Plans for Stellarator Research

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Preparing for the NIF and ITER Era

FPA, Oak Ridge   Dec. 5, 2007

US Stellarator Program in the Post-ITER Era

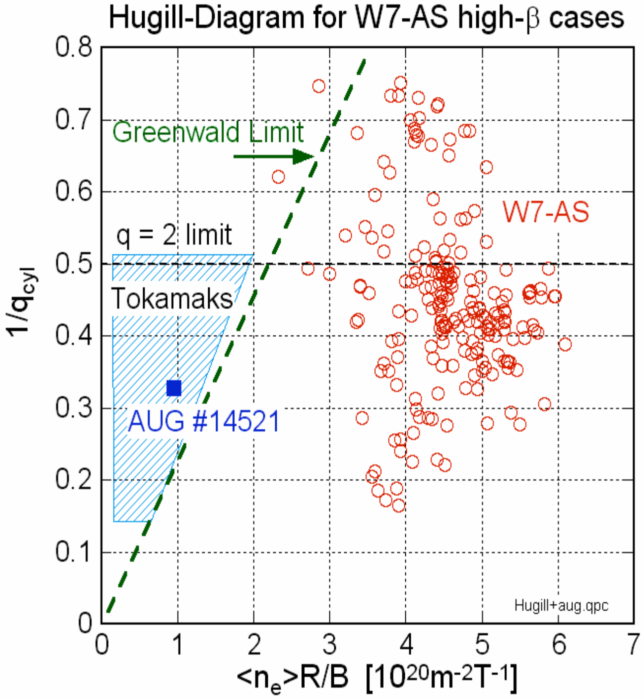
- **Exploit compact stellarator advantages as steady-state reactors**
  - quiescent, steady-state, high-β, disruption-free operation
  - no power input to sustain current or rotation ⇒ true ignition
  - no profile control or close fitting walls for stability
  - high density limited only by power density to ease divertor issues
- **Goal:** operation of a large next-generation compact stellarator (NGCS) ***in combination with*** other fusion program elements to establish physics, technology and cost basis for a compact stellarator approach to DEMO
- **Key prerequisites** needed by 2018-20 that would allow start on an NGCS
  - adequate understanding of main compact stellarator physics issues
    - * low thermal & fast ion losses, confinement scaling, density and β limits, particle & power handling, disruption and ELM avoidance
  - optimization of magnetic configuration (symmetry, ripple, constraints)
  - simplification of coil and device fabrication and assembly ⇒ only tokamak-like accuracy needed in construction

Community Plan for the Next Decade

- Modify present approach to incorporate
  - physics advances on LHD, W 7-AS, CHS, HSX
  - fabrication advances on NCSX, W 7-X, QPS
  - input from FESAC subcommittees and reviews, ARIES-CS study
- Develop compact stellarator approach to DEMO
  - demonstrate high-β disruption-free operation in NCSX with its tokamak-like geometry and 3-D shaping
  - develop tools for 3-D control of tokamaks
- Strengthen basis for compact stellarators
  - advantages of quasi-symmetry and low effective ripple In HSX
  - explore current-related issues and 3-D reconstruction in CTH
  - improve theory and computation for interpretation and configuration improvement, comparison with tokamaks
- Address feasibility and optimization issues for compact stellarators
  - reduce complexity, cost and required assembly accuracy and explore potential of quasi-poloidal symmetry in QPS

Compact Stellarators as DEMO Candidate

- Compact stellarators $\Rightarrow$ confinement physics as in tokamaks, high-β performance determined by equilibrium, not stability?
- Have crucial advantages as steady-state reactors
  - quiescent, steady-state, high-β, disruption-free operation
  - no power input to sustain current or rotation $\Rightarrow$ true ignition
  - no profile control or close fitting wall
  - high density limited only by power density
    - * faster α slowing-down $\Rightarrow$ reduced α instability drive
    - * less energetic particle fluxes to wall
  - 3-D shaping of plasma edge
  - optimal control of particle fluxes, radiation losses



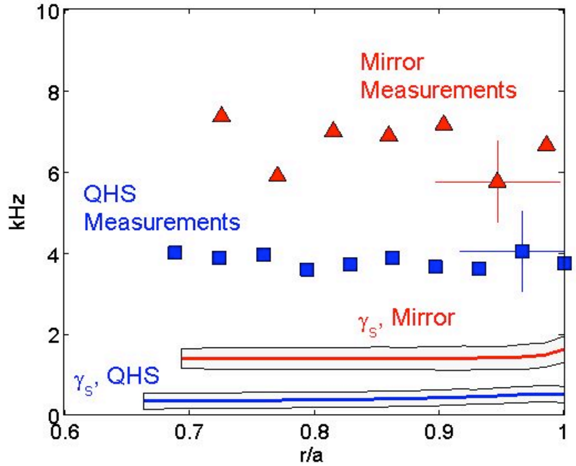
- Features demonstrated in high-*R*/*a*, non-sym. stellarators

