National Compact Stellarator Experiment

The National Compact Stellarator Experiment (NCSX) is a new magnetic confinement fusion experiment, currently being constructed at the Princeton Plasma Physics Laboratory (PPPL) in partnership with the Oak Ridge National Laboratory (ORNL). It will be used to acquire physics data needed to evaluate the compact stellarator as a fusion concept and to advance the physics understanding of 3-D plasmas for fusion and basic science. In addition, technological developments made in the course of constructing NCSX, for example the design and manufacture of complex-shaped parts, are important contributions to fusion technology.

Among the family of toroidal magnetic plasma configurations, stellarators are of interest because they solve important problems for fusion energy — achieving steady-state operation and avoiding disruptions. Stellarators have unique flexibility to resolve scientific issues, for example the effects of 3-D plasma shaping and of strong external control on confinement, that are important to all magnetic configurations.

The compact stellarator shares the attractive properties of existing stellarators but has the additional advantages of lower aspect ratio and a quasi-symmetric magnetic field structure. In a quasi-*axi*symmetric stellarator (QAS) like NCSX, the charged particle trajectories and plasma flow damping are similar to those of its axisymmetric relative, the tokamak, so a QAS is expected to share the tokamak's good confinement performance. This physics link with tokamaks means compact stellarators can advance rapidly and economically, building on advances in the more mature tokamak concept, including the expected future advances in burning plasma physics and technology from ITER.

NCSX Stellarator Configuration

The compact stellarator is a result of the large advances in plasma physics understanding and computation that have occurred in recent years. The NCSX was designed by performing computer simulations of hundreds of thousands of plasma configurations to optimize the physics properties: stability at high beta, degree of quasi-axisymmetry, quality of magnetic surfaces, and aspect ratio. Algorithms based on the free-boundary VMEC and PIES equilibrium codes were used to optimize the coil geometry, targeting the desired physics properties while satisfying coil feasibility metrics such as minimum bend radius, minimum coil-to-coil spacing, and minimum coil-to-plasma spacing. Research on NCSX will test this modern approach to experiment design.

The NCSX plasma is designed to have an aspect ratio of 4.4 instead of the more typical (for stellarators) ~10; to have a quasi-axisymmetric magnetic field with an effective ripple less than 1.5%; to be MHD stable without active feedback control, current drive, or rotation drive; and to have good magnetic surfaces; all at high beta (4%). The magnet system consists of eighteen modular coils, six each of three different shapes (Figure 1), plus toroidal field coils, poloidal field coils, and helicalfield trim coils. These coils generate the 3-D magnetic fields required to realize the target equilibrium properties, and provide the flexibility needed to vary the plasma configuration and test the physics. The device size (major radius $R = 1.4$ m), magnetic field range ($B = 1.2 - 2.0$ Tesla), pulse length (0.3 – 1.2 s), and planned plasma heating power (1.5 – 12 MW) are set to produce the plasma conditions and profiles needed to test critical physics issues over a range of beta and collisionality values. The NCSX machine (Figure 2) was designed on the basis of on this configuration and these parameters and is now well into construction.

Component Production Progress in FY06

Production of major device components was the NCSX project's main focus in FY06. The year began with the delivery of the first modular coil winding form to the Laboratory. Modular coil fabrication began immediately thereafter, applying the process developed through fabrication and testing of the "twisted racetrack" R&D coil the preceding year. During FY06, coil manufacturing operations passed through a start-up phase marked by improvements in process efficiencies and delivery intervals. By year's end, modular coil winding forms were being produced at the target rate of one per month, with eight having been delivered to the project site. Modular coils were being produced at PPPL at a rate of about one every six to seven weeks, with four modular coils having completed fabrication. Manufacture of the vacuum vessel sub-assemblies was completed in FY06. A contract for manufacture of the toroidal field coils was placed and the supplier's tooling preparations were well under way by year's end.

Modular coils

Each modular coil (Figure 3) 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). In the completed device, the eighteen MCWFs will be bolted together at mating flanges to form a toroidal structural shell, which locates the windings within ±1.5 mm of their nominal trajectories and supports them against operating loads.

