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SCIENCE DIRECT®
Fusion Engineering and Design 66–68 (2003) 205–210
Fusion Engineering and Design
www.elsevier.com/locate/fusengdes

Design of the quasi-poloidal stellarator experiment (QPS)

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Abstract

The Quasi-poloidal stellarator (QPS), currently in the early design phase, is a low-aspect-ratio (R/a = 2.7), concept exploration experiment with a non-axisymmetric, near-poloidally-symmetric magnetic configuration. The QPS design parameters are $\langle R \rangle = 0.9$ m, $\langle a \rangle = 0.33$ m, B = 1 T, and a 1 s pulse length. The QPS device will be located at the Oak Ridge National Laboratory. Lyon et al. [http://qps.fed.ornl.gov/pvr/pdf/qpsentire.pdf, 2001] describes the physics and engineering features in detail. The QPS device is estimated to require 4 years from start of design to first plasma in 2007.

Keywords: Quasi-poloidal stellarator; Compact stellarator; Modular coils

1. Stellarator core

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

1.1. Modular coils

The modular coils are the most difficult part of the core design and fabrication. Spong [2] and Strickler [3] outline the basic ideas behind quasi-poloidal stellarators and the formulation of the modular coil geometry, respectively. The coil set has two field periods with eight modular coils per period. Due to symmetry, only four different coil types are required. The coils are connected electrically in four circuits such that all the coils of a given shape are in the same circuit. Thus, each coil circuit can be independently powered to provide maximum flexibility. The maximum TF at 0.9 m produced by the modular coils with a flattop of ~ 1 s is 1.0 T. The TF on axis can be raised above 1 T

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0920-3796/03/$ - see front matter
doi:10.1016/S0920-3796(03)00203-5

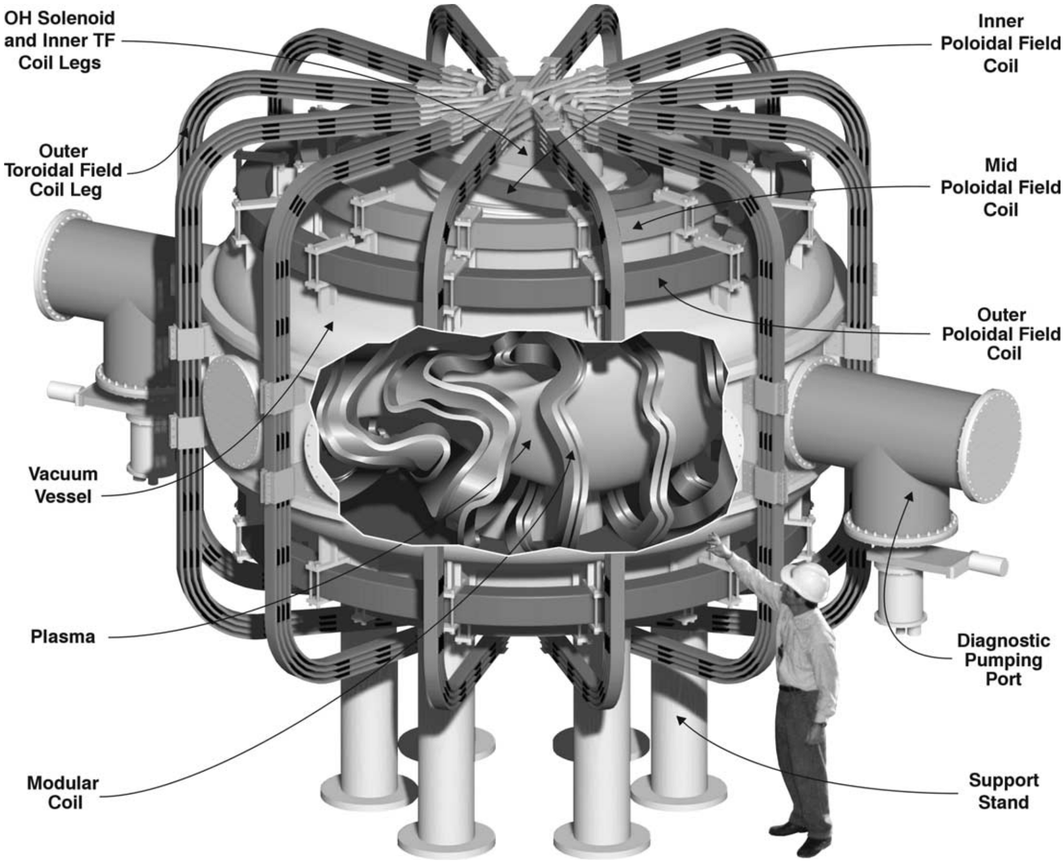

Fig. 1. Cut-away view of QPS stellarator.

by energizing the TF coils, which can add ±0.2 T to the field generated by the modular coils. Fig. 2 shows the geometry of the coil windings. As shown in the figure, the two winding packs that form the coils in the center of the long section were allowed to follow independent winding paths to improve the magnetic configuration.