Compact Stellarators Exploit Quasi-Symmetry

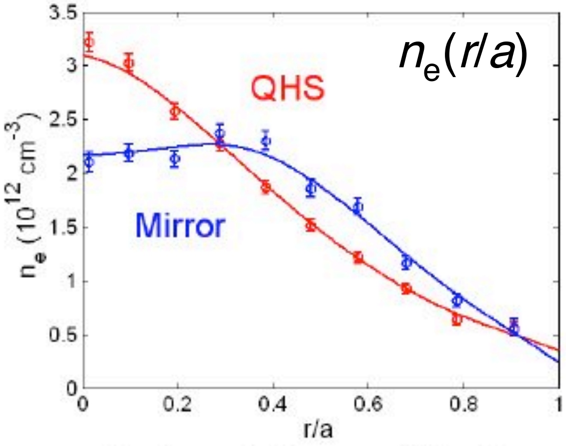
- Quasi-symmetry ⇒ very small variation of |***B***| in symmetry direction in straight field line coordinates
  - toroidal, poloidal or helical quasi-symmetry
  - conserved canonical momentum as in axisymmetric system
    ⇒ good orbit confinement
  - reduced effective field ripple along ***B***
    ⇒ reduced neoclassical transport (depends only on |***B***|)
    ⇒ allows strong rotational transform at lower *R*/*a*
  - reduced viscous damping in the symmetry direction
    ⇒ promotes large ***E*** x ***B*** flow shear ⇒ reduced anom. xport
- Physics commonality with tokamaks
- An area of world leadership for the US program

Quasi-Symmetry Advantages Shown in HSX

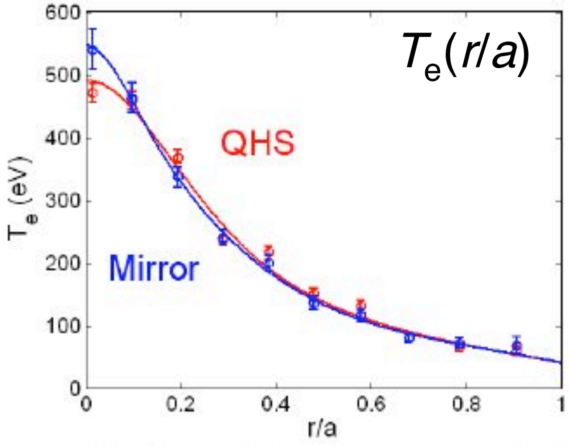
- Benefits demonstrated using auxiliary mirror coils to spoil quasi-helical symmetry
- Parallel viscous damping is reduced with quasi-helical symmetry (more rotation/shear)



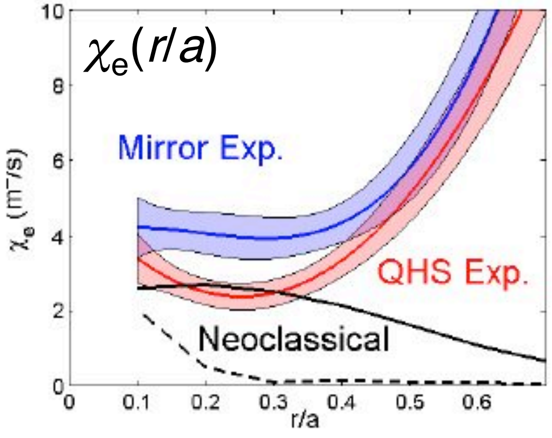
- Reduced thermo-diffusion & lower χ_e



Reduced thermodiffusion with quasisymmetry

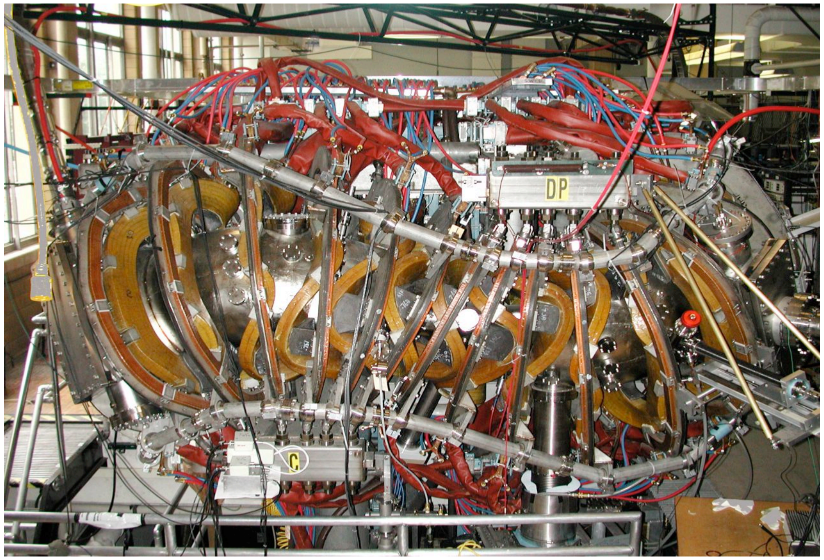


2.5 times the power needed in mirror to match T_e profiles



Calculated reduced central χ_e even in electron root (T_e>>T_i)

HSX Explores the Potential Benefits of Quasi-Symmetry



- First experimental test of quasi-symmetry: reduced parallel viscous damping and reduced thermo-diffusion
- Importance of high effective transform; low effective ripple at moderate aspect ratio

HSX research addresses critical issues

- Quasi-symmetry as solution to large neoclassical transport
- Variation of flows/damping & plasma currents
- Dependence of turbulent transport on magnetic structure

