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Accomplishments in Field Period Assembly for NCSX*

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Abstract—**The National Compact Stellarator Experiment (NCSX) was a collaborative effort between ORNL and PPPL. PPPL provided the assembly techniques with guidance from ORNL to meet design criteria. The individual vacuum vessel segments, modular coils, trim coils, and toroidal field coils components were delivered to the Field Period Assembly (FPA) crew who then would complete the component assemblies and then assemble the final three field period assemblies, each consisting of two sets of three modular coils assembled over a 120° vacuum vessel segment with the trim coils and toroidal field coils providing the outer layer. The requirements for positioning the modular coils were found to be most demanding. The assembly tolerances required for accurate positioning of the field coil windings in order to generate sufficiently accurate magnetic fields strained state of the art techniques in metrology and alignment and required constant monitoring of assembly steps with laser trackers, measurement arms, and photogrammetry. The FPA activities were being performed concurrently while engineering challenges were being resolved. For example, it was determined that high friction electrically isolated shims were needed between the modular coil interface joints and low distortion welding was required in the nose region of those joints. This took months of analysis and development yet the assembly was not significantly impacted because other assembly tasks could be performed in parallel with ongoing assembly tasks as well as tasks such as advance tooling setup preparation for the eventual welding tasks. The crew technicians developed unique, accurate time saving techniques and tooling which provided significant cost and schedule savings. Project management displayed extraordinary foresight and every opportunity to gain advanced knowledge and develop techniques was taken advantage of. Despite many risk concerns, the cost and schedule performance index was maintained nearly 1.0 during the assembly phase until project cancellation.**

In this paper, the assembly logic, the engineering challenges, solutions to those challenges and some of the unique and clever assembly techniques, will be presented.

Keywords-field period; assembly; coil joint; metrology; welding

I. INTRODUCTION

DOE discontinued the National Compact Stellarator Experiment (NCSX) project due to cost and schedule overruns at the machine assembly point where the three vacuum vessel segments were complete, two of the six modular half periods (MCHP) were complete and one half period was installed over one of the vacuum vessel segments. Most of the known assembly risk was retired.

This paper will provide a detailed description of the FPA stations and activities along with the challenges and solutions that were met in each assembly step.

II. ASSEMBLY DESCRIPTION

A. *Overview of the Four Stations*

The NCSX field period assembly was initially divided into five assembly stations. Ultimately, the fourth and fifth stations were combined due to process simplification. The resource-loaded schedule was based on a single shift team consisting of one very talented and experienced lead technician with 2 capable technicians and two 2-man metrology teams. Available on call to this core crew were two rigger/material handlers and two welders. We also had a team of ORNL and PPPL engineers to address tooling and design issues as well as a "back office" consisting of three engineers to support all metrology issues. One key element of the success of the field period assembly and maintaining cost and schedule was a daily afternoon ORNL/PPPL conference call that was held at the end of the shift to address issues and provide the next day with immediate engineering support. The design was entirely 3-dimensional and model based; nothing was straight that could be measured by a ruler. Clearly this was a metrology intensive assembly and the metrology systems were being used at their limits. Other papers are being presented at this symposium that address metrology reliability and capability [1] [2] [3].

B. *Station One*

The first station was set up for the assembly of components on the vacuum vessel subassembly (VVSA). The VVSAs were 1/3 sections of the vessel and included a short spool piece that was to serve as a welded interface between the VVSAs to accommodate final alignment. A total of 99 ports were welded onto the vacuum vessel and then cut off at the fabricator's facility to allow the modular coils to be installed over the vessel. Each port was pre-fit to its respective opening to verify that the weld prep would allow for the final welding of the port back onto the vessel from the inside. The VVSAs required a layer of 205 plasma flux loop diagnostic coils to be precisely placed onto the vacuum vessel along with thermocouples for

