

Dimensional Control for the National Compact Stellarator Experiment

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Outline of Talk

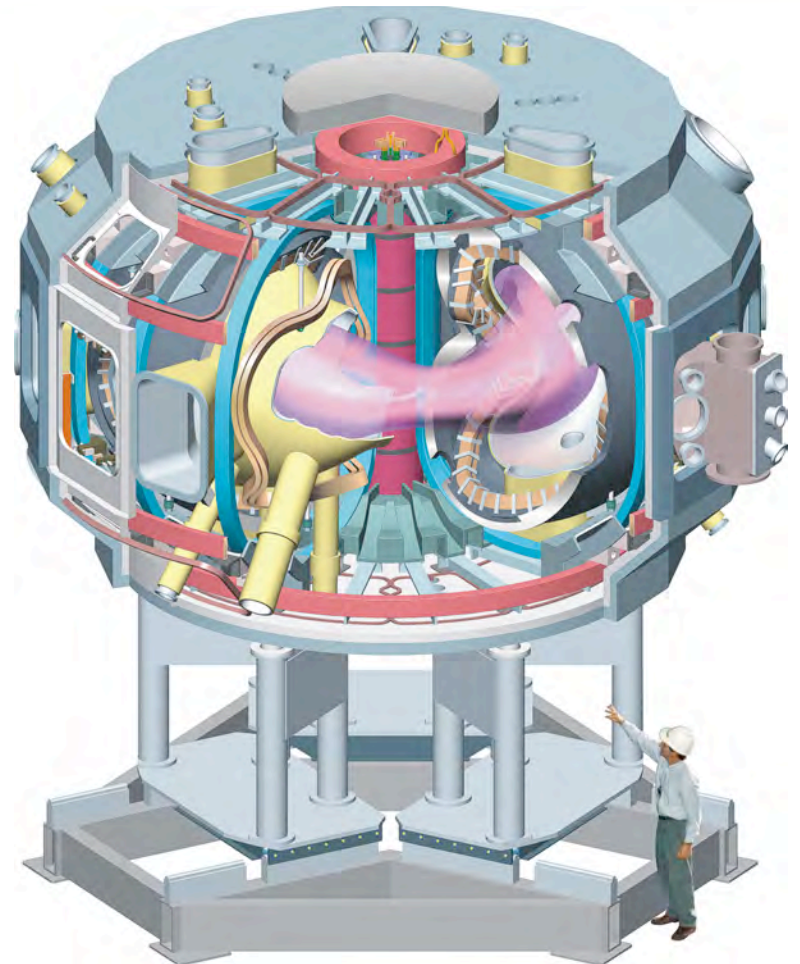


- NCSX Overview
- Dimensional Control Requirements
- Measurement Technology
- Dimensional Control of Modular Coils and Field Period Assembly
- Half Period Assembly Trials
- Summary

NCSX Overview



- NCSX 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



Dimensional Control Requirements Result from Consideration of Many Design Issues



- 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



- 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



- 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



- Vendor machining and in-house winding $\pm 0.5\text{mm}$ [.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] $\pm 0.25\text{mm}$ [.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 $\pm 0.5\text{mm}$ [.020in]
 - C-C alignment