Parameters

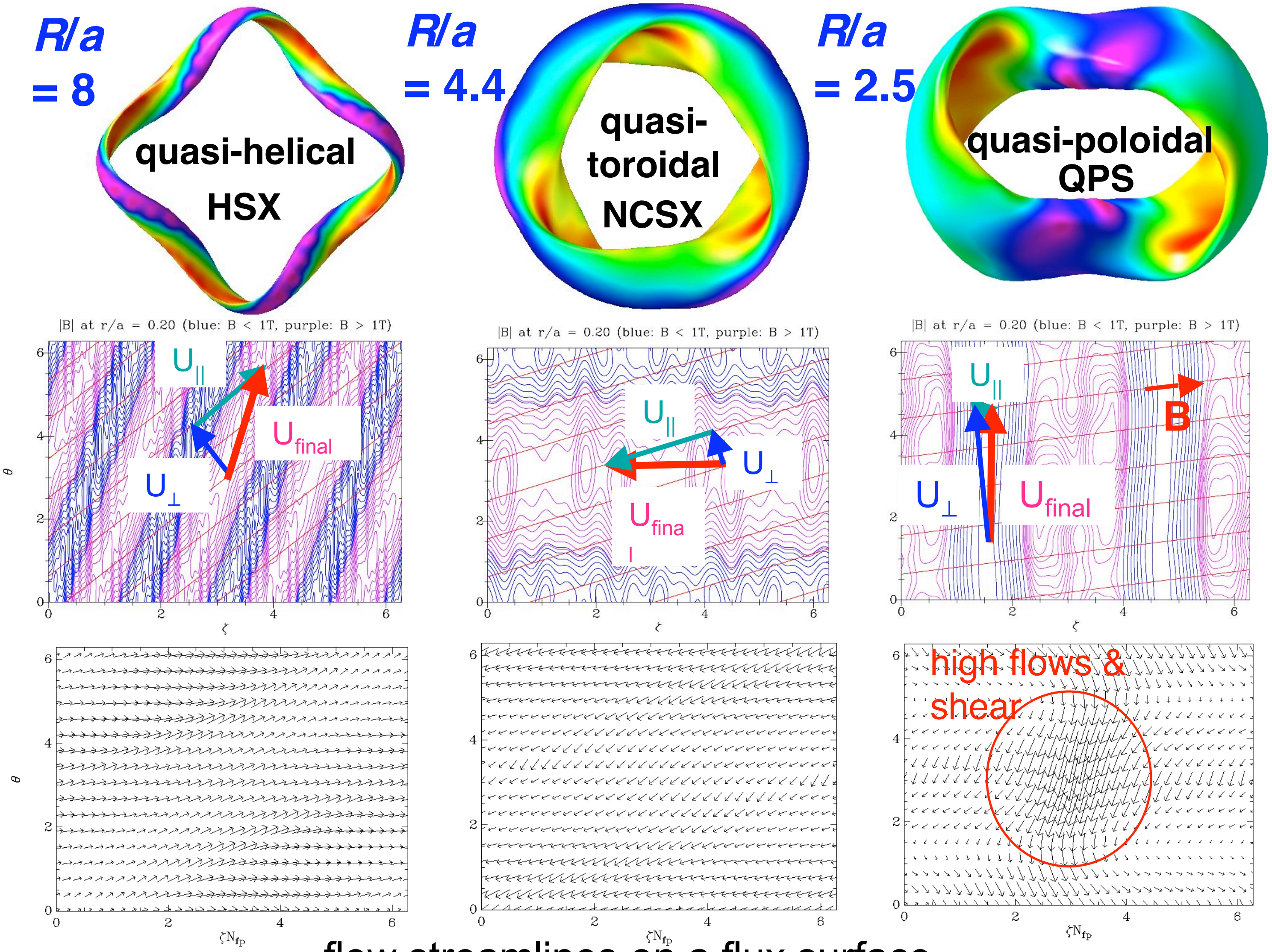
$R = 1.2$ m, $\langle a_p \rangle = 0.15$ m, $B = 1$ T

P_{ECH}: 200 kW, 28 GHz now
200 kW in progress

To date: $T_{e0} \sim 2.3$ keV
$\langle n_e \rangle = 6 \times 10^{18}$ m^{-3}

HSX can span the range between quasi-helically-symmetric and non-symmetric configuration

Quasi-Symmetric Concepts Have Different Properties: e.g., Flows & Flow Shearing



R/*a* = 8

quasi-helical HSX

R/*a* = 4.4

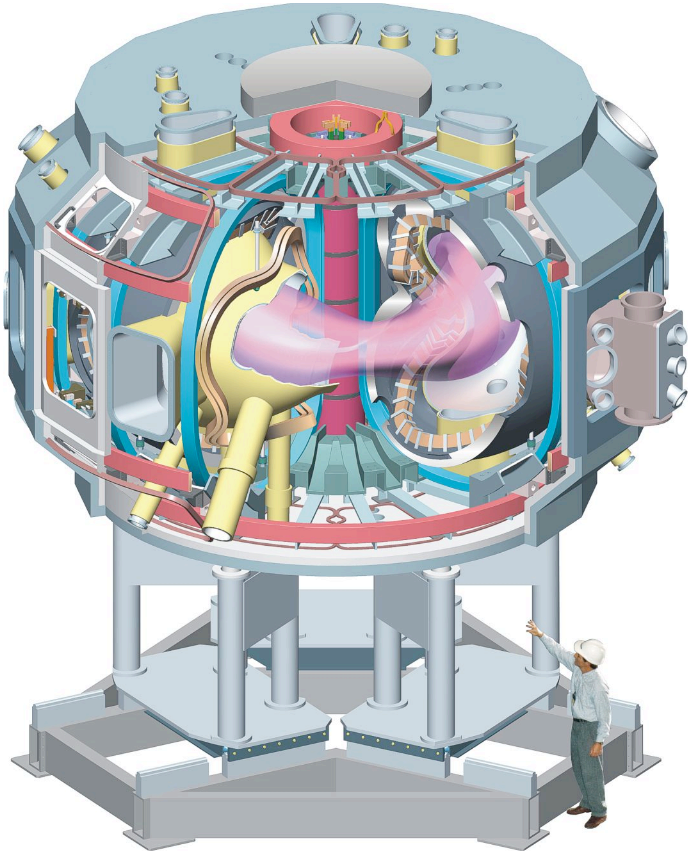
quasi-toroidal NCSX

R/*a* = 2.5

quasi-poloidal QPS

flow streamlines on a flux surface

NCSX Paves Path for Tokamak-Like CS DEMO



- $\langle R \rangle = 1.42$ m, $\langle a \rangle = 0.32$ m
- Magnetic field (pulse length)
  2.0 T (0.2 s), 1.2 T (1.7 s)
- Plasma heating up to 12 MW

