Princeton Plasma Physics Laboratory

PPPL- 4462

PPPL- 4462

Metrology Techniques for the Assembly of NCSX

C. Priniski, T. Dodson, M. Duco, S. Raftopoulos, R. Ellis, and A. Brooks

September, 2009

Prepared for the U.S. Department of Energy under Contract DE-AC02-09CH11466.

Metrology Techniques for the Assembly of NCSX*

C. Priniski, T. Dodson, M. Duco, S. Raftopoulos, R. Ellis, and A. Brooks
Engineering Infrastructure Department
Princeton Plasma Physics Laboratory
PO Box 451 Princeton, NJ 08543
cpriniski@pppl.gov

Abstract— **In support of the National Compact Stellerator Experiment (NCSX), stellerator assembly activities continued this past year at the Princeton Plasma Physics Laboratory (PPPL) in partnership with the Oak Ridge National Laboratory (ORNL). The construction program saw the completion of the first two Half Field-Period Assemblies (HPA), each consisting of three modular coils. The full machine includes six such sub-assemblies. A single HPA consists of three of the NCSX modular coils wound and assembled at PPPL. These geometrically-complex three-dimensional coils were wound using computer-aided metrology and CAD models to tolerances within +/- 0.5mm. The assembly of these coils required similar accuracy on a larger scale with the added complexity of more individual parts and fewer degrees of freedom for correction. Several new potential positioning issues developed for which measurement and control techniques were developed. To accomplish this, CAD coordinate-based computer metrology equipment and software similar to the solutions employed for winding the modular coils was used. Given the size of the assemblies, the primary tools were both interferometer-aided and Absolute Distance Measurement (ADM)-only based laser trackers. In addition, portable Coordinate Measurement Machine (CMM) arms and some novel indirect measurement techniques were employed. This paper will detail both the use of CAD coordinate-based metrology technology and the techniques developed and employed for dimensional control of NSCX sub-assemblies. The results achieved and possible improvements to techniques will be discussed.**

Keywords-component; metrology; stellerator assmbly; CMM; Laser Tracker; modular coil assembly

I. Introduction

Metrology and stellerator construction go hand-in-glove due to the complex and exacting requirements of the magnetic fields of these machines. A precise dimensional control program needed to be implemented to assure that the project's tolerances were met. This consisted of a back office analysis team and an in the field metrology group. The metrology group at PPPL was responsible for performing measurements during fabrication and assembly of major stellerator components. Early on PPPL recognized the need for an extensive metrology program for coil winding and machine assembly. The scale of the effort however, was not fully appreciated until significant experience had been gained in winding the modular coils. Once NCSX assembly had begun the need was recognized, if not fully met. After NCSX's complex modular coils, the half period assemblies and even the vacuum vessel became major employers of metrology.

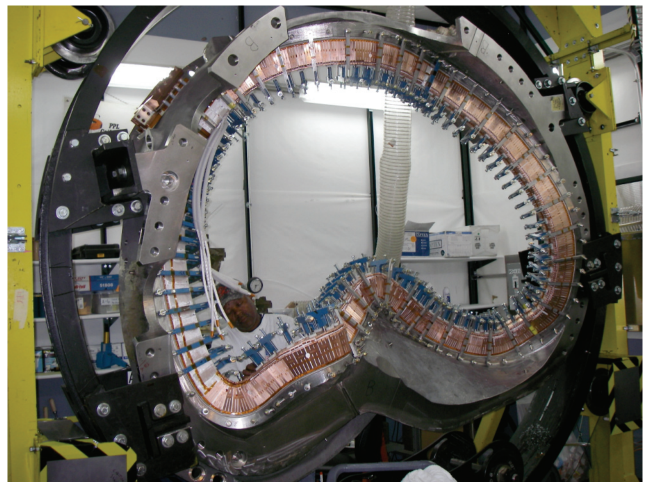

Figure 1. A-type coil in ring support for winding in the PPPL coil shop

II. Coil Winding Metrology Background

A. Premeasument

Prior to winding the modular coils, the modular coil winding form castings were measured and inspected by PPPL. For initial inspection the forms were mounted in winding rings and aligned using CAD models and tooling ball fiducial locations installed and surveyed by the vendor, Major Tool, on a Coordinate Measurement Machine (CMM). These tooling balls were located around the perimeter of the flanges on the coils which were not suitable for use during winding at PPPL. Instead the alignment was transferred to welded on conical seats on the inner (plasma side) surface of the cast material. CMM arms could directly be placed in these seats in order to realign accurately and quickly during the winding process [1] .

