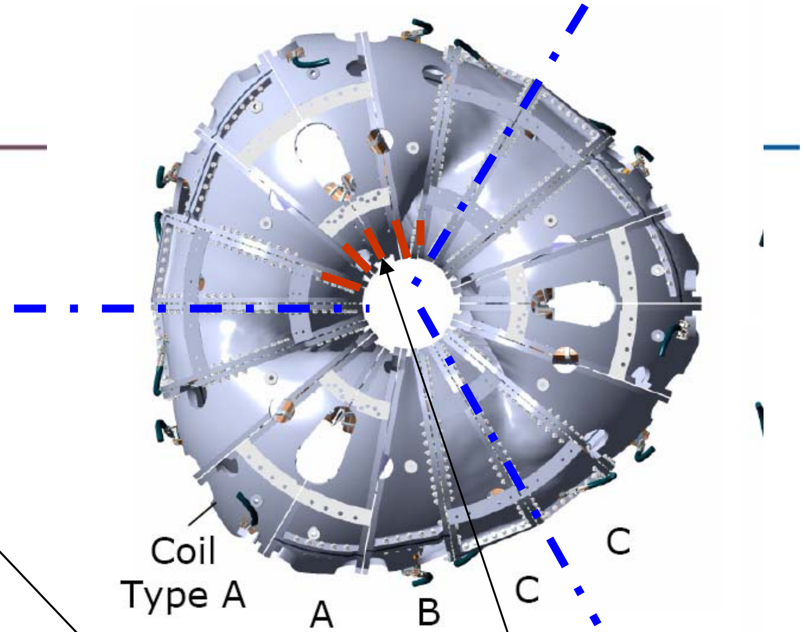
# Design and Development of the NCSX Modular Coil Interfaces

**NCSX Engineering Group**

**October, 2007**

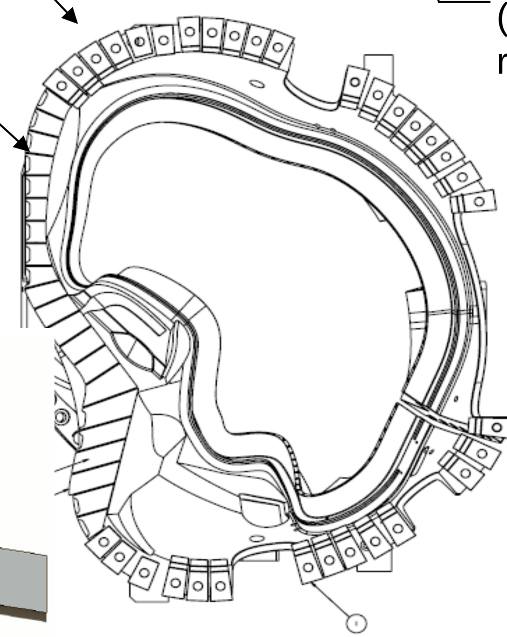
# Overview of interfaces

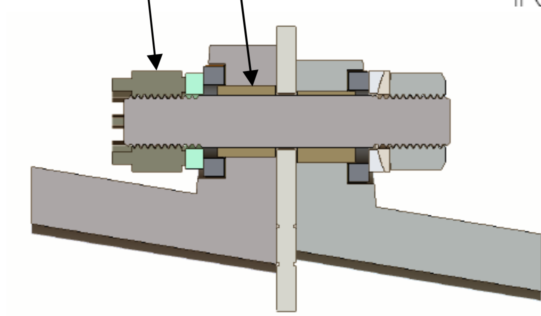
NCSX
National Compact Stellarator Experiment




- 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.

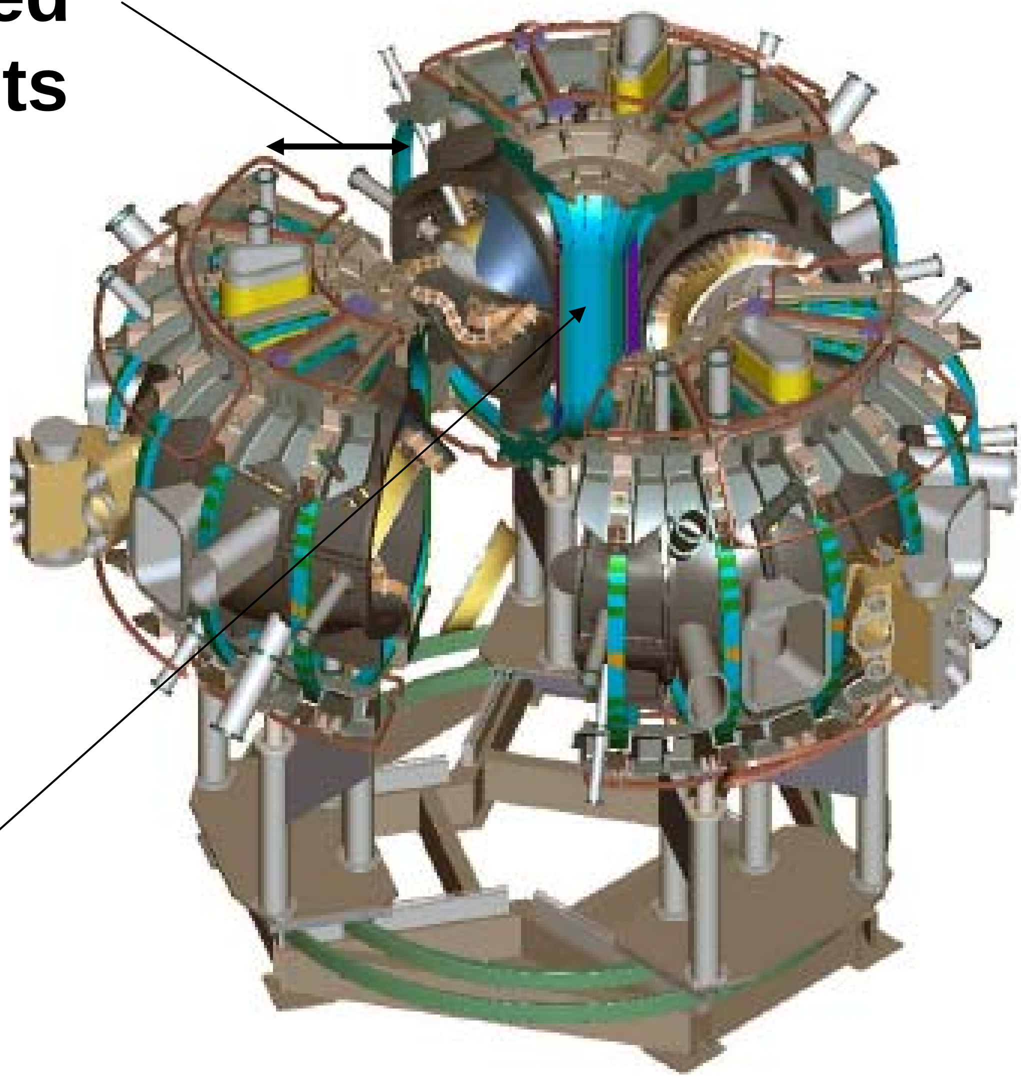
5 welds/period (typ.) in central region.





