WBS 14
Modular Coils

D. Williamson – Design and Analysis
P. Heitzenroeder –Winding Form Fabrication and R&D
J. Chrzanowski – Modular Coil Fabrication and R&D
D. Williamson – Cost / Schedule and Summary

for the NCSX Team

NCSX Performance Baseline Review
November 18-20, 2003
PPPL

Introduction

NCSX

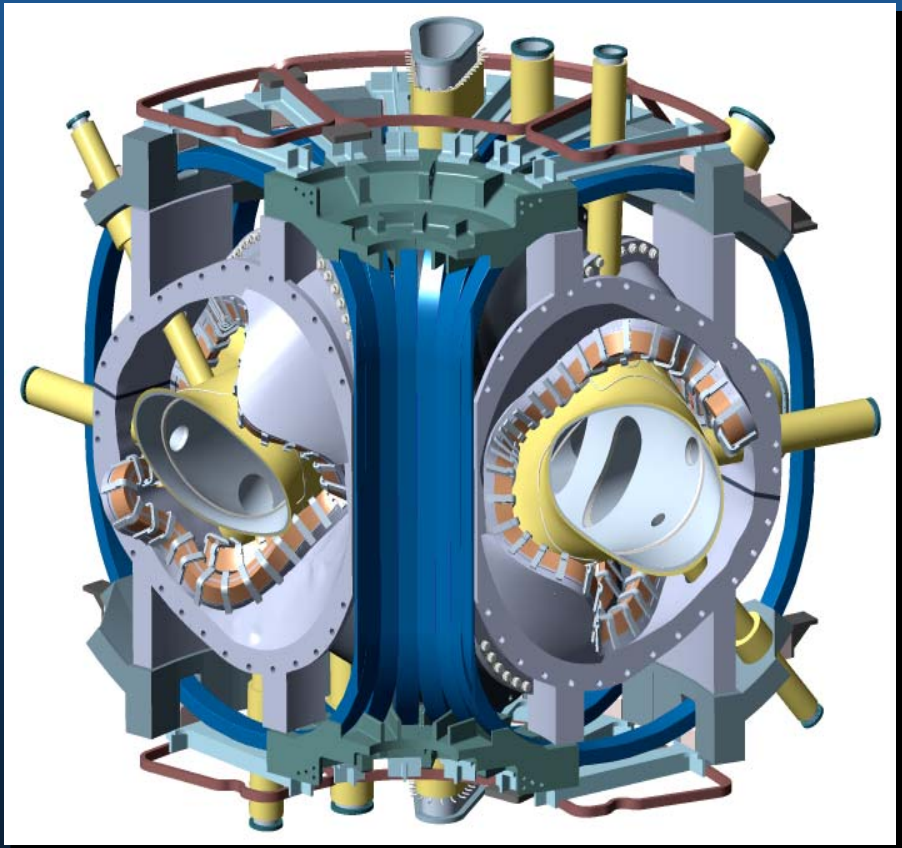
- Modular coil system has improved significantly since CDR:
  - Winding center changed to improve physics, engr parameters
  - Introduced poloidal break; developed details for leads, cooling
  - Performed winding, potting, and properties tests on conductor
  - Engaged multiple vendors in winding form development
  - Developed design of winding fixtures and autoclave
  - Requirements, interfaces, and design basis established
- We are ready to proceed with final design

Presentation Outline

- Modular Coil Design, Analysis, and Implementation
  - System Requirements
  - Design Description
  - Analysis
  - Winding Form Manufacturing (P. Heitzenroeder)
  - Winding Facility and R&D (J. Chrzanowski)
- Cost and Schedule
- Summary

Scope

- Modular coil WBS includes:
  - Winding forms
  - Windings and assembly
  - Coil instrumentation
  - Winding facility



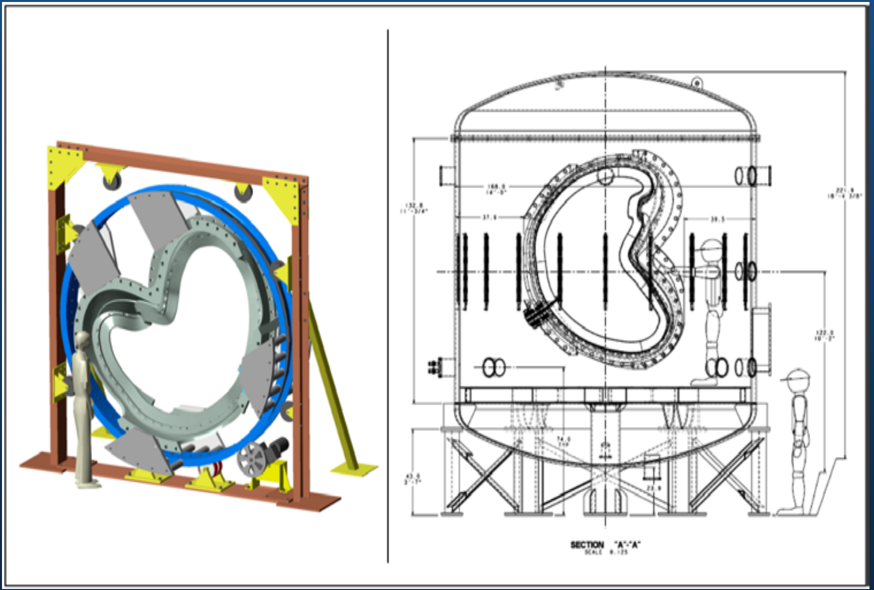
Requirements

- 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 magnetic 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
  - Instrumentation to provide feedback for coil protection system

Requirements (cont'd)

NCSX

- Winding fixtures and tooling are required to position and support the conductor during fabrication
  - Fixtures interface with three coil shapes, provide access for conductor spools and tooling
  - Efficient and accurate
- Autoclave is required for "bag mold" vacuum pressure impregnation (VPI) process
  - Capable of <1-torr to 15-psig, heating to 135-C in <24-hrs

