Engineering Aspects of Compact Stellarators[*]

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Abstract. Compact stellarators could combine the good confinement and high beta of a tokamak with the inherently steady state, disruption-free characteristics of a stellarator. Two U.S. compact stellarator facilities are now in the conceptual design phase: the National Compact Stellarator Experiment (NCSX) and the Quasi-Poloidal Stellarator (QPS). NCSX has a major radius of 1.4 m and a toroidal field up to 2 T. The primary feature of both NCSX and QPS is the set of modular coils that provide the basic magnetic configuration. These coils represent a major engineering challenge due to the complex shape, precise geometric accuracy, and high current density of the windings. The winding geometry is too complex for conventional hollow copper conductor construction. Instead, the modular coils will be wound with flexible, multistrand cable conductor that has been compacted to a 75% copper packing fraction. Inside the NCSX coil set and surrounding the plasma is a highly contoured vacuum vessel. The vessel consists of three identical, 120° segments that are bolted together at double sealed joints. The QPS device has a major radius of 0.9 m, a toroidal field of 1 T, and an aspect ratio of only 2.7. Instead of an internal vacuum vessel, the QPS modular coils will operate in an external vacuum tank.

1. Introduction

Stellarators have a toroidal magnetic configuration that does not require a net plasma current to produce closed magnetic surfaces. This is accomplished with a set of nonplanar coils, and the resulting plasma shape is not axisymmetric but has a rather complex, albeit periodic, geometry. The absence of the plasma current results in an inherent steady state device and eliminates the problem of a sudden current quench (plasma disruption). Stellarators constructed to date, or under construction, have relatively high aspect ratios, up to 10, and these configurations tend to extrapolate to a large reactor size. The compact stellarator is a new approach with a much lower aspect ratio. These devices retain the inherent steady state nature of other stellarators, but do allow a small bootstrap current in the plasma.

Two compact stellarators are now in the design phase. The National Compact Stellarator Experiment (NCSX) has a quasi-axisymmetric magnetic configuration and will be constructed at the Princeton Plasma Physics Laboratory (PPPL) [1]. The Quasi-Poloidal Stellarator (QPS) is a lower aspect ratio device with a quasi-poloidal magnetic configuration and will be constructed at the Oak Ridge National Laboratory (ORNL) [2]. The principal feature of both devices is a set of modular coils that provide the magnetic configuration. These coils represent a major engineering challenge due to the complex shape, precise geometric accuracy, and high current density of the windings. In addition, the complex plasma shape can require highly shaped vacuum vessel and first wall components. The engineering aspects of NCSX and QPS are described in the balance of this paper.

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2. NCSX Design Features

NCSX is a proof-of-principle experiment with a major radius of 1.4 m, a nominal toroidal field of 2 T, and an aspect ratio of 4.3. The stellarator core includes the assembly of four coil systems and associated structure, the vacuum vessel, and the plasma-facing components (PFCs). The coil systems provide magnetic fields for plasma shaping and position control, inductive current drive, and error field correction. The coils operate at cryogenic temperatures, so the entire core is surrounded by a cryostat for thermal insulation. A cut-away view of the stellarator is provided in Fig. 1.

