Dimensional Control for the National Compact Stellarator Experiment

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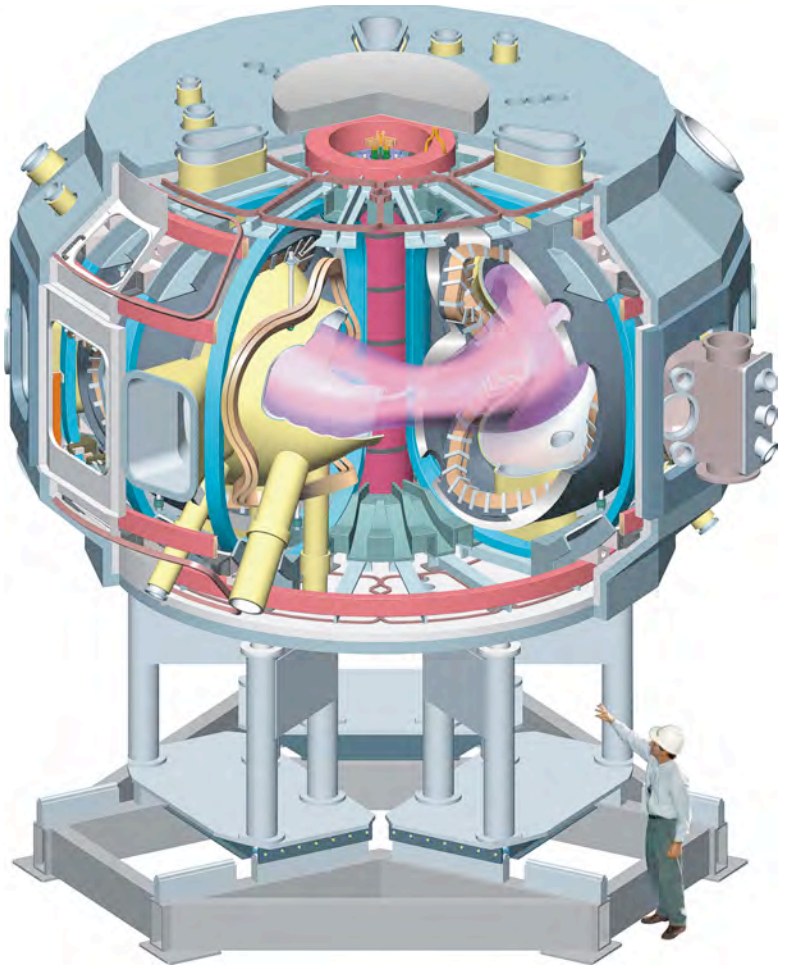
Outline of Talk

- NCSX Overview
- Dimensional Control Requirements
- Measurement Technology
- Dimensional Control of Modular Coils and Field Period Assembly
- Half Period Assembly Trials
- Summary

NCSX Overview

NCSX
National Compact Stellarator Experiment

- NCSX is the centerpiece of the U.S. effort to develop the physics of the compact stellarator.
- Quasi Symmetric
- 18 Modular Coils
  - 6 each of type A, B, and C
  - Modular coils are connected by bolted joints with shims.
- 18 Toroidal Field Coils
- 6 pairs of Poloidal Field Coils
- Trim coils
- Major Radius 1.4m
- Aspect Ratio 4.4
- Magnetic Field 1.2T – 1.7T



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Dimensional Control Requirements Result from Consideration of Many Design Issues

NCSX
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- Physics requirements on installed coil current centers.
- Coil tolerances.
- Allocation of tolerances for different assembly steps.
- As-wound accuracy of modular coils.
- Possible improvements through coil realignments after manufacture.

The Physics Requirements for Dimensional Control Relate to Field Errors

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- 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.
- Tolerances were set based partially on experiences of other machines.
  - 1 part in 1000, or 1.5mm [.060in] for a 1.5m machine.
- Extensive tolerance studies were performed to verify that, with trim coils, this tolerance will result in the desired field quality.
- Tolerances on coils further from the plasma were relaxed, because they have less impact on field errors.
- Field error correction [trim] coils shall be provided to compensate for fabrication deviations.

The Physics Requirements Led to a Set of Coil Tolerance Specifications

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- These coil tolerances pertain to the location of the current centers of the installed coils relative to the ideal [theoretical] position.
  - Modular Coils +/- 1.5mm [.060in]
  - PF Coils +/- 3.0mm [.120in]
  - TF Coils +/- 3.0mm [.120in]
  - Trim Coils +/- 3.0mm [.120in]
- The modular coils are the most critical.
- An allocation of the modular coil tolerance for each major assembly step has been defined.

Tolerances are Allocated to Each Modular Coil Assembly Step

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- Vendor machining and in-house winding +/- 0.5mm [.020in]
  - Manufacturing deviations in the winding forms are compensated for during winding.
  - Realignment offers a chance for improved performance.
- Half Period [3-pack] Assembly [B-A, C-B] +/- 0.25mm [.010in]
  - We expect this to be the most difficult requirement.
  - Flange to flange alignment determines overall alignment.
  - A-A alignment performed prior to half period assembly.
- Full period assembly over vacuum vessel
  - HPA + FPA tolerance = 0.5mm [.020in].
  - A-A alignment will bring us close to this goal.
- 3 period assembly in test cell +/- 0.5mm [.020in]
  - C-C alignment

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There are Three Types of Modular Coil

