QPS Project Validation Review

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Jim Lyon

- Progress in QPS Development since PVR
- Status of Disposition of PVR Comments
- QPS Physics Development Plans for FY 2002-3
- Preparations for QPS Operation FY's 2004-7

Brad Nelson

- Progress on QPS Engineering Design
- Plans for Conceptual Design (and R&D) in FY's 2002/2003
- Plans for Accomplishing the QPS Project in FY's 2004-2007

- Discussion/Follow-up Issues, Reviews

Multi-Laboratory QPS Team

- ORNL – D.B. Batchelor, 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, D.A. Spong, D.J. Strickler, J.C. Whitson, D.E. Williamson
- U. Texas at Austin – W.H. Miner, jr., P.M. Valanju
- U. Montana – A. Deisher, D. Heskett, A.S. Ware
- PPPL – A. Brooks, G.Y. Fu, S. Hudson, D. Mikkelsen, D.A. Monticello, N. Pomphrey
- Universidad Carlos III de Madrid, Spain – R. Sanchez
- U. Tennessee – T. Shannon

QPS Progress Since PVR

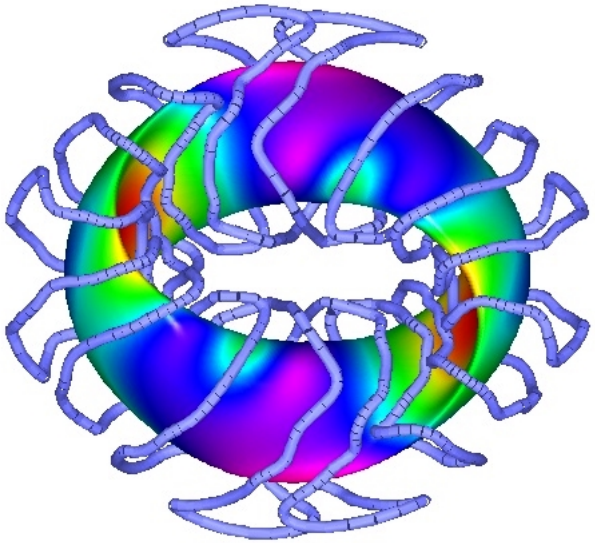
- **PVR Panel Recommendation**
  - **The Committee feels that the combination of low aspect ratio and quasi poloidal symmetry is an attractive stellarator option**
  - **The ORNL-led team has identified the scientific issues of equilibrium, ballooning stability, and transport that should be able to be addressed by the proposed experiment**
  - **A clear majority of the Committee feels that these properties fully justify proceeding with the QPS project**
- **PVR Panel Comment**
  - **The committee encourages recent improvements in the coils/configurations and directions to pursue before a design freeze is required.**
- **Status -- that's what we've done**
  - **The present QPS configuration has greatly improved confinement with practical coils; we have what we need**
  - **Most of the PVR issues have already been addressed; we found no new ones**

Success Due to Optimizer Development

- Previously Plasma and Coil Optimization had been separate
  - We had optimized plasma configuration with STELOPT and then found the coil configuration that best created the optimized physics configuration with COILOPT
- Some improvements were made to COILOPT
  - Targeted coil complexity and distance across the center of the torus to allow adequate space for TF and OH solenoid coils
  - Split modular coils near middle of long section (with variable center "T") for better match to plasma B_{normal}
- Real success was due to merging STELLOPT and COILOPT for combined free-boundary plasma/coil optimization
  - this advance produced the 0411 configuration
  - needed at low aspect ratio, also applied to NCSX

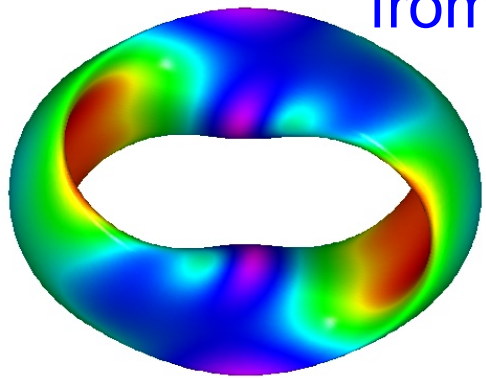
Improvement of the QPS Plasma and Coil Configuration

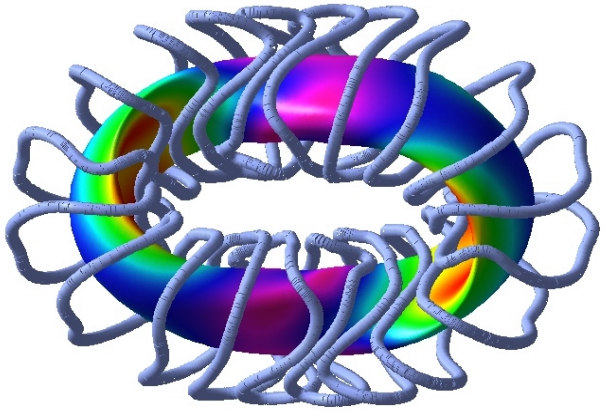
- **Some of the many (~150) QPS plasma and coil configurations studied since the PVR**



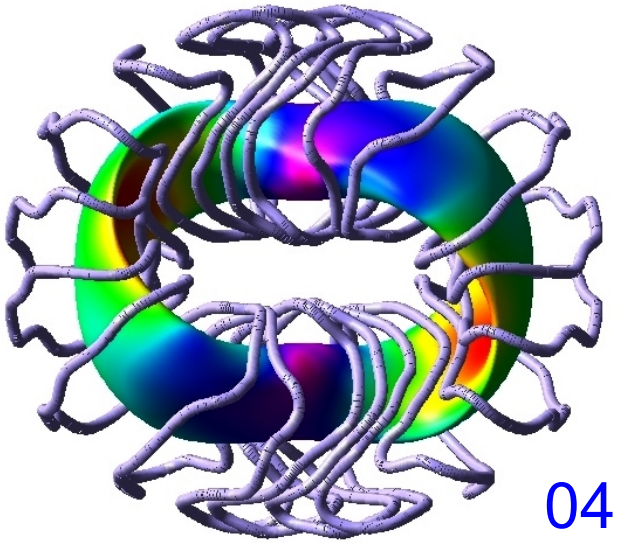
GB4
PVR Ref.

