EXECUTIVE SUMMARY

The concept-exploration-level quasi-poloidal stellarator (QPS) can make unique contributions to development of the compact stellarator, the niche identified for U.S. improvement of the stellarator. These contributions are (1) exploring key issues pertinent to a high-β ($\langle\beta\rangle > 10\%$) low aspect ratio ($R/a = 2.7$) compact stellarator reactor concept and (2) exploration of the physics consequences of very low aspect ratio and quasi-poloidal symmetry on the optimization of compact stellarators. This information is needed in a 10-year time frame both to meet the objectives laid out by FESAC for the compact stellarator and as input for decisions on the next step in the world stellarator program after LHD and W7-X. Although there is a large world stellarator program focused on the high-aspect-ratio, currentless approach to stellarator optimization, and a concept-exploration level stellarator program in the U.S. exploring unique aspects of stellarator research, the critical missing component is optimization of stellarators at low plasma aspect ratio that could lead to a more attractive fusion reactor than either the advanced tokamak (AT) or conventional currentless stellarator.

The QPS is needed because there is no existing experimental database which would allow one to reasonably predict the behavior of a low aspect ratio, high-β stellarator. A CE-level experiment, although limited by heating capability to relatively low β ($< 3\%$) compared to the reactor embodiment, would nevertheless allow the exploration of key physics issues relevant to transport (both neoclassical and anomalous) and stability in a configuration with quasi-poloidal symmetry. The study of the physics of quasi-poloidal symmetry at very low aspect ratio in a stellarator with finite bootstrap current (at finite β) uniquely differentiates the CE-level QPS from the W7-X experiment.

QPS could make unique contributions relating to some of the key fusion science areas outlined by the DOE Integrated Program Planning Activity (IPPA): the physics of neoclassical confinement improvement at very low aspect ratio, flux surface robustness at $\langle\beta\rangle$ up to 2-3% in the presence of strong toroidal/helical coupling, the dependence of bootstrap current on configuration properties at low aspect ratio, and the electric potential and its influence on enhanced confinement regimes.

1. Toroidal Confinement Approaches.

The most developed magnetic confinement approaches for fusion research are based on the advanced tokamak (AT) and currentless stellarators. Both use helical (toroidal plus poloidal) magnetic fields for confinement and stability. The AT approach has low plasma aspect ratio ($R/a_p \sim 3$), good confinement properties, a high volume-average beta limit ($\langle\beta\rangle \sim$5-10%), and relies on axisymmetry and a large bootstrap-driven toroidal plasma current for its good performance. Here R and a_p are the toroidally averaged major and minor radius of the plasma. Challenges for the AT approach (some external current drive and high recirculating power in a reactor, potential for disruptions, need for a close conducting wall and active feedback systems for stability against external kink instabilities and vertical instability) result from the large internal plasma current

needed to produce the confining poloidal magnetic field. Currentless stellarators are inherently steady-state and avoid these problems by creating the poloidal field with currents flowing solely in external windings. But they tend to have large plasma aspect ratios (R/a_p = 6-11) which leads to large reactor sizes (R ~ 22 m for the W 7-X-based HSR compared to R ~ 5.5 m for an advanced tokamak reactor). Also, they can have potentially larger neoclassical transport due to departures from canonical symmetry, and have lower beta limits ($\langle\beta\rangle$ ~5%).

Compact stellarators could combine the best features of both confinement approaches by using 3-D shaping of the last closed flux surface (LCFS), using quasi-symmetry features to improve neoclassical transport, and employing some bootstrap current to provide a fraction of the required rotational transform. Here quasi-symmetry is a property of magnetic configurations in which |B| expressed in magnetic flux ("Boozer") coordinates has a predominant symmetry. In such a system there is an ignorable coordinate in the drift Hamiltonian (which depends only on |B|) and therefore a corresponding constant of motion, which leads to low viscosity in the symmetry direction and low neoclassical transport. Most importantly for a stellarator reactor, the notorious "1/ν" transport hill, in which the neoclassical losses due to departures from symmetry rise steeply with falling collision frequency (ν), is greatly reduced in magnitude so that reactor temperatures become accessible.

The main component of the proposed compact stellarator proof-of-principle program, the National Compact Stellarator Experiment (NCSX), would use *quasi-axisymmetry* and some bootstrap current to produce plasmas with R/a_p = 4.3 that have good neoclassical confinement, are stable at $\langle\beta\rangle$ ~4% to ballooning modes, external kinks and vertical modes (without a conducting shell). The smaller concept-exploration-level Helically Symmetric Experiment (HSX) is testing another quasi-symmetry feature, *quasi-helical symmetry*.

