Engineering Analysis & Design Confirmation Overview

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6 October 2008

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

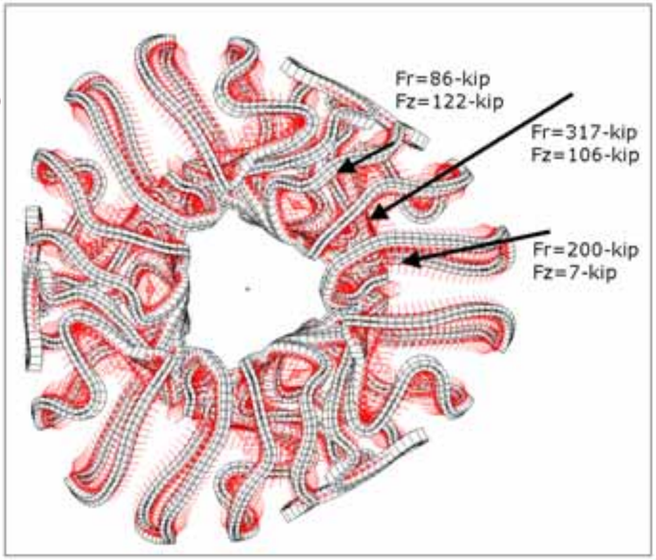

Table 1 Net EM Force on Modular Coils

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

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

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 by the modular coil torus.
  – VV supported from the modular coil torus. 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

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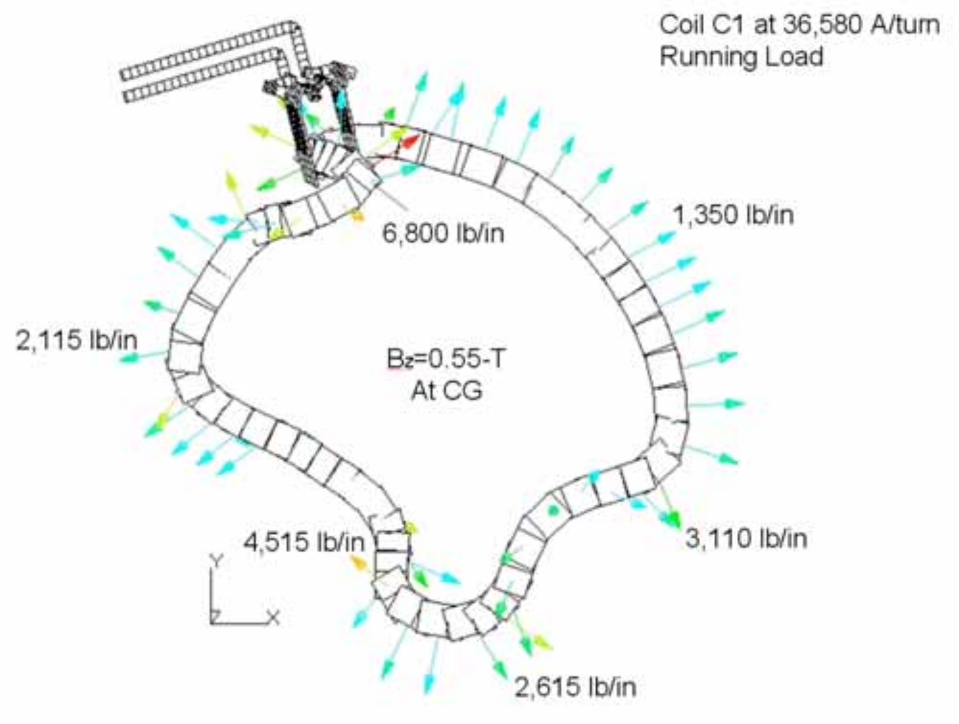
There is considerable force variation in modular coil



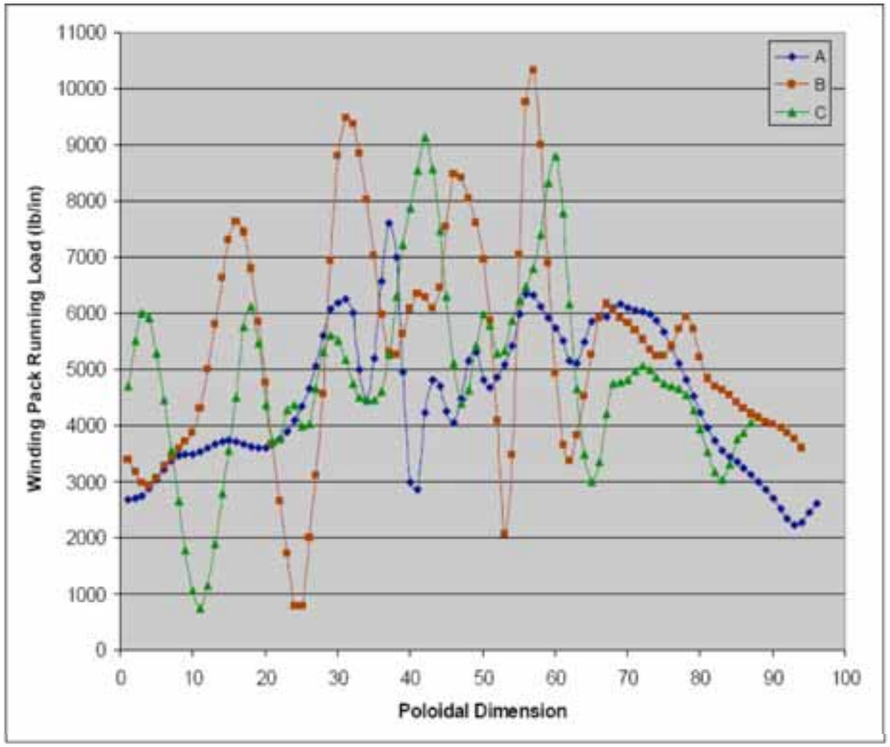
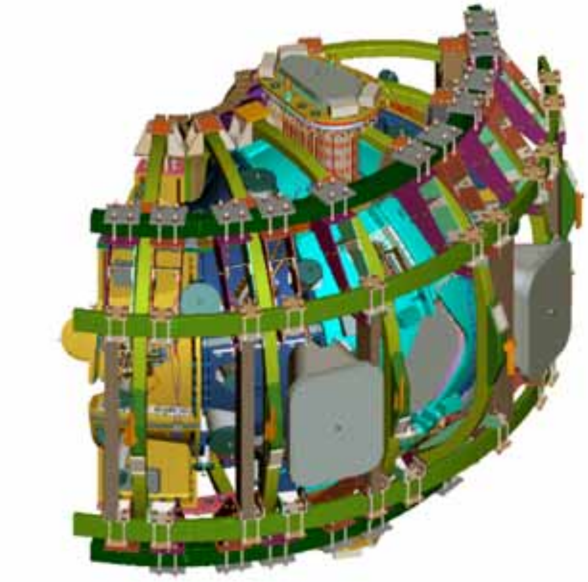
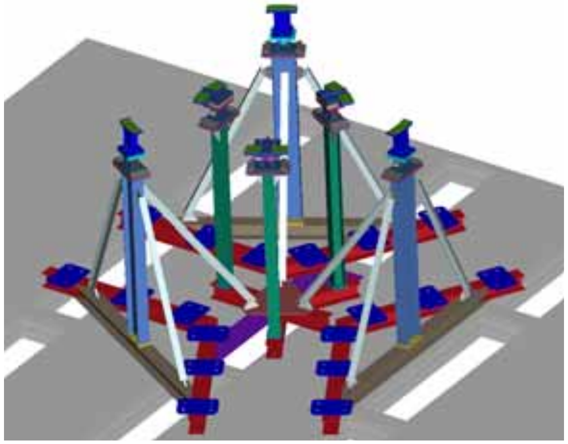


