QPS PAC Chosen to Meet QPS Needs

- **QPS PVR and NCSX PAC**
  - H. Weitzner (chair); D. Anderson; S. Knowlton
- **NCSX PAC**
  - B. Blackwell; S. Luckhardt; S. Okamura; A. Weller
- **PPPL NCSX Team**
  - H. Neilson; W. Reiersen; M. Zarnstorff; H. Kugel
- **NSTX**
  - S. Kaye

QPS Project Advisory Committee meeting

Wednesday, Dec. 11
8:30 PAC Executive Session

8:50 Welcome and charge -- S. Milora

9:00 QPS Overview -- J. Lyon

10:00 QPS Experimental Plan -- L. Berry

10:45 Break

11:00 Physics Properties and Flexibility of QPS Configuration -- D. Spong

12:00 Lunch and PAC Executive Session

1:00 Engineering Design Overview -- B. Nelson

2:30 Power and Particle Control and Vacuum Conditions in QPS -- P. Mioduszewski

3:15 Break

3:30 Project Implementation -- B. Nelson

4:30 PAC Executive Session

5:30 PAC's Questions for the QPS Team

Thursday, Dec . 12
8:30 PAC Executive Session

9:00 QPS Team Response to PAC's Questions

10:00 PAC Executive Session and Report Preparation

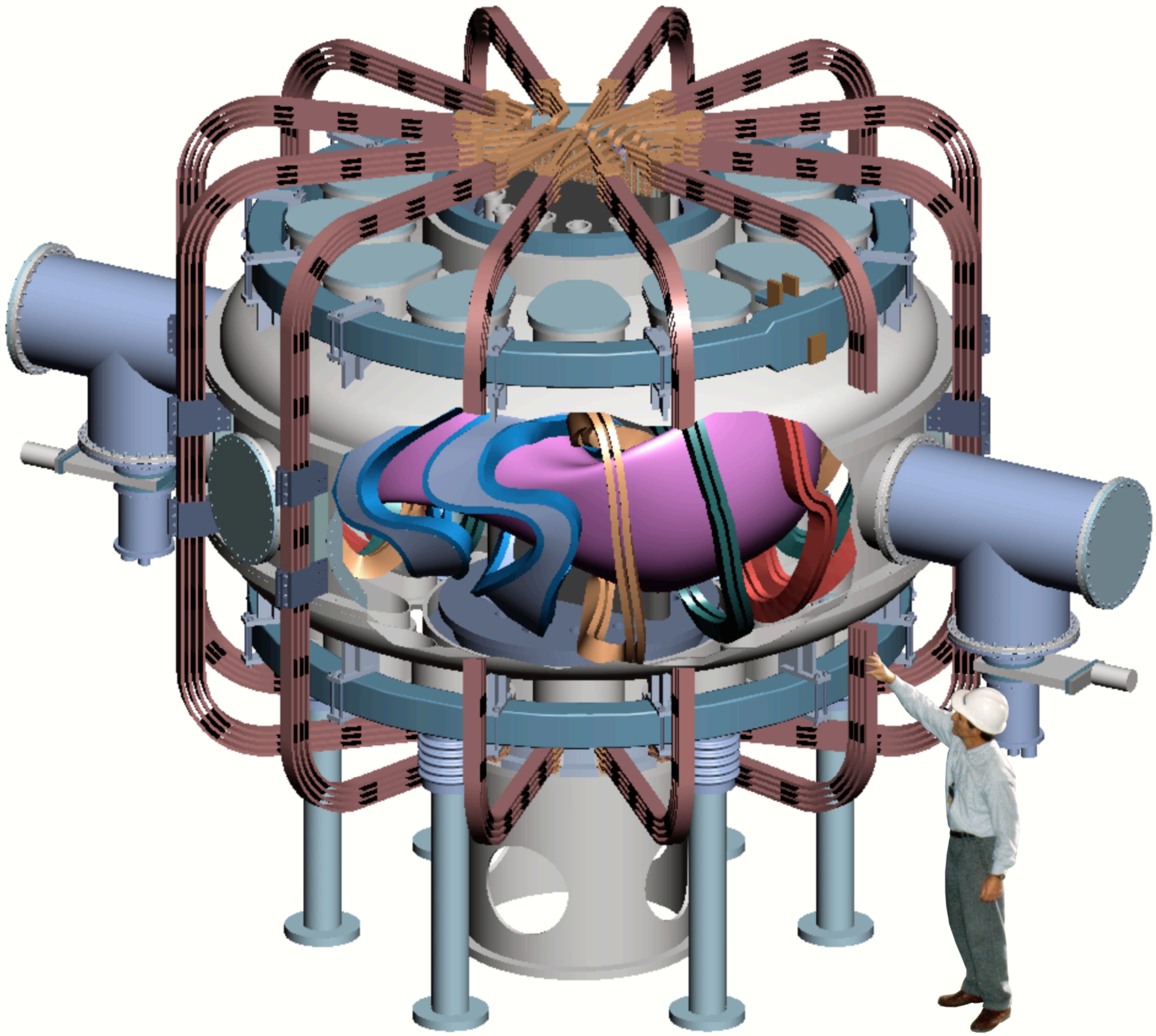
3:00 PAC Reports Draft Findings to QPS Team

QPS Overview

J. F. Lyon, ORNL
representing the QPS Team

QPS PAC meeting Dec. 11, 2002

THE QUASI-POLOIDAL STELLARATOR



- $\langle R \rangle = 0.9$ m
- $\langle a \rangle = 0.34$ m
- $V_{pl} = 2.1$ m^3
- $B_{mod} = 1$ T (1 s)
- $B_T = \pm 0.2$ T
- $P = 1$-3 MW

Multi-Institution QPS Team

- ORNL – D.B. Batchelor, R.D. Benson, L.A. Berry, M.J. Cole, R.H. Fowler, P. Goranson, E.F. Jaeger, S.P. Hirshman, J.F. Lyon, P.K. Mioduszewski, B.E. Nelson, D.A. Rasmussen, J.A. Rome, D.A. Spong, D.J. Strickler, J.C. Whitson, D.E. Williamson
- PPPL – A. Brooks, G.Y. Fu, S. Hudson, D. Mikkelsen, D.A. Monticello, N. Pomphrey
- U. Montana – A.S. Ware, A. Deisher, D. Heskett, J. Hoff, L. Todd, J. Liu
- Universidad Carlos III de Madrid, Spain – R. Sanchez
- U. Tennessee – T. Shannon, D. Irick, M. Madhoukar
- ORNL/GA/Auburn collaboration on equilibrium reconstruction

Large overlap with the NCSX Team

ORNL Responsibility on NCSX

- WBS 1. Stellarator core -- B. Nelson
  - WBS 11. in-vessel components -- P. Goranson
  - WBS 12. vacuum vessel -- P. Goranson
  - WBS 13. conventional coils -- D. Williamson
  - WBS 14. modular coil design and analysis -- D. Williamson
  - WBS 16. coil services design -- D. Williamson
  - WBS 19. stellarator core management & integration -- B. Nelson
- Deputy project manager for program -- J. Lyon
  - ORNL WBS 84 elements: project physics
research preparations

Relationship to NCSX Project

- The U.S. Compact Stellarator Program
  - NCSX explores quasi-axisymmetry and connection with tokamak understanding; the PoP CS experiment
  - QPS explores quasi-poloidal symmetry and connection with W 7-X approach at low aspect ratio; a CE experiment
- Many fabrication issues in common with NCSX
  - modular coil fabrication approach
  - QPS fabrication start is a year later than NCSX, benefits from the NCSX R&D
- Common tasks for NCSX and QPS expedite transfer of experience in both the project and the program
  - synergism in design and analysis tools and in the basic design approach

April 2001Physics Validation Review

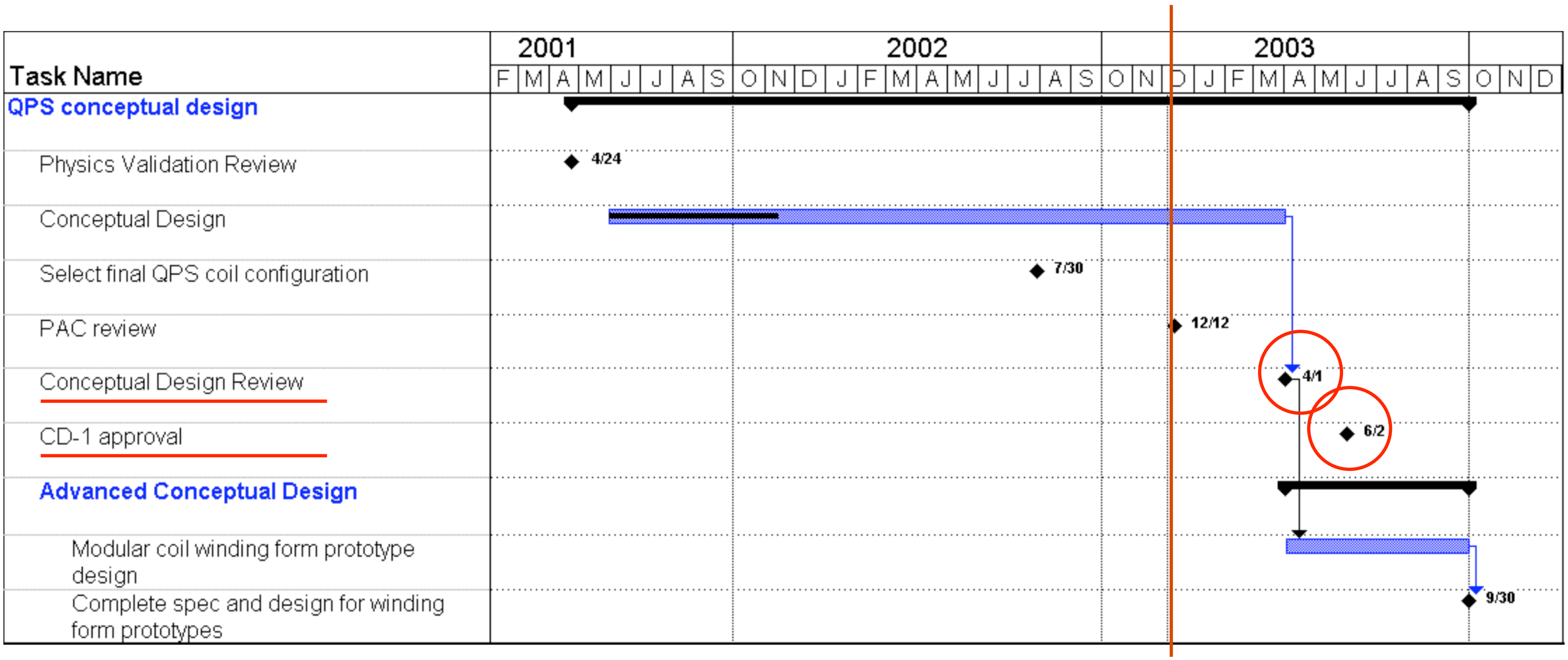
- **PVR Panel Recommendation**
  - The combination of low aspect ratio and quasi poloidal symmetry is an attractive stellarator option
  - The QPS properties fully justify proceeding with the QPS project
- **PVR Panel Comment**
  - Committee encourages recent improvements in the coils and configuration before a design freeze is required
- **PVR Panel raised a number of issues to be addressed by the QPS Team**

DOE Approved QPS Mission Need and CD-0

- **Explore the physics consequences of quasi-poloidal symmetry**
- **Extend compact stellarator configurations to much lower aspect ratio**
- **Complement NCSX in completing the basis needed for advancing the development of the compact stellarator concept to the next stage**

Next Step is CDR and CD-1

- Refine design and physics assessments
- Manufacturing and winding studies
- Update cost estimate and schedule for CDR
- Prepare for modular coil R&D in FY 2004



QPS CDR Will Address the Same General Topics as for NCSX CDR

- **Scope, cost and schedule to some extent, but will concentrate more on**
  - **the technical issues that the team has identified as a result of the conceptual design studies**
  - **plans for addressing these issues in the future**

We Ask Your Advice on Our Preparations for the QPS CDR

- **Are we on the right track for an April CDR?**
  - comment on physics and engineering studies thus far
  - comment on the work we plan before the CDR
  - are we addressing the PVR issues?
- **Are there areas where we need more emphasis or arguments that need strengthening?**
- **Are there areas that we should be concerned about or have not addressed?**
- **Although the CE-level QPS is smaller in scope (field, power, physics mission) than the PoP NCSX, we are trying to maintain the high standards we are using for NCSX but at 1/10 the budget level**

What We Plan to Cover Today

- **General Overview and Project Issues -- J. Lyon**
- **QPS Experimental Program -- L. Berry**
  - physics we will pursue and experimental plan to accomplish it
  - requirements on plasma and device parameters, heating, diagnostics
- **Physics Properties & Flexibility of QPS Configuration -- D. Spong**
  - performance of the base configuration meets experimental needs
  - configuration has the flexibility needed to address QPS physics issues
- **Engineering Design Overview -- B. Nelson**
  - credible design exists that meets the QPS program needs
- **Power and Particle Handling -- P. Mioduszewski**
  - vacuum conditions and divertor will meet experimental needs
- **Project Implementation -- B. Nelson**
  - QPS schedule, fabrication plans & options, infrastructure are satisfactory

Overview Topics

- Review of motivation for the QPS Project
  - QP symmetry and low-R/a
- QPS description
  - configuration properties and flexibility
  - experimental plan and capabilities
  - engineering design and modular coils
- Plans
  - schedule, R&D and cost reduction measures
  - plans for completing the project
- Disposition of PVR Issues

Motivation for the QPS Project

- **Explore potential advantages of QP symmetry**
  - neoclassical transport reduction
  - poloidal flow shear to reduce anomalous transport
  - reduction of bootstrap current
  - ballooning stability
  - □ extend understanding of confinement understanding
  - □ basis for a higher-□ QP configuration?