There are Three Types of Modular Coil

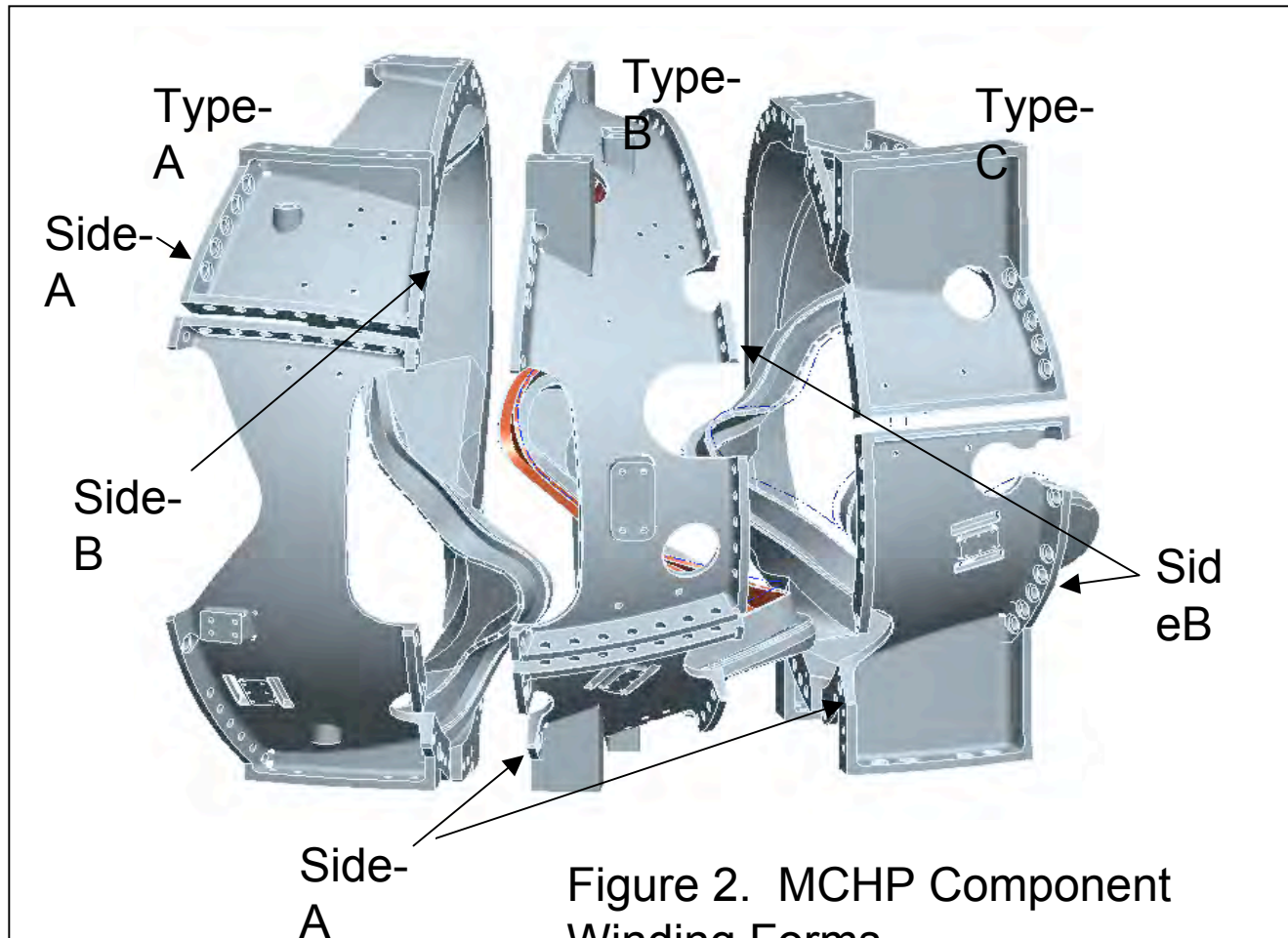


Figure 2. MCHP Component Winding Forms

The Assembly Tolerances are at the Limits of our Measurement Technology



- 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



- 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.

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



- 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.



Measurement Software Works with Measuring Arm/Laser/CAD Models

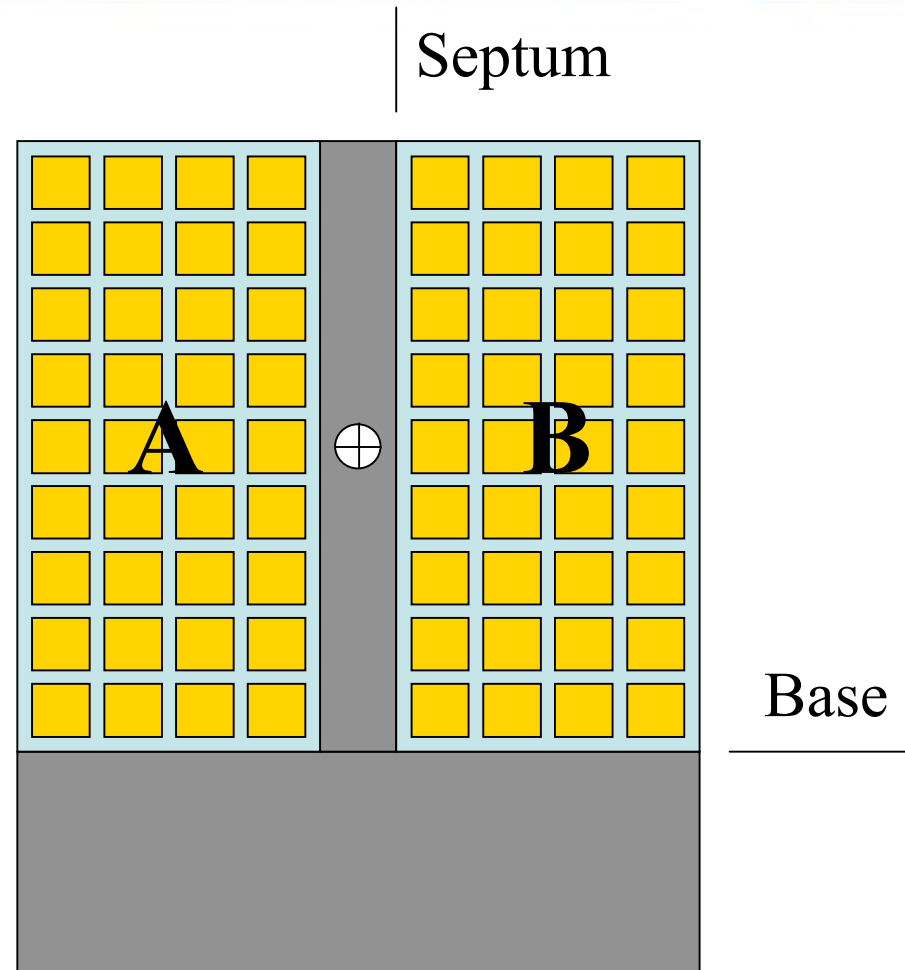


- A coordinate system is established by measuring a number of points, and performing a best fit to the corresponding locations on the CAD model.
 - More points \diamond more confidence in best fit.
 - ~8 points are typically used to establish a coordinate system.
- The quality of the best fit is verified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

