NCSX
Construction Feasibility Review

NCSX Engineering Team

(presented by P. Heitzenroeder)

10/31/2007

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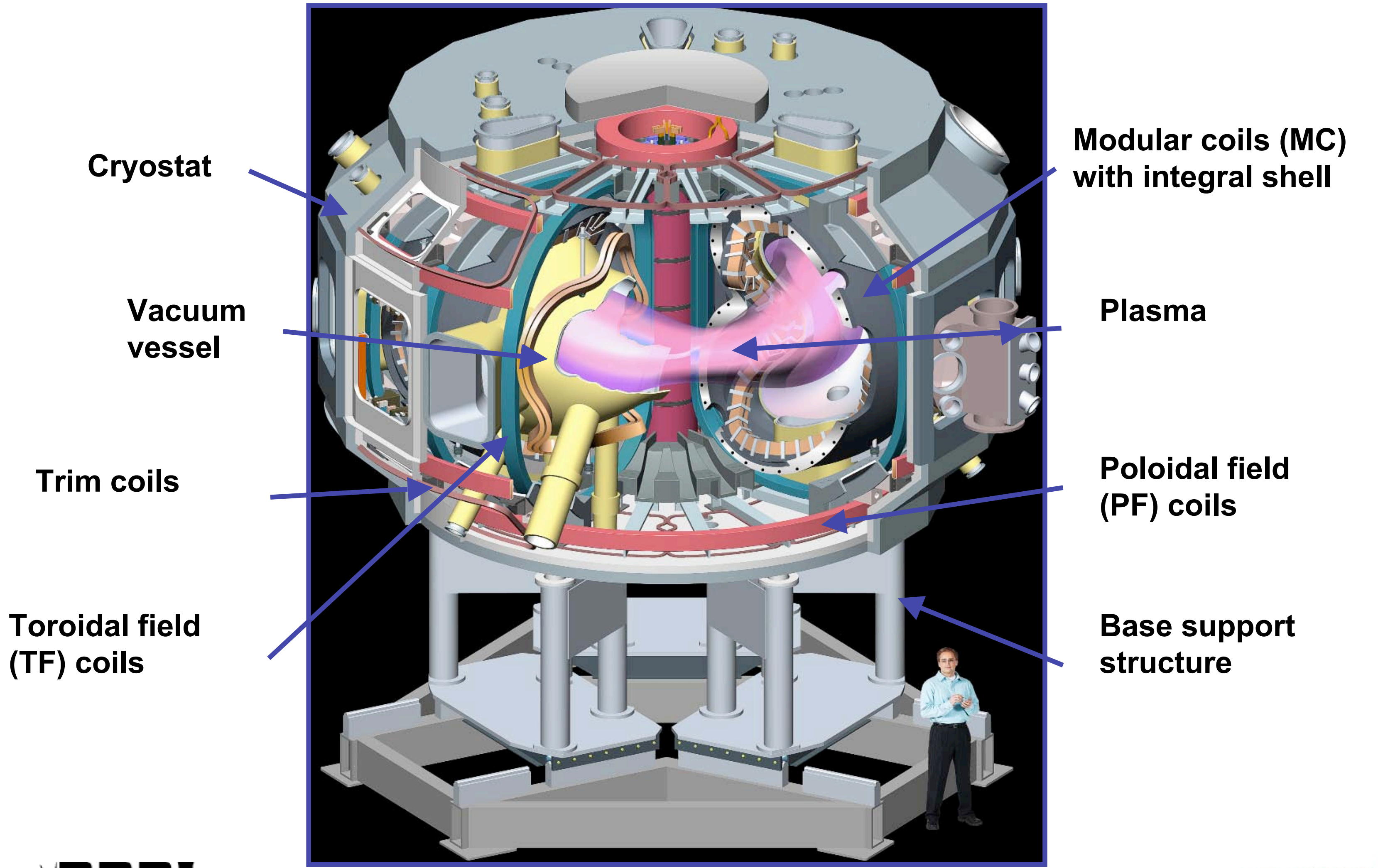
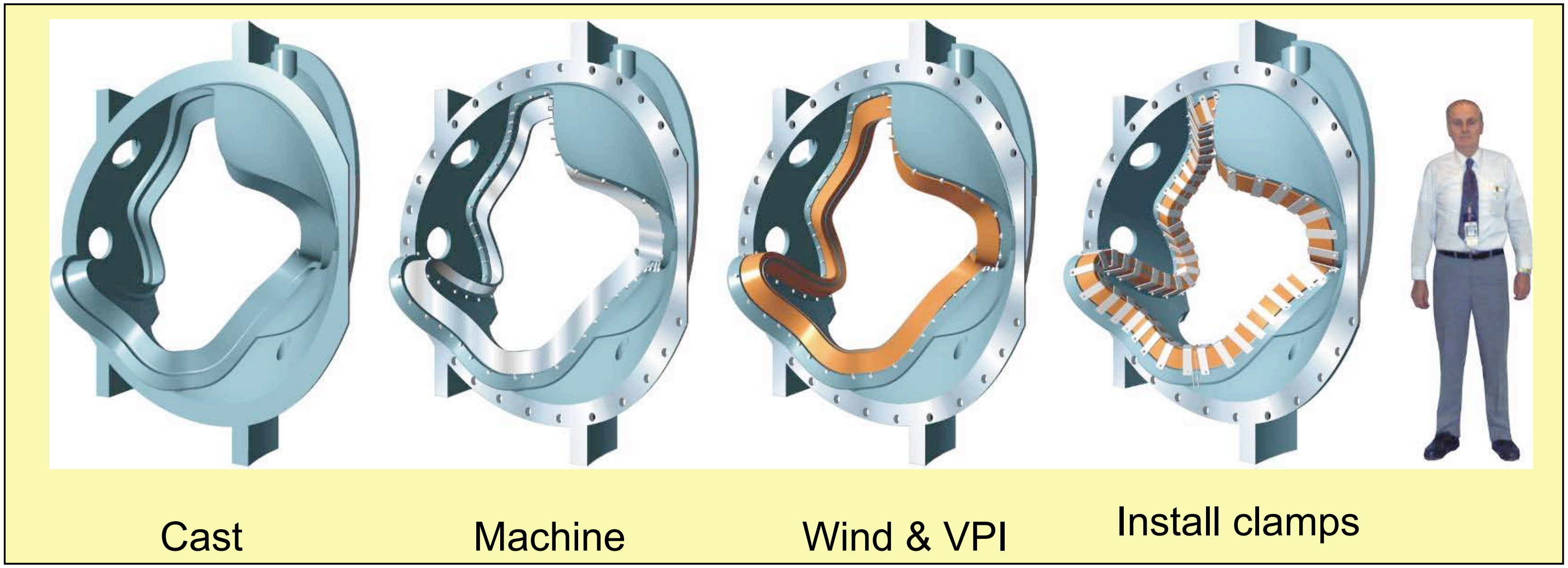
Outline

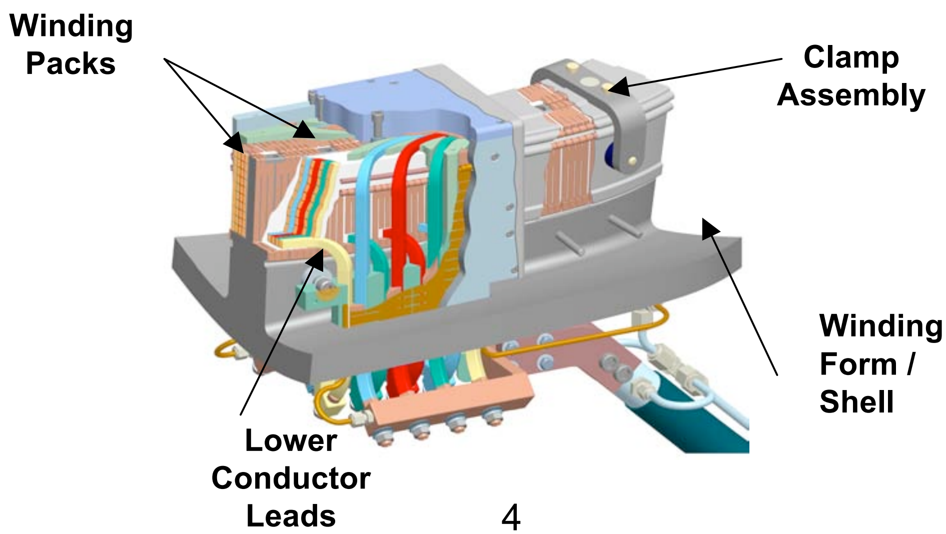
1. Overview of the NCSX core systems
2. Tolerance requirements & allocation
3. Engineering analysis & design confirmation
4. Metrology capabilities
5. Modular and TF coil status & achievements
6. Significant remaining core system / assembly design tasks
7. Conclusion

NCSX


Cryostat
Modular coils (MC) with integral shell
Vacuum vessel
Plasma
Trim coils
Poloidal field (PF) coils
Toroidal field (TF) coils
Base support structure

The modular coil windings are wound directly on cast stainless steel winding forms

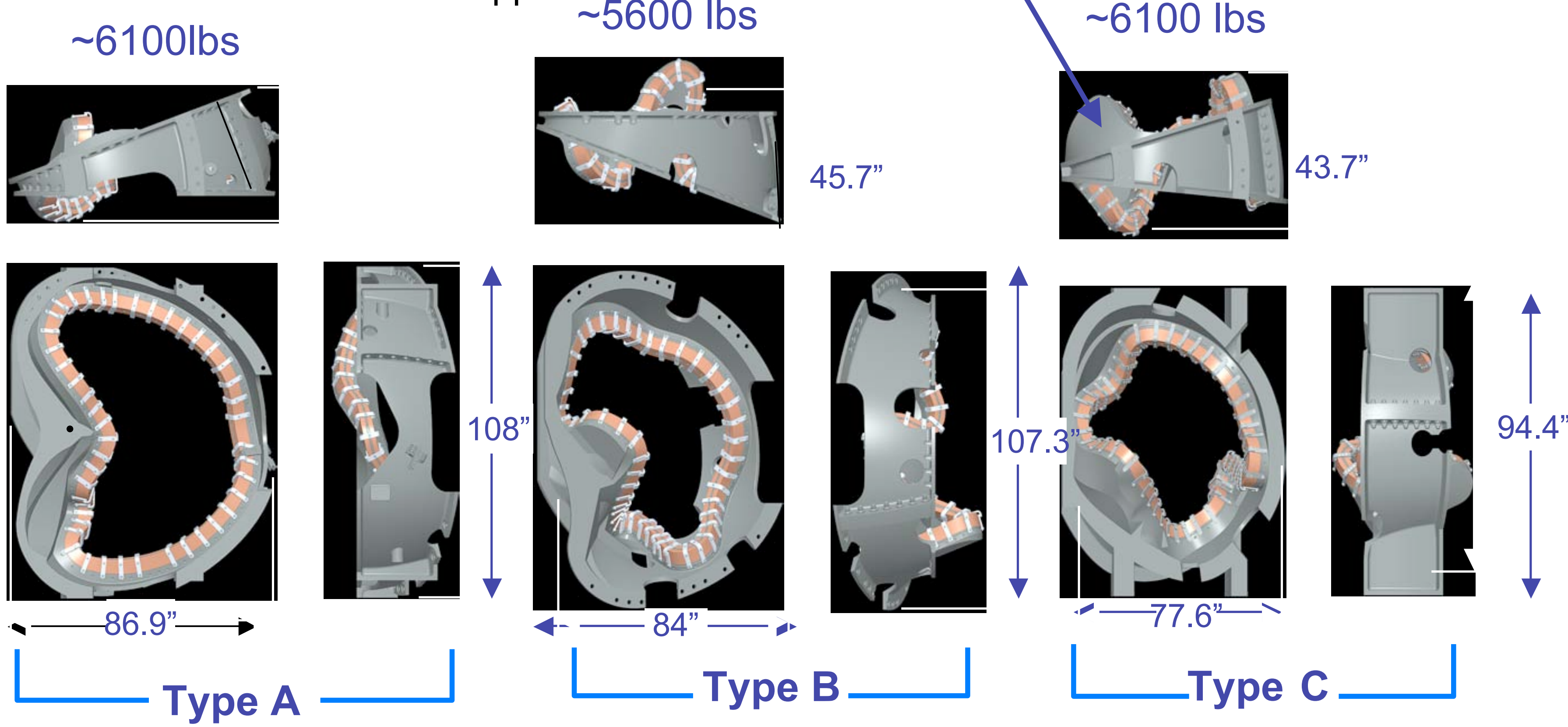




The 3 modular coil types

NCSX
National Compact Stellarator Experiment

Wings. Inflatable epoxy-glass shims are installed at assembly for support.



- 6 of each type; 18 in total.
- Castings made of “Stellalloy” which was specifically developed for NCSX.

  -Magnetic permeability <1.02 and good welding characteristics.

