ENGINEERING DESIGN OF THE QUASI-POLOIDAL STELLARATOR (QPS)

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Abstract. The Quasi-Poloidal Stellarator (QPS), currently in the design phase, is a low-aspect-ratio (R/a = 2.7) experiment with a non-axisymmetric, near-poloidally-symmetric magnetic configuration. The QPS design parameters are $\langle R \rangle$ = 0.9 m, $\langle a \rangle$ = 0.3-0.4 m, and B = 1 T for a 1.5-s pulse length. The design features a modular coil set that provides the primary magnetic field configuration, vertical field and toroidal field coils, an Ohmic current solenoid, machine structure, and a vacuum vessel external to the modular coils.

1. The QPS Experiment

The Quasi-Poloidal Stellarator (QPS) [1], currently in the design phase, is a very-low-aspect-ratio ($R/a \geq 2.5$, 1/2-1/4 that of existing stellarators) experiment with a non-axisymmetric, near-poloidally-symmetric magnetic configuration. The main device parameters are listed in Table 1. An overall view of the QPS experiment is shown in Fig. 1. The main components are: [1] 20 non-planar modular coils that create the main magnetic field configuration; (2) an external vacuum vessel; (3) three sets of external circular poloidal field (PF) coils for additional plasma shaping and position control; (4) the twelve TF coils; and (5) a center stack (not visible in Fig. 1) that contains the central legs of the TF coils and solenoidal coils for driving a plasma current. Parts of the structural shell that connects the individual modular coils and the divertor plates that control particle recycling are also visible in cutaway in Fig. 1. A bellows is provided between the center stack and the upper dome for alignment and to reduce the time constant for poloidal eddy currents induced in the vacuum tank.

Table 1. Main QPS device parameters

Average major radius $\langle R_{plasma} \rangle$	0.9 m
Average plasma radius $\langle a_{plasma} \rangle$	0.3–0.4 m
Plasma aspect ratio	>2.5
Plasma volume V_{plasma}	2-3 m^3
Central, edge rotational transform ι_0, ι_{edge} at β = 2%	0.26, 0.34
Average field on axis from the set of modular coils	B = 1 T for a 1.5-s pulse
Auxiliary toroidal field ΔB_T	± 0.2 T
Ohmic current I_{plasma}	≤ 100 kA
ECH power	0.6-2 MW
ICRF heating power	2–4 MW

2. The Modular Coils.

The set of non-planar modular coils that surround and shape the plasma is illustrated in Fig. 2. There are two field periods with 10 modular coils per period. Due to stellarator symmetry, only five different coil types are required. The coils of type 1 are located near the middle of