GB5
from PVR





110801



041102

QPS Plasma Properties Have Been Improved

- **041102 configuration has much improved transport properties**

Plasma	PVR BG4	GB4 (Apr 01)	041102
Aspect ratio *R/a*	2.62	2.53	2.71
waist (cm)	25.5	22.0	23.3
I_{plasma} (kA)	47.5	42.8	46.8
$\langle\beta\rangle$ (%)	1.88	1.82	1.78
ι(center)	0.27	0.30	0.29
ι(edge)	0.40	0.39	0.36
$\varepsilon_{eff}^{3/2}(r/a)$ 1/ν neoclassical transport at low collisionality			
r/a = 0.22	0.011	0.0021	0.0010
r/a = 0.61	0.012	0.0024	0.0014

- **21 QPS plasma configurations were studied *in detail* since the PVR**
  - Waist is midplane thickness in the bean cross section
  - Low collisionality 1/ν transport $\propto$ $\varepsilon_{eff}^{3/2}$

QPS Coil Properties Have Also Improved

- **041102 coil properties are attractive; result of merged optimizer**

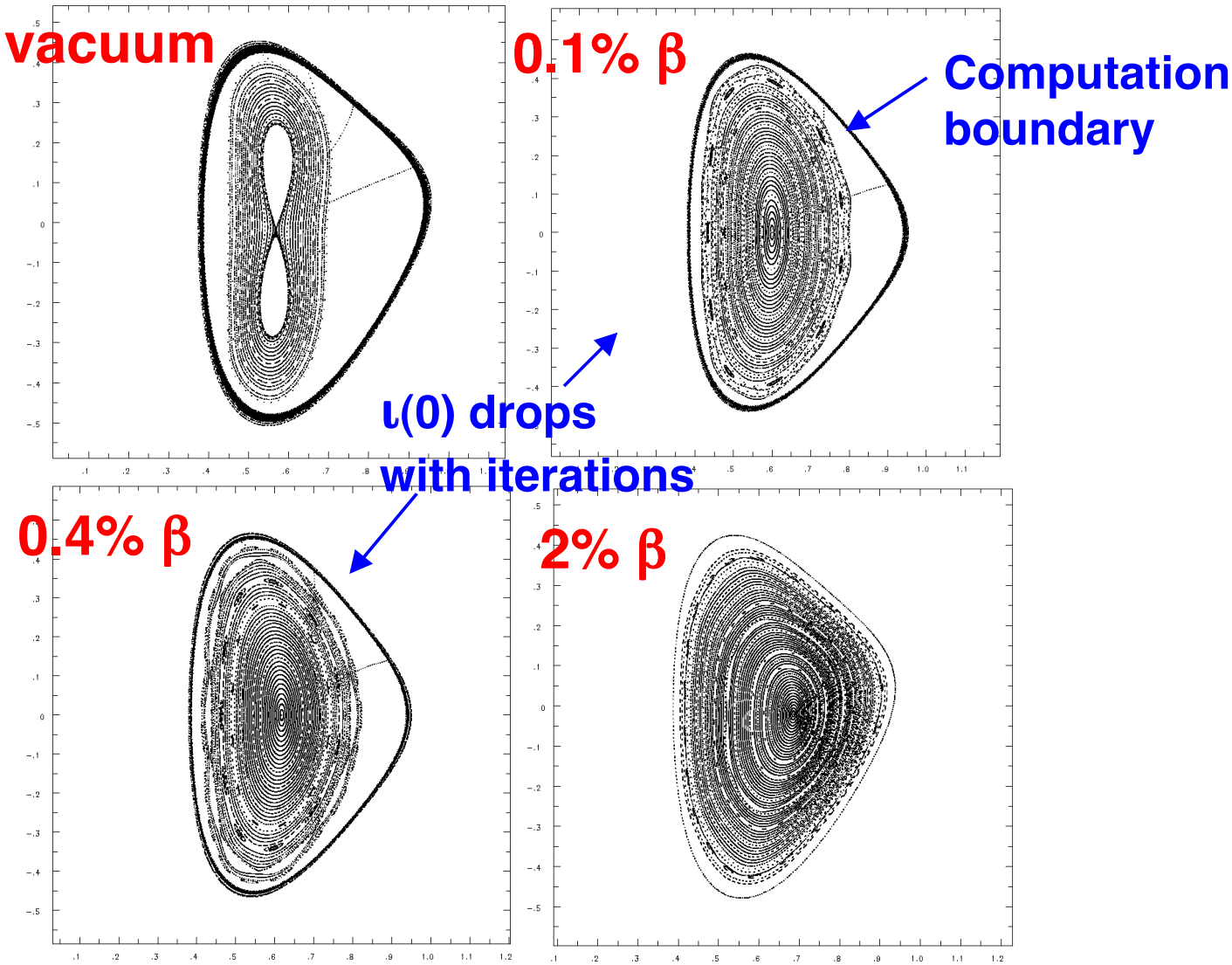
Plasma	PVR GB4	GB4 (4/01)	110801	041102
$\Delta_{coil\text{-}coil}$ (cm)	11.4	10.55	10.0	10.1
$\Delta_{coil\text{-}plasma}$ (cm)	13.4	14.8	14.1	14.6
ρ_{min} (cm)	7.2	7.5	6.0	10.1
lyl_{min} (cm)	18.3	12.5	18.2	18.0
ι(center)	0.252	0.289	0.150	0.291
Comment	PVR reference case	Improved transport over GB4	Good trans-port at high β, but a doublet at lower β	Merged coil-plasma optimiza-tion

- **~150 QPS coil configurations were studied since the PVR**

$\Delta_{C\text{-}C}$ is minimum coil-coil separation; $\Delta_{C\text{-}P}$ is minimum plasma-coil separation
ρ_{min} is the minimum coil bend radius; lyl_{min} is the coil-coil distance across the center

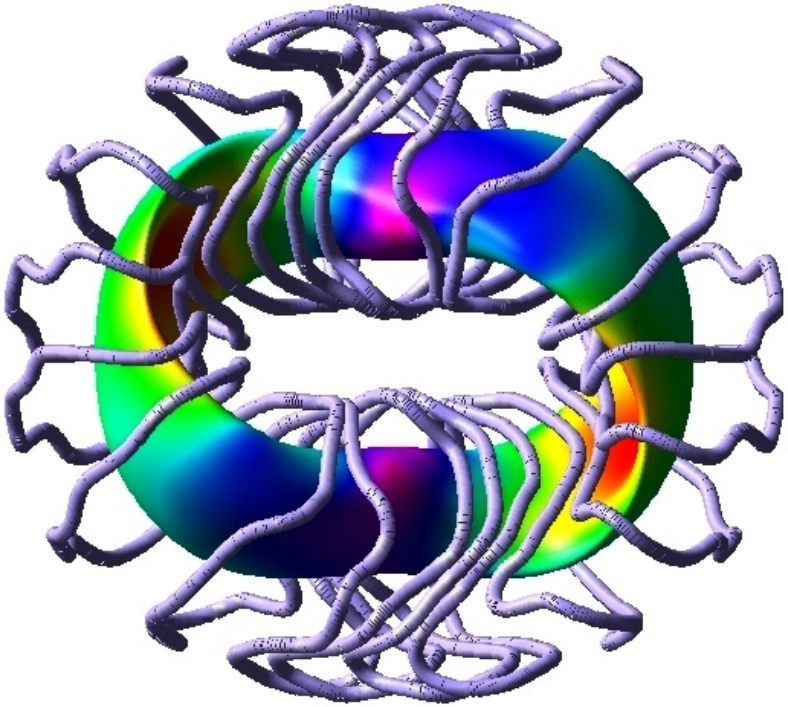
Important to Check All Properties in Optimizing

