Progress in NCSX Construction

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Abstract*—The National Compact Stellarator Experiment (NCSX) is being constructed at the Princeton Plasma Physics Laboratory (PPPL) in partnership with the Oak Ridge National Laboratory (ORNL). Its mission is to develop the physics understanding of the compact stellarator and evaluate its potential for future fusion energy systems. Compact stellarators use 3D plasma shaping to produce a magnetic configuration that can be steady state without current drive or feedback control of instabilities. The NCSX has major radius 1.4 m, aspect ratio 4.4, 3 field periods, and a quasi-axisymmetric magnetic field. It is predicted to be stable and have good magnetic surfaces at $\beta \geq 4\%$ and to have tokamak-like confinement properties. The device will provide the plasma configuration flexibility and the heating and diagnostic access needed to test physics predictions. Component production has advanced substantially since the first contracts were placed in 2004. Manufacture of the vacuum vessel was completed in 2006. All eighteen modular coil winding forms have been delivered, and twelve modular coils have been wound and epoxy impregnated. A contract for the (planar) toroidal field coils was placed in 2006 and manufacture is in progress. Assembly activities have begun and will be the project's main focus in the next few years. The engineering challenge of NCSX is to meet the requirements for complex geometries and tight tolerances within the cost and schedule constraints of a construction project. This paper will focus on how the engineering challenges of component production have been resolved, and how the assembly challenges are being met.

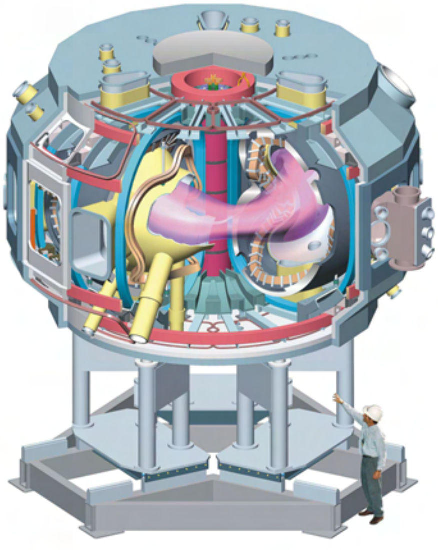

Figure 1. NCSX stellarator core

I. INTRODUCTION

The NCSX stellarator is a proof-of principle scale experiment to develop the physics understanding of the compact stellarator and evaluate its potential for future fusion energy systems. The stellarator core is illustrated in Figure 1. The NCSX plasma is highly shaped and features three field periods. It has a major radius of 1.4 m. A magnetic field on axis of 2 T can be provided for 0.2 s. The vacuum vessel is outside the plasma and conforms to the plasma shape. The vacuum vessel is bakeable to 350 C. There are eighteen modular coils outside the vacuum vessel with three unique coil types. These types are dubbed Type A, Type B, and Type C. Three coils, one of each type, are joined to form a half period. The half period on the left-hand side of a field period is flip-symmetric with the half-period on the right-hand side. The coils are wound with compacted copper cable conductor for ease of winding. They are cooled with liquid nitrogen to permit operation at higher current densities. (The resistivity of copper drops markedly between room temperature and liquid nitrogen temperature, 77 K.)

Field error requirements have driven the design and construction of NCSX. Field errors are important because that can spoil plasma stability and confinement. The overarching requirement is that the toroidal flux in islands regions shall not exceed 10% of the toroidal flux in the plasma. Many design requirements and features are derived from this overarching requirement. Low permeability materials are used throughout. For example, Inconel is used in the construction of the vacuum vessel. Poloidal and toroidal electrical breaks were added to the modular coil structure to break up eddy currents. Trim coils were added to actively suppress islands. Tight tolerances have been applied to the construction and installation of coils. The winding center of the modular coils in the installed position must be within 1.5mm (60 mils) of the ideal winding center. The winding centers for the TF and PF coils, which are further away from the plasma, must be within 3mm (120 mils) of the ideal winding center.

NCSX has progressed from being dominated by design and fabrication activities to a construction project. The design and procurement of the most difficult stellarator core components have been completed. All three vacuum vessel subassemblies have been delivered by Major Tool and Machine. All eighteen modular coil winding forms have been delivered by Energy Industries of Ohio.

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II. COIL FABRICATION

The modular coils are being fabricated at PPPL. Winding operations have been optimized and are progressing well. Fabrication of the fourteenth modular coil has begun. Twelve of the eighteen modular coils have been wound and epoxy impregnated.