We propose to test the physics implications of the remaining type of quasi-symmetry, that is quasi-poloidal symmetry, in a concept exploration (CE) level experiment. A concept-exploration-level QPS will: (1) broaden our understanding of toroidal magnetic configurations through exploration of quasi-poloidal symmetry; (2) allow exploration of very low aspect ratio (~2.6) in a stellarator; (3) establish a database and lay the physics foundation for QPS configurations having high β limits relative to conventional stellarators ($\langle\beta\rangle$ ~10% - 15%), and (4) complement NCSX in completing the knowledge base needed for advancing the development of the compact stellarator concept to the next stage.

2. The Potential of Quasi-Poloidal Symmetry.

The CE-level QPS experiment being proposed here has been motivated by calculations which indicate the existence of a high-β QPS with potentially attractive features for a compact stellarator reactor. Recent magnetic configuration optimization studies have yielded very low aspect ratio (R/a_p = 2.7-3.7) QPS configurations having good neoclassical confinement which are stable to all modes (ballooning and moderate n modes) in the range $\langle\beta\rangle$ = 10-15%. The B| spectrum of these "high-β" QPS configurations is dominated by the toroidal mirror term (m = 0, n = 1, in units of N

= number of field periods), even more so than in the case of the CE device. This results in a reduced bootstrap current (by a factor ~ ι/N) that is 1/5-1/3 that of a tokamak with a similar transform profile but which is sufficient to produce a large fraction of the internal transform profile (similar to a high bootstrap fraction AT). Near the edge of the plasma, where ι is small ($\iota \sim 0.1$), the external transform from coils and the bootstrap current make equal contributions to the total rotational transform. This, together with the relatively low bootstrap current ($\iota < 0.4$, high "q") leads to the high β limits for the kink and vertical modes. In addition, the finite bootstrap current seems to reduce the helical curvature which leads to second-regime ballooning stability at these high values of β. Studying the accessibility to this regime might be possible in the CE-level experiment and remains an issue for further investigation. These configurations also have a magnetic well over the entire plasma cross section. In addition, these high-β QPS configurations have the property that the degree of quasi-poloidal symmetry and therefore the confinement of both thermal and alpha particles improve as β increases. This leads to a type of configurational invariance in which the bootstrap current remains nearly constant over a range of β. These configurations offer the possibility for a modest sized, disruption-free reactor at significant β, requiring no externally driven current.

The large (R = 5.5 m) Wendelstein 7-X (W 7-X) stellarator under construction in Germany exploits this type of quasi-symmetry to some extent (actually, it uses drift-orbit alignment with flux surfaces, which is more general than quasi-poloidal symmetry) to obtain good neoclassical confinement, but at an aspect ratio R/a_p = 10.6 that is much larger than that of the CE-QPS. W 7-X is projected to be stable at $\langle\beta\rangle$ = 5%. The mechanism for achieving configurational robustness with increasing β is much different for W7-X as compared to QPS. W7-X achieves essentially zero bootstrap current throughout its operating range by cancellation of the contribution from different magnetic helicities of |B|. Whereas QPS achieves reduced, but β dependent, bootstrap current by a dominantly toroidal variation ("linked-mirror") in |B|. The field ratio B_{11}/B_{10} is reversed in QPS from that in W 7-X, so there is no cancellation effect in QPS. Calculations of the Onsager coefficient relating the bootstrap current to the pressure gradient show that it decreases with β in such a way that the bootstrap current is nearly independent of β for $\langle\beta\rangle > 7\%$. This imparts a degree of configurational invariance to the high-β QPS that is similar to that achieved in W 7-X at zero bootstrap current.

<u>2.1. Role of the CE-scale device in the development of QPS physics.</u> The proposed CE-level device is designed to have sufficient flexibility to change the controlling magnetic configuration properties: ι, shear, magnetic well, helical axis excursion, mirror ratio, and plasma current. It is the logical first step in understanding the key physics issues important for optimizing and accessing high-β QPS configurations.

(1) It is critical to understand quasi-poloidal symmetry and its effect on confinement improvement. In order to access the high-β QPS configurations it is particularly important to understand how to obtain enhanced confinement regimes, the dependence of energy confinement on quasi-poloidal-

symmetry features, and the role (and control) of the ambipolar electric field in confinement improvement.

(2) Understanding the configuration dependence and β dependence of the bootstrap current at very low aspect ratio is important for understanding the relationship to the high-β QPS.

(3) The plasma equilibrium changes from a first stability regime to a second stability regime as β increases. By optimizing the plasma shape (outer flux surface), rotational transform profile, and pressure profile for a target β, ballooning stable configurations with good bootstrap alignment in the range $2\% < \langle\beta\rangle < 23\%$ were obtained. Understanding MHD stability at $\langle\beta\rangle < 2\text{-}3\%$ is expected to begin to develop an understanding of this transition and the importance of ballooning modes on confinement.

