ENGINEERING DESIGN STATUS OF THE QUASI-POLOIDAL STELLARATOR (QPS)

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***Abstract*—The engineering design status of the Quasi-Poloidal Stellarator Experiment (QPS) is presented. The overall configuration and the design, manufacturing R&D and assembly techniques of the core components are described**

Keywords-stellarator: experimental fusion device

I. INTRODUCTION

The Quasi-Poloidal Stellarator, QPS, is a low-aspect-ratio (R/a = 2.7), concept exploration experiment with a non-axisymmetric, near-poloidally-symmetric magnetic configuration. The facility includes the stellarator core, the plasma heating, diagnostics and data acquisition systems, the power supplies and cooling systems, and the test cell. The experiment will be built at the Oak Ridge National Laboratory (ORNL) and is a partnership among ORNL, the University of Tennessee, and the Princeton Plasma Physics Laboratory (PPPL). Reference 1 describes the physics and engineering features in detail.

The stellarator core consists of the modular coil set that provides the primary magnetic field configuration, auxiliary coils including vertical field and toroidal field coils and an ohmic heating solenoid, machine structure, and an external vacuum vessel. A cut-away view of the stellarator is provided in Figure 1. The general design parameters are given in Table 1.

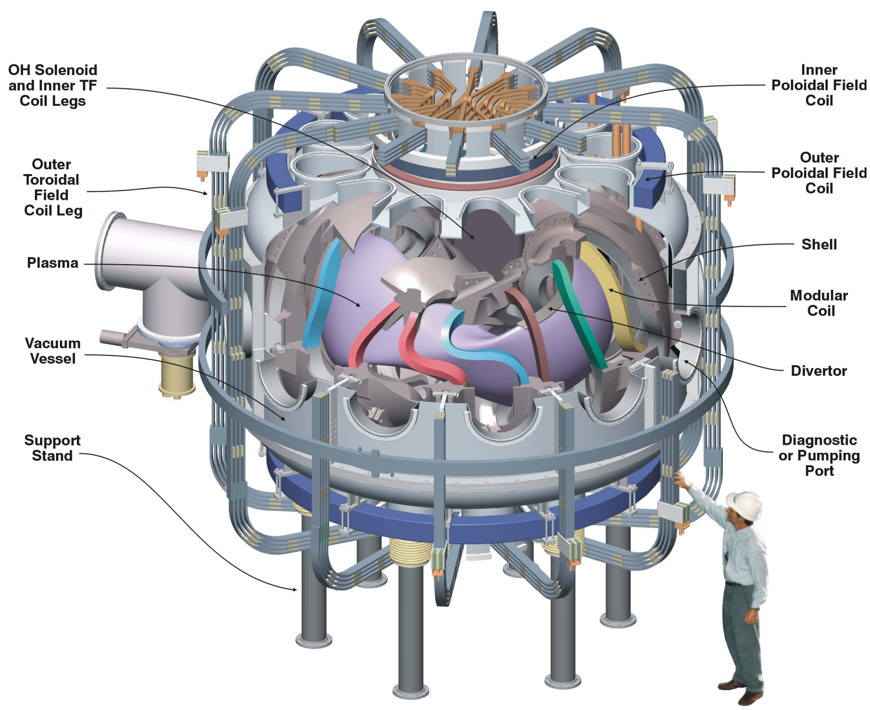

Figure 1 Cutaway view of QPS Stellarator Core

Work supported by U.S. Dept. of Energy under Contract DE-AC05-00OR22725 with UT-Battelle, LLC

TABLE 1 QPS General Design Parameters

Parameter	Value
Major radius, R_o	0.9 m
Minor radius	0.3 – 0.4 m
Bmax	1-1.2 T
Plasma current, I_p	Up to 50 kA
Auxiliary heating, P_{aux}	0.9 MW @ 28 GHz
	1 MW @ 56 GHz
	2 MW @ 6-20 MHz
	1.5 MW @ 40-80 MHz

II. MODULAR COILS

The modular coils represent the most difficult part of the core design and fabrication. The coil set has two field periods with 10 modular coil windings per period. Due to symmetry, only five different coil types are required. The coils are connected electrically in 5 circuits so like coils are independently powered to provide maximum flexibility. The maximum toroidal field at 0.9 m produced by the modular coils with a flattop of ~1.5 s is 1.0 T. The toroidal field on axis can be raised above 1 T by energizing the TF coils, which can add ± 0.15 T to the field generated by the modular coils. Figure 2 shows the geometry of the coil windings.

