stellarator news

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Innovation in design and fabrication for QPS

The Quasi-Poloidal Stellarator (QPS), shown in cutaway view in Fig. 1, is being developed at Oak Ridge National Laboratory (ORNL) to test key physics issues at very low plasma aspect ratio (1/2–1/4 that of existing stellarators): reduced neoclassical and anomalous transport, and MHD stability limits. QPS has a quasi-poloidal (linked-mirror-like) rather than quasi-toroidal (tokamak-like) magnetic configuration, which allows large poloidal flows to more efficiently break up turbulent eddies and suppress anomalous transport. QPS has 2 field periods with 10 modular coils per period. Due to stellarator symmetry, there are only five different coil types. There are also 3 sets of poloidal field (PF) coils and 12 toroidal field (TF) coils.

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 greater than 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). 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. 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. Figure 2 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.)

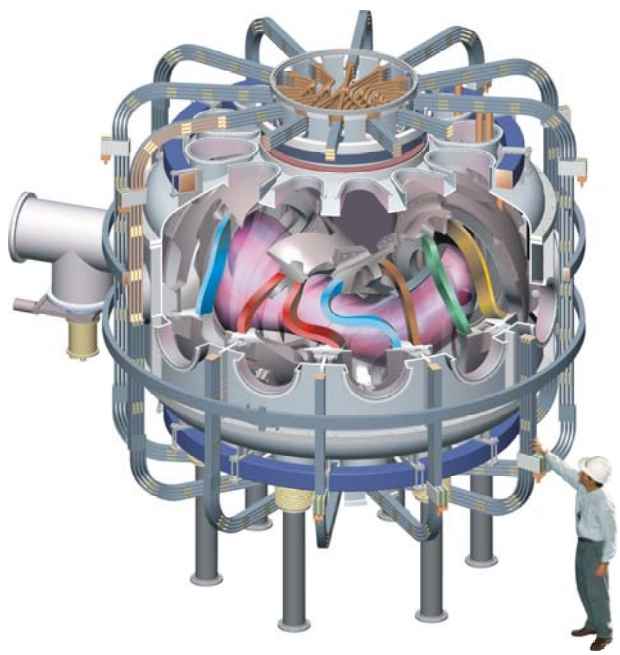

Fig. 1. Cutaway view of QPS.

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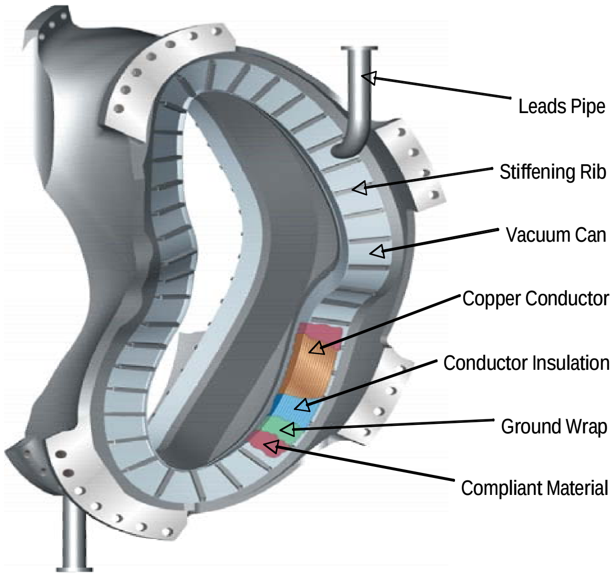

Fig. 2. Cutaway view of one of the QPS modular coils.

The winding forms are bolted together to form a structural shell inside the vacuum vessel. The engineering challenges result from the steps to be followed in fabricating QPS: (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. These steps are described in detail below.

1. *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 red coil 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 Figs. 4 and 5, is a superior casting with more than an order of magnitude fewer major weld repairs than a conventional sand casting using hard patterns. Finish machining of the 3.5-tonne cast winding form is expected in September. The modular coil winding forms will be shipped from the machining vendor on a cart, as shown in Fig. 3, and will stay on the cart until final device assembly throughout winding, canning, potting, and shipping to the experiment assembly area. This approach avoids major handling issues.

