US CE Stellarator Program: HSX, CTH, QPS

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FY 2005 Budget Planning Meeting

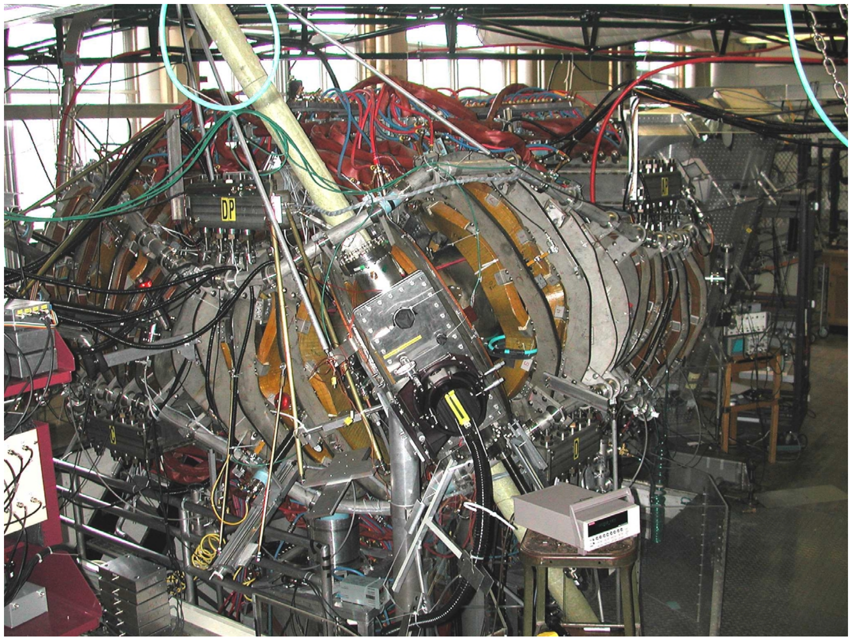
March 19, 2003

US CE-Level Experiments Complement PoP-level NCSX

- NCSX has R = 1.4 m, a = 0.33 m, R/a = 4.3, B = 2 T, P = 3–6 MW and quasi-toroidal symmetry
  - aims at reduction of anomalous transport, disruption suppression, $\beta > 4\%$

	HSX	CTH	QPS
Device parameters	R = 1.2 m, a = 0.15 m, B = 1 T, P = 0.2–0.55 MW	R = 0.75 m, a = 0.2 m B = 0.5 T, I = 50 kA	R = 0.9–1 m, a = 0.3–0.4 m B = 1 ± 0.2 T, P = 2–4 MW
Status	Operating	Under construction, operate in late 2003	In conceptual design, operate in 2007/8
Magnetic configuration	Quasi-helical symmetry, R/a = 8	Torsatron with Ohmic current, R/a = 3.8	Quasi-poloidal symmetry, R/a > 2.3
Program issues	Reduction of neo-classical transport, E_r control, anomalous transport and turbulence, β limits	3-D reconstruction, disruption suppression, effect of islands on stability	Reduction of neoclass-ical transport, poloidal flow damping, flux surface robustness, low R/a, ballooning β limits

HSX Explores Improved Neoclassical Transport with Quasi-helical Symmetry



R = 1.2 m, <a> = 0.15 m, B = 1.0 T

ECH: 28 GHz, 200 kW

(additional 350 kW at 53 GHz in progress)

University of Wisconsin-Madison

Worlds First Test of Quasi-symmetry

- Test reduction of direct loss orbits and electron thermal conductivity
- Demonstrate lower parallel viscous damping of plasma flows
- Explore E_r control through plasma flow and ambipolarity constraint
- Investigate turbulence and anomalous transport
- Test stability limits to Mercier and ballooning modes

HSX Progress

- **Physics results demonstrate improved confinement with quasi-helical symmetry**
  - Demonstrated reduced direct losses with quasisymmetry
    - *faster ECH plasma breakdown
    - *collector plates near ECH antenna show fewer losses
  - Longer damping time for plasma flows due to reduced parallel viscosity
  - Better confinement of energetic particles: larger HX flux, longer ECE decay rates

