

ITER Central Solenoid Module Fabrication

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Abstract. The fabrication of the modules for the ITER Central Solenoid (CS) has started in a dedicated production facility located in Poway, California, USA. The necessary tools have been designed, built, installed, and tested in the facility to enable the start of production. The current schedule has first module fabrication completed in 2017, followed by testing and subsequent shipment to ITER.

The Central Solenoid is a key component of the ITER tokamak providing the inductive voltage to initiate and sustain the plasma current and to position and shape the plasma. The design of the CS has been a collaborative effort between the US ITER Project Office (US ITER), the international ITER Organization (IO) and General Atomics (GA). GA's responsibility includes: completing the fabrication design, developing and qualifying the fabrication processes and tools, and then completing the fabrication of the seven 110 tonne CS modules. The modules will be shipped separately to the ITER site, and then stacked and aligned in the Assembly Hall prior to insertion in the core of the ITER tokamak.

A dedicated facility in Poway, California, USA has been established by GA to complete the fabrication of the seven modules. Infrastructure improvements included thick reinforced concrete floors, a diesel generator for backup power, along with, cranes for moving the tooling within the facility. The fabrication process for a single module requires approximately 22 months followed by five months of testing, which includes preliminary electrical testing followed by high current (48.5 kA) tests at 4.7K. The production of the seven modules is completed in a parallel fashion through ten process stations. The process stations have been designed and built with most stations having completed testing and qualification for carrying out the required fabrication processes.

The final qualification step for each process station is achieved by the successful production of a prototype coil. Fabrication of the first ITER module is in progress. The seven modules will be individually shipped to Cadarache, France upon their completion.

This paper describes the processes and status of the fabrication of the CS Modules for ITER.

1. Introduction

The Central Solenoid is a one of the three major superconducting coil systems for ITER. It is the largest transient magnet system for ITER. When completed, it will be 17 meters tall and weigh nearly 1000 tons. The solenoid stack consists of six modules and a steel structure to preload the stack and support it back to the toroidal field coil system. The peak field for the central solenoid is 13.1 Tesla and stores 5.5 GJ of energy. US ITER has responsibility for the design of the central solenoid and its structure with input from ITER Organization and General Atomics.

GA is currently under contract to UT-Battelle/Oak Ridge National Laboratory to fabricate the Central Solenoid modules for ITER. The contract is managed by US ITER at Oak Ridge National Laboratory, under the sponsorship of the Department of Energy Office of Science. GA's responsibility includes the design of the processes and tools necessary to build the

modules, and then qualifying them by building a non-superconducting mockup coil prior to manufacturing the seven modules. The seven modules are fabricated in quasi-parallel fashion; when one module is completed at a station, the next module is started at that station as the first module transfers to the next station placing up to 6 coils in production at one time.

Each module of the central solenoid is made from nearly 6 kilometers of conductor, Nb₃Sn cable in stainless steel conduit, provided by a Japanese Domestic Agency as ITER in-kind contribution. A completed module is 2.2 m tall and 4 m in diameter weighing 110 tonnes. The coil consists of 40 pancake wound layers each with 14 turns. Seven lengths of conductor are required to fabricate one module with six splice joints.

With the Nb₃Sn conductor, forming and welding of the module is accomplished prior to heat treatment of the strands when the superconducting alloy is formed. Insulation is applied after heat treatment and the module is resin impregnated to form a monolithic structure. At the completion of the fabrication, the modules undergo a full current test after cooling down to 4.7K.

In preparation for the fabrication of the CS modules, a 6,000 m² dedicated facility was established to build the coils. General Atomics replaced the existing concrete floor with 0.6 m thick reinforced concrete to support the 110 tonne modules and their manufacturing workstations. Tight flatness requirements were held on the concrete to enable the modules to be transported in the facility using an air-bearing cart. Three cranes were installed to assist in moving spools of conductor, tools and materials in the facility. In addition, a 1 MW diesel generator, two high volume air compressors to power the tools, the air transporter, and a liquid argon tank were also installed. The air transporter was designed and built by AirFloat of Decatur, Illinois. Using four air bearings, the transporter floats itself and a module across the floor to the next process station. The tool was proof loaded and tested using 180 tonnes of steel plate. The test confirmed the carts load capability and the concrete floor flatness (3 mm over 3 m).