The MCWFs are manufactured under a contract with Energy Industries of Ohio, Inc. (EIO), of Independence, OH. The EIO supplier team consists of C.A. Lawton Company of De Pere, WI (casting patterns), MetalTek International of Pevely, MO (castings), and Major Tool and Machine, Inc. of Indianapolis, IN (finish machining). The forms are sand cast of a custom stainless steel alloy named Stellalloy. This material was developed for NCSX to have low magnetic permeability ($\mu < 1.02\mu_0$) and structural properties that meet or exceed performance requirements. Its good welding characteristics facilitate repair of defects that typically exist in the raw casting. Only air quenching is needed to develop the required mechanical properties, thus avoiding the risks of distortion associated with water quenching. With the shipment of the last rough casting to the machining supplier in June 2006, all foundry operations on MCWF program were completed.

The MCWF winding surfaces and flanges are machined to a tolerance of ±0.25 mm using a series of multi-axis numerically controlled milling machines. After machining, 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. Development of an efficient manufacturing and inspection process, suitable for production, proved to be a significant challenge due to the highly complex geometry and tight tolerances required. The process development cycle took longer than expected, and as a result the deliveries of completed winding forms were initially very slow, threatening the project schedule. The project team, using a value engineering approach, carefully re-examined and relaxed some of the less critical technical requirements in light of the schedule impacts which by then were apparent. The machining supplier, Major Tool and Machine, Inc., presented a new production plan, applying additional technical and labor resources to the MCWF program. A contract modification was negotiated, providing the supplier with financial incentives for improved schedule performance and the project with a more favorable delivery sequence of the three MCWF types. Schedule performance improved markedly following these actions, and a reliable delivery rate of one MCWF per month was soon established. It is expected that the last winding form will be delivered around the middle of FY07.

The coils are wound onto the MCWF with a compacted copper cable conductor, 9 mm x 10 mm in cross section, whose flexibility facilitates handling and placement of its current center within ±0.5 mm of its nominal position on the form. The conductor turns are repositioned and reshaped after winding to improve conformance to the dimensional specifications and achieve the required accuracy without the use of shims. Measurements of position errors in the completed winding pack (Figure 4a) demonstrate the success of the modular coil dimensional control strategy.

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 filled with epoxy using a vacuum-pressure impregnation process. A completed coil is shown in Figure 4b.

Following manufacture, each coil undergoes electrical and pneumatic tests to verify terminal-to-terminal resistance, insulation strength, and cooling line integrity. In addition, the first coil was cooled to cryogenic temperature and subjected to several full-current pulses to verify the overall mechanical design and construction integrity. Room-temperature insulation tests on the first coil revealed a weakness in the lead area. The fault was found to be in an accessible area and was easily corrected with a design change that had no impact on performance. Only the first two coils had to be repaired to correct the fault; subsequent coils were constructed according to the new design.

Manufacture of the first modular coil was completed in March 2006, meeting an important project milestone on schedule. Costs were significantly above estimates, however, and improving cost performance in manufacturing operations was an area of management focus throughout the year. With time and experience, the efficiency of the coil fabrication team has continually improved. A value improvement program was instituted, leading to the implementation of numerous process improvement suggestions. Coil winding cost trends were tracked at the task level to identify problem areas and guide improvement actions. By year's end, the fabrication costs per coil had decreased to about half the cost of the first coil.

Vacuum Vessel

The NCSX vacuum vessel (Figure 5) is designed to provide a vacuum boundary between the modular coils and the plasma. 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. An array of 99 ports provides ample access for diagnostics and heating systems. 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 weld seams.

The vessel was fabricated by Major Tool and Machine, Inc. of Indianapolis, IN. The assembly includes three identical 120-degree segments, corresponding to the three NCSX field periods. Each segment was constructed from twenty press-formed panels of ten different shapes. The panels were assembled into shell segments over accurately machined skeletal welding fixtures, which facilitated precise positioning of the panels and control of the dimensions as the panels were welded together. The ports were welded on for fit-up and vacuum testing, then all except the large vertical and horizontal ports at the middle of the segment were removed and supplied separately, to be reattached by PPPL during assembly. Three custom-machined 20-cm wide spacers (shown as bands in Figure 5a), designed to facilitate the final assembly of the device, were also supplied. Vacuum vessel manufacture, including all segments, spacers, and ports was completed in September 2006.

