NCSX
National Compact Stellarator Experiment

Design and Development of the NCSX Modular Coil Interfaces

NCSX Engineering Group

October, 2007

First, a few slides on drivers of fundamental engineering requirements

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- The relationship between field error limitations, fabrication inaccuracies (tolerances), and field error correction coils is defined in the General Requirements Document (GRD) NCSX-ASPEC-GRD-05:

[i.e. Trim Coils]

3.2.1.5.1 Field Error Requirements

a. Field error correction 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).

Significance of this requirement: It is necessary to compensate for achieved fabrication inaccuracies, magnetic materials, and eddy currents with trim coils to meet the 10% total flux limit in islands.

Engineering has to balance the cost of correction against lesser achievements in tolerances and other factors which affect field accuracy!

Engineering requirements

In setting tolerance and deflection limits, the ramifications of tolerances on field error requirements and trim coils needed to compensate for them and world-wide stellarator experience were considered.

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.

Allocation of Tolerances

- Was initially allocated equally - i.e., +/- 0.020, modular coil form + winding; +/- 0.020 for FP assembly, and +/- 0.020 final assembly.
  - No credit taken for re-alignment when the tolerance allocation was made.
  - The actual modular coil fabrication tolerances were ~met.
  - Knowing the as-built dimensions, we can compensate for them by realigning the coils during FP assembly.
  - **In this way, the entire 1.5 mm tolerance is still available for assembly.**

Revised tolerance allocation for assembly

- The entire 1.5 mm (0.060”) tolerance is still available for all assembly steps subsequent to field coils – modular coil half period (MCHP) assembly, modular coil full period (MCFP) assembly, and final machine assembly (FMA) .
  - This will be allocated:
    - 0.020 for MCHP (welding involved)
    - 0.020 for MCFP (welding involved)
    - 0.020 for FMA (bolted connections)

Forces on Modular Coils & Interfaces

Table 4.1-1: Net forces on the modular coils

	Fr, N	Fθ, N	Fz,N
Coil-A,R	-859495	-58278	-38550
Coil-A,L	-859495	58278	38550
Coil-B,R	-1343701	-152699	-459628
Coil-B,L	-1343701	152699	459628
Coil-C,R	-298928	27737	-463462
Coil-C,L	-298928	-27737	463462
Total	-5004250	0	0

NCSX-CALC-14-001-001

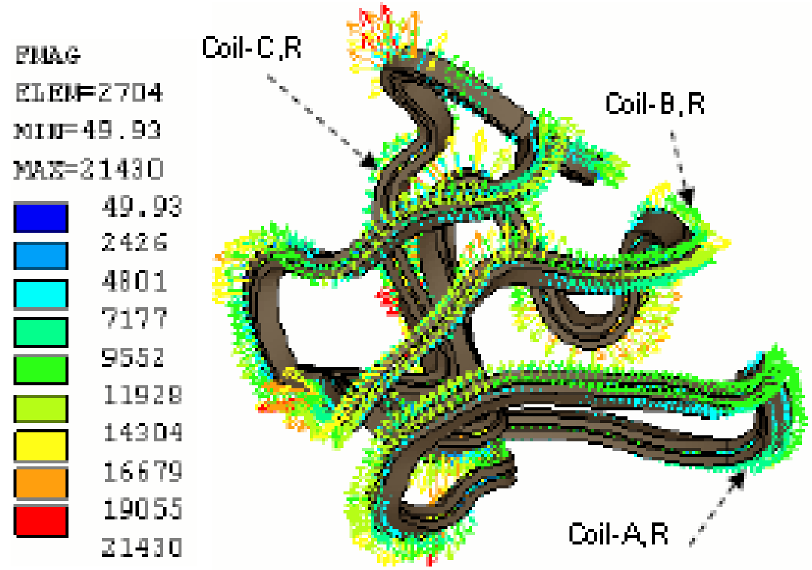


Fig. 4.1-2: Element vector forces of Type B modular coils

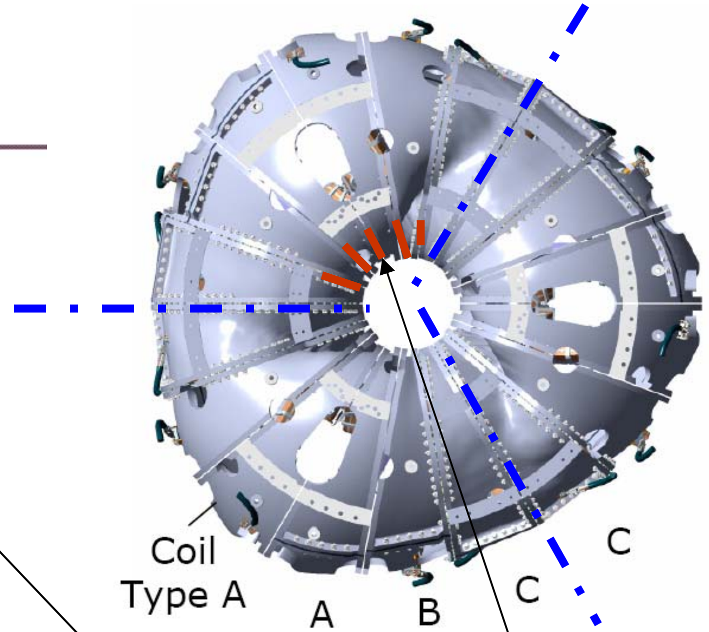
The loads at the welded interfaces are:

Shear force: ~4-6 kips/in.

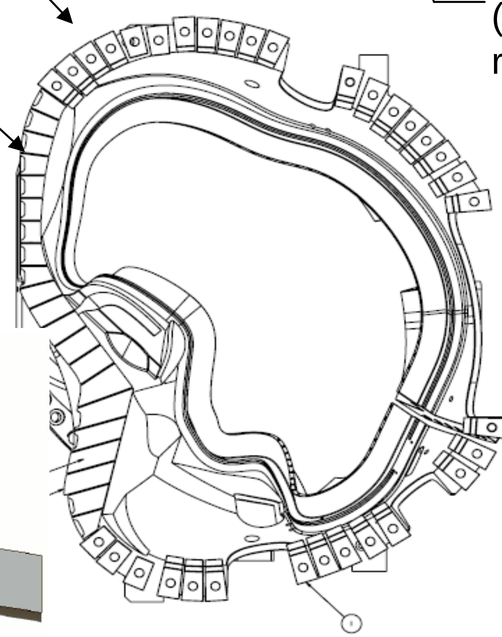
Compression at flanges: ~10-12 kips/in.

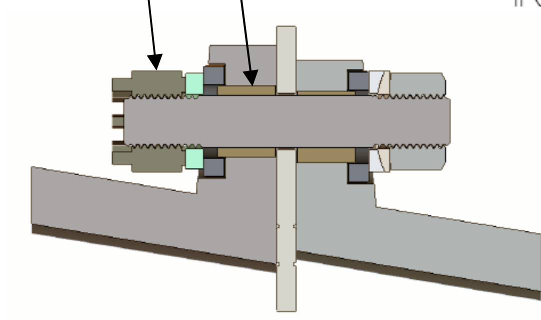
Overview of interfaces

- 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.



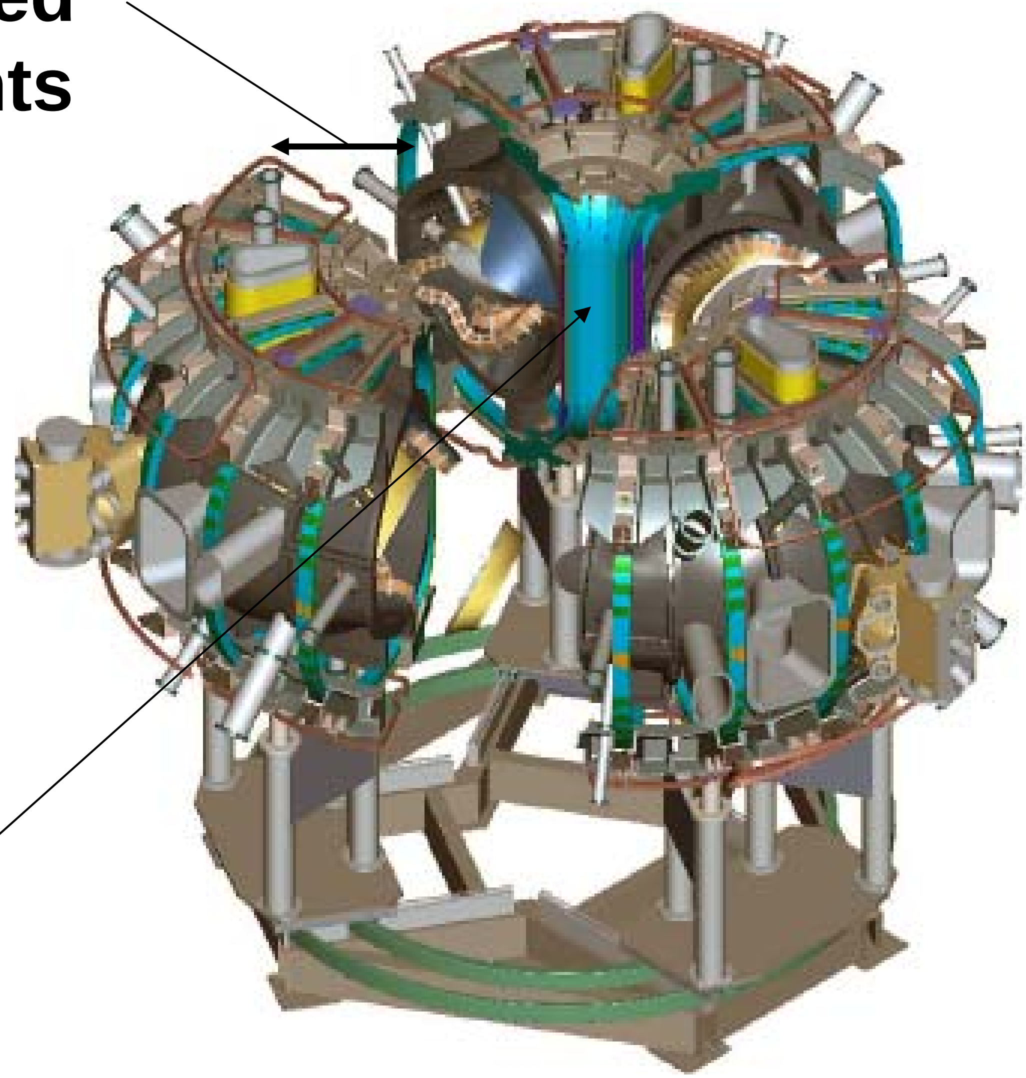
5 welds/period (typ.) in central region.