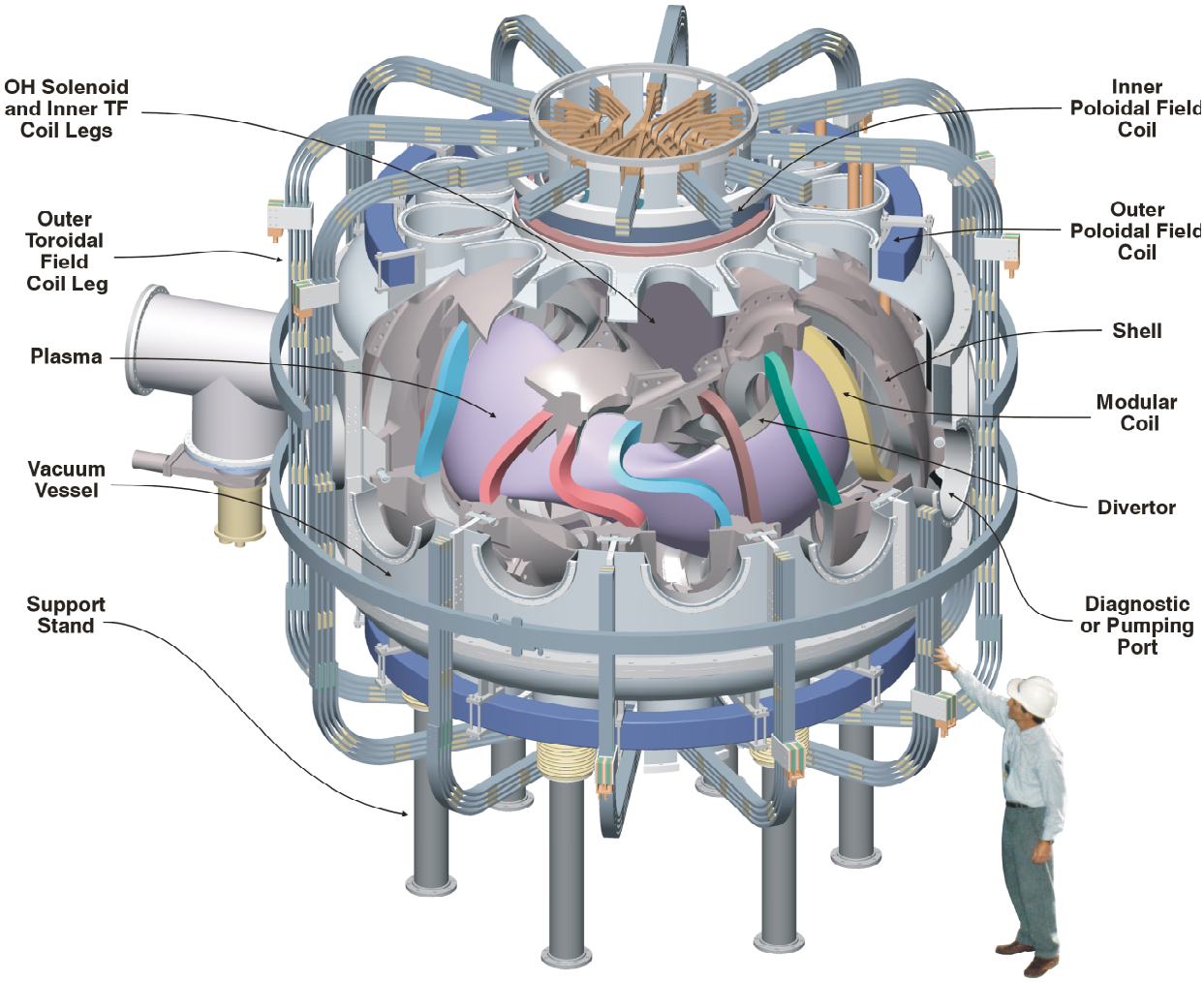

Figure 1. Cutaway view of QPS showing the main components.

the long side and the coils of type 5 are at the ends. The coils are connected in five circuits so like coils are independently powered for maximum flexibility.

The modular coils are paired for structural reasons and coils within a pair are allowed a smaller separation target distance than those that are not joined by a structural web. This pairing allows more spacing between coils separated by structural joints and the flexibility to orient the winding packs to improve fabricability. The coil pairs 1' and 1, 2 and 3, and 4 and 5in Fig. 2 are more closely spaced and wound on the same structural winding form. The coils on either side of the symmetry plane in the long side are part of one winding form while the coils on each side of the symmetry plane at the ends belong to different winding forms. This allows more space near the bean-shaped cross section for diagnostic access to the plasma. The arrangement of paired and unpaired coils allows the twist of the coil cross-section to more closely match a free-form or developable orientation, which should make winding the coils easier. The geometry of the supporting

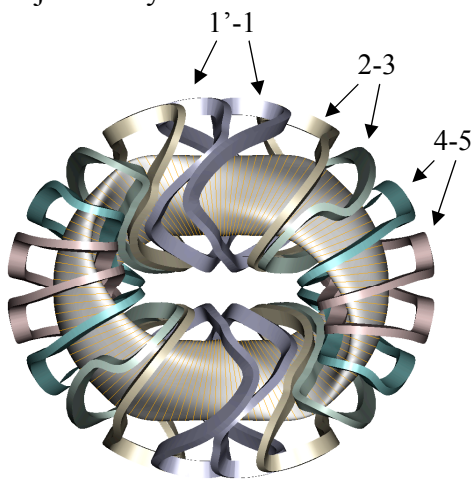

Figure 2. Top view of the QPS plasma and coils.