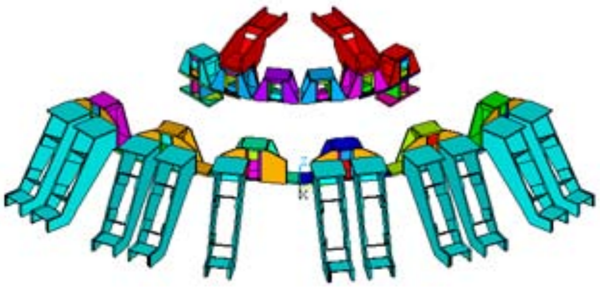
Fig.-6 Poloidal Variation of Running Load at Time=0.050-s

NCSX Structural Details

- The TF / PF support structure is bolted to the MCWF.
- The base structure supports the modular coils at inboard & outboard locations. The model reflects these support locations.

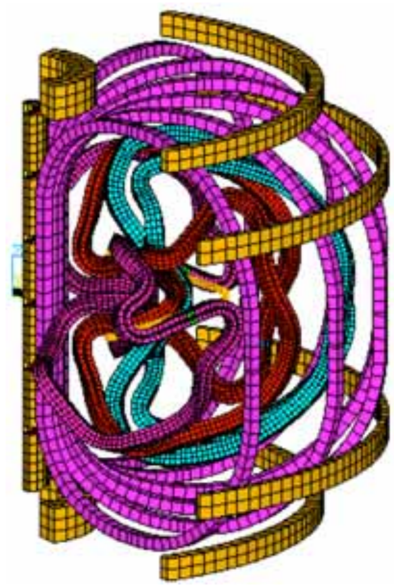






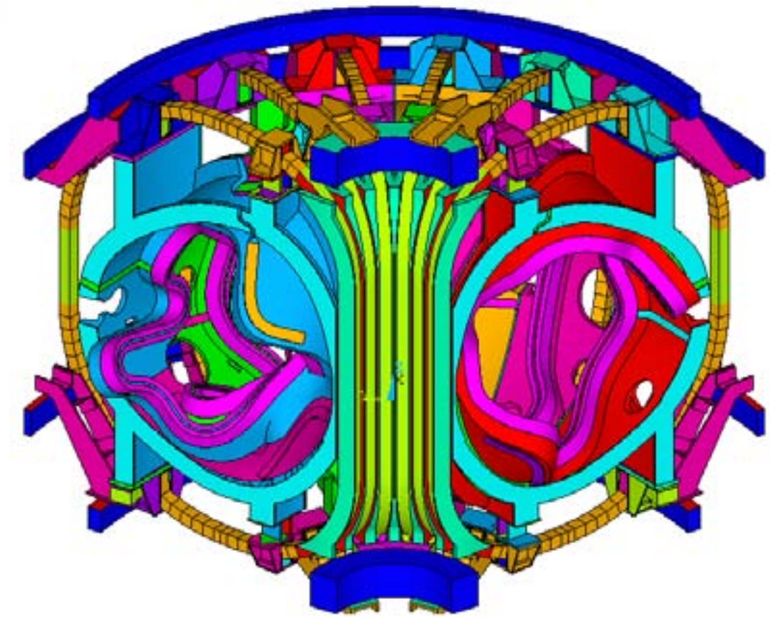
PF/TF bracket details

Details of the Analysis Models



EM Model

- Loads were generated from EM model and applied to structural model.
- Common mesh used to facilitate mapping of loads onto structural model



Structural 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.
- All bolted joint interfaces are treated as bonded contact surfaces.