- **Good start on diagnostics needed for physics understanding**
  - First results with 1 point Thomson scattering: 350 eV at 1 x 10^{12} cm^{-3} up to 600 eV at 5 x 10^{11} with 50 kW input power
  - 4 channel ECE, 16 channels H_α, SX and HX detectors, UV Ion Doppler spectroscopy, ECH absorbed power monitors

HSX Plans

- FY 2004
  - Complete 10 channels TS, extend ECE to 8 channels
  - Preparations for operation at B = 1 T
  - Determine quasi-symmetry effect on $\chi_e(r)$
  - Edge probe study of turbulence (in collaboration with TJ-K)
  - Site modifications, transmission line, power supplies for 53-GHz, 350-kW gyrotron
  - Begin collaboration with ORNL/PPPL on ICRF, if funded

- FY 2005
  - Improve magnet current control; Operate at B = 1.0 T
  - Operate at lower ν^* to test for improved neoclassical transport
  - Compare HX and SX spectrum to Fokker-Planck modeling of ECH
  - Begin commissioning of 53-GHz system
  - Microwave scattering and ECEI systems for core turbulence studies, if funded
  - Implement lower power ICRF prototype, if funded

HSX FY05 Budget Planning

- Extensive peer review of 3-year renewal (effective 2/1/2002) supported a FY03 budget at $1720K ; presently funded at $1601K
- The present budget provides for operations, but constrains our ability to increase diagnostic capability
- 10% reduction to $1441K
  - Operations at a reduced level, cut 1 post-doc position and scale back the associated turbulence program
- Level funding (at $1601K)
  - Maintain the present pace of the program with minimal diagnostic improvements
- Increments needed to study core turbulence & increase parameters

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

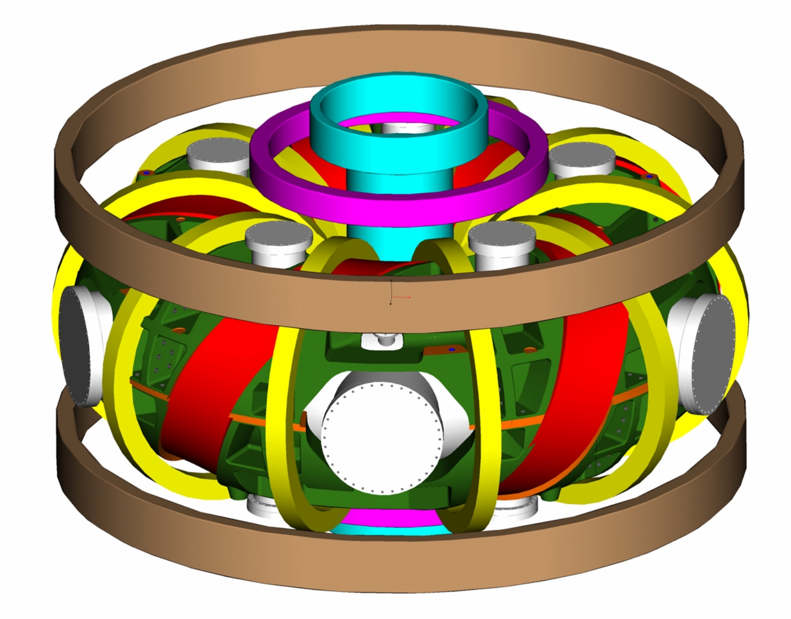
  + $100K for collaborations with PPPL/ORNL on RF heating

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

Compact Toroidal Hybrid (CTH) Experiment

Auburn University

Performs 3-D equilibrium reconstruction; targets current-driven disruptions in low-A, current-carrying stellarators



- R = 0.75 m, $\langle a \rangle$ = 0.2 m, B = 0.5 T, I_{plasma} = 50 kA
- Under construction
- Completion expected in late 2003