Tokamak-like characteristics with capability for high-β disruption-free operation

Develops understanding of

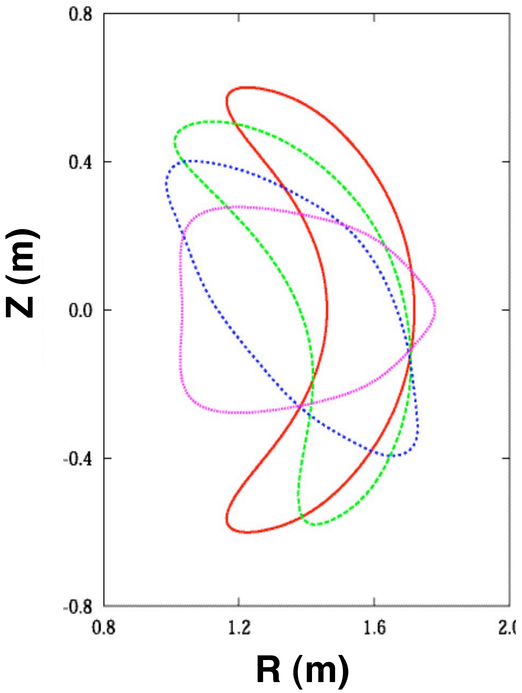
- Beta limits and limiting mechanisms
- Effect of 3-D magnetic fields on disruptions
- Reduction of neoclassical transport by quasi-axisymmetric design
- Confinement scaling; reduction of anomalous transport
- Equilibrium islands and neoclassical tearing-mode stabilization
- Compatible power and particle exhaust
- Alfvénic mode stability in reversed shear

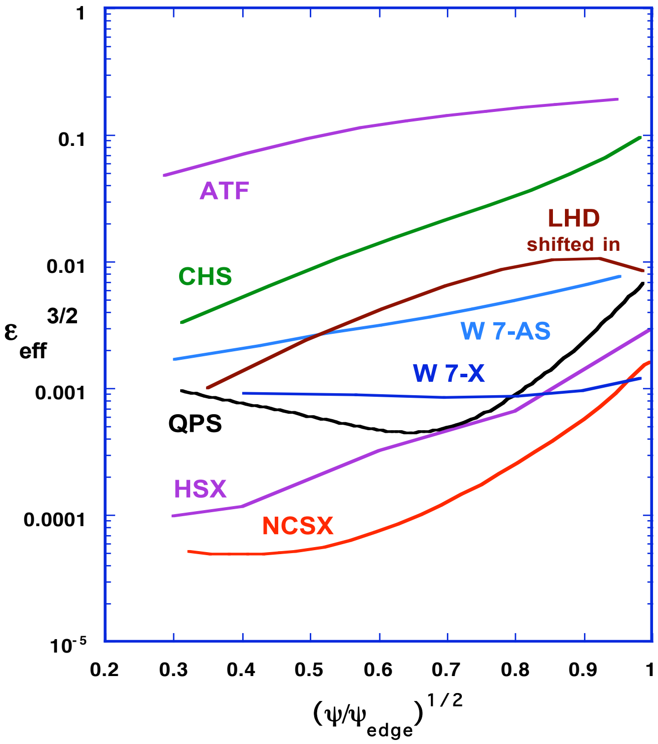
NCSX Configuration Properties

Configuration was optimized for target physics properties

- Low $R/\langle a\rangle$ (4.4)
- Quasi-axisymmetric with low effective ripple
- Stable at $\beta = 4.1\%$ to vertical, kink, ballooning, NTM instabilities
- Reverse shear q profile
- 25% of transform from bootstrap current
- Good magnetic surfaces at high β
- Constrained by engineering feasibility

Plasma Cross Sections





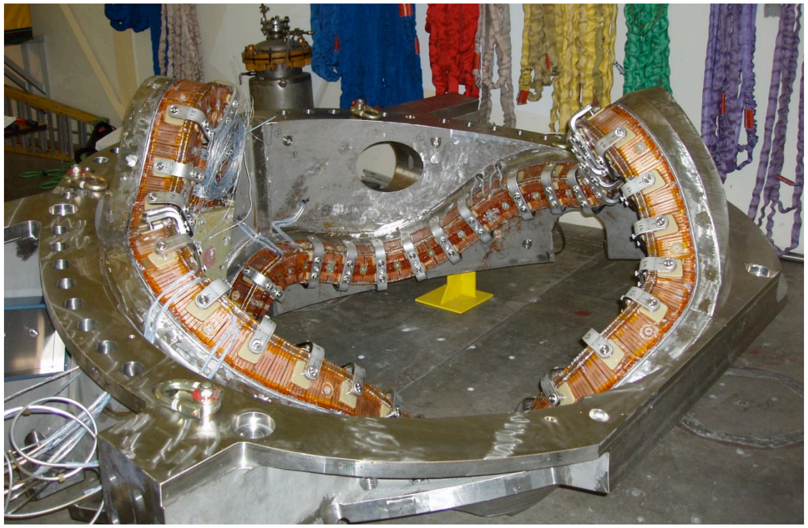
Understanding of 3-D quasi-axisymmetric shaping can also lead to tokamak improvements, e.g., improved stability, disruption avoidance

