Progress in the Construction of NCSX*

G. Neilson 1), B. Nelson 2), N. Pomphrey 1), W. Reiersen 1), A. Boozer 3), A. Brooks 1), T. Brown 1), M. Cole 2), L. Dudek 1), J. Chrzanowski 1), H. M. Fan 1), P. Fogarty 2), E. Fredrickson 1), G. Gettelfinger 1), P. Goranson 2), P. Heitzenroeder 1), E. Lazarus 2), J. Lyon 2), F. Malinowski 1), S. Raftopoulos 1), B. Stratton 1), R. Simmons 1), R. Strykowsky 1), M. Viola 1), M. Williams 1), D. Williamson 2), and M. Zarnstorff 1)

1) Princeton Plasma Physics Laboratory, Princeton, NJ 08543, U.S.A.
2) Oak Ridge National Laboratory, Oak Ridge, TN 37831, U.S.A.
3) Columbia University, New York, NY 10027, U.S.A.

e-mail contact of main author: hneilson@pppl.gov

Abstract. The National Compact Stellarator Experiment (NCSX) is currently being constructed at PPPL in partnership with ORNL. It is motivated by the need for a compact confinement configuration for steady-state operation disruption-free MFE systems. Technological challenges in the construction of NCSX are 1) realizing the complex magnetic field geometry with the accuracy required to obtain attractive plasma properties, and 2) providing for the physical measurements needed to diagnose those properties in experiments. Design and manufacturing solutions, including materials, processes, and inspection methods coupled to CAD modeling and analysis, were developed for key components. Manufacture of the modular coils and vacuum vessel began in 2004. Currently, the modular coils and toroidal field coils are in production, vacuum vessel fabrication is complete, and layout of an innovative diagnostic flux loop array is in the early stages. The project is on schedule for completion in July, 2009.

1. Introduction

The National Compact Stellarator Experiment (NCSX), a new experiment to study the physics of compact stellarators, is in construction at the Princeton Plasma Physics Laboratory (PPPL) in partnership with the Oak Ridge National Laboratory (ORNL). The motivation for NCSX is the need for physics solutions to the problems of achieving high-β steady-state operation and avoiding disruptions in MFE confinement systems, while building on the performance and understanding that has been obtained from tokamaks. The NCSX [1, 2] will test a compact stellarator design characterized by: a lower aspect ratio ($R/\langle a\rangle = 4.4$) than previous optimized stellarator designs, a quasi-axisymmetric (QA) magnetic field that has low effective ripple (< 1.5% at the plasma edge) and tokamak-like particle orbits and plasma flows, and good equilibrium magnetic surfaces and stability to ideal MHD modes at $\beta \geq 4\%$.

The NCSX design is based on a magnet system consisting of eighteen modular coils, six each of three different shapes, with toroidal field, poloidal field, and helical field trim coils for plasma configuration flexibility. An integrated machine design (Fig. 1) was developed in 2001-2003 based on this configuration with major radius R = 1.4 m, magnetic field B = 1.2 - 2.0 T, and pulse length 0.3 - 1.2 s. Component fabrication began in 2004 and assembly activities began in 2006.

Key technological challenges in the construction of NCSX are: 1) realizing the complex magnetic field geometry with the accuracy required to obtain required physics properties and 2) providing for the physical measurements needed to diagnose those properties in

* Research supported by the U.S. DOE under Contracts No. DE-AC02-76CH03073 with Princeton University and No. DE-AC05-00OR22725 with UT-Battelle, LLC.

experiments. These requirements are met through materials and innovative construction processes that minimize magnetic permeability and eddy currents, attention to dimensional control in manufacturing and assembly, and advanced inspection methods coupled to computer-aided design (CAD) modeling and analysis.

