National Compact Stellarator Experiment

NCSX Design and System Integration Overview

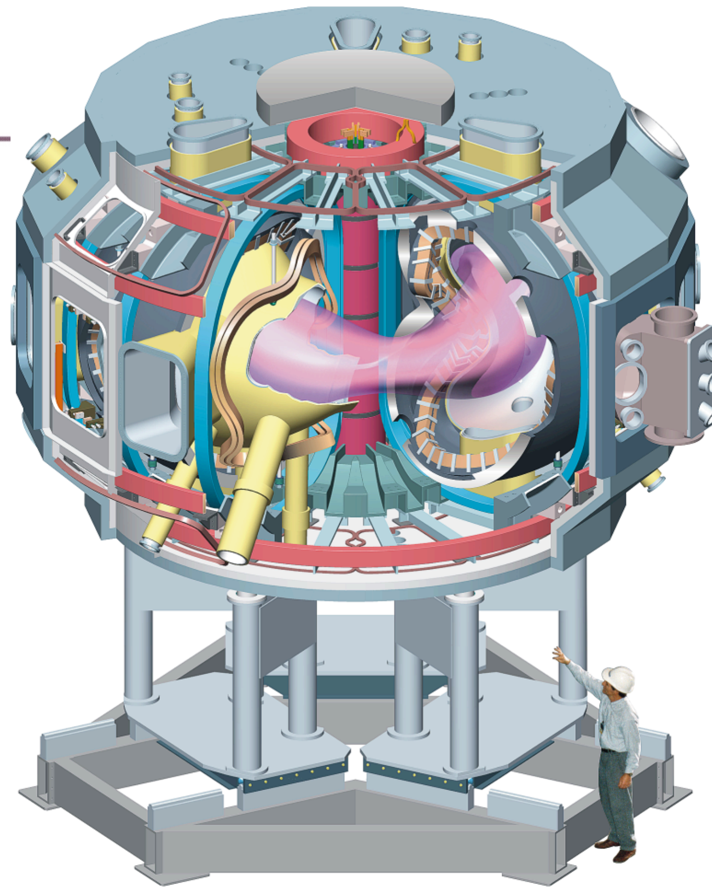
Presented by Phil Heitzenroeder & Hutch Neilson

For the NCSX Project Team

SC Project Review of NCSX, April 8-10, 2008

Outline

- Status of Components
- Progress since start of FY-08
- Recent key core-focused activities
  - Interface designs
  - Trim coil system
- Conclusion

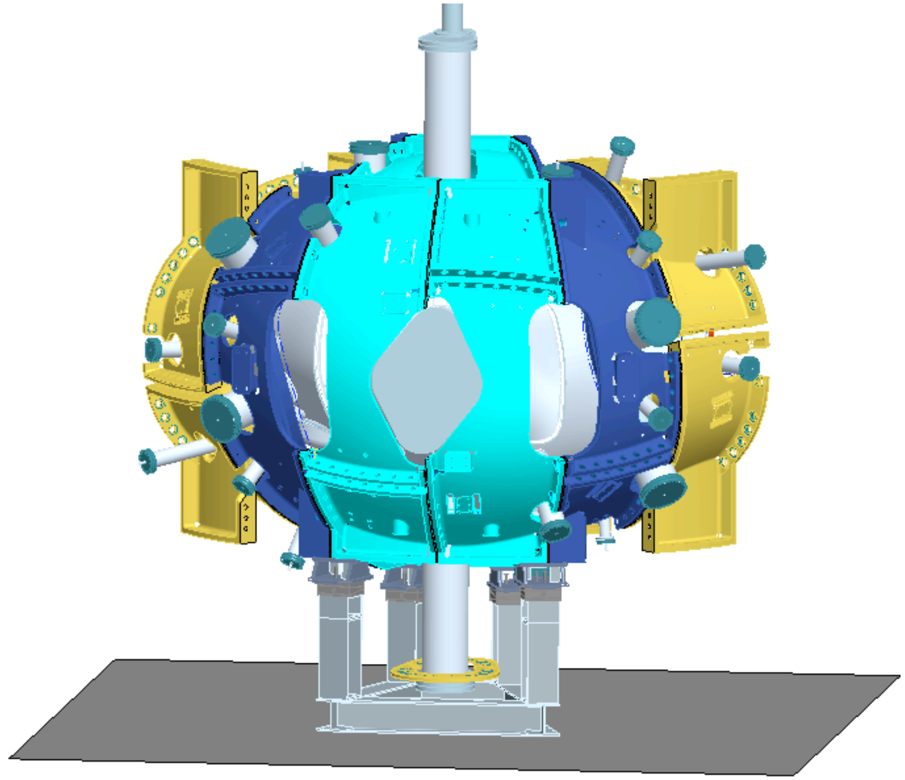


NCSX Stellarator
Major Radius 1.4 m
Magnetic Field 2.0 T
Pulse length ~1 s

Inner Core: Stellarator Core Out to MC Shell and VV Port Flanges

NCSX National Compact Stellarator Experiment

Assembling modular coils into half-period assemblies (Assembly Station 2)



1/3 of the Inner Core (after Assembly Station 3)

Our Riskiest Procurements Are Behind Us

Vacuum Vessel Sub-Assys. ($5M) September, 2006.

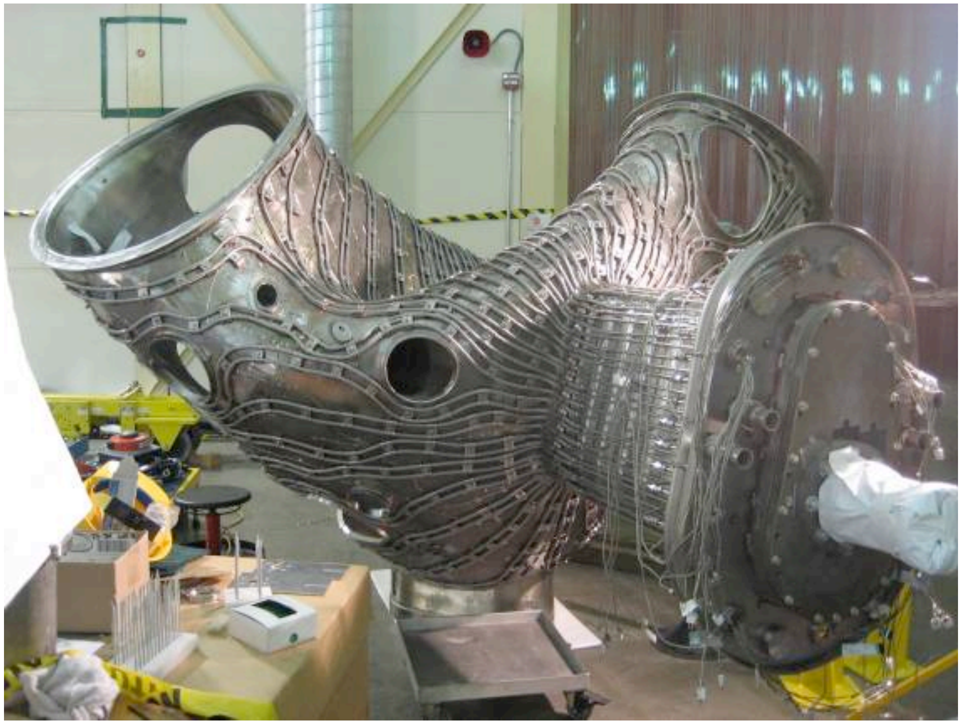
Modular Coil Winding Forms ($9M) completed June, 2007

- Challenging technical requirements (geometries, tolerances) stretched PPPL, ORNL, and supplier capabilities. Drove cost and schedule growth.
- Remaining procurements are smaller (≤$1M) and simpler.
  - PF and Trim Coils are ≥10 months off critical path.

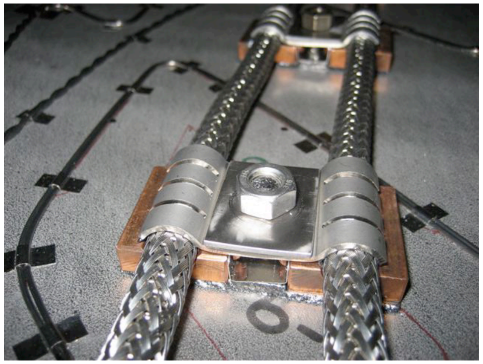
Vacuum Vessel Assemblies Are Nearly Complete

Components installed on vacuum vessel sub-assemblies

- Cryostat interface flanges
- Diagnostic flux loops.
- Heating & cooling hoses.
- Heater tapes.
- Thermocouples



All 3 complete except for lead termination and final testing.



8 months off critical path.

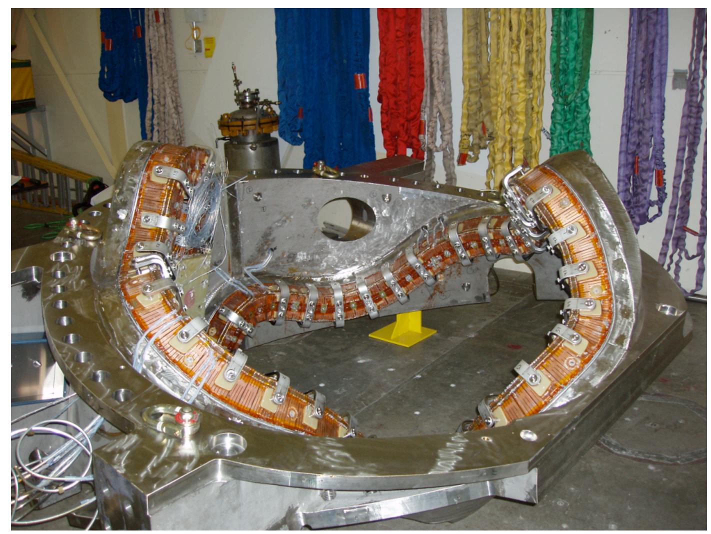
Modular Coil Production is Progressing Well

16 coils (of 18) have been wound and VPI'd.

Production operation has been smooth, with no major issues for over 1.5 years.

- Tolerance on current center position (±0.5 mm) is being met.
- Technical risks have been retired.

Last coil will be VPI'd in August (5 months off critical path)

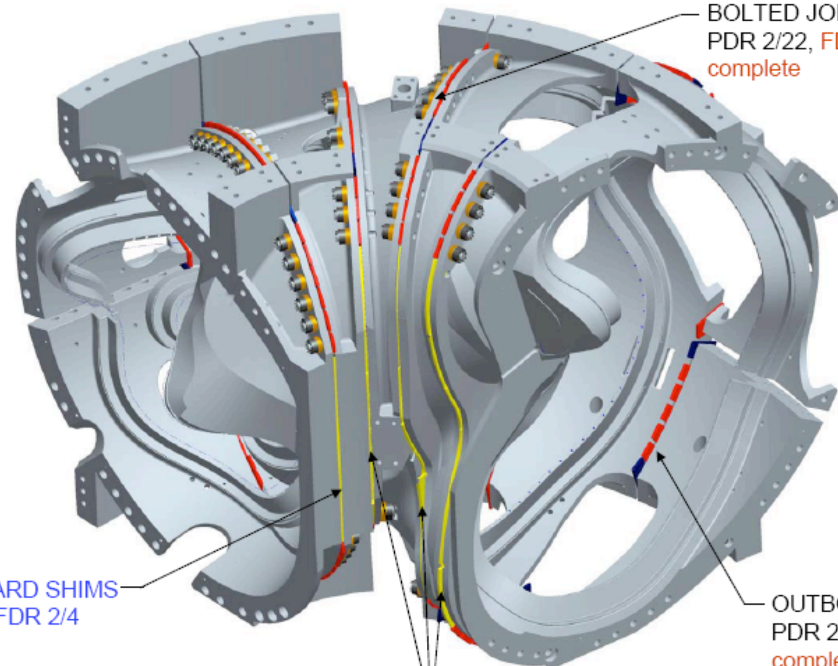


Modular Coil Interfaces

NCSX National Compact Stellarator Experiment

Hardware

- Bolts, nuts, washers, bushings, etc.
- Medium-friction shims (A-A, A-B, B-C)
- High-friction shims (C-C)
- Shear plates (C-C)
- Compression pucks (C-C)
- Inflatable shims



Assembly Processes

- Metrology
- Welding (low distortion)
- Handling and accurate positioning of components.

Status

- **Design was completed Nov., 2007**
- Many critical operations prototyped.
- Parts and procedures for half-period assembly (A-B-C) are in hand.

Half-period assembly has started

Inner Core Design Maturity

WBS	Scope	Job Mgr.	CDR	PDR	FDR
Inner Core (Stellarator Core out to MC Shell & VV port flanges)					
12	Vacuum Vessel	Goranson	■	■	■
14	Modular Coil Assemblies	Williamson	■	■	■
14	MC AA, AB, BC Interface	Williamson / Cole	■	X	X
14	MC CC Interface	Williamson / Cole	■	■	X
18	FPA Tooling:				
18	Station 3 stands and lift fixtures	Brown	■	■	X
18	Station 3 module alignment sys	Brown	■	■	X
82	Assembly Sequence Plan Maturity		Assessment	Envisioned future changes	
82	Station 2	Brown	99%	probably none	
82	Station 3	Brown	90%	module alignment system	

Legend	
■	Completed prior to FY-08
X	Completed in FY-08

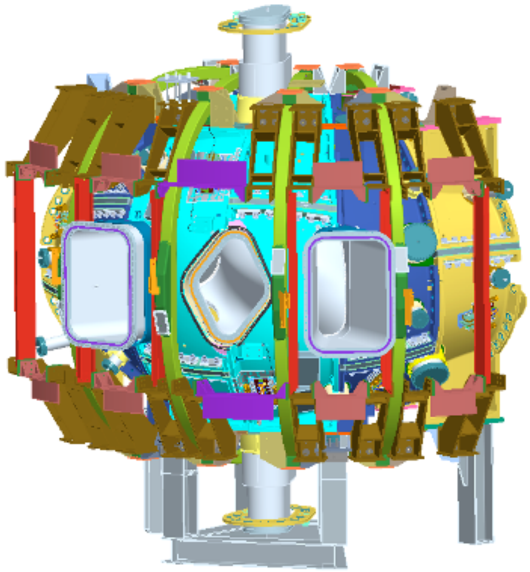
Design has matured in FY-08.

- Equipment design is now complete.
- Component fabrication is nearly complete. Mature activity.
- Assembly tooling and sequence plans (basis for assembly estimates) are very mature.
- Risk of further design-driven cost & schedule growth is reduced, though not eliminated.

Risks now are mostly process-related, for example:

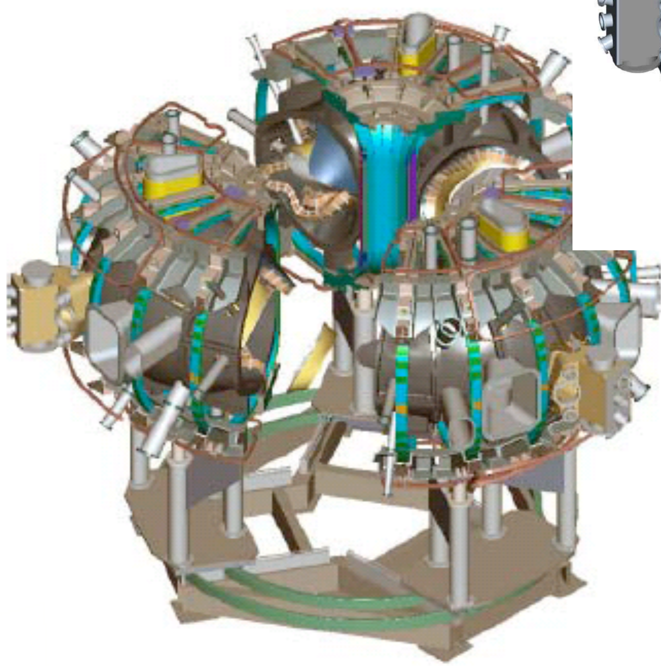
- Part deflection during assembly: mitigated by design, rigid fixturing, low-heat weld process, process development, careful monitoring with metrology.
- Parts interfering or not matching up: mitigated by design, pre-assembly fit-up trials, CAD modeling with as-built dimensions.

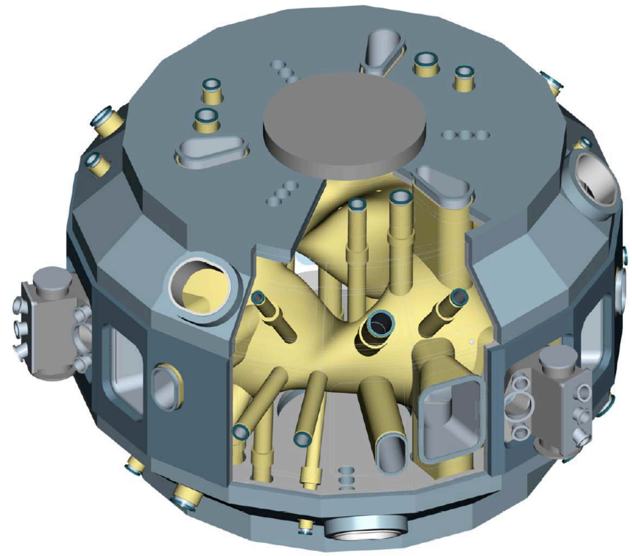
Outer Core: Stellarator Core Outside MC Shell and VV Port Flanges



Completed
Field Period
(after Station 5)

Final Machine
Assembly
(Station 6)





Cryostat
completes the
Outer Core
(Station 6)

Toroidal Field Coil Production is Progressing Well

Everson Tesla, Inc., Nazareth, PA

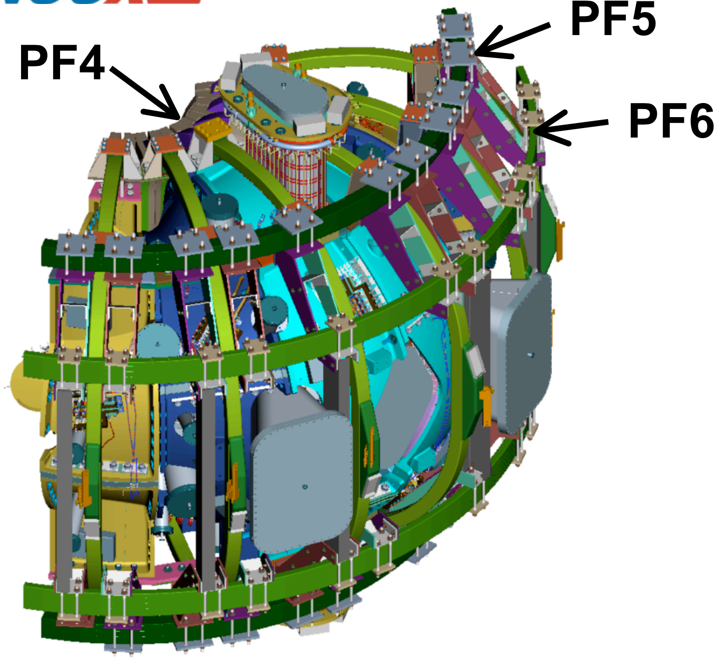
10 coils (of 18) have been completed.

