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Recent Developments in Quasi-Poloidal Stellarator Physics

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Abstract. QPS is a very-low-aspect-ratio quasi-poloidally-symmetric stellarator with $\langle R \rangle$ = 0.95–1 m, $\langle a \rangle$ = 0.3–0.4 m, $\langle B_{axis} \rangle$ = 1 T for a 1.5-s pulse, and $P_{heating}$ = 2–5 MW. This paper describes the QPS configuration, calculated flows, and modular coil construction.

I. QPS EXPERIMENT AND MAGNETIC CONFIGURATION

The QPS compact stellarator [1] is being developed to test key features of quasi-poloidal symmetry at very low plasma aspect ratio, 1/2-1/4 that of existing stellarators: robustness of the MHD equilibrium, reduced neoclassical and anomalous transport, and MHD stability limits. Figure 1 shows a cutaway view of the QPS; the main device parameters are listed in Table 1. There are two field periods with 10 modular coils per period. Due to stellarator symmetry, there are only five different coil types. There are also three sets of poloidal field coils, 12 toroidal field coils, and an Ohmic current solenoid. Nine independent controls on the coil currents permit a wide range of magnetic configuration properties for physics studies. Changes in coil currents of +/–20% allow a factor >30 variation in the neoclassical ripple-induced heat diffusivity in the low-collisionality limit for no electric field. A factor of 9 variation is also obtained in the degree of poloidal symmetry defined by the ratio of the magnetic energy in the non-symmetric modes (with poloidal mode number $m \neq 0$) to those that have poloidal symmetry (with $m = 0$). The fraction of the magnetic energy in the $m \neq 0$ field components is <0.4% in the plasma core ($r/a < 0.4$) and rises to 3% at the plasma edge

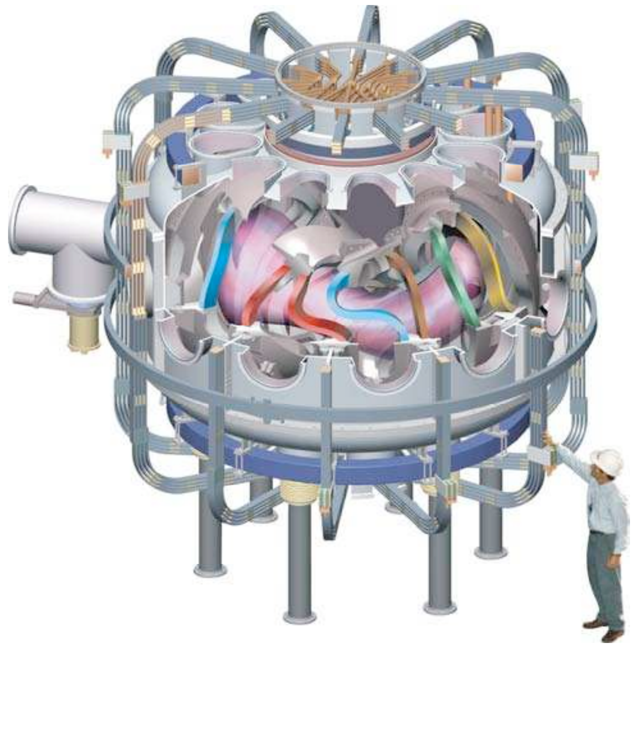
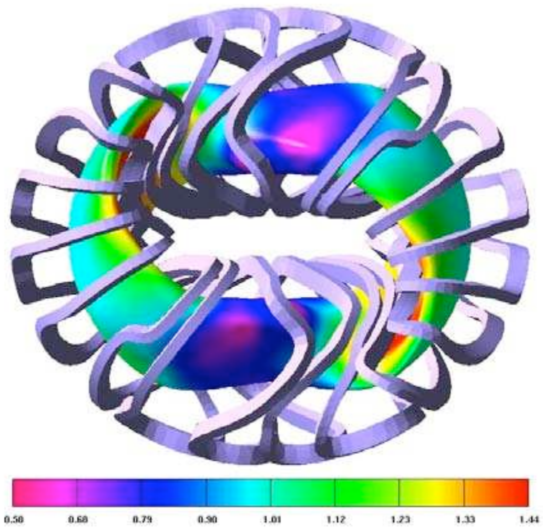