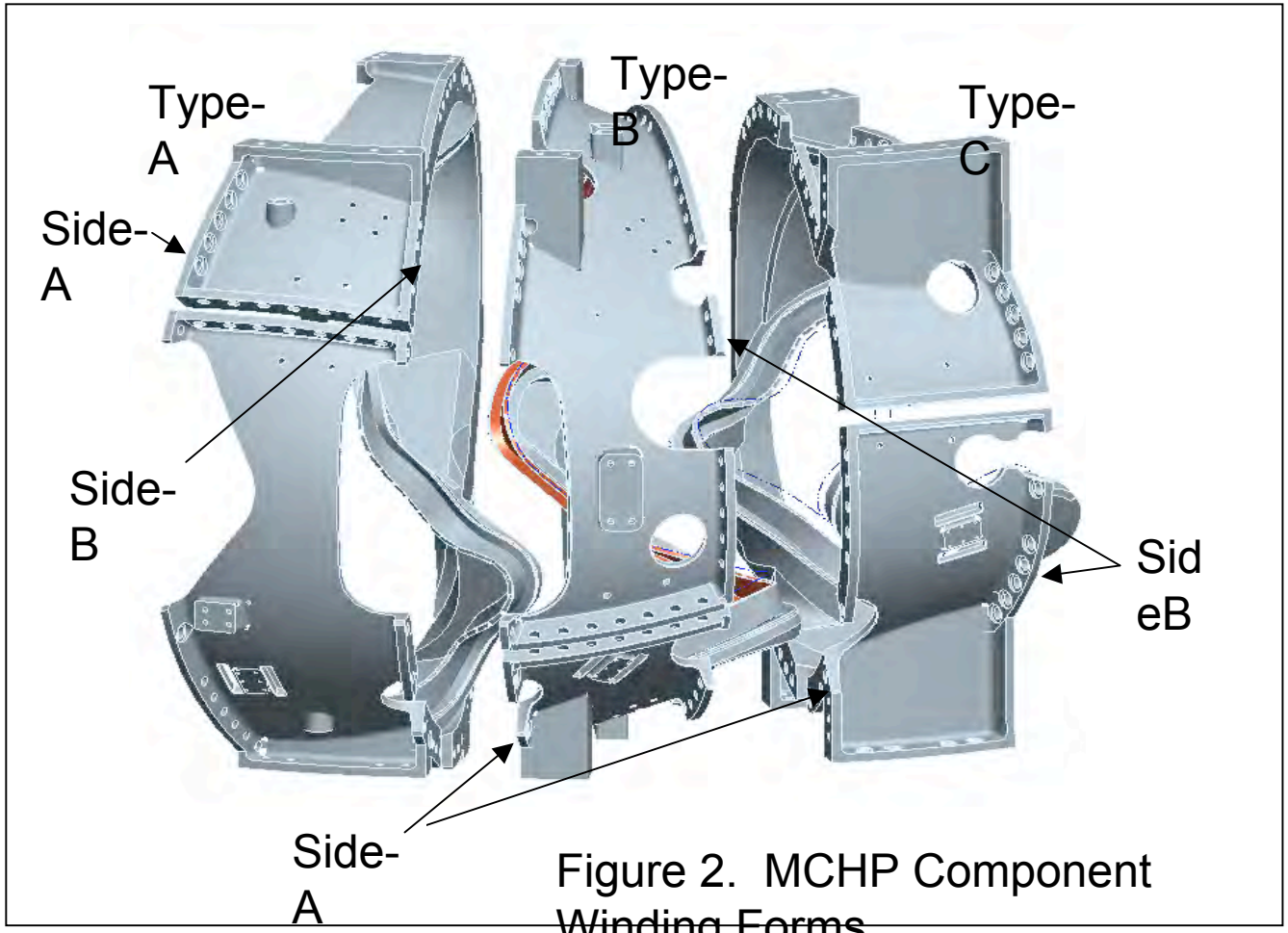

Figure 2. MCHP Component Winding Forms

The Assembly Tolerances are at the Limits of our Measurement Technology

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- The position of the coil throughout assembly is defined by a set of fiducial monuments.
  - The winding geometry is measured in a coordinate system referenced to these monuments.
- A mechanical measuring arm is used for the coil winding process.
- A laser tracker is used for subsequent assembly tasks.
- Measurement software works with the measurement arm, laser tracker and CAD models to expedite measurement of each winding form.

The Position of the Coil is Defined by a Set of Fiducial Monuments on the Winding Form

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- Most monuments are 0.5in diameter tooling balls that fit into precise .25in diameter holes.
- During MCWF manufacture, 9 holes [10 on type C] are drilled into each flange.
- At PPPL, monuments for the probe on the measuring arm are installed on each MCWF.
  - Conical seats accept the 15mm diameter probe tip.
  - Coil winding measurements are taken with respect to the conical seats.
- After coil winding, receptacles for additional tooling balls are welded to the MCWF body.
- Positions of all tooling balls are measured with respect to conical seats.
  - Position of coil current centers w.r.t. tooling balls is established.

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Mechanical Arm and a Laser Tracker are Used During Manufacture/Assembly

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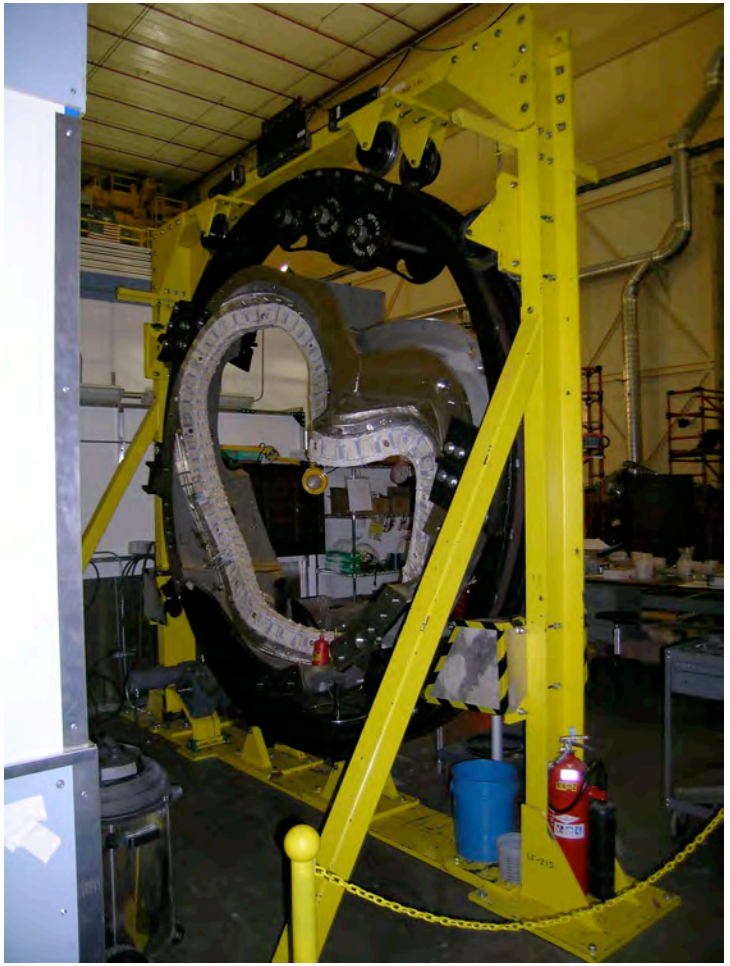
- Mechanical arm is used during coil winding.
  - The modular coil is mounted in a ring which can be rotated in the winding fixture.
  - The conical seats are used to establish a coordinate system for measurement of winding geometry.
  - Each time the ring is rotated, the conical seats are used to re-establish the coordinate system for measuring the windings.
- Laser tracker is used for subsequent operations.
  - Covers a larger assembly.