Modular coil fabrication tolerances are being met. The installed tolerance of ± 1.5mm (60 mils) was allocated in equal parts for coil fabrication, assembly into field periods, and assembly into a full torus. The winding center is determined by measurements using a coordinate measurement machine (CMM) of the machined winding surface and the outside edge of the winding pack as shown in Figure 2. The location of the current center is controlled by adjusting the clamp positions after winding.

Figure 2. CMM being used to determine current center

The goal of ± 0.5mm (20 mils) is achieved over most of the coils but not everywhere, as shown in Figure 3. In order to minimize symmetry breaking field errors, coils are wound to match the current center locations achieved on prior wound coils rather the targeting the ideal current center for each coil.

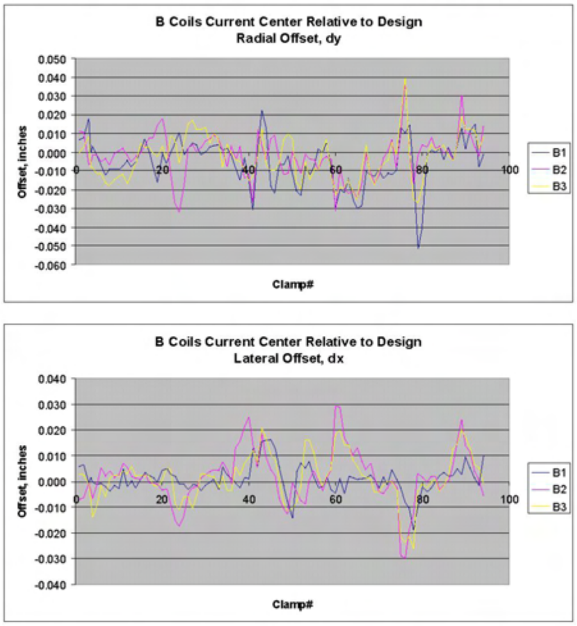

Figure 3. Radial and lateral offsets for first 3 Type B coils

Field errors from as-built coils have been calculated. Island sizes have been estimated from the calculated field errors. The reference iota profile is shown in Figure 4. The low order resonant surfaces within the plasma include the n/m = 1/2, 3/6, and 3/5 surfaces.

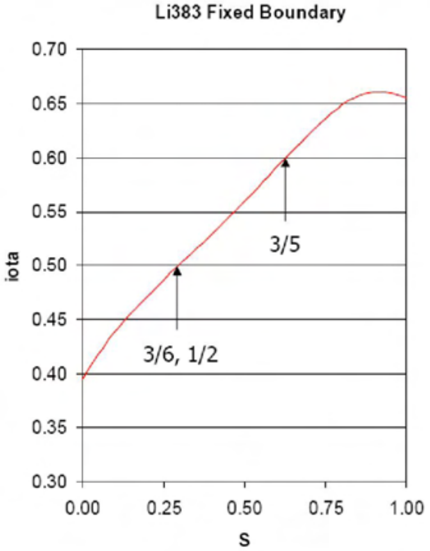

Figure 4. Low order resonant surfaces within plasma boundary

Aggregate field errors from as-built coils are not much different from the worst coil considered separately as shown in Figure 5. The largest island due to a single coil would be the 1/2 island from the B2 coil with a toroidal flux of 4.2%. The largest island for all the coils wound to date would also be the 1/2 island with a toroidal flux of 4.0%. Field error correction coils will be provided with the capability of actively suppressing the size of these islands to well below 1%.

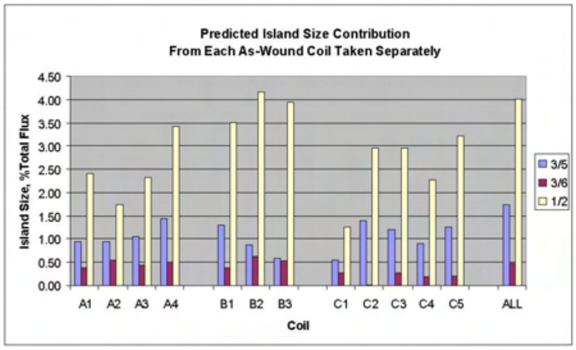

Figure 5. Island sizes from as-built coils

Fabrication of the first TF coil is nearing completion at Everson Tesla. The wedge castings in the nose region have been attached to the sides of the winding pack, as shown in Figure 6. Cold testing of the first coil is expected to take place soon. The ground wrap has been applied to the second coil. Winding of third coil is in progress.