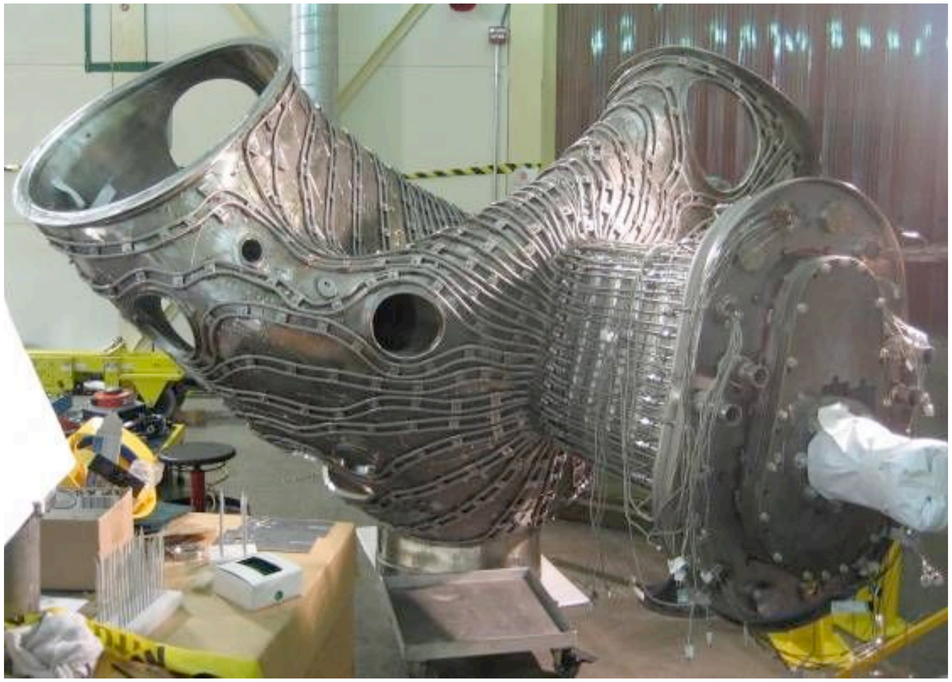
NCSX Construction Well Under Way

- 16 of 18 coils have been wound; last coil scheduled for May 2008

- 18 TF coils in production, 5 finished; last coil scheduled for Sept. 2008

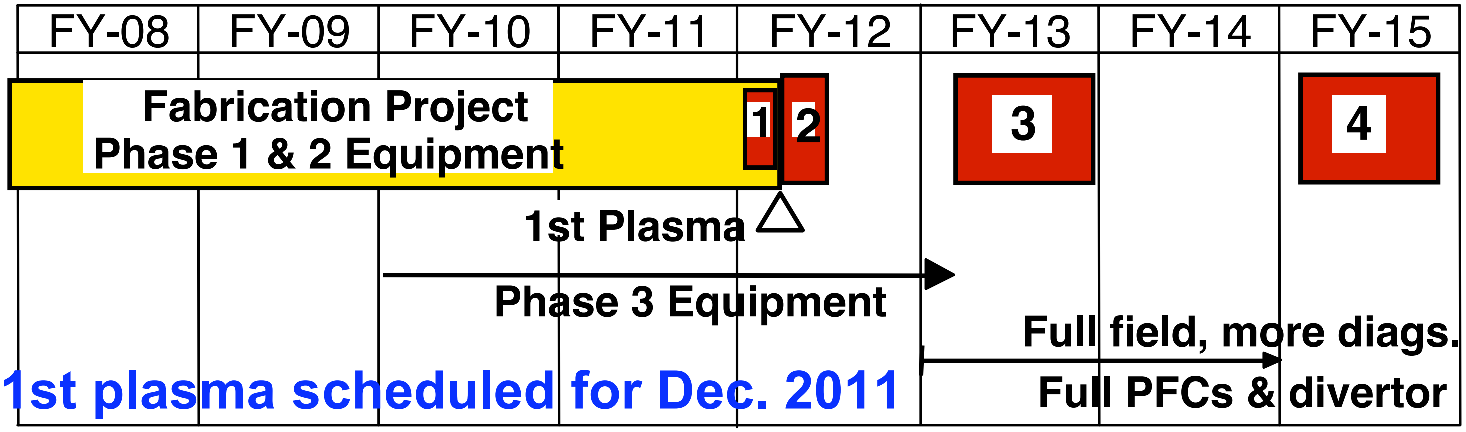
- Vacuum vessel sectors complete





- Start of assembly preparations

NCSX Program and Schedule



FY-08 FY-09 FY-10 FY-11 FY-12 FY-13 FY-14 FY-15

Fabrication Project
Phase 1 & 2 Equipment

1 2 3 4

1st Plasma △

Phase 3 Equipment

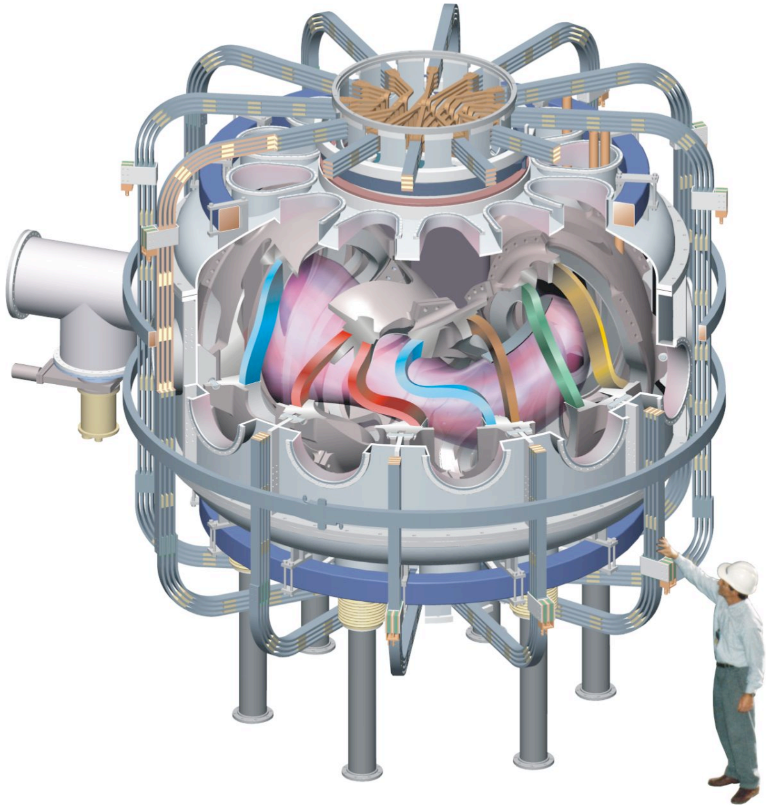
Full field, more diags.

Full PFCs & divertor

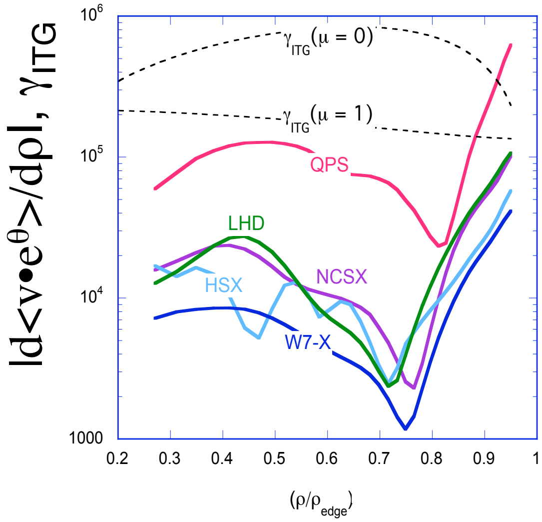
1st plasma scheduled for Dec. 2011

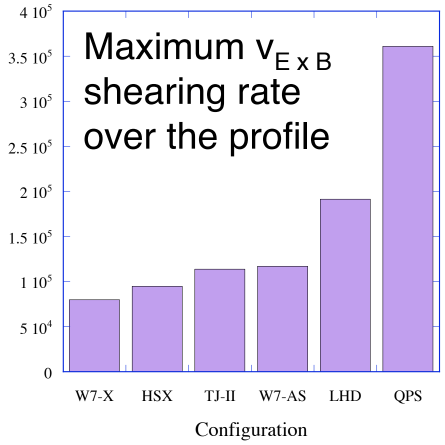
1. Stellarator acceptance testing and first plasma (ends fabrication project)
2. Magnetic configuration studies: electron-beam mapping studies (2012)
3. Initial experiments (2013) with 3-MW NBI, B ≥ 1.2 T to study effect of quasi-axisymmetric shaping and effective ripple on confinement
