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PROGRESS IN NCSX AND QPS DESIGN AND CONSTRUCTION

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1. Introduction

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). The stellarator core is designed to produce a compact 3-D plasma that combines stellarator and tokamak physics advantages. The engineering challenges of NCSX stem from its complex geometry. From the project's start in April, 2003 to September, 2004, the fabrication specifications for the project's two long-lead components, the modular coil winding forms and the vacuum vessel, were developed. An industrial manufacturing R&D program refined the processes for their fabrication as well as production cost and schedule estimates. The project passed a series of reviews and established its performance baseline with the Department of Energy. In September, 2004, fabrication was approved and contracts for these components were awarded. The suppliers have completed the engineering and tooling preparations and are in production. Meanwhile, the project completed preparations for winding the coils at PPPL by installing a coil manufacturing facility and developing all necessary processes through R&D. The main activities for the next two years will be component manufacture, coil winding, and sub-assembly of the vacuum vessel and coil subsets. Machine sector sub-assembly, machine assembly, and testing will follow, leading to First Plasma in July, 2009.

The Quasi-Poloidal Stellarator Experiment (QPS) is an experiment to explore the quasi-poloidal approach to compact stellarators. It will be constructed at ORNL and is a partnership between PPPL, ORNL, and the University of Tennessee. The coil design is very similar to NCSX, but QPS has a smaller aspect ratio and will have an external vacuum vessel. Activities for the next year will focus on R&D, including completion of a prototype modular coil. Detailed design will start in 2007 and the first plasma is expected by late 2010.

2. NCSX Design and Construction

The NCSX modular coil current-center winding trajectories were optimized to produce a free-boundary high-beta, QAS plasma equilibrium possessing the desired physics properties while satisfying engineering constraints, such as minimum coil-to-plasma spacing, coil-to-coil spacing, and bend radius, for finite component builds and neutral-beam access [1]. Toroidal field coils, poloidal field coils, and helical-field trim coils complete the magnet system and ensure that the device has sufficient flexibility to vary the plasma configuration and test the physics. Stable equilibria having low effective ripple ε_h can be made with β ranging from 0 to 4% and plasma current from 0 to 100% of its reference value (equal to the calculated self-consistent bootstrap current at $\beta = 4\%$). Stable equilibria at higher beta (at least 6%) can be made with modest increase in ripple. Stability beta limits can be lowered from the nominal 4% to about 1% so theoretical stability limits can be studied over a range of beta values. The effective ripple can be increased by almost an order of magnitude, while preserving stability, to test the dependence of transport on the degree of quasi-symmetry. The rotational transform and its spatial derivative (magnetic shear) can be varied. Start-up pathways from vacuum to high beta through stable equilibria with low ripple and good magnetic surfaces have been calculated.

The NCSX 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 plasma heating power are set to produce the plasma conditions and profiles needed to test critical physics issues over a range of beta and collisionality values. Four 1.5-MW, 0.3-s neutral beam injectors, formerly used on the PBX-M experiment, are available to heat the plasma. They will be arranged for tangential injection with a mix of co- and counter-injection to control the effects of beam-driven currents. With the full complement of neutral beams (6 MW) and $B = 1.2$ T, the NCSX physics models predict plasmas with $\beta = 4\%$ and collisionality $\nu^* = 0.25$. Radio frequency waves can be launched from the high-field side to more directly heat electrons than with the neutral beams. Electron cyclotron heating options are being evaluated. The NCSX magnet system is designed for pulsed operation with magnetic fields up to 2.0 T (for 0.2 s) for low-collisionality plasma studies and pulse lengths up to 1.2 s (at $B = 1.2$ T) for experiments with pulse lengths long compared to current equilibration times. The magnet and heating system pulse lengths of NCSX are