CTH Goals

- Measurement of 3-D magnetic equilibrium of current-driven stellarator
  - 1st implementation of new 3-D reconstruction method developed collaboratively
  - Essential to understanding stability of finite-β, finite-current stellarator plasmas (NCSX & QPS)
- Passive disruption suppression by 3-D helical fields
  - Kink, vertical and tearing instability thresholds studied w/ knowledge of background equilibrium
  - Addresses physics underlying passive external stability control in finite-β stellarators
- Influence of magnetic islands on stability
  - External control of magnetic errors, measurement of islands in plasma

CTH Progress

- CTH construction proceeding w/ some delays but w/o significant problems
  - Vacuum vessel delivered, tested & accepted by 11/02
  - Poloidal field coils fabricated on-site; completed
  - MG power plant operating
  - Helical coil frames delayed 6 months (est.).
- CTH actively participating in V3FIT equilibrium reconstruction collaboration with Hirshman and Lazarus (ORNL), Lao (GA), and Hanson (Auburn)
  - Now designing and constructing magnetic diagnostics using prototype V3FIT code

CTH Plans

- FY 2004
  - Completion and initial operation in early FY 2004
  - Proceed with experimental 3-D reconstruction as most immediate scientific need of US compact stellarator program
- FY 2005
  - Internal measurement of magnetic field for accurate 3-D equilibrium reconstruction
  - MHD instability and disruption studies with Ohmic current
  - Magnetic island studies

CTH Out-year Budget Planning

- **CTH will make essential contributions to development & understanding of NCSX & QPS equilibrium measurement & stability**

Budget determines expected rate of achieving milestones

FY 2003 Budget base: $515K

Scenario	Base	Decrement	Increment
FY 2004	**$509K**	**$458K**	**$559K (+10%)**
FY 2005	**$515K**	**$464K**	**$580K (+15%)**

FY 2004

Base: Proceed w/ equilibrium and stability studies
Decrement: Delay effort & diagnostics for stability studies
Increment: Speed up implementation of RF heating & diagnostics for stability

FY 2005

Base: Continue equilibrium and stability studies; hire post-doc
Decrement: Delay implementing internal-B diagnostic, postpone mag. island studies
Increment: Speed up implementation of internal-B diagnostic

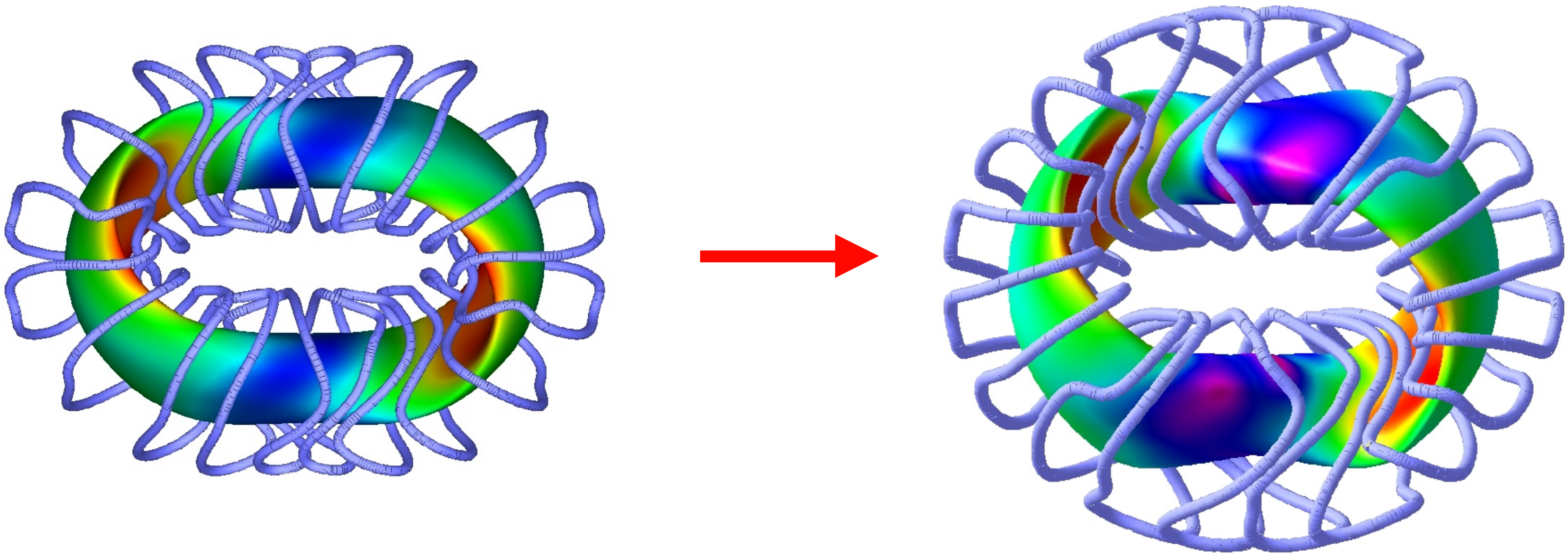
Key issue: **Under decrement budget, data acquisition & basic diagnostics are delayed, leading to delay in 3-D equilibrium reconstruction studies (6 months)**

