METROLOGY FOR THE NCSX PROJECT

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Abstract—**The National Compact Stellerator Experiment (NCSX) is being constructed at the Princeton Plasma Physics Laboratory (PPPL) in partnership with the Oak Ridge National Laboratory (ORNL). The complex geometry and tight fabrication tolerances of the NCSX's non-planar coils and vacuum vessel necessitate the use of computerized, CAD-based metrology systems capable of very accurate and reasonably quick measurements.**

To date, multi-link, portable coordinate measuring machines (pCMM) are used in the fabrication of the non-planar coils. Characterization of the CNC machined coil winding form and subsequent positioning of the conductor centroid (to within +/- 0.5mm) are accomplished via multiple sets of detailed measurements.

A Laser Tracker is used for all phases of work on the Vacuum Vessel including positioning magnetic diagnostics and vessel ports prior to welding. Future tasks requiring metrology include positioning of the magnet systems and assembly of the three vacuum vessel sub-assemblies onto the final machine configuration.

This paper describes the hardware and software used for metrology, as well as the methodology for achieving the required dimensional control and will present an overview of the measurement results to date.

I. GENERAL DISCUSSION

While measurements of fusion devices with a constant cross sectional is relatively straightforward, the free-form, complicated shapes of the NCSX stellerator require the use of CAD-based, computer driven measurement systems, such as multi-link articulating arms and laser trackers.

Metrology can be approached as a complimentary, stand-alone function, however when integrated early into the process, especially during the design and fabrication phases, the probability of successfully meeting critical tolerances is greatly improved. For example, the placement and precise measurement of fiduciary points, when defined during the design phase and measured as part of the manufacturing inspection phase, make the in-house metrology process simpler and hence more reliable. The manufacture of NCSX stellerator core components (Vacuum Vessel and Modular Coils) required computerized, five-axis machining for which the fabricator required a set of "alignment points". These alignment points also serve as the means for initial alignment to the component once delivered to PPPL. From this point, comprehensive measurements of the critical surfaces, resulting in a characterization of the part, provides a quality control check and allows the opportunity for a final "best fit" transformation prior to further work.

Fixturing for the components being measured and a stable platform for the measuring device are also critical for successful measurements. Ideally, the measuring system and measured component will remain motionless in a stable, temperature controlled environment throughout the measurement process. If either the part or the measuring device moves, the resulting errors can render measurements invalid. When the motion is large and hence obvious, the operators will most likely recognize the problem and take mitigating steps. When relative motions are small they are very difficult to detect and may be completely ignored or only detected during post processing and data analysis. Another error-inducing event is deformation of the part. While we often assume that large, heavy structures act as rigid bodies, they may deform when their support or fixturing is changed, or when the temperature is not held constant. If enough deformation is induced, the alignment will be compromised, introducing errors in subsequent measurements.

II. METROLOGY HARDWARE

The metrology for the NCSX project is being accomplished using two types of measurement systems – articulating arm, portable Coordinate Measuring Machines (pCMMs) and laser trackers. Three, Romer pCMM arms were purchased primarily for Modular Coil winding, and are occasionally used in other applications. The pCCMs, which have six articulating joints, have a 12-foot diameter reach and stated accuracy of +/- 0.1mm. Using statistical analysis of repeatedly measured points, we have determined that the performance in the field is slightly better than the manufacturer's advertised value.

For the measurements required after the completion of the coil winding phase, the distances are too great for an articulating arm, therefore laser trackers are utilized. The project currently employs one Leica LTD-500 and one Faro-X Tracker. The Leica unit has a built-in interferometer, which increases the accuracy of the distance component of measurements. While the interferometer provides a more accurate distance measurement, the overall accuracy of any measurement is primarily dependent on the resolution of the angular encoders, which is typically an order of magnitude worse that the interferometer resolution. Since most of our measurements occur in three-dimensional space (which induces changes in the angular component) the advantages of the interferometer are mitigated.

III. METROLOGY SOFTWARE

The metrology for the NCSX project is being performed using two software packages. The pCMM arms are operated

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under PowerINSPECT while the laser trackers are operated under the Verisurf software platform.