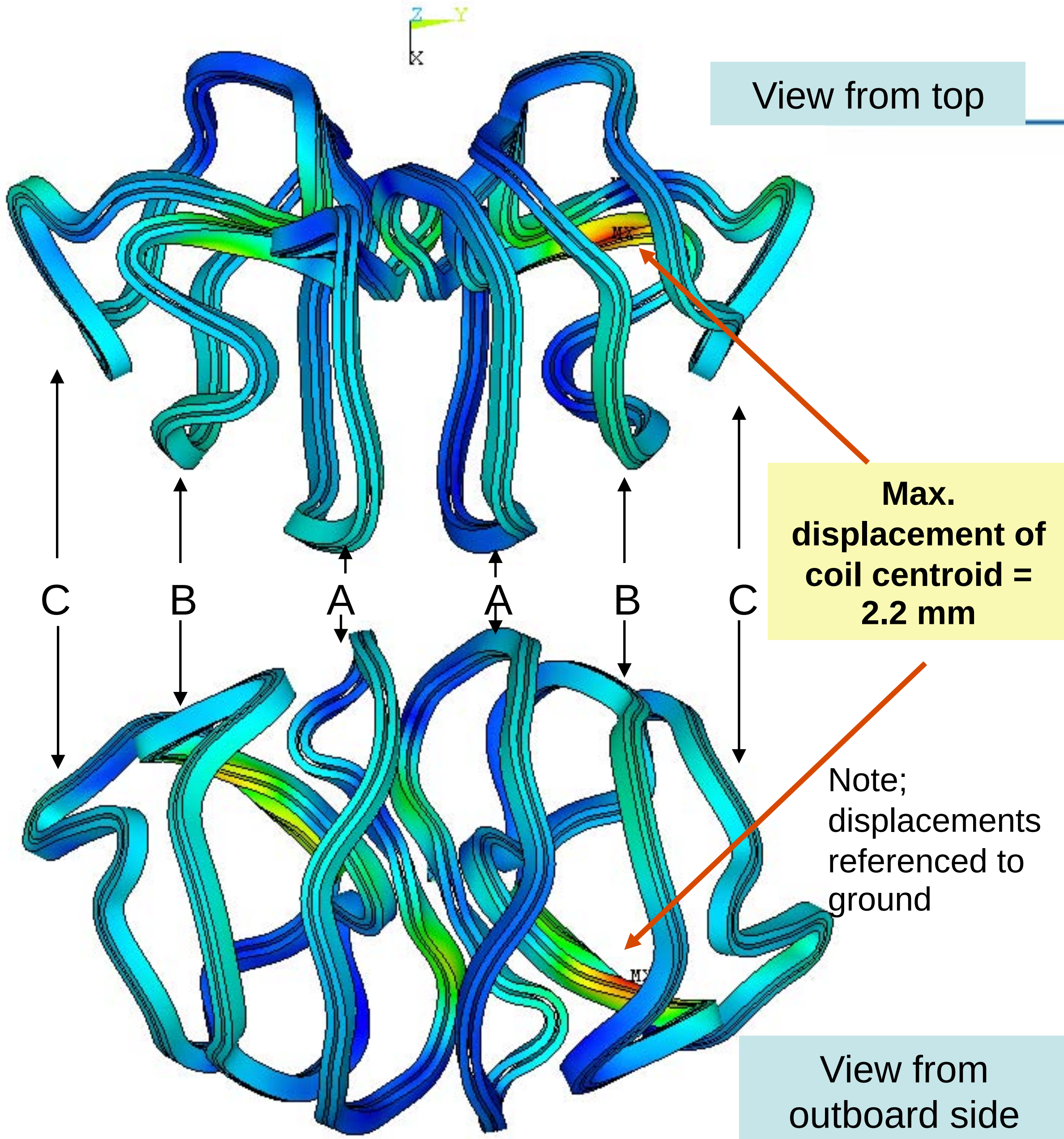
Modular Coil Displacements

- **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

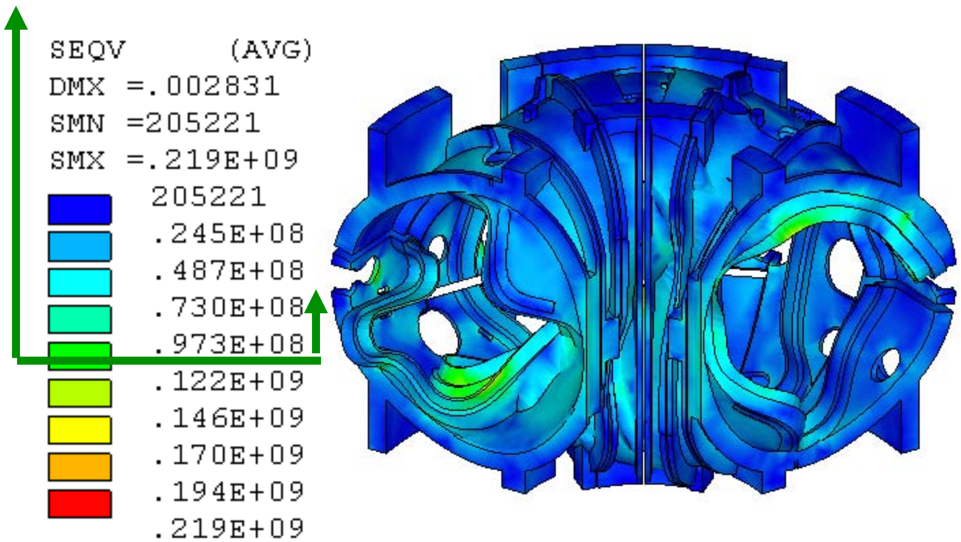
Winding Form Average Properties

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

We have good margins on static stresses

