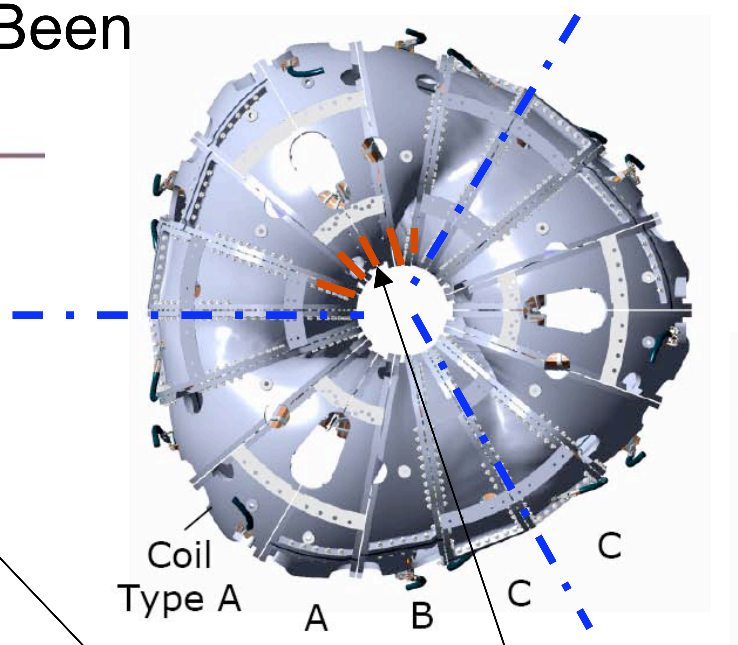
Design and Development of the NCSX Modular Coil Interfaces

Presented by Phil Heitzenroeder

For the NCSX Team

August, 2007

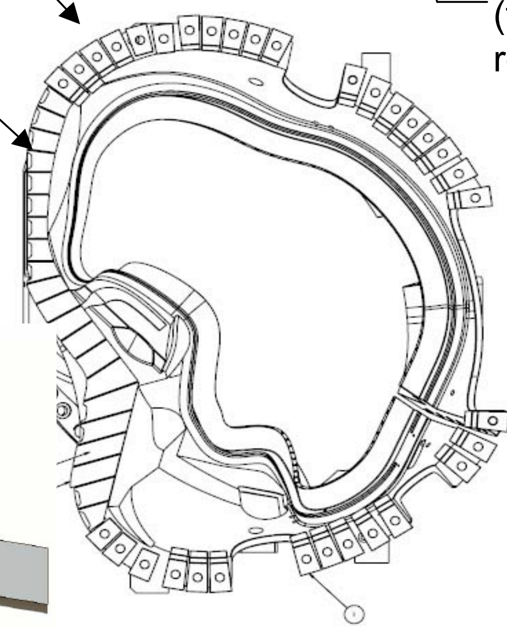
Robust Coil-Coil Interfaces Have Been Developed

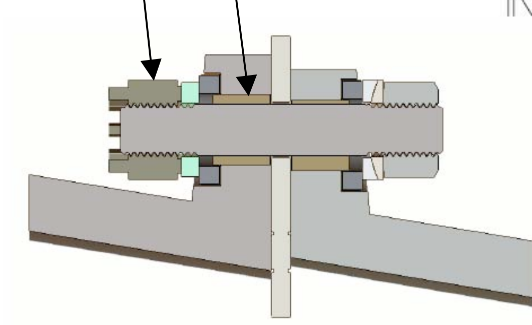


5 welds/period (typ.) in central region.

- 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.

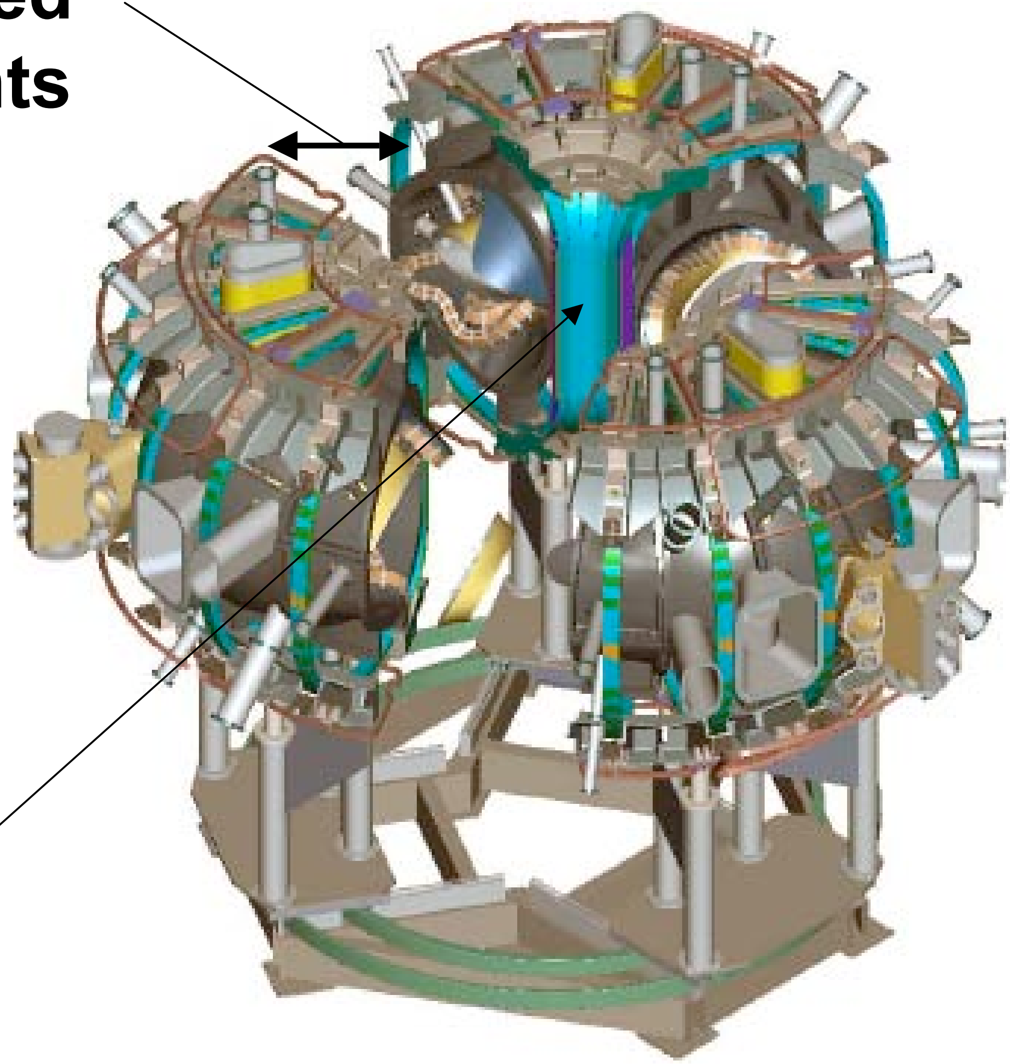
It won’t move now!





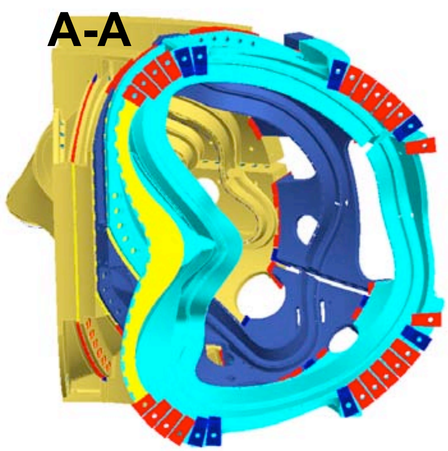
The C-C bolted interfaces are compatible with assembly plans

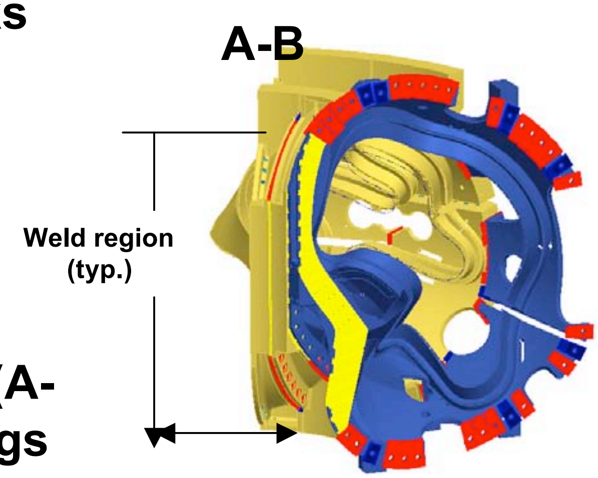
C-C bolted field joints



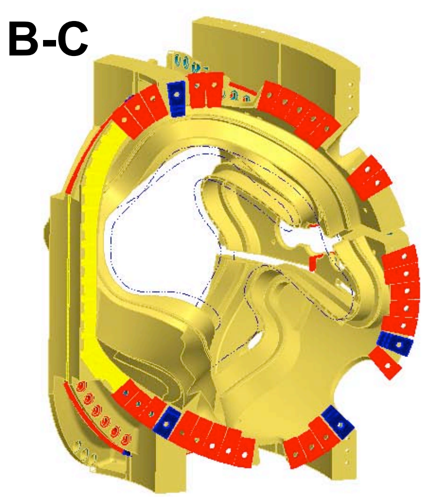
In-period weld regions are readily accessed prior to assembly.

