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ENGINEERING ACCOMPLISHMENTS IN THE CONSTRUCTION OF NCSX*

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The National Compact Stellarator Experiment (NCSX) was designed to test a compact, quasi-axisymmetric stellarator configuration. Flexibility and accurate realization of its complex 3D geometry were key requirements affecting the design and construction. While the project was terminated before completing construction, there were significant engineering accomplishments in design, fabrication, and assembly. The design of the stellarator core device was completed. All of the modular coils, toroidal field coils, and vacuum vessel sectors were fabricated. Critical assembly steps were demonstrated. Engineering advances were made in the application of CAD modeling, structural analysis, and accurate fabrication of complex-shaped components and sub-assemblies. The engineering accomplishments of the project are summarized

I. NCSX MISSION AND REQUIREMENTS

The National Compact Stellarator Experiment (NCSX) was designed to test the physics of a compact, quasi-axisymmetric stellarator (QAS) configuration.[1,2] The QAS uses three-dimensional stellarator magnetic fields for steady-state, disruption-free operation but has a tokamak-like magnetic field symmetry when viewed in magnetic coordinates. A steady-state QAS would have a net toroidal current due to the bootstrap effect but could eliminate requirements for external current drive and active feedback control of ELMs and other instabilities.

The NCSX was based on a magnet configuration design that was generated by a numerical optimization process to provide high-beta plasmas with attractive physics properties: quasi-axisymmetric with low ripple, stable, good magnetic surfaces. The magnets were designed to produce a 3-period QAS plasma with $\beta = 4\%$, effective ripple ~1.5% at the plasma edge, and aspect ratio $R/\langle a\rangle = 4.4$. The magnet system consists of 18 modular coils (six each of three different shapes), plus toroidal field, poloidal field, and trim coils. The modular coils and plasma are depicted in Fig. 1. The coils provide the flexibility needed to start up a high-β plasma from vacuum flux surfaces and to vary configuration properties in order to test their effect on the physics. The major radius R is 1.4 m, the magnetic field on axis B_0 is ≤ 2 T, toroidal currents I_P up to 320 kA are supported, and the pulse length is 0.5 to 2 s depending on the magnetic field strength.

Accurate realization of the magnetic configuration is a key requirement that has been achieved in the construction of stellarators based on modular coils, e.g., HSX[3], Wendelstein 7-AS[4], and Wendelstein 7-X[5] (under construction) and on helical coils, e.g., LHD[6] and ATF[7]. Of greatest concern for NCSX were low mode-number resonant magnetic field perturbations which can produce islands at magnetic surfaces where the rotational transform goes through rational values. The fundamental accuracy requirement in NCSX was to limit the calculated size of islands to enclose less than 10% of the total toroidal magnetic flux in the plasma, using a linear island-width approximation which neglects the plasma response. The project addressed this requirement by following a multi-part strategy to minimize resonant field errors in design and construction:

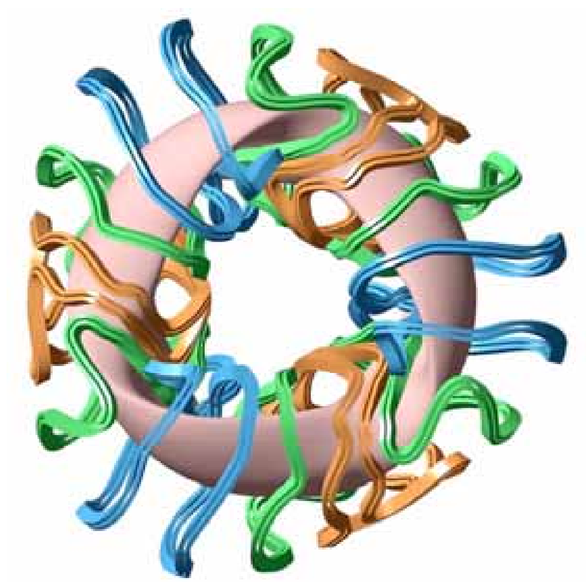

Fig. 1. Modular coils and plasma configuration.