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 epoxy so the winding pack becomes a monolithic copper-glass-epoxy composite. The typical coil cross section for coil types 1–3 is shown in Fig. 3 and the basic coil parameters are listed in Table 2. The cross section for coil type 4 is the same, except the winding packs have a variable separation. The modular coils are gas cooled and operate above room temperature because they are located inside the plasma vacuum space.

Table 1
QPS general design parameters

Parameter	Value
Major radius, R_o	0.9 m
Aspect ratio, R_o/a	2.7
TF at R_o, B_o	
From modular coils	1 T
From TF coils	± 0.2 T
Number of field periods	2
Plasma current, I_p	< 150 kA
Flattop Pulse length at 1 T	~1.0 s
Plasma heating power, P_{aux}	1–3 MW

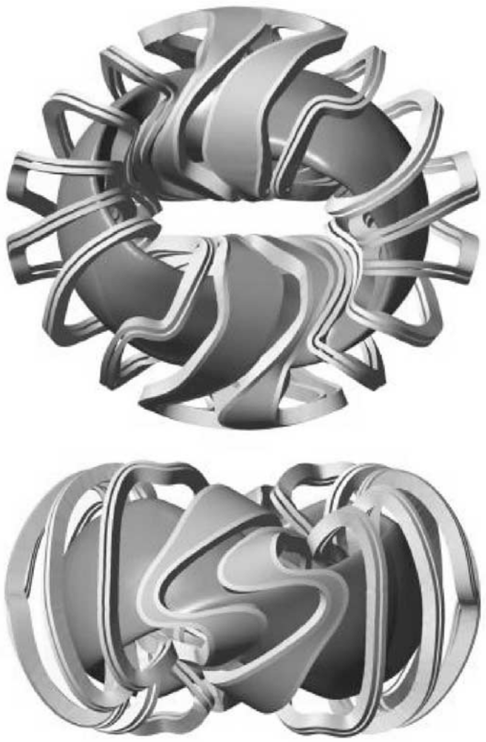

Fig. 2. Modular coil winding geometry showing split windings in the middle of the long section.

The windings are wound on and supported by the tee-shaped structural member, which is an integral part of the coil winding form. The winding form locates the coil windings within the ±1 mm tolerance and supports them against the electromagnetic loads. The forces on the winding packs tend to push them radially outward against the form and clamp them laterally against the central member of the "tee". A compliant layer is provided in the outboard region between the structure and windings to reduce thermal stresses. Stainless steel sheets are seal-welded around the windings to provide a vacuum-compatible coil. Some development will be required to insure that no distortion of the coil occurs during the welding process. In local areas requiring reinforcement, intermittent ribs are bolted to the sides of the coil as structural retainers for the windings.

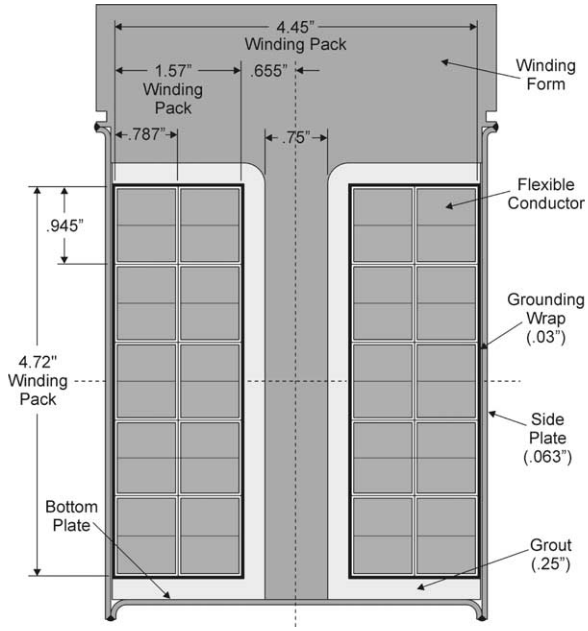

Fig. 3. Modular coil cross section (dimensions in inches).

