National compact stellarator program

J. H. Harris

For the US stellarator community

DOE/OFES Budget Planning Meeting

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Stellarator features fit the Greenwald Panel Template

Predictable, high-performance steady-state plasmas

- Equilibrium from external fields ⇒ no disruptions, avoids ELMs
- Quiescent high-beta plasmas with confinement similar to tokamaks
- Good alpha particle confinement in optimized configurations
- No need for current drive, rotation drive, or profile control systems
- Very high density operation reduces fast-ion instability drive
- Strong coupling between theory, design, & experiment aids predictability
- Variety of coil schemes to realize desirable magnetic configurations

Taming the plasma material interface

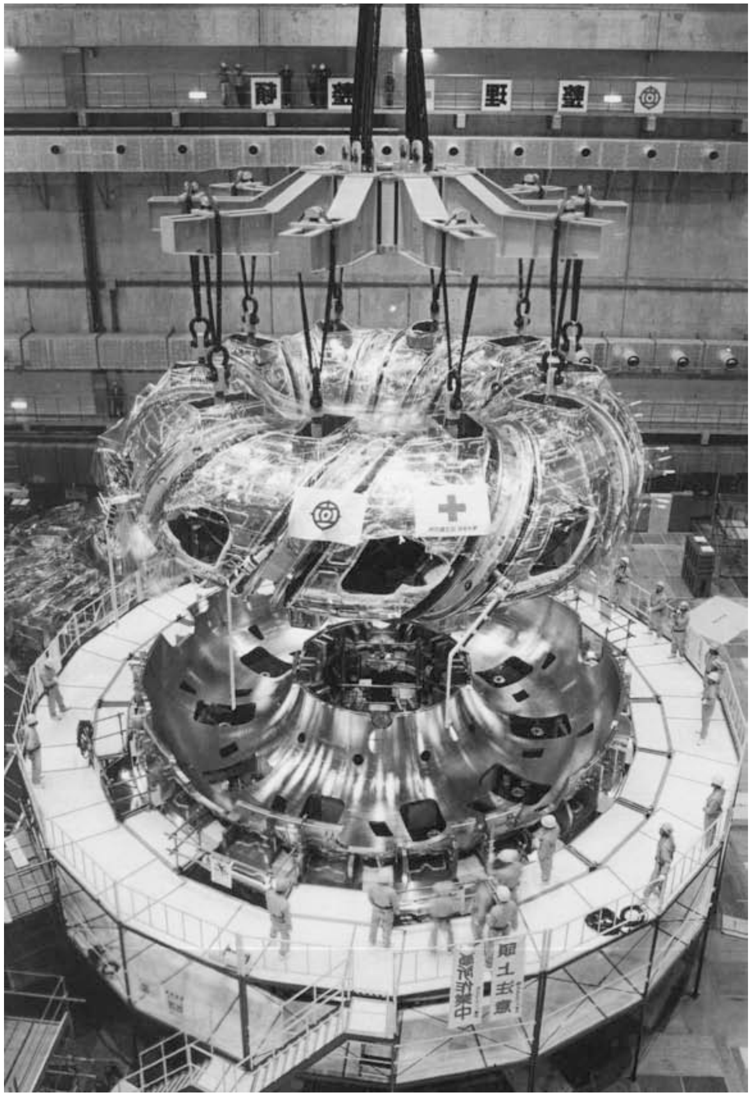
- 3-D divertor (islands, stochastic field lines)
- Very high density operation leads to easier plasma solutions for divertor

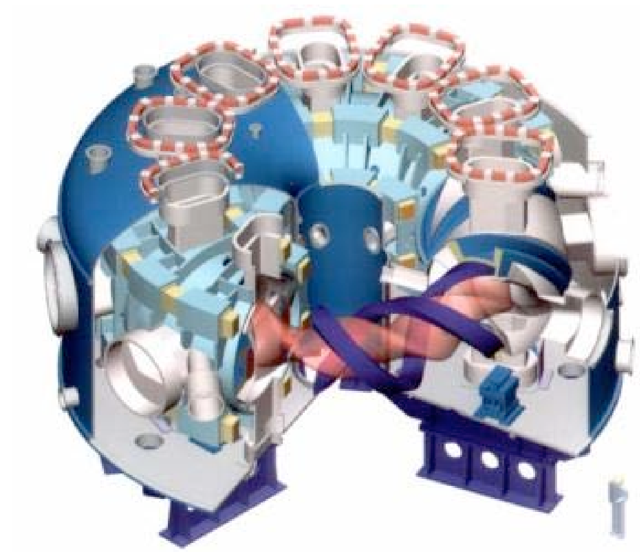
Harnessing fusion power

- Fully ignited operation: turn off external power
- High power density (similar to ARIES-RS and –AT)
- Not limited by macroscopic instabilities

Large stellarators have been successfully built and operated

Large Helical Device (LHD), Japan (1997)