The C-C bolted interfaces are compatible with assembly plans

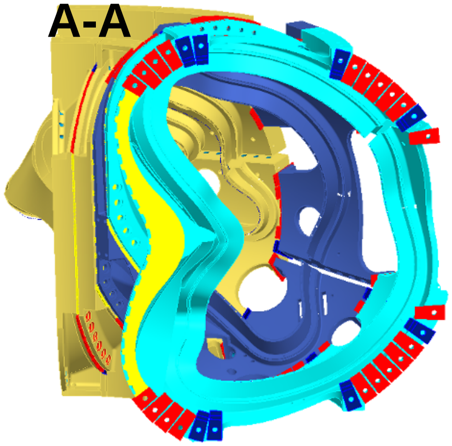
C-C bolted field joints



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

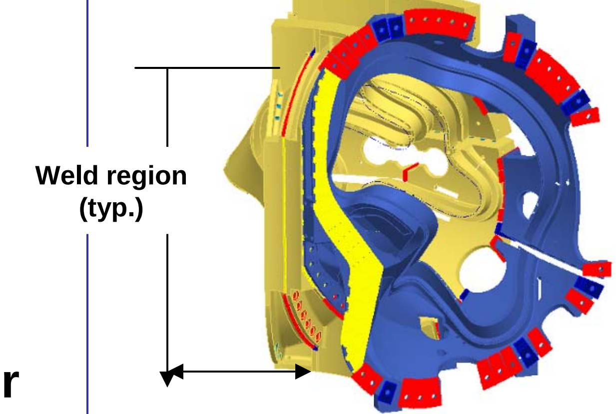
Interface details

A-A

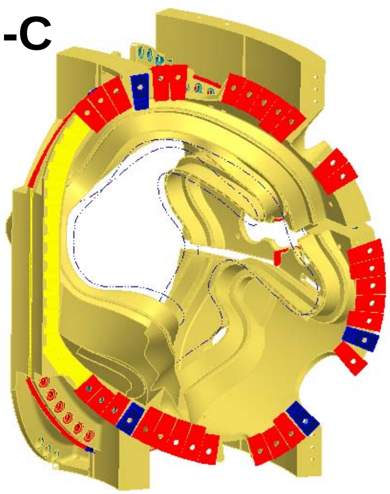


- Partial toroidal electrical breaks between coils in a field period (A-A; A-B; B-C).
- Full toroidal electrical break between field periods (C-C)
- Welded mid-period interfaces (A-A; A-B; B-C) along the inner legs (YELLOW SHIMS)
- Friction shims in the outboard regions (RED & BLUE SHIMS)
- Bolted /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

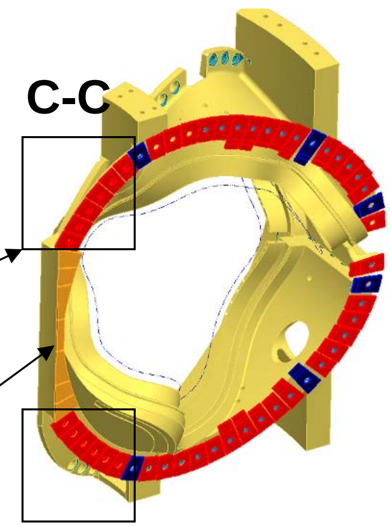
A-B



B-C

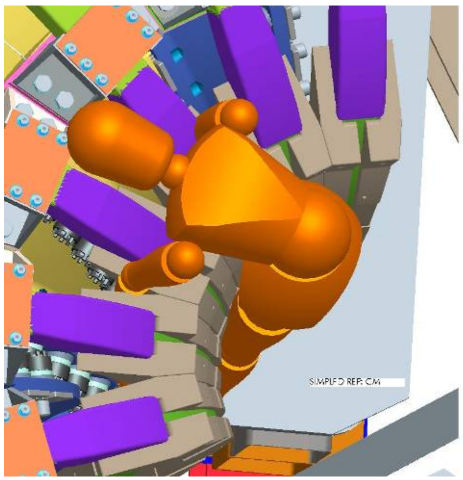


C-C

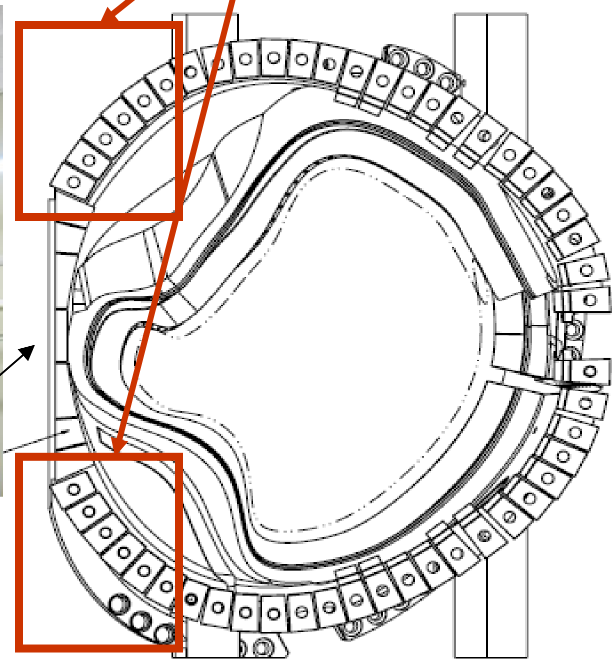


C-C interface access & mock-up studies

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



(6) Additional bolts & shims top & bottom



Compression shims

- ***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

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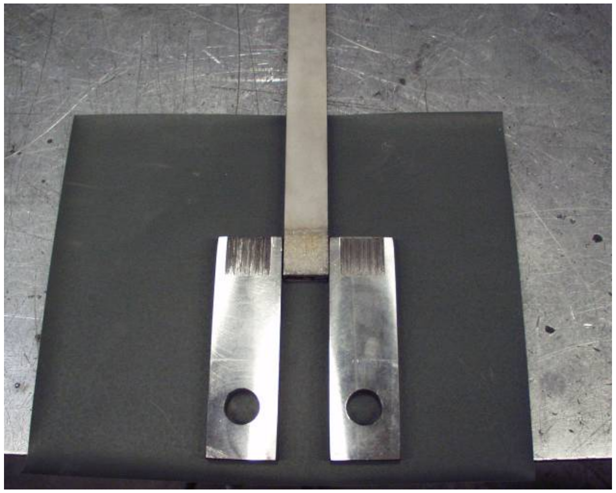
Side rams apply normal pressure to test specimens simulating bolt pressure; tensile tester applies shear load