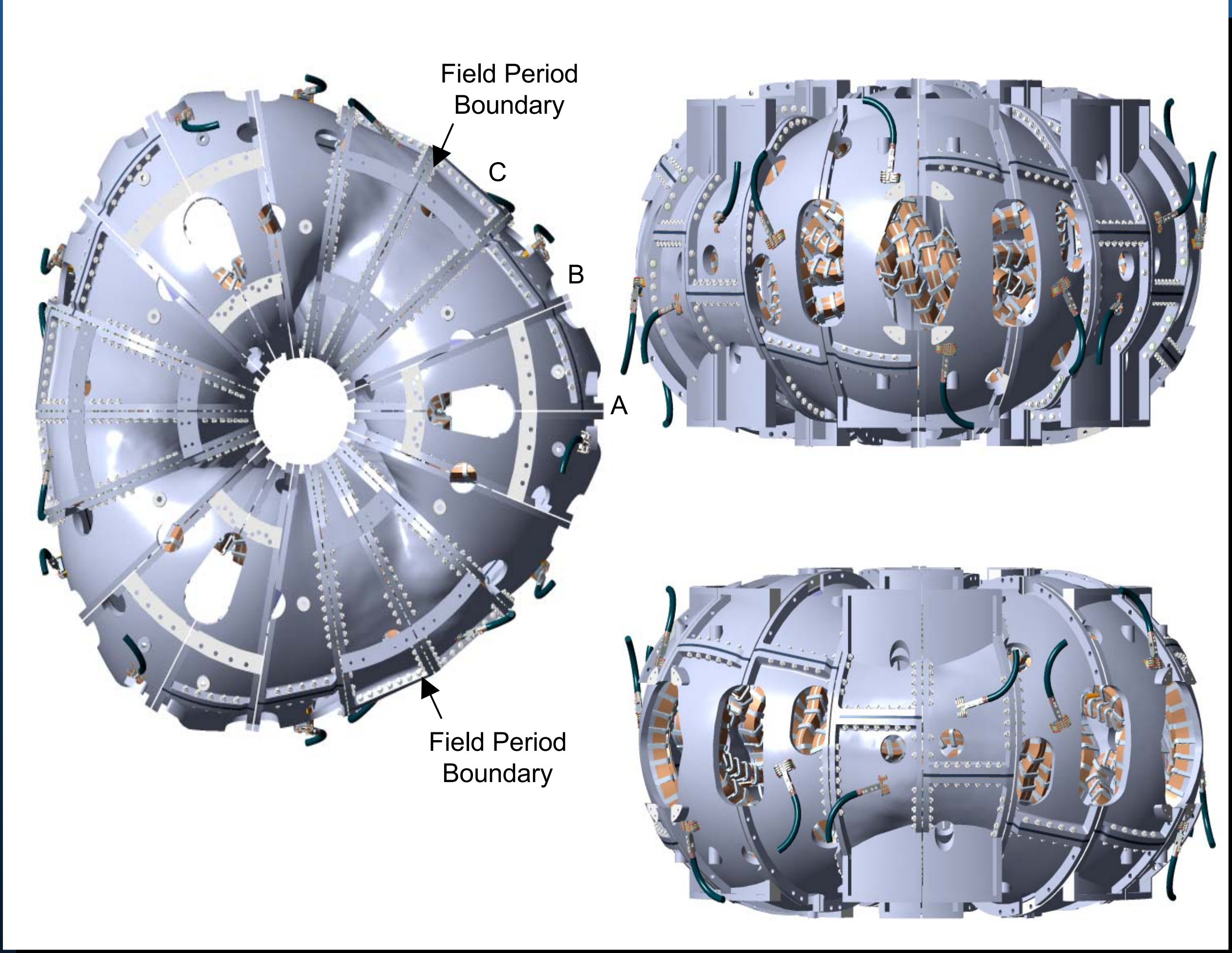


Ref: J. Chzranowski

Modular Coil Assembly

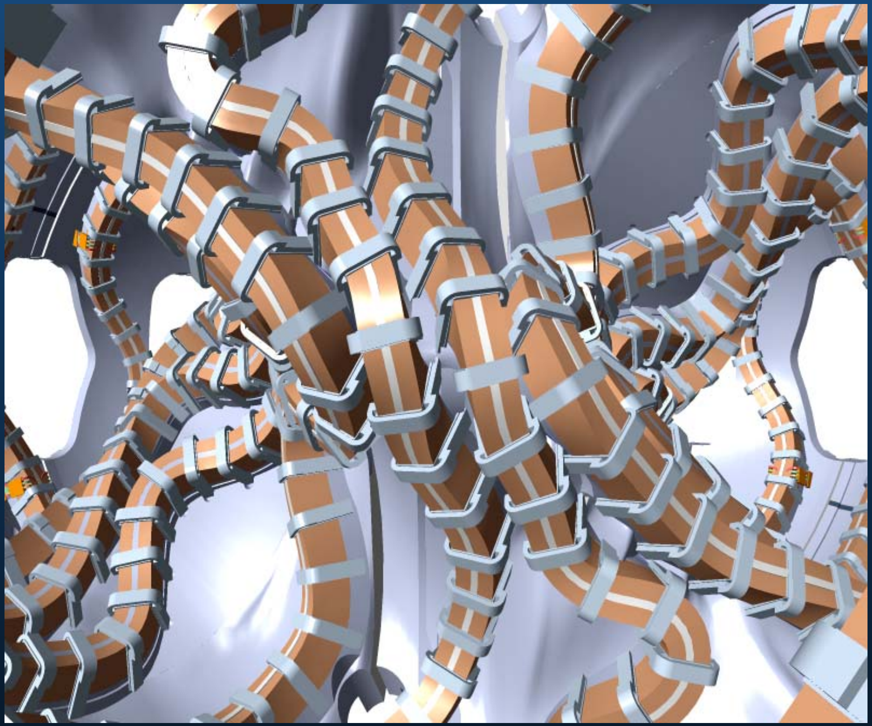
NCSX

- 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

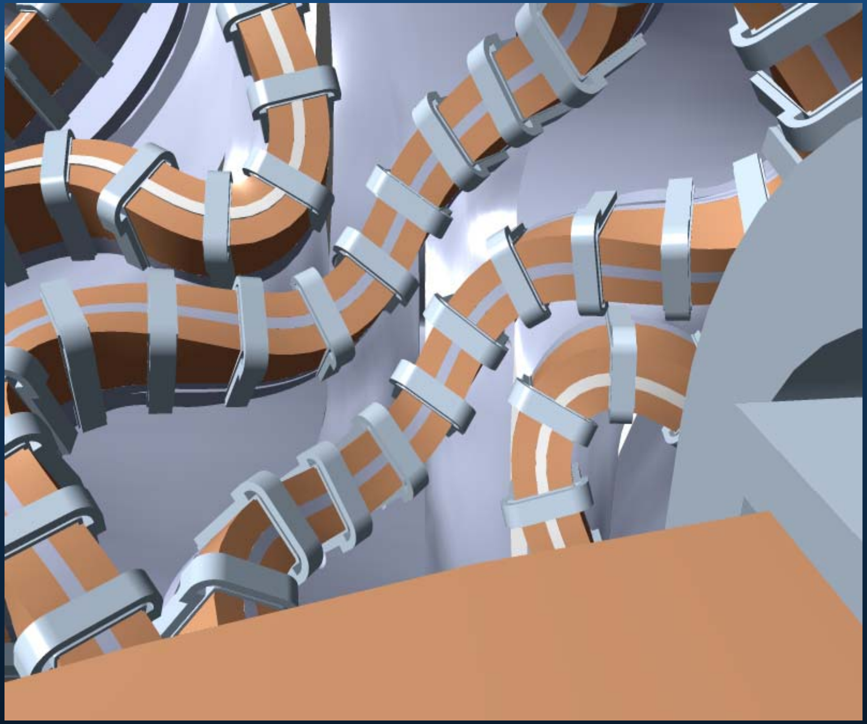


Interior View of Structure

NCSX



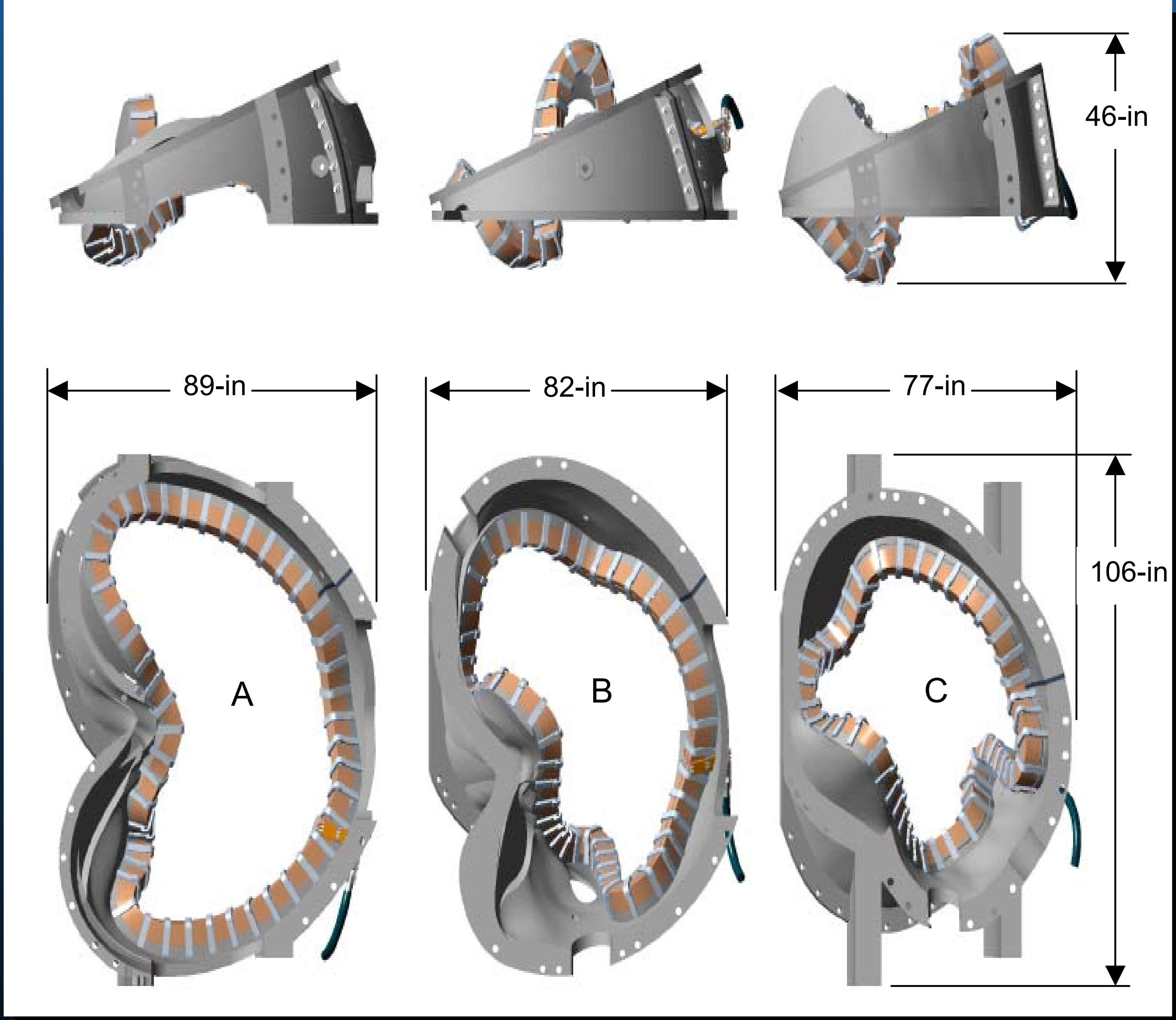
Wide Angle View at Coil Type A-A



Wide Angle View at Coil Type C-C

Modular Coil Types

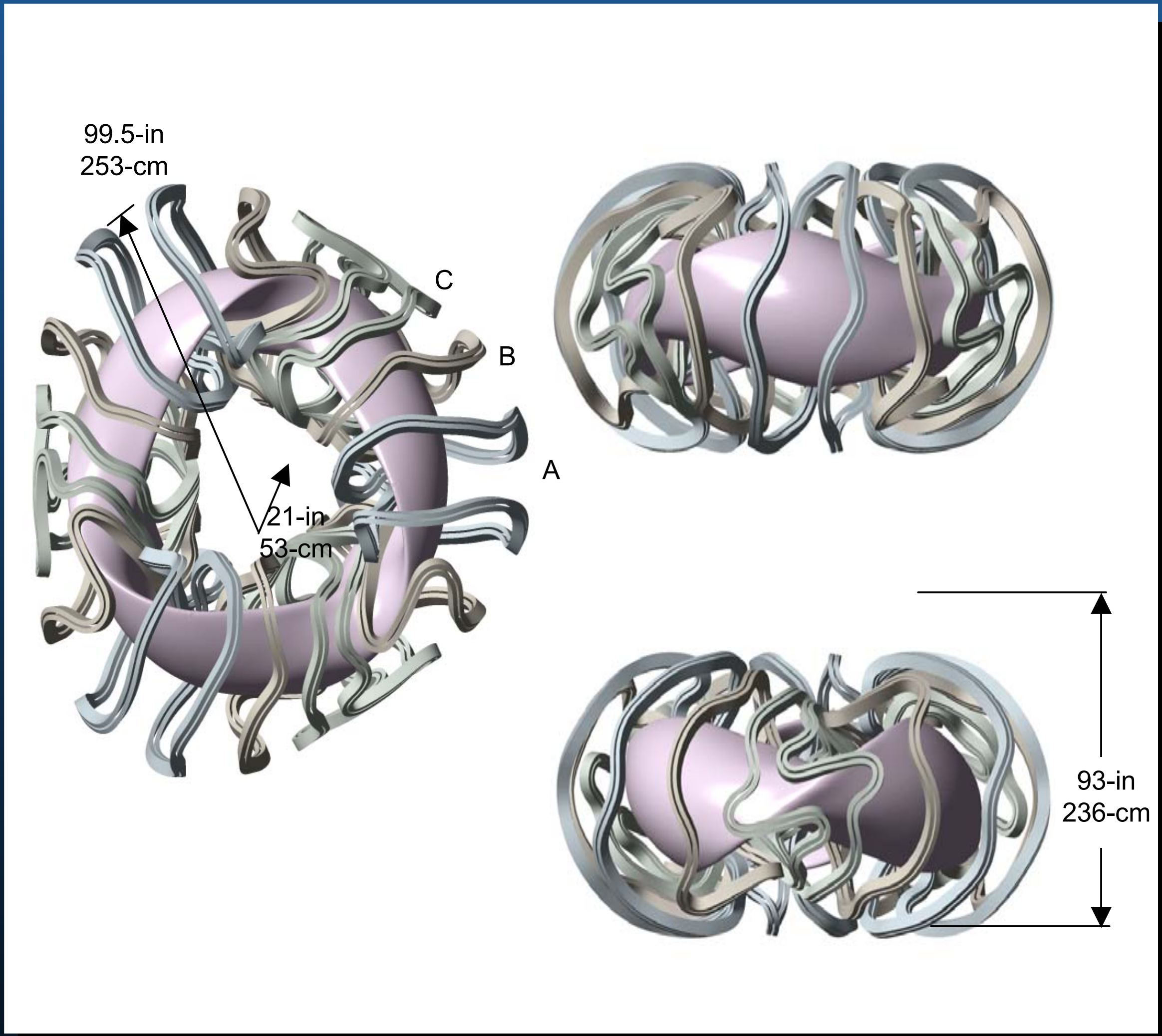
NCSX



Coil Configuration

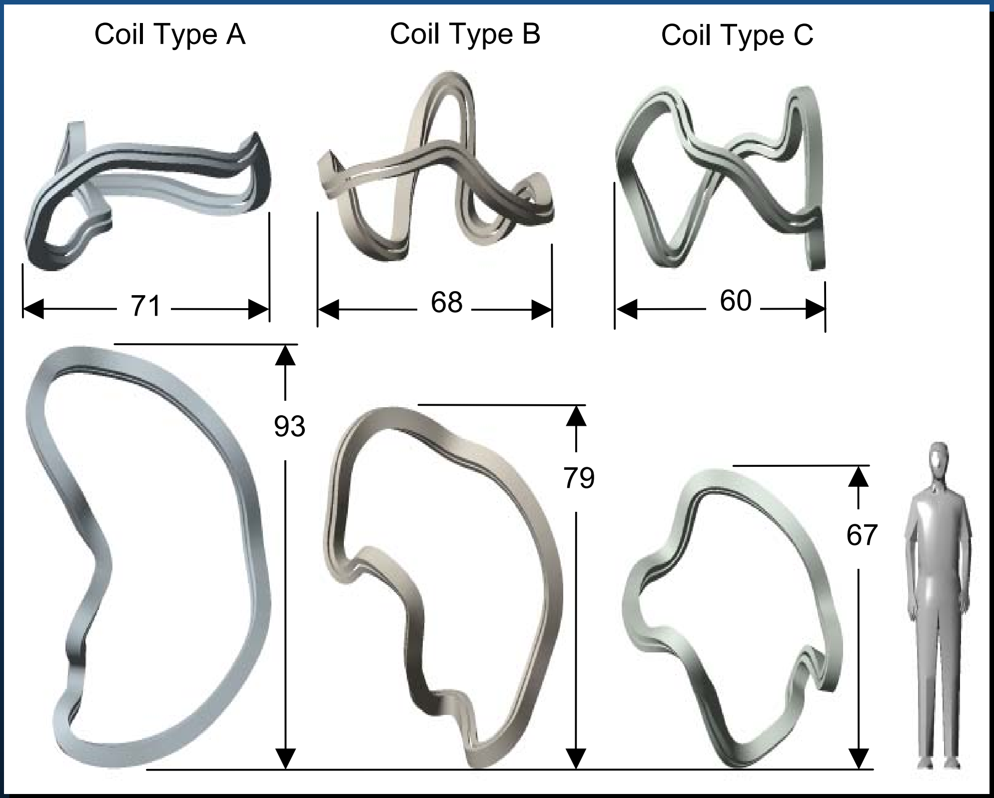
NCSX

- 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

NCSX



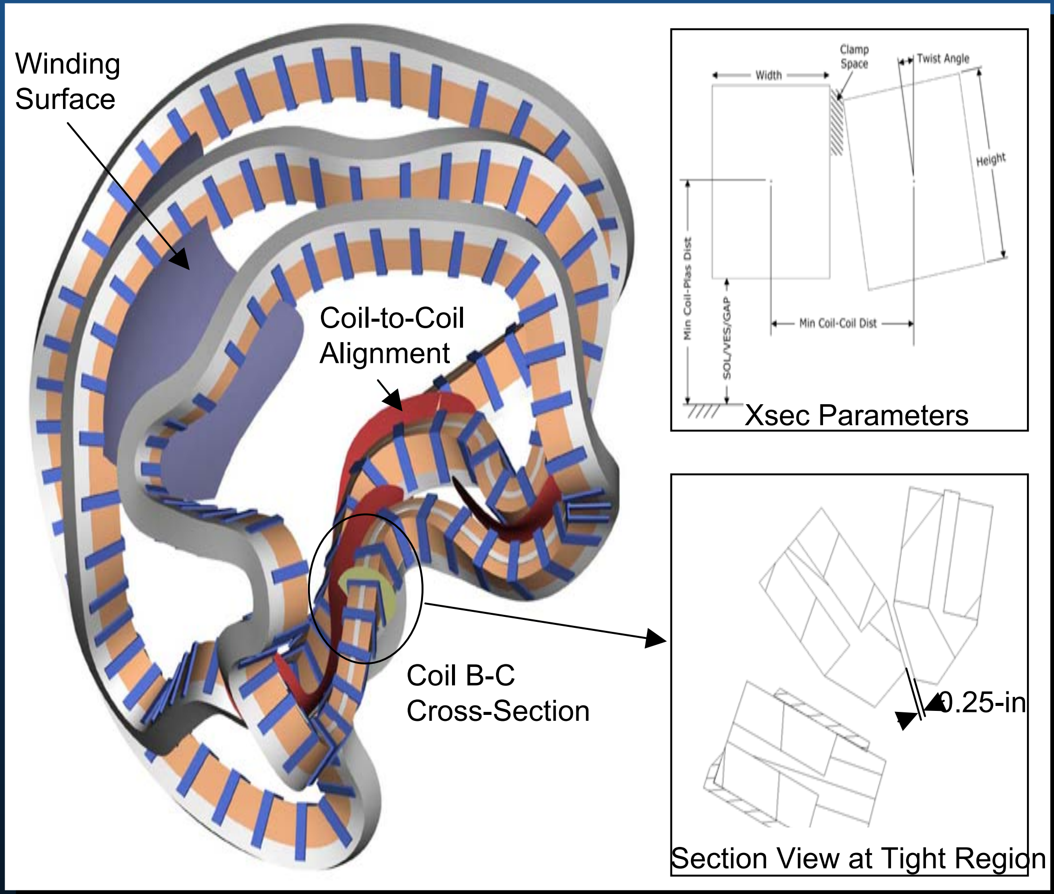
- Min bend radius at winding pack surface is 2.5-in, 2.7-in, and 3.1-in for coils A, B, and C respectively

