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OVERVIEW OF THE QPS EXPERIMENT

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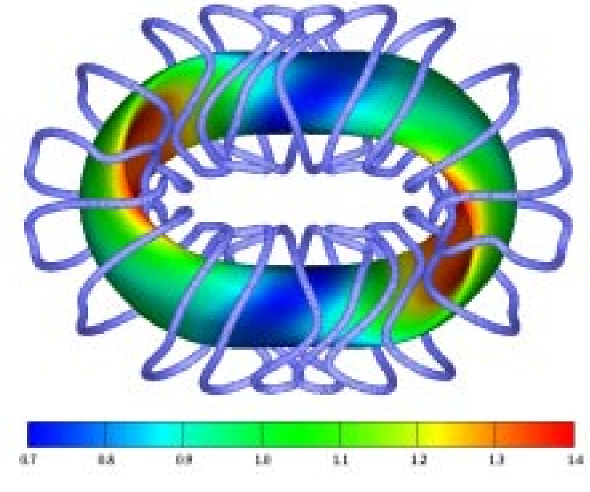
Abstract. QPS is a very-low-aspect-ratio quasi-poloidally-symmetric stellarator with $\langle R \rangle = 0.9$ m, $\langle a \rangle = 0.33$ m, $\langle B_{axis} \rangle = 1$ T for a 1-s pulse, and $P_{heating} = 1\text{-}3$ MW. Quasi-poloidal symmetry leads locally to small B x grad B particle drifts out of a flux surface over most of the plasma cross section, minimum flow damping in the direction of E_r x B, trapped particles localized in low curvature regions, and properties that improve with increasing β. The paper describes the confinement and MHD stability properties, the engineering design, and the status and plans for the QPS experiment.

I. MAGNETIC CONFIGURATION

A quasi-poloidal stellarator with very low plasma aspect ratio ($\langle R \rangle / \langle a \rangle \sim 2.7$, 1/2-1/4 that of existing stellarators) is a new magnetic confinement approach that could ultimately lead to a high-beta ($\langle \beta \rangle = 7\text{-}15\%$) disruption-free compact stellarator reactor. Here $\langle R \rangle$ and $\langle a \rangle$ are the average major and minor radii of the non-circular and non-axisymmetric plasma. An experiment, the Quasi-Poloidal Stellarator (QPS) [1] shown in Fig. 1, is being developed to test key features



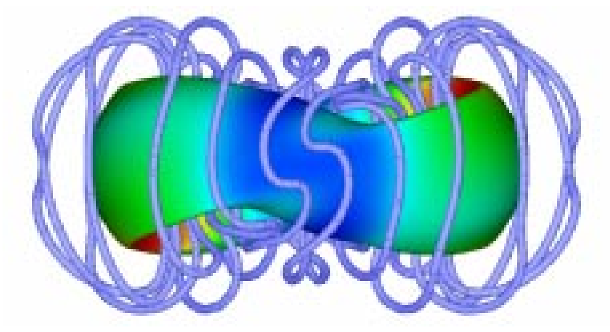


Fig. 1. Top (left) and side (above) views of the QPS plasma and the modular coils that create it. The colors indicate contours of |B| in T on the last closed flux surface.