1.2. Toroidal and poloidal field coils

A set of 12 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. Fig. 4 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.

Table 2
Modular coil parameters

Number of coils	16 (2 × 8)
Winding length	4.3–4.8 m per turn
Number of turns/coil	20
Gross cross section	2 × 40 mm × 120 mm
Current per coil[a]	360 kA
Current density in Cu	8 kA/cm^2
Peak power, coil set	~40 MW

[a] At nominal 1.0 T operating scenario.

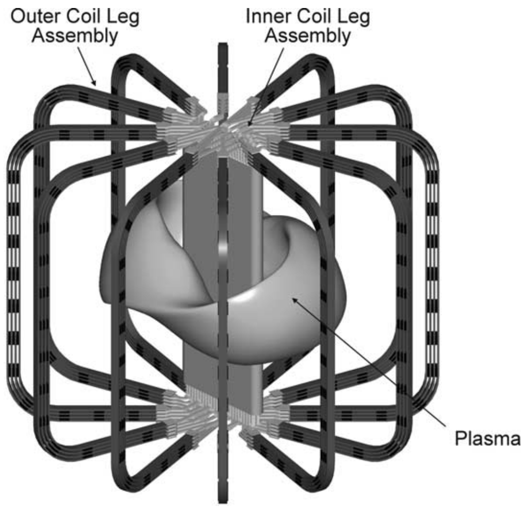

Fig. 4. TF geometry showing the oblong inboard leg assembly.

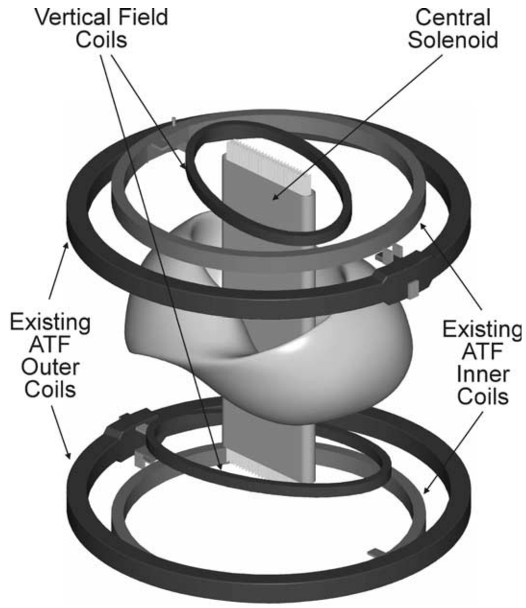

Fig. 5. PF coil geometry showing solenoid, elliptical coils and existing ATF coils.

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, a pair of elliptical coils, and two pairs of ring coils. Coil pairs are stellarator symmetric about the horizontal mid-plane and each coil pair is connected in an independent circuit. The solenoid is located just outside 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 facility are used for the outer ring coils. All PF coils operate at room temperature. Fig. 5 illustrates the PF coil geometry.

1.3. External vacuum vessel

The Quasi-poloidal stellarator (QPS) vacuum vessel is a large external tank that encases the modular coil set. The external tank has several advantages. First, it is less costly than an internal, contoured vessel. Second, it provides better access to the plasma since all the gaps between coils are potential sight lines and there is no constraint imposed by fixed port extensions, which otherwise use much of the space for thermal insulation and clearance. Third, there are no complex assembly steps required as would be the case with an internal vessel, where the modular coils must slide over the highly contoured vessel. However, the disadvantage of the external vessel is the requirement for canning the modular coils and the necessity of operating the coils at high temperature.

The vessel has numerous ports and is divided into a lower dished head, a middle spool piece and an upper dished head. All sections will be fabricated from 316L series stainless steel. The vessel size relative to the rest of the device is illustrated in Fig. 6. All ports will have metal seals, and the large head-to-spoolpiece 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 solenoid winding in the center-stack The basic vessel parameters are listed in Table 3.