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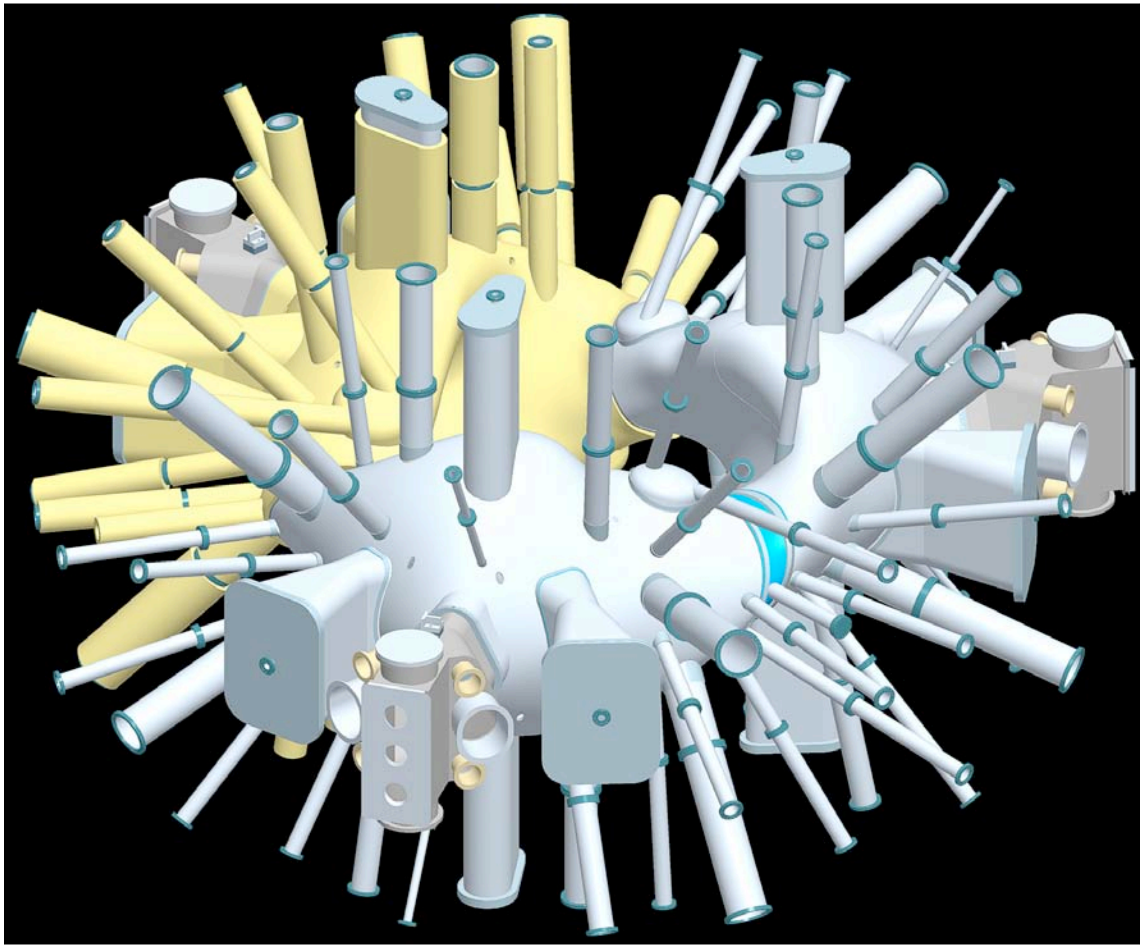
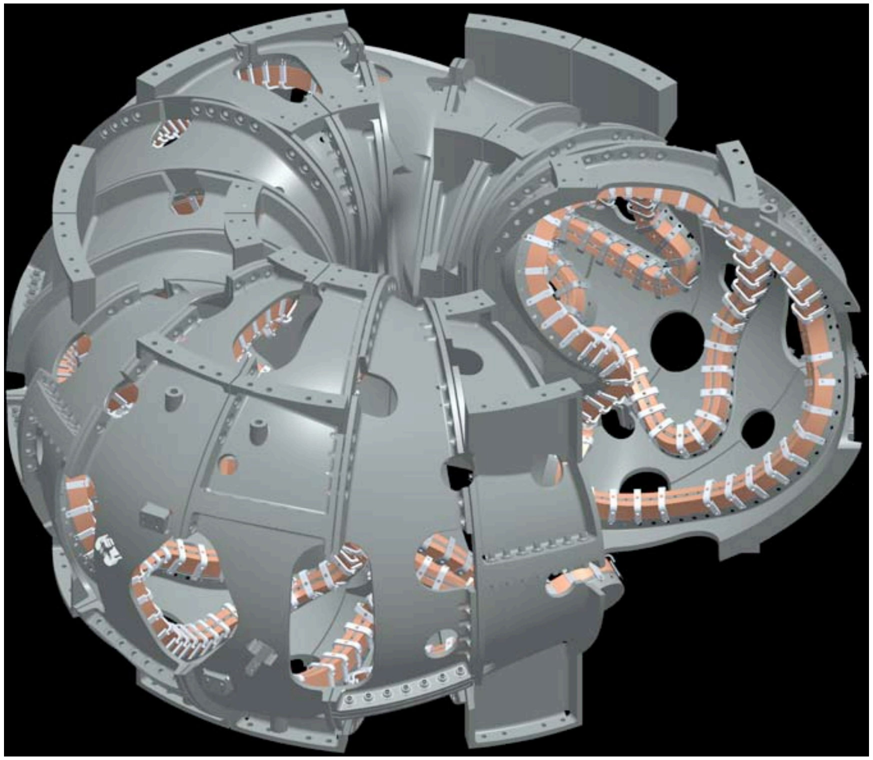
Vacuum Vessel

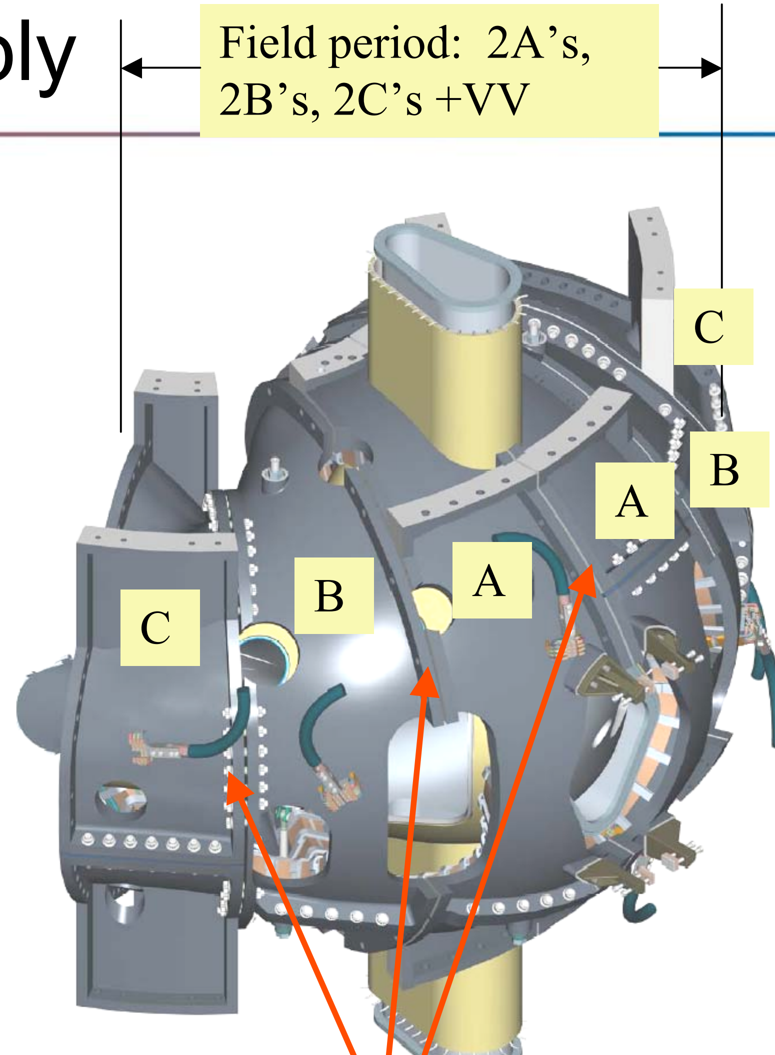
Shell material : Inconel 625
Thickness : 0.375 inch
Time constant: 5.3 ms
Total wt w/ports ~ 20,000 lbs
Welded joints connect field periods
Traced with He gas lines for heating (to 350C) and cooling



Modular Coil Assembly

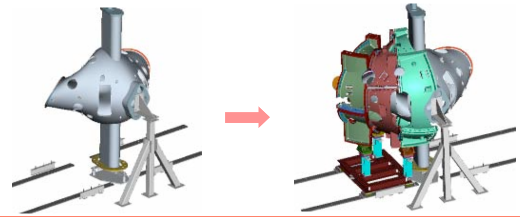


Modular coil assembly consists of 3 field periods. It serves as the structural backbone of the machine – the VV, PF, TF, and trim coils are all supported from it.

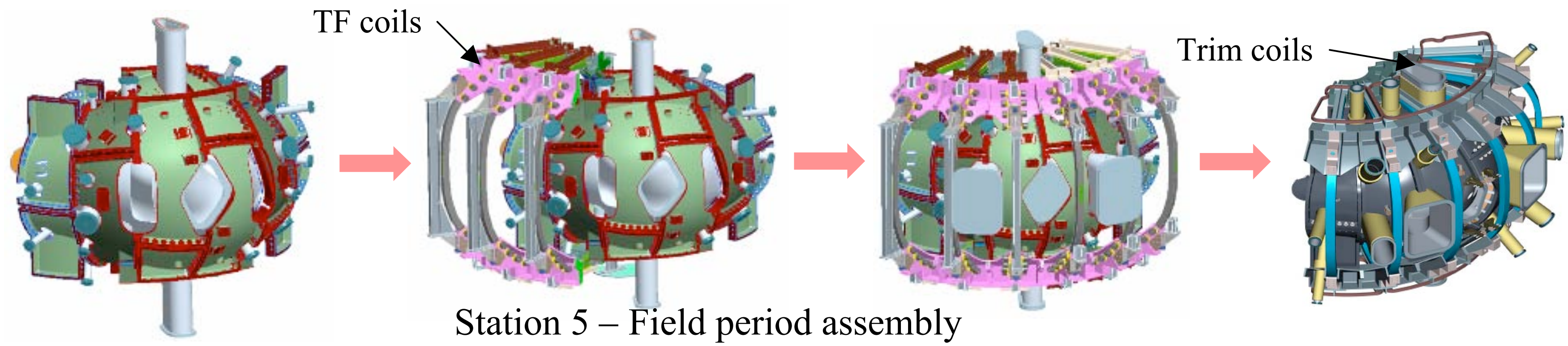


Custom shims at flanged joints between adjacent coil winding forms

Assembly

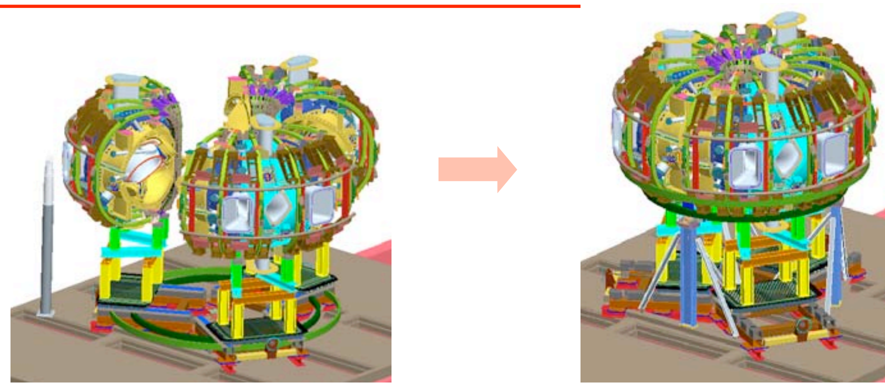


Station 3 – Modular coils installed around VV



Station 5 – Field period assembly

Station 6 –
Machine assembly



2. Tolerance requirements & allocations

Modular coil tolerance requirements

3.2.1.2.5.4 Winding Tolerance

The local current centroid of each modular coil shall be located within 1.5 mm of the nominal location defined in Section A.1.1 Coil Centroids with the modular coils at the pre-pulse operating temperature with zero current.

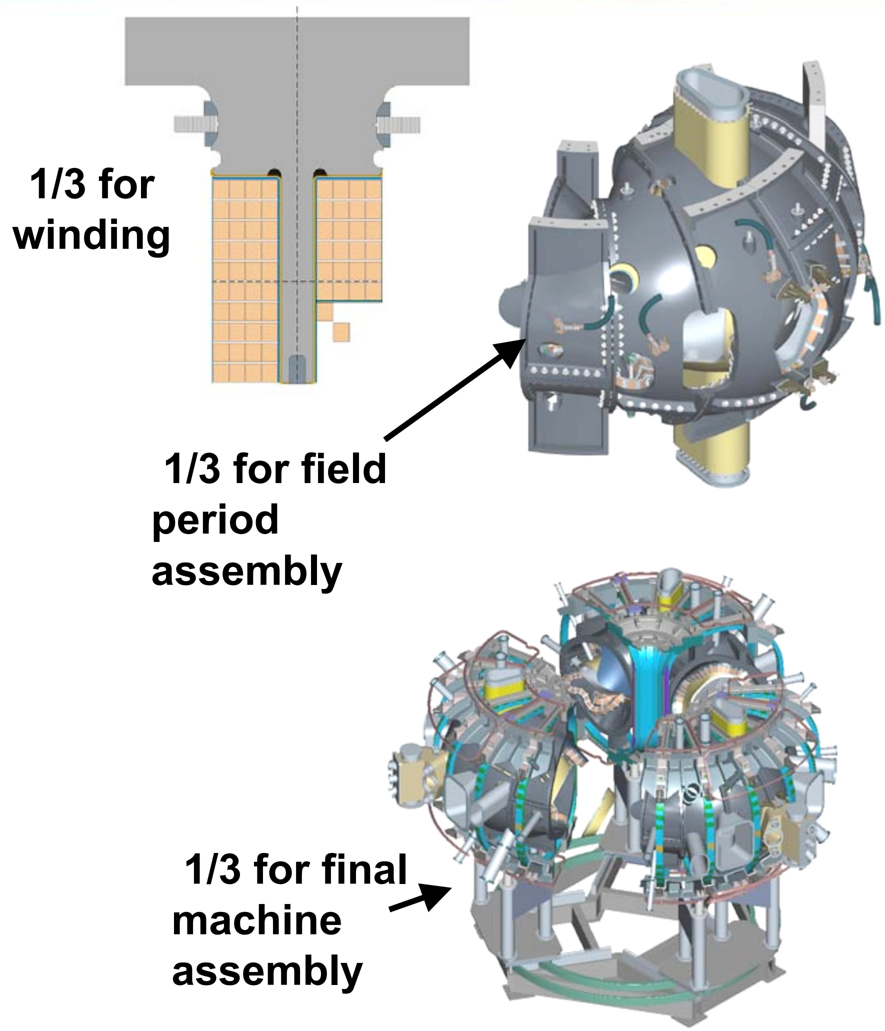
3.2.1.2.5.5 Deflections under Load

a. Modular coils shall be designed such that deflections due to thermal growth and due to electromagnetic loads preserve stellarator symmetry.
b. Deflection of the nominal current centroid due to electromagnetic loads shall not exceed 3 mm.

[Ref.: *Modular Coil System Requirements NCSX BSPEC-14-01*

Tolerance Allocation

- Initially allocated equally between modular coils coil, FP assembly, and final assembly; i.e., +/- 0.5 mm (0.020") for each.
    - No credit taken for re-alignment when the tolerance allocation was made.
    - The actual modular coil fabrication tolerances were met in most, but not all locations.
- Based on actual MC dimensions, we will adjust their position to compensate for their actual dimensions. New allocation:
    - +/- 0.040" (1 mm) for field period assembly
    - +'- 0.020" for final assembly



Dimensional requirements for other coils

- PF Coils +/- 3.0mm [0.120in]
- TF Coils +/- 3.0mm [0.120in] [1]
- Trim Coils +/- 3.0mm [0.120in]

(Note[1]: tolerance can probably be relaxed)

3. Engineering Analysis & Design Confirmation

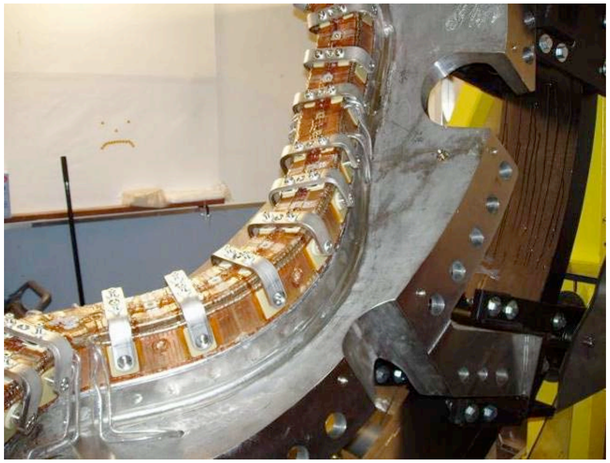
Dimensional considerations have been emphasized in NCSX's Engineering / Design /Construction plans from the start!

1. Cool-down deformations.
2. Deformations due to gravity loads.
3. Deformations due to electromechanical loads.
4. Manufacturing tolerances.
5. Eddy currents
6. Assembly tolerances.
7. Metrology accuracy & repeatability.

Cool-down & thermal deformations

- Accounted for in design and assembly.
  - Most of the structural materials are variants of stainless steel with very similar coefficient of thermal expansions (CTEs).
    - Biggest thermal growth item: modular coil windings on winding forms. Cu windings are clamped onto winding form; EM load clamps winding onto winding form except for a few wing areas. These are reflected in the EM analyses.
  - PF and TF coils are supported on the modular coil torus by aluminum brackets.
  - VV supported from the modular coil shell. Assembly position will be compensated for 150 C operating temperature.

