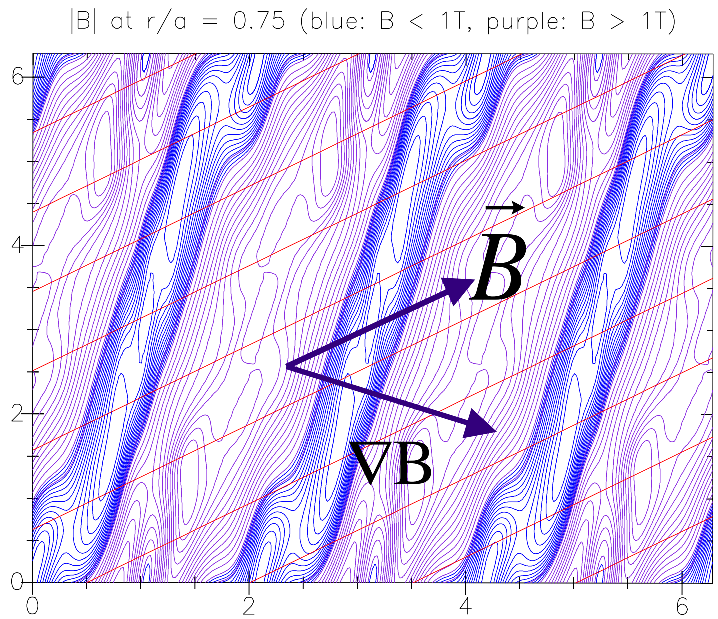
US CE Stellarator Program: HSX, CTH, QPS