(4) The high-β QPS configurations have a high shear, tokamak-like transform profile (ι *decreasing* radially) which could increase the size of magnetic islands and destabilize neoclassical tearing modes. Mitigating this is the absence of the $\iota = 1/2$ resonance (internal disruptions are suppressed) and other low-order resonances. Changing (and reversing) the shear in QPS would allow a careful study of the impact of stabilizing and destabilizing magnetic islands and neoclassical tearing modes on confinement and equilibrium quality.

3. QPS Contributions to Fusion Science.

The proposed experiment will provide specific information of importance regarding quasi-poloidal symmetry and its implementation for high-β configurations. In addition, QPS will broaden our basic understanding of toroidal confinement physics in a number of ways.

(1) <u>Three dimensional equilibria at low aspect ratio.</u> There are a number of basic questions related to the existence of highly shaped equilibria at low A, and to our ability to predict them numerically. It was shown by Grad in the early 1970's that there is no mathematical guarantee of the existence of MHD equilibria in 3D. Stellarator experiments give demonstration of the practical, if not mathematical, existence of surfaces at high A. QPS will extend this database to very low aspect ratio, $R/a = 2.6$, less than half that of existing stellarators. QPS can study equilibrium quality, magnetic islands, and ergodic regions through external coil variations which effect the plasma shaping (and hence the $|B|$ spectrum), ι profile , and magnetic shear.

(2) <u>Physics of the bootstrap current.</u> QPS can extend the study to very low aspect ratio of the configuration dependence of the bootstrap current in stellarators. QPS also has the interesting property that the number of trapped particles in the toroidal ripples do not vanish near the magnetic axis, thereby permitting finite bootstrap current at the plasma center. While this is not so important for configurations – such as NCSX – which have a large rotational transform contribution at the magnetic axis from external coils – it mitigates the need for seed current and on-axis current drive in the high-β QPS. In addition, the direction of bootstrap current and the sign of shear should decrease the size of magnetic islands as β increases.

(3) Anomalous transport. There is no information on anomalous transport in stellarators at aspect ratio <5. QPS can test the validity of transport scaling laws such as ISS95 and extend the database upon which such scalings are based.

(4) Poloidal flow and transport barrier formation. The direction of symmetry in a QPS is nearly perpendicular to the magnetic field (far enough from the edge of the plasma), so damping of the toroidal flow will be much stronger than in an axisymmetric system and for the *same* radial electric field the parallel flow in QPS should be much smaller. On the other hand, damping in the poloidal (symmetry) direction is expected to be much weaker in QPS, thus allowing the possibility of both self-generated and externally-driven poloidal flow. QPS can study the impact of poloidal flows on electric fields and enhanced confinement as well as the level of helical ripple than can be tolerated while achieving significant control of the electric field (and its shear) through external momentum input.

These objectives respond to the key scientific issues of fusion science that were identified in the DOE Integrated Program Planning Activity as those that carry particular leverage for the progress of fusion research. The specific issued addressed by the CE QPS experiment include:

1. Transport and Turbulence -- *What are the fundamental causes of heat loss in magnetically confined plasmas, and how can heat losses be controlled?*

2. Plasma Fluid Behavior and Macrostability -- *What are the fundamental causes and nonlinear consequences of plasma pressure limits in magnetically confined plasma systems?*

3. Wave-particle Interaction -- *What are the fundamental causes and nonlinear con-sequences of wave interactions with thermal and non-thermal particles?*

4. Plasma-wall Interaction -- *What are the fundamental processes occurring near the boundary of a confined plasma and how can the interaction between the plasma and material surfaces be controlled* ?

4. Relation of QPS to Other Stellarator Experiments.

QPS is both complementary and supportive of other stellarator experiments.

(1) Low aspect ratio: QPS is unique in having the lowest aspect ratio of any stellarator, ≈1/2 that of CHS, presently the stellarator with the lowest R/a_p. Figure 1 shows the aspect ratio of present and proposed world stellarators where the size of the circles is proportional to the cross sectional area of the plasma. QPS will allow significant extension of the data base on 3D equilibrium, stability, neoclassical and anomalous transport to low R/a_p.

Geometric effects become important at low R/a_p, leading to the need to study their impact on equilibrium and transport and to benchmark experiments with theory and computation. In addition, the quasi-poloidal symmetry is expected to lead to low poloidal viscosity and hence low rotation damping in the poloidal direction, as contrasted with low helical viscosity in HSX and low toroidal viscosity in NCSX.