	E (MPa)	G (MPa)	CTE (m/m/°K)	Density (kg/m^3)	Poisson's Ratio
MCWF	145,000	*	1.700E-05	7750	0.31
Modular coil	63,000	26250 / 525	1.720E-05	8500	0.20
MCWF toroidal shim	150,000	*	1.700E-05	7750	0.27
MCWF poloidal shim	193,000	*	1.700E-05	7750	0.31
MCWF wing bag	13,750	*	3.000E-05	1820	0.32
Wing bag image	6,894	*	3.000E-05	0.1	0.32
PF coil	120,000	*	1.600E-05	8300	0.33
PF6 coil bracket	193,000	*	1.700E-05	7750	0.31
PF coil support shim	22,000	440	1.720E-05	1900	0.21
TF coil	120,000	*	1.600E-05	8300	0.33
TF coil side shim	22,000	440	1.720E-05	1900	0.21
TF coil top/bot shim	95,000	950	1.700E-05	7750	0.31
TF coil wedge spacer	145,000	*	1.700E-05	7750	0.31
TF structure	145,000	*	1.700E-05	7750	0.31
TF structure tie bar	145,000	*	1.700E-05	7750	0.31
TF structure shim	22,000	*	1.720E-05	1900	0.21
Connecting block	145,000	*	1.700E-05	7750	0.31
Base support block	193,000	*	1.700E-05	7750	0.31



NCSX-CALC-14-003-00

Analyses based on 2T, High Beta operating mode which produces the maximum EM forces

Reference: Design Description
Modular Coils (WBS 14)
NCSX MCWF Final Design Review
May 19-20, 2004, pg. 22

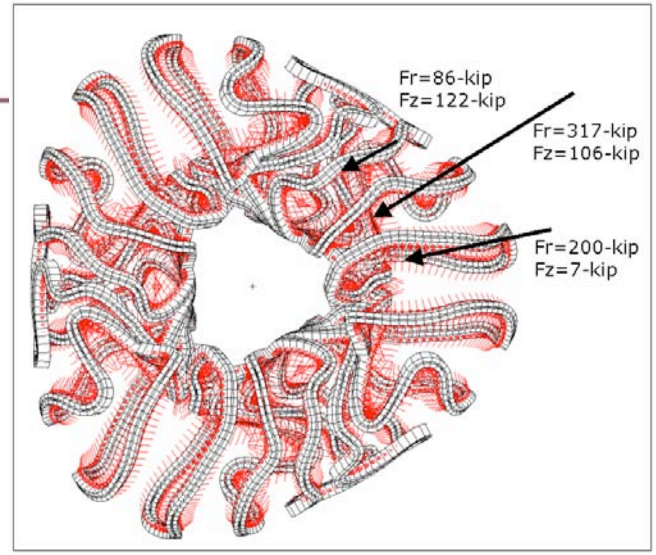
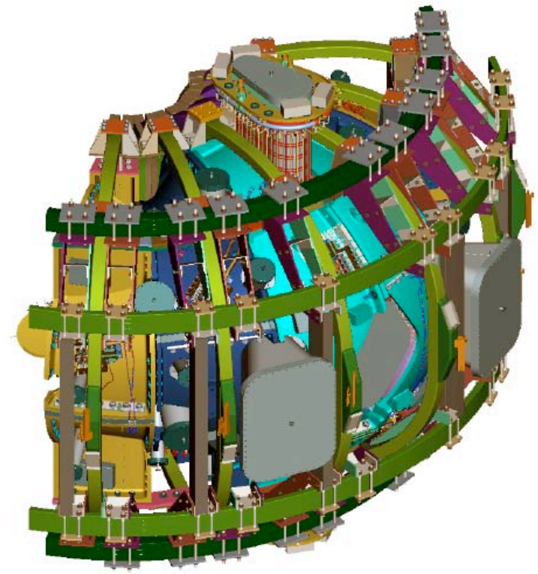


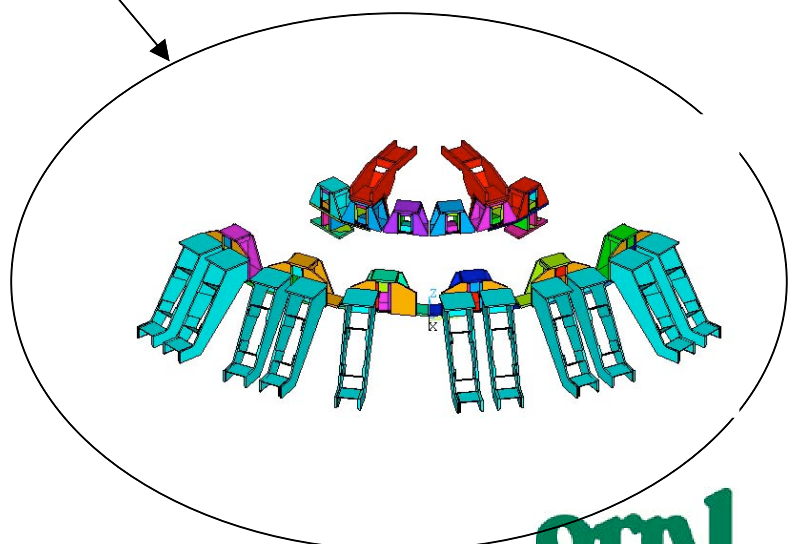
Table 1 Net EM Force on Modular Coils

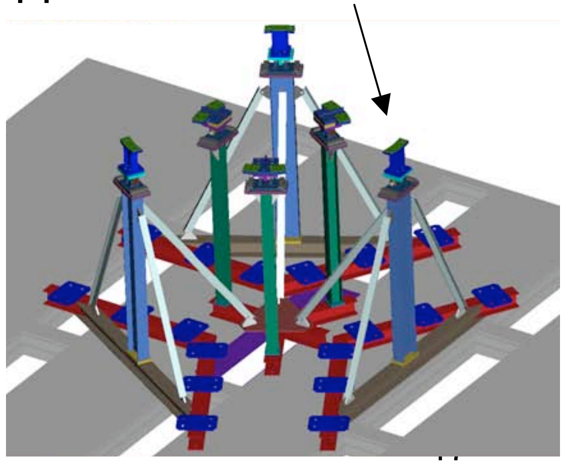
Coil	Field/Force Component	0.5-T 1st Plasma	Field Mapping	1.7-T Ohmic	1.7-T High Beta	2-T High Beta	1.2-T L. Pulse	320-k Ohm
	Max Field at Coil (T)	1.2	0.2	4.2	4.2	4.9	2.9	4.2
Type A	Net Radial Load (kip)	13	1	152	152	200	76	147
	Net Vert Load (kip)	0.5	0	9	9	7	5	7
Type B	Net Radial Load (kip)	20	1	228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

Model includes the latest structural features

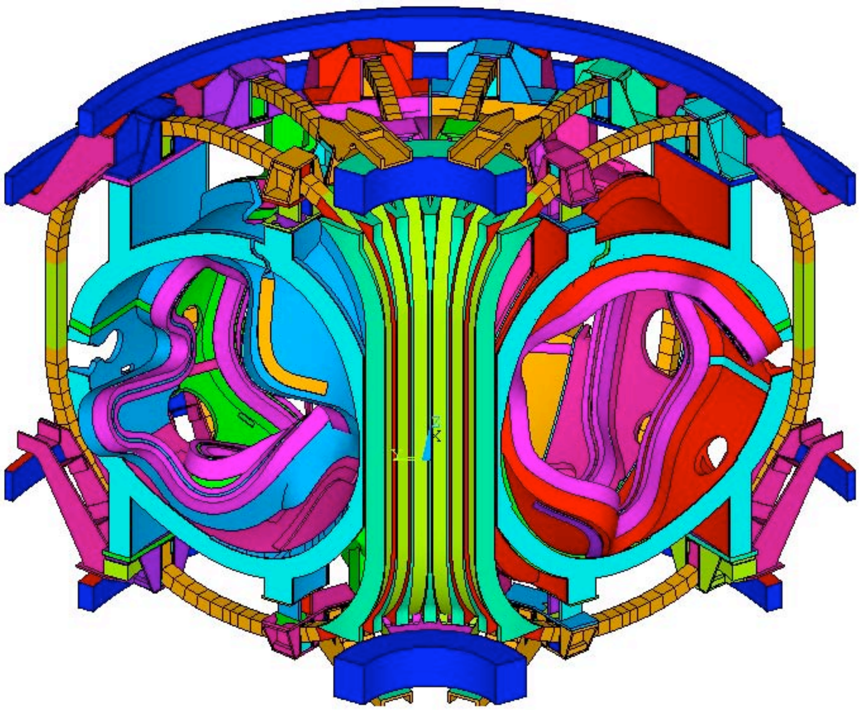
- The revised TF, PF, and support structure with improved dead-load support and cost advantages is reflected in this latest analysis.
  - The integrated TF and PF support structure is bolted to the MCWF.
  - Uses weldments of aluminum alloy 5083-H32.
- The base structure supports the modular coils at inboard & outboard locations. The model reflects these support locations.







Details of the Analysis Model



•Loads due to VV and center stack included, but those structures were not.

• Bolt details, fillets, chamfers, edges and corners omitted to simplify the model.

• Modular coils are bonded to the winding forms.

• The impacts of trim coils are not included, but are small.

• All bolted joint interfaces are treated as bonded contact surfaces.

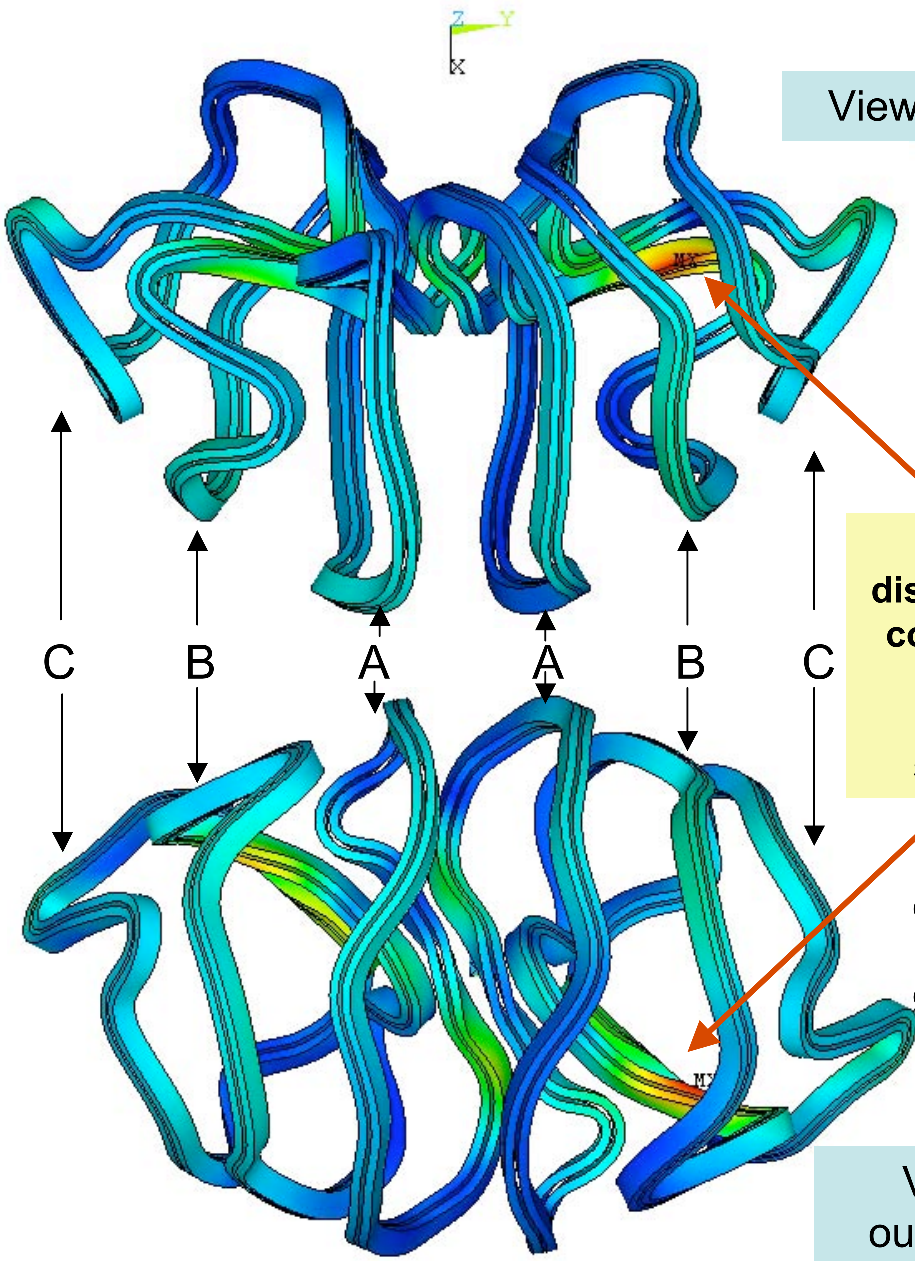
Modular Coil Displacements

- **Dead Load + EM Load with Wing shim E = 2,908 MPa**

USUM (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.002831
SMN =.384E-04
SMX =.002831

.384E-04
.349E-03
.659E-03
.969E-03
.00128
.00159
.0019
.002211
.002521
.002831

Displacement in meters



Actual Stellalloy properties exceed specifications

NCSX National Compact Stellarator Experiment

Winding Form Average Properties

At 77 K	Specification	C1	C2	C3	A-1
Elastic Modulus	144.8 Gpa	160.9	176.1	171.9	175.8
0.2% Yield Strength	496.4 Mpa	678.5	642.6	669.5	670.9
Tensile Strength	655 Mpa	1174.0	1129.6	1124.8	1146.6
Elongation	32.0%	55.7%	54.3%	55.7%	56.0%
Charpy V – notch	47.4 J	104.9	113.9	134.6	106.2
At 293 K	**Specification**	**C1**	**C2**	**C3**	**A1**
Elastic Modulus	137.9 Gpa	159.5	156.3	148.9	149.4
0.2% Yield Strength	234.4 Mpa	241.9	252.1	263.8	252.6
Tensile Strength	537.8 Mpa	576.9	568.4	570.2	567.9
Elongation	36.0%	52.0%	53.5%	52.5%	53.2%
Charpy V – notch	67.8 J	191.7	203.4	212.4	221.0

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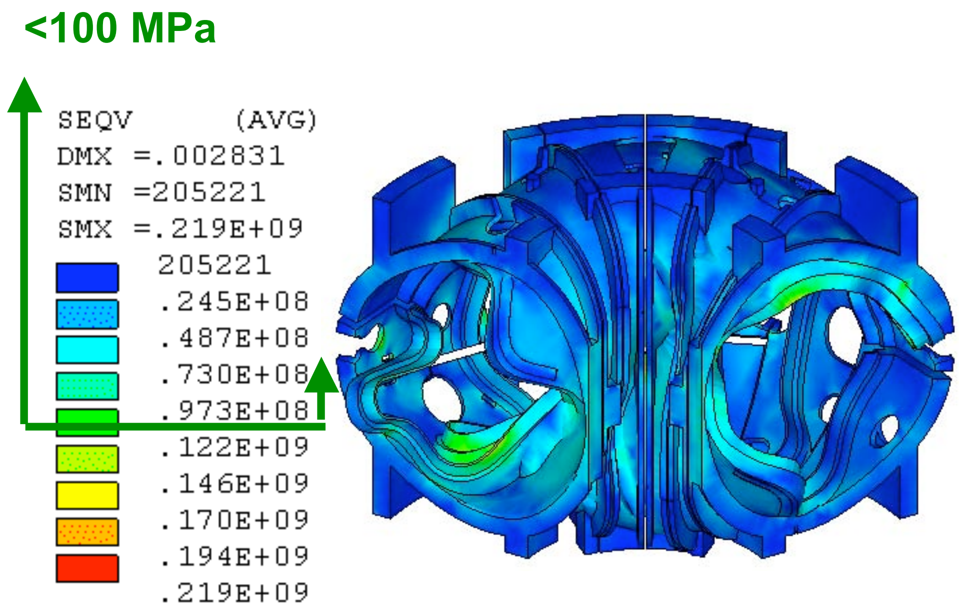
We have good margins on static stresses