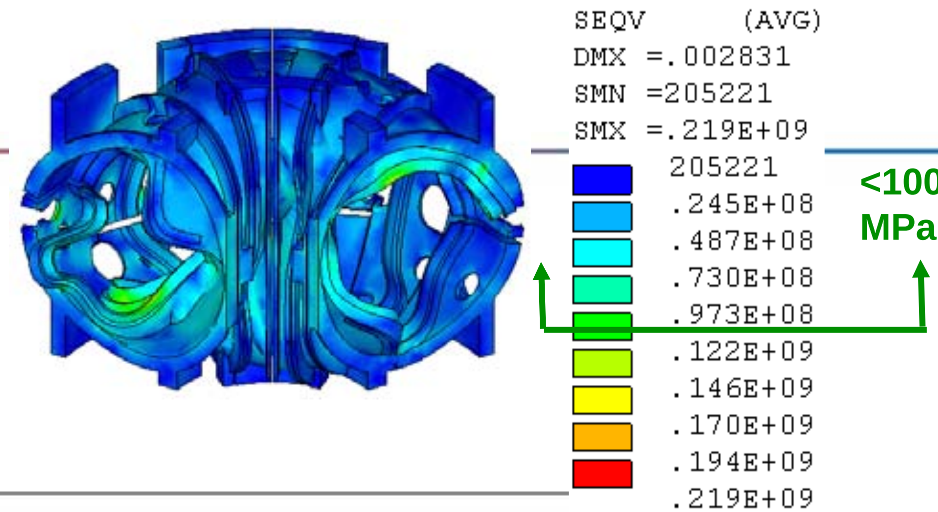
<100 MPa



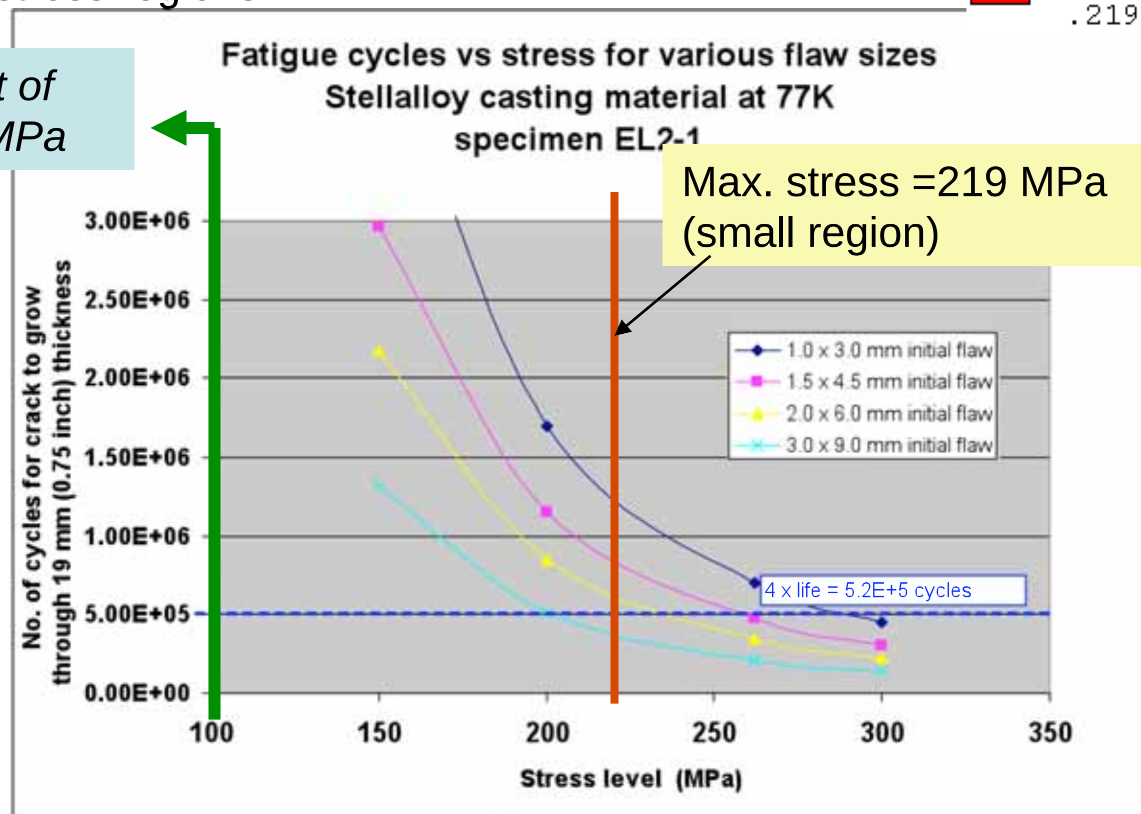
- **Max. stress is 219 MPa.**
  - •Allowable = 327 MPa.
  - Factor of Safety (F.S.) on allowable is 1.5 (based on specified material properties for Stellalloy; based on actual FS~2.5
- Average stress is <100 MPa.