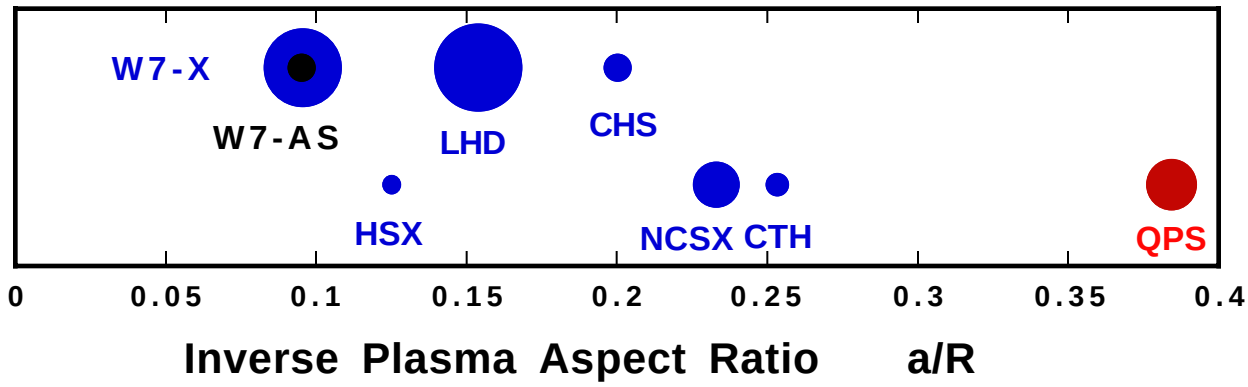

Figure 1. Inverse plasma aspect ratio for the world stellarators.

(2) Quasi-poloidal symmetry. The quasi-poloidal symmetry of QPS complements the quasi-axisymmetry of NCSX and the quasi-helical symmetry of HSX. It tests quasi-poloidal symmetry at ~1/4 the aspect ratio of W7-X. It will allow investigation of the physics associated with neoclassical transport reduction and the low poloidal viscosity associated with quasi-poloidal symmetry at an aspect ratio unattainable in any other stellarator experiment.

(3) Bootstrap current. The bootstrap current properties of QPS are expected to be quite different from those of NCSX, HSX and W7-X. The bootstrap current will be much smaller than in a quasi-axisymmetric device (NCSX) with the same ι and larger than that in W7-X for comparable device scale and plasma parameters. The mechanism for bootstrap control in QPS will primarily be the adjustment of the toroidal ripple relative to the smaller $1/R$ component of $|B|$. QPS is expected to have finite bootstrap current on-axis.

5. QPS Physics Design Optimization.

QPS is based on an optimized two-field-period, quasi-poloidally symmetric, low-aspect-ratio stellarator configuration with a low plasma (bootstrap) current. The base QPS configuration was determined through a systematic optimization procedure that balanced **physics requirements** (magnetic surface quality, ballooning/Mercier/kink/vertical stability, bootstrap consistency, and neoclassical confinement quality), **design goals** (low aspect ratio, maximum plasma waist for good neutral shielding, rotational transform $\iota = 1/q$ mostly from coils, and an $\iota(r)$ profile which avoids major resonances) and **engineering constraints** (adequate coil-plasma and coil-coil separation, minimum coil bend radius, and sufficient space in the center for an Ohmic current transformer and toroidal field [TF] coil legs). Figure 2 shows the last closed flux surface for the QPS reference configuration and the $|B|$ contours on that surface. Here magenta indicates the lowest $|B|$ value and red the highest. Figure 3 shows cross sections through the magnetic surfaces indicating the surface shaping, helical axis excursion, and global magnetic well.