Case m50_e04 Coil Parameters									
Coil #	A'		A		B		C		C'
Coil Length (in)			291		283		263		
Min Coil-Coil Dist (in)		7.6		6.3		6.1		6.8	
Max Coil-Coil Dist (in)		35.0		36.4		30.7		26.6	
Min Rad of Curvature (in)			4.2		4.8		4.3		
Min Coil-Plas Dist (in)			8.8		8.1		9.0		
Max Coil-Plas Dist (in)			28.5		22.6		20.2		

Cross-Section Development

NCSX

- 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

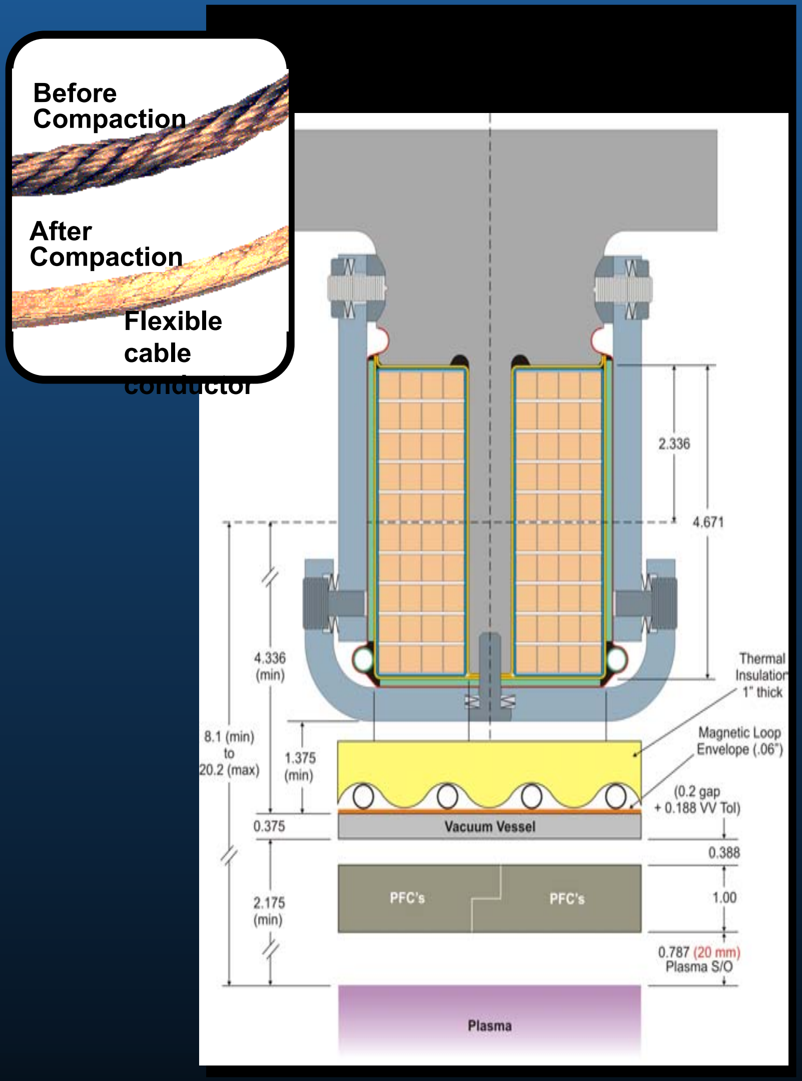


Winding Pack Configuration

NCSX

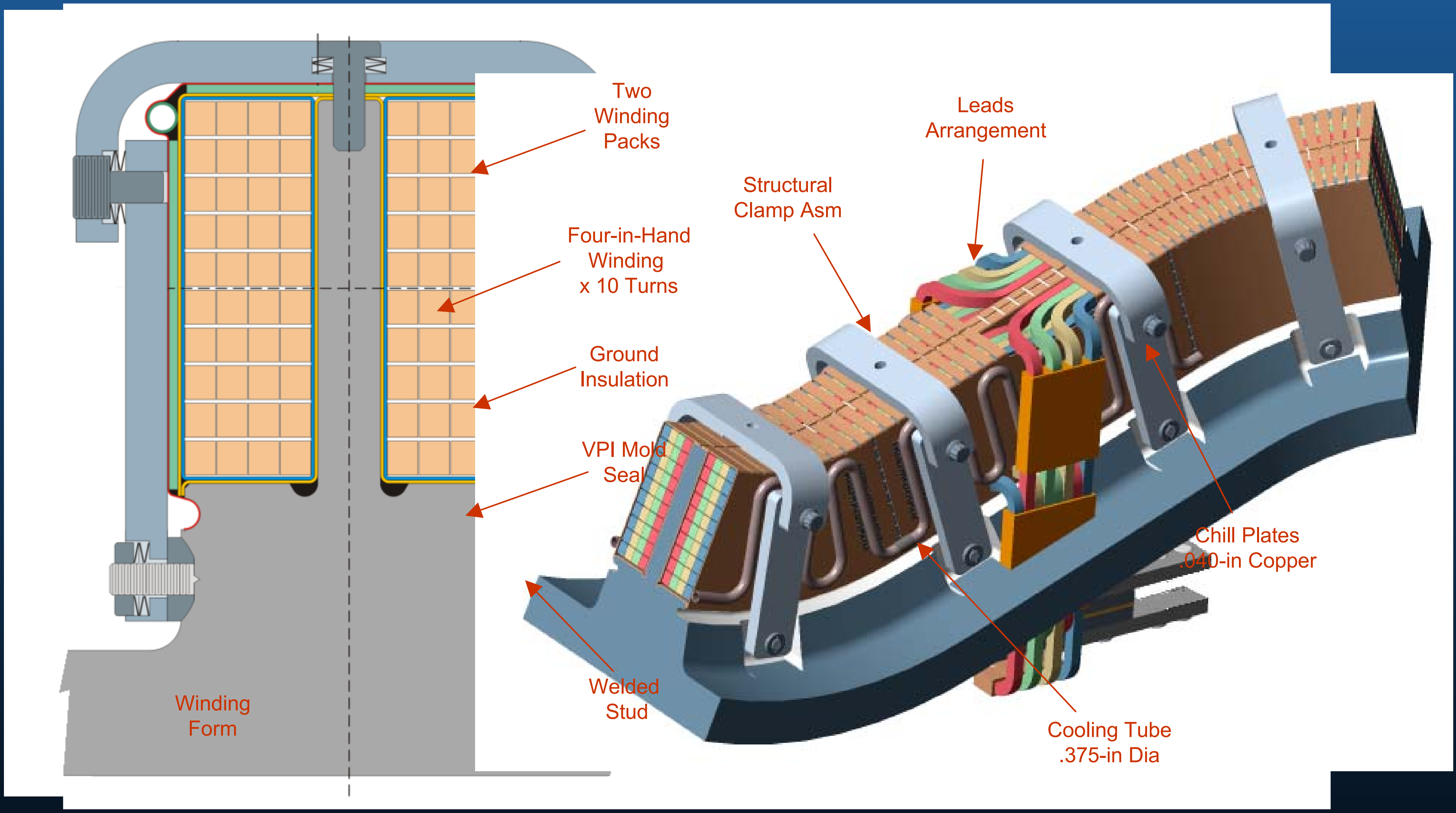
- Parameters:
  - Coil Envelope = 2 x 1.675 x 4.671-in
  - Current / Coil = up to 831-kA-turns
  - Number of Turns = 20 (A, B) and 18 (C)
  - Max Current / Turn = 41.6 –kA
  - Conductor Size = .391 x .35 in (9.9 x 8.9 mm)
  - Cu Current Density = 15.1-kA/cm2 (Max)
  - Conductor operating temp. range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



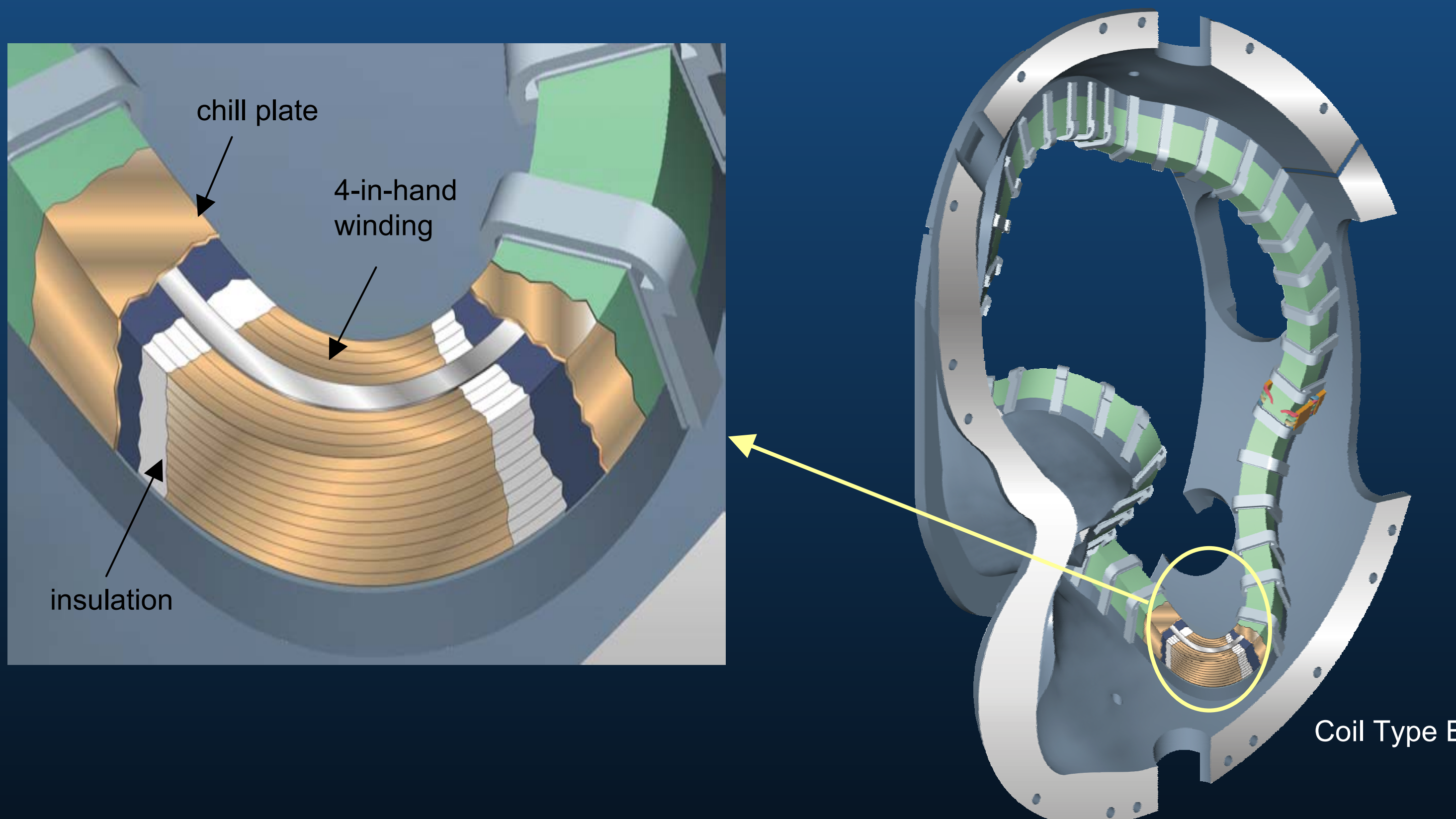
Winding Pack Configuration (cont'd)