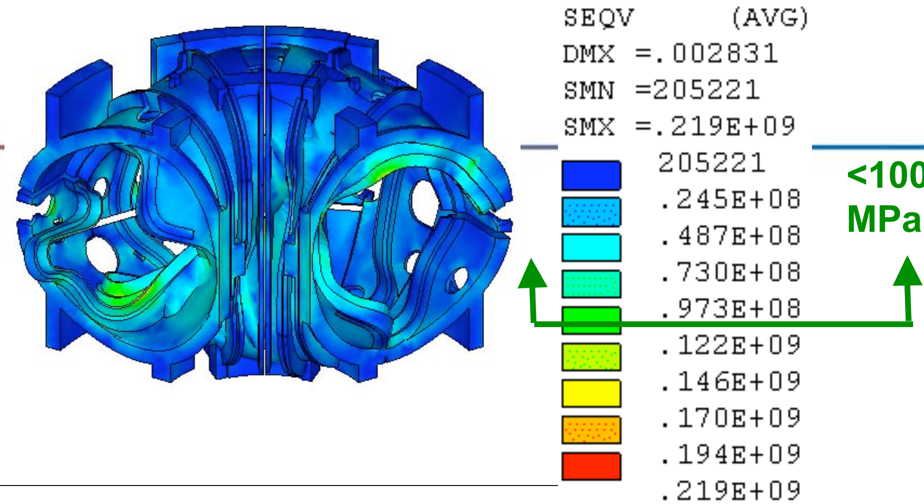


- **Max. stress is 219 MPa.**
  - •Allowable = 327 MPa.
  - Factor of Safety (FS) on allowable is 1.5 (based on specified material properties for Stellalloy; based on actual FS~2.5
- Average stress is <100 MPa.

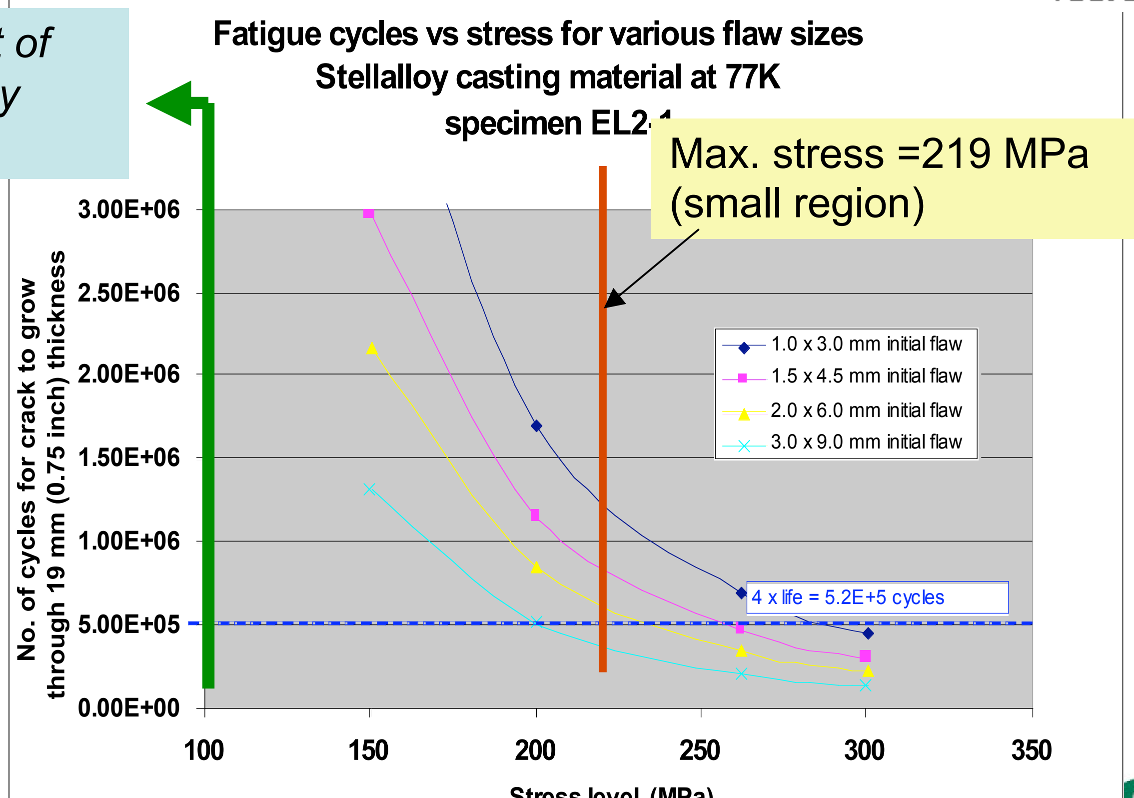
Fatigue

NCSX National Compact Stellarator Experiment

- Compact test specimens were used to characterize of Stellalloy and welds at 77K.
- Castings 100% radiographed; flaws limited to <2 mm in major dimension in high stress regions of T.



The stress in most of the shell is typically <100 MPa



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Vacuum vessel analyses results

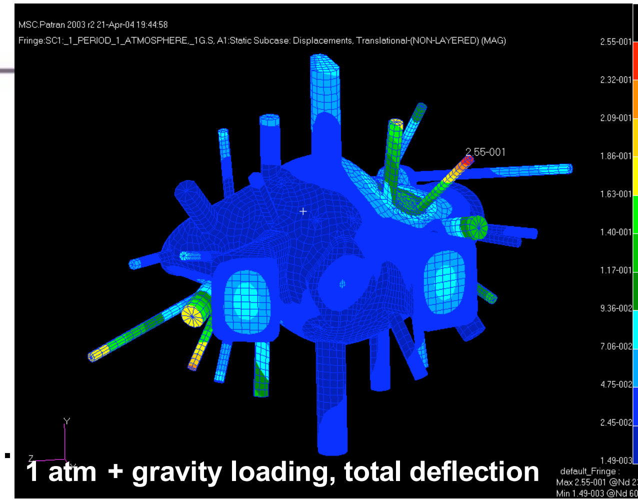
<u>Gravity and Pressure loads:</u>
•Deflections: 0.25 in. (ports), 0.12 in. (shell), Tresca stress: 16 ksi, safety factor > 2 in welds

<u>Disruption loads:</u>
max vertical load of 18,000 lbs, deflections 0.45 in. (ports), 0.25 in. (shell)
Tresca stress ~ 28 ksi for combination of VDE, pressure, gravity loads, safety factor > 2 in shell, > 1.2 in welds

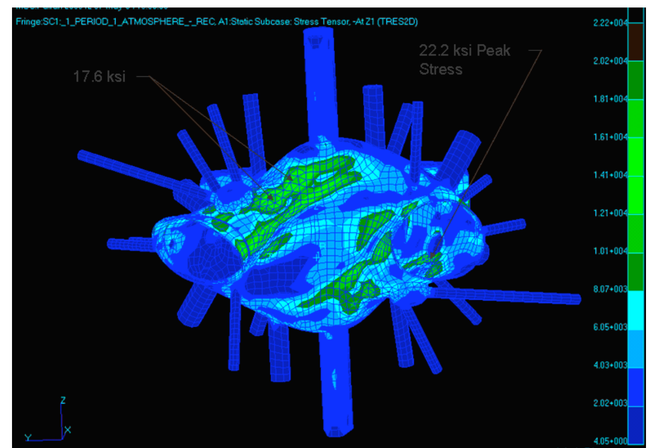
<u>Buckling:</u> critical pressure =10 x max pressure (vacuum + VDE load)

<u>Thermal analysis:</u>
Pre-shot load on cold systems, VV at 40C: 13 kW
350 C VV bakeout load on cold systems: 43 kW

<u>EM analysis:</u> (VV material: Inconel 625)
Time constant 5.3 ms compared to 10 ms reqmt.



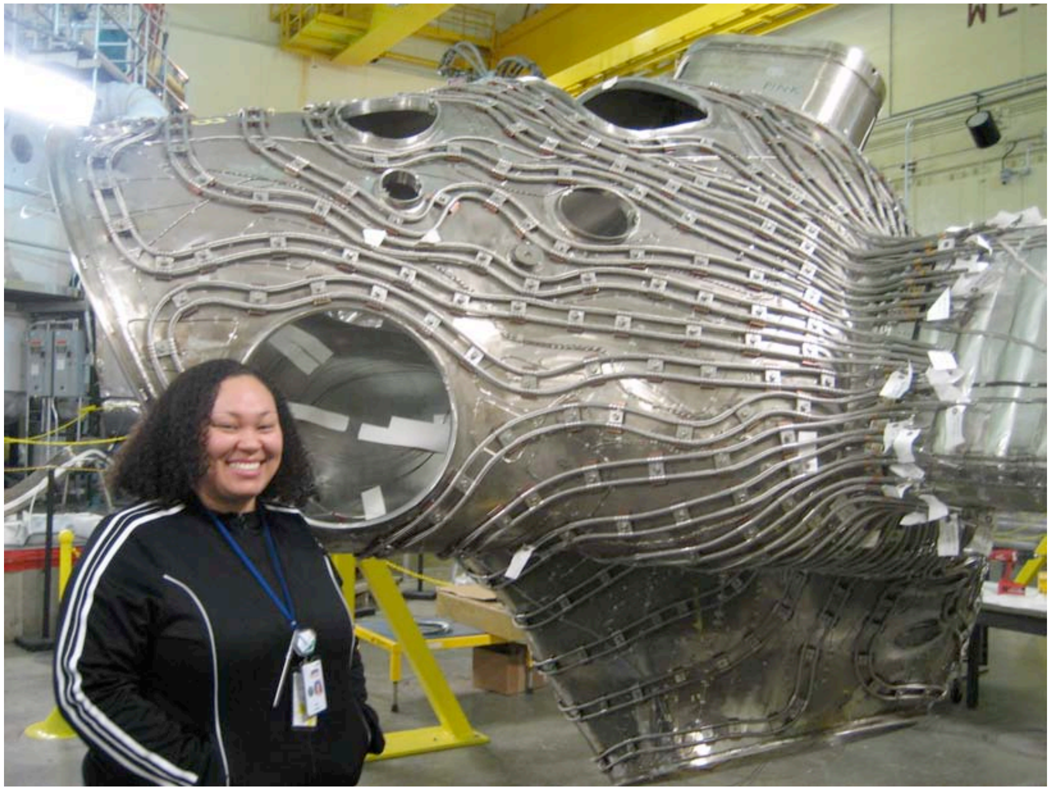
1 atm + gravity loading, total deflection



VDE + pressure + gravity tresca stress

All 3 VV segments are nearing completion

- All 3 vessel segments were delivered by September, '06.
- Diagnostic loops, heating & cooling lines, and thermocouples have been installed.
- Work remaining: flow testing and final I&C terminations.

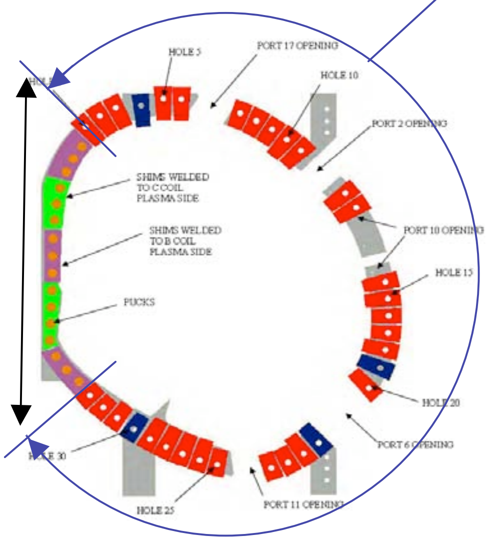


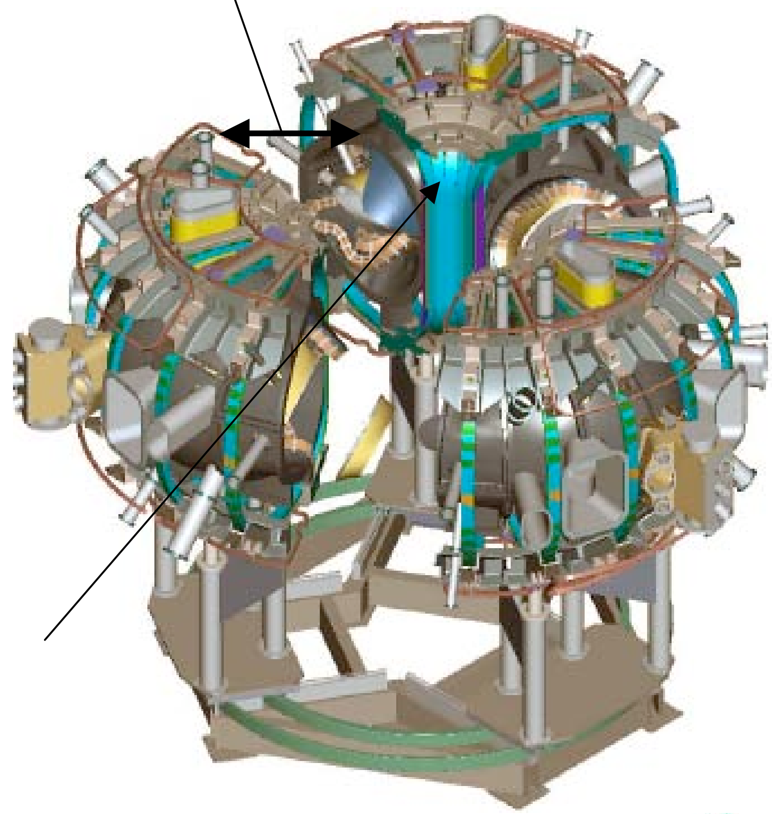
Robust coil-to-coil interfaces have been developed

Alumina coated high friction shims used in the outer flange locations to lock coil positions relative to each other.

Type 1 - C-C field assembly bolted joints for ease of assembly.

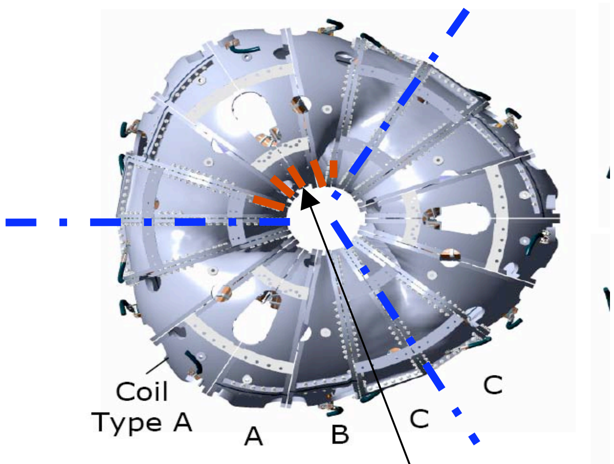
Inner leg (two types)





Type 2 - Low-distortion welded inner leg interfaces used intra-period. Good solution for interfaces where there is inadequate space for studs.