# 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 for the new configuration

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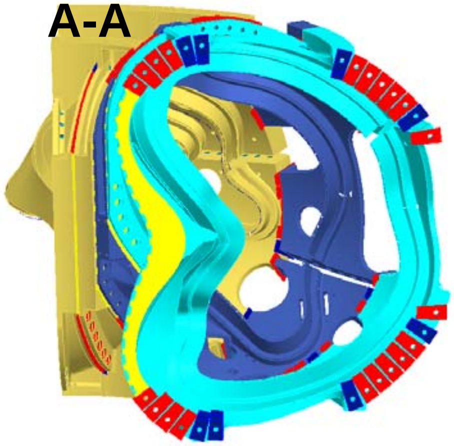
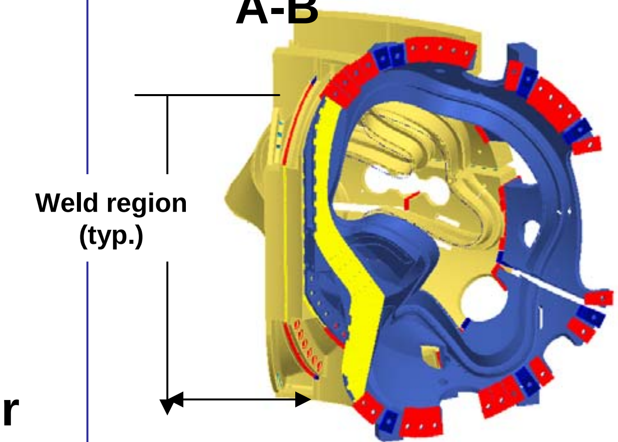
A-A

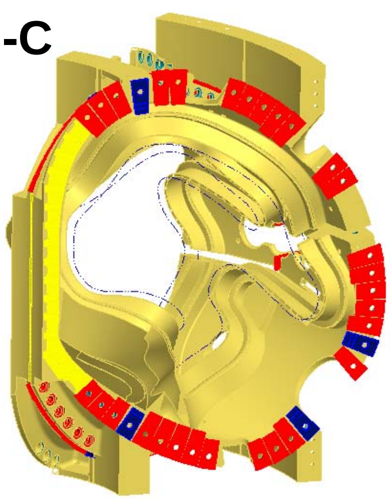


A-B

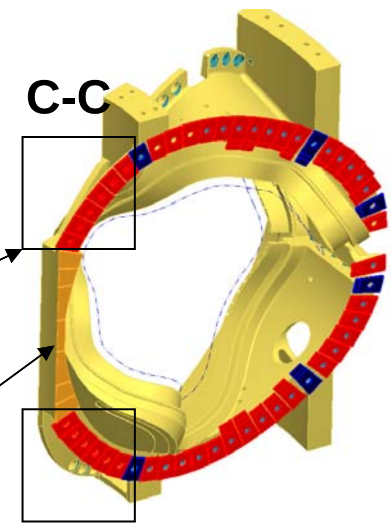



- **Partial toroidal electrical breaks between coils in a field period (A-A; A-B; B-C).**
- **Full toroidal electrical break between field periods (C-C)**
- **Welded mid-period interfaces (A-A; A-B; B-C) along the inner legs (YELLOW SHIMS)**
- **Friction shims in the outboard regions (RED & BLUE SHIMS)**
- **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.**

B-C



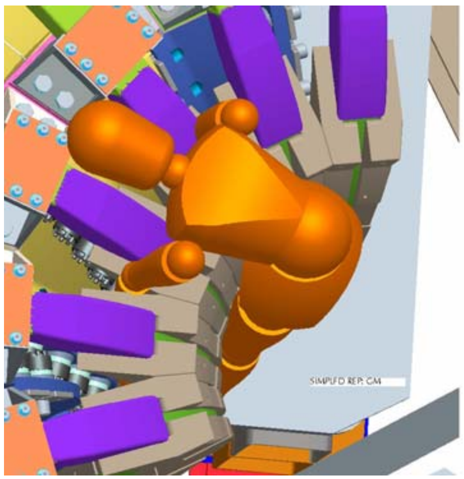
C-C

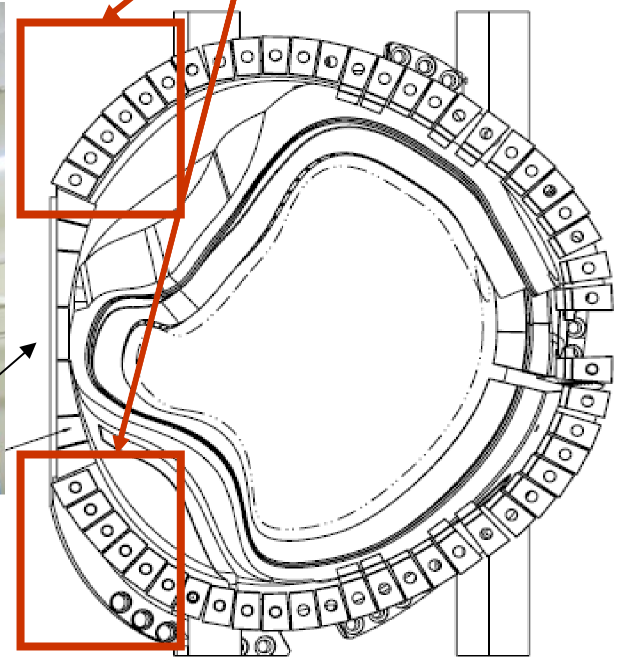


# C-C interface access & mock-up studies

***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

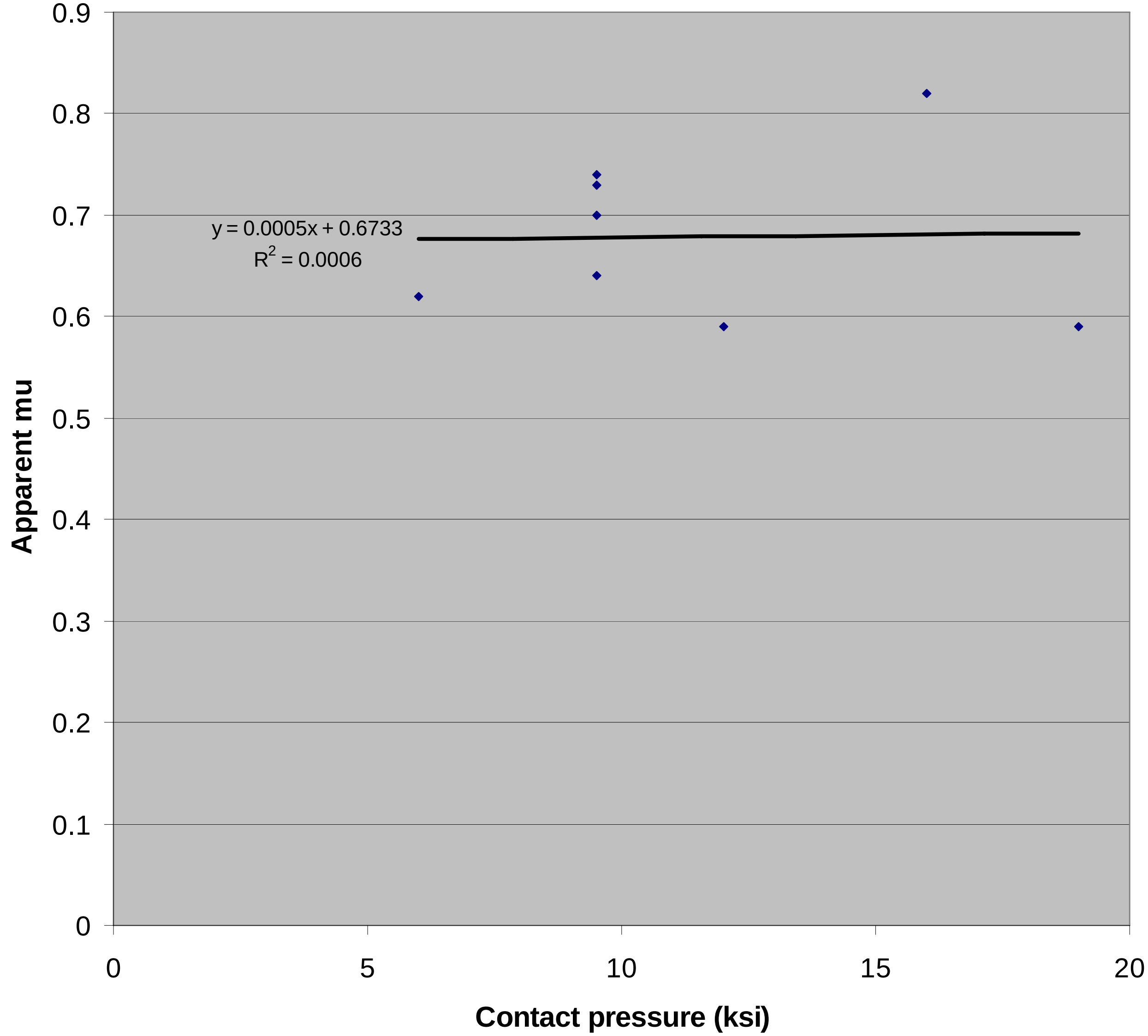
*Side rams apply normal pressure to test specimens simulating bolt pressure; tensile tester applies shear load*

