Compact Stellarator Research Opportunities

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Topics

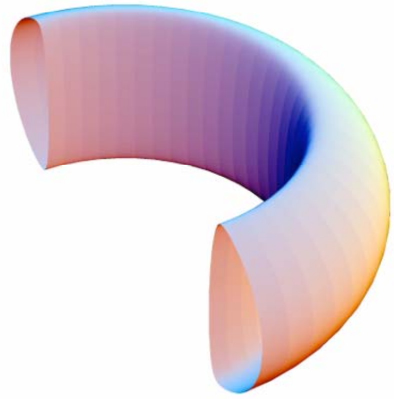
- Compact stellarator motivation.
- NCSX mission, design, and opportunities.
- Experimental program.

Axisymmetric Toroidal Plasmas Have Brought Magnetic Fusion Research a Long Way

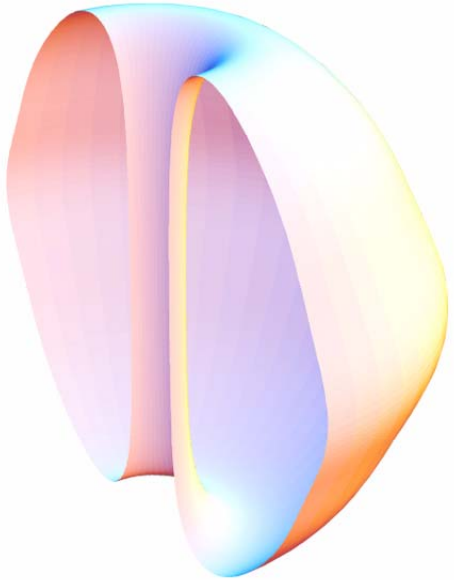
Long record of accomplishments in performance and understanding.

Potential: Reactor-scale burning plasmas in **ITER**.

Practical issues: Disruptions, steady state, understanding of transport and energetic particle effects.



Tokamak



Spherical Torus

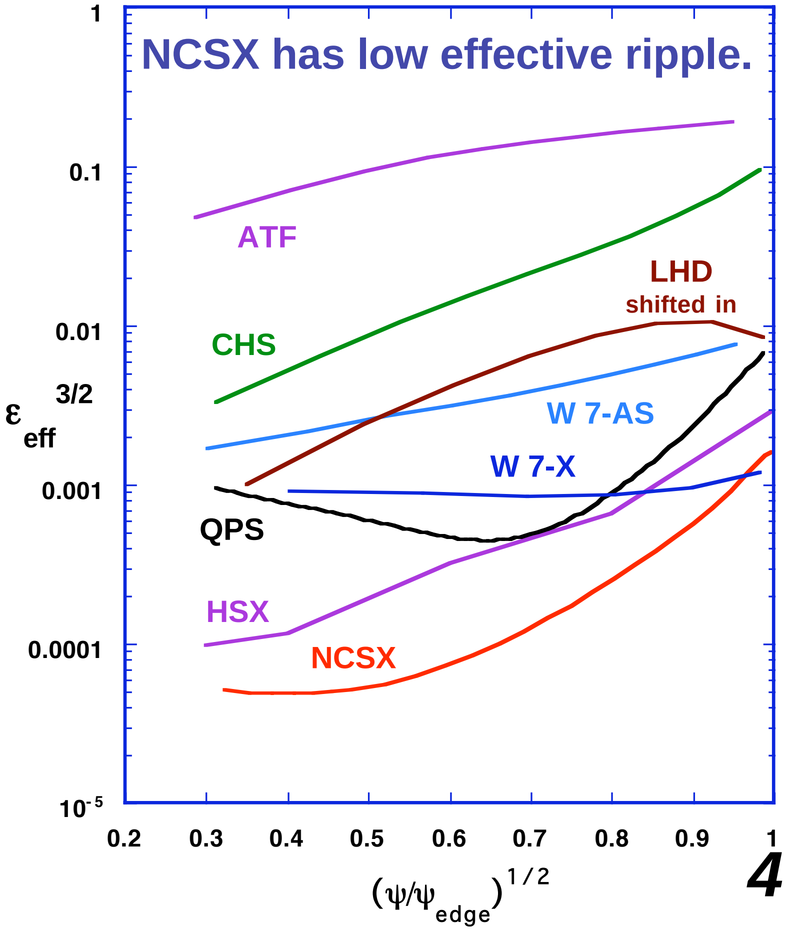
Compact Stellarator Benefits for Magnetic Fusion

Stellarators solve critical problems.

- Steady state without current drive.
- No disruptions: stable without feedback control or rotation drive.
- Unique flexibility to resolve 3D plasma physics issues.

Compact Stellarators have additional benefits

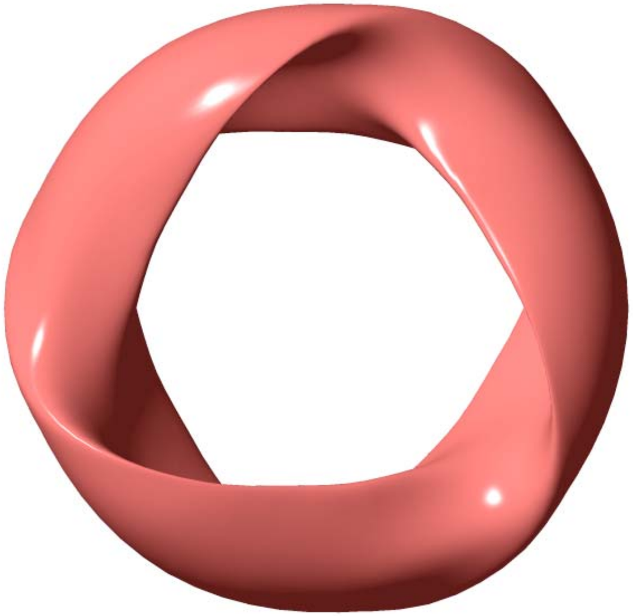
- Magnetic quasi-symmetry. In NCSX:
  - Quasi-*axi*symmetric configuration with effective ripple <1.5%.
  - Low flow damping, tokamak-like orbits ⇒ enhanced confinement
  - Makes full use of tokamak advances, allowing rapid and economical development.
- Lower aspect ratio than typical stellarators.
  - 4.4 in NCSX *vs.* ~11 in W7-X.



NCSX has low effective ripple.