LHD parameters

R = 3.9 m

a = 0.6 m

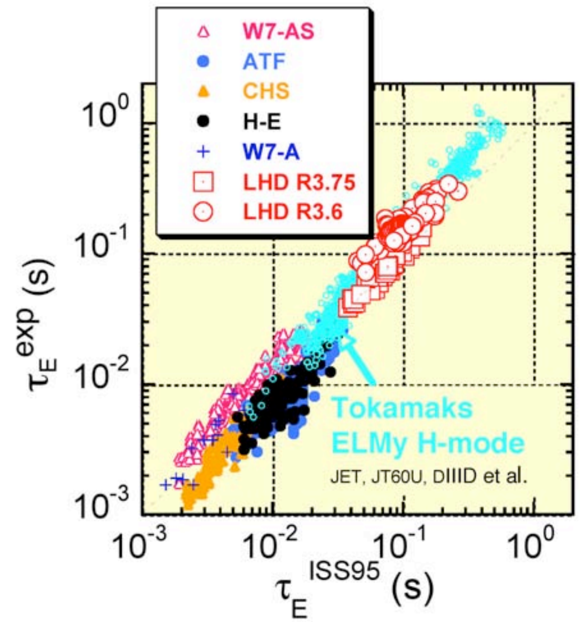
B = 4 T

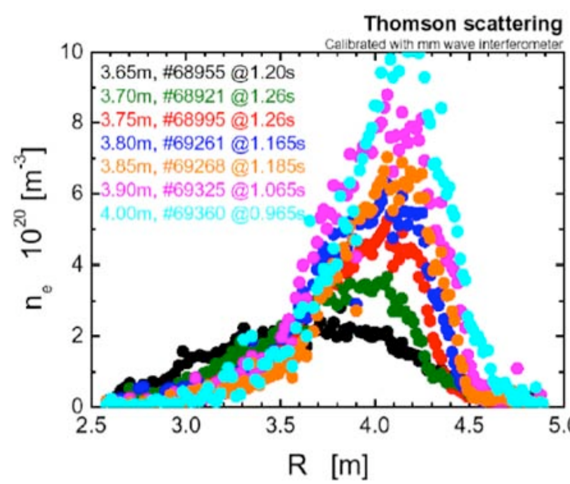
superconducting coils

total weight = 1500 tonnes

Stellarators are achieving outstanding results

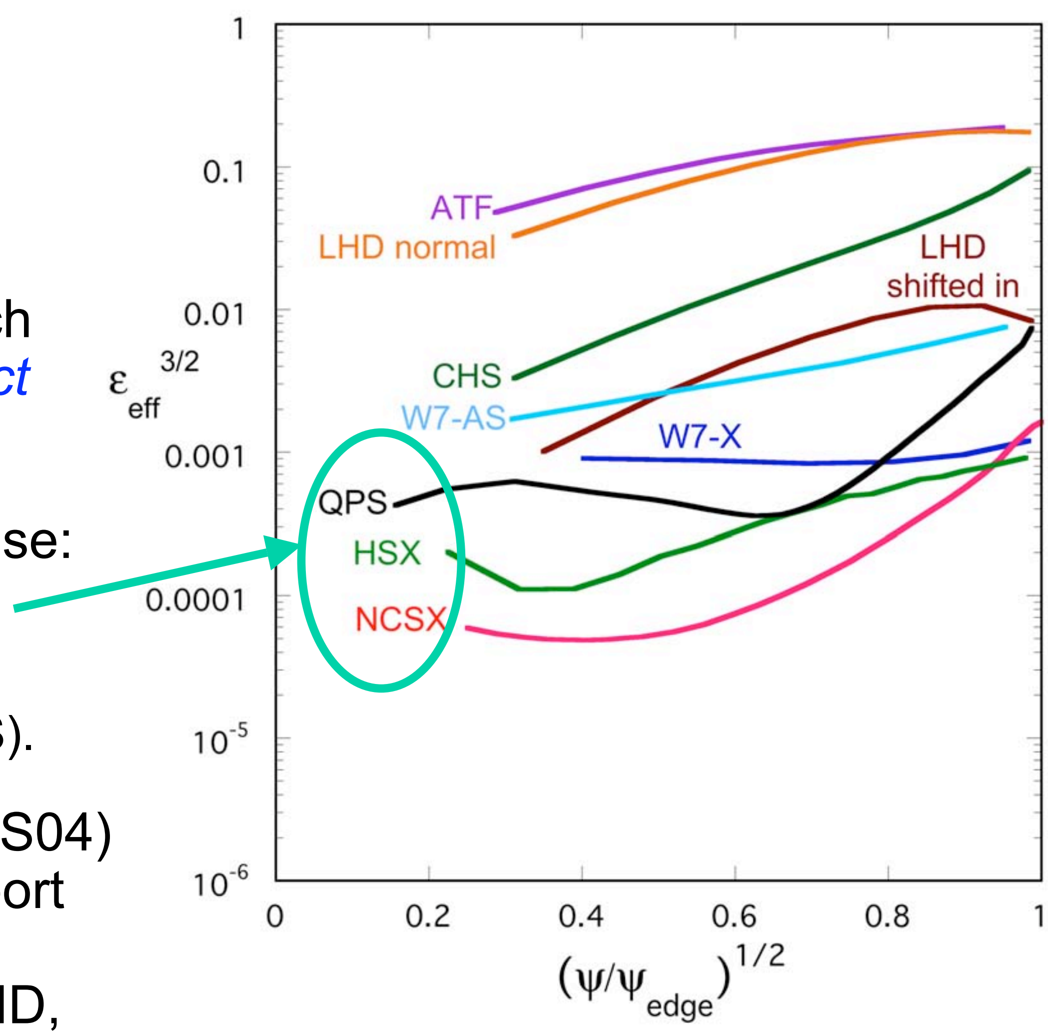
- Quiescent high beta plasmas, limited by heating power & confinement
  - LHD β = 5.2% transiently; 4.8% sustained
  - W7AS β > 3.2% for 120 τ_E
- τ_E similar to ELMy H-mode
- Improved confinement with quasi-symmetry
  - HSX finds reduced transport of momentum, particles, and heat with quasi-symmetric config.
- Very high density operation, limited only by heating power, without confinement degradation
  - Up to 5x equivalent Greenwald density (W7AS)
  - LHD $n_e(0) \sim 10^{21}$ m^{-3} at B=2.7T !
  - Importance of divertors to control recycling
- Steady state: LHD ~0.7 MW pulse lengths ≤ 54m