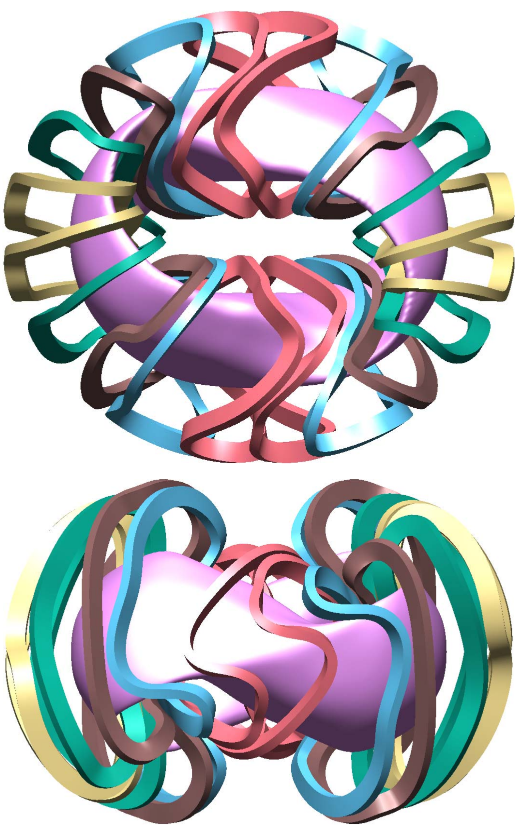

Figure 2 Modular Coil Winding Geometry

The design concept uses flexible, copper cable conductor to facilitate winding into the complex shape. The cable is compacted from round cable to a packing fraction of over 75 %. Once wound, the conductor is vacuum impregnated with cyanate ester resin so the winding pack becomes a monolithic copper-glass-epoxy composite. The coil cross section is shown in Figure 3 and the basic coil parameters are listed in Table 2.

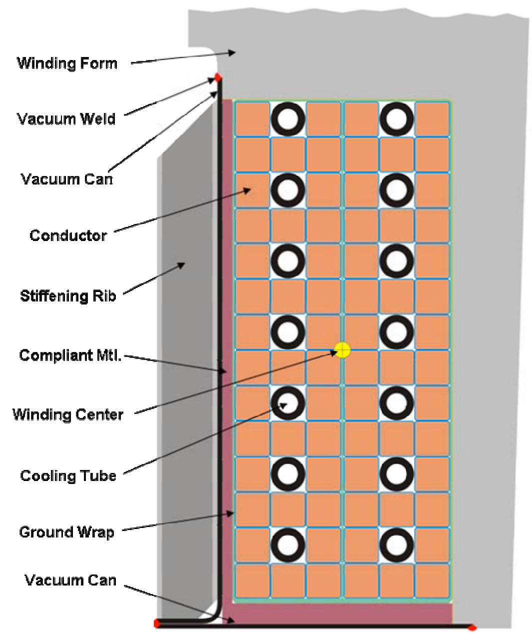

Figure 3 Modular Coil Cross Section

The windings are wound on and supported by the ell-shaped structural member, which is an integral part of the coil winding form. The winding form locates the coil windings within the +/- 1.0 mm tolerance and supports them against the electromagnetic loads. The forces on the winding packs tend to push them radially outward against the form. Lateral loads are reacted directly against the “ell” member or through stiffening ribs and back to the “ell. Formed, stainless steel sheets are welded around the winding pack and to the coil form to provide a vacuum-compatible coil. Some development work has been performed to show negligible distortion occurs during the welding process, but additional R&D is planned. The winding process and finished shell structure are illustrated in Figures 4 and 5.