Stellarator Benefits Are Due to its 3D Geometry

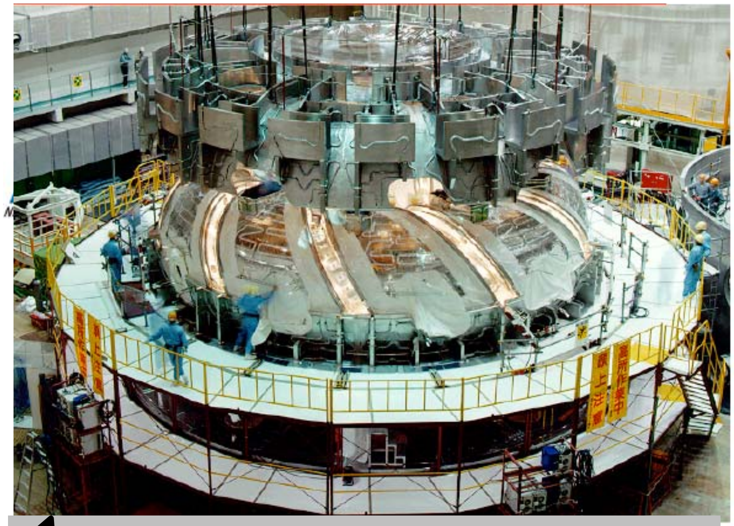
- Stellarators create confining magnetic configuration with magnets alone.
  - Robust mode of operation, simple control.
- Compact stellarators take advantage of 3D shaping flexibility to design for additional attractive properties.
  - Compactness, good confinement, high-β stability, etc.
- The magnets can be designed to allow the shape to be varied.
  - Provides the flexibility needed to test the physics.



NCSX Plasma Design

3D geometry produces benefits and costs. We need to quantify both.

Stellarators Are Making Good Progress



Large Helical Device (S/C magnets - Japan)

β ~ 4.5%.

$T_e \approx 10$ kev, $T_i \approx 10$ keV.

enhanced confinement.

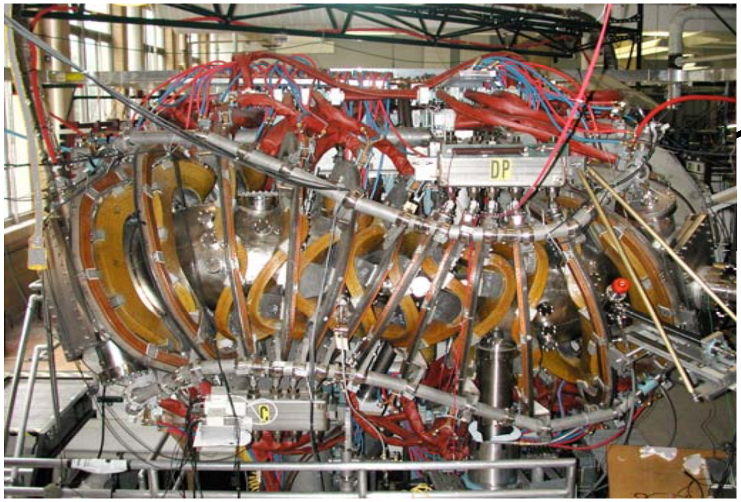
2-minute pulses.

Wendelstein 7-AS (Germany)

β ~ 3.5%.

enhanced confinement.

density control & enhanced performance w/island divertor.



Helically Symmetric Experiment (U. Wisc.)

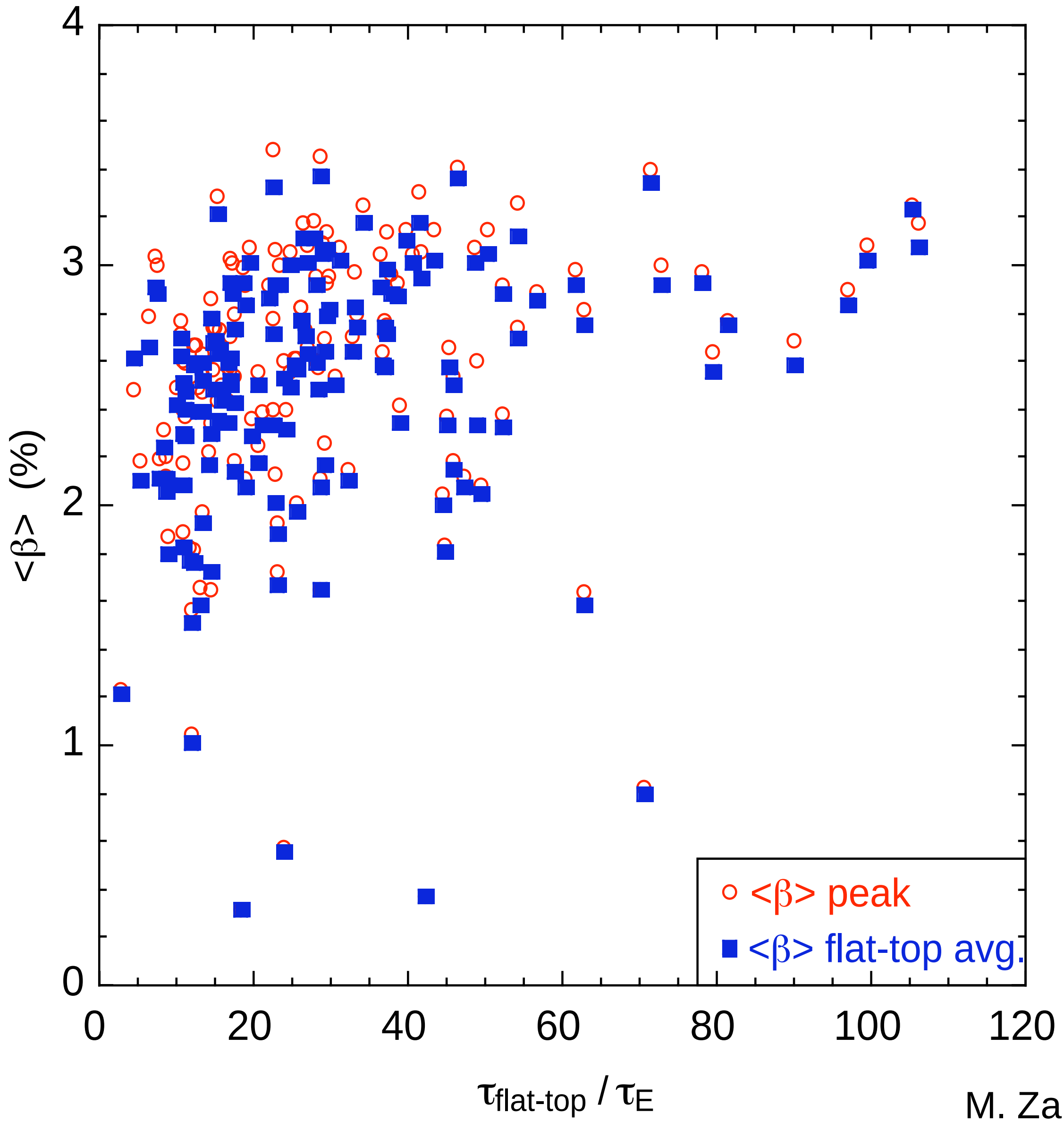
- Test and understand quasi-symmetry.

Wendelstein 7-X (Germany)

Optimized Design - S/C magnets

Under construction - Ops. In 2012

⟨β⟩ > 3.2% maintained for > 100 τ_E in W7-AS



- Peak <β> = 3.5%
- ⟨β⟩-peak ≈ ⟨β⟩-flat-top-avg
  ⇒ very stationary plasmas
- No disruptions
- Duration and β not limited by onset of observable MHD
- High-β maintained as long as heating maintained, up to power handling limit of PFCs.
- β limit may be set by equilibrium degradation.
  ⇒ can avoid by design.

