Innovation in Design and Fabrication of Compact Stellarators

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Abstract. The Quasi-Poloidal Stellarator (QPS) is being developed to test key physics issues at very low plasma aspect ratio, 1/2-1/4 that of existing stellarators. Engineering innovation is driven by both the complex 3-D design requirements and the need for reduced cost and risk in fabrication. Complex, highly accurate stainless steel modular coil winding forms are cast and machined; conductor is wound directly onto the modular coil winding forms; a vacuum-tight cover is welded over each coil pack; the coils are vacuum pressure impregnated; and the completed coils are installed in an external vacuum vessel. As a result, QPS differs significantly in design and construction from other toroidal devices. Figure 1 shows a cutaway view of the QPS device.

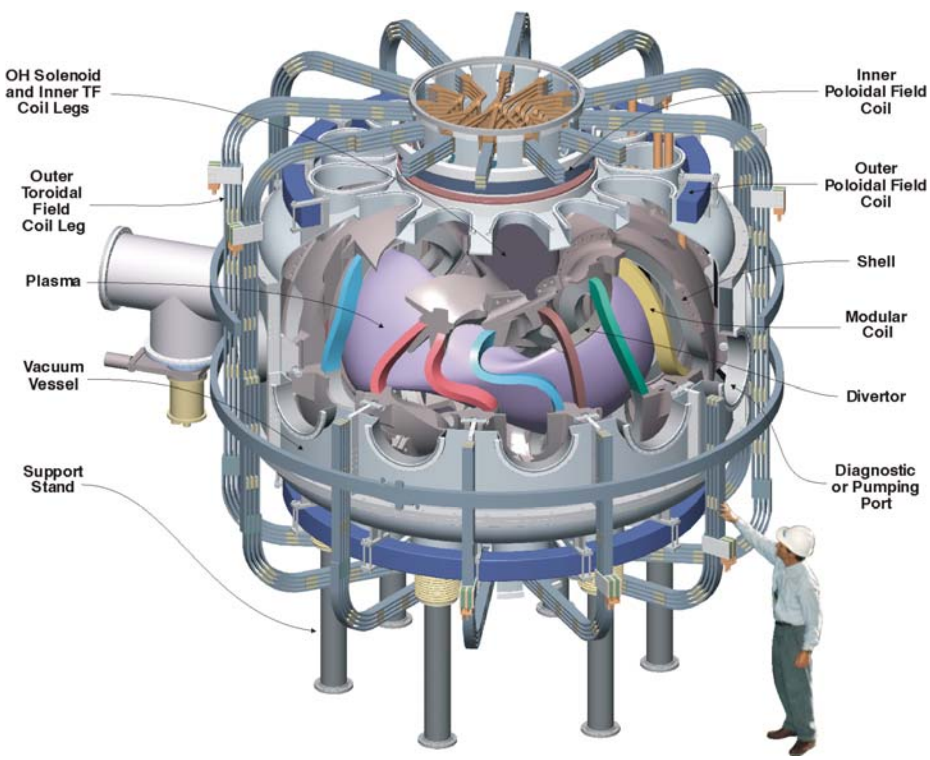

Figure 1 The QPS device

1. Introduction

The Quasi-Poloidal Stellarator (QPS), currently in the R&D and prototype construction phase, is being developed to test key toroidal physics issues at very low plasma aspect ratio ($\langle R\rangle/\langle a\rangle \geq 2.3$, 1/2-1/4 that of existing stellarators): reduced neoclassical and anomalous transport,

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MHD equilibrium and stability limits, and divertors. Here ⟨R⟩ is the average major radius and ⟨a⟩ is the average plasma radius for the non-circular, non-axisymmetric stellarator plasma. Figure 2 [1] shows the last closed flux surface and the coils that create it. The colors indicate the strength of the magnetic field on the plasma surface. QPS has a quasi-poloidal (linked-mirror-like) rather than quasi-toroidal (tokamak-like) magnetic configuration, which allows large sheared poloidal flows to more efficiently break up turbulent eddies and suppress anomalous transport. The QPS design parameters are ⟨R⟩ = 0.95 m, ⟨a⟩ = 0.3-0.4 m, an average on-axis field ⟨B⟩ = 1 T, a 1.5-s flat-top pulse length, and 3-5 MW of ECH and ICRF heating power [2].