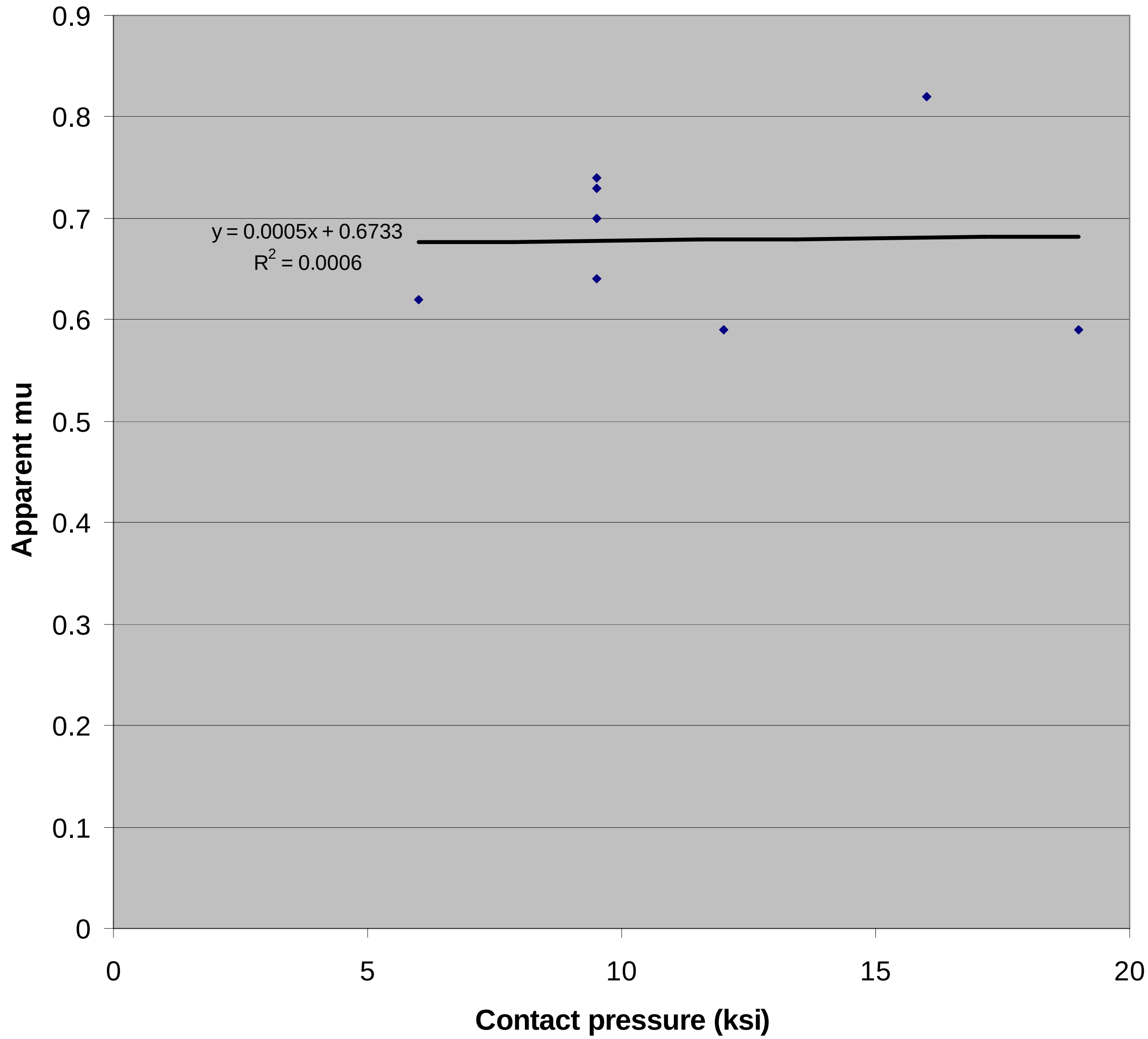
The test setup is cooled to 80 K for testing.



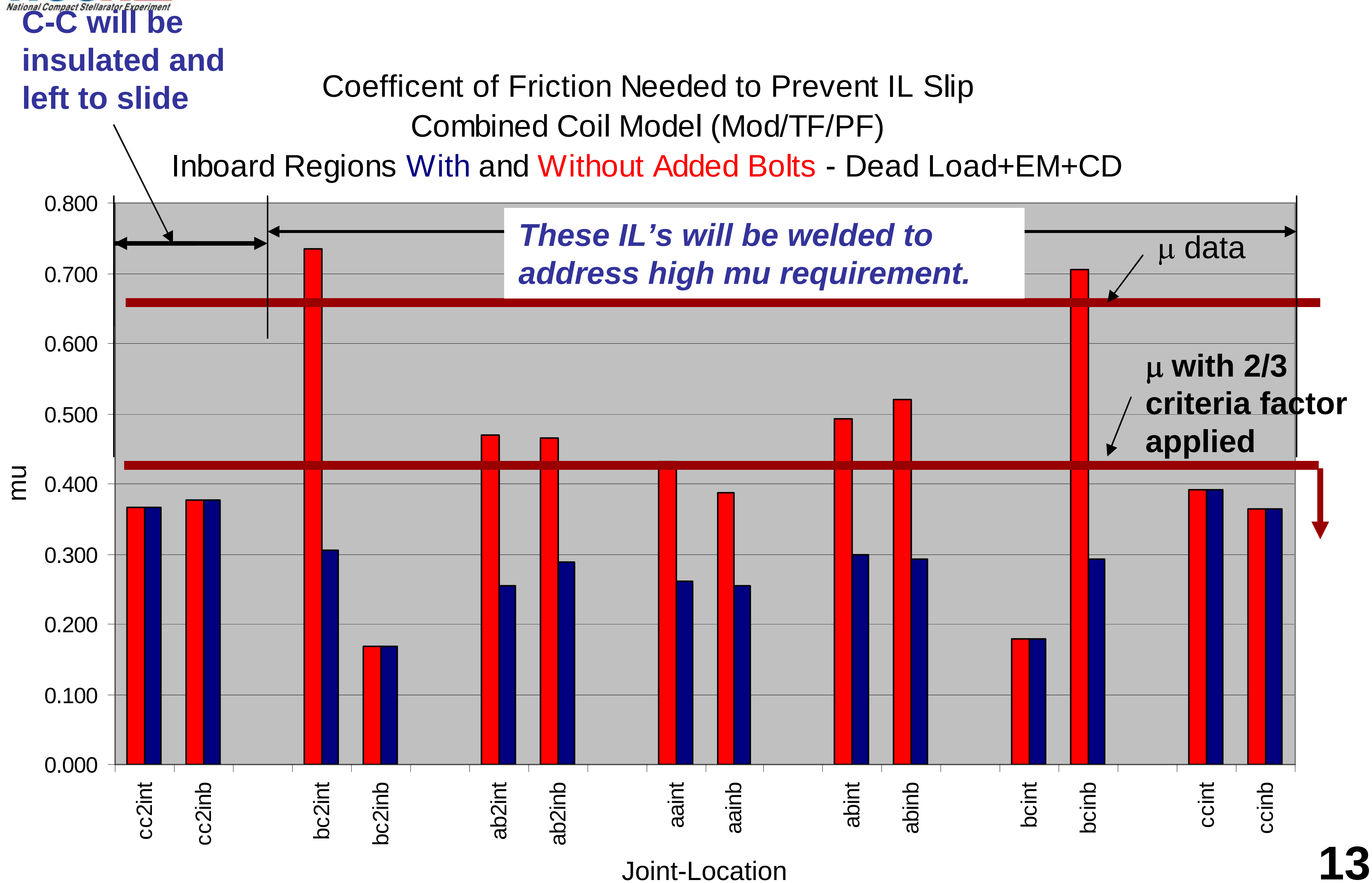
Test specimen – two alumina coated SS sideplates sandwich SS center bar.

- 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) .

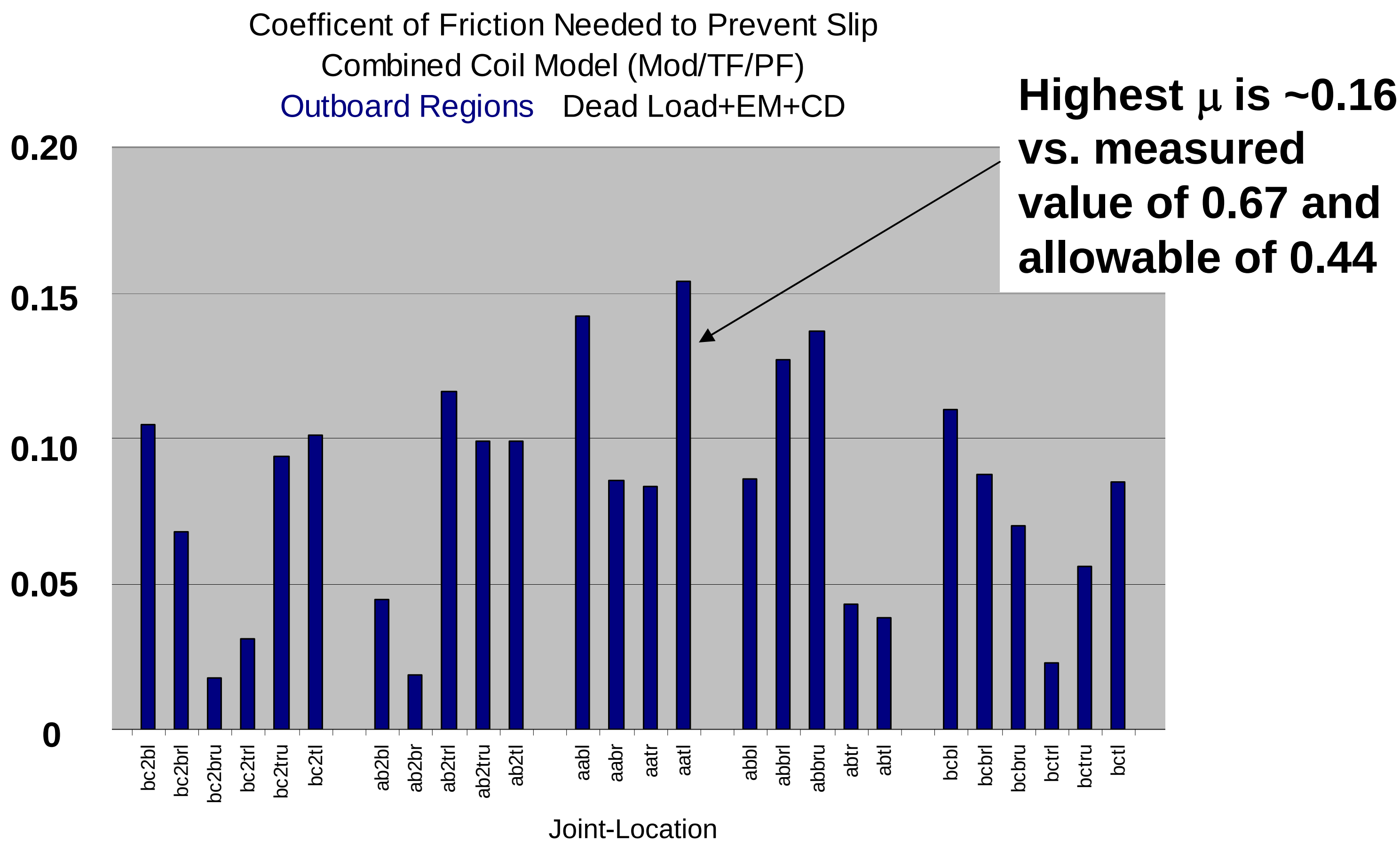
Alumina Coated SS Shim Friction Characteristics



