

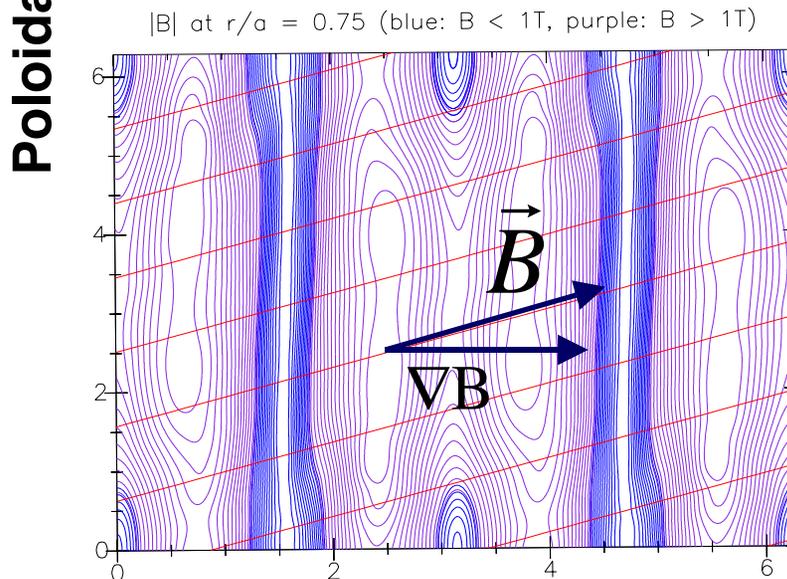
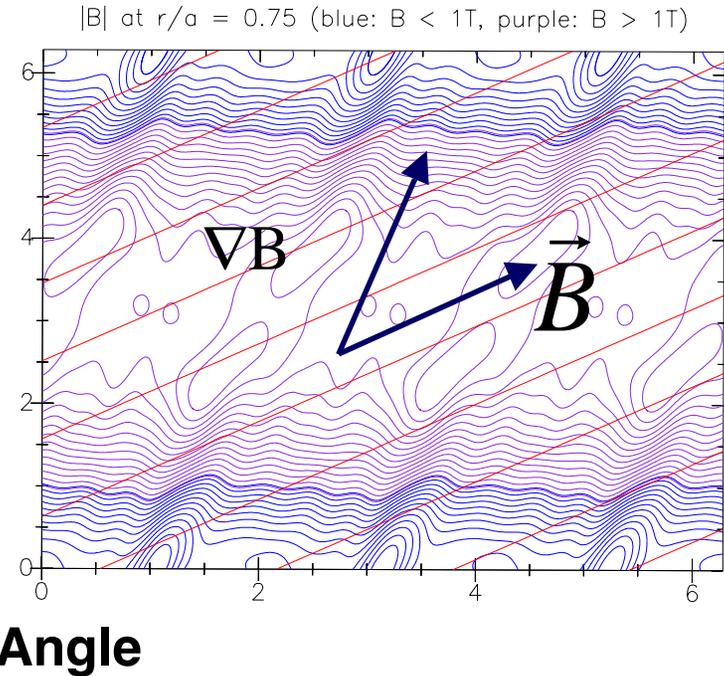
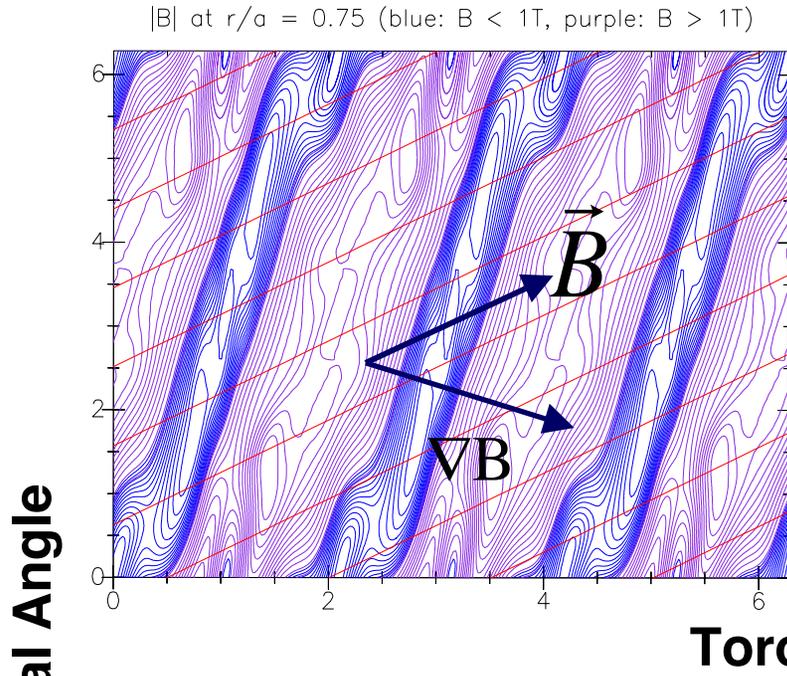
US CE Stellarator Program: HSX, CTH, QPS