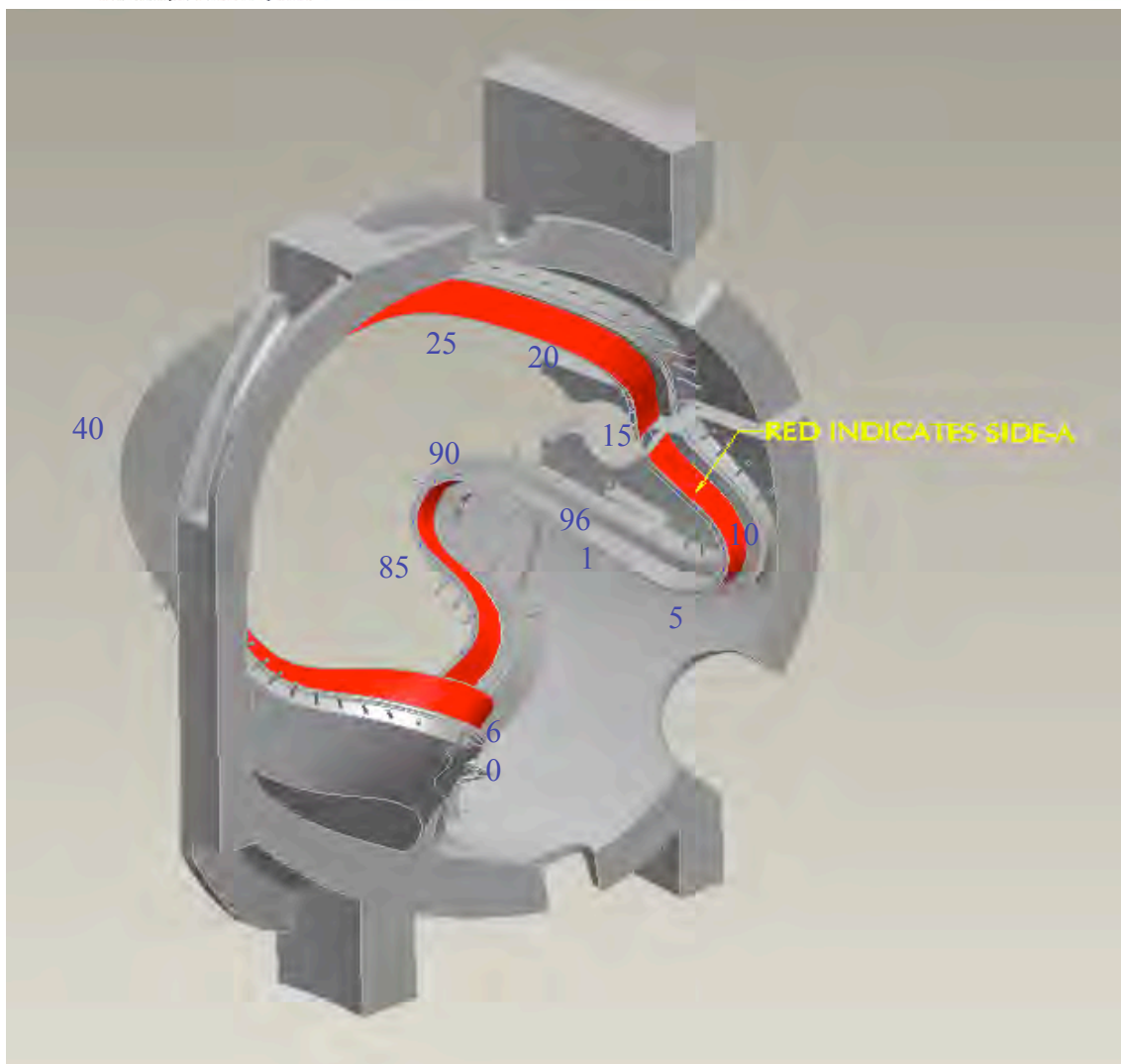
Modular Coil Current Centers Have Been Positioned Within Accuracy Requirements



- 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.