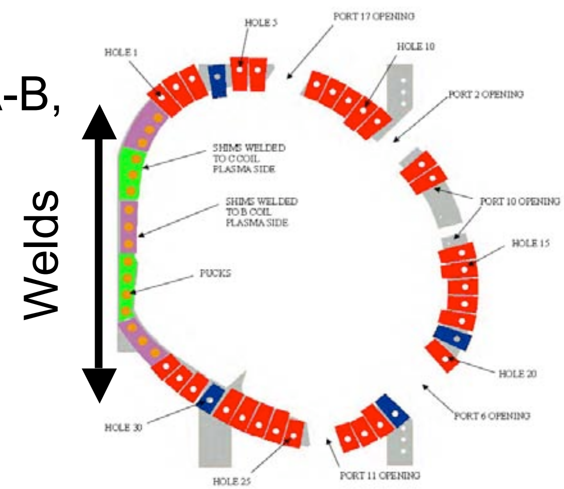
The two inner leg interface types



5 welds/period (typ.) in central region.

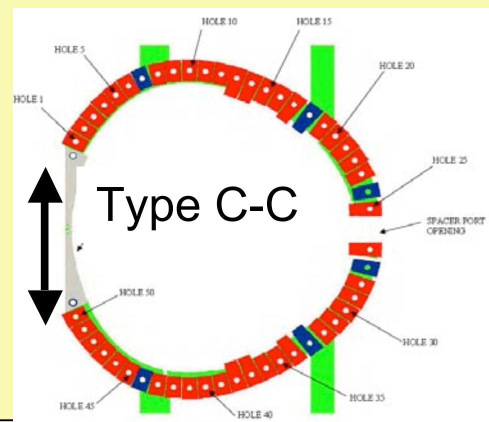
(1) Welded inner leg interfaces

Types A-A, A-B, and B-C



(2) Bolted inner leg interface

Compression shim



Outer shims will be custom fitted in each location to assure coil alignment and good friction lock-up:

- Red outer shims: high friction alumina coated SS shim with A286 high strength bolt through it.
- Blue outer shims: high friction alumina coated SS without bolt

Eddy currents in modular coils

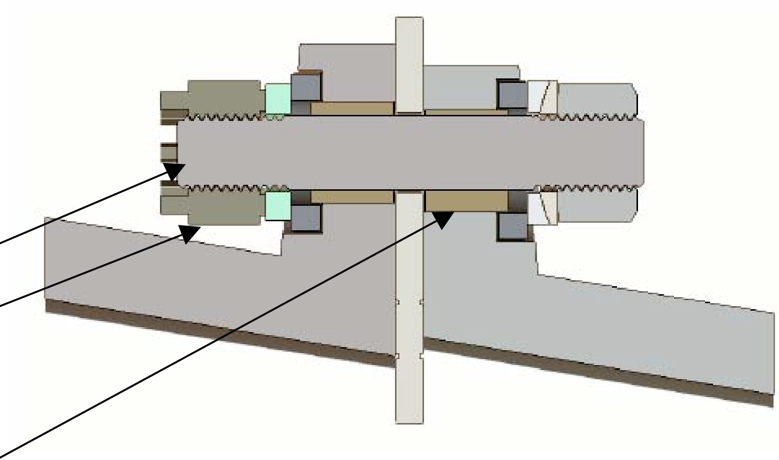
NCSX National Compact Stellarator Experiment

- Poloidal electrical breaks are provided in each modular coil.
- The (3) C-C (assembly) toroidal breaks are fully electrically insulated.
- The remaining (15) are partially electrically insulated:
  - Insulated alumina shims in outboard and top and bottom regions.
  - Welded non-insulated connections in the inner leg regions.
- Time constant ~28 msec.

Studs

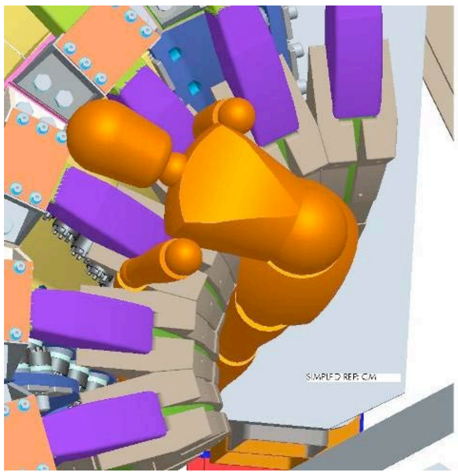
Developing and maintaining adequate clamping force for the friction shims is assured by :

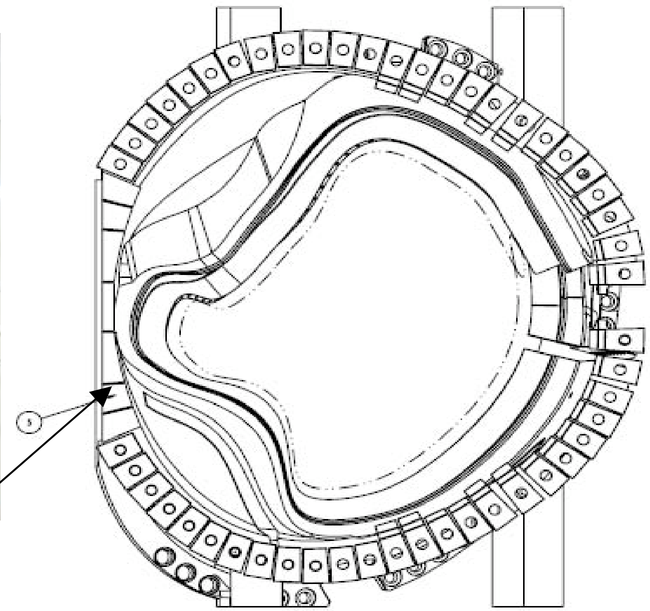
- Using high strength A286 studs
- Using "Supernuts"
- Providing tight fitting bushings around each stud to assure that alignment is maintained during cool-down.
- Verifying stud tension with a ultrasonic tension measuring device.
- Periodically re-checking the stud tension.



C-C interface access & mock-up studies

Stud access was demonstrated first by a Pro-E model and then by a mock-up.





Compression shims

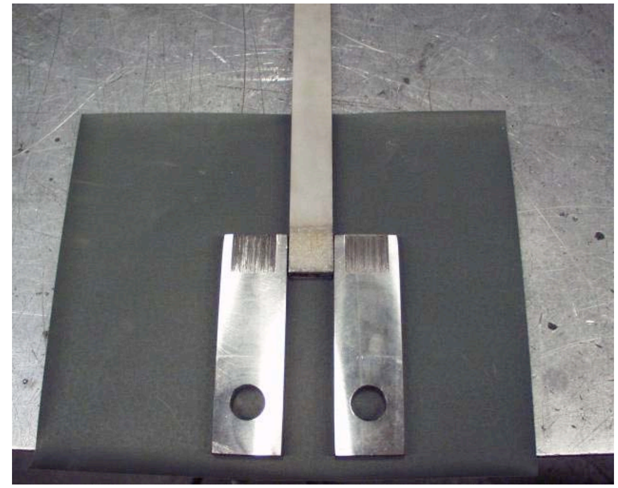
The inner leg deflection is 0.1 mm.

Friction required = 0.39

Alumina coated shim friction characteristics & stability have been verified by tests

Side rams apply normal pressure to test specimens simulating bolt pressure; tensile tester applies shear load

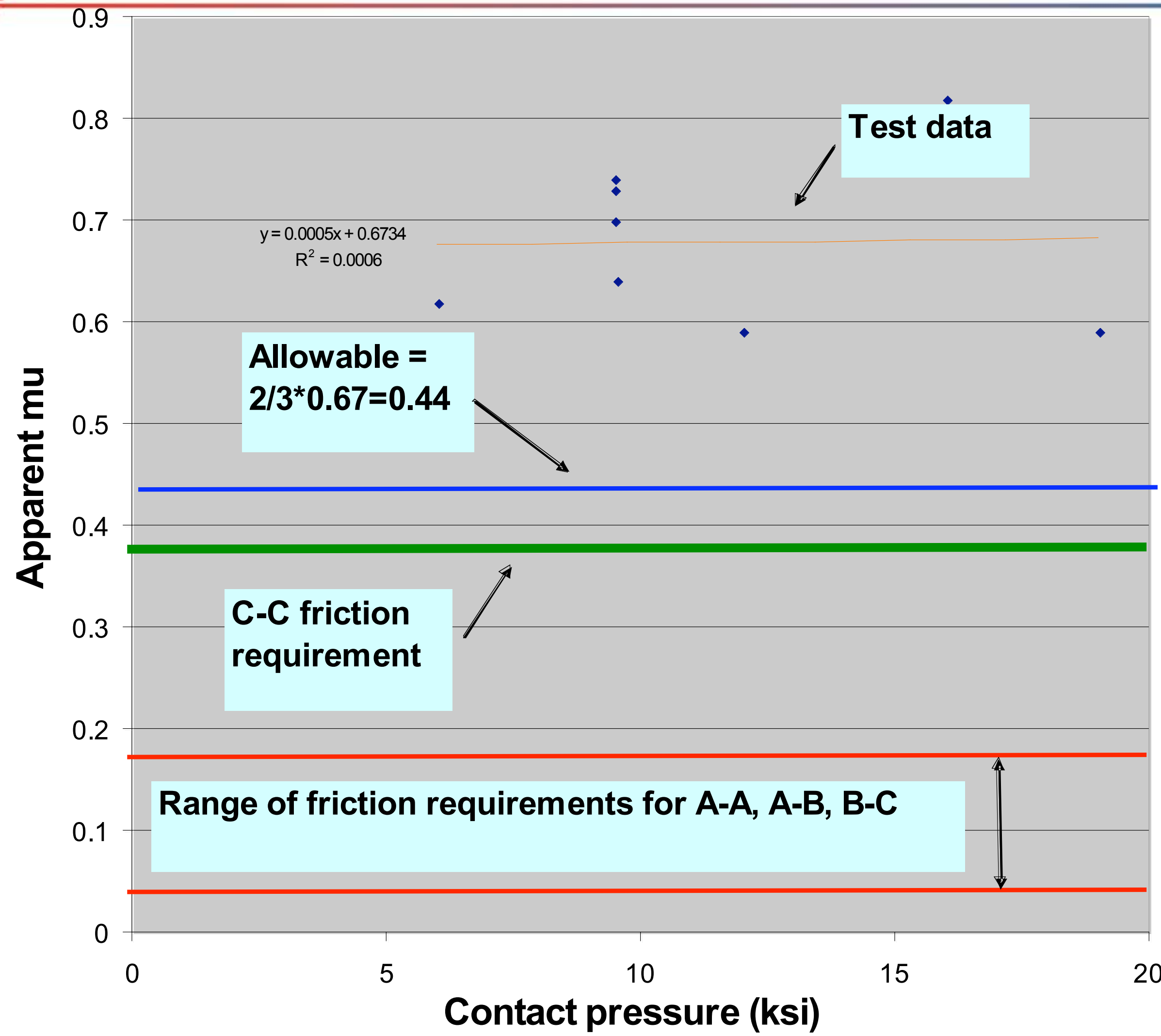
The test setup is cooled to 80 K for testing.



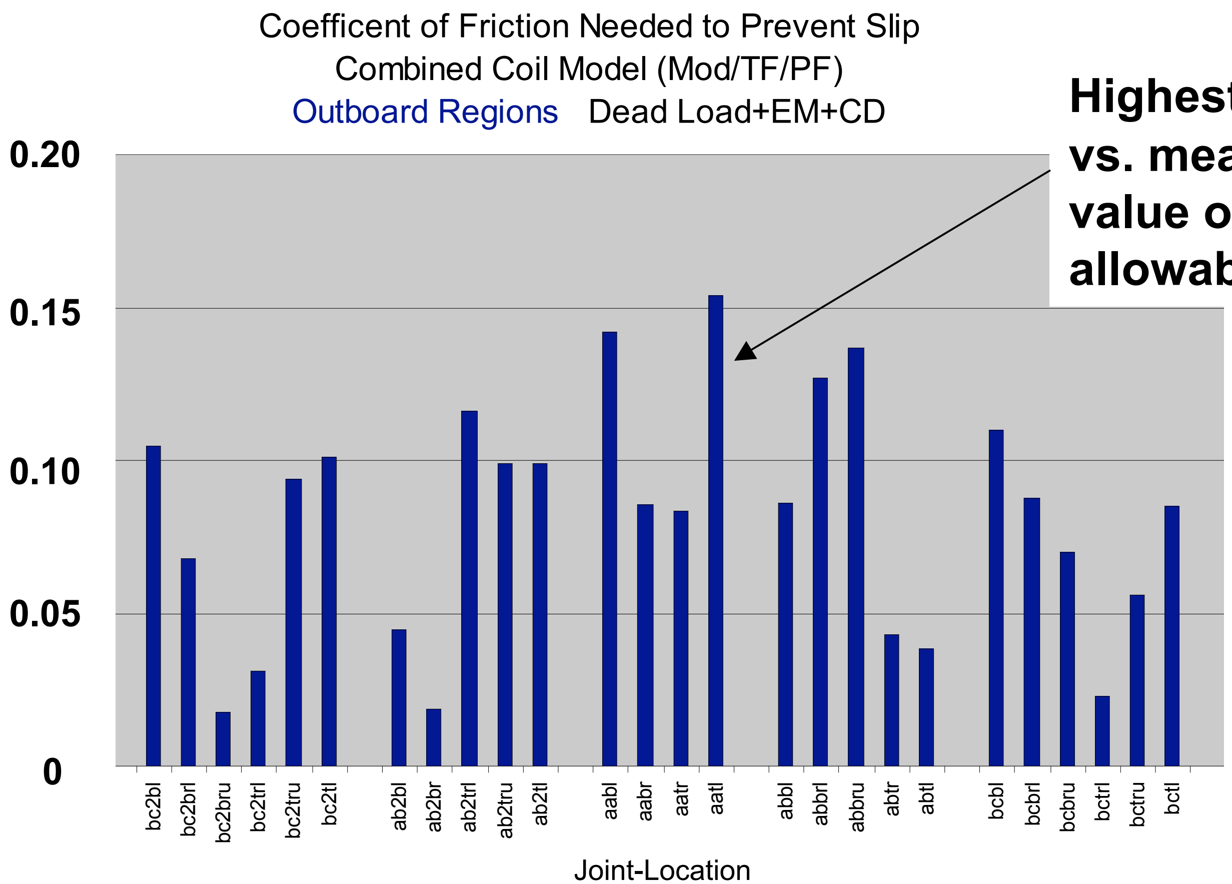
Test specimen – two alumina coated SS sideplates sandwich SS center bar.

- The coefficient of friction, μ, required is 0.39 for the C-C interface and ~0.16 elsewhere; measured value is 0.67.
- Our design criteria allowable is 2/3 of this, or 0.44. **All shims meet the criteria.**
- Life tests were performed - a stable μ of 0.4 has been demonstrated for 130,0000 cycles (full machine life) & “overload” values 0.5 for 130,000 cycles and 0.6 for 48,000 cycles (when the test was stopped due to hydraulic system problems) . No degradation in electrical insulation characteristics.