   - resilience to disruptions from MHD instabilities, density limits
   - initial comparisons with calculated MHD stability thresholds
4. High-beta experiments (2015) with 6-MW heating, B = 2 T
   - β-limits and limiting mechanisms
   - safe operating area against disruptions
   - local transport properties; impurity transport
   - fast ion transport with ripple; Alfvenic-mode stability
   - initial divertor effectiveness; scrape-off layer characteristics

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



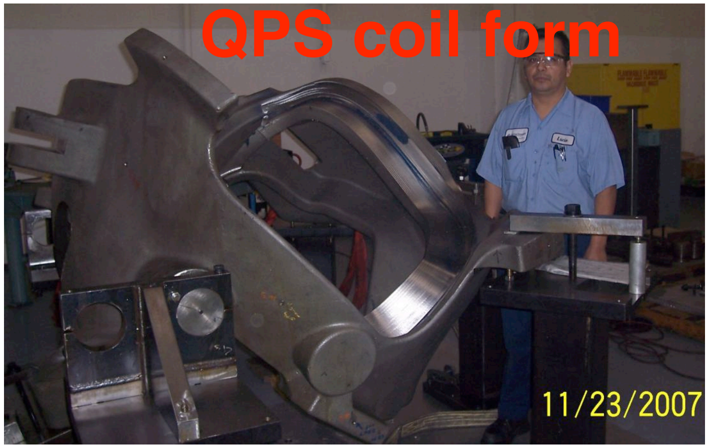
- $\langle R \rangle = 0.95$ m, $\langle a \rangle = 0.38$ m
- Magnetic field (pulse length)
  1.0 T (1.5 s), 1.2 T (1 s)
- Plasma heating up to 5 MW



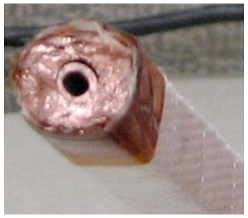


- Reduced growth rates for trapped particle, ITG modes
- Increased flows/shear to suppress turbulence, influence MHD stability
- Low bootstrap current
- Robust equilibrium and healing of magnetic islands
- Allows connection with large W 7-X with *R*/*a* = 10.4