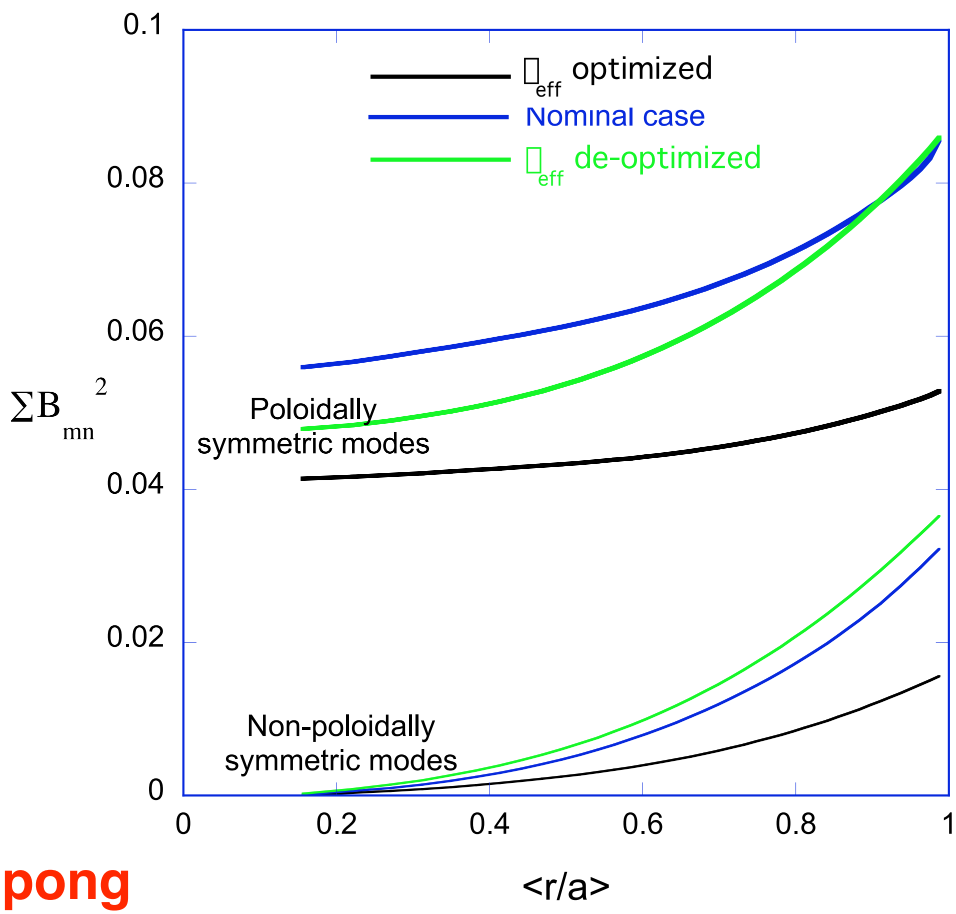
- **Explore limits of very low stellarator aspect ratio**
  - benchmarking and improvement of 3-D theory
  - □ basis for a more compact stellarator reactor?

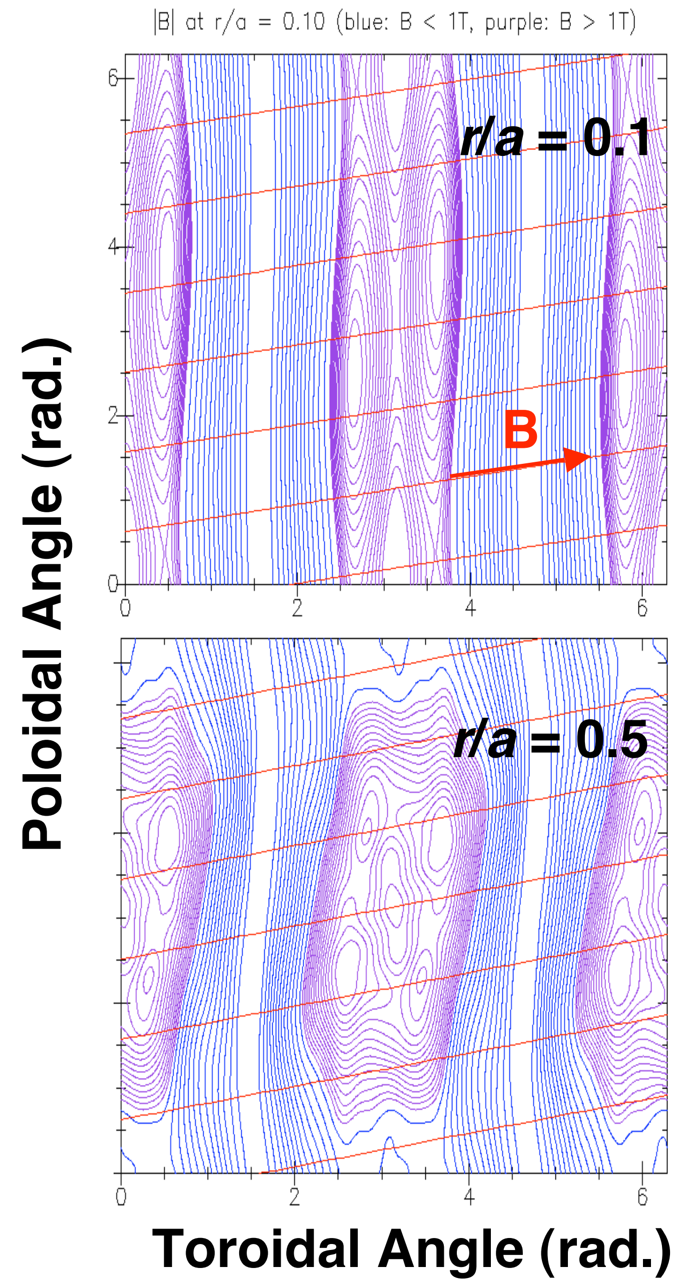
Poloidal Symmetry

- **For a toroidal system in the limit of *exact* poloidal (θ) symmetry, $p_\theta = mv_\theta + eA_\theta$ is conserved**
  - **orbit excursions from a magnetic 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)**
  - **there is no flow damping in the poloidal direction**
  - **the bootstrap current is reduced by □/N**
  - **the implied smaller poloidal flux does not necessarily lead to increased neoclassical losses because the limiting orbit size is the toroidal gyroradius, which remains quite small**

Quasi-Poloidal Symmetry

- **While *exact* poloidal symmetry is not possible in a 3-D configuration, approximate quasi-poloidal symmetry exists**
  - **the dominant components of the |B| Fourier series are poloidally symmetric in flux coordinates**

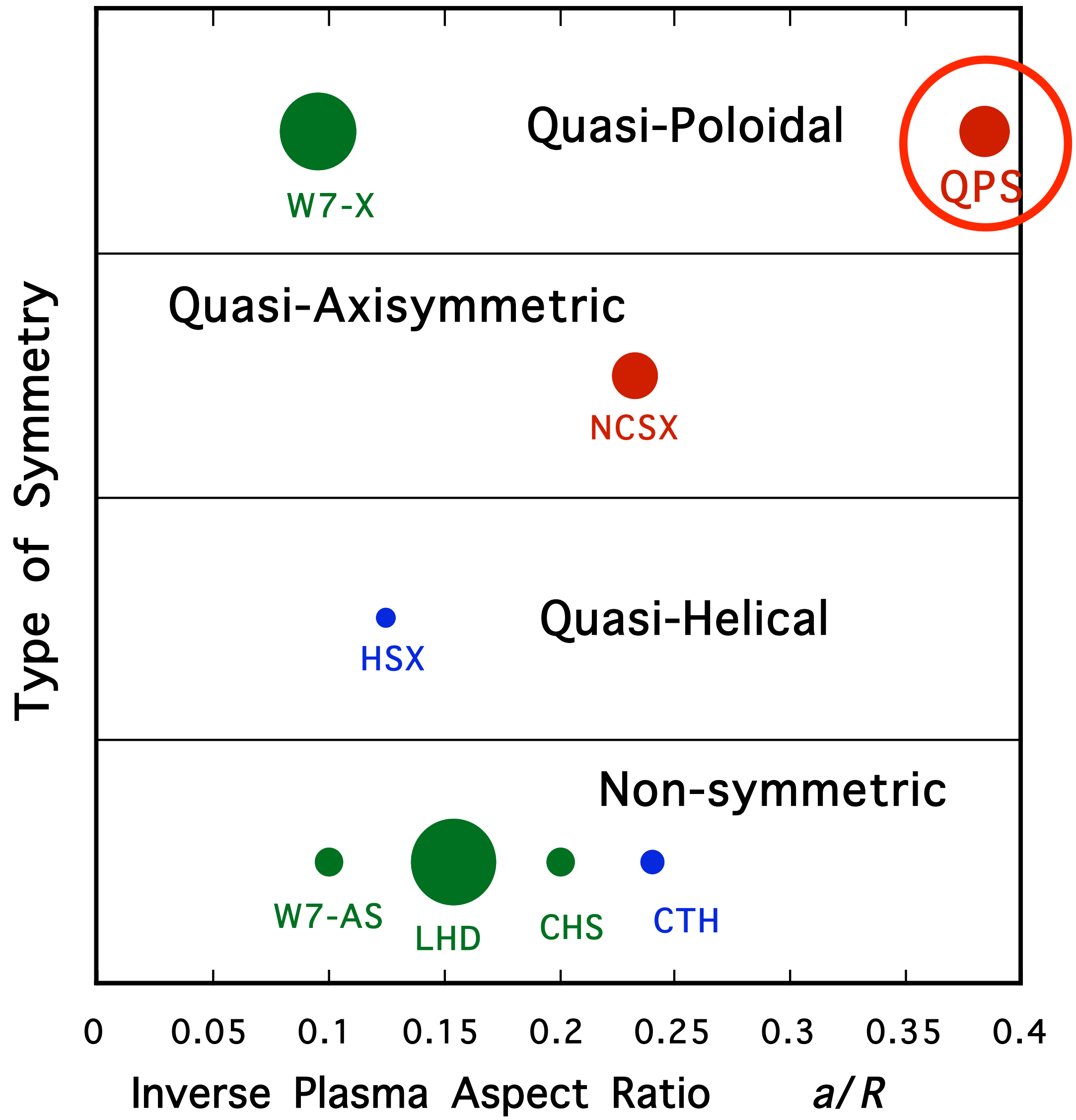




D. Spong

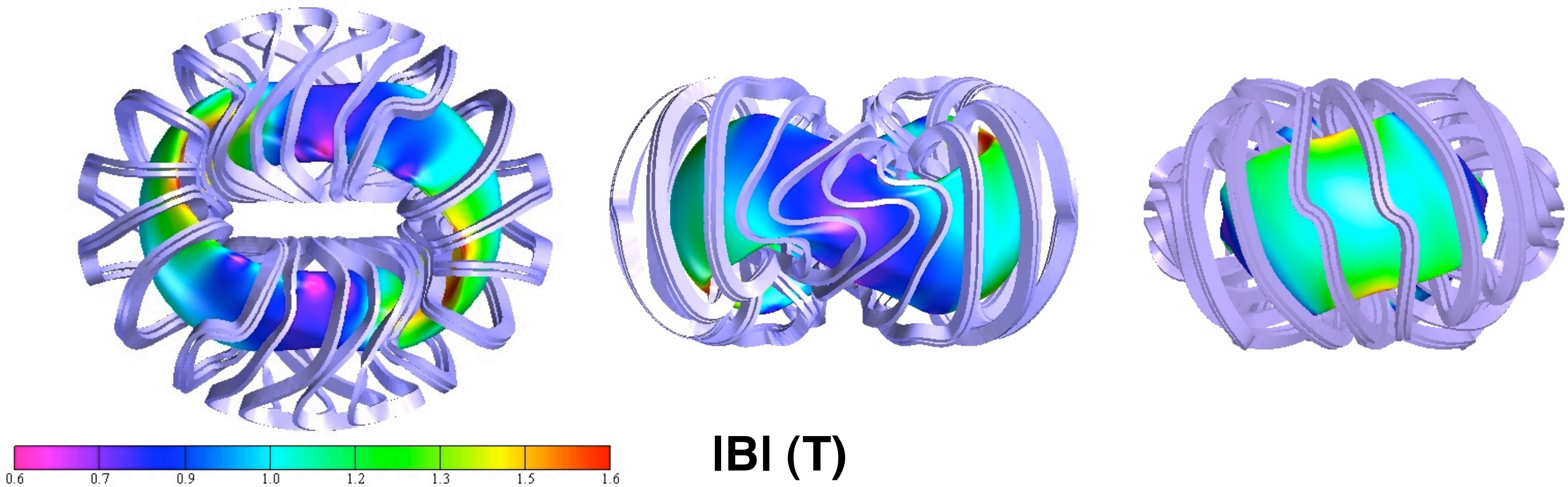
QPS Fills Niche in World Stellarator Program