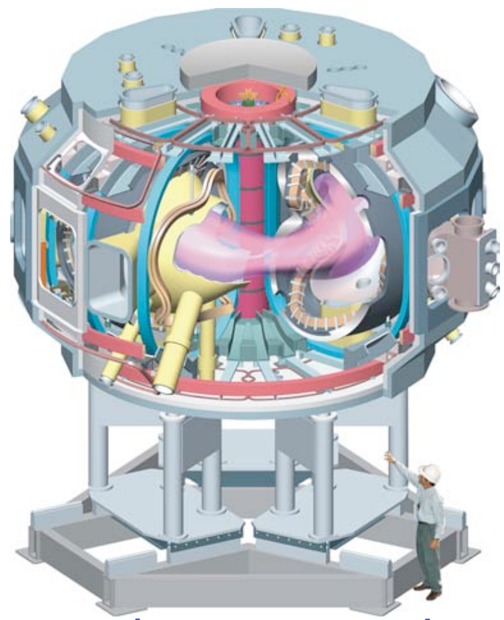
Configuration optimization has produced compact "quasi-symmetric" stellarators

- Helical field ripple from stellarator coils enhances neoclassical transport losses. Configuration optimization that minimizes the *effective ripple* ε_{eff} along one coordinate produces "quasi-symmetric" configurations which can be built at low R/a: *compact stellarators*.
- US-developed configurations use:
  - quasi-axisymmetry (NCSX);
  - quasi-helical symmetry (HSX);
  - quasi-poloidal symmetry (QPS).
- Global confinement studies (ISS04) suggest that anomalous transport may also decrease with ε_{eff} . Physics of this under study (LHD, HSX).



National Compact Stellarator Experiment (NCSX)

- **Mission: acquire physics data needed to assess the attractiveness of compact stellarators; advance understanding of 3D fusion science.**
  - Beta limits and limiting mechanisms.
  - Effect of 3D magnetic fields on disruptions
  - Reduction of neoclassical transport by quasi-symmetry.
  - Confinement scaling; reduction of anomalous transport by quasi-symmetry.
  - Equilibrium islands & neoclassical tearing-mode stabilization.
  - Power & particle exhaust compatibility with good core performance.
  - Alfvénic mode stability in reversed shear compact stellarator.
  - Conditions for high-β, disruption-free operation.