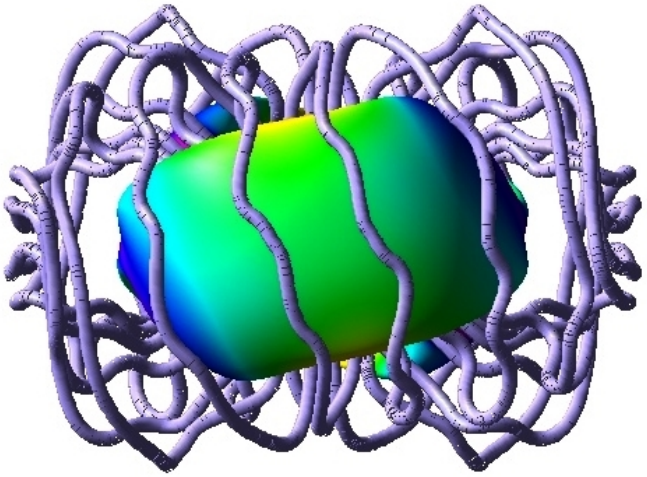
- **Reduced neoclassical transport, but PIES and AVAC showed a doublet configuration at low β for 110801 case -- ι(0) too low**

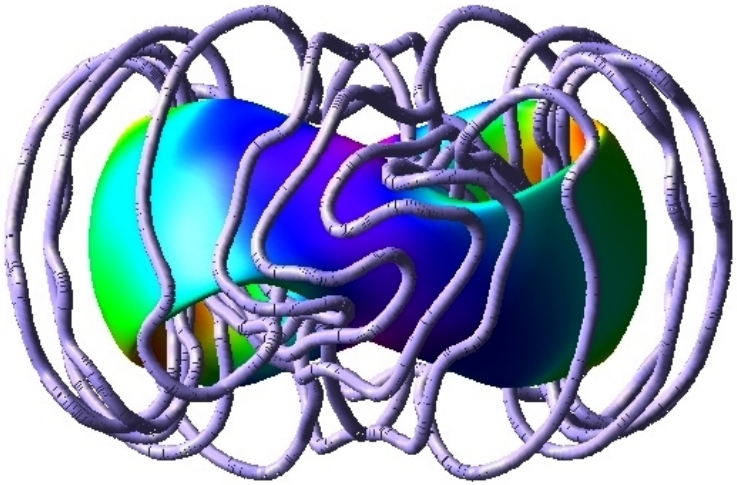


QPS Plasma and Coil Configuration

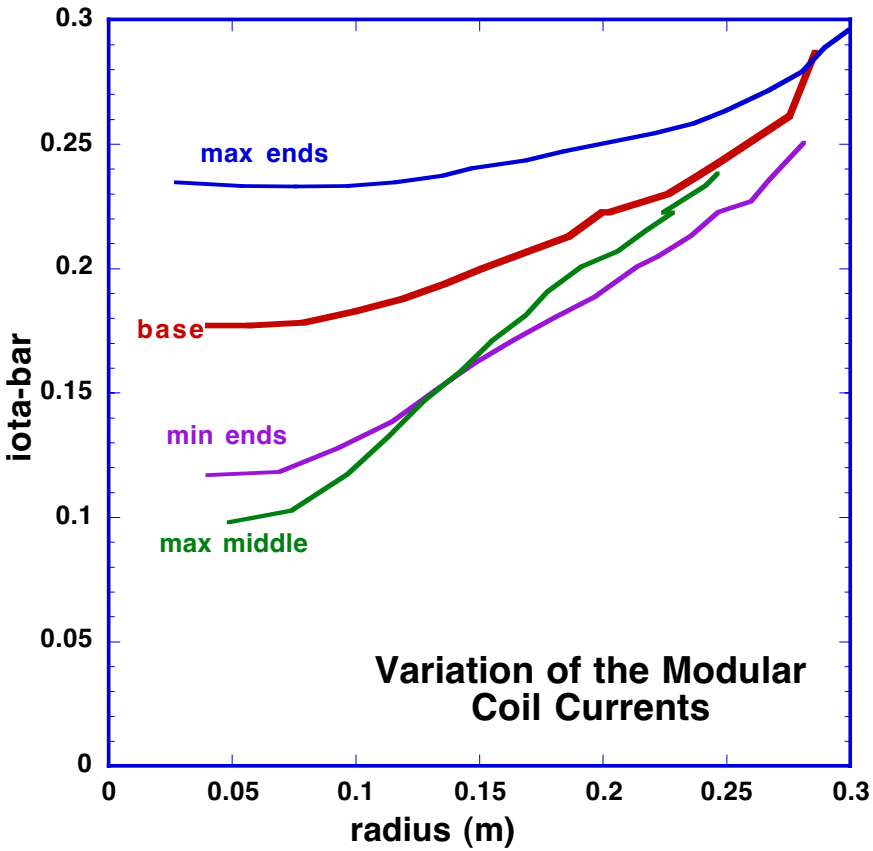
- *R/a* = 2.7, waist 23 cm
- ι(0) = 0.29, ι(a) = 0.36
- transport similar to W 7-X, but at 1/4 *R/a*
- large plasma-coil, coil-coil spacings and minimum bend radius
- good access between coils for diagnostics and heating