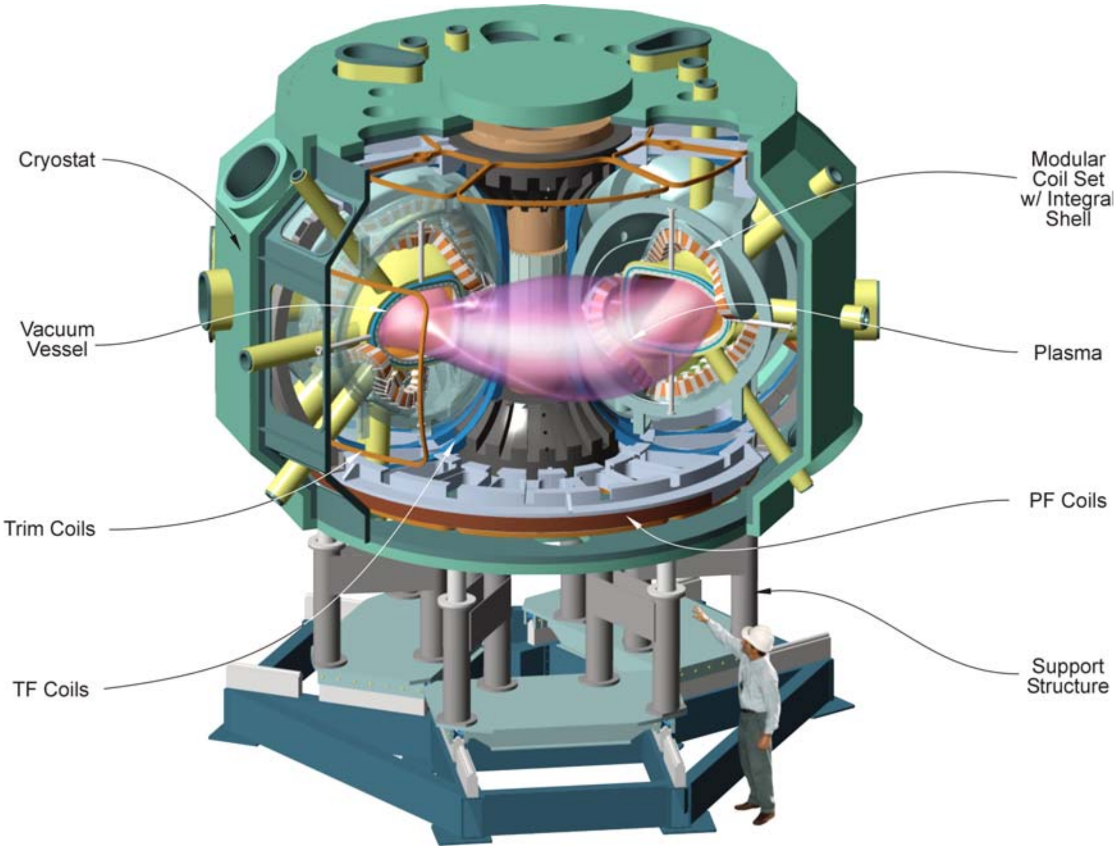


FIG.1. NCSX device illustrating major systems and overall configuration.

2.1. NCSX Modular Coils and Issues

NCSX has three types of modular coils, each repeated six times to form the complete coil set. (Fig. 2). Specially developed computer codes have been used to optimize the winding path trajectory to satisfy stringent physics requirements while not violating engineering constraints on bending radii, coil-to-coil spacing, coil-to-plasma spacing, and access for neutral beam injection [3]. The winding cross section is oriented around the winding path to provide minimal twisting while maximizing coil-to-coil spacing and coil-to-plasma spacing. In spite of the careful optimization, the winding geometry is too complex for conventional hollow copper conductor construction. Instead, the NCSX coils will be wound with flexible, multi-strand cable conductor that has been compacted to a 75% copper packing fraction. The cable is wound on a cast-and-machined winding form that provides both the needed accuracy and structural support (Fig. 3). Each coil is split into two winding packs, one on either side of a central “web” extending from the winding form (Fig. 4). This configuration provides good access for winding the conductor and moves the conductor as close as possible to the plasma. (Conventional winding forms tend to be in the bore of the coil, which moves the winding away from the plasma.). After a coil is wound, it is vacuum-pressure-impregnated with epoxy to form a monolithic structure. The winding forms are then bolted together at planar flanges to form a continuous shell structure to resist the electromagnetic loads. This system minimizes the accumulation of geometric errors and provides a very robust structural system. The maximum toroidal field at 1.4 m produced by the modular coils with a flattop of ~0.5 s is 1.7 T. The toroidal field on axis can be raised above 2 T by energizing the toroidal field (TF) coils, which can add ±0.5 T to the field generated by the modular coils. Due to the high current density (~ 14 kA/cm^2), the coils are cooled to liquid nitrogen temperature via chilled copper surfaces in intimate contact with the winding packs.

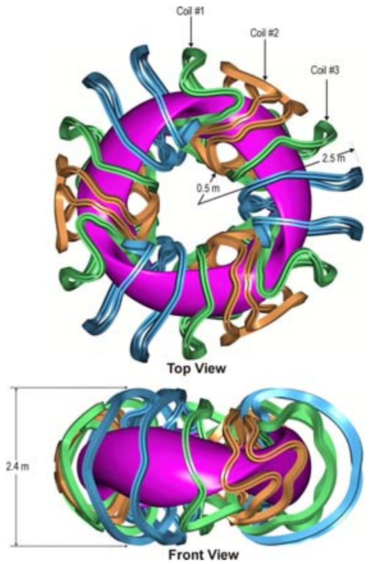


FIG. 2. NCSX modular coil windings and plasma geometry; 3 coil shapes are repeated 6 times for a total of 18 coils.