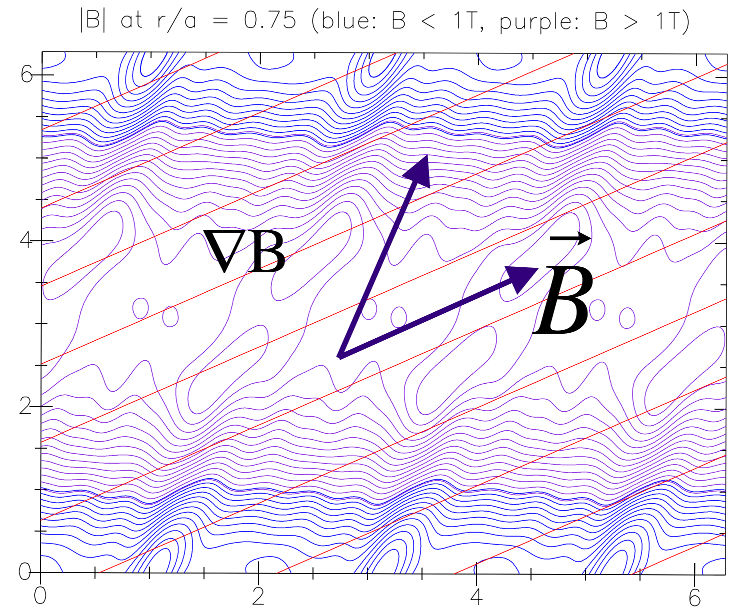
J.F. Lyon, ORNL

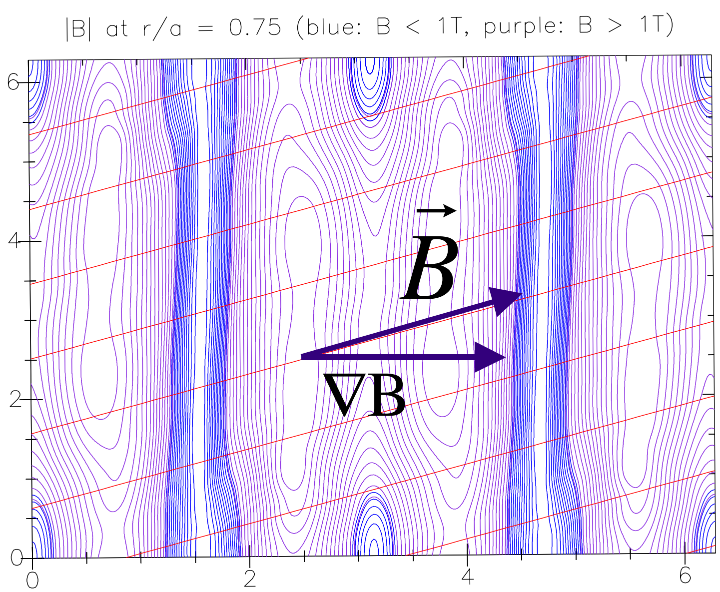
FY 2004 Budget Planning Meeting

March 13, 2002

US Stellarator Approach Tests Quasi-Symmetry



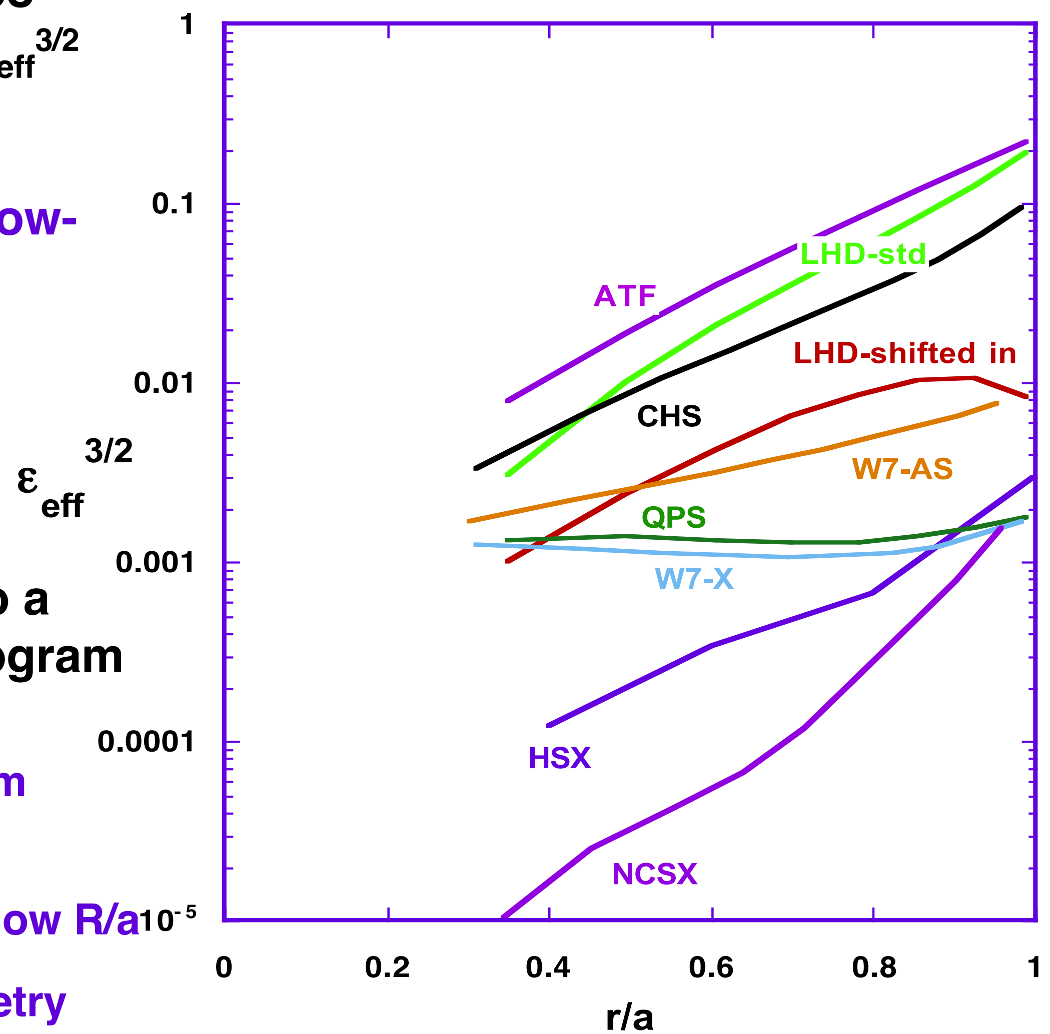




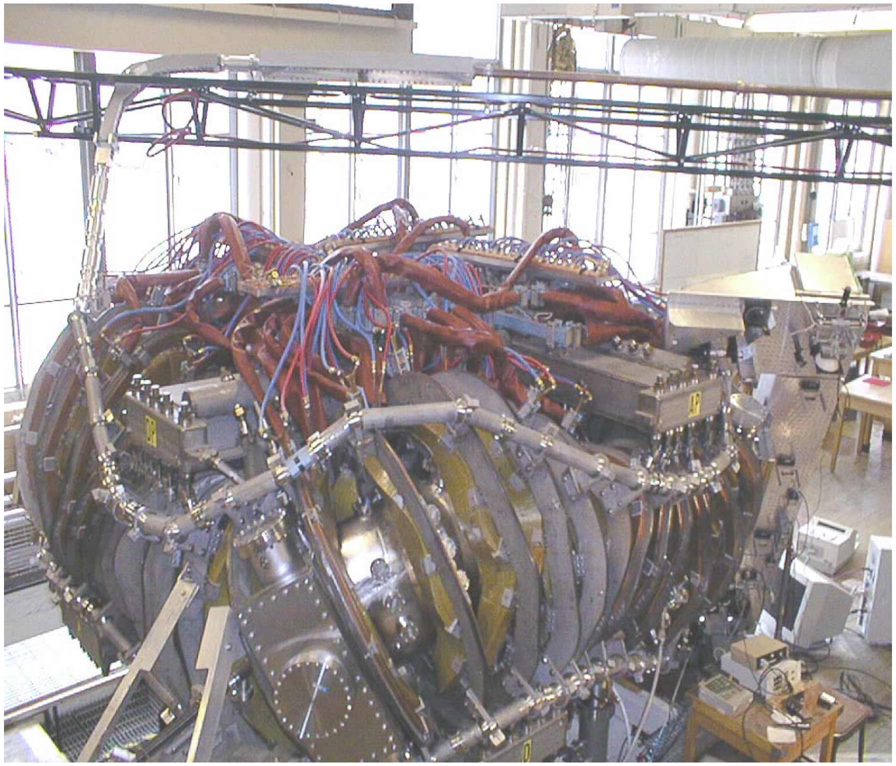
- **Quasi-helical: lBl like a stellarator with very large *R/a* -- test in HSX (*R/a* = 8)**
- **Quasi-axisymmetric: lBl like a tokamak -- test in NCSX (*R/a* = 4.3)**
- **Quasi-poloidal: lBl like toroidally linked mirrors *with* rotational transform -- test in QPS (*R/a* = 2.7)**

New US Stellarators Use Quasi-Symmetries for Improved Neoclassical Transport and Stability with Plasma Current

- In $1/\nu$ regime, asymmetrical neo-classical transport scales as $\epsilon_{eff}^{3/2}$
- Low flow-damping
  - manipulation of flows for flow-shear stabilization
  - zonal flows like tokamaks
- Initial (successful!) test in HSX, studies continuing
- Stability with finite current also a key issue for the stellarator program
  - CTH focused on kink & tearing stability with external transform
  - QPS will test quasi-poloidal symmetry and current at very low R/a
  - NCSX will test quasi-axisymmetry and current at low ν_* and high β