J.F. Lyon, ORNL

FY 2004 Budget Planning Meeting

March 13, 2002

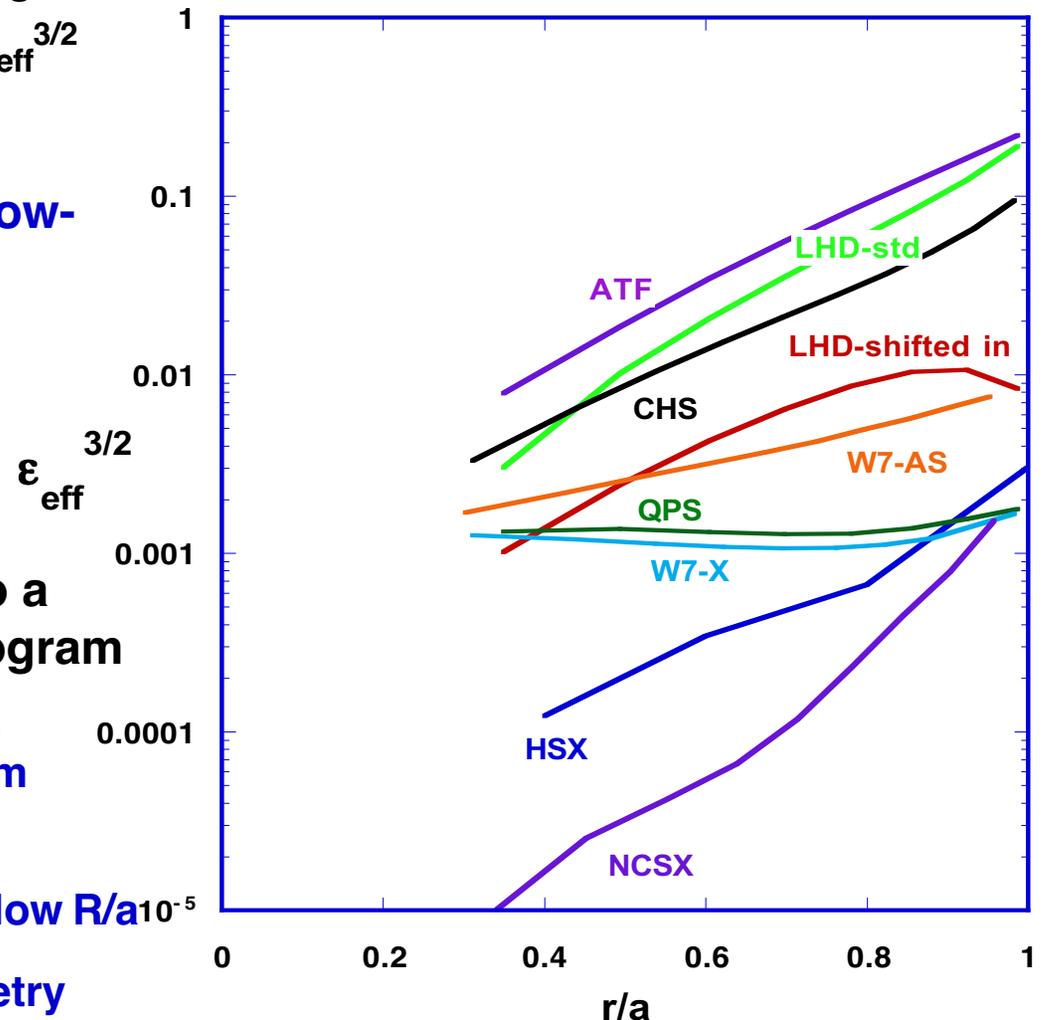
US Stellarator Approach Tests Quasi-Symmetry