The flexible copper cable conductor is readily formed to shape, but its cross section distorts, or “keystones”, around tight radii. One option being considered to minimize this effect is to use multiple parallel cables within one insulation jacket. The windings are wound on and supported by the tee-shaped structural member, which is an integral part of the coil winding form. The winding forms are bolted together to form a structural shell that both locates the windings within the +/- 1.5-mm accuracy requirement and supports them against the electromagnetic loads. The forces on the winding packs tend to push them radially outward against the shell and clamp them laterally against the central member of the “tee”, so only intermittent clamps are provided to preload the windings against the structure. Several

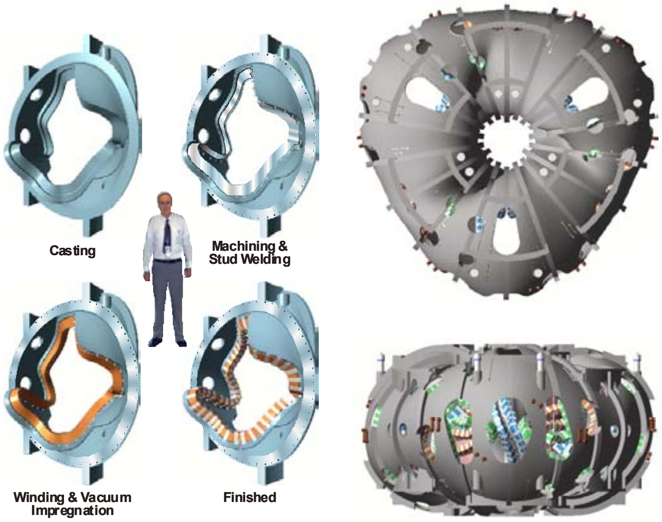


FIG. 3. Structural support for modular coil showing stages of fabrication of coil one and completed assembly of 18 coils into continuous structure.

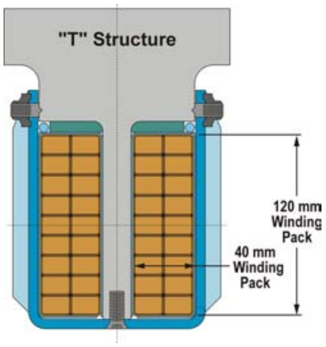


FIG. 4. NCSX modular coil cross section showing winding packs on either side of structural support

potential manufacturers in industry have conducted studies that confirm the feasibility of coil fabrication at reasonable cost.

2.2. NCSX Toroidal, Poloidal, and Correction Coils

A set of 18 identical, equally spaced, TF coils is included to provide flexibility in the magnetic configuration. Adding or subtracting toroidal field is an ideal "knob" for lowering and raising the rotational transform. A set of poloidal field (PF) coils is provided for inductive current drive and plasma shape control. Two types of correction coils are also envisioned for NCSX. The first is a set of window-pane coils provided on the top, bottom and outside perimeter of the coil support structure to reduce 1-1, 2-1, 3-1, and 3-2 resonant errors that may result from manufacturing or assembly errors in the modular coil geometry. Figure 5 illustrates the PF, TF, and external trim coil geometry relative to the machine cross section. All these coils are of conventional construction, wound from hollow copper conductor, and insulated with glass-epoxy. They operate at ~ 85K, the same temperature as the modular coil set. The second set of trim coils consists of 12 saddle coils located inside the vacuum vessel at the symmetry planes with the "bean-shaped" plasma. These coils are not included in the baseline configuration, but may be provided as a future upgrade during the operation of NCSX to control m = 5 and m = 6 resonant field perturbations.