TABLE 2. Modular Coil Parameters

No. of modular coils	20 (2 x 10)
No. of winding forms	10
Winding length	4.9 to 5.3 m per turn
Number of turns /winding	14
Gross cross section	70 mm x 157 mm
Nominal current per coil	300 kA
Maximum current per coil	380 kA

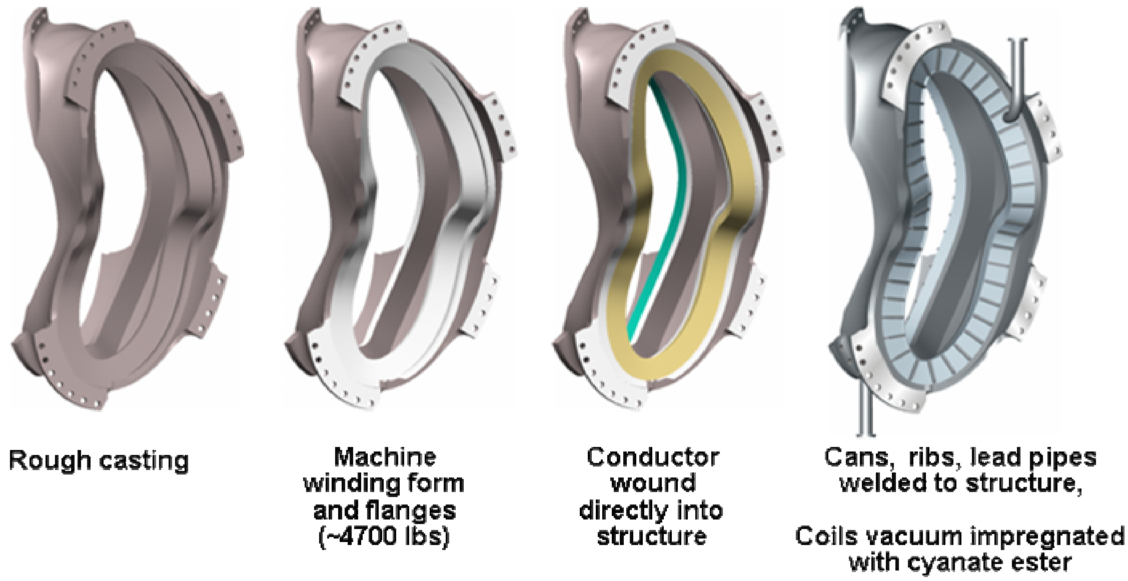

Figure 4 Modular coil fabrication sequence, showing casting, machining, winding, canning and potting

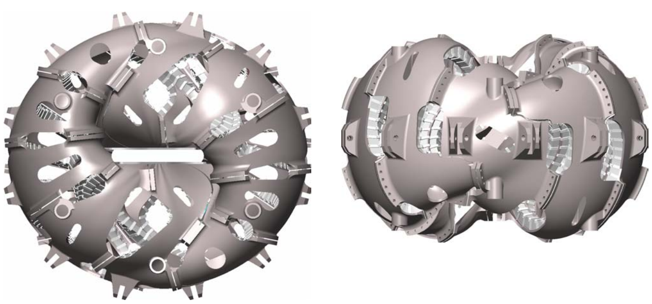

Figure 5 Modular Coils bolted together to form shell structure

Significant R&D has been undertaken with respect to the modular coils in the area of winding form fabrication, conductor cooling, winding techniques, and vacuum impregnation. A full scale prototype casting has been produced for the M1 casting, which represents the most difficult winding form by size and complexity. The casting was produced using the machined sand mold method. This method uses no pattern. Compacted green-sand blocks are machined with a multi-axis router to provide mold parts, which are assembled into the completed mold. This technique is cost effective for prototypes where only one or two parts will be cast. It is also very accurate, and since no pattern is removed from the mold, requires no special draft angles on the part. The casting is shown in Figure 6. The material is a modified CF8M material with low permeability even in welds. The alloy can also be air-cooled after heat treatment instead of water-quenched, which substantially reduces distortion of the part.

Figure 6 Prototype casting prior to machining

The conductor for QPS is cooled by water flowing through tubes imbedded in the winding pack. Several configurations are being investigated, including copper tubes imbedded within each conductor, co-wound copper tubes, and co-wound flexible (helically corrugated) stainless steel tubes. Typical cross sections are illustrated in Figure 7. The best cooling is achieved with the tubes internal to each conductor, but the copper tubes make the conductor very stiff and difficult to wind. The tubes in this option must also be filled with a lead-bismuth eutectic to avoid damage during the cabling and compaction operation. Melting and removing the eutectic after winding is difficult. Additional R&D is planned prior to final selection of the conductor configuration.