NCSX



Conductor Insulation

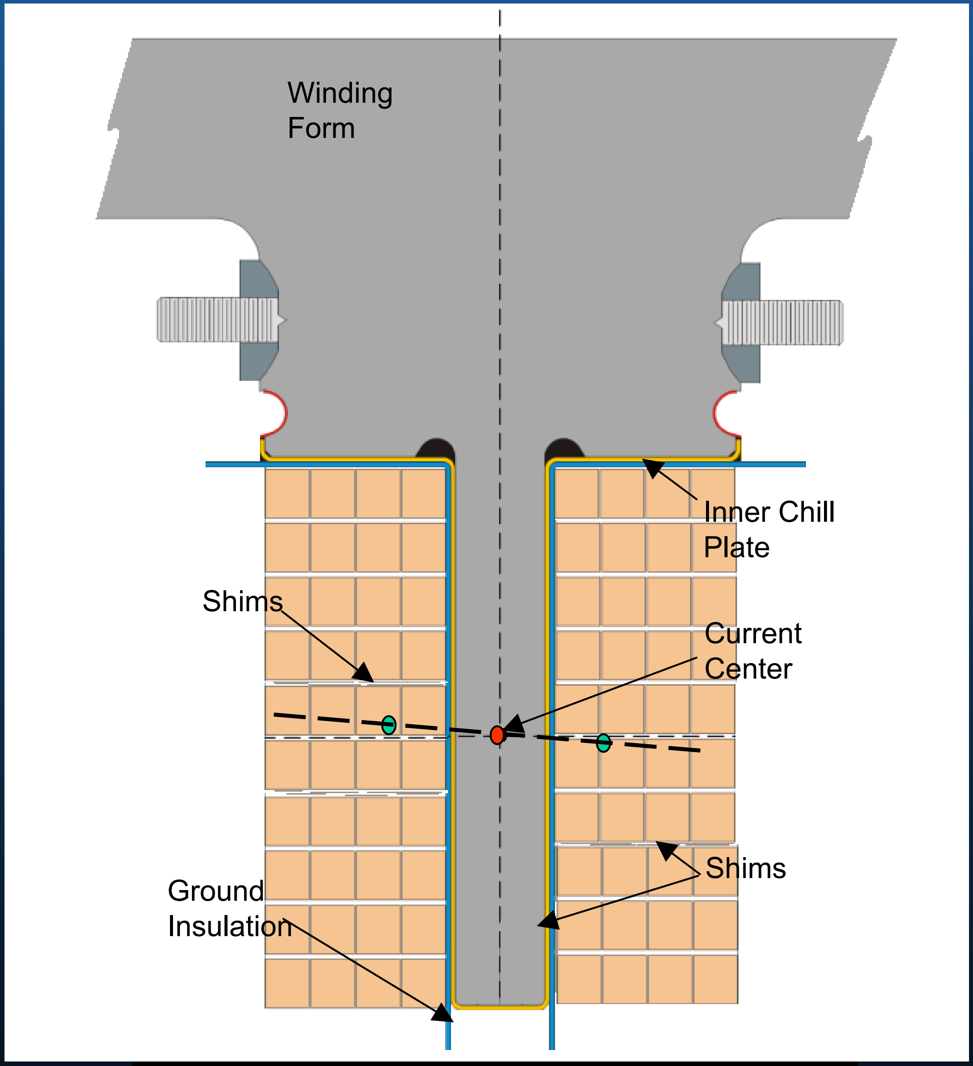
- Conductor insulated with 0.004-in nylon serve and two half-lapped layers of 0.004-in glass cloth (0.6-kV)
- Ground wrap consists of 0.030-in glass cloth and 0.008-in Kapton (2.3-kV)



Winding Accuracy

NCSX

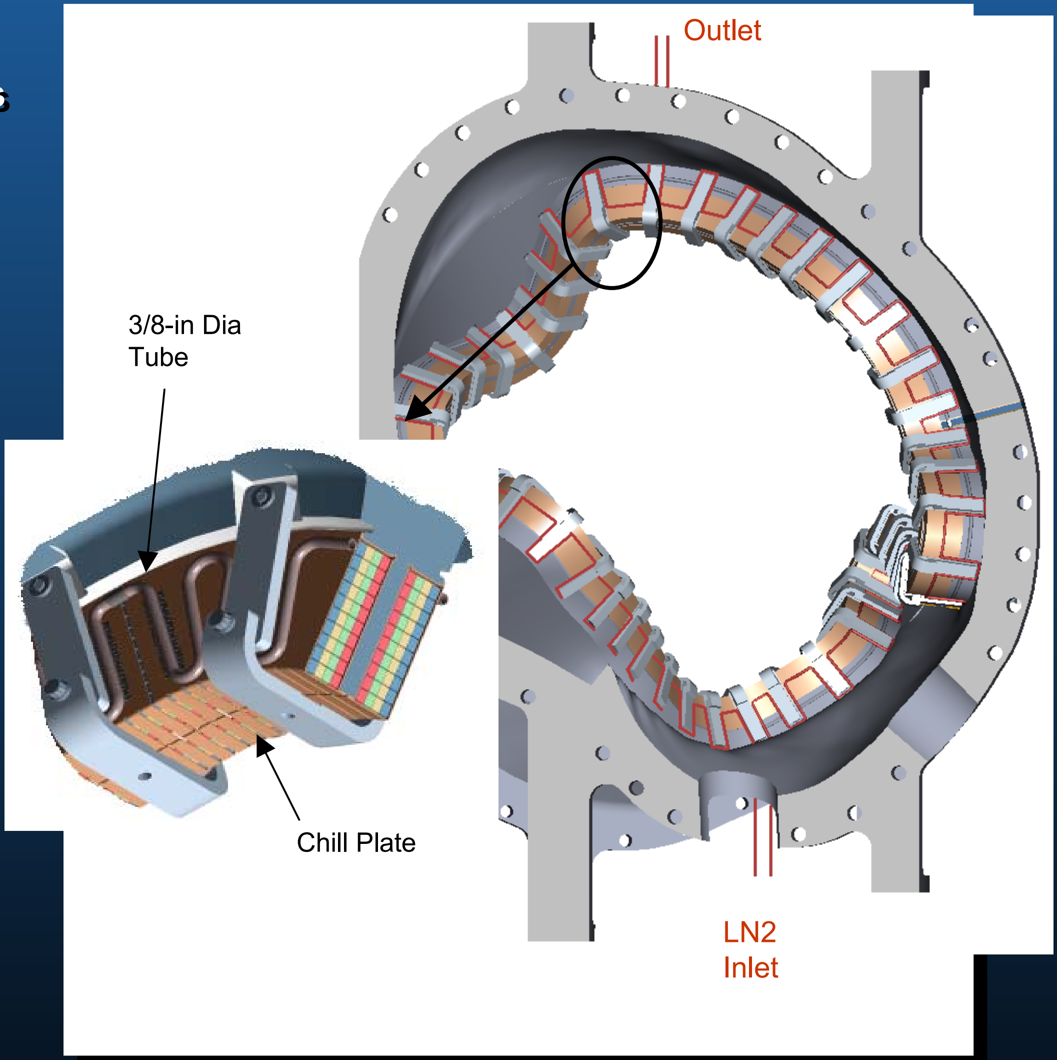
- Winding position is continuously monitored and adjusted to avoid tolerance stack-up
- Tolerance issues:
  - Machined surfaces of winding form are accurate to +/- 0.010-in (0.5-mm)
  - Conductor w/o insulation has a dimensional tolerance of +/- 0.010-in (0.5-mm)
  - Geometry requires up to 0.036-in (.91-mm) per layer allowance for conductor keystoning
- Current center can be adjusted by use of shims between layers



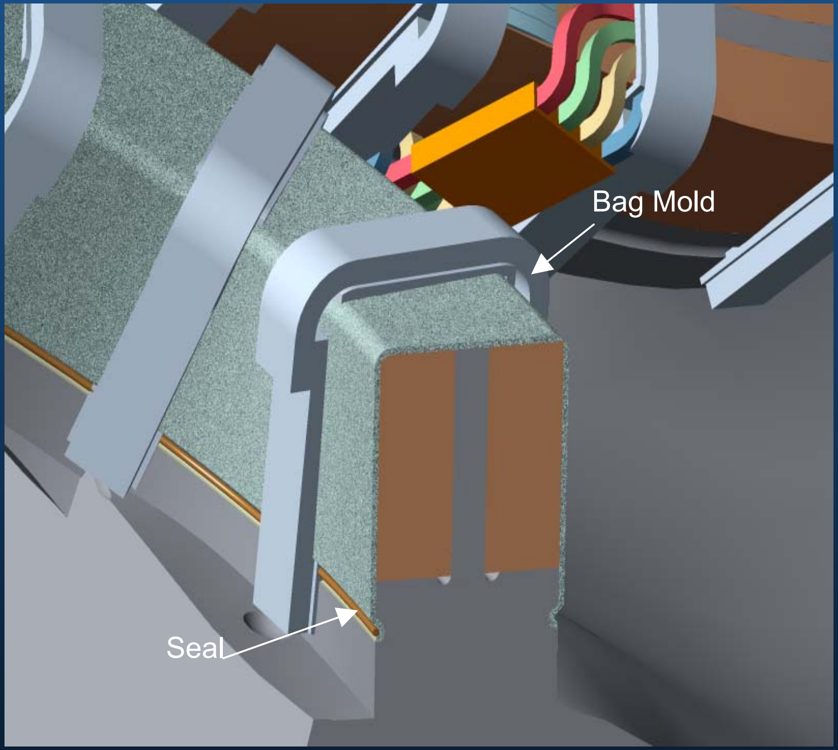
Coil Cooling

NCSX

- 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 Feature

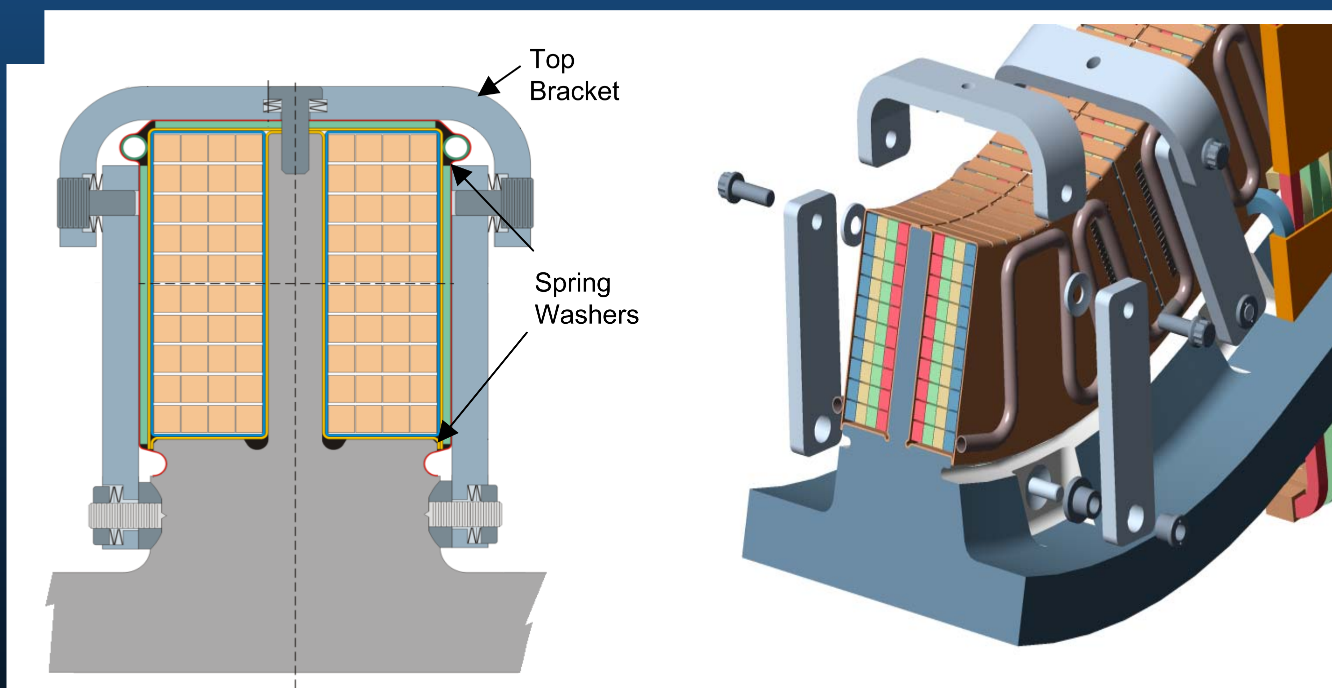


- VPI mold is composed of epoxy impregnated felt and silicon rubber tape
- Located between winding pack and clamps
- Sealed by pressing tube into continuous half-round or v-groove at base of tee

Winding Pack Clamps

NCSX

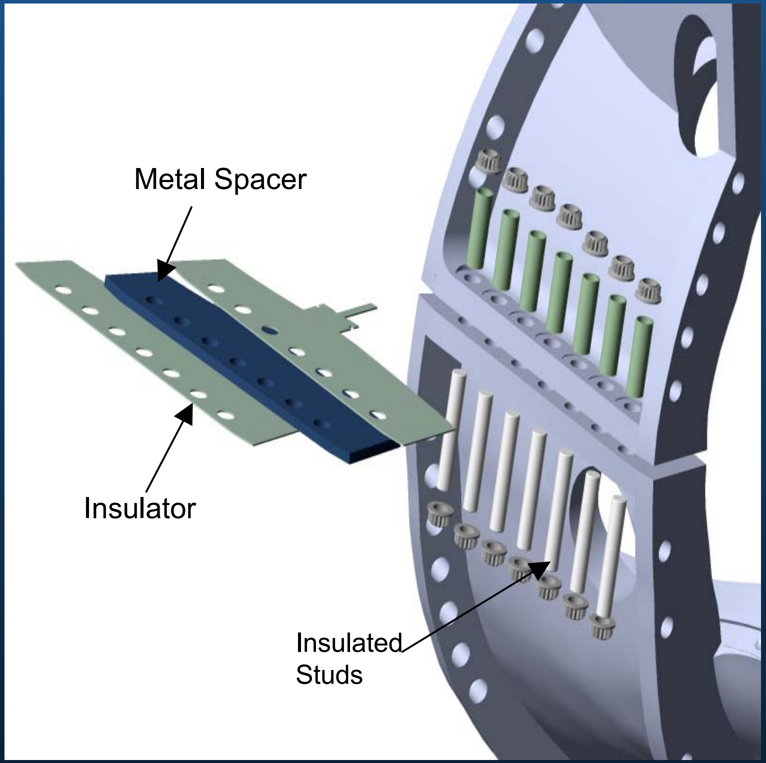
- Winding packs are clamped by discrete bracket assemblies, spaced approximately every 6-inches
- Clamp is attached by studs at base of tee and tapped holes in web of tee, shimmed to fit winding pack
- Spring washers provide compliance, allow clamp to preload winding pack to structure