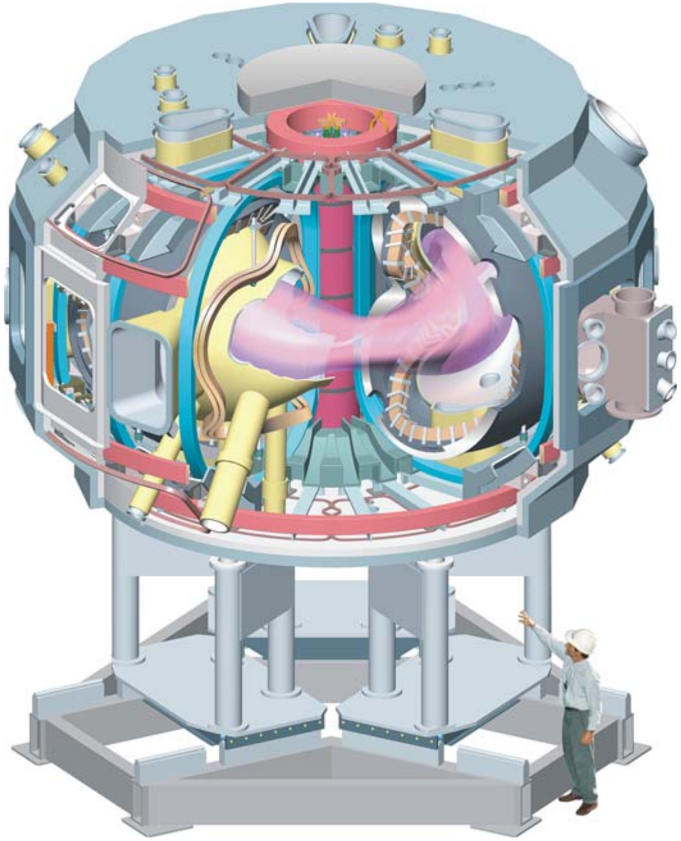
M. Zarnstorff (PPPL) & W7-AS Team.

NCSX Mission: Physics of Compact Stellarators

Acquire the physics data needed to assess the attractiveness of compact stellarators; advance understanding of 3D fusion science.

Understand…

- Beta limits and limiting mechanisms.
- Effect of 3D magnetic fields on disruptions
- Reduction of neoclassical transport by QA design.
- Confinement scaling; reduction of anomalous transport.
- Equilibrium islands and neoclassical tearing-mode stabilization.
- Power and particle exhaust compatibility w/good core performance.
- Alfvénic mode stability in reversed shear compact stellarator.



Demonstrate…

- Conditions for high-beta, disruption-free operation.

NCSX Device is Designed for its Broad Mission

Stellarator

Major radius: 1.4 m

Magnetic Field (B)

@ 0.2 s pulse: 2.0 T

@ 1.7 s pulse: 1.2 T

Plasma current ≤350 kA.

Plasma Heating Flexibility (planned)

NBI: 6 MW (tangential)

ICH: 6 MW (high-field launch)

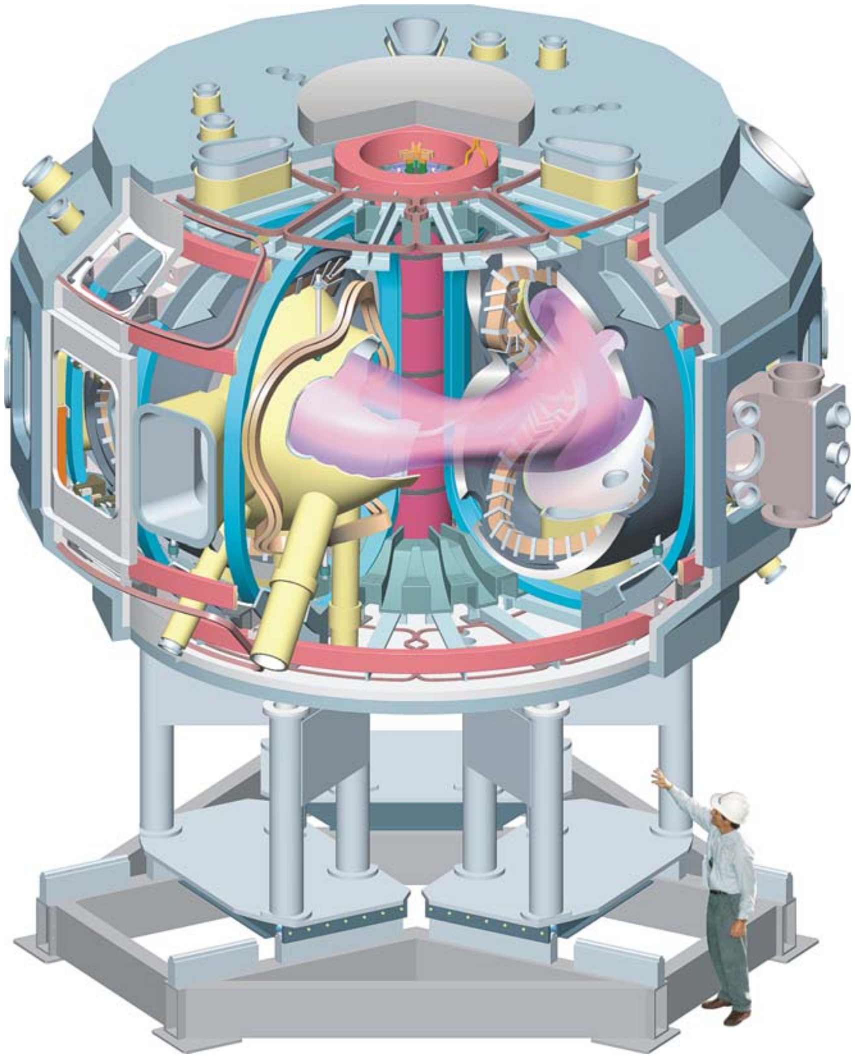
ECH: 3 MW

High β (4%) Plasma Scenario

B = 1.2 T, P = 6 MW

($\tau_E = 2.9 \times$ ISS95 ≈ L-mode assumed)