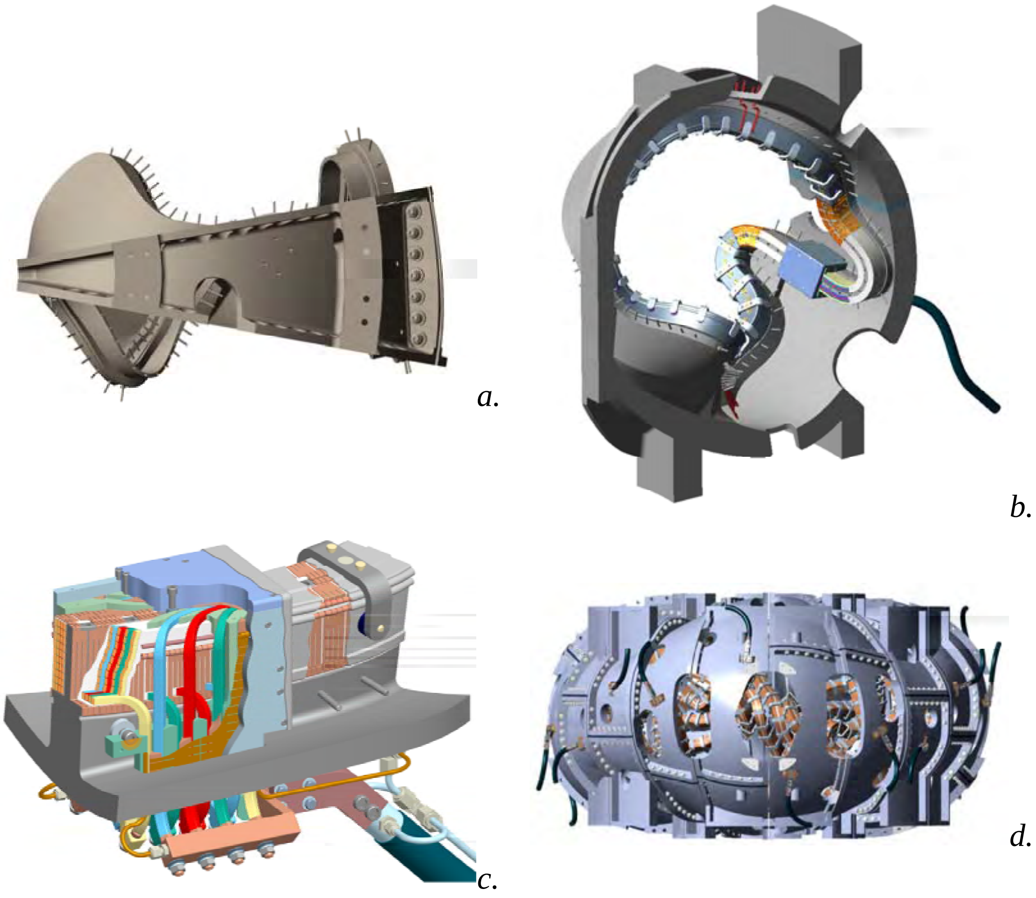

Fig. 1. NCSX modular coil set design. (a) winding form, (b) coil, (c) winding pack and lead details, (d) completed coil set..

long enough to produce the plasmas needed to test the physics properties of a high-beta compact stellarator configuration and determine the conditions for disruption-free operation.

In the engineering implementation of NCSX, the key physics requirement affecting the magnets is to produce modular coils whose current centers accurately follow the winding trajectories specified by the physics optimization. This is accomplished by winding each coil on a tee-shaped support feature that is an integral part of a structure called a modular coil winding form, or MCWF (Fig. 1). Each MCWF comprises one-eighteenth of a complete toroidal shell and has the tee feature machined on its interior surface, precisely following the physics-specified trajectory. The coils are wound with a compacted copper cable conductor which is flexible to facilitate handling and to allow manipulation of the coil cross section needed to place its current center within ±0.5 mm of its nominal position on the winding form. The winding forms are bolted together at precision machined flanges to form the structural shell which both locates the windings within ±1.5 mm of their nominal position in space and supports them against electromagnetic loads.

The key physics requirements affecting the vacuum vessel (Fig. 2) are to provide: a high-vacuum environment for plasma operation, sufficient interior space for the plasma boundary layer and plasma-facing components, and access for heating and diagnostic viewing. The solution is to locate the basic 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 non-axisymmetric vacuum vessel shell with a shape that resembles that of the plasma and which must be achieved within ±5 mm accuracy. Heating and diagnostic access requirements, including contingencies to allow for future innovations, are accommodated by providing nearly 100 ports of various shapes, sizes, and orientations causing the vacuum boundary to protrude through all available openings in the surrounding magnets.

Fig. 2. NCSX vacuum vessel design.

The geometry is both the basis for the compact stellarator’s physics benefits as well its key engineering challenge. The aim of the NCSX construction project is the accurate realization of the unusual geometries required of the magnets, vacuum vessel, and associated structures.