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Measurement Software Works with Measuring Arm/Laser/CAD Models

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- A coordinate system is established by measuring a number of points, and performing a best fit to the corresponding locations on the CAD model.
  - More points ◊ more confidence in best fit.
  - ~8 points are typically used to establish a coordinate system.
- The quality of the best fit is verified by checking the rms and maximum deviations.
- A variety of output formats are available after measurements.
  - IGES file for further CAD processing.
  - Spreadsheet format

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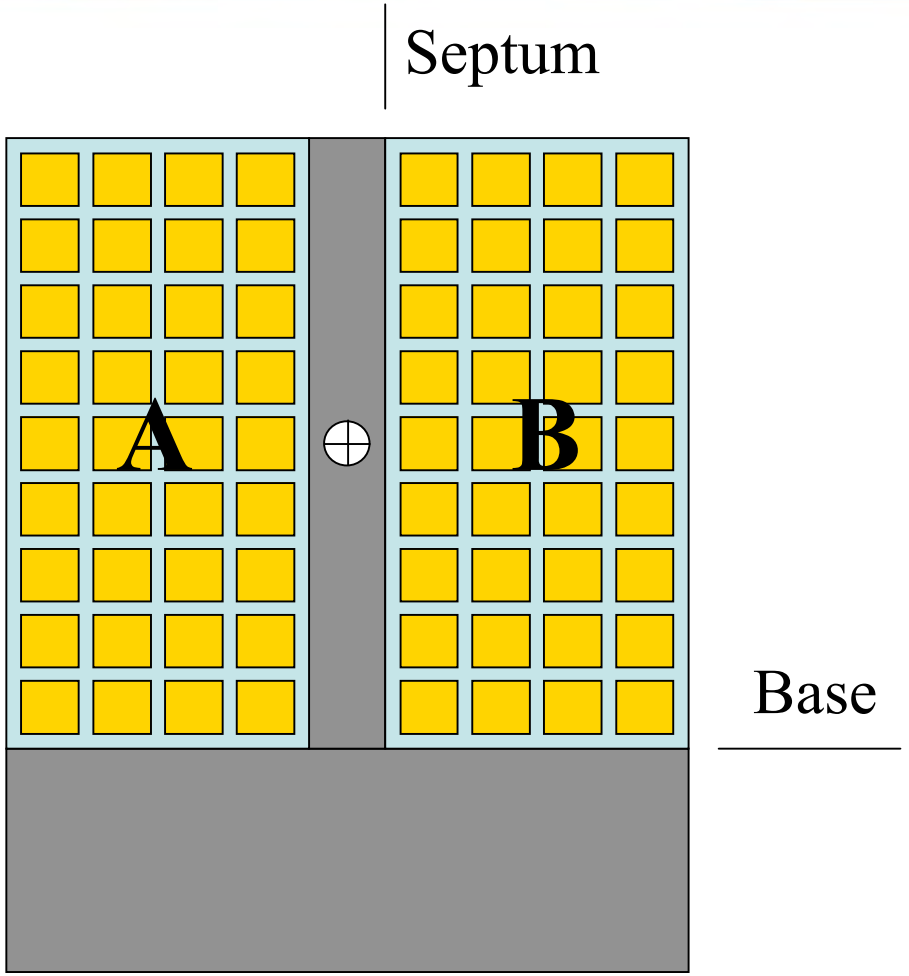
Modular Coil Current Centers Have Been Positioned Within Accuracy Requirements

- Some locations of winding surfaces were up to .050in out of position.
- Adjustments were made during coil winding to improve accuracy of current center position.