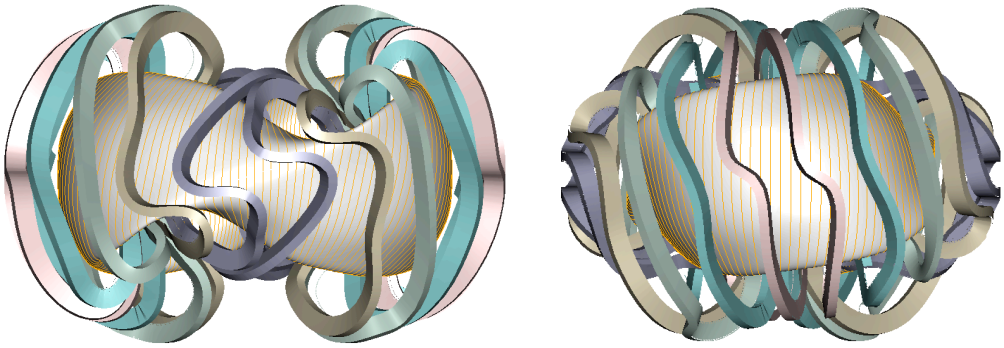

Figure 3. Side views of the QPS coils and the plasma surface.

structure allows more space between coils in the region of the assembly joint at the end of the two field periods. Figure 3 shows side views of the plasma and coils from the middle of the long section and from the end.

The coils consist of flexible copper cable conductor wound on a cast and machined stainless steel winding form that locates the coil windings within a ±1-mm design tolerance and supports them against the electromagnetic loads. The conductor bundle is compacted from a round cable to a square form with a packing fraction of >75 %. Once wound, stainless steel sheets are seal-welded around the windings to provide a vacuum-compatible coil. The conductor pack is then vacuum impregnated with epoxy so the rectangular winding pack becomes a monolithic copper-glass-epoxy composite. A compliant layer may be provided in the outboard region between the structure and windings to reduce thermal stresses. In local areas requiring reinforcement, intermittent clamps are bolted to the sides of the coil as structural retainers for the windings.

Two coils are wound on each stainless steel winding form, which forms 1/10 of a structural shell. The cross section shape and size of the coil pack were determined by the bend radius, the coil twist, the coil-coil spacing, and the allowable current density. Bend tests with a prototypical conductor indicate that the minimum bend radius of 12.7 cm allows winding rectangular cross section coils without excessive distortion of the winding pack. Figure 4 shows a cut through a winding form. The distance from the plasma edge to a coil case varies from 7.6 cm to 40 cm. The distance between paired coils in a common structural form varies from 0 (a common web) to 56 cm. The distance between coils separated by a structural joint varies from a minimum of 4 cm to a maximum of 75 cm. Near the largest separations for paired coils where there is less distance between separated coils, there is room for large openings in the connecting shell for diagnostic and heating access. Near the minimum separation for paired coils there is more distance between separated coils for diagnostic and heating access.

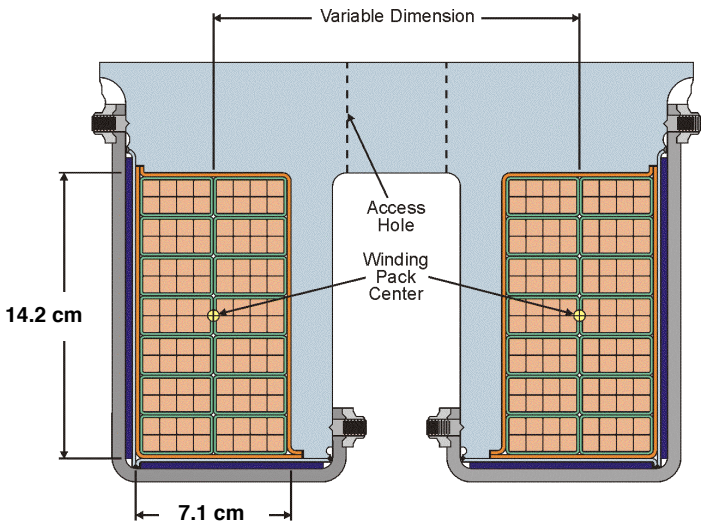

Figure 4. Cross section through a winding form showing two adjacent coils.

