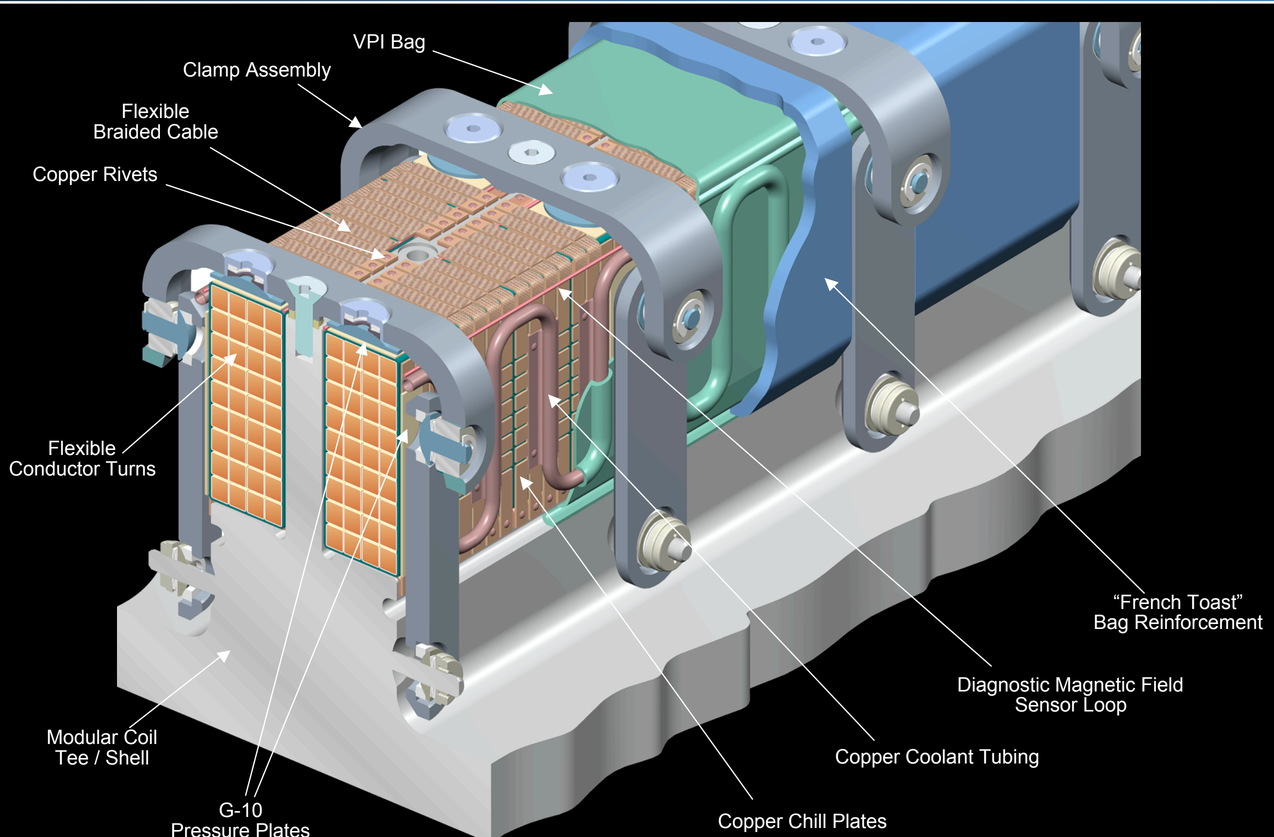
- VPI mold and temporary clamps



5

- Felt / epoxy reinforcement ("French Toast")

Winding Pack Assembly



Coil Cooling

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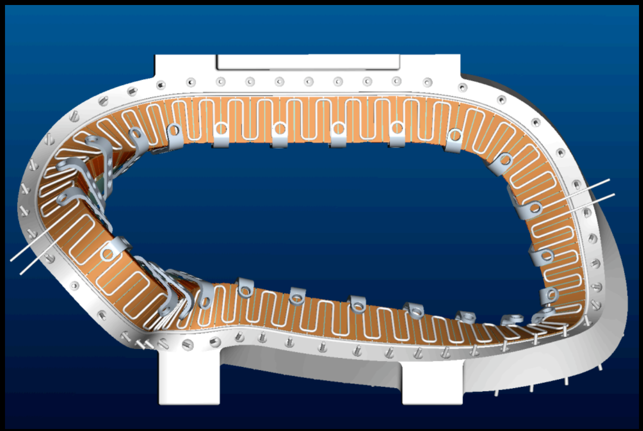
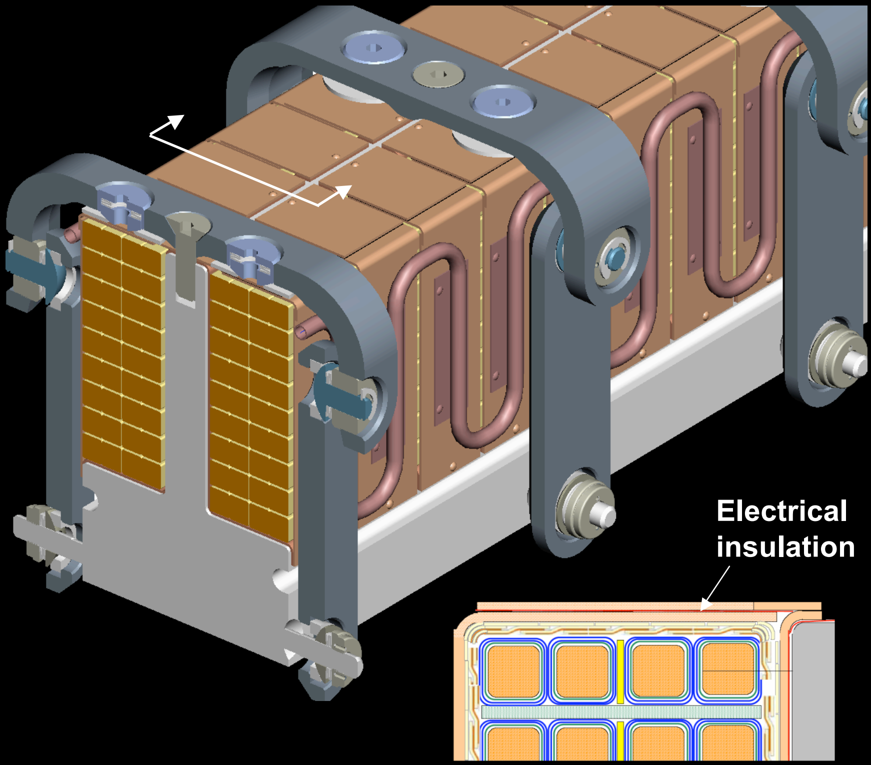
- Copper chill plates, .040-in thick, to be fabricated from flat patterns
- Outer plates are cooled by pre-bent tubing, .375-dia x ~ 45-ft long, four circiuts per coil
- Attachment schemes identified and will be tested during Twisted Racetrack coil winding

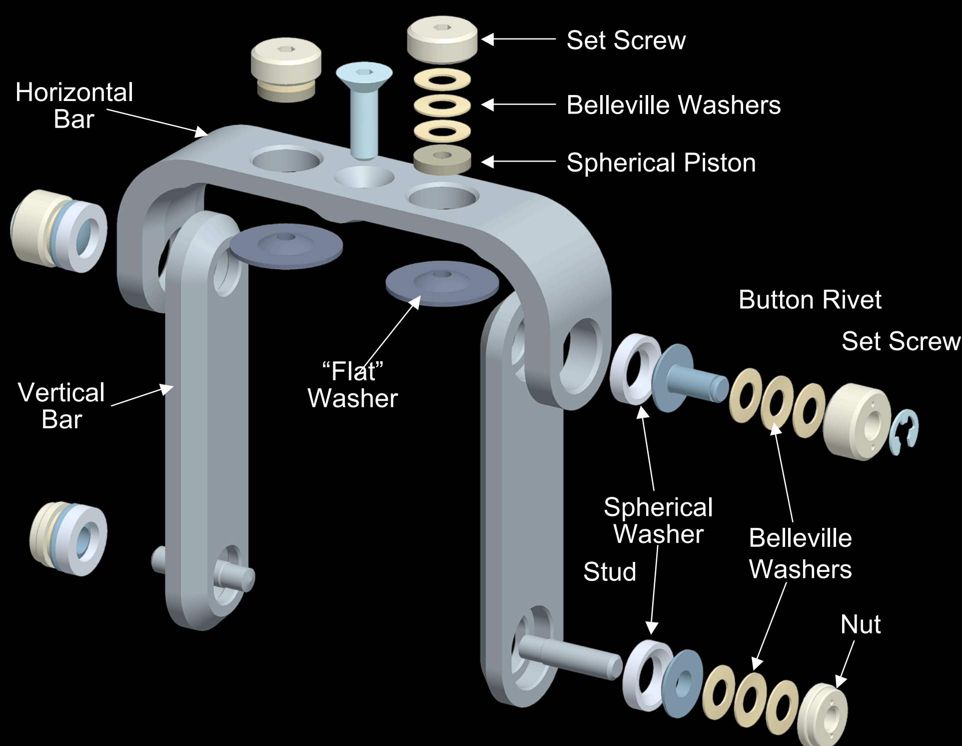


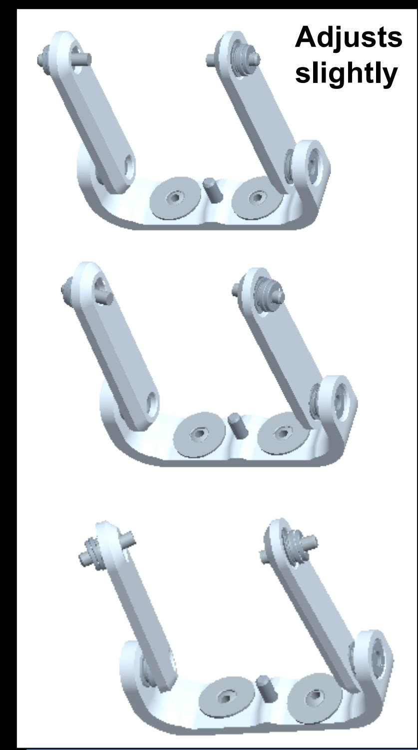
Twisted Racetrack Coil



Clamp Assembly

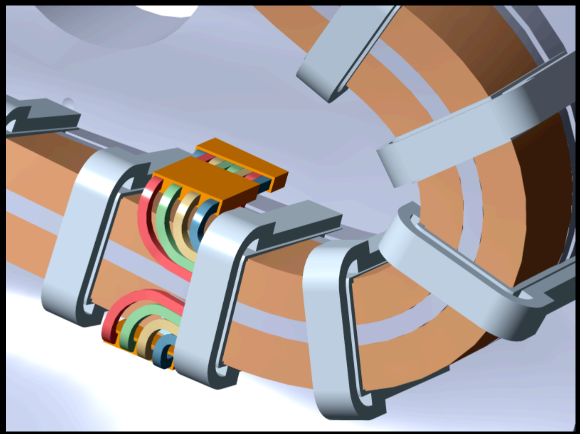
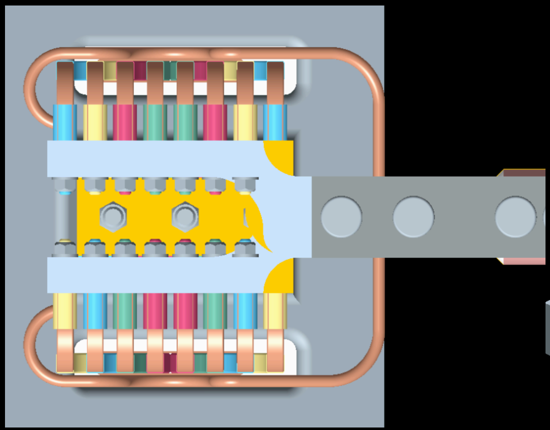
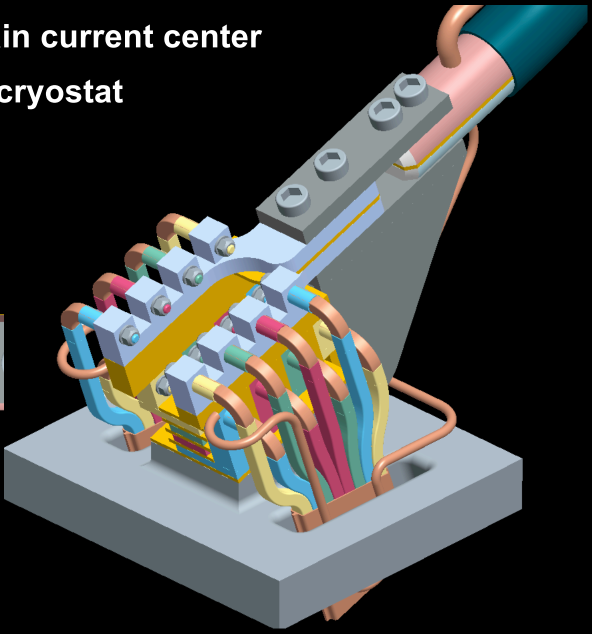
- **Stainless steel clamps (48 per coil) support EM loads and preload winding pack to structure**