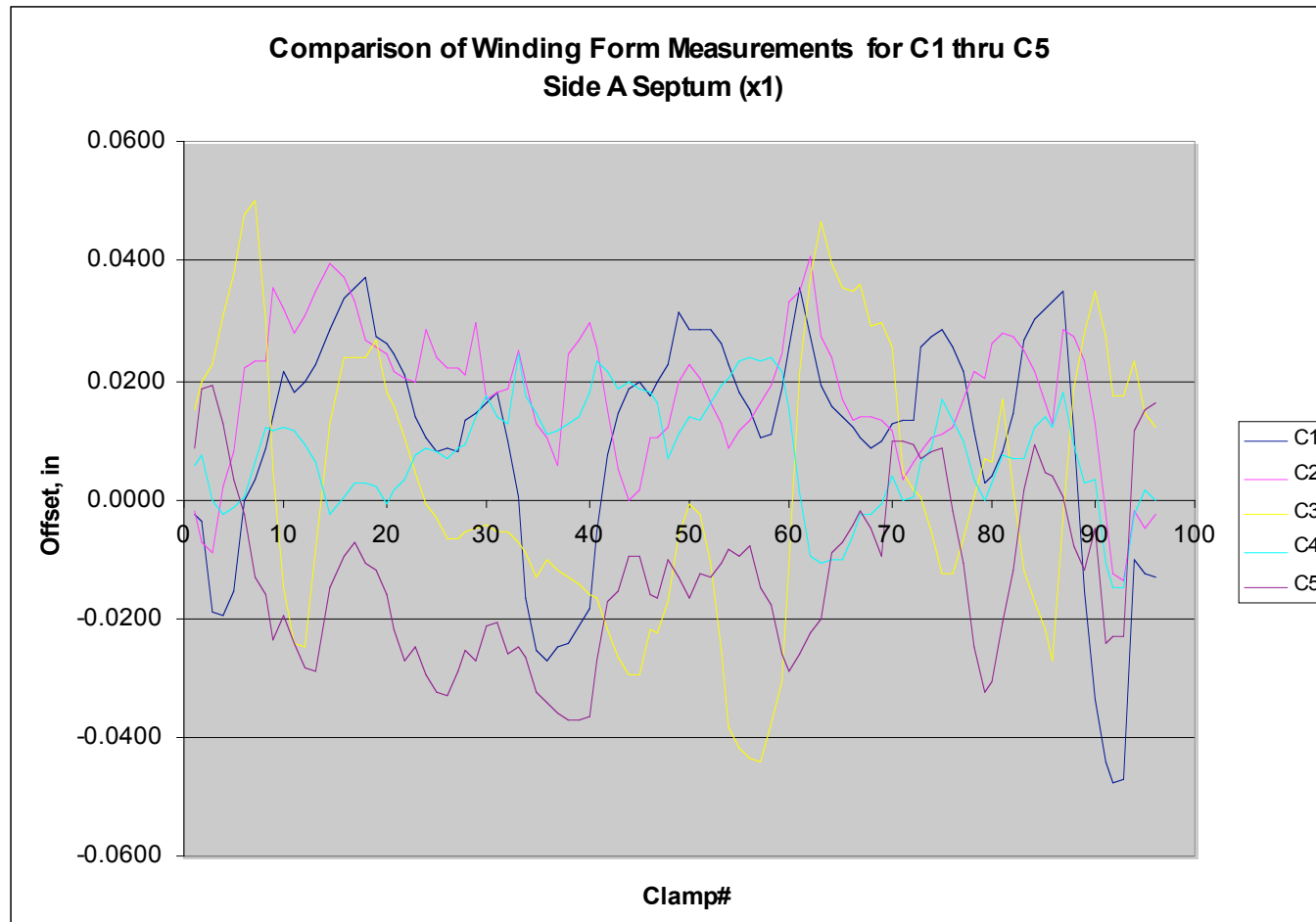


Type C Modular Coil, Clamp Number Convention and Side A/B Designation

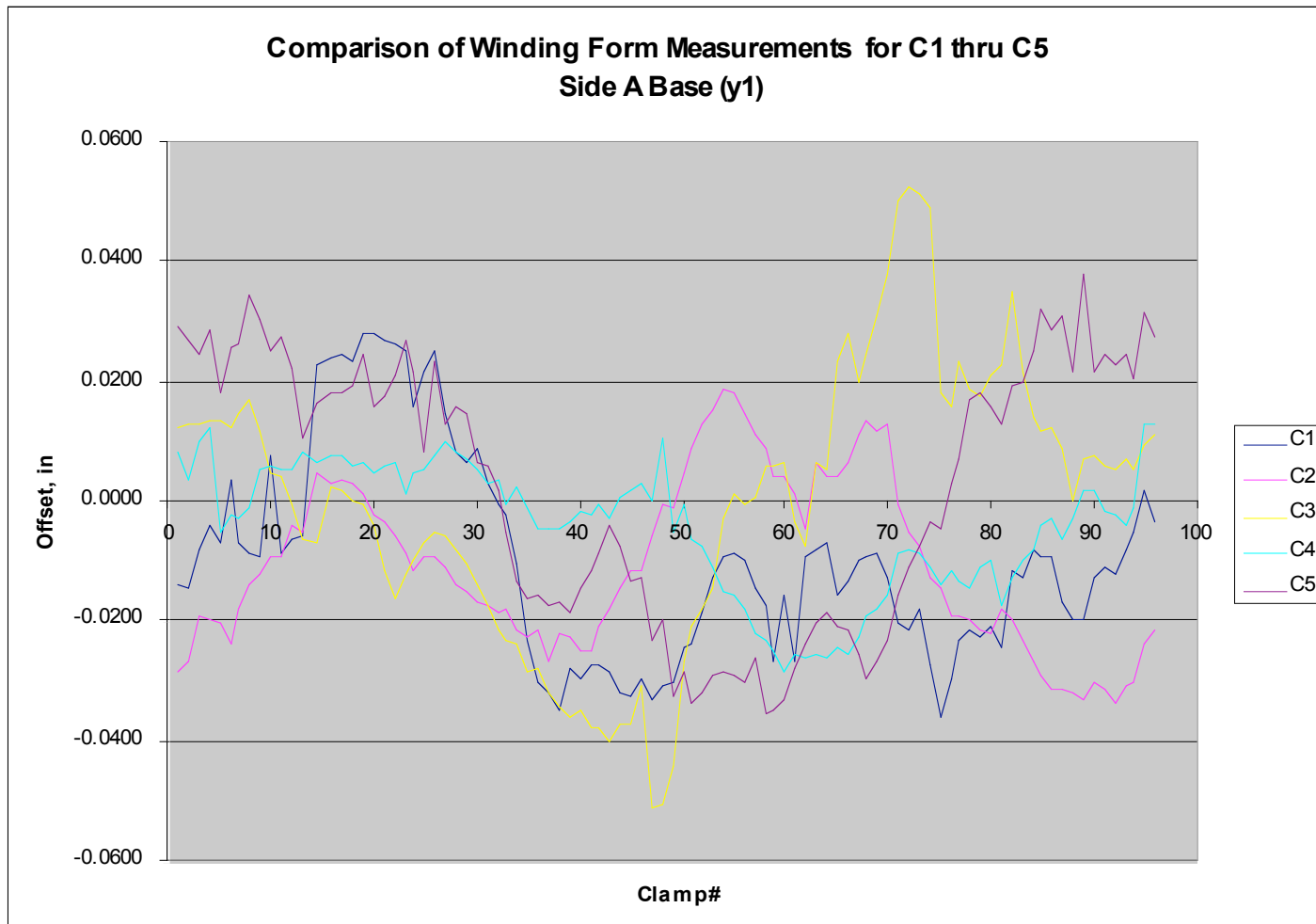


- ~6000 measured points characterize winding surface

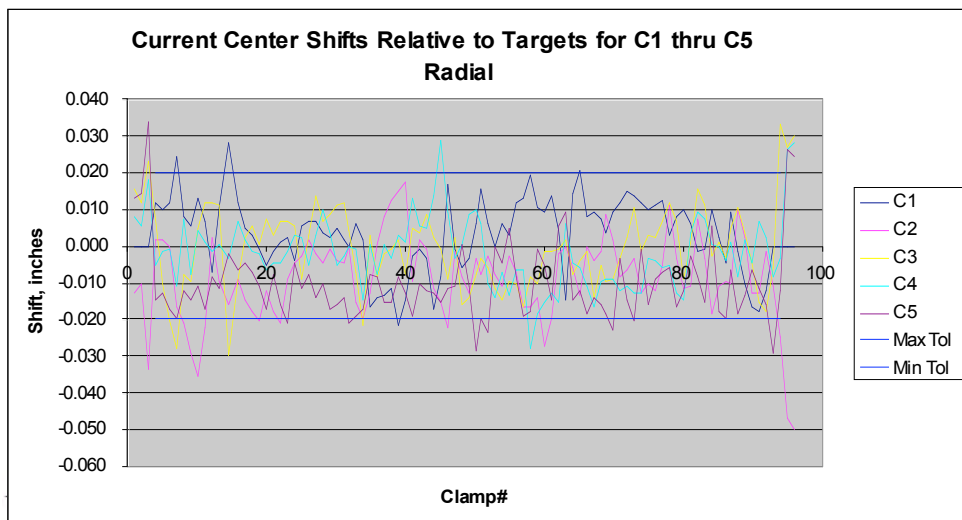