Smooth production operation has been established.

- Producing 1 every 3-4 weeks.
- Technical risks have been retired.
- ±3 mm tolerance is being met.

Last coil to be shipped in October (>1 year off critical path)

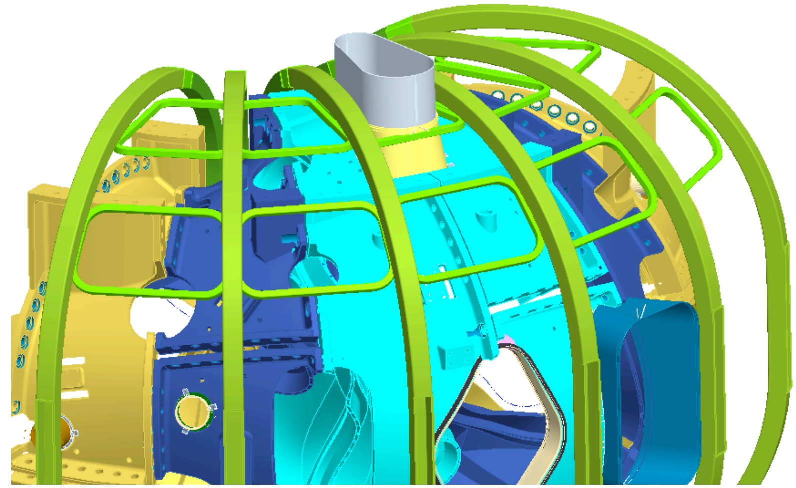
Poloidal Field Coils and Trim Coils



Poloidal Field Coils

Vendor selection in progress.

- Proposals received 4/2.
- Award by 5/30.
- PF 5L and 6L due Feb. '09. (~1 year off critical path)
- Balance due Sept. '09.



Field Error Compensation Coils (Trim Coils)

- 48-coil array controls magnetic islands due to field errors.
- Compensates for fabrication errors with margin (≥100%) available to cover out-of-tolerance conditions if necessary.
- In final design; ~10 months off critical path.

Outer Core Design Maturity

WBS	Scope	Job Mgr.	CDR	PDR	FDR	Free Float (days)	Start fab. / Award
Outer Core (Stellarator Core Beyond MC Shell & VV port flanges)							
12	NB Transition Ducts	Goranson	■	9/30/08	1/12/09	318	3/9/09
13	TF Coils	Kalish	■	■	■	■	■
13	PF Coils	Chrzanowski	■	X	X	303	5/30/08
13	Trim Coils	Kalish	X	X	4/28/08	218	6/10/08
15	TF/PF Coil Structures	Dahlgren	■	■	6/16/08	188	9/2/08
15	Central Solenoid Structure	Dahlgren	■	■	■	188	9/2/08
16	LN2 Manifolds	Goranson	■	6/3/08	9/5/08	197	10/10/08
16	Electrical Leads	Goranson	■	8/22/08	3/27/09	337	9/30/09
17	Base Structure	Dahlgren	■	X	4/30/08	147	9/30/08
17	Cryostat	Raftopoulos	10/1/08	7/6/09	2/12/10	115	8/17/10
18	Assembly Tooling:						
18	Station 5	Brown	■	X	4/21/08	200	8/14/08
18	Station 6 module supports ("sle	Brown	■	6/10/08	7/8/08	255	9/30/08
18	Station 6 spool piece support	Brown	■	6/10/08	8/5/08	439	9/30/08
82	Assembly Sequence Plan Maturity		Assessment	Envisioned future changes			
82	Station 5	Brown	90%	coil support details, cryostat supports, lifting features			
82	Station 6	Brown	75%	cryostat details, carts-base integration, racks, cable trays, unknowns			

Legend	
■	Completed prior to FY-08
X	Completed in FY-08
xx/xx/xx	Baseline early finish

FY-08 priorities: Push design. Order remaining coils and structures.

- Design work has been accelerated, but still maturing.
- Interfaces are critical. Being addressed by a strengthened design integration team.

Risks

- Further growth in assembly estimates as component designs and assembly sequence plans mature. Mitigated by pushing design, emphasizing integration.
- Parts interfering or not matching up: mitigated by design, fit-up trials, CAD modeling.
- Assembly schedule delays due to unavailability of parts. Mitigated by pushing design and procurements, and having free float (≥8 months) in the schedule.

Ancillary Systems

WBS	Scope	Job Mgr.	CDR	PDR	FDR	Free Float (days)	Start fab. / Award
Ancillary Systems (Facility Beyond Stellarator Core)							
12	Heater control sys	Gernhardt		5/1/09	8/4/09	107	8/31/10
2	Fueling	Blanchard		4/29/09	6/29/09	318	1/13/10
2	Vacuum Pumping System	Blanchard		2/6/09	6/2/09	361	2/12/10
3	Diagnostics:						
3	VV spacer flux loops	Stratton		N/A	10/2/08	426	10/20/08
3	Visible camera system	Stratton		10/1/09	11/25/09	309	3/10/10
3	Electron beam mapping sys.	Stratton		4/27/09	6/24/09	372	10/1/10
4	Coil Protection System	Ramakrishnan	X	9/22/08			
4	Power Systems	Ramakrishnan		9/22/08	10/27/09	305	FY-10
5	Central I&C	Sichta		FY-09	FY-10		FY-10
62	Cryogenic Systems (LN2)	Raftopoulos	12/23/08	10/27/09	3/12/10	132	3/29/10
62	Cryogenic Systems (GN2/Cryostat	Raftopoulos	12/23/08	7/6/09	2/12/10	115	6/1/10
63	Utility Systems	Dudek		10/29/10	11/15/10	134	11/16/10
64	VV heating and cooling system	Kalish		2/4/10	5/14/10	221	10/1/10
85	Startup	Gentile	Starting safety docs. & ISTPs in FY-08				

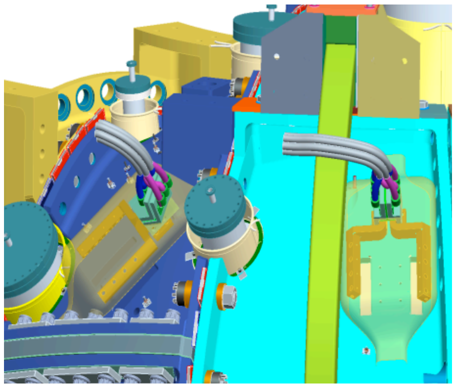
FY-08 priority: Push power systems design.

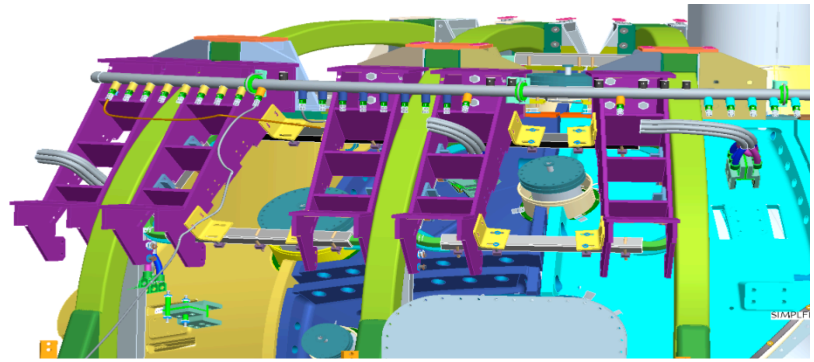
- Systems are conventional and similar to past projects, e.g. NSTX.
- Consulting with outside experts on cryo. system.
- Most of the design work will start in FY-09.

Legend	
	Completed prior to FY-08
X	Completed in FY-08
xx/xx/xx	Baseline early finish

Emphasis now: design integration & interface control – an example: coil leads with machine core

NCSX
National Compact Stellarator Experiment





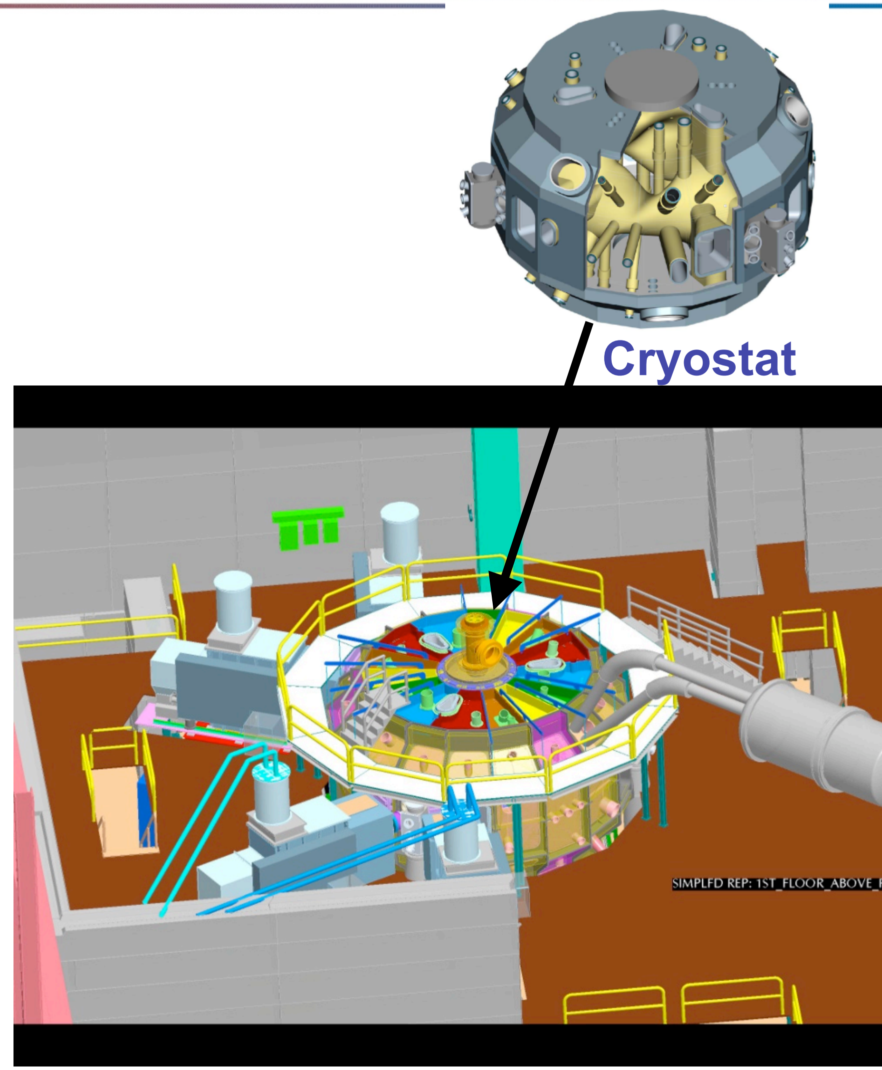
MC Lead stub connections shown on Station 6

Lead stub connection to Type A and B MC

Services will be routed to each of the three C-C interfaces.

(Cont'd)- Emphasis now: design integration & interface control – a 2nd example: the cryostat

- Has many interfaces and is critical to operation.
- Consequently, work has been pulled back and re-started to assure that design details & interfaces are wisely chosen and adequately defined to minimize downstream costs and schedule impacts.

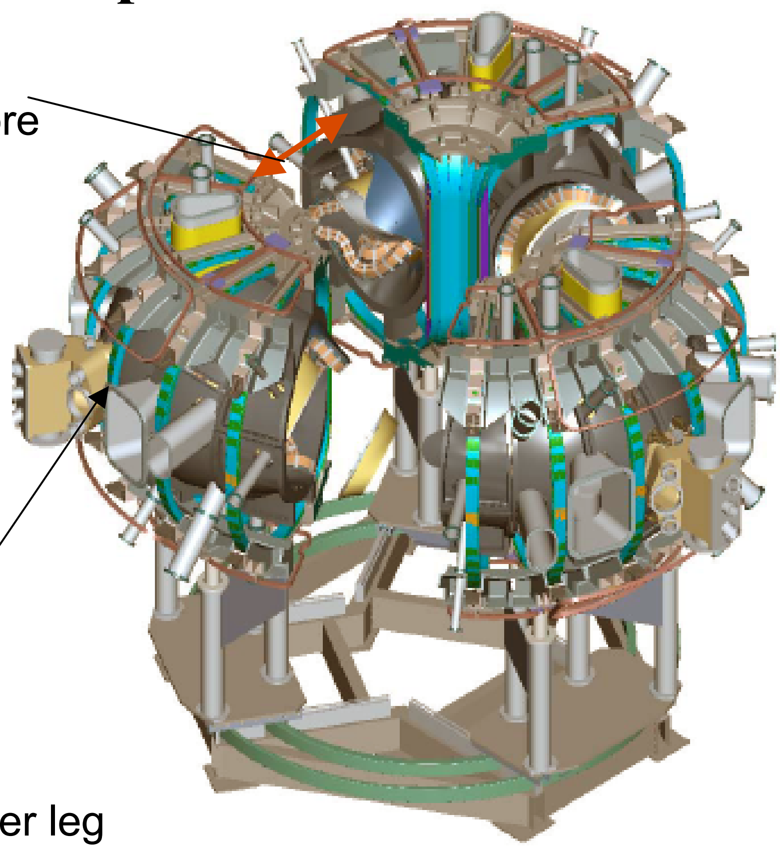


2. Recent key core-focused activities
   a) Interface designs
   b) Trim coils

a. Robust coil-to-coil interfaces have been developed & are being implemented.

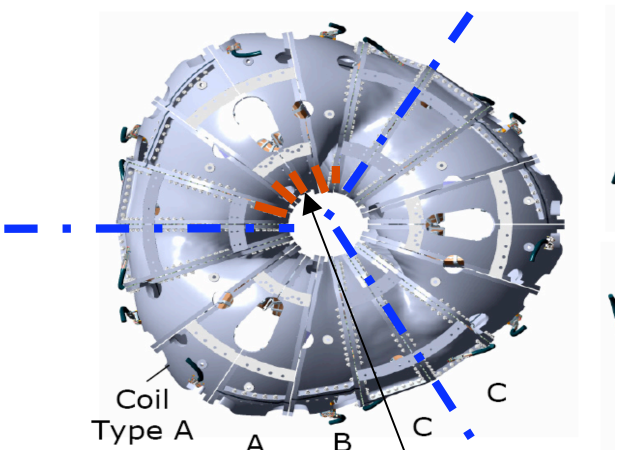
Two types of interfaces developed:

Type 1 - C-C "field assembly" joints have more studs added.



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

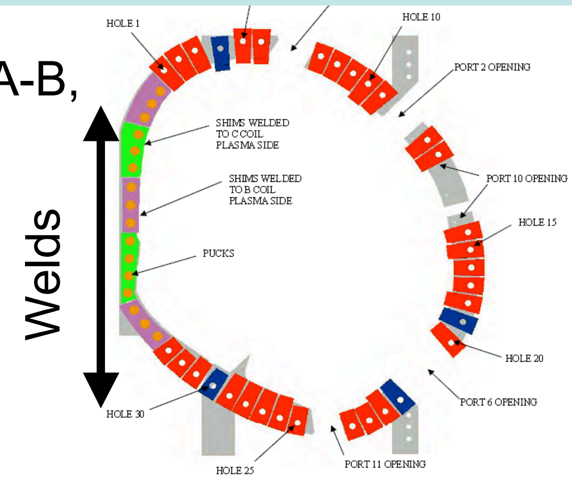
The two inner leg interface types



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

(1) Welded inner leg interfaces

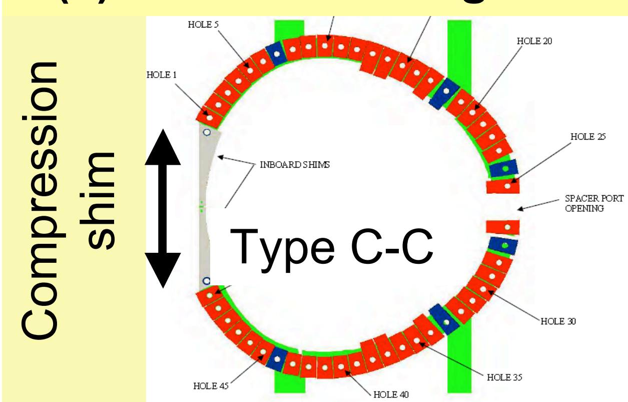
Types A-A, A-B,
and B-C



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

- Red outer shims: Friction shims clamped via A286 high strength through bolts.
- Blue outer shims: Friction shims without bolt

(2) Bolted inner leg interface

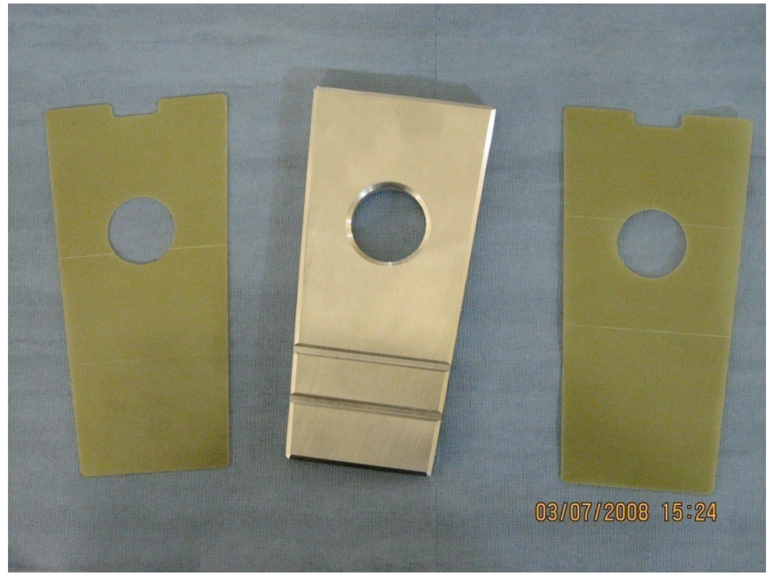


Two types of friction shims cover the range required

- The high friction shims were found to be difficult to manufacture to the tolerance required (flat and parallel +/- 0.002”); therefore, used only where necessary.