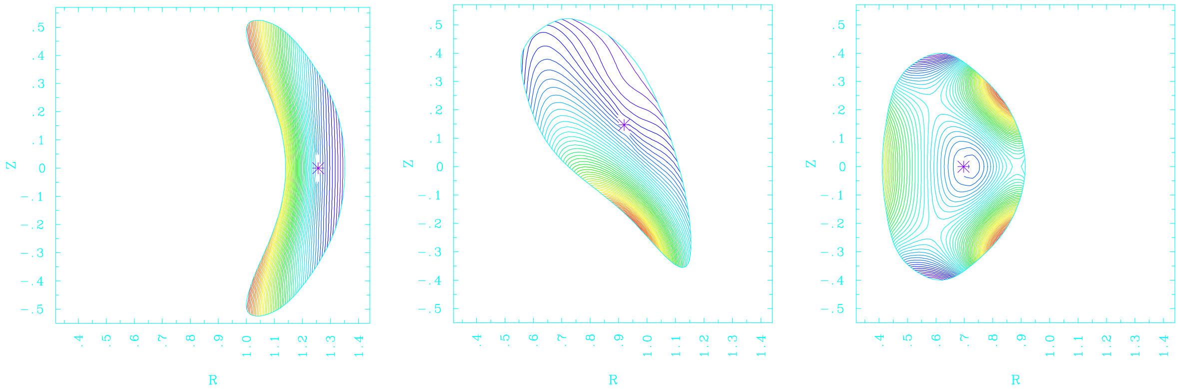


Fig. 2. Cross sections of the QPS flux surfaces at three toroidal angles: 0 deg. (left), 45 deg. (middle), and 90 deg. (left). The colors indicate the same contours of |B| in T as in Fig. 1.

of this approach. The main QPS parameters are $\langle R \rangle = 0.9$ m, $\langle a \rangle = 0.33$ m, $\langle B_{axis} \rangle = 1$ T for a 1-s pulse, and $P_{heating} = 1$-3 MW. Figure 2 shows that the shape of the QPS flux surfaces varies from bean-shaped at the higher-field ends to D-shaped in the middle of the long straight sections. A helical variation of the magnetic axis is also indicated in Fig. 1.

In this approach the dominant components in the magnetic field spectrum are poloidally symmetric in flux coordinates. For exact poloidal (θ) symmetry, the canonical angular momentum p_θ is conserved and: (1) orbit excursions from a flux surface are limited to the gyroradius in the *toroidal* magnetic field ρ_T rather than in the *poloidal* magnetic field ρ_p (the banana width) where $\rho_T \ll \rho_p$; (2) there is no flow damping in the poloidal direction; and (3) the bootstrap current is reduced by ι/N where ι is the rotational transform (= $1/q$) and N is the number of field periods.

Figure 3 shows contours of |B| on two flux surfaces in flux coordinates in which the magnetic field lines are straight. The degree of quasi-poloidal symmetry varies with plasma radius r. In the plasma core ($r/\langle a \rangle < 1/2$) the magnetic energy in non-poloidally symmetric field components is <10% of that in the poloidally symmetric field components; that fraction rises to ~30% at the plasma edge. B and ∇B are more closely aligned than is possible with other forms of symmetry; this reduces radial particle drift and banana width. Quasi-poloidal symmetry leads locally to small B x grad B particle drifts out of a flux surface over most of the plasma cross section rather than close alignment of globally averaged drift surfaces and flux surfaces (quasi-omnigenity) as in Wendelstein 7-X (W 7-X). However near the edge, quasi-omnigenous features also occur in QPS that help to reduce neoclassical transport.

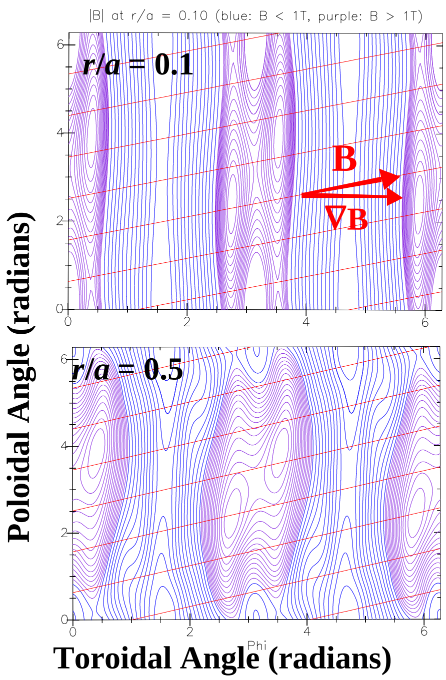


Fig. 3. QPS |B| contours & field lines.