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- Accurate construction (tolerance on the completed modular coil system ±1.5 mm, or ~R/1000 as is typically achieved in stellarator construction)
- Low magnetic permeability ($\mu_r < 1.02$ for components close to the plasma).
- Low eddy currents (material choices; insulating breaks in structures)
- Low stray fields from coil leads, feeds, crossovers.
- Stellarator-symmetric design.
- Minimize coil deflections under load.

In addition, an array of trim coils provided the capability to compensate for construction errors.

For physics flexibility, the NCSX device was designed to support several pulsed operating scenarios which were specified in detail in the project requirements document. In all scenarios, the plasma is initiated inductively in a stellarator vacuum field configuration with good flux surfaces. Inductive current drive provides capabilities that are useful for physics experiments: rapid startup and flexibility to operate over a continuous range of magnetic field strengths. After initiation, the coil currents vary in time to control the plasma equilibrium as beta and current evolve. The currents in the three types of modular coils can be varied independently. There are assumed to be six PF coil circuits and one TF coil circuit. The important scenarios from a structural point of view are found to be:

- 2 T High-Beta: $B_0 = 2\ T$, $\beta = 4\%$, $I_P = 200\ kA$
- 1.7 T Ohmic: $B_0 = 1.7\ T$, $I_P = 120\ kA$.

The device was designed with the capability to vary plasma configuration properties to test their effects on plasma stability and transport as part of the planned flexibility studies. Variable properties include the external rotational transform (iota), global shear (edge iota minus central iota), quasi-symmetry (using effective ripple as the metric), theoretical instability beta thresholds, and radial and vertical position. Extensive equilibrium studies were performed to check the flexibility of the NCSX coils. The most important casesfrom a structural point of view, all at $B_0 = 1.7\ T$, are:

- Iota = 0.65 (reference plus 0.2).
- Iota = 0.19 (reference minus 0.26).
- Global shear at reference plus 0.20.
- Global shear at reference minus 0.10.

A self-consistent conceptual design (Fig. 2) satisfying all mission requirements was completed in 2003. Construction began in 2004 but was terminated by the sponsor for cost and schedule reasons in 2008. While the project was not completed, design of the stellarator core device was completed, all of the most difficult components were fabricated and critical assembly steps were demonstrated. The engineering accomplishments of the Princeton Plasma Physics Laboratory and Oak Ridge National Laboratory team in the course of design and partial construction of NCSX made significant advances in fusion engineering science. The over-arching accomplishment was the translation of an optimized physics design into actual equipment, consistent with the mission requirements for performance, flexibility, geometry, and accuracy. In the remaining sections we summarize the main engineering accomplishments of the NCSX project.

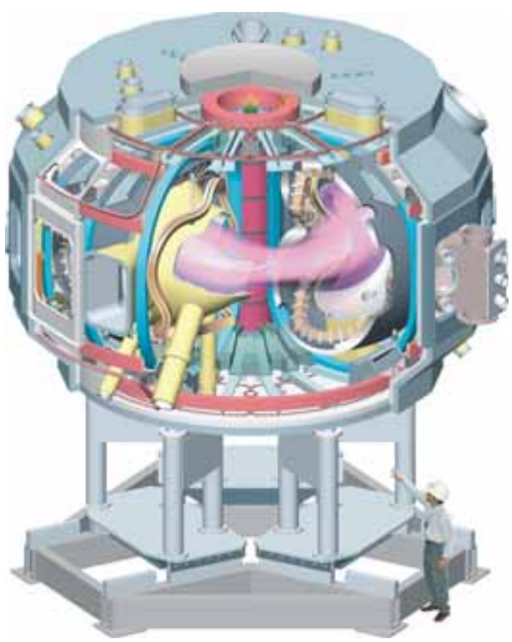

Fig. 2. NCSX stellarator device design (CAD model).