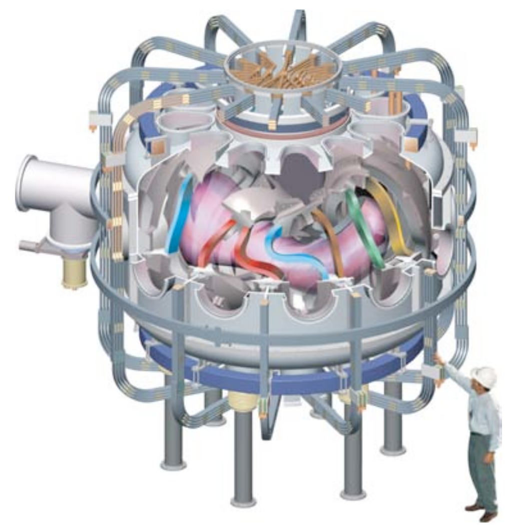
under construction

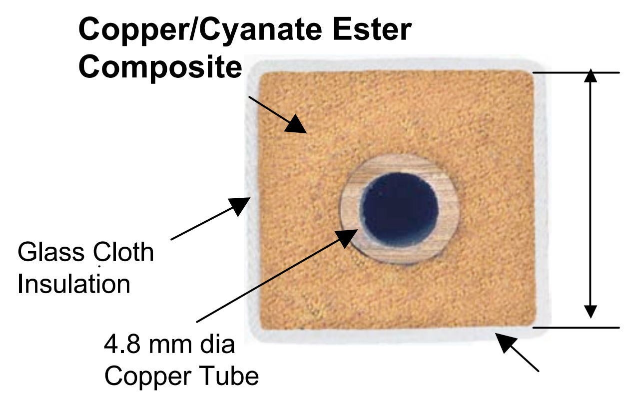
N = 3 quasi-axisymmetric
⟨R⟩ = 1.4 m, ⟨a⟩ = 0.33 m
B ≤ 2 T; pulse 0.2-1.2 s
Heating (planned):
P_{NBI} = 6 MW
P_{ICH} = 6 MW
P_{ECH}= 3 MW

PPPL PRINCETON PLASMA PHYSICS LABORATORY ornl

QPS (Quasi Poloidal System)

- Quasi-poloidal symmetry ⇒ low poloidal flow damping ⇒ reduced anomalous transport
- Extends stellarator physics to very low aspect ratio with robust flux surfaces at $R/a \geq$ 2.5 and $\beta \leq 5\%$.
- Simplified construction with bell jar vacuum vessel and internally mounted, vacuum-canned coils.
- ORNL/Univ.of Tenn./PPPL have developed flexible, internally-cooled conductor for stellarator coils, new potting techniques using cyanate ester, & streamlined winding methods using test coils.
- **Funding:** FY08: $1.1 M ; FY09: $0
- QPS staff continue to contribute to NCSX.



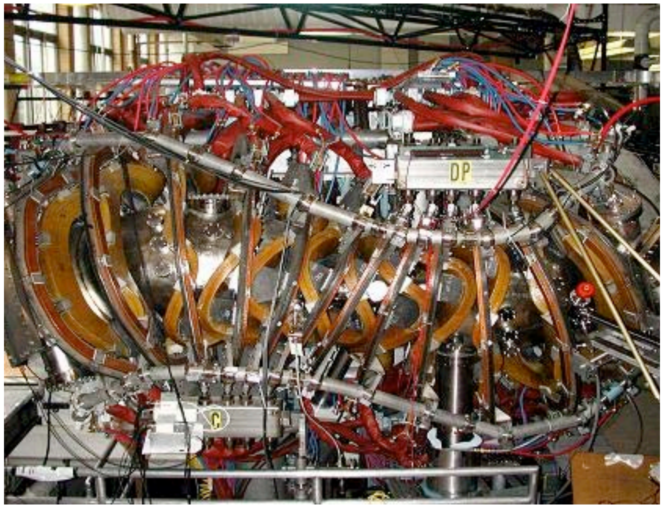


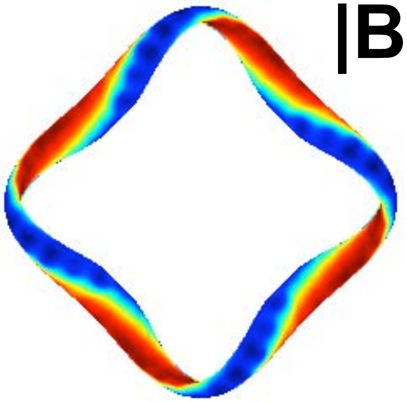
QPS conductor x-c

ornl PPPL PRINCETON PLASMA PHYSICS LABORATORY

HSX: Helically Symmetric Experiment

Major Radius	1.2 m
Minor Radius	0.12 m
Number of Field Periods	4
Coils per Field Period	12
Rotational Transform	1.05 -1.12
Magnetic Field	1.0 T
ECH Power	<100 kW 28 GHz



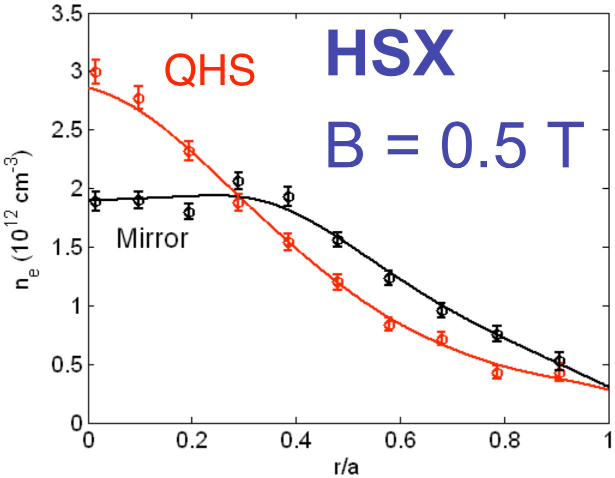


Can spoil symmetry
by changing coil currents:
= *“mirror configuration”*

quasi-helical
symmetry

In 2nd harmonic ECH plasmas, quasi-symmetry reduces core transport and *may* also reduce core turbulence