*The test setup is cooled to 80 K for testing.*

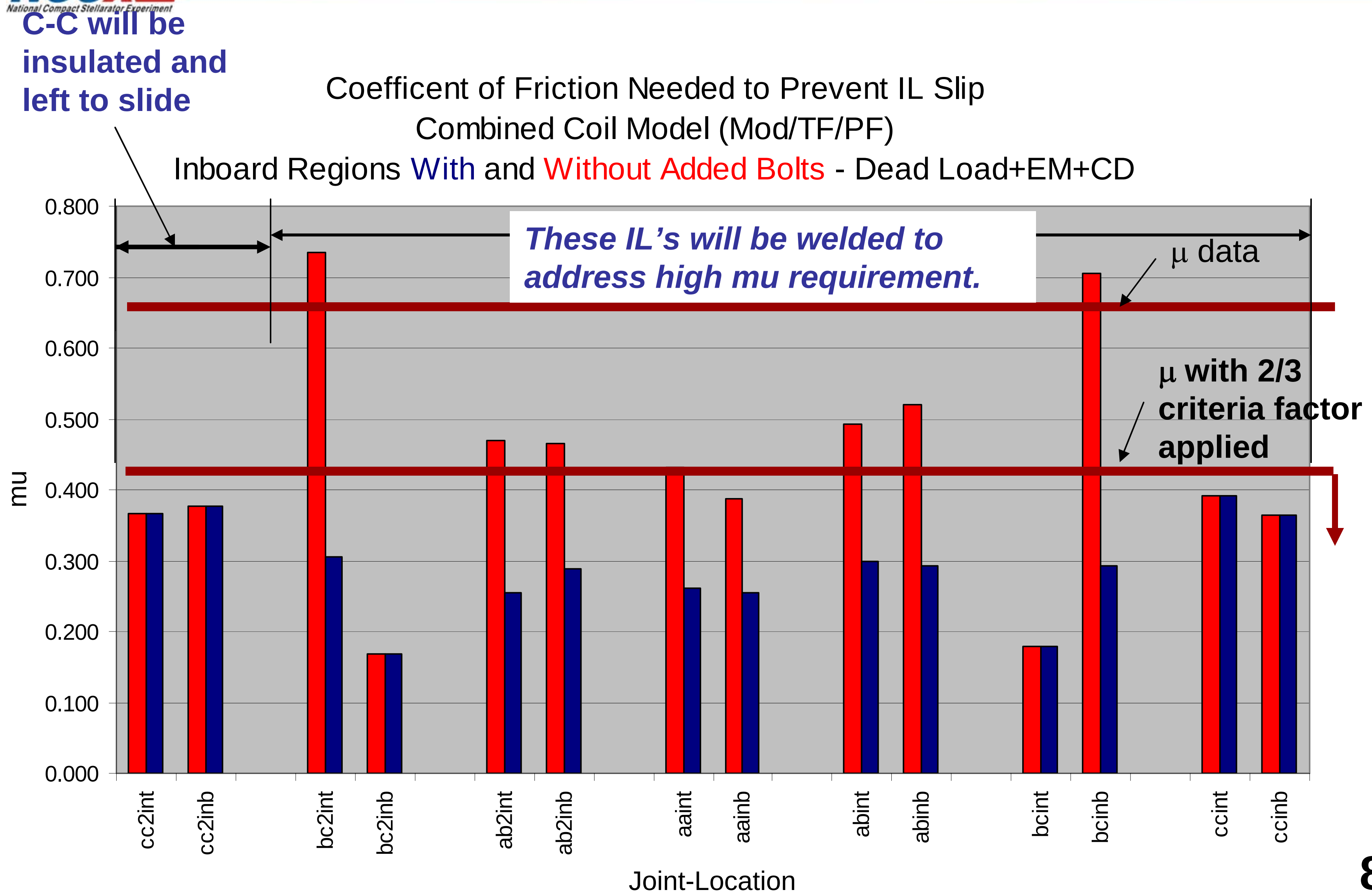
*Test specimen – two alumina coated SS sideplates sandwich SS center bar.*

- The coefficient of friction, $\mu$, 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 $\mu$ 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) .

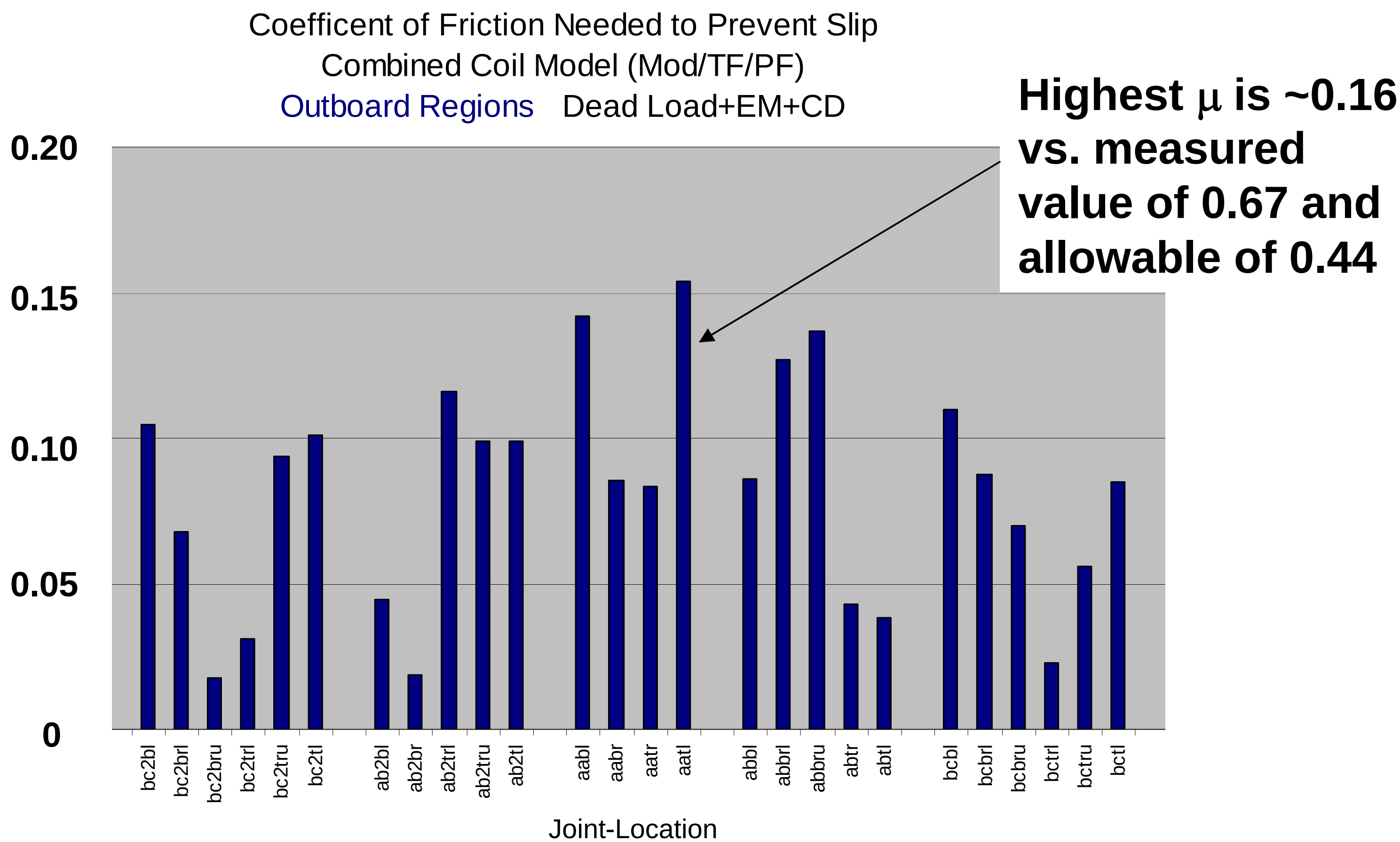
# Alumina Coated SS Shim Friction Characteristics