Type C Modular Coil, Clamp Number Convention and Side A/B Designation

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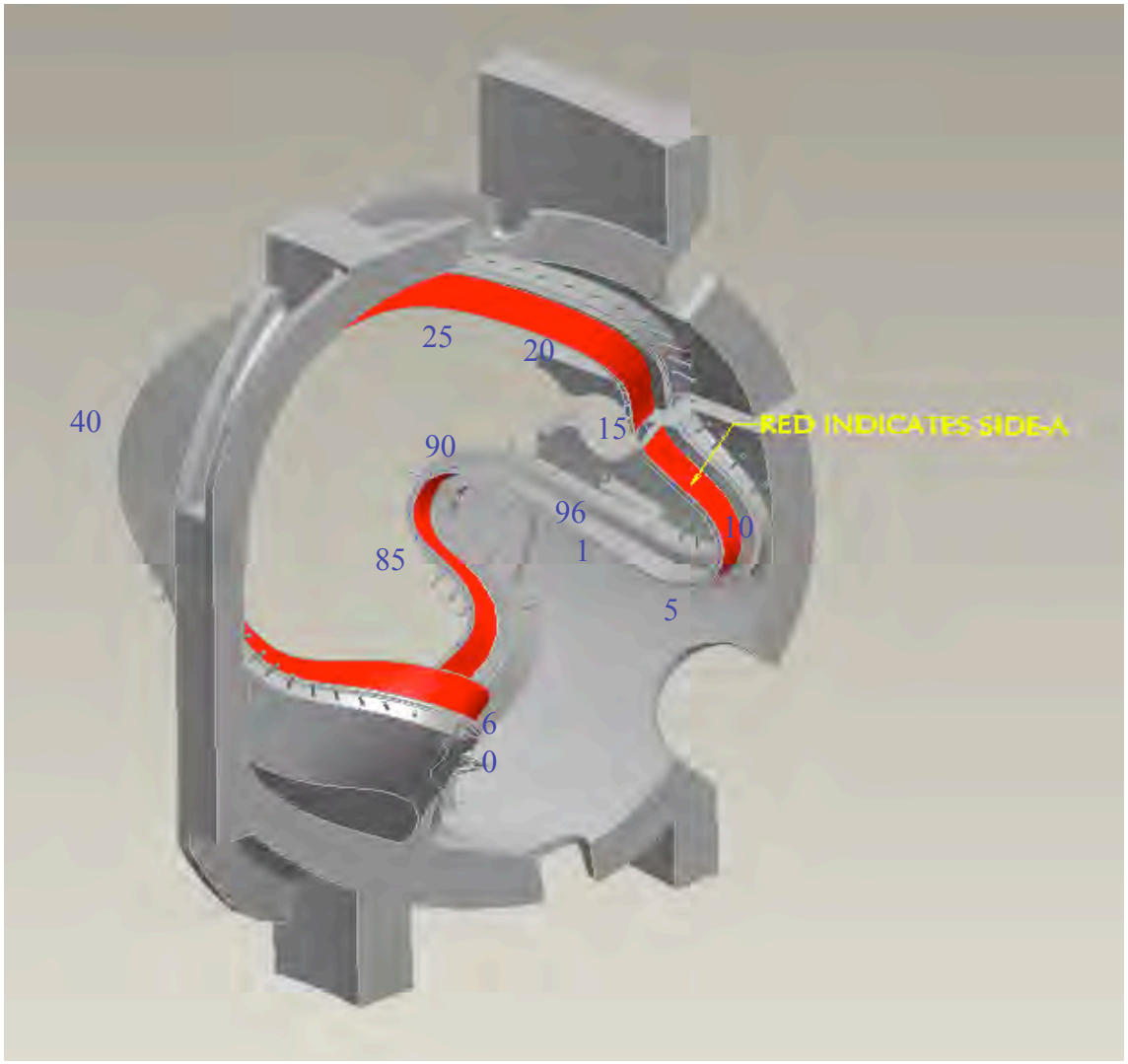
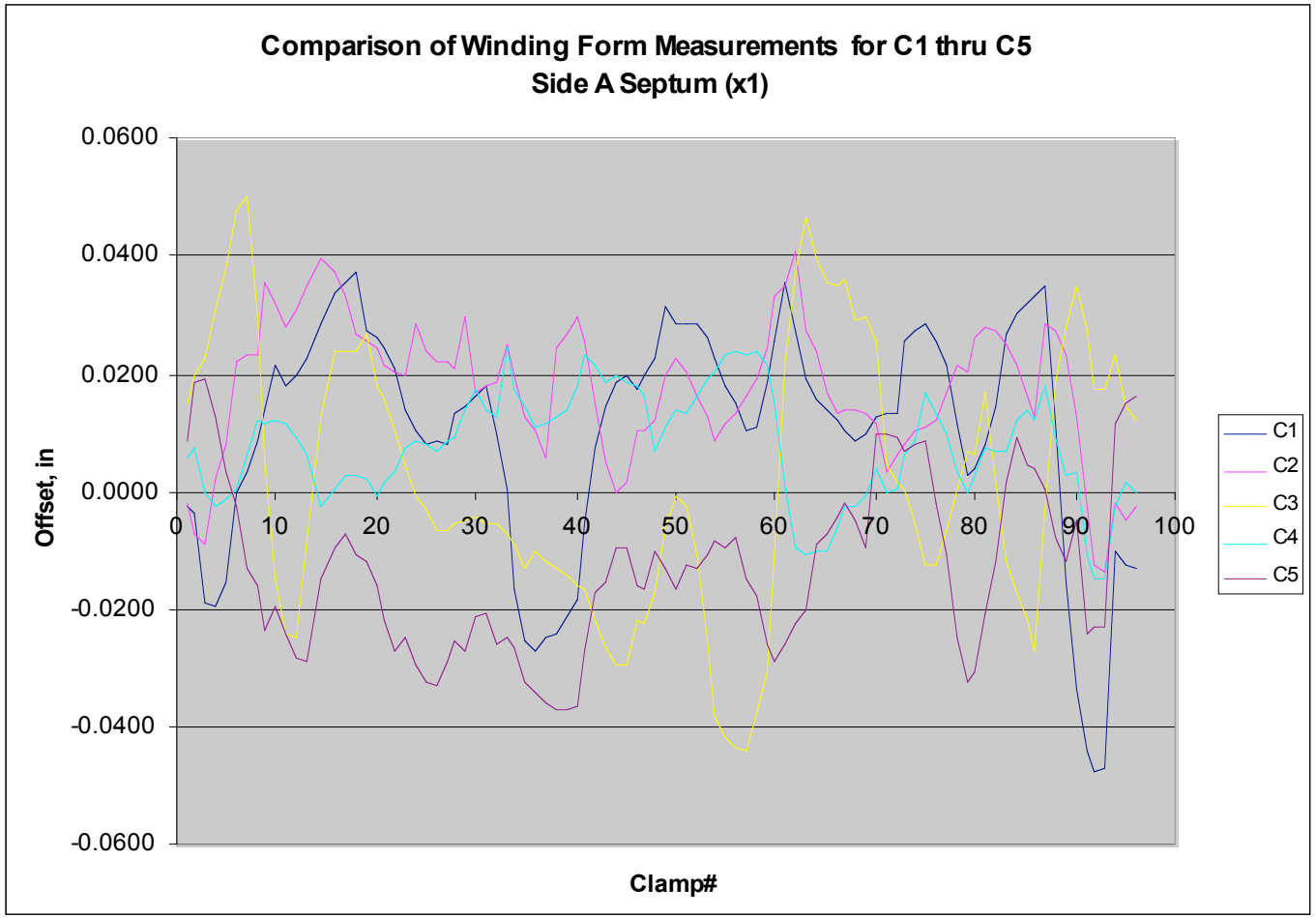