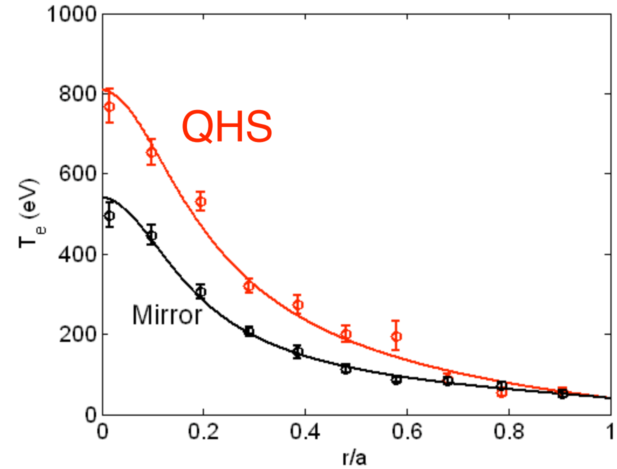
Particles



Peaked density profiles in QHS

➔ Reduced thermo-diffusion

Heat

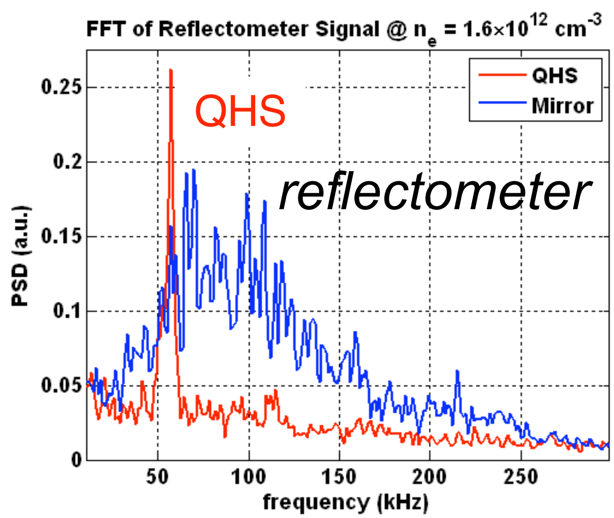


Higher T_e in QHS w/ same P_{abs}

➔Lower χ_e

consistent w/ neoclassical thy

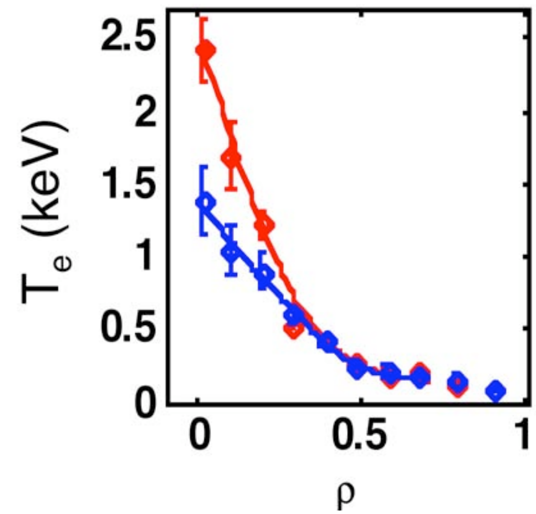
Turbulence NEW!

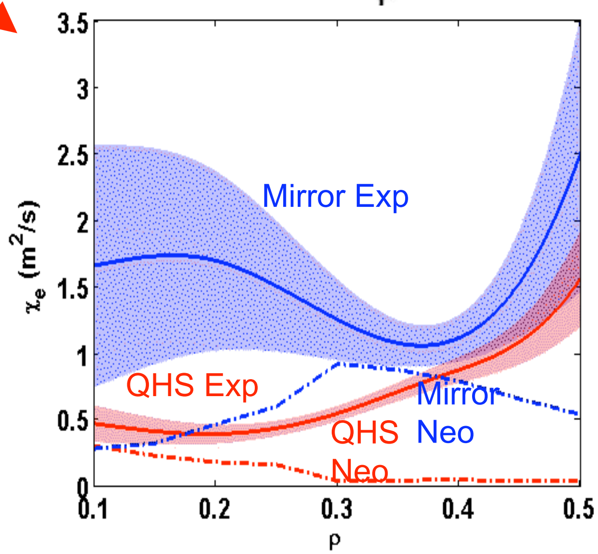


$\Rightarrow$ *Lower ñ in QHS*

Anomalous transport and electric field measurements are the next research objectives in HSX

- Fundamental ECH at B=1.0 T with increased density & power ⇒ T_e (0) ~ 2.5 keV. Further increase in ECH power underway.
- Initial transport analysis (with ambipolar estimate for E_r) suggests that core anomalous transport *may* be reduced with quasi-symmetry as compared to mirror.
- E_r measurements needed. Diagnostic neutral beam for CHERS being installed. For longer term, heavy ion beam probe being developed with Interscience.
- *Does reduced zonal flow damping with quasi-symmetry or $E \times B$ shear lead to reduction of turbulence & anomalous transport?*
- Connect with ISS04 confinement scaling with ripple (ε_{eff}), turbulence and zonal flow experiments in LHD, CHS (Japan). *Priority topic for NCSX and CS development.*





The unique HSX research facility is underutilized

- Budget cuts and cost escalation from FY03-FY08 have resulted in 1/3 reduction in staff

  layoffs: 1 engineer, 1 scientist, 1 post-doc, 1 technician, 3 students

- Exciting opportunities are being missed in studies of

  anomalous transport and quasi-symmetry;

  connections to tokamaks

  simultaneous optimization of both neoclassical and anomalous transport.