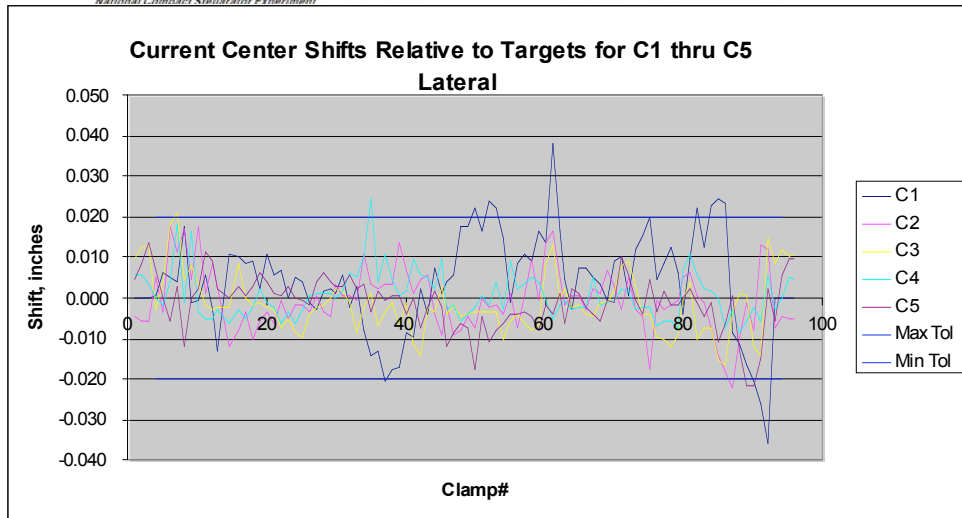
Some As-Built Dimensions of Type C Coils are Out of Tolerance



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



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



- 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.

