Compact Stellarators and NCSX

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The Toroidal Research Frontier: Understanding the Physics that Determines Configuration Attractiveness

Toroidal plasmas have many configuration variables:

- Geometry (aspect ratio, 2D shape, 3D shape)
- Magnetic symmetry (toroidal, poloidal, helical, none)
- Rotational transform source (internal, external)
- Divertor configuration (X-point, island, ergodic)
- Startup and sustainment control strategy (active, passive)

Challenge for tomorrow's designers: find the most the attractive configuration. What combination of variables is optimum?

Challenge for today's researchers: quantify how costs and benefits depend on these variables. ⇒ Understand the physics.

- Exercise the variables (devices)
- Make detailed measurements (diagnostics)
- Construct accurate predictive models (theory and computation)

Stellarators Advance the Frontier in Unique Ways

Stellarators: 3D plasma shapes, externally generated rotational transform from 3D helical fields, can be quasi-symmetric in |B|.

Potential solutions for attractive fusion energy

- Passively stable without active feedback; no disruptions.
- Steady state with minimal recirculating power.
- Low aspect ratio and high beta $\Rightarrow$ high power density (~3 MW/m^2).