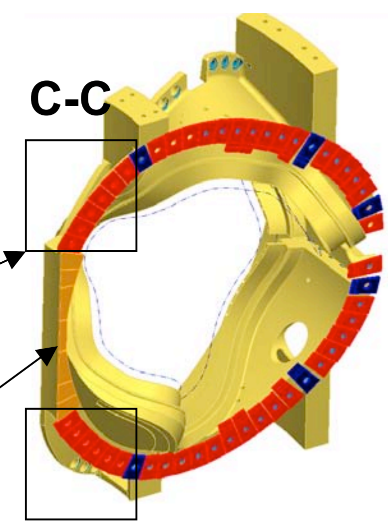
Interface details for the new configuration





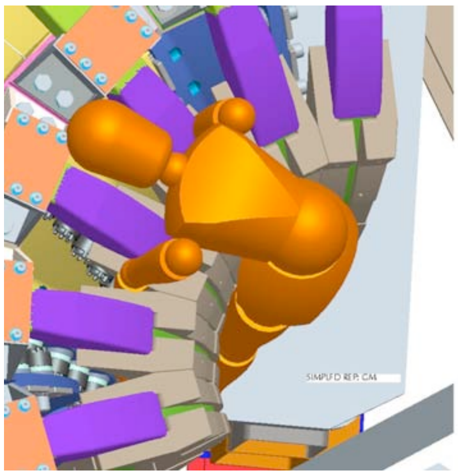
- Partial toroidal electrical breaks between coils in a field period (A-A; A-B; B-C).
- Full toroidal electrical break between field periods (C-C)
- Welded mid-period interfaces (A-A; A-B; B-C) along the inner legs (YELLOW SHIMS)
- Friction shims in the outboard regions (RED & BLUE SHIMS)
- Bolted / insulated interface between the field periods (C-C).
  - (6) bolts & friction shims added T&B
  - Compression shims in mid region to react centering force.

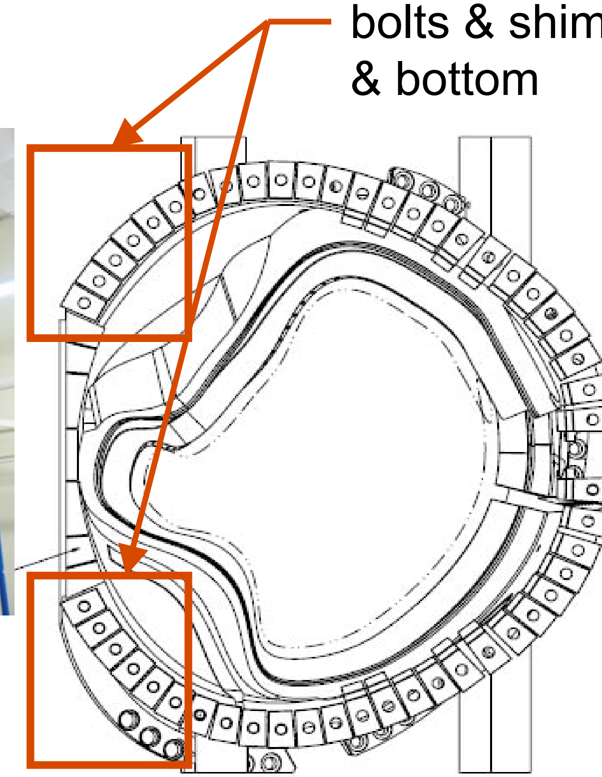




C-C interface access & mock-up studies

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





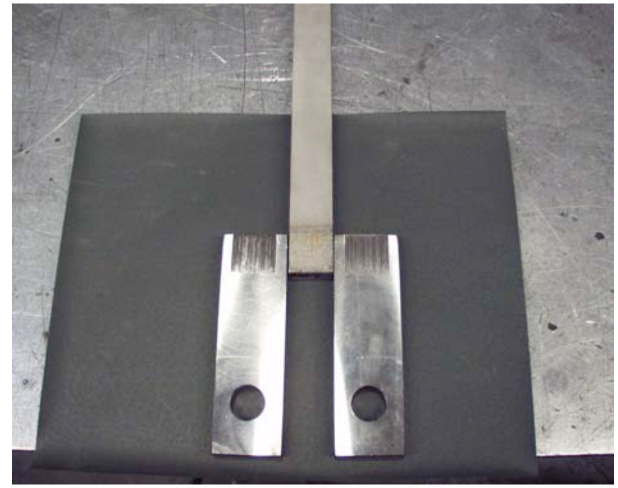
- ***If all 6 bolts are added, IL deflection is reduced from 0.5 mm to 0.1 mm.***
  - ***Will require tooling to reach all, but it can be done.***
- ***Fewer bolts still provide an acceptable solution, but with more IL deflection.***

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

NCSX National Compact Stellarator Experiment

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

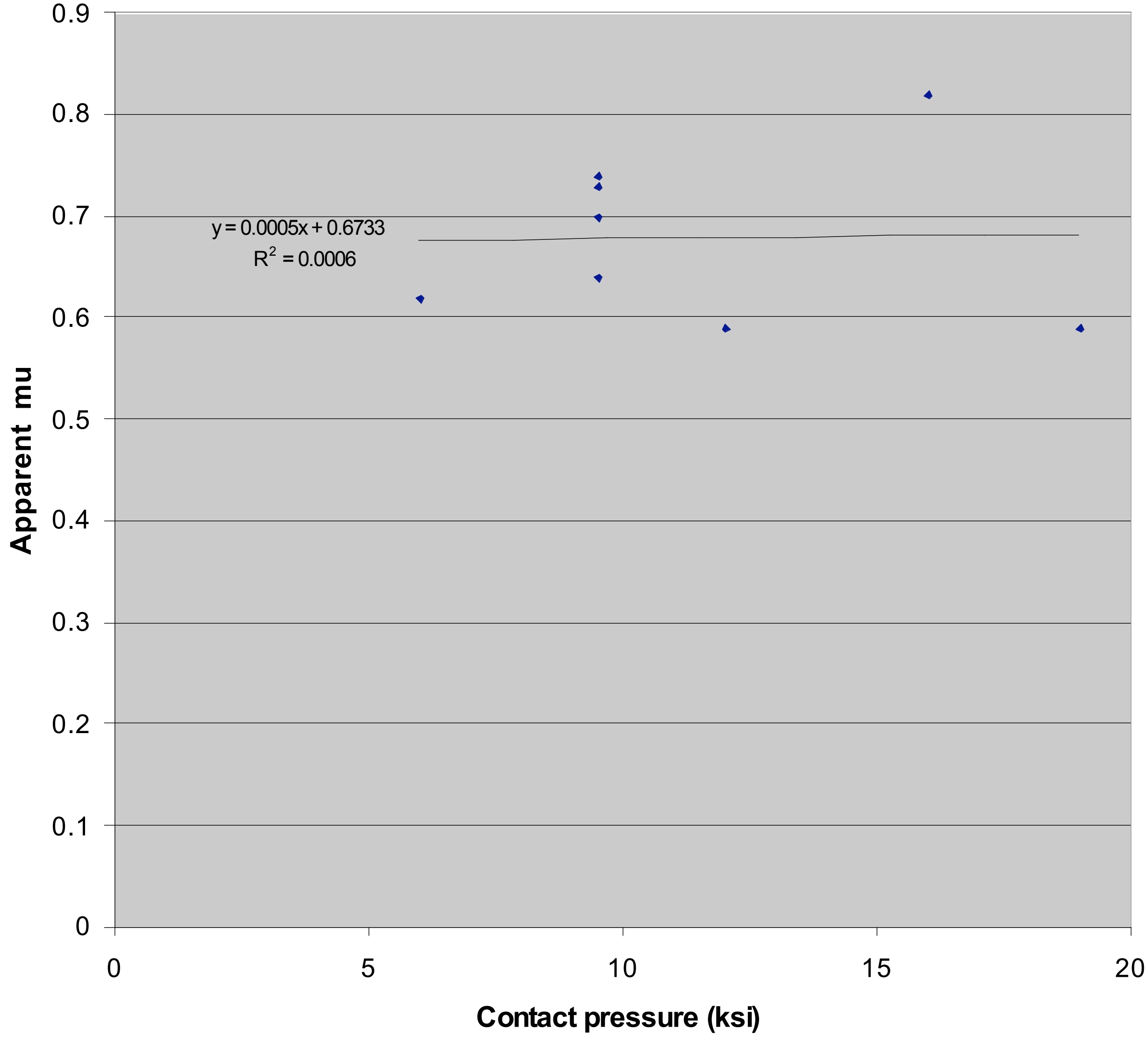
The test setup is cooled to 80 K for testing.