A total of ten process stations comprise the manufacturing line. As part of the development process, each station undergoes a series of five reviews with the final two reviews being a Manufacturing Readiness Reviews. At the first of these review's successful conclusion, processing of a qualification coil with dummy copper cable commences. The mockup coil is processed identical to a module except it has only sixteen layers as compared to forty for a module; the mockup serves as the final qualification step for each station. Upon completion of the qualification coil at a station, a second readiness review is held and with US ITER and IO acceptance, production module fabrication can start. Each process station has controlled travelers and procedures for completing the manufacturing process at that station.

2. Process Stations

2.1 Conductor Receiving

The cable in conduit conductor (CICC) in lengths of 900 or 600 m are received at the GA fabrication facility where it is unloaded from a truck, inspected, and prepared for winding. Lifting fixtures, designed and built to interface with the conductor-shipping fixture, are used to transfer the conductor to a custom wheeled cart. The cart transports the conductor from the receiving area to the winding station.

2.2 Winding

At the winding station, the 900 or 600 m length spools of conductor are continuously wound into six or four layer pancakes, respectively with each layer consisting of fourteen turns. The winding station features a custom designed and built system by Tauring S.p.A., a maker of computer controlled bending machines. Due to the potential variability in the material properties of the conductor, precise forming of the conductor was not viewed possible. Instead, the length of each conductor turn is measured and marked at quadrants. The marks on the formed turns are aligned on the winding table giving an average turn radius within the acceptable limits of 0.5mm. A calibration curve is generated at the beginning of each spool of conductor to account for variability between spools and the results are fed back into the bending software. When all turns of a layer have been formed, radial marks are created across all turns that allow the coil to be re-assembled to the original form after turn insulation. Finally, vertical transitions are created with a hydraulic powered offset tool. A completed hexapancake can be seen in Fig. 1.

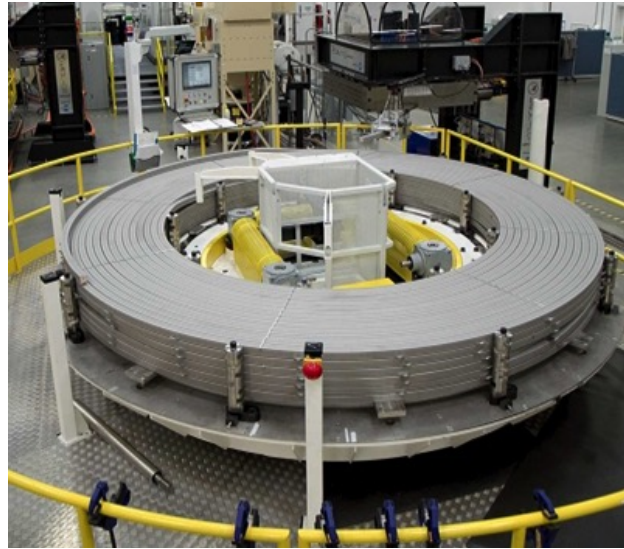


Figure 1. Tauring's winding system with completed hexapancake for Module 2

2.3 Joint Preparation Station

After winding, the hex/quad pancakes are transferred to the third station, the Joint Preparation Station. At this station, a length of the jacket is removed from around the superconducting cable in preparation for making the joints at the Joining Station. To remove the jacket, specialty tools are used to machining nearly through the stainless steel jacket but leaving between 0.5 and 1mm which is then fractured using hydraulic tools. The jacket is then removed from the cable followed by utilization of a reverse plating process to remove the chrome from the cable strands.

2.4 Joining Station

The pancakes are joined together by splicing the conductor together much like a rope would be spliced. A large structure was designed to support a 16 tonne hex pancake while the outer lower turn is separated to allow creation of the joint (Fig. 2). The jacket is welded together using automated welding equipment developed by Liburdi Dimetrics Inc. Helium leak tests are performed after each joint is completed. After the joints are welded, penetrations through the jacket are milled for helium inlets and outlets. The penetrations are milled within 0.5 mm of the conductor. The penetration is completed by using a hydraulically powered punch. Bosses are welded to the jacket using another Liburdi designed welding machine. All welds undergo a process qualification and all welders are similarly qualified using an approved plan.