HSX Explores Improved Neoclassical Transport with Quasi-helical Symmetry



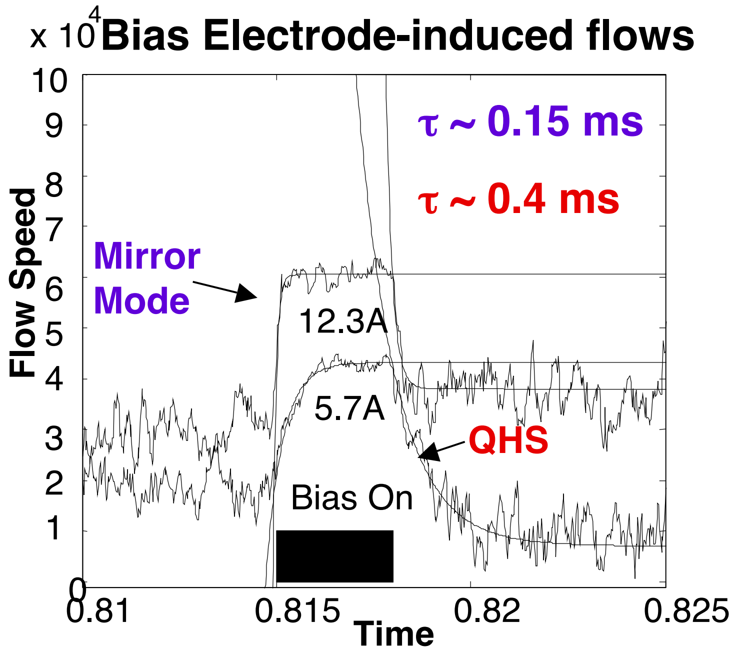
R = 1.2 m, $\langle a \rangle$ = 0.15 m, B = 1.0 T
4 periods, 200-kW 28-GHz ECH
(additional 350 kW at 53 GHz in progress)
University of Wisconsin-Madison

- Worlds first operating quasi-symmetric stellarator
- High effective transform (q_{eff} = 1/3)
  – large minor radius/banana width
  – very low plasma currents
  – very low neoclassical transport
- Neoclassical transport, stability and viscous damping can be varied with auxiliary coils

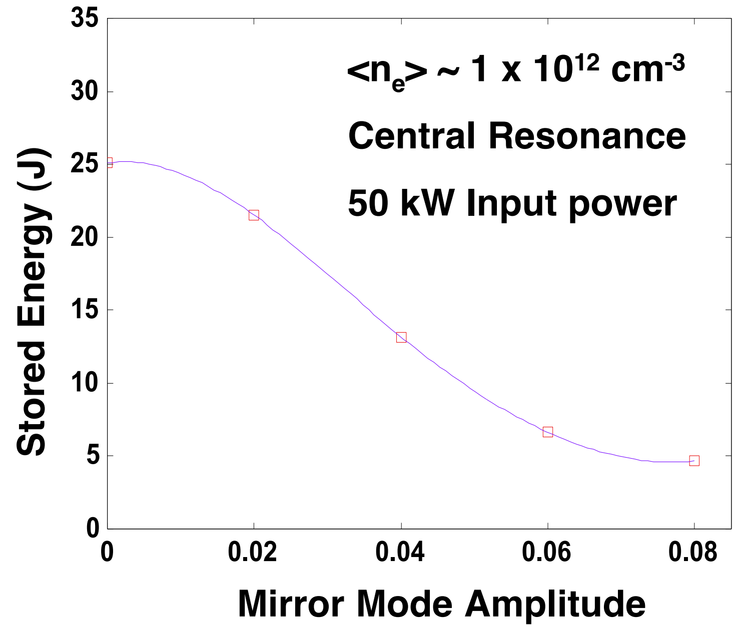
Goals

- Test reduction of neoclassical electron thermal conductivity at low collisionality
- Test E_r control through plasma flow and ambipolarity constraint
  – low viscous damping in the direction of symmetry may lead to larger flows
- Investigate anomalous transport and turbulence
- Test Mercier and ballooning limits

HSX Results Show Symmetry Matters



QHS Has Comparable Flow Speed to Mirror Mode with Less Drive and Factor ~2 Smaller Damping