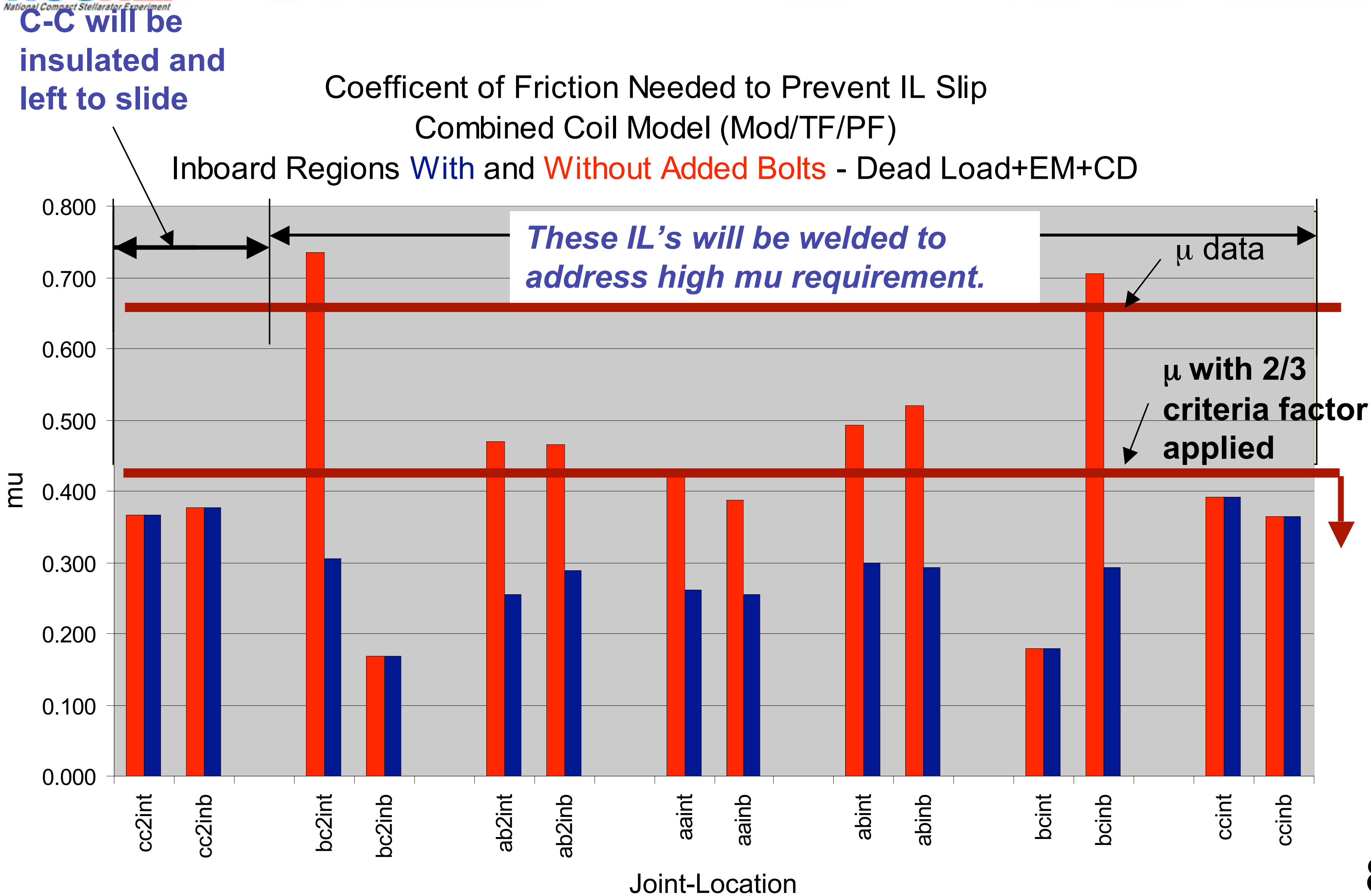
Test specimen – two alumina coated SS sideplates sandwich SS center bar.

- The coefficient of friction, μ, required is 0.4 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) .

Alumina Coated SS Shim Friction Characteristics

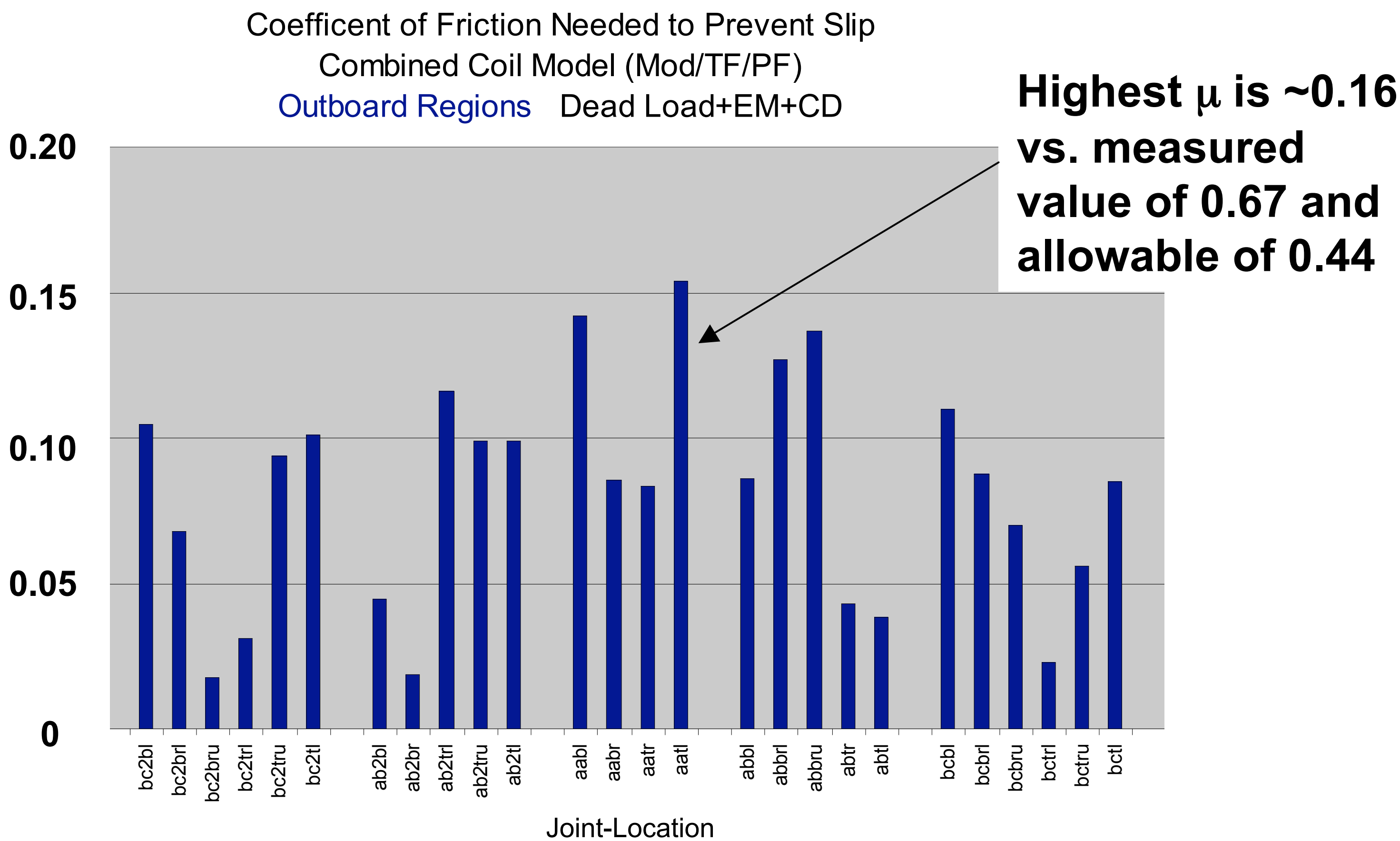


Welding provides a very robust solution to regions needing a higher coefficient of friction