Figure 6. First TF coil

III. FIELD PERIOD AND FINAL ASSEMBLY

A detailed assembly sequence plan has been developed. Field period and final assembly will be accomplished in five stations. In Station 1, diagnostic loops, cooling tubes, heater tapes, and thermocouples are applied to the vacuum vessel subassemblies. The cooling tubes are made of corrugated tubing with a braided sleeve. The cooling tubes are clamped to the vessel via a copper saddle with a grafoil pad underneath, as shown in Figure 7. An extensive array of diagnostic loops is installed on each vacuum vessel subassembly. The diagnostic loops enable plasma reconstructions during operation. Installation of these components on the first vacuum vessel subassembly (VVSA1) is nearing completion as shown in Figure 8. Work on VVSA2 is also in progress.

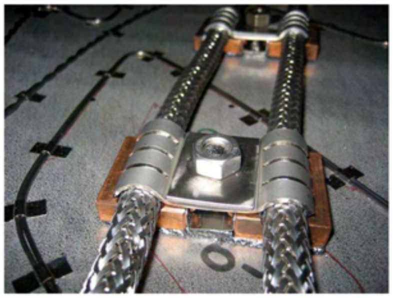

Figure 7. Clamping of cooling tubes to vacuum vessel

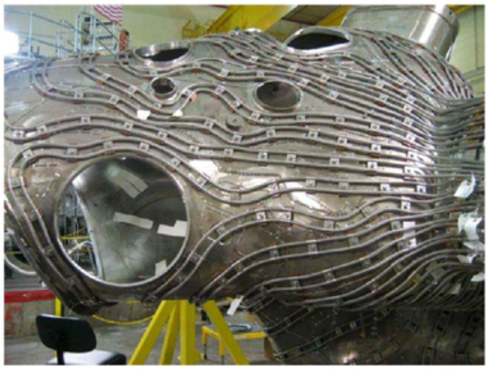

Figure 8. VVSA1 nearing completion

On Station 2, modular coils are assembled into half-period assemblies. A half-period assembly consists of three modular coils, one of each type, as shown in Figure 9.

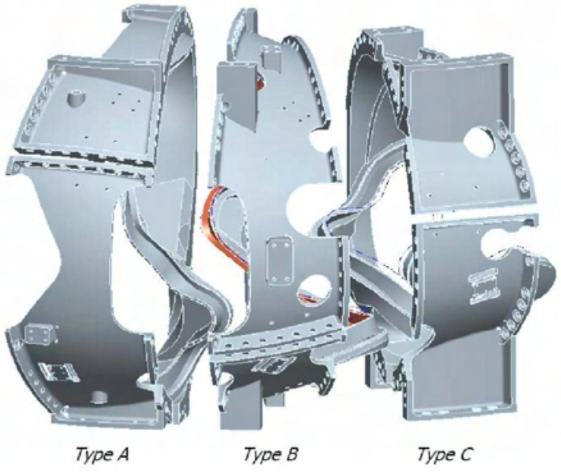

Figure 9. Modular coil half-period assembly

Work on Station 2 is being paced by completion of the modular coil interface design. Bolted joints along the outboard perimeter of the coils react compression and shear loads. A cross-section of a typical bolted joint assembly is shown in Figure 10. Most of the bolted joints feature tapped holes as shown in Figure 10, but some feature through holes with longer studs and a backing nut.

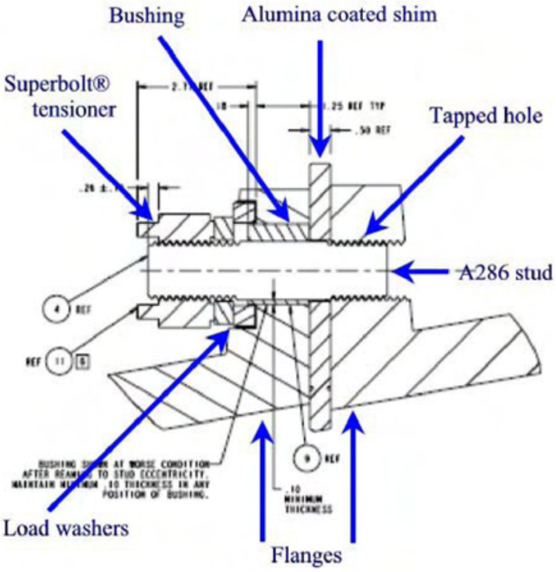

Figure 10. Typical bolted joint assembly

The bolted joint assembly features a 35mm (1.375") A286 stud. The stud is tensioned using a Superbolt® tensioner to 329 kilo-Newtons (74 kips). An alumina coated shim between the flanges serves to properly space the flanges, transmit the stud preload, and react shear loads. The alumina coating provides a high coefficient of friction, approximately 0.67, between the shim and stainless steel flanges and also provides electrical isolation.