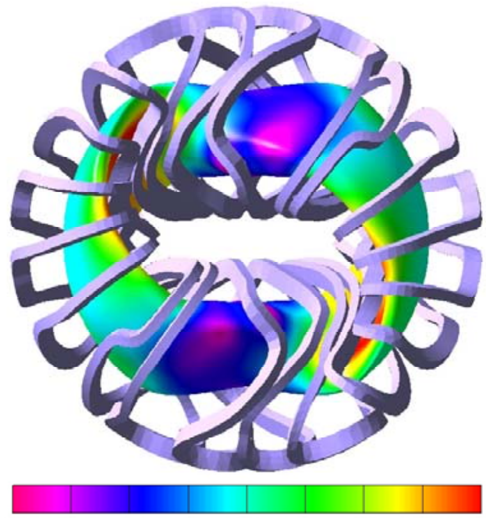

Figure 2 QPS coil set and last closed flux surface showing contours of constant field

The stellarator core (shown in cutaway view in Fig. 1) consists of a set of modular coils that provide the primary magnetic field configuration, auxiliary coils including three sets of poloidal field coils and 12 toroidal field coils, machine structure, and an external vacuum vessel. There are two field periods with 10 modular coils per period, but due to stellarator symmetry, there are only five different coil types. The coils are wound on 10 stainless steel winding forms (three different types) that are bolted together to form a structural shell (shown in Fig. 3) inside the cylindrical, domed vacuum vessel. The coils are up-down symmetric within a field period, so two of the winding forms contain coils of the same shape (the red coils in Fig. 2), and the other eight winding forms hold two coils of different shapes. Figure 4 shows a cutaway view of the coil in the coil winding form at the bean-shaped cross section, the simplest (least non-planar) of the QPS coils. This is the yellow coil in Fig. 1 and the red winding form in Fig. 3.

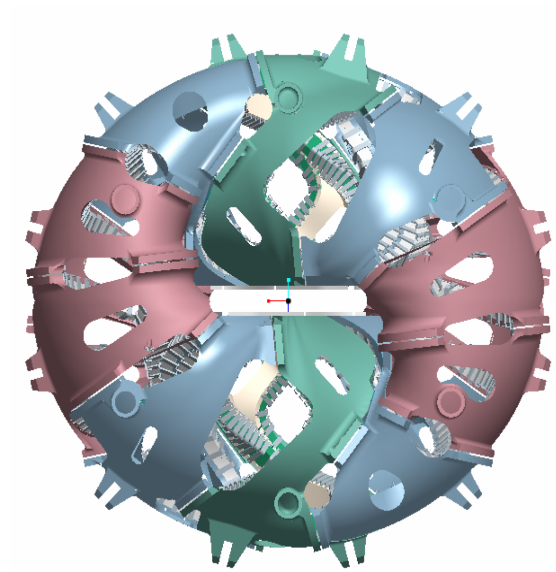

Figure 3 Winding forms bolted together to form a robust structural shell

Nine independent controls on the coil currents permit a wide range of magnetic configuration properties for physics studies. Changes in coil currents of +/–20% allow a factor >30 variation in $\varepsilon_{\mathrm{eff}}^{3/2}$ (proportional to the neoclassical ripple-induced heat diffusivity in the low-collisionality limit for no electric field, where $\varepsilon_{\mathrm{eff}}$ is the effective helical ripple at $r = 2/3a$). Similarly, a factor of 9 variation is obtained in the degree of poloidal symmetry, defined by the ratio of the magnetic energy in the non-symmetric modes (with poloidal mode number $m \neq 0$) to those that have poloidal symmetry (with $m = 0$). The fraction of the magnetic energy in non-poloidally symmetric field components is <0.4% in the plasma core ($r/a < 0.4$) and rises to 3% at the plasma edge for the base case. Also, changes in the coil currents allow a factor of 30 variation in the poloidal viscosity, which permits studying the role of poloidal flows in suppressing turbulence.

Innovation for QPS is driven by both the complex design requirements (large plasma radius at very low aspect ratio, a plasma cross section that varies toroidally from bean-shaped to D-shaped, and different toroidally-elongated non-planar coils that are close to the plasma edge at some locations) and the need for reduced cost and risk in fabrication of a practical experiment. The modular coils represent the most difficult part of the core design and fabrication and required the most innovation: (1) complex, highly accurate stainless steel modular coil winding forms are cast and machined; (2) conductor is wound directly onto the modular coil winding forms; (3) a vacuum-tight cover with reinforcing ribs and extension pipes for cooling and current feeds is welded over each coil pack; (4) the coils are vacuum pressure impregnated with cyanate ester resin; and (5) the completed coils are installed in an external vacuum vessel. As a result, QPS differs significantly in design and construction from other toroidal devices.