The modular coils operate above room temperature. Water cooling allows a 15-minute rep rate for 1-T, 1.5-s flat-top pulses and a 5-minute rep rate for shorter pulses. The coils operate above room temperature as practical to minimize adsorbed gas that otherwise might enter the plasma during operation from the plasma facing surfaces of the modular coil cases. Figure 5 illustrates the start temperature vs. current density for the windings based on temperature limits for the epoxy in the coil winding and the coil resistance and power supply voltage limits. The required start temperature for the modular coils is shown for two conditions: a peak temperature of 100 C (the practical limit under load for the high-temperature-cured epoxy) and the 2600-V limit for the power supplies. The nominal current density in the conductor for 1-T, 1.5-s flat top operation is ≈5.7 kA/cm^2. Only about 50% of the modular coil cross section is occupied by the winding; the rest is part of the winding form structure. The nominal operating range is between 38 C and 65 C. The maximum practical current density in the conductor is ≈7.5 kA/cm^2, which allows 25% higher currents the modular coils for magnetic configuration flexibility studies or 1.25-T operation for shorter pulses.

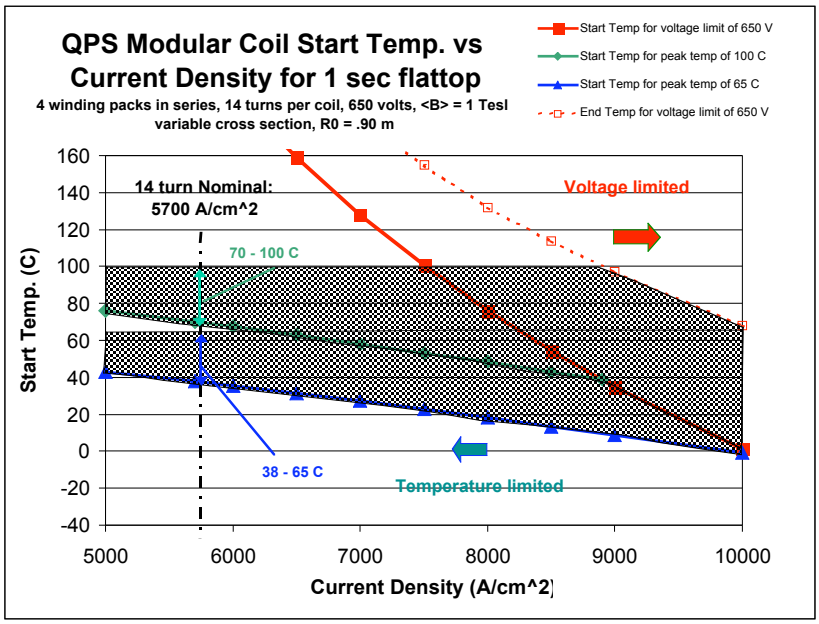

Figure 5. Start temperature vs. current density for the modular coils based on temperature limits for the epoxy in the coil and the coil resistance and power supply voltage limits.

For an external TF field of –0.07 T, the magnetic field on the modular coils peaks at 2.19 T with the highest magnetic field on the plasma-facing inboard sides of the modular coils in the end regions. The maximum centering force is approximately 516,000 N on the end coils. The forces vary along the conductor packs but are always directed radially outward from the plasma except for a small (~100 lbs/in) radially inward force in the tight bend region of coil type 1. The forces on the winding packs tend to push them radially outward against the winding form and clamp them laterally against the supporting web. External clamps are provided in places where the forces are directed away from the supporting web. The maximum radial running load is ~4400 N/cm and the maximum lateral forces away from the supporting web are ~2500 N/cm in localized regions.