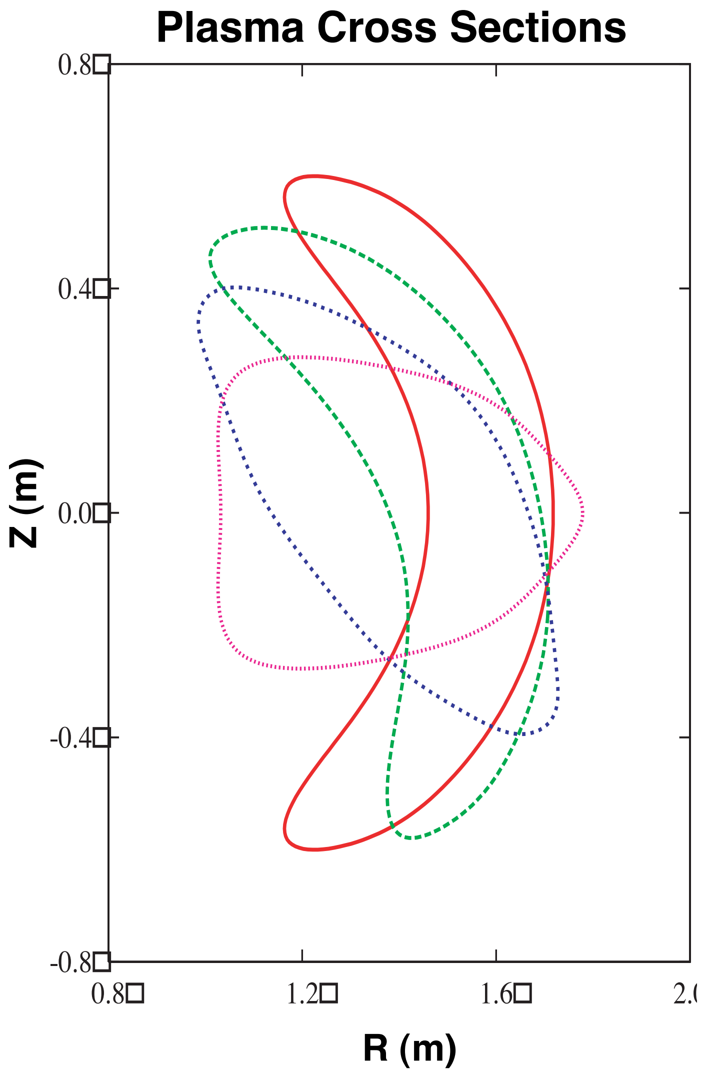
- $n_e = 6 \times 10^{19}$ m^{-3}
- $T_i(0) = 1.8$ keV
- $\nu_i^* = 0.25$



coils cooled to cryogenic temperatures, vacuum vessel at room temperature.

NCSX Physics Design

- Plasma / coil configuration was optimized to realize target physics properties.

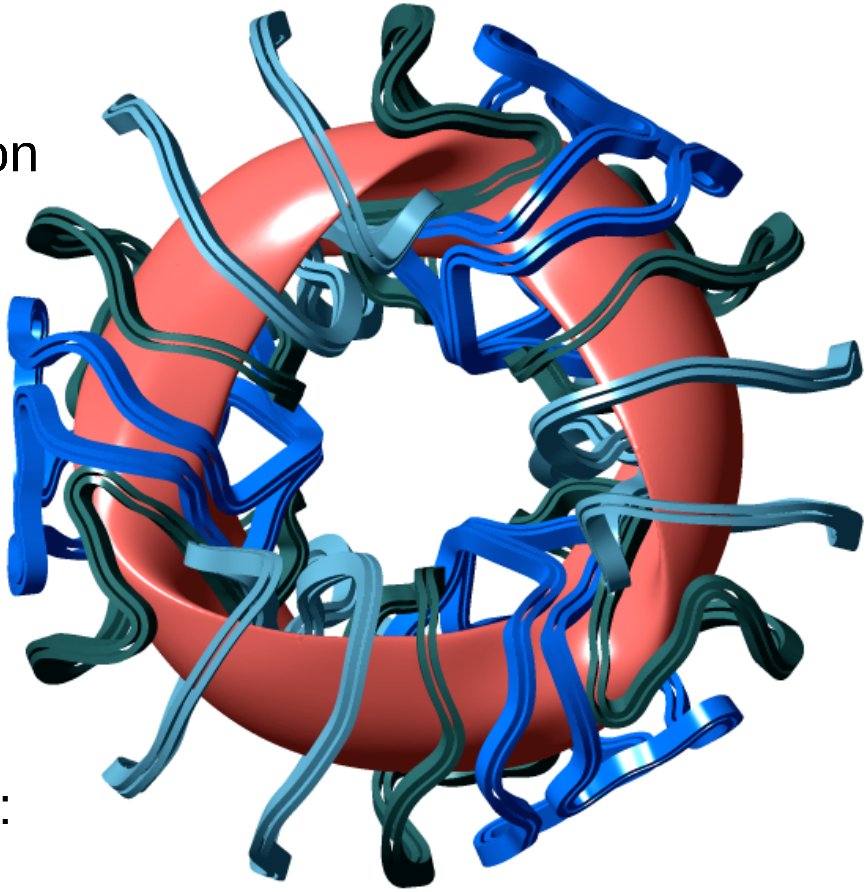


Physics Properties

- 3 periods, low R/⟨a⟩ (4.4).
- Quasi-axisymmetric w/ low ripple.
- Stable at β=4.1% to specific MHD instabilities.
- Reverse shear q-profile.
- 25% of transform from bootstrap.
- Good magnetic surfaces at high β.
- Constrained by engineering feasibility metrics:
  - – coil-coil spacing
  - – min. bend radius
  - – tangential NBI access
  - – coil-plasma spacing.

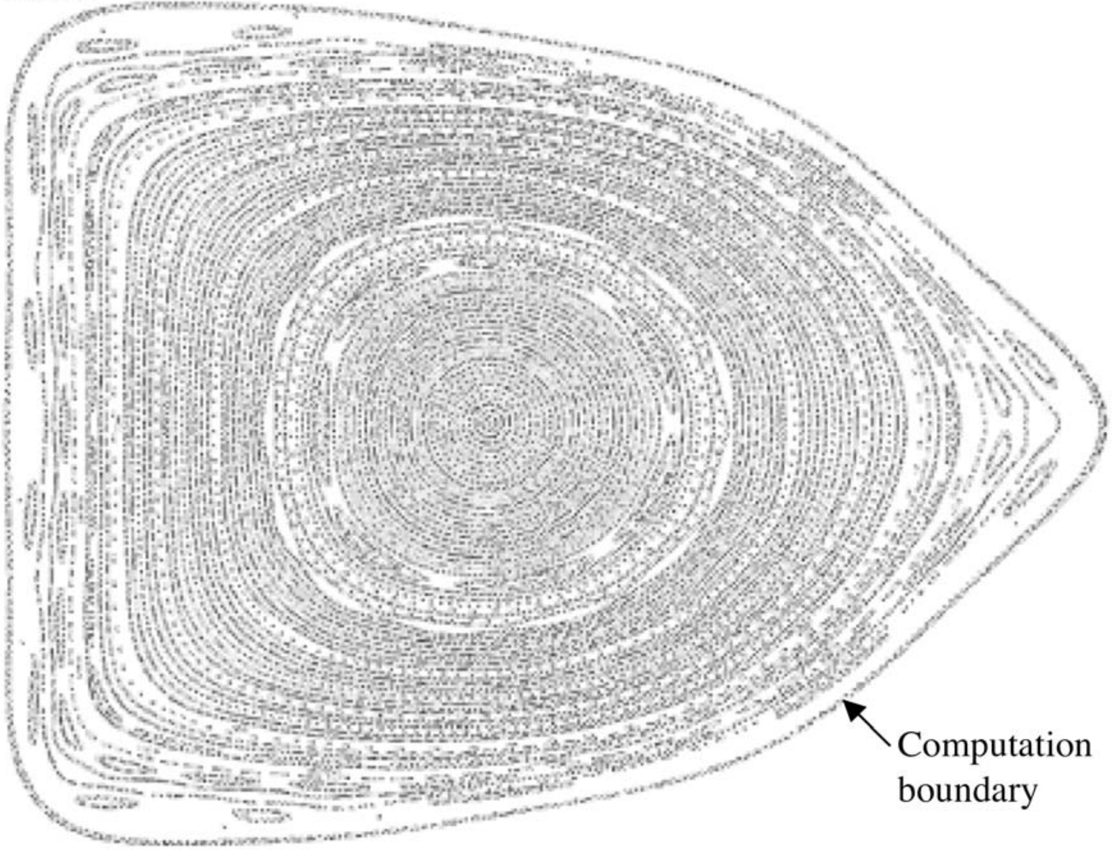
NCSX Design Satisfies Physics & Engineering Criteria