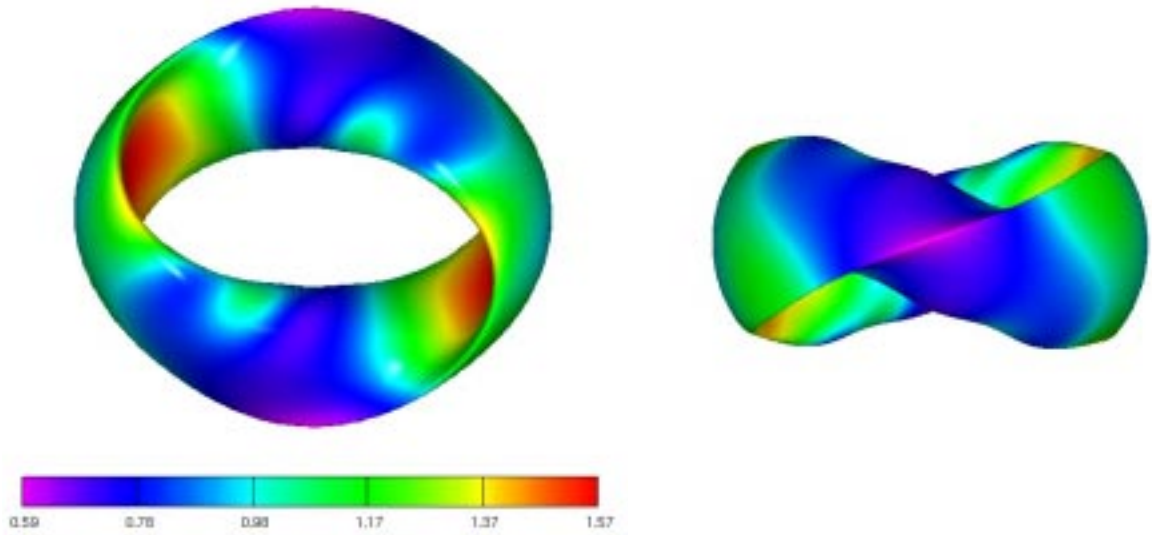

Figure 2. Top and side views of the QPS magnetic configuration.

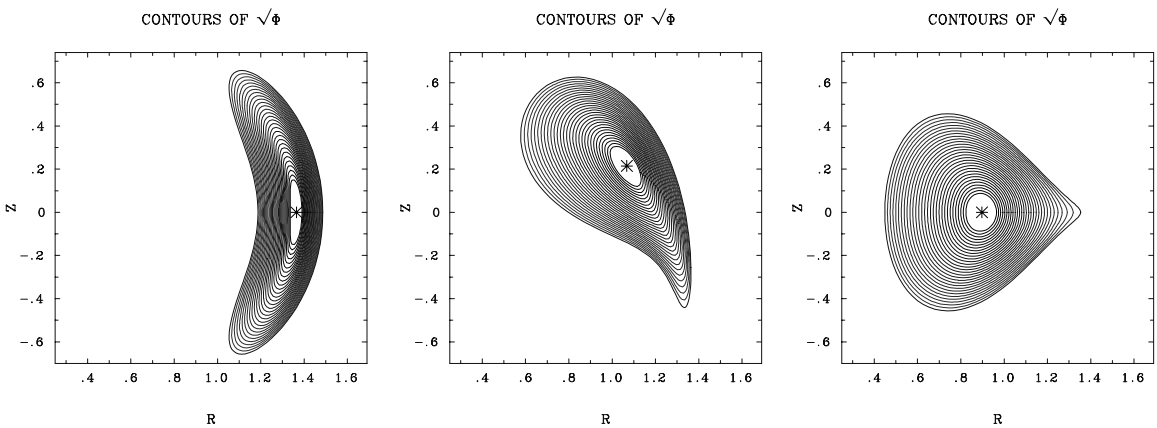

Figure 3. Nested magnetic flux surfaces at the beginning, at 1/4, and at 1/2 of a field period.

6. QPS Engineering Design Optimization.

A set of 16 modular coils (shown in Figure 4 consisting of four different coil shapes) has been optimized to recreate the reference QPS magnetic configuration shown in Figure 2. These coils satisfy the required physics constraints on allowable differences in the magnetic field on the LCFS and engineering constraints on allowable minimum distances between coils, between the LCFS and the coils, and across the middle for TF coil legs and ohmic current solenoid, and minimum bend radius for the coils). In addition there are two sets of vertical field coils, 12 toroidal field coils, and an ohmic current solenoid designed to provide the experimental flexibility needed to change the magnetic configuration properties (ι, shear, magnetic ripple, aspect ratio, etc.) for determining their effect on the plasma behavior (equilibrium, stability, transport, etc.). The coil sets, used to create the QPS configuration, including the existing large outer poloidal field coil set, are shown with the existing vacuum tank in Figure 5. The center stack contains the center legs of the toroidal field coils and the ohmic current solenoid; the return legs for the TF coils are outside the vacuum tank.

The absence of an internal vacuum vessel gives large access between coils for plasma heating and diagnostics.