<u>High Friction type, for C-C</u>

Plasma sprayed alumina coating, 0.007”/side

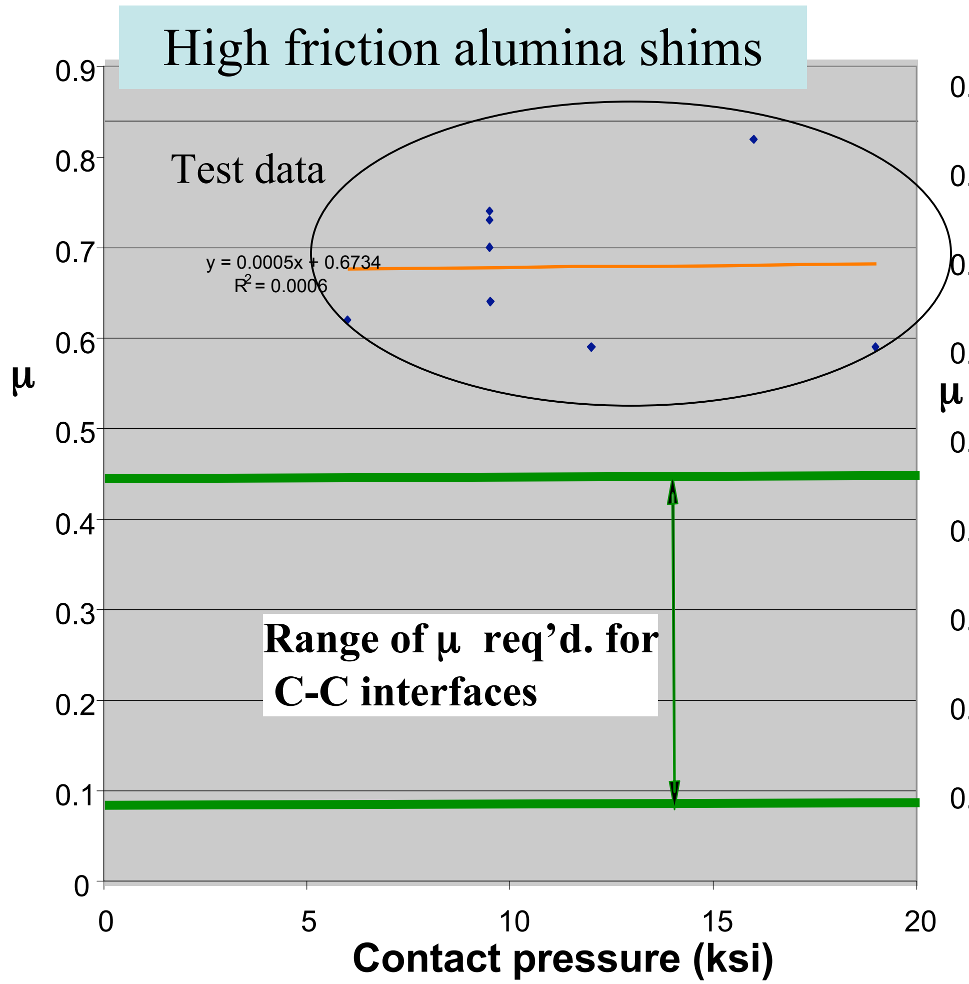


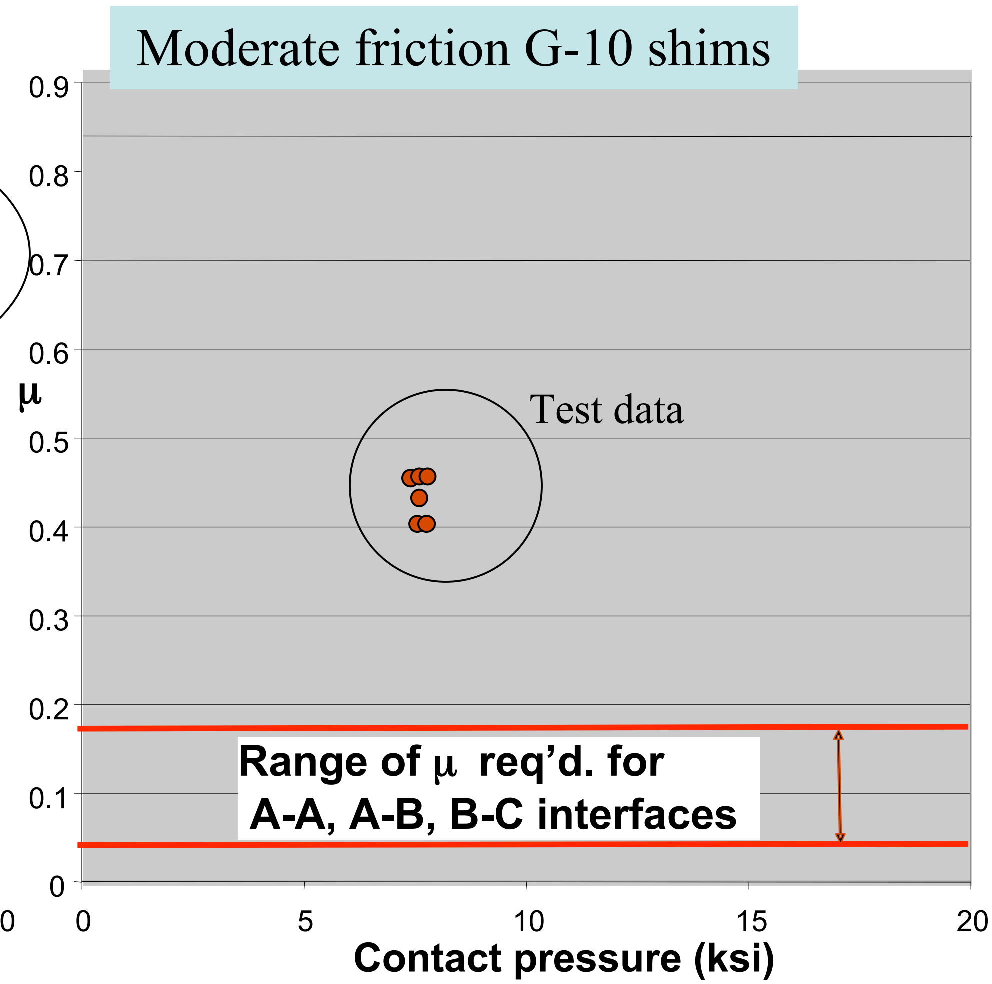
<u>Moderate Friction type, for all other locations</u>

G-10/ SS/ G10 sandwich.

G10 thickness 0.010-0.032”

Friction test results vs. requirements





The friction requirements were also confirmed by non-linear analyses

NCSX National Compact Stellarator Experiment

- Non-linear analyses based on a half field period model with anti-cyclic symmetric conditions on the end C-C and A-A flanges. Bolts are simulated in model.
- Electromagnetic loads based on 2T, high β load case (which has highest loads/in.).

Results: (A-A; A-B; B-C interfaces with moderate friction shims)

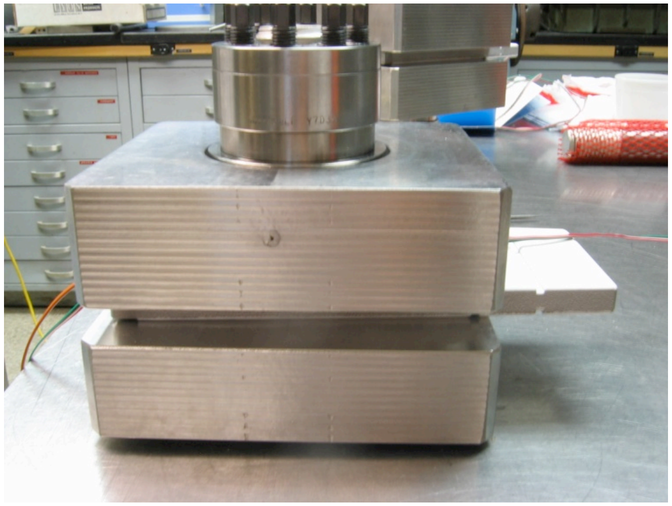
- No slippage under any outboard bolts with μ of 0.3 assumed for all locations (even welds).
  - Loads on inboard end bolts are acceptable, even with this conservative assumption.
- *Limit analysis performed simulating ALL outer bolt preloads lost indicates NCSX would still operate, but in a fatigue limited mode.*

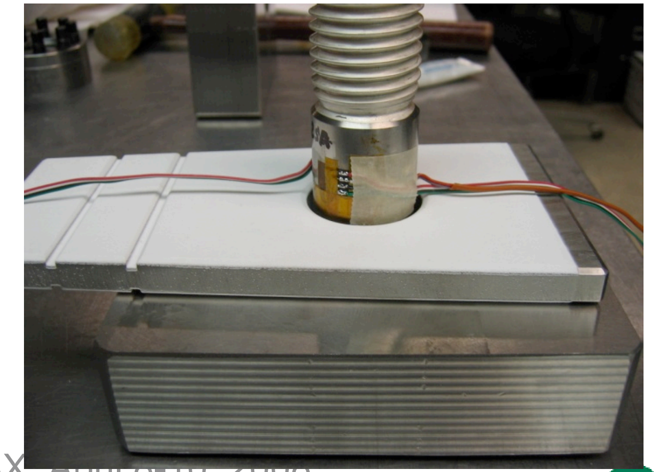
Results: (C-C interface with high friction shims)

- With μ 0f 0.4 assumed for all friction shim locations and 0.04 assumed for inner leg compression shims, the inner leg motion is a very acceptable ~0.004" and there is no slippage under any bolts.

Joint stability tests

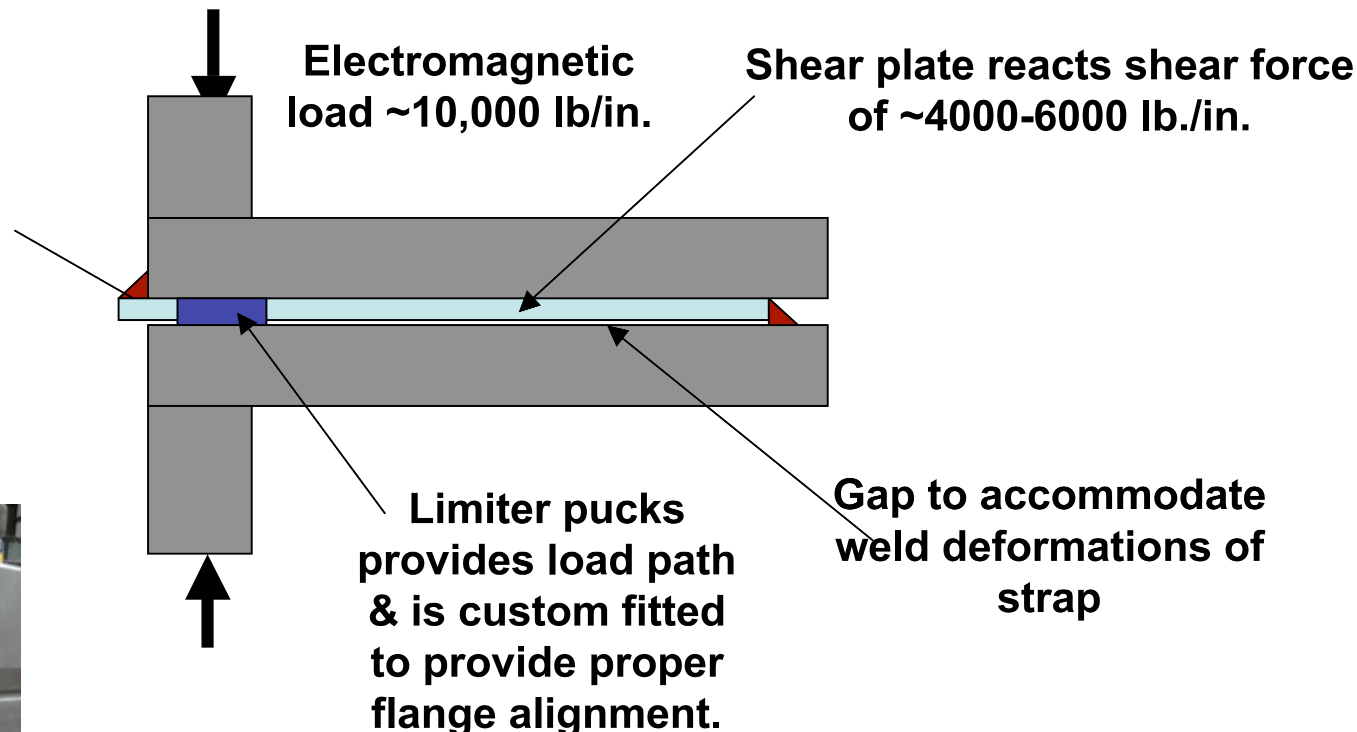
- Performed on alumina coated shims.
  - Showed virtually no change in bolt load after 3 cycles between 80 K & 273 K.
- Will be repeated for G10 sandwich shims.





The first half period assembly based on the low distortion welded interface is being assembled now and going well!

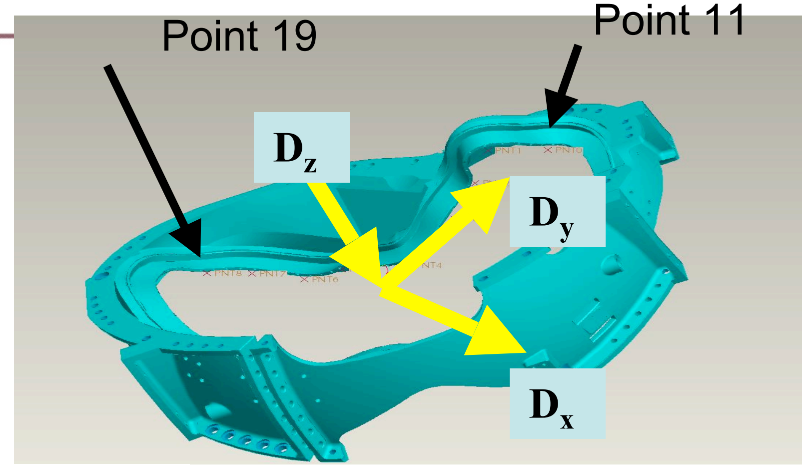
- Shear plate shapes & weld geometries were refined during trials.
- Welded distortions at an acceptable level so far with the A1 and B1 plasma side welds completed.

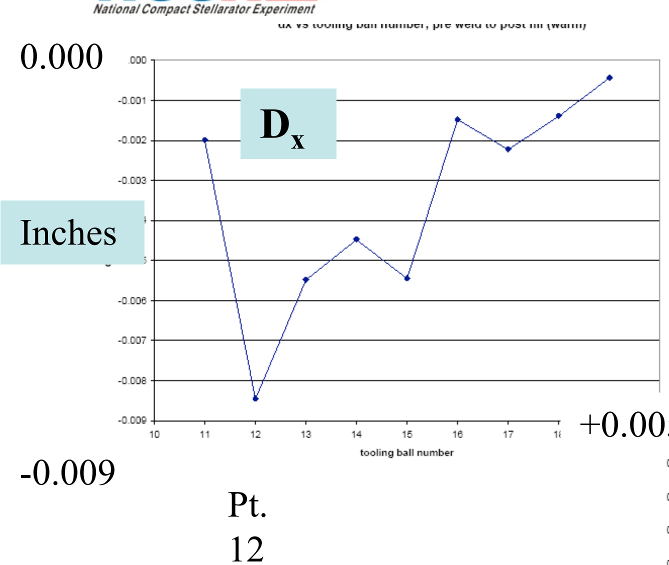


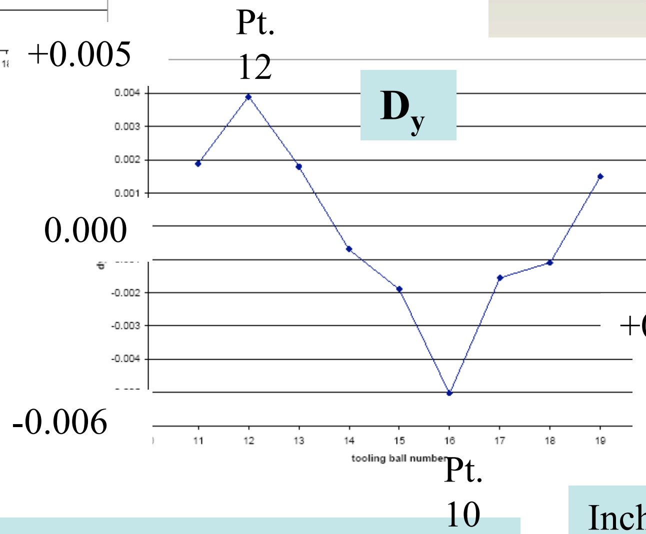
This welding concept minimizes weld shrinkage forces between the flanges and provides a load path as near as possible to the shell–to– shell interface.

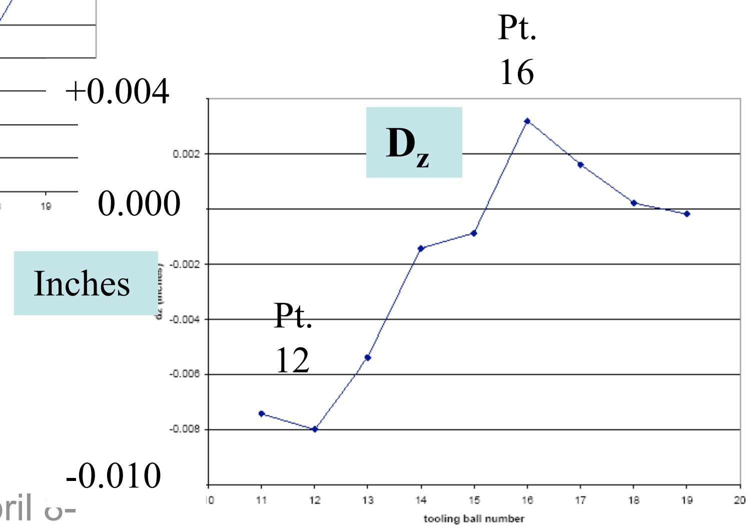
Distortion data, A1 plasma side welds

NCSX National Compact Stellarator Experiment







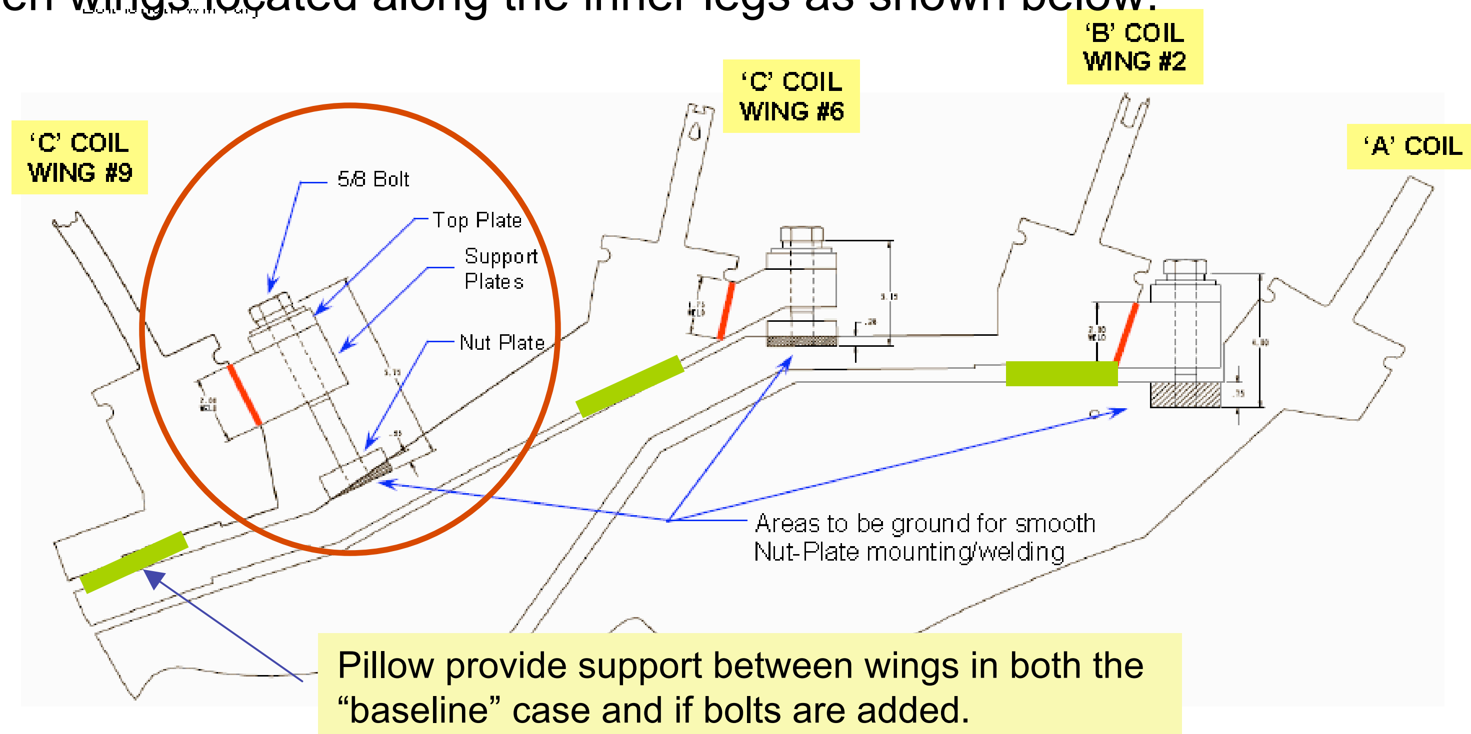


Max. dS 0f 0.012" at this stage is reasonable; Criteria for wing displacement < 0.040" (1 mm).