Quasi-poloidally-symmetric stellarators also have some other unique features.

* There is minimum flow damping in the direction of E_r x B. Flow shear could be self-sustained through E_r driven by ambipolar diffusion or externally produced.

* Trapped particles are localized in low curvature regions; this should improve stability to dissipative trapped electron modes.

* Properties improve with increasing β: access to a second stability region, omnigeneity, and thermal and fast ion confinement. The configuration becomes relatively insensitive to increasing β and the bootstrap current becomes nearly independent of β at higher β.

II. TRANSPORT AND STABILITY

A measure of the reduction in neoclassical transport is shown in Fig. 4. For $E_r = 0$ in the low-collisionality limit, the neoclassical ripple-induced heat diffusivity is proportional to $\varepsilon_{eff}^{3/2}$ where ε_{eff} is the effective ripple in a single helicity 1/ν transport model that gives the same transport as a full 3-D calculation in this limit. QPS has similar transport to that in the W 7-X configuration, but at 1/4 the plasma aspect ratio. Reducing $\varepsilon_{eff}^{3/2}$ further in QPS would not be effective since the implied energy confinement time due to purely neoclassical losses would greatly exceed the ISS-95 stellarator scaling, and other losses would likely be dominant. The degree of quasi-poloidal symmetry and the reduction in neoclassical transport increase as β (and the plasma current) increases. The high degree of quasi-poloidal symmetry and the reduced effective field ripple may also reduce the poloidal viscosity, enhancing the naturally occurring E x B poloidal drifts and allowing larger poloidal flows for possible shear damping reduction of anomalous transport.

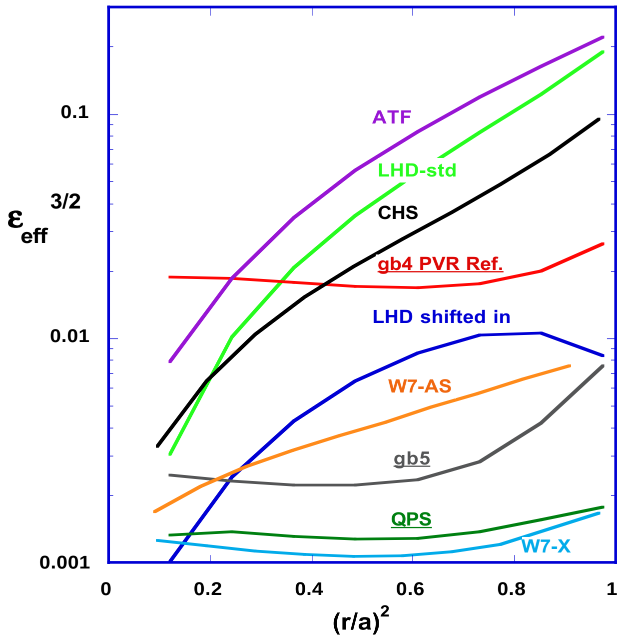


Fig. 4. Coefficient of thermal diffusivity in the 1/ν regime for different stellarators (gb4 and gb5 are earlier versions of QPS).

While the QPS experiment is designed to study regimes in which either anomalous transport or neoclassical transport is dominant, it can also test stability limits, the configuration dependence of the bootstrap current, and equilibrium robustness at $\langle\beta\rangle \sim 2.5\%$. The QPS magnetic configuration is relatively insensitive to increasing β, similar to that for W 7-X. However, a self-consistent bootstrap current is incorporated in the QPS configuration optimization. The plasma is Mercier stable for $\langle\beta\rangle \sim 2.5\%$, although experiment and recent theory indicate that this is not a limit. Infinite-*n* ballooning modes are also stable up to $\langle\beta\rangle > 2\%$, as shown in Fig. 5 (a) for an earlier QPS configuration. The plasma current required for equilibrium in these free-boundary calculations is consistent with the bootstrap current, as shown in Fig. 5(b). Infinite-*n* ballooning modes are unstable for $\langle\beta\rangle = 2.5\text{-}5.5\%$, but stable for higher β (second stability region). Kink and vertical modes are stable at $\langle\beta\rangle \sim 5\%$ without feedback or close conducting walls. The stellarator rotational transform and bootstrap current should suppress magnetic islands and neoclassical tearing modes.