- **Low aspect ratio and quasi-poloidal symmetry**

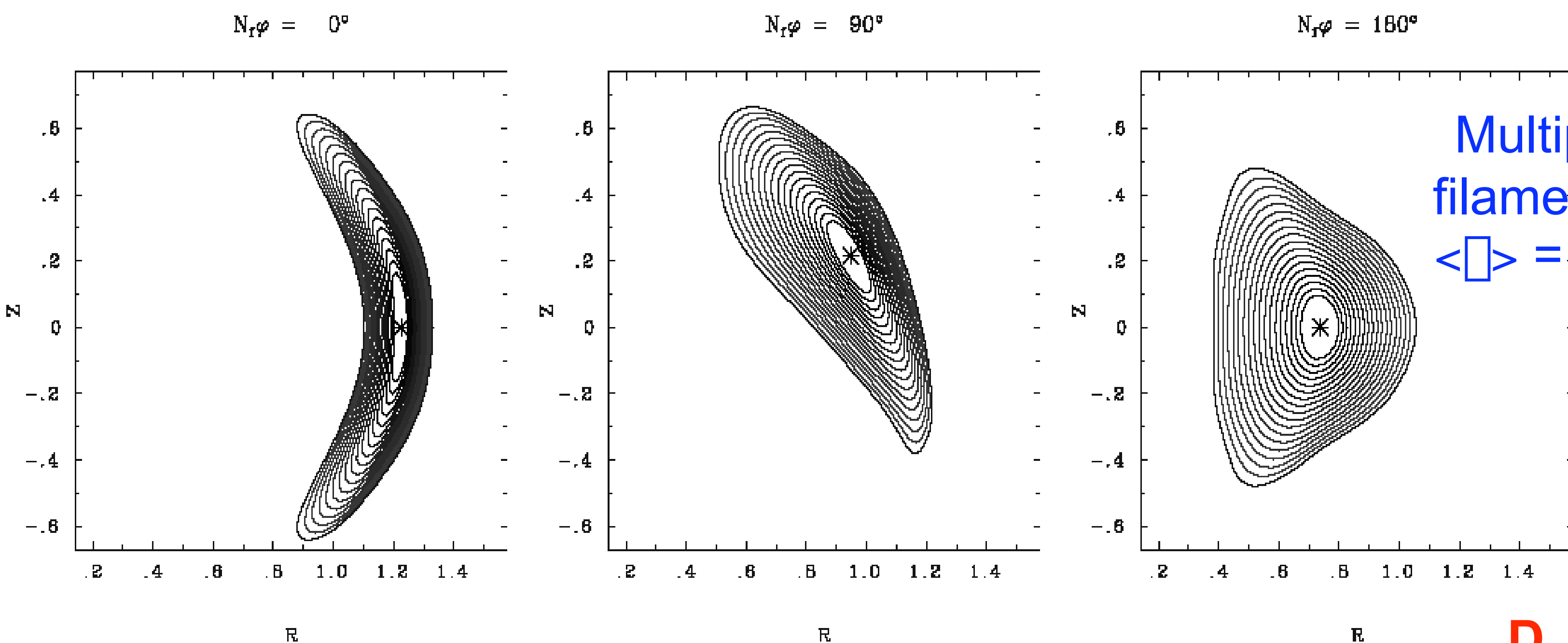


area of a dot is proportional to the cross sectional area of the plasma

QPS Geometry



|B| (T)

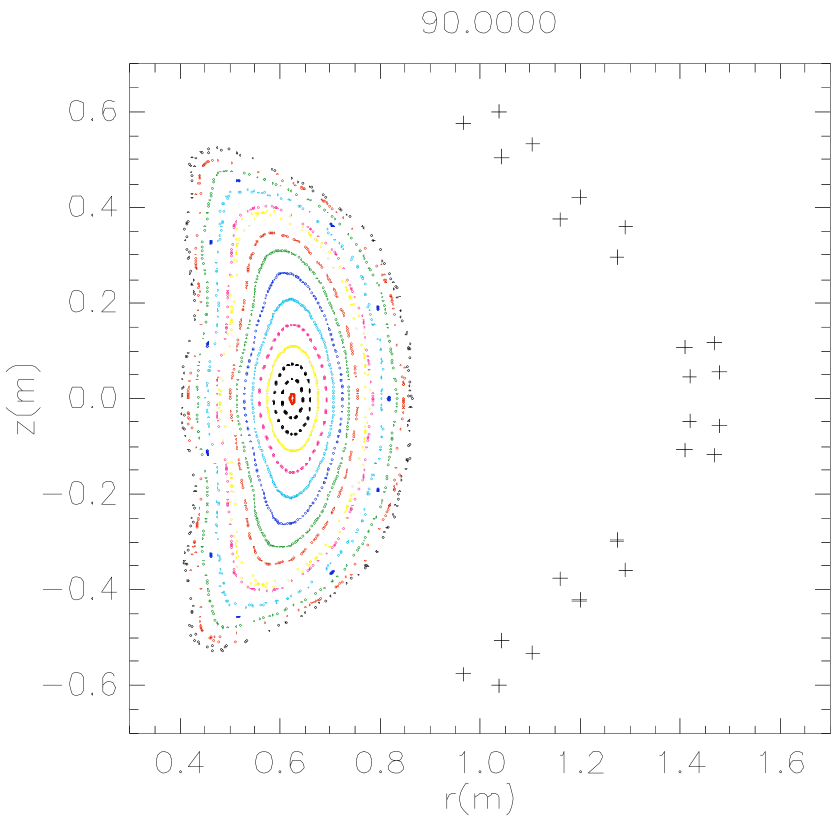


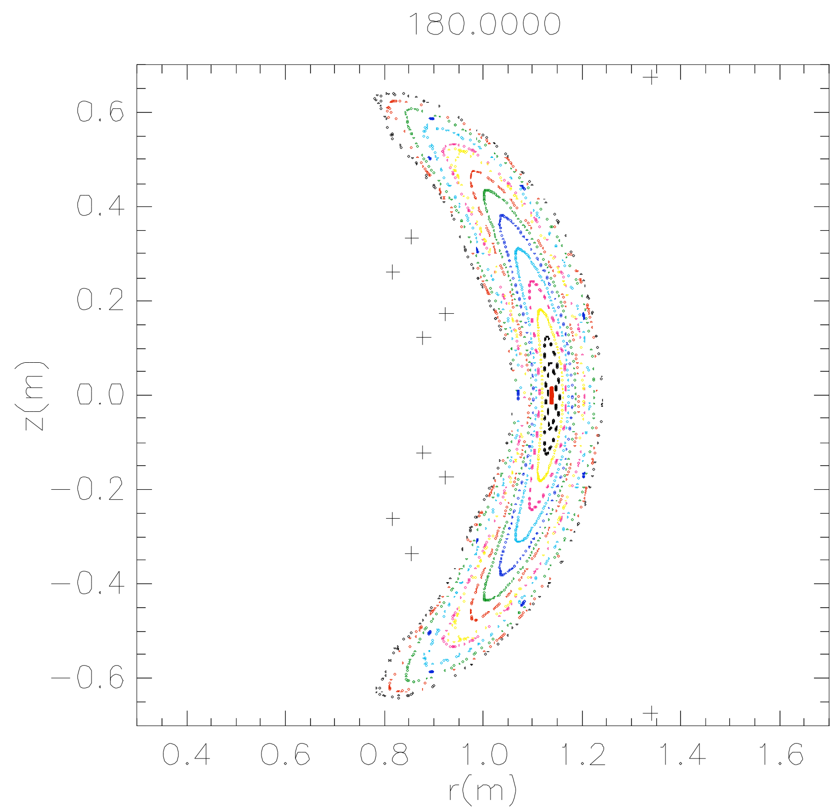
Multiple filaments, <β> = 2%

D. Spong

QPS Has Good Vacuum Flux Surfaces

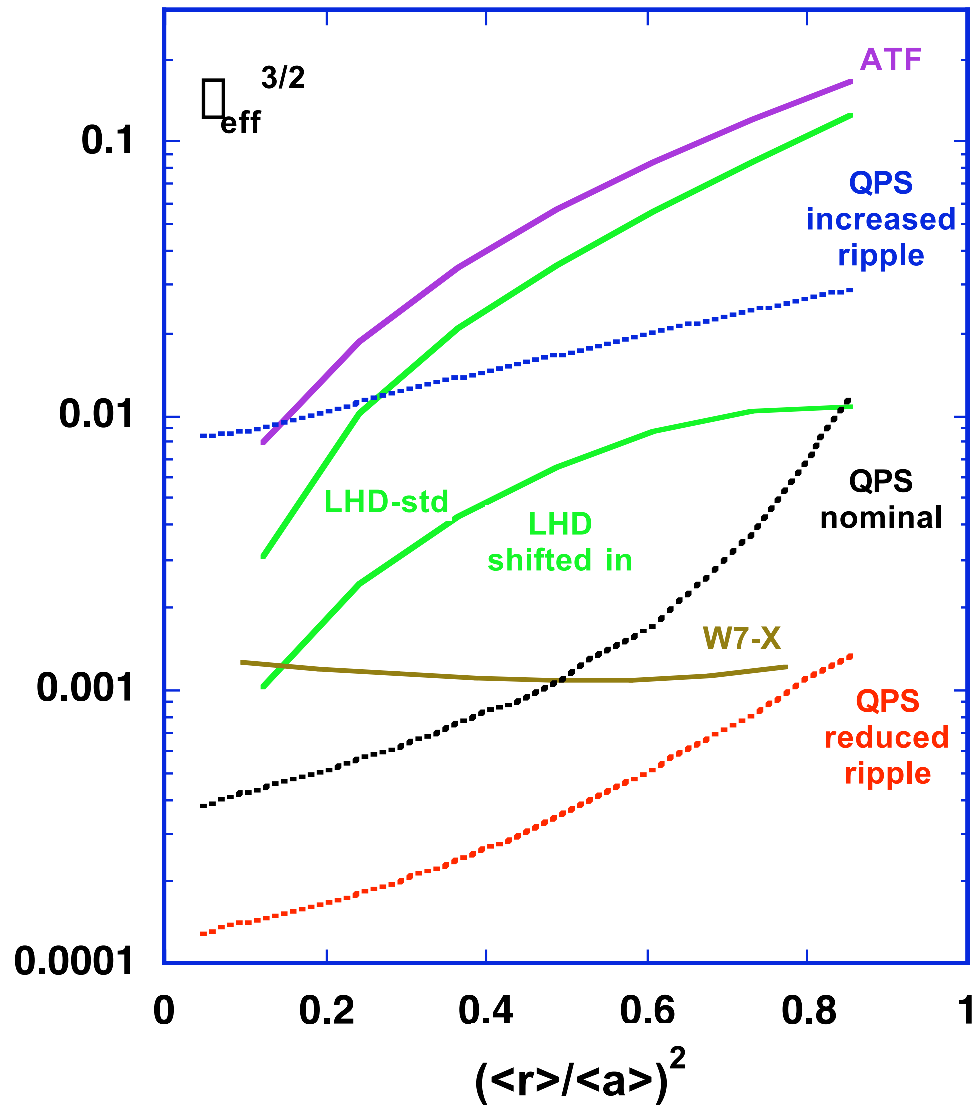
- **4-filament calculation with reversed TF coil currents**





QPS Coil Flexibility Allows Tests of Neoclassical Transport

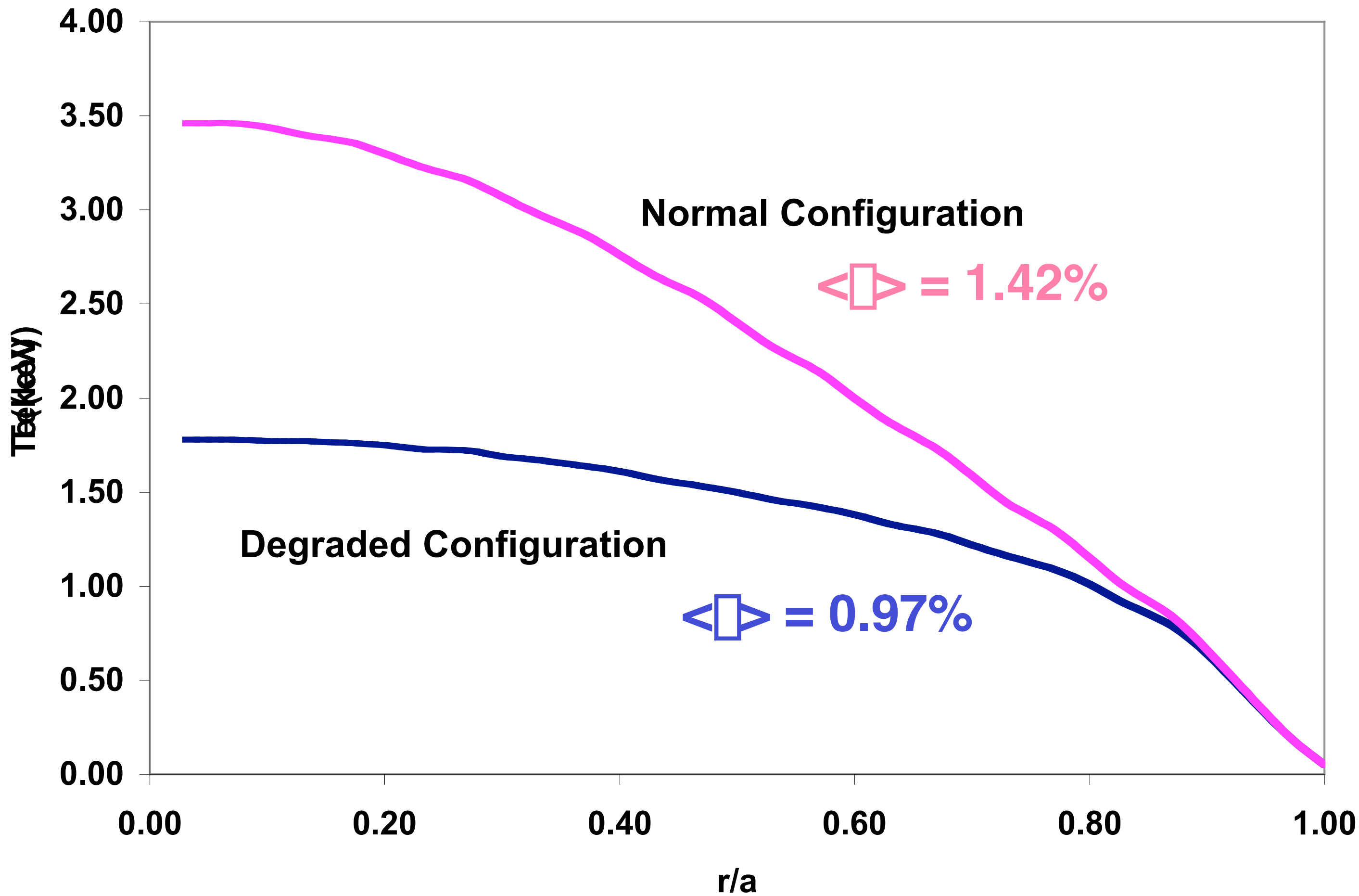
- □$^{3/2}$ is coefficient of 1/□ neoclassical transport
- Changing currents in QPS coils varies neoclassical transport by factor 20-80
- Can change from neoclassical being dominant over plasma core to not being significant