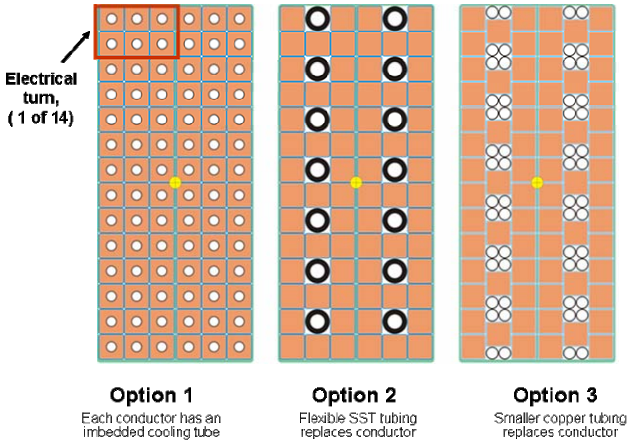

Figure 7 Conductor cooling options

Winding and vacuum impregnation of the conductor has been performed on small sample coils. The resin system is not epoxy but a cyanate ester material, CTD 403, supplied by Composite Technology Development. This material has a higher glass transition temperature than epoxy, up to 170C. Since the QPS modular coils are inside the vacuum vessel, the higher temperature limit of the cyanate ester provides both higher bakeout and operating temperatures and improves vacuum performance. The first vacuum impregnated coil is shown in Figure 8.

Figure 8 Practice coil vacuum impregnated with cyanate ester

III. TOROIDAL AND POLOIDAL FIELD COILS

A set of twelve toroidal field (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 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. Figure 9 illustrates the TF coil geometry. The coils are formed from hollow copper conductor and insulated with glass-epoxy. They operate at room temperature and are connected in series.

A set of poloidal field coils is provided for inductive current drive and plasma shape and position control. The coil set consists of an inner solenoid, and four pairs of ring coils. Coil pairs are symmetric about the horizontal mid-plane and each coil pair is connected in an independent circuit. The solenoid is located immediately around 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. All coils are of conventional construction, wound from hollow copper conductor and insulated with glass-epoxy. Existing PF coils from the ATF and PBX-M facilities are used for the ring coils. All PF coils operate at room temperature. Figure 10 illustrates the PF coil geometry.

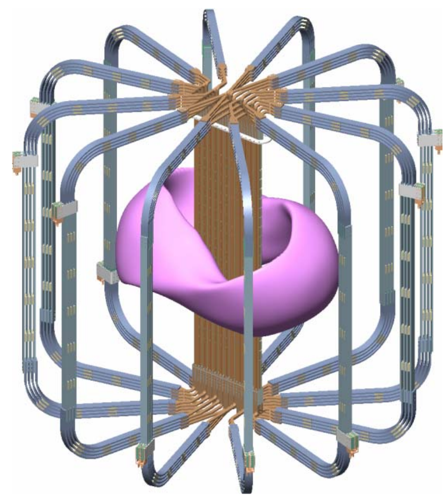

Figure 9 TF coil set showing flat inboard leg region

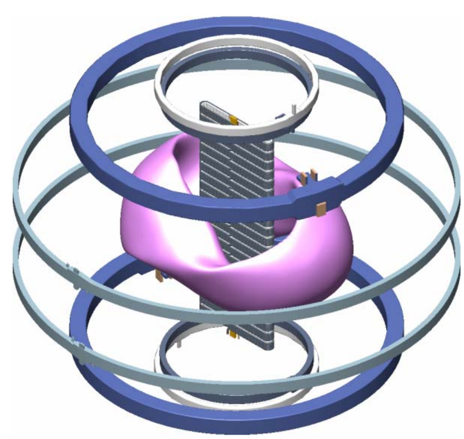

Figure 10 PF Coil set showing oblong central solenoid

IV. External vacuum vessel

The QPS vacuum vessel is a large, external tank of conventional design. The vessel has numerous ports and is divided into upper and lower dished heads and a middle spool piece. All sections will be fabricated from 316L series stainless steel. The large seal surfaces will accommodate double o-rings with interstitial pumping. Thermal insulation blankets and heaters will be added to provide a bake-out capability with a temperature goal of 150 C. The temperature limit will be based on the temperature limit of the modular coils and solenoid winding in the center-stack The basic vessel parameters are listed in Table 3.