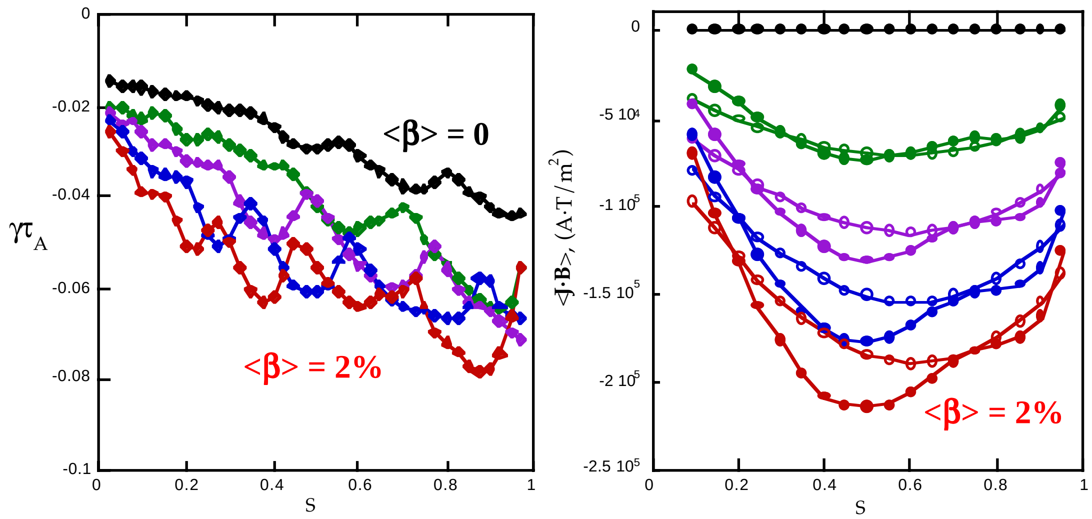


Fig. 5. (a) Normalized ballooning growth rate vs. flux ($\propto \{r/a\}^2$) and (b) near alignment of the equilibrium (open circles) and bootstrap currents (closed circles) for different values of $\langle\beta\rangle$.

III. ENGINEERING DESIGN

The QPS coil set shown in Fig. 1 has two field periods with 8 modular coils per period. Due to stellarator symmetry, only four different coil types are needed. The coils are connected in four circuits so like coils are independently powered for maximum flexibility. The space in the central bore has been chosen to allow a center stack (Fig. 6) containing the central legs of twelve toroidal field (TF) coils for configuration flexibility and coils for driving up to 150 kA of plasma current.

A cutaway view of QPS in its bell jar vacuum tank is shown in Fig. 7 and the main QPS device parameters are given in Table 1. The open coil geometry allows good access between the coils for heating and diagnostics. The two rectangular winding packs that form the coils are separated by a