An Integrated Assembly Sequence has been Prepared



- 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.

Assembly Sequence...



- 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



Assembly Sequence...



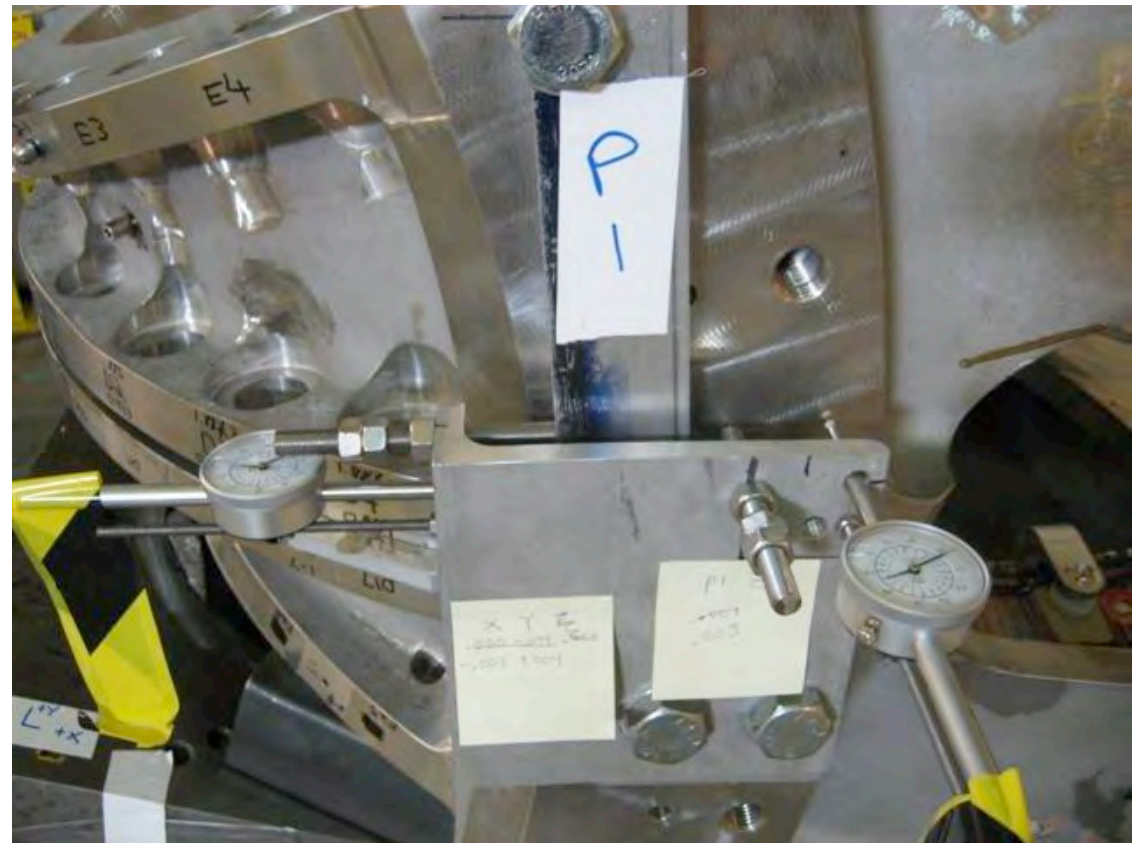
- Three of the shims are placed on top of the first coil.
- The second coil is lowered into position.
- The monuments on the bottom coil are re-measured, and the coil is jacked where necessary to restore its shape.



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...



- 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.