D. Spong

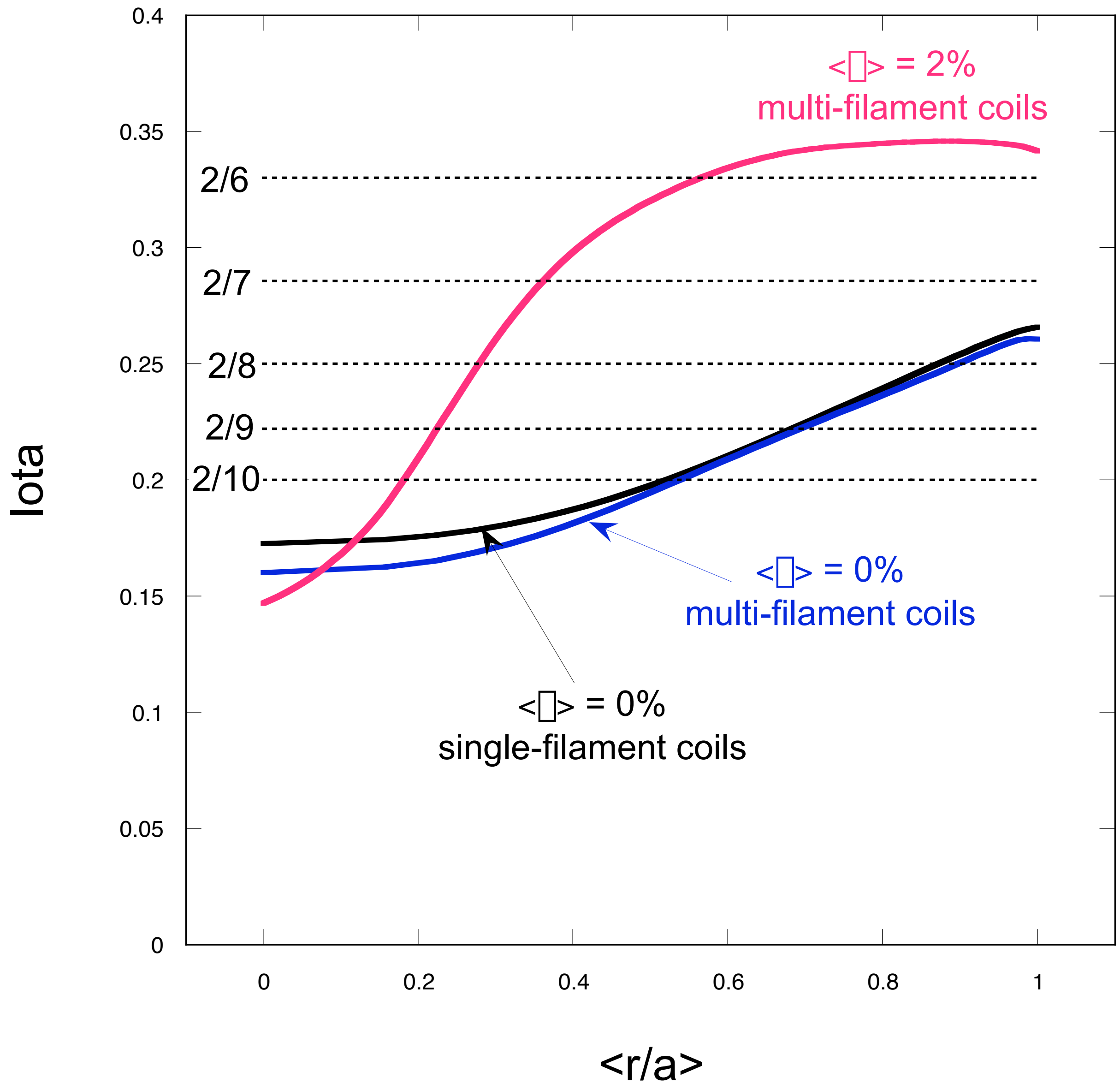
Coil Flexibility Allows Tests of Neoclassical Transport

Example: for same B (0.5 T), P (1 MW), and anomalous □, increasing effective ripple reduces $T_e(0)$ and flattens $T_e(r)$

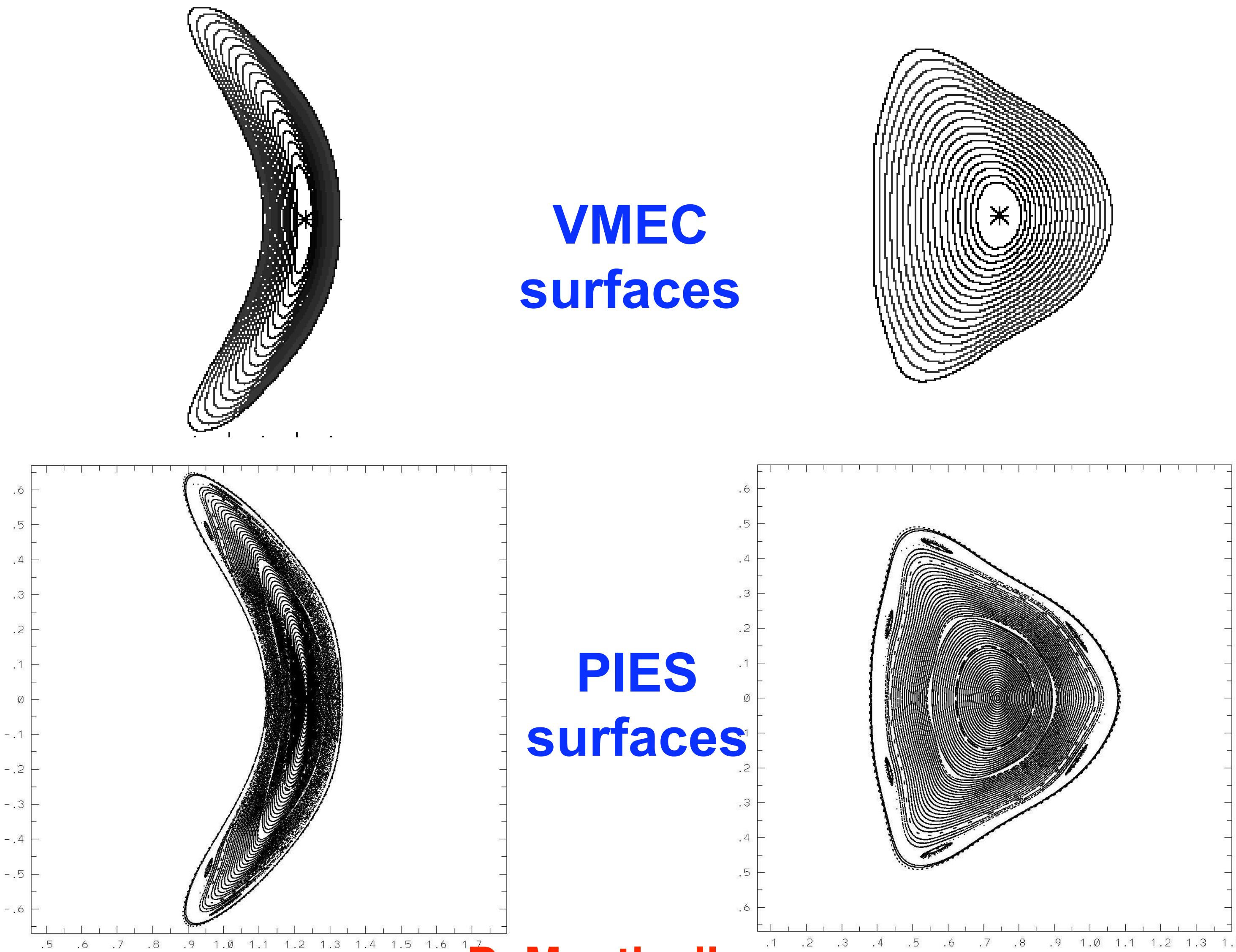


D. Mikkelsen

Finite Plasma Pressure Introduces Strong Central Shear



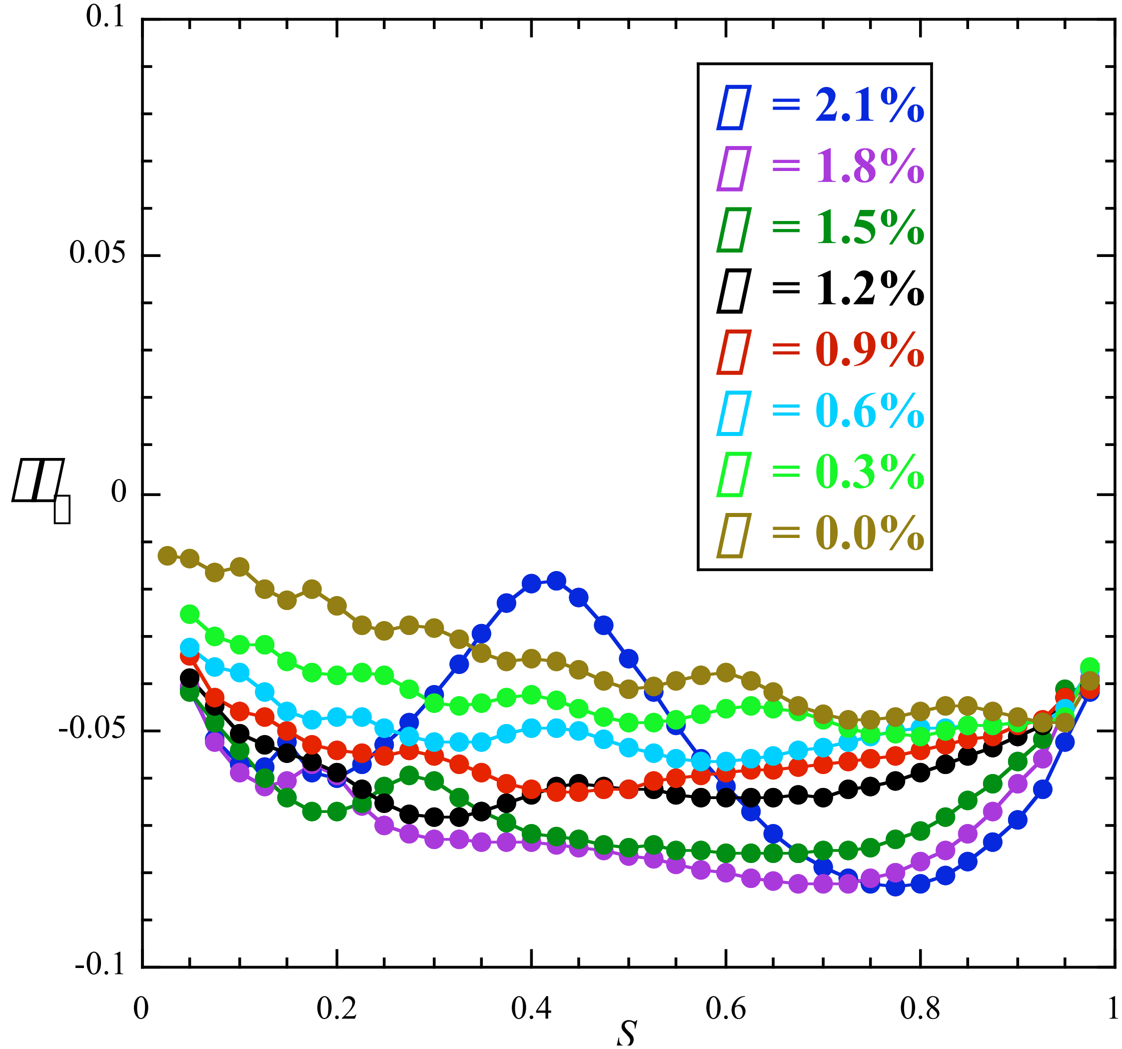
□= 1/3 Surfaces at <□> = 2% Introduce Only Small 2/6 Islands