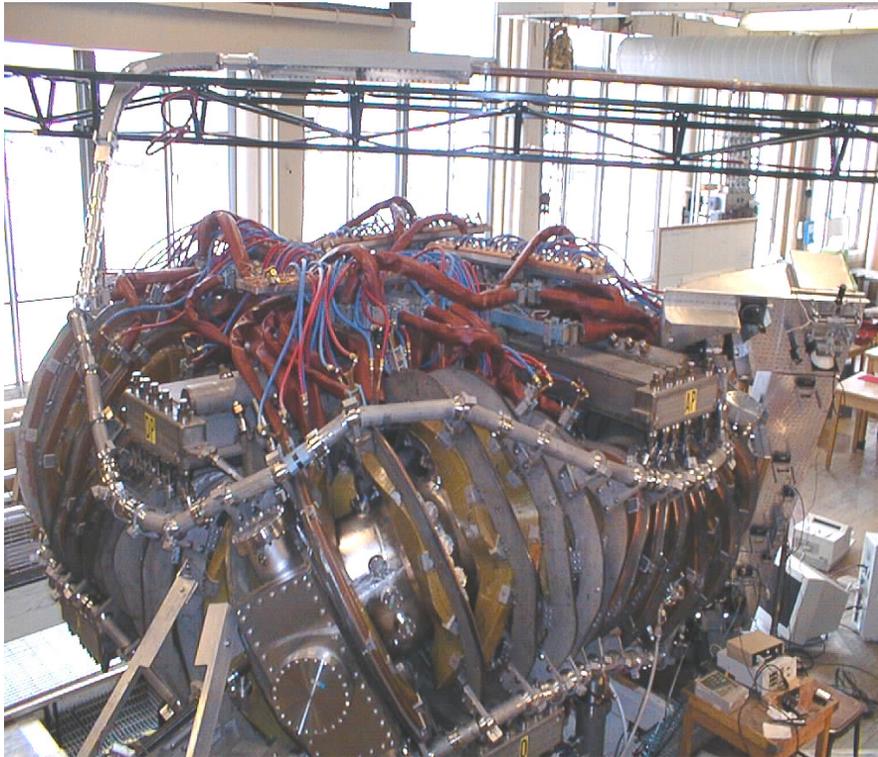
- Quasi-helical: $|B|$ like a stellarator with very large R/a -- test in **HSX ($R/a = 8$)**
- Quasi-axisymmetric: $|B|$ like a tokamak -- test in **NCSX ($R/a = 4.3$)**
- Quasi-poloidal: $|B|$ like toroidally linked mirrors *with* rotational transform -- test in **QPS ($R/a = 2.7$)**

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

- In $1/\nu$ regime, asymmetrical neoclassical transport scales as $\epsilon_{\text{eff}}^{3/2}$
- 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