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

Design Evaluation

Design analysis has been completed for

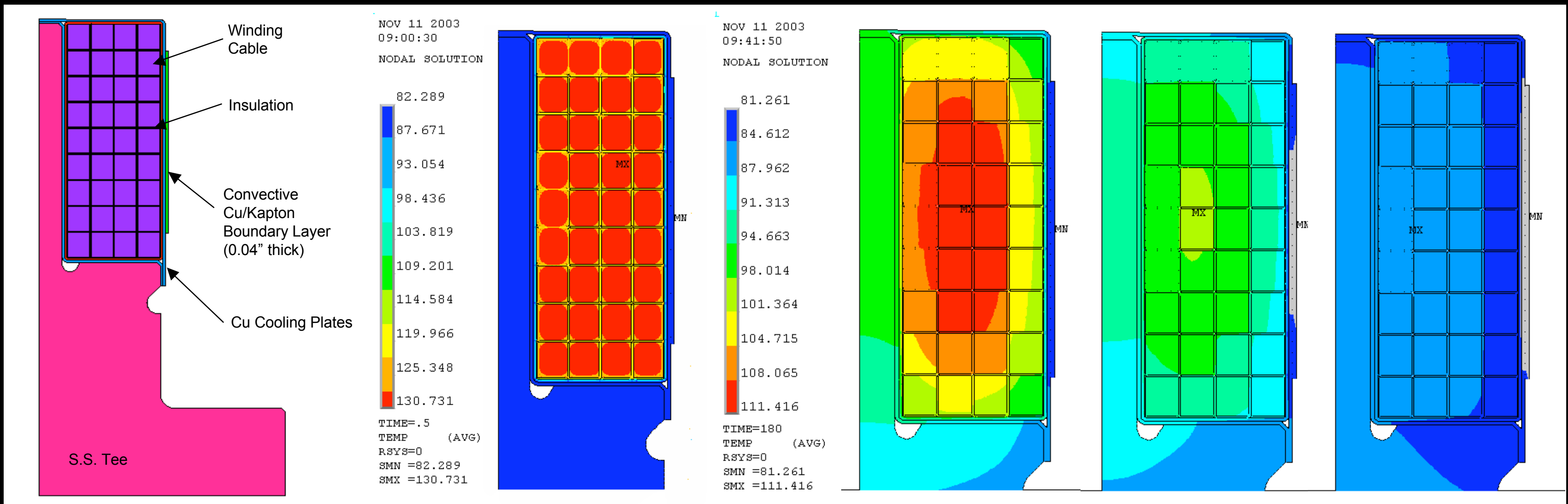
- Coil and lead field errors
- Eddy currents in modular coil structure
- Thermal and thermo-hydraulic response
- Electromagnetic field and forces
- Stress due to thermal and electromagnetic loads

Structural analysis models:

- Linear global deflection and stress in the winding forms
- Nonlinear behavior of coil and winding form interaction

Thermal Performance

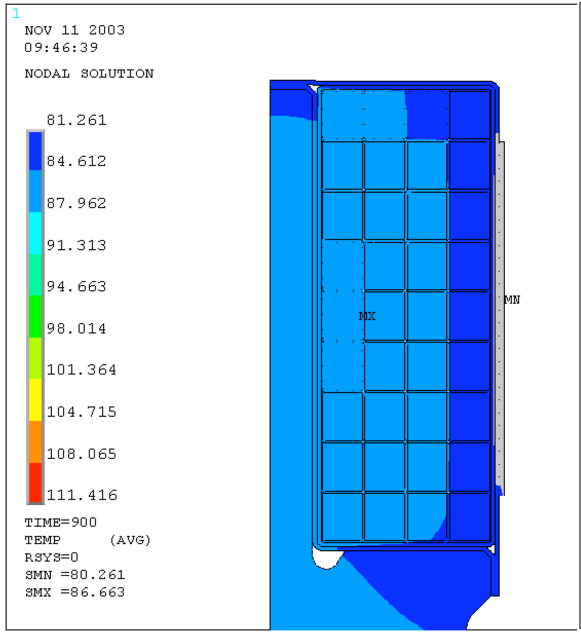
- Transient 2D analysis of cooling after adiabatic heating to 130-K during pulse
- Initial temp = 85-K, cooling by conduction to trace-cooled copper chill plates
- Analysis shows cooldown in 15-min, with most heat removed after 7-min

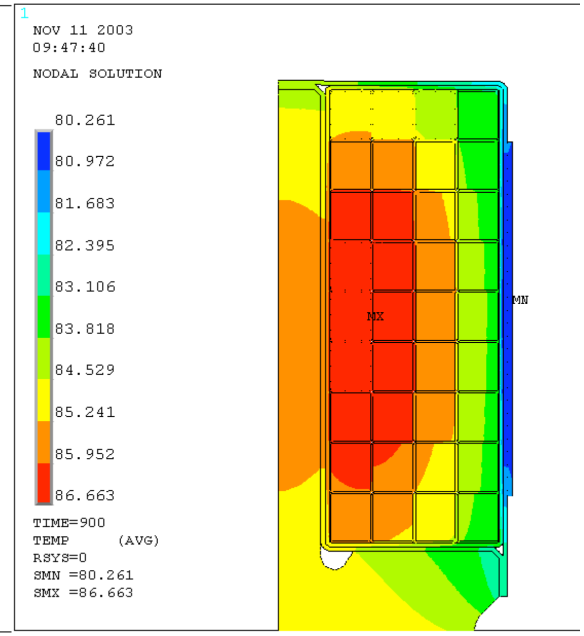


Analysis Model | Temp at End of Pulse | 3 minutes | 7 minutes | 15 minutes

Temperature After 15-min

Gradient at end of 15 minute cool-down is only 3 K within winding pack



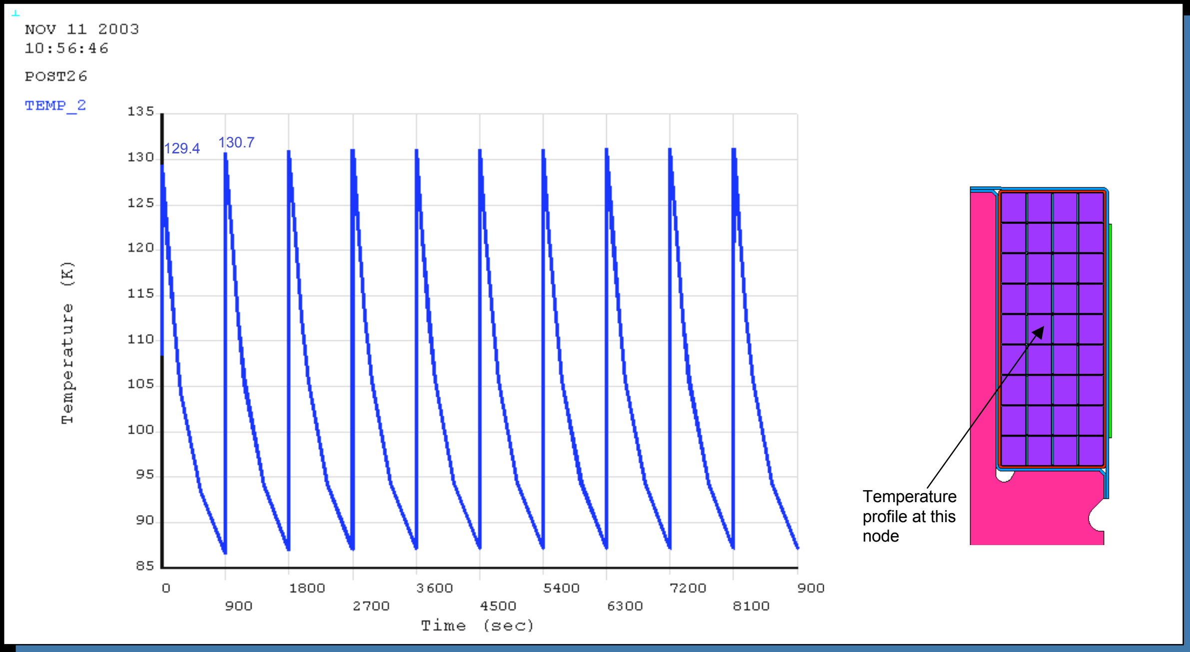


Same Scale as previous at 15-min

Automatic Scale at 15-min

Temperature After 10 Cycles

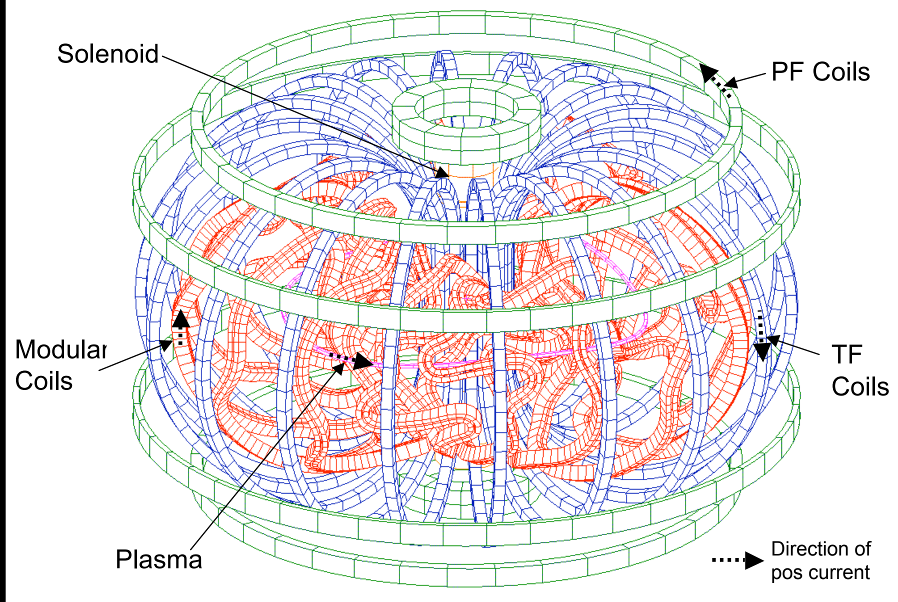
Minimal ratcheting on subsequent cycles (< 1 deg K)



Electromagnetic Loads Analysis

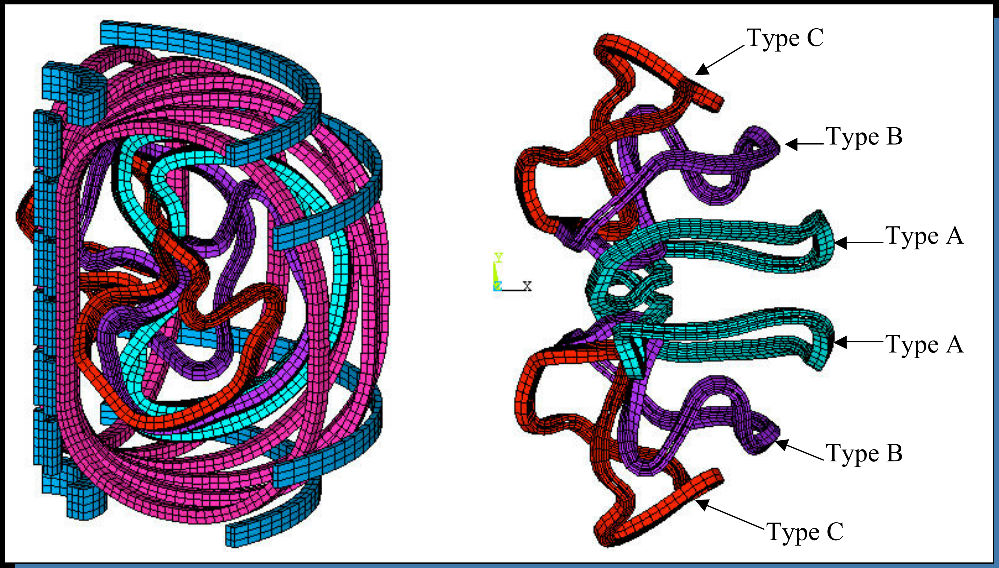
- Two independent calculations have been performed using ANSYS, MAGFOR codes
- Seven reference scenarios examined at time step with maximum modular coil current
- Scan of possible coil currents for a more severe fault load condition also conducted

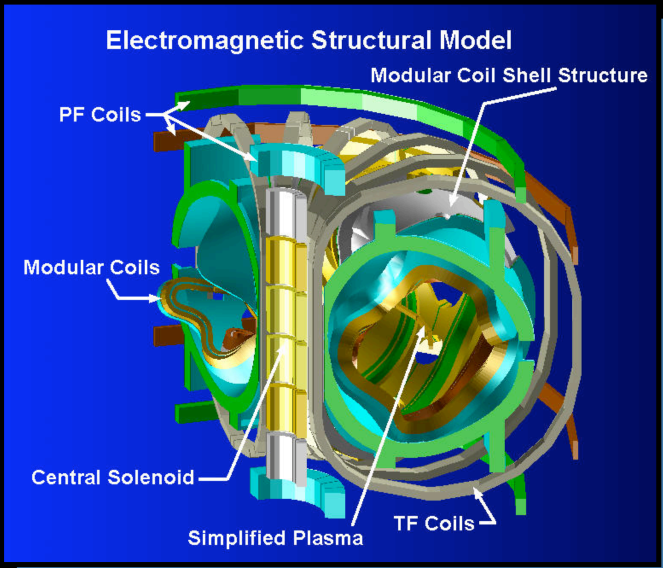
		Maximum Current / Coil for Reference Scenarios (kA)						
Circuit	Coil Set	0.5-T 1st Plasma	Field Mapping	1.7-T Ohmic	1.7-T High Beta	2-T High Beta	1.2-T L. Pulse	320-kA Ohmic
1	TF	13	13	43	45	53	30	26
2	PF1	673	0	1479	1120	1340	1191	1632
	PF2	673	0	1479	1120	1340	1191	1632
3	PF3	673	0	1286	998	1208	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	A	224	224	763	763	818	539	695
8	B	209	209	710	710	831	501	707
9	C	188	188	638	638	731	451	621