II. STELLARATOR CORE DESIGN AND COMPONENT FABRICATION

II.A. Modular Coils

The design of the NCSX magnet systems and the vacuum vessel, the central core of the device, was completed. The most critical subsystem, and the structural "backbone" of the device, is the modular coil array. A

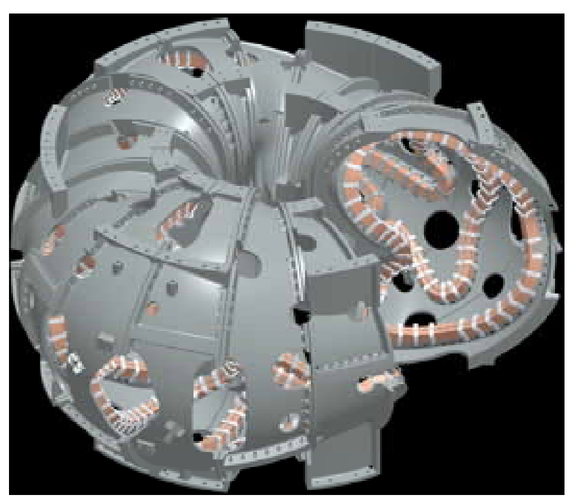

Fig. 3. Modular coil system design.

shell-type structure, with the coils supported on the inside surface, was adopted during conceptual design as a robust solution to the problem of minimizing deflections under a wide range of operating conditions (Fig. 3). This decision was intended to ensure that the basic concept would succeed even though the structural analysis had not then matured to the point where the detailed stress distributions were well known. The modular coil shell was divided into eighteen sectors, one per coil, each subtending twenty degrees of toroidal angle between planar flanges. Cutouts, some of which span the sector joints, were provided to accommodate port penetrations into the vacuum vessel. The coils were wound directly onto accurately machined support features on these shell sectors, called modular coil winding forms (MCWF, Fig. 4), which served a dual function as both the primary tool for accurate coil construction and a permanent part of the structure. The coils were wound with copper conductor and then epoxy-impregnated. The entire magnet system was designed to be pre-cooled to cryogenic temperature (80 K) with heat removed between pulses.

Final design drawings and specifications for MCWF manufacture were issued in 2004, while the design of the winding packs was completed in 2006. The design effort accomplished the complex tasks of modeling the modular coil geometries and orienting the winding packs about their current centers to avoid interferences, a challenge even with the powerful computer-aided design (CAD) tools that were used. The coil design was strongly guided by manufacturing input both from the MCWF industrial suppliers and from the PPPL coil fabrication team. The information came partly from dedicated manufacturing R&D programs, including the construction of prototypes, that supported the preliminary and final design efforts.[8] Those programs led to key design decisions, for example the selection of a specially developed low permeabilty casting alloy with good welding properties (Stellalloy, developed by MetalTek International) for the MCWF and the choice of a winding pack design concept compatible with achieving the tolerance (±0.5 mm, or 0.020 in., on the position of the current center) allocated to modular coil fabrication. The validity of these decisions, and the value of the R&D programs that supported them, has now been borne out by the successful manufacture of all 18 modular coils. A completed coil is shown in Fig. 5. The required accuracy of the coil current center position was achieved over ~90% of the circumference. Special procedures were employed to impose stellarator symmetry by making the coils as nearly alike as possible. Results are shown in Fig. 6.

The design of the inter-coil joints and the associated interface hardware was completed in 2008. Here we summarize the main features, while details are provided in Ref. 9. The coils were designed to be bolted together at their flanges using 25-30 high-strength bolts per joint,

Fig. 4. Modular coil winding form.

Fig. 5. Completed modular coil.

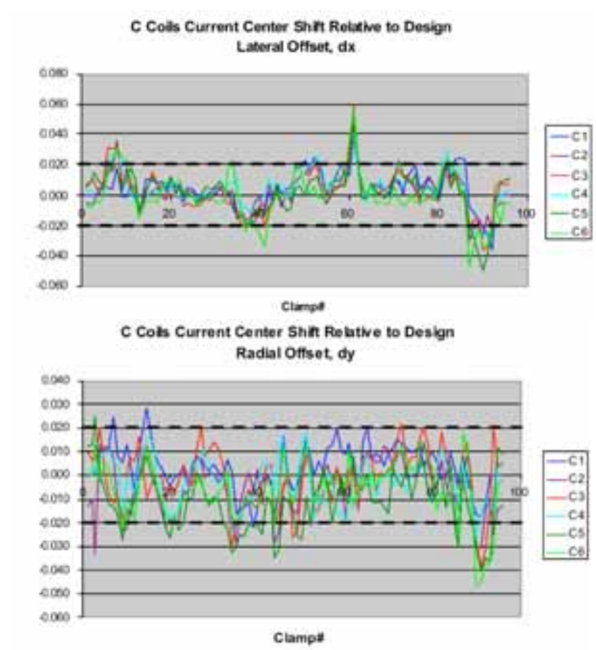

Fig. 6. Modular coil current center position data for all Type C coils. Dashed lines show tolerance bands.