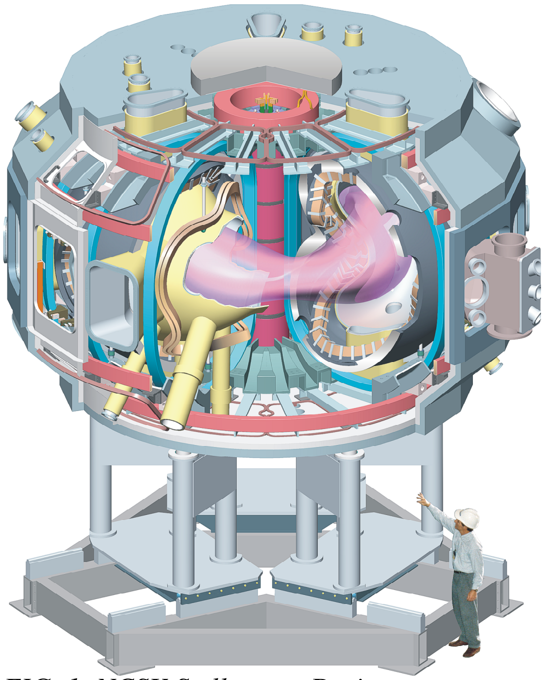


FIG. 1. NCSX Stellarator Design.

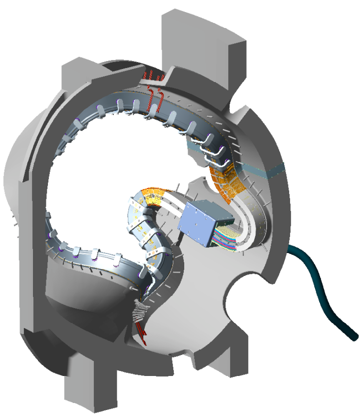
2. Component Design and Fabrication

2.1. Modular Coils

The modular coils are designed to locate their current centers within ±1.5 mm of nominal winding trajectories determined by physics optimization. Each modular coil (Fig. 2) is wound on a tee-shaped support feature machined on the interior of a stainless steel ring-like structure called a modular coil winding form (MCWF). The eighteen MCWF are bolted together at mating flanges to form a toroidal structural shell which accurately locates and supports the windings against operating loads.

The MCWF are sand cast of a variant of CF8M stainless steel named Stellalloy 2 (CF8MnMN Mod), an alloy specifically developed for NCSX to have favorable characteristics for both operation and manufacture. It has a low magnetic permeability ($\mu < 1.01\mu_0$) to minimize field errors and has structural properties at both room temperature and operating temperature (77 K) which meet or exceed project requirements. Its good welding characteristics facilitate repair of defects which typically exist in the rough casting. Only air quenching is needed to develop the required mechanical properties, thus avoiding the risks of distortion associated with water quenching.

The casting molds and feed system were designed using computer simulations of the flow and solidification of molten metal. The goal of this iterative analysis is to achieve controlled directional solidification of the alloy along with an adequate supply of molten metal



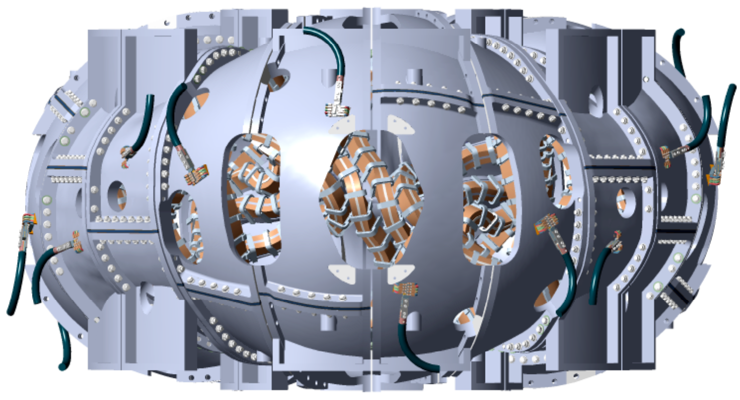


FIG 2. NCSX modular coil design- single coil and complete 18-coil set.

throughout the solidification process in order to avoid voids in the castings. Hard wood patterns are used to make the sand molds to assure casting repeatability. The patterns are contour milled from mahogany using CAD models of the part, dimensionally adjusted to compensate for solidification shrinkage and thermal contraction of the casting and to provide additional metal to allow for uncertainties and to assure the final part can be machined from the casting.