- ~6000 measured points characterize winding surface

Some As-Built Dimensions of Type C Coils are Out of Tolerance



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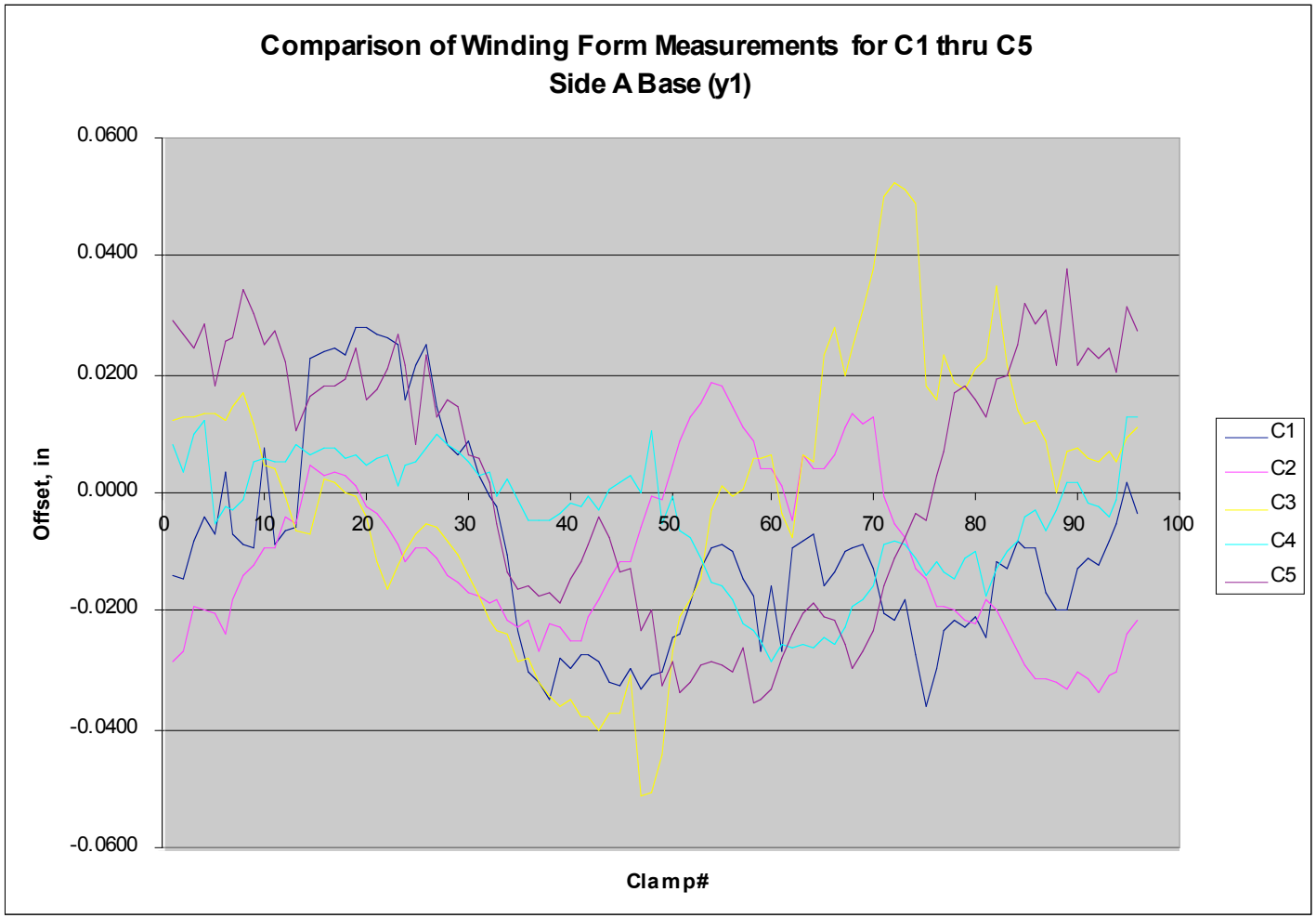
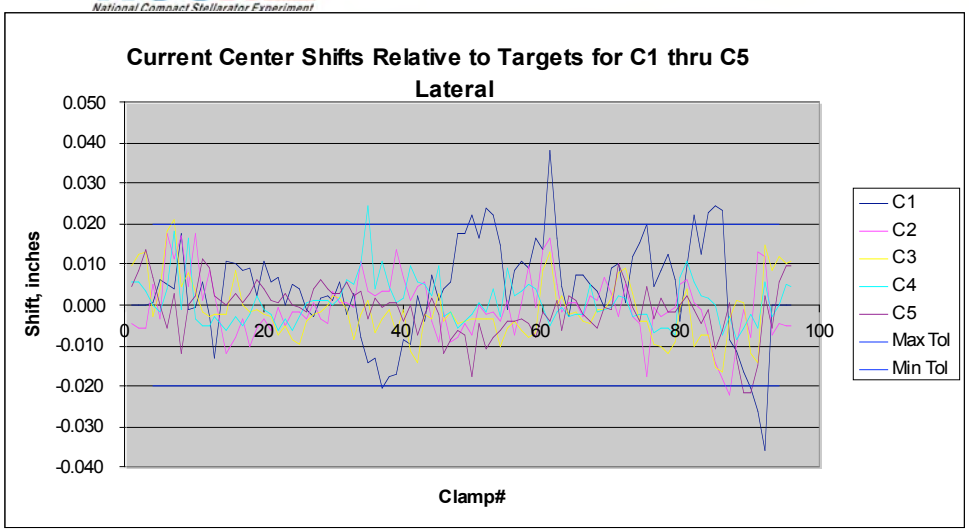
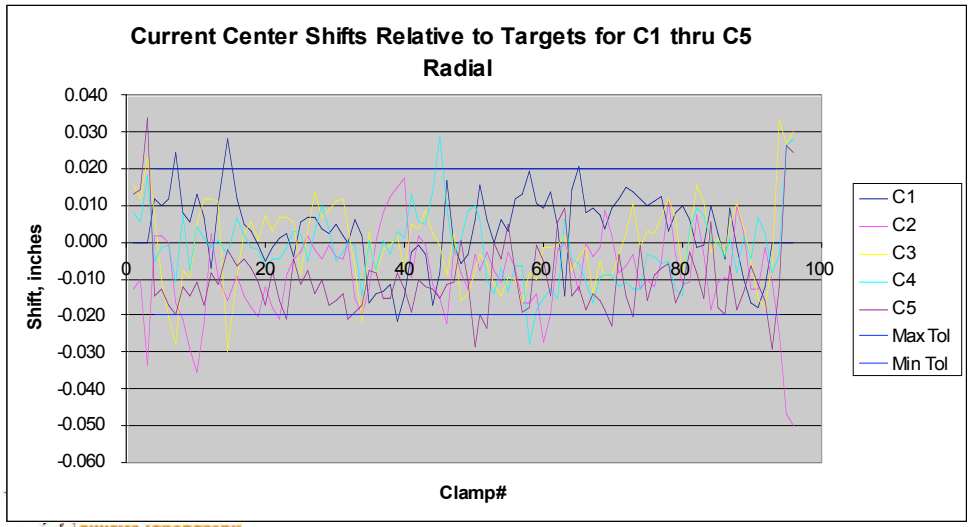


Adjustments During Winding can Correct Manufacturing Variations





- Adjustable clamps allow tailoring of the cross section of the winding pack on either side of the septum.
- As-built winding form measurements are used to set clamp positions.
- Clamp positions define a cross section of the winding pack.
- Compliance of the insulation, prior to potting, allows for adjustments.
- As-wound coils are mostly within tolerance

Half Period Assembly

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- The 0.25mm [.010in] tolerance for half period assembly is possibly the most stringent requirement in the assembly sequence.
  - Modular coils are ~2m [79in] “diameter”.
  - Modular coils are not rigid bodies.
- Precise assembly is necessary for proper load sharing between shims, as well as for dimensional control.
- An integrated metrology and assembly sequence has been prepared.
  - Laser metrology will play a key role in assembling the modular coils within the tolerance goal.
  - Fujipaper is used to monitor shim compression.
  - Stiff fixtures are required for assembly.
- Results of initial trials are encouraging.