Bolt locations on the inner perimeter would be inaccessible for re-tensioning following machine assembly so welded shims are used within a field period. Flat shims are placed between mating flanges to react compression loads. These shims are welded to the flanges at the outside end of the shims to react shear loads. The shims are custom ground to the right height to achieve the proper spacing between flanges. Weld distortion is a concern. Development trials are current underway to develop weld configurations and procedures that result in acceptably low distortion.

Coils within a half-period are required to be positioned within ±0.25mm (10 mils). This precise positioning requirement requires the use of a laser tracker for measuring coil position. The location of the coil current centroid is known with respect to a set of tooling balls which are used to determine the position of the coil. Coil position is set in the vertical direction (normal to the mating flanges) by adjusting the shim thicknesses. Coil position in the lateral plane (parallel to the mating flanges) is adjusted using set screws and dial indicators. When the coils are properly positioned they are bolted and then welded together. The fixture for supporting two modular coils while joining them is shown in Figure 11. The capability to meet positioning requirements has been demonstrated. The A1 and A2 coils were positioned and bolted together. The required fit-up of ±0.25mm (10 mils) was achieved.

Figure 11. Station 2 fixture

Modular coils are assembled over the vacuum vessel in Station 3. The vacuum vessel subassembly is first attached to a fixture. Then modular coil half-period assemblies are screwed over each end of the vacuum vessel subassembly. Figure 12 show a vacuum vessel subassembly with one modular coil half-period installed.

The half-period assemblies must follow a precise trajectory during this operation. When the half-period subassemblies are being screwed over the vacuum vessel subassembly, they are supported by the overhead crane through three linear actuators. The crane provides precise lateral and vertical position control. The linear actuators provide rotational control about the x and y axes in addition to vertical position control. Rotation about the vertical z axis is provided manually. The riggers control the trajectory by having three laser beams follow tracks on three screens mounted on two sides and beneath the modular coil half-period. The feasibility of this approach has been demonstrated using a large concrete block. The design of tooling and fixtures for Station 3 is nearly complete.

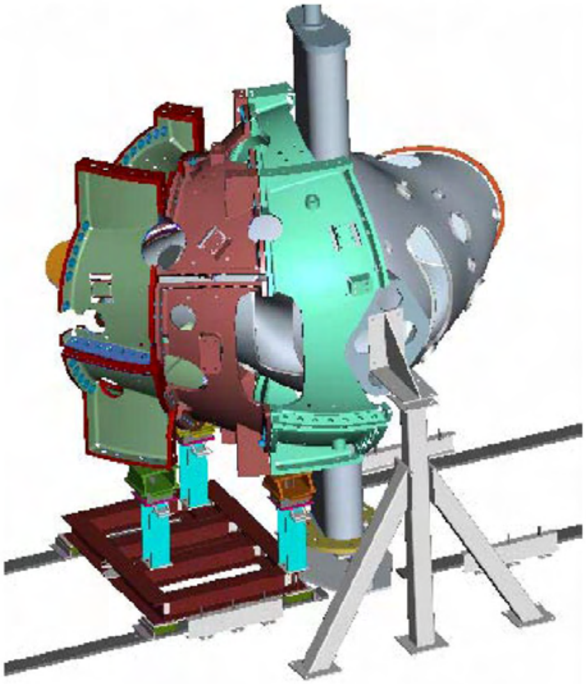

Figure 12. VVSA with one modular coil half-period installed

Tooling design is underway for Stations 5 and 6. In Station 5, the vacuum vessel ports are attached. Leak checking will be performed as each port is welded. The inner four TF coils (not the end TF coils) are installed. The TF and PF coil support structures are also installed. A completed field period on Station 5 is shown in Figure 13.