Table 1. QPS Device Parameters

Ave. major radius $\langle R \rangle$	0.9-1 m
Ave. plasma radius $\langle a \rangle$	0.3-4 m
Plasma aspect ratio	2.7
Plasma volume V_{plasma}	2-3 m^3
Central, edge rotational transform ι_0, ι_a	0.21, 0.32
Average field on axis from modular coils	$B_{modular}$ = 1 T for 1.5 s
Auxiliary toroidal field	± 0.15 T
Ohmic current I_{plasma}	≤ 50 kA
ECH power	1.9 MW
ICRF heating power	1.5-3.5 MW

Fig. 1. Cutaway view of QPS.



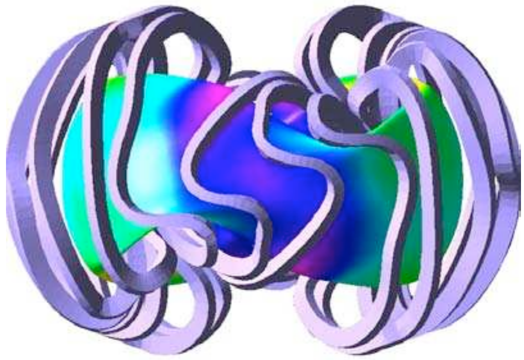


Fig. 2. Top (left) and side (above) views of the QPS plasma and the modular coils used to create it. The colors indicate contours of constant |B|(T) on the last closed surface.

for the base case. Changes in the coil currents also allow a factor of 10 variation in the poloidal viscosity, permitting study of the role of poloidal flows in suppressing turbulence.

The shape of the QPS flux surfaces shown in Fig. 2 varies from bean-shaped at the high-field ends to D-shaped in the middle of the long sections; the plasma elongation varies from 2 to 4.3. There is also a large helical excursion of the magnetic axis: $\Delta R/\langle R\rangle = 0.53$ and $\Delta z/\langle R\rangle = 0.45$. The dominant components in the magnetic field expansion are poloidally symmetric in flux coordinates, leading to reduced neoclassical transport and decreased poloidal viscosity.

II. FLOWS AND FLOW DAMPING

Understanding plasma flows in stellarators is important for access to enhanced confinement regimes, impurity transport, bootstrap current analysis, and magnetic island growth. Unlike axisymmetric devices, where there is a preferred direction (toroidal) for undamped plasma flows, QPS is characterized by non-zero levels of plasma flow in both the toroidal and poloidal directions. The drive mechanisms for these flows differ from those in tokamaks due to the ambipolar electric field, which provides an additional drive for plasma rotation. Also, both the magnitude and direction of plasma flows in stellarators can have significant variation within a flux surface. A unique feature that distinguishes QPS from other toroidal confinement devices is a lower level of damping for poloidal plasma flows, so poloidal flows are enhanced over toroidal flows. The relatively low level of externally produced rotational transform ($\iota \approx 0.15$ to 0.25) also means that the plasma diamagnetic and $\mathbf{E} \times \mathbf{B}$ flows are oriented in a direction that is close to that (poloidal) in which the viscous damping is minimal. This characteristic should facilitate the generation of sheared plasma flows, which can suppress turbulence and allow the formation of transport barriers.