Alumina coated SS shim friction vs. requirements

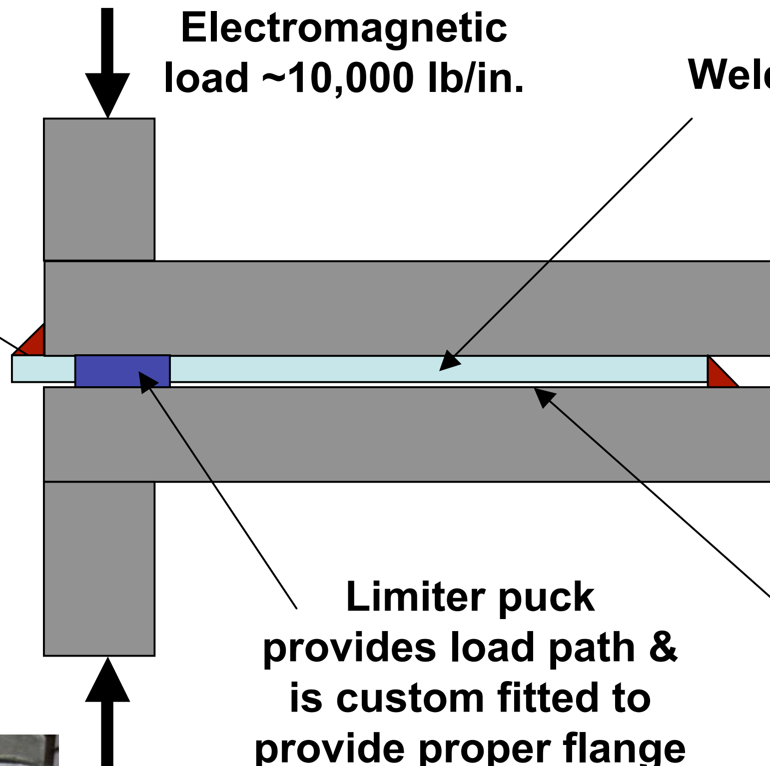


The welded coils have a very comfortable margin on μ



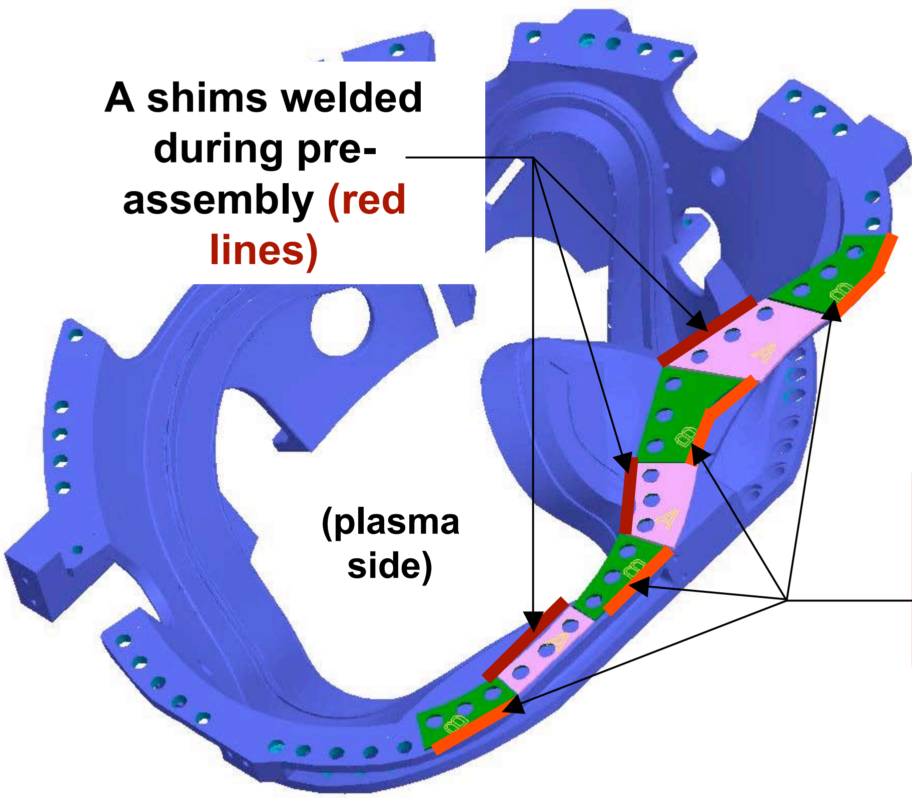
Highest μ is ~0.16 vs. measured value of 0.67 and allowable of 0.44

A Low Distortion Welded Interface Has Been Developed



This welding concept minimizes weld shrinkage forces between the flanges and provides a load path as near as possible to the shell–to– shell interface.

Shim Layout Chosen to Minimize Longitudinal Weld Distortion



Type A casting shown.

- **the pink shims will be welded to it on the plasma side pre-assembly;**
- **the green shims will be welded to the B casting during pre-assembly.**

B shims welded (orange lines) to the A casting during coil-coil assembly

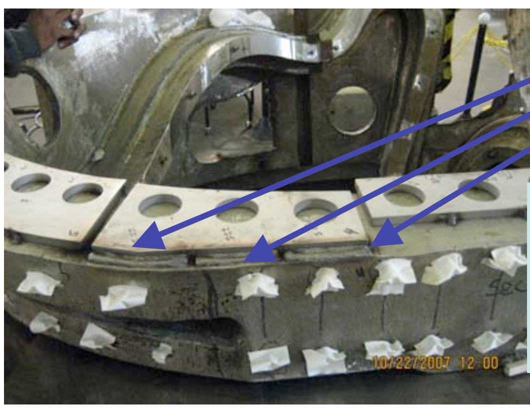
The shim welds are balanced along the two edges of the inboard leg.

A weld test was performed to measure weld shrinkage using the Type C Prototype Casting.

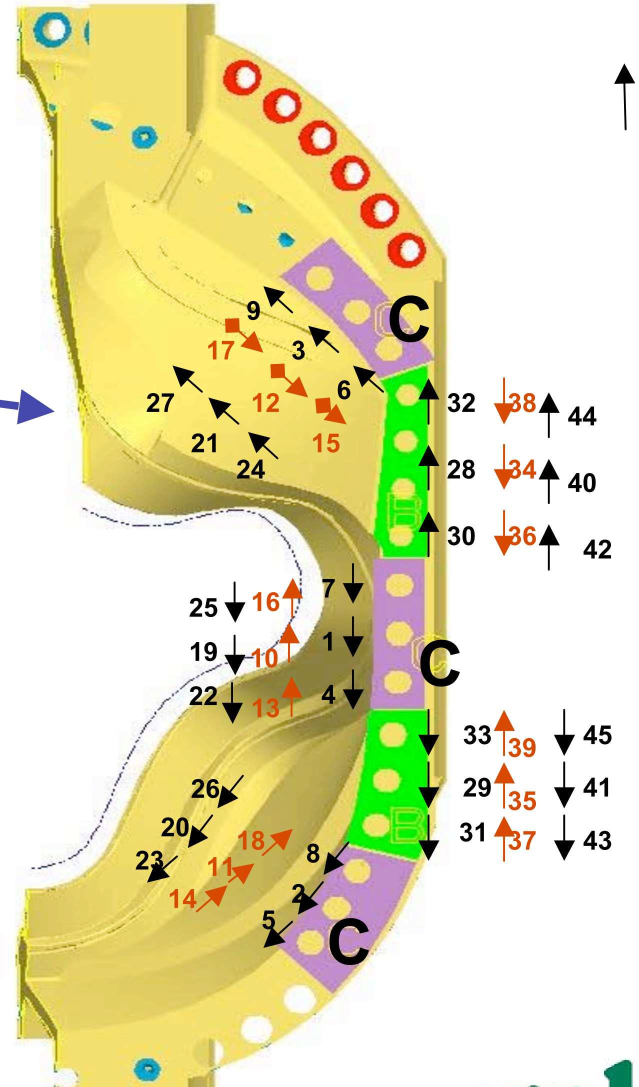
Weld distortion minimization

Our thanks to input received from CERN and W7X, which influenced these plans:

- MIG welds.
- Welding pattern carefully selected to minimize distortion.
- 3 stringers / fillet weld.
- Welds: in segments; typically 4” long with ½” gaps between segments



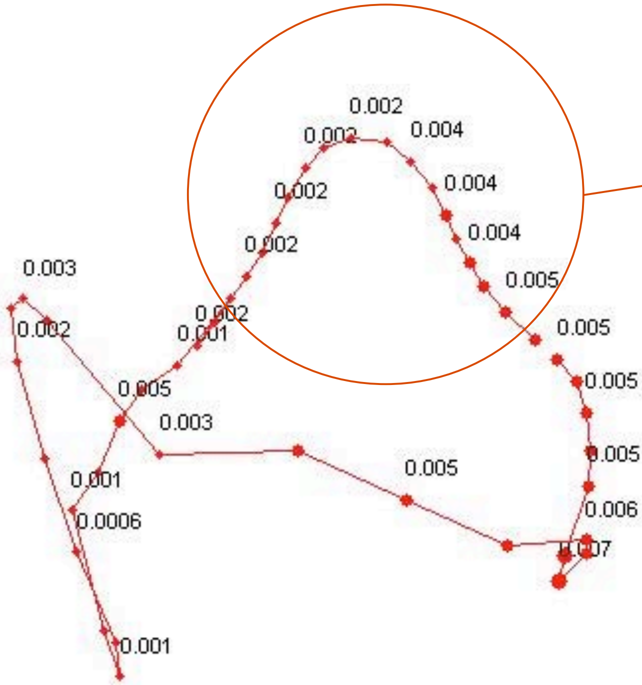
C-prototype casting longitudinal weld shrinkage test



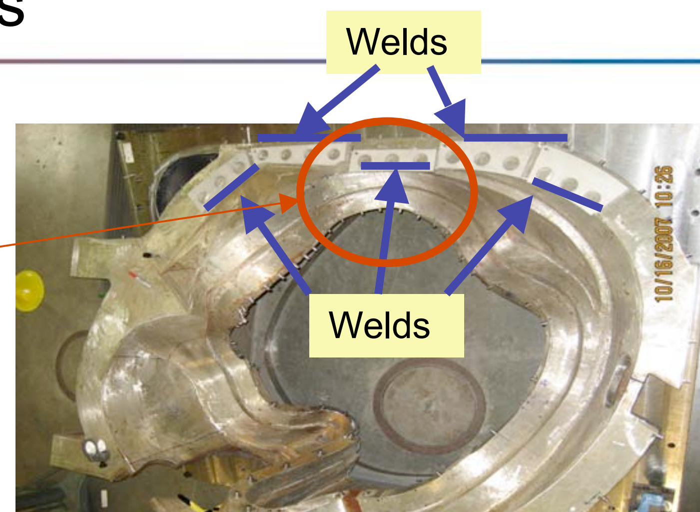
PPPL
PRINCETON PLASMA PHYSICS LABORATORY

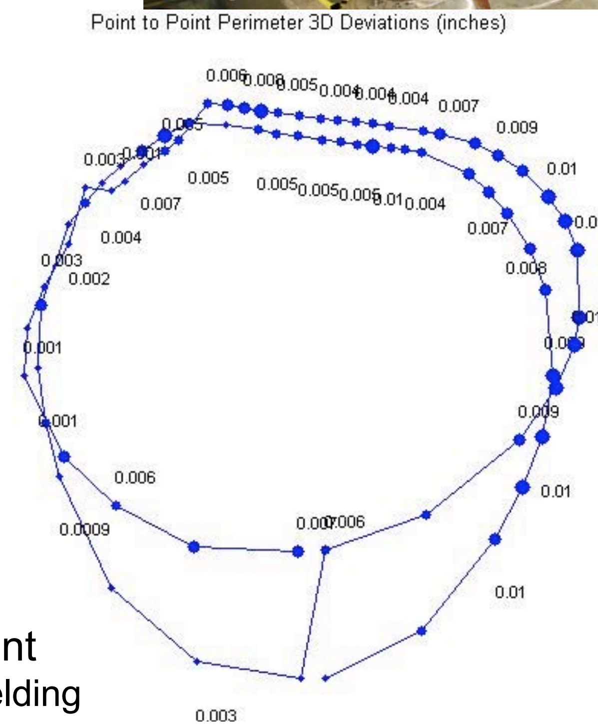
ORNL
OAK RIDGE NATIONAL LABORATORY

C-Prototype Casting Longitudinal Weld Shrinkage Test Results



Casting T septum displacement measurements post-welding

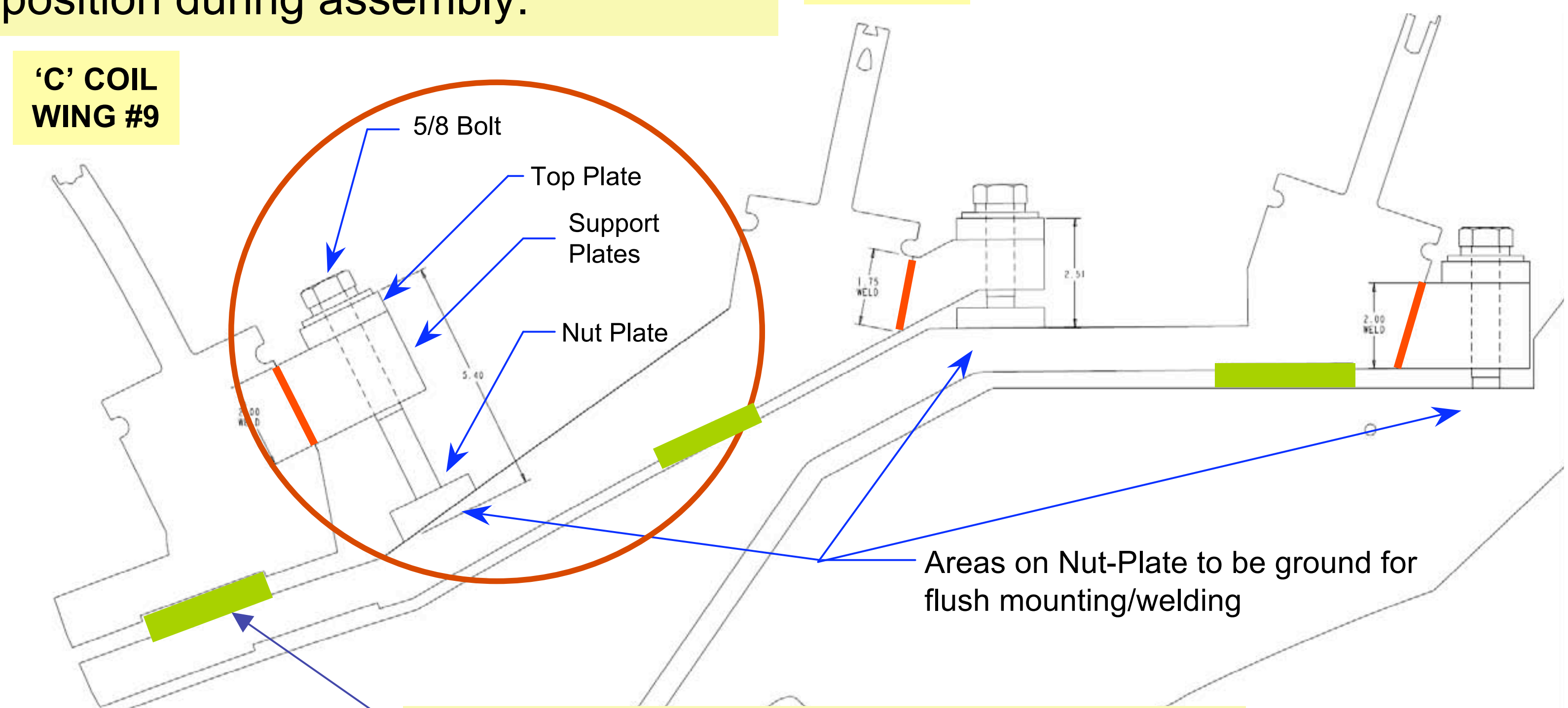




Flange displacement measurements post-welding

Contingency plans are in place to address any unanticipated wing deformations from welding or assembly

Bolts can be added between inner leg wings if needed to adjust wing position during assembly.