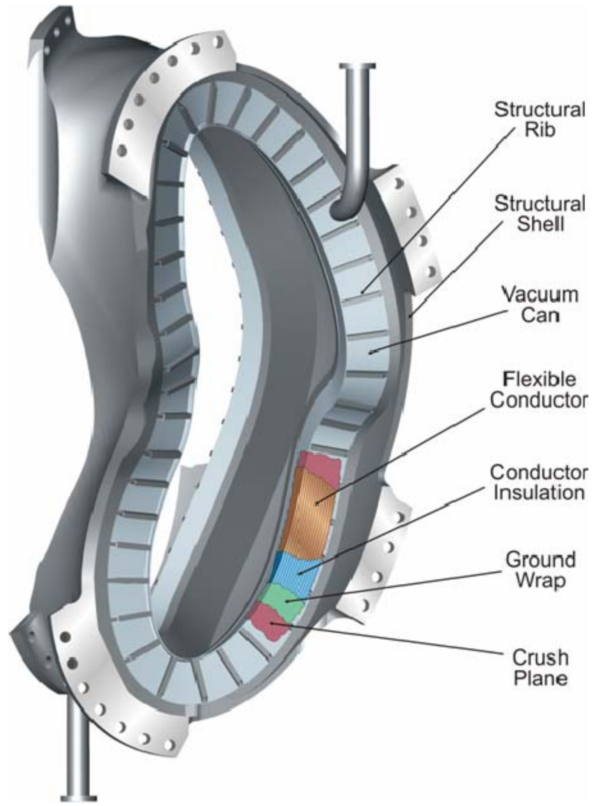

Figure 4 Single winding form cutaway showing winding form, windings, vacuum can and insulation

2. Modular Coil Winding Forms.

A prototype of the largest and most complex of the three types of modular coil winding forms, the green winding form in Fig. 3 that contains the two red coils in Fig. 1, has been cast using a patternless process (machining the sand mold), a high-temperature pour simultaneously from three ladles, and an effective riser design. The result, shown in Fig. 5, is a superior casting with more than an order-of-magnitude fewer major weld repairs than a conventional sand casting using hard patterns. The machining of the 3.5-

Figure 5 Prototype, cast winding form ready for machining

tonne cast winding form is expected to be completed in January. The modular coil winding forms will be shipped from the machining vendor on a special cart that allows rotation of the winding form. The winding form will stay on the cart until final device assembly throughout winding, canning, potting and shipping to the experiment assembly area. This approach avoids potentially unsafe handling issues.

2. Coil Winding Pack and Coil Cooling. Detailed calculations were done to assess the thermal performance of the modular coils, including temperature gradients during cool-down and temperature ratcheting during repeated cycling. Several variations on the cooling configuration were investigated including cooling external to the winding pack using a complex arrangement of cladding and chill plates with soldered cooling and cooling internal to the winding pack with various tubing and conductor arrangements. The result was selection of a cable conductor with internal cooling. Internally-cooled conductor has superior performance, allowing a coil pack to cool in ~1/3 the time required with external cooling using cladding and chill plates. In order to match power supplies and provide reasonable ease of winding, six conductors are used for each of the 12 electrical turns. The coolant travels 6 times around the coil circumference, for a total of about 30 meters. The velocity of the water is between 2 and 3 m/s. The cross section through a typical coil is shown in Figure 6.