B. Coil Winding Metology

During coil winding operations measurements were taken of the copper conductor directly by the arms, and clamps were used to shape the windings in order to maintain the current center of the overall coil within 0.5 mm [0.020"] [1]. After prototyping and a great deal of trial this became a repeatable and highly accurate process that was able to deliver coils that were consistently better than the 0.5mm specified tolerance. The finished conductor was covered with cooling chill plates

*This work is supported by the U.S. Department of Energy Contract No. DE-AC02-CH0911466

and fiberglass to complete the windings. The coils were then placed in a bag mold and set permanently in epoxy in an on-site autoclave. From this point on the conductor itself was no longer accessible for direct measurement. The finished coils were checked and handed off to the Field Period Assembly (FPA) group [1][2].

III. HALF PERIOD ASSEMBLY

The Half period assembly stage consisted of stacking a set of an *A*, *B*, and *C*-type coils on a stable platform while installing spacing/insulating shims and then bolting each coil interface together. While this sounds like a simple assembly job, due to the tolerances required in controlling the alignment of the coils to each other and the need to carefully control the gap between the coils, this was another precision job driven by metrology support at each step. The overall alignment error budgeted to the assembly of the field period was once again only 0.5mm [3].

A. Initial Pre-measurement

Similar to the pre-measurement done prior to winding, the hand off from the coil winding team to the FPA team marked the beginning of a whole new set of metrology actions. One of the first actions was to realign to the coil's original external tooling ball fiducials and install additional coil "body" tooling ball locations on the shell of the casting outside the wound conductor locations to track the winding surface's relative movement. This step produced the first warnings that metrology challenges were here to stay. In the course of doing some pre-measurement of the first *A* coil, it was stood vertically on the floor supported only by its feet and a stabilizing strut bolted from the top of the coil to the floor. This was done to speed pre-measurement so all sides of the coil were accessible simultaneously. The added point load of the strut deformed the upper part of the coil by approximately 0.25mm [0.010"], or roughly half of the allowable tolerance, with only a fraction of the weight leaning on the strut. All of the rigid body assumptions for assembly were now in question. Coils would be laid flat on a steel plate for assembly, but they were not necessarily in a dead flat state when wound. This presented an early challenge for dimensional control [2].

B. The Reality of Metrology Equiment in Use

Laser Tracker systems were used to measure the larger assemblies of multiple coils. The CMM arms used during winding had only a measurement volume of roughly a 2m sphere which would not span the external dimensions of the coils. Laser trackers, by comparison can measure the 3-D location of a retro-reflector-equipped probe to sub-millimeter accuracy even across a room-sized volume. However, this equipment was sensitive to environmental factors, some within our control, others that remained a mystery though the close of the project. The first difficulties during this pre-measurement time happened when we just could not achieve repeatable or even necessarily accurate measurements. These technical difficulties lead to several days of down time to tease out exactly what was causing the problems.

We had two types of Laser Trackers on site, one an older Leica Tracker with Absolute Distance Measurement (ADM) and InterFerometery Measurement (IFM) capabilities and a newer FARO ADM-only system. Each system had its advantages, and under normal operating conditions the largest source of error was the sensitivity of the angular measurement of the tracker head. However, atmospheric conditions, temperature, pressure, and humidity all needed to be tracked and compensated for by the tracker's software. In addition, vibration and other environmental noise (electrical and otherwise) could affect measurements on a given day. Even when we had thought we had all these problems controlled, there could be severe drift in our measurements, forcing a delay in measurement until conditions improved. Over the course of metrology activities we also suffered two major laser hardware problems leading to the loss of use of a tracker while it was repaired. Eventually, due to these reliability questions, we purchased an additional tracker to ensure two were always available for critical measurements. Frequent checks of recently-measured points were carried out to ensure that the trackers remained accurate throughout a given task. Morning start up of trackers included two-face checks of the tracker to compensate for run out error in the mechanism and scale bar measurements to assure the systems were functioning properly.