A1-A2 Fitup Trials

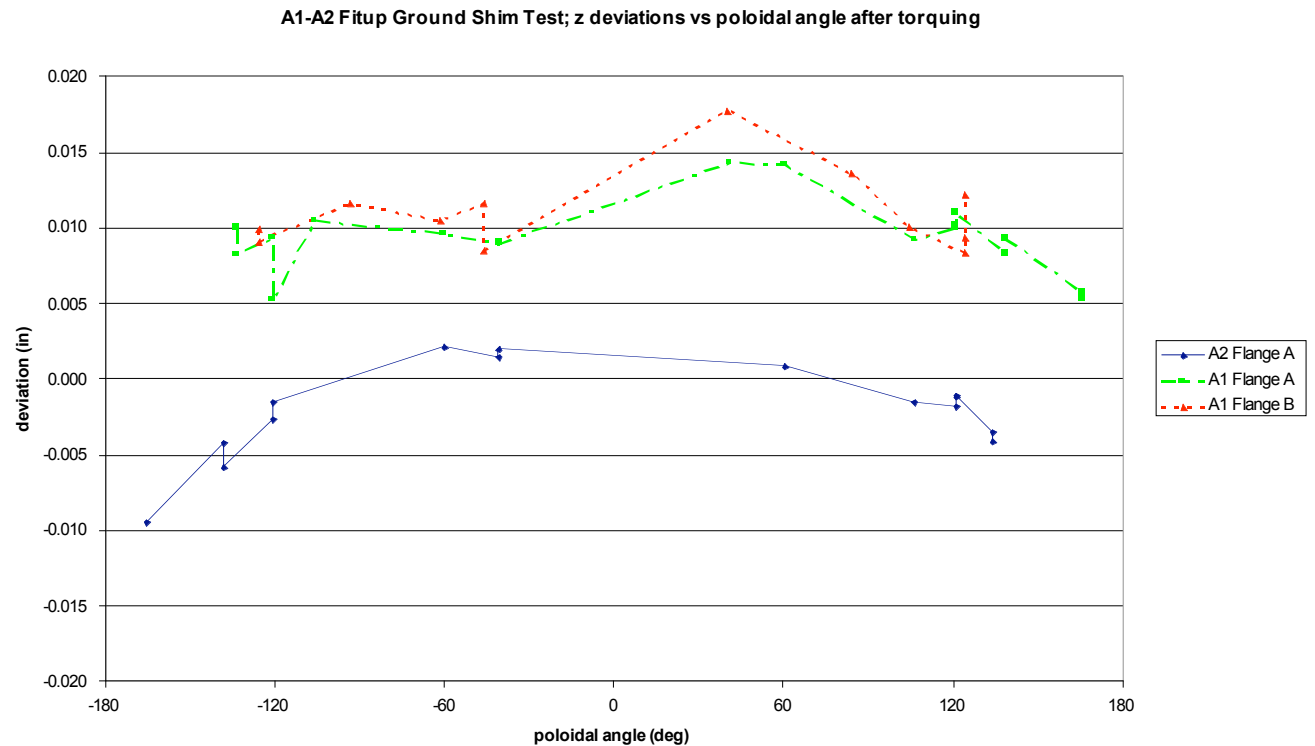


- The A1 and A2 coils were pre-assembled using the steps described previously.
- Shim thicknesses were calculated, a uniform .008in compensation was added, and a full set of ground stainless steel shims was fabricated.
 - The .008in compensation, in retrospect, should not have been used.
- Fujipaper [.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



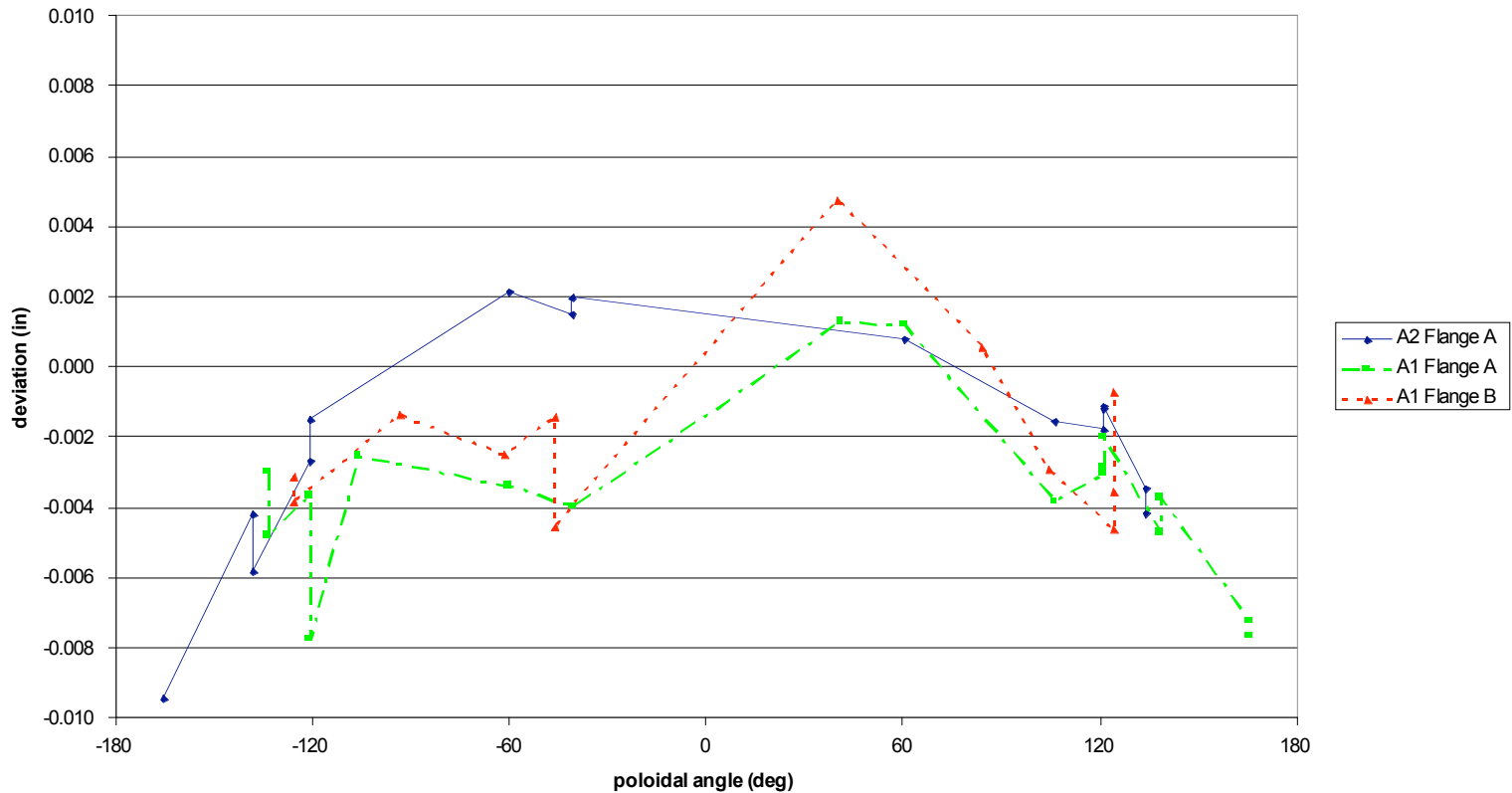
- The bottom [A2] coil maintains its shape.
- The mating flanges track each other.
- The two flanges of the top [A1] coil track each other.