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



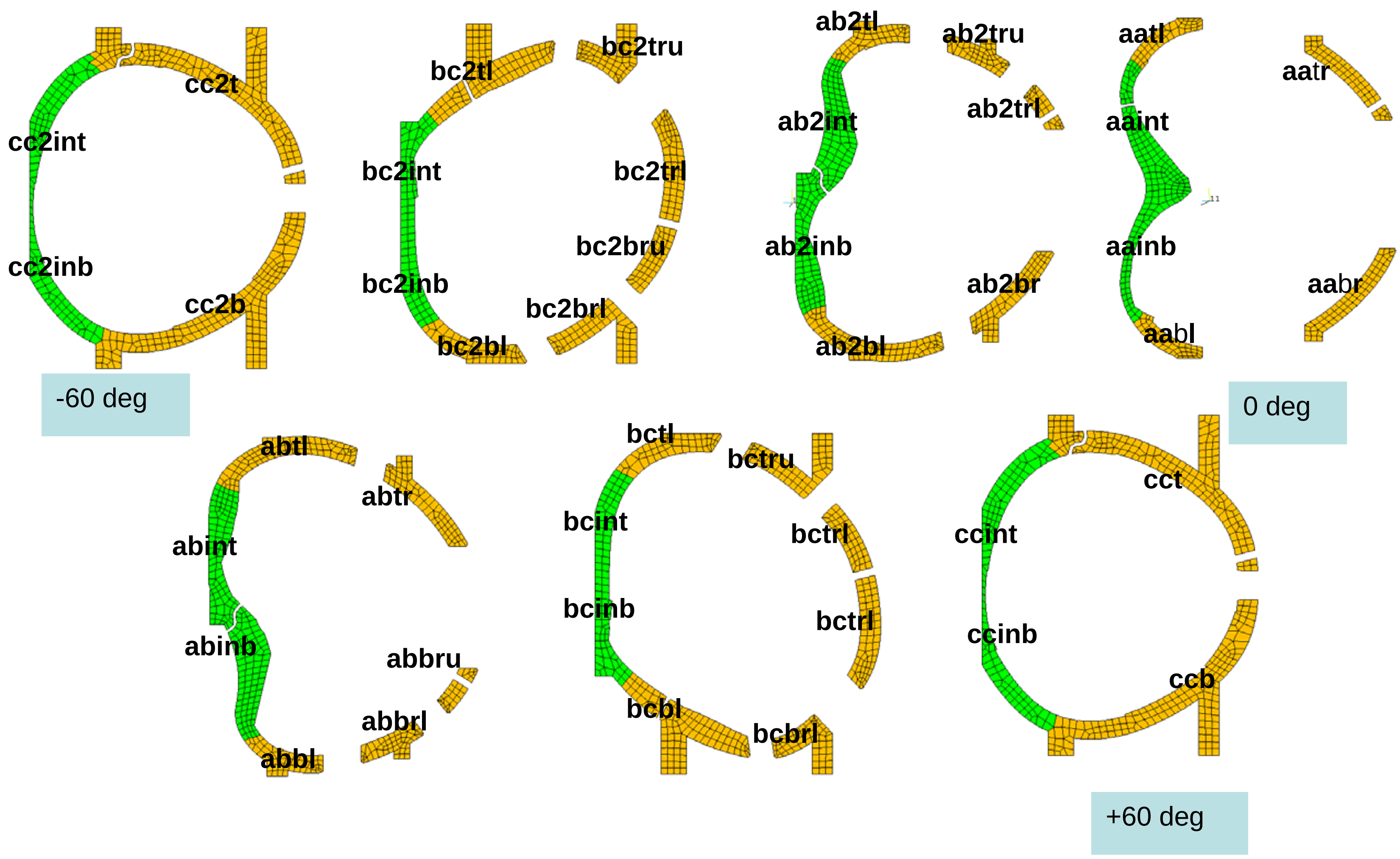
With welding, there is a very comfortable margin on μ



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

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Completed June 15

Welding completed July 23; evaluation of results pending.

Completed

Underway now

4 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). TIG weld process.
- **Phase III: A6/B6 casting to casting weld tests**. Primary goal: to gain an understanding of **weld distortion** and to refine assembly and weld procedures. TIG weld process.
- **Phase IV: Refinement of the welded interface design**, with emphasis on distortion minimization; change in weld process from TIG to MIG based on discussions with CERN and W7X

Phase I

Phase I weld test specimen

Examples from EWI's report

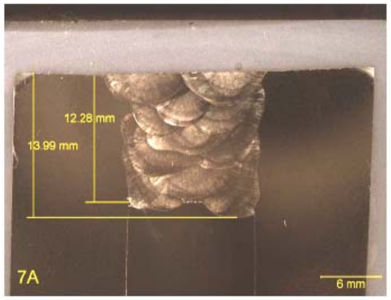


Figure C1. Macrograph of Weld in Sample 7A (Note lack of fusion in center of shim.)