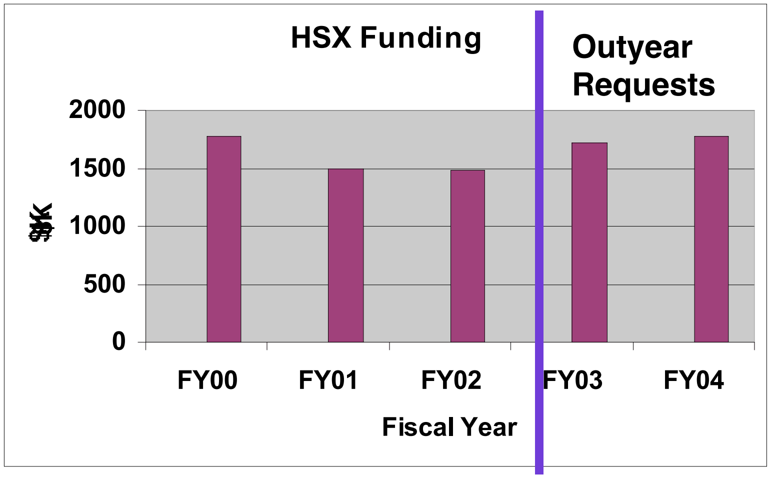


Plasma Stored Energy Falls Rapidly as the Mirror Term is Added to the IBI Spectrum

- 2nd Harmonic ECH (28 GHz, B = 0.5 T) is used to generate hot trapped electron population
  - Hard x-ray flux (100-300 keV) up 1-2 orders of magnitude for QHS compared to mirror mode; signal persists 15-20 ms after ECH for QHS
  - Measurement of electron drift fluxes show virtually no direct loss orbits for QHS, but significant fluxes for the mirror mode

HSX Funding is Declining as Research Opportunities Soar

- Budget reductions from FY00 through FY02 have constrained the installation of diagnostics and available manpower on HSX
  - the only quasi-symmetric stellarator in the world program until 2007



- The HSX budget has declined by 16% from FY00 to FY02
- Extensive peer review of three year renewal (effective 2/1/2002) supported an FY03 budget at $1720K

- 10% reduction to $1548K

  Operations only at present level with little available funds for diagnostic improvements or equipment; slows investigations into impact of quasi-symmetry on anomalous transport and stability limits.

- Increments needed

  + $130K for an ECE imaging system and post-doc for time-resolved temperature and turbulence measurements

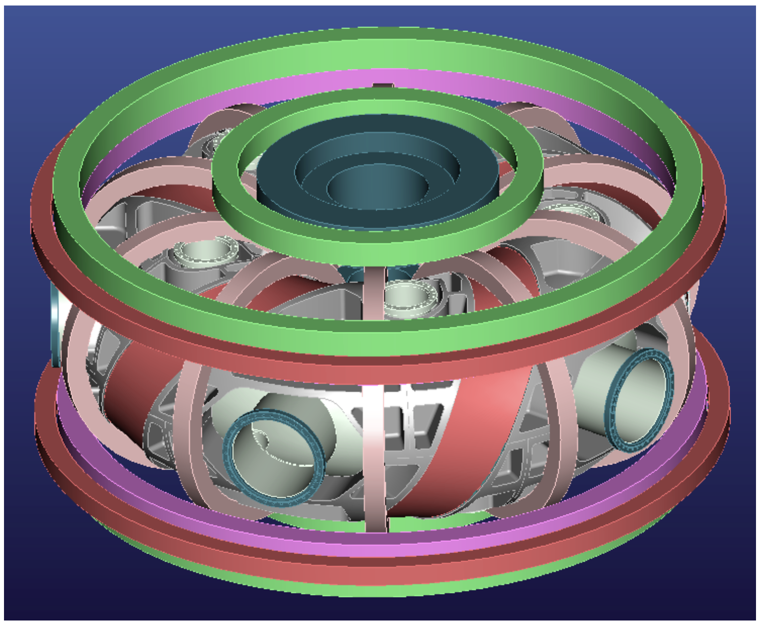
  + $90K for microwave scattering for fluctuation measurements and anomalous transport studies