- 18 modular coils (3 shapes)
  - Also TF, PF, and helical trim coils.
- Massively parallel computer optimization used to target required properties.
  - Over 500,000 designs analyzed.
- Required physics properties realized:
  - Low aspect ratio.
  - Stable at high beta.
  - Quasi-axisymmetric.
  - Flexible.
- Engineering feasibility metrics satisfied:
  - Coil-coil spacing
  - Coil bend radius
  - Coil-plasma spacing.



NCSX Plasma and Modular Coils

NCSX Coils Are Designed to Produce Good Surfaces at High β

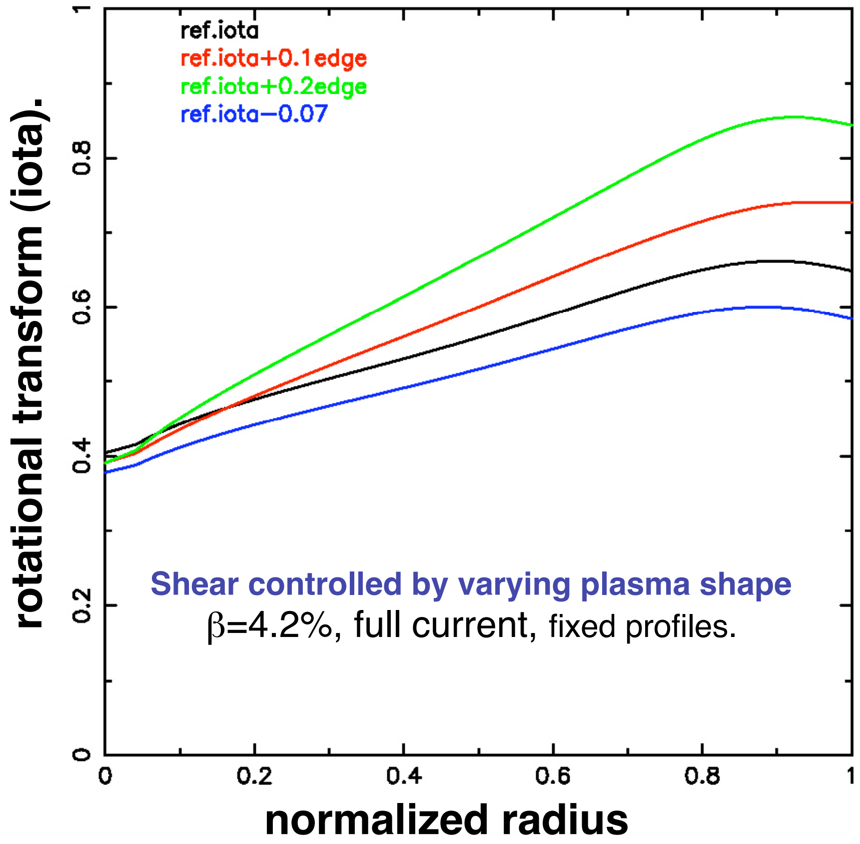


Poincare: PIES, free boundary 3D equilibrium code. β = 4%

< 3% flux loss.

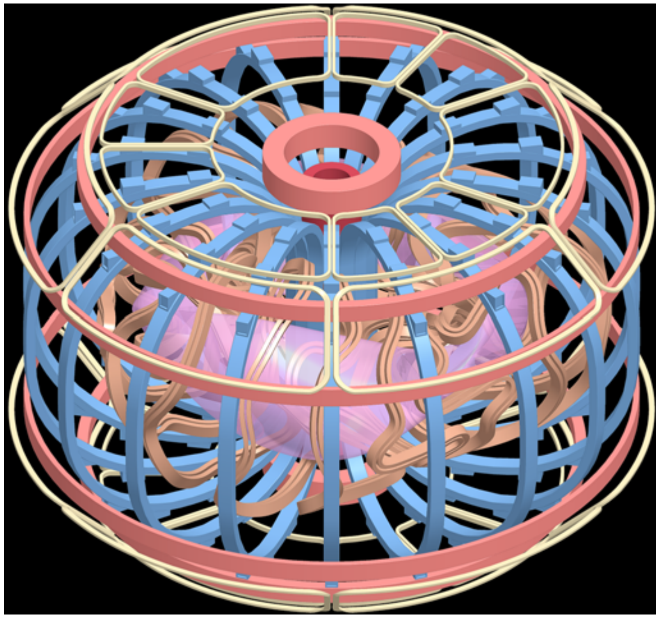
- Explicit numerical design to eliminate resonant field perturbations
- ‘Reversed shear’ configuration ⇒ neoclassical healing of equilibrium islands and stabilization of tearing modes (already observed in LHD)
- What are the limits? How strong are flow & other kinetic effects?

NCSX Coils: Flexibility to Vary Physics Properties



Shear controlled by varying plasma shape

β=4.2%, full current, fixed profiles.

