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 $\varepsilon_{\text{eff}}^{3/2}$
- 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 $\nu$ and high $\beta$
HSX Explores Improved Neoclassical Transport with Quasi-helical Symmetry

- 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

$R = 1.2\ m$, $<a> = 0.15\ m$, $B = 1.0\ T$
4 periods, 200-kW 28-GHz ECH
(additional 350 kW at 53 GHz in progress)

University of Wisconsin-Madison
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
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.

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

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
Compact Toroidal Hybrid (CTH) Experiment
Auburn University

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

- $R = 0.75 \text{ m, } <a> = 0.2 \text{ m, } B = 0.5 \text{T, } I_{\text{plasma}} = 50 \text{ kA}$
- 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

- $\langle R \rangle = 0.9 \text{ m}; \: \langle a \rangle = 0.33 \text{ m}$
- $B = 1 \text{ T (1 s)}; \: P_{RF} = 1-3 \text{ MW}$
- 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 $\beta$
- Can study fundamental issues common to low-$\beta$ and high-$\beta$ quasi-poloidal configurations
  - scaling of the bootstrap current and quasi-poloidal symmetry with $\beta$
  - 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 $\nabla B$
- 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 $\beta$ and dependence of bootstrap current on configuration properties
- Ballooning $\beta$ 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 => 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