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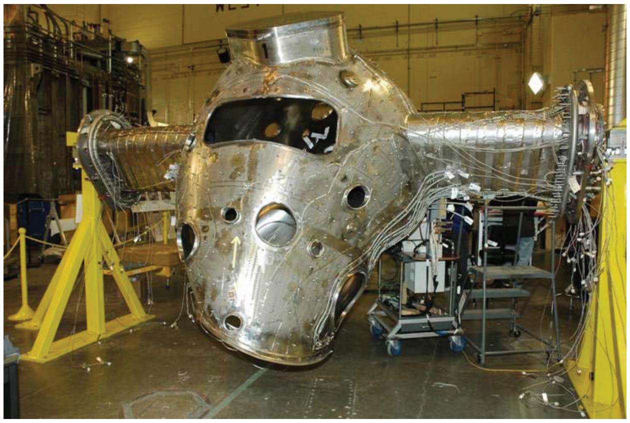
monitoring the vessel temperature and finally an array of duplex redundant cooling tube paths. The unique challenges in station one were the deflection of the VVSA while held in the "rotisserie" for assembly which greatly complicated the accurate placement and measurement of the diagnostic coils and correct installation of the clamps for attaching the cooling tubes to achieve proper thermal conduction.



C. *Station Two*

The second station was devoted to assembling the three types of modular coils (A, B, C) into half period assemblies (MCHP). The outer region of these coils was bolted while the inner nose region was welded. There were many unique challenges in station two. The modular coils were more flexible than expected and it proved difficult to reestablish the coordinate system that the coils windings were wound to. Laser tracker systems that were being used to take measurements were at the limits of their accuracy/resolution; the metrology systems were not entirely reliable; the outer bolted regions had many difficult criteria; and finally, the inner nose regions required high compressive and shear forces which drove the design to a welded joint that in turn required strength with a low-distortion weld design.

D. *Station Three*

The third station was setup for the purpose of assembling the MCHP assembly fabricated in station two over the vacuum vessel assembly fabricated in station one. Originally a large support manipulator mounted on a manipulated three-axis frame was to be used. Upon further examination of the process, it was believed that simpler handling with standard rigging techniques could be employed while guided by three lasers pointing to predetermined paths drawn on paper. This was tested out by manipulating a 25,000-pound concrete block with chain hoists along laser-guided paths and proven valid.

E. *Station Five*

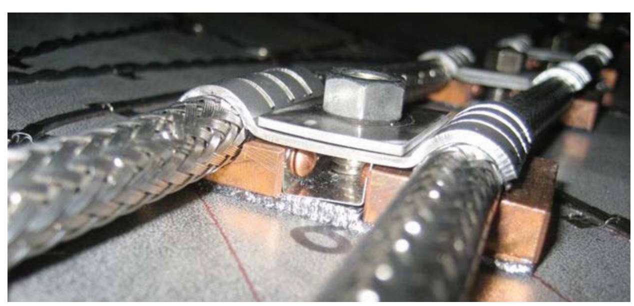
Station four was originally for the preassembly of the toroidal field coils but was combined into station five since the tooling was essentially the same. This final FPA station performed the tasks to complete assembly of each of the three sections of the machine. This would include the reattachment of the 99 ports to the vacuum vessel previously cut off to allow the modular coils to be placed over the vessel segments; the installation of the trim coils; the installation of the cooling manifolds and buswork; the collection and termination of instrumentation cables in junction boxes; and finally the installation of the toroidal field coils.

III. ENGINERING AND ASSEMBLY CHALLENGES

A. *Station One*

Station one was our first exposure to using laser trackers for assembling complex shaped components. The first hurdle was the fact that the vessel was installed on a rotisserie for ease of accessing the vessel surface. The vessel sagged on the order of 0.060" We learned that while this was a global effect we could use a local set of fiducials placed on the vessel itself to determine a local coordinate system. In the past we have performed in-vessel surveys of components and locating datums and assembly points using laser trackers but this involved the precise location of flexible 3-dimensional curved diagnostic flux loop coils. A clever technique was offered to manufacture copper templates that could be precisely located and then the flux loops could be wound around the perimeter of these templates. This worked very well. Once installed, we could then measure the loops by simply tracing a laser tracker probe around the loop.

Another challenge of station one was achieving the correct contact pressure of the clamps that held the cooling tubes in place. These employed a Grafoil interface to provide sufficient contact area and pressure to achieve good thermal conduction between the flat clamp and the curved vessel. Over or under compression seriously limits thermal conduction through the Grafoil. The team performed several tests to determine the best, easily repeatable method to attach the clamp and torque the hold-down nut.