Toroidal Field Coils

The NCSX machine includes an array of eighteen planar toroidal field (TF) coils to provide experimental flexibility. The inner legs, which must be positioned to an accuracy of ±3 mm to reduce field errors, are supported by wedging. The wound coils will be epoxy 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 forward wedge supports will be cast from a low-permeability ($\mu < 1.02\mu_0$) alloy.

Prior to FY06 we planned to wind the TF coils and assemble them to procured wedge supports at PPPL. While this plan offered quality assurance advantages, cost concerns led us to re-examine the option of procuring complete assemblies (coils attached to wedge supports) from an outside supplier. A competitive procurement action was undertaken, ultimately resulting in a contract award to Everson Tesla, Inc. of Nazareth, PA. The wedge supports will be supplied by Tesla, Ltd. (UK), and Österby Gjutery (Sweden), under a subcontract to Everson, while the conductor and other coil materials were furnished by PPPL. Everson will perform the winding, impregnation, assembly, and final machining operations. Outsourcing the TF coil manufacture to a single integrating contractor results in a greatly streamlined acquisition plan, while Everson's proximity to PPPL facilitates quality oversight of the most critical fabrication steps. By the end of FY06, tooling preparations and material purchases were well underway in preparation for producing the first coils in FY07.

Summary

In FY06, the second year of NCSX construction, the project's fabrication activities made a successful transition from startup to production. The vacuum vessel contract, the project's second largest, was completed. The largest contract, for modular coil winding form manufacture, realized a reliable production rate after overcoming some significant challenges initially. A contract for toroidal field coil manufacture was awarded. In-house manufacturing operations also had notable successes. The first modular coil was fabricated and tested, and costs steadily came down and delivery intervals steadily improved as the year progressed. By year's end, four coils were completed.