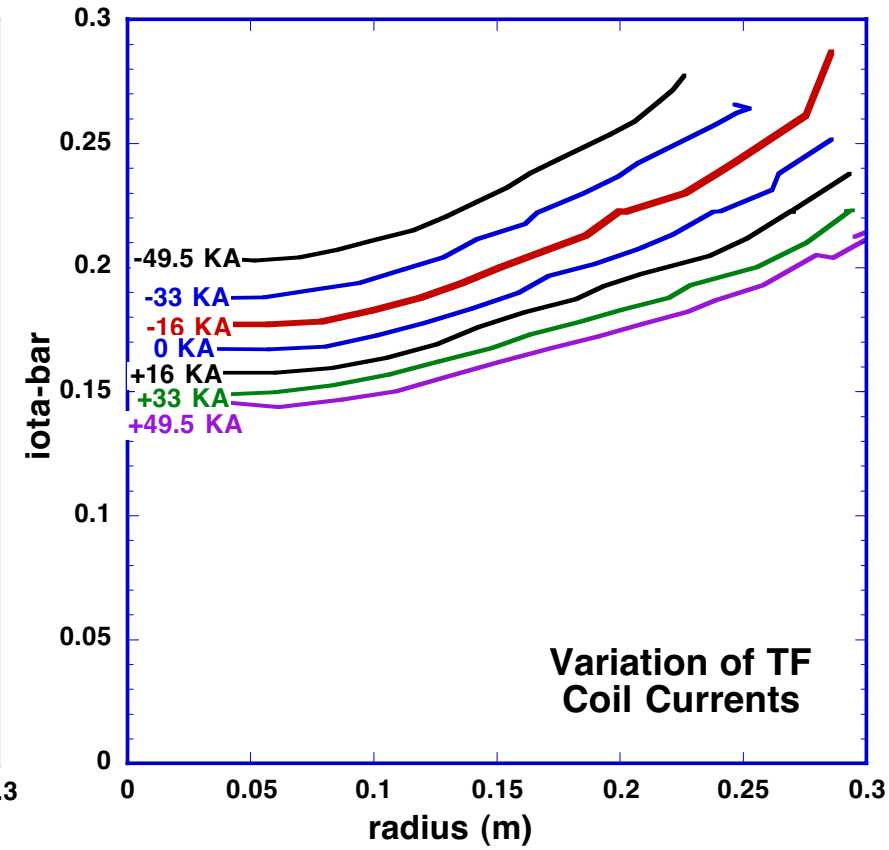






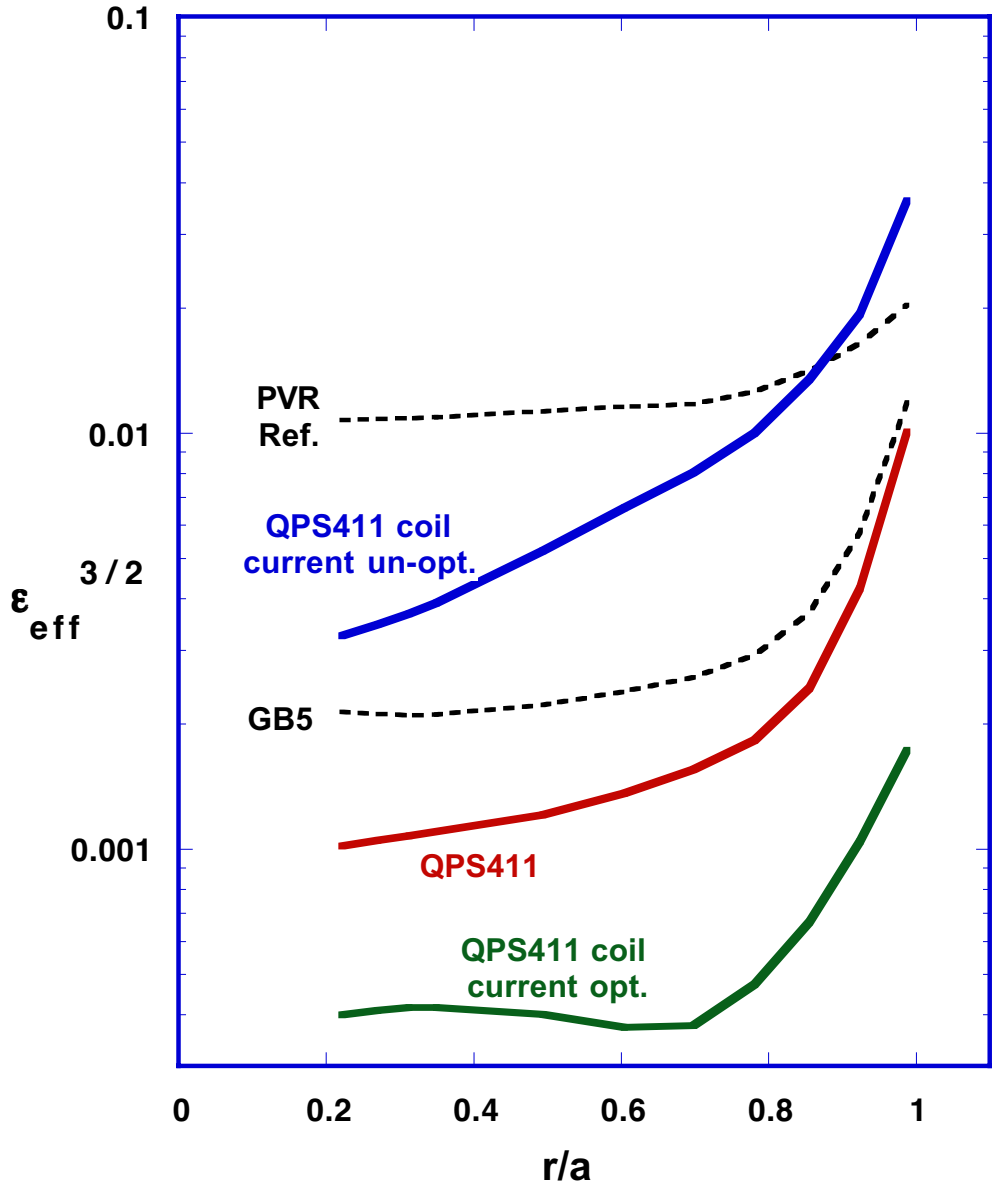
041102 QPS Coils Allow Variation of Rotational Transform and Shear





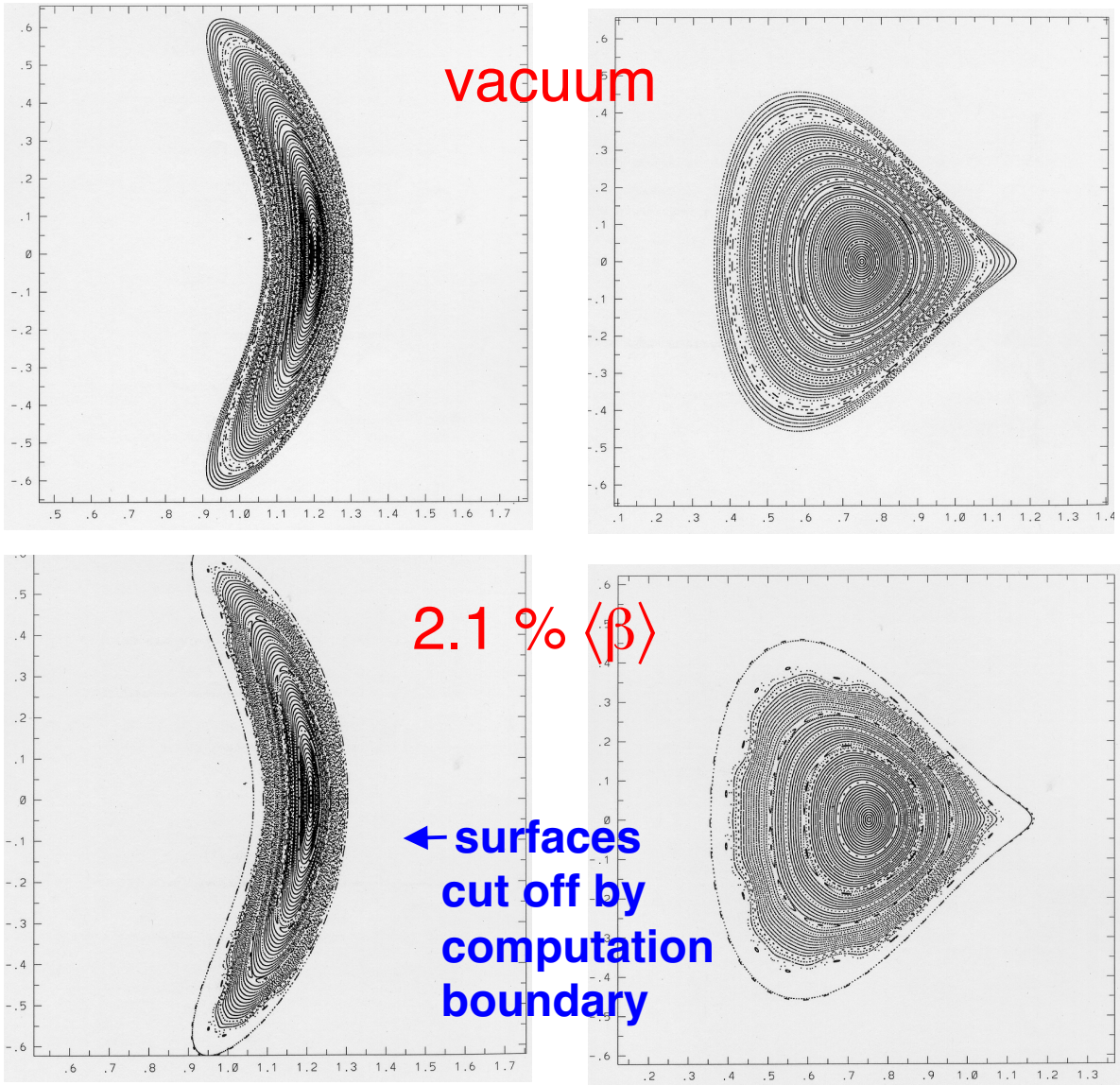
041102 QPS Coil Set Allows Testing Neoclassical Transport