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



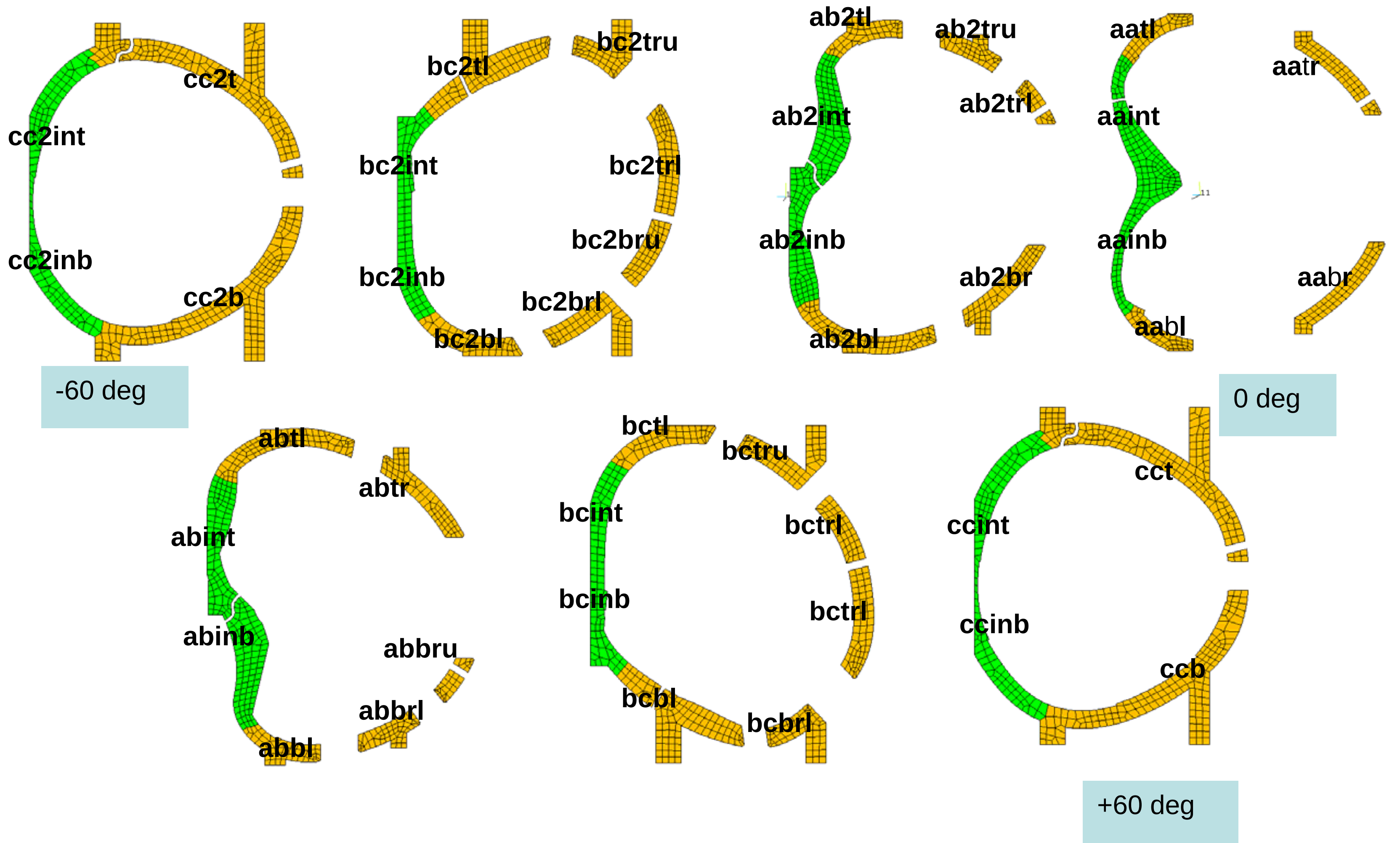
# With welding, there is a very comfortable margin on $\mu$




***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 $\mu$) 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

4 phase program:

Completed June 15

– **<u>Phase I:</u> On-site Assessment** of NCSX's plans by Edison Welding Institute.

Welding completed July 23; evaluation of results pending.

– **<u>Phase II:</u> 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).

Completed

– **Phase III: A6/B6 casting to casting weld tests**. Primary goal: to gain an understanding of **weld distortion** and to refine assembly and weld procedure.

Underway now

– **Phase IV:** Refinement of the welded interface design, with stress on distortion minimization.

# Phase I


*Phase I weld test specimen*

**Examples from EWI's report**

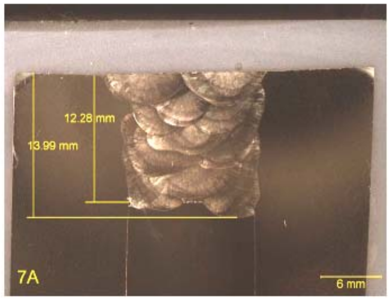



Figure C1. Macrograph of Weld in Sample 7A (Note lack of fusion in center of shim.)