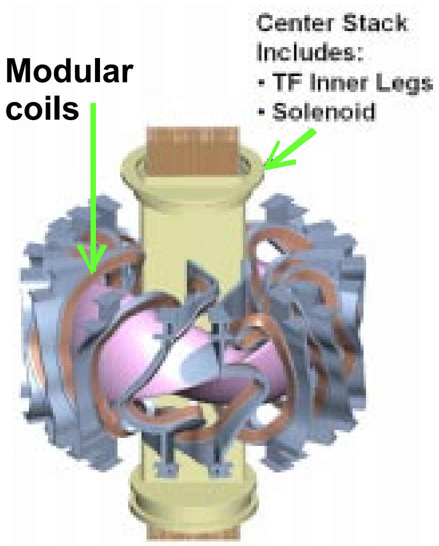


Fig. 6. QPS center stack

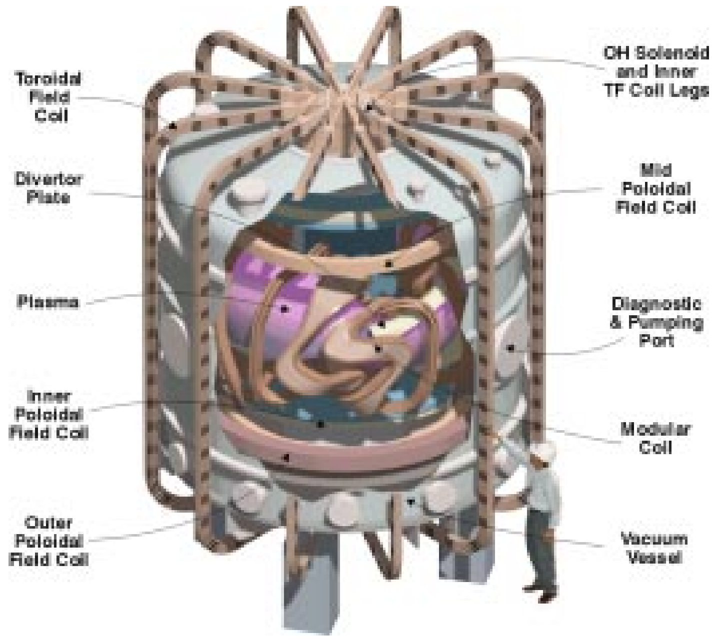


Fig. 7. Cutaway view of QPS coils in the vacuum tank.

thin stainless steel structural "T" except in the center of the long section in Fig. 1 where the two winding packs are allowed to follow independent paths to improve the magnetic configuration properties. These modified coils have a wider "T", as seen in Fig. 7. In addition, there are three sets of poloidal field coils for driving plasma current and for plasma shape and position control.

Table 1. QPS Device Parameters

Ave. major radius <R>	0.9 m
Ave. plasma radius <a>	0.33 m
Plasma aspect ratio <R>/<a>	2.7
Plasma volume V_{plasma}	2 m^3
Central, edge rotational transform ι_0, ι_a	0.21, 0.32
Average field on axis from modular coils	B_{mod} = 1 T for1-s pulse
Auxiliary toroidal field	± 0.2 T
Ohmic current I_{plasma}	≤ 150 kA
ECH power	0.6-1.2 MW
ICRF heating power	1-3 MW

All coils are cooled using helium gas and have a stainless steel vacuum-tight case since they share the same vacuum as the plasma. The buildup of neutral pressure in the vessel will be minimized through local concentration of recycling. 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 (indicated in Fig. 7) and then be largely reionized by the boundary plasma. Mechanical baffling and local recycling with reionization should lead to high-recycling divertor operation and low electron temperatures at the divertor plate. Connection lengths in the scrapeoff region are long enough for effective island divertor operation. Large areas are available in the top and bottom of the bell jar for titanium getter pumping, providing 4-5 x 10^5 l/s pumping speed (including conductance to the pumping region).

Additional neutrals control will be achieved by boronization. Thermal insulation blankets and heaters will be added to the bell jar to provide bakeout capability with a temperature goal of 150 C and helium glow discharge cleaning will also be used during operation. There are twelve 61-cm-diameter ports around the midplane of the vacuum tank for heating, diagnostics, and maintenance access, and numerous smaller ports for coil services and instrumentation feedthroughs.

V. STATUS AND PLANS

The QPS project is now in the conceptual design phase. A successful physics reviews was held in April 2001. The plans are to further improve the plasma and coil configuration, complete assessment of the QPS physics properties, assess the configuration flexibility obtained with the VF, TF, and OH solenoid coils, and improve the engineering design and cost/schedule estimates. A final design, cost and schedule review is scheduled for Spring, 2003, with the remaining R&D, design and construction in the 2003-2007 period. First plasma operation is planned for mid-2007.

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