MAGFOR Analysis Model

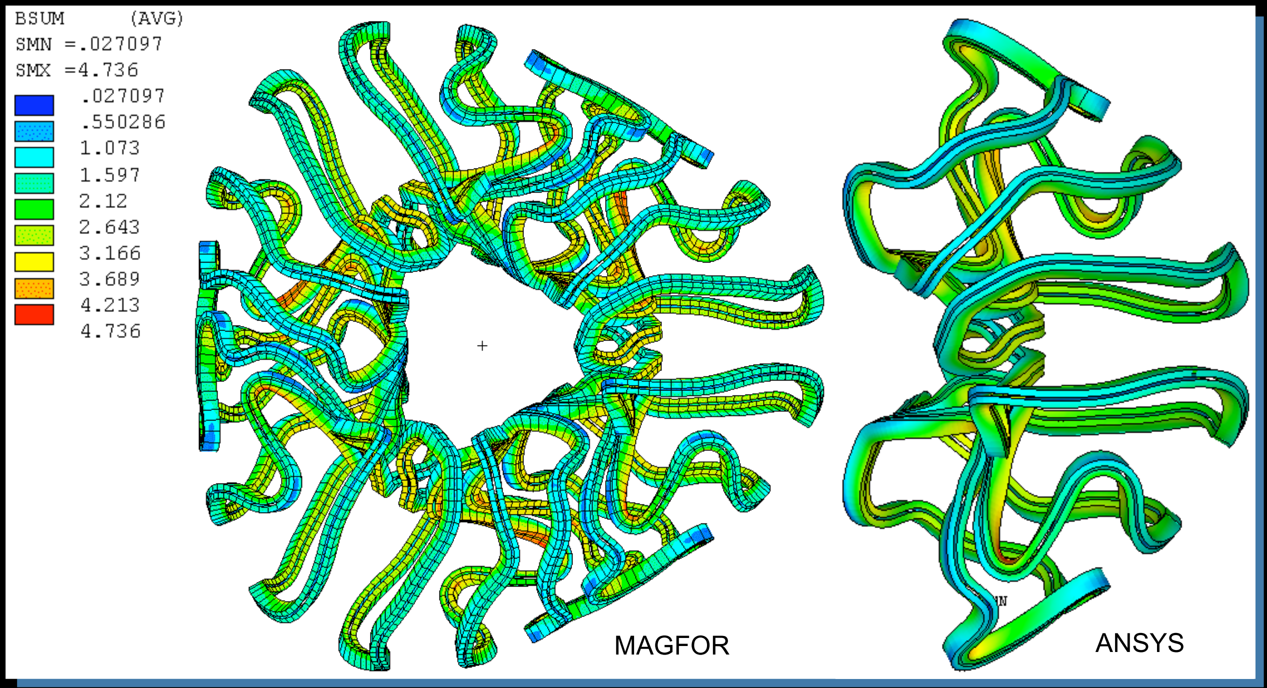
ANSYS EM Models





Magnetic Field Distribution

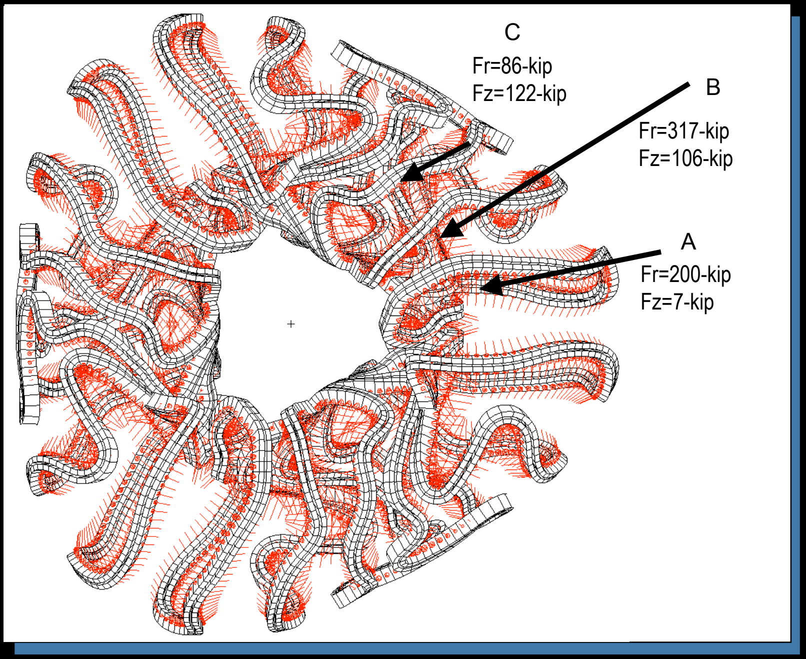
- Maximum magnetic flux density at windings is 4.7-T for 2-T reference scenario
- ANSYS, MAGFOR results differ by ~4% due to mesh and integration differences



Force Distribution

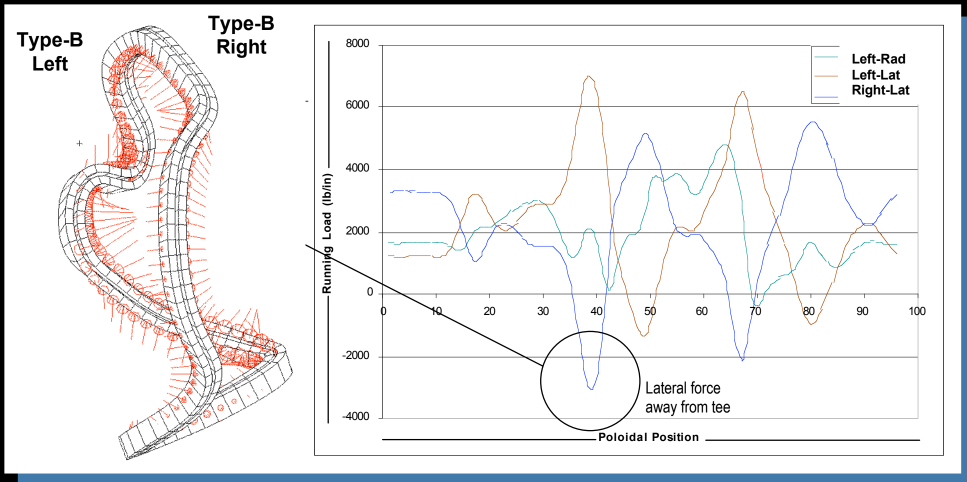
- Force distribution indicates large centering force up to 317-kip (1.4-MN) per coil
- Net vertical load up to 122-kip (.5-MN)
- 2T case much more severe than other operating scenarios

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



Force Details

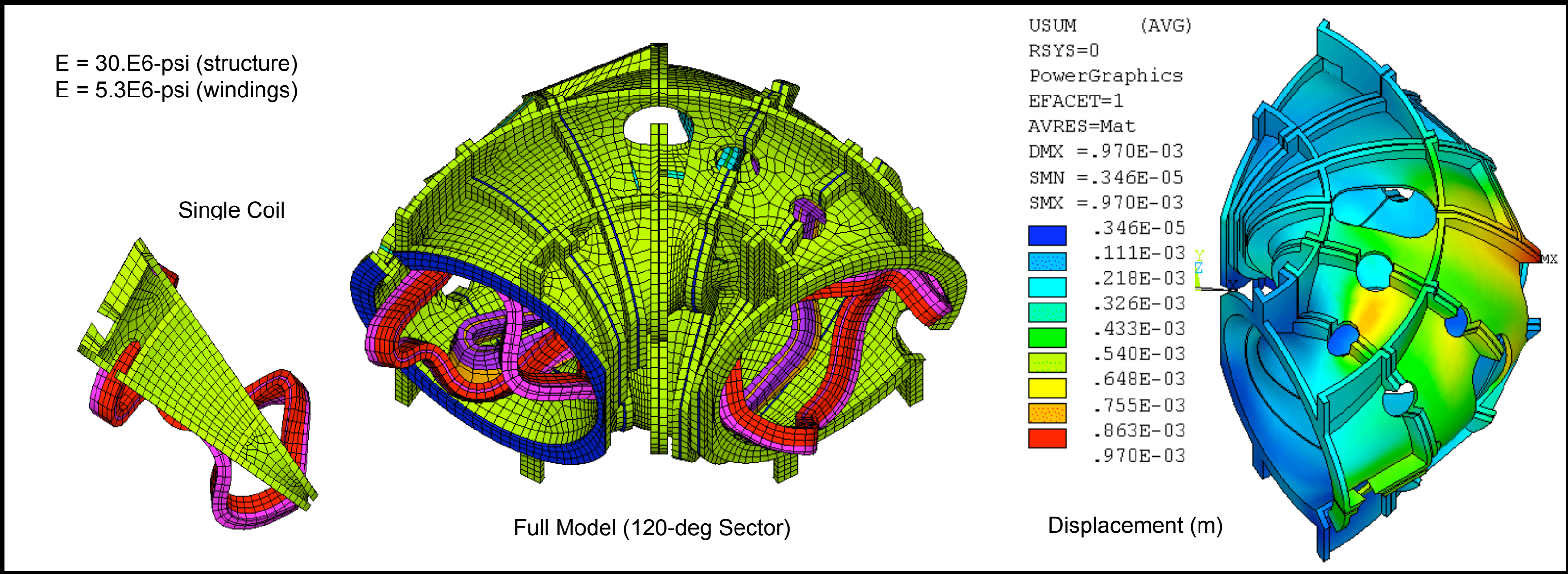
- Forces have been resolved into “radial” (away from plasma) and “lateral” (toward tee web) directions
- In general, radial load is toward structure and lateral load is countered by equal force in other wp
- Sharp bends can result in lateral force away from tee; reacted by clamps and beam behavior of 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
A	Rad Load (lb/in)	200	8	2272	2279	2869	1134	2053
	Lat Load (lb/in)	434	17	4995	4997	5831	2490	4163
B	Rad Load (lb/in)	351	14	4077	4076	5591	2031	4050
	Lat Load (lb/in)	430	17	4982	4983	6982	2483	5059
C	Rad Load (lb/in)	233	9	2698	2698	3540	1344	2615
	Lat Load (lb/in)	418	17	4830	4830	6405	2407	4552

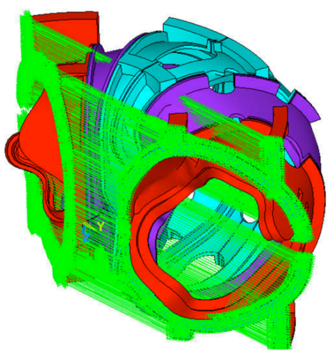
Global Deflection and Stress

- 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 MCWF

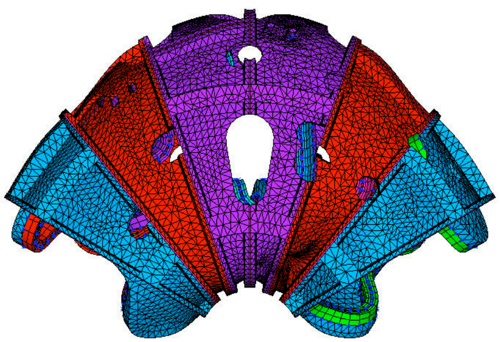


Four Analyses Models Assess Structural Behavior

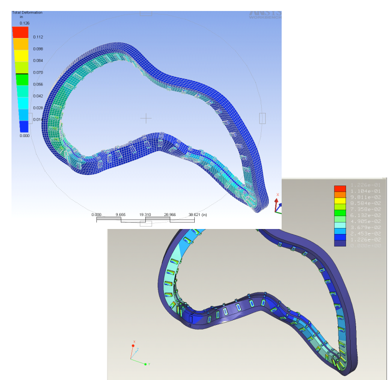
- **Less detailed, linear, 120 degree sector of shell and windings, windings attached to shell**
- **More detailed, linear, 120 degree sector of shell and windings, windings attached to shell**
- **Non-linear, single coil models with windings sliding on rigid shell**
- **Non-linear, single coil models with windings sliding on finite stiffness shell**



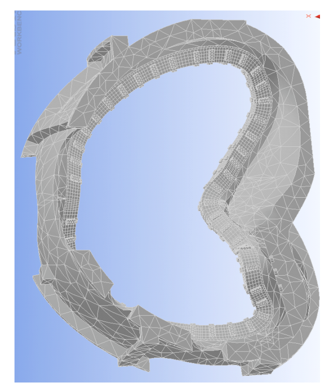
Less detailed linear model
Showing coupling constraints
Ref Len Myatt



More detailed linear model
Includes poloidal breaks
Ref HM Fan



Non-linear model with rigid shell,
sliding winding packs, clamps, preload
Ref K Freudenberg



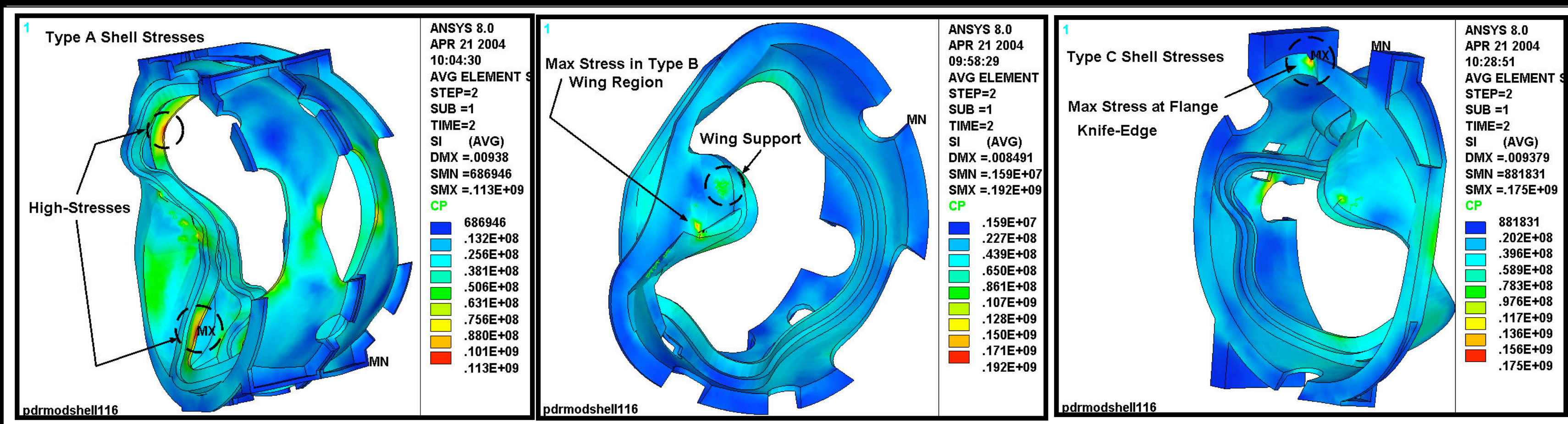
Non-linear model with finite stiffness shell,
sliding winding packs, preloaded clamps
Ref K Freudenberg