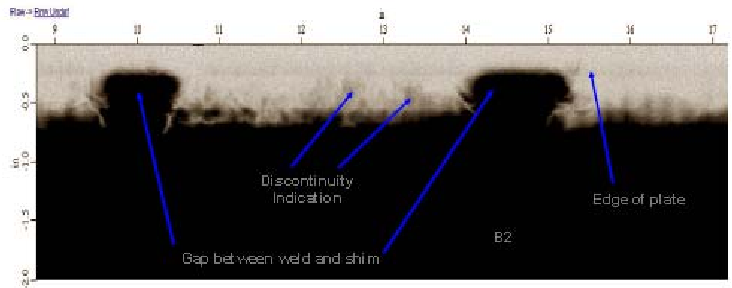


Figure A8. UT Scan of Area 2 from Side B

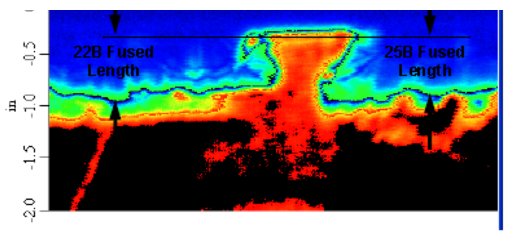
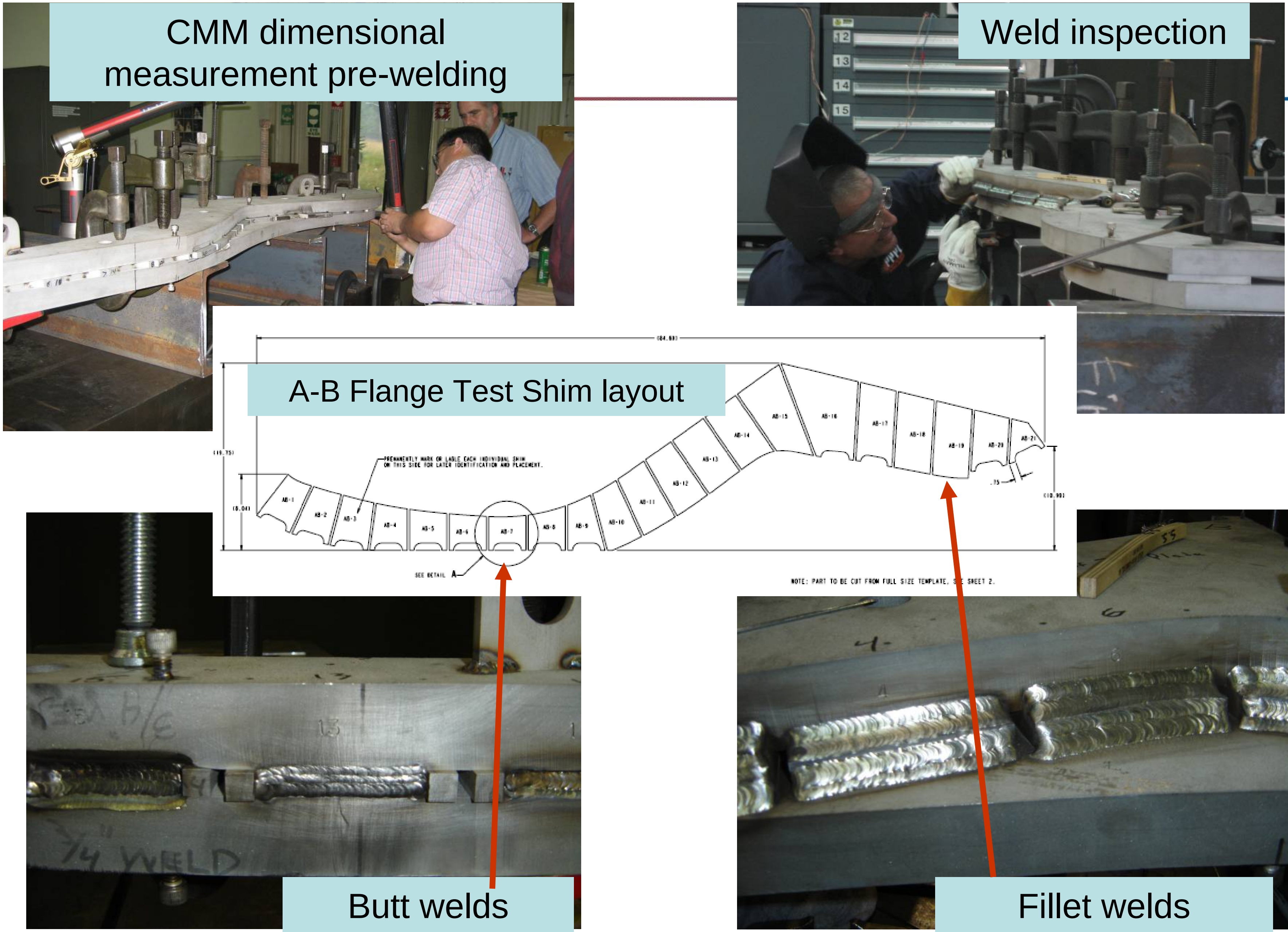


Figure D2. Penetration Depth Measurements by UT on Samples 22A and 25A (Upper: A side – Lower: B side.)

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. "

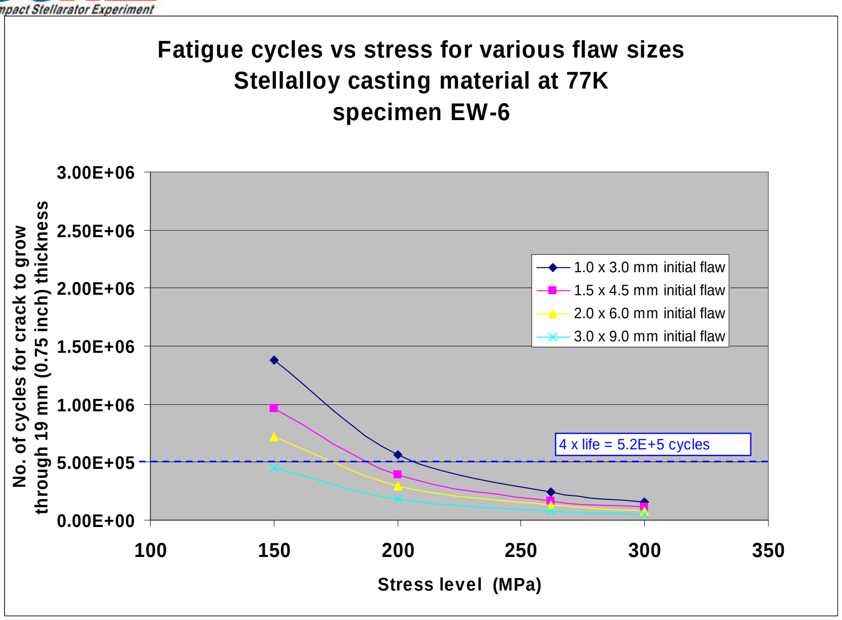


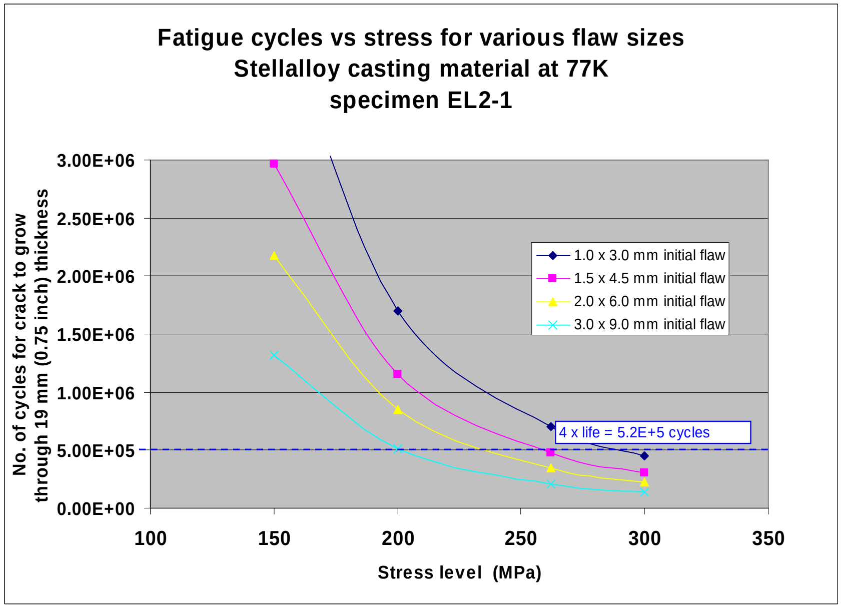
Phase II weld tests

Weld tests show good control of magnetic permeability

- Shims are made from 316L 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



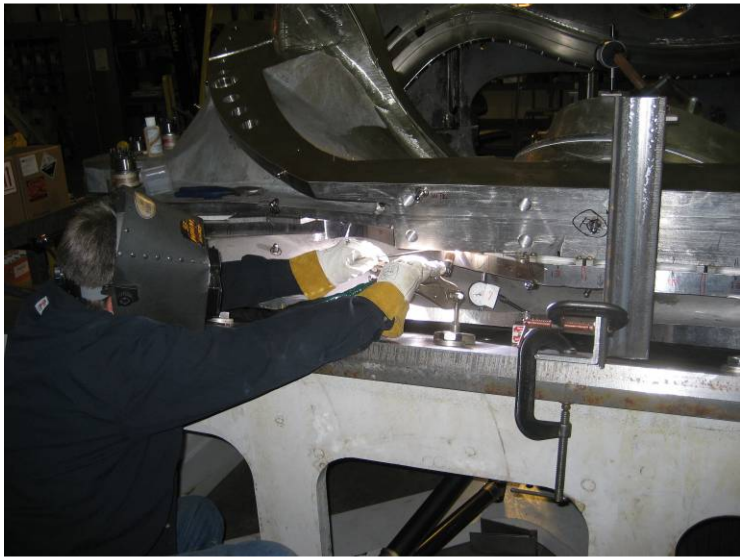


Fatigue data for welds in Stelalloy

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 expected highest average stress of 20 ksi (138 MPa). (final calculation underway).
- 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 III Welding Process



Deflection Monitoring

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Phase III wing deflections after 25% weld deposited