The magnetic loads are taken by a robust, continuous self-supporting shell (Fig. 6) that is supported in turn by the vacuum tank. The shell consists of ten winding forms, each containing two modular coils, that are bolted together with two toroidal electrical breaks. The coil-to-coil structure is sufficient to limit the maximum deflection to <1 mm. The stresses are limited to ~200 MPa in local regions and to <100 MPa in most areas. The estimated time constant for poloidal eddy currents in the structure is ≈28 ms, which reduces the effective flat top time for experiments by ≈100 ms. Large openings are cut in the shell structure for heating and diagnostic access, as shown in Fig. 6. The vacuum vessel ports and the structural shell limit some of the open access between the modular coils.

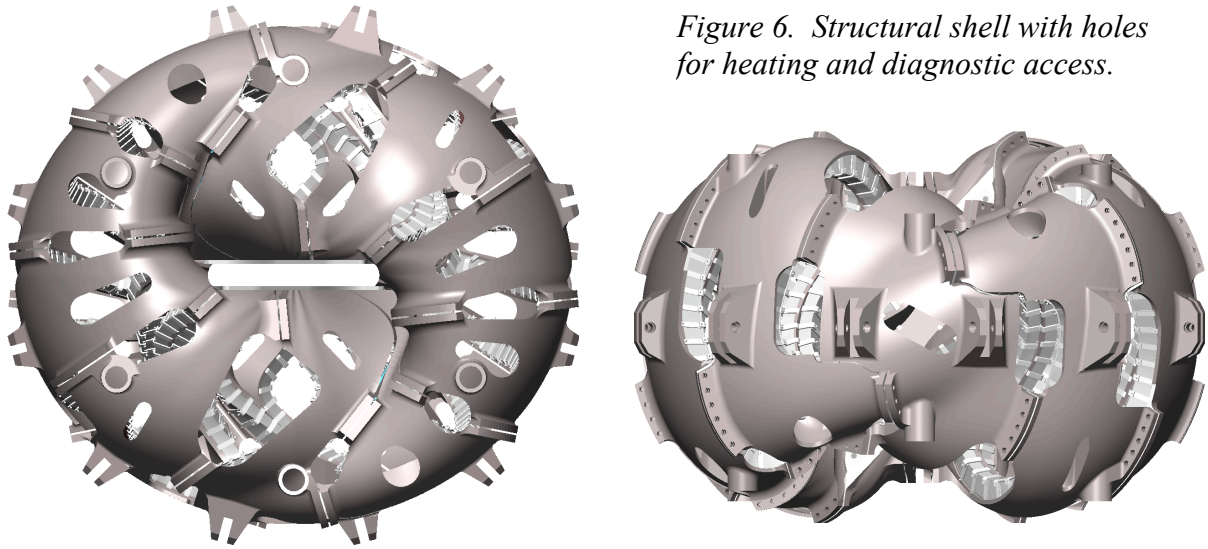

Figure 6. Structural shell with holes for heating and diagnostic access.

The twelve TF coils shown in Fig. 1 can provide an additional ±0.15 T for configuration flexibility studies. The outboard legs of the TF 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 (the open rectangular space seen in the top view in Fig. 6). The TF coils are demountable at the top and bottom of the inboard region for assembly purposes. The central bore also contains an 8-coil central solenoid for driving up to ±50 kA of plasma current. The solenoid is located just outside the TF coil inner legs and is contained in the self-supporting center-stack assembly. The center-stack casing forms the inner vacuum wall of the toroidal vacuum tank that fills the oblong region inboard of the modular coils. Structural ties are needed to restrain the magnetic loads on the solenoid and the internal pressure load on the center-stack casing. The three sets of PF coils shown in Fig. 1 should allow adequate plasma shape and position control. The poloidal, TF, and solenoidal coils are of conventional construction, wound from hollow copper conductor, and insulated with glass-epoxy. These coils operate at room temperature in air.