More than anything, station one was a very tedious and time-consuming evolution that gave us an opportunity to develop metrology skills. We learned that metrology equipment requires a significant amount of maintenance and backup equipment is vital. Metrology arms and laser trackers failed several times a year. Laser tracker software basically works by selecting a specific point from a large sample during a period of time. This is random and does not represent the average of the time period's point cloud. Sometimes this point cloud would grow significantly in size for periods up to 2 weeks for no apparent reason. For critical baseline measurements that reestablished coordinate systems, a technique called "super points" was developed which would sample up to 100 measurements of a single point and then use the average of the result.

B. Station Two

Before actually beginning the station two assembly activity, it was noticed that there were some variations between coil castings. Upon further investigation, it was discovered that there were some significant over cast areas that would interfere with the coil-to-coil assembly. Not only were there interferences with the actual windings but also some of the pockets created for the stud and nut assemblies were too small.

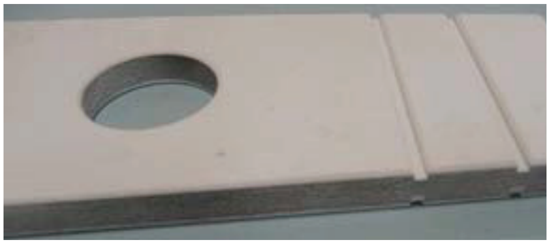
The only solution was to proceed with a 100% pre-fit of mating coils. After a few pre-fits, it was determined that this was a significant undertaking worthy of assigning a separate work crew and engineer in charge. Fortunately, the foresight to check into this issue avoided significant assembly delays. The coils were thoroughly checked and hand ground where needed until at least ¼" clearance was available. The coils were then delivered to the FPA crews ready for assembly.

The first hurdle on station two was to place and align the modular coils on 20° wedges to position the top flange horizontally. It was determined that the modular coils were flexible and once removed from the coil winding ring, lost their shape, so it became necessary to rack the coils back into shape to reestablish the coordinate system. This took some development. A clever spreadsheet was developed that allowed the laser tracker operators to input measurement data from specific locations and then it would output what adjustments were required. It became obvious that the selection of the location of input points was critical; also, the number of points used was important for best results. The coil was clamped down to a stiff 20° wedge that allowed the top flange to be positioned horizontal to the floor plane for ease of mounting the second coil on top of the bottom coil. While engineering and the assembly crews were developing the best methods for attaching the mating coil, there were several challenges involved with bolting the outer flange region and welding the inner nose region that had to be resolved.

- Coils were aligned using conical seat datums established during the initial coil winding operation. These datums were measured using the super point technique and then input into the spreadsheet calculator. A simple but clever clamp was installed on each of the four legs that allowed fine X-Y positioning of the coil. Coils were positioned within ±0.002" in a couple of hours.

Measurements were retaken and the spreadsheet would readout the required changes in X, Y, Z directions to achieve acceptable alignment. Once the X and Y directions were aligned, the coil was then lifted or jacked when possible and surrogate shims were installed to set the correct Z position. These allowed the actual coil winding centers to be quickly realigned within the required tolerance.

- A high friction bolted joint design that would also serve as a pinned connection for shear was required. The joints were designed with a nominal 0.5" gap to accommodate a shim to allow for the aforementioned alignment. A survey of the gap was made on two coils that were aligned and the gap was determined to range from 0.44" and 0.56". The first design employed a set of stainless steel shims that were coated on both sides with 0.020" of Alumina with various thicknesses within this range. The Alumina increased the coefficient of friction to approximately 0.7µ and also provided electrical insulation.



- A series of pressure film tests were performed with coil sets to determine what the thickness accuracy was required to allow the best load sharing. Note the varying indications on the third column, which was varied by 0.001" increments. It was determined that if adjacent shims varied by more than 0.002" then the thinner shim would not be loaded as is indicated on the top row. Also it was important that the shims were flat and parallel to assure even load sharing across the shim. Unfortunately, the final thickness of each alumina shim varied across the shim by as much as 0.010". After much discussion, it was determined that shims with varying thicknesses of stainless steel sandwiched between two G-10 sheets also of varying thicknesses could be easily assembled to size [4].