Contingency plans developed to address unanticipated excessive wing deformations from welding or assembly

- Unexpected stellarator-symmetric deformations up to ~ 1 mm will be addressed by trim coils.

- In the very unlikely case that deformations exceed this, bolts can be added between wings located along the inner legs as shown below:



Issues and Risk Mitigations Associated with Interfaces

NCSX
National Compact Stellarator Experiment

Issue	Risk Mitigation
MCs may move during operationoperation.	• Custom fitted friction shims. • High strength studs & Supernuts • Stud monitoring –a subset of the studs. • Welded inner leg interfaces at 15 of 18 interfaces & enhanced bolted inner leg interface at the remaining 3. • Tight-fitting bushings at each stud as backup.
MCs may distort due to welding	• TIG/MIG to reduce weld heating. • Low distortion welded interface design with laser monitoring. • Contingency plan for wing movements: compensate w/trim coils; add wing restraints.
Accurate coil positioning	• Custom fitted shims and pucks. • Laser tracker & photogrammetry metrology. • Tight-fitting bushings to assure accurate coil position maintenance even if thermal gradients develop during cool-down.

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

ornl
OAK RIDGE NATIONAL LABORATORY

b. Trim Coil requirements & mitigation of as-built conditions

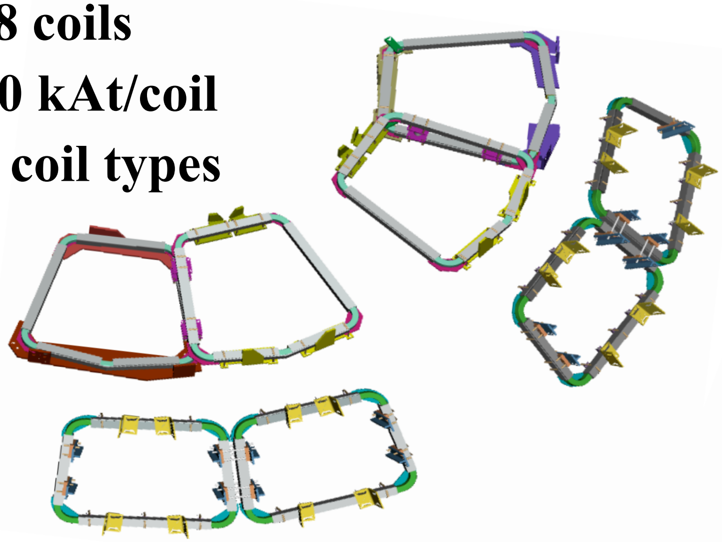
The trim coil requirements are defined in the NCSX General Requirements Document:

3.2.1.5.1 Field Error Requirements
a. Field error correction (trim) coils shall be provided to compensate for fabrication errors.
b. The toroidal flux in island regions due to fabrication errors, magnetic materials, and eddy currents shall not exceed 10% of the total toroidal flux in the plasma (including compensation

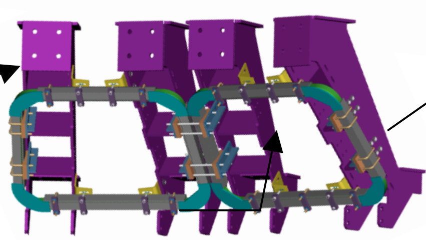
- Recent efforts focused on gaining a better understanding of the trim coil system's capability to compensate for fabrication errors and in defining NCSX's trim coil system design has been very successful.
- ***The trim coil system is an important tool in allowing us to mitigate schedule risks due to as built conditions***.

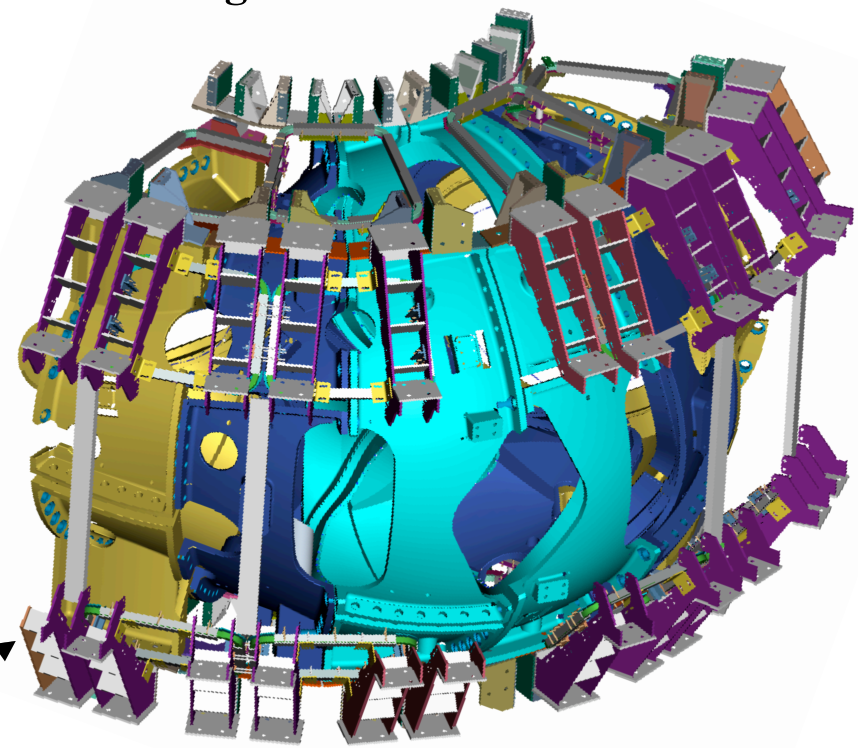
Trim Coil Design Overview

- **Can compensate for projected coil mis-aligments, expected deformations, lead field errors, and +/- 1 mm of "wing" distortions with 100% reserve on A-t.**
- **48 coils**
- **20 kAt/coil**
- **2 coil types**



PF/TF support structure





Trim coils are located between modular & TF coils; supported from the TF / PF structure

Conclusions

NCSX has made tremendous progress since the last Office of Science Review in August, 2007, and has retired a significant amount of risk:

- Designs of all core components are now complete (VV, modular coils, TF coils, PF coils).
- 11 system design reviews were successfully completed.
- The critical modular coil interface designs were competed.
- Two half field period assemblies in Station 2 are now underway based on these interface designs.
  - Assembly / metrology techniques so far are comfortably within tolerance requirements of 0.5 mm for a half period.
  - Welding on the first half period (A1 &B1) shims along the plasma side demonstrates adequate distortion control.
- An effective trim coil system has been developed which has the capability of mitigating all projected sources of error.
  - Has enough reserve capacity to compensate for up to 1 mm wing deflections, if encountered.
  - This reserve will be used to mitigate schedule delays due to construction tolerances.

We remain focused on driving towards design maturity and completion as rapidly as possible to reduce risks.

Backup Slides

-the major components of NCSX

-assembly

-tolerance requirements

-analyses

NCSX

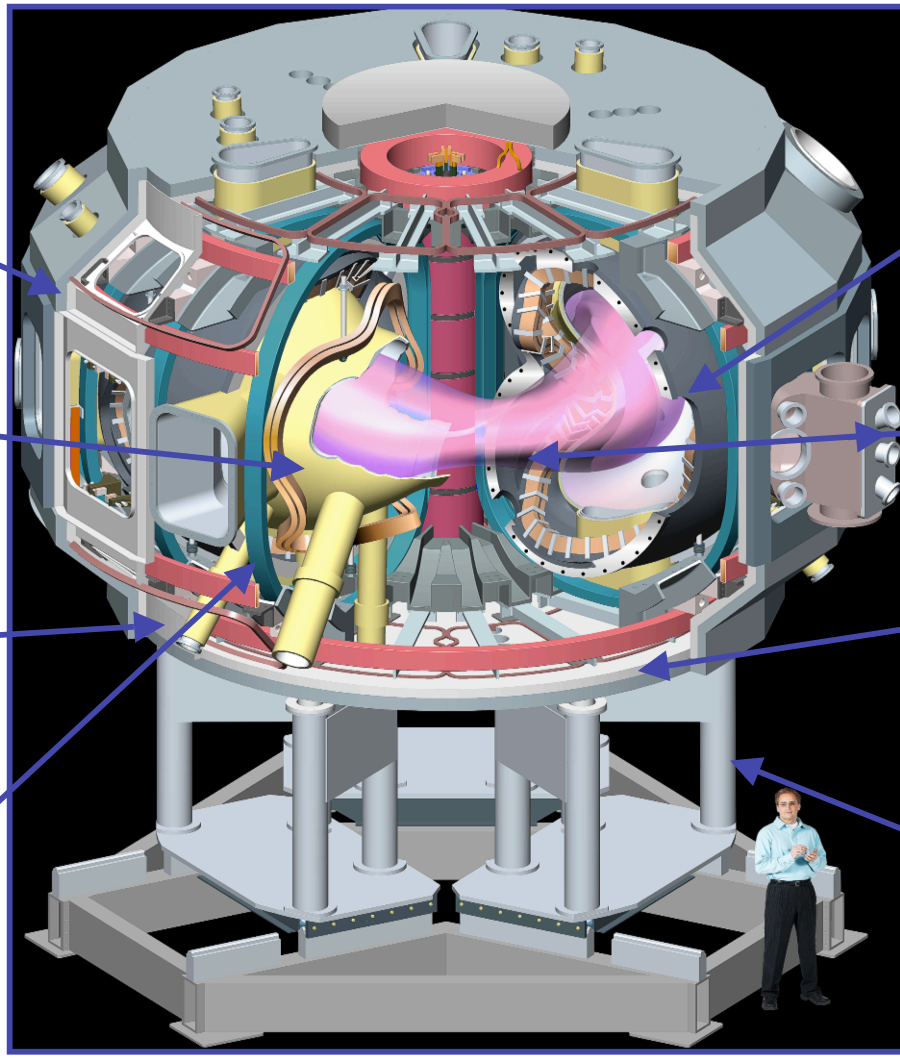
NCSX National Compact Stellarator Experiment

Cryostat

Vacuum vessel

Trim coils

Toroidal field (TF) coils



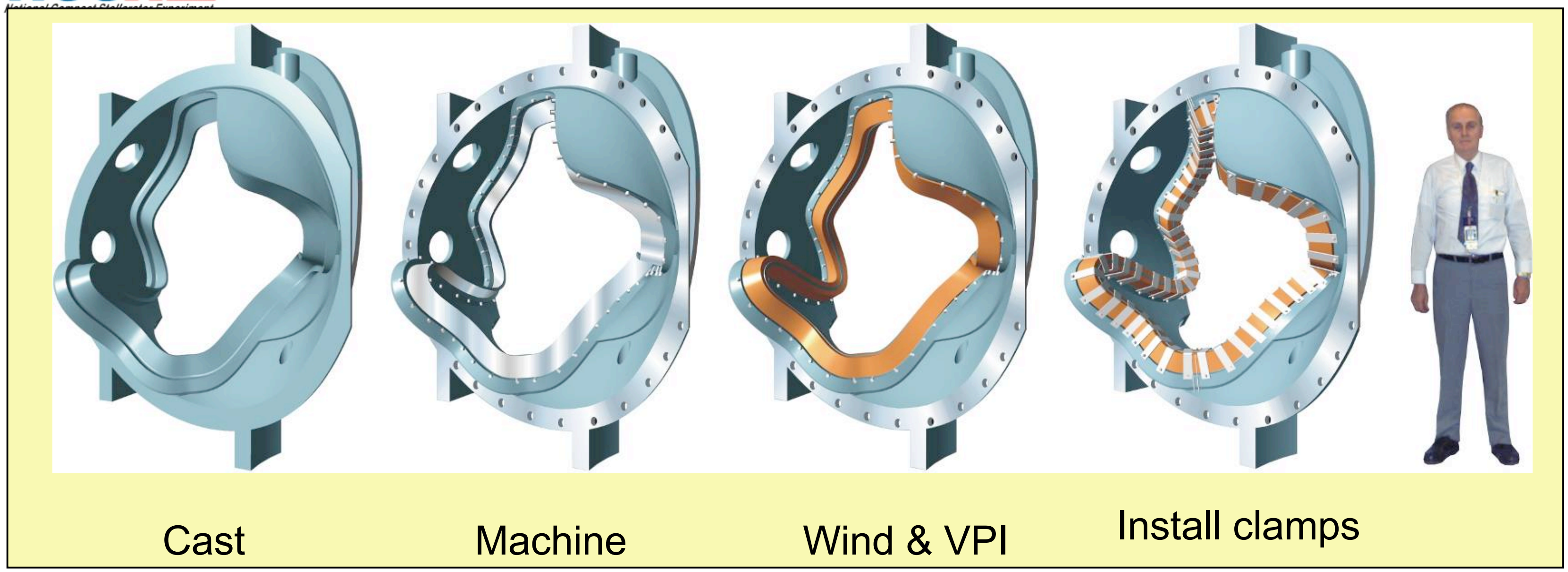
Modular coils (MC) with integral shell

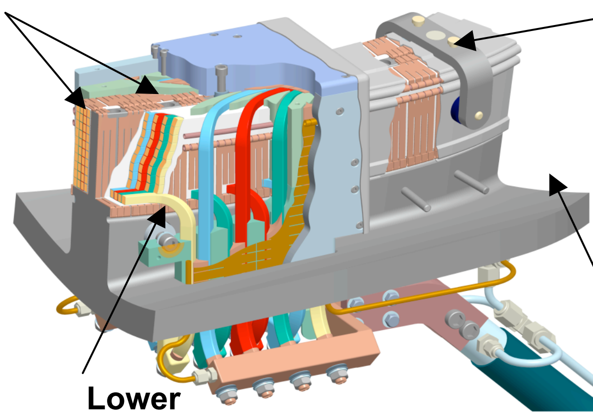
Plasma

Poloidal field (PF) coils

Base support structure

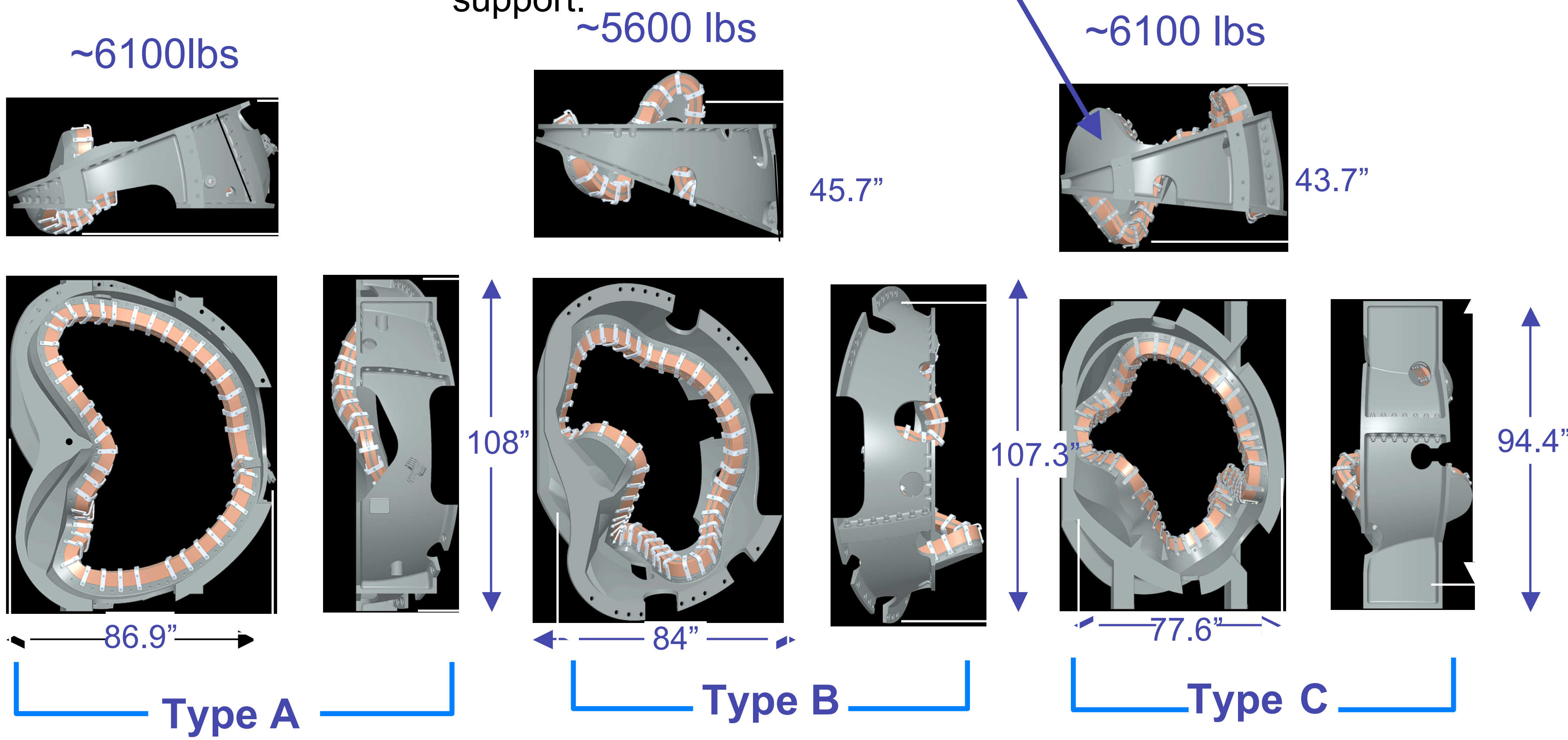
The modular coil windings are wound directly on cast stainless steel winding forms