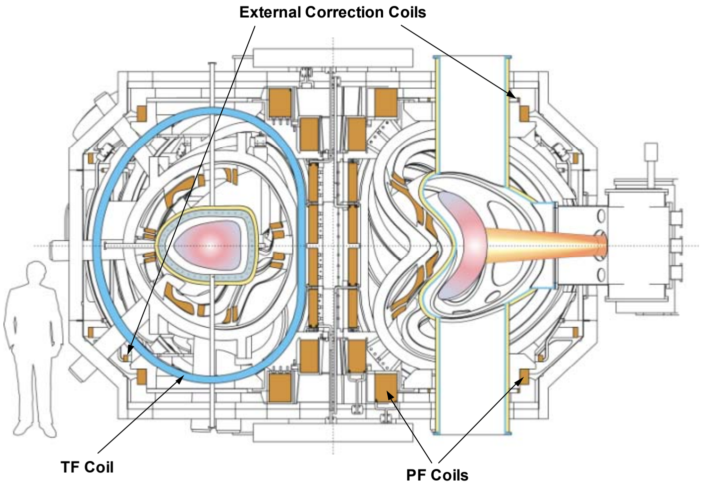


FIG. 5. NCSX cross section showing TF, PF, and correction coils relative to other components and plasma.

2.3. NCSX Vacuum Vessel

Inside the coil set and surrounding the plasma is a highly contoured vacuum vessel. The vessel consists of three identical, 120° segments (corresponding to the three field periods of the magnetic configuration) that are bolted together at double-sealed joints. Each segment is fabricated from 9.5-mm-thick Inconel 625 that has been press-formed, explosively formed, or perhaps investment cast to the required shape. Inconel has been selected due to its low magnetic permeabilility (even after welding) and high electrical resistivity.

As shown in Fig. 6, numerous ports are provided for heating, diagnostics, and maintenance access. Several sizes and shapes best utilize the limited access between

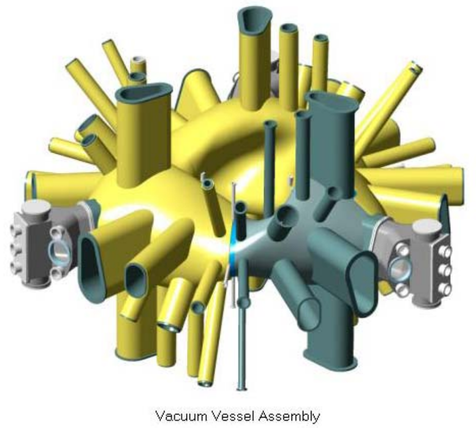


FIG. 6. NCSX vacuum vessel with ports showing all three field period segments assembled. Insulation layer is removed from one segment

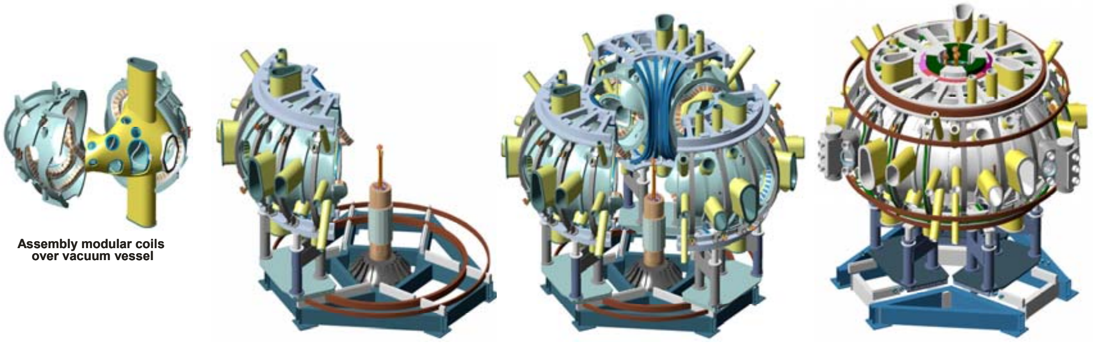
modular coils. A spacer section is used between field periods to provide ports on the bullet-shaped symmetry plane and to provide a means for final adjustment and fit-up of the whole assembly. The vessel will be baked to 150ºC and operate at 20ºC using helium gas circulated through tracing lines attached to the vessel exterior. The vessel is insulated on its exterior surface to provide thermal isolation from the modular coils. Potential manufacturers in industry have conducted studies confirming the feasibility of fabricating the vessel at reasonable cost.