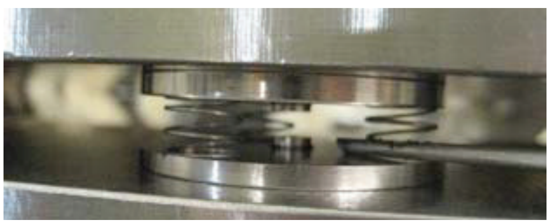
- A clever hydraulic press was developed to perform the measurement of the sandwiched shim assembly.

- The pinned connection to satisfy the shear requirement was met through the use of a custom G-10 bushing. Each bushing was prefit for a press fit to the inner diameter of the mating coil through-hole. Then after the coils were aligned, a clever aluminum gauge was used to measure the offset of each stud in its hole. That hole's bushing was custom drilled to the precise diameter of the stud with the measured offset. Fortunately each stud was very accurately machined to within 0.001" of each other. This resulted in a very tight-pinned connection [5].

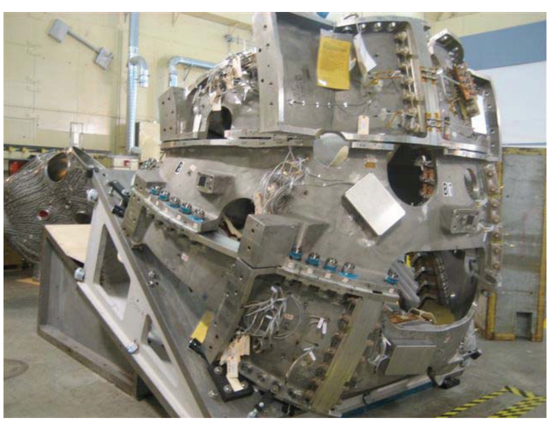
- The nose region required a strong shear connection that could also react highly compressive loads. Several mechanical designs were considered but because of the tight tolerances, and the high shear strength requirement it was finally determined that a welded connection was required. Once welding became the option of choice, reduced distortion techniques were investigated. Originally the joint design utilized a custom fit shim that would be welded on each of its side to the adjacent coil. However, the weld distortion was excessive.

- Ultimately the shear plate design was developed which provided high shear strength without transferring weld distortion. The shear plates were sized to be 0.040" thinner than the measured gap. Custom made pucks that fit into holes included in the shear plates met the compression requirement. The elegance of the shear plate was that the plates were welded in alternate succession to the coil pair. Also, the inner and outer weld of each shear plate was welded to the alternate coil as well. This resulted in sort of a leaf spring effect – strong in shear but weak in tension [6].

- Another simple and clever tool was a precisely machined spring-loaded gage used to measure the puck locations thickness. Optical measurements were taken of the gap between the opposing nubs at the center of the gage.



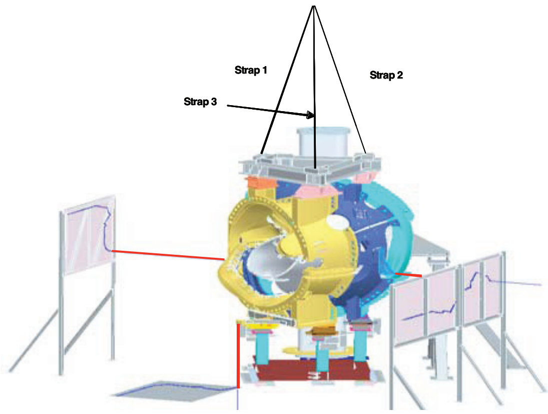
- The addition of the third coil to the previously assembled two coils was at first believed to be a simple repetition of the same steps. However, these two coils had to be tilted an additional 20 degrees to set the top flange horizontal to the floor. The main concern was to maintain the coordinate system established for aligning the first two coils. It was decided to lift and place the two coils along with the wedge that they sat onto a second 20° wedge.