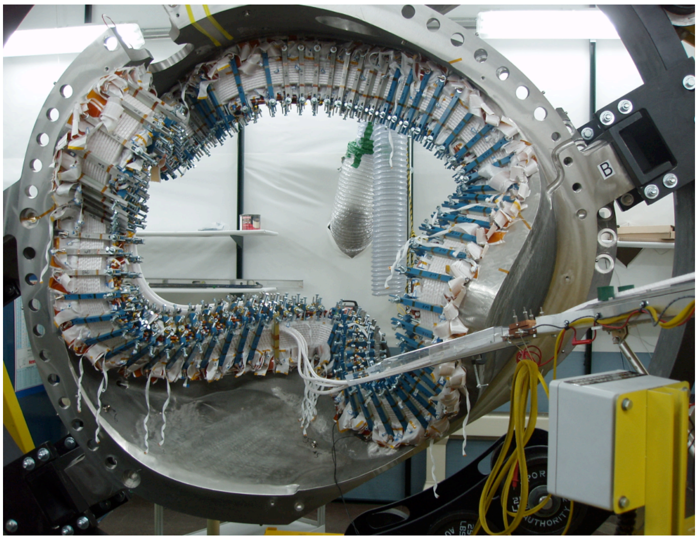


FIG. 3. Modular coil being wound onto the MCWF.

The winding surfaces and flanges are machined to a tolerance of ±0.25 mm using a series of multi-axis CNC milling machines. After completion, each winding form is dimensionally inspected using a coordinate measuring machine to develop a "point cloud" which is superimposed on the winding form CAD model to identify any dimensional deviations.

The MCWF are manufactured by a team led by Energy Industries of Ohio, Inc., and including C.A. Lawton Company, MetalTek International, and Major Tool and Machine, Inc. The alloy and manufacturing process for the casting were developed and demonstrated by constructing a full-scale prototype winding form casting in 2004, prior to placing the production order. As of September, 2006, all eighteen forms have completed foundry operations and eight machined winding forms have been delivered to the project site for coil fabrication.

The coils are wound with a compacted copper cable conductor, 9 mm x 10 mm in cross section, which is flexible to facilitate handling and placement of its current center within ±0.5 mm of its nominal position on the MCWF. The pre-insulated conductors are wound 4-in-hand using a system that allows direct positioning of the turns (20 or 22 per coil) onto the winding form, as shown in Fig. 3. The conductor and process were designed to minimize cross section deformation ("keystoning") that could occur during the winding operation. Bench tests showed that the conductor turns could be repositioned and reshaped after winding to improve conformance to the dimensional specifications. The winding strategy takes advantage of this to achieve the required accuracy without the use of shims.

The current center position is inferred from coordinate measurements of the winding form and conductor taken throughout the winding process using a portable coordinate measuring arm. The conductor is wound into a rectangular cross section envelope bounded on two sides by the MCWF winding tee and on the third side by winding clamps set to predetermined positions based on coordinate measurements of the winding surface. The side clamps are removed a few at a time as each layer of conductor is wound, and then returned to position with the aid of gage blocks. Top clamps are adjusted to maintain constant pressure on the winding pack as each layer of conductor is added. Once the winding packs are complete, they are re-measured and adjusted with the clamps to put the current center in the required location. The winding packs are bound with glass cloth strips to minimize changes in the pack dimensions after the clamps are removed. The completed winding pack assembly, consisting of flexible conductor, turn-to-turn insulation, and enclosing layers of ground insulation, copper cooling strips, and cooling tubes, is epoxy encapsulated to secure the dimensions and provide the required structural rigidity. Due to the complex geometry, a "bag" mold is constructed over the winding pack with layers of silicone rubber tape instead of a rigid machined mold. The mold is finally filled with epoxy using a vacuum-pressure impregnation process. A completed coil is shown in Fig. 4.

FIG. 4. Completed modular coil.

The winding pack design and manufacturing processes were demonstrated by constructing a prototypical "twisted racetrack" coil (TRC) in 2005. The TRC, as well as the first production coil, were tested at design temperature and current to confirm cooling performance and mechanical integrity through cooldown and pulsing. The TRC was sectioned, verifying satisfactory epoxy penetration and dimensional accuracy. All coils are tested at room temperature for terminal-to-terminal resistance and insulation strength. As of September, 2006, modular coil production is under way with six coils having been wound and four vacuum pressure impregnated.