D. Monticello

A Stable Path Exists from Vacuum to β > 2.1%

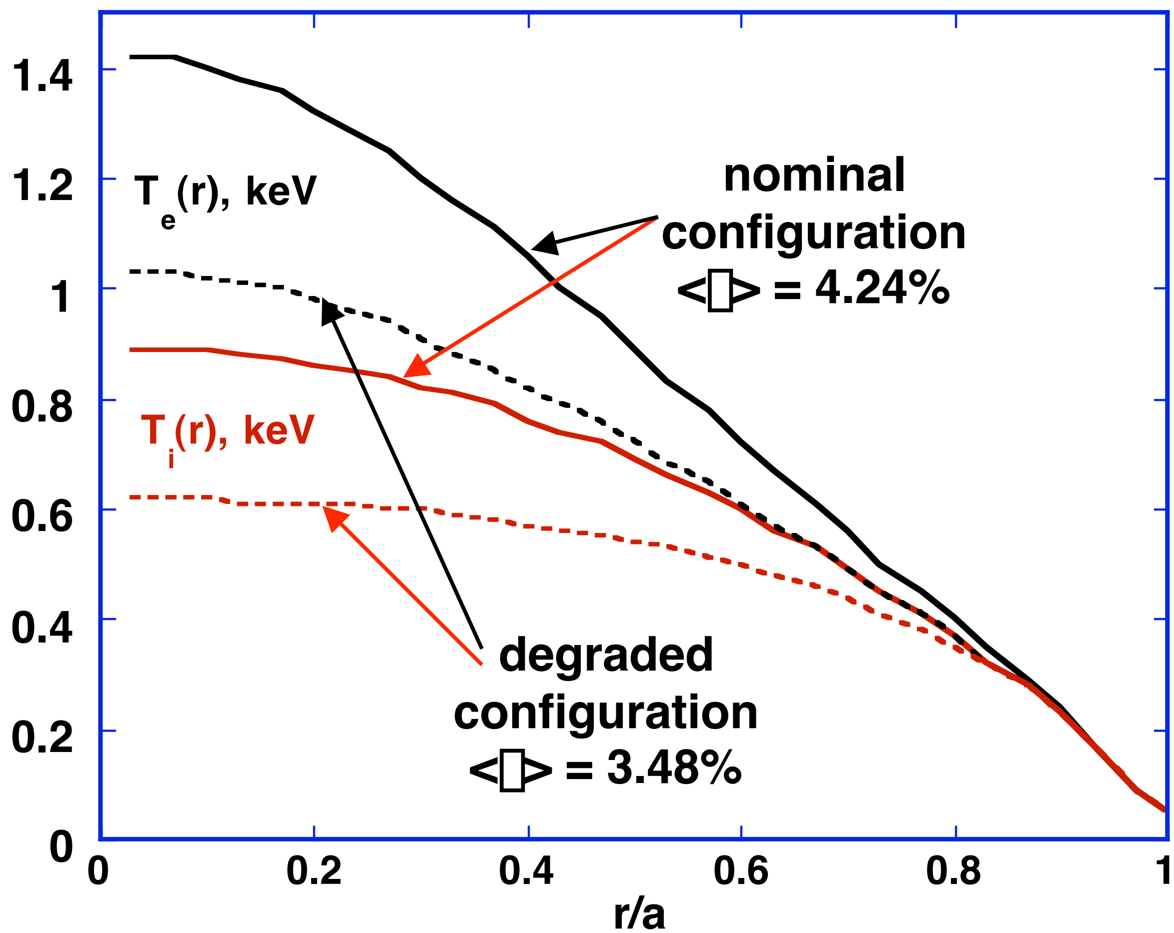
- **Infinite-n ballooning growth rates vs. S = (r/a)^2 with fixed (unoptimized) plasma pressure profiles**



A. Ware

Coil Flexibility Allows Tests of Neoclassical Transport at Higher Beta

Example: for same B (1 T), P (2.5 MW), and anomalous , increasing effective ripple reduces T(0) and flattens T(r)

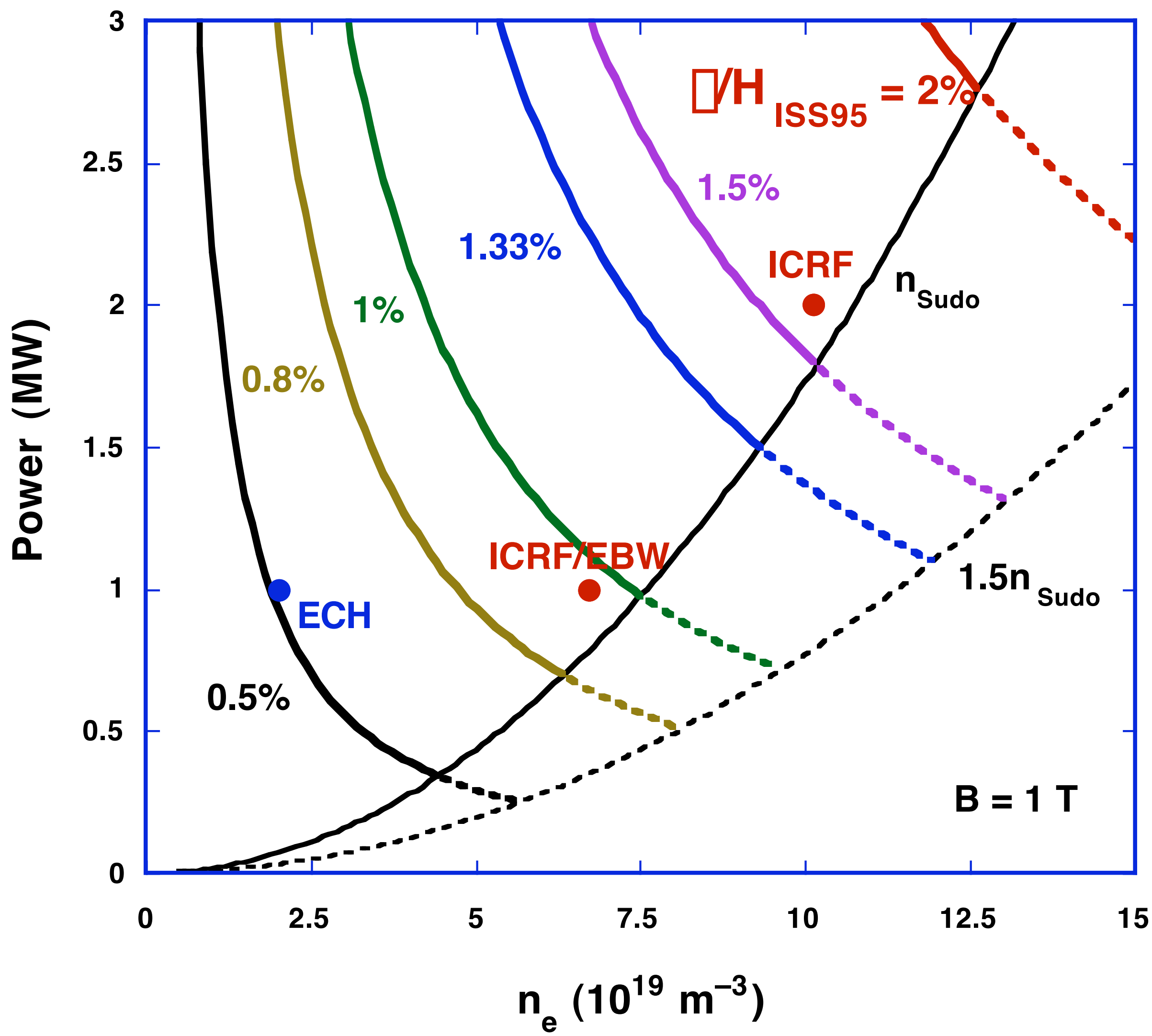


D. Mikkelsen

QPS Program: Extend Stellarator/Toroidal Physics Understanding to Very Low *R/a* and Quasi-Poloidal Symmetry

- **Anomalous transport, internal transport barriers, and flow shear**
- **Reduction of neoclassical transport**
- **Impact of poloidal flows on enhanced confinement**
- **Equilibrium quality (islands, ergodic regions) at *R/a* ~ 2.6**
- **Flux surface robustness with □ and dependence of bootstrap current on configuration properties**
- **Ballooning □ character and limits**

P = 1-3 MW Gives the Parameters Needed for the QPS Objectives



ECH/EBW

- 0.6 MW at 53.2 GHz
- 0.2 MW at 56 GHz
- 1.2 MW at 28 GHz

ICRF

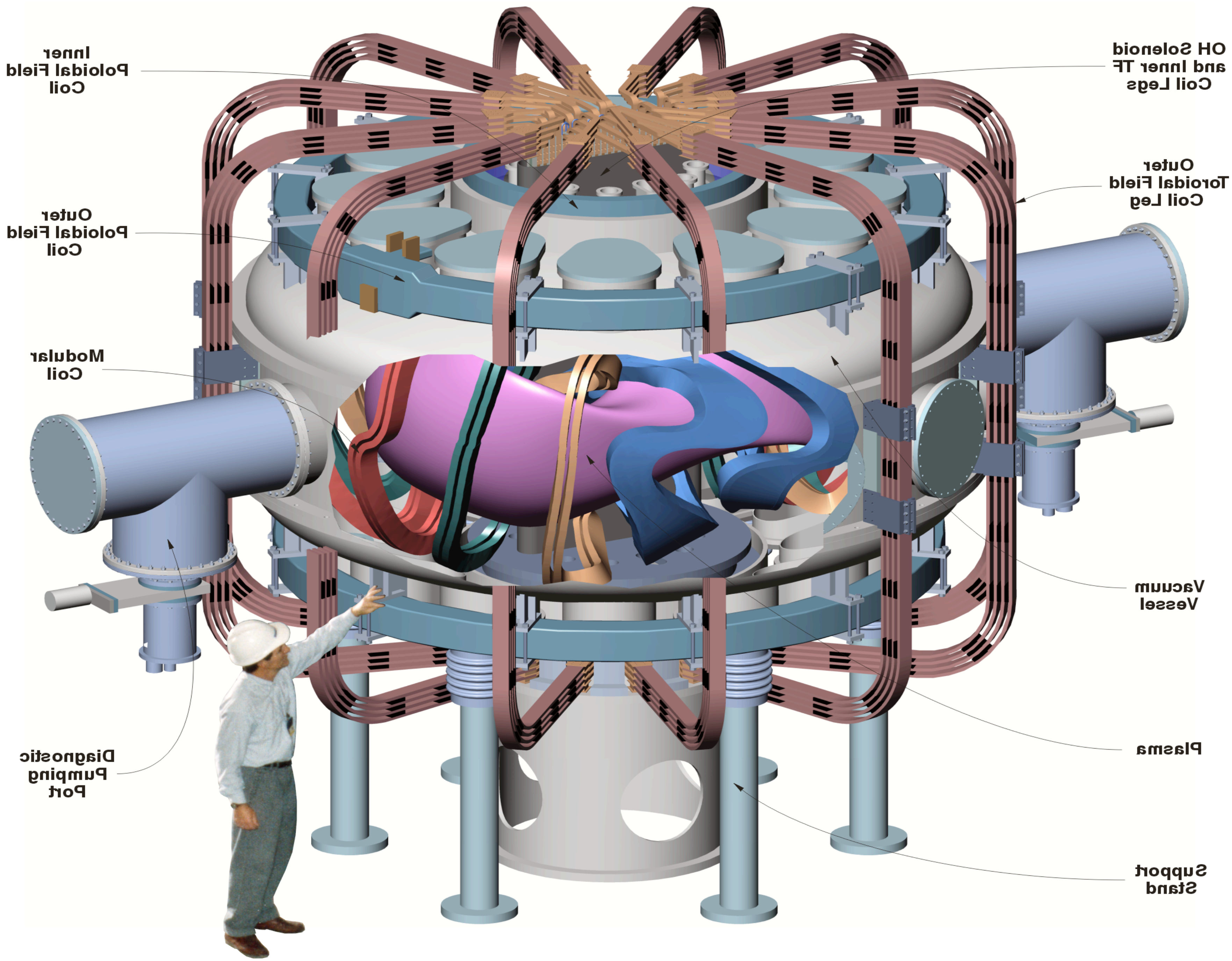
- 2 MW at 6-20 MHz
- 1.5 MW at 40-80 MHz

Multiply contour values by H_{ISS95} (= 1-2.5 in experiments)

Experimental Planning

PROGRAM AREA	PHYSICS ISSUES	DIAGNOSTIC
VACUUM MAGNETIC GEOMETRY, FLEXIBILITY	startup/low beta geometry: dominant IBI components, ergodic regions, islands, aspect ratio, ellipticity, triangularity, helical axis, etc.	electron beam with fluorescent screen or rods and CCD camera: low energy -- flux surfaces; high energy — lowest IBI components and energetic orbits.
MHD EQUILIBRIUM, ROBUSTNESS OF FLUX SURFACES	finite-beta geometry: flux surfaces, magnetic axis shift, interior ergodic regions and magnetic islands	soft X-ray diode arrays YAG Thomson scattering
BOOTSTRAP CURRENT	variation (reduction) with coil currents, effect on magnetic islands, ergodization of flux surfaces, and tearing modes	Rogowski coils, magnetic loops
POWER BALANCE	power deposition power losses	fast diamagnetic loop, YAG Thomson scattering, reflectometer bolometers, spectroscopy fast ion loss cups
TRANSPORT	electron density profile electron temperature profile ion temperature profile electric field	2-mm/FIR multi-channel interferometer ECE, Thomson scattering spectroscopy, charge-exchange probes, spectroscopy, HIBP
MHD INSTABILITY	frequency spectrum, mode structure, correlations	high frequency magnetic probes soft X-ray array
PLASMA EDGE, DIVERTOR GEOMETRY	limiting aspect ratio, edge magnetic structure and islands, diverted flux bundle	Langmuir probes, filtered CCD cameras, edge interferometer, IR camera, bias on divertor plates