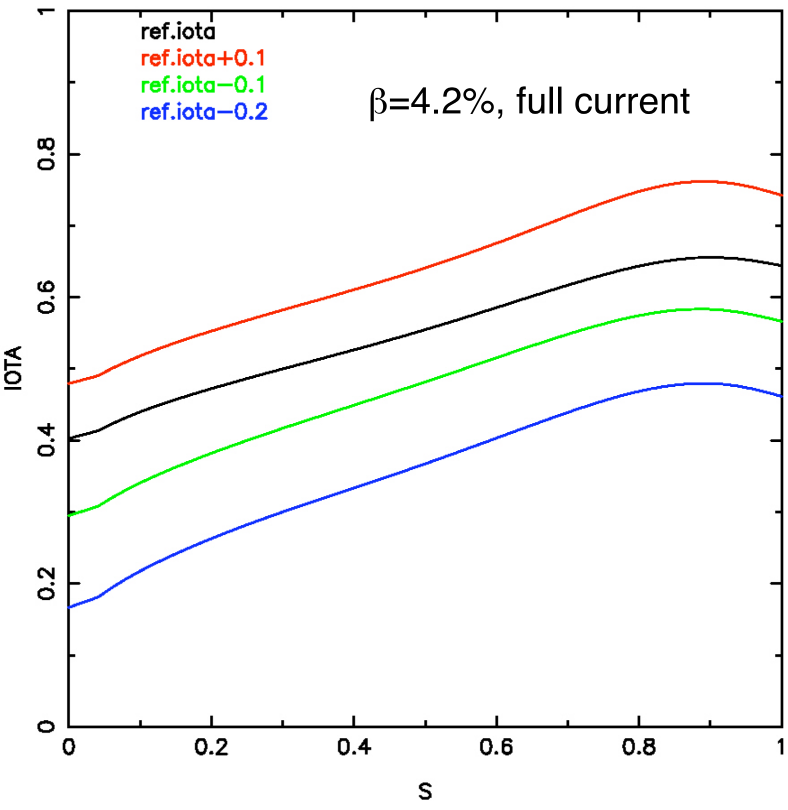


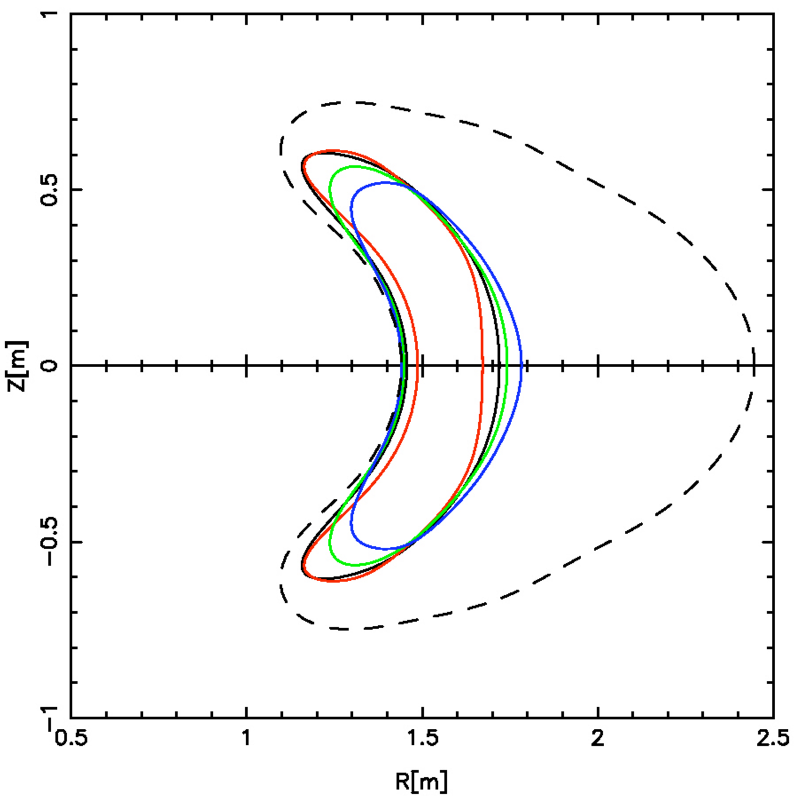
- Magnet system has 4 coil sets
  - Modular, TF, PF, trim.

Also

- Can externally control iota.
- Can increase ripple by ~10x, preserving stability.
- Can lower theoretical β-limit to 1%.
- Can cover wide operating space in β (to at least 6%), I_P, profile shapes.

Properties Are Determined By Plasma Shape





External rotational transform (iota) controlled by plasma shape at fixed profiles.

NCSX Trim Coil Design

Trim coils have been very effective on existing experiments:

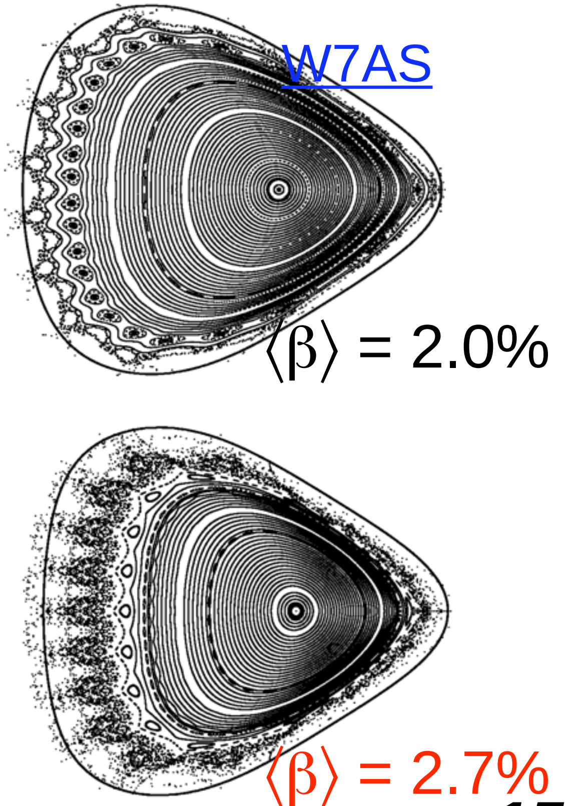
- W7AS and LHD, small saddle trim coils are used to control resonant fields to control islands
- On W7AS, trim coil was used to increase the maximum beta by ~50%, probably by controlling the edge magnetic stochasticity

NCSX external trim coils being designed for

- Control resonant field perturbations from assembly errors and plasma currents
- Give fine control on 3D plasma shape, to control physics
- Divertor strike-point control

Candidate trim-coil arrays of saddle coils, mounted outside modular coil shell being analyzed.

Control strategy to be developed..



Vacuum Vessel Provides Good Diagnostic Access

Physics Requirements

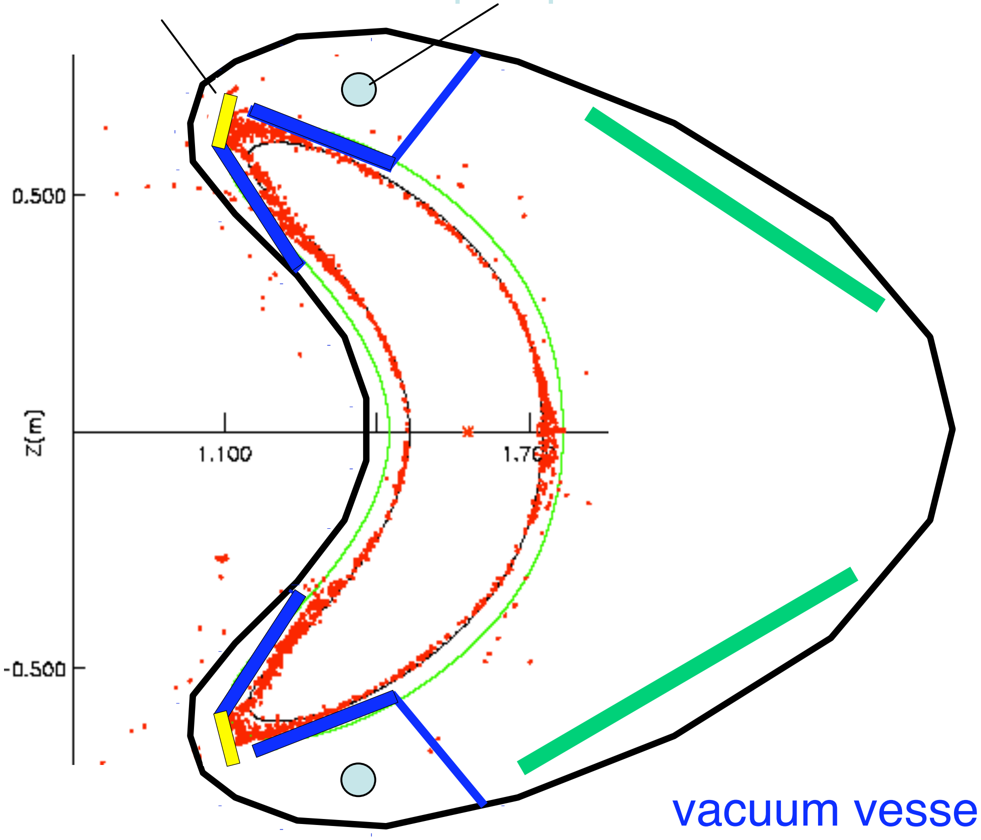
- Access for heating and diagnostic viewing.
- Sufficient interior space for plasma, boundary layer, and PFCs.
- High-vacuum environment for good plasma performance.
- Low field errors.