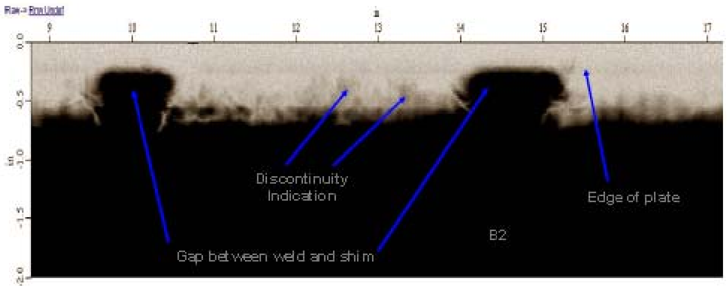



Figure A8. UT Scan of Area 2 from Side B

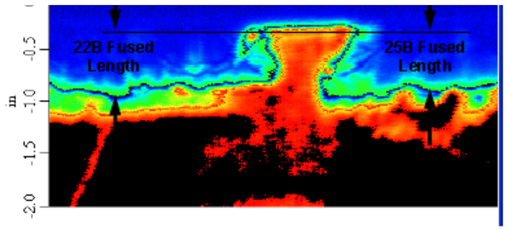
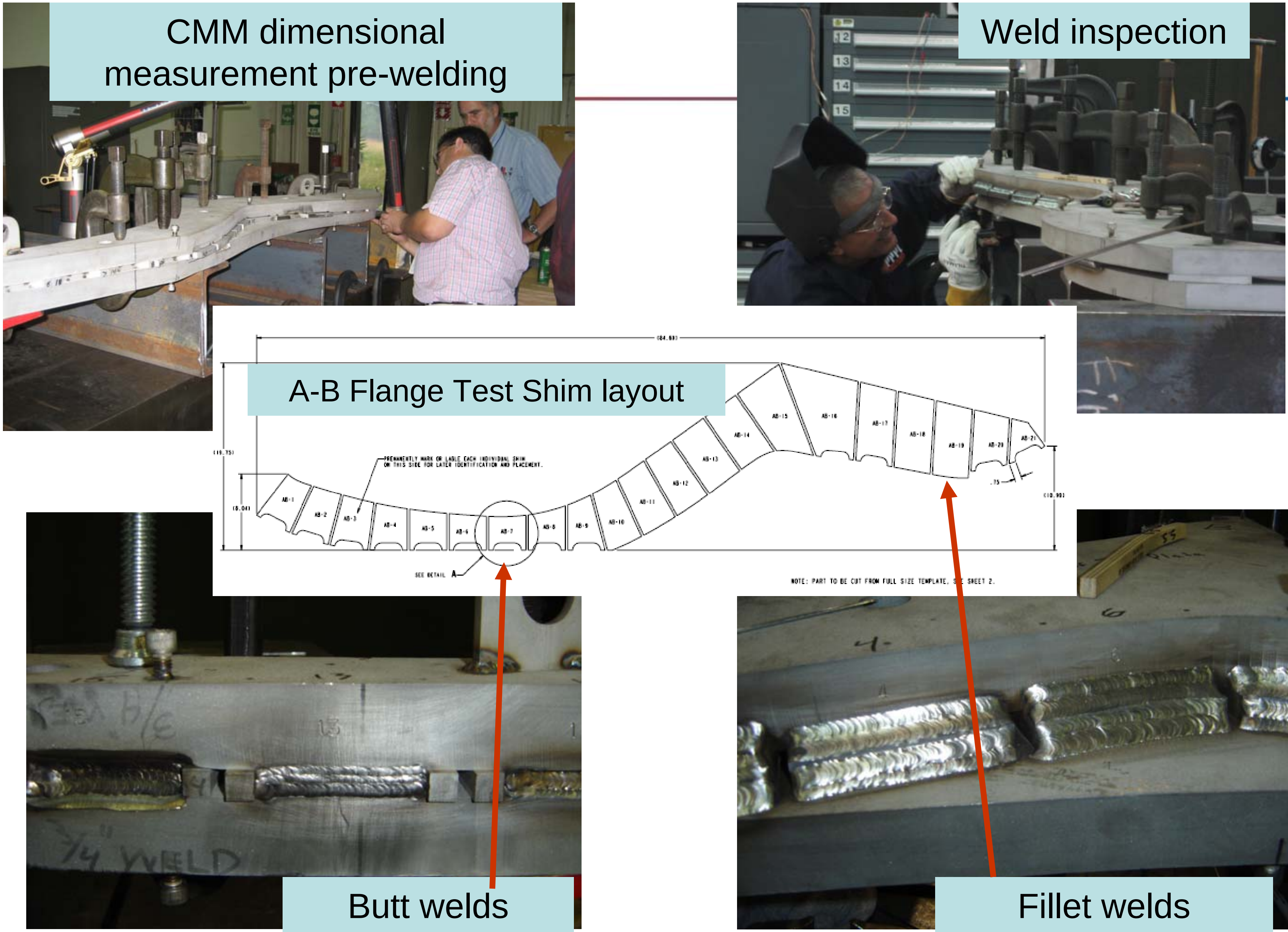



Figure D2. Penetration Depth Measurements by UT on Samples 22A and 25A (Upper: A side – Lower: B side.)

**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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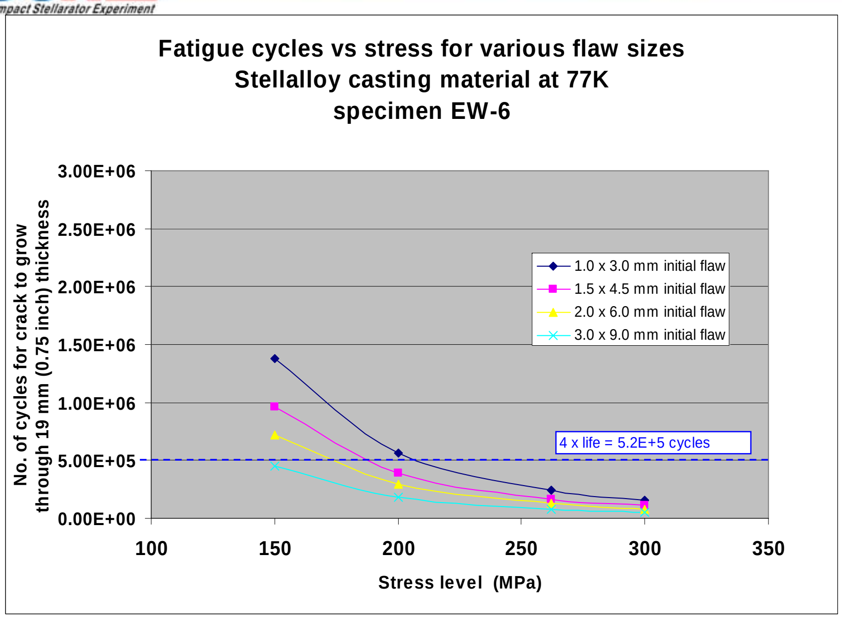
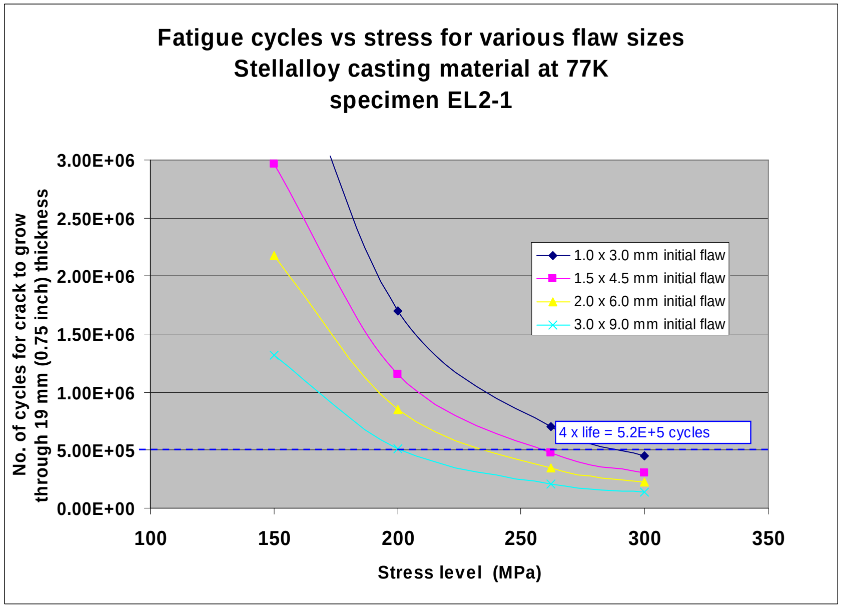
- Shims are made from 316L SS
  - solution annealed at 1150 C followed by rapid air cool to reduce magnetic permeability after all machining and grinding is completed.
- Specified $\mu_r$ is 1.02; localized areas slightly higher can be accepted.
- Results from the weld tests are excellent:
  - 1.5" plate before & after welding: all below $\mu_r$ 1.02.
  - 1/2" shims before welding: average $\mu_r$ 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 $\mu_r$ to >1.03 but <1.04 ; shims
    - 11 & 20 rose slightly from isolated spots of >1.03 but <1.04 $\mu_r$ 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 $\mu_r$ .