- Changing currents in QPS411 coils varies neoclassical transport by factor 8-20
- Can change from neoclassical being dominant over plasma core to not being significant
- Base QPS411 is a factor 10 better than PVR, ~ W 7-X value



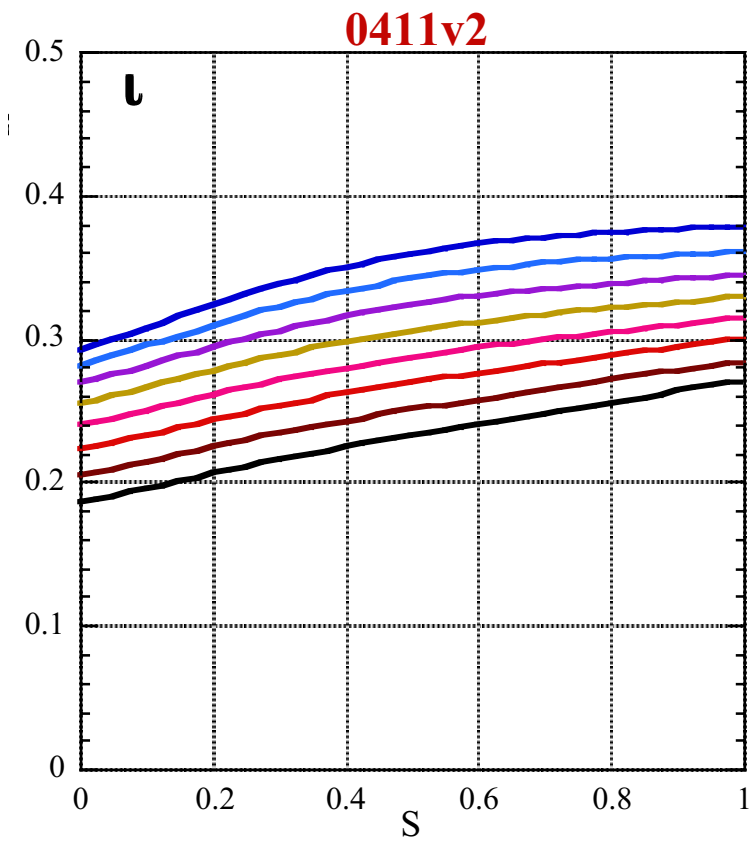
041102 Flux Surfaces Do Not Require Healing

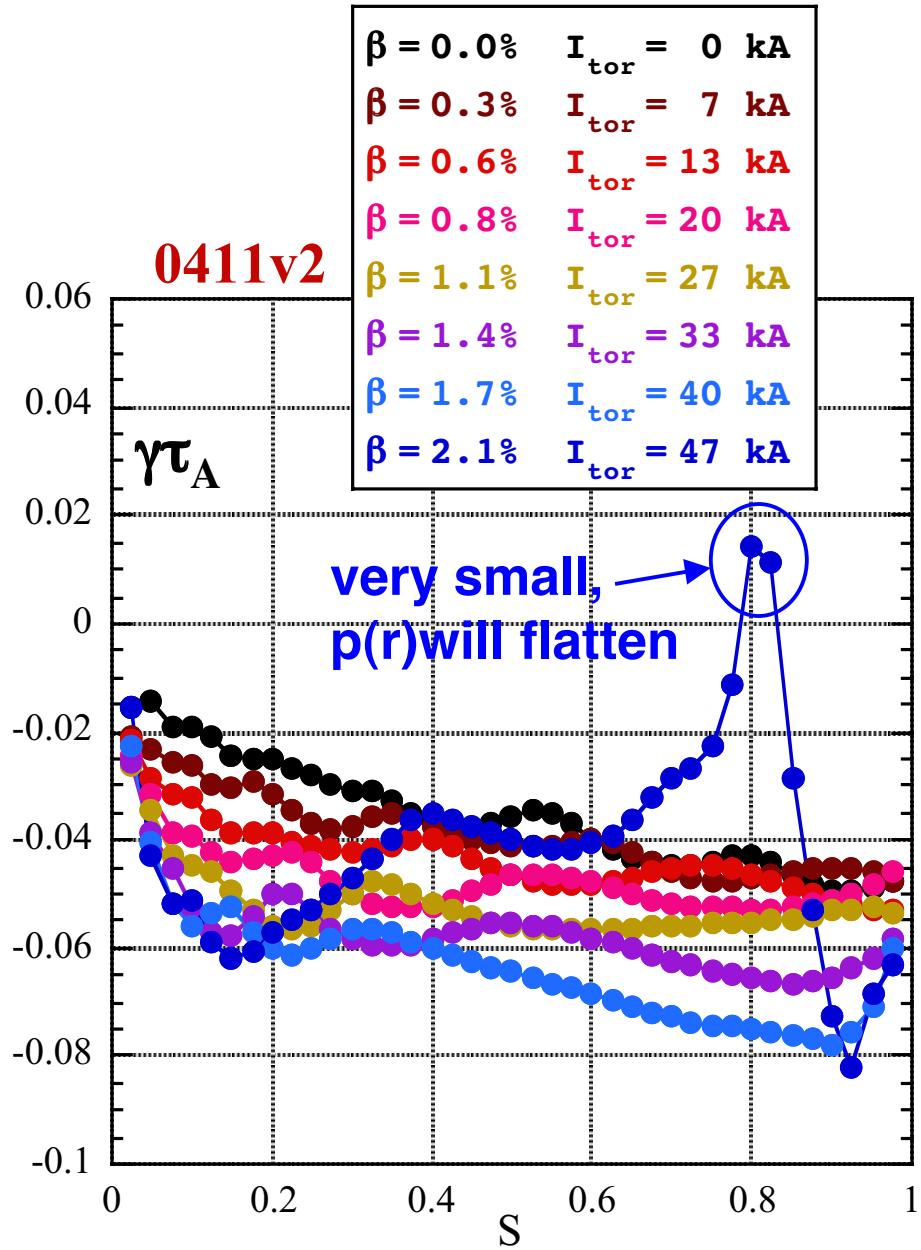
- **PIES show only small islands which plasma would cure**