Manufacturing R&D for the MCWF and vacuum vessel was accomplished through a series of contracts with industrial suppliers over a two-year period. For example, vacuum vessel manufacturing studies were conducted during the conceptual design phase of the project by five different suppliers. They examined different methods (e.g., cold, hot, and explosive forming; welding) for realizing the NCSX geometry, identified critical issues, and estimated costs and schedules. These studies prototyped a successful model for electronically communicating the project’s design data (CAD models, drawings, product specifications) to suppliers and they established the basic feasibility of constructing the NCSX vacuum vessel. During preliminary and final design, the project contracted with two suppliers to, first, develop specific manufacturing, inspection, test, and quality assurance plans for the vacuum vessel and, then, to apply them by constructing prototype sectors. These contracts demonstrated viable industrial manufacturing processes for meeting the critical requirements (i.e., vacuum integrity, geometrical accuracy, and low magnetic permeability) and qualified two suppliers to compete for the production order. The manufacturing R&D program for the vacuum vessel and MCWF (which followed a very similar R&D path) were successful in preparing for construction. Both components are currently being produced in accordance with project requirements by capable suppliers under fixed-price contracts (Fig. 3).

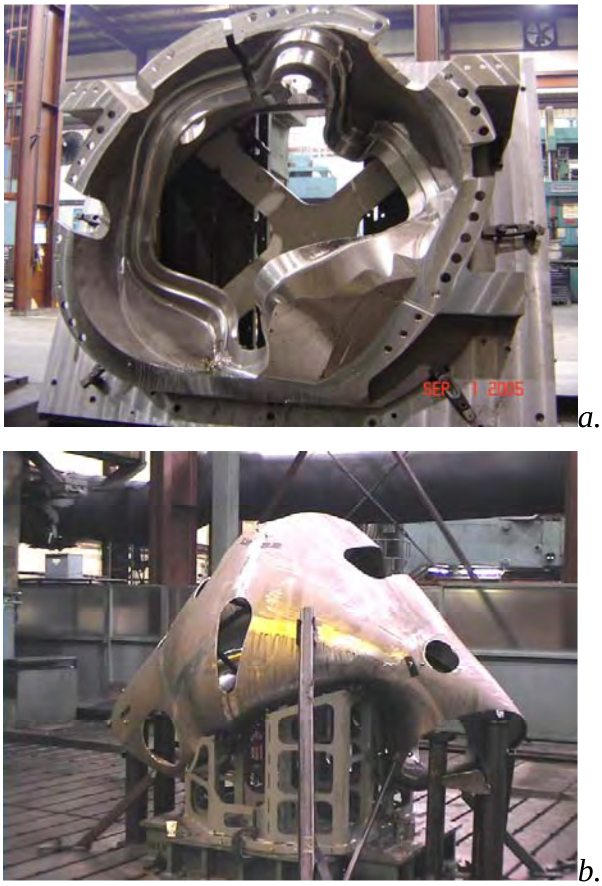

Fig. 3. NCSX components in manufacture: (a) MCWF, (b) vacuum vessel.

Modular coil R&D at PPPL and industrial conductor suppliers supported the design and manufacturing development for the modular coil winding. Initially, small-sample tests addressing both manufacture and performance issues supported decisions on conductor design (i.e., cable construction and dimensions), winding scheme, cooling scheme, insulation system, and epoxy impregnation materials and processes. Winding trials with flexible cable conductor on 2D and 3D tee-shaped winding forms developed methods for feeding the conductor and securing it in place during winding. Finally an integrated manufacturing demonstration was performed by constructing a “twisted racetrack” coil (TRC) on a winding form that is prototypical of the MCWFs in terms of tee cross section and worst-case bends and twists. The manufacturing R&D for the modular coils is now complete and electrical and thermal performance tests of the TRC to validate the analysis predictions are nearing completion. The modular coil R&D program has refined the winding pack design and demonstrated the manufacturing processes for the production coils that can achieve the required geometries and tolerances. Manufacturing procedures, tooling, and staff capabilities developed through this program have fully prepared the project to begin constructing the modular coils upon delivery of the first MCWF.