2.2. Toroidal Field Coils

The NCSX machine includes an array of eighteen planar toroidal field (TF) coils to provide experimental flexibility. They are supported against centering forces by wedging of the inner legs, which must be positioned to an accuracy of ±3 mm to reduce field errors. The wound coils will be vacuum-pressure impregnated in a precisely machined mold with tolerances in the range of ±0.25 mm in order to tightly control the geometry of the coil in the cured condition. The coil support structure will be adjustable, providing the ability to compensate for shape relaxation that may occur as the coil is removed from the mold, and configured to minimize field errors due to deflections in operation. To further minimize field errors, the leads and layer to layer transitions are located near the center of the back leg of the TF coil, where they have a minimal effect on field errors. The forward wedge supports will be cast from a low-permeability ($\mu < 1.02\mu_0$) alloy. Accuracy of the wedge dimensions will be controlled by performing the final machining operation after assembly to the coil.

The TF coil manufacturing team is led by Everson Tesla, Inc. (USA), who will fabricate the coils and assemble them to wedge supports supplied by Tesla, Ltd. (UK) and Österby Gjutery (Sweden). Facility preparations are in progress, with coil manufacture scheduled to begin by the end of 2006.

2.3. Vacuum Vessel

The NCSX vacuum vessel (Fig. 5) is designed to provide a vacuum boundary just inside the modular coils and as far from the plasma surface as possible, leaving the minimum assembly clearance to install the modular coils over the vacuum vessel. This results in a vacuum vessel shell geometry that approximately conforms to the plasma and which must be realized within ±5 mm accuracy to avoid interferences. Access for plasma measurements is provided with a stellarator-symmetric array of 99 ports configured to accommodate the diagnostics planned for NCSX [3] as well as heating systems. Additional ports are provided to allow for future innovations, such that the vacuum boundary protrudes through all available openings in the surrounding magnets. To minimize field errors, the vessel is fabricated of Inconel 625 alloy because of its high resistivity (to reduce eddy currents) and low magnetic permeability ($\mu < 1.02\mu_0$) at the welds. Stellarator symmetry is imposed as an additional measure to reduce the possibility of non-stellarator symmetric field perturbations.

The vacuum vessel manufacturing processes were developed and demonstrated by constructing a full-scale 20 degree prototype vacuum vessel segment in 2004, prior to placing the production order. The production vessel is fabricated in three identical 120-degree segments, corresponding to the three NCSX field periods. The shell segments are constructed of 60 press-formed panels of ten different shapes, welded together. The number of panels was minimized to minimize the amount of welding and the attendant risk of distortion. The panels are formed at room temperature using accurately machined Kirksite dies, then annealed to remove internal stresses and reduce attendant distortion risks. The panels are assembled into shell segments over accurately machined skeletal welding fixtures, which facilitate precise positioning of the panels and control of the dimensions as the panel seams are welded. Both the forming and welding processes involve constant dimensional inspections, using technologies ranging from simple go/no-go gauges to mechanical coordinate measuring arms and laser scanners, with iterative adjustments as necessary to achieve the required accuracy. The ports are welded on for vacuum testing, and then all except the large vertical and horizontal ports at the middle of the segment are cut off within 2.5 cm of the vessel surface. The removed extensions are supplied separately to be reattached during assembly. Three custom machined 20-cm wide spacers (shown as bands in Fig. 5), designed to facilitate the final assembly of the device, are also supplied. Vacuum vessel manufacture, including all segments, spacers,