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An Integrated Assembly Sequence has been Prepared

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- Prior to assembly, the locations of all tooling balls on each modular coil are measured, and the side “A” flange is scanned.
  - It is necessary to reposition the laser tracker several times around the periphery of the coil, in order to see all of the monuments.
    - The different scans overlap.
    - Measurements of a given monument from different positions illustrate the accuracy of the process.
- The coordinate system for this measurement is established from the conical seats.
  - Locations of new monuments are established.
  - Locations of original monuments are verified.
  - The coil current centers are now linked to the tooling ball positions.
- The first coil is placed on the assembly fixture, “B” side up.

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Assembly Sequence…

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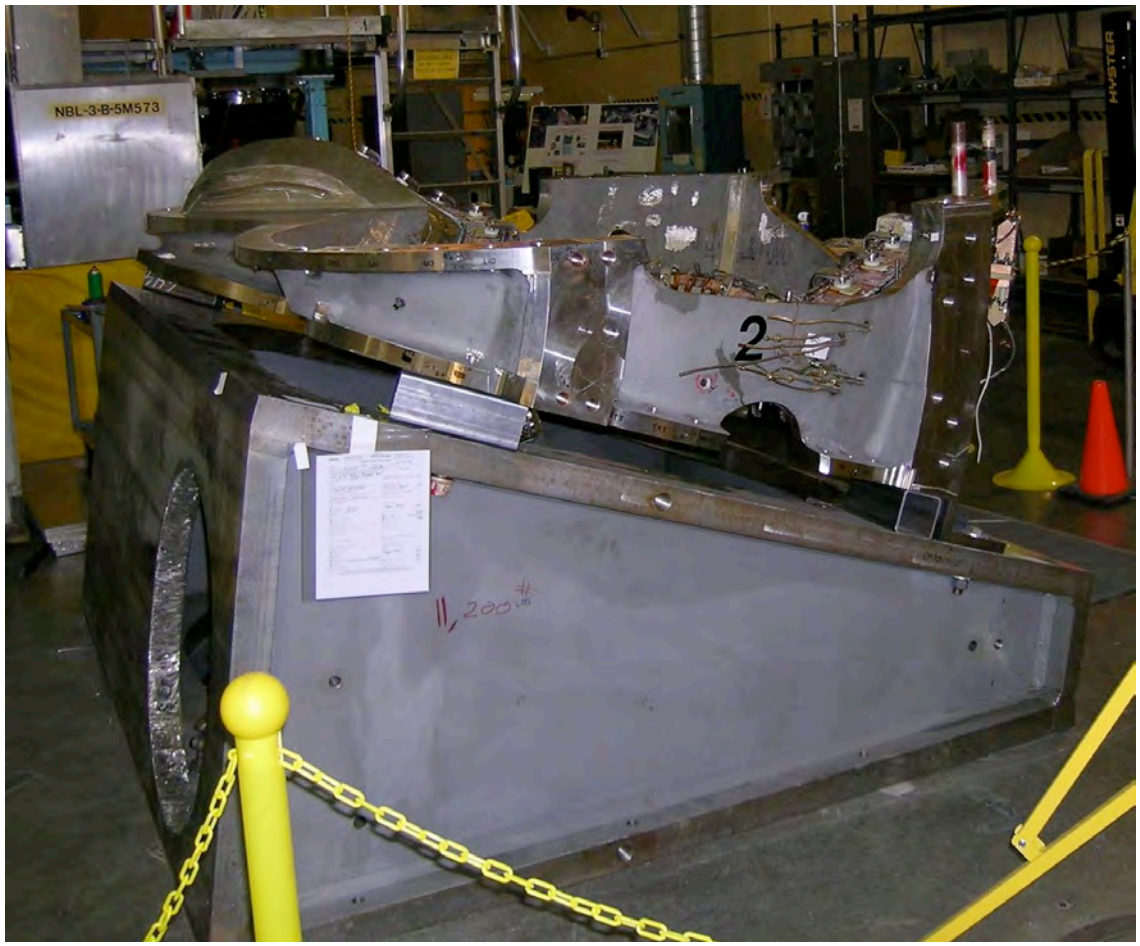
- The first coil is placed on the assembly fixture, “B” side up.
- The laser tracker is aligned to the monuments on the coil.
- The “B” (upper) flange is scanned.
- Using the “B” flange measurements and the “A” flange from the mating coil, a set of shim thicknesses is calculated



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Assembly Sequence…

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- Three of the shims are placed on top of the first coil.
- The second coil is lowered into position.
- The monuments on the bottom coil are re-measured, and the coil is jacked where necessary to restore its shape.

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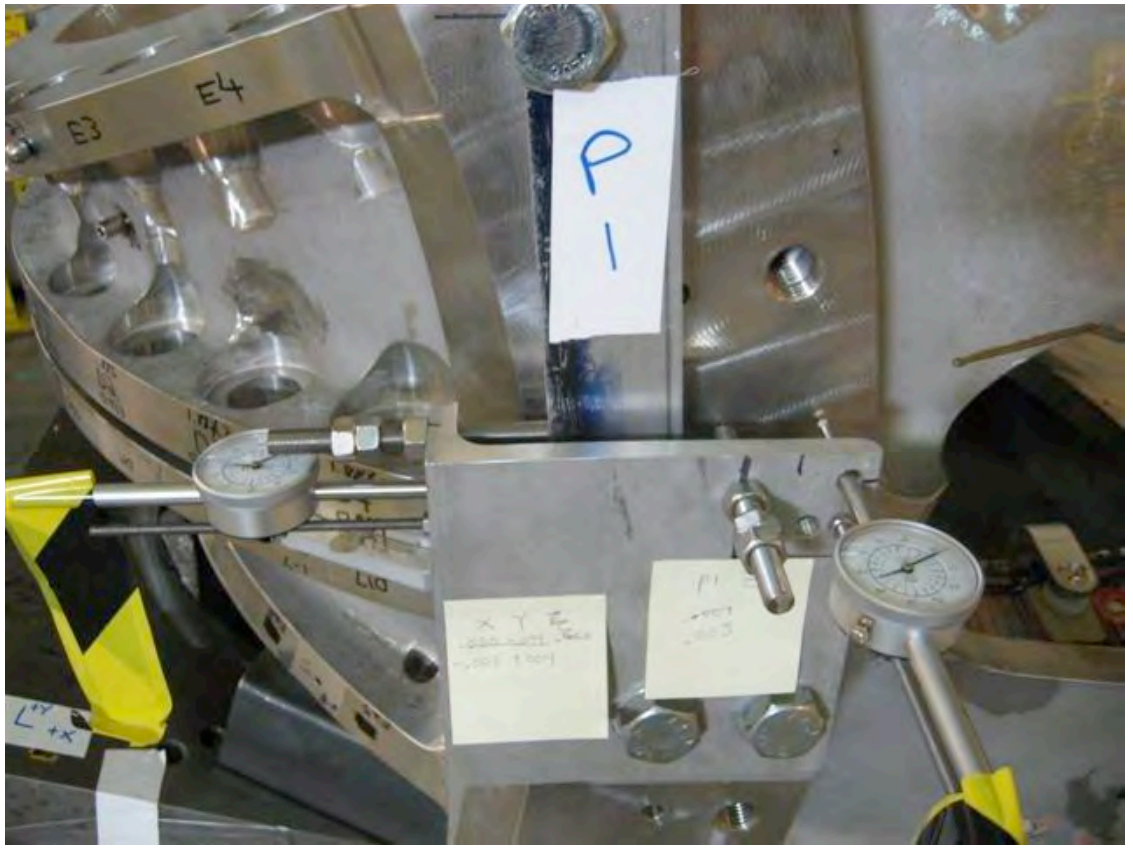
Assembly Sequence…