Fatigue

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



The stress in most of the shell is <100 MPa



Forces on leads were carefully analyzed

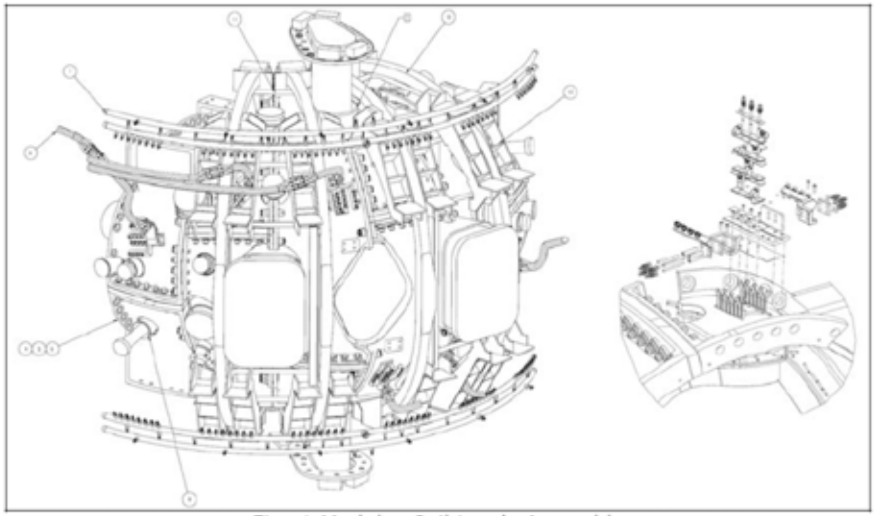


Fig.-1 Modular Coil Leads Assembly

EM Analysis of Modular Coil Leads

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8 Septmeber 2008

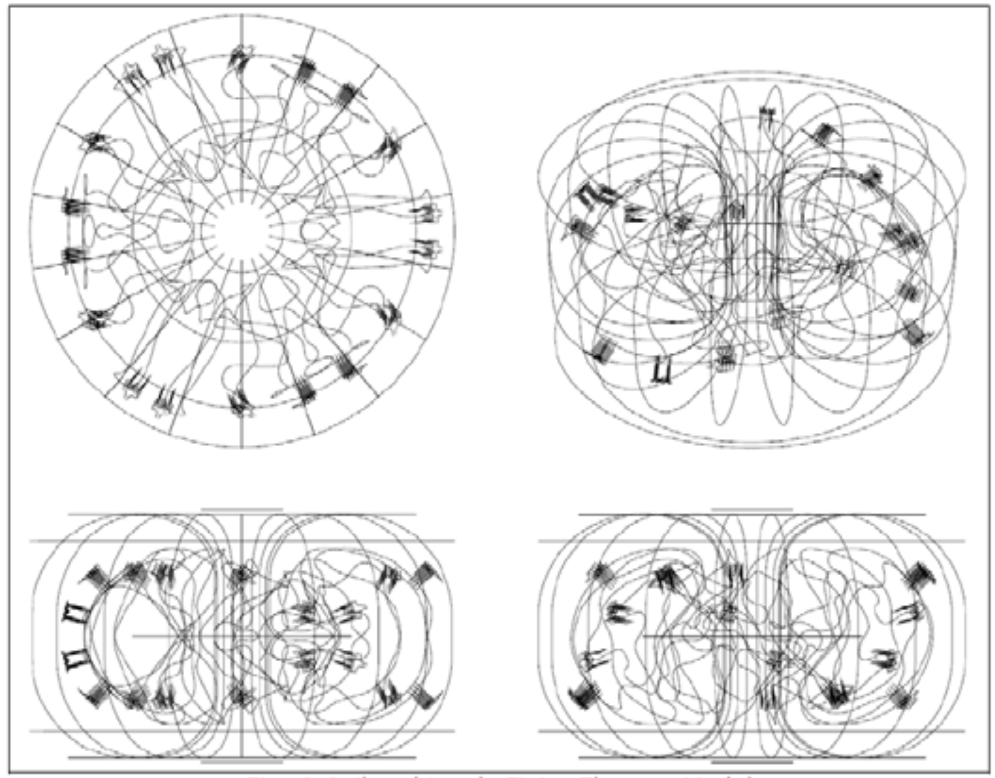


Fig.-2 Coil and Leads Finite Element Model

Conductor and lug forces

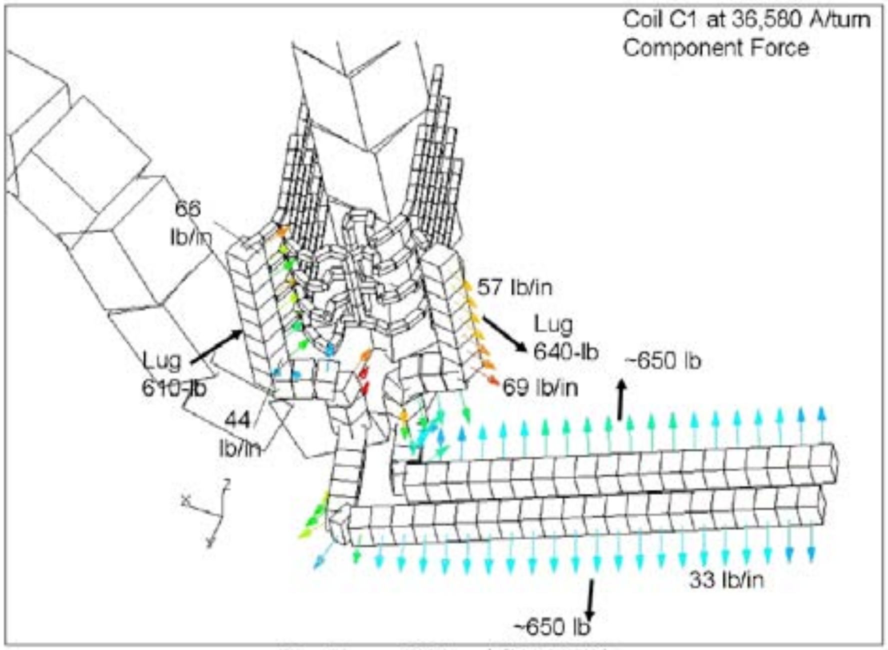


Fig.-5 Lugs EM Load (MAGFOR)

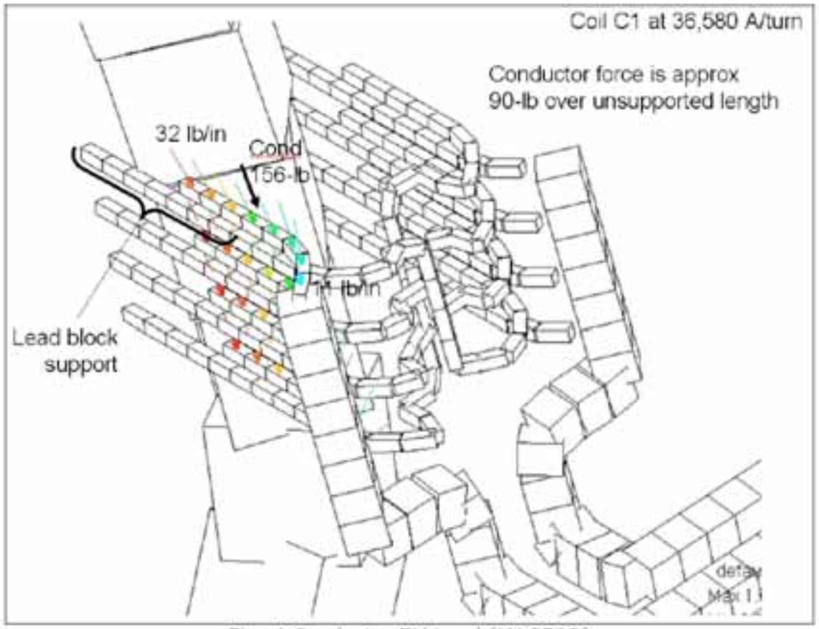


Fig.-4 Conductor EM Load (MAGFOR)