The 3 modular coil types

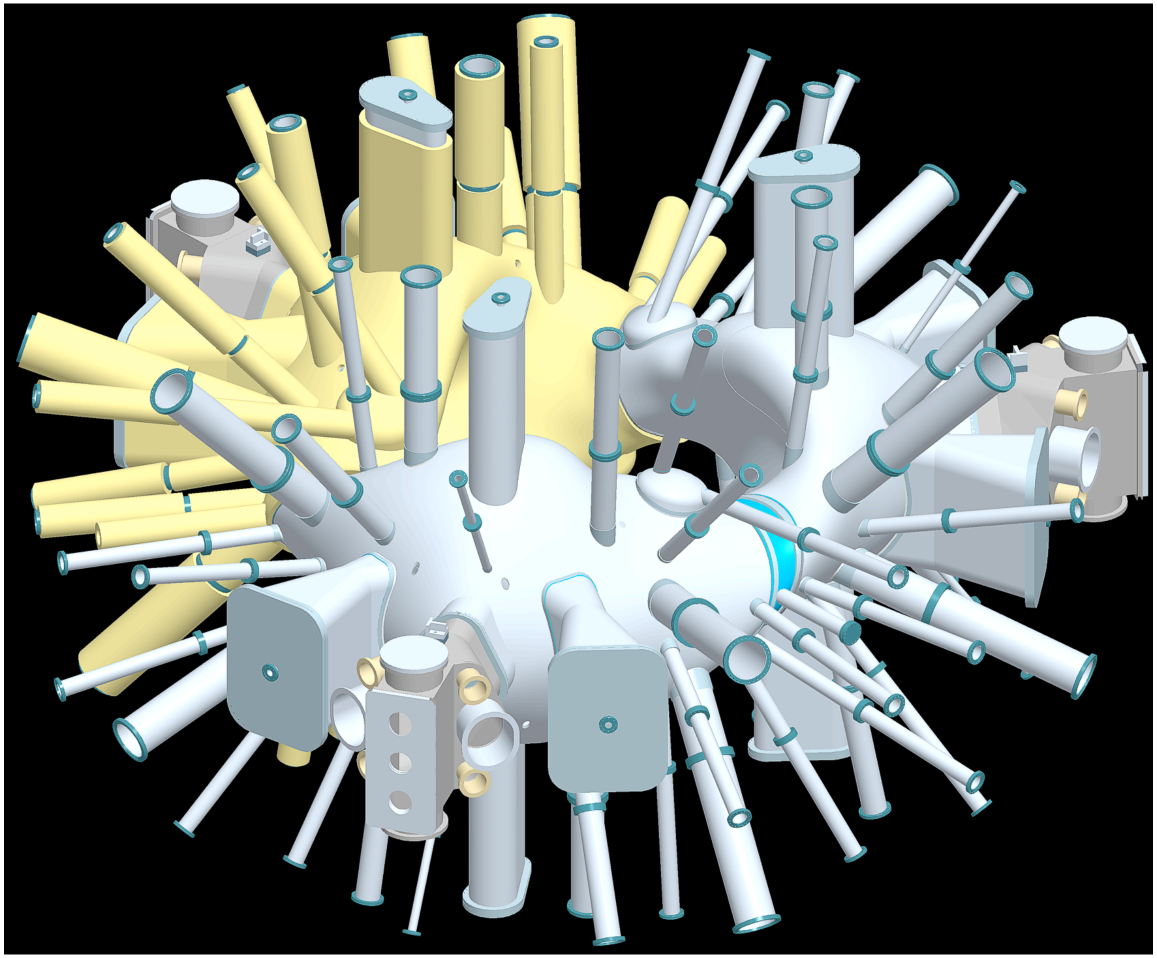
Wings. Inflatable epoxy-glass shims are installed at assembly for support.



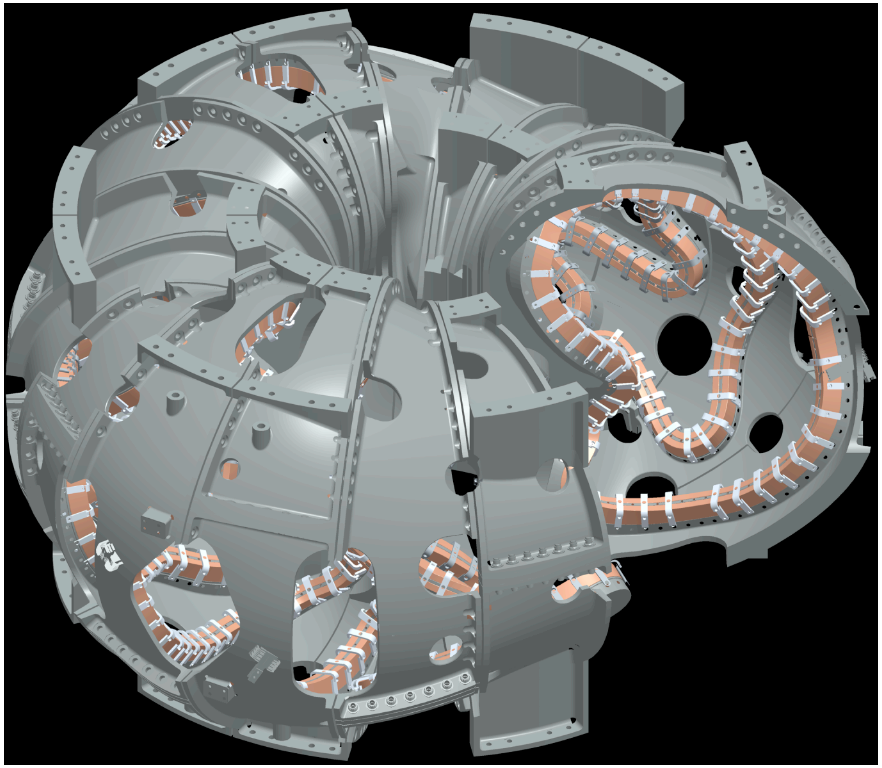
- 6 of each type; 18 in total.
- Castings made of “Stellalloy” which was specifically developed for NCSX.
  - -Magnetic permeability <1.02 and good welding characteristics.

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

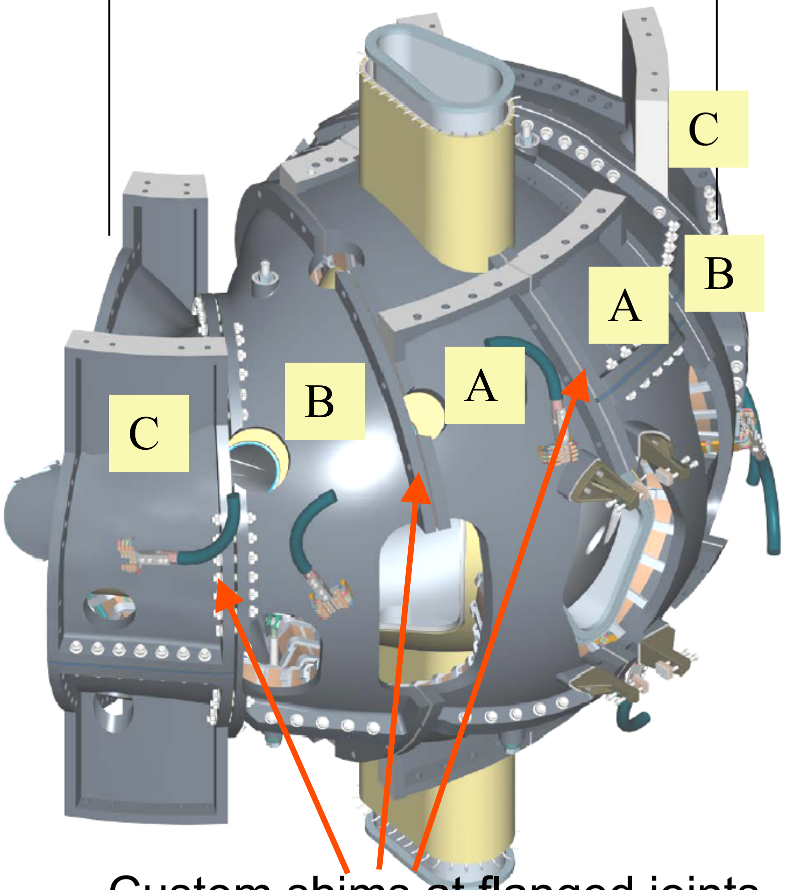


Modular Coil Assembly



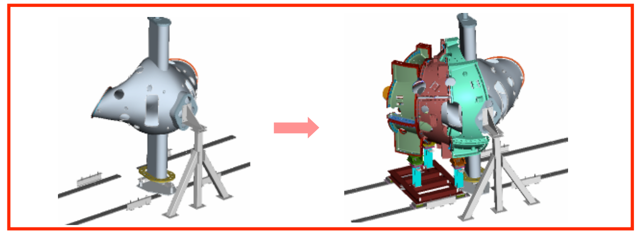
Modular coil assembly consists of 3 field periods. It serves as the structural backbone of the machine – the VV, PF, TF, and trim coils are all supported from it.

Field period: 2A's, 2B's, 2C's +VV

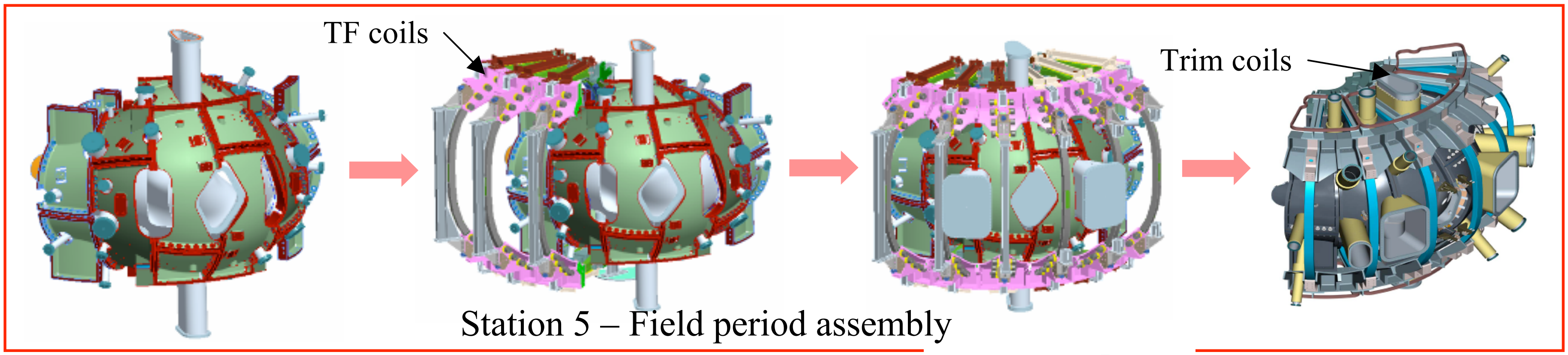


Custom shims at flanged joints between adjacent coil winding forms

Assembly

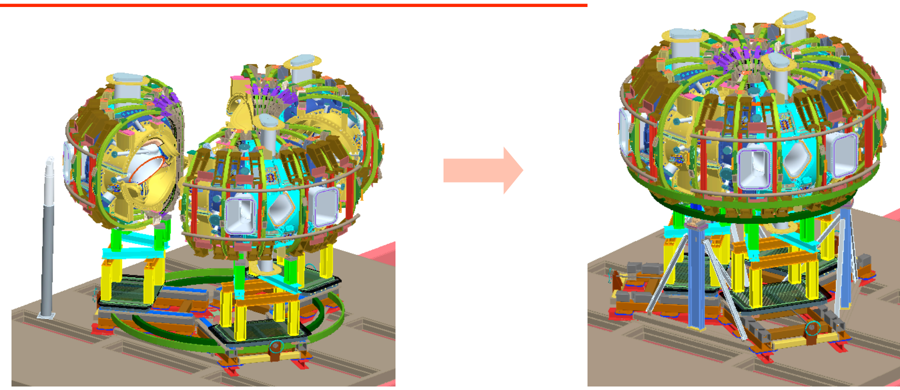


Station 3 – Modular coils installed around VV



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.

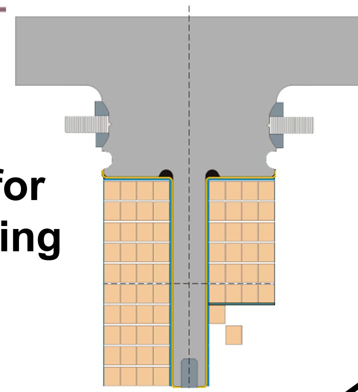
3.2.1.2.5.5 Deflections under Load

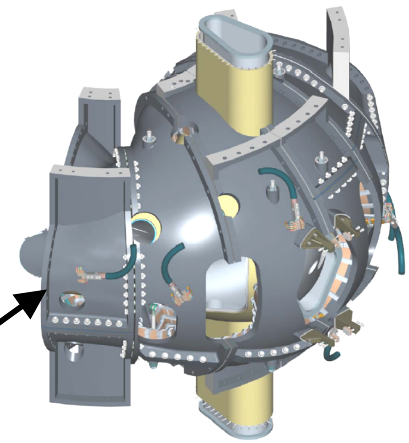
a. Modular coils shall be designed such that deflections due to thermal growth and due to electromagnetic loads preserve stellarator symmetry.
b. Deflection of the nominal current centroid due to electromagnetic loads shall not exceed 3 mm.

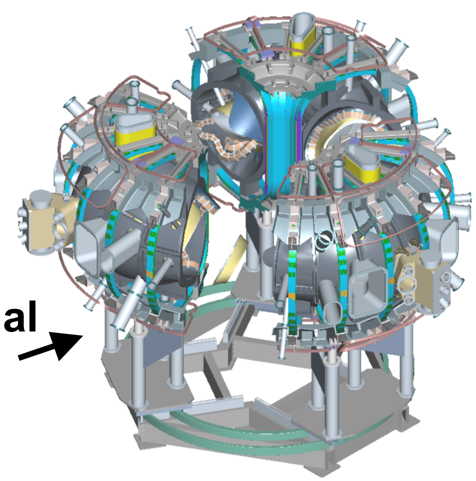
[Ref.: *Modular Coil System Requirements NCSX BSPEC-14-01*

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)

Analyses Back-up Slides

The friction requirements were then confirmed by non-linear analyses

- The non-linear (frictional) analysis of this structure is based on the half-field period model with anti-cyclic symmetric conditions on the end CC and AA flanges.
- The intent is to determine if the number of studs and shims is sufficient to prevent motion on the outboard side of the coils. Using discrete bolts instead of averages from a linear model gives a higher confidence.
- A friction factor of **0.3** used under all studs and on the entire flange surface.
- 2T high-β Magnetic loads, TF coil loads also applied.
- Preload compressive force of roughly 75 Kips applied to all bolts.

The non-linear analyses confirm that μ=0.3 is acceptable for A-A, A-B, and B-C flanges

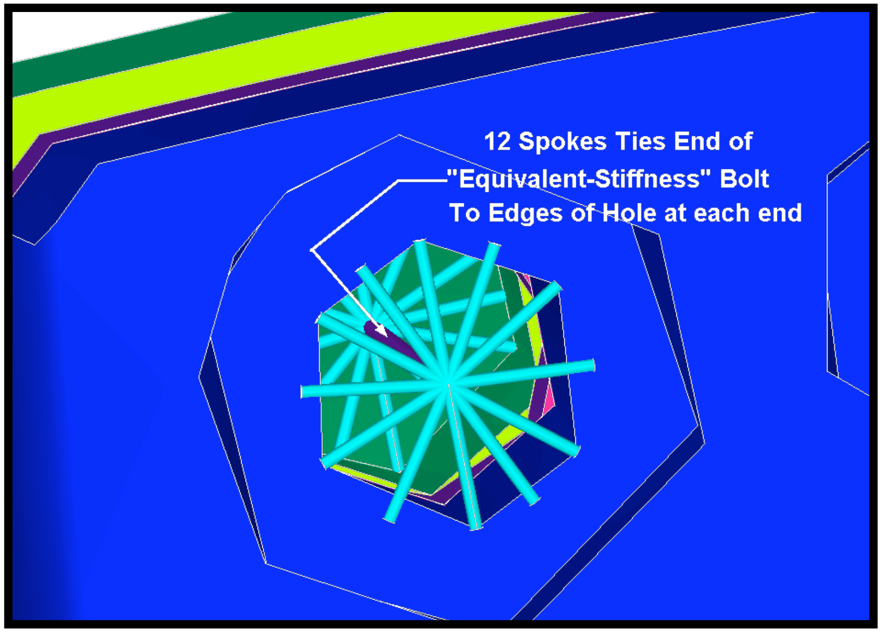
Earlier run with μ= 0.4 for comparison

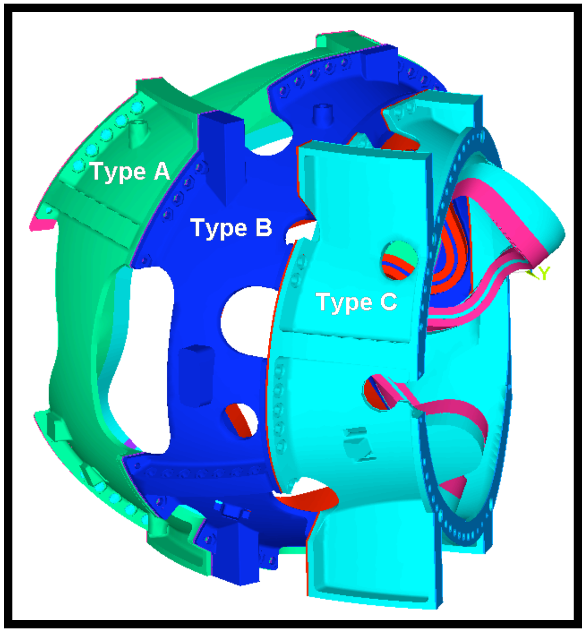
Flange Set	Max Bolt Shear, kip	Max Outboard Slippage mm
A-A	1.5	< 0.05
A-B	1.2	< 0.05
B-C	1.8	< 0.05

Design Point with μ =0.3

Flange Set	Max Bolt Shear, kip	Max Outboard Slippage mm
A-A	3.6	< 0.10
A-B	1.5	< 0.05
B-C	5	<0.12