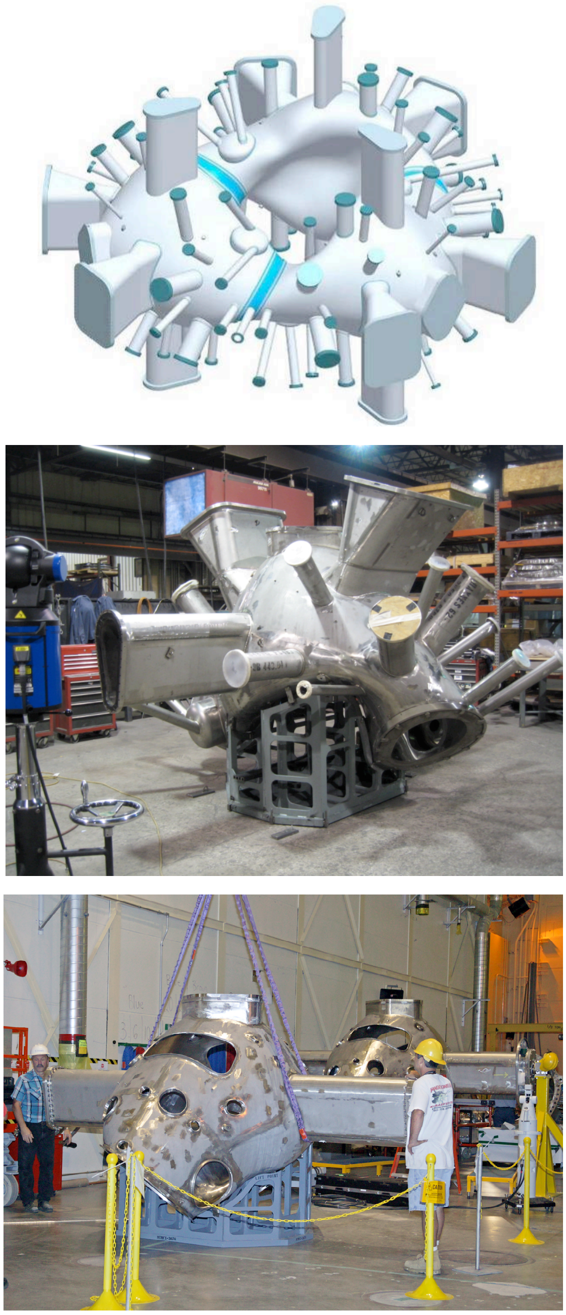


FIG. 5. NCSX Vacuum Vessel design; one segment in manufacture, prior to vacuum testing; and two segments as delivered, with most ports removed.

and ports was completed in September, 2006, by Major Tool and Machine, Inc.

2.4. Magnetic Diagnostics

The NCSX stellarator is being constructed with a set of integral magnetic flux loops, mounted on the vacuum vessel (VV) surface, whose main purpose is the diagnosis of plasma equilibrium magnetic fields. [4] Signals are expected to be predominantly stellarator symmetric (SS) with toroidal mode numbers, n, per torus equal to multiples of 3. However, the flux loop design must also take into account that plasma instabilities and coil imperfections will generate non-SS fields with n = ±1, ±2, etc.

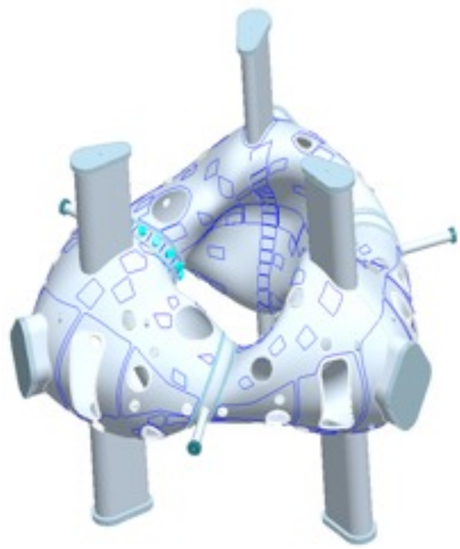


FIG. 6. NCSX flux loop array design.