With welding, there is a very comfortable margin on μ

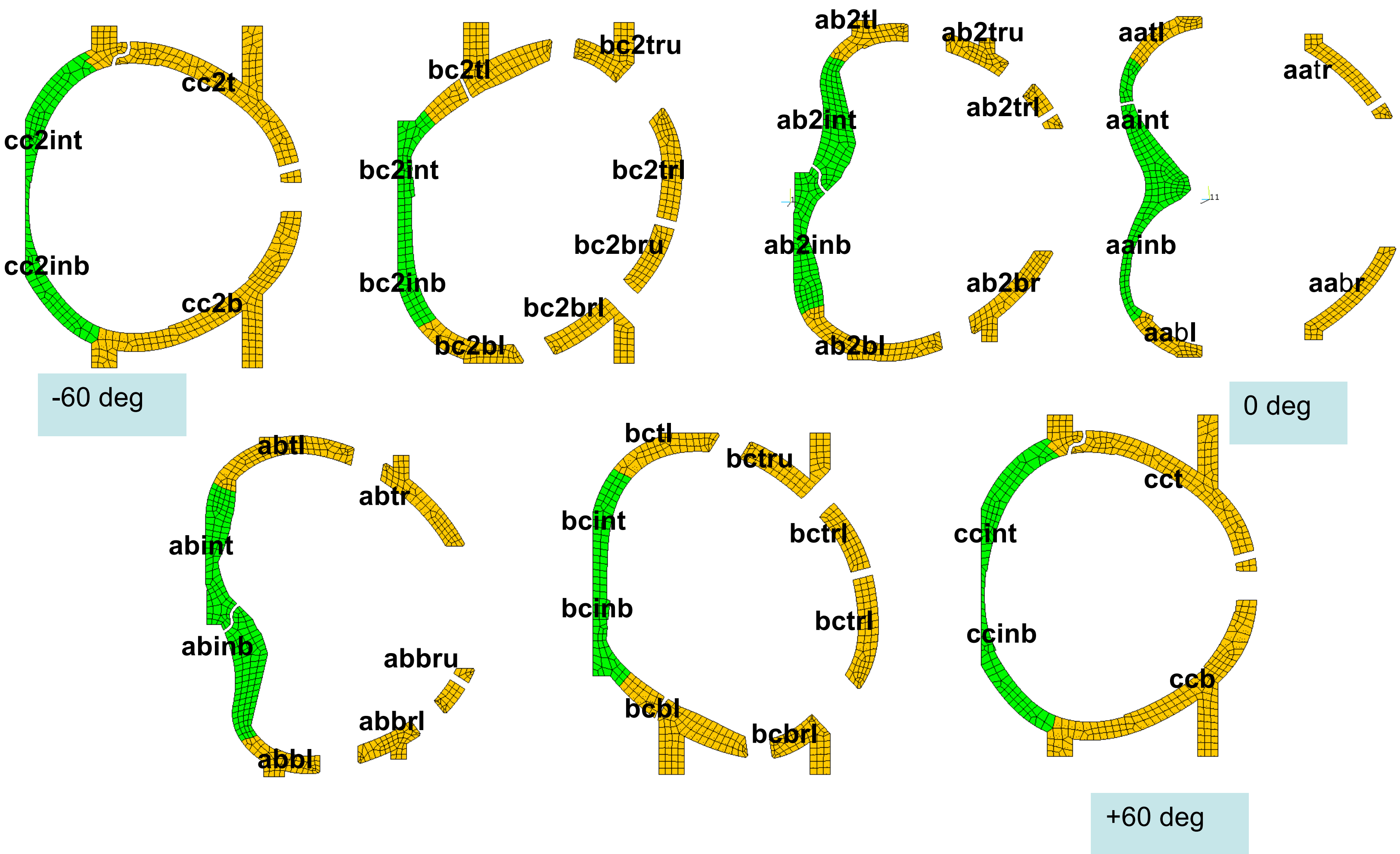
NCSX National Compact Stellarator Experiment



The required coefficient of friction meets our criteria in all areas and has a comfortable factor of safety of 2.75 (based on allowable of 2/3 μ) in the welded coils.

Bolt tension will be measured by UT to assure good friction lock-up

Definition of shim segments



NCSX Modular Coil Weld Development

NCSX National Compact Stellarator Experiment

3 phase program:

- **Phase I: On-site Assessment** of NCSX's plans by Edison Welding Institute.
- **Phase II: Mock-up welding tests** of a Type A-B winding form flange. Primary goal: to determine likely **weld quality & likely flaw size distribution** in welds (for fatigue life assessment & to determine if NDT is required).
- **Phase III: A6/B6 casting to casting weld tests**. Primary goal: to demonstrate **distortion control** and to refine assembly and weld procedure.

Completed June 15

Welding completed July 23; evaluation of results pending.

Underway Now

Phase I

Phase I weld test specimen

Examples from EWI's report

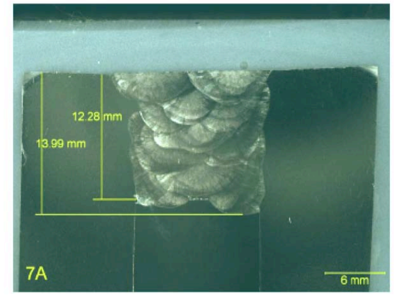


Figure C1. Macrograph of Weld in Sample 7A (Note lack of fusion in center of shim.)