- The positions of three selected monuments on the top coil are measured.
- These locations are compared to theoretical locations, and a position adjustment of the upper coil is defined.
- This step is repeated until a satisfactory result is obtained.



Assembly Sequence…

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- The steps for mating the first two coils in a half period are repeated, on a different fixture, when the third coil is joined.
- The new fixture is tilted 40deg instead of 20deg, so that the mating surface will be horizontal.
- Because the top flange of the second [middle] coil is measured in its as-assembled condition, the accumulation of errors is minimized.
- A complete field period is assembled by bolting two half periods together at the interface between two “A” coils.
- Pre-fitting two mating type A coils prior to half period assembly will maximize the likelihood of successful full period assembly with a minimum of iterations.
- A trial of the A-A fitup will demonstrate the feasibility of our assembly sequence.

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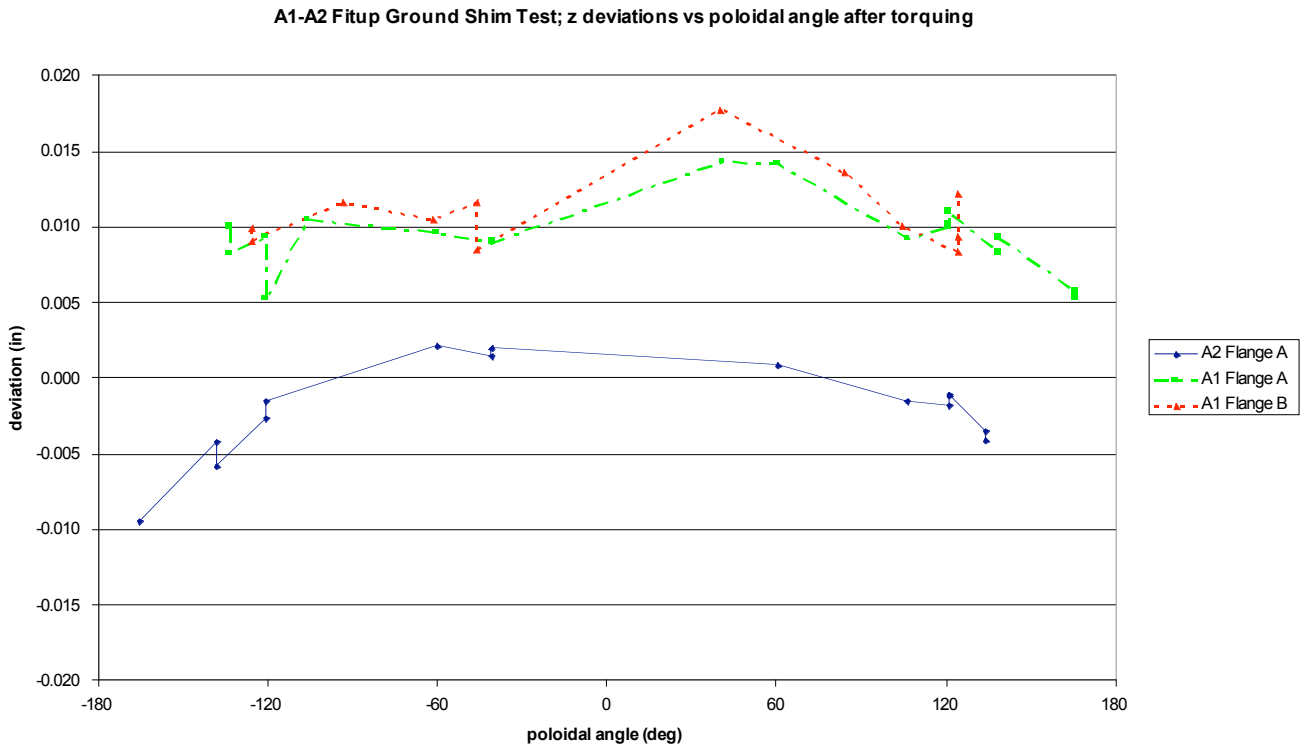
A1-A2 Fitup Trials