Vacuum vessel analyses results

Gravity and Pressure loads:

•Deflections: 0.25 in. (ports), 0.12 in. (shell), Tresca stress: 16 ksi, safety factor > 2 in welds

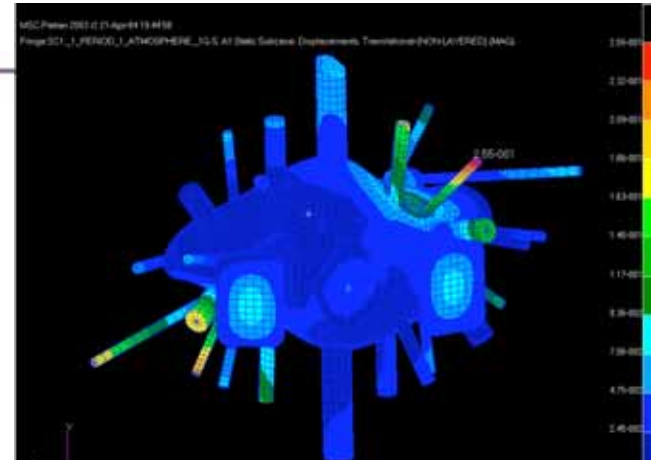
Disruption loads:

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

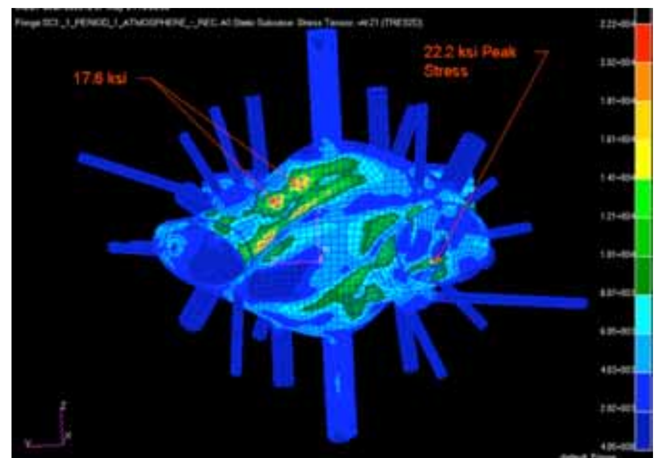
Buckling: critical pressure =10 x max pressure (vacuum + VDE load)

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

EM analysis: (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

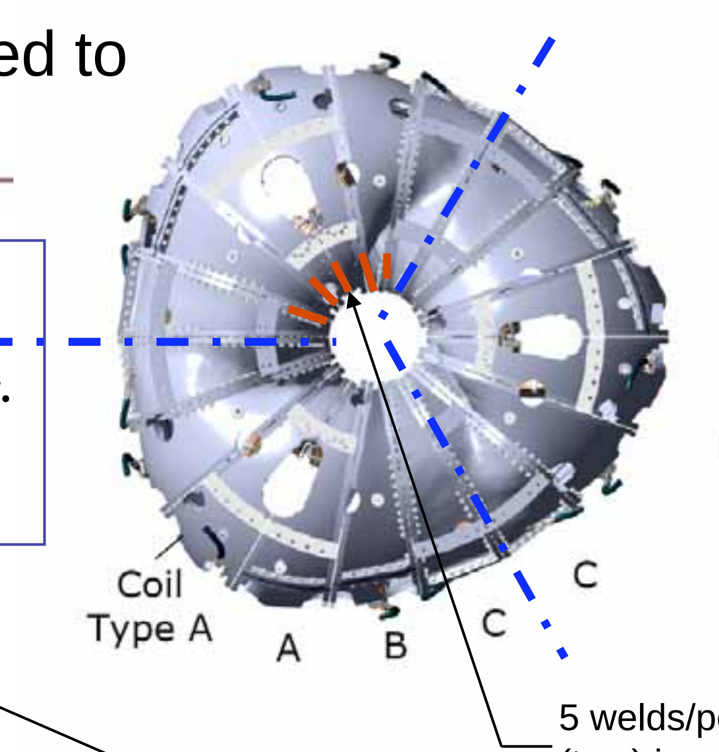
The Coil-Coil Interfaces were revised to address inner leg concerns

NCSX National Compact Stellarator Experiment

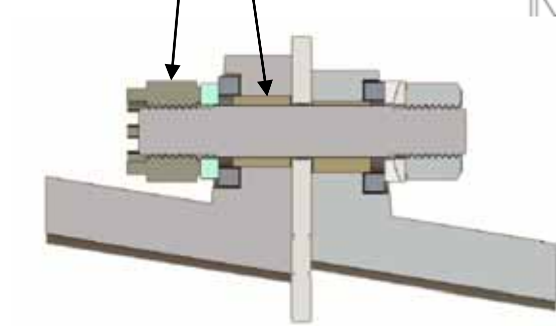
The concerns:

- ***Mostly due to no bolts here because of inadequate space.***
- ***Inner leg deflected ~0.5 mm – marginally OK for physics.***
- ***Load on end bolts too high.***
- ***The Dimensional stability of the assembly was a concern.***

- High friction alumina coated shims under all bolts.
- Welded coil-coil inner legs on mid-field period coils.
- Tight fitting bushings around studs as backup.
- “Supernuts” with ultrasonic measurement of stud tensioning.