Poloidal Insulating Break

NCSX

- 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

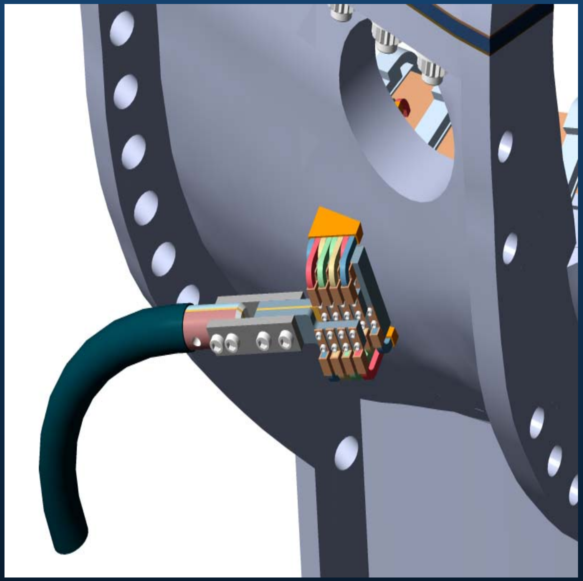


Coil Leads

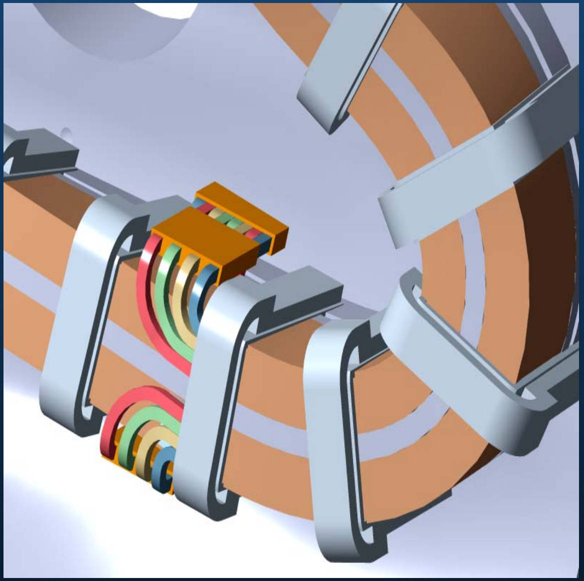
NCSX

- 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



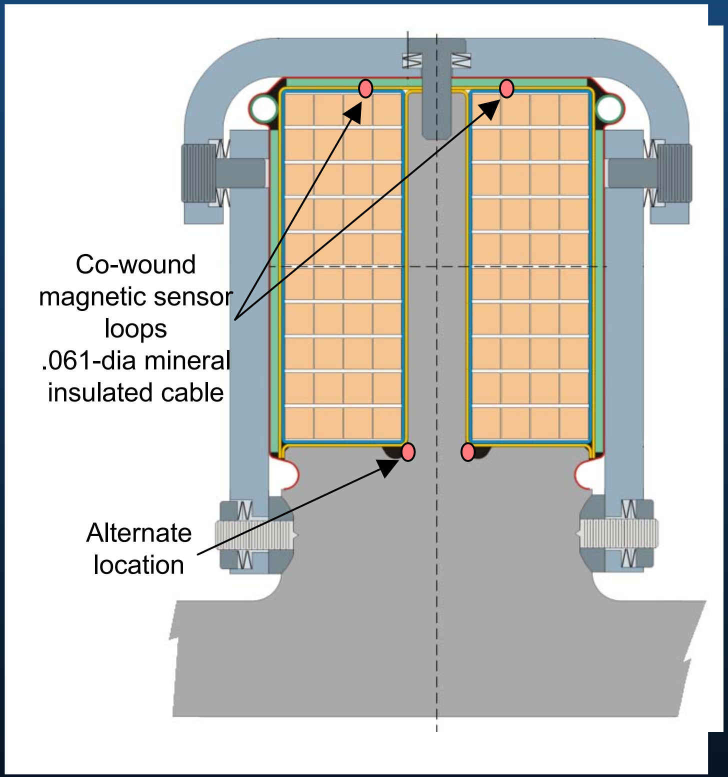
Plasma Side of Winding Pack

Coil Instrumentation

NCSX

- 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

NCSX

- 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 desig
  - 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

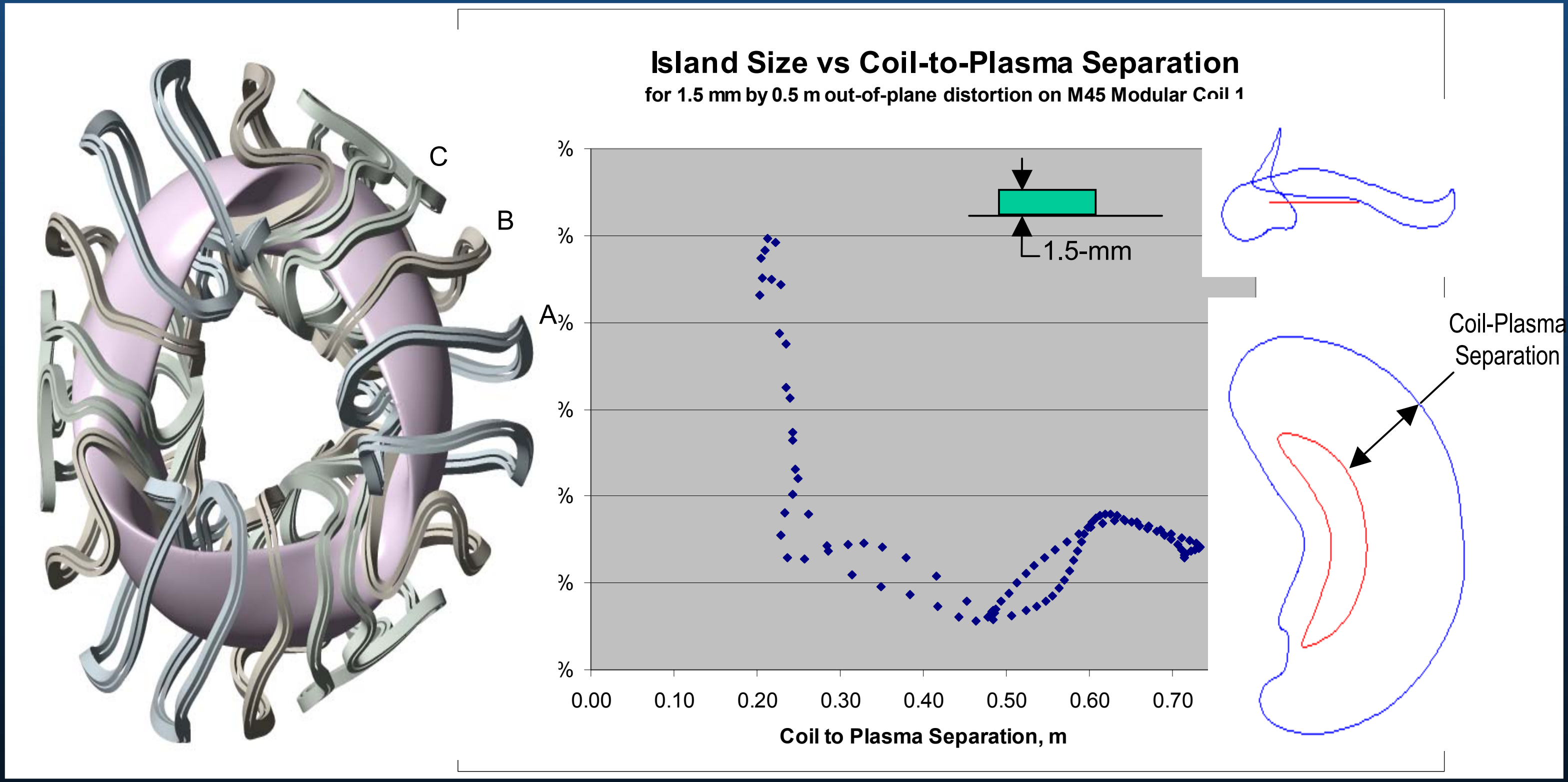
Design Evaluation

- 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 (racetrack coil)
- Detailed analysis, checking to be completed during final design

Coil Position Field Errors

NCSX

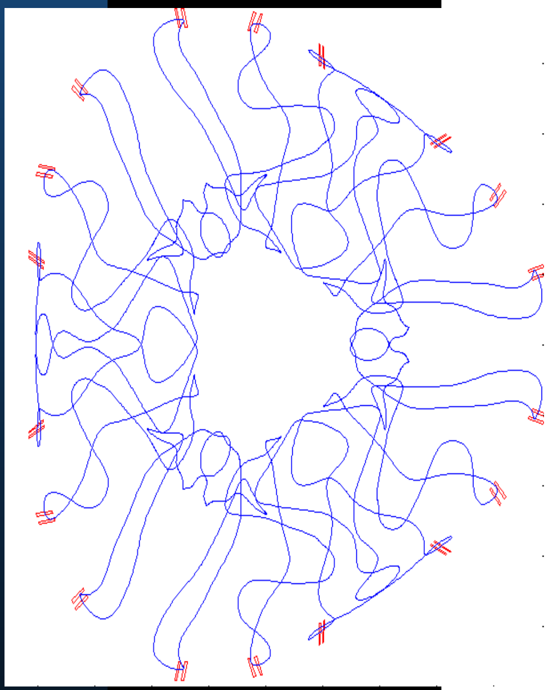
- Analysis of magnetic islands due to random errors in position of coil winding center
- Displacement error types are 1) Fourier series, 2) short wavelet, and 3) broad displacement
- Results show strong effect where coil-plasma separation <30-cm, however correctable with trim coils

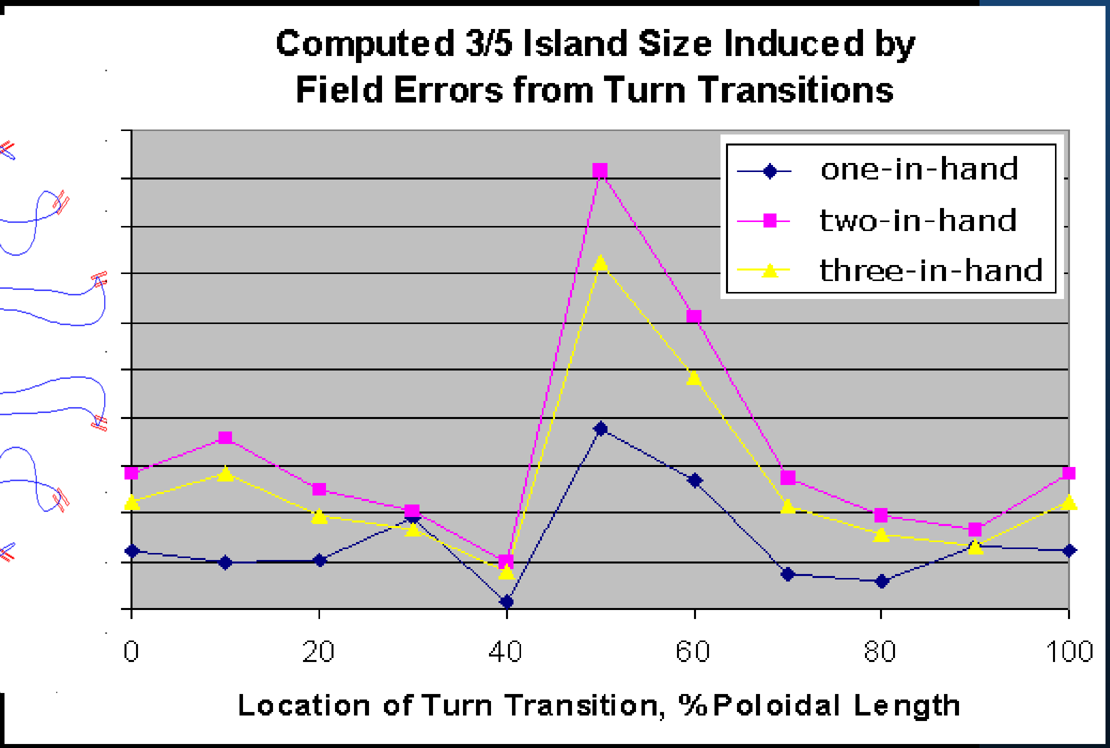


Field Error due to Leads

NCSX

- Analysis performed with VACISLD code to determine effect of large lead currents on magnetic islands
- Poloidal location of leads was varied from outboard midplane to less practical inboard positions
- Best position appears to be 80-90% of poloidal length, near outboard midplane