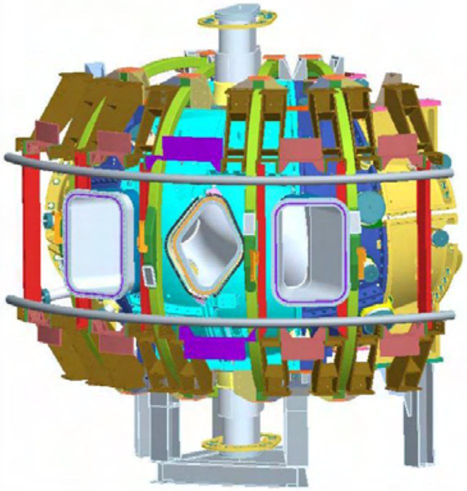

Figure 13. Completed field period on Station 5

Three field periods are brought together to form a full torus on Station 6. This operation is called final assembly. The field periods need to be brought together simultaneously to avoid interferences that would otherwise occur. The field periods are each mounted on sleds that sit on radial rails as shown in Figure 14.

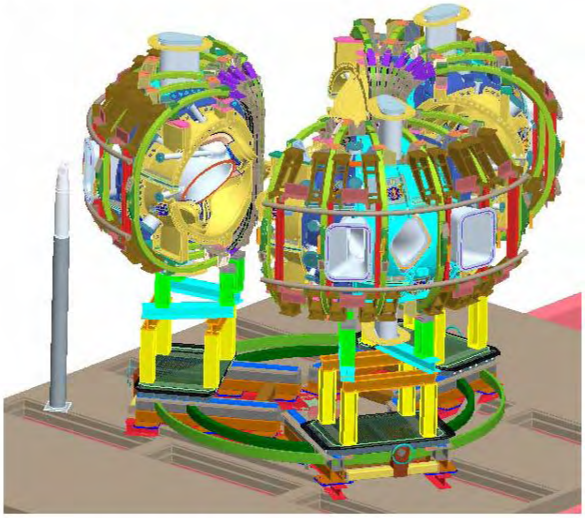

Figure 14. Three field periods mounted on sleds in Station 6

Modular coils are joined together via bolted joint assemblies. Where there is no access for bolted joints near the inboard midplane, a sliding interface is provided. Fit-up of the shims is checked by leaving the end TF coils out. Once the fit-up of the modular coils has been checked, the end TF coils are installed and the three field periods are assembled. Modular coils are bolted together. Vacuum vessel subassemblies are welded together through spool pieces which are machined to ensure proper fit-up. TF coils are moved radially to wedge together in the nose region. The lower PF ring coils are then installed.

Once the stellarator core has been assembled, the weight of the stellarator core is transferred to a permanent support system consisting of three columns underneath the parting planes between field periods. An illustration of the stellarator core mounted on the permanent supports is shown in Figure 15.

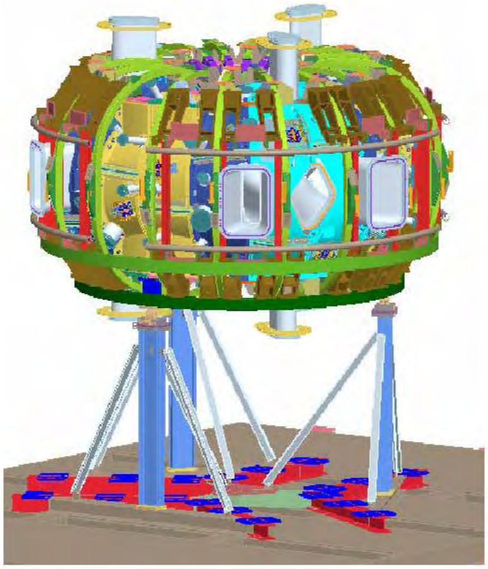

Figure 15. Stellarator core mounted on permanent supports

Once the stellarator core has been assembled, the balance of the assembly and startup activities are very similar to those of a tokamak. The vacuum pumping system will be installed and initial pumpdown will commence. The annulus between the vacuum vessel and modular coils will be filled with pourable aerogel insulation. The solenoid and upper PF ring coils will be installed. All of the coils will be testing at room temperature prior to installation of the cryostat. The cryostat will then be installed along with the machine platforms. The coils will be cooled to cryogenic temperature for first plasma and field line mapping.

IV. SUMMARY

NCSX has progressed through design and procurement activities to construction. All vacuum vessel subassemblies and modular coil winding forms have been delivered. Modular coil winding operations at PPPL are progressing well. Twelve of the eighteen modular coils have been epoxy impregnated. Coil tolerances are being met. TF coil fabrication is underway.