plus custom shims and other hardware to accurately control the inter-coil spacing, provide insulating toroidal breaks, and react shear and compressive forces. A bolt assembly design was developed, key elements being the use of a commercial compact in-situ tensioner (Supernuts™) to provide the compressive preload, a steel shim sandwiched between thin G10 layers for shear and insulation, and insulated bushings around the bolts as further protection against slippage.

The coil flanges are not continuous around the poloidal circumference, but have gaps at the port cutouts and are very narrow on the inboard leg of the coil where space and access limitations preclude bolting. The port gaps were not an issue but providing adequate shear support on the inboard leg was a significant engineering challenge. For the fifteen intra-period joints (each field period has six coils), the solution was to use a welded connection to carry the shear in combination with a custom-thickness shim to control spacing and handle compression. The resulting toroidal electrical connection produces a small, and acceptable, increase in the eddy current time constant because it is localized to the inboard leg poloidally and to within a field period toroidally. For the three inter-period joints, where the shear forces are less severe and the bolt-free length along the inboard leg is shorter, the shear is carried by a high-friction coating applied to the compression shims. The coating material (alumina) also provides a durable insulating layer which allows a complete toroidal break to be preserved at the inter-period joints.

The design of the modular coil interfaces was a greater challenge than anticipated. Its success from a technical standpoint was due to the following key engineering accomplishments:

- Advances in global structural analysis of a complex structure, with analytical models derived directly from CAD models for accurate representation.
- Development of a low-distortion welded joint design based on a hardware configuration and a low-heat-input process (using MIG welding and flux core weld wire) to minimize the deflection of nearby windings during assembly.
- Development of enhanced-friction insulating shim designs using thin G10 layers for medium friction (COF ≈ 0.4) and alumina coatings for high friction (COF ≈ 0.6).
- Development of special long-reach tooling to assemble bolts in limited-access areas, making it feasible to reduce the bolt-free length on the inner leg of the inter-period joint.
- Development, concurrent with and supportive of the design effort, of an assembly process compatible with dimensional control requirements, metrology capabilities, and cost-effective assembly approaches.

The performance and long-term stability of all aspects of the joint design were validated by testing at room and cryogenic temperatures. The manufacturing feasibility of the intra-period joint design was validated by the successful construction of the first half-period subassembly (three coils) to within the required ±0.5 mm tolerance allocated to that step (Section IV).

Fig. 7. Vacuum vessel sector with installed service.

II.B. Vacuum Vessel

The second critical component, after the modular coils, is the vacuum vessel. The vessel was designed to provide a high-vacuum environment for the plasma with as much interior volume as possible, while leaving the minimum clearance for installation of the modular coils over the vessel sectors (with ports removed). This results in a non-axisymmetric vacuum vessel shell with a shape that resembles that of the plasma and which must be realized within ±3 mm accuracy. Computer-aided design (CAD) modeling, supported by manufacturing R&D including the construction of prototypes, was used to generate a shell design that could be constructed from a minimum number (60) of formed panels to minimize weld distortion risks. Inconel was chosen as the vessel material based on field-error considerations: it reduces the risk of high permeability welds and its high resistivity reduces eddy current decay times. Heating and diagnostic access requirements are accommodated by providing about 99 ports of various shapes, sizes, and orientations causing the vacuum boundary to protrude through all available openings in the surrounding magnets. The design was validated by the successful manufacture of the vacuum vessel body and port nozzles by industry in 2006.