3. Vacuum Considerations.

The QPS vacuum vessel is a large external tank that encases the modular coil set. The only components that are in the same vacuum as the plasma are the stainless-steel vacuum-tight cases for the modular coils and their support structure. All other components are in air including the modular coil conductors. The disadvantages of the external vacuum vessel are the requirement for vacuum canning the modular coils, the necessity of operating the modular coils above room temperature, and a large gas reservoir/sink near the plasma. However, the external tank approach has several compensating advantages.

(1) It allows a significantly larger plasma radius and avoids complex assembly steps. A vacuum vessel inside the bore of the modular coils would require significantly more space between the plasma surface and the modular coils to permit highly contoured modular coils with different shapes to slide over a highly contoured vessel with toroidally varying shape.

(2) It provides better access to the plasma because all the gaps between coils are potential sight lines and there is no constraint imposed by long, fixed port extensions.

(3) It is less costly than an internal, highly contoured vessel.

There are twelve 61-cm-diameter ports around the midplane for heating, diagnostics, and personnel access; twelve large oblong (30 cm x 50 cm) ports on both the top and bottom of the vacuum tank for additional diagnostics, coil services, and instrumentation feedthroughs; and smaller (5 to 10 cm diameter) ports on the top and bottom around the center stack for viewing the inside edge of the long straight sections of the plasma.

The large external vacuum vessel (34 m^3, ten times the plasma volume) requires special attention to vacuum and particle control issues. The design requirements are an integrated leak rate $<10^{-5}$ Torr•l•s^{-1}, and a base pressure $<10^{-8}$ Torr for impurities and $<10^{-7}$ Torr for hydrogen. All vacuum vessel ports will have copper conflat seals except the large-diameter toroidal seal surfaces above and below the midplane and the large oblong top and bottom ports, which will have double viton O-rings or a metal seal and a viton seal with differential pumping. Heaters and thermal insulation blankets on the vacuum tank will be used to provide bakeout capability with a temperature goal of 150 ºC based on the temperature limit of the solenoid winding in the center stack. The internal modular coils and support structure will be baked by convection heating using high-pressure argon or nitrogen gas in the vacuum tank.

The buildup of neutral pressure in the vacuum tank will be minimized through local concentration of recycling and gas feeds in divertor baffles to minimize the gas fed directly into the large vacuum chamber. Poincaré plots show that field lines (particles) leave the plasma predominantly at the top and bottom of the bean-shaped cross sections where recycling neutrals will be confined mechanically by divertor baffles and then be largely reionized by the boundary plasma. Monte Carlo neutral transport simulations indicate that neutral penetration to the plasma core would not be a problem even at low electron density because the decay length of the neutrals in the core plasma is short. Impurity control is obtained through baking, helium glow discharge cleaning, and boronization and control of the plasma-surface interactions on the divertor baffles.

Field line following outside the last closed flux surface (LCFS) shows that connection lengths in the scrapeoff region are >100 m, long enough for effective island divertor operation. The long connection lengths should allow a high-temperature pedestal for H-mode confinement and a low temperature at the divertor plate for erosion and impurity control. Four divertor target and baffle plates (top and bottom in each field period) will extend along the ridge of the plasma cross section from the tips of the bean-shaped cross section towards the outside of the D-shaped cross section, a shown in Fig. 1.

4. Status

The final QPS plasma and coil configuration has been selected and refined. The design allows the plasma parameters, configuration flexibility, heating and diagnostic access, and vacuum conditions needed for studies of very-low-aspect-ratio quasi-poloidal stellarator plasmas. The next steps are R&D studies for casting the stainless steel winding forms and the winding, vacuum canning, and potting of a prototype coil.

Acknowledgments: This work was supported by the U.S. Dept. of Energy under contract DE-AC05-00OR22725 with UT-Battelle, LLC.

References

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