# 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 III  Welding Process


# Deflection Monitoring




# Phase III wing deflections after 25% weld deposited

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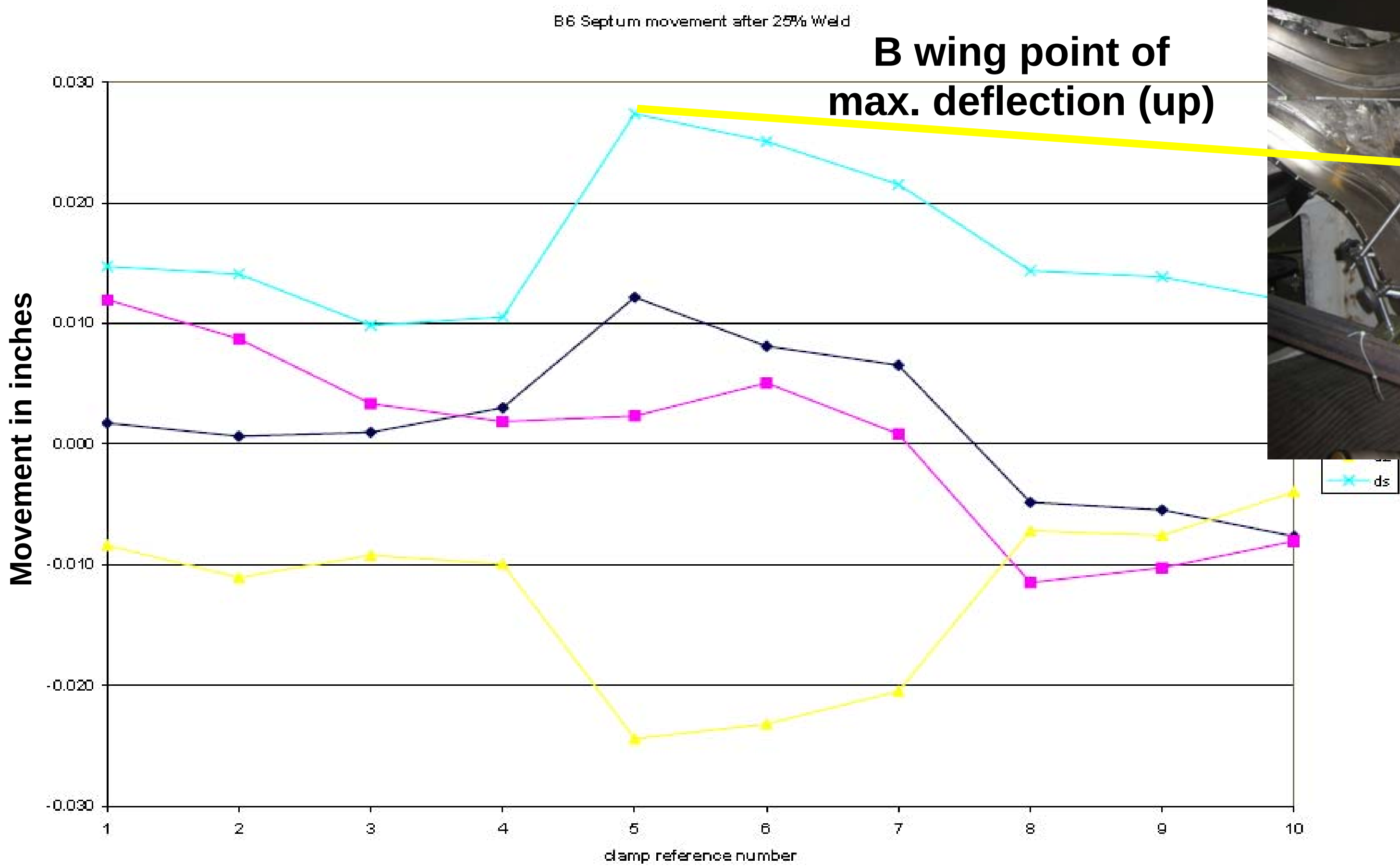


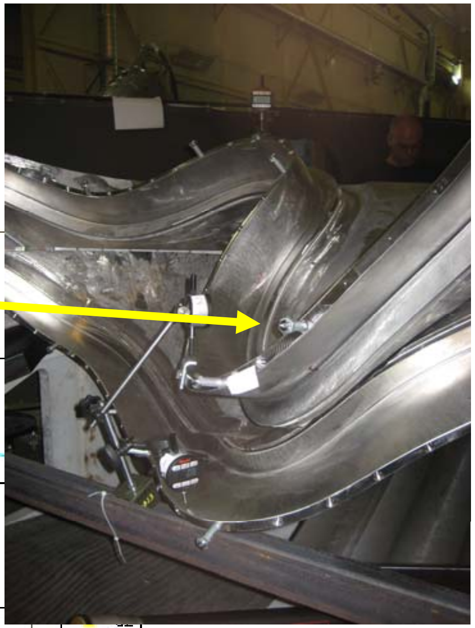

# Casting movement due to bolt tightening

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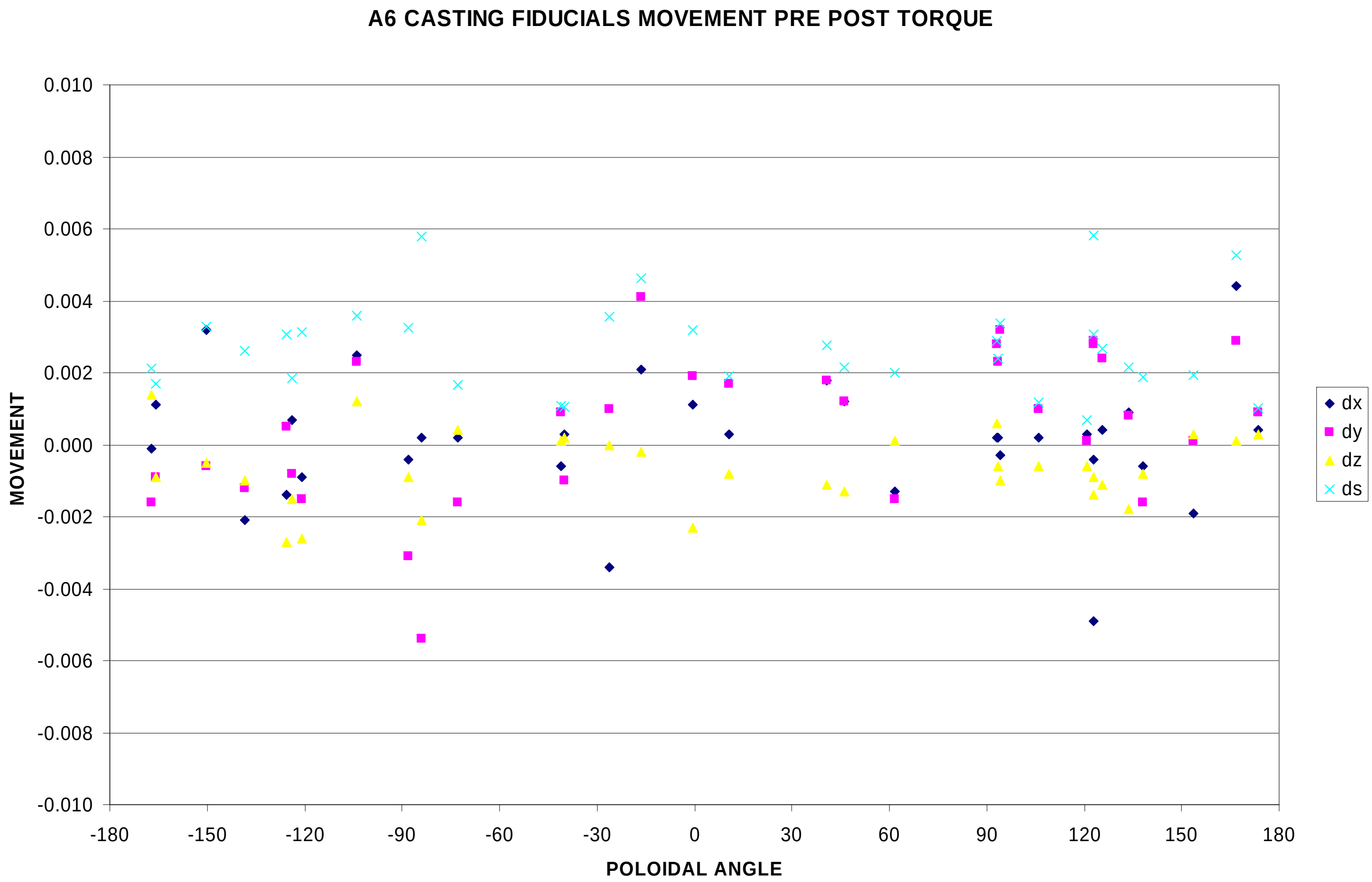