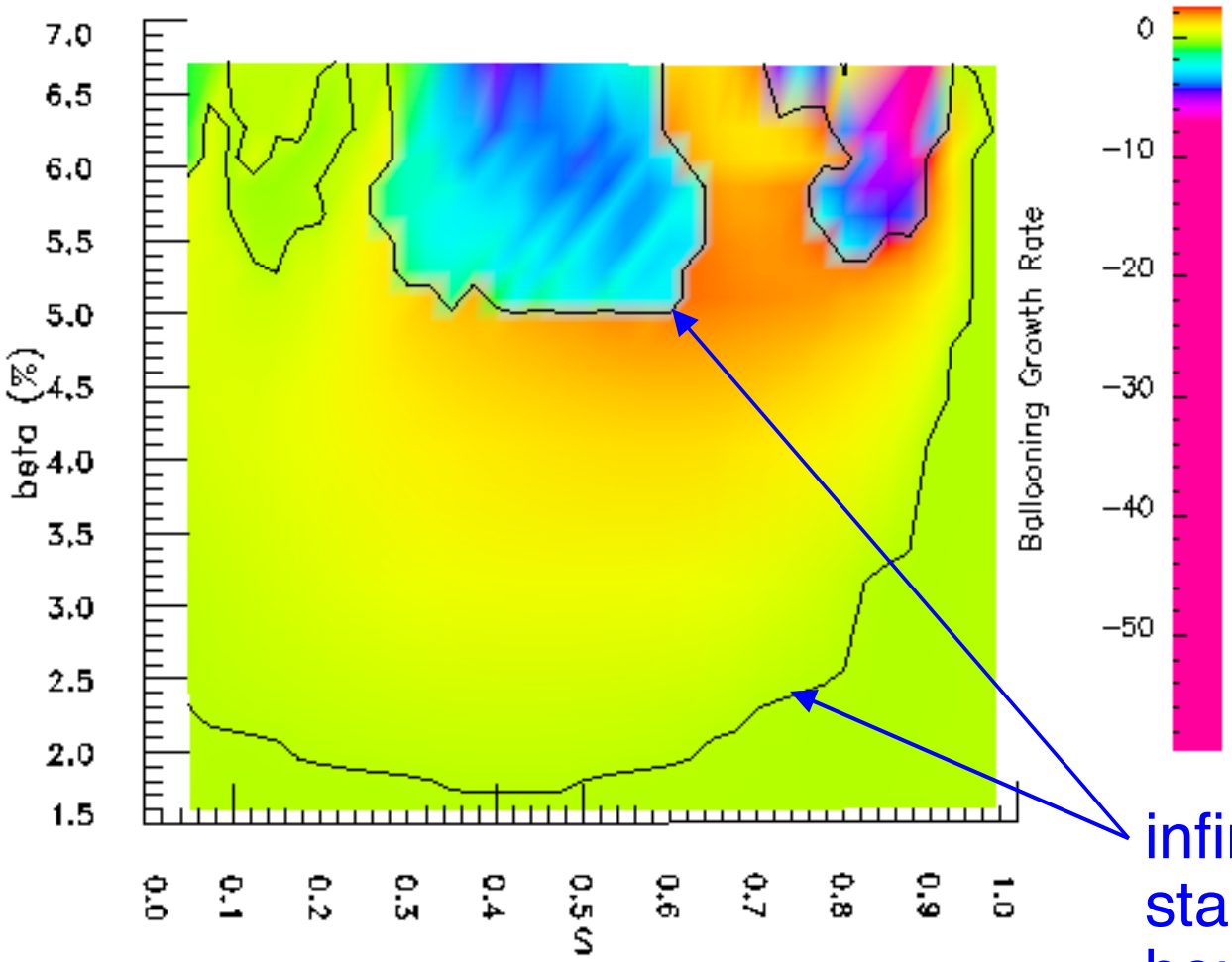
A Stable Path Exists from Vacuum to β = 2.1%

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





A Second Stability Region Exists for β > 5%

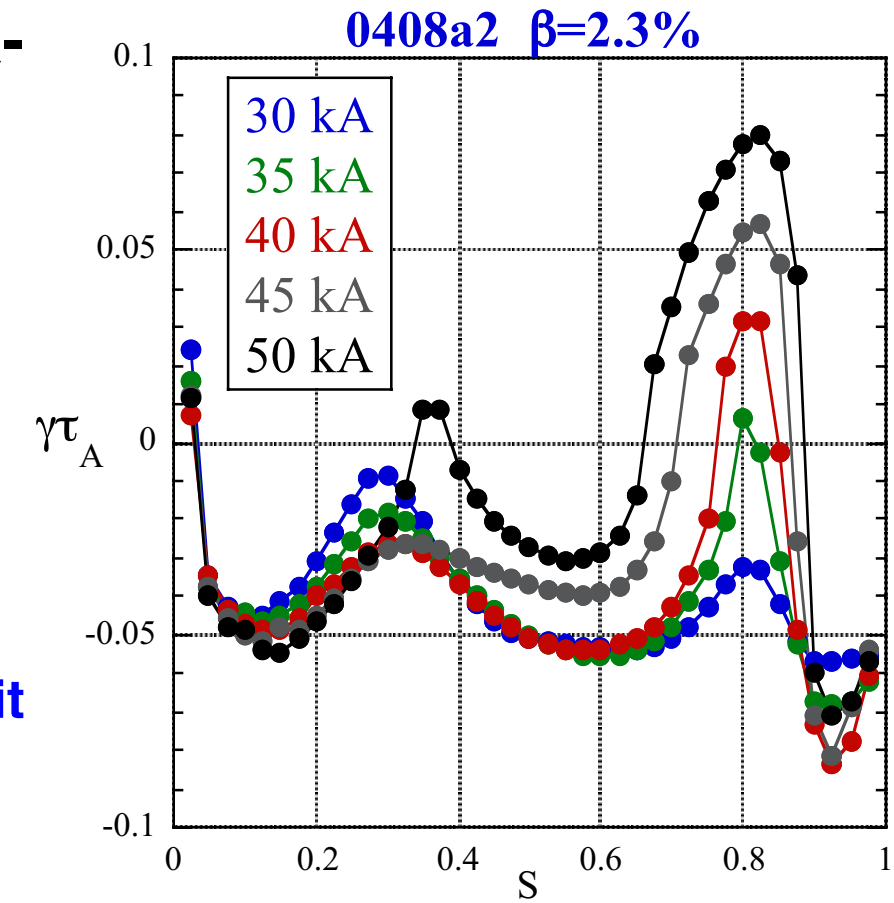


infinite-n stability boundary

Changing pressure and current profile and coil currents will change stability boundaries