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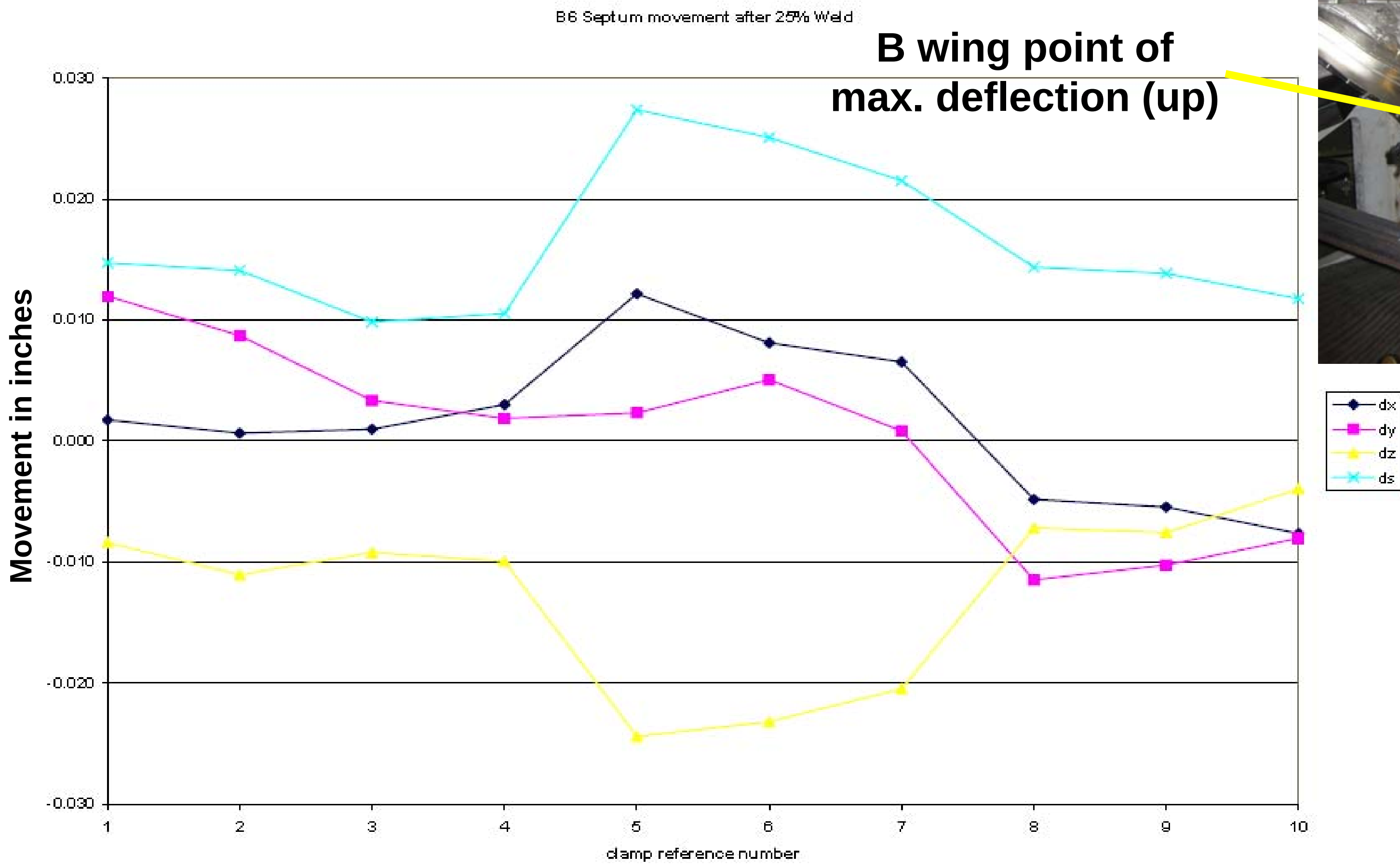
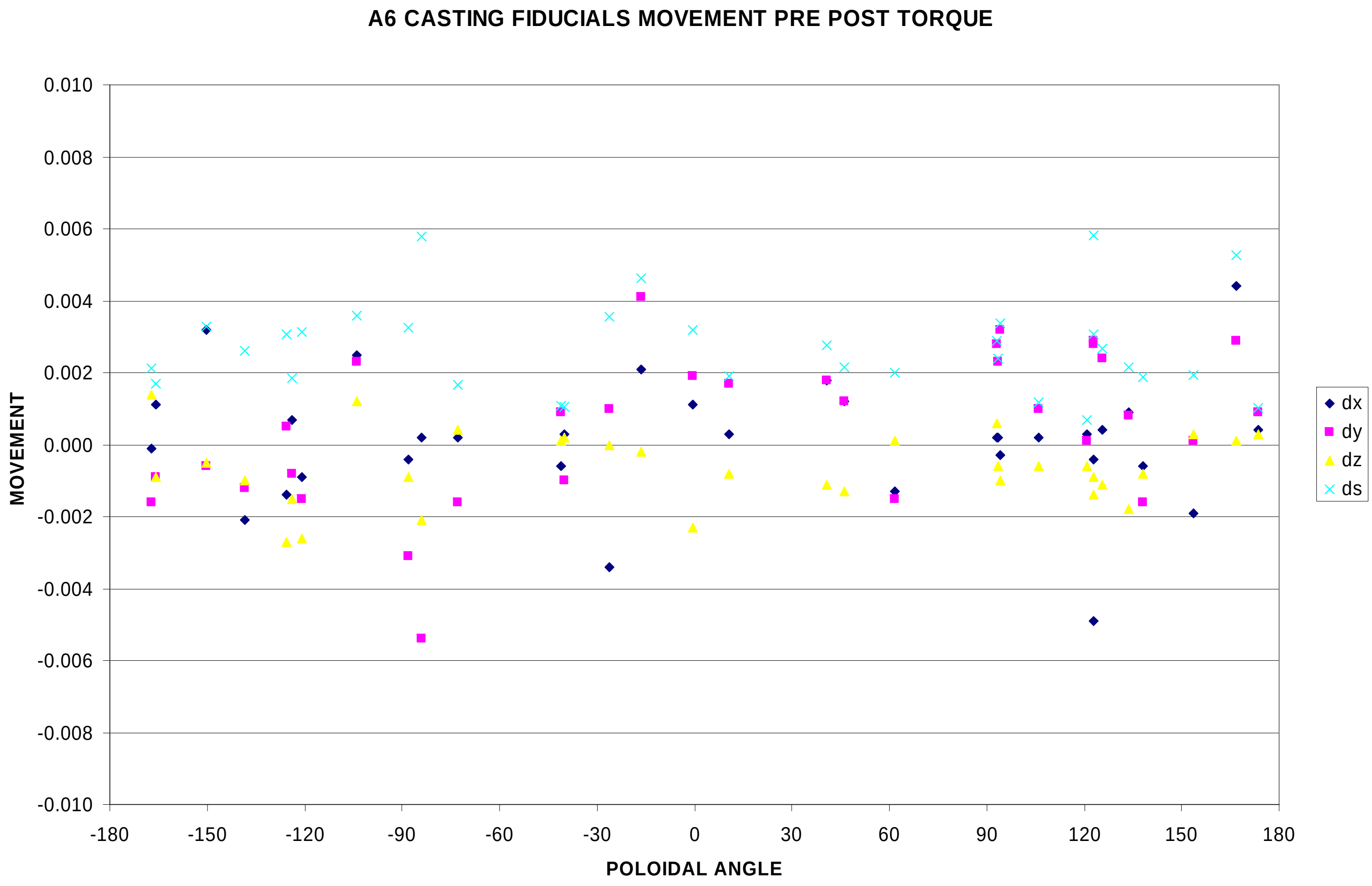


Casting movement due to bolt tightening



Phase I, II, and III weld test results

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Satisfactory results, except for distortion:

- ✓ Permeability control demonstrated.
- ✓ Weld fatigue acceptability verified for Phase III welds.
- ✓ Weld procedures developed.
- ✓ Welders qualified.
- ✓ BUT "wing" motion due to weld shrinkage was ~1 mm with 75% of the weld, when the test was terminated.
  - ✓ If all the wing areas were displaced 1 mm in a "stellarator symmetric" fashion, this would use up about 40% of our 10% requirement for the total flux in islands.
  - ✓ Our goal: to reduce wing deflections to < 0.3 mm.

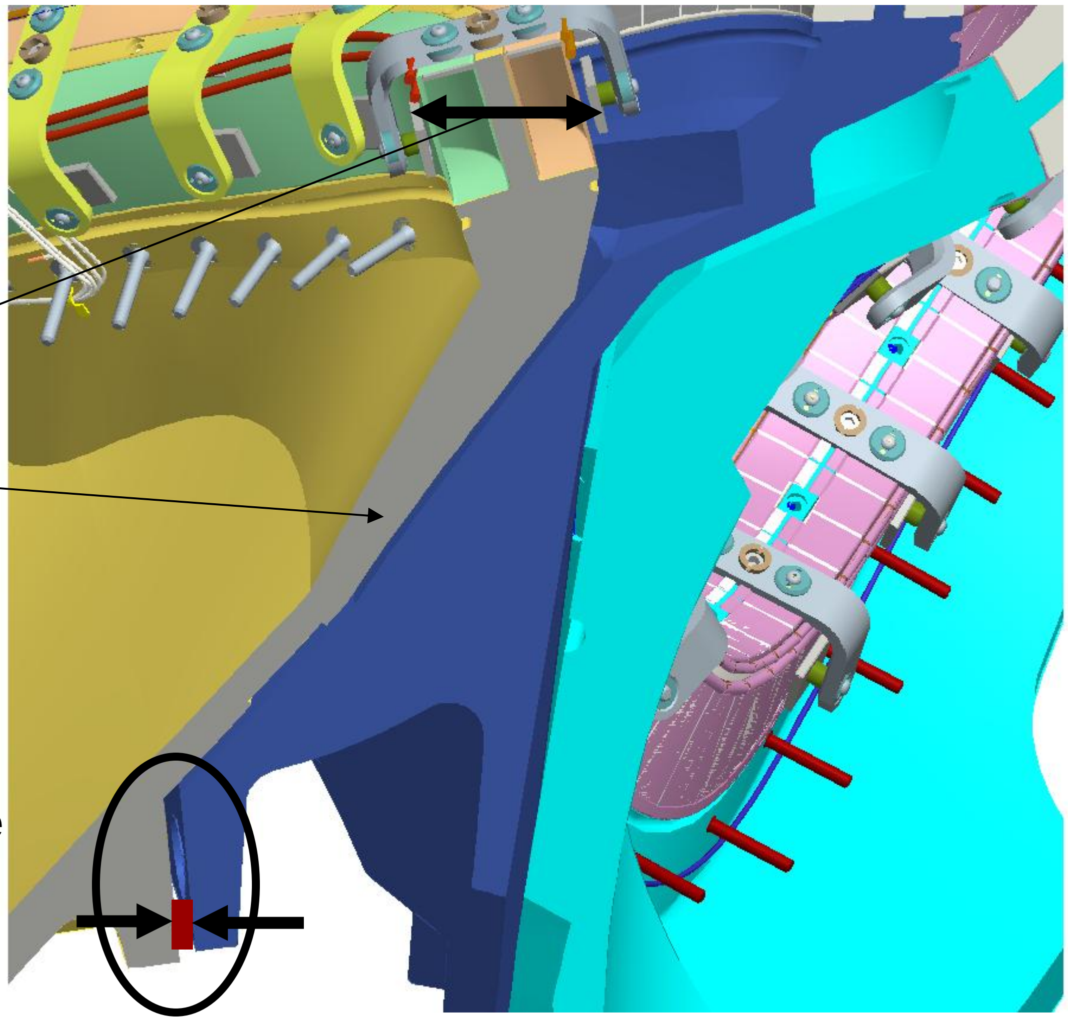
Consequently, a Phase IV weld concept was developed.