All Models Show Margin on MCWF Stress

NCSX

- Stress concentrations around modeling discontinuities, constraints
- Allowables based on minimum specified, expect much better properties in real parts
- MCWFs show no stress problems

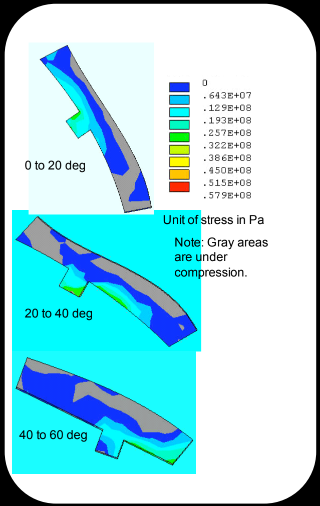
	Linear analyses			Non-linear analyses		
	membrane stress (ksi)	membrane + bending (ksi)	peak stress (ksi)	membrane stress (ksi)	membrane + bending (ksi)	peak stress (ksi)
Allowable stress	35	52	104	35	52	104
Coil type A	7	11	36		13	25
Coil type B	11	28	43		25	39
Coil type C	15	25	39		19	32
minimum factor of safety	2.3	1.9	2.4		2.1	2.7



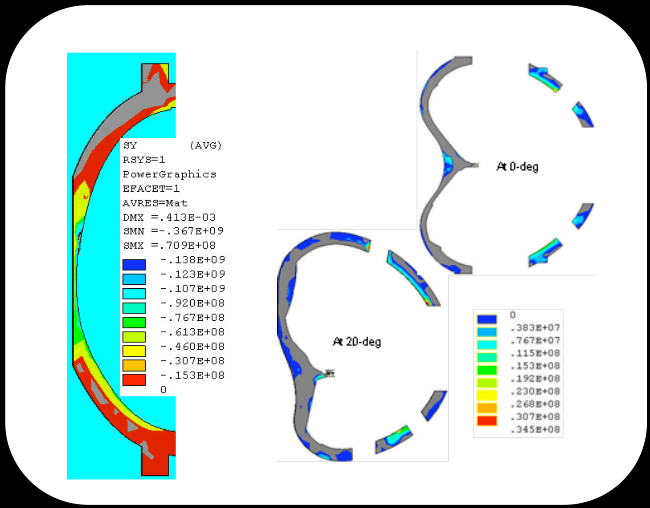
Figures per Len Myatt

Bolted Joints have margin

- Two types of bolted joints, poloidal break and toroidal connection flanges
- All joints use 1.375 x 6 UNC A-286 alloy studs and 12 point nuts with G11-CR insulation
- Poloidal breaks all have 7 pre-loaded studs
- Toroidal Connection flange bolt patterns vary from 20 at the A-A joint to 32 at the C-C joint, inboard region always in compression



	poloidal break	toroidal flanges
Preload at room temperature (lbs)	68700	68700
Preload at LN2 temperature (lbs)	46700	45800
applied load, max per stud (lbs)	30000	40000
bolt load, max (lbs)	51100	50500
Max stress at temperature (ksi)	44	44
Allowable stress at temperature (ksi)	87.5	87.5
Factor of safety	2	2
Alternating stress (ksi)	2.2	2.35
G11-CR stress (ksi)	10.5	10.5
Allowable stress at max load (ksi)	50	50
factor of safety	5	5

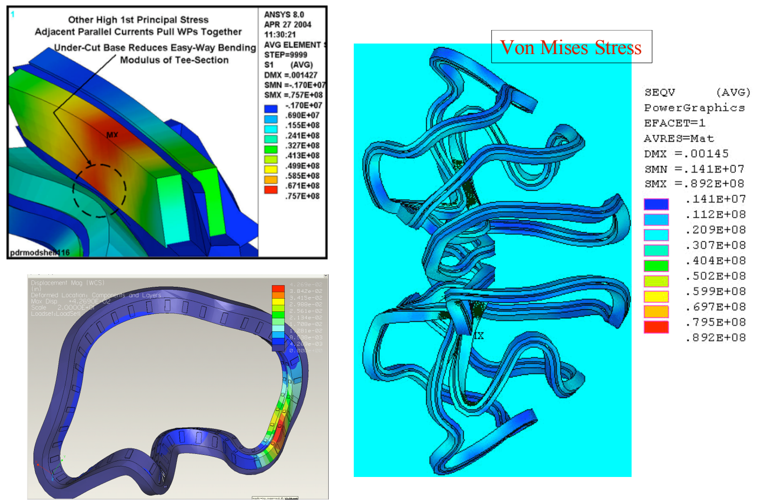


Figures per HM Fan

All models show margin on winding pack stress, strain

- Winding pack strain tracks MCWF for linear models, depends on modulus of winding
- Tests show smeared modulus should be about 9.1 Msi at LN2 temperature
- Models indicate similar results, winding has positive margin

Modular Coil winding stress summary									
	linear analyses			non-linear analyses rigid shell			non-linear analyses finite stiffness shell		
	membrane stress (ksi)	membrane + bending (ksi)	max strain **	membrane stress (ksi)	membrane + bending (ksi)	max strain **	membrane stress (ksi)	membrane + bending (ksi)	max strain **
Allowable, LN2 temp *	14	21	0.0020	14	21	0.0020	14	21	0.0020
Coil type A	7	12	0.0010	7	11	0.0010	11	18	0.0017
Coil type B	11	13	0.0009	8	12	0.0009			
Coil type C	9	11	0.0009	8	13	0.0009			
minimum factor of safety	1.3	1.6	2.0	1.8	1.6	2.0			
* no evidence of yielding at 20 ksi									
** no damage at 130,000 cycles, .002 strain									

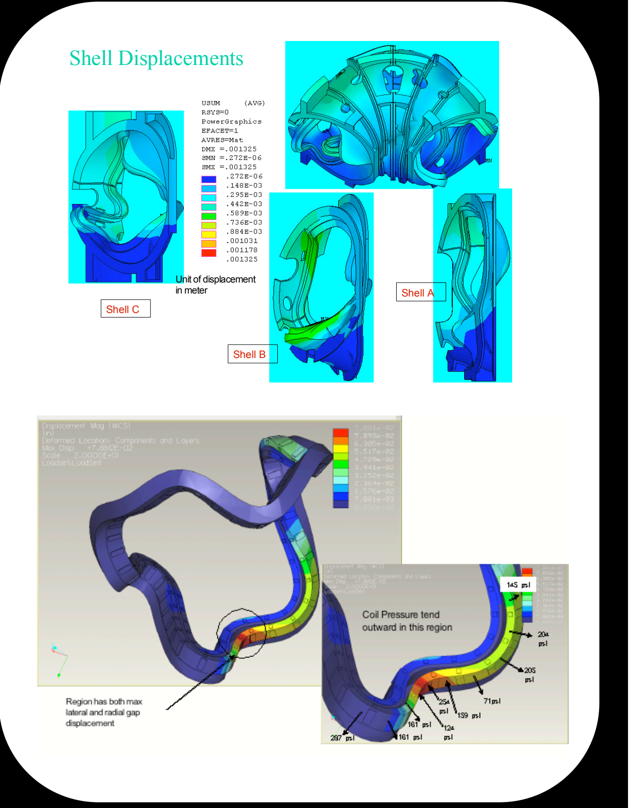


Deflections depend on restraints

- Deflections of linear models show windings tracking shell
- Deflections for non-linear models show windings deviating from shell
  – Deflections depend on local shape and initial strain in conductor
  – Clamps help maintain contact in most regions
- All models have deflections less than 2 mm
- Deflected coil shapes used for magnetic analysis

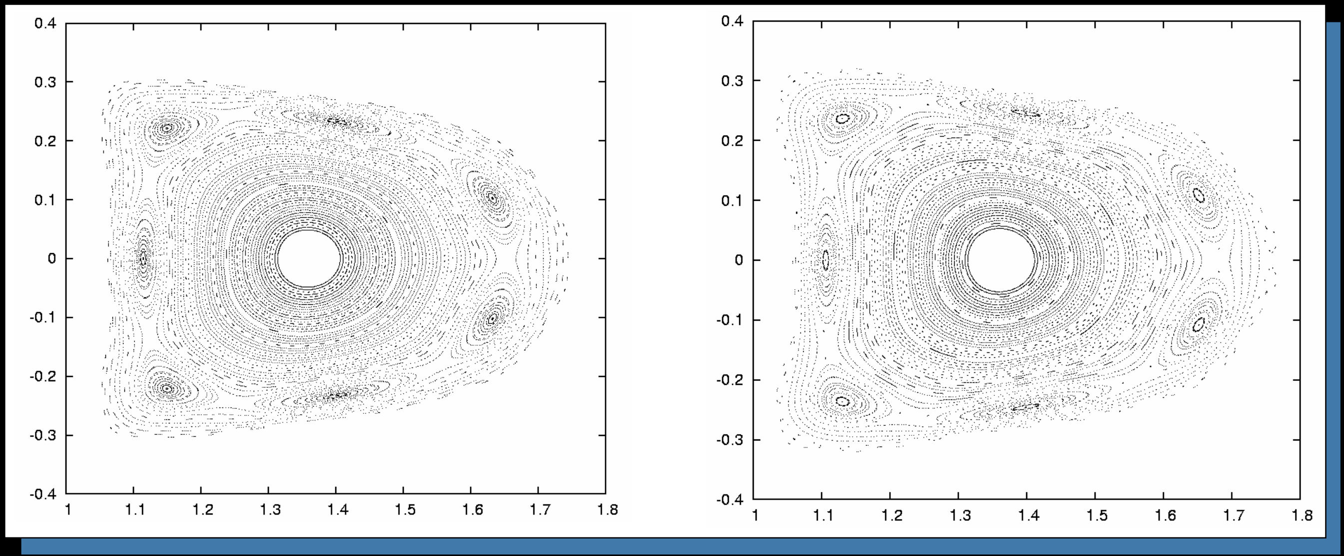
Modular Coil deflection summary

	linear analyses		non-linear analyses rigid shell				non-linear analyses finite stiffness shell			
	winding form (inches)	winding pack (inches)	"tee" web (inches)	winding pack (inches)	lateral gap (inches)	radial gap (inches)	winding form (inches	winding pack (inches)	lateral gap (inches)	radial gap (inches)
Coil type A	0.0280	0.0024	0.0100	0.0150	0.0010	0.0120	0.0700	0.0660	0.0004	0.0100
Coil type B	0.0520	0.0570	0.0300	0.0300	0.0230	0.0070				
Coil type C	0.0250	0.0320	0.0140	0.0780	0.0640	0.0080				



Deflections do not increase island size

- Typical deflected shape analyzed in comparison to theoretical shape
- Vacuum configuration does not change



“perfect” coils

Windings deflected - .06 in.
(2T operating loads)

Structural Analysis Summary

- Worst case loading is 2T, High Beta scenario
- MCWFs are in good shape
  - All models show factor of safety for MCWF of ~ 2, based on minimum allowables
  - Bolted joints have 2+ safety factor in fasteners and insulators
- Winding pack response depends somewhat on modeling assumptions
  - Linear models: winding strain tracks shell strain
  - Non-linear models: winding response affected by initial strain in conductor from cooldown
- Magnetic analysis of deflected shapes indicates no increase in island size
- Detailed, non linear analysis of winding pack will continue, using latest material property data from testing

Winding Form Specification

- Specification NCSX-CSPEC-141-03-00 establishes the manufacturing and acceptance requirements for the 18 winding forms

- Outline of specification:
  - 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

CF-8M		
	Min	Max
Cr	18.00	21.00
Ni	9.00	12.00
Mo	2.00	3.00
Si	---	1.50
Mn	---	1.50
P	---	0.04
Si	---	0.04
Cr	---	0.08

Models and Drawings

NCSX

- Specification of machined part is defined by both models and drawings
- Vendors have demonstrated use of models for casting development and dimensional inspection
- Drawings provide dimensions, tolerances, surface finish, etc which cannot be represented in model