Fig. 4. View of the finished, cast QPS modular coil winding form at the Waukesha Kramer foundry.

Fig. 3. The structural shell, a winding form casting, and winding of a QPS modular coil.

Fig. 5. Another view of the QPS casting showing the form of the winding surface (before finish machining) onto which the coil pack will be wound.

2. *Coil Winding Pack and Coil Cooling*. Detailed calculations were done to assess the thermal performance of the modular coils, including temperature gradients during collodion and temperature ratcheting during repeated cycling. Several variations on the cooling configuration were investigated using a combination of cladding, chill plates, and cooling tube placement. This resulted in selection of a cable conductor with internal cooling as the final design choice. The complex curves, reverse curvature regions, and small radii of curvature require a flexible conductor. Internal rather than external cooling of the winding pack avoids the cost and installation time needed for a complex arrangement of cladding and chill plates with brazed cooling lines. The internally cooled conductor has superior performance, allowing a coil pack to cool in less than one-third the time required by external cooling that would be provided by the cladding and chill plates concept. A flexible cooled conductor that can be wound into complex three-dimensional (3-D) shapes was developed by winding stranded copper filaments around an internal copper cooling tube and compacting to a square shape for winding. A 46-m (150-ft) length of prototypical internally cooled conductor was procured from New England Wire Technologies for winding tests. The internal cooling tube was filled with a low-melting-temperature eutectic, to prevent crushing the cooling tube during cable manufacture, as shown in Fig. 6. The eutectic is flushed from the cooling tube with hot water prior to winding the conductor on the coil form. Subsequent tests to see if the internal tube would kink indicated that the cable wrapped around the conductor acts as the same way as a tube bending tool and allows winding in a small radius without distortion or buckling. Several alloy formulations were investigated before the Cerrobend alloy was selected. Tube filling and removal techniques were also investigated, and the procedures for these processes were developed and demonstrated on 61-m-long (200-ft-long) tubes.

A "twisted T" coil winding form was fabricated from two existing castings and some additional fabricated parts. This winding form has the curvature and twist of a typical modular coil and provides a means for developing full-scale conductor winding, clamping, and measurement techniques. A rotating stand for the coil form and a gantry crane were also procured as part of the winding development setup. The coil spool is suspended overhead. Figure 7 shows the setup used for winding the twisted T coil. Clamps were designed and fabricated with an open design that allows 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, as shown in Figs. 7 and 8. Options for the winding geometry in the crossover and lead region are being investigated.

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 may be much easier than alternating layers of Kapton and glass cloth that are tedious and expensive to apply. A small mock-up of a section of winding with the Kapton outer layer shows this approach to be

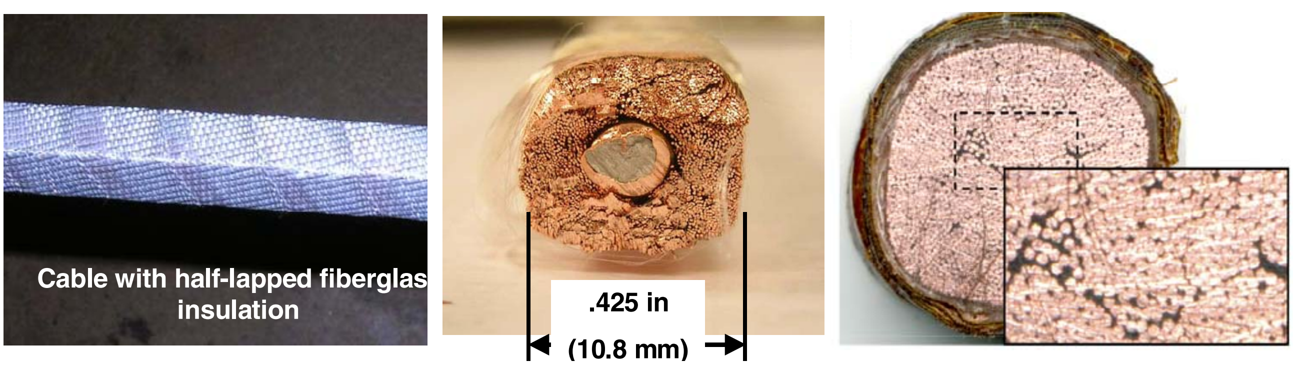

Fig. 6. QPS cable conductor with filled cooling tube and cross section showing wicking.

workable. An alternative is the use of some type of electrical varnish. The primary issue is the temperature that these materials experience during the welding of the vacuum can to the casting. Detailed analysis is under way and testing of attractive insulation systems, via trial welding, will follow.