Why the Phase III welds resulted in significant wing deflections

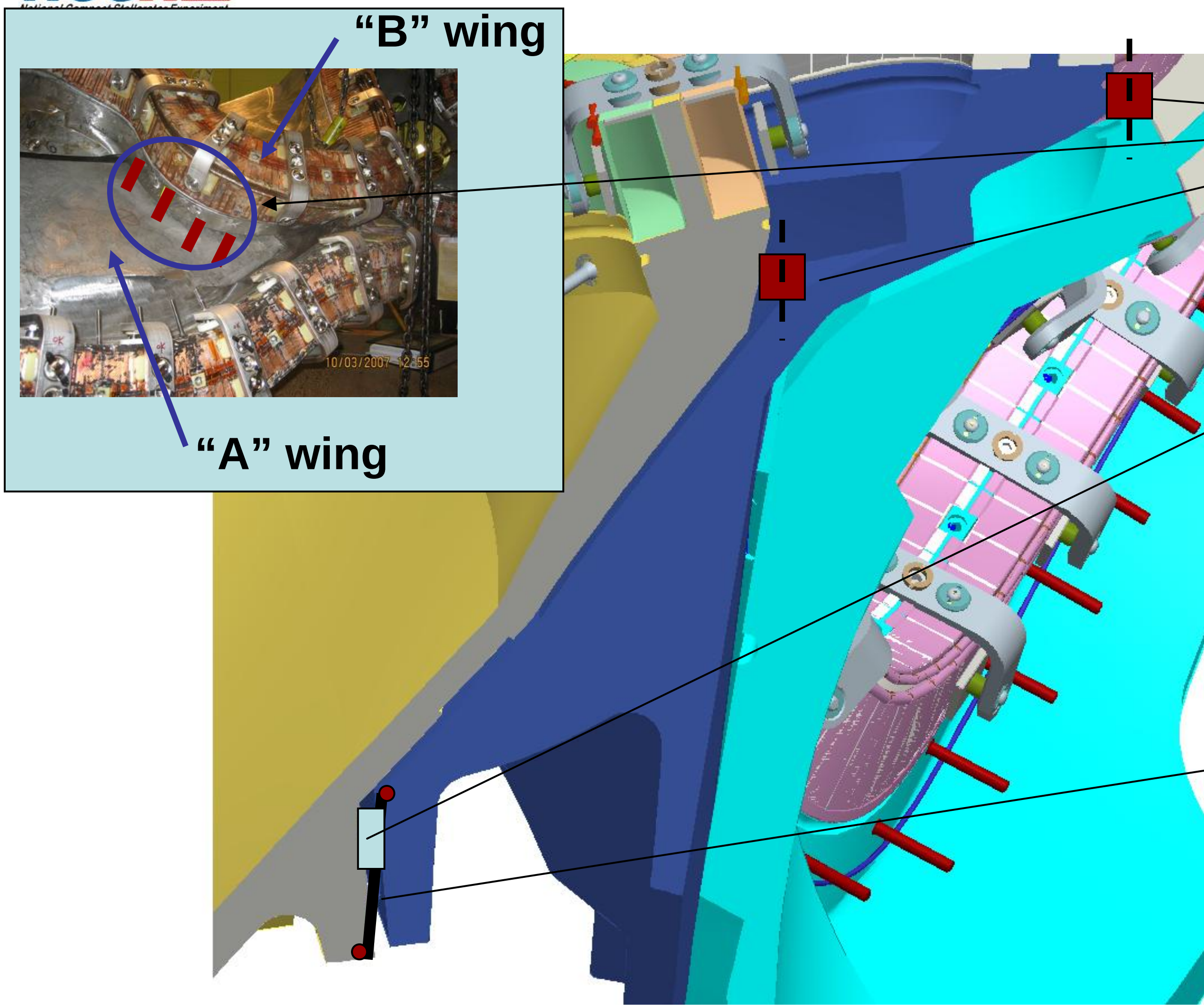
3…..results in significant deflection at the winding

2. …magnified by this long lever arm

1. Small deflections due to weld shrinkage between the flanges



Phase IV interface concept addresses the Phase III wing deflection issues



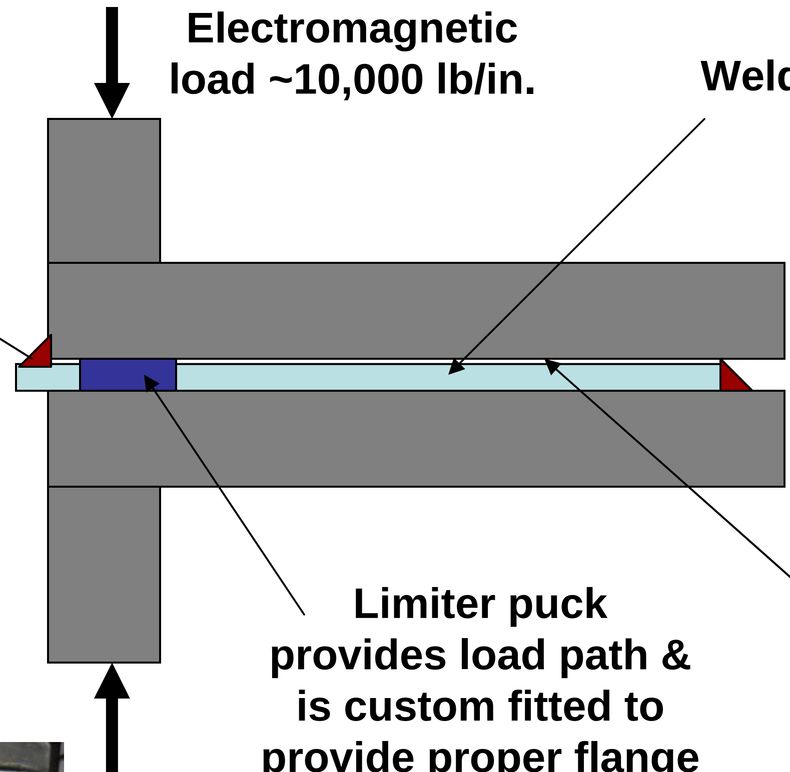
1. Add wing restraints

2. Add custom fitted "limiter pucks" to properly space flanges & react EM compressive forces

3. Use a welded "flex strap" design which restricts shear but does not result in shrinkage deformations between flanges

4. Minimize longitudinal weld shrinkage effects (by shim design and layout and weld techniques – details on next slide)

Phase IV Interface Design Details



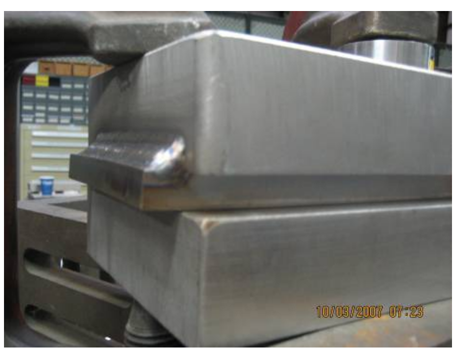
Electromagnetic load ~10,000 lb/in.

0.44” Fillet welds (typ. – 2 ends)

Welded strap reacts shear force of ~4000-6000 lb./in.

Limiter puck provides load path & is custom fitted to provide proper flange alignment.

Undercut gap to accommodate weld deformations of strap



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.

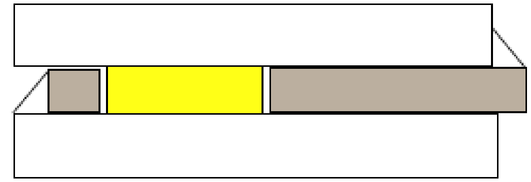
Weld distortion minimization

Our thanks to input received from CERN and W7X, upon which our weld plans are based:

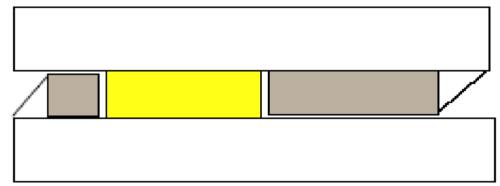
- MIG welds.
- Welds: in segments; typically 4” long with ½” gaps between segments.
- Welding pattern carefully selected to minimize distortion.
- CO_2 pellet blast cooled immediately after weld.
- 3 stringers / fillet weld.