Full Use Budget in FY10: $1817K

Recent review strongly supported increase of $400K over FY09 guidance

$75K microwave scattering
$100K replace engineer
$100K subcontract to RPI for HIBP implementation/operation
$82K replace two graduate students
$43K additional operating funds/travel

FY10 +2% from FY09 guidance ($1445K) :

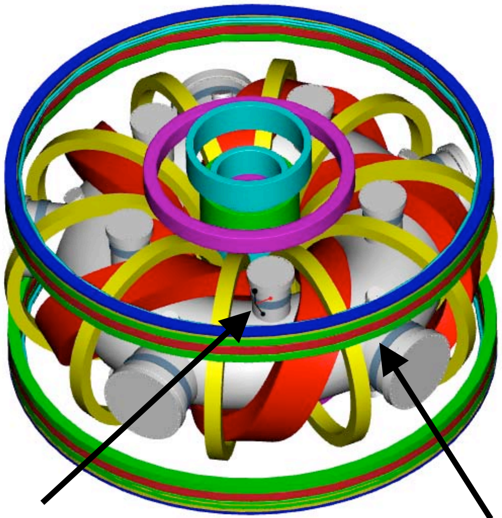
- Loss of add'l student to cover escalation; continued minimal operation, travel, maintenance
- No new diagnostics except CHERS

FY10 10% decrement ($1275K):

- Loss of 1 add'l FTE scientist and last remaining technical support person

The Compact Toroidal Hybrid (CTH)

Auburn University

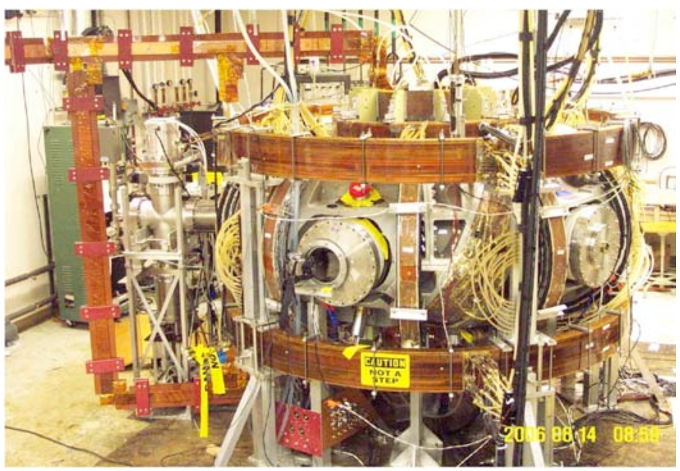


trim coils wound around ports

use to induce/correct magnetic islands

Configuration research for CS development

- Disruption avoidance & immunity
- Validation of new schemes for 3-D magnetic equilibrium reconstruction (V3FIT collab.)
- Use of static islands to influence equil. & stability
- Applications to NCSX



CTH parameters

5 field periods

circular Inconel vacuum vessel

R_0 = 0.75 m, $R/\langle a \rangle \geq 4$

$B_0 \leq 0.7$ T; $I_p \leq 40$ kA; $\Delta\iota \leq 0.5$

P_{in}= 12 kW ECRH @18GHz

60 kW OH

Vacuum $\iota(a)$: 0.05 – 0.6

Discharge duration: 0.5 s

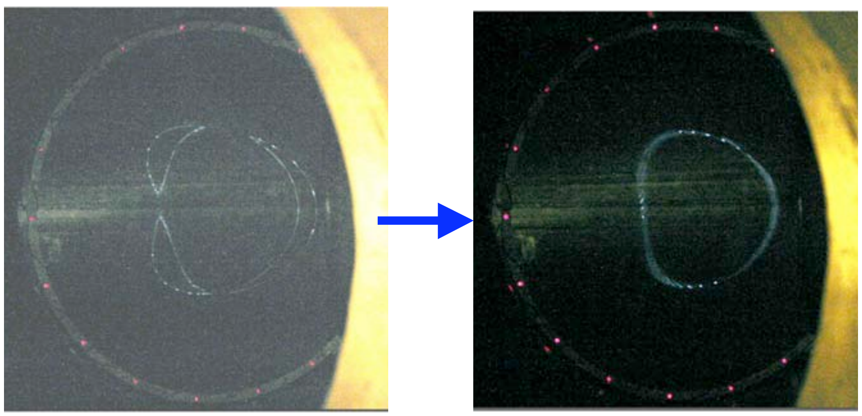
w/ OH: 0.1 s

$\langle n \rangle$ = 0.2 - 1 x 10^{19} m^{-3}

CTH explores magnetic island effects & stability in current-carrying compact stellarators