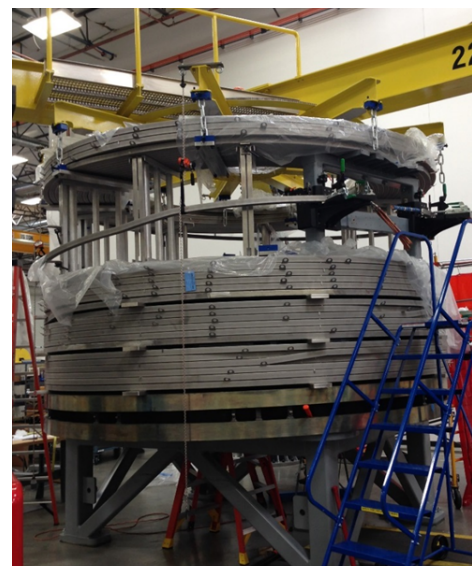


Figure 2. Joint between hex and quad pancake in process for Module 1

2.5 Reaction Heat Treatment Station

The formed and joined coil is heat treated to form the superconducting material Nb₃Sn. The heat treatment process takes nearly a month with extended hold times at 570 and 650° C. An allowable temperature difference of 10° C within the coil during the reaction process drove a forced convection furnace design using fans to circulate argon within the furnace.

Seco-Warwick designed and built the furnace system to meet the requirements for temperature uniformity and minimize the reaction time. The furnace is also used to perform a helium leak check of the coil before and after the heating cycle. The system has been installed at GA's facility, and qualification completed with the processing of the mockup coil. The first module's heat treatment should start by the end of the calendar year.



Figure 3. The Seco-Warwick Furnace at completion of installation

2.6 Turn Insulation Station

After heat treatment, the conductor is strain sensitive and strain on the cable must be limited to less than 0.1% yet each turn of the module must be insulated with six layers of a combination of fiberglass and Kapton® tape to provide up to 1 kV of isolation between turns. The station developed by GA lifts the module, separates each turn while staying within the strain limits, insulates the turns and then rebuild the coil as it was wound. While the turns are separated, three wrapping heads designed and built by Ridgway Machines LTD, wrap the layers of glass and Kapton around the turns. As part of the process, vision systems are used on each wrapping head to perform inspection of the wrapped insulation.

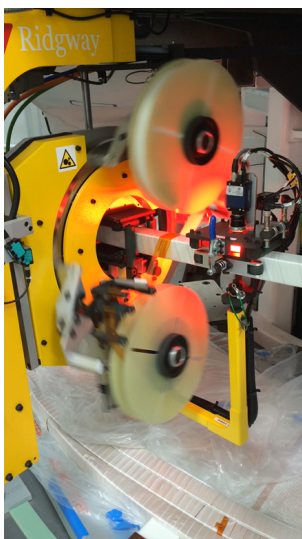


Figure 5. Tape wrapping head in process on the qualification coil

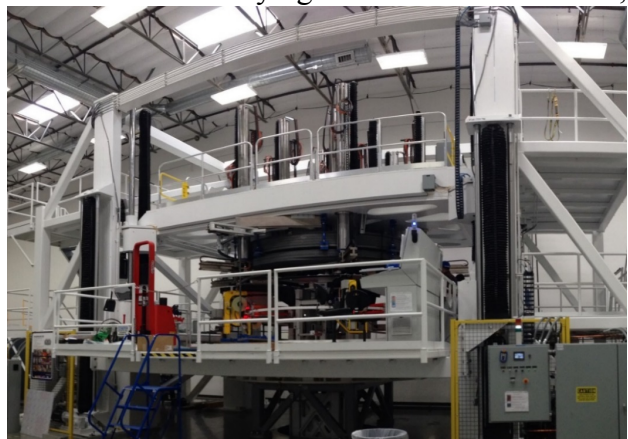


Figure 4. Turn Insulation Station structure

The main element of the station is a large structure capable of lifting the 110 tonne module via a set of nine links on the inside and outside diameters of the module Figure 4. These links release one hex/quad pancake at a time to a conductor lowering system which releases one turn at a time to be insulated. The whole system process is monitored by a control system to maintain the safe operation of the station. The station is fully qualified having processed the mockup coil.