Bolt Modeling



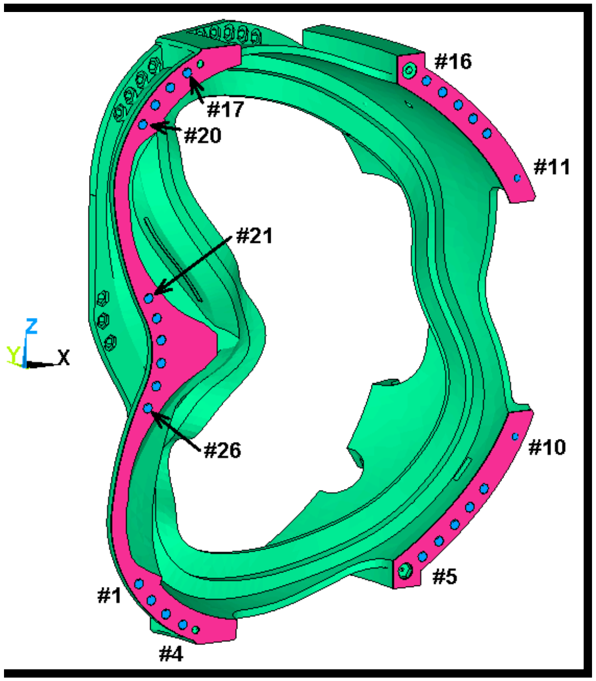


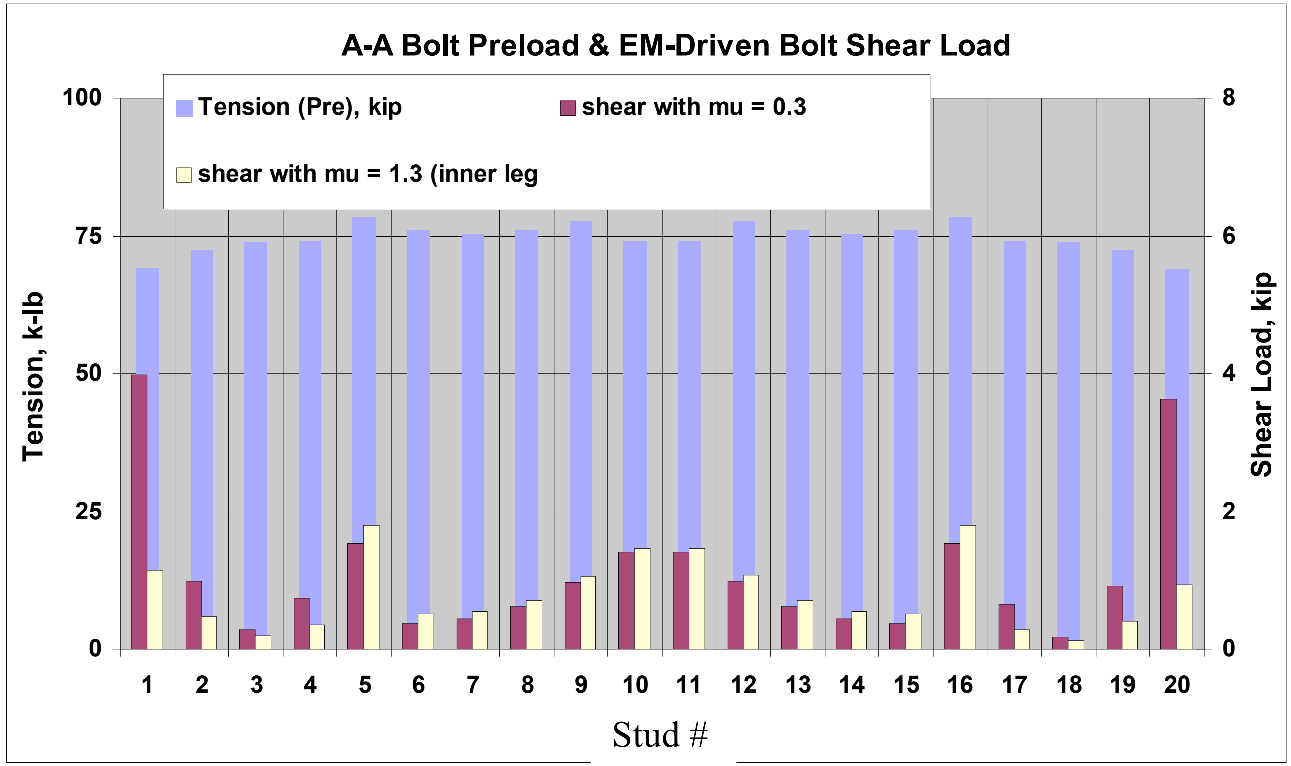
At one particular interface, pipe elements with appropriate section properties are used to represent the characteristics of a bolted interface. Contact elements at this interface are allowed sliding contact (no separation).

The other bolted interfaces are modeled with "Bonded Contact.“

**Any deflection of the top flange face (that connects to the bolt) relative to the bottom flange face or distortion of the hole itself could result in some minimal (usually less than 2 kips) shear in the bolt.

A-A Stud loadings (outboard)

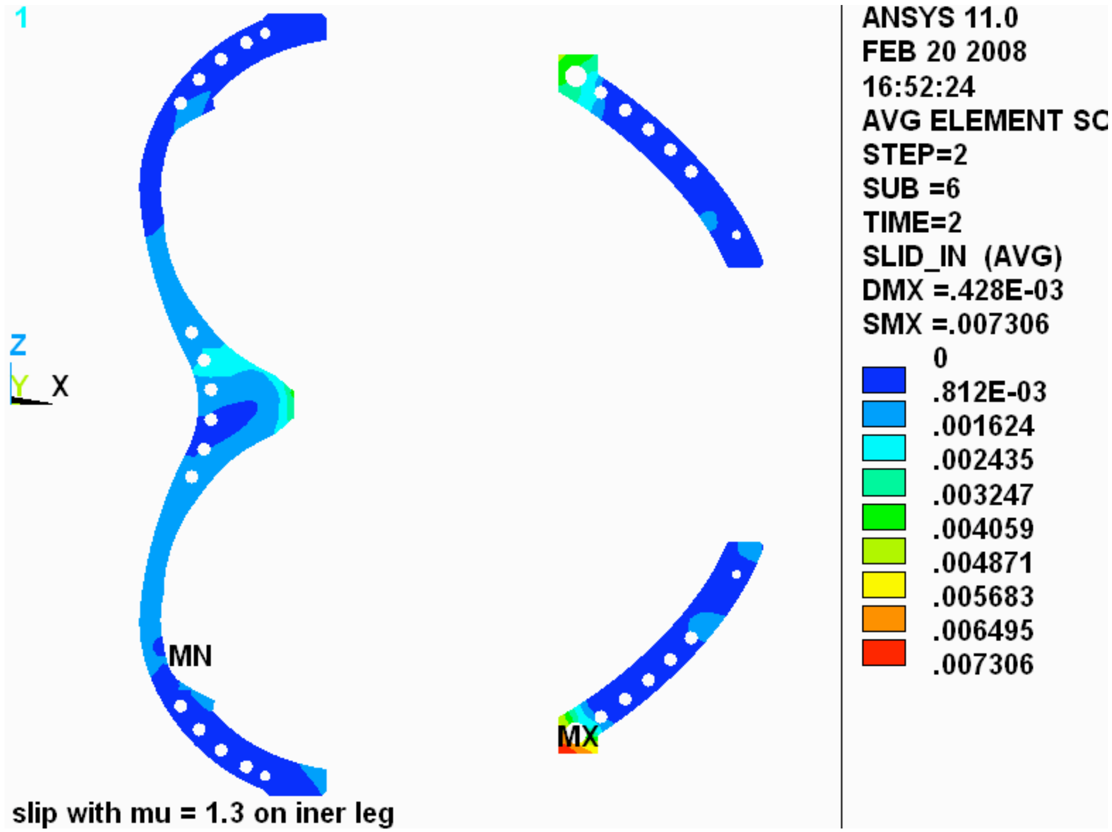




Studs 21-26 are no longer in the design and are not presented.

Even with mu = 0.3 everywhere (much wimpier than weld), the end bolts see less than 4 kips in shear. (fatigue limit is 9 kips)

AA Joint slip plot

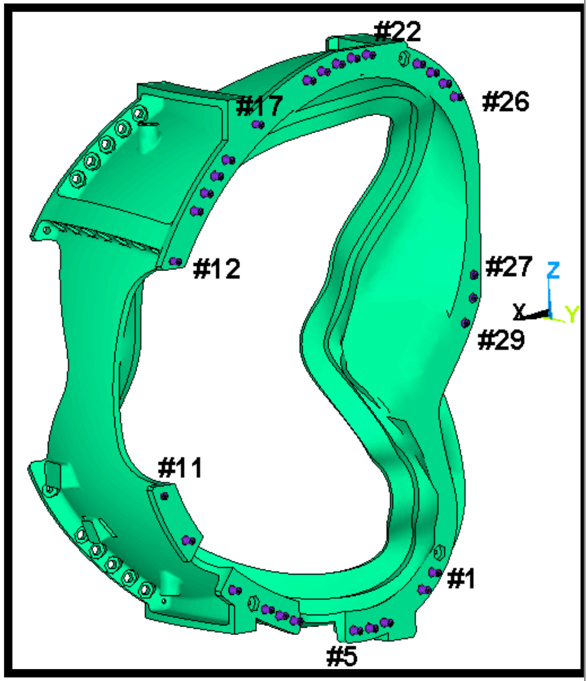


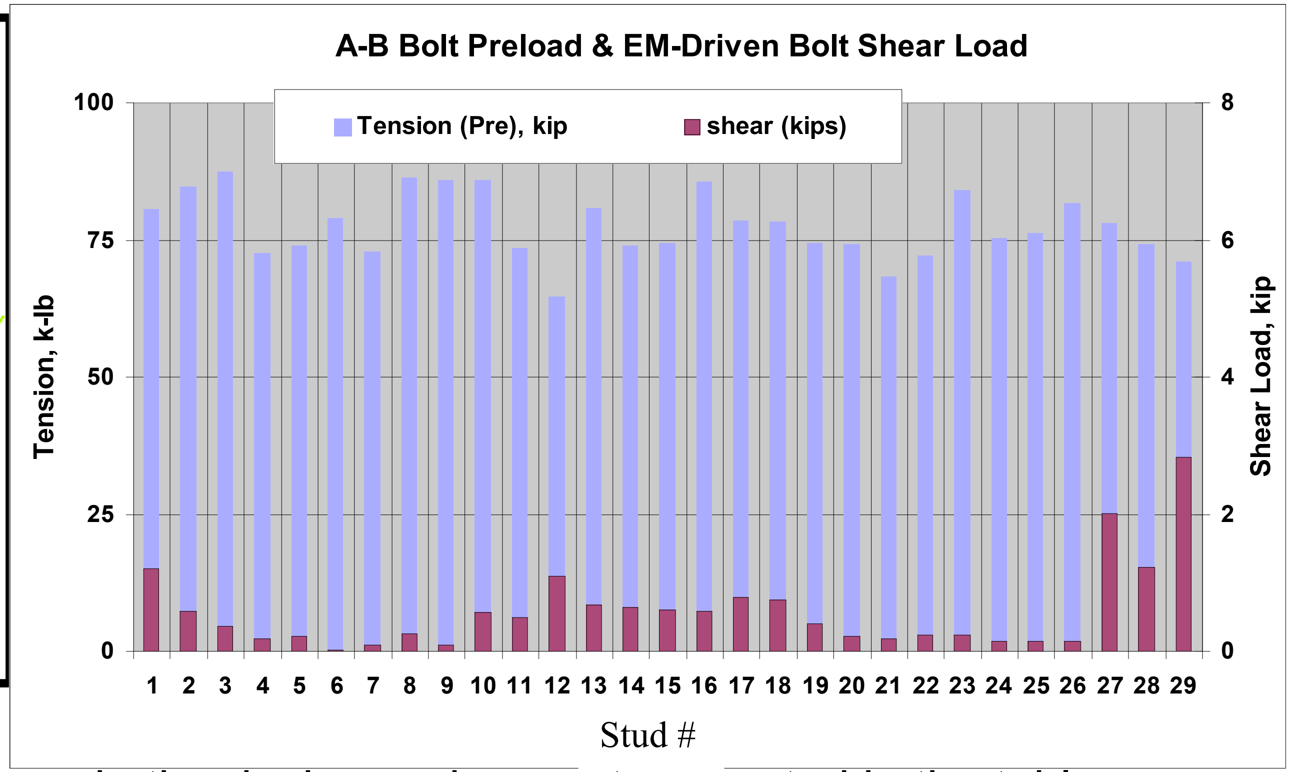
- μ = 0.3 in outboard regions
- Weld region modeled as having μ =1.3 on inboard region to simplify the analysis. (Conservative assumption).

A-B joint

NCSX National Compact Stellarator Experiment

Friction = 0.3 over the entire flange



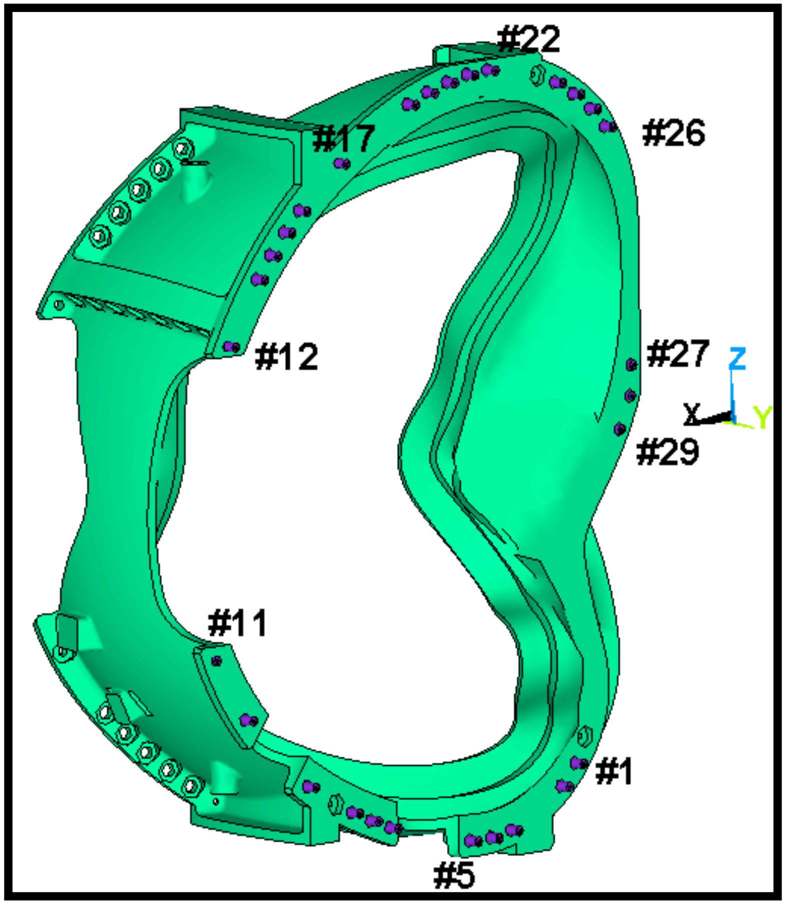


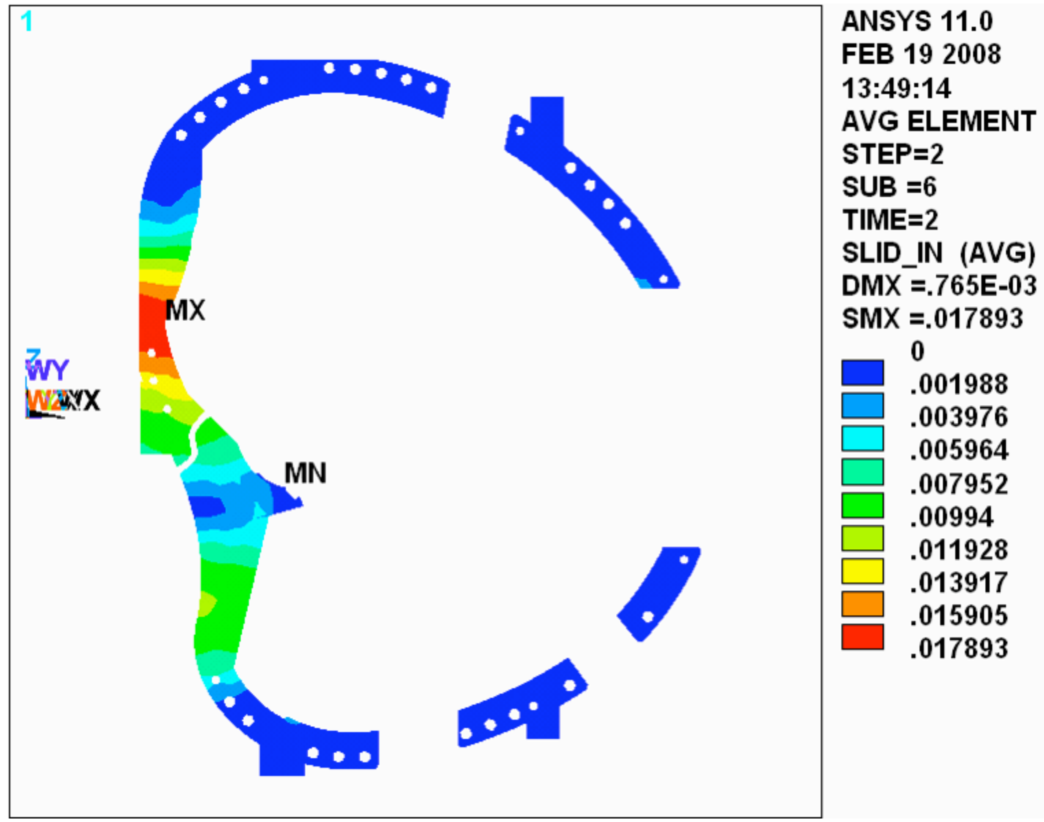
Studs 27-29 are no longer in the design and are not presented in the table.

Even with mu = 0.3 everywhere (much wimpier than weld), the end studs remain stuck and do not see any appreciable shear.