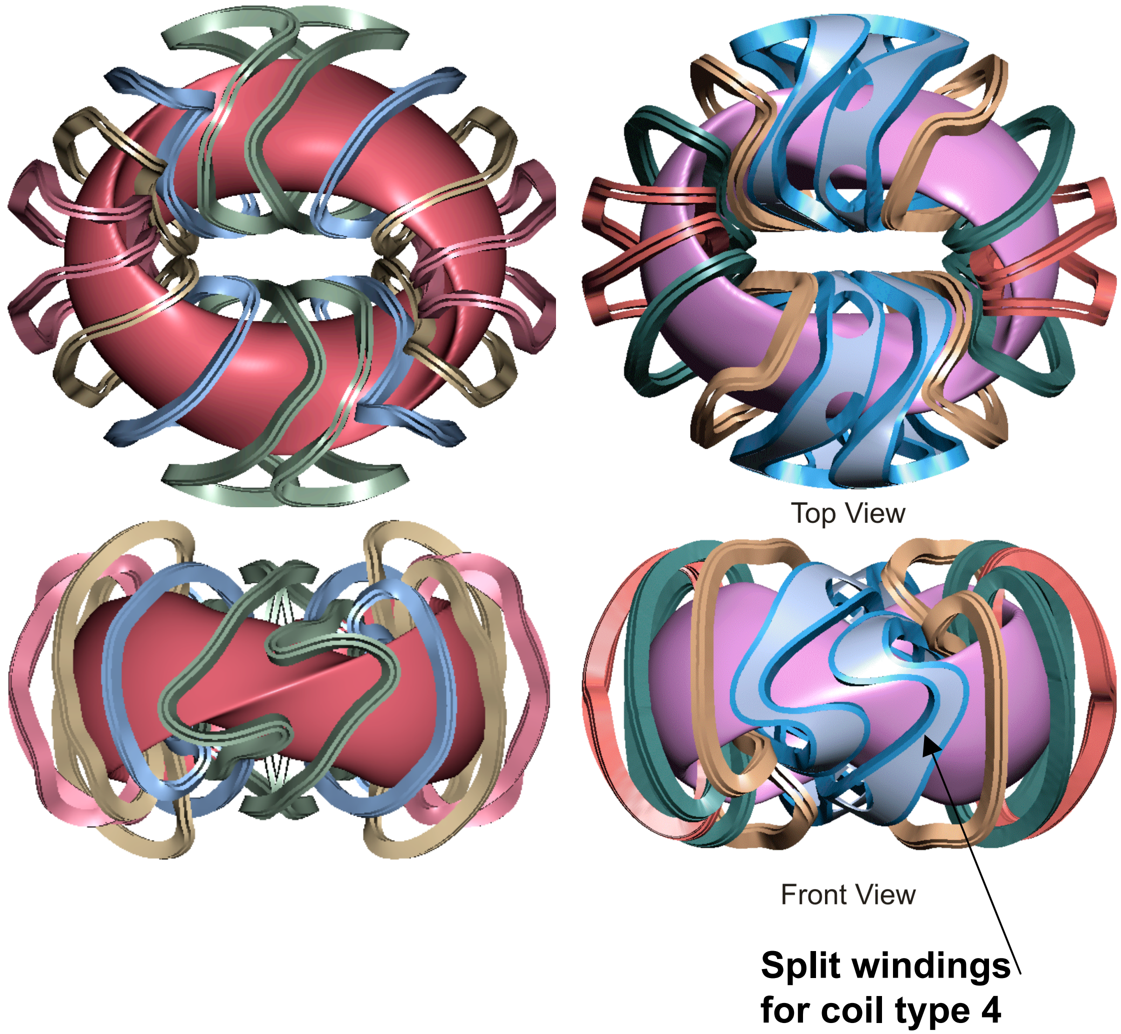
L. Berry


Inner Poloidal Field Coil
OH Solenoid and Inner TF Coil Legs
Outer Toroidal Field Coil Leg
Outer Poloidal Field Coil
Modular Coil
Vacuum Vessel
Plasma
Diagnostic Pumping Port
Support Stand

Evolution of QPS Modular Coils

- We have studied ~200 QPS plasma and coil configurations since the PVR
- Neoclassical confinement coefficient ($\epsilon^{3/2}$) has improved by factor ~50
- Integrated physics and engineering optimization

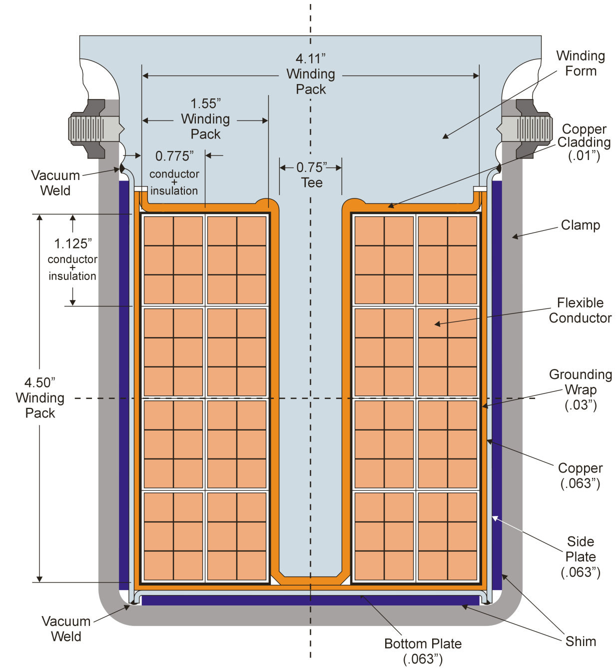
April 2001 (PVR) **November 2002**

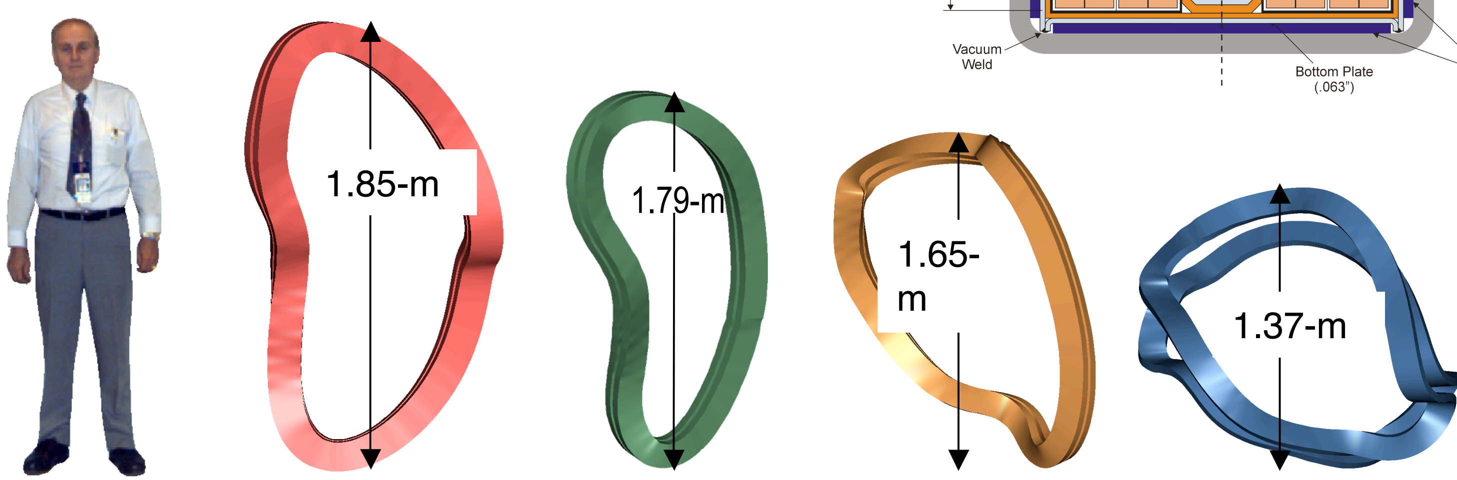


B. Nelson

Modular Coil Design Features

- 16 modular coils, 4 different types; similar to NCSX coils
- B = 1 T for 1-s flat top
- Vacuum canned, operate above room temperature





Coil M1

"bean" section

Coil M2

Coil M3

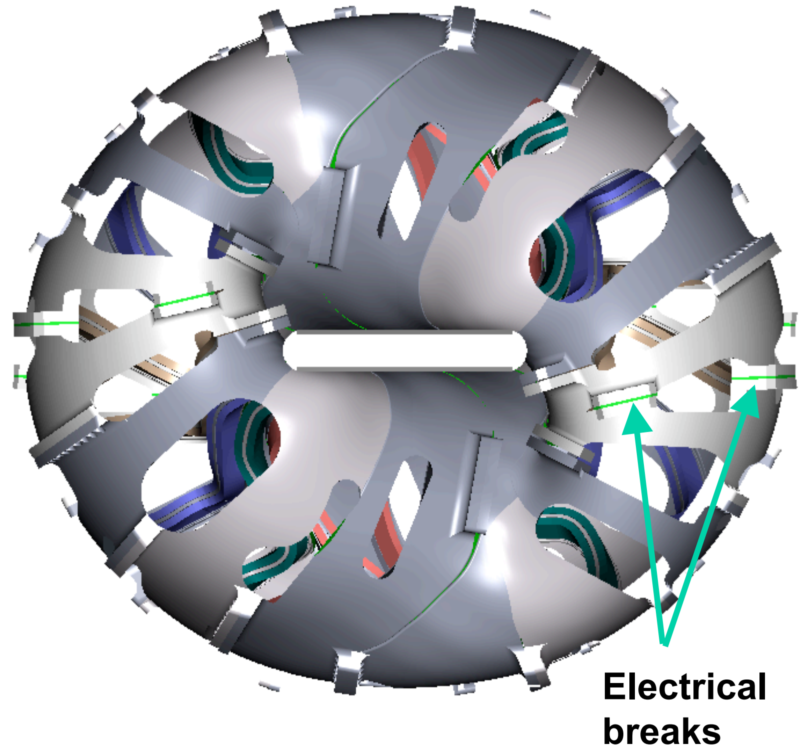
Coil M4

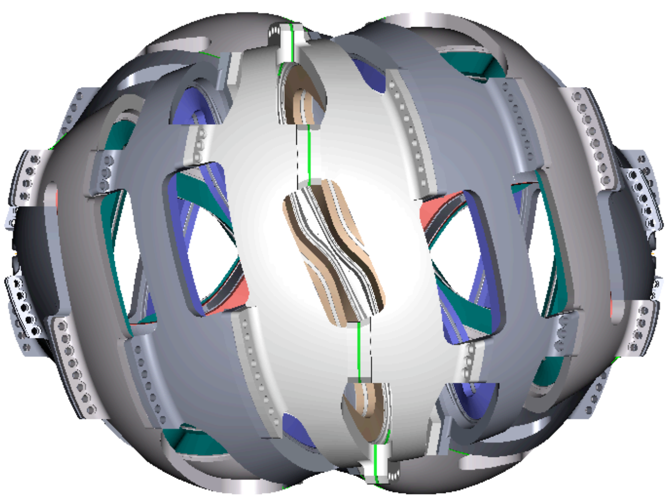
"Split windings"

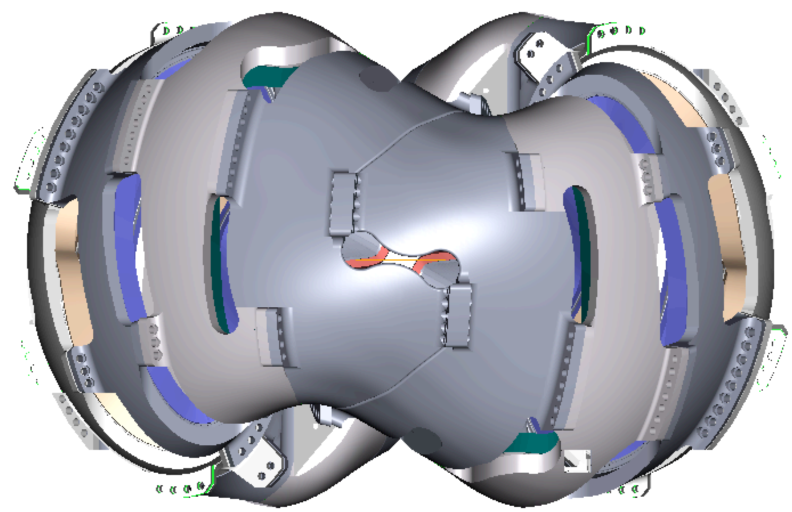
B. Nelson

Structural Shell Segments Connect Modular Coils

- Shell consists of individual modular coil forms that are bolted together
- Penetrations for access are provided wherever needed
- Thickness can be varied to optimize / reduce stresse
- Stellarator symmetry preserved, at least two toroidal electrical breaks