This is an important issue for NCSX & QPS development

QPS Will Extend Physics Understanding to Very Low *R/a* and Quasi-Poloidal Symmetry

- **Dependence of anomalous transport, internal transport barriers, and flow shear on configuration**
- **Reduction of neoclassical transport**
- **Impact of poloidal flows on enhanced confinement**
- **Flux surface robustness at *R/a* > 2.3 and β up to 2-3% in presence of strong toroidal/helical coupling**
- **Ballooning β character and MHD stability limits**
- **Benchmarking and improvement of 3-D theory**

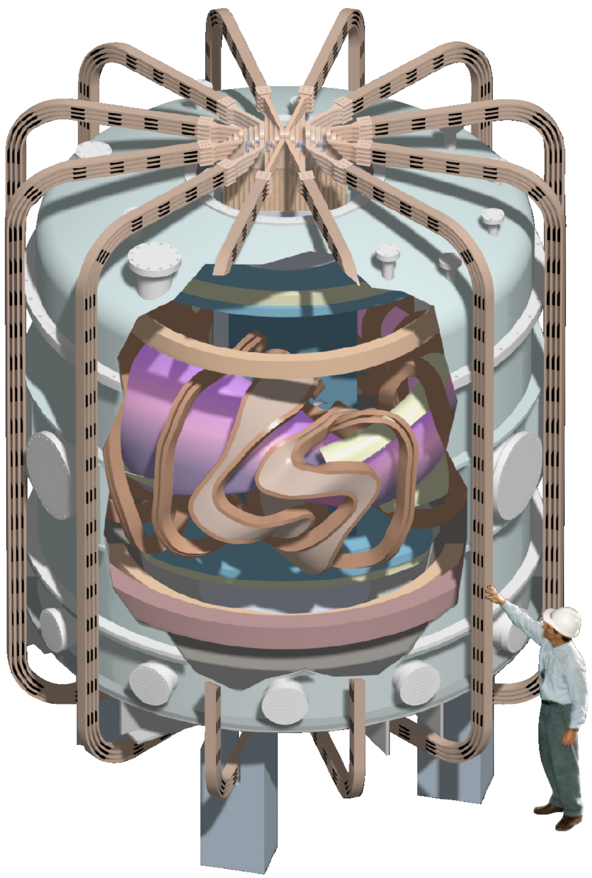
QPS Configuration Has Improved Since Last BPM