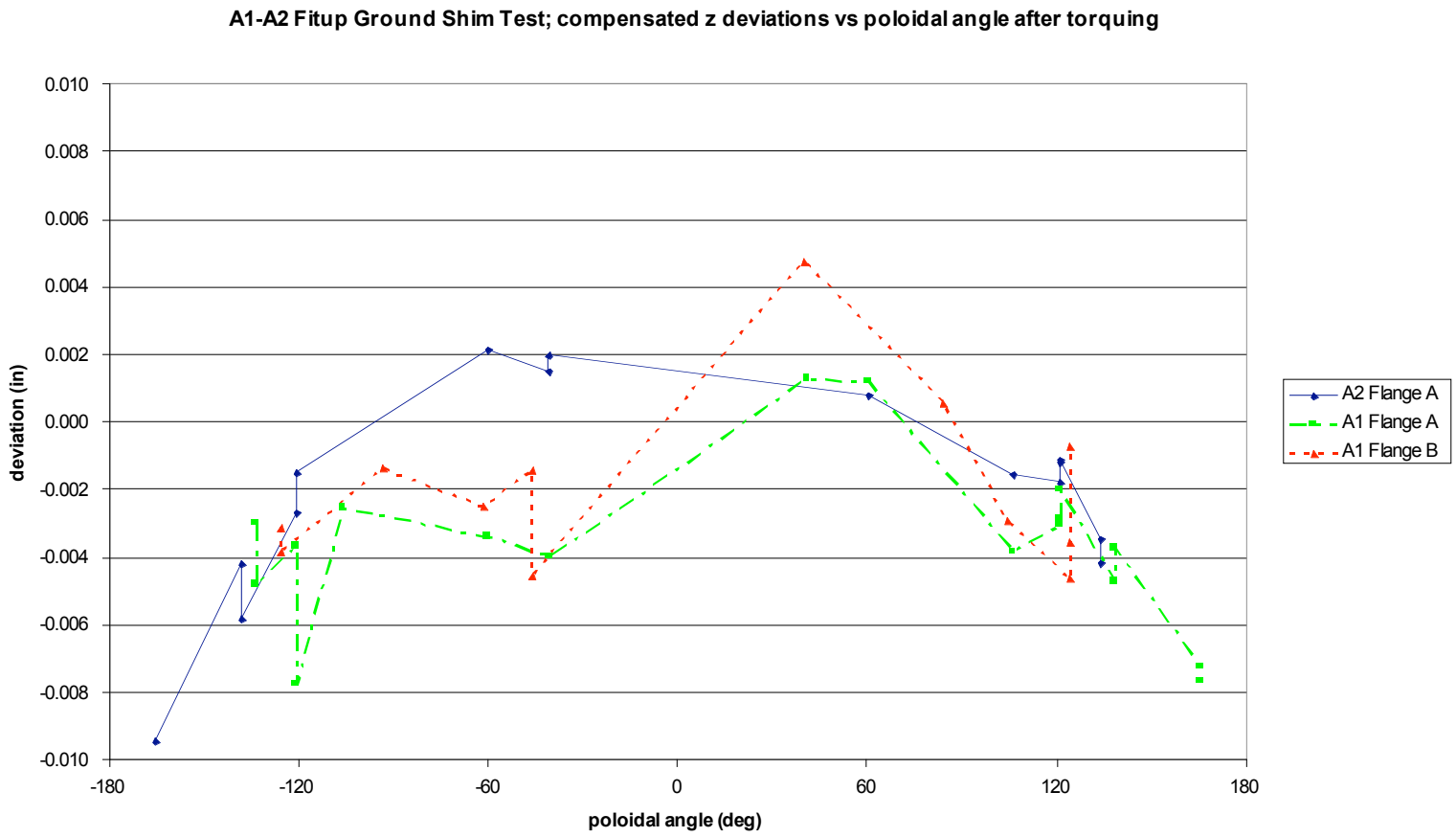
- The A1 and A2 coils were pre-assembled using the steps described previously.
- Shim thicknesses were calculated, a uniform .008in compensation was added, and a full set of ground stainless steel shims was fabricated.
  - The .008in compensation, in retrospect, should not have been used.
- Fujipaper [.005in thick] was added to each shim.
- Tooling ball positions were measured before and after bolts were tightened.

A1-A2 Fit-up trials Verify Feasibility of Assembly Sequence

- The bottom [A2] coil maintains its shape.
- The mating flanges track each other.
- The two flanges of the top [A1] coil track each other.



With Compensation and Without Fujipaper, z-Deviations are Acceptable.



Vector Sum of Deviations is Close to Goal on First Pass

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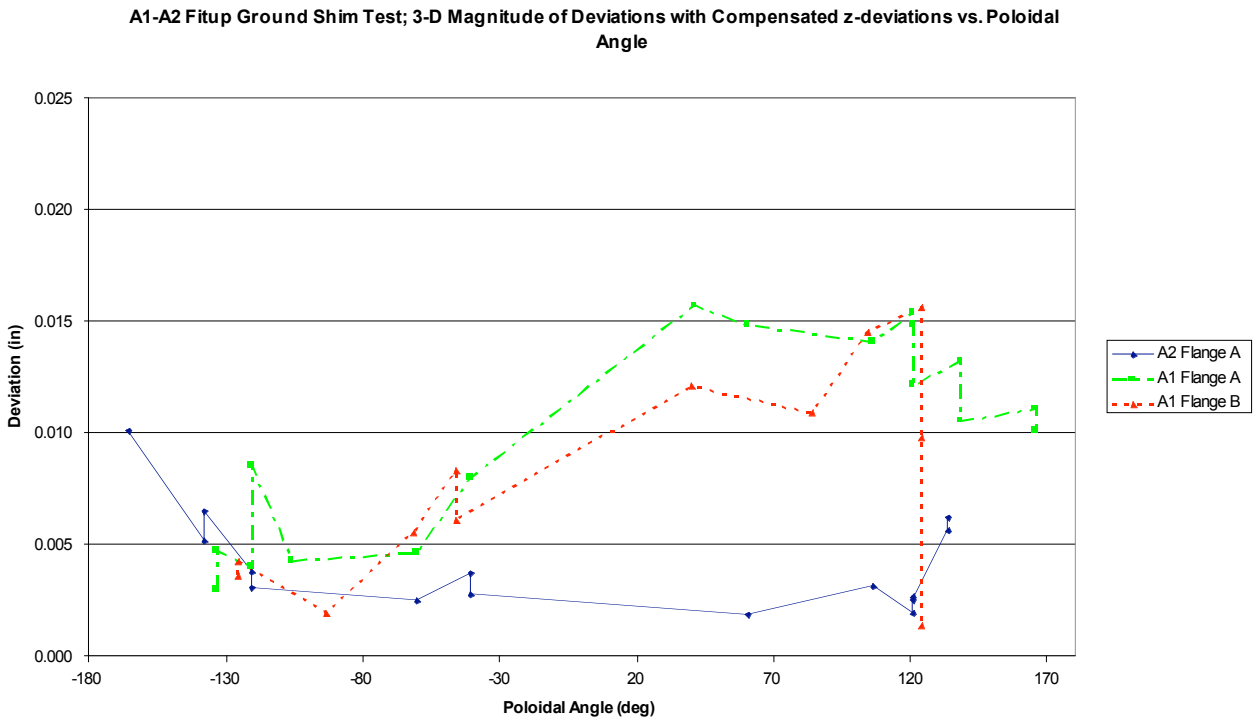
- This result represents the first pass during the assembly process.
  - The assembly sequence provides for one additional iteration.



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Fujipaper Shows Acceptable Load Sharing

Summary

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- Dimensional control for the modular coil manufacturing process has been implemented, and the desired tolerances have been achieved.
- Dimensional control and assembly procedures for the half period and full period assembly steps are nearing completion.
- Initial tests are encouraging.
  - The knowledge gained from the first full period assembly will be applied to the assembly of the entire machine, including toroidal field and poloidal field coils.

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