The vessel was designed to be heated to 350 C to effect the bakeout of plasma-facing components that would be installed during operations. To support this, an array of flexible metal heating and cooling hoses, resistance heater tapes, and thermocouples was designed and installed on the vacuum vessel. An array of magnetic diagnostic flux loops and a set of Rogowski loops were also designed and installed. One vessel sector, complete with installed services, is illustrated in Fig. 7. A thermal

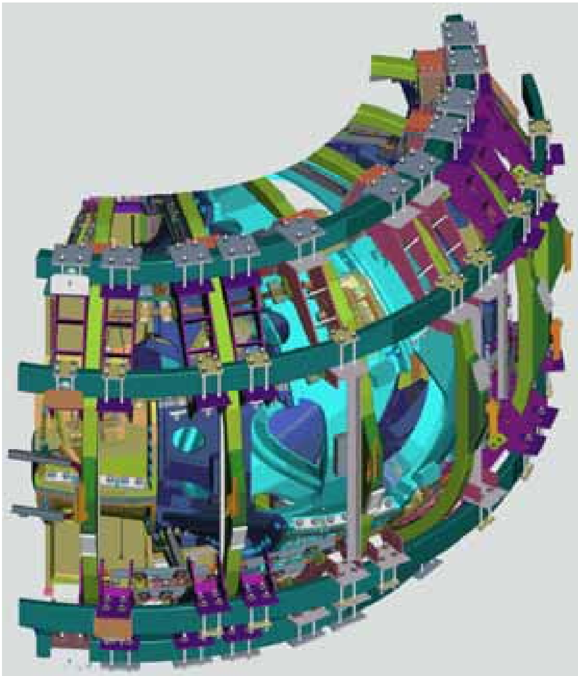

Fig. 8. Poloidal and toroidal field coil design.

insulation system, using aerogel materials in pourable and blanket forms, was designed to reduce heat transfer between the vacuum vessel and the surrounding cryogenically cooled modular coils.

Throughout the design process, CAD simulations of coil installation over the vacuum vessel with its installed services were performed to verify assembly feasibility, in spite of limited clearance (5 mm). Assembly tooling including a novel guidance system was designed and fabricated to support this critical operation. A successful trial installation of a coil assembly over the vacuum vessel validated the equipment design, tooling, and assembly procedures.

II.C. Conventional Coils

The NCSX device also includes three systems of planar coils- toroidal field (TF) coils, poloidal field (TF) coils, and trim coils. The TF and PF coils are illustrated in Fig. 8. These coils provide the plasma configuration flexibility that is required for physics experiments. Final design drawings and fabrication specifications were completed for all of these. Fabrication of the 18 TF coils was completed by industry.

The trim coils were a key element in the project's field error control strategy. Their design made use of Monte Carlo simulations of construction errors, i.e. displacements within tolerances of coils and subassemblies from their nominal positions, and an inventory of field errors from known sources such as coil leads, magnetic materials, etc., to set requirements. (It was found that the effects of modular coil fabrication errors could be nulled by making slight adjustments in their alignment in the 18-coil array so those errors did not drive trim coil requirements.) The trim coils, shown in Fig. 9, were planar and rectangular in geometry, placed in a saddle-like orientation just outside the modular coil shell for maximum effectiveness. Their arrangement and number (24 each of two different shapes) were chosen to be able to control islands at all of the most important plasma resonances. The performance was set to meet the fundamental island-width requirement (<10% of the toroidal flux) in the presence of the simulated and known construction errors. It was found that a safety factor of at least 2 in the required current could be obtained cost-effectively, providing extra margin that could be used to compensate for larger construction errors if necessary as well as provide additional physics flexibility.