2.4. NCSX Plasma -Facing Components (PFCs)

The baseline design consists of simple poloidal graphite limiters at the three "bullet" symmetry planes. The device is designed for an upgrade configuration that utilizes a contoured liner, constructed of molded carbon fiber composite (CFC) panels mounted on a frame of poloidal rings. The plasma-facing surface is located as close to the vacuum vessel as possible to provide maximum flexibility for plasma shaping. Investigations are under way for adding a baffled region at the tips of the plasma (akin to a divertor in a tokamak). The plan is to stage the installation of the liner, with limited wall coverage during the early phases of operation and with the addition of the remainder of the liner during later operation. When the full complement of panels is installed, they will shield the entire interior surface of the vessel from the plasma. The liner is baked at 350ºC while maintaining the vessel at 150ºC. During normal operation, the liner will have a lower preshot temperature in the range of 20ºC to 150ºC.

2.5. NCSX Core Assembly

The NCSX stellarator core will be assembled from three field period subassemblies that are bolted together atop the support stand in the test cell. Each of the three field periods are pre-assembled in a separate area at PPPL and consist of one-third of the vacuum vessel, TF and modular coils, PFC support rings, trim coils, and in-vessel diagnostics. The TF and modular coils will first be assembled over the vacuum vessel segment. The vacuum vessel will then be supported (hung) from the modular coil structure, and the port extensions will be welded into place. The completed field period subassembly will be transported to the test cell and placed in a temporary position on the test stand. When all three subassemblies are in place, they are moved radially into final position. All three subassemblies are moved simultaneously to avoid interference with the interlocking modular coil boundaries, which extend past the shell and vessel connecting flanges. The assembly sequence is illustrated in Fig. 7.



Assembly modular coils over vacuum vessel

One field period sub-assembly placed on support stand in retracted position

Three field period sub-assemblies in retracted position

Field period sub-assemblies bolted together and PF coils installed in final position

FIG. 7. NCSX assembly sequence, showing field period subassembly and final assembly.

3. QPS Design Features

The QPS device is a smaller, concept exploration experiment with a major radius of 0.9 m, a nominal toroidal field of 1 T, and an aspect ratio of only 2.7. The device is illustrated in Fig. 8. The coil set is similar to NCSX, with modular, TF, and PF coils. Allowance will be made for auxiliary trim coils if they are deemed necessary. The toroidal field on axis can be raised above 1 T by energizing the TF coils, which can add ± 0.2 T to the field generated by the modular coils. Instead of an internal vacuum vessel, the QPS modular coils will operate in a bell jar. This eliminates the complexity of the contoured vacuum vessel, but places additional requirements on the coil design to achieve good vacuum properties for plasma operation.

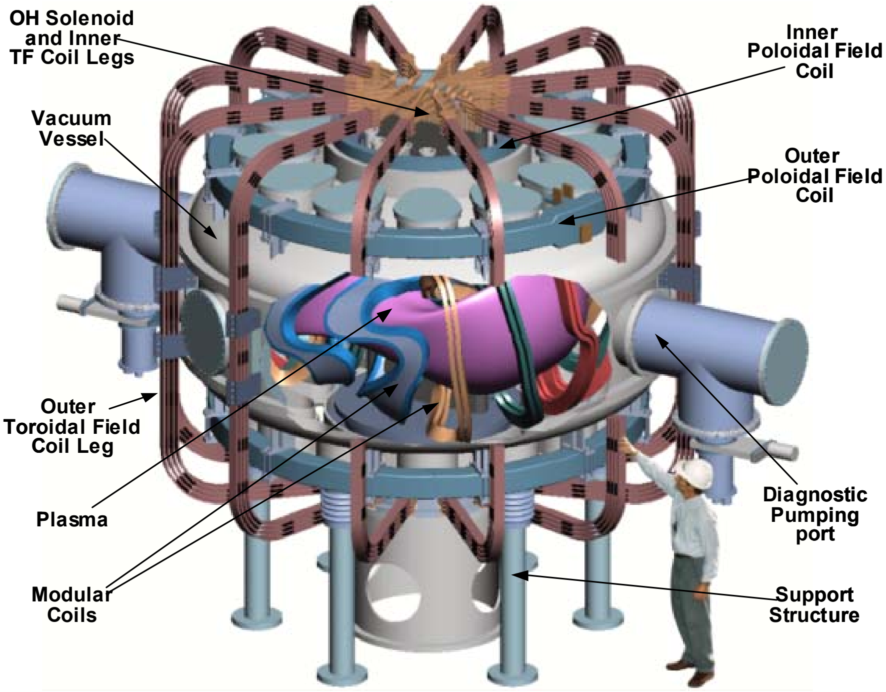


FIG.8. QPS device illustrating major systems and overall configuration.