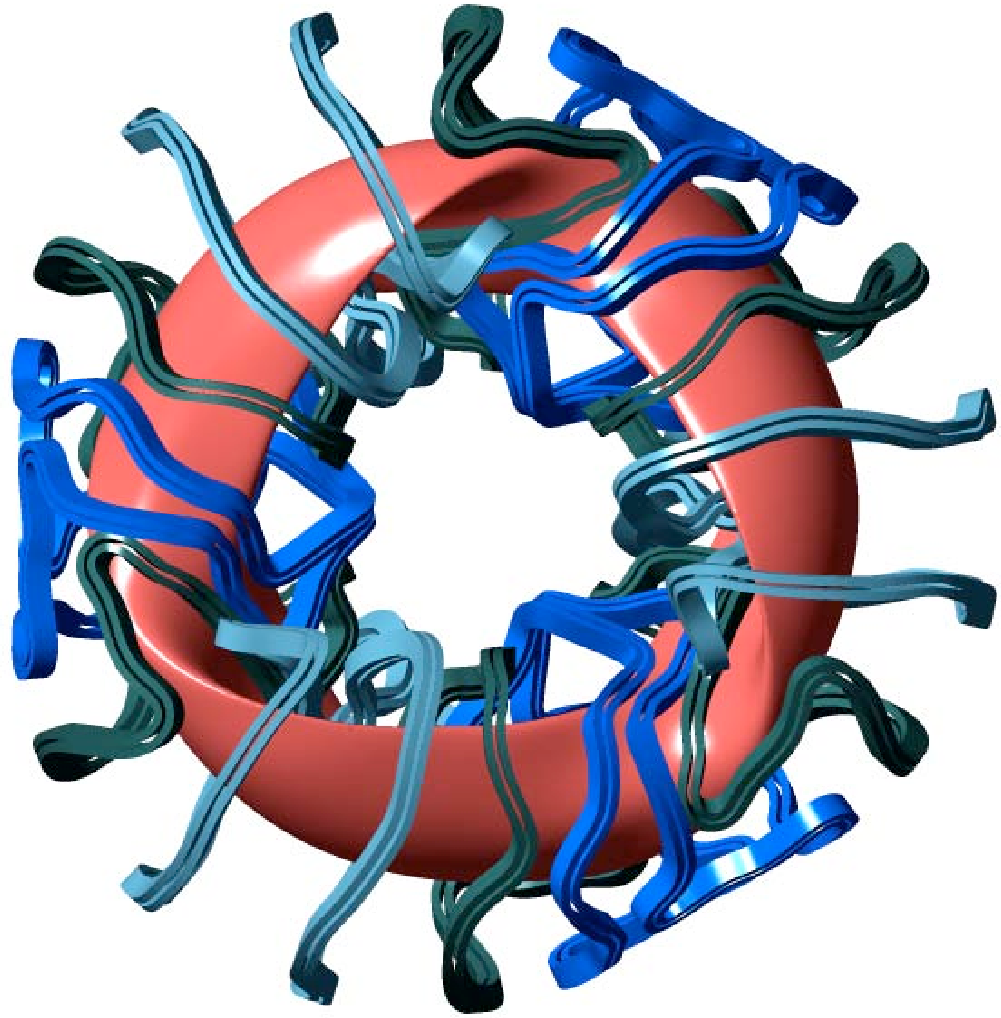


Figure 1. NCSX plasma and modular coils.