A-B Joint slip plot

Friction = 0.3 over the entire flange (even weld)

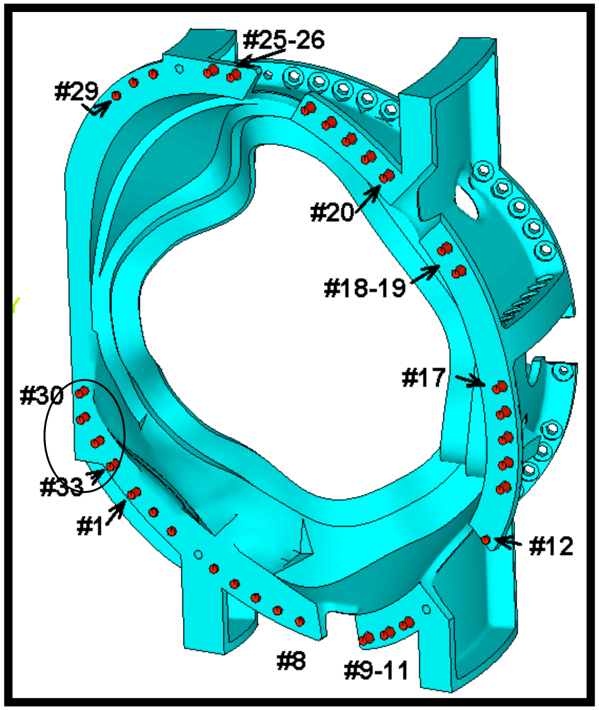


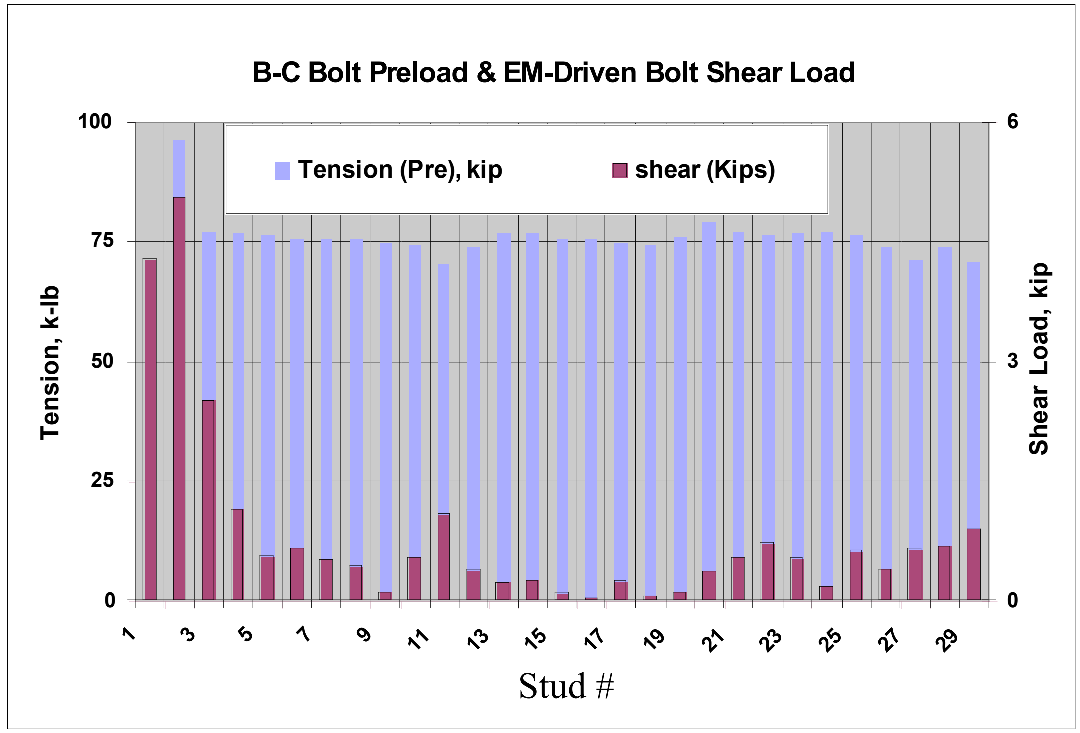


No slippage at any of the shims with mu = 0.3.

B-C Joint stud shear loads

Friction = 0.3 over the entire flange (even weld- very conservative assumption)





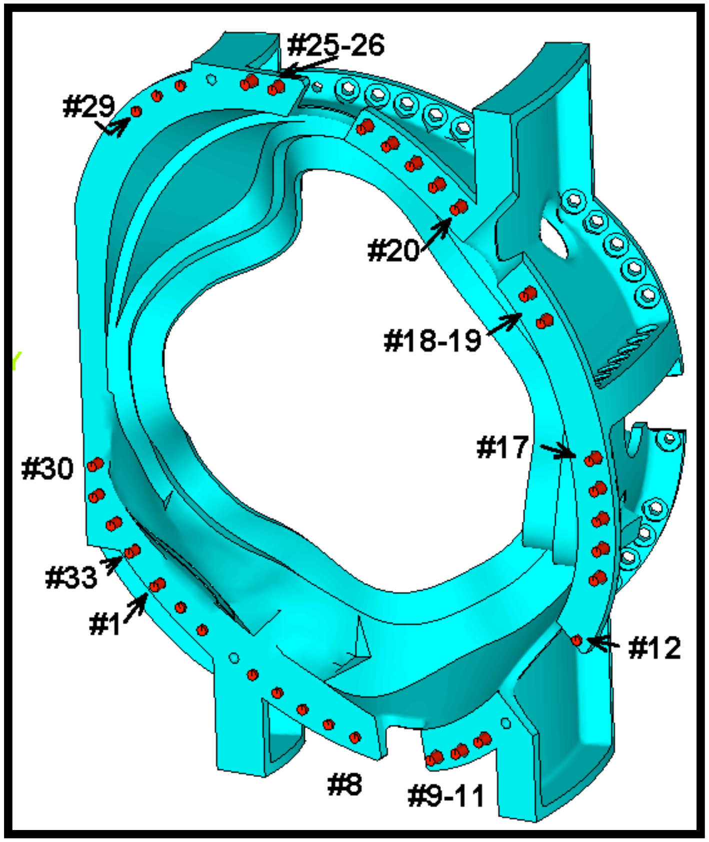
Studs 30-33 are no longer in the design and are not presented in this table.

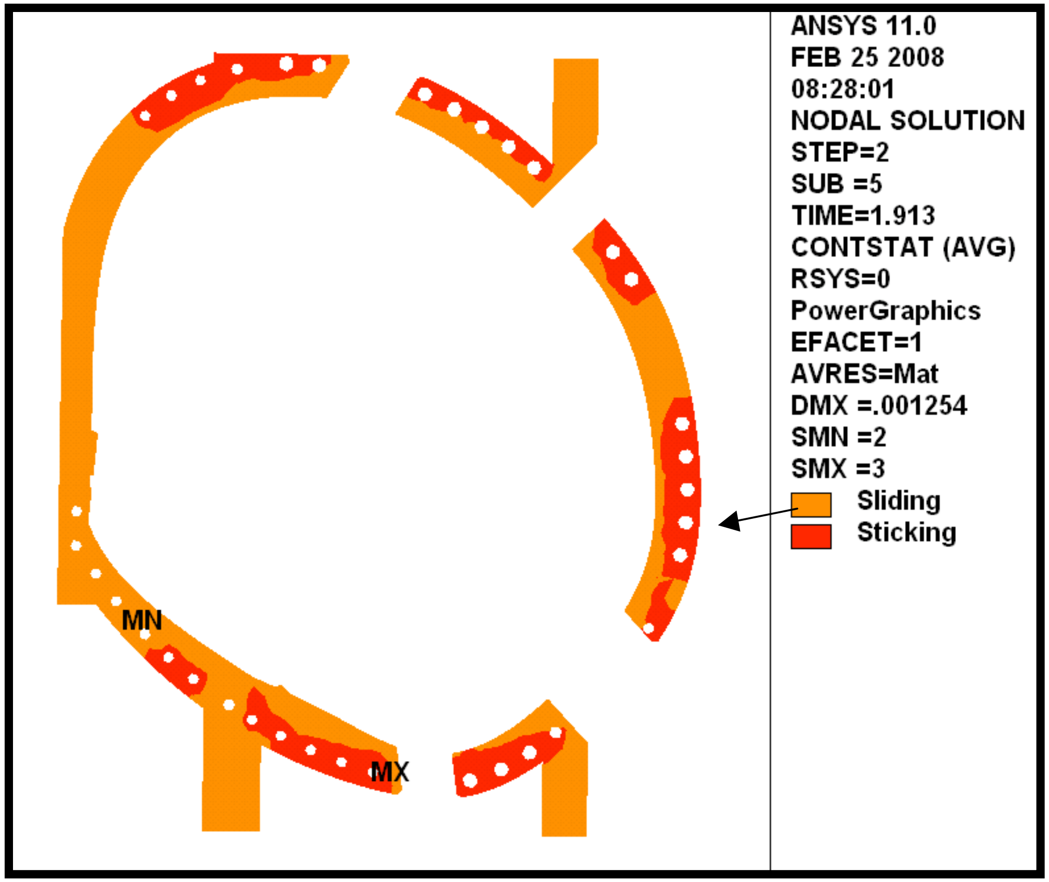
Studs 1 and 2 have shear > 4 Kips.

As with the AA joint, the weld will provide a stiffer connection than a mu = 0.3 on the inboard leg.

B-C Joint slip plot

Friction = 0.3 over the entire flange

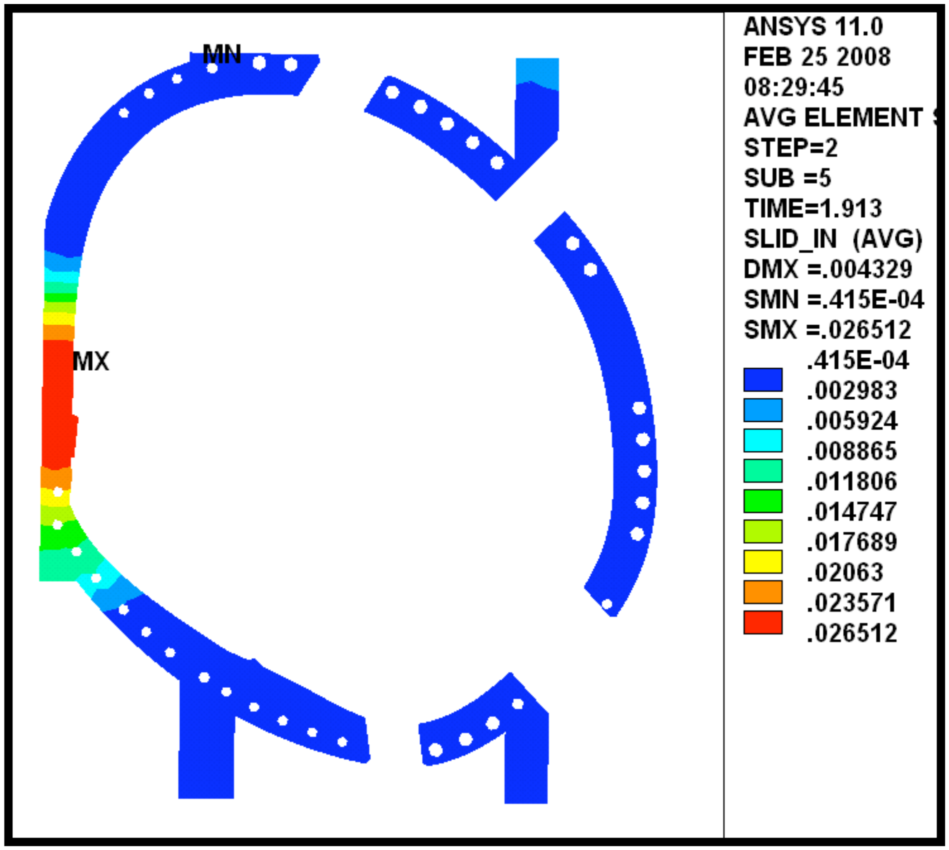


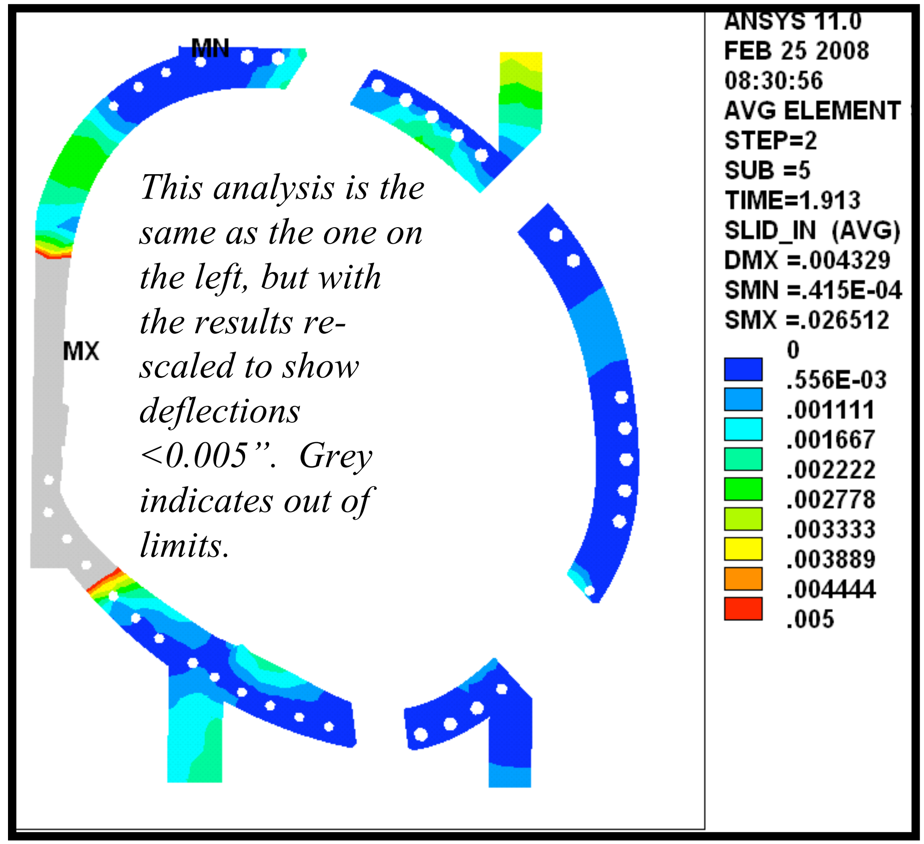


The Joint is stuck under every outboard stud.

B-C Joint slip plot

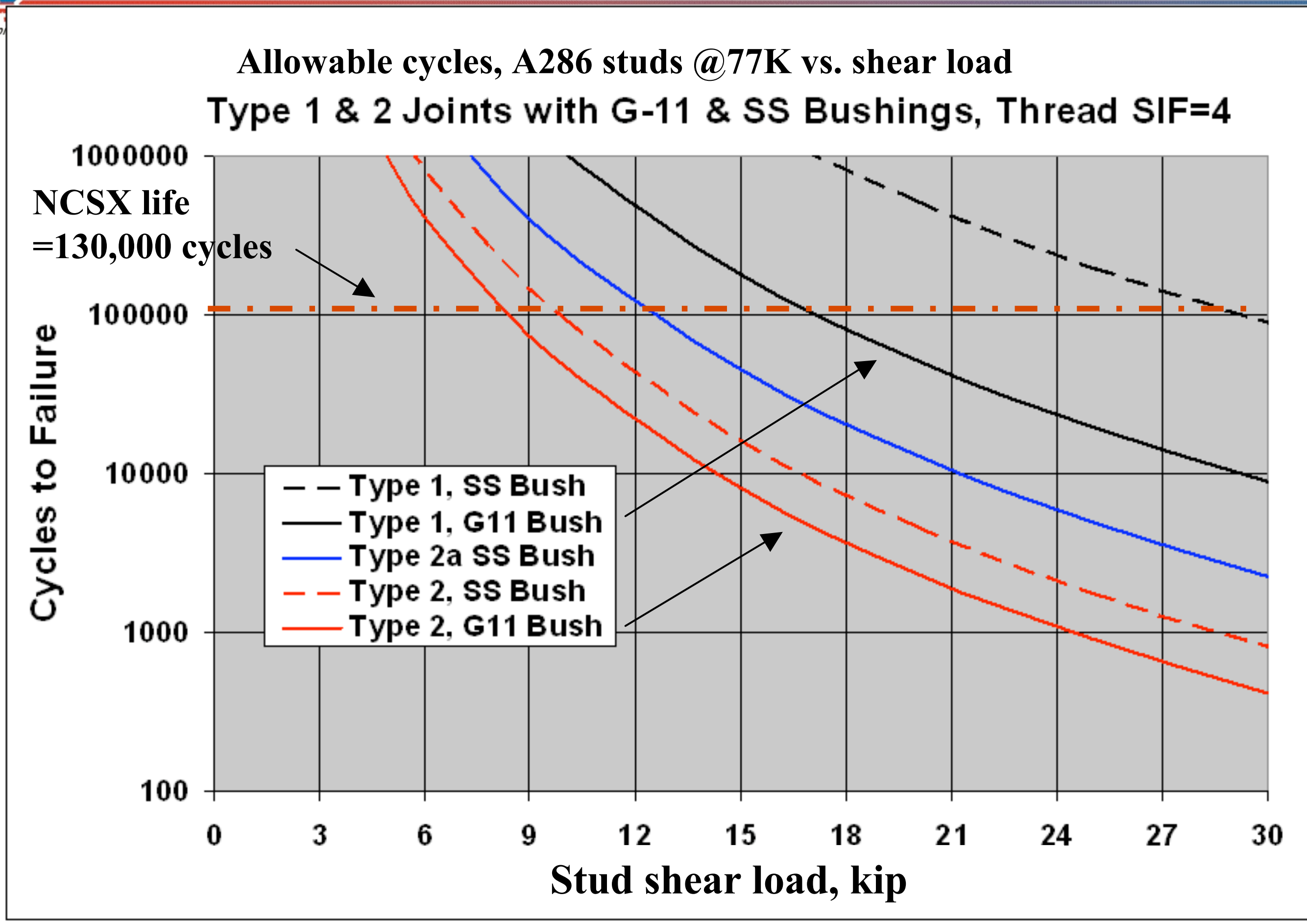
Friction = 0.3 over the entire flange





The Joint is stuck under every outboard stud.