C. Modular Coil "Racking"

A new procedure was developed in light of our pre-measurement discoveries on the larger coils which we referred to as Racking. This process entailed warping the coil back into the shape it held while in the winding ring (Figure 1). As the coils were bolted up in the rings some slight twist was induced into the shape. This deformation was small; however, in order to maintain our 1.5mm tolerance, every error had to be removed, if possible. Fortunately, the conical seats that were used to align the CMM arms during winding were measured in each step of winding metrology. The resulting coordinates were averaged for each seat to create a picture of the coil and casting material in an "as-wound" shape. Rather than lay the coils on a flat bed for pre-measurement, one flange was supported on a set of small jacks located around the perimeter of the coil. Where possible, these jacks were placed near the location of the conical seats. The jacks would use the weight of the coil to drive it back into as near the "as-wound" state as possible (Figure 2) [2].

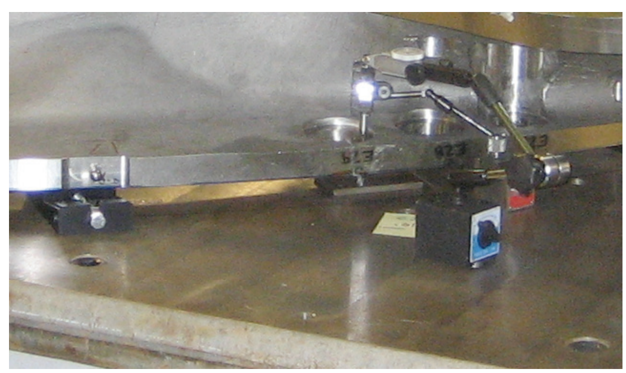

Figure 2. Jack and dial indicator under B-1 Coil on wedge plate

The laser trackers were used to re-align to the seats using a 15mm ball bearing, which replicated the probe of the arms, and a spherical fit adapter bar which held a retro-reflector at a fixed distance from a built-in conical seat at the tip. This tool was swept through several arcs while taking 10 single point readings that were automatically used to calculate the center of the sphere, which was the center of the 15mm probe in the seat. This became a standard method for measurement of our ½" tooling balls that were not line-of-site to the tracker as well. The software we used by FPA was Verisurf, a CAD-CAM based package which allowed multiple alignments from multiple devices to be integrated into a single measurement file, which over-laid the CAD design geometry. This software automatically reported the maximum error of each swept sphere making it a valuable tool for alignment since errors in the sphere fit were immediately reported so the measurement could be redone before it was ever used in an alignment. Catching errors early was a vital part of the metrology philosophy, as later measurements often depend on earlier alignments. After all of the conical seats were measured, Verisurf would attempt to do a best-fit alignment of the tracker to the coil coordinate system. In the coil's coordinates X and Y were radial and vertical (with respect to the stelerator). The Z plane was through the coil's winding. During the racking process we were looking to minimize the out-of-Z plane errors of the conical seats. Once the alignment was established, the Z error of each location was noted, and the jack or jacks nearest the largest error were adjusted up or down while being monitored by a dial indicator at the jack location. Adjustments as small as .025mm were possible driving the coil back to its wound shape. Care had to be taken not to disturb adjacent locations around the coil, so several people monitored the racking process, watching dials around the coil. The process was iterative, after each set of corrections were applied, the coil's conical seats were re-measured and a new set of corrections were calculated.

The goal was to drive the winding fiducial points back to within 0.13mm [0.005"] of their averaged wound locations[2]. This was not always realized as it was not always possible to push directly on one seat and not move neighboring locations, and occasionally it was not possible to fit a jack in due the geometry of the casting. Once the final alignment was completed and the go-ahead received from dimensional control, the *A* -type coil would be locked down to the plate with clamps, holding it and the jacks in place for the duration of the half period assembly.

D. Pre-measrument, Part II

With the coils warped, the process of preassembly measurement could proceed. ½" Tooling balls were reinstalled on the rims of the coil flanges. Additional body fiducial bushings were tack welded onto the shell of the coil that also accepted tooling ball targets to track the movement of the casting, and therefore the coil wound on it throughout assembly. All of these tooling balls were carefully mapped into the aligned coil files using the sphere-fit method or Leica Surface Reflector (LSR). The LSR used a mirror and retro reflector to create a virtual point for the laser at the tip of a physical probe. The probes were calibrated and interchangeable and varied from a point probe to various ruby tips, and a ½" conical seat which allowed direct measurement of tooling ball centers. This tool was limited by line-of-site, but was reliable and fast for measurement and subsequent realignment.

