

Recent Developments in Quasi-Poloidal Stellarator Physics and Design

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Abstract. QPS is being developed to test key physics issues at very low plasma aspect ratio: reduced neoclassical and anomalous transport, and MHD stability limits. Recent physics studies and innovations that reduce cost, fabrication schedule and technical risk are described.

1. QPS Physics Properties

Quasi-poloidal stellarators have little $|B|$ variation in the poloidal direction and larger $|B|$ variation in the toroidal direction, and so are more like linked magnetic mirrors than tokamaks and other stellarators. QPS (shown in Fig. 1) was designed to test this confinement concept; it is now in the R&D and prototype development phase. QPS has very low plasma aspect ratio ($\langle R \rangle / \langle a \rangle > 2.3$), $< 1/2$ that of existing stellarators), and extends stellarator confinement research into a new regime.

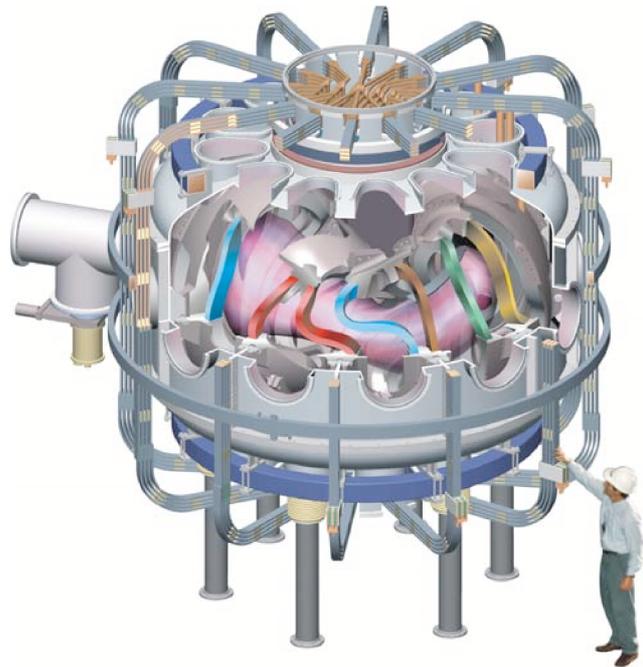


Fig. 1. Cutaway view of QPS.

QPS optimization has two elements: (1) reduced effective helical field ripple ϵ_{eff} decreases neoclassical transport, and (2) quasi-poloidal symmetry reduces anomalous transport by decreasing the poloidal viscosity by a large factor. This leads to large self-generated sheared $E \times B$ poloidal flows that can break up turbulent eddies without external momentum input. Figure 2 shows the flux-surface averaged poloidal flow component for an ECH plasma case for different stellarators. The self-generated flow shearing is also sufficient to impact temperature gradient modes, as shown in Fig. 3. Also, the very

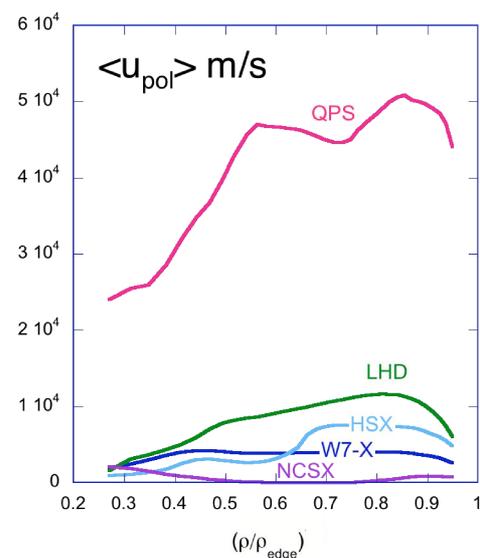


Fig. 2. Poloidal flow velocities for different stellarators (ECH plasma).

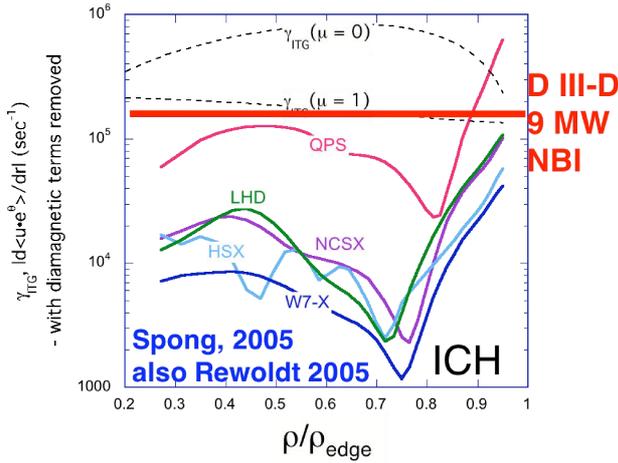


Fig. 3. $E \times B$ shearing rate for different stellarators and ITG growth rates for QPS.