3.1. QPS Modular Coils

The modular coils for QPS are similar to NCSX and consist of flexible copper conductor wound on a cast and machined winding form. Unlike NCSX, they cannot operate at cryogenic temperatures but must operate at as high a temperature as practical to minimize adsorption of gas on the coil surfaces. As with the NCSX coil set, the QPS coil winding trajectories have been optimized for the best combination of physics and engineering properties. However, the QPS coil set has only two field periods (Fig. 9), which forms a racetrack configuration with a narrow central bore. Special constraints are required to maintain a sufficient opening through the central bore for an elongated solenoid and the set of auxiliary TF coils. To open up the bore while maintaining acceptable ripple, the two winding packs for the central coils of each field period are allowed

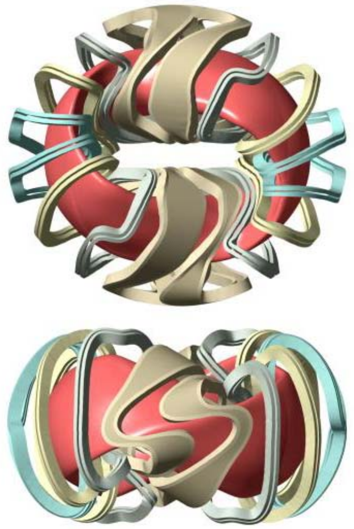


FIG. 9. QPS modular coil set with split windings

to separate and follow independent trajectories. The winding form concept is preserved, but the central "web" structure is not uniform in width, and the winding packs are not parallel to each other for these coils.

The modular coils are gas-cooled and operate above room temperature because they are located inside the plasma vacuum space and it is desirable to minimized adsorbed gas. The nominal operating range is between 37 and 65°C, but the coils could also operate between 68 and 100°C if the epoxy formulation can accommodate the higher temperature. A compliant layer is provided in the outboard region between the structure and windings to reduce thermal stresses. Stainless steel sheets are seal-welded around the windings to provide a vacuum-compatible coil. Some development will be required to ensure that no distortion of the coil occurs during the welding process. In local areas requiring reinforcement, intermittent ribs are bolted to the sides of the coil as structural retainers for the windings.

3.2. QPS Toroidal And Poloidal Field Coils

As shown in Fig. 10, a set of 12 TF coils is included to provide flexibility in the magnetic configuration. The outboard legs of the coils are identical and equally spaced, but the inboard legs are spread out to nest in the oblong opening through the center of the modular coil set. For assembly purposes the coils are demountable at the top and bottom of the inboard region. A set of PF coils is provided for inductive current drive and plasma shape and position control. The coil set consists of an inner solenoid and two pairs of ring coils. The solenoid is located just outside the TF coil inner legs and is contained in a common vacuum can that forms a center-stack assembly. This assembly is self-supporting and fills the oblong region inboard of the modular coils. Structural ties are required to restrain the magnetic loads on the solenoid and the internal pressure load on the centerstack casing. All coils are of conventional construction, wound from hollow copper conductor, and insulated with glass-epoxy. Existing PF coils from the Advanced Toroidal Facility (ATF) are used for the outer ring coils. All PF coils operate at room temperature. Fig. 10 illustrates the TF and PF coil geometry, including the centerstack assembly.

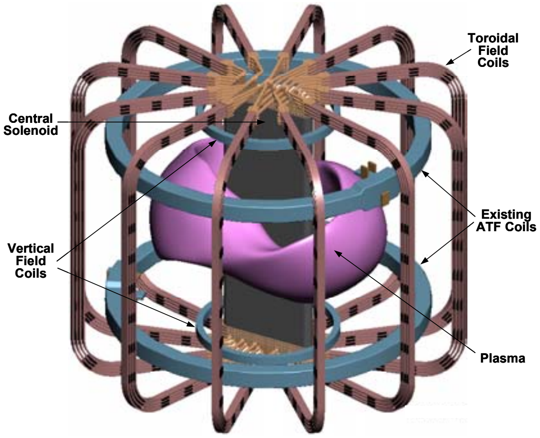


FIG. 10. QPS TF and PF coil sets with center stack assembly and plasma shape for reference