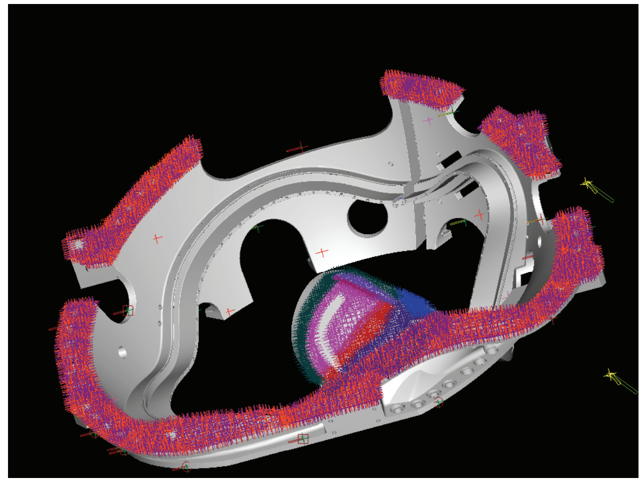

Figure 3. Coil-to-coil interface scan

For the *A* coil additional world or global points were measured out on stable objects surrounding the coil, magnetic nests on the plate coil was on, nests on the wall, or other objects. These were used to realign routinely as we moved the tracker around the part. They were global points and were measured as averages of 300 tracker readings. It could take 4 or more tracker locations to fully measure a coil, so being able to realign to the coil coordinates was vital to metrology [2].

Next, the exposed flange and protruding surfaces were scanned by running a spherically-mounted retro-reflector over the surface recording points in a dense grid (Figure 3). This data was used to evaluate the coil-to-coil interface.

As the *A*-type coil was undergoing pre-measurement the *B*-type coil was going through the same process on an adjacent wedge plate. However, the B coil was not clamped down because it would be assembled on top of the *A* coil. The flange to be mated with *A* was left up so it could be scanned. With data from both *A* and *B* coil scans the gap to be created by shims between coils could be calculated for each bolt location around the flange. The thickness of the shims conforms to and holds the warped-as-wound shapes.

E. Monitoring Weld Distotion

Due to high predicted coil-to-coil sheer forces, it was determined that the nose shims, those furthest inboard, where there was no room for a bolted joint, would need to be welded to the coil castings themselves. This allowed them to effectively carry the sheer loading that would have endangered the first bolt on either side of the nose if not restrained in some manner. Welding, of course, introduces stress and distortions in any part. In spite a great deal of R&D done to mitigate weld distortion of the castings, some movement was inevitable and had to be closely monitored to ensure that the distortion did not exceed allowable error [4]. As noted earlier, the conductors were now covered and the direct movement of the windings

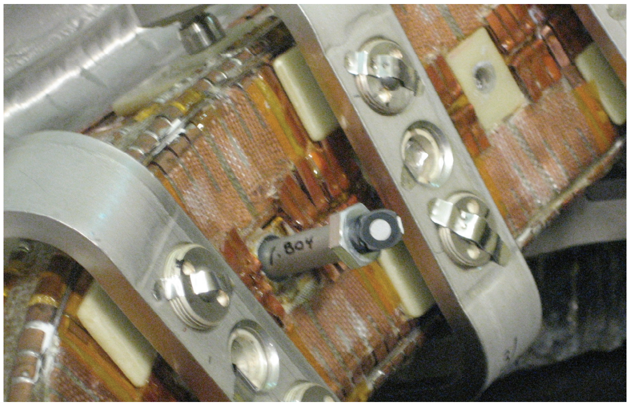

Figure 4. Septum monitoring bolt in place near weld zone

could not be monitored directly. Instead, a novel idea was created to monitor the septum, the steel wall dividing and supporting the two halves of the winding packs in the middle. A shoulder bolt prepared for this job was screwed into a previously-abandoned tapped hole in the septum left over from the winding process. The bolt had a tooling target hole drilled in its head that would accommodate a nest for a retro-reflector (Figure 4) This reflector could be measured before, during, and after the welding process to evaluate the movement of the septum and attached windings. For all the production coils we welded shims on, we were able to record less than 0.5mm deviations following welding, holding our tolerance successfully. The welding of the inner (plasma side) shim edges was completed prior to coils being assembled together. The outer edges were welded from outside the coil stack after assembly, but the measurement technique was identical.