  + $100K for collaborations with PPPL/ORNL on RF heating

Compact Toroidal Hybrid (CTH) Experiment

Auburn University

Targets current-driven disruptions and macroscopic stability in low aspect ratio, current-carrying stellarators



- R = 0.75 m, $\langle a \rangle$ = 0.2 m, B = 0.5T, I_{plasma} = 50 kA
- Now under construction
- Operation to begin in 2003

CTH fully integrated into IPPA process

→ ISSUES

- Disruption suppression by 3-D helical fields
  - IPPA 3.1.2.2: understanding physics underlying external stability control
  - IPPA 3.2.3.2: advance stellarator physics with small exploratory experiments
  - IPPA 3.3.2: disruption mitigation
- Measurement of 3-D magnetic equilibrium of current-driven stellarator [new task]
  - 1st implementation of new 3-D reconstruction method; important deliverable to US program
- Influence of magnetic islands on stability
  - external control of magnetic errors, measurement of islands in plasma

CTH Challenges

- University lab addresses design & fabrication problems of high-precision, 3-D system with targeted collaborations & linkages.
  - Engineering & theory support from PPPL, consultation with HSX group
  - Collaboration with GA/ORNL team in 3-D reconstruction method
- Scientific staff shortages being addressed.
  - Search for new experimental plasma physics faculty near completion
  - New grad students (thanks to approved CTH project as a recruiting tool)
  - Seeking additional post-doc support