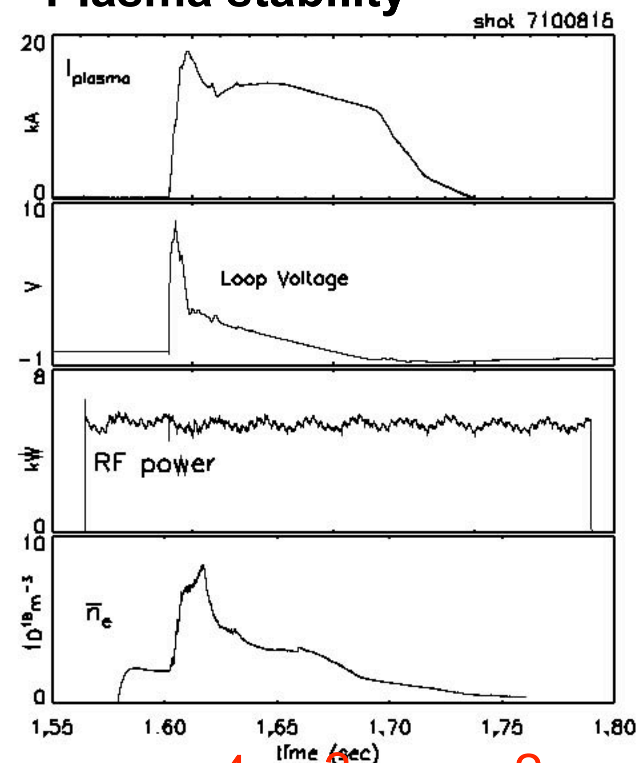
Vacuum configuration studies

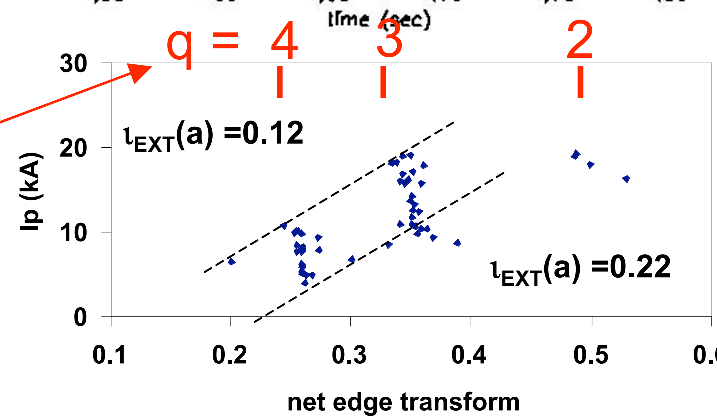
Measurement & control of deliberately induced $m = 3/n = 1$ island (operation at $B < 0.03$ T)



e-beam traces flux surface on fluorescent screen
Use trim coils to null, enhance, or rotate island.
Tools, analysis, experience apply to NCSX etc.

Plasma stability





Transient instabilities linked with rational edge transform values

CTH will apply range of new experimental capabilities in FY10

FY08 progress and ongoing work

- Vacuum field-mapping of all independent coil sets complete
- Reducing i_{EXT} to attempt to “recover” disruptions to understand transition to stability.

FY09 goals

- Add’l ECRH power (25 kW @ 14 GHz) for hotter target plasmas
- Fully employ V3FIT code for 3D equilibrium reconstruction.
- Implement electron temperature and current profile diagnostics
- Effect of controlled static islands, stochastic fields on edge plasma & flows

FY10 plans

- Investigation of stability of current-carrying stellarator plasmas w/island effects
- Contribute to NCSX field-mapping, equilibrium reconstruction and other research preparation

FY10 plan geared to completing main CTH goals

Current staff: **1 academic PI, 1 research scientist co-PI, 3 graduate students, 3 undergraduates, replacing engineer with technician; additional contributions from 2 faculty**

Base Budgets

FY2008	**$419K**		
FY2009	**$429K**		
FY2010	**10% decrement**	**target**	**full-use**
	$389K	**$440K**	**$680K**

FY10 full use plan

- Full 3D equilibrium reconstruction with external + internal magnetic measurements, SXR arrays (post-doc 100K)
- ICRF electron heating (60K for antenna, transmitter)
- 4+ graduate students (40K/student)
- 40K travel & consumables

FY10 target

- Cost-of-living increases from FY08 budget maintain present level of effort.
- Maintenance of CTH facility, diagnostics, and data acquisition.
- No additional plasma heating, reduced scope forf internal B measurement.
- 3 graduate students.