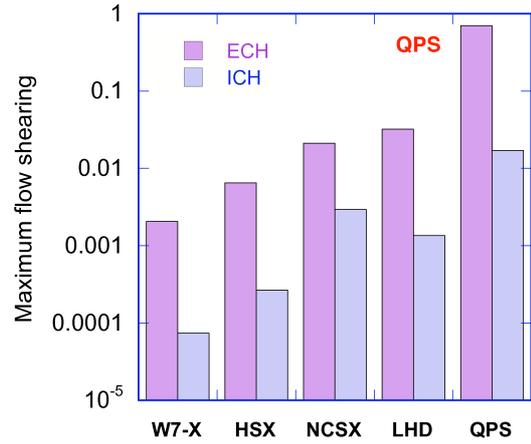


Fig. 4. Maximum flow shearing rates for different stellarators.

low plasma aspect ratio leads to large variations in the plasma flows along a field line within a flux surface, which may help to stabilize MHD instabilities. The maximum parallel shearing rates within a flux surface are plotted in Fig. 4 for ECH and ICH plasma parameters. The flow shearing rates are $\sim 0.5 \tau_{\text{Alfven}}$, much higher than for other stellarators. QPS is the only toroidal device stable to drift wave turbulence over a range of temperature and density gradients, which should reduce anomalous transport even in absence of flow shearing. Quasi-poloidal symmetry also reduces the bootstrap current and damps toroidal flows. The stability of trapped particle modes is different in this geometry, which features long regions of low field-line curvature and short high-field regions of higher curvature. The large fraction of trapped particles in regions of low/favorable curvature strongly reduces the drive for a class of trapped-particle instabilities. All other toroidal devices have a significant fraction of the trapped particles in regions with bad curvature. The magnetic configuration is also stable to finite- n ballooning modes, external kink modes, and vertical instabilities to $\langle \beta \rangle \sim 5\%$, and has sufficient flexibility to avoid magnetic islands and test predictions of stability theory.

Nine independent controls on the QPS coil currents permit a wide range of magnetic configuration properties. Changes in coil currents of $\pm 20\%$ allow a factor >30 variation in $\epsilon_{\text{eff}}^{3/2}$ (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, and a factor of 30 variation in the poloidal viscosity, which permits studying the role of poloidal flows in suppressing turbulence.

2. QPS Design and Fabrication Innovations

Innovations in design and fabrication techniques were needed to meet challenging design requirements: large plasma radius (30–40 cm) at very low aspect ratio, strong toroidal variation of the plasma cross section, and toroidally-elongated non-planar coils—and to meet cost and schedule constraints. Complex, highly accurate stainless-steel modular coil winding forms are cast and machined; a novel, internally-cooled conductor is then wound directly onto the modular coil winding forms; a vacuum-tight stainless steel cover is welded over each coil pack; the coils are vacuum/pressure impregnated with cyanate ester resin; and the completed coils are installed in a simple external vacuum vessel, as shown in Fig. 1. As a result, QPS differs significantly in design and construction from other toroidal devices.

Figure 5 shows the set of stainless steel winding forms that are bolted together to form a structural shell for the coils inside the vacuum vessel. A cut-away view of one of the 4 red winding forms, each containing two coils, is also shown. A prototype of the largest and most complex of the three types of modular coil winding forms, a green winding form in Fig. 5 that contains the red coils in Fig. 1, has been cast using a patternless process (machining the sand mold), a high temperature pour simultaneously from



Fig. 6. Casting of a QPS modular coil winding form.