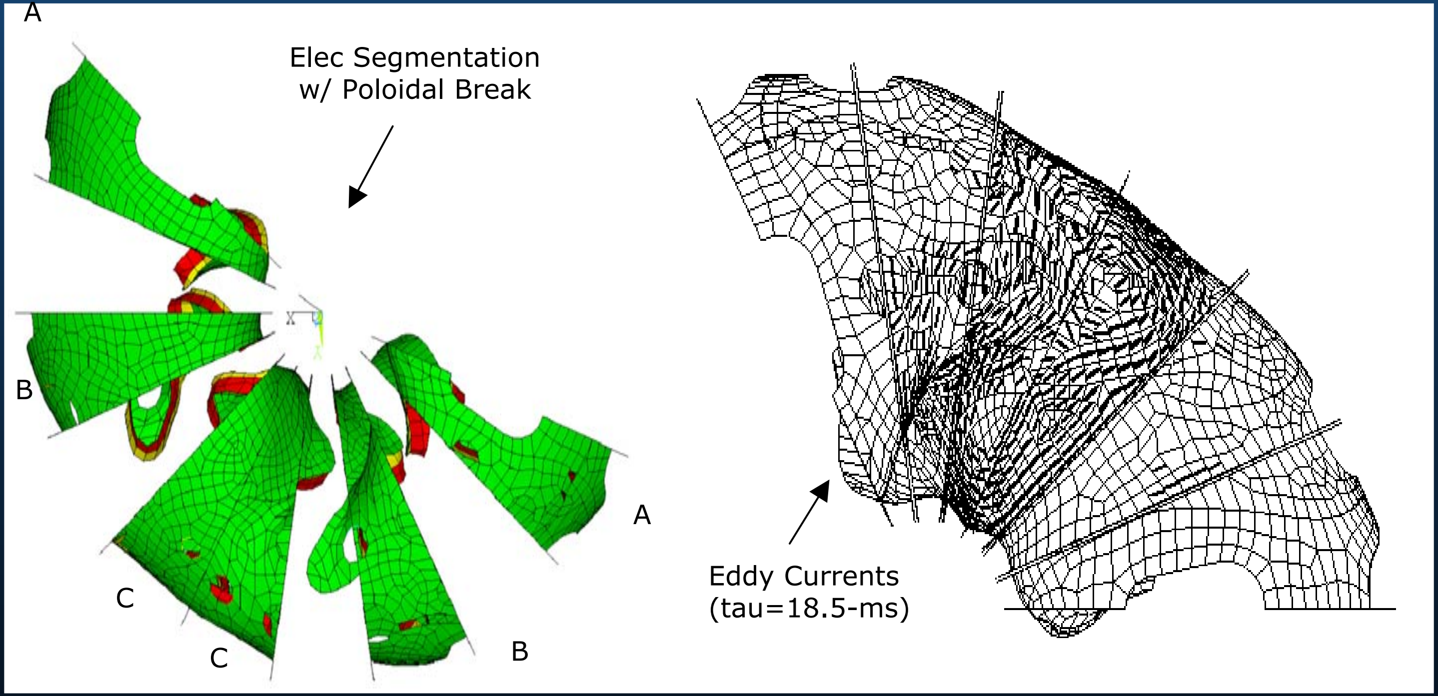




Eddy Current Evaluation

NCSX

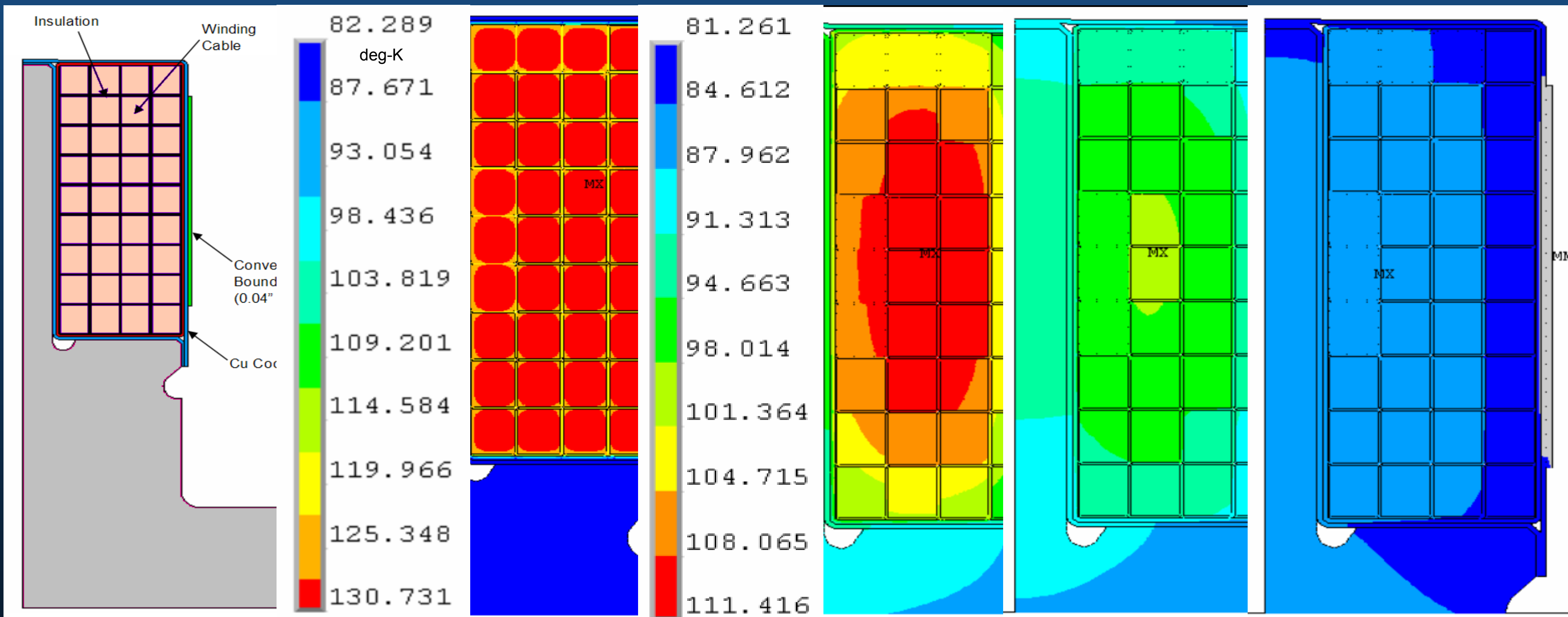
- Analysis performed with SPARK to determine eddy currents due to varying modular coil currents
- Looked at insulating break options (toroidal and poloidal), as well as segmentation of copper chill plates
- Results show longest time constant is <20-ms with one poloidal break, toroidal breaks shown
- Field period assembly joint (C-C) does not need to be insulated