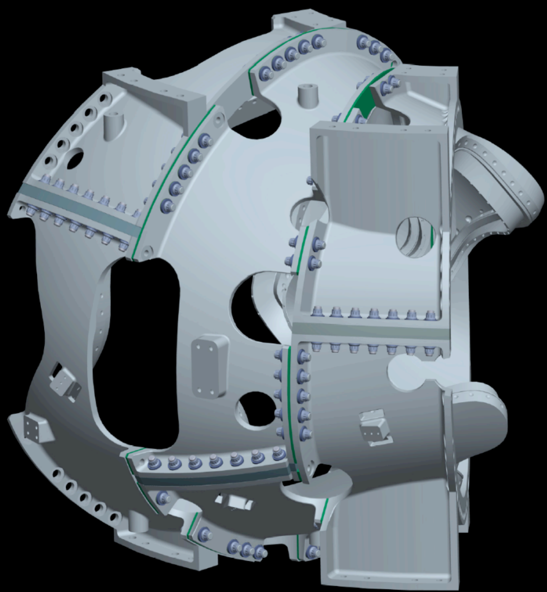
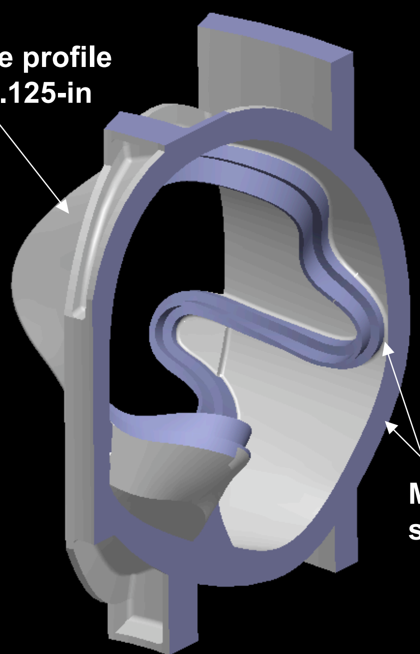


Table 3-3 - Production Winding Form Models and Drawings

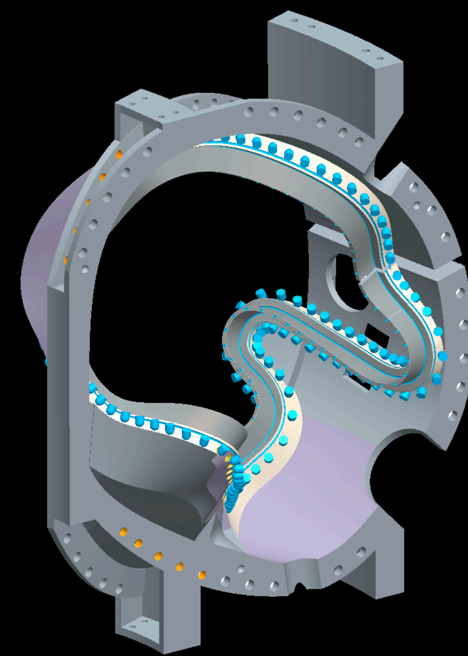
Level	Next Assembly	Find #	Doc / Part #	Type	Rev	Title / Description
1	SE140-101	2	SE141-101	ASM	-	Modular Coil Type-A Winding Form Assembly
1	SE140-102	2	SE141-102	ASM	-	Modular Coil Type-B Winding Form Assembly
1	SE140-103	2	SE141-103	ASM	-	Modular Coil Type-C Winding Form Assembly
2	SE141-101	1	SE141-101_SKEL	PRT	-	Type-A Machining Features Layout
2	SE141-101	2	SE141-114	PRT	-	Type-A Winding Form, 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, 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, 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, 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, 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, SS
2	SE141-103	5	SE141-075	PRT	-	Type-C Poloidal Break Upper Insulator, G11CR

Use of Model Data during Prototype Development



• Identify surface tolerances

• Compare “stocked” model to part



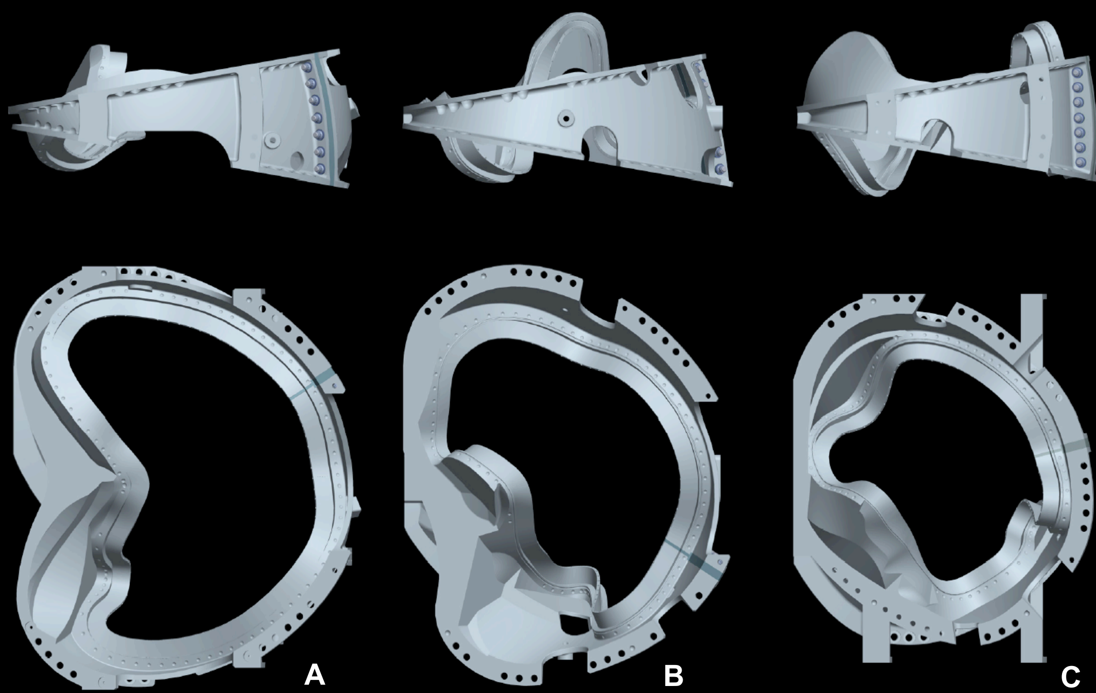
• Extract machined features as “tool solids”

Production Winding Forms

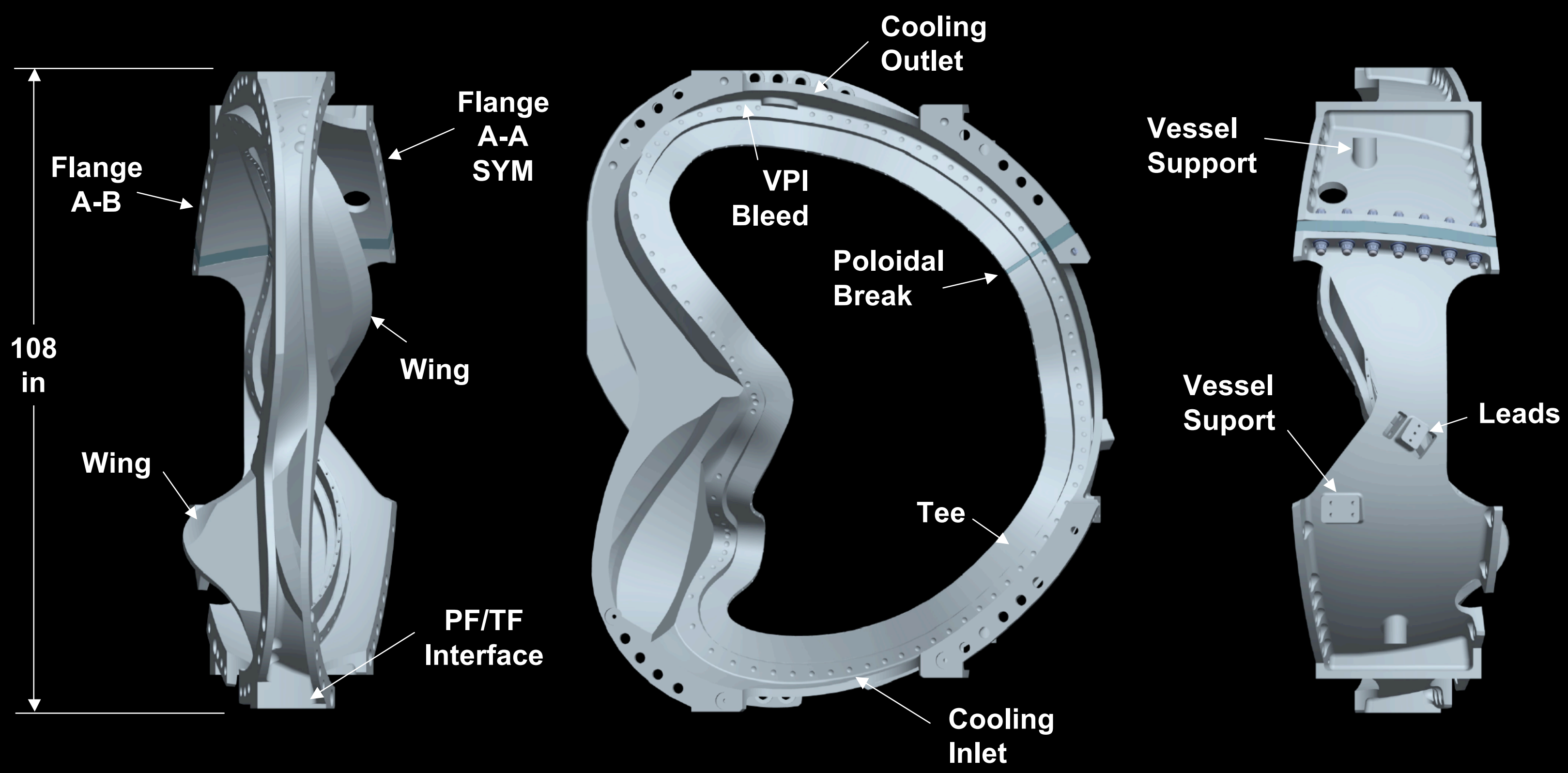
NCSX

- Order of production is Type-C, A, B
- Type-C varies slightly from prototype:
  - Port openings adjusted
  - Clamp position adjusted
  - Leads hole made smaller

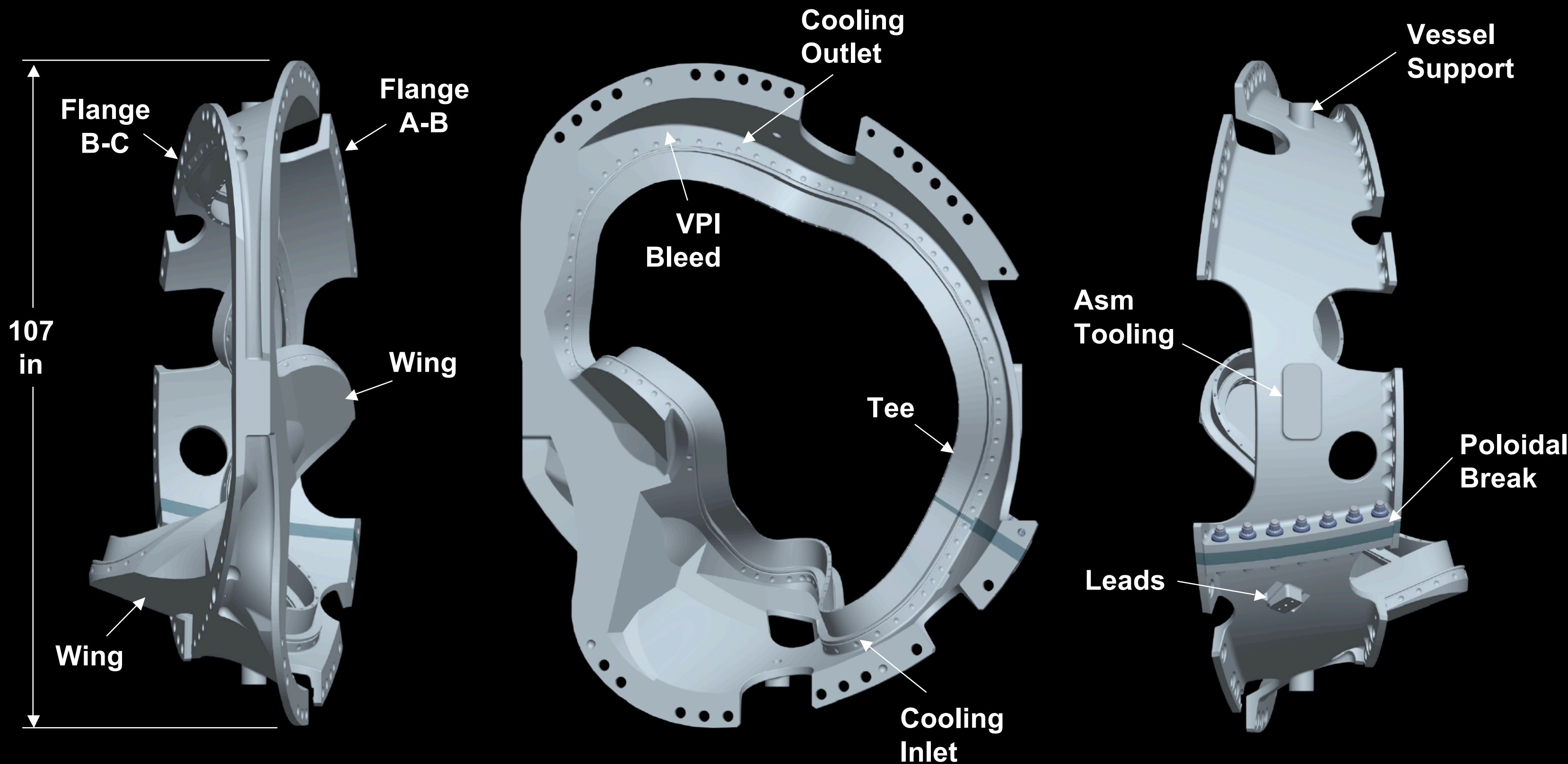
Modular Coil Asm Weight (lb)			
	Type-A	Type-B	Type-C
Winding Form	4940	4376	5051
Coil Winding	1001	973	810
Cooling / Clamps	214	212	208
Total	6155	5561	6069