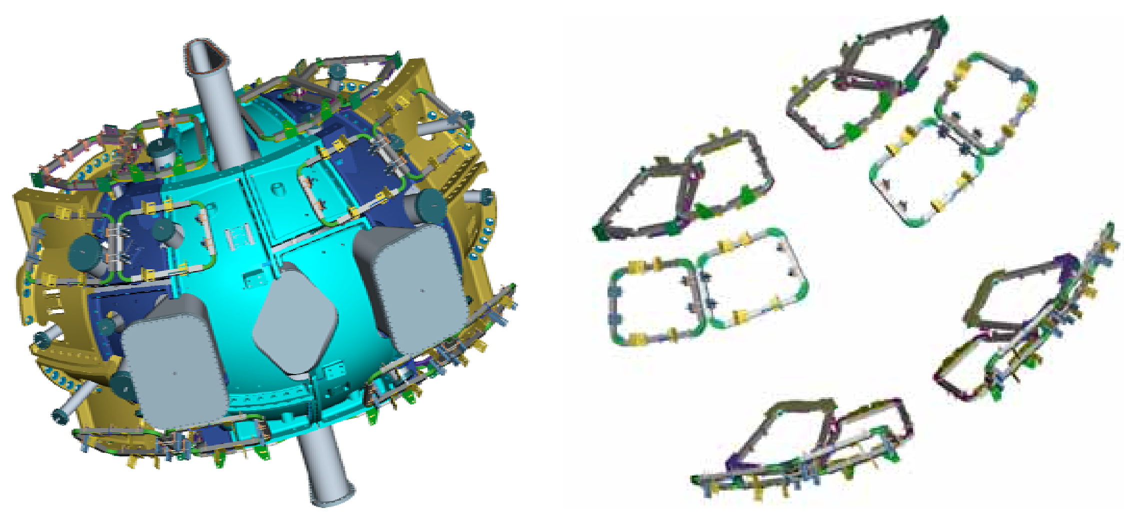

Fig. 9. Trim coil design (one period shown).

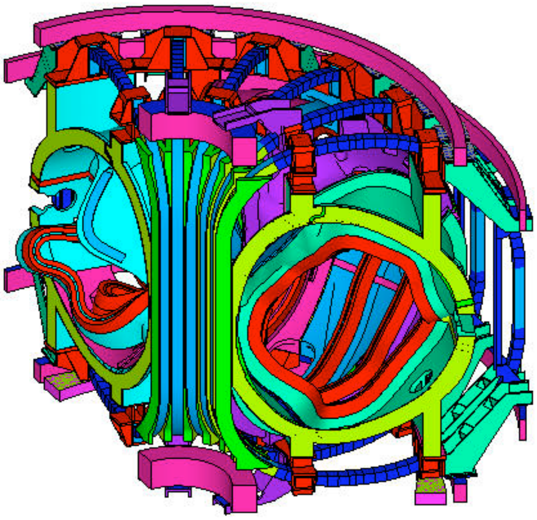

Fig. 10. Global structural model of NCSX magnets.

III. STRUCTURAL ANALYSIS

The combination of complex geometry, physics requirements, and engineering design choices drove significant advances in structural analysis on NCSX. Since excessive coil deflections under operating conditions could produce unacceptable field errors, such deflections had to be controlled, although stellarator-symmetric design meant that the tolerance on such deflections, which would also be stellarator symmetric, could be relaxed to ±3 mm. The use of bolted connections, with shear loads carried through friction layers, posed the risk that any relative motion at the coil interfaces could unacceptably degrade the joint over time. This was more restrictive than the field error requirements in the design of the inboard modular coil interfaces. The completed designs for the modular coils, conventional coils, and coil structures satisfied these requirements.

The global analytical model for the NCSX magnet system is illustrated in Fig. 10. The modular coils are assumed to be bonded to the shell (winding forms) while the modular coil interfaces are treated as bonded contact surfaces. Static linear analyses of the multiple load cases representing the reference scenarios and flexibility equilibria confirmed that the 2 T high beta scenario produces the maximum net electromagnetic forces on the modular coils (1.4 MN radially inward) and maximum loads at the flange interfaces of 2.6 MNt/m of compression and 0.7 MNt/m of shear. Local nonlinear models were used to analyze coil deflections and design details of the modular coil interface.. The maximum deflection of the modular coils is 2.2 mm. The moderate-friction shims with COF = 0.4 that the project developed are sufficient to prevent slippage at the outboard bolts. The high-friction alumina-coated shims with COF = 0.6 are sufficient to handle the shear at the inboard inter-period joints.