Fatigue curves for outboard studs



Maximum fatigue loading of type 2 (tapped) ~ 8 kips

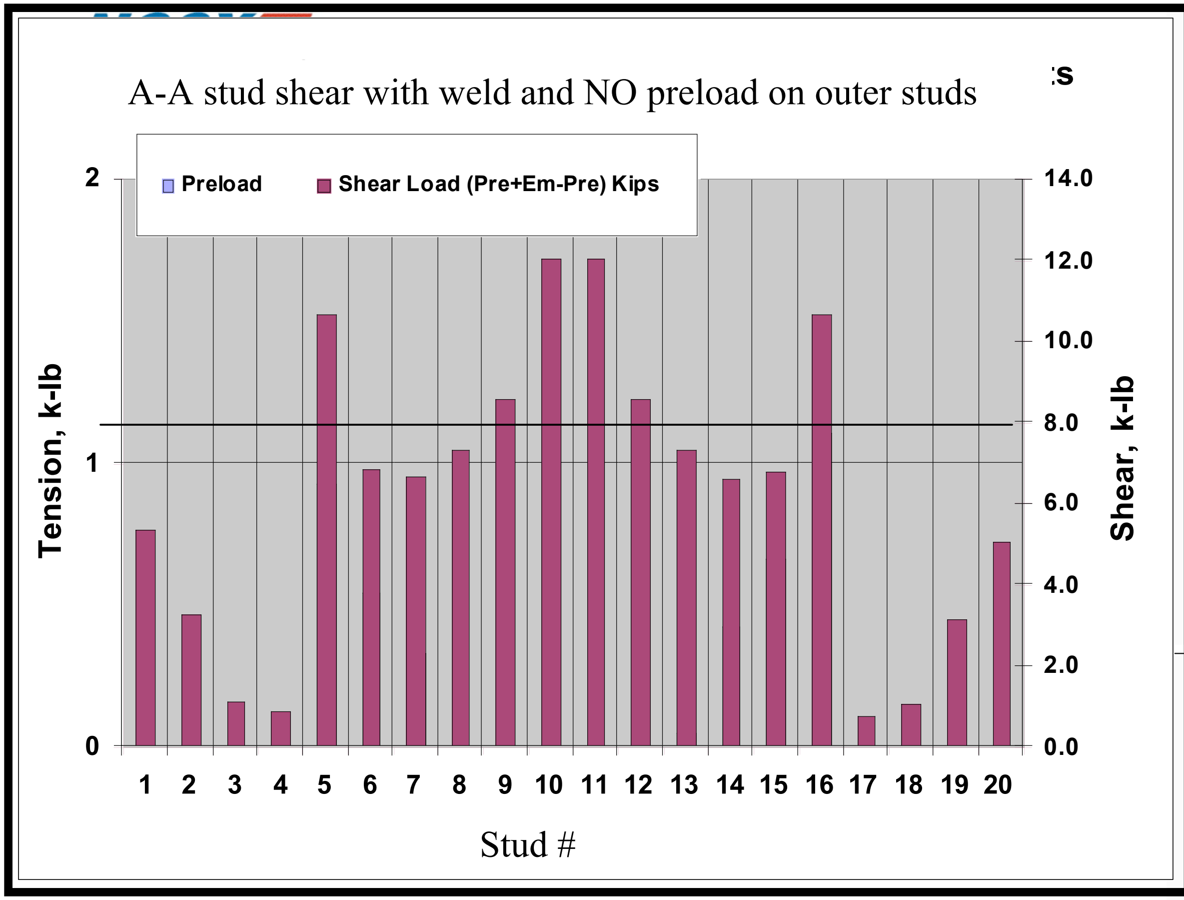
Maximum fatigue loading of type 1 (thru studs) ~ 16 kips

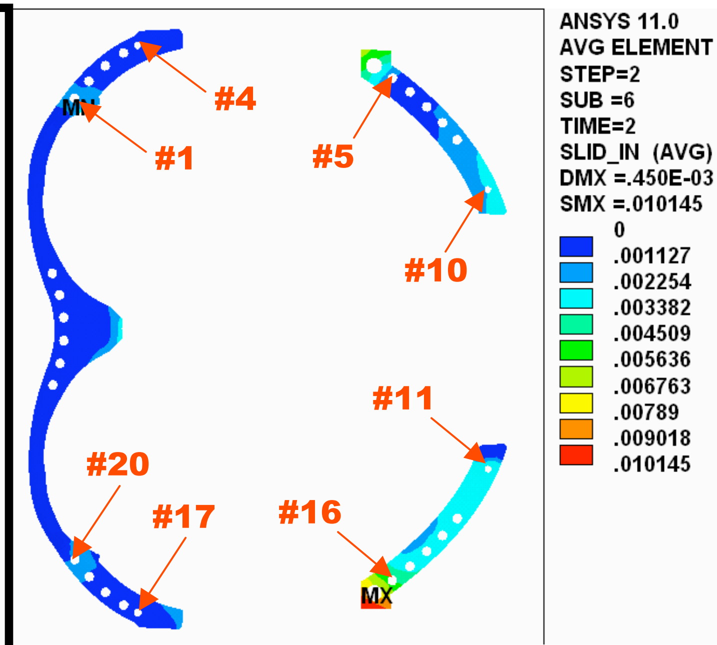
If ALL stud preloads were lost, NCSX would still operate in but a fatigue-limited mode

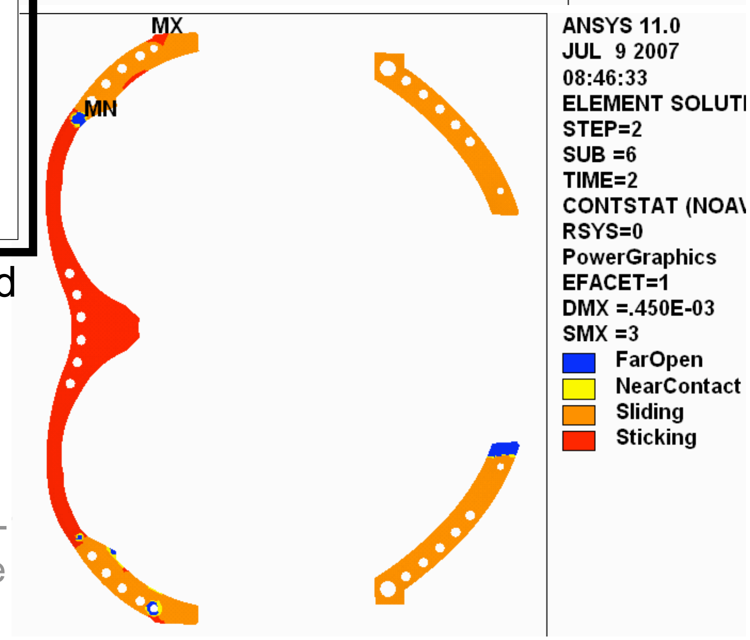
- **What If Preload is lost on outer leg now that we are welding the inner leg?**
- **Which bolts should we be monitoring during operation? Are some more critical than others?**
- **The Next slides show the effect of bonding the inner leg (weld) and removing the preload on the outer bolts.**

Interface Joint	Largest Shear Load (k-lb)	Number of Bolts Exceeding Fatigue Limit of 8 Kips	Max Slip (inches)
A-A	12	4	0.01
A-B	14	3	0.007
B-C	12	2	0.008
C-C	8	0	0.004

A-A outboard stud slip plot – no preload



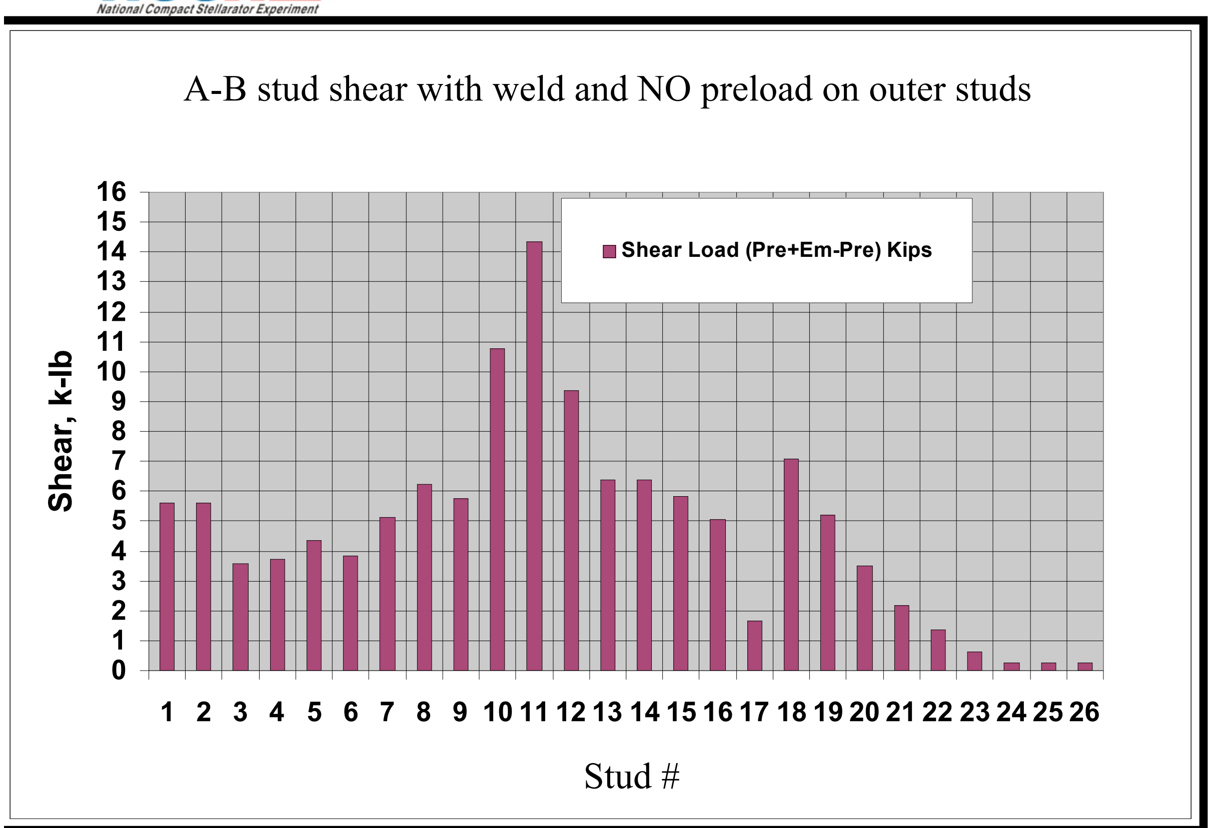


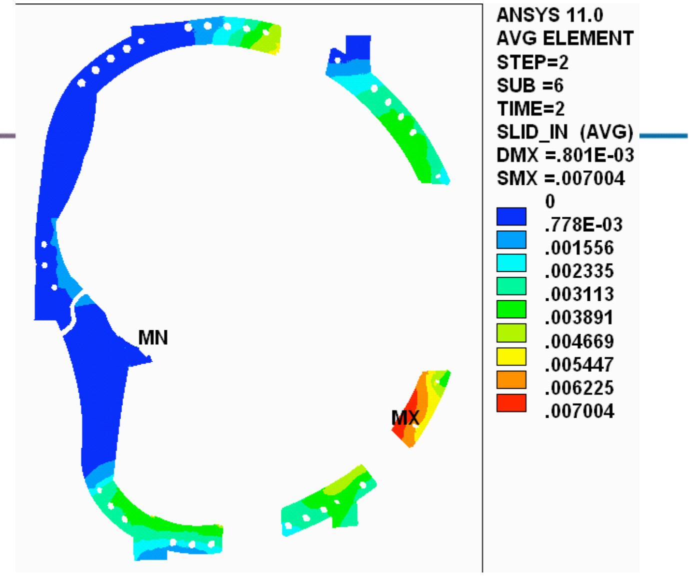


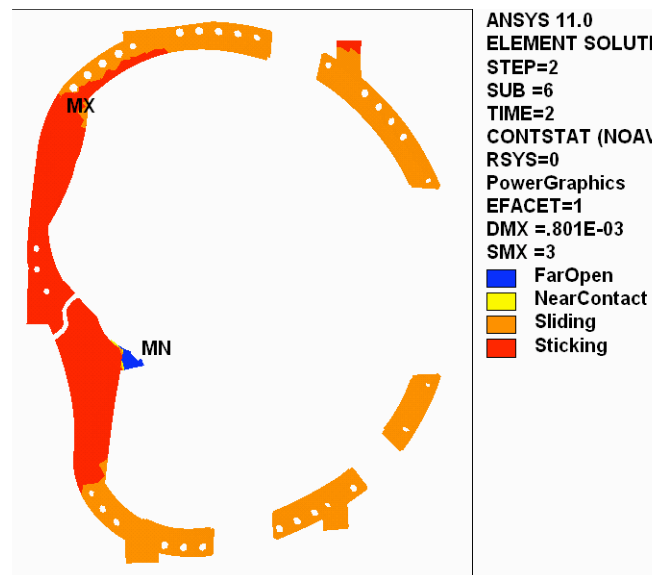
Studs 5,9,10,11,12, & 16 have shear greater than 8 kips and are likely candidates for monitoring during operation.

Preload is not really important in these plots and is only shown as a references aid.

A-B outboard stud slip plot- no preload

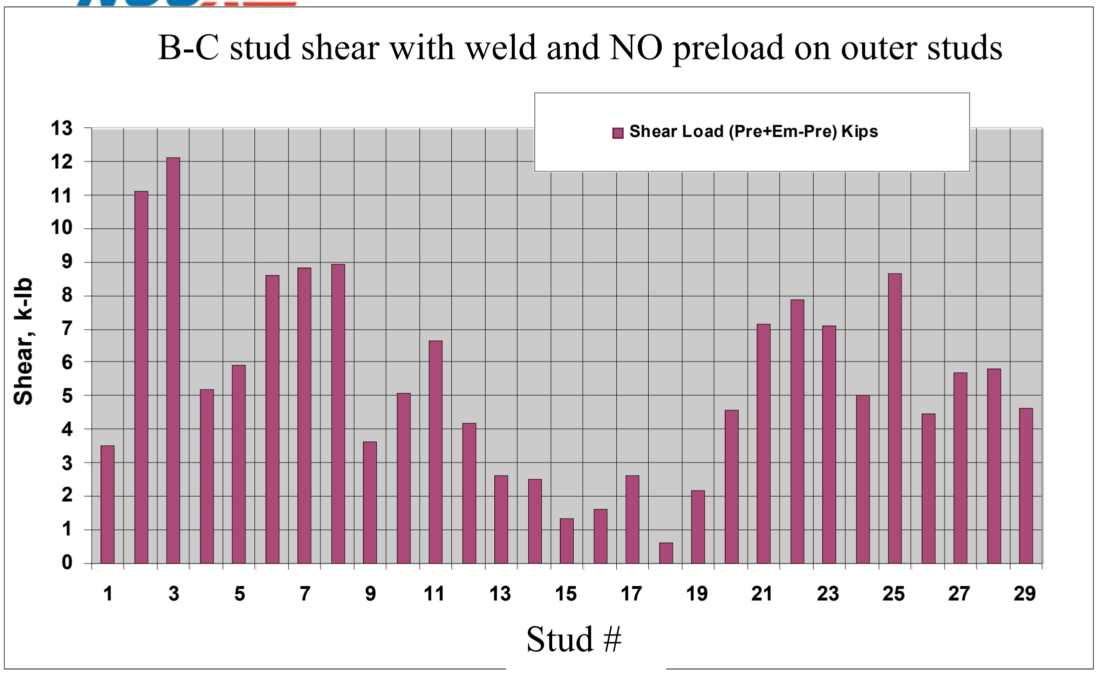


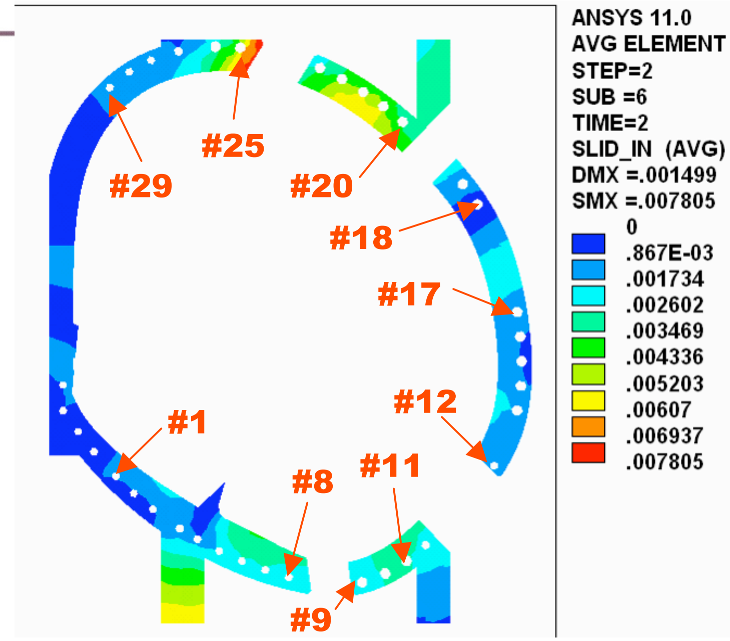


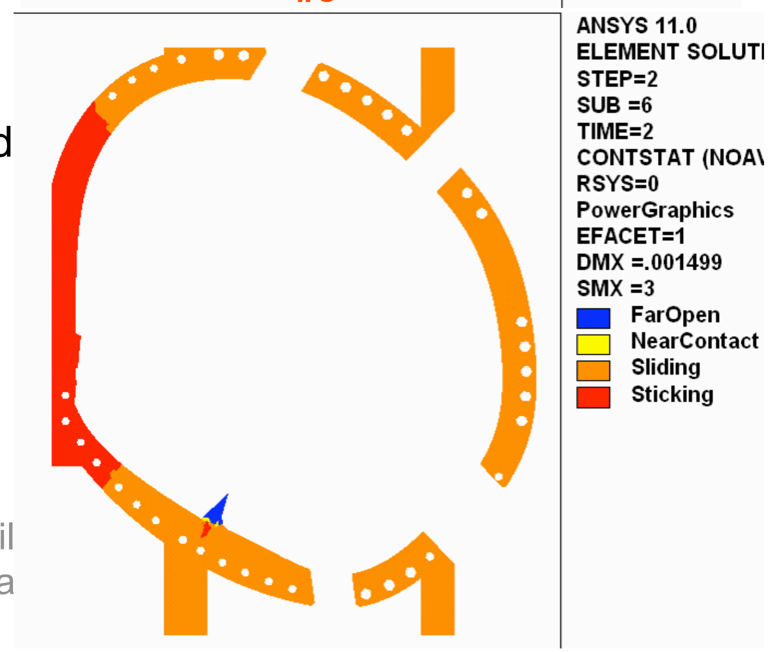


Studs 10-12 have shear greater than 8 kips and are likely candidates for monitoring during operation.

B-C outboard stud slip plot – no preload





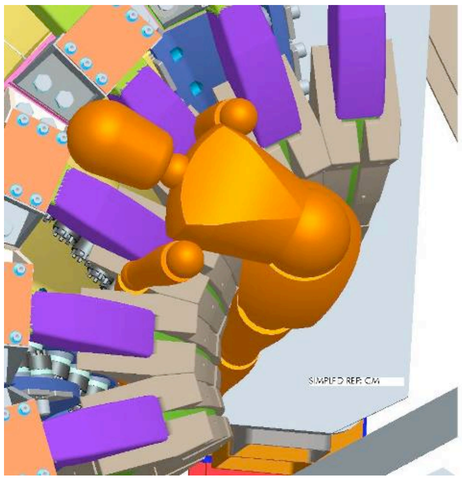


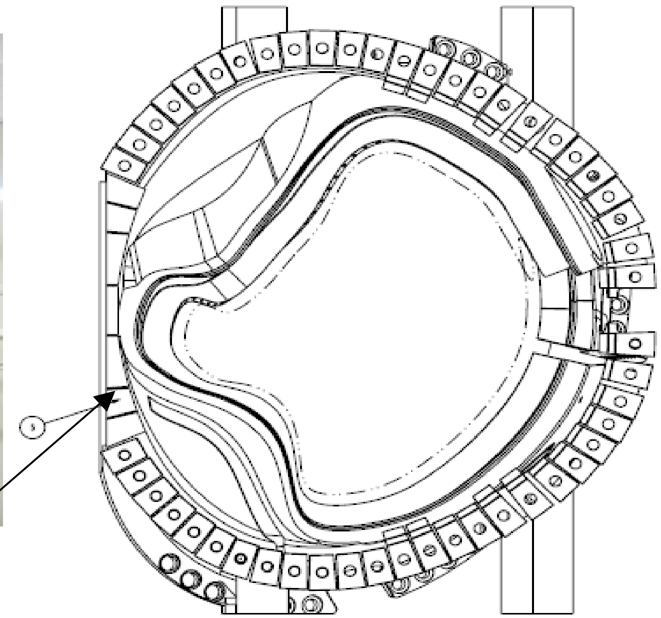
Studs 2,3,6,7,8, and 25 have shear greater than 8 kips and are likely candidates for monitoring.

Although stud 1 shows low shear, it should also be looked at since it is immediately adjacent to the weld.

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

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.

•Periodically re-checking the stud tension.

•Under study - Verifying stud tension with a ultrasonic bolt tension measuring device.

  - Short bolt length & configuration are issues affecting accuracy.