Pillow shims provide support between wings in both the "baseline" case and if bolts are added.

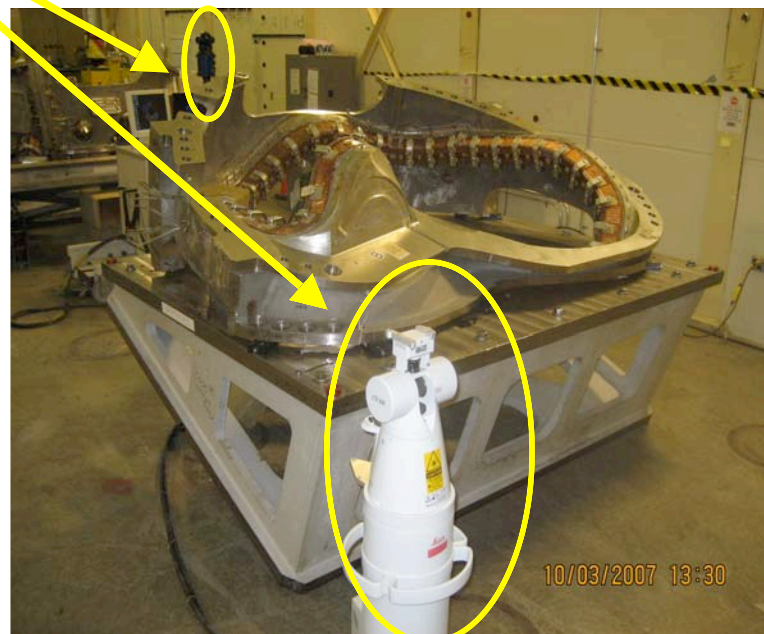
Risk Mitigation Associated with Interfaces

Issue	Risk Mitigation
MCs may move during operation.	• High friction alumina shims • High strength bolts & Supernuts • Bolt monitoring • Welded inner leg interfaces at 15 of 18 interfaces & enhanced bolted inner leg interface at the remaining 3. • Tight-fitting bushings provided at each bolt as backup.
MCs may distort due to welding	• Evolved from TIG to MIG welding - risk remaining is small, but need to demonstrate on assembly. • Low distortion weld interface design developed. • Developed low distortion welded interface design. • Laser monitoring during process • Close weld process control
Accurate coil positioning	• Custom fitted shims and pucks will be used, but obtaining shims with req'd. dimensional and permeability control still under development. • Laser tracker metrology (possible photogrammetry) • Tight-fitting bushings provided at each bolt location for additional assurance that accurate coil position will be maintained even if thermal gradients develop during cool-down.

4. Metrology Capabilities

Metrology Capabilities

- At present, PPPL uses two types of metrology systems:
  - Mechanical measuring arms are used for the coil manufacturing process.
    - PPPL has four.
  - Laser tracker systems are used for subsequent assembly operations.
    - PPPL has two.
- Recent visits to CERN and W7X convinced us that photogrammetry is a very worthwhile addition to NCSX's metrology capabilities. We are in the process of procuring a photogrammetry system to supplement our existing capability and possibly speed up assembly operations.



Accuracy and Repeatability

- Accuracy + repeatability ~ +/- 0.10 mm (0.004”) for the laser trackers at the range required for NCSX (typ. 3-5 m.)
  - “Superaveraging” used to improve accuracy of measurement - hundreds of measurements are made at each measurement point and averaged.
- Accuracy + repeatability ~ +/- 0.075mm (0.003”) for the Faro & Romer arms has been realized in the range typically used to measure the coils.

5. Modular coil and TF coil status & achievements

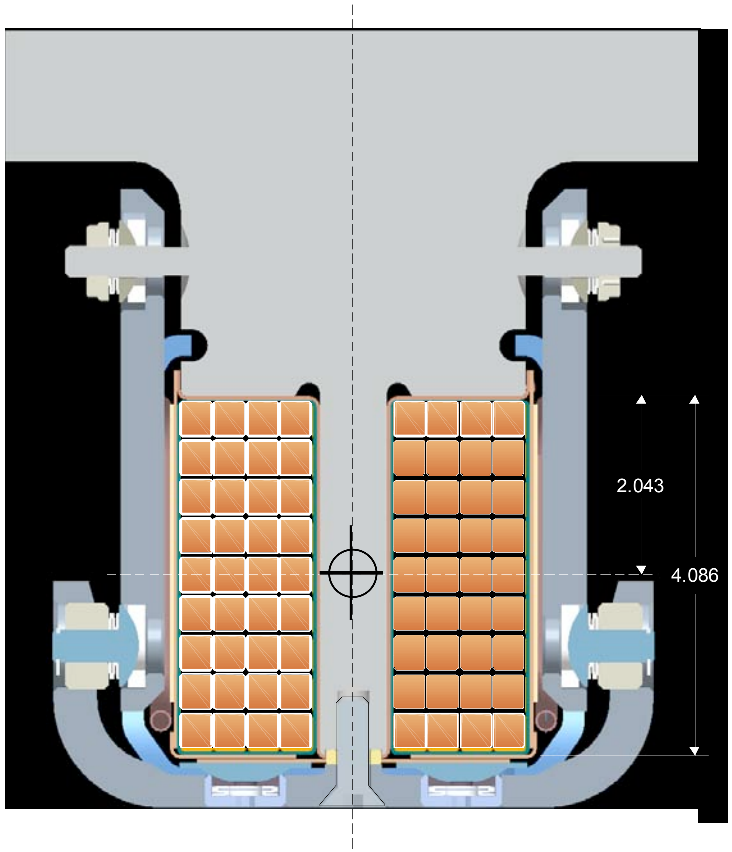
Modular Coil Status & Achievements

- 14 of 18 modular coils wound and current centers measured
  - A1 thru A5
  - B1 thru B4
  - C1 thru C5

- Design Goal of +/- .020" achieved over most of coils but not everywhere (details follow).

- Coils wound to match current center achieved on prior wound coils to minimize symmetry breaking field errors (details follow).

Modular Coil Winding Cross Section



Current Center determined by averaging casting measurements
(prior to winding)
and bundle measurements
(after winding) at each turn.

Metrology usage during modular coil winding

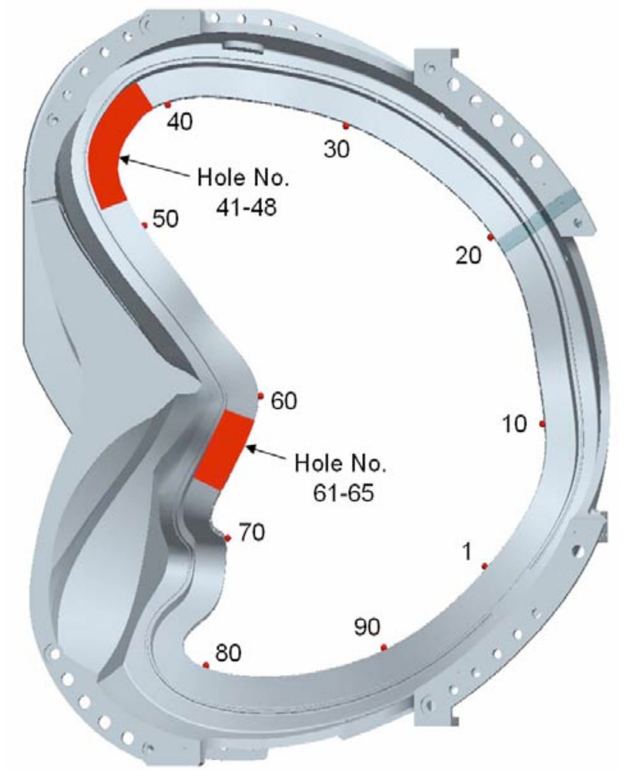
Dimensional casting characterization

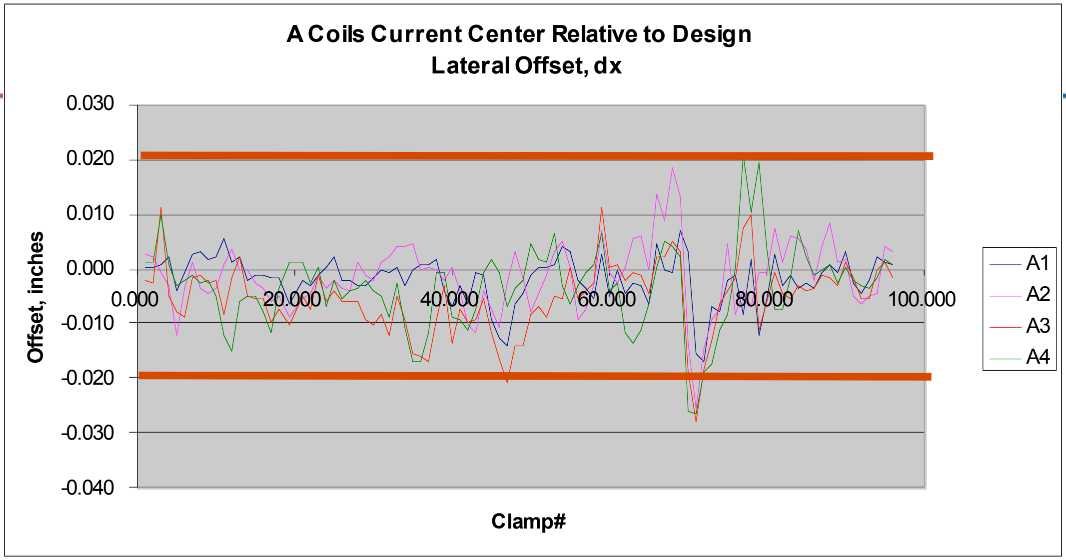
- ~8000 measured points characterize winding surface

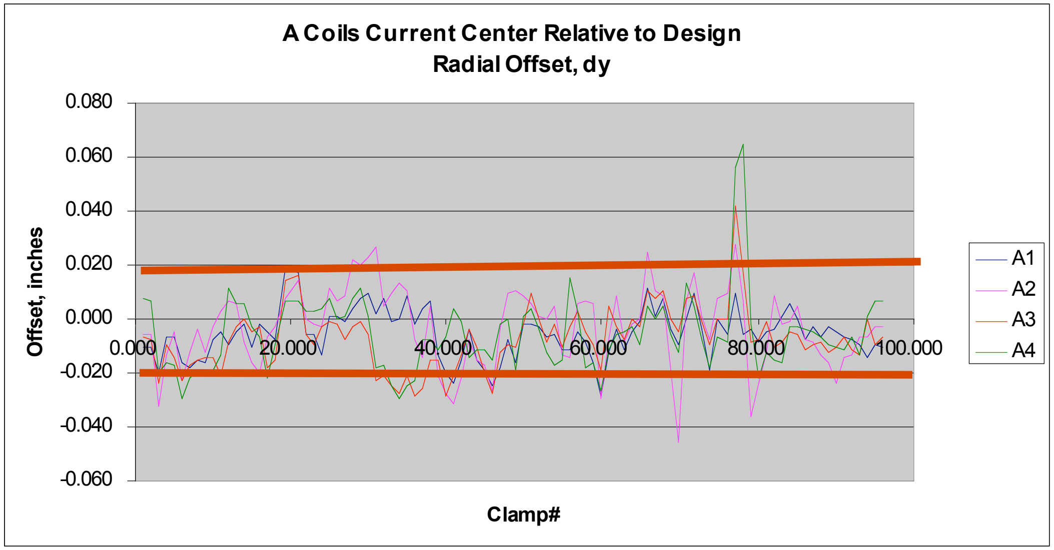
Winding Measurement & Re-Sizing

- Adjustable clamps allow tailoring of the cross section of the winding pack on either side of the septum.
- As-built winding form measurements are used to set clamp positions.
- Clamp positions define a cross section of the winding pack.
- Compliance of the insulation, prior to potting, allows for adjustments.

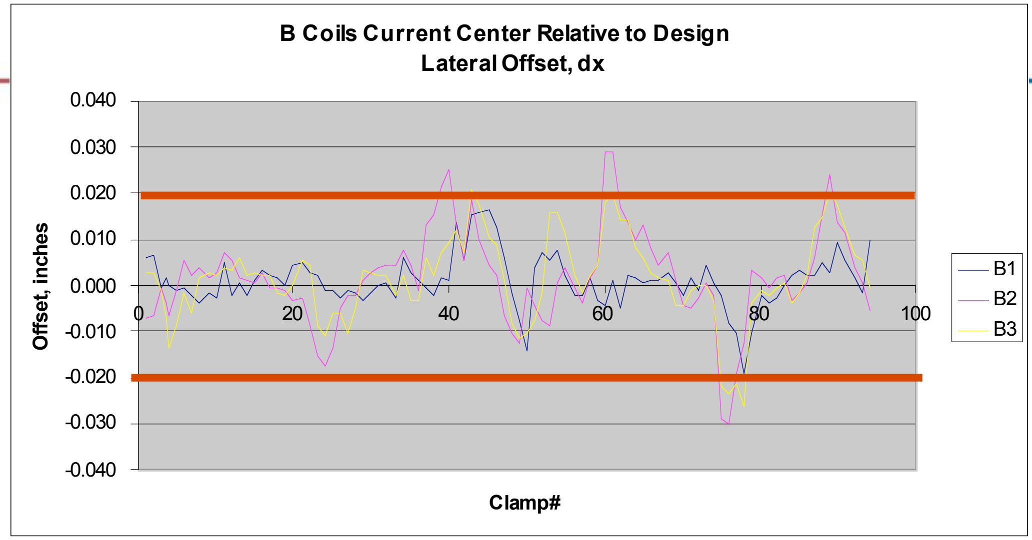
Modular Coils - Type A Lateral & Radial Offsets