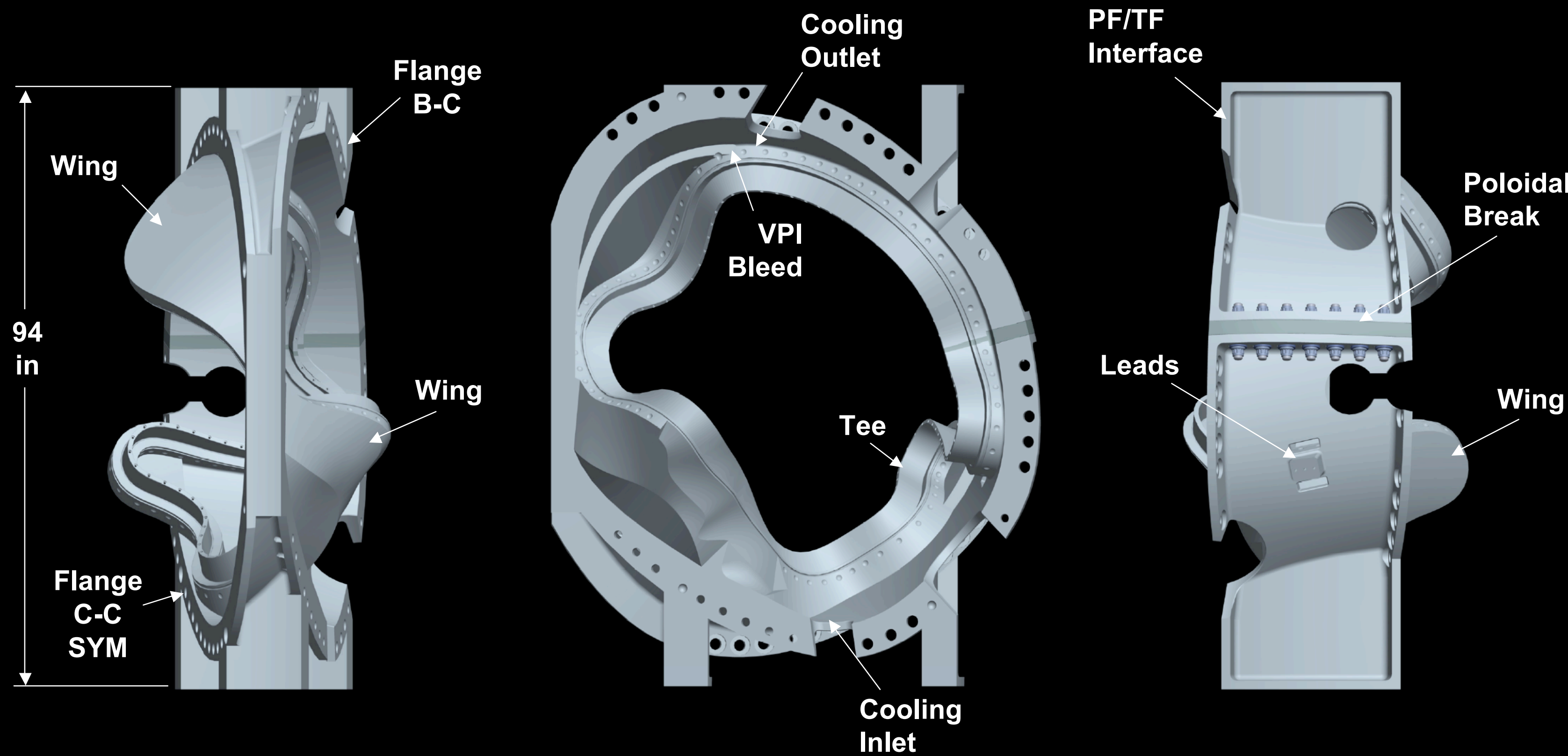
Type-A Assembly



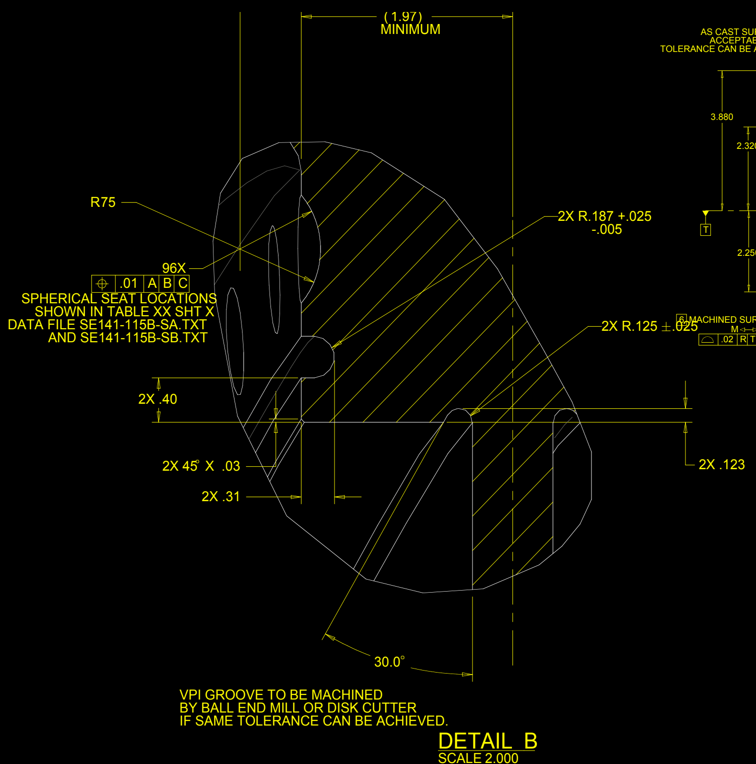
Type-B Assembly

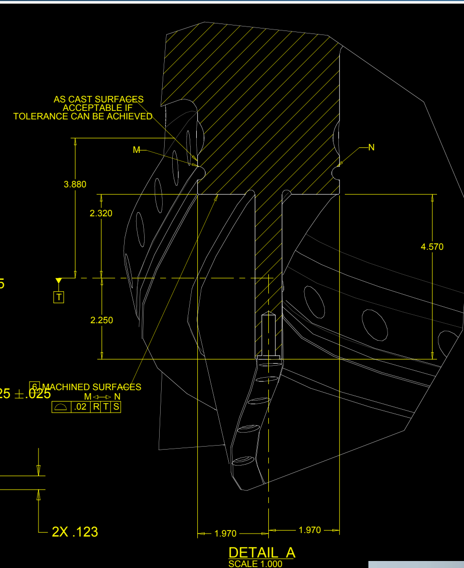


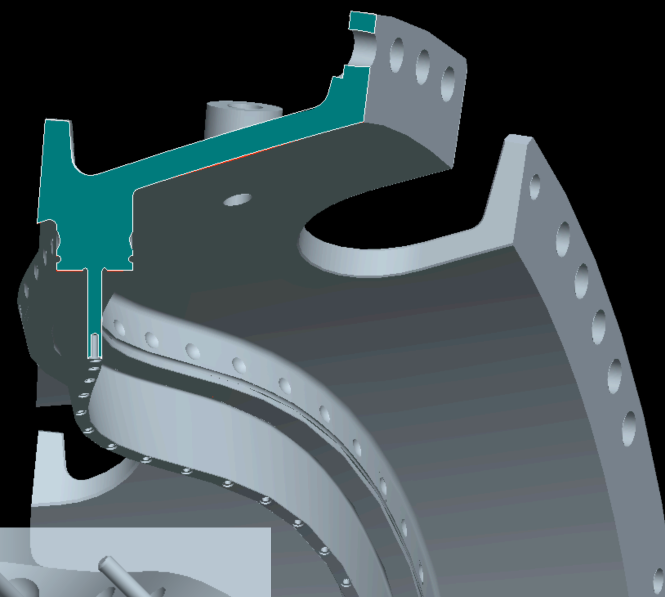
Type-C Assembly

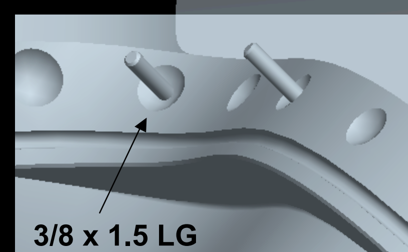


Tee Machined Features



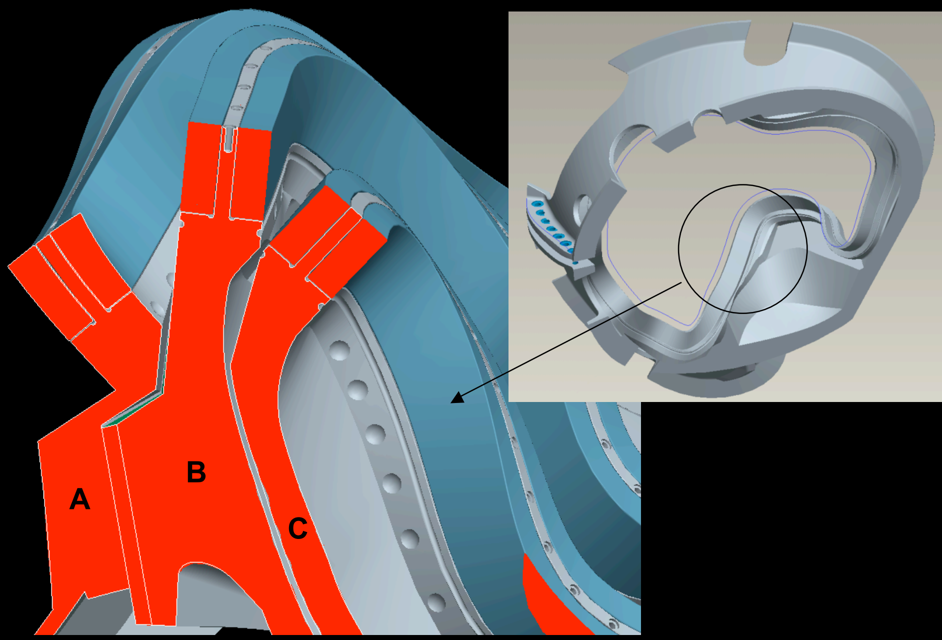


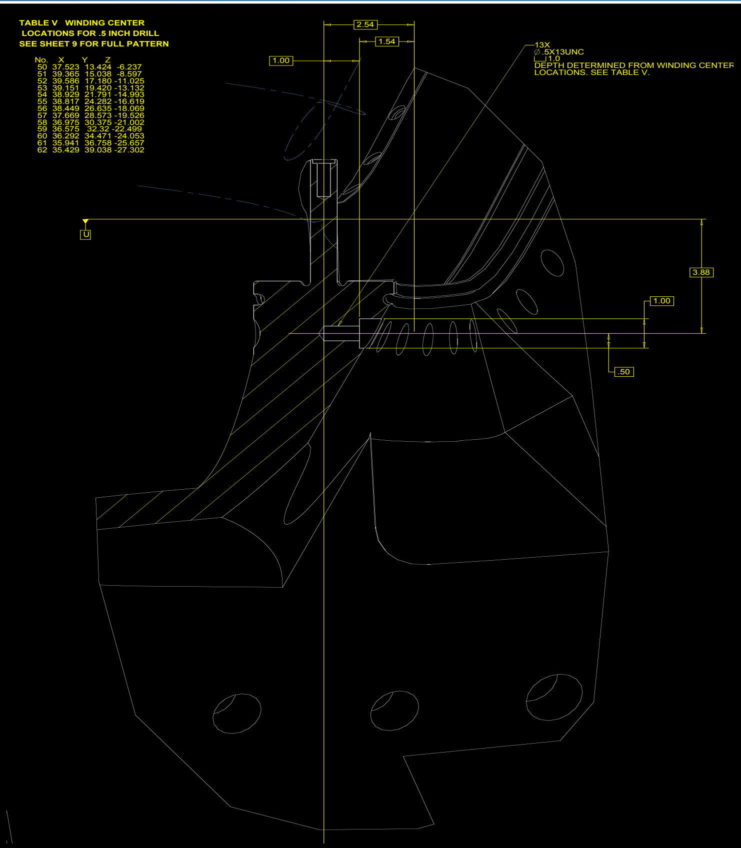




Cut Away Tee Region

- Coil assembly requires cuts that interrupt tee base features
- Part includes .5-dia x 1-in deep countersunk holes, aligned to standard holes in base and web, for winding clamps