Thermal Analysis

NCSX

- 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



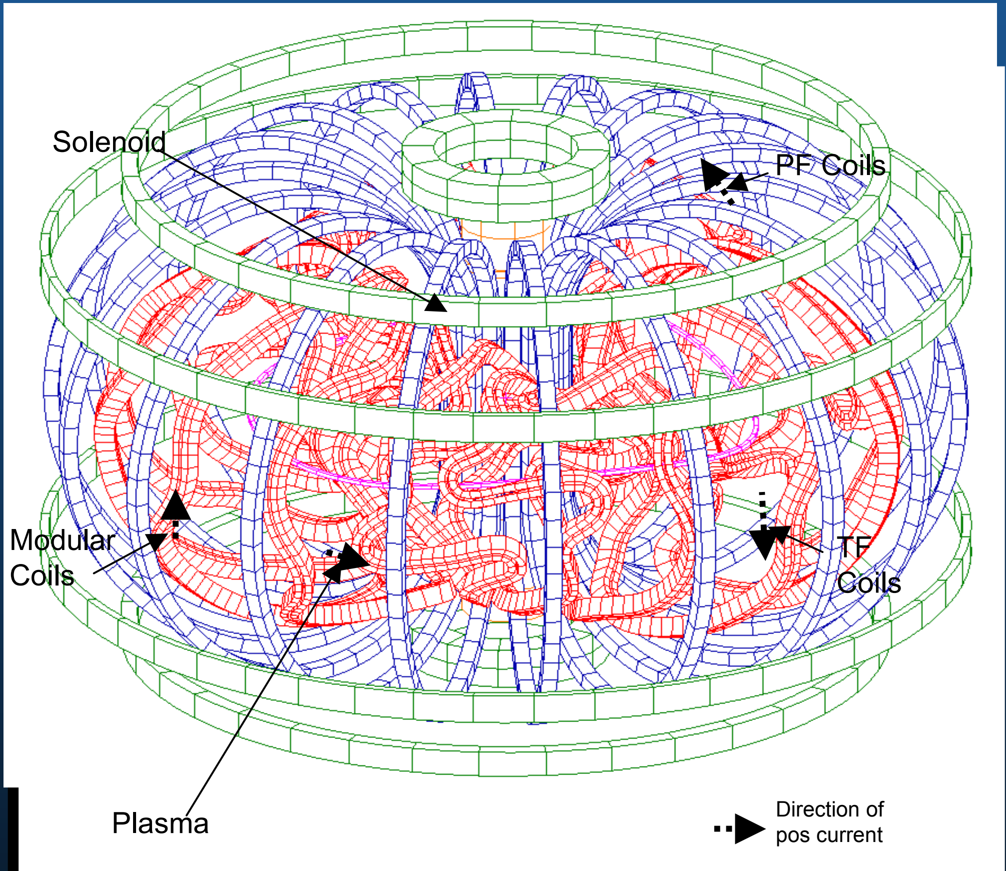
End of Pulse 3-min 7-min 15-min

Electromagnetic Loads Analysis

NCSX

- 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

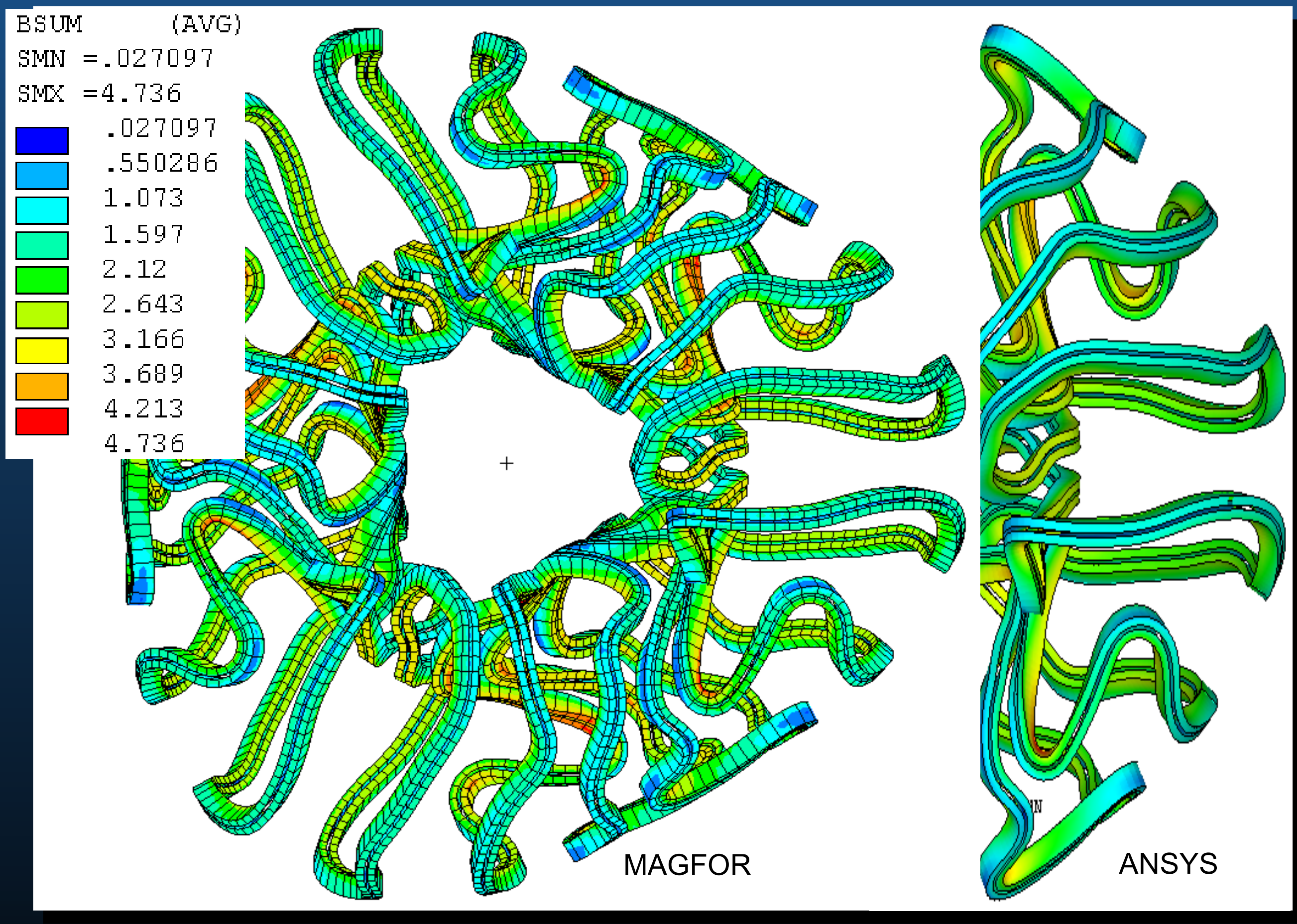


MAGFOR Analysis Model

Magnetic Field Distribution

NCSX

- 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

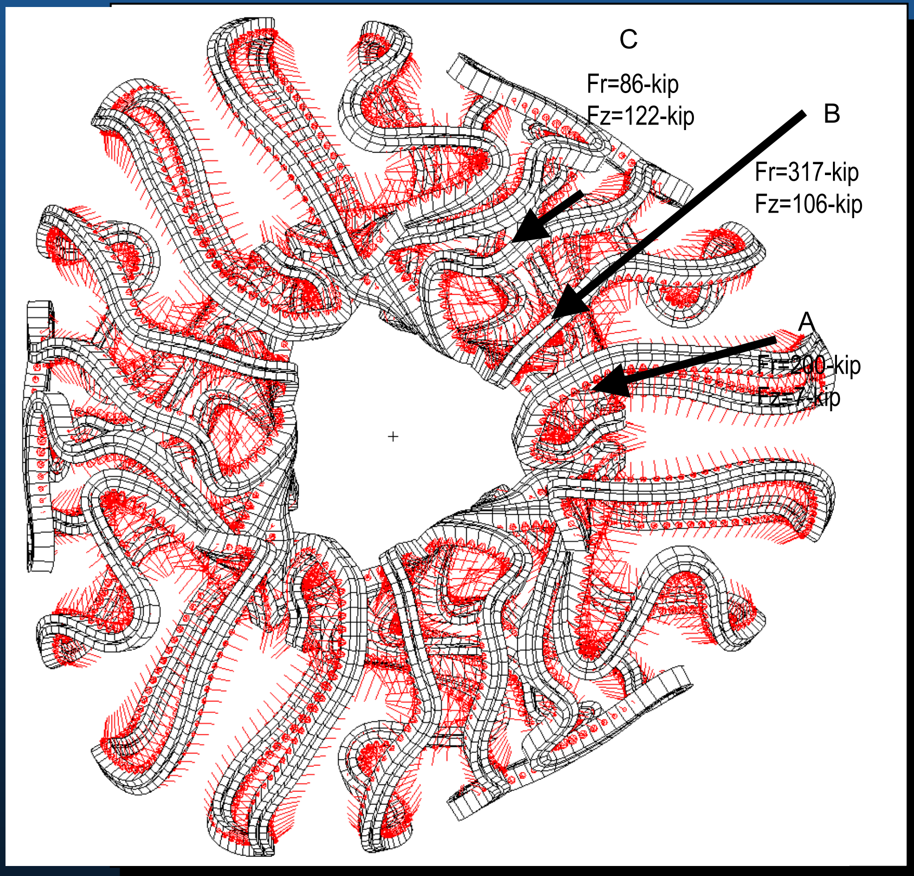


Force Distribution

NCSX

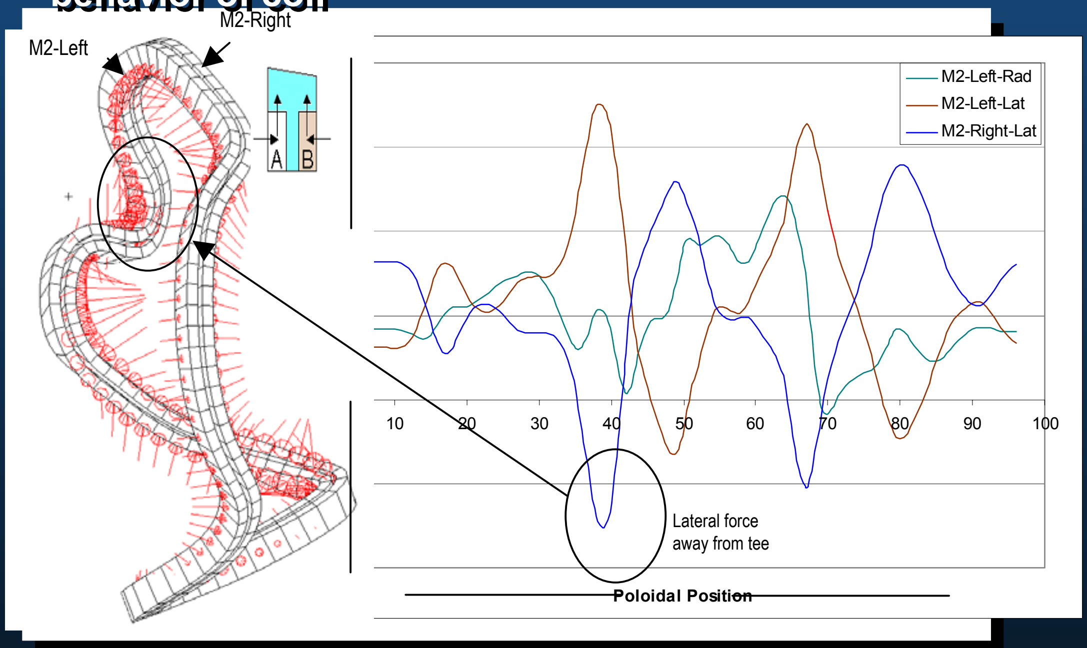
- Force distribution indicates large centering force up to 317-kip (1.4-MN) per coil
- Net vertical load up to 122-kip (.5-MN)

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

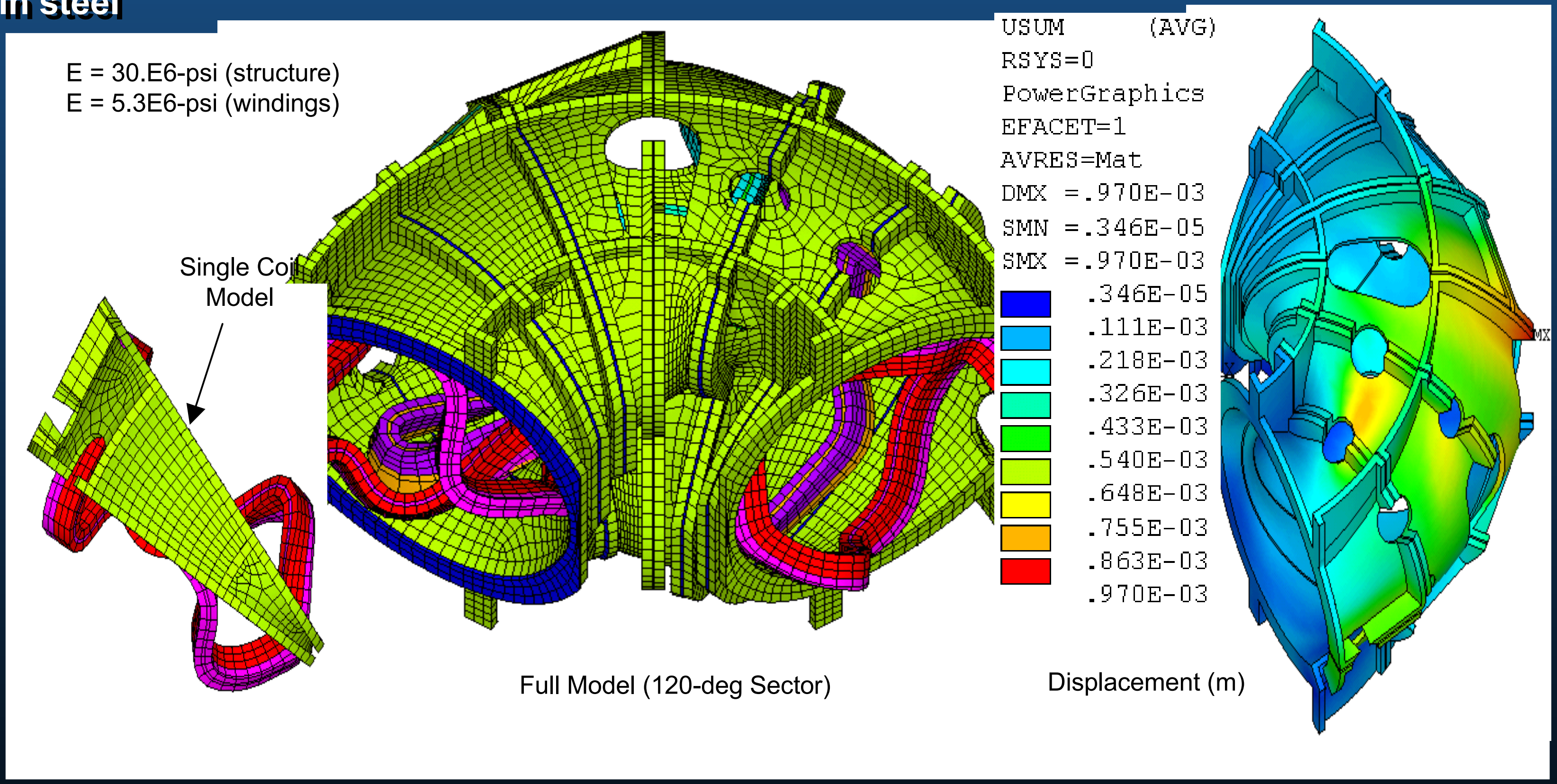


Maximum Running Load on Modular Coils (lb/in)								
Coil	Field/Force Component	0.5-T 1st Plasma	Field Mapping	1.7-T Ohmic	1.7-T High Beta	2-T High Beta	1.2-T L. Pulse	320-kA Ohmic
M1	Rad Load (lb/in)	200	8	2272	2279	2869	1134	2053
	Lat Load (lb/in)	434	17	4995	4997	5831	2490	4163
M2	Rad Load (lb/in)	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

NCSX

- CDR analysis model has been updated to investigate 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