# Phase I, II, and III weld test results

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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

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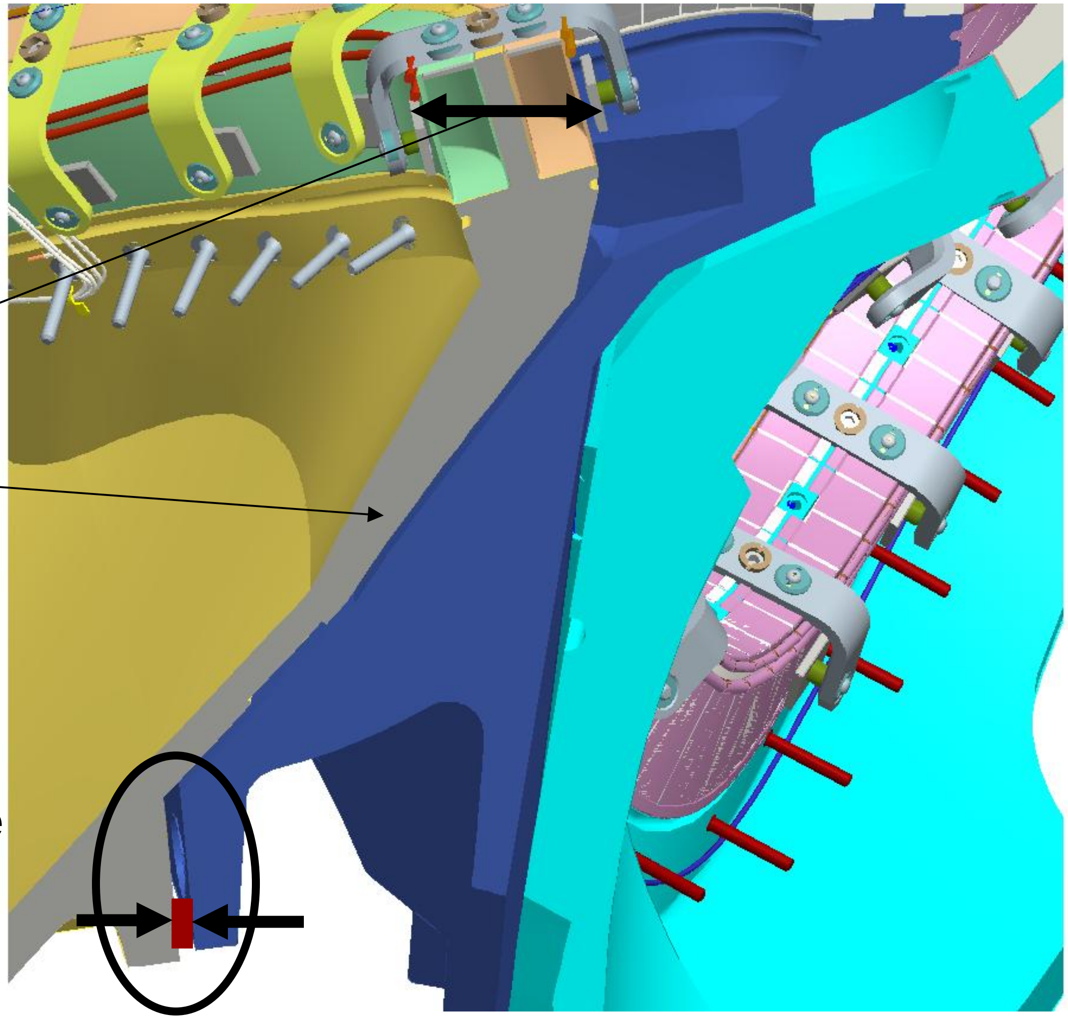
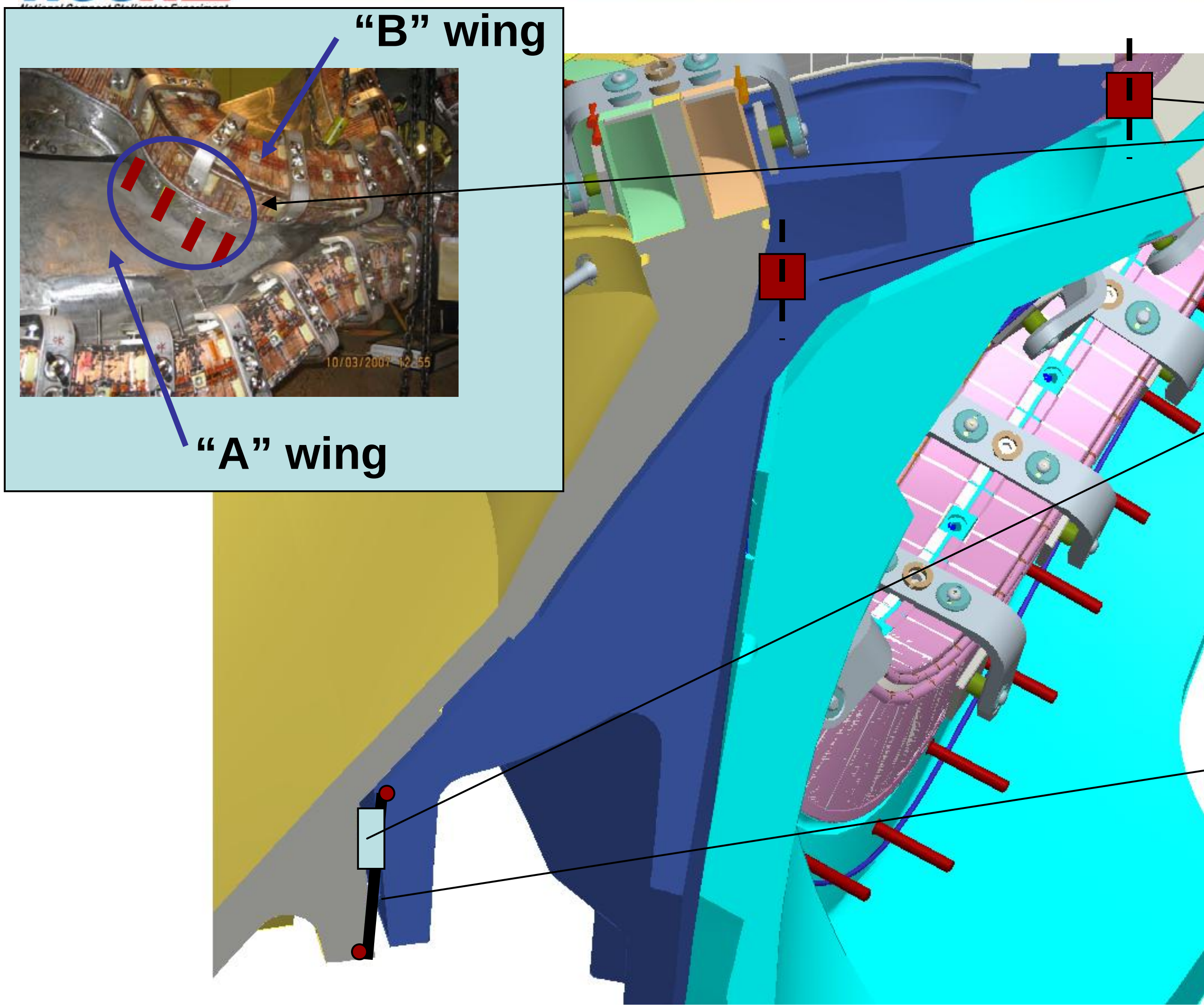
**3…..results in significant deflection at the winding**