The design optimization involved the generation of a database of 2,500 SS free-boundary VMEC [5] equilibria incorporating random combinations of current and pressure profiles and spanning the range of plasma parameters and shapes that can be achieved in NCSX. Magnetic field values from the plasma and coils were calculated on the surface of a close-fitting vacuum toroidal surface (TS) surrounding all of the equilibria. A trial set of 100 flux loops that completely tile one half-period of the VV surface was used in the analysis. A least-squares regression of the flux loop signals was performed with respect to the field values on the TS. Singular value decomposition (SVD) algorithms were developed for ranking the effectiveness of the flux loops in reconstructing the equilibrium magnetic fields on the TS. Highly ranked trial loops identify regions of the VV surface that are important for placing actual flux loops. A good correlation is found between regions of the VV surface where high-ranking flux loops are located and regions where the plasma contribution to the total flux signal is large enough in magnitude and as a fraction of the total signal to be readily measured. As expected, there is also a correlation between signal strength and plasma-to-VV separation distance. Analytic estimates of plasma-to-VV signal attenuation indicate that flux loop dimensions should be of order the plasma-to-loop separation distance. A dedicated sub-array of loops was designed to detect n=3 islands, along the inside wall of the vertically elongated cross-section. Additional sub-arrays, continuous in the toroidal and poloidal directions, were also included.

Combining the results from these analyses, an array of 227 flux loops, shown in Fig. 6, was designed for NCSX. There are 151 distinct locations and shapes specified, with the primary function of resolving SS modes. These loops would completely cover one of the six available half-periods of the VV, however loops for detecting SS modes can be distributed to equivalent locations among the half-periods for practical reasons such as minimizing crowding of loops and their leads. From the point of view of resolving non-SS modes, however, there is no such equivalence– distributing loops over the full torus is essential. Calculations of the condition number of the matrix of diagnostic signals for non-SS modes for various spatial distributions of the flux loops show that randomly distributing loops over all 6 half periods is the preferred choice, leading to a more robust inversion of the diagnostic signals. If the plasma is SS, the loops will measure the complete distribution of the normal field, at the available spatial resolution, providing information necessary to determine the 3D plasma shape and determine moments of the plasma profiles.

The engineering implementation of the flux loop array is currently in progress. Metal templates have been fabricated to an accuracy of ±0.13 mm for each of the distinct shapes. The mounting locations are being laid out on the actual vacuum vessel surface, using metrology equipment as described in the next section. Since the vacuum vessel surface can deviate within the tolerance from its nominal location, so also can the loops, so the actual coordinates of each loop will be measured after installation.

3. Assembly

Assembly of the NCSX device will proceed by first building up three field-period subassemblies through a sequence of operations at five stations. The three periods will be joined into a complete torus during final machine assembly. The assembly process, associated fixtures, and metrology systems are designed such that the completed coils will be constructed to within ±1.5 mm of their nominal coil current centers.

The field period assembly process is illustrated in Fig. 7. At Station 1, flux loops and coolant tubes are installed on the surface of the 120 degree vacuum vessel sectors. At Station 2, half-periods of modular coils– consisting of three coils (one of each type)– are assembled using shims and fixtures to accurately align and position the coils relative to each other, and to pre-align mating pairs of three-coil assemblies. At Station 3, two half-period modular coil assemblies are installed, one from each end, over a vacuum vessel segment. In this operation, the three-coil sets are suspended from an overhead crane and manipulated by operators using screw-driven actuators to follow a prescribed assembly trajectory over the vessel. The operators are guided by the beams from three laser pointers which are attached to the coil assembly and by traces on the side walls and floor surrounding the assembly station. The traces, which are pre-computed from the CAD models, constitute a mapping of the assembly