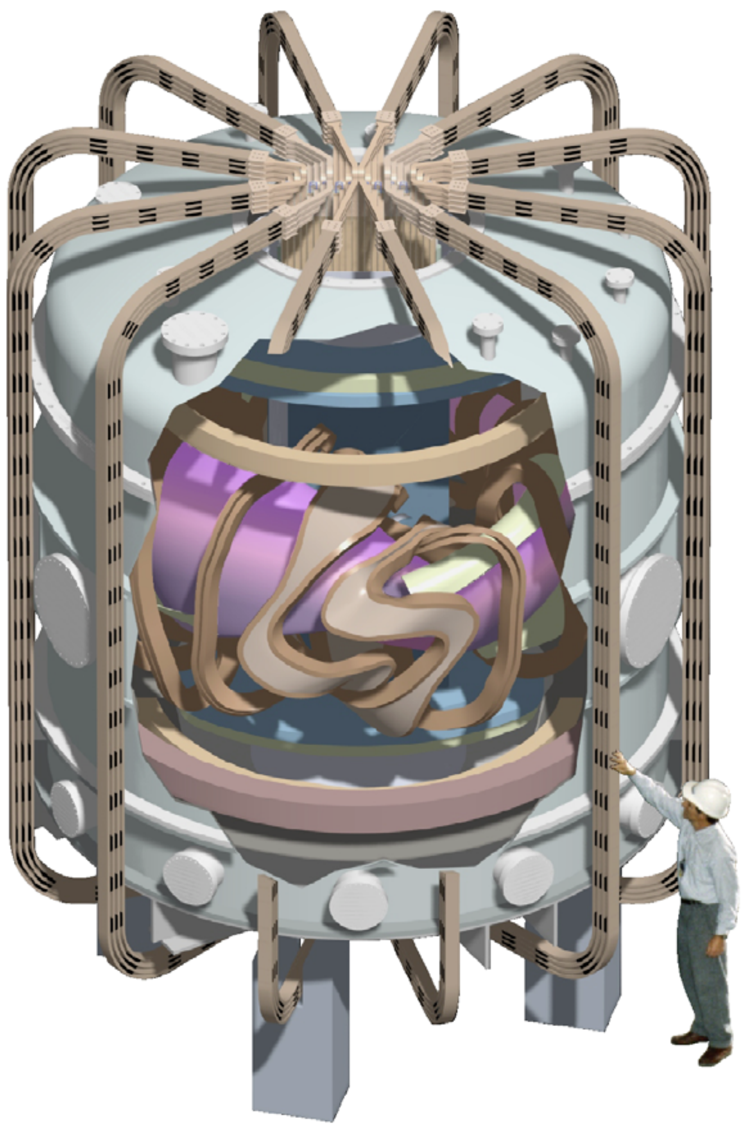
CTH Milestones

- Completion & initial operation in FY 2003
  - Vacuum vessel delivery 5/2002; helical coil frame delivery 11/2002,
  - Final assembly by summer 2003
  - Field line mapping & shakedown 8/2003; Ohmic operation late in 2003
- Experimental results on 3-D reconstruction beginning in early 2004
- Stability studies with magnetic & soft X-ray diagnostics in 2004/2005
- Development of MSE/LIF for planned implementation in late 2005

CTH FY 2004 budget

- **CTH will make essential contributions to development & understanding of NCSX & QPS equilibrium measurement & stability.**
  Budget determines expected rate of achieving milestones.
- **Level case: $525K/year**
  - **Completion & initial operation in late 2003 with equilibrium reconstruction; interpretations beginning to be delivered in early 2004**
  - **Measurement of internal B field (MSE/LIF) for reconstruction in late 2005**
  - **Diagnosed stability experiments in 2004 & 2005**
- **Decrement case: $470K/year => all science results slip, timely contributions to NCSX delayed**
  - **With reduced & delayed data acquisition & basic diagnostics, even initial equilibrium interpretation delayed**
    This is an important issue for NCSX & QPS development
  - **Development of more novel diagnostic (e.g. MSE/LIF) delayed substantially or shelved; all stability experiments delayed for lack of SX and diagnostics**
- **Increment case building from $470K decrement case**
  - * **+ $30K -- restoration of initial reconstruction capability**
  - * **+ $100K -- acceleration of MSE/LIF internal B-field diagnostic implementation**
  - * **+ $100K -- post-doc concentrating in diagnostics**

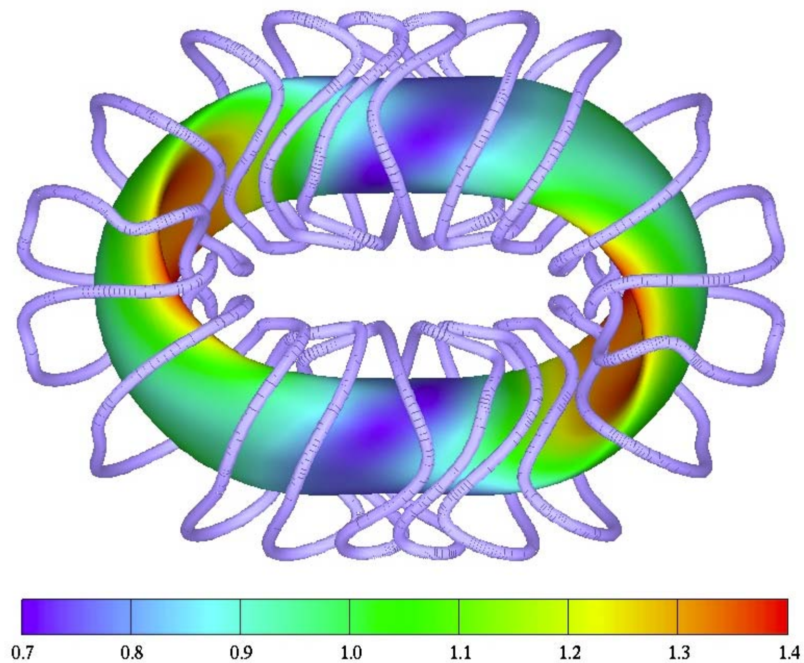
QPS Will Pioneer Good Confinement and Stability in Very Low Aspect Ratio Stellarators