**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



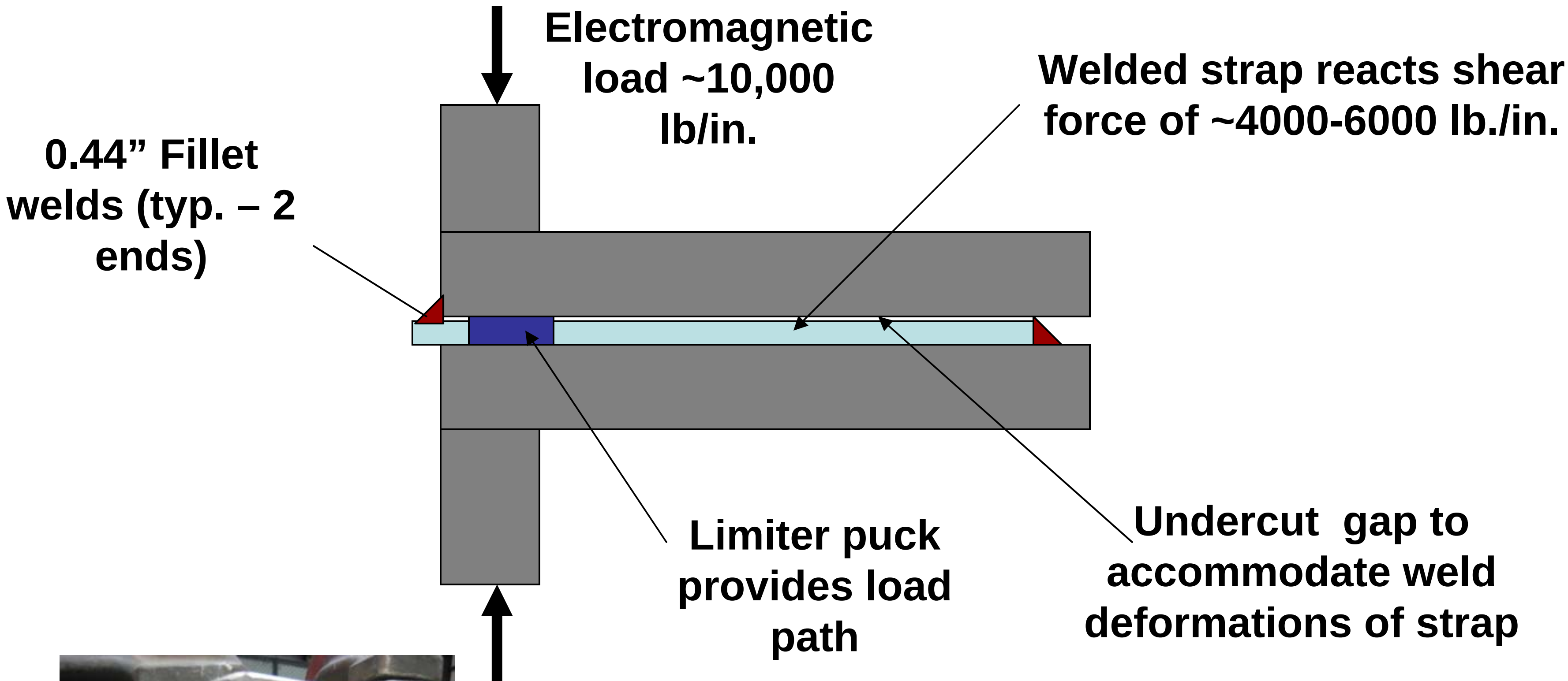

**1. Add wing restraints**

**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




***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.***

# Minimization of Longitudinal Weld Distortion

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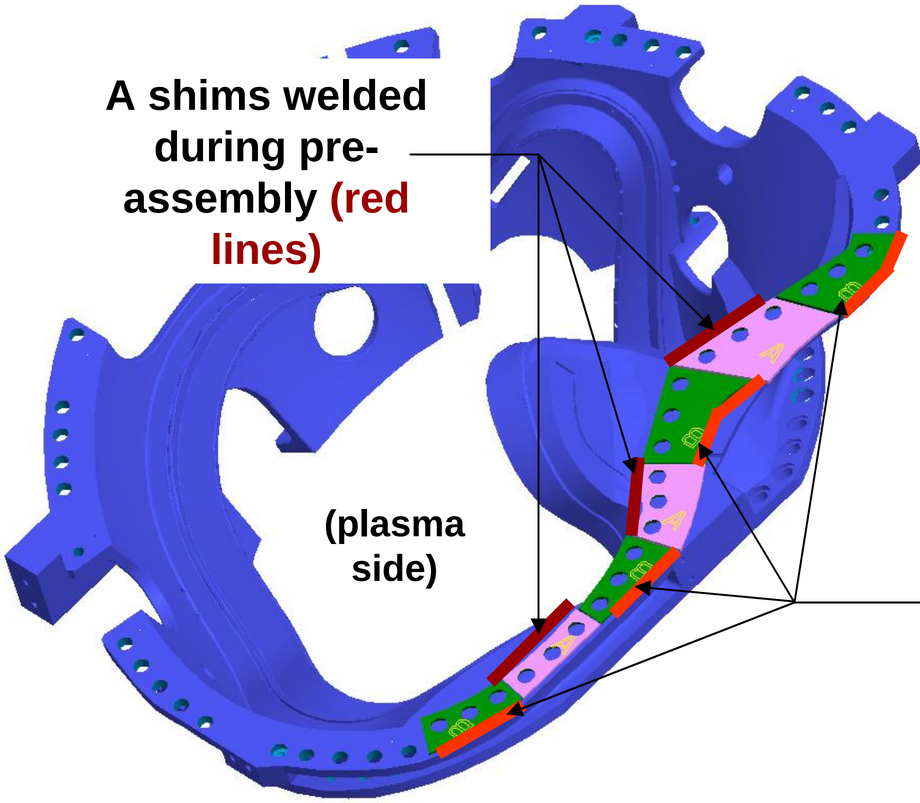


**Type A casting shown.**

- **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.**

**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.***

# Weld distortion minimization

- TIG welds.
- 7 stringers / fillet weld.
- Cooled to the touch between passes.
- Only half of a shim stringer welded per pass (i.e., ~6” per pass).
- Backstep welding used.

# 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. Can photogrammetry be more efficient?
  - 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

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- **We believe the design 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.