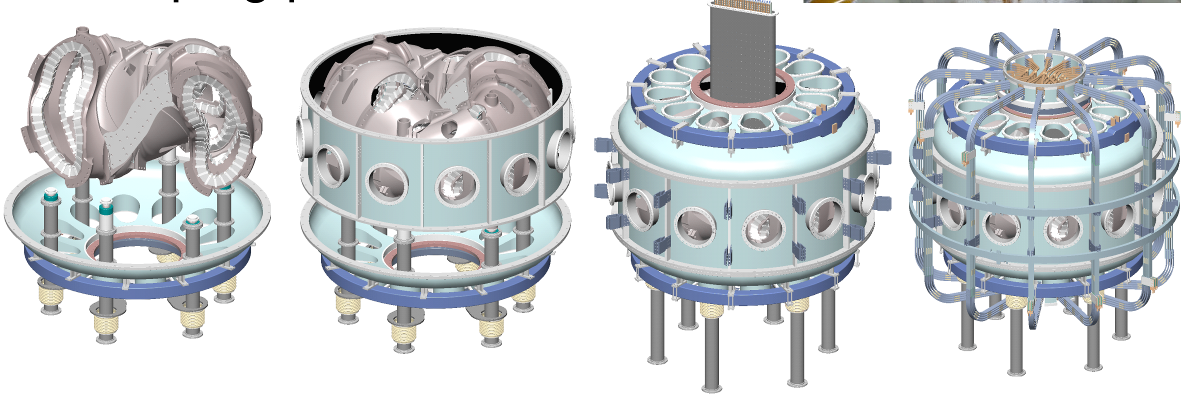
QPS R&D and Prototype Coil Address Main Stellarator Fabrication Issues



- Use trim coils and varying coil currents to compensate for inaccuracies in coil fabrication and device assembly
  - avoid need for very tight tolerances and extensive metrology

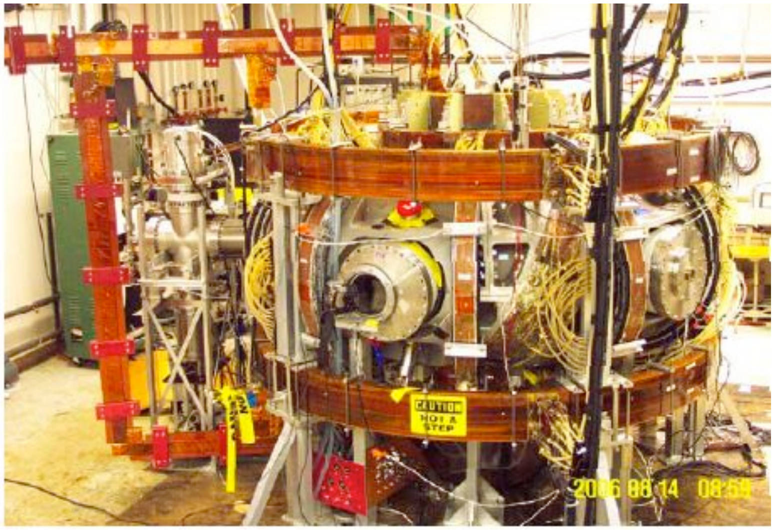


- Simple internal cooling to avoid complex, expensive external cooling approach
- Accurate winding clamps to avoid extensive metrology and calibrated clamping pressure



- QPS allows a simple vacuum vessel and a simple device assembly process

CTH Studies Equilibrium and Stability in Stellarators with Current



$R = 0.75$ m, $\langle a_p \rangle = 0.18$ m

$B = 0.65$ T, $I_{OH} \sim 50$ kA

vacuum $\iota_a = 0.1 - 0.5$, 5 periods

one helical coil; TF & PF coils

$\Rightarrow$ large variation possible in ι_{pl}/ι_{ext}

100-kW OH + 15-kW 18-GHz ECH

adding soon 30-kW 14-GHz

- Not quasi-symmetric, but uses 3-D shaping, vacuum transform to passively control MHD instabilities
- Validating new V3FIT method of magnetic equilibrium reconstruction in 3-D plasmas
- Detection and control of magnetic islands
- Innovative procedures to determine most accurate model for as-built coils

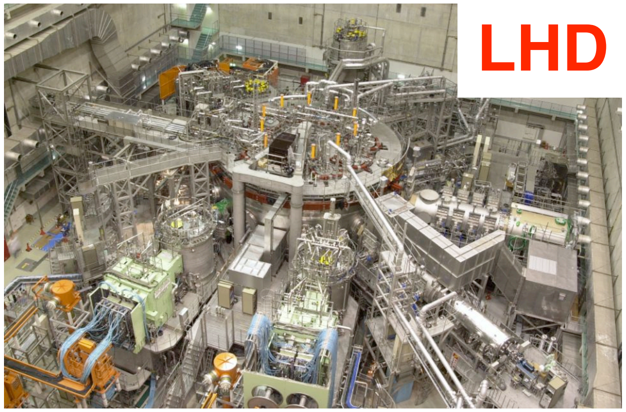
These topics central to robust equilibrium and stability control of compact stellarators

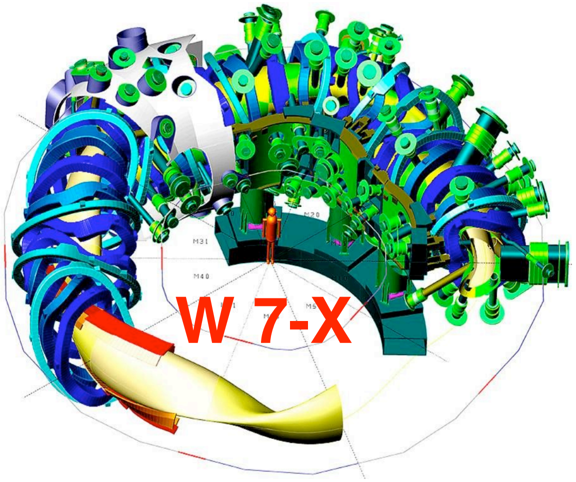
- Extended program:

  ICRF electron heating ⇒ higher pressure MHD studies

International Collaboration

- Allows access to stellarators with capabilities well beyond the scope of the US program
- Although not compact stellarators (R/a = 6-7 in LHD and 10.4 in W 7-X vs ~2.5 in QPS), they can obtain important information on
  - plasma behavior at high parameters: density (>10^{21} m^{-3}), ion and electron temperatures (5-13 keV), $\beta \sim 5\%$ for $50\tau_E$
  - energetic-ion stability and transport
  - steady-state operation and β maintenance at high power (3 MW)
  - 3-D power and particle exhaust methods
- They are additional sources of information on
  - the effect of lower effective ripple on neoclassical and anomalous transport
  - density & β limits and mechanisms



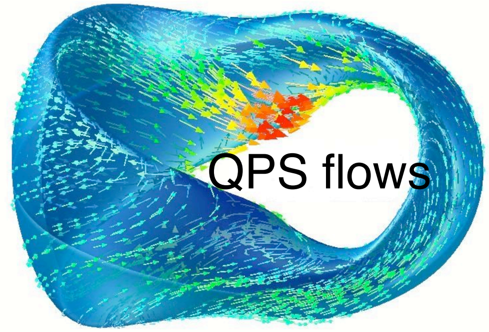


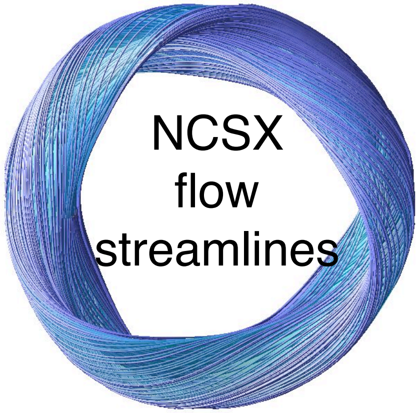
B = 3-4 T superconducting coils, V_{plasma} = 30 m^3
a_{pl} = 0.53–0.6 m
$P_{heating}$ = 15–30 MW

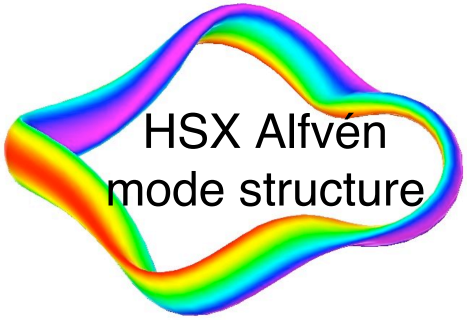
Theory and Computation Are Critical Innovating and Integrating Elements

US theory develops world-class tools for stellarator interpretation and configuration improvement

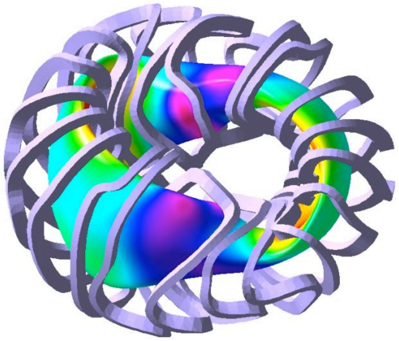
- 3-D MHD equilibrium (VMEC, PIES, SIESTA) and stability (COBRA, Alfvén mode codes, M3D)
- Transport (DKES, Monte Carlo codes, PENTA)
- Plasma heating (NBI, full wave/ray tracing codes)
- Concept improvement (STELLOPT); reactor optimization (MHHOPT)
- These codes have been used to optimize NCSX & QPS
  - direct optimization from coils to free boundary equilibrium
- Benchmarked with tokamak results
  - integrates common understanding of these devices

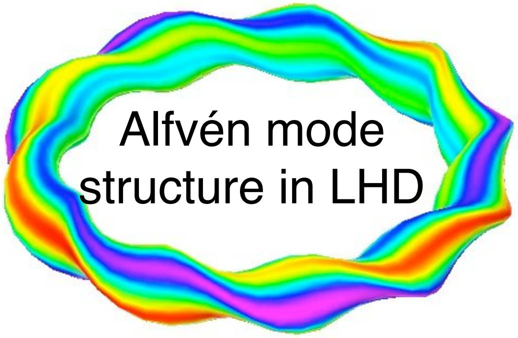

QPS flows


NCSX flow streamlines


HSX Alfvén mode structure

QPS $|\mathbf{B}|$ structure and coils




Alfvén mode structure in LHD

~10 Year Compact Stellarator Program

By 2018-20 the stellarator program needs to determine if it is on a path to DEMO and what intermediate facility would be needed

- Physics basis and magnetic configuration optimization firmly established -- requires adequate funding of a broadly based, integrated program
  - **NCSX** to demonstrate high-β disruption-free operation in a compact stellarator configuration with quasi-toroidal (tokamak-like) symmetry
  - **HSX** to provide fundamental tests of quasi-symmetry and very low effective ripple
  - **CTH** to study plasma equilibrium and stability in a current-carrying stellarator and develop 3-D reconstruction techniques
  - **QPS** to extend compact stellarator physics to low R/a and quasi-poloidal symmetry, and demonstrate simpler, cheaper construction
  - **Theory** to provide world-class tools for stellarator interpretation and configuration improvement as well as benchmarking with tokamak results to integrate common understanding of these devices
- Use of LHD and W 7-X to demonstrate adequate thermal and fast-ion confinement, size scaling, reduction of α-losses, workable steady-state high-power divertor, and simulate burning plasma issues