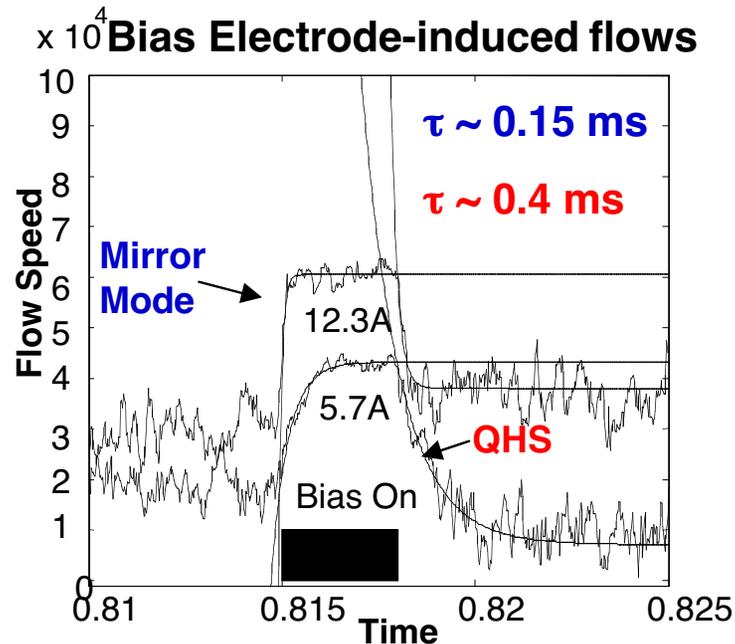
$R = 1.2$ m, $\langle a \rangle = 0.15$ m, $B = 1.0$ T
4 periods, 200-kW 28-GHz ECH
(additional 350 kW at 53 GHz in progress)
University of Wisconsin-Madison

- World's first operating quasi-symmetric stellarator
- High effective transform ($q_{\text{eff}} = 1/3$)
 - 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