- ⟨*R*® = 0.9 m; ⟨*a*® = 0.33 m
  B = 1 T (1 s); P_{RF} = 1-3 MW
- Consequences of poloidal symmetry
  - closer alignment of B and ∇B reduces radial drift and banana thickness
    - * same ripple transport as W 7-X, 1/4 R/a
  - minimum flow damping in E_r x B direction
  - trapped particles are localized in low curvature regions
  - properties improve with increasing β
    - * access to a second stability region
    - * omnigeneity, thermal and fast ion confinement
    - * relatively insensitive to increasing β
    - * bootstrap current independent of β
- Can study fundamental issues common to low-β and high-β quasi-poloidal configurations

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

- **Anomalous transport, internal transport barriers, and flow shear in low-*R/a* configurations with quasi-poloidal symmetry**
- **Reduction of neoclassical transport due to near alignment of *B* and ∇B**
- **Impact of poloidal flows on enhanced confinement**
- **Equilibrium quality (islands, ergodic regions) and its repair at *R/a* ~ 2.7**



|B| in T

- **Flux surface robustness with β and dependence of bootstrap current on configuration properties**
- **Ballooning β character and limits for quasi-poloidally symmetric configurations at very low *R/a***

QPS Highlights This Year

- Successful Physical Validation and Project Validation Reviews in 2001. Mission Need (CD-0) approved. QPS now in conceptual design phase.
- Neoclassical transport losses reduced by a factor ~15 since the PVR reference case; now at the same level as in W 7-X.
- Addressing issues raised by PVR panel
  - flux surface quality, confinement, vacuum, diagnostics
- Significant design improvements
  - Open space in the center has been increased to accommodate the TF coil legs and an OH solenoid
  - Plasma-coil and coil-coil spacings have been increased
  - Modular coils have been modified to reduce errors by factor 2.2
  - Vacuum vessel has been modified to reduce eddy currents, give lower base pressure, and allow twelve 61-cm diameter ports for diagnostics and heating

QPS Budget Requests and Milestones

- **FY 2003 -- $983k at ORNL, $246k at PPPL**

  <u>Milestones</u>
  - Conceptual Design Review for QPS -- 5/03
  - Complete design for modular coil prototypes -- 9/03
  - Document plans for research preparation activities for QPS -- 9/03

- **FY 2004 -- $2179k (MIE), $240k (prep) at ORNL**
  $965k (MIE), $60k (prep) at PPPL

  <u>Milestones</u>
  - Award contract for full-scale modular coil prototypes - 11/03
  - Complete fabrication of full-scale modular coil prototypes - 8/04
  - Complete final design for QPS modular coils - 9/04
  - Summarize status of research preparation activities for QPS - 9/04
  - Complete design of vacuum vessel - 9/04

- **Incremental request**
  - FY 2003 -- $240k at ORNL, $60k at PPPL for research preparations
  - FY 2004 -- $160k at ORNL, $40k at PPPL for research preparations

Summary

- HSX, CTH, and QPS support and complement NCSX in the US (and world) stellarator program
  - Each has unique features and contributions to toroidal physics
    - HSX pioneers quasi-helical symmetry
    - CTH addresses disruption suppression
    - QPS pioneers quasi-poloidal symmetry and very low aspect ratio
- Balanced program with a range of device scales, aspect ratios, features, and status from operating to conceptual design
  - HSX (R = 1.2 m, a = 15 cm, P = 0.2 => 0.55 MW, operating)
  - CTH (R = 0.75 m, a = 20 cm, Ohmic, 2003)
  - QPS (R = 0.9 m, a = 33 cm, P = 1-3 MW, 2007)
- Key tasks for FY 03-04
  - HSX: ambitious experimental program
  - CTH: complete construction and start operation
  - QPS: Conceptual Design Review, complete design, build prototypes
- Incremental budget would allow taking better advantage of program capabilities