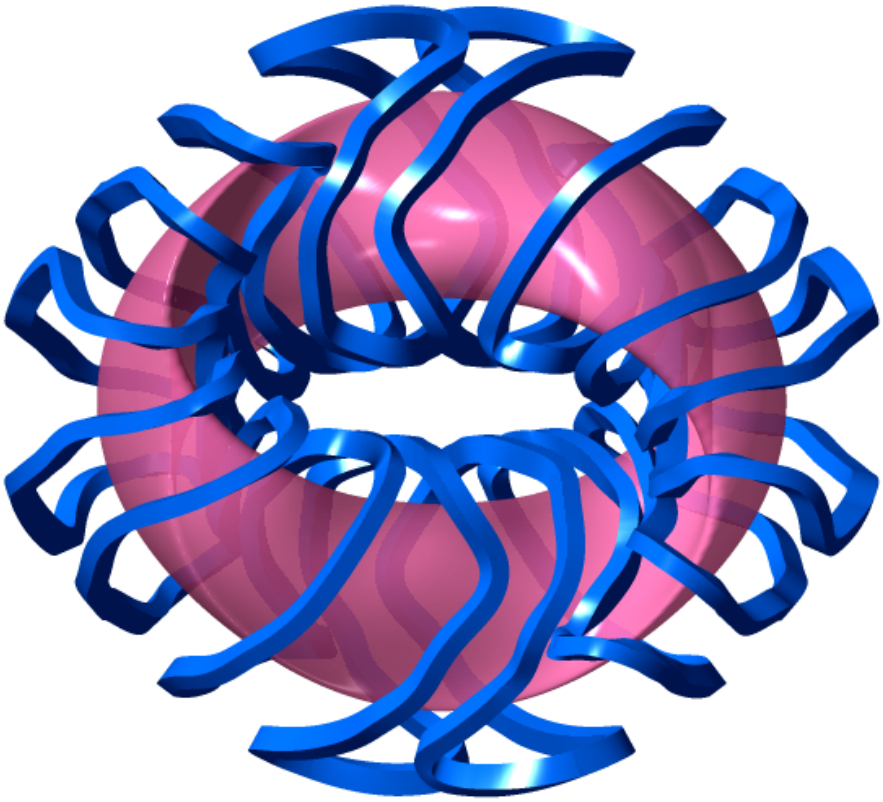

Figure 4. Top view of the modular coils and the LCFS for the reference QPS configuration.

The main device parameters are listed in Table 1. The ECH/EBW and ICRF transmitters, power supplies, and associated equipment are also existing equipment.

Table 1. QPS Device Parameters

Average Major Radius	0.9 m
Average Plasma Radius	0.35 m
Plasma Volume	2.1 m^3
Maximum On-Axis Average Magnetic Field	1 T for 0.5 s
Additional Toroidal Field	+/- 0.15 T
Ohmic Current Capability	+/- 50 kA
ECH/EBW Heating Capability	0.6-1.2 MW
ICRF Heating Capability	1-3 MW