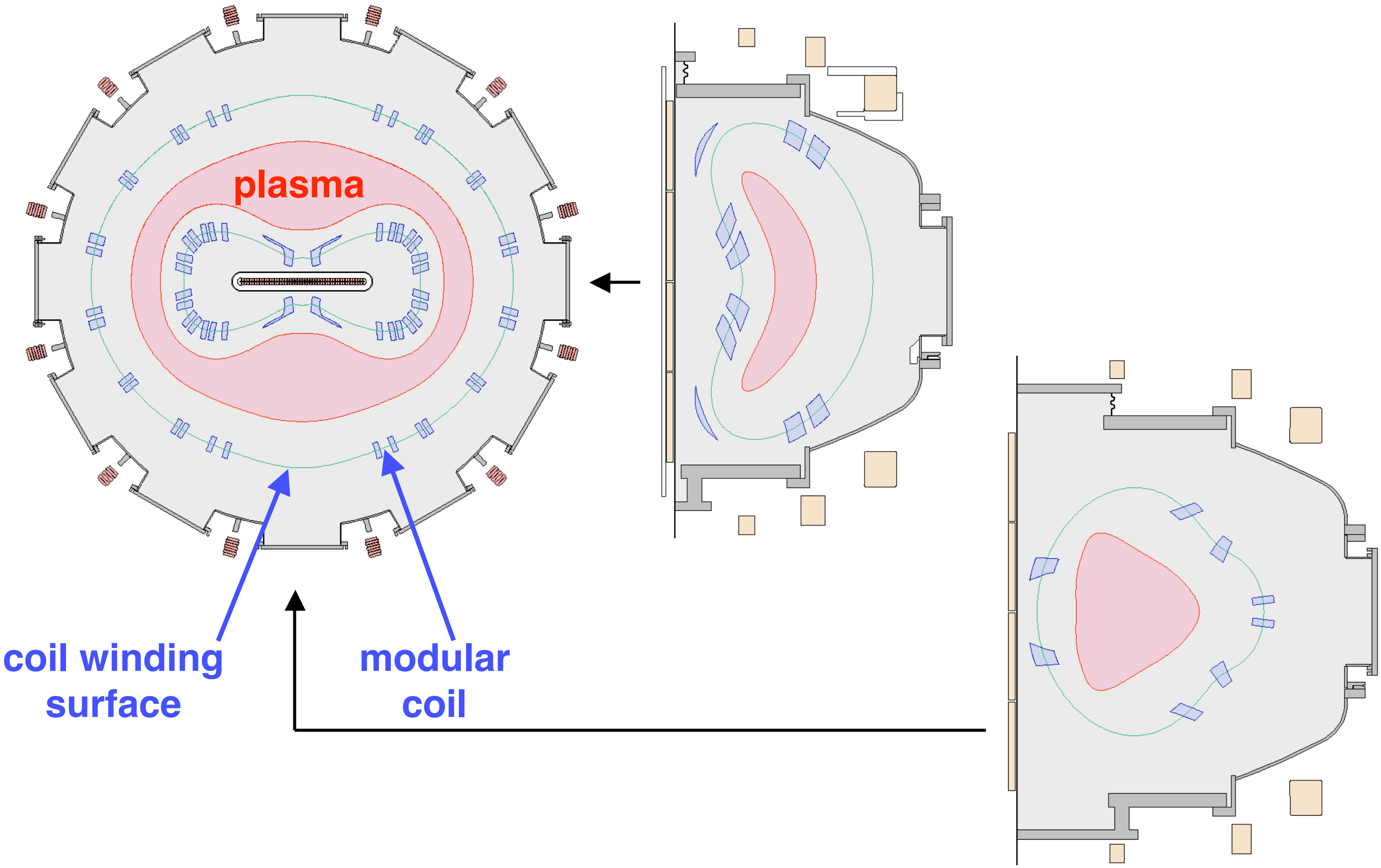






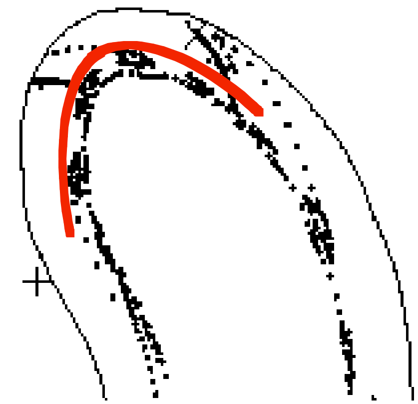
QPS Has Good Access between Coils

- No interior vacuum vessel,   twelve 2-foot diameter side ports



B.Nelson

Vacuum Conditions and Divertor Designed to Meet Experimental Needs



- **Strategy for density control**
  1. Control of the neutral sources through mechanical confinement with divertor baffles and re-ionization of neutral particles
  2. Recycling control through surface pumping via boronization of all plasma-facing components
  3. Titanium pumping of neutral gas in external tanks
  4. Direct fueling of the core plasma with gas injectors at the divertor baffles

- **Wall conditioning for impurity control**
  - baking, glow-discharge cleaning and boronization

P. Mioduszewski

QPS Project FYs 2004-2006

- **2004**
  - Complete modular coil detailed design
  - Start fabrication of 4 R&D modular coils
  - Begin TF and PF coil design
- **2005**
  - Procure full set of modular coil winding forms and begin winding final modular coils
  - Vacuum vessel, detailed design of structures, and ancillary systems
  - Begin fabrication of OH, TF and Center-stack assembly
- **2006**
  - Complete fabrication of modular coil set
  - Complete fabrication of OH coils, TF coils, center-stack assembly, day 1 diagnostics, ECH system
  - Complete on-site assembly
  - Complete integrated systems testing
  - First plasma in Sept. 06 (unconstrained budget)

QPS Project Schedule

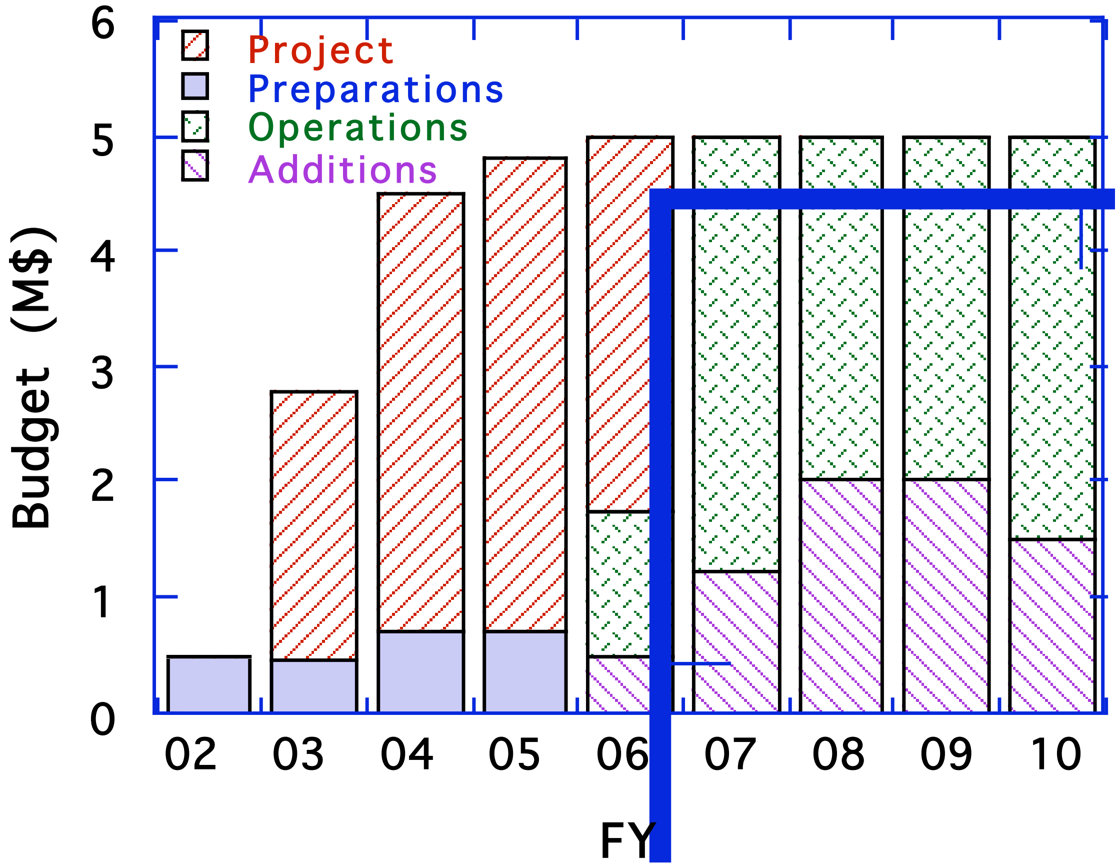
Task/milestone	Start	Finish
Project Start	**1-Oct-03**	
Mod coil R&D	**1-Oct-03**	**24-May-05**
Mod coil fab.	**26-Jul-04**	**30-Dec-05**
Vacuum vessel	**25-Oct-04**	**29-Jul-05**
Centerstack	**31-Jan-05**	**30-Dec-05**
Machine Assy	**10-Aug-05**	**25-Jul-06**
Checkout	**26-Jul-06**	**29-Sep-06**
First Plasma		**29-Sep-06**

QPS-Specific R&D

- **Stainless steel winding forms**
  - Use experience from NCSX manufacturing studies and prototype T's
  - Plan manufacturing study with qualified vendor in January
- **Coil winding and potting**
  - Use experience from NCSX
  - Develop experience at UT-Knoxville (2004)
- **Vacuum canning of modular coil cases**
  - Subcontract with UT-Knoxville
- **Staff development**
  - Collaborations on US and foreign stellarators

PVR Estimate of Project Cost and Budget

- **Estimated cost of QPS at PVR was $13.9M; replacing vacuum tank increased cost to $14.9M (as spent $)**
  - this was before industry estimate that NCSX modular coils would cost more than we had projected at the PVR
  - QPS project was delayed to FY 2004, need to revise budget



QPS Cost Reduction Measures

- Feedback from industry on the cost of the NCSX modular coils is also a concern for QPS
- We are taking steps to reduce modular coil costs
  - Simplified the shape of the coils and the winding surface
  - Reduced the circumference of the modular coils
  - Planning manufacturing studies with industry to estimate QPS coil costs and ways to reduce it
  - Examining alternative ways to fabricate coils
- We have already reduced size of the vacuum vessel, will use existing VF coils, and moved them and Ti gettering regions outside the vacuum tank

Existing Infrastructure for QPS

- ***Modular Coil Power Supplies*****:** Existing modular power supplies: four independent units each providing 1.3 kV, 120 kA for >5-s pulses.
- ***VF, TF, Trim Power Supplies*****:** Three existing units: two provide 625 V, 15 kV for 5-s pulses; one power supply provides 625 V, 10 kA for 5-s pulses.
- ***ECH and ICRF Heating*****:** Available power supplies provide 80-kV, 100-A for 30-s pulses. Four sockets with 28 GHz to 53.2 GHz capability provided; a fifth socket is available if required.
- ***Bus Work*** will be available from QPS to the power source.
- ***Cooling Water*** will be available from QPS to the source. Two Cooling Towers provide 8 MW of average cooling.
- ***ICRF Transmitters*****:** The FMIT Transmitter can deliver 1.5 MW for 30-s pulses. The BBC Transmitters can provide 2 MW of 30-s power.

B. Nelson

Planning for the April CDR

- Continue assessments of QPS performance and flexibility
- Refine experiment and diagnostic planning
- Refine structural shell design and analyze stresses and time constants
- Manufacturing study to estimate cost and schedule for winding forms
- Use NCSX coil winding study to estimate time (and cost) of winding the QPS coils
- Update cost estimate and budget profile needed
- Refine staffing and management plans
- Develop CDR documentation appropriate to a CE-level project
- Complete disposition of PVR issues

Outstanding Issues/Concerns

- Realistic cost estimate
  - need information from manufacturing studies and coil winding times
- R & D issues
  - vacuum canning of the modular coils
- Adequacy of Research Preparation budget
- Budget profile for the project

We Have Addressed Issues Raised by the PVR Panel

- **Flux Surfaces Quality** -- only small islands, no healing needed
- **Confinement Issues** -- QPS coil set allows large variation in neoclassical transport and beta limits
- **Vacuum Issues** -- smaller vacuum vessel with hard seals and baking
- **Coils** -- same measurement procedure as for NCSX
- **Diagnostics** -- port configuration allows good access to the plasma
- **High Beta** -- startup scenarios from vacuum to 2% □ and second stability region examined
- **RF Heating** -- W 7-AS has demonstrated EBW heating and NSTX has demonstrated HHFW heating
- **Personnel and Management** -- more mid-career people will be brought into the QPS project as funding permits

Status of QPS PVR Comments -- 1

QPS PVR Disposition Plan Status -- December 1, 2002

Item	PVR Panel Comment	Response
C-1	A reasonable set of coils to achieve the QPS configuration has been proposed, although the engineering issues are not yet fully settled.	The purpose of the present conceptual design activity is to address these issues. The status of the engineering design will be discussed at the December QPS PAC meeting and presented at the Conceptual Design Review in April 2003.

Item	PVR Panel Recommendation	Response
R-1	The Committee feels that the combination of low aspect ratio and quasi poloidal symmetry is an attractive stellarator option. The ORNL-led team has identified the scientific issues of equilibrium, ballooning stability, and transport that should be able to be addressed by the proposed experiment. A clear majority of the Committee feels that these properties fully justify proceeding with the QPS project.	We agree with the PVR Panel recommendation and have continued to improve both the QPS plasma configuration, the modular coil system that creates it, and the vertical field coil system that allows configuration flexibility and ohmic plasma current. We are currently in the conceptual design phase heading for the December QPS PAC meeting and an April 2003 DOE Conceptual Design Review.

	PVR Panel Comments	Status/Response
	Relationship to Other Stellarators	
I-1	The QPS experiment is planned to test the effectiveness of quasi-symmetry in reducing stellarator transport losses in low collisionality regimes and to test bootstrap current predictions. Some of these proposed studies partially overlap the work or proposed work on the cited devices.	The partial overlap of the QPS program with that on other stellarators and the complementary features of QPS are the main strengths of the QPS program. The fact that QPS can address issues of equilibrium, bootstrap current, stability, confinement, and particle handling at much lower aspect ratio and with a different magnetic symmetry will allow extension of understanding of toroidal confinement to new regimes.