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



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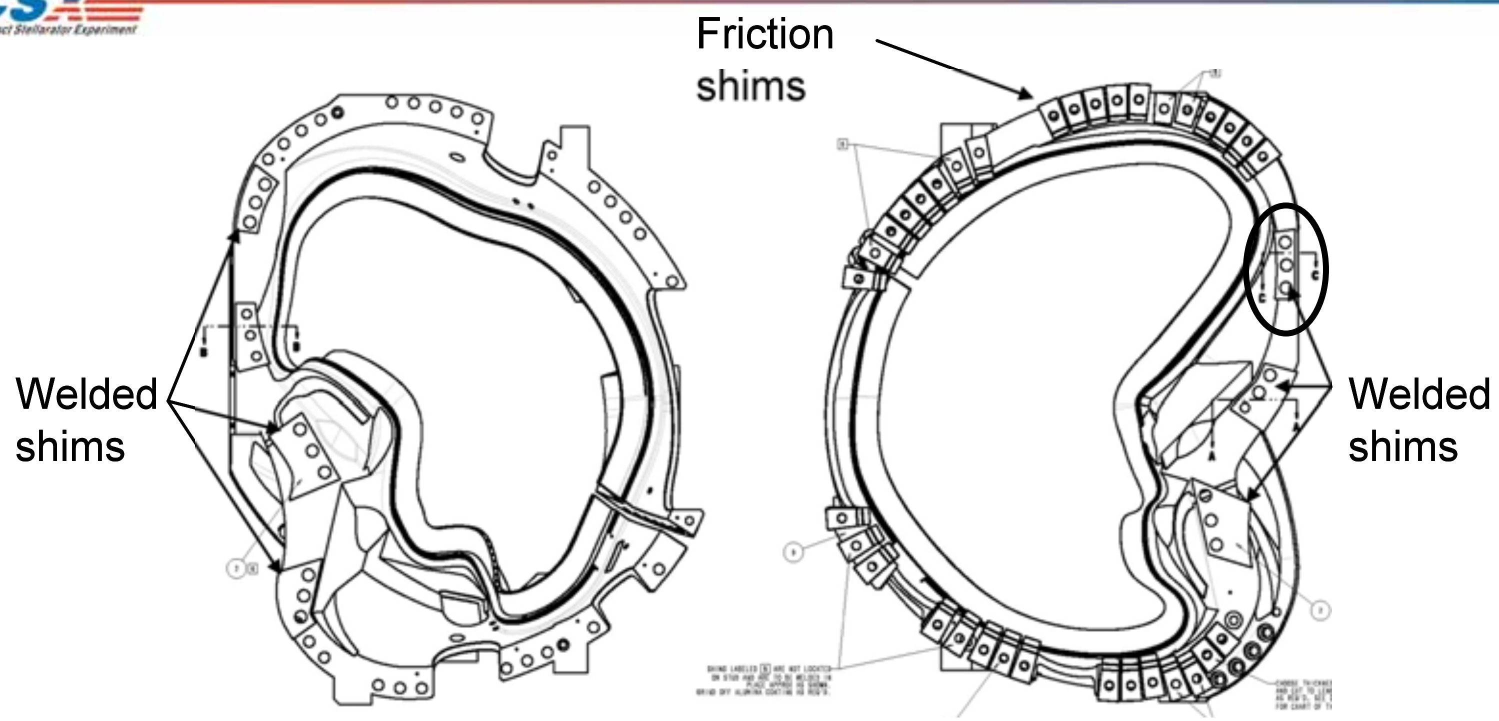
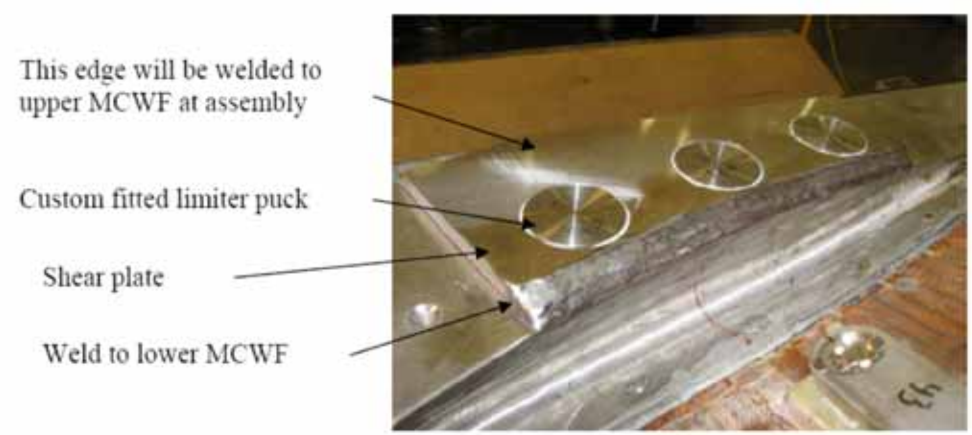
The Revised Intra-Period Interfaces *(A-A, A-B, and B-C):*



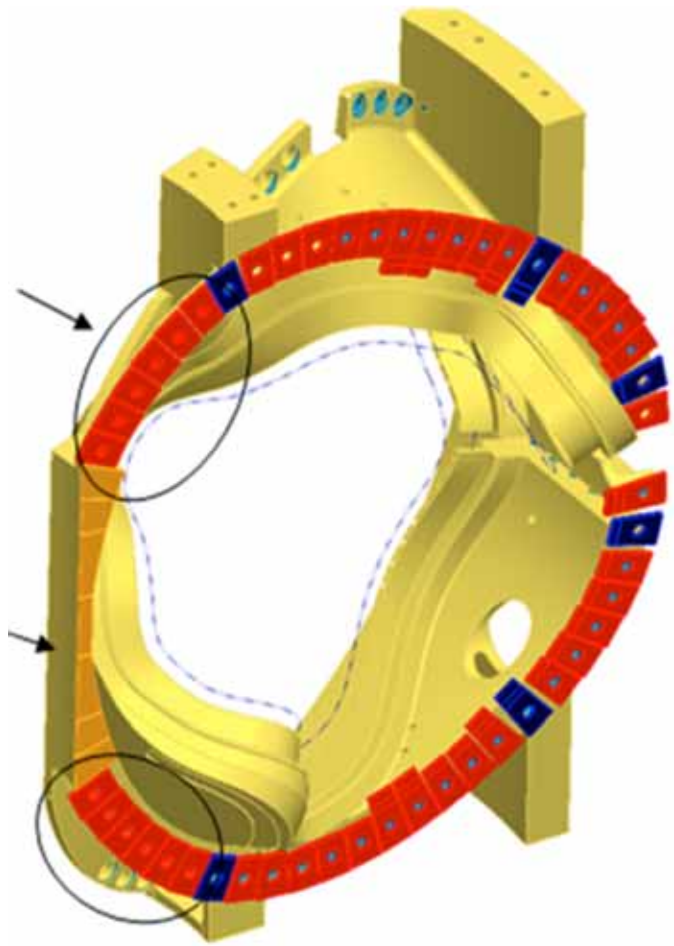
Note that the welded shims are interleaved to balance the weld shrinkage stress on both sides of the inner leg to minimize bending



The revised C-C (field period) interface

6 additional studs & alumina coated SS high friction shims on both ends of inner leg.