Design

- About 100 ports, filling all available openings in surrounding magnets.
- Vacuum boundary inside coils, as far from plasma surface as possible.
  - Shell geometry similar to plasma's. Tolerance ±5 mm.
- Bakeable to 350 C.
- Inconel material.

NCSX Offers a Robust Divertor Concept

- Divertors in bean tip region
- Strong flux-expansion (> 10:1) always observed in bean-shaped cross-section. Allows isolation of PFC interaction.
- Can we design/control divertor to accommodate a wide range of configurations?



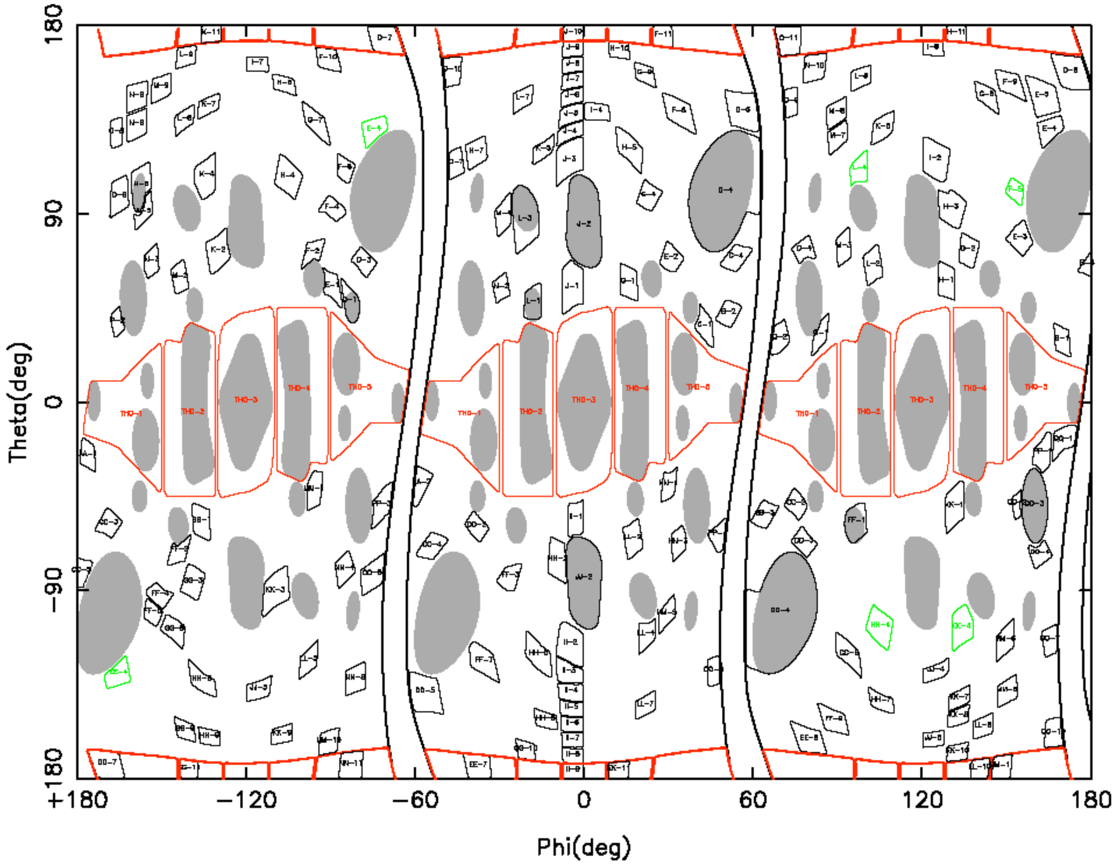
divertor

pumps

vacuum vessel

MFBE field-line tracing

Ex-Vessel Magnetic Diagnostics Designed for Reconstuction



- **saddle coils mounted on vessel**
- **~2500 free-boundary equililbria analyzed to identify critical regions for measurement**
- **Array distributed across 3 periods + extra coils to sense symmetric and non-symmetric components**

N. Pomphrey, PPPL
E. Lazarus, ORNL

Several strategies being developed for equilibrium reconstuction:

- V3FIT – reconstruction code based on VMEC (cannot represent islands)
- PIES – 3D equilibrium with islands
- 3D external flux fit (e.g. filament code), to find boundary shape and characteristics

NCSX Construction is Well Under Way

Vacuum Vessel

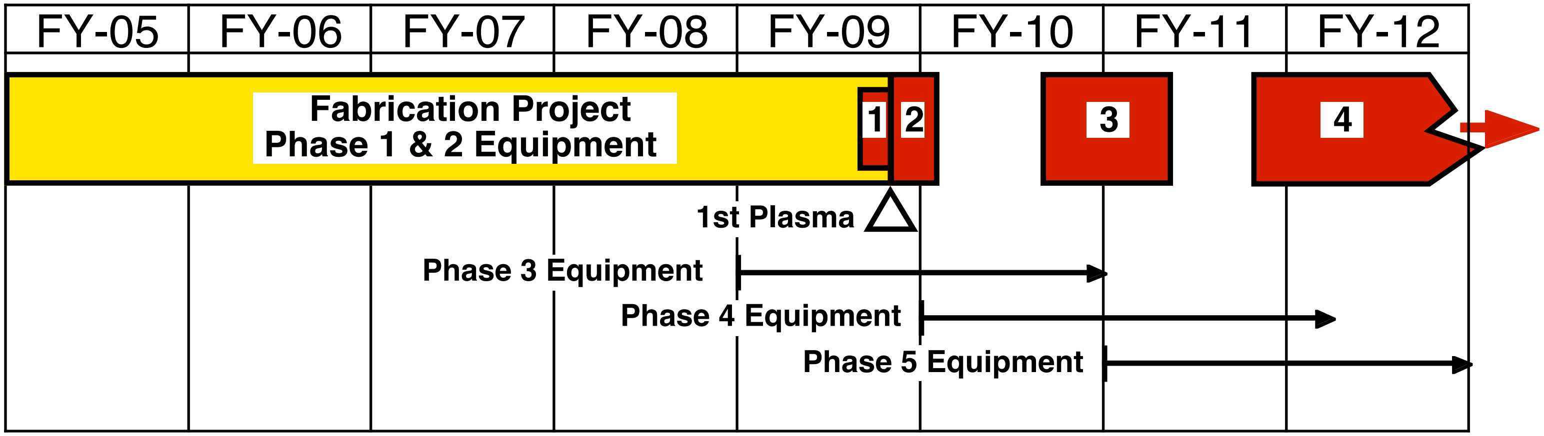
Modular Coils

Segment #1 of 3
Sealed for Pump-down

Completed Coil
(#1 of 18)