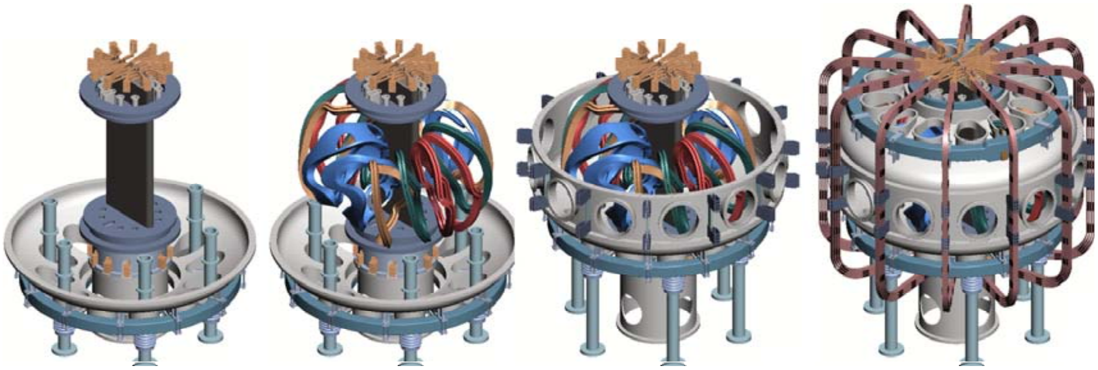
3.3. QPS External Vacuum Vessel

The QPS vacuum vessel is a large external tank that encases the modular coil set. The external tank has several advantages. First, it is less costly than an internal, highly contoured vessel. Second, it provides better access to the plasma because all the gaps between coils are potential sight lines and there is no constraint imposed by fixed port extensions, which otherwise use much of the space for thermal insulation and clearance. Third, there are no complex assembly steps required as would be the case with an internal vessel, where the modular coils must slide over the highly contoured vessel. However, two disadvantages of the external vessel are the requirement for canning the modular coils and the necessity of operating the coils at higher temperature.

Twelve 0.6-m-diameter ports around the midplane and 12 oblong ports in each of the two domes of the vacuum tank are provided for heating, diagnostics, and maintenance access, and numerous smaller ports are provided for coil services and instrumentation feed-throughs. These ports will have metal seals, but the large head-to-spoolpiece seal surfaces will have double O-rings with interstitial pumping. Thermal insulation blankets and heaters will be added to provide a bakeout capability with a temperature goal of 150ºC.

3.4. QPS Core Assembly

The QPS stellarator core will be assembled from two field period sub-assemblies that are bolted together around the center-stack assembly and tank base in the test cell (Fig 11). Both field periods are pre-assembled in a separate area, and consist of half of the modular coils and associated inter-coil structure. The internal coil services are routed through the vacuum tank upper and lower domes, and then the main spool piece, tank lid, and outer TF legs are added.



Install centerstack with dome and coils on base

Assemble modular coil field period sub-assemblies with structure around centerstack

Add vessel spool piece & upper dome with PF coils

Move domes to final position, leak check vessel, & install TF coils

FIG. 11. QPS assembly sequence, showing assembly inside external vacuum tank.

4. Summary

The NCSX and QPS compact stellarators pose many engineering challenges. The modular coils for both devices have complex shapes that must be fabricated, assembled, and operated within very tight geometric tolerances. The coils also operate at high current density, with rapid temperature rise in the windings. The proposed design solution for both devices is to wind a flexible cable conductor onto an accurate winding form, then connect the winding forms together to provide a continuous toroidal shell support. NCSX has a highly contoured vacuum vessel nested between the plasma and modular coil set that must be formed and welded into field period sections that are bolted together at assembly. QPS has a simple bell jar vacuum vessel external to the modular coils, but this requires that the modular coils be "canned" for vacuum compatibility. R&D programs are in place to develop prototypes of the modular coils for both devices as well as a full-scale, half-period of the NCSX vacuum vessel.

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[1] G. H. Neilson and the National Compact Stellarator Team, "The National Compact Stellarator Experiment Physics Validation Report", http://www.pppl.gov/ncsx/pvr/, March, 2001.

[2] J. F. Lyon and the QPS team, "QPS, A Low Aspect Ratio Quasi-Poloidal Concept Exploration Experiment", http://qps.fed.ornl.gov/pvr/docment.htm, April 2001.

[3] D. J. Strickler, L. A. Berry, S. P. Hirshman, *Fusion Science and Technology*, 41 (March, 2002).