Flow velocities in QPS have been analyzed both for ICH and ECH parameters. Low-density [n(0) = 2 x 10^{19} m^{-3}] ECH cases typically result in electron ambipolar electric field roots while higher density [n(0) = 8 x 10^{19} m^{-3}] ICH cases have ion roots. Typical profiles for the flux-surface-averaged toroidal (ζ) and poloidal (θ) flow velocities for the ECH case are shown in Fig. 3. The flux-surface-averaged flow consists of the **E** × **B** and diamagnetic components, the parallel flow (determined from neoclassical parallel momentum balance), and the Pfirsh-Schlüter velocity (required to maintain incompressibility). For both ECH and ICH cases the poloidal flow velocity component dominates. Larger flows occur for the ECH case because the electric field and temperature gradients are larger and the diamagnetic and **E** × **B** flows are in the same direction (for ions) whereas they are in opposite directions (partially canceling) for the ICH case. The associated ambipolar electric field profiles have significant shearing, even in the absence of external torques; the **E** × **B** shearing rates obtained may suppress certain classes of ion-temperature-gradient-driven turbulence.

Figure 3 shows the flow velocity variation within a flux surface for an ECH plasma. Toroidal flow components are present for both ECH and ICH cases, but these reverse direction in going from the inboard side to the outboard side. This reversal is largely due to the Pfirsh-Schlüter flow component, which has a stronger variation at low aspect ratios. The flows are non-uniform and are especially large in the low-field regions of the flux surface. This structure is driven by the 1/B dependencies of the **E** × **B** and diamagnetic flows, resulting in a large velocity shear within the flux surface, both with respect to the direction of the flow and its magnitude. This flow characteristic may provide an additional mechanism for turbulence suppression in QPS and could also impact ideal and resistive ballooning mode stability.

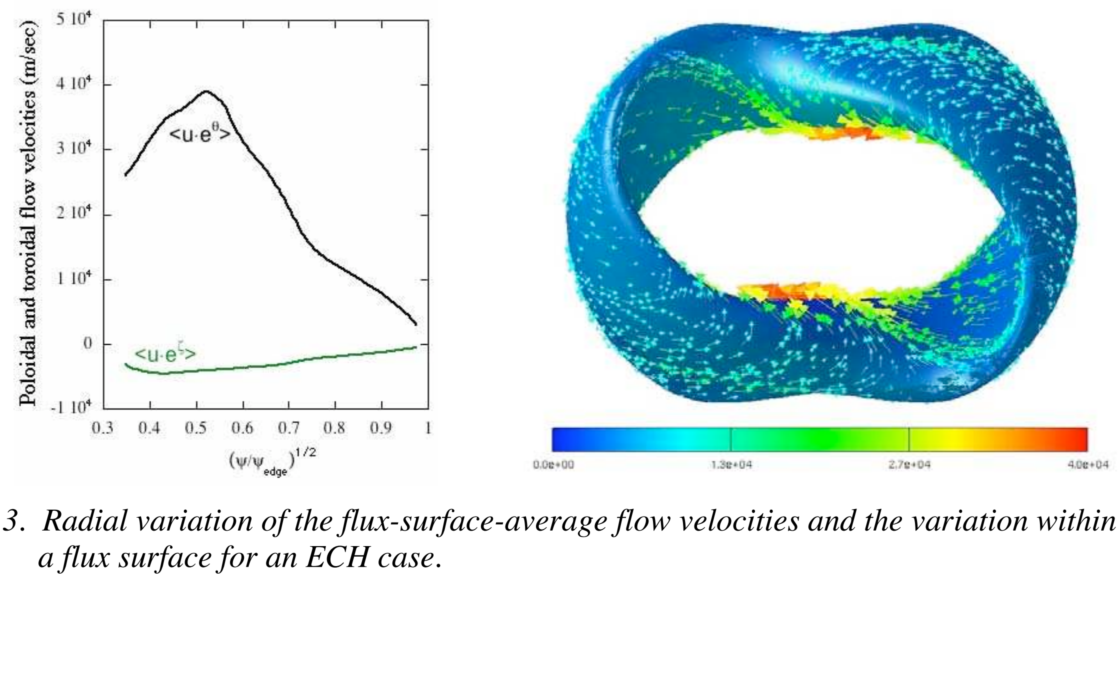


Fig. 3. Radial variation of the flux-surface-average flow velocities and the variation within a flux surface for an ECH case.