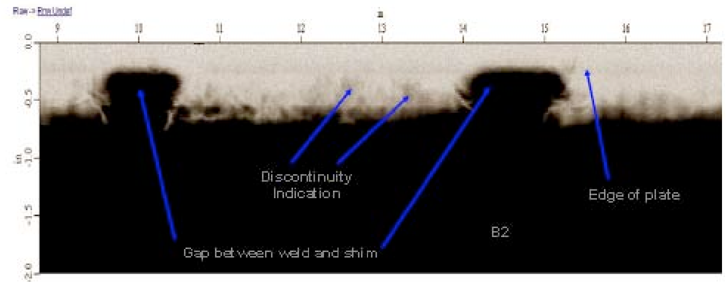


Figure A8. UT Scan of Area 2 from Side B

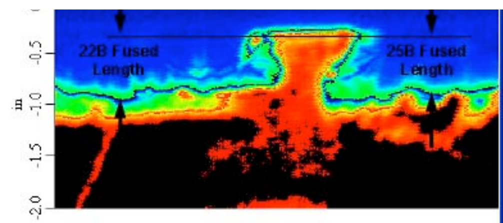
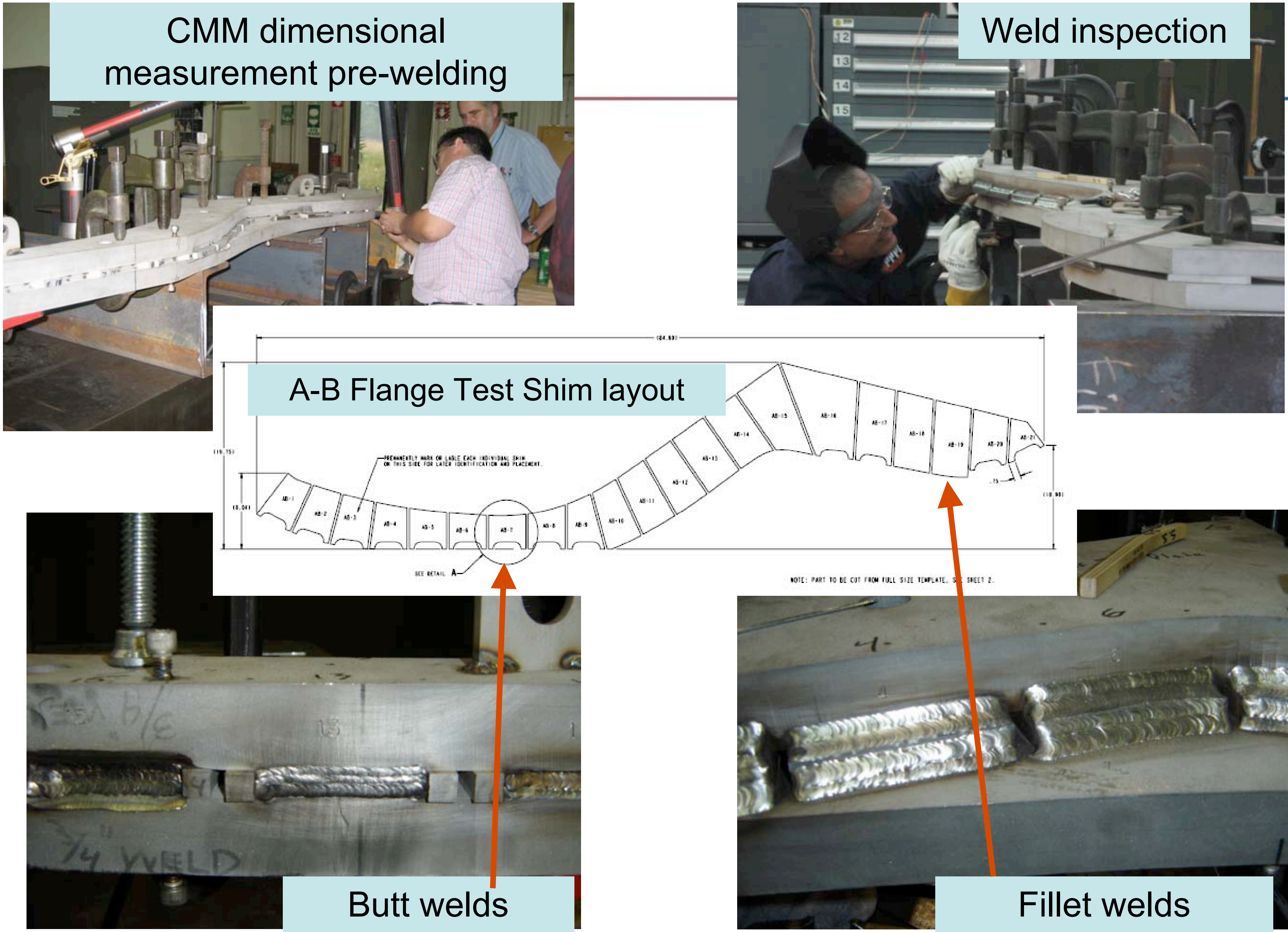


Figure D2. Penetration Depth Measurements by UT on Samples 22A and 25A (Upper: A side – Lower: B side.)

From EWI's Visit Report:

"Conclusions and Recommendations: The information provided in this meeting indicates that it is appropriate to go forward with welding plans for the inboard sides of the modular coil supports using intermittent welds.

EWI supports the plan for two types of welding trials, one on plate and one on full castings. "



Phase II weld tests

Weld tests show good control of magnetic permeability

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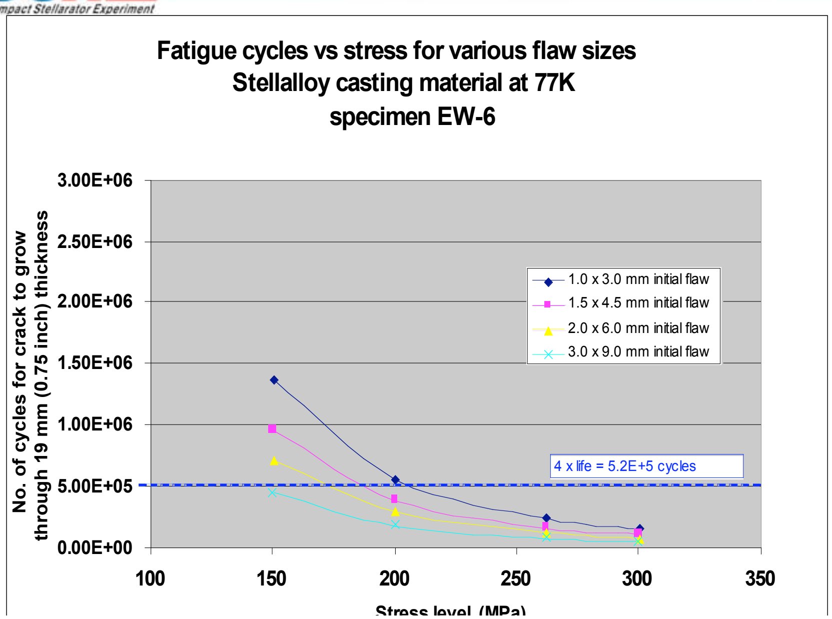
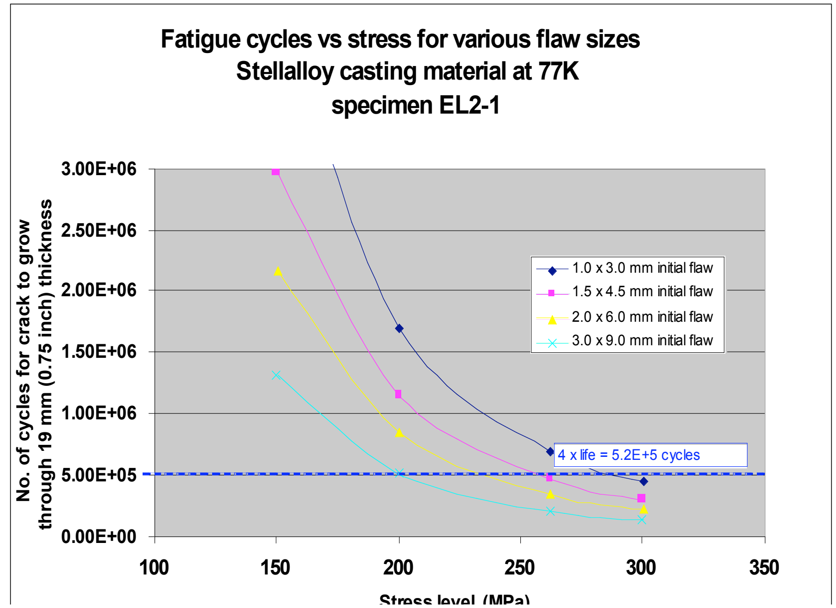
- Shims are made from 316 SS
  - solution annealed at 1150 C followed by rapid air cool to reduce magnetic permeability after all machining and grinding is completed.
- Specified μ_r is 1.02; localized areas slightly higher can be accepted.
- Results from the weld tests are excellent:
  - 1.5" plate before & after welding: all below μ_r 1.02.
  - 1/2" shims before welding: average μ_r of >1.02 u but <1.03 with isolated readings of >1.03 but <1.04
  - 1/2" shims after welding:
    - shims 2 & 3 rose slightly from >1.02 but <1.03 μ_r to >1.03 but <1.04 ; shims
    - 11 & 20 rose slightly from isolated spots of >1.03 but <1.04 μ_r to isolated spots of >1.04 but <1.05 ; shim 18 rose from isolated spots of >1.03 but <1.04 to an isolated spot of >1.06 but <1.08. (acceptable – small volume)
  - Weld metal: all below 1.02 μ_r .

Weld fatigue is satisfactory



Fatigue data for welds in Stelalloy



Fatigue data for Stelalloy

- As can be seen in the curves above, crack growth is faster in the welds (but OK!).
- Calculations indicate that an initial flaw size of 5 mm can be tolerated for 4 x life (520 K cycles) at the highest average stress of 20 ksi (138 MPa).
- Flaws of this size can be avoided by using qualified welders and procedures.
    - Will be validated by NDT and macrophotographs of welds from the flange mock-up weld tests.

Phase I and II weld test results

Resolved to date:

- ✓ Weld shim designs verified.
- ✓ Butt weld and fillet weld details verified.
- ✓ Permeability control demonstrated.
- ✓ Weld fatigue acceptability verified.
- ✓ Weld procedures developed.
- ✓ Welders qualified.
- ✓ Low weld-induced distortion observed so far has been encouraging.

The most significant weld issue yet remaining - a demonstration of acceptably low weld-induced distortion in the castings – is the focus of the Phase III weld studies currently underway.