TABLE 3 Vacuum vessel parameters

Material	316L ss
Thickness	0.5 inches
Time Constant	< 2 ms poloidal
	~ 10 ms toroidal
Inside surface area	~56 m^2
Enclosed volume (with ports)	~34 m^3
Bakout temperature	150 C
Nominal operating temperature.	20-100 C

Three sets of twelve large ports around the mid-plane, top and bottom of the vessel are provided for heating, diagnostics, and maintenance access and numerous smaller ports are provided for coil services and instrumentation feed-throughs.

VI. Core assembly

The QPS stellarator core will be assembled from two field period sub-assemblies that are bolted together in the test cell. Both field periods are pre-assembled, and simply consist of half of the modular coils. The two periods will be assembled atop the base support columns to form the complete shell structure. The central spool piece of the vessel will be attached to the shell, followed by the upper and lower dished heads, PF coils, central solenoid, and TF coils. The assembly sequence is illustrated in Figure 11.

VII. Ancillary systems

The QPS facility will take advantage of existing infrastructure at ORNL, including plasma-heating systems (0.9 MW ECH @ 28 GHz, 1 MW ECH @ 53 GHz, 2 MW ICRF @6-20 MHz and 1.5 MW ICRF @ 40-80 MHz), power supplies (>40 MW), de-mineralized water system, and other equipment In addition, a new building will be available to site the facility, and will include an experimental enclosure, control room, and all utility services.

VIII. Design status

The QPS device is presently in the R&D and prototyping stage. The magnetic configuration has been selected and baseline concepts exist for all the primary design features. Specific R&D as well as detailed analysis and design refinement will be carried out until project start.

References

[1] J. F. Lyon and the QPS team, "QPS Conceptual Design Report", June 2003.

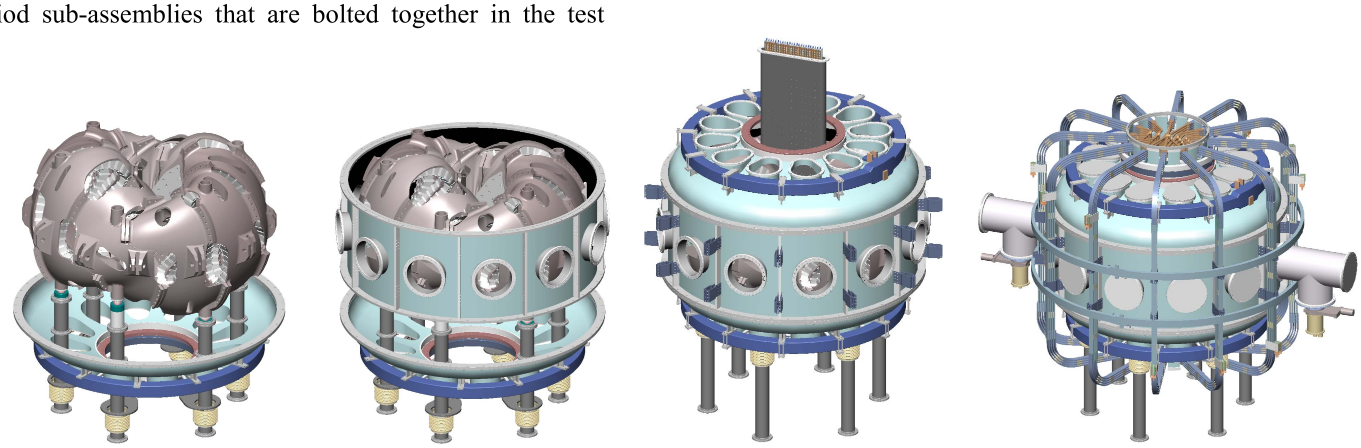

Figure 11 QPS stellarator core assembly sequence