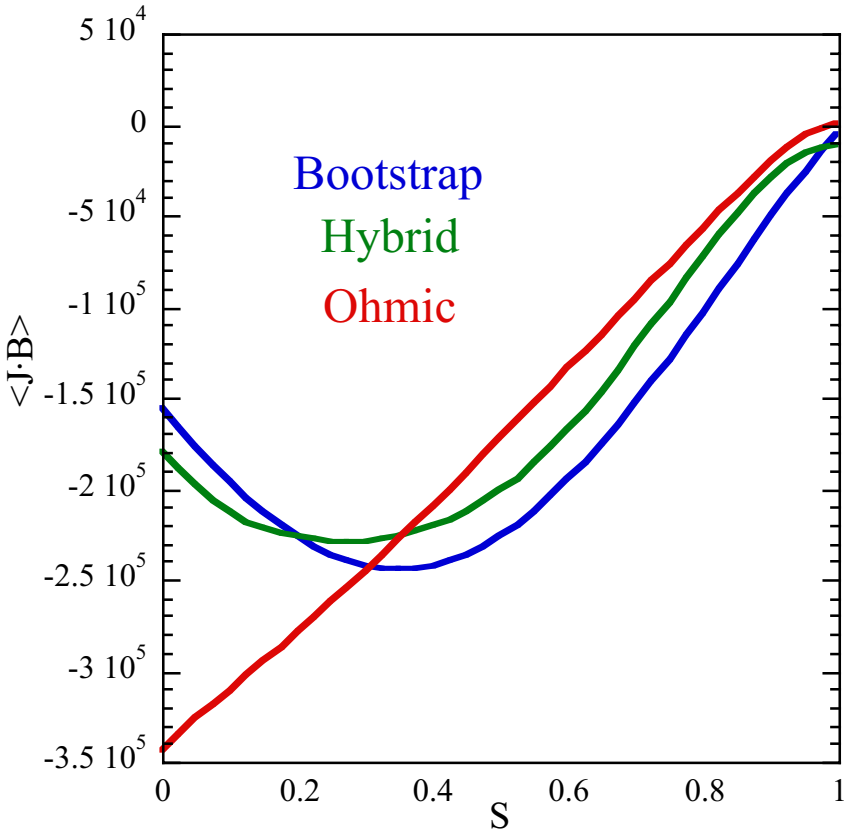
Infinite-n Ballooning Limits Likely to be Exceeded

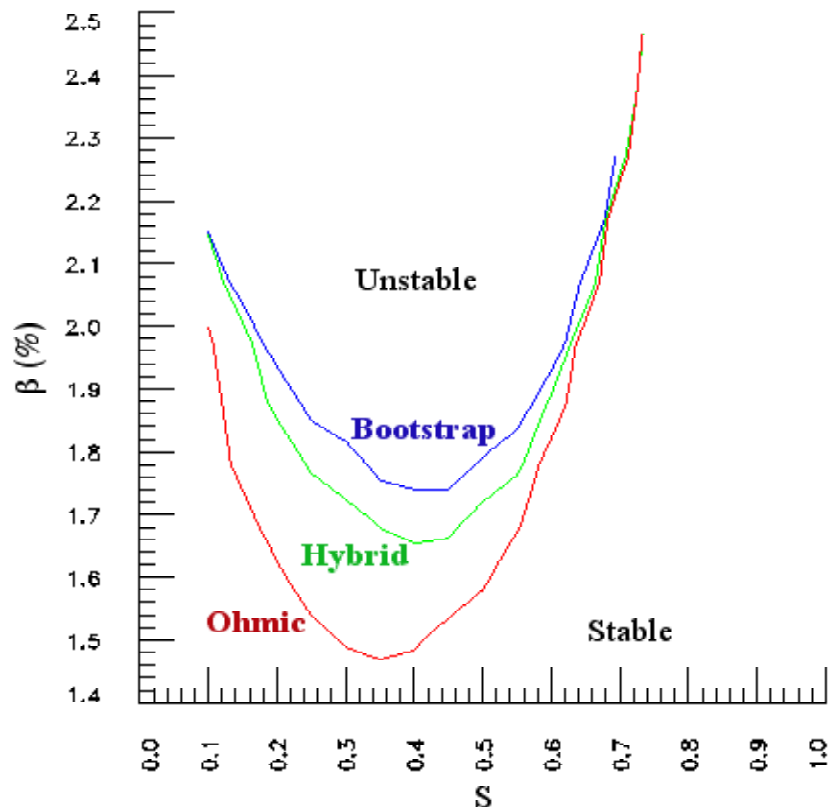
- **NCSX stability calculations indicate that finite-n ballooning limits are typically ~50% higher than infinite-n limits**
  - **have not yet explored reduction of second stability "gap" with finite n or path around it**
- **Bootstrap current is overestimated**
  - **lower plasma current leads to higher β limits**



Ballooning Stability Can Be Degraded for Testing

- **Tools are available to lower the ballooning beta limits**
  - **Plasma current profile, Plasma pressure profile**
  - **Increased Ohmic current**
  - **Vary modular coil or PF coil currents**





Status of QPS PVR Comments -- 1

- **Flux Surfaces Quality -- 3 of 4 comments addressed**
  - Only small islands, no healing needed
  - Will study impact of errors in coil shape and positioning
- **Confinement Issues -- all comments addressed**
  - QPS coil set allows large variation in neoclassical transport and beta limits and separating neoclassical from anomalous transport
- **Vacuum Issues -- all comments addressed**
  - Smaller vacuum vessel with hard seals and baking
- **Coils -- the comment addressed**
  - Same measurement procedure as for NCSX

Status of QPS PVR Comments -- 2

- **Diagnostics -- 1 addressed, other 3 are long term**
  - **Port configuration allows good access to the plasma**
- **High Beta -- all comments addressed**
  - **Startup scenarios from vacuum to 2% β and second stability region examined**
- **RF Heating -- all comments have been or are being addressed**
  - **W 7-AS has demonstrated EBW heating and NSTX has demonstrated HHFW heating; further calculations planned**

Status of QPS PVR Comments -- 3

- **Personnel and Management -- comments being addressed**
  - University collaborations discussed; more mid-career people will be brought into the QPS project as funding permits; ORNL gave approval for critical hire
- **Budget and Project Plans -- comment being addressed**
  - Costs will be addressed for external November assessment
- **Relationship to FESAC Goals -- both comments being addressed**
  - Possibility for high beta in later device will be explored
  - QPS group will participate in ARIES compact stellarator reactor study

QPS Physics Development: Rest of 2002

- Continue fine-tuning QPS plasma and coil configuration; optimize PF coils and startup scenario
- Use PIES code to examine islands at finite beta for a variety of QPS cases and look at island healing and trim coil options
- Assess the effects on the flux surfaces of various types of errors in coil shape or positioning
- Continue QPS flexibility and second stability assessments
- Extend poloidal flow damping calculations