PowerINSPECT was chosen primarily for its ability to acquire and process point cloud data in real time. The program allows for the creation of a pre-defined measurement routine, in which all required measurements can be identified off-line and later executed by the metrology technicians in the field. The metrology requirements for the modular coils are very precisely defined and lend themselves to this structured format.

Verisurf is a metrology platform which is an add-on to the MasterCam CAD/CAM package. As part of a CAD package, it allows the operator greater manipulation of the imported CAD model(s), as well as the creation of new layers into which the measurement data is saved. This flexibility demands a larger learning curve, but rewards the user with flexible and powerful options, and is ideally suited to the metrology needs of the Vacuum Vessel, Field Period Assembly and Machine Assembly phases.

IV. DESIGN/DRAFTING & ANALYSIS SUPPORT

Throughout the NCSX metrology program, support and coordination with the design group is critical. Both PowerINSPECT and Verisurf operate in two modes; in "inspection mode" they measure against a CAD model, data is linked and projected against a CAD entity and deviations are calculated. Outside of "inspection mode", both programs can acquire points which are in the part coordinate system, and can be used to generate standard geometric CAD shapes (planes, lines, splines, etc). NCSX metrology is typically in the inspection mode, using the CAD models generated by the design/drafting group as the foundation for measurements. Typically, engineering design models include more data than is necessary for metrology. Hidden surfaces, bolt holes and complex assemblies consisting of multiple elements are a hindrance to the metrology and have to be "cleaned up" before measurements are taken. Consider a CAD model with parallel surfaces that are 0.080" apart and an "as-built" component that is deviated by approximately 0.040". Once a point is measured, the software attempts to project it to the closest available surface, often projecting to the wrong one, unless we remove or exclude that surface. The refinement of the models for use in metrology is a task that should be accounted for when determining design/drafting resource needs.

Analysis of metrology data has been critical to maintaining an efficient flow of work. Typically, the field crews perform measurements and forward a summary to the engineering analysis group for review. The summary is an excel-based report which includes the coordinates of all measured points. The analyst(s) digest this information and provide feedback that field crews require to undertake the next phase of the fabrication or assembly. Quick turn around of the analysis task is paramount to keeping the work flowing in the field.

V. MODULAR COILS

A. Initial inspection, and alignment.

The modular coils are delivered with provisions for 18 tooling balls with coordinates that are defined during the fabricating vendor's inspection process. These tooling balls are used as fiducial points for alignment to the part. Since the vendor's Coordinate Measuring Machine (CMM) is more accurate than the metrology equipment available to the NCSX project, we initially believed that alignment using the tooling balls would produce the most accurate results. Unfortunately, the modular coils are deflecting during the handling process which introduced errors into the alignment. To compensate, we use the tooling ball alignment as a "gross" registration to the part and proceed to measure the surface that the conductor will be wound against. The measurement data, which consists of approximately 6000 discreet points, is used to refine the alignment via a "best fit". A new set of fiducial points are defined and all future alignments to the coils are based on these references.

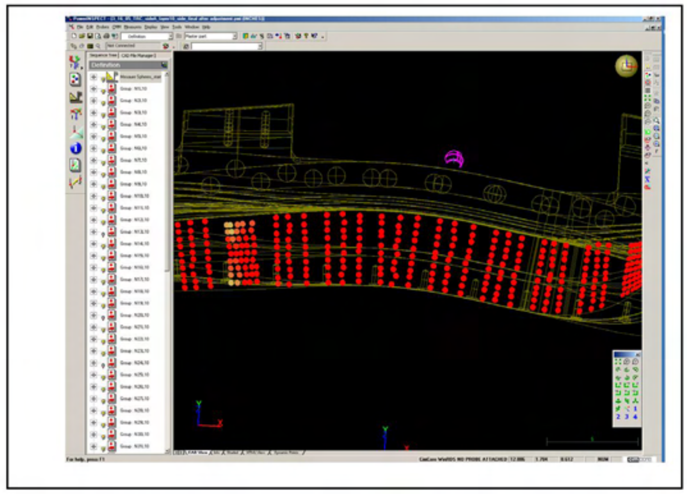

Figure 1. Data points acquired for characterizarion of the Modular Coil Winding Form. Points are segregated into sequentially numbered groups, linked with a particular location of the coil.