Now underway: A6-B6 Weld Tests

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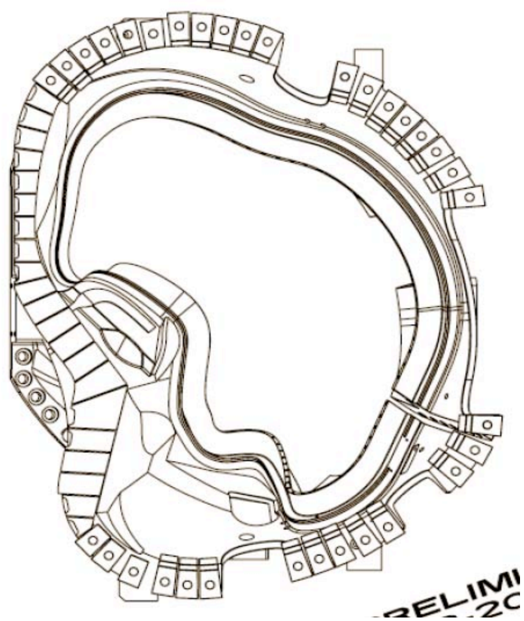
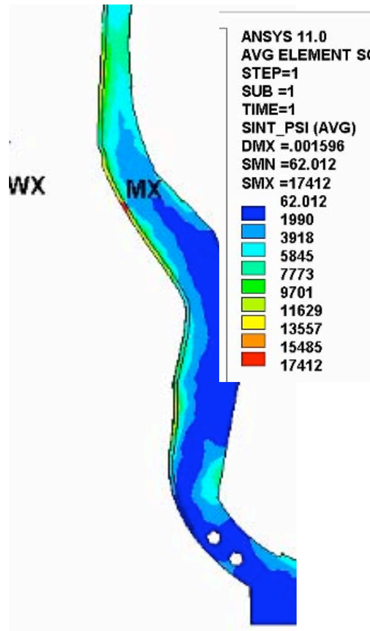
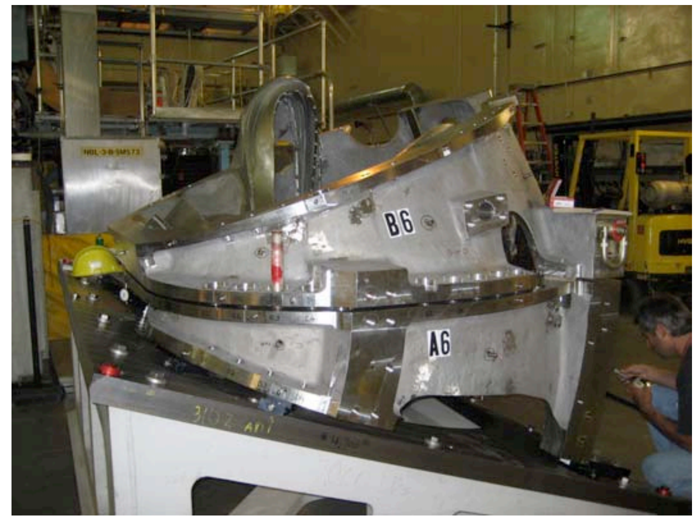




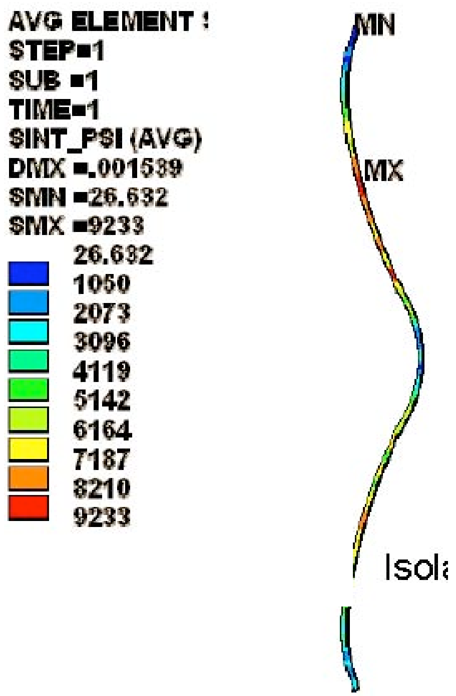


Shim Layout –welded shims along inboard edge can be identified by absence of bolt holes.

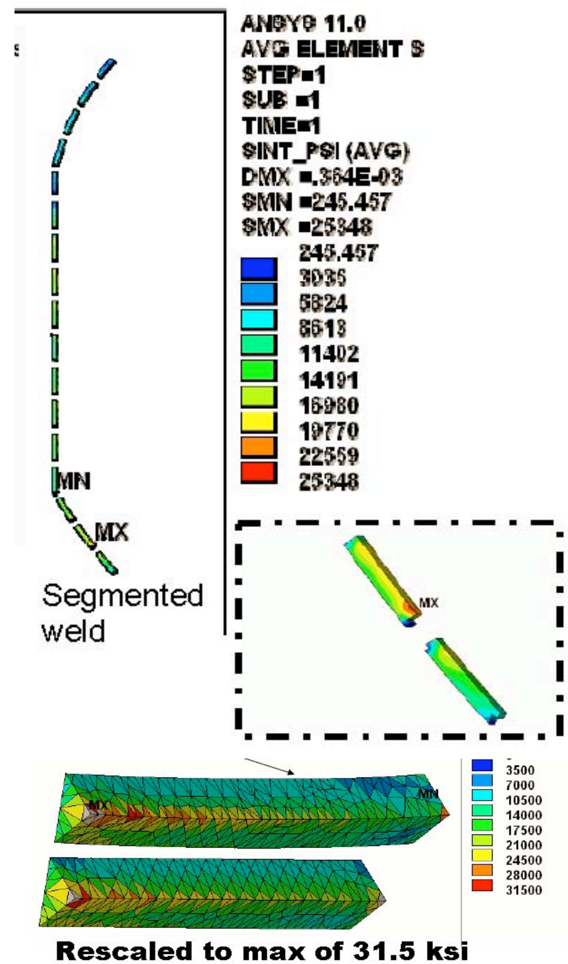
Average stress in the most highly stressed region of A6/B6 is ~16.7 ksi; s_m allowable is 31.5 ksi.

A6 & B6 being aligned for weld test

A-A and A-B Weld Stresses Are Also Acceptable



A-A has the lowest average stress: ~9.2 ksi



B-C welds have the highest stress – av. ~20 ksi, local peak stress ~31.5 ksi

Welding Process

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Deflection Monitoring

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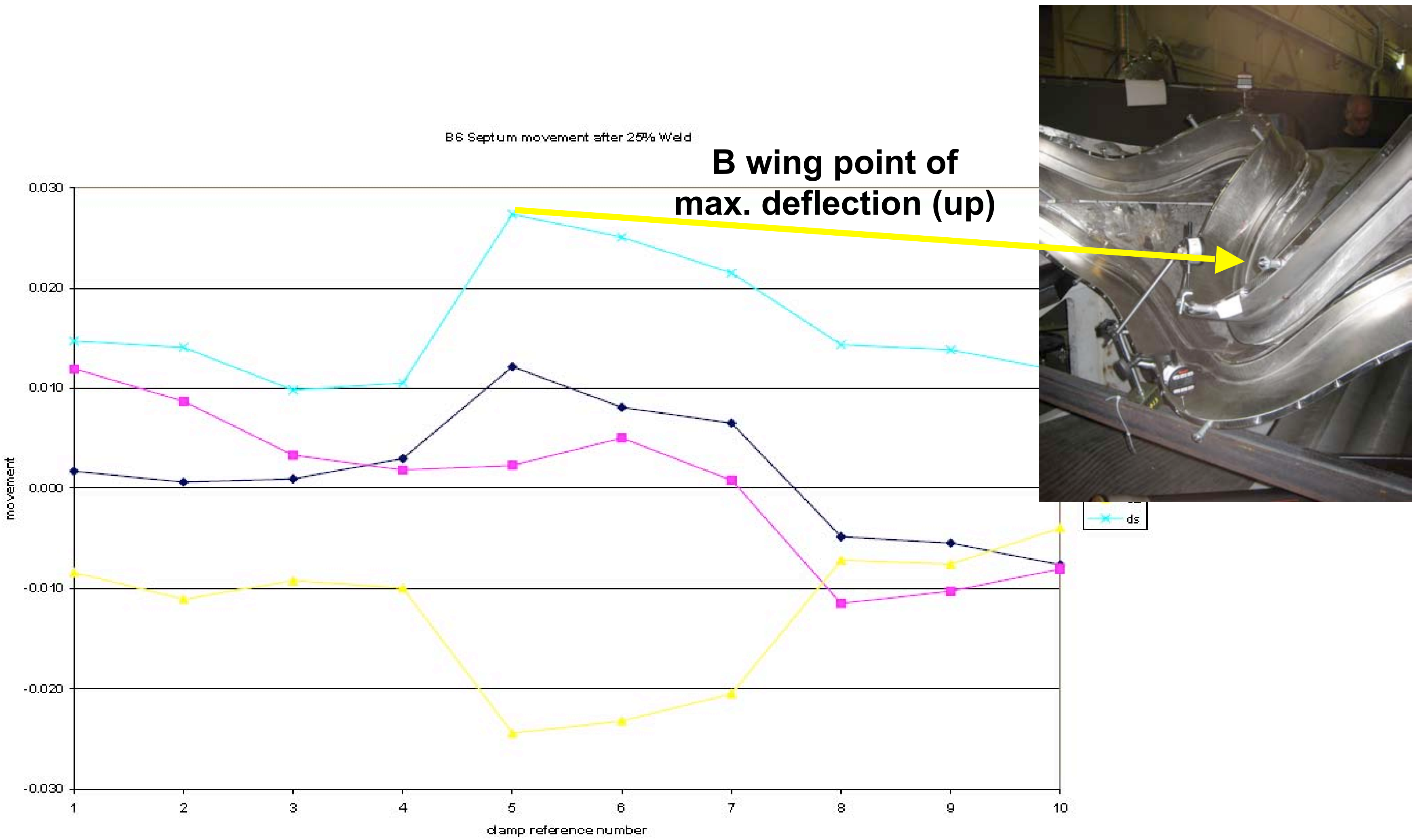