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



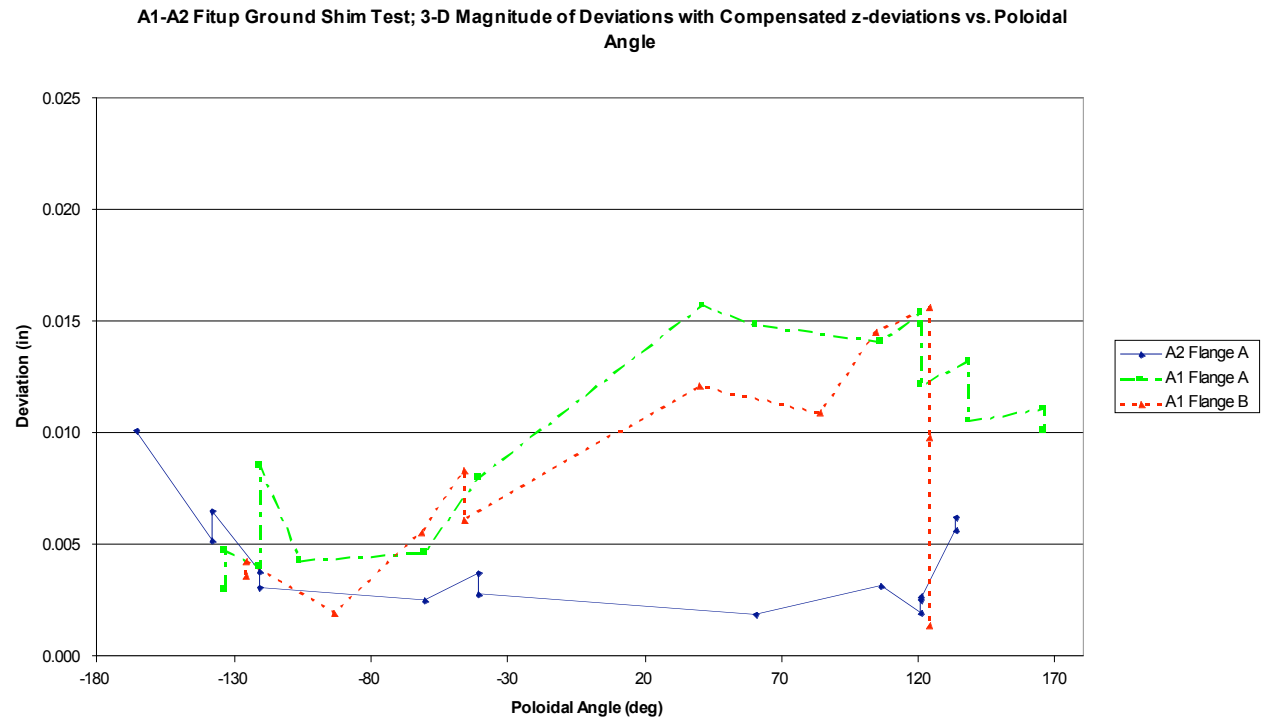
A1-A2 Fitup Ground Shim Test; compensated z deviations vs poloidal angle after torquing



Vector Sum of Deviations is Close to Goal on First Pass



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



Fujipaper Shows Acceptable Load Sharing



Summary



- 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.