B. Conductor placement

During the modular coil winding, the placement of the conductor and its resultant current center has a positional tolerance of +/- 0.020" (~0.5mm). Unfortunately, the manufacturing deviations of the winding forms have often exceeded this tolerance. In order to compensate, comprehensive measurements of the winding form and the outer surface of the coil pack are used to determine the "as-wound" geometric centroid of the coil pack. The cross section is then intentionally distorted to compensate for the winding form errors. To achieve the resolution needed to accomplish these corrections, a specific pattern of measurements of the bare winding form is taken and the same pattern is repeated on the conductors after they are laid onto the form. While random measurements of the winding form would produce sufficient data to characterize it's shape, by using a controlled pattern that is reproduced on the outside of the coil pack, we are able to characterize the cross sectional area of the coil pack and infer the current center at approximately one-inch intervals. Using a restraining system that employs adjustable clamps, the coil's cross-sectional geometry is intentionally distorted to manipulate the current center to the desired location.

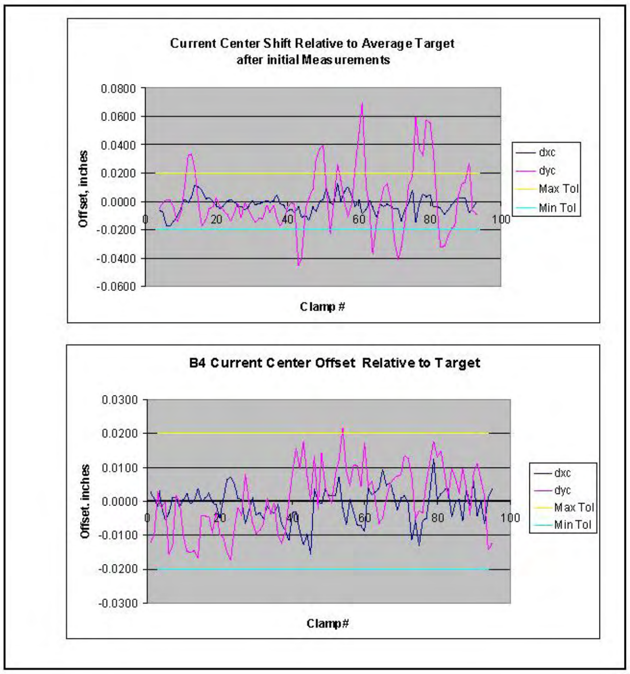

Figure 2. Calculation of the current center (based on pCMM measurements) before and after the coil pack adjustment phase. The pCMM was used as a positional gauge to guide the coil pack to the "corrected" shape.

C. Co-Wound Flux Loops

Co-wound flux loops are magnetic diagnostics that are mounted onto a modular coils and sense the magnetic flux produced by that coil. Their installation is not guided by metrology; however an accurate measurement of the as-installed location is important to the interpretation of the data that they acquire. The pCMM is aligned to the modular coil and is used to take a series of points at approximately one-inch intervals along the length of the loop. Unlike the other measurements which are linked to the CAD model, these points are not projected onto a surface; rather this data is converted to IGES form which is forwarded to the design and physics groups.

VI. VACUUM VESSEL MEASUREMENTS

A. Inspection/Best fit

Metrology for the vacuum vessel presented different challenges than for the modular coils. While the modular coils were machined to relatively tight tolerances (+/-0.010" for machined surfaces), the vacuum vessel is a stamped and welded assembly with 3/8" profile tolerance. There are sections of the vacuum vessel that were as far out as 0.4" from the CAD model, or almost ¼" out of tolerance. Like the modular coils, the vacuum vessel was received with a vendor installed set of tooling balls that were used for initial alignment. A net of fixed reference points surrounding the vacuum vessel was established immediately after the initial alignment. The tracker was moved and re-aligned to the reference net, essentially re-establishing the initial alignment to the tooling balls. By using the reference net to leap-frog the tracker around the part, a scan of the entire surface was obtained while remaining in a consistent coordinate system.

Since clearance of the plasma to the vacuum vessel is a critical parameter, a "best fit" of the vessel scan data to the CAD model was then performed. With the coordinate system finalized, the other features of the vacuum vessel (port openings, support points, etc.) were measured.