FY10 decrement

- Operational funds restricted to support key maintenance issues.
- Critical reduction of manpower: 2 graduate students (max.), academic PI participation reduced

US compact stellarator research program is developing basis for attractive reactor concepts, e.g. ARIES-CS

Ref. baseline parameters:

NCSX-like (QA): 3 periods

$\langle R \rangle$ = 7.75 m

$\langle a \rangle$ = 1.72 m

$\langle R \rangle / \langle a \rangle \sim 4.5$

$\langle n \rangle = 4.0 \times 10^{20}\ m^{-3}$

$\langle T \rangle$ = 6.6 keV

$\langle B \rangle_{axis}$ = 5.7 T

$\langle \beta \rangle$ = 6.4%

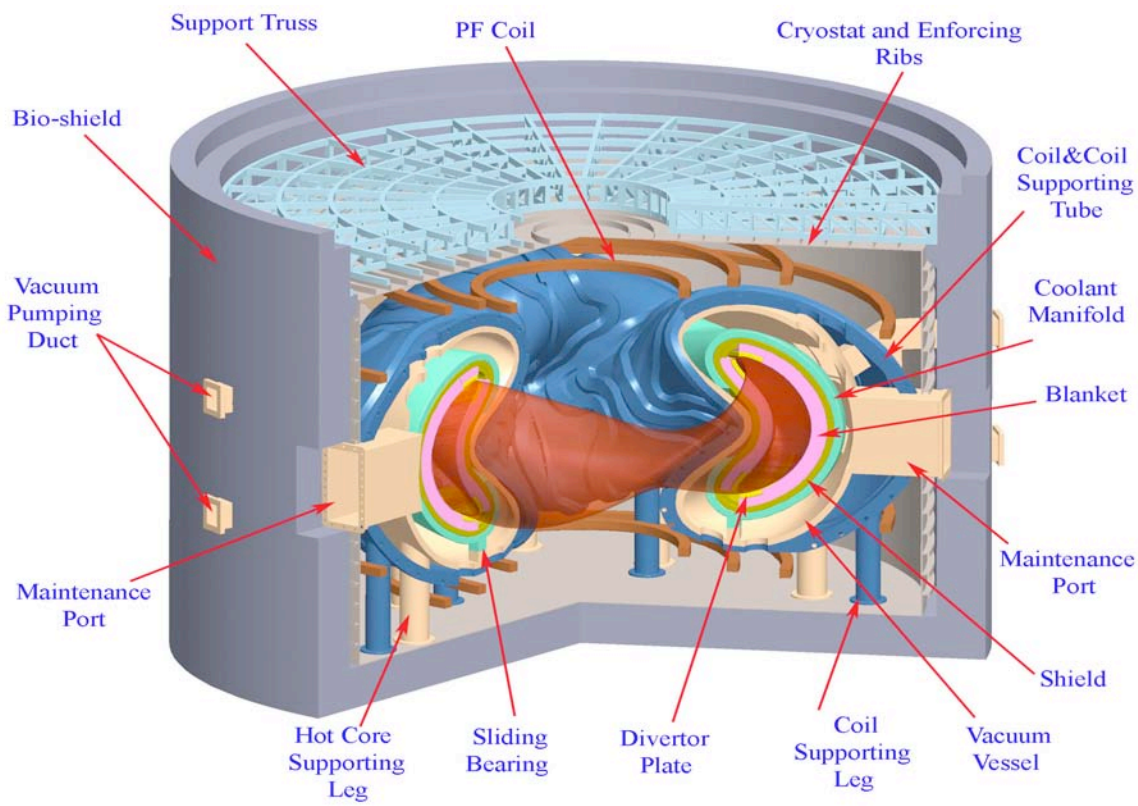
H(ISS04) = 1.1

I_{plasma} = 3.5 MA (bootstrap)
25% of rotational transform

P(fusion) = 2.364 GW

P(electric) = 1 GW

Fully ignited ($P_{ext} = 0$)



Aries-	-I	-RS	-CS	-AT	-CS
Blanket			LiPb/FS	LiPb/SiC	LiPb/SiC
COE(92)	99.7	75.8	61.3	47.5	48.

Stellarator reactor designs have also been developed in EU & JP

Planning for fusion development should include stellarators

- **Compact stellarators (CS) offer solutions for fusion energy science**
  - Fully ignited, high β, steady-state, quiescent, disruption-free plasmas. No need for external power for sustainment or control. High density eases divertor solution, reduces drive for fast-ion instabilities.
  - Key CS physics/engineering science issues are being explored in coordinated US experiments (HSX, CTH, NCSX), in supporting theory and design studies, in an international context.
  - Present CS research extrapolates coherently through larger exp'ts (NCSX) to attractive reactor embodiments (ARIES-CS . . .). Also offers pathway to modify tokamaks with quasi-sym. helical fields.
  - Continuing strong commitment to stellarator research in EU (W7X, construction) and Japan (LHD, plans to upgrade to > 30 MW NBI pulsed, 3 MW RF steady-state, cooled divertor).
- **Broader engagement of the US fusion community in stellarator research is opportune and welcome.**