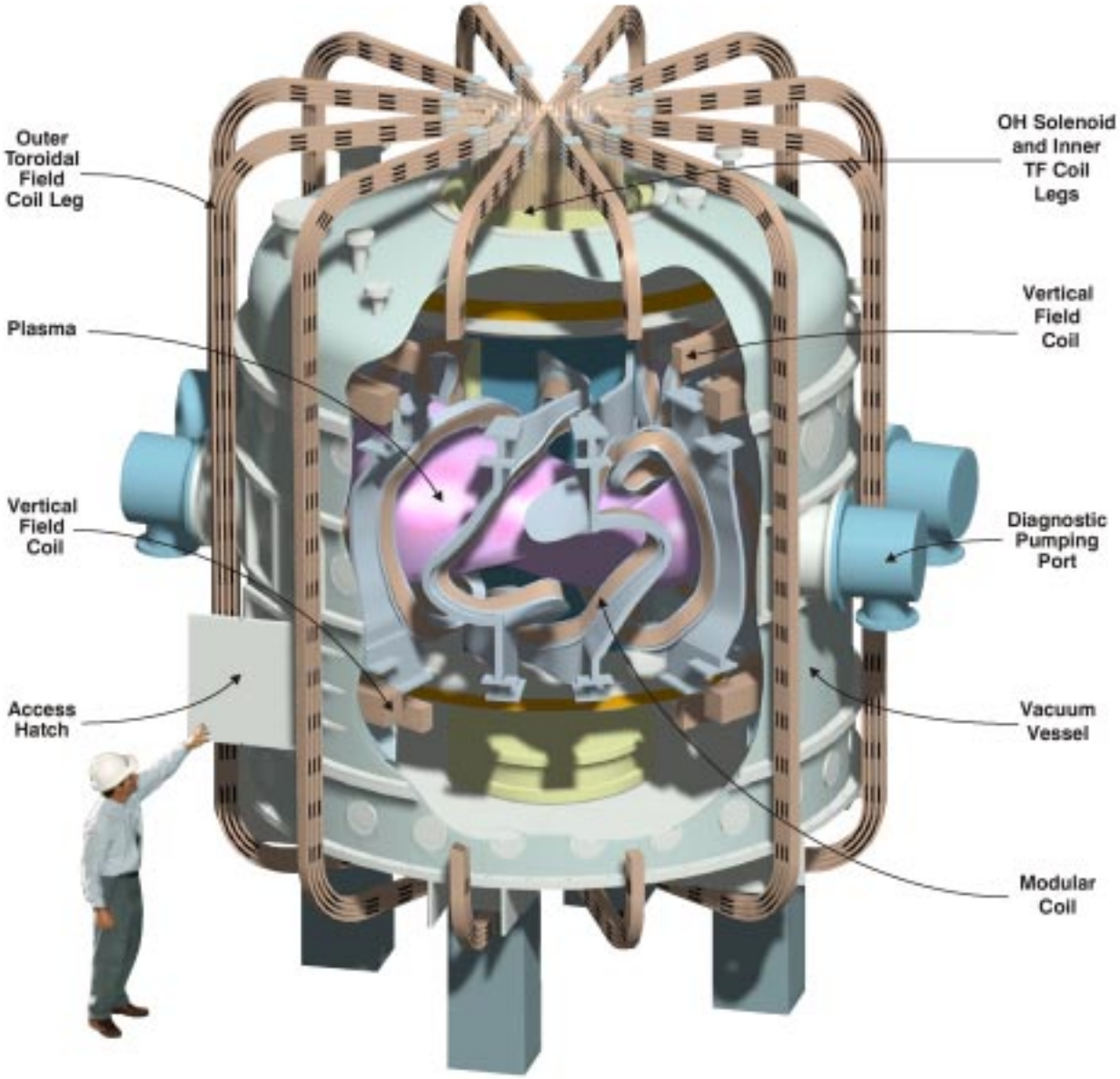

Figure 5. The QPS Experiment.

7. Projected Performance.

QPS should be limited by anomalous (turbulent) transport and the available heating power rather than instability β limits or neoclassical transport losses. Possible exceptions may occur if very low collisionality is reached in which electron neoclassical transport may dominate or if a large confinement improvement is achieved such that β can be pushed beyond stability limits. Either case would be very interesting to study.

Projected MHD stability limits for the reference QPS configuration are 2-3% from fixed-boundary equilibria and free-boundary equilibria (calculated directly from the coil sets). The reference

equilibria are stable to $\langle\beta\rangle$ > 2% for Mercier modes, but this criterion is routinely violated in stellarator experiments without significant effects. The stability comes from a global magnetic well, not shear, and the plasma should be stable against resistive tearing modes. Fixed-boundary equilibria are stable to $\langle\beta\rangle$ = 2.6% and free-boundary equilibria are stable to $\langle\beta\rangle$ = 2.4% against high-n ballooning modes. Similarly, fixed-boundary equilibria are stable to $\langle\beta\rangle$ > 3% and free-boundary equilibria are stable to $\langle\beta\rangle$ > 2% for external kink modes and vertical instabilities. Both types of equilibria are stable to $\langle\beta\rangle$ > 5% for neoclassical tearing modes because the bootstrap current is in the direction to reduce magnetic islands and stabilize these modes. Optimization of plasma pressure profiles and the currents in the different coil sets is expected to yield higher β limits as was found in related NCSX calculations. Higher β values may be possible depending on the effect of the instabilities on the energy confinement time.

Neoclassical confinement times are long enough that anomalous confinement should be the determining factor for energy confinement. For the high-collisionality (high-density low-temperature) plasmas expected at higher β with ICRF or EBW heating, the global neoclassical energy confinement time τ_E^{NC} *without* taking into account the expected ambipolar electric field is >6 times the standard (ISS-95) confinement time $\tau_E^{ISS\text{-}95}$. A large improvement in τ_E^{NC} is obtained for even a small electric field. For the low-electron-collisionality plasmas expected with ECH at low density, $\tau_E^{NC} \approx \tau_E^{ISS\text{-}95}$, but higher values may be obtained for τ_E^{NC} if energy scattering is included along with sufficient heating sources to maintain a steady state.

Assuming $\tau_E = 1.5\tau_E^{ISS\text{-}95}$ and density $n = 1.5n_{Sudo}$ as found in some stellarator experiments gives T_e = 2.1 keV, T_i = 0.4 keV, and $\langle\beta\rangle$ = 0.94% for 1.5 MW ECH at B = 1 T. For 2 MW ICRF + EBW, T_e =0.5 keV, T_i = 0.5 keV, and $\langle\beta\rangle$ = 3%. If $\tau_E = 2.25\tau_E^{ISS\text{-}95}$ as found in W 7-AS, these values should be multiplied by a factor of 1.5. If no improvement over ISS-95 values can be obtained, these values should be divided by a factor of 1.5. In either case the available heating power allows the plasma parameters needed for the QPS physics objectives.

8. Plans for Completing the Design and R&D.

The reference plasma and coil configuration are adequate for the QPS mission, but further improvements have been identified that can be made in both; these are discussed in Chapters 3 and 4. Refinement of the plasma and coil configuration will be pursued during the remainder of 2001 to improve the physics capabilities and reduce the cost of the coils. Chapter 9 describes a preconceptual design that should be adequate for the QPS mission, but improvements are needed in the modular coils, the force support structure, the central stack with the TF coil center legs and Ohmic current solenoid, and fabrication techniques for the modular coils, as discussed in that chapter. The major emphasis in the engineering studies will be increasing the confidence in the design and reducing the cost of building QPS. These physics and engineering design tasks, described in Chapter 12, are needed to prepare for a Conceptual Design, Cost, and Schedule Review, planned for April 2002.