III. MODULAR COIL CONSTRUCTION

Figure 4 illustrates the five types of QPS modular coils and how one of the coils (M5) is fabricated. Figure 5 shows the prototype stainless-steel casting that contains two M1 coils as it came out of the sand mold. This is the heaviest and most complex of the modular coil winding forms. It will now be cleaned up and machined to the precise shape needed for winding the red (M1) coils in Figs. 1 and 3. Coils M2 and M3 are wound one another form and coils M4 and M5 are wound on a third form.

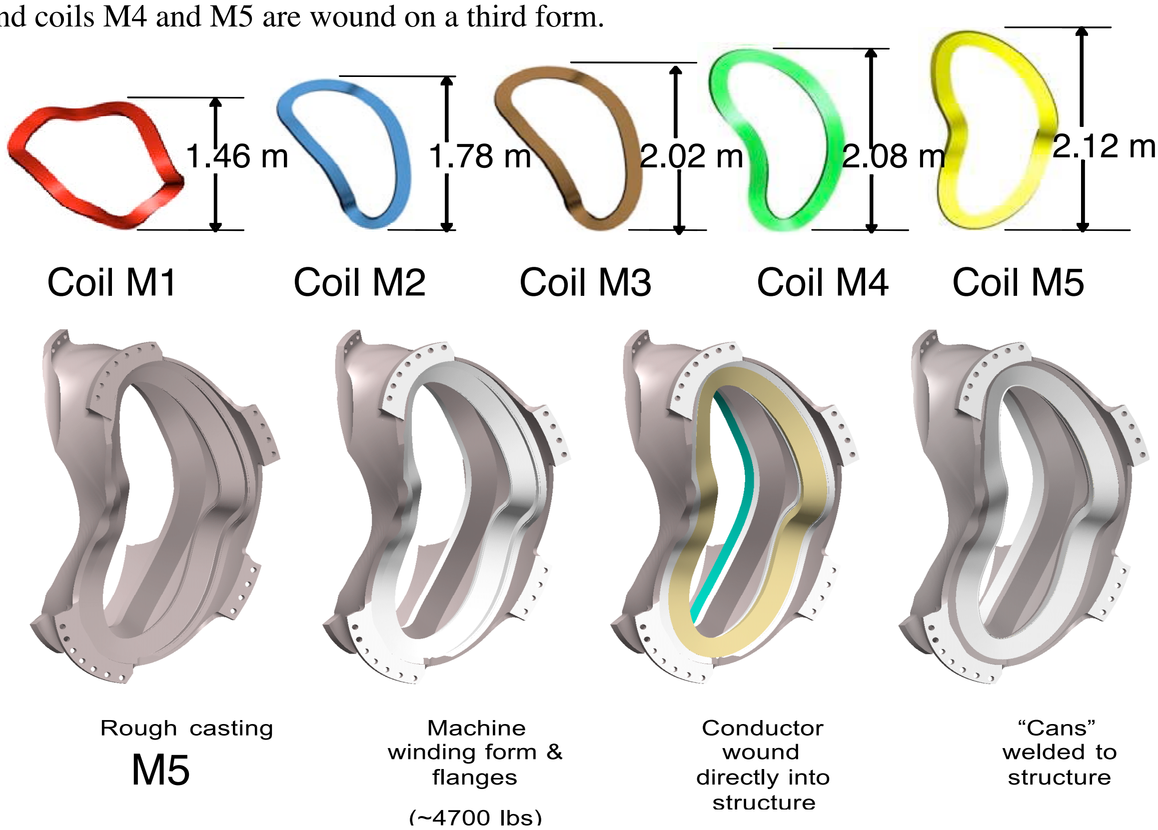


Fig. 4. The five types of modular coils and the fabrication steps after machining.

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Fig. 5. QPS coil form M1 before machining.

References

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

[2] D. A. Spong et al., "Recent Advances in Quasi-Poloidal Stellarator Physics Issues", to be published in *Nucl. Fusion* (2005).