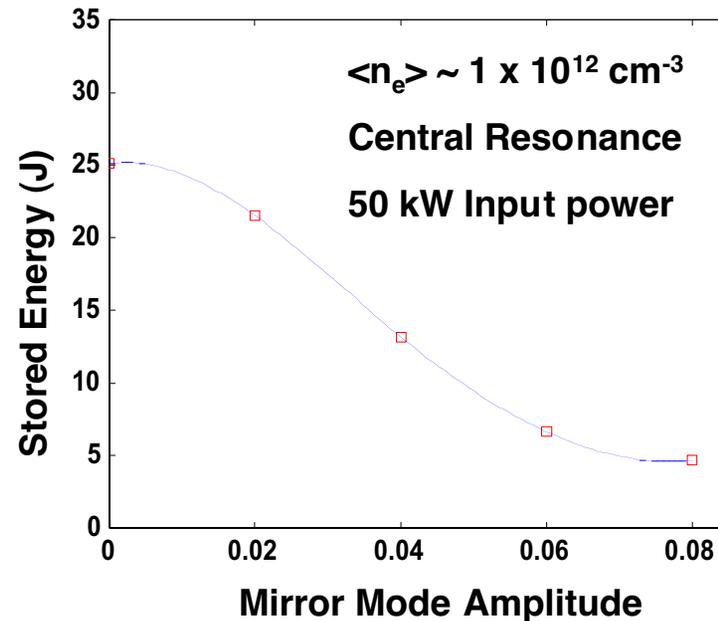
Goals

- 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

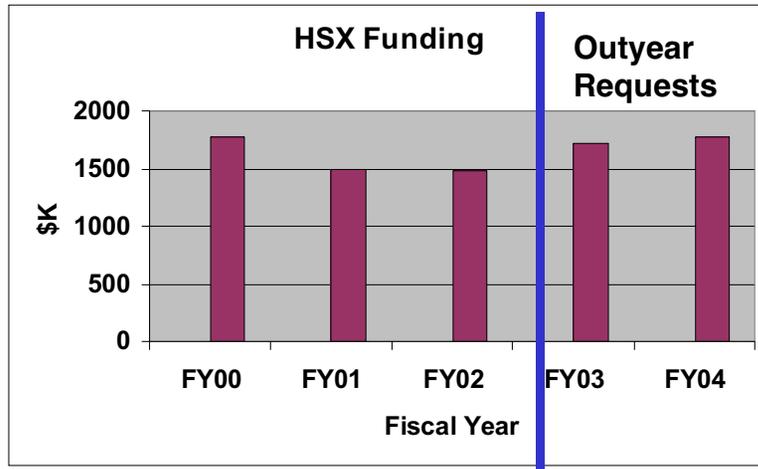


Plasma Stored Energy Falls Rapidly as the Mirror Term is Added to the IBI Spectrum

- **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.

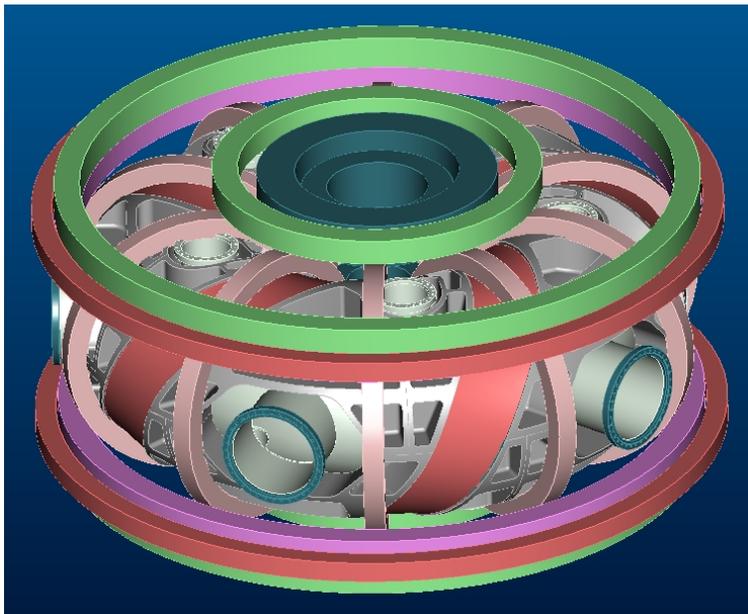
- **Increments needed**

- + \$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, $B = 0.5$ T, $I_{\text{plasma}} = 50$ 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**