The vacuum vessel shell geometry simultaneously satisfies the physics requirement that the interior must be as large as possible and the feasibility requirement that the modular coils must be installed over the vacuum vessel shell (with ports removed). The design solution was found using a CAD modeling technique. The modular coils will be assembled into three-coil sub-assemblies which will then be translated and rotated over the vacuum vessel along an optimum trajectory. Installing the coils one at a time or following an unoptimized trajectory would have resulted in a smaller vessel with less physics capability.

The modular coils must be wound such that, when completed, their current centers accurately follow the trajectories specified by the physics optimization. The overall tolerance (±1.5 mm) budget is distributed equally among the coil manufacture, coil sub-assembly, and final assembly steps. An economical coil manufacturing solution was found that takes advantage of the precision-machined winding form tee and the cable conductor's flexibility and lack of significant keystoning in the tight bends. Clamping pressure and coordinate measuring equipment are used to achieve a rectangular shape and accurately position the overall winding packs such that the current center is located within ±0.5 mm of the required trajectory. This strategy eliminates the need for time-consuming shimming and in-process metrology as the coil is being wound and provides the ability to compensate for any inaccuracies in the winding form.

Construction of NCSX began with the award of contracts for the vacuum vessel, modular coil winding forms (MCWF), and modular coil conductor in September 2004 (Fig. 5) Modular coil fabrication at PPPL will begin upon delivery of the first MCWF, expected in September 2005, and will be completed by the end of 2007. Attachment of cooling tubes and other components to the vacuum vessel will begin upon delivery of the first vacuum vessel sector (one-third of the torus), expected in November 2005. Build-up of the three field-period sub-assemblies will start in 2007. Each of these includes six modular coils, six toroidal field coils, and a vacuum vessel sector with associated ports and attachments. Installation of these major assemblies on the machine base will start in mid-2008. Machine assembly and testing will occur in 2009. Electron-

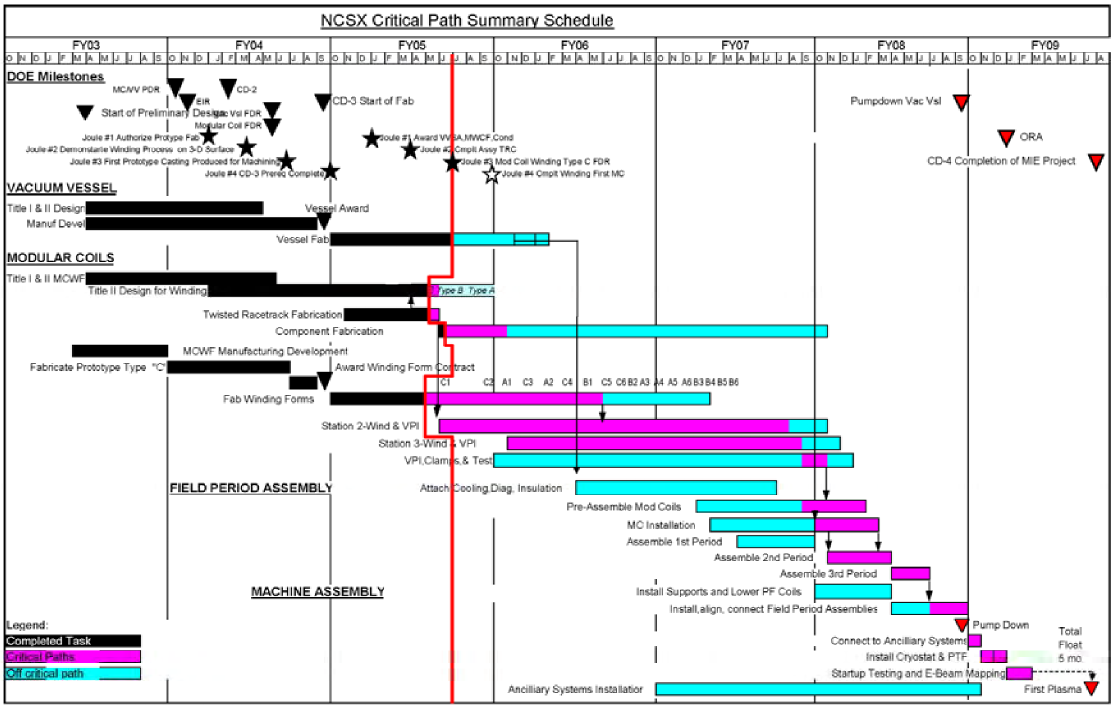

Fig. 5. NCSX Construction schedule.

beam measurements of the magnetic surfaces will be carried out as a final sensitive test of the overall construction accuracy of the magnet system. The construction project will be completed with First Plasma in July, 2009.