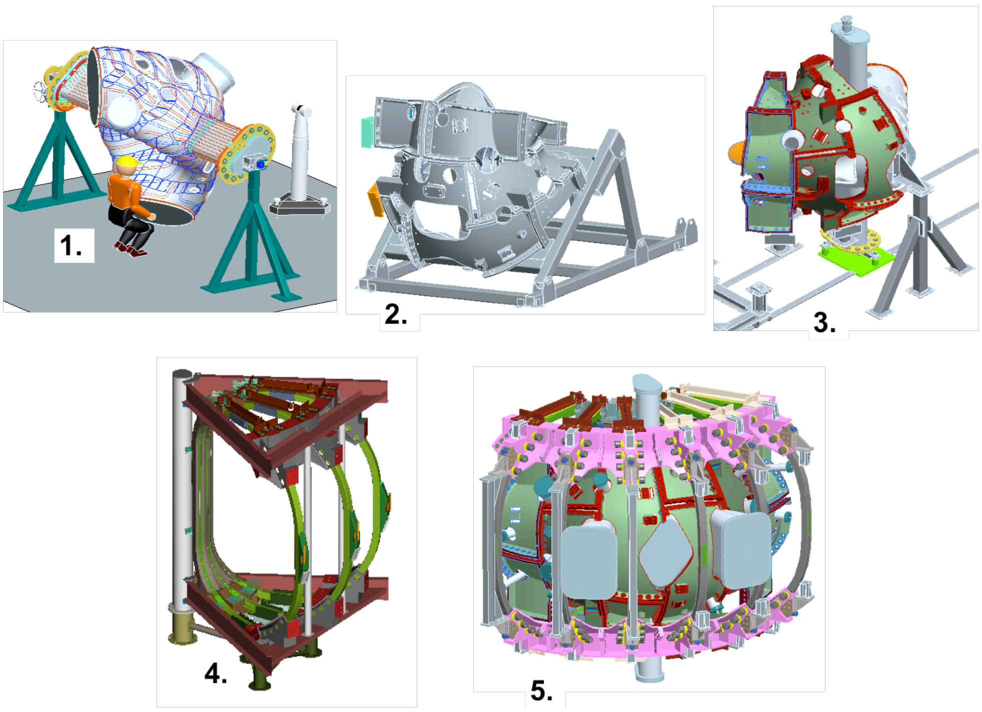


FIG. 7. Field Period Assembly sequence. 1. Vacuum vessel assembly. 2. Modular coil sub-assembly. 3. Modular coil-to-vacuum vessel assembly. 4. TF coil subassembly, 5. Final field period assembly.

trajectory onto those surfaces. By tracking the three traces with the laser beams, the operators will guide the coil assembly over the vacuum vessel. End views and many port openings permit visual observation of the coil-vessel interface to aid in avoiding assembly interferences. Once installed over the vessel, the two three-coil assemblies are aligned, shimmed, and bolted together. A proof of principle demonstration of this inexpensive manipulation technique was performed using a large concrete block to represent the coil mass.

Three-coil sets of TF coils are assembled in Station 4. In Station 5, the vacuum vessel port extensions are welded to the port stubs left when the ports were removed by the manufacturer. Next, two three-coil TF sets are installed, one from each end, followed by re-attachment of the remaining large ports.

During final assembly, completed field periods are installed on movable sleds which are used to translate them simultaneously along radial paths to their final position. Modular coils are aligned and bolted together first, followed by the vacuum vessel and TF coils. The vacuum vessel spacers are custom machined to match up the vacuum vessel segment ends for the final seal weld. After installation of poloidal field coils and trim coils, the temporary sleds are replaced by three permanent machine supports at the planes where the three field periods are joined together.

Station 1 field period assembly (FP1) activities have begun with a complete dimensional scan of the first two vacuum vessel segments. A comparison of metrology tools found the laser tracker to be preferable to the coordinate measuring arm for vacuum vessel measurements because of its greater precision (~0.05 mm *vs.* ~0.25 mm) and its ability to measure over greater distances, provided a line-of-sight to the laser is maintained. Layout of the magnetic flux loop templates and coolant tube attachment points has begun.

4. Conclusions

The NCSX construction project, which began in April, 2003 and is scheduled for completion in July, 2009, has passed the half-way point. The technological challenges associated with manufacturing major components with complex geometries and tight tolerances have been resolved through design and prototyping. Production of the vacuum vessel is complete and production of modular coils and toroidal field coils is on schedule. Provision has been made for physics measurements including an extensive array of vacuum vessel ports and an innovative set of magnetic flux loops attached to the vessel surface. The assembly sequence and associated tooling have been designed, critical assembly operations have been demonstrated through R&D, and the first sub-assembly operations have begun.

[1] ZARNSTORFF, M. C., et al., Plasma Phys. Control. Fusion 43 (2001) A237–A249
[2] NEILSON, G. H., et al., Phys. Plasmas 7 (2000) 1911.
[3] JOHNSON, D., et al., Rev. Sci. Instrum. 74, 1787 (2003).
[4] STRATTON, B., et al., Rev. Sci. Instrum. 77, to be published (2006).
[5] HIRSHMAN, S.P. and WHITSON, J.C., Phys. Fluids 26 (1993) 3553.