Basic weld tests

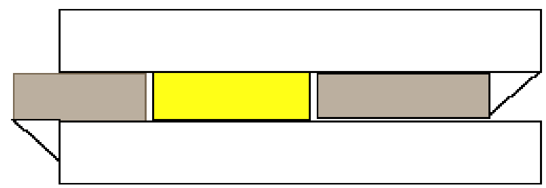
- **3 basic weld configurations required were tested.**
- **TIG was used. We now plan to use MIG - deflections and forces should be less.**
- **Load cells were used to measure lifting force when 1 end of the shim was welded.**
  - **Upwards deflection was ~ 0.060” for 6” long shims. This determined the gap allowance for shim deflection.**
  - **Force required to flatten was 600-2300 lbs. If the shims lift beyond the clearance allowance due to weld shrinkage, they could readily be pushed down so as to not interfere with casting alignment.**



Type 1



Type 2



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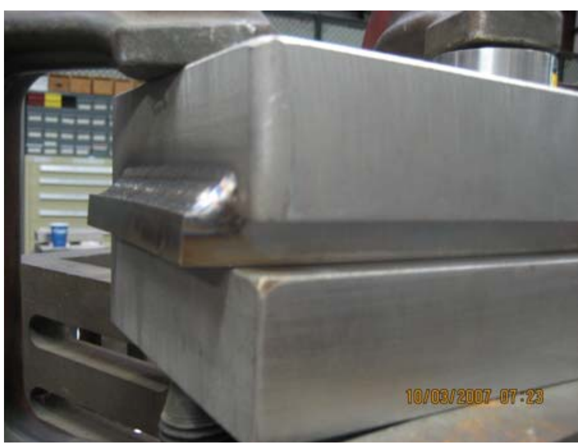
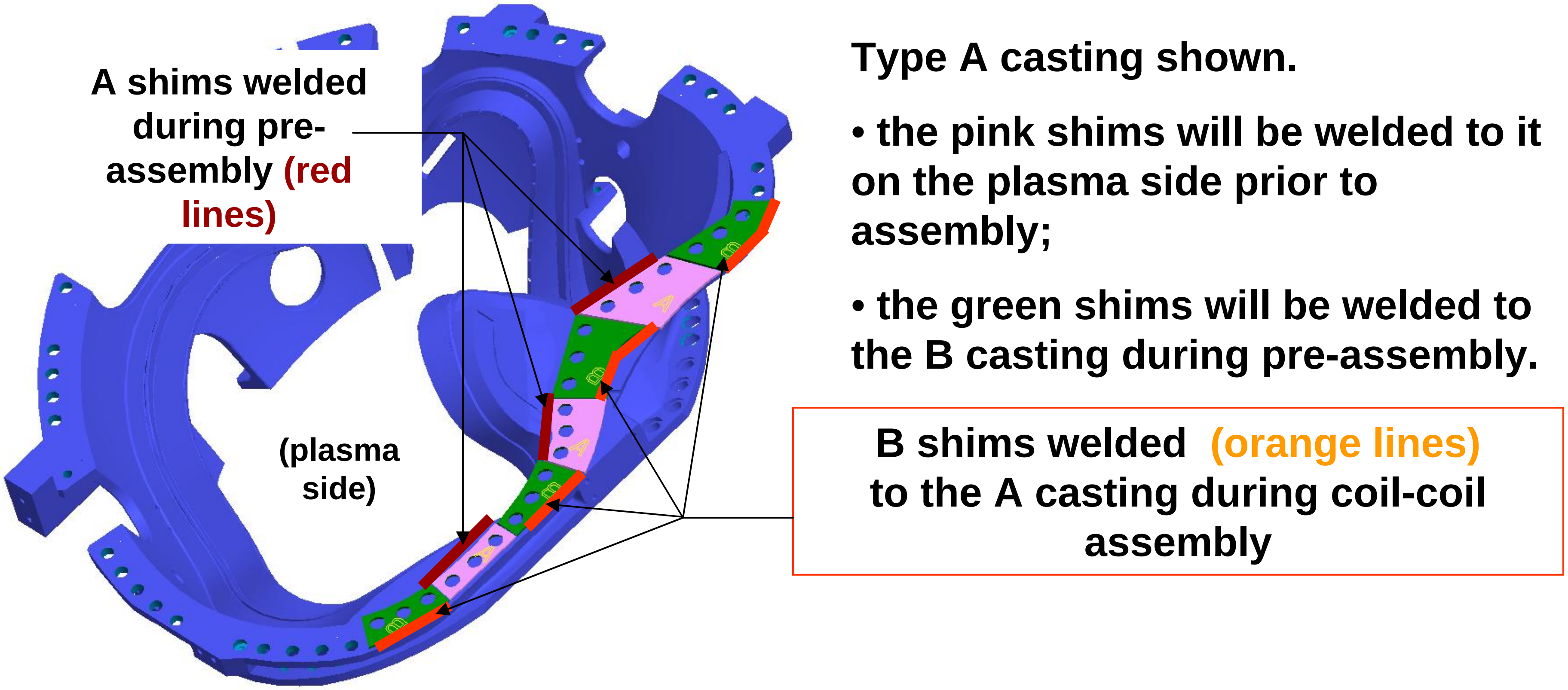


Shim Layout Chosen to Minimize Longitudinal Weld Distortion



Type A casting shown.

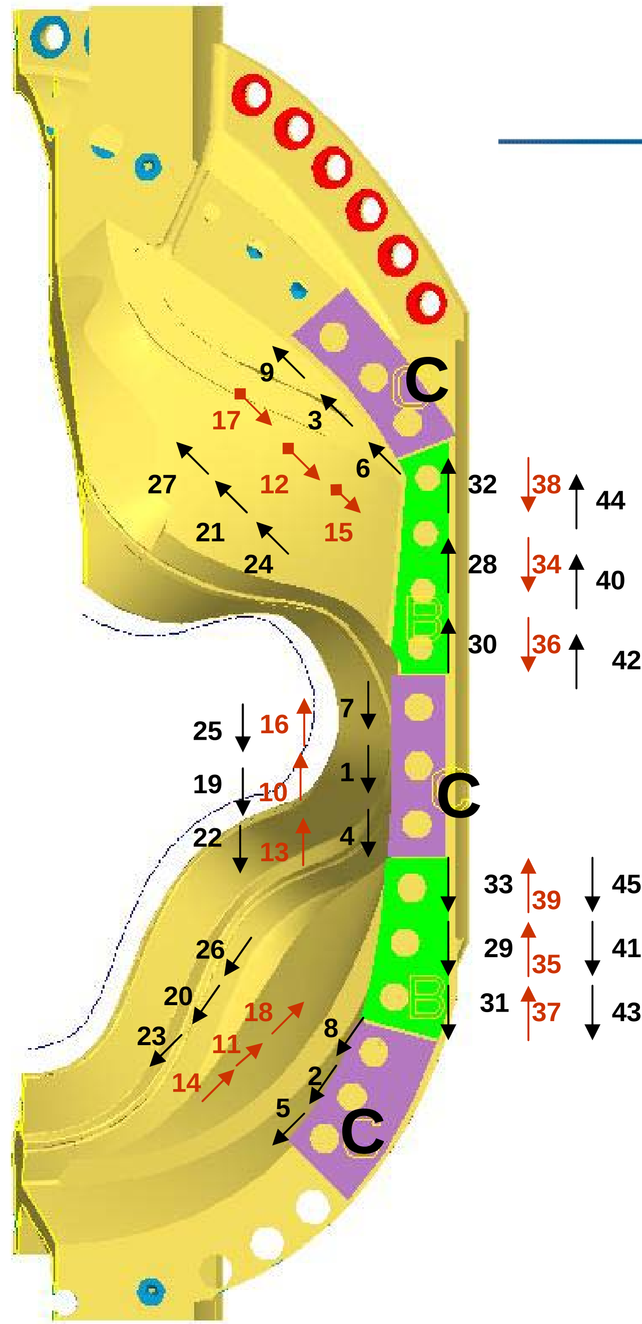
- **the pink shims will be welded to it on the plasma side prior to assembly;**
- **the green shims will be welded to the B casting during pre-assembly.**

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

A weld test is underway, using the Type C Prototype Casting.

Welding sequence

- Work from center out.
  - On casting
  - On shims
- 3 passes:
  - First pass, 50%
  - 2nd & 3rd passes as needed to complete the weld.



Assembly & metrology techniques are being refined

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- Much has been learned about metrology and assembly techniques during these development trials. Examples:
  - A reliable metrology methodology has been developed – measurement results duplicate factory CMM measurements.
  - Casting handling and locating techniques have been simplified.
  - Outboard 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 were simplified; schedule time improved.

Conclusions

- **We believe the interface designs which evolved is consistent with our goal of being able to assemble NCSX to the tolerances required with reasonable costs and schedule, and that it will reliably maintain alignment during operation**.

Features:

- 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.