QPS Physics Development: FY2003

- Complete documentation of near-term PVR disposition items
- Continue assessments of MHD equilibrium, stability, neoclassical transport, flow damping, ambipolar electric fields, and RF heating for a range of QPS configurations (flexibility)
- Examine different operating scenarios and range of magnetic configurations accessible, power supply constraints
- Calculate ECH power deposition profiles
- Follow field lines for locating divertor plates
- Better define the QPS experimental program and the diagnostics and analysis/modeling tools needed for it

QPS Diagnostics Will Be Staged

Resource/Phase	Phase 0	Phase 1	Phase2	Phase 3	Phase 4	Phase 5
Objective	**Commissioning**	**Vacuum configurations**	**Configuration characterization**	**Heating, confinement**	**Power, particle control**	**MHD limits**
Heating			**ECH 500 kW B = 0.5 T**	**ECH 1 MW B = 1.0 T**		**ECH + ICH 1-3 MW**
CCD camera, H-alpha filter Fast diamagnetic loop 2 mm interferometer Fluorescent screen/rods						
Soft X-ray arrays Spectroscopy Rogowski coils/magnetic loops Bolometers Probes						
Charge exchange YAG Thomson scattering Reflectometer						
Filtered CCD cameras Divertor probes IR camera Divertor bias plates						
Edge interferometer High frequency magnetic probes Fast X-ray array						

QPS Research Preparation -- 1

These tasks are to develop or apply tools and prepare for experimental operation -- tasks not covered elsewhere

- **2004**
  - **Analyze placement of magnetic loops and sight lines for soft X-ray detectors & Thomson scattering for 3-D equilibrium reconstruction**
  - **Refine plan for staged implementation of key diagnostics**
- **2005**
  - **Decide placement of magnetic loops and sightlines for SX detectors, Thomson scattering, CCD cameras for 3-D equilibrium reconstruction**
  - **Plan divertor plate diagnostics**

QPS Research Preparation -- 2

- **2006**
  - Develop plasma control algorithms for configuration flexibility studies targeting QP symmetry, NC transport, MHD stability, plasma/bootstrap current
  - Study trim coil options
  - Initiate work on Phase 2 profile diagnostics
- **2007**
  - Complete on-line analysis codes needed for characterizing initial plasma operation
  - Complete flux surface mapping tools needed for comparison of measured and calculated flux surfaces
  - Test codes for 3-D equilibrium reconstruction using simulated experimental data
  - Analyze ICRF heating options for initial antenna design

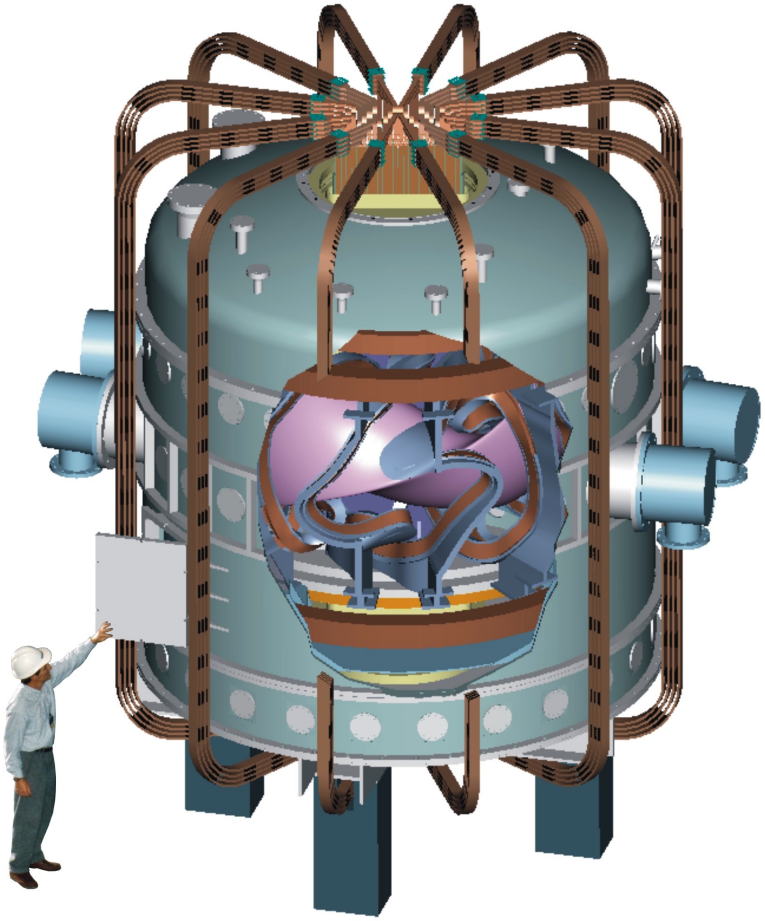
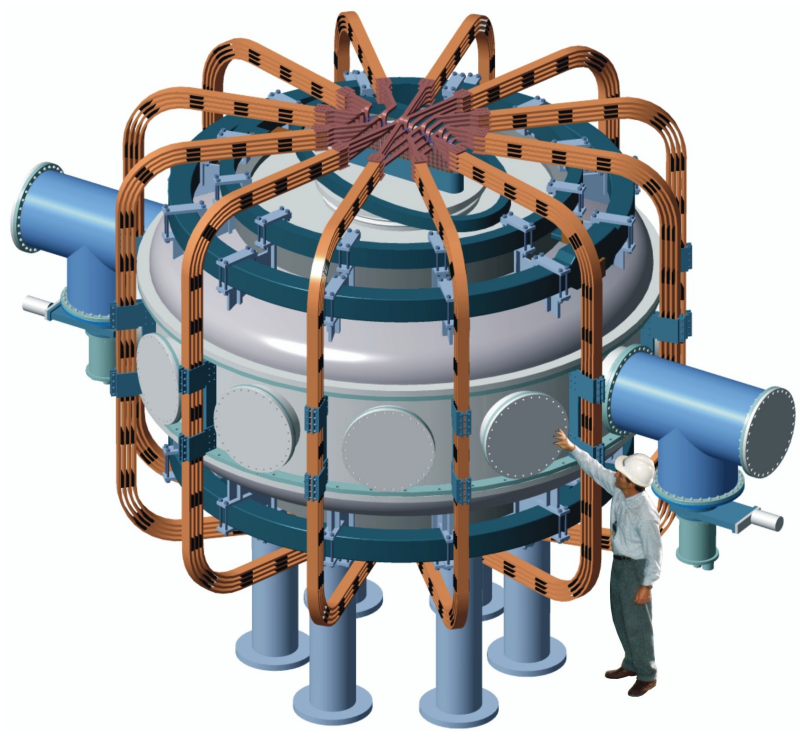
Summary

- Substantial progress has been made in QPS plasma and coil development since the PVR
- Merged optimizer has produced the plasma and coil configuration that we need
- Disposition of PVR comments is mostly complete
- QPS physics plans have been developed for FY's 2002–2003
- Preparations for QPS operation have been outlined for FY's 2004–2007

⇒ On track for November design assessment and April CDR

Significant Progress Has Also Been Made in QPS Engineering

at PVR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