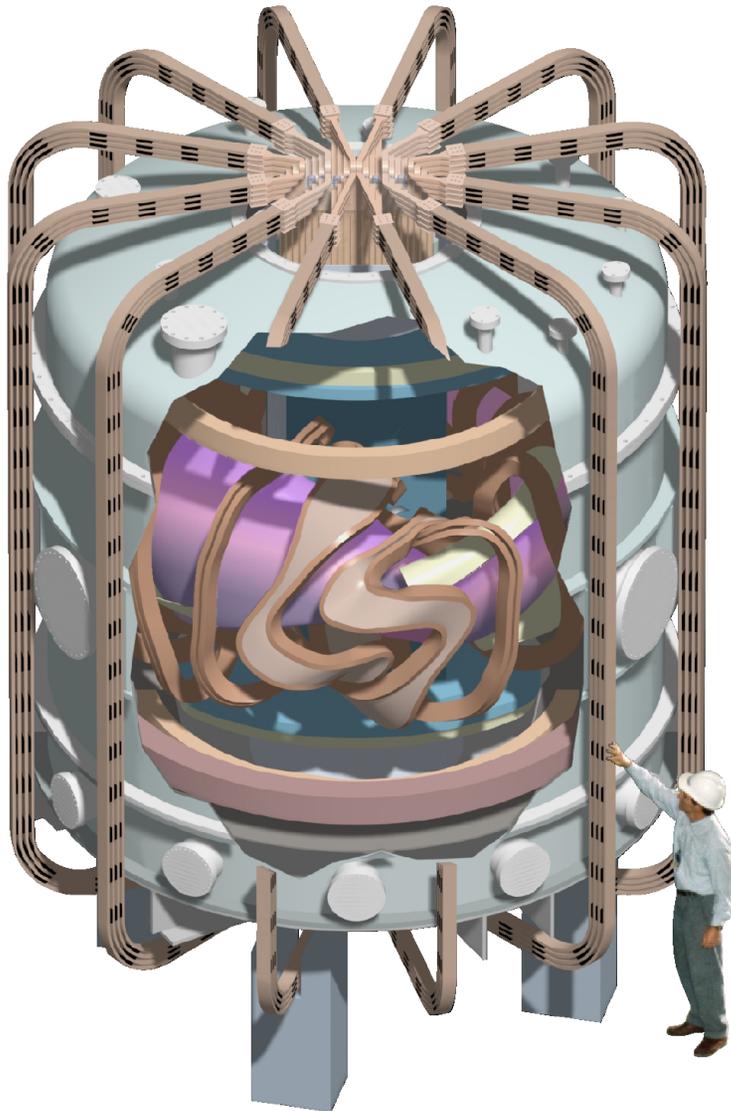
CTH Milestones

- **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

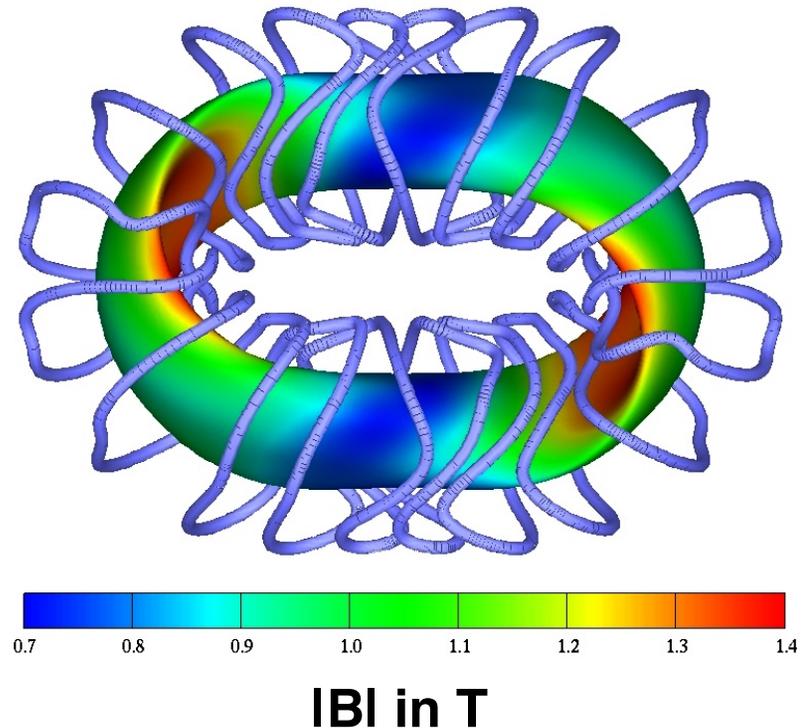
QPS Will Pioneer Good Confinement and Stability in Very Low Aspect Ratio Stellarators



- $\langle R \rangle = 0.9$ m; $\langle a \rangle = 0.33$ m
 $B = 1$ T (1 s); $P_{\text{RF}} = 1\text{-}3$ MW
- Same ripple transport as W 7-X but at 1/4 the aspect ratio
- Consequences of poloidal symmetry
 - may lower H-mode power threshold
 - lower parallel bootstrap current leads to robust equilibrium with β
- Can study fundamental issues common to low- β and high- β quasi-poloidal configurations
 - scaling of the bootstrap current and quasi-poloidal symmetry with β
 - reduction of neoclassical transport
 - flux surface robustness
 - ballooning instability character & limits

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 $R/a \sim 2.7$
- 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**

Milestones

- **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**

Milestones

- **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, $P = 0.2 \Rightarrow 0.55$ 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**