2.7 Ground Insulation Station

For protection of the module, ground insulation and a ground plane is applied to all of the the external surfaces. The ground insulation is comprised of fiberglass and Kapton sheets overlapped to achieve a 150 kV voltage standoff capability requirement, although the highest test voltage is only 30 kV, with the expected largest voltage seen during a fault condition being 14 kV. The insulation layers are overlapped to attain a 175 mm tracking distance from the coil surface to the outside of the insulation. The application of the ground insulation is a manual process. A ground plane is added to the outside of the ground insulation to define the electric field in the insulation.

Special areas of insulation are required where the module terminals exit the coil and also around the helium penetrations. For each of these areas, custom molded polyimide shapes are used in conjunction with fiberglass sheets to meet the insulation requirements. Scale tests of these special areas have been performed and tested to verify the design and manufacturing.

The ground insulation of the qualification coil is in progress.

2.8 Vacuum Pressure Impregnation (VPI) Station

At the VPI station, the insulated coils are impregnated with a two-part resin. The resin is injected at 50° C, jelled at 90° C, and cured at 128° C. The impregnation process starts with the installation of metal panels designed to apply radial compression to the ground insulation on the vertical surfaces of the coil. The panels on the outside coil diameter will remain part of the coil, whereas the panels on the inside diameter are removed after the resin is cured. With the compression panels installed, rigid cylindrical molds are placed around the coil and the mold is closed with a top plate. Redundant o-rings seal the mold. A space between the o-rings can be used for vacuum leak checking the mold.

The coil is raised to 50° C during injection by passing DC current in the conductor providing volumetric heating of the module. The external surfaces of the mold are kept at module temperature by pad heaters to reduce thermal losses from the mold. The two-part resin is injected into the mold from a mixing and metering pumps. After curing, the top of the coil is machined to final height and flatness using a custom milling machine. Manufacturing of the external mold and resin pumping systems are complete and installed at GA as shown in Figure 6. Commissioning of the entire process is complete and processing of the qualification coil will start in October.



Figure 6. Completed VPI mold and resin pumping systems

2.9 Piping Station

Insulated helium pipe assemblies are welded in place at the piping station. The geometry of the coil is measured with a laser tracker and each of the 39 helium pipes of a module is custom formed to fit the module. The pipes are wrapped with 20 layers of Kapton with a b-stage prepreg and cured. Orbital welding completes the attachment to the module. Over the weld joints, 20 layers of insulation is applied to maintain the 150 kV standoff design requirement for the ground insulation.

2.10 Final Test Station

Each module undergoes multi-step testing. First is a series of tests at room temperature followed by tests at 4.7K and followed up with additional room temperature tests. Electrical tests consisting of 30 kV DC hi-pot and Paschen tests verify the integrity of the ground insulation followed by helium leak testing are performed at room temperature. Upon successful completion, the module is then cooled down to 4.7K, where a series of operational tests are performed including full current operation. The first module has additional testing to confirm the conductor operational design and modules



Figure 7. Final Test Chamber and feeder system

2-7 are tested to verify the manufacturing. The vacuum chamber and feeder for the final test station is shown in Figure 17. The feeder was supplied by ASIPP and the chamber by Babcock Noell. A full description of the final test station can be found in Reference [Schaubel 2016 SOFT]. Construction of the test facility is complete and integrated operational testing is planned for November of 2016.

3. Program Status

All of the ten process stations are installed and commissioned in GA's Magnet Technologies Center in Poway, CA. Currently, the qualification coil is being processed in the Ground Insulation station with its expected completion of manufacturing in early 2017, followed by final testing, including cooldown to 4.7K, and several kilo-amps of current passed through the coil for a short period of time since the coil is non-superconducting.

For the production modules, it takes 22 months to fabricate a module from start to finish followed by five months of testing. The coils are produced progressively through the stations and the current schedule shows up to six modules in production at one time. Following its completion, each module is shipped directly to ITER. The first module is completely wound and currently being joined together in the fourth process station and the second module is currently being wound. The scheduled delivery of the modules to France is currently ahead of the need date for assembly. The seventh module is currently scheduled to be completed in early 2021.

Acknowledgement

This work was supported by UT-Battelle/Oak Ridge National Laboratory under sponsorship of the US Department of Energy Office of Science under Awards 4000103039 and DE-AC05-00OR22725.