F. Coil-to-Coil Assembly

Once we were ready to proceed with assembly, the *A* coil base would be inclined 20 degrees, which leveled the upper flange to prepare for the *B* coil. Preassembled shims were laid out on the *A*-to-*B* flange of the *A* coil according to the calculated required thickness, and select studs were installed to prepare to bolt up the two coils. Meanwhile, a new metrology file was prepared with the *B* coil placed in its ideal location above *A*, including all measured tooling ball fiducial points from *B* in their appropriate final locations. Next, the *B* coil was lowered over the studs onto *A* by crane to approximately the final position. An alignment frame was bolted to the *A* coil with jack screws and dial indicators to assist in the final X-Y alignment of the *B* coil [3]. Four of the fiducial tooling balls were measured and fed into a spreadsheet created for the purpose of computing a translation matrix for the coil. This spreadsheet produced X and Y adjustment of the coil feet to drive the coil to the final location. The *B* coil's weight was briefly taken up by the overhead crane and the coil was repositioned by the jack screws in 2-D translation and rotation (the Z, or height, was fixed by the shims). Once the coil was set down, the sample fiducials were remeasureed and the rechecked by the spreadsheet. If necessary, the process was repeated until the *B* coil was aligned to within 0.1mm [2]. The entire *A*-*B* assembly had all of its tooling ball locations measured and recorded in the assembled state.

At this point, the remaining studs were put in and tightened. Once again, the coils were surveyed for a final check. The upper, now exposed, *B* flange was scanned in the pre-measurement step to accept the *C* coil which completed the HPA.

The addition of the *C* coil was no less challenging than the *A* to *B* assembly. However, from the metrology viewpoint, the steps were similar so they are not included in this paper.

IV. Conclusions

Heavy demands were placed on the metrology group due to many unknowns in assembling the complex three-dimensional coils that made up the field periods. The group measured, in all probability, more points at more assembly stages than we had to in order assemble the coils and learned a great deal in the process. The warping of the coils would never have been discovered without the extensive measurements taken. The first Field Period was both a product and a prototype, so we erred on the side of more data is better than not enough data. If NCSX had moved on into a production mode, subsequent HPAs would have been faster as we had learned where the trouble spots were.

The experience gained helped make better metrology teams since a great deal of adaptation was required to make accurate field measurements. Early on, many technicians rotated through the program, but the few who stayed on board until the end were invaluable assets. Metrology has a steep learning curve, and those working had to learn to make few mistakes and catch the ones that were made quickly.

The fact that metrology was considered in the design of most of the components was also a key to success. Patterns of fiducial coordinate points could easily be machined into parts while they were still fixtured at the manufacturer at little cost and could later be used for quality assurance inspection and alignment of finished assemblies. Conversely, it is very difficult to align to a part with no precise features known ahead of time, resulting in hours of taking best-fitting data to create a rough alignment.

Lastly, the temptation to overuse coordinate metrology equipment must be tempered by common sense. Sometimes, a bubble level and square were the right tools for the job. Other times, adjustments to the assemblies were performed using dial indicators to monitor relative movement successfully. CAD-based metrology, while powerful, is one of many tools to aid measurement and should be used properly and as appropriate for the needs of a project.

References

[1] S. Raftopoulos, "Metrology for the NCSX Project" 2007, SOFE

[2] R. Ellis, "Dimensional control of NCSX field period assembly," 2009, SOFE

[3] M. Viola, "Accomplishments in Field Period Assembly for NCSX," 2009, SOFE

[4] M. Denault, "Low distortion welded joints for NCSX," 2009, SOFE

The Princeton Plasma Physics Laboratory is operated
by Princeton University under contract
with the U.S. Department of Energy.

Information Services
Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08543

Phone: 609-243-2750
Fax: 609-243-2751
e-mail: pppl_info@pppl.gov
Internet Address: http://www.pppl.gov