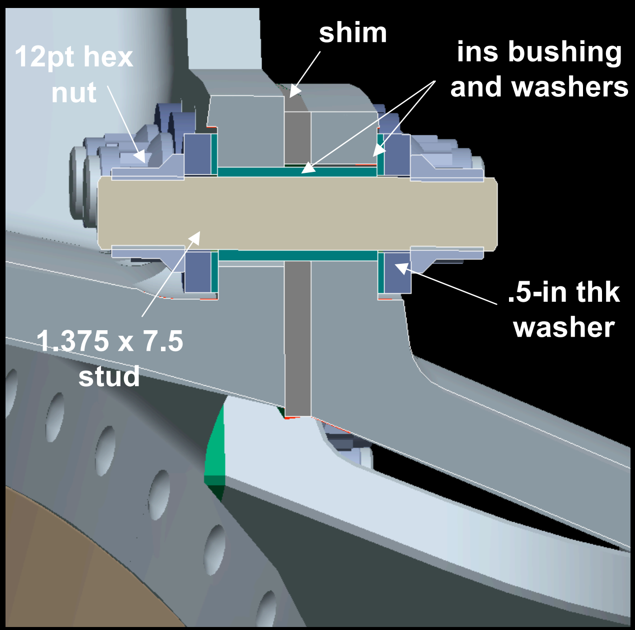


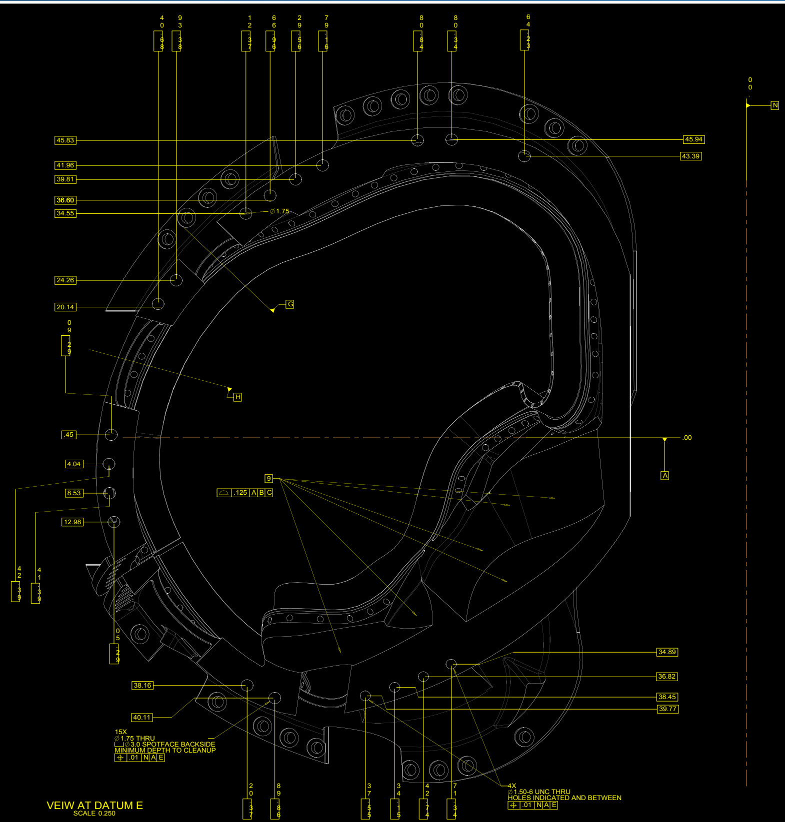


No.	X	Y	Z
50	37.523	13.424	-6.237
51	39.365	15.038	-8.597
52	39.586	17.180	-11.025
53	39.151	19.420	-13.132
54	38.929	21.791	-14.993
55	38.817	24.282	-16.619
56	38.449	26.635	-18.069
57	37.669	28.573	-19.526
58	36.975	30.375	-21.002
59	36.575	32.32	-22.499
60	36.292	34.471	-24.053
61	35.941	36.758	-25.657
62	35.429	39.038	-27.302

Toroidal Flanges and Bolting

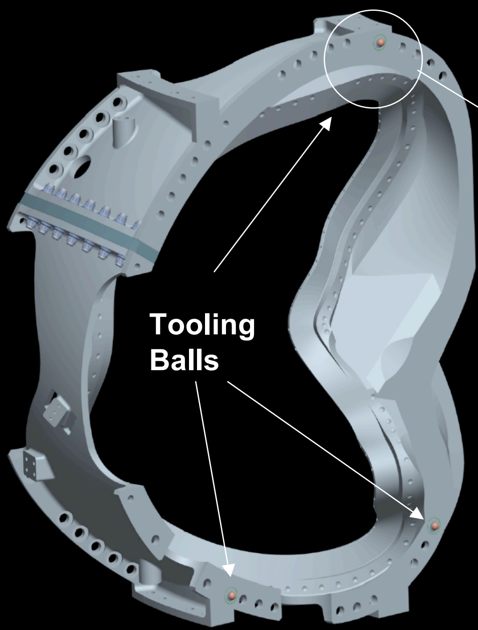
- Hole size = 1.875-in dia, 0.5-in larger than bolt asm
- Back spotface 3.25-in dia x min depth
- Flange flatness, hole tolerance = 0.01-in

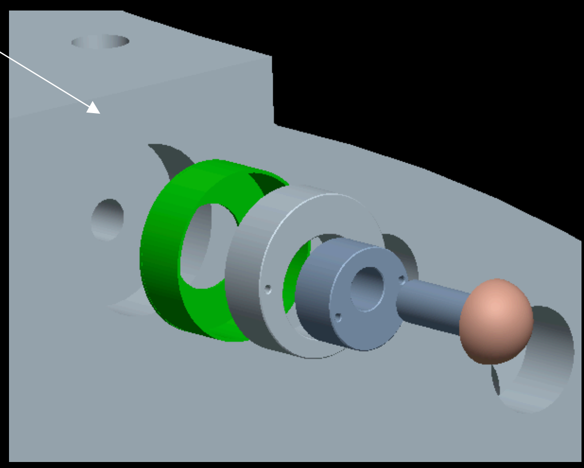




Tooling Ball Positioner

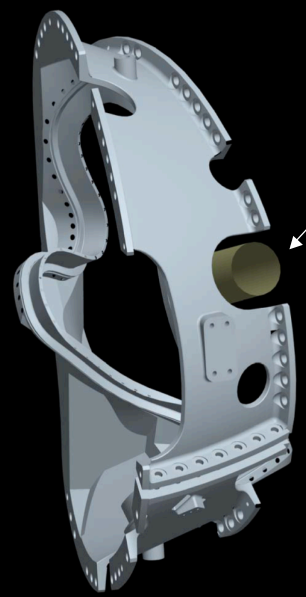
- Flange machining includes 3-in dia socket and mating spherical seat for coil-coil alignment tooling
- Double-eccentric positioner used to place coil assemblies for shim measurement and fabrication
- Flanges A-B and B-C have 3 positioners, symmetry planes (A-A, C-C) have six

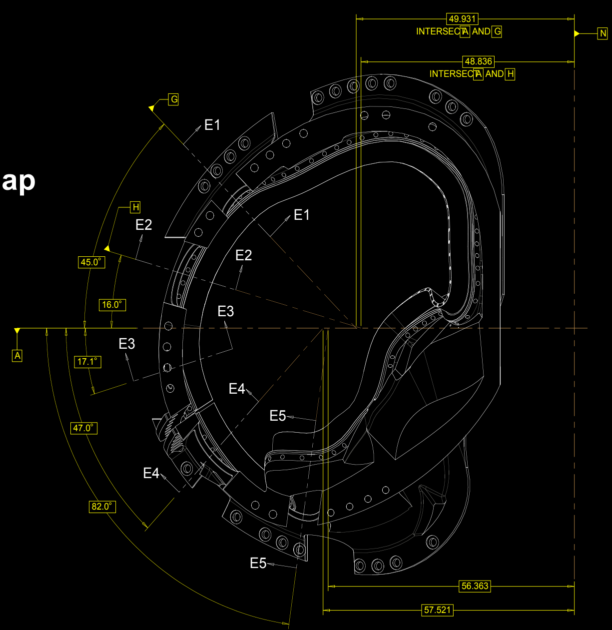


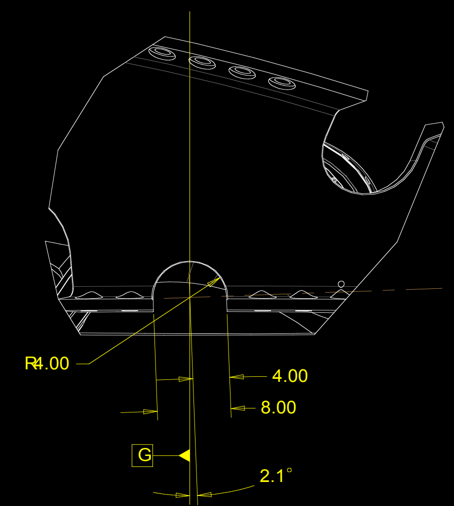


Port Openings

- There are ~7 port openings in each winding form, position defined by angles to the plasma magnetic axis
- Larger ports may be cast in, but size and shape would likely interfere with metal flow
- Drawing establishes locating dimensions at RT, position tolerance of 0.03-in

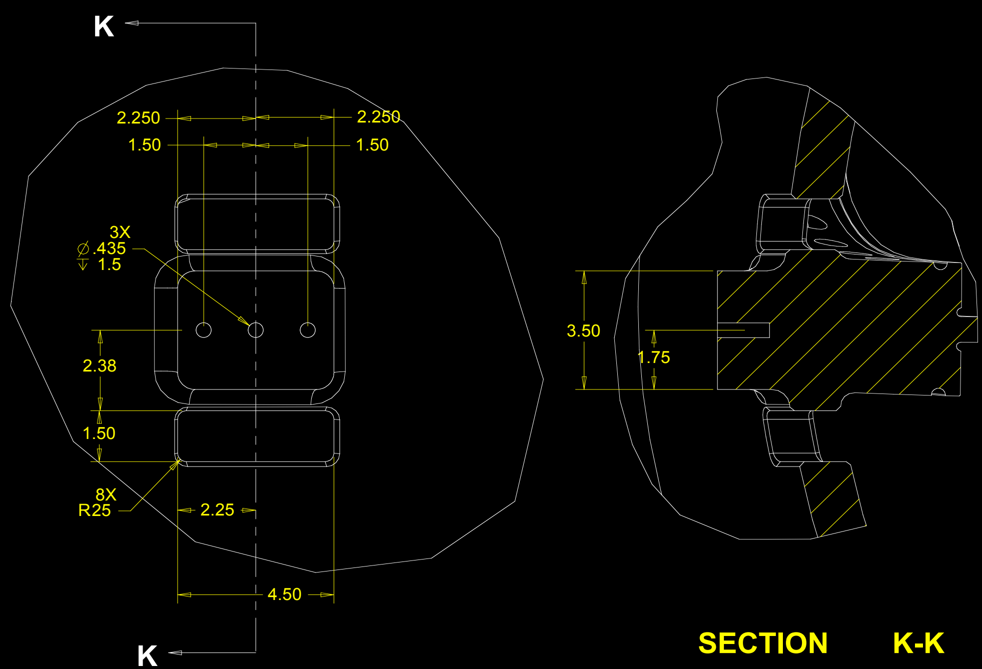


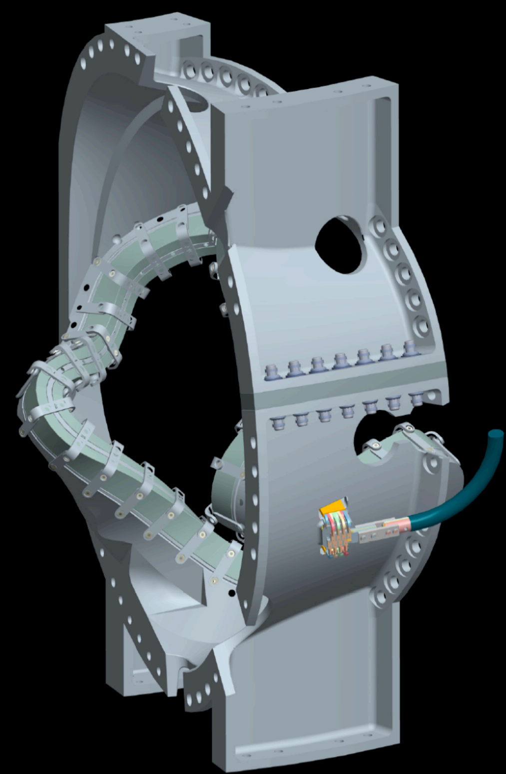




Electrical Leads

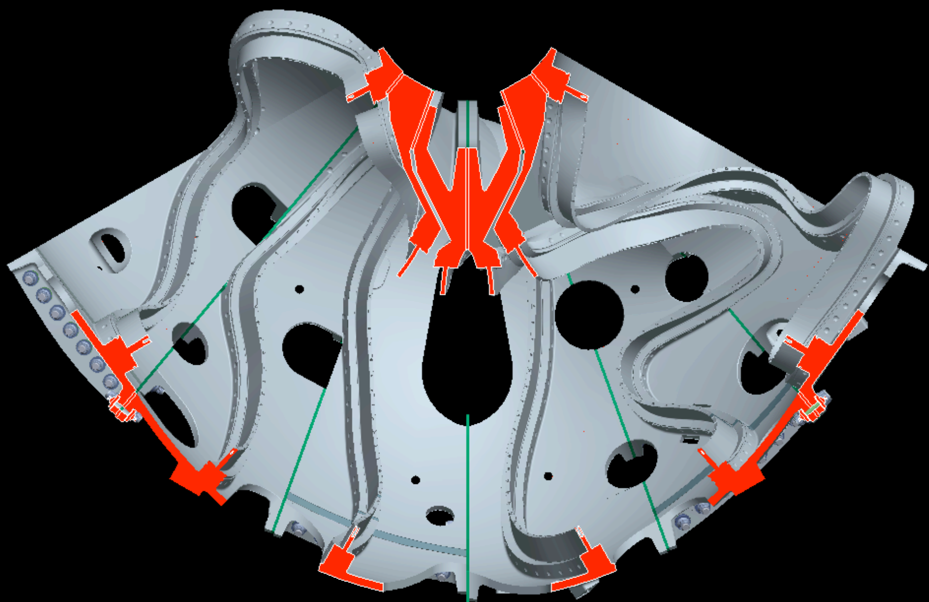
- Rectangular opening in winding forms near outboard midplane