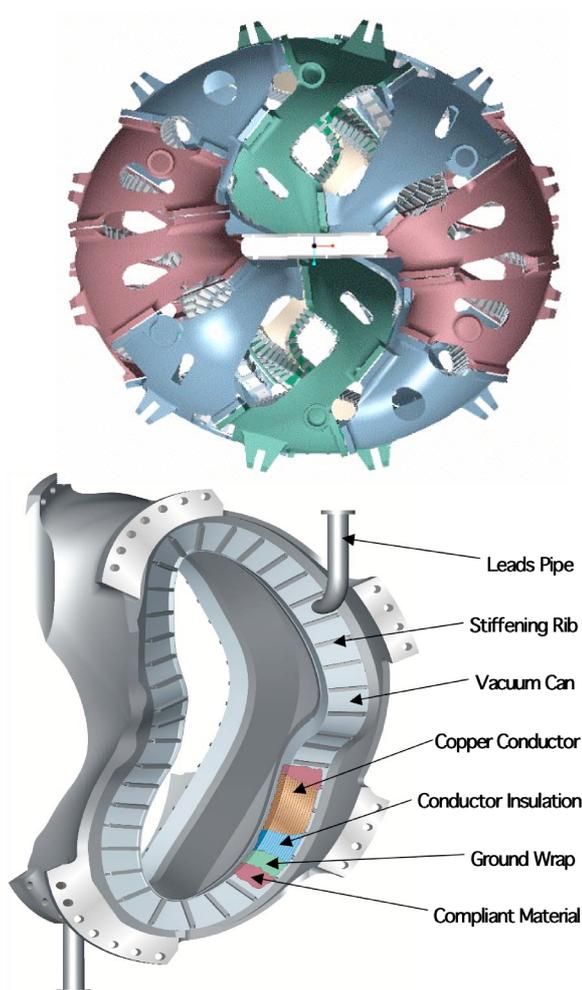


Fig. 5. (top) QPS winding forms, (bottom) a cutaway view of one of the coils.

three ladles, and an effective riser design. The result, shown in Fig. 6, is a superior casting with <10% of the major weld repairs than a conventional sand casting using hard patterns would have. Machining of the 3.5-tonne casting is scheduled for completion in October 2006.

Detailed calculations were done to assess the thermal performance of the QPS modular coils, including temperature gradients during cool-down and temperature ratcheting during repeated cycling. The complex curves, reverse curvature regions, and small radii of curvature of the QPS coils 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 copper cladding and chill plates with soldered cooling lines. The 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. A flexible cooled conductor that can be wound into complex 3-D shapes was developed by winding stranded copper filaments around an internal copper cooling tube and compacting to a square shape for winding (Fig. 7).

The internal cooling tube was filled with a low-melting-temperature eutectic, as shown in Fig. 7, which avoids crushing the cooling tube during cable manufacture. The eutectic is flushed from the cooling tube with hot water prior to winding the conductor on the coil form. Tests to see if the internal tube would kink indicated that the cable wrapped around the cooling tube acts in the same way as a tube bending tool and allows winding in a small radius without distortion or buckling.

The modular coils will operate at 40–100 C to maintain good vacuum properties, so a high-temperature cyanate ester resin (CTD 403) is used 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; 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, 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 much better for CTD 403. Examination of four-turn racetrack potted coils indicates good wicking into the interstices between filaments in the cable conductor.

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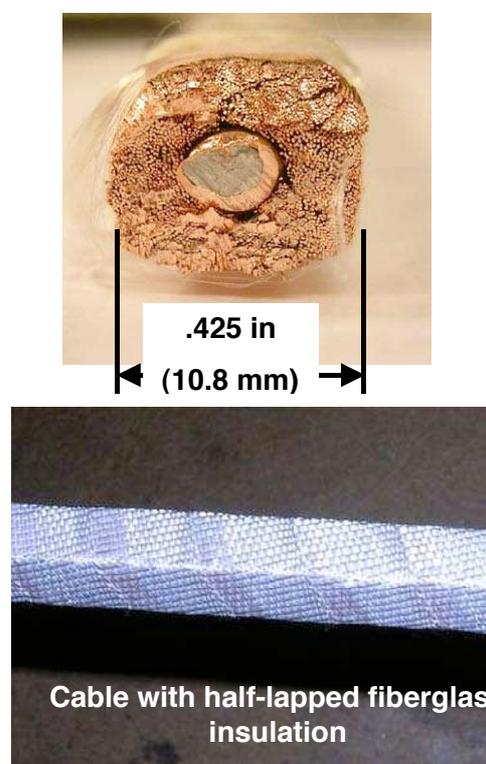


Fig. 7. QPS cable conductor.