9. Cost and Schedule.

An accurate estimate of the cost of QPS can not be obtained until a conceptual design is completed. However, the estimate based on the present preconceptual design using the same costing approach and assumptions as in the NCSX study gives an estimated total project cost of 11.5 M$ in FY-1999 $ (13.9 M$ in as-spent dollars), of which the largest component is the modular coils. Various cost reduction schemes were investigated including reducing the size of the modular coil set. While cost savings can be realized through taking advantage of the R&D needed for NCSX and staging the heating and diagnostic systems, reducing the major radius of the modular coil set is not effective in reducing the overall cost because the coil cross sections interfere as *R* decreases. Reducing the coil cross section by increasing the coil current density further would require operating the modular coils at cryogenic temperatures, necessitating a complex and expensive internal vacuum liner to prevent absorbed condensables on the coils from flooding the plasma.

The pace of the QPS project would depend on the DOE budget preparation schedule and the annual budget for the QPS program, which is requested at the high end of the range defined by FESAC for a CE-level program. Figure 6 gives the projected funding profile. The earliest time that actual fabrication of QPS could begin is October 2003. This date is determined by the Project Validation Review in May 2002 for inclusion of QPS construction in the FY-2004 budget, which follows the April 2002 Conceptual Design, Cost, and Schedule Review. Approval to construct QPS would depend on a successful outcome of these reviews. Title I and Title II design, R&D, and development of prototype modular coils and validation of fabrication techniques would occur in FY-2003, but award of construction contracts must await the beginning of FY-2004. First plasma would occur at the end of FY 2006.

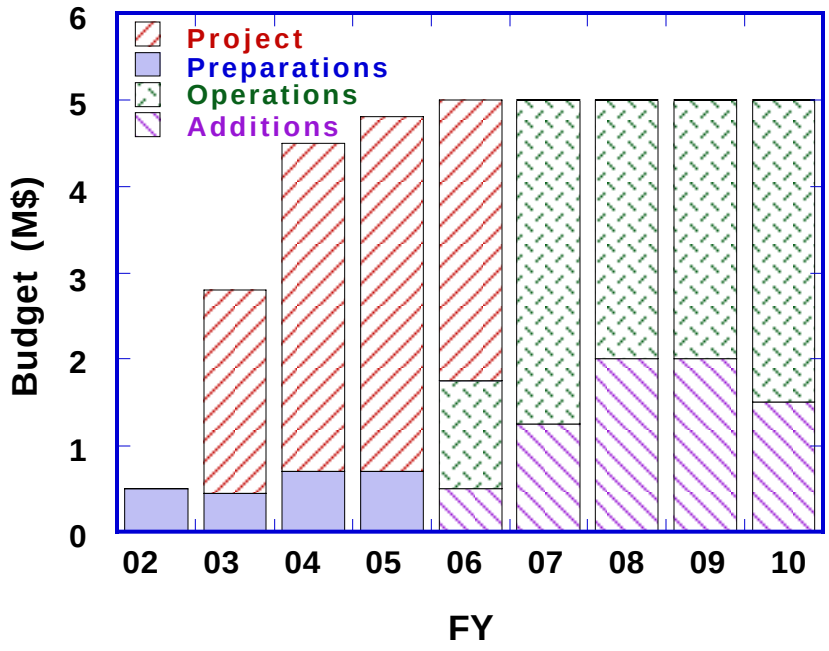

Figure 6. Projected QPS spending profile.

10. Program Management.

The QPS is proposed by Oak Ridge National Laboratory with Princeton Plasma Physics Laboratory as the principal collaborator. These two national laboratories are collaborating in the design, operation, and physics research for the QPS project. ORNL has the lead responsibility for project execution and PPPL provides important support in key physics and engineering areas. The University of Texas at Austin has been a partner in the development of the QPS concept and strong university participation in the program will be a goal. The ORNL-led team of senior physicists and engineers has extensive experience in stellarator design, construction, and operation, as well as in other fusion projects much larger than QPS.

In the conceptual design and fabrication phases, stronger participation with a university and PPPL will be sought to broaden involvement and reduce costs. ORNL will continue to lead the team and necessarily be responsible for all procurement, fabrication, installation, testing, and commissioning in these phases. In the experimental operations phase of the QPS program, ORNL would further broaden participation with collaborating universities and other institutions. This model was used successfully in the ATF program and led to numerous student theses. It also fits well with ORNL's goal for broader participation of universities in ORNL research. It is anticipated that ORNL technicians will be needed for operations and facility modifications, but ~1/2 the participants in the physics program will be from PPPL, universities, and foreign institutions.