IV. PROGRESS IN ASSEMBLY

The NCSX device was planned to be assembled in a series of sub-assembly stages. Key engineering challenges in the assembly of NCSX include 1) achieving the required ±1.5 mm tolerance in the final position of the coil current centers relative to their specified position; 2) installing the modular coils over the vacuum vessel without collisions. Although assembly of NCSX was not completed, sufficient progress was made to prove the

Fig. 11. Completed modular coil half-period assembly.

feasibility of meeting these requirements.[10]

In fabricating all 18 modular coils, the required ±0.5 mm tolerance on the position of the coil current center was achieved over at least 90% of the circumference (see Fig. 6). The methods used in winding compensated for as-built errors in the winding forms. The out-of-tolerance areas were replicated on all coils of a given type, thus taking advantage of stellarator symmetry to mitigate the effects of these errors on plasma islands. Further mitigation was accomplished by adjusting the specified position and orientation of each coil in the 18-coil array to null the effects of as-built coil fabrication errors. This had the effect of fully "recovering" the tolerance originally allocated to coil fabrication and making it available to assembly.

During coil manufacture, measurements of the coil conductor dimensions were made on a fine grid to support manufacture and establish the as-built current-center geometry. However, the conductor becomes inaccessible to measurements starting with the installation of ground insulation and increasingly so with epoxy impregnation of the coil and subsequent assembly steps. For this reason, metrology monuments were installed on the exterior of each coil for use in assembly. It was also discovered that coils are flexible, and subject to significant deformations (~0.5 mm) depending on how they are supported and oriented. Therefore, a procedure was developed to reform each coil into its proper geometry prior to assembly.

The first step in machine assembly is the construction of modular coil half-period assemblies (HPAs). In total there are six HPAs, each consisting of three coils, one coil of each type. One HPA was completed (Fig. 11), achieving the required ±0.5 mm coil positioning tolerance allocated to the HPA step. A second is nearly complete. The work completed on HPA construction validated the assembly tooling and procedures, including the dimensional control strategy for achieving required assembly tolerances. Coil position measurements relied on the exterior monuments and the use of laser tracker metrology equipment. It also validated the construction feasibility of the intra-period modular coil joint design, including control of distortion due to welding of the inner leg interface hardware to the coils.

The next step in machine assembly is the construction of field period modules. In total there are three such modules, each consisting of two HPAs installed over the ends of a vacuum vessel sector and joined in the middle. Because of the geometry and the close clearance (≥5 mm) between the coils and the vessel, the HPAs must be translated and rotated, using all six degrees of freedom, to maintain clearance during installation. Custom lift equipment was designed and fabricated to provide the necessary control. An economical technique was developed, using laser beams attached to the HPA pointing to curves traced on the walls of the assembly station, to guide the operators in manually moving the HPA along its assembly path. The curves are CAD-generated mappings of the optimum assembly trajectory onto two dimensional surfaces. A trial assembly of one HPA over a vessel sector was successfully completed (Fig. 12). No interferences or other unexpected difficulties were encountered. This test demonstrated the assembly tooling, guidance technique, and procedures. It validated the CAD modeling basis of the component designs, including as-built dimensions of critical features, and the assembly process.

Fig. 12. Modular coil half-period lift and guidance apparatus under test and half-period assembled over vacuum vessel sector.

V. CONCLUSIONS

Although the construction of NCSX was only partially completed, the progress that was made in design, component fabrication, and assembly was substantial and was made possible by significant advances in fusion engineering science. The over-arching accomplishment was the rigorous translation of a physics-optimized magnetic configuration design into actual equipment, consistent with the mission requirements for performance, flexibility, geometry, and accuracy. Key engineering accomplishments were:

In design:

- Development of an integrated computer-aided design (CAD) model of a complex system and its use in the design, fabrication, and inspection of all critical components and sub-assemblies.
- Development of global and local structural models derived from CAD models, and their use in detailed analyses supporting the design of a complex magnet assembly.
- Development of a detailed, self-consistent design for an optimized stellarator meeting mission requirements, and final design documentation for the magnet systems and vacuum vessel.

In fabrication

- Development of manufacturing processes for producing the modular coils and vacuum vessel, consistent with field-error control requirements for dimensional accuracy, low magnetic permeability, and stellarator symmetry.
- Fabrication of the modular coils, toroidal field coils, and vacuum vessel sectors.

In assembly

- Developed procedures and tooling for assembling the stellarator core, consistent with the equipment design, dimensional accuracy requirements, and practical assembly operations.
- Demonstrated critical assembly operations by completing the fabrication of one HPA and performing a trial installation of an HPA over a vacuum vessel sector.

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