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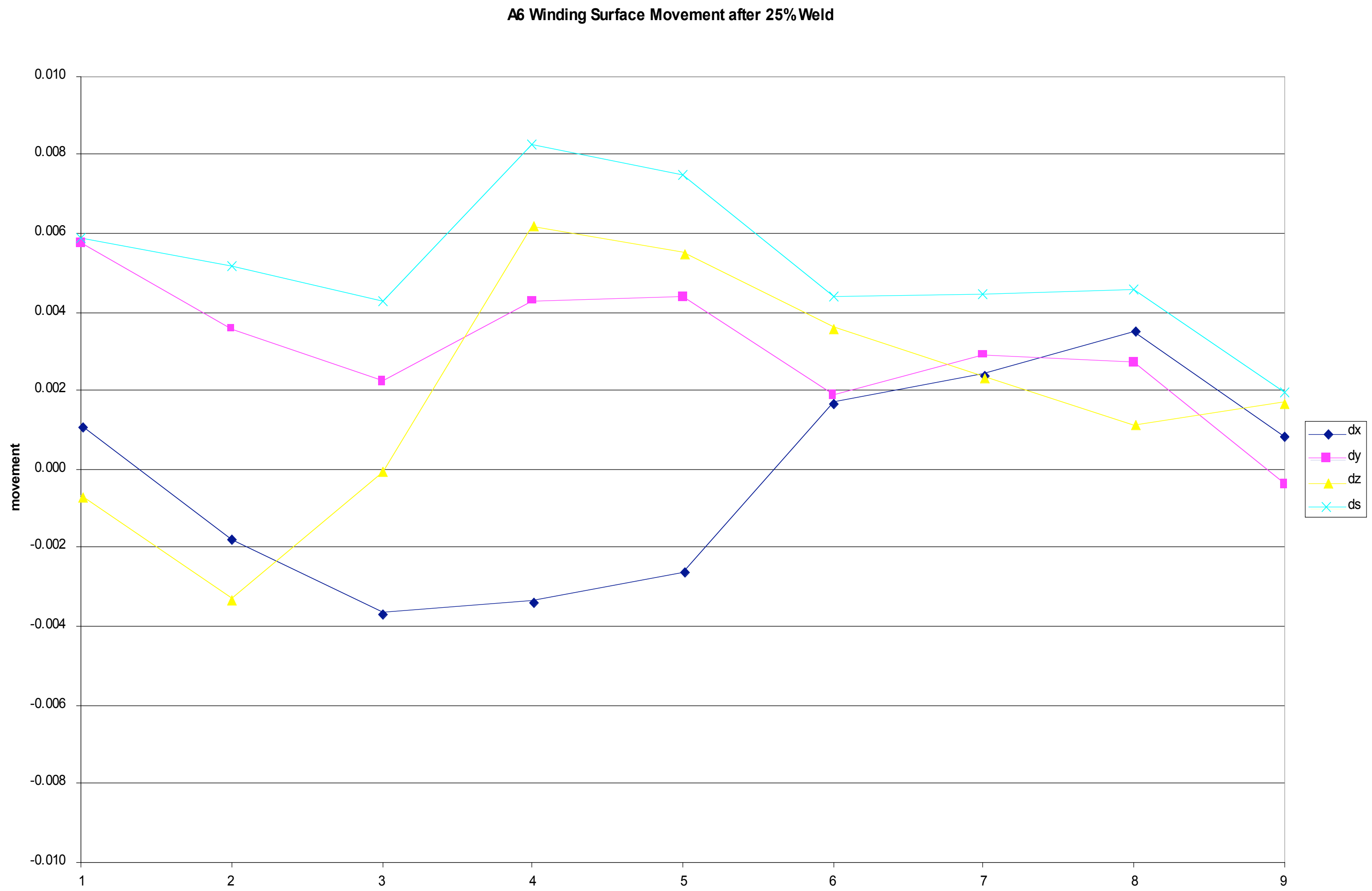
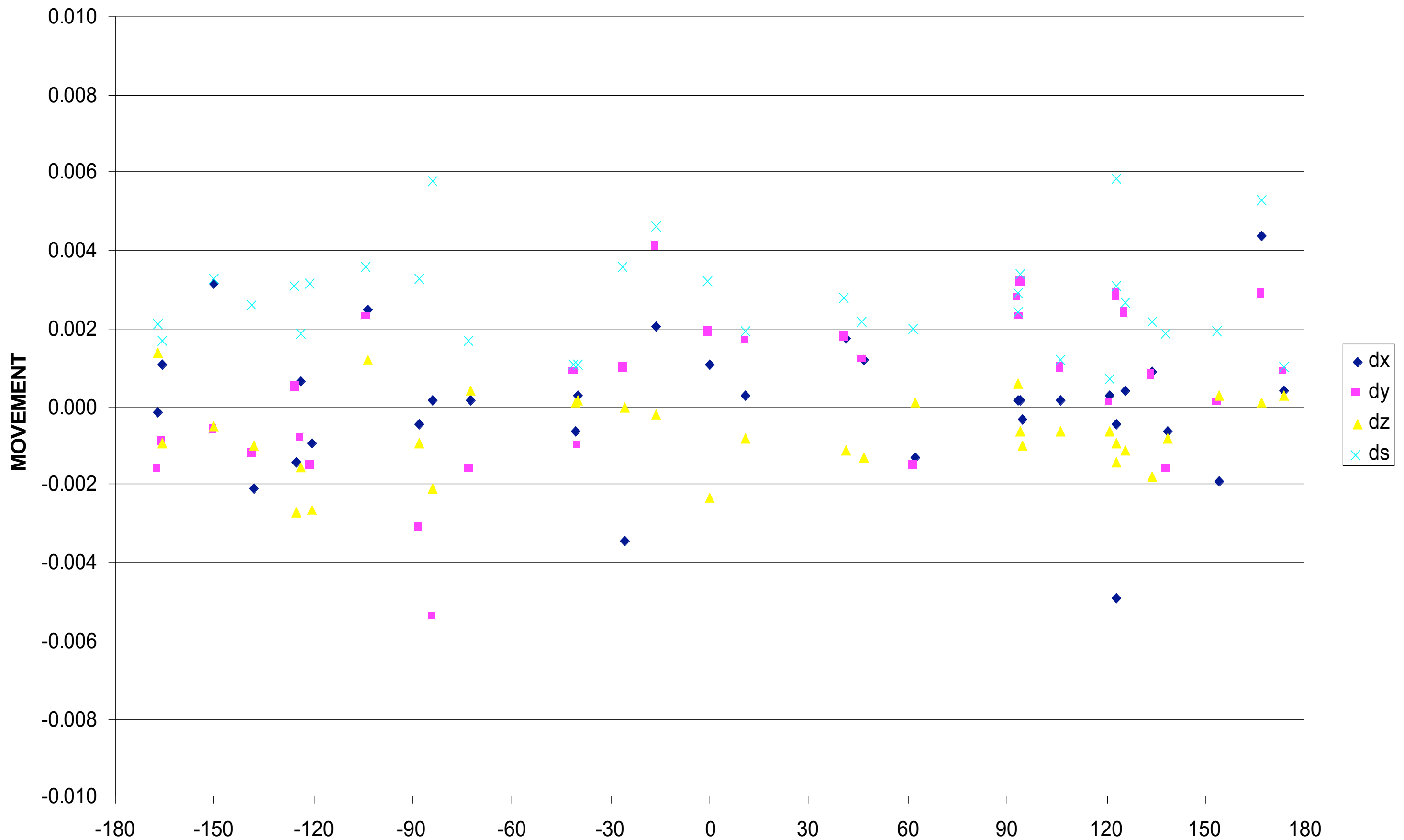