Twelve large ports around the mid-plane of the vacuum tank are provided for heating, diagnostics,

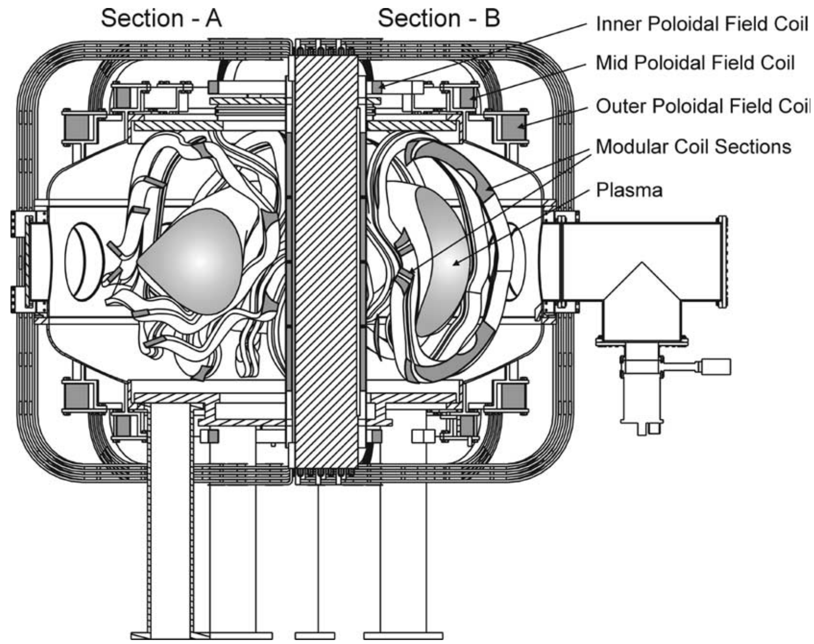

Fig. 6. QPS elevation view showing relationship of vacuum tank to internals.

Table 3
Vacuum vessel parameters

Material	316L ss
Nominal outer radius	1.9 m
Maximum height	2.5 m
Inside surface area	~ 45 m^2
Enclosed volume (with ports)	~ 21 m^3
Bakout temperature	150 °C
Nominal operating temperature	20–100 °C

and maintenance access and numerous smaller ports are provided for coil services and instrumentation feed-throughs.

1.4. Core assembly

The QPS stellarator core will be assembled from two field period sub-assemblies that are bolted together around the center-stack assembly and tank base in the test cell. Both field periods are pre-assembled in a separate area, and consist of half of the modular coils and associated inter-coil structure as well as half of the outer PF coil support rings and vacuum cans. The internal coil services will be routed through the vacuum tank lower dome, and the main spool piece, tank lid, and outer TF legs will be added. The assembly sequence is illustrated in Fig. 7. The intercoil structure is omitted for clarity.

2. Ancillary systems

The QPS facility will take advantage of existing infrastructure at ORNL, including plasma-heating systems (1.2 MW ECH, 3 MW ICRF), 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.

3. Design status and conclusion

The QPS device is presently in the early design phase. The general configuration has been selected and baseline concepts exist for most of the primary design features. Additional analysis and concept

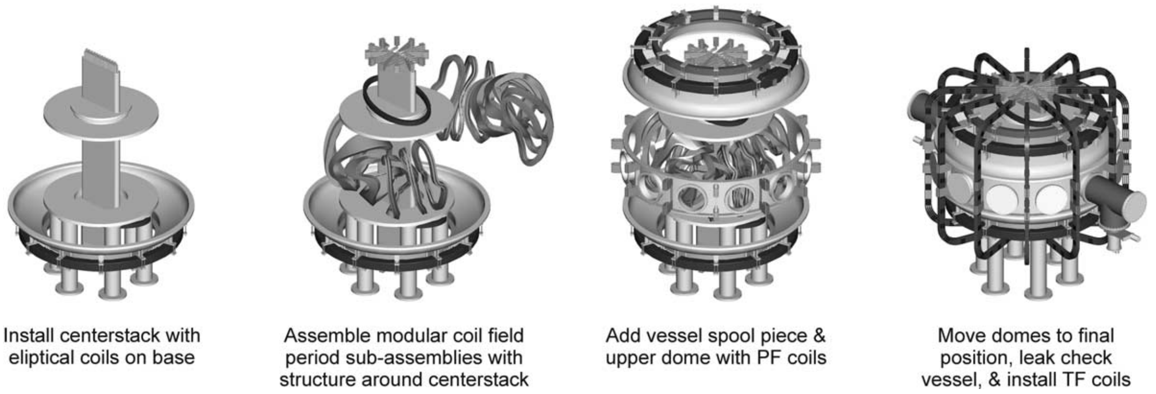

Fig. 7. Stellarator core assembly sequence.

refinement will be carried out through April 2003, prior to an independent design review.

Acknowledgements

This work was supported by the US DOE under Contract No. DE-AC05-00OR22725 with UT-Battelle, LLC.

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