3. QPS Design

The QPS device is significantly different than NCSX although they are both compact stellarators. From a physics perspective, QPS features quasi-poloidal symmetry instead of quasi-axisymmetry. QPS is a 2-period (instead of 3-period) device with a lower aspect ratio (2.3 v. 4.5), smaller major radius (0.9m v. 1.4m), and lower toroidal field (1T v. 2T) [2]. The engineering design choices for the QPS device were somewhat different than for NCSX. The modular coils for QPS are wound directly on the winding form using cable conductor like NCSX but the coils operate at room temperature and are internally cooled. The modular coils are inside the plasma vacuum chamber instead of outside. A picture of the QPS design is shown in Fig. 6.

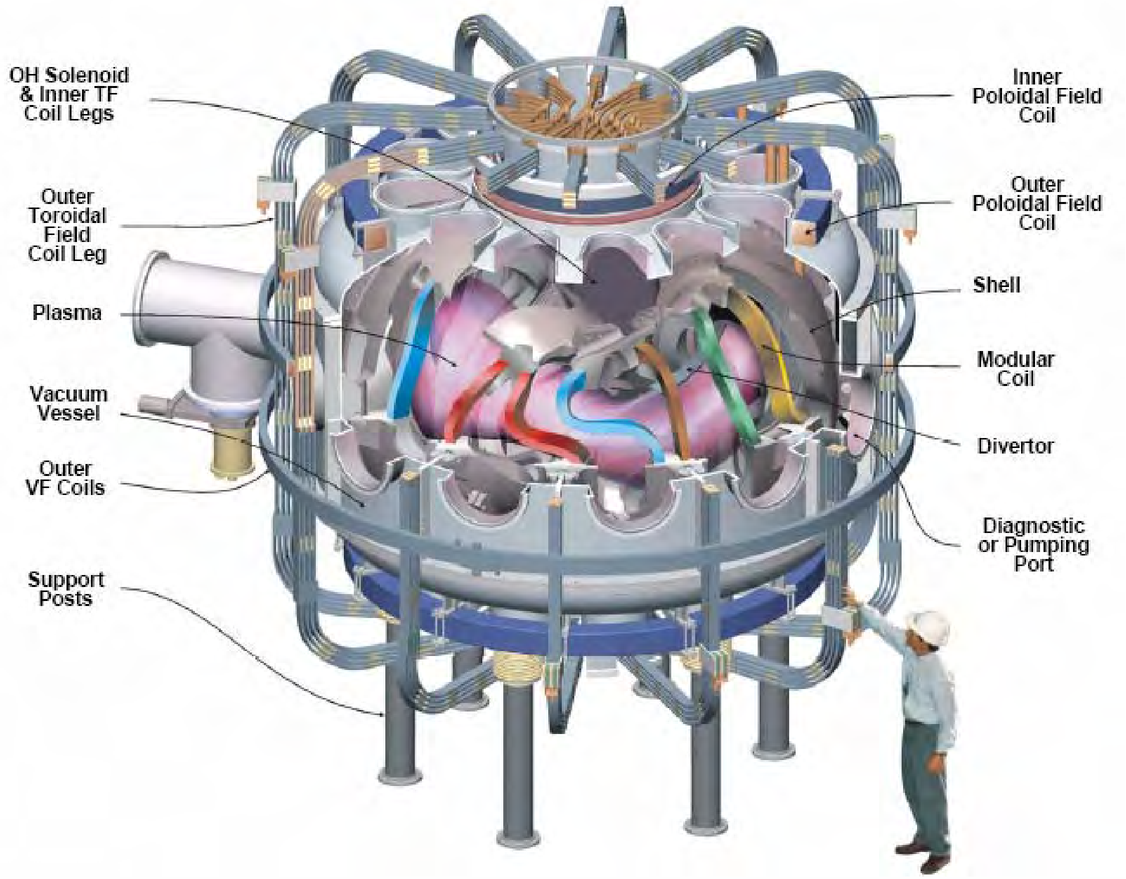

Fig. 6 QPS Stellarator Core

The QPS project has been performing the R&D necessary to provide an adequate basis for the QPS design. A prototype winding form is in production. It has already been cast using a modified CF8M alloy. Machining is expected to start in November. A picture of the QPS casting is shown in Fig. 7.