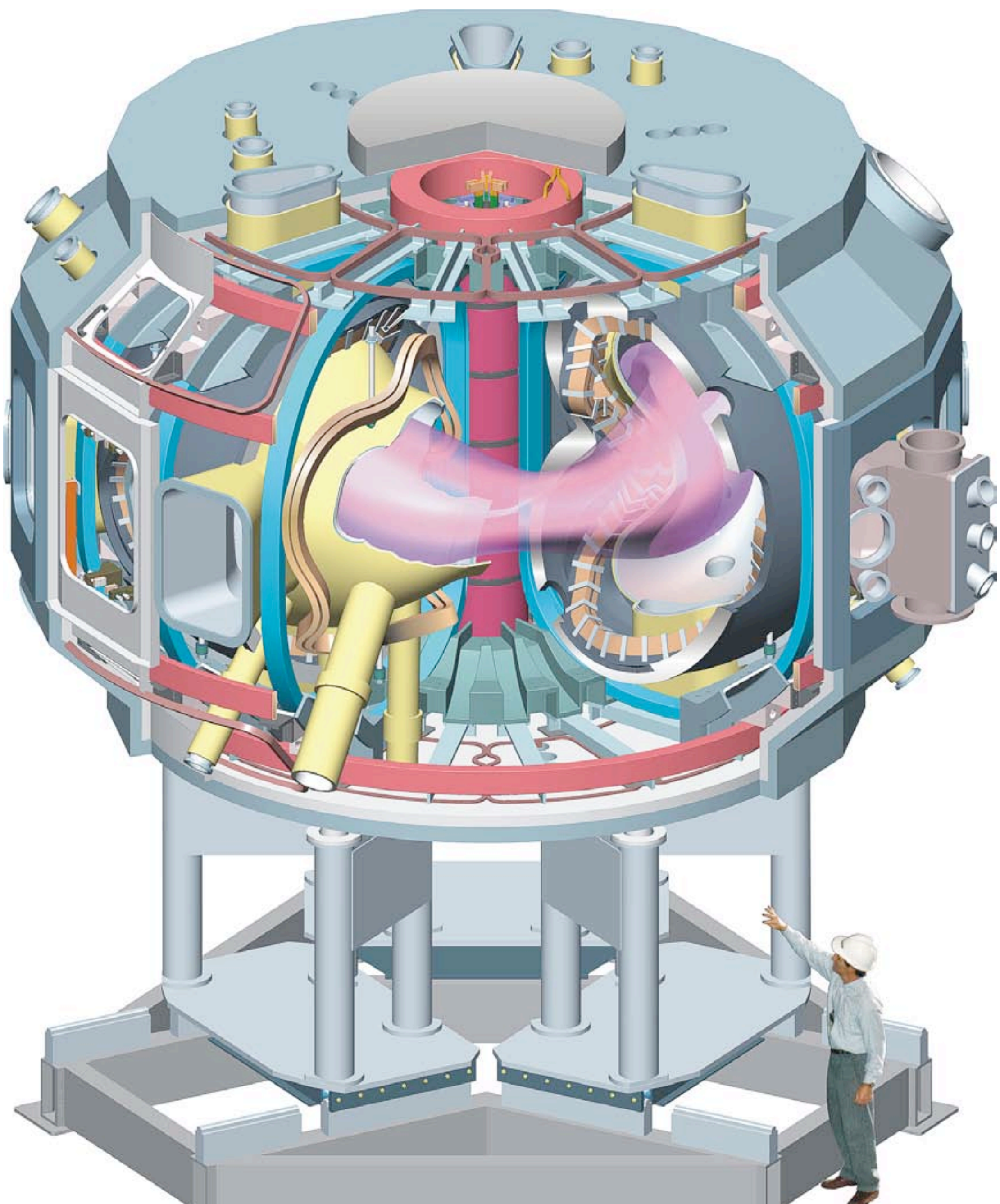
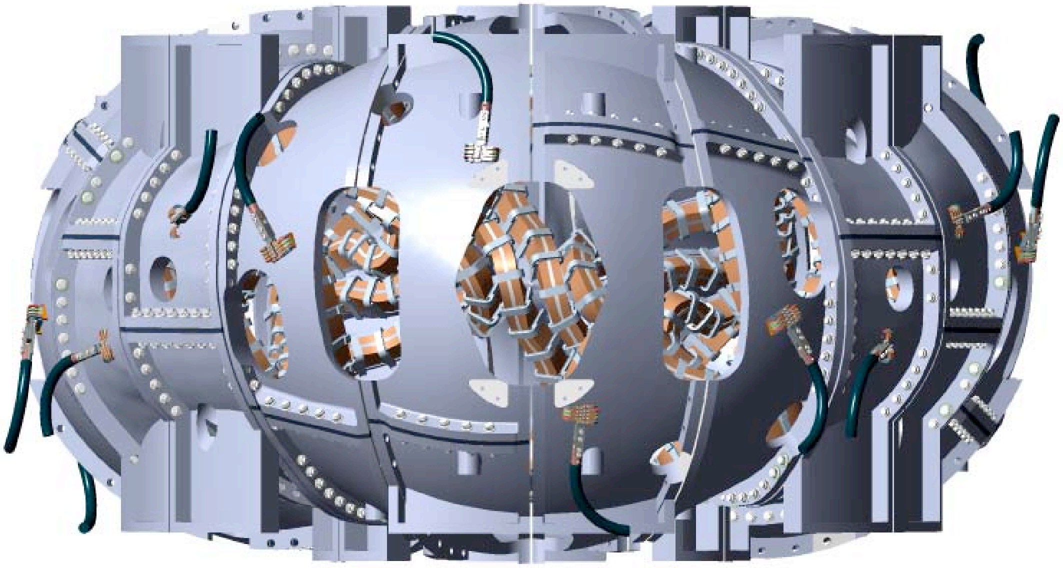
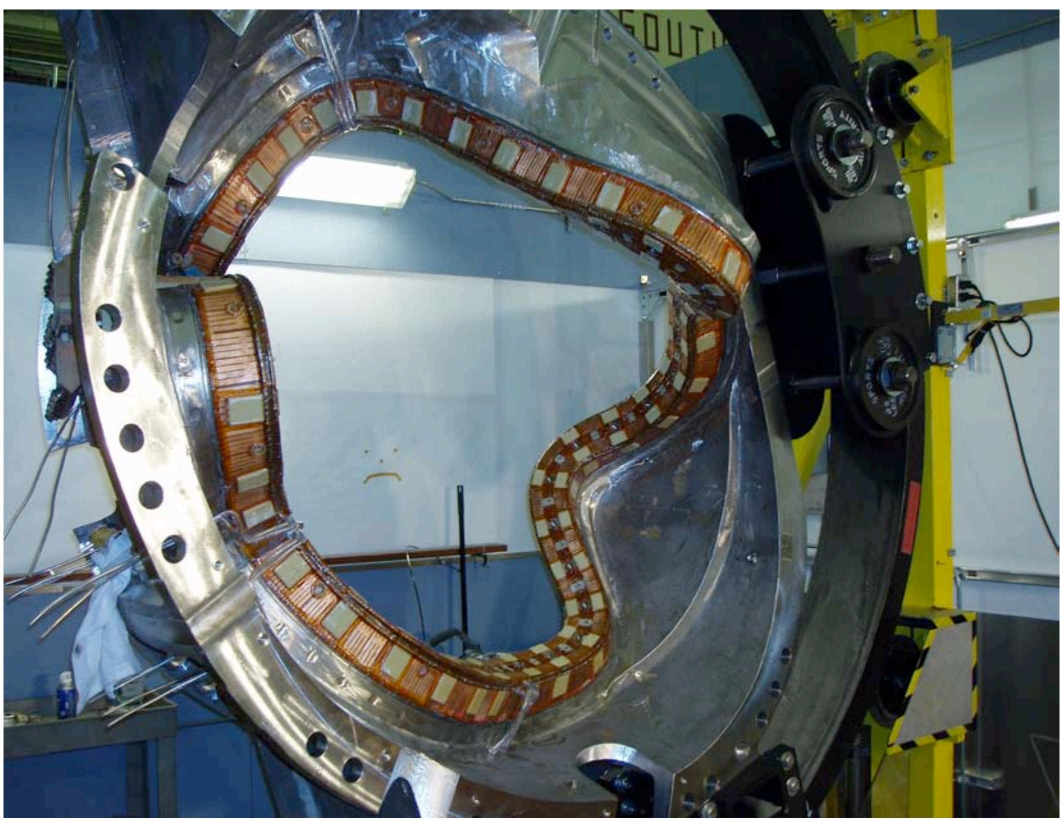