Status of QPS PVR Comments -- 2

	PVR Panel Comments	Status/Response
	Flux Surfaces Quality	
II-A1	The committee encourages recent improvements in the coils/configurations and directions to pursue before a design freeze is required.	We have studied many variations of the basic QPS plasma and coil configuration since the PVR with the result that a much improved plasma configuration with a more practical coil set has evolved. The final plasma and coil configuration will confirmed in September for the December QPS PAC meeting.
II-A2	There is concern that the 1/3 (2/6) and 2/5 resonances could result in loss of useable flux volume. The PIES code, which does not a priori assume good magnetic surfaces, has been employed in a limited manner, given the slowness of PIES runs. The runs completed look good, although one is far from having thoroughly convincing arguments for flux surface quality. Additional studies of flexibility in the device and the ability to trim out resonance problems with trim coils should be carried out.	PIES runs have been made for different variants of the QPS configuration. The present QPS configuration exhibits a very small island chain at the 2/6 resonance that would be stabilized by the plasma. The 2/6 islands could easily be cured by the same process used to cure much larger islands on NCSX, although this may not be needed since neoclassical effects should reduce the island size by a factor of ~3 as in NCSX. The effect of the 2/6 resonance on the quality of the flux surfaces can also be reduced by changing the background TF field or by changing the shear with the poloidal field coil system. Additional studies of flexibility in the device and the ability to trim out resonance problems with trim coils will be carried out.
II-A3	The team has not yet sufficiently analyzed the problem of break-up of magnetic flux surfaces due to symmetry-breaking and symmetry-preserving errors. Coil errors and other inaccura-cies in design or manufacture have not been considered for their effects on the configuration.	AVAC will be used to assess the effects on the flux surfaces of different types of errors in coil shape and positioning. In addition, the analytic and VMEC-based procedures used for this purpose for NCSX will be applied to QPS as well.
II-A4	Some measure other than qualitative visual exam-ination of flux surface plots should be developed. Demonstration of these capabilities with the AVAC code would lend a reasonable degree of confidence in managing potential problems.	AVAC is used to assess the volumes associated with magnetic islands, ergodic field regions, and well-formed surfaces for different coil currents for the QPS configuration. The PIES runs for QPS also calculates the island sizes.

Status of QPS PVR Comments -- 3

Item	PVR Panel Comment	Status/Response
	Confinement Issues	
II-B1	At low density, EC-heated plasmas allow experiments on the dependence of neoclassical transport on the degree of poloidal symmetry. Methods of breaking the symmetry that do not affect flux surface quality should be confirmed by modeling.	Good flux surface quality has been obtained for different currents in the vertical field coils and for unequal currents in the modular field coils that produced a variation of a factor of 20-80 in the low-collisionality neoclassical transport.
II-B2	Adequate profile diagnostics and modeling capability should be available for unraveling the roles of neoclassical and anomalous transport.	1-D self-consistent calculations of plasma profiles, power flows, and energy confinement times show that it is possible to clearly distinguish neoclassical transport from anomalous transport. A plan to implement profile diagnostics is being developed and will be presented at the April 2003 CDR.
II-B3	As a consequence of the differing symmetries in |B| of QAS and QPS, plasma flows may appear. Such fields open the possibility of differing modes of access to enhanced confinement regimes.	Access to modes of enhanced confinement does not affect the design or construction of QPS, so there is no near-term action. However, this will become important as we near operation, so we will devote more effort on calculations of flow damping as will also be done in the NCSX program. As tools become available for evaluating flow damping rates from the theory community and the NCSX project, we will apply them to the different experimental regimes we can access in QPS and identify scenarios whereby flow damping rates can be varied.

Status of QPS PVR Comments -- 4

Item	PVR Panel Comment	Status/Response
Vacuum Issues		
II-C1	The committee is concerned about the ability to achieve good vacuum conditions and maintain plasma cleanliness. More detailed interaction with operating devices dealing with problem of achiev-ing good vacuum conditions and maintaining plasma cleanliness.	Discussions have been held with the MAST and H-1 groups on in-vessel components and vacuum issues which gives confidence that the combination of baking, cleaning procedures and pumping will be successful in QPS. All leads and cooling lines will be routed from each coil separately outside the vacuum through commercial feedthroughs. Further discussions will be held with groups with relevant experience before the CDR.
II-C2	Neutral penetration may be a problem and should be examined for both high and low density regimes.	Experimental results from the W 7-AS and CHS stellarators indicate that this is not an issue for QPS; the QPS plasma radius is larger than in these experiments and the same as in NCSX. Placement of the divertor plates in the bean-shaped cross sections will also minimize recycled neutral penetration.
II-C3	Baking internal components to as high a temperature as feasible is encouraged; the limitation of 65 ˚C causes concern.	We plan epoxy curing at 150°C and operating the coils up to 100°C. We plan to bake as close as possible to 150°C as allowed by the thermal stress at the bakeout temperature and the creep properties of the cable-epoxy composite.
II-C4	Although polymer seals can work reasonably well, consider hard seals wherever possible.	Hard seals will be used on all ports except for the large seals on the bell jar , which will be differentially pumped, double viton seals for affordability.
II-C5	Reconsider use of the ORMAK vessel because of concern about the aluminum center ring.	The ORMAK bell jar has been replaced with a smaller stainless-steel vacuum tank that allows locating the VF coils outside the vacuum vessel.
Coils		
II-D1	Establish basis for position and alignment tolerance required for the coils, and reasonable methods of coil adjustment during assembly and adjustment or trimming during operation period.	The basis for the position and alignment tolerance for the coils is discussed in II-A3. The plan for the QPS coils is the same as that for the NCSX coils. It will be reported at the April 2003 CDR.

Status of QPS PVR Comments -- 5

Item	PVR Panel Comment	Status/Response
	Diagnostics	
II-E1	Attention must be paid to good diagnostic access early in the design process (e.g., in determining apertures in the vacuum vessel).	The vacuum vessel has 12 ports 61 cm in diameter for side access to the plasma and large diagnostic access from the top and bottom as well. The open interior of QPS (absence of a view-limiting interior vacuum vessel) allows maximum access to the QPS plasma from all directions.
II-E2	Measurement of the plasma current profile will be needed, to characterize the equilibrium and particularly to separate inductive and bootstrap currents.	The CTH group at Auburn and the NCSX group propose to make this measurement a part of their programs. The QPS group will collaborate with the CTH group on implementing this measurement on QPS and take advantage of the development being done for NCSX. This measurement will be augmented by the 3-D equilibrium reconstruction being developed for NCSX and QPS, which will give information on the moments of the current distribution.
II-E3	The 'radial' electric field is a major player in both neoclassical transport and plasma flow. Some method for determining this field is needed.	Methods for determining the radial electric field are a long-term need for the QPS and NCSX programs. Advantage will be taken of developments and collaborations in this area as operation of QPS approaches. This need has no impact on the design and construction phases of the QPS program.
II-E4	There should be preparation, both theoretical and in diagnostic development, to implement equilibrium and profile reconstruction from experimental data.	An ORNL/GA proposal for development of 3-D equilibrium reconstruction from experimental data based on the 3-D VMEC code and the EFIT experience has been partially funded. The results will be applied to both QPS and NCSX.

Status of QPS PVR Comments -- 6

Item	PVR Panel Comment	Status/Response
	High Beta	
II-F1	A minority feels that the facility should be capable of addressing the question of accessibility of the high beta regime.	No action item is required because the QPS design allows the potential for a possible later upgrade to explore possible regimes of second stability operation in QPS. The QPS program will address issues related to the accessibility of a higher beta quasi-poloidal stellarator regime, as discussed in the July 2, 2001 "High-Beta Studies on QPS" report to DOE.
II-F2	It would be desirable if a proposed experiment, possibly with heating upgrades, could access a second stable high beta regime and address the physics of high beta stellarators. The majority finds that high beta is not critical to QPS, or the combination of experimental stability studies at low beta and theoretical analysis will be adequate.	We agree with the clear majority that high-beta operation is not critical to the QPS mission and the combination of experimental stability studies at low beta and theoretical analysis will be adequate for accessing the possibility of high beta. The issue of accessing a possible second stability regime is addressed in IIF-1 (above) and in the July 2, 2001 "High-Beta Studies on QPS" report to DOE.
II-F3	Additional work is necessary to treat start-up scenarios going from zero beta to relevant beta values.	Sequences of free-boundary equilibria have been calculated as □ is increased from 0 to 2%. Transport modeling will be used for the evolution of the plasma from □□□= 0 to 2%; the results will be part of the documentation for the April 2003 CDR.

Status of QPS PVR Comments -- 7

Item	PVR Panel Comment	Status/Response
RF Heating		
II-G1	The beta studies rely on ICRF (or EBW) to achieve high densities due to the favorable dependence on density of ISS95 scaling. This is a less proven technique in stellarators, especially at the $10^{20}m^{-3}$ densities for the QPS beta studies.	A series of experiments should be done on LHD to determine if there is a density limit for ICRF heating. Data on HHFW heating from NSTX shows successful heating of ECH target plasmas expected in QPS. It is expected that ICRF should work better at high density and high beta. These experiments will allow testing different ICRF scenarios and thus guide the choice for QPS.
II-G2	Efforts should be undertaken to strengthen the underpinnings of the EBW approach through collaborations on existing stellarators to define the limits and applicability of this approach.	Since the PVR, W 7-AS has demonstrated effective EBW heating at densities above $10^{20}m^{-3}$. ORNL is involved with PPPL and MIT in studying EBW on CDX-U and NSTX. Results from EBW emission on NSTX have been very encouraging: 50-70% mode conversion efficiency, which agrees with theoretical expectations. We are also involved with U. of Wisconsin and GA in studying EBW on MST.
II-G3	As a potential upgrade, and to ensure beta limits can be tested, the team should undertake an inves-tigation of this possibility including the access requirements and beam coupling/thermalization.	The QPS team decided against neutral beam injection (NBI) because of the high costs associated with NBI heating and the adequacy of RF heating, but the potential for an upgraded heating system using NBI is available. This issue was discussed in the July 2, 2001 "High-Beta Studies on QPS" report to DOE.

Status of QPS PVR Comments -- 8

Item	PVR Panel Comment	Status/Response
	Personnel and Management	
III-1	It is essential to identify and bring mid-career physicists, particularly experimentalists, into the project now. These people are needed to bring current hands-on experience and to assume leadership roles in the activity.	The work to date has been done by mid-career physicists (including experiment-alists) and engineers. While bringing additional mid-career physicists into the QPS project is important, our ability to increase staffing on QPS has been limited by the relatively small funding level for QPS and the need to put the highest near-term priority on QPS physics and design development. ORNL will identify people who will assume leadership roles in the design, construction, and program planning phases of the QPS project as part of the CDR preparations.
III-2	Since collaborations are essential for the success of the project, collaborative agreements with other laboratories and universities should be developed.	ORNL will broaden participation with collaborating universities and other institutions, as was done in the ATF program. Two-way collaborations will be developed in which more ORNL personnel can renew their experience on stellarator experiments and collaborators from other stellarator experiments and diagnostic development groups can take advantage of, and make significant contributions to, the QPS program. Discussions have already been held with U. Wisconsin-Madison, Auburn, UCSD, RPI, U. Montana, Morehead State University, and U. Tenn. It is anticipated that ~1/2 the participants in the QPS program will be from PPPL, universities, and foreign institutions.

Status of QPS PVR Comments -- 9

Item	PVR Panel Comment	Status/Response
	Budget and Project Plans	
IV-1	The committee feels that the final costs of the project may increase somewhat from the projected levels due to increases in diagnostics and design changes prior to a cost and schedule review.	The PVR recommendation to replace the ORMAK vacuum tank and the vendor information obtained on the NCSX coils do point to an increase in cost. The QPS team is working to hold down additional costs and to seek cost reductions wherever possible. Diagnostics needed *after* the commissioning and characterization of vacuum configurations phases of the QPS program are not part of the QPS Project; they are part of the operating costs as on NCSX.
	Relationship to FESAC Goals	
V-1	The QPS project would credibly extend stellarator investigations to low aspect ratio with reasonable confinement, a programmatic FESAC goal. The possibility of high beta in a follow-on device enhances the connection to those goals. Further-more, it may have the potential for even higher beta configurations, although access to such configurations is far from certain.	The possibility of high beta in a follow-on device to QPS would enhance the connection to those goals, but its feasibility will depend on the outcome of the QPS experiment and the programmatic situation at that time. However, QPS can lay the groundwork for such a follow-on experiment by addressing the basis for such an experiment, as discussed in the July 2, 2001 "High-Beta Studies on QPS" report to DOE.
V-2	The increased plasma-coil separation at a fixed, low aspect ratio allows for smaller stellarator reactors than previously envisioned, contributing to the FESAC goal of assessing the potential of a stellarator as a reactor. A thorough investigation of the possible reactor embodiment of QPS principles has not yet been done.	This same recommendation was made for NCSX at their March 2001 PVR. An intial assessment of NCSX and QPS base reactors was reported at the Sorrento IAEA confereence. The ARIES group is starting work on a compact stellarator reactor study. The first 1 1/2 years of the study will be devoted to preparing the tools needed and examining options before selecting a compact stellarator coil configuration for a point design the last year of the 2 1/2 year study. The QPS team is participating in this study.

Summary

- QPS will extend confinement understanding by addressing physics of quasi-poloidal symmetry at very low aspect ratio
- Experimental program and device requirements are defined
- Projected performance meets experimental needs
- Configuration has the flexibility to address QPS physics issues
- QPS design can be built, and a credible plan to do it exists
- Vacuum conditions and divertor meet experimental needs
- Steps needed for the QPS project have been outlined for FY's 2004–2007
- Disposition of PVR comments is mostly complete