Fig. 7. QPS Prototype Modular Coil

The QPS conductor is wound directly onto the winding form using cable conductor. Three options for cooling the conductor are being considered. In the first option, each conductor has an embedded cooling tube. Note that an electrical turn consists of six conductors. In the second option, one out of every six conductors is replaced with a flexible (helically corrugated), stainless steel cooling tube. In the third option, four smaller copper tubes are used in place of the larger stainless steel tube. Conductor R&D is currently underway to select among these options.

The modular coils must be “canned” because they operate within the plasma vacuum boundary. The canning concept is shown in Fig. 8. A mockup of this approach has been fabricated and welded. The welds were made without filler material or special weld preparations. The temperature at the windings was benign. The glass insulation was not damaged.

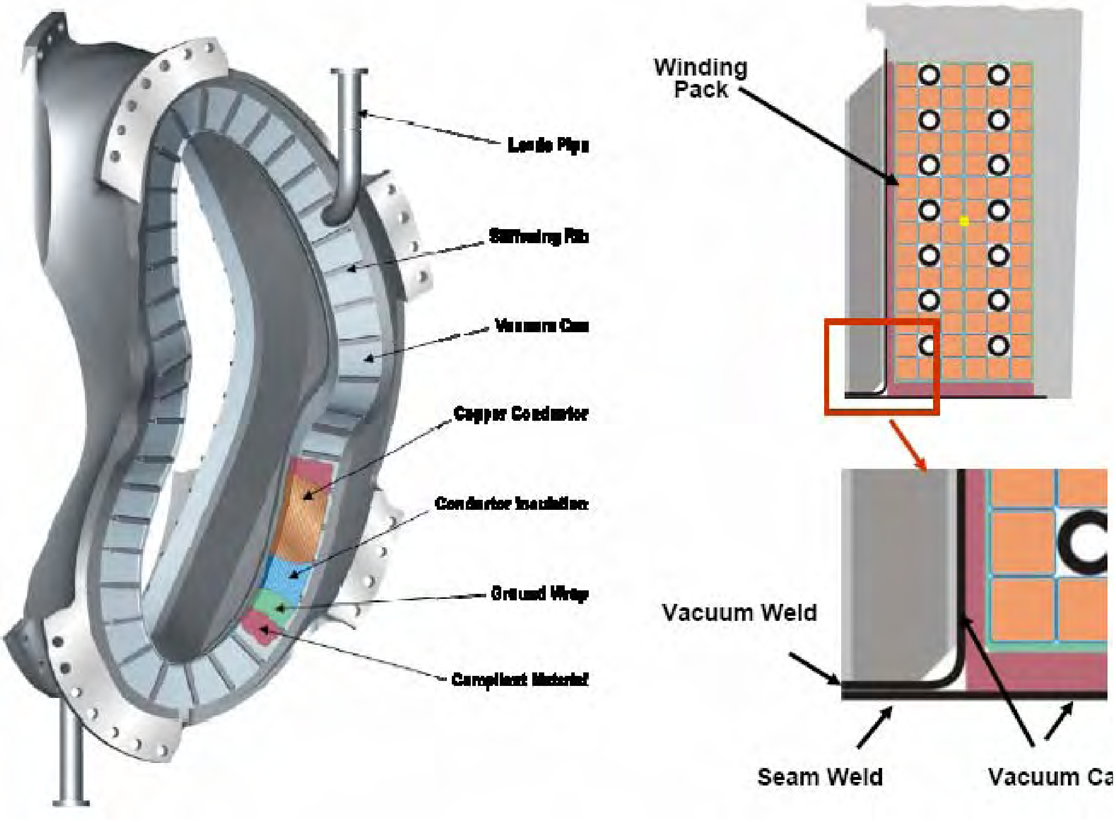

Fig. 8. QPS Modular Coil Canning Concept

Outgassing from the castings were a concern so vacuum testing was performed on prototypical cast material. The results were that the pressure continued to drop after several days. There was no indication of connected porosity or virtual leaks.

The plan is to wind the modular coils at the University of Tennessee (UT). Space has been prepared in a recently completed Magnet Development Laboratory, which is a UT facility. All of the winding, canning, and potting processed are being developed through R&D being conducted at this facility. Detailed design will start in 2007 and the first plasma is expected by late 2010.

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