Figure 2. NCSX machine design.

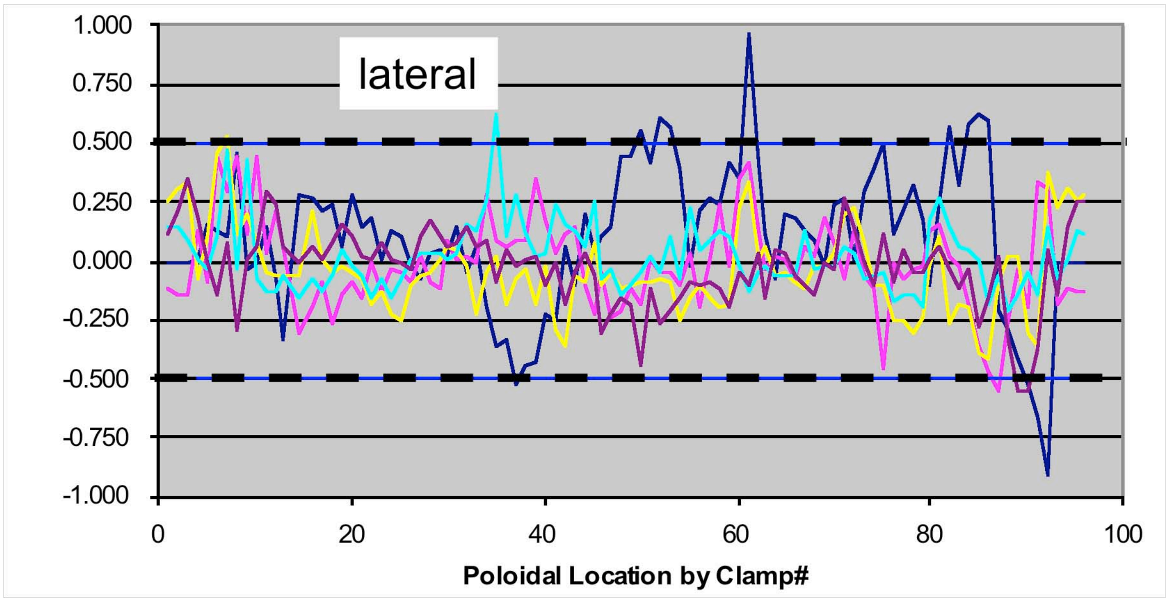


a.



b.