B. Vacuum VesselFlux Loops

The vacuum vessel flux loops are diagnostics that measure magnetic flux perpendicular to the plasma surface. They are designed to be mounted directly onto the vacuum vessel and require precise positioning at predetermined locations relative to the plasma. Installing them in their reference locations is complicated by the fact that the vessel surface deviates from the design. The location of each flux loop is defined by a series of points which were used as targets for Verisurf's "Build" function, which reports the deviation from these predefined points. The flux loops were located as close as possible to their nominal design positions and precisely measured after installation. The as-installed data will be utilized in correction factors when resolving magnetic flux data.

C. Heating/Cooling tubes

The heating/cooling system is an essential component of the vacuum vessel, with requirements governing the spacing and distribution of the cooling hardware. Heat transfer from the vacuum vessel is accomplished through numerous metallic pads that are thermally linked to the vessel surface. The locations of the mounting hardware for these pads and the associated piping system were laid out using the laser tracker. Interferences with flux loops and vacuum vessel ports necessitated a continuous compromise amongst this hardware, with priority given to the flux loops and to immovable structures. Using the nominal locating positions as provided by the design model as starting points, the metrology technicians employed the laser tracker to identify and resolve interferences, to relocate mounting positions, and install the hardware.

VII. TF COIL MEASUREMENTS

To date, we have performed measurements on the first production TF coil. The measurements were taken after the coil had been through the Vacuum Pressure Impregnation (VPI) process, and before the wedge casting underwent final machining. The purpose of the measurements was to verify that the coil geometry was within specification and to ensure that the coil was properly located in the vendor's fixture, which would be used for the final machining of the wedge. The choice of scan data to use in the "best fit" refinement of the initial alignment was carefully selected so that it would reproduce the alignment that the machining vendor would establish when setting up to perform final machining of the wedge.

VIII. DATA & RESULTS

The goal of the metrology program is to provide the guidance to fabricate and assemble critical components to their design specifications. To that end, the metrology of the fabricated modular coils shows that we are achieving the desired results.

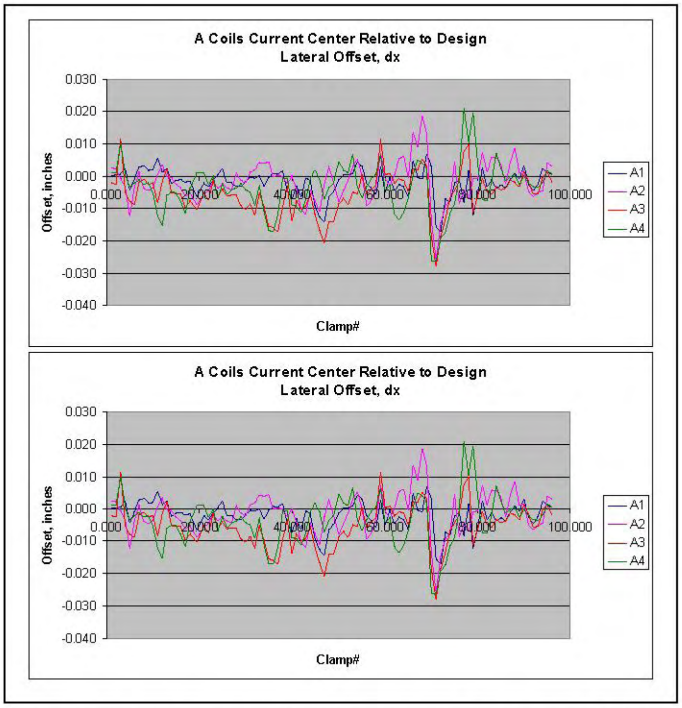

Figure 3. Current center position relative to target for the C-type Modular Coils. Note that where the current center deviates more than the +/- 0.020" alloted tolerance, the deviation is present for all the coils, which is important for stellerator symmetry.

IX. CONCLUSION

Metrology plays an important role in the NCSX project. While winding the modular coils involves the installation of thousands of discrete components that do not involve metrology, the precise placement of the conductor which is most critical aspect of the fabrication, is accomplished by employing the Romer pCMM. The Leica and Faro laser trackers have been used to fully measure and characterize the three vacuum vessel segments and spool pieces – a task that could not have been performed without this equipment. For the future, the laser trackers will be instrumental in positioning the vacuum vessel, planar and modular coils into field period assemblies and for assembling the three field periods into the completed device.

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