This allowed us to transfer the coils with the first wedge and not disturb the coordinate system. This worked fairly well accept that the top wedge settled a few thousands of an inch after a few days. It was determined that the shims that the leading edge of the top wedge was placed on were a bit too compliant.

C. Station Three

Station three was exclusively for assembling two MCHPs over the vacuum vessel segment and then joining them together using the same technique (bolting and welding) for the individual modular coils. This formed a Field Period Assembly (FPA). The tooling for this assembly operation was considered very complex and several concepts were considered including a manipulator owned by NASA that would have been very expensive. Then a six-axis frame was designed to provide the required motion capability. The field period assembly manager is also the PPPL lift manager for PPPL and familiar with rigging techniques. An animation was created that showed the required movement to manipulate the coils over the vacuum vessel. Upon seeing this motion, it became immediately apparent that this could be accomplished with a three legged rigging arrangement while guided by three lasers pointing to a sequence track drawn on paper. A test was proposed utilizing a 25,000-pound block of concrete. With simple chain hoists combined with the overhead crane, the concrete block was successfully manipulated point to point through the track with about ½ inch of wiggle due to the hand jerking to operate the chain hoists. This test proved that the concept was valid. Three 75.000–pound capacity, 30” stroke, gear reduced, position encoded hydraulic actuators were chosen driven by variable frequency drives (VFD). This provided very fine variable speed control down to increments of only 0.005”. Also the VFDs were programmed with an on and off ramp that eliminated any possible jerking. This three-legged manipulator system worked perfectly. It required 9 people – one watching each of the three tracks, one operating the manipulator station, one operating the crane for X-Y translation, a lead orchestrating the movement, and three overall safety observers watching for potential interferences. The most difficult task was to get the team to feed positional information to the lead with clear, precise and useful language. The assembly team practiced for two weeks manipulating a MCHP along the track without the vacuum vessel in place. Once the team was confident, the vacuum vessel was set into place precisely using laser trackers. Then the alignment of the screens was double-checked and the MCHP was set to the starting position of the tracks. The track line had numbered circles placed along the path. The process was to simply point each laser to each successive number. First all three lasers were pointed to number 1 then number 2 and so on. This “walked” the MCHP along the prescribed path. The size of the circle indicated the amount of clearance at each of the points. The largest circle was about ½” in diameter and would shrink down to about ¼” where the clearance was significantly reduced to warn the lead technician. The nominal closest point of approach between the coils and the vessel was about 0.5” using the predetermined CAD path. In fact, we had a minimum of about ¾” at the closest point of approach and the entire evolution took only about 4 hours to perform.



D. Station Five

Station five involved the use of extensive tooling to hold the FPA and allow for layers of components previously mentioned to be installed over the FPA. This involved the need to design special tooling that could approach the FPA from all angles vertically and horizontally. While we did not reach the need to build this tooling, much of it would consist of small carts and handlers to handle components from below as well as standard rigging techniques to handle components from above.

IV. The Final Act

A. Orderly Storage

The NCSX experienced significant cost and schedule growth that caused it to be cancelled [7]. However, an orderly collection of procedures and data as well as the storage of components was conducted during the summer of 2008. This in itself provided useful information about the final transportation of components into the actual NCSX test cell. For example, a specially designed lowboy truck trailer was used that allowed the station three FPA to be easily transported to the test cell. Also the 4 remaining MCHPs were assembled using nominal ½" shims in only a few days each. This proved that there are no future potential interferences that could further delay the assembly.

B. Summary

Although NCSX was not completed, much was learned which will undoubtedly be of value to future projects. The team greatly expanded its knowledge and capabilities in many areas. There were several clever techniques described above. Probably the two most significant lessons learned from this project were 1) Metrology is still a quickly developing technology which often has unexpected challenges. A significant amount of extra time and backup equipment must be allotted to achieve a successful schedule. 2) Communication at all levels must be maintained to provide an avenue for immediate feedback. Our weekly meetings were invaluable – especially in a collaborative effort. Team efforts must have everyone involved on the same page and working in harmony toward a common goal. This may seem obvious but with teams of very intelligent people with competing ideas, can sometimes be difficult to maintain focus and achieve timely solutions. The NCSX managed this extremely well much to the credit of its senior management.

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