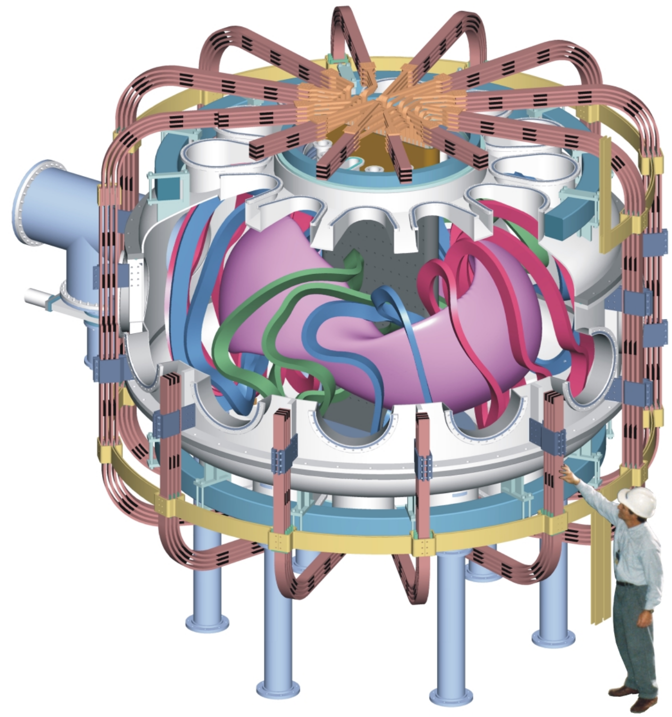


- Neoclassical transport losses can be changed by factor ~20-80
- Varying coil currents allows changing the degree of quasi-poloidal symmetry and poloidal flow damping over a wide range
- Vacuum magnetic configuration closer to full-beta configuration
- Magnetic islands are not an issue in vacuum or at higher beta
- Second stability β for infinite-n ballooning reduced from 9% to 6%

QPS Conceptual Design Nearing Completion

- $\langle R_{pl} \rangle$ = 0.9-1 m, $\langle a_{pl} \rangle$ = 0.3-0.4 m
- V_{pl} = 2-3 m^3, Aspect ratio > 2.3
- B = 1 ± 0.2 T (1.5 s), P_{RF} = 2-4 MW





- Reduced cost of modular coils: winding types from 4 to 3, winding forms from 16 to 10, winding packs from 32 to 20
- Increased plasma-coil and coil-coil spacings and plasma size
- Simple shell design, reduced current density, longer pulse length

QPS FY 2004 Budget and Milestones

- FY 2003 -- preparing for August CDR
  - Explore configuration flexibility; trim coils to create/eliminate islands
  - Complete engineering design study; update cost and schedule estimate
  - Complete design of R&D coil winding form for manufacturing study

- FY 2004 Plans
  - Assessments of configuration flexibility, equilibrium, stability, transport
  - Start conceptual design of TF/OH centerstack assembly

Milestones

  - Complete design for an R&D modular coil winding form -- 1/04
  - Award contract for a full-scale R&D modular-coil winding form -- 3/04
  - Summarize status of QPS research preparation activities -- 9/04

- FY 2004 Presidential budget is $646k at ORNL, $300k at PPPL
  - $209k *reduction* from FY 2003 and $2,494k *reduction* from FY 2004 plan

- Incremental request for FY 2004: $650k at ORNL + UTK, $350k at PPPL
  - Regains 5 months in fabricating an R&D coil
  - Allows FY 2005 delivery of all type A production winding forms and first of type B

QPS FY 2005 Budget and Milestones

- FY 2005 -- $2450k (MIE), $400k (research prep) at ORNL + UTK
  $2380k (MIE), $320k (research prep) at PPPL

- Plans
  - Award contracts for modular coil forms
  - Complete preliminary design for all core components
  - Begin final design of TF/OH centerstack and vacuum vessel

  Milestones
  - Delivery of an R&D modular coil winding form - 1/05
  - Fabricate R&D coil tooling - 1/05
  - Complete R&D modular coil conductor winding - 4/05
  - Award contract for production modular coil winding forms - 5/05
  - Complete R&D modular coil - 8/05
  - Delivery of first type A production winding form - 8/05
  - Update preparations for initial QPS operation - 9/05

- 10% decrement
  - Delay completion of R&D modular coil and centerstack design
  - Delay delivery of first production winding form

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, late 2003)
  - QPS (R = 0.9–1 m, a = 30–40 cm, P = 2–4 MW, 2007/2008)
- Key tasks for FY 04-05
  - HSX: ambitious experimental program
  - CTH: complete construction and start operation
  - QPS: CDR and CD-1, complete design, R&D coil forms
- Incremental budget would allow taking better advantage of existing experiments and regain 5 months on QPS R&D schedule