3. *Vacuum-tight Coil Cover*. Using vacuum-tight cans to cover the QPS modular coil winding packs avoids the need for closely spaced clamps on the coil pack and allows the use of a vacuum vessel external to the coils. A mock-up weldment of a vacuum-tight coil can and a section of prototypical casting showed negligible weld distortion and benign weld temperature at the location of the windings. Vacuum testing on prototypical cast material was satisfactory. The pressure continued to drop after several days and there was no indication of connected porosity, virtual leaks, etc. The surface was as-cast, but will be polished on the production coils.

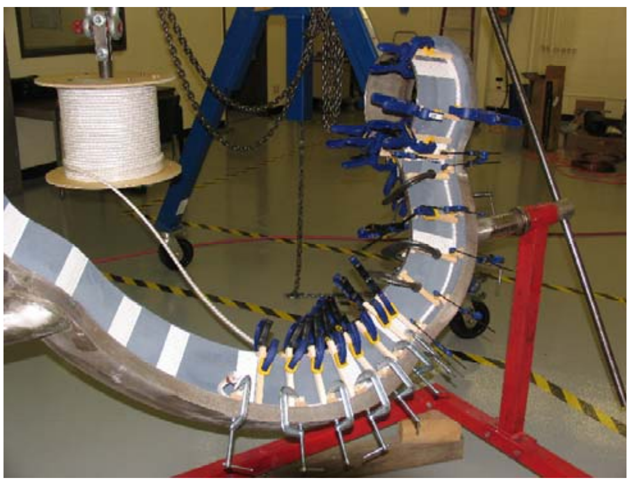

Fig. 7. Winding a test coil.

4. *Coil Potting*. The modular coils will operate at 40–100 °C to maintain good vacuum properties, so a high-temperature cyanate ester resin (CTD 403) with several advantages over the usual epoxy has been selected and tested. While the mechanical properties are similar for both, CTD-403 can be used up to 150 °C instead of <100 °C; it does not absorb water, which provides another barrier against water leaks; and it is easier to work with—it has the viscosity of water and an essentially unlimited pot life at room temperature, and it does not start to set until the temperature exceeds 100 °C. The coil bakeout temperature is limited by thermal stress and creep properties, which are much better for CTD 403. Three small-scale racetrack coils were wound, and two 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 four-turn racetrack potted coils indicates good wicking into the interstices between filaments in the cable conductor, as shown in Fig. 6.

Fig. 8. Clamping of the conductor layers.

5. *Vacuum Vessel*. QPS has a simple external vacuum tank rather than a highly shaped internal vacuum vessel between the plasma and the modular coils. This geometry avoids the need to slip complex-shaped nonplanar coils over a complex-shaped vacuum vessel with toroidally varying cross section, followed by welding of a large number of vessel port extensions. However, the coils must be enclosed in a vacuum-tight cover and extra care taken with the coil structure to ensure vacuum quality in the plasma region. The vessel provides the structural support for the TF and PF coils, which are outside the vacuum region. The vessel is suspended from the midplane of the modular coil assembly to ensure that all the coil sets remain accurately registered.

The need for a center stack solenoid winding has been reassessed. The central solenoid is not required as part of the basic physics design; it only provides a "knob" for experimental variations. The outer vertical field 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. This eliminates the need for the central solenoid windings, and the solenoid has been removed from the baseline design. This is a major improvement in design and reduces both cost and risk for the center stack because previously the center stack had to support large magnetic forces from the solenoid windings as well as the vacuum loads. This would have required hundreds of welded pins between the TF center legs and solenoid windings, which in turn would have made maintaining a good vacuum difficult.

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