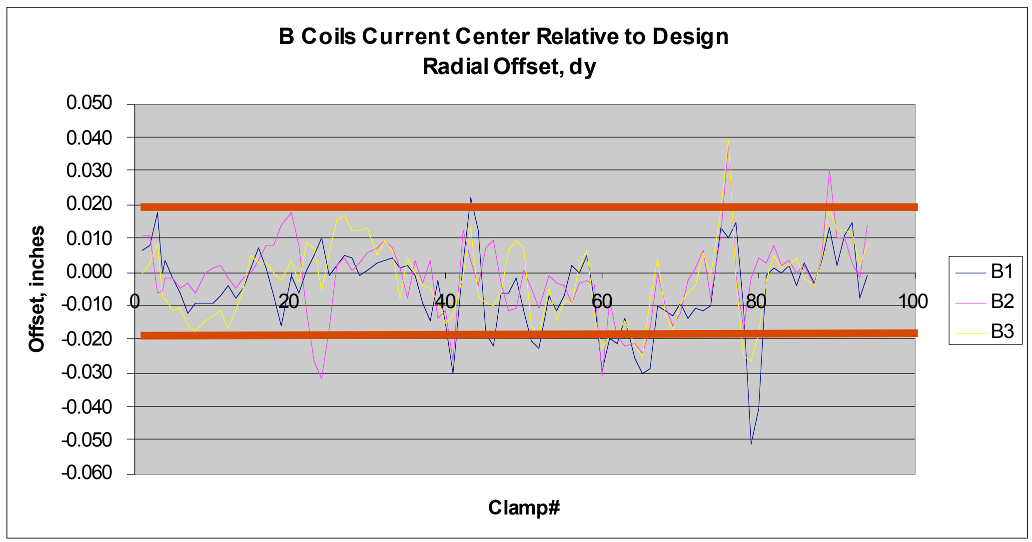


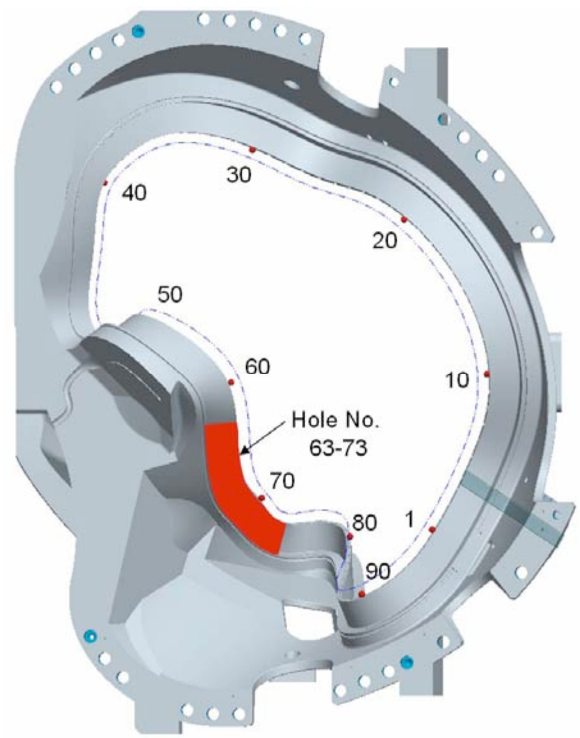




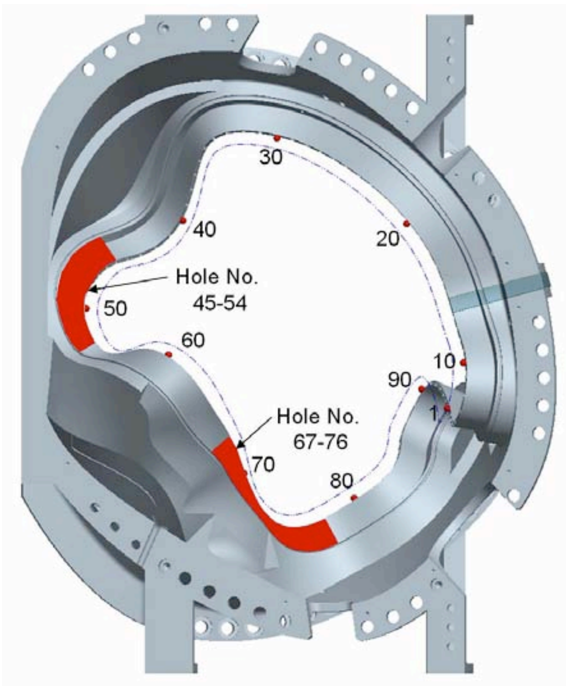
Modular Coils – Type B Lateral & Radial Offsets

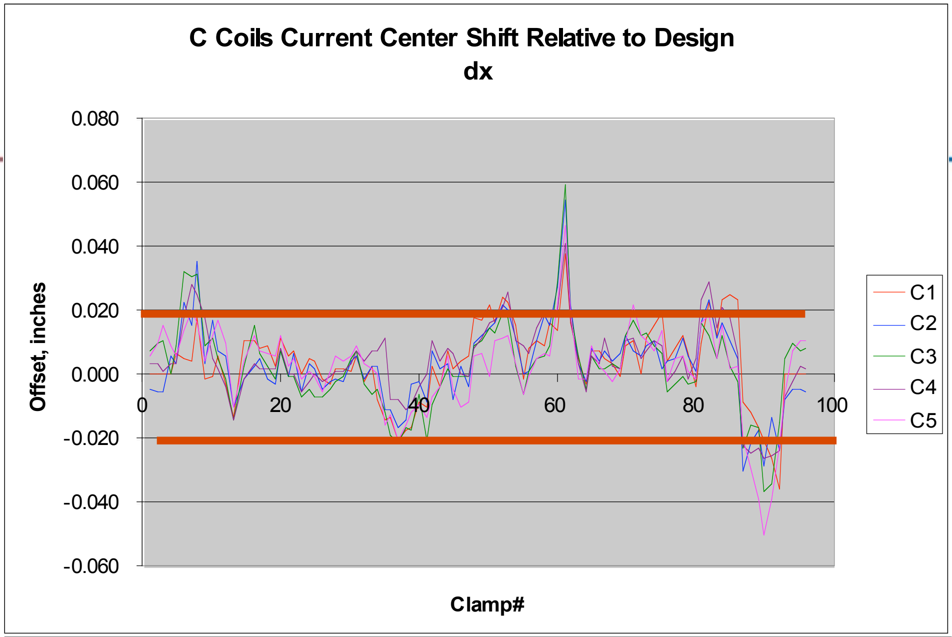


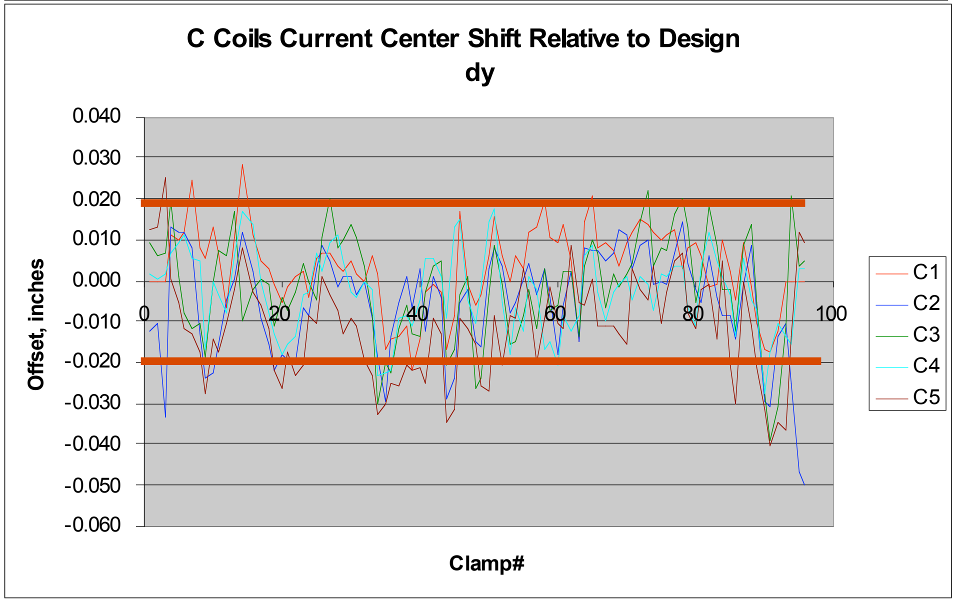




Modular Coils - Type C Lateral & Radial Offsets







Tolerance Compensation

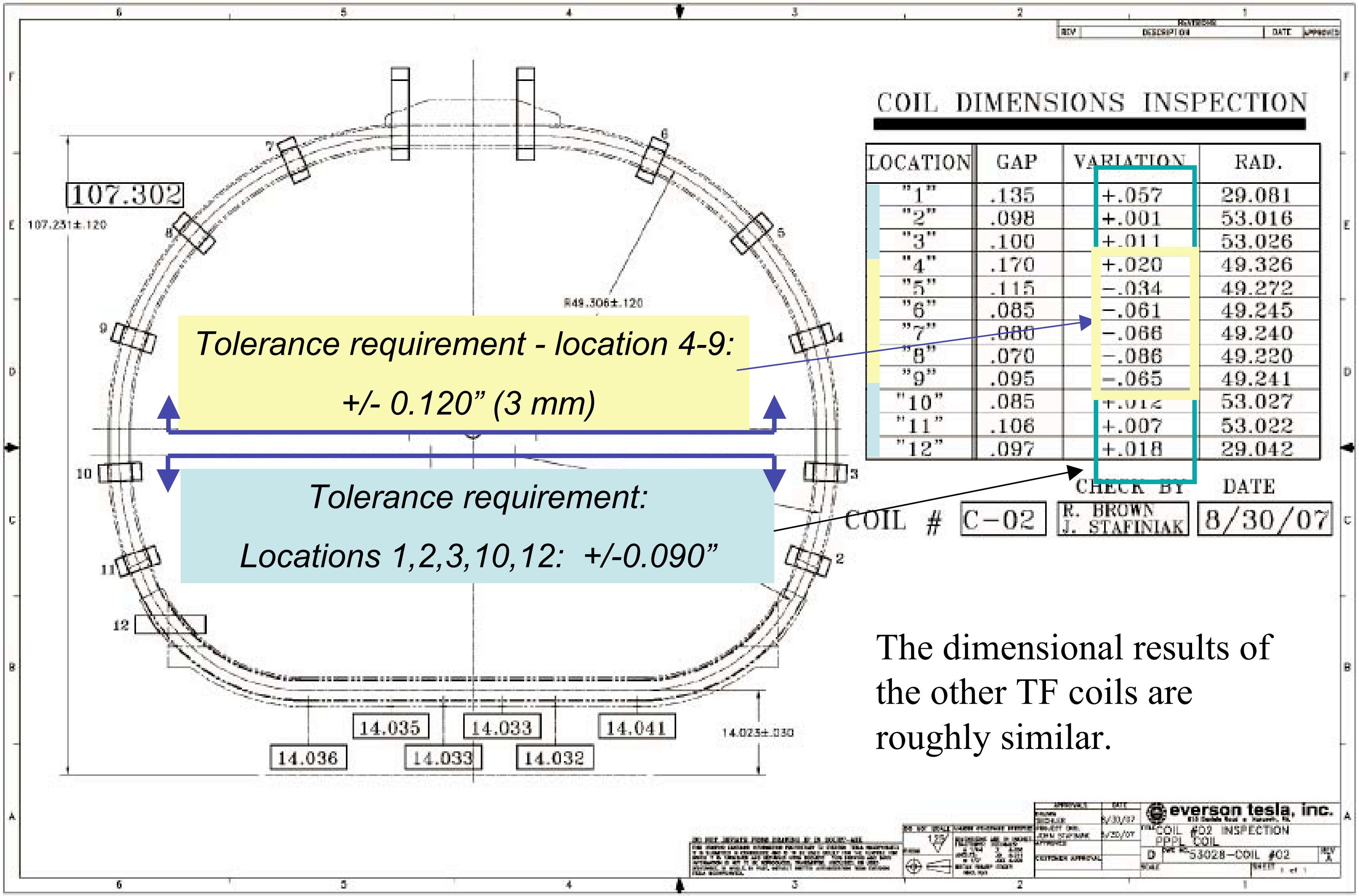
- Knowing the as-built dimensions, we can compensate for them by choosing the alignment of the coils during FP assembly.
    - **In this way, the tolerance allocated to the modular coils can be made available for assembly.**

TF coils are dimensionally checked at the factory

Includes checks of:

- X-Y geometry
- Planarity
- Wedge geometry

Dimensional Inspection Report Example TF#2



LOCATION	GAP	VARIATION	RAD.
"1"	.135	+.057	29.081
"2"	.098	+.001	53.016
"3"	.100	+.011	53.026
"4"	.170	+.020	49.326
"5"	.115	−.034	49.272
"6"	.085	−.061	49.245
"7"	.080	−.068	49.240
"8"	.070	−.086	49.220
"9"	.095	−.065	49.241
"10"	.085	+.012	53.027
"11"	.106	+.007	53.022
"12"	.097	+.018	29.042

The dimensional results of the other TF coils are roughly similar.

7. Significant remaining core system / assembly design tasks

- Preliminary Design Review of the PF coils – November ’07.
- Final Design Review of the MC welded interfaces - November ’07.
- Preliminary Design Review of the trim coils – December, ’07.
- Final Design Review of TF/PF coil structures - December ’07.
- Preliminary Design Review of the base structure - March, ’08
- Final Design Review for tooling & specs for Station 5 - April ’08.
- Final Design Review for tooling & specs for Station 6 - October ’08.

8. Conclusion

- We are confident tolerance goals of +/- 1.5 mm for the modular coil current centers pre-pulse, and +/- 3 mm for the TF, PF, and trim coils can be met.
  - Knowing the dimensions of the modular coils, we can adjust their position at assembly. Accordingly, +/-1.5 mm is left for the assembly steps.
- Analyses confirm that NCSX will meet essential requirements:
  - Maximum calculated modular coil current center displacement (gravity + EM) is 2.2 mm vs. 3 mm requirement; stellerator symmetry maintained. This occurs in only a few localized regions; **most are <1.5 mm.**
  - Actual Stellalloy properties exceed specifications; for example, yield strength is ~25% higher and ultimate is ~60% higher.
  - The maximum stress in the modular coils is 219 MPa vs. an allowable of 327 MPa. This level of stress occurs in only a few localized regions; **most are <100 MPa.**
  - At the maximum stress of 219 MPa, a flaw size of 2 x 6 mm can be tolerated for 4 x life. Most of the casting has a stress level <100 MPa and has a much higher flaw tolerance.
  - The vacuum vessel has a factor of safety of 2 on stress in welds due to gravity and pressure loads and a factor of safety of 1.2 on stress in welds due to plasma disruption, gravity, and pressure loads.

8. Conclusion (cont'd.)

Robust coil interfaces have been incorporated in NCSX to assure dimensional stability throughout NCSX's experimental program.

- Alumina coated shims in all outboard regions provide electrical isolation and high friction interface to lock coils in position.
  - Measured μ of 0.67; allowable is 2/3*0.67=0.44
  - 0.39 required for C-C; 0.16 (max.) for the other interfaces.
- High strength bolts with Supernuts and ultrasonic tension measurement to assure adequate preload. Bolt tension will be periodically re-checked to assure maintenance of preload.
- Tight fitting bushings used in all locations to guard against motion during cool-down and to provide extra assurance of alignment during assembly and experimental operation.
- Welded interfaces provided for the intra-period coils: i.e., A-B, B-C, A-A.
  - 15 of the 18 inner legs are welded interfaces.
  - Low distortion welded interface and MIG based weld process; low distortion verified by weld tests which included a C-prototype casting longitudinal weld test.
  - Limiter pucks provide stiff continuous load path.
- Bolted/friction shim interface used in the (3) C-C interfaces (the field assembly joints).
  - More bolts & shims than the other interfaces.
  - Compression/sliding shim on small remaining center leg region.

8. Conclusion (cont'd.)

–PPPL has established strong metrology capabilities:

- 4 mechanical digital measuring arms (Faro and Romer).
- 2 laser trackers
- Photogrammetry equipment is being purchased.

–Dimensions of modular coils and TF coils produced to date are consistent with the requirements:

- 14 of 18 modular coils manufactured; most but not all regions within the 0.5 mm tolerance band; errors within a family of coils were made to be ~similar so that stellarator symmetry can be maintained.
- Knowing the dimensional data, the coils can be re-positioned to compensate, leaving +/-1.5 mm left yet for assembly.
- 4 TF coils delivered to date – all are comfortably within their manufacturing tolerances of +/- 3 mm for the outboard regions and +/- 2.5 mm for the inboard regions.

NCSX's ample engineering margins, dimensional achievements to date, strong metrology capability, and well-experienced NCSX staff both at ORNL and PPPL form the basis of our confidence that NCSX can be built and maintained within its required tolerances.