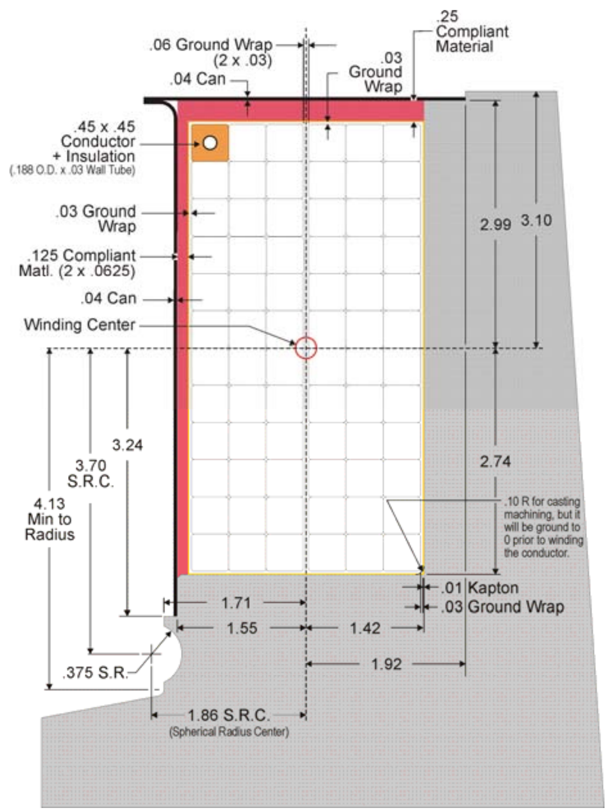

Figure 6 Cross section through winding pack

The complex geometry of the modular coils requires a flexible conductor to facilitate the winding operation. A flexible, internally cooled conductor that can be wound into complex 3-D shapes was developed by cabling stranded copper ropes around an internal copper cooling tube and compacting to a square shape for winding. Figure 7 shows the square cable conductor half-lapped with fiberglass wrap as well as a cross section cut through the cable. Tests to see if the internal tube would kink during handling indicated that the cable wrapped around the conductor acts as the same way as a tube-bending tool and allows bending about a small radius without distortion or buckling. The internal tube can be included in the cable only if the cable has a square cross section. For rectangular cross sections the tube must be filled with a low melting temperature eutectic alloy, which is subsequently melted and flushed from the tube after manufacture of the cable is completed.

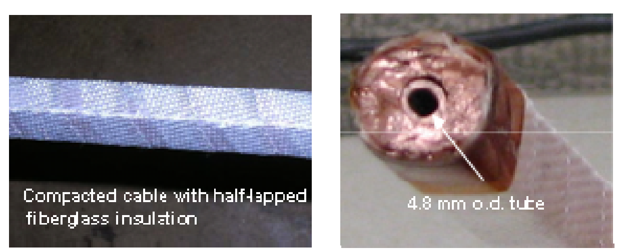

Figure 7 Cable conductor views showing fiberglass insulation and cross section with internal cooling tube

The winding process was developed using a "twisted tee" winding form mockup that has approximately the same circumference, curvature, and twist of a typical modular coil. This provided a means for full scale demonstration of internally-cooled cable conductor winding, clamping, and measurement techniques. Figure 8 shows the setup used for winding the twisted tee coil consisting of a rotating stand for the coil form and a gantry crane from which the conductor spool is suspended. Precision winding guides, shown in Fig. 9, were fabricated with an open design that allows the conductors to be placed and positioned in both the lateral and vertical directions automatically, without the need for additional geometric measurement or calibrated clamping pressure. Both the guides and the special insulating guide blocks used in the crossover and lead region will be made using the stereolithography technique.

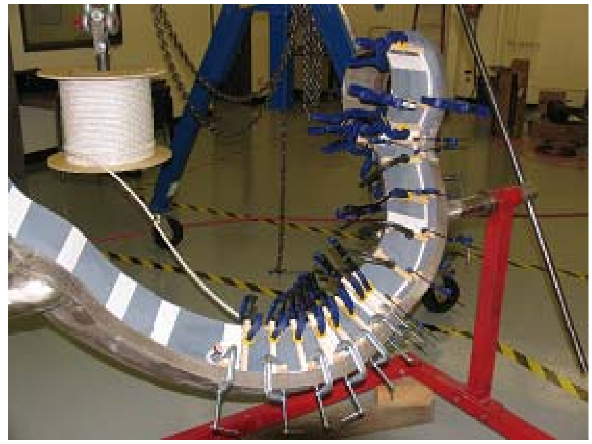

Figure 8 "Twisted tee" winding form and trial winding

Figure 9 Winding guides being demonstrated on twisted tee with internally cooled conductor

Another issue being investigated is simplification of the ground wrap electrical insulation. It appears that kapton applied directly to the winding form followed by a "wicking layer" of glass will have equivalent performance to alternating layers of kapton and glass cloth that are tedious and expensive to apply. A small mockup of a section of winding with the kapton outer layer shows this approach to be workable. An alternative is the use of some type of an electrical varnish. The primary issue with all insulation schemes is the temperature that these materials see during the process of welding the vacuum can to the casting. Detailed analysis is underway and testing of attractive insulation systems, via trial welding, will follow.