NCSX National Compact Stellarator Experiment

A6 CASTING FIDUCIALS MOVEMENT PRE POST TORQUE



PPPL	PRINCETON PLASMA PHYSICS LABORATORY	CASTING TO CASTING WELD TEST	NCSX Page 8 of 8

Appendix B
Gaps Between Shims and Casting

Location	Before Bolt Torquing		After Bolt Torquing		Measure 1		Measure 2		Measure 3		Measure 4	
	Gap between shim and casting (mils)											
	Outboard	Inboard	Outboard	Inboard	Outboard	Inboard	Outboard	Inboard	Outboard	Inboard	Outboard	Inboard
Date/Time	8/10/07	8/10/07	8/10/07	8/10/07	8/12/07 6:20			8-13-07 7:45				
13	.514	T -.003 B -.00	.514	T .003 B .001	.497	T .003 B .00	N/A	T .003 B .00				
14	.515	.514	.515	.514	.501	.513	N/A	.513				
15	.515	.514	.514	.514	.496	.513	N/A	.513				
16	.514	T .003 B .00	.514	T .004 B .00	.496	T .000 B .000	N/A	T .00 B .001				
17	.514	T .003 B .00	.513	T .003 B .00	.497	T .000 B .000	N/A	T .00 B .001				
18	.513	T .005 B .00	.512	T .003 B .00	.499	T .000 B .000	N/A	T .001 B .001				
19	.513	T .004 B .00	.511	T .004 B .00	.499	T .002 B .00	N/A	T .002 B .001				
20	.512	T .004 B .001	.509	T .002 B .00	.500	T .002 B .00	N/A	T .001 B .000				
21	.511	T .002 B .00	.508	T .00 B .00	.498	T .00 B .00	N/A	T .000 B .000				

Comments

Casting to Casting Weld Test Dial Indicator Readings & Weld Sequence Pattern - 8/11 & 8/13/07

		Dial Indicator No.s (in.) (-x.xxxx = part moved up, +x.xxxx = part moved down)						
Weld Pass No.	Shim No. to Casting No.	1	2	3	4	5	.6/7	8
1	10 to B6	-0.0060	0.0000	-0.0010	0.0000	-0.0005	0.0010	0.0010
2	10 to A6	-0.0050	0.0000	0.0000	-0.0010	-0.0020	0.0010	0.0010
3	9 to A6	-0.0050	0.0000	-0.0005	-0.0010	-0.0030	0.0000	0.0010
4	9 to B6	-0.0050	0.0000	-0.0010	-0.0015	-0.0040	0.0000	0.0010
5	11 to B6	-0.0060	0.0000	-0.0005	-0.0015	-0.0045	0.0010	0.0010
6	11 to A6	-0.0040	0.0000	-0.0005	-0.0010	-0.0035	0.0015	0.0010
7	8 to B6	0.0000	0.0000	-0.0020	-0.0025	-0.0045	-0.0020	0.0005
8	8 to A6	0.0010	-0.0015	-0.0040	-0.0030	-0.0070	-0.0020	0.0005
9	12 to B6	-0.0010	-0.0015	-0.0030	-0.0020	-0.0045	-0.0010	0.0005
10	12 to A6	-0.0010	0.0020	-0.0025	-0.0025	-0.0050		0.0005
11	7 to B6	0.0015	0.0030	-0.0040	-0.0020	-0.0070	-0.0020	0.0000
12	7 to A6	0.0005	-0.0030	-0.0030	-0.0020	-0.0040	-0.0030	0.0000
13	13 to B6							0.0000
14	13 to A6	-0.0005	-0.0030	-0.0030				0.0000
15	6 to B6	-0.0010	-0.0035	-0.0035	-0.0020	-0.0040	-0.0040	0.0000
16	6 to A6	0.0015	-0.0055	-0.0055	-0.0020	-0.0070	-0.0060	
17	14 to B6	-0.0050	-0.0070	-0.0040	-0.0020	-0.0050	-0.0050	0.0000
18	14 to A6	-0.0015	-0.0075	-0.0040	-0.0025	-0.0050	-0.0040	0.0000
19	5 to B6	-0.0010	-0.0080	-0.0045	-0.0015	-0.0050	-0.0050	0.0000
20	5 to A6	-0.0015	-0.0090	-0.0040	-0.0015	-0.0040	-0.0050	0.0000
21	15 to B6	-0.0025	-0.0090	-0.0035	-0.0015	-0.0040	-0.0040	0.0000
22	15 to A6	-0.0030	-0.0090	-0.0030	-0.0015	-0.0030	-0.0040	0.0000
23	4 to B6	-0.0040	-0.0090	-0.0030	-0.0015	-0.0030	-0.0040	0.0000
24	4 to A6	-0.0025	-0.0095	-0.0040				
25	16 to B6	-0.0035	-0.0095	-0.0040				

Assembly & metrology techniques are being refined

- Much has been learned about metrology and assembly techniques during the preparations for the A6/B6 coil weld tests. Examples:
  - A reliable metrology methodology has been developed – measurement results duplicate factory CMM measurements.
  - Casting handling and locating techniques have been simplified.
  - Shim installation techniques have been developed compatible with the fit-up requirements of the friction shims.
  - Bolt tensioning by “Supernuts” have been adopted. They are both easier to torque than standard nuts and address access issues.
    - Tension will be accurately measured by ultrasonic bolt tension measuring device.
  - Bushing design and installation techniques are being optimized.
    - Comparing baseline design to double eccentric design.
    - Investigating in-field machining workstation to reduce time.
    - Custom fitting in advance reduces this critical path activity by 70%.

More details will be presented by Mike Viola

Bushings

- Tight fitting insulating bushings are installed around studs after the coils are aligned.
- Each bushing needs to be custom fitted to accommodate stud positions and flange hole dimensions.
- These insure against casting movement as the nuts are tightened and also could provide resist movement if preload is lost due to cool-down lags, nuts loosening, etc.
- This photo shows the stock G-11 fiberglass bushing and a prototype aluminum double eccentric mock-up being evaluated to compare fit-up time. (if used, one of the bushing parts would be made of G-11 to insulate the stud).

Double eccentric bushing prototype

G-11 bushing

Activities are underway to address risks

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Risk	**Mitigation Activity**
Modular coil interface design needs to change significantly from baseline due to unforeseen technical reasons	A task force formed to address this issue developed the current interface configuration. This design is now well along in the design validation and review process. We will be able to retire this risk after the final design reviews are completed by January.
As a result of the development trials for weld distortion, the welding time increases significantly above the present allowance.	We are now in the third phase of a 3-phase weld R&D program; this risk will be retired at the successful conclusion of this.
Unacceptable distortion in a field period when welding modular coil shims.	Welding currently underway is focusing on distortion control. We believe the procedures now being developed will be adequate, but additional weld distortion techniques including those developed by W7X could also be employed if necessary. It should be noted that welds can be ground out and re-made, if necessary.

Conclusions

- **A robust interface configuration has been developed**.
  - Partial toroidal electrical breaks between mid-period coils and full toroidal breaks at end period coils.
  - High friction, electrically insulating shims in outboard regions of all coils.
  - Inboard legs of the mid-period coils joined by welding.
  - Additional bolts and midplane sliding shims provide the restraint needed between the end period C-C coils.
  - Bolts with tight-fitting bushings provide backup restraint.
    - Tensioned by "Supernuts" and measured by ultrasonic tension measuring instrument.
- **This design is well along the in the validation process.**
  - Now in the 3rd phase of a 3-phase weld verification program; expect to complete in the next month.
  - Alumina friction shim verification tests completed.
  - Coil-coil weld test being used to refine metrology methods and overall assembly techniques.
- **Design reviews are well underway.**
  - FDRs completed for outboard shims & bolt assemblies; PDRs completed for inboard welded interface and C-C interface.
  - FDR for the welded interface is scheduled for Sept. 4; FDR for the C-C is scheduled for Jan. 7, '08 after bolt installation tooling designs are complete.