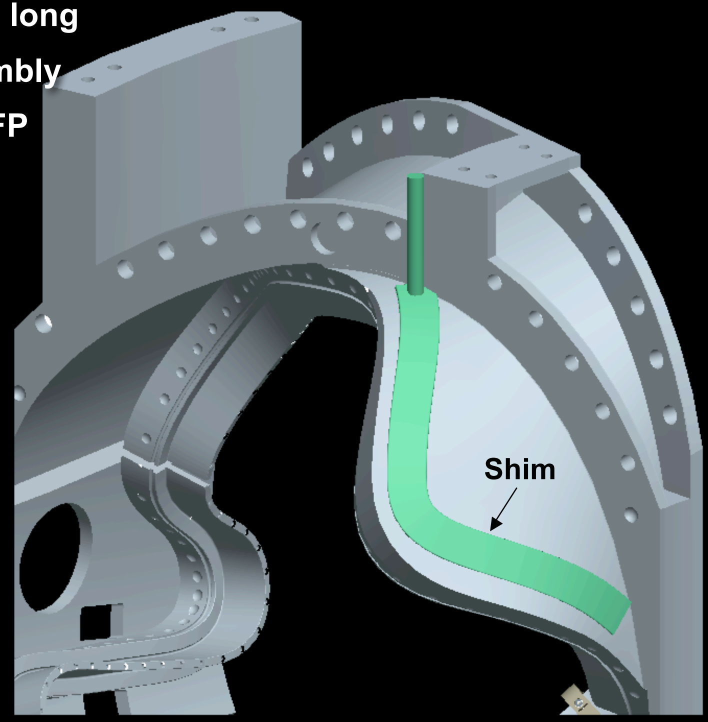




Wing Shims

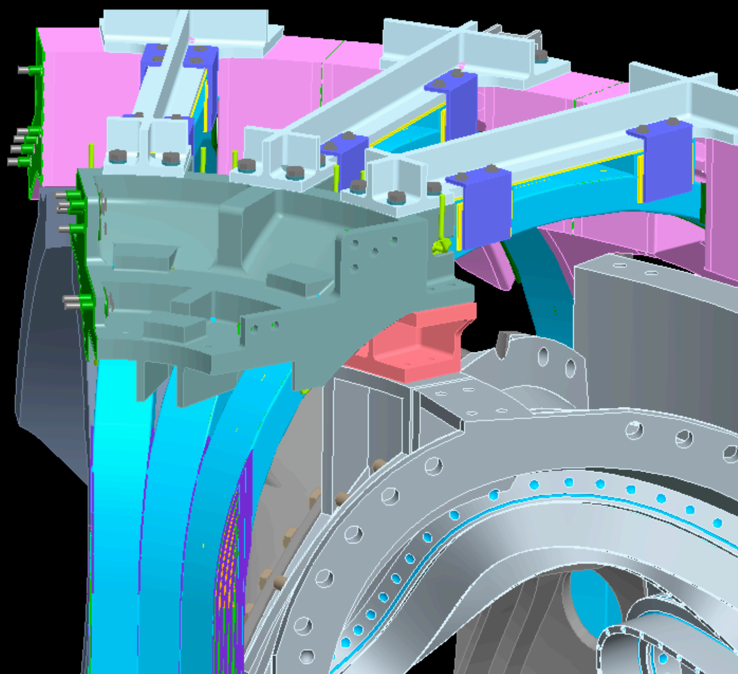
- Structural analysis indicates need to tie coil “wings” to adjacent winding form to minimize deflection
- Plan to use epoxy-filled thin metal pillow shims, 4-in wide x ~30-in long
- Wing outer surface machined to .125-in profile tolerance for assembly
- Trough cut for shim not presently in model, to be added before RFP

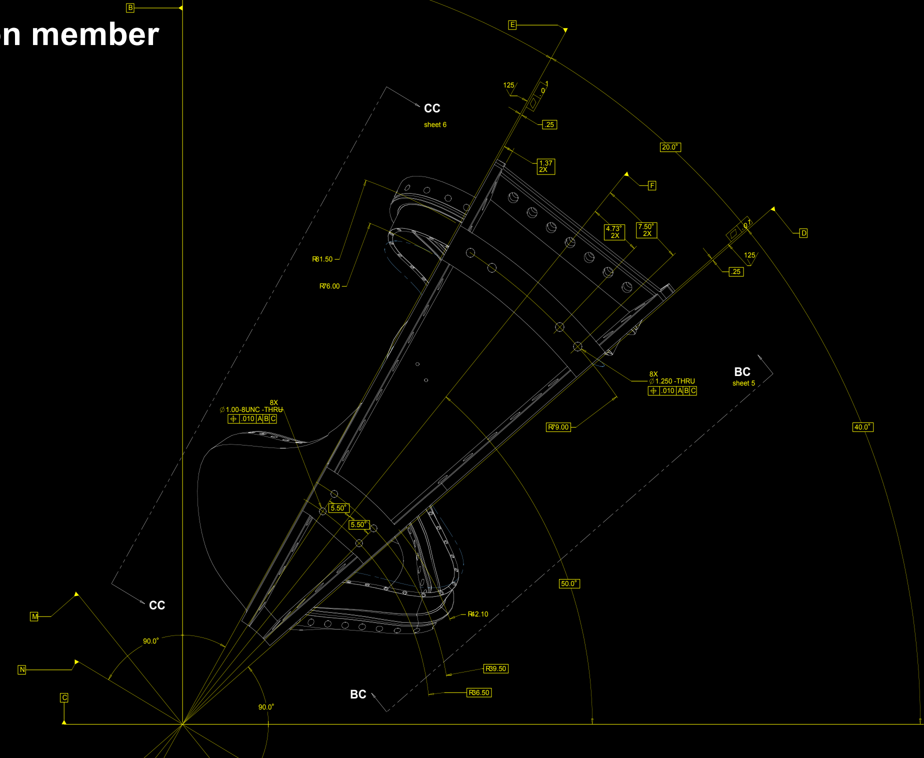




Structural Supports

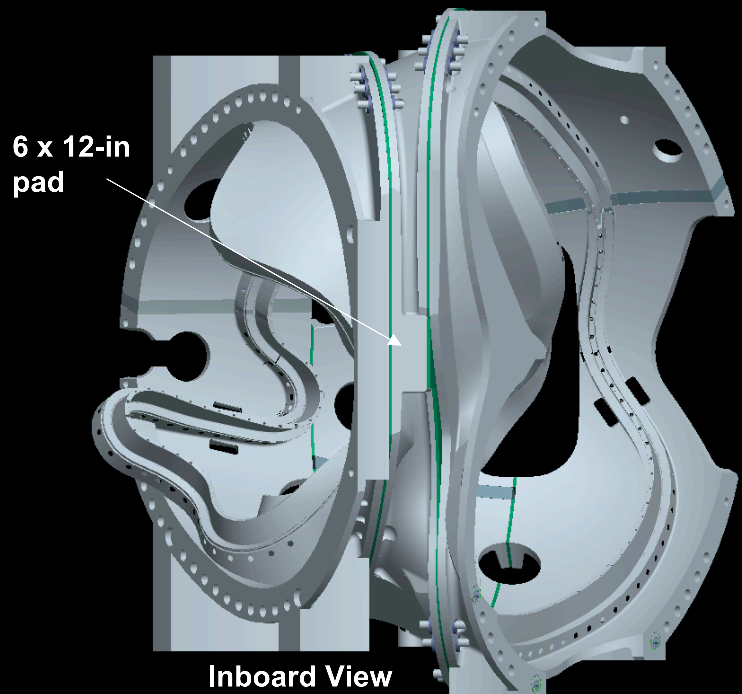
- Up/dn symmetric supports are close to shell to improve casting, assembly access
- Connection to support structure requires transition member

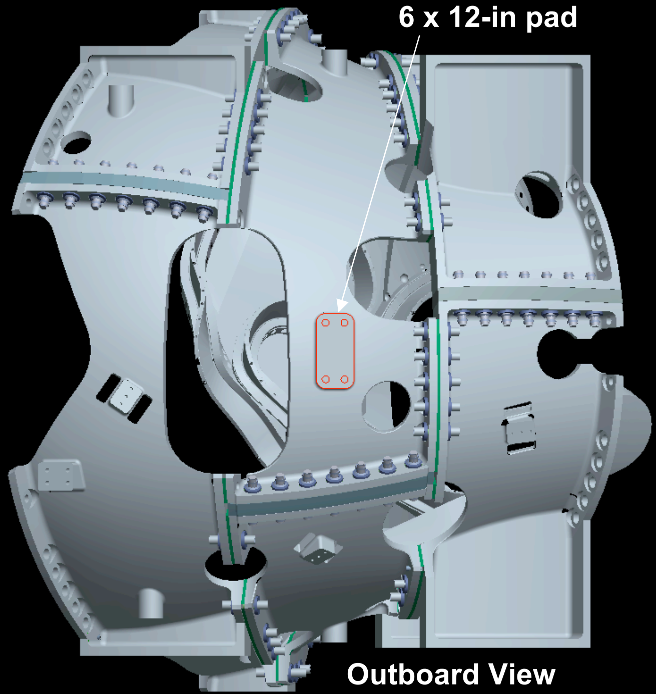




Assembly Fixture Mount

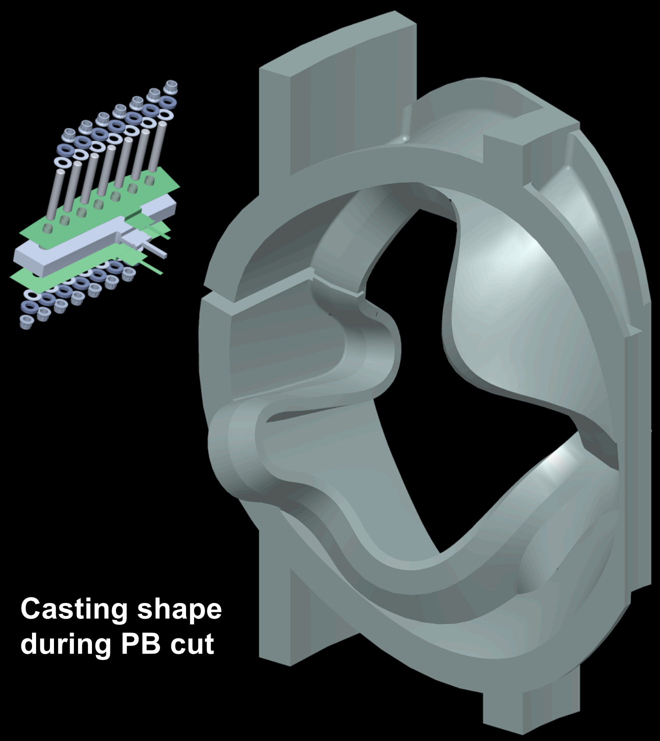
- Half field period assembly mounts to fixture at inboard / outboard midplane



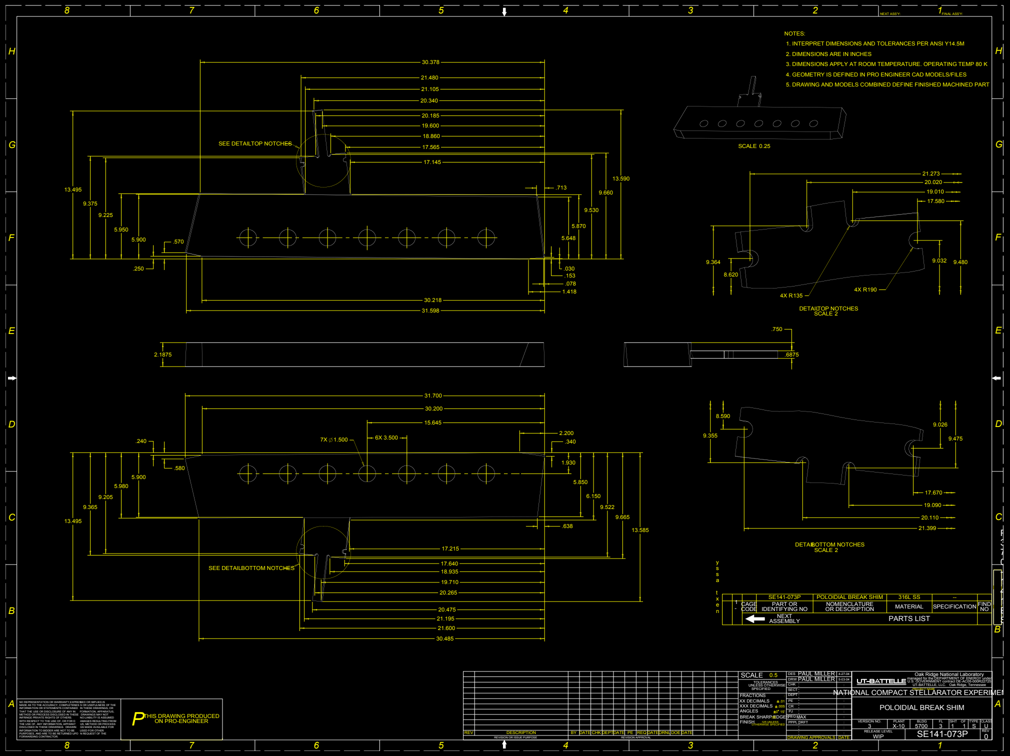


Poloidal Break Asm and Parts

- Drawing represents finished dimensions of stainless steel plate



Casting shape during PB cut



Verification and Inspection

- Supplier is responsible for verification of requirements:
  - Chemical composition
  - Mechanical properties
    - As heat-treated condition, at RT and 77K
  - Magnetic permeability
    - Flange faces and edges checked by Severn Gage on 4-in grid
    - Weld repair areas checked every 2-in, multiple locations
    - Other surfaces checked on 6-in grid
  - Dimensional inspection
    - Machined sections checked on 2-in grid
    - Cast surfaces checked on 4-in grid

Summary

- Modular coil winding forms are ready for procurement
  - Winding form specification is complete
  - Winding form models incorporate all features that are anticipated for coil fabrication and assembly
  - As-machined drawings of winding forms are undergoing checking
  - A few details need to be corrected (bolt fit, LN2 holes, thermocouples, etc)
  - MCWF related assembly details, such as shims and bolt assemblies, have been designed and analyzed

Backup Slides

Poloidal Break Tee Reinforcement

NCSX