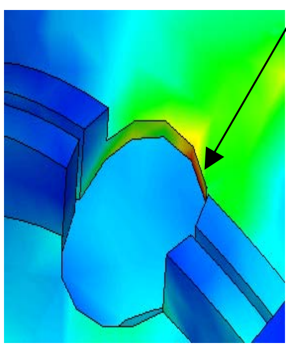


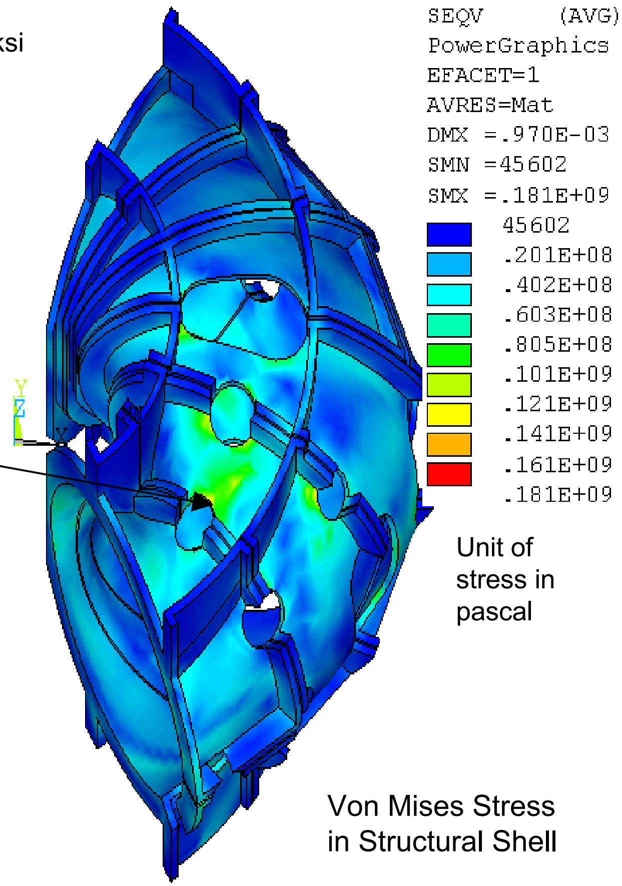
Stress in Shell And Windings

Peak Stress = 26.3-ksi
Avg Stress = 9-ksi

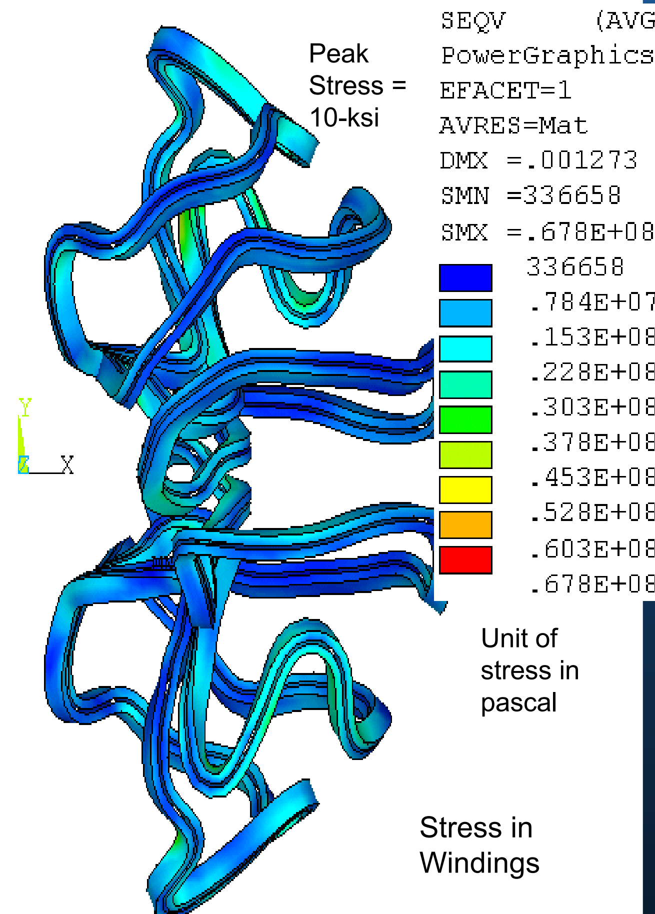
Sm = 50-ksi

Max. stress occurs at edge of opening





Von Mises Stress in Structural Shell

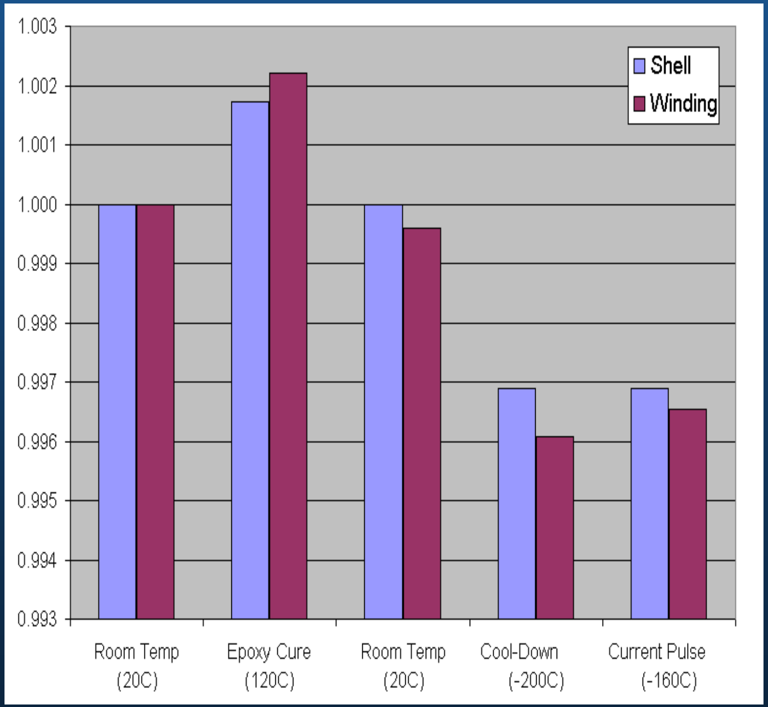


Stress in Windings

Winding Thermal Stress

NCSX

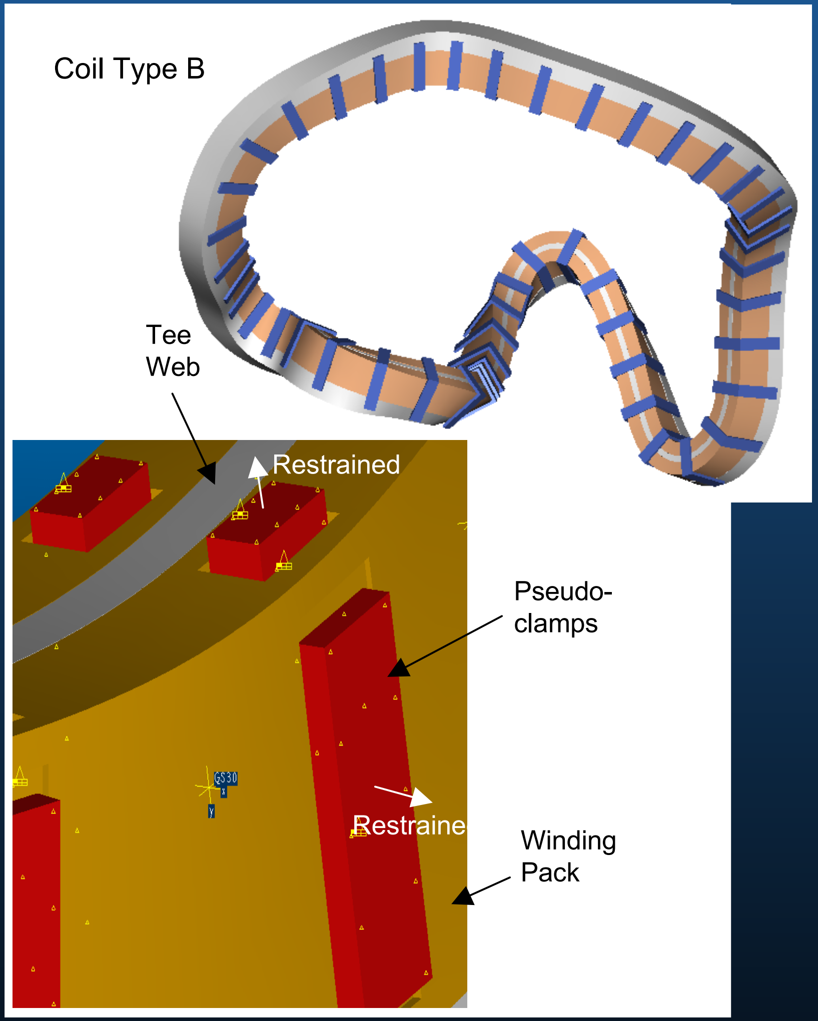
- Relative strain between winding pack and winding form due to:
  - Cure shrinkage (~ 0.04%)
  - Cooldown to LN2 temperature (~0.04%)
- Winding moves away from coil form and gaps may open in localized regions
- Provides room for coil expansion during current pulse - *0.04% expansion relative to winding form*



Thermal Stress Model

NCSX

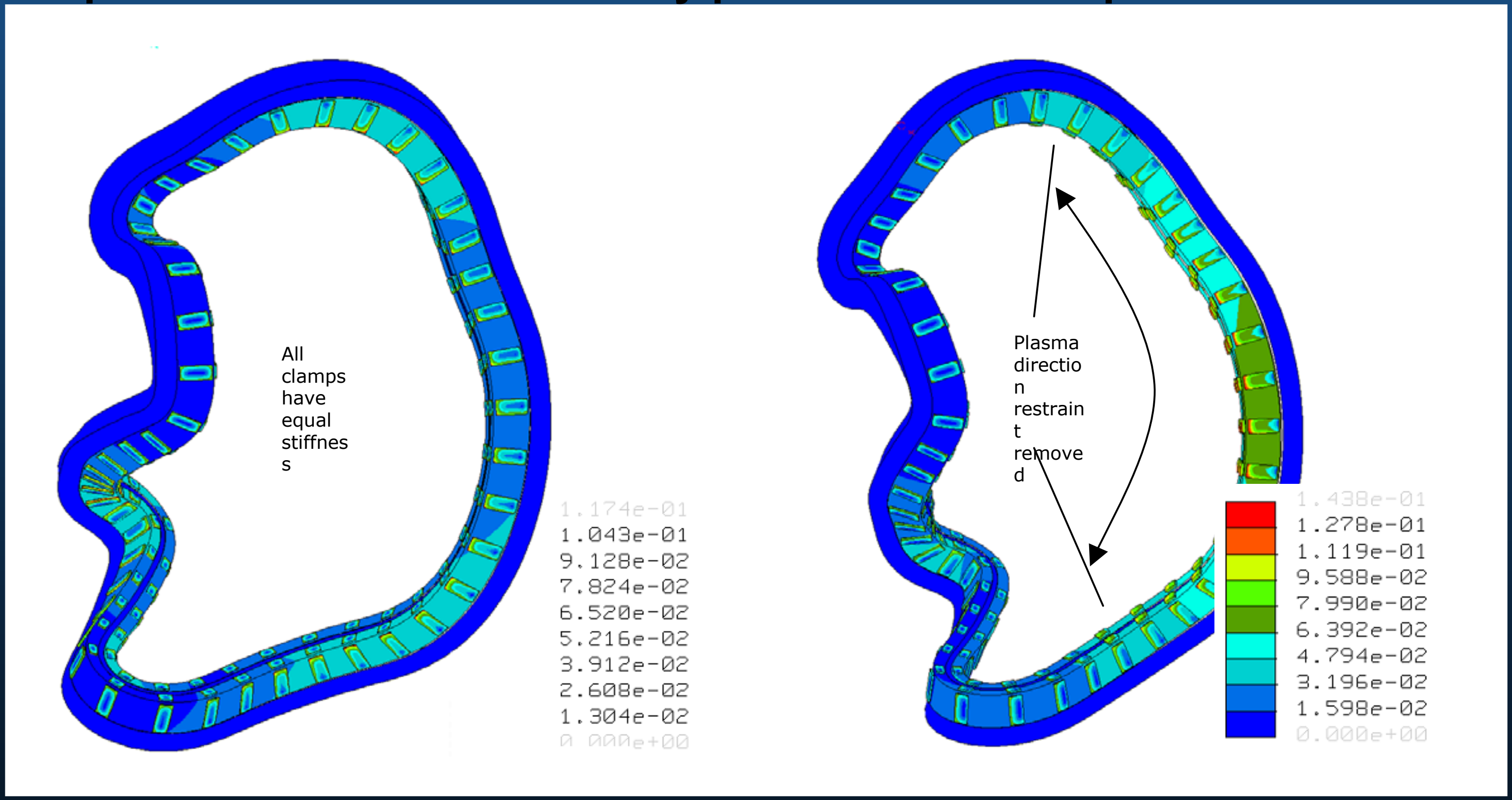
- Non-linear model of windings on fixed tee has been developed using Pro/MECHANICA
- Contact surfaces between winding and tee allow winding to separate from and slide along tee
- Pseudo-clamps (48) are represented by low modulus material with directional restraints
- Properties of block simulate clamp spring force (26,000 lb/in) and preload (~1000 lb)



Displacement Due To Cooldown

NCSX

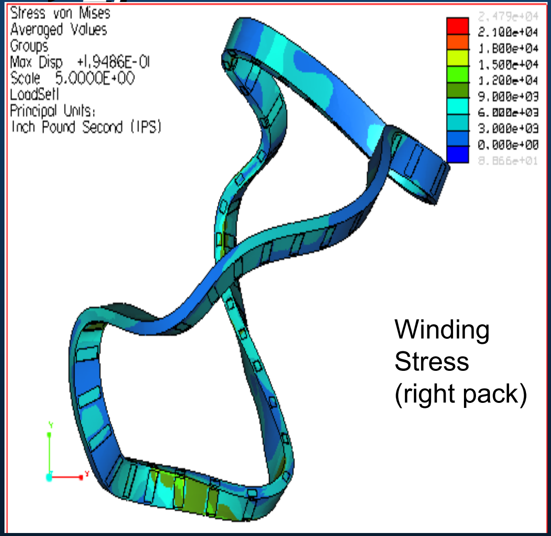
- Relative displacement due to cooldown is approximately 0.040-in (1-mm)
- Displacement can be tailored by placement of clamps

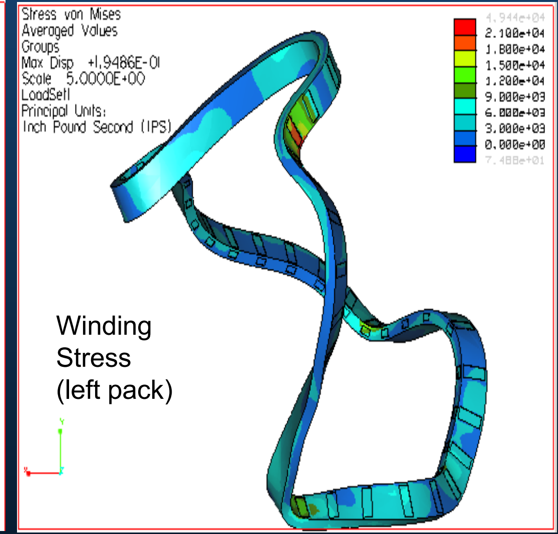


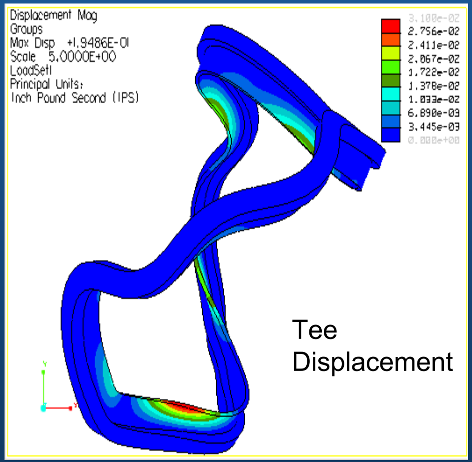
Combined EM And Thermal Loads

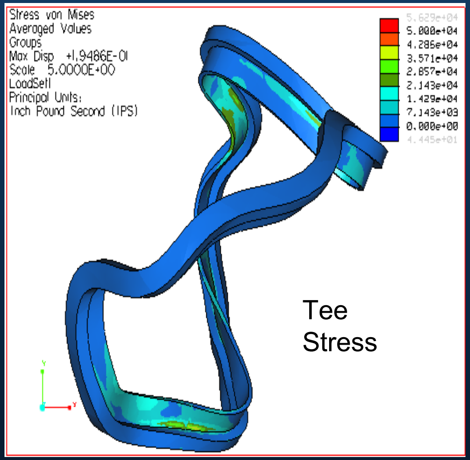
NCSX

- Displacement due to max loads and cooldown is approximately 0.080-in (2-mm)
- For initial strain of 0.08%, stress ~ 16 ksi (S.F. = 1.3)
- For initial strain of 0.0%, stress ~ 10 ksi (S.F. > 2)









Modular Coil Design/Analysis Summary

NCSX

- Preliminary design concept meets performance requirements
  - Accurately built 18 coil, 3 period modular coil set with integrated structure
  - 0.5-T, 0.3-s room temperature operation for first plasma, field-line mapping
  - 2-T, 1-s operation at cryogenic temperatures
  - Low permeability material, segmentation to limit eddy currents
  - Access for diagnostics, heating, vacuum pumping
  - Interface with other stellarator core components
- Analysis shows design to be adequate for reference operating scenarios
  - Coil cools from 40-deg temperature rise after pulse in 15-min with no ratcheting
  - Deflection of coil structure due to EM loads is <0.04-in, stress minimal (FS=2)
  - Winding stress depends on properties, initial strain due to cure and thermal shrinkage
  - Initial analysis shows stress up to 16-ksi, FS=1.3
  - Further non-linear analysis is planned during final design