Figure 39(a). Modular coil assembly design. (b). Modular coil in process.



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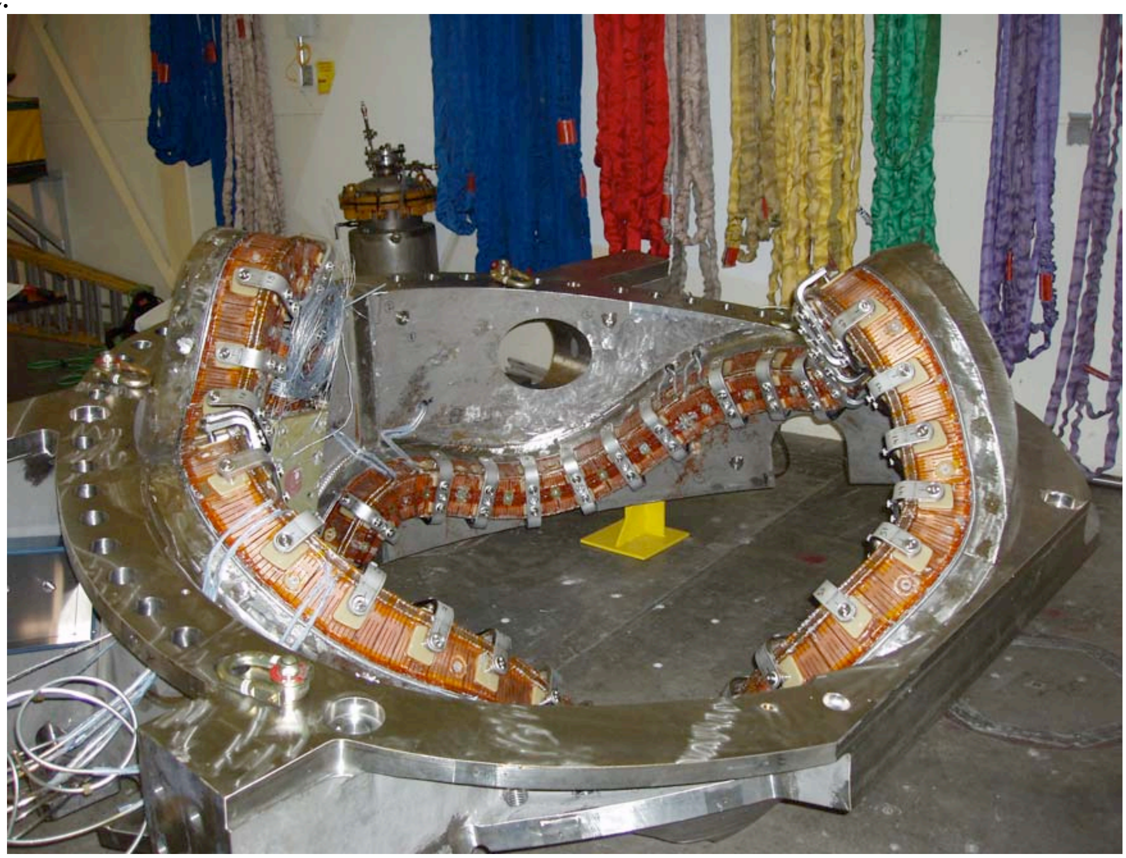

b.

Figure 4(a). Achieved modular coil current center position error. (b). Completed modular coil.

a.

b.

Figure 5(a). Vacuum vessel design. (b). Field period sector with ports installed for vacuum testing.