3. Vacuum-tight Coil Cover.

The non-planar coils must be enclosed in a vacuum-tight cover, as illustrated in Figures 4 and 6. Extra care must be taken with the coil structure to ensure vacuum quality in the plasma region. A mockup weldment of a vacuum-tight coil can and a section of prototypical casting showed negligible weld distortion and benign weld temperature, during the welding operation, at the location of the windings. These results were also in agreement with calculations [4]. Vacuum testing on prototypical cast material was also satisfactory [5]. The pressure continued to drop after several days under vacuum and elevated temperature. There was no indication of connected porosity or virtual leaks. The surface of the test article was as-cast, but will be polished on the production coils.

4. Coil Vacuum Pressure Impregnation.

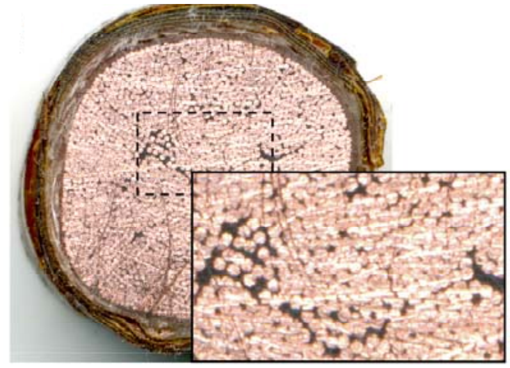

Figure 10 Cross-section of cable conductor showing impregnation with cyanate ester resin

The modular coils will be baked out at up to 150 C and operated at 40-100C to establish and maintain good vacuum properties. Therefore a high-temperature cyanate ester resin (CTD 403 [6]) has been selected and tested that has several advantages over the usual epoxy. While the mechanical properties are similar for both, CTD-403 can be used up to 150 C (instead of <100 C for the epoxy material) and it doesn't absorb water, which provides another barrier against water leaks. The cyanate ester resin is easier to work with than epoxy since it has the viscosity of water, an essentially unlimited pot life at room temperature, and it does not start to set until the temperature is raised past 100 C. The coil bakeout temperature is limited by thermal stress and creep properties, which are superior for CTD 403 at higher temperatures. In order to test the cyanate ester resin system, several small 4-turn racetrack coils were wound, and three were successfully vacuum pressure impregnated with cyanate ester resin. The CTD 403 was injected at room temperature and the cure cycle was controlled with a temperature feedback system. Examination of the first impregnated coil indicated good wicking into the interstices between filaments in the cable conductor, as shown in Fig. 10, and subsequent optimization of the process resulted in very good impregnation for the third coil, as shown in Figure 11.

Figure 11 4-turn racetrack coil and results of original and optimized (VPI) process

5. Vacuum Vessel and Assembly.

QPS has a simple external vacuum tank with a large number of ports rather than a highly shaped internal vacuum vessel between the plasma and the modular coils with a much larger number of small ports. This avoids the need to slip the complex-shaped nonplanar coils over an equally complex-shaped vacuum vessel, followed by welding a large number of vessel port extensions. Figure 12 illustrates the QPS assembly procedure: (a) install the support columns, the lower dome with VF coils, and a half period of the modular coils; (b) assemble the other half of the modular coil set and the cylindrical part of the vacuum vessel; (c) raise the lower dome and VF coils, and install the upper dome with VF coils and the central TF legs; and (d) install the outer legs of the TF coils and add other VF coils, add the port covers and the pumping ducts and pumps. The outer cylindrical section of the vacuum vessel is suspended from the midplane of the modular coil assembly to ensure that all the coil sets remain accurately registered to each other. The vacuum vessel also provides the structural support for the TF and PF coils, which are outside the vacuum region. Twelve large 62-cm diameter ports on the horizontal midplane, 24 large oval ports on the top and bottom domes, and the ability to raise or lower the sections of the vacuum vessel provide access to the internal modular coils for maintenance and for installation of interior diagnostics.