Construction Will be Completed in 2009

NCSX Research Program Will Address Physics Issues for Compact Stellarator Attractiveness.



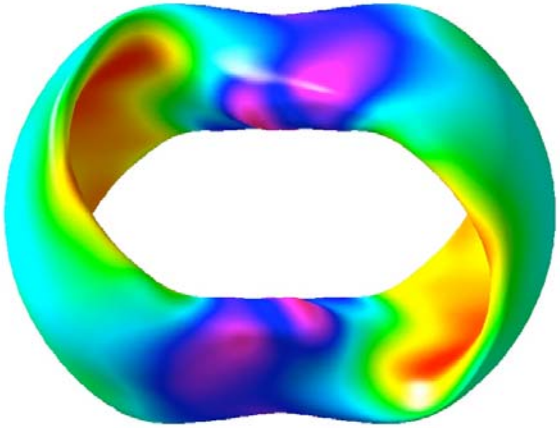
Phase / Research Goals	Key Equipment
1. Stellarator Acceptance Testing • Verify construction accuracy • First Plasma **2. Magnetic Configuration Studies** • Vacuum flux surface documentation. • Magnetic configuration control w/ coils.	• Stellarator @B = 0.5 T • Ohmic heating, 150 C bake. • E-beam & ex-vessel magnetics
3. 1.5MW Initial Experiments • Explore plasma operating space • Confinement, stability, operating limits	• Stellarator @B = 1.2 T • 1.5 MW NBI, NB Armor, 350 C bake • Thomson scattering, in-vessel magnetics, interferometer/polarimeter, SX arrays
4. 3MW Heating Experiments • Confinement *vs.* 3D shape • Stability at moderate β *vs.* 3D shape • Local transport, effects of quasi-symmetry • SOL characterization. • Transport barriers & enhanced confinement.	• Stellarator @B = 2 T • 3 MW NBI, Full liner • Diag. beam, CHERS, MSE

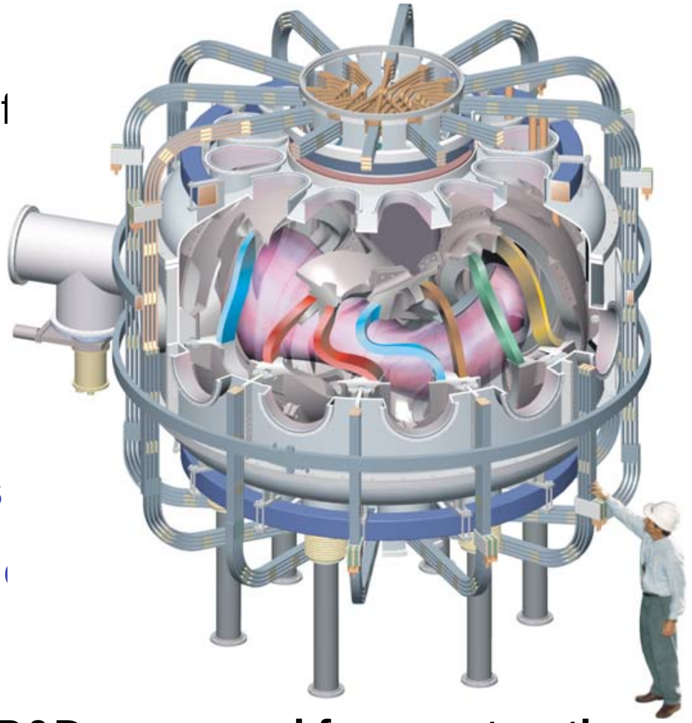
QPS Physics Mission Complements that of NCSX

QPS

Exploits quasi-poloidal symmetry to advance physics understanding

- This magnetic geometry allows low damping of the poloidal flows that most effectively disrupt turbulence causing anomalous transport
- low neoclassical and anomalous transport (low effective ripple; low poloidal viscosity
  ⇒ large sheared E x B flows)
- long region of low curvature and short high-field region o higher curvature increases stability for trapped electron and ITG modes; instabilities may be different in this geometry
- variation of B in the toroidal direction allows reduction of the bootstrap current and damping of toroidal flows





Robust equilibrium & healing of magnetic islands

Extends stellarator scaling to very low aspect rati

QPS Status: in prototype fabrication and R&D; proposed for construction.

Compact Stellarator Research Will Advance Fusion Science in Unique Ways

- Can limiting instabilities, such as external kinks and neoclassical tearing modes, be stabilized by external transform and 3D shaping? How are the non-linear dynamics and disruptions affected? How much external transform is enough? What limits beta?

- Can the collisionless orbit losses from 3D fields be reduced by designing the magnetic field to be quasi-axisymmetric? Is flow damping reduced?

- Do anomalous transport reduction mechanisms that work in tokamaks transfer to quasi-axisymmetric stellarators? How much effective-ripple is too much?

- How do stellarator characteristics such as 3D shape, islands and stochasticity affect the boundary plasma and plasma-material interactions?

Energy Vision: a More Attractive Fusion System

Vision: A steady-state toroidal reactor with

- No disruptions
- No near-plasma conducting structures or active feedback control of instabilities
- No current drive (⇒ minimal recirculating power)
- High power density (~3 MW/m^2)

Likely configuration features (based on present knowledge)

- Rotational transform from coils and self-generated bootstrap current (how much of each?)
- 3D plasma shaping to stabilize instabilities (how strong?)
- Quasi-axisymmetry to reduce ripple transport, alpha losses, flow damping (how low must ripple be?)
- Power and particle exhaust via a divertor (what topology?)
- $R/\langle a \rangle$ ~ 4 (how low?) and β ~ 4% (how high?)

Design involves tradeoffs.

Need experimental data to quantify, assess attractiveness.

Summary

- The NCSX project is implementing an optimized 3D system to test compact stellarator benefits.
  - Low-R/⟨a⟩, high-beta, quasi-axisymmetric stellarator plasma.
  - Flexible coil set and vacuum vessel
  - Component geometries determined by physics optimization.

- The compact stellarator offers unique research opportunities.

- The NCSX will be operated as a collaborative experiment.
  - Opportunities for U.S. and international collaborators.