Alumina coated stainless steel compression shims



Two types of friction shim were developed

a. Alumina-coated SS shim

b. G-10/ SS / G10 shim

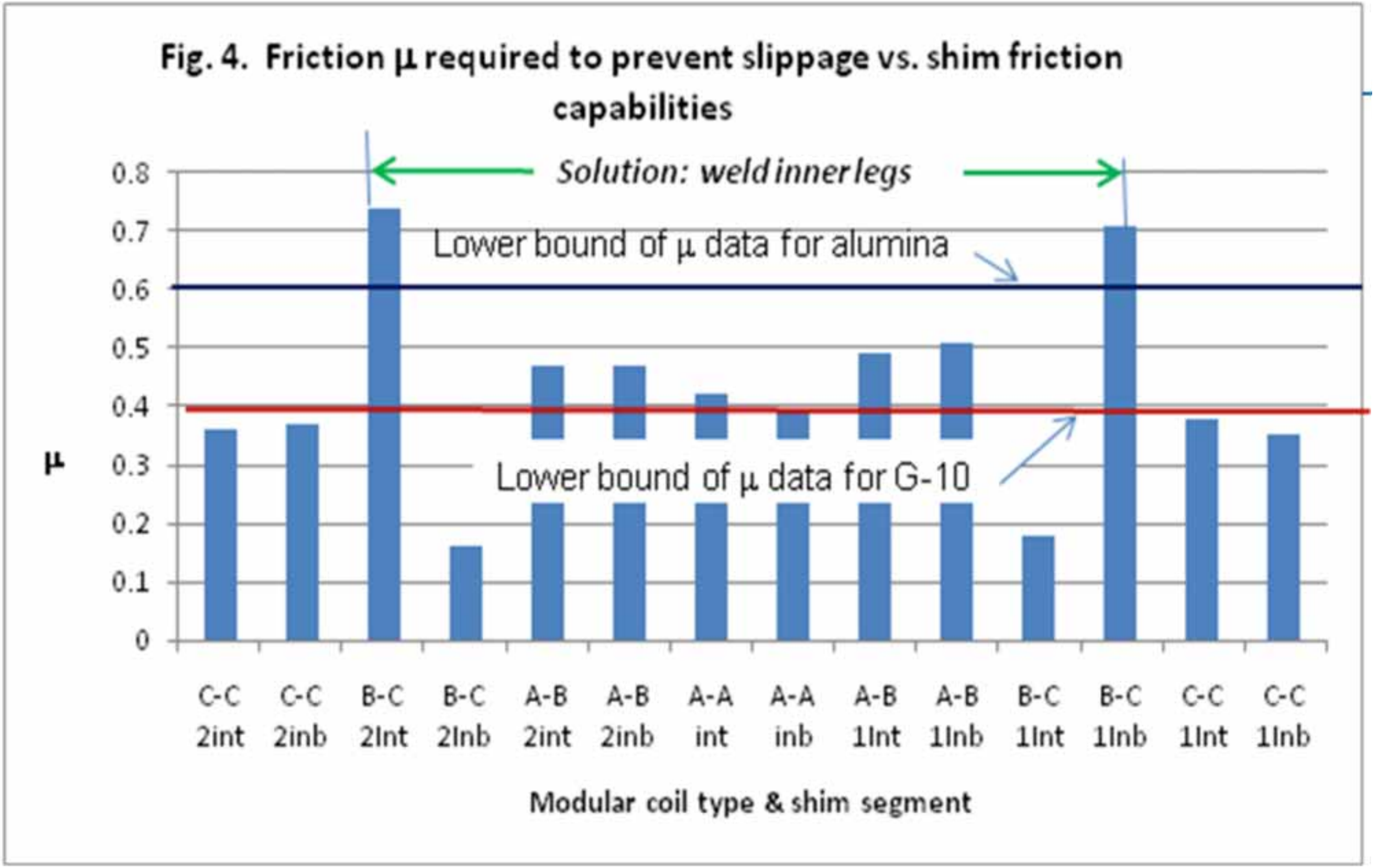


Fig. 4. Friction μ required to prevent slippage vs. shim friction capabilities
Solution: weld inner legs
Lower bound of μ data for alumina
Lower bound of μ data for G-10
μ
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
C-C 2int
C-C 2inb
B-C 2Int
B-C 2Inb
A-B 2int
A-B 2inb
A-A int
A-A inb
A-B 1Int
A-B 1Inb
B-C 1Int
B-C 1Inb
C-C 1Int
C-C 1Inb
Modular coil type & shim segment

Summary

- NCSX analyses were challenging because of its complex geometry, many interfaces, and because of its being the first of its kind.
  - The analyses confirmed that we have adequate margins on static and fatigue stresses. We were able to meet virtually all of the requirements defined for the machine.
  - Realization of shortcomings with the interface only surfaced late in the project as the analyses matured. This caused significant delays in development of assembly methods, tooling, and assembly costs and schedules and caused the Project to lose some credibility.
    - We did not have the opportunity to take advantage of the “learning curve” to refine the estimates.
  - The NCSX team considerably improved its design & analysis, metrology, fabrication expertise, and continually improved project management during the execution of the project.
  - NCSX is being phased out in excellent technical health – we are well poised for re-start, should the opportunity arise.