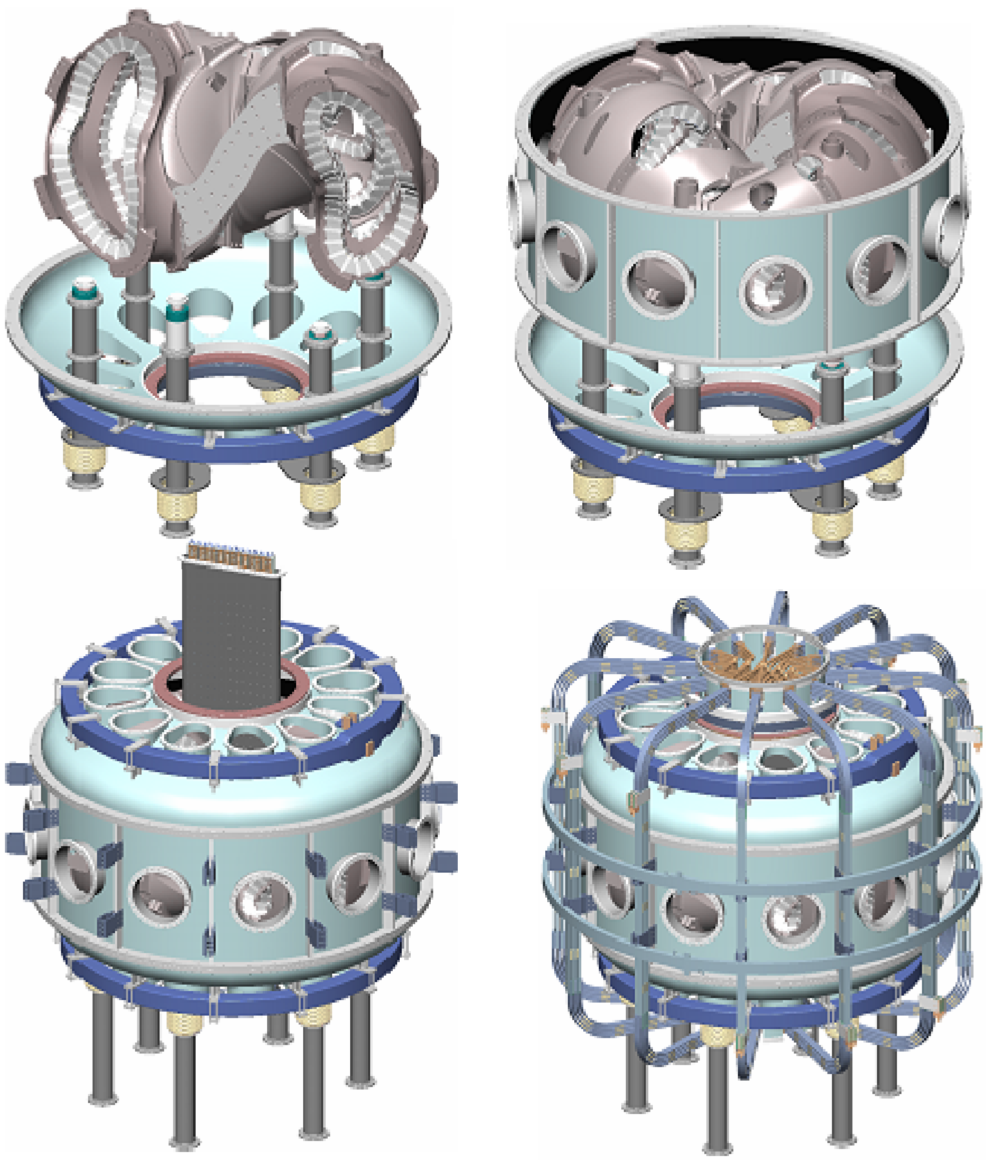

Figure 12 QPS assembly sequence

A central solenoid is shown as an option, but is not required as part of the basic physics design; it only provides a “knob” for experimental variations. The outer VF coils can easily provide sufficient flux change to drive the level of plasma current needed for flexibility studies. Studies show that a 10-15% variation in the vertical field is allowed during a shot because the plasma only moves 1-3 cm, which is acceptable. Eliminating central solenoid windings reduces both cost and risk for the central column because it would have to support large magnetic forces from the solenoid windings as well as the vacuum loads.

6. Status and Summary.

The QPS device is currently in the R&D and prototype construction phase. The complex 3-D coil geometry as well as the need to minimize cost and risk in fabrication requires innovation in the design and with manufacturing techniques. To this end, the modular coils are wound from flexible cable conductor with an internal cooling passage onto cast and machined winding forms. The windings are vacuum canned, impregnated with cyanate ester resin, and assembled inside an external vacuum vessel. Prototypical conductor manufacture, winding techniques, and vacuum impregnation processes have been successfully demonstrated and a winding form casting has been successfully produced. The next steps are to machine the cast winding form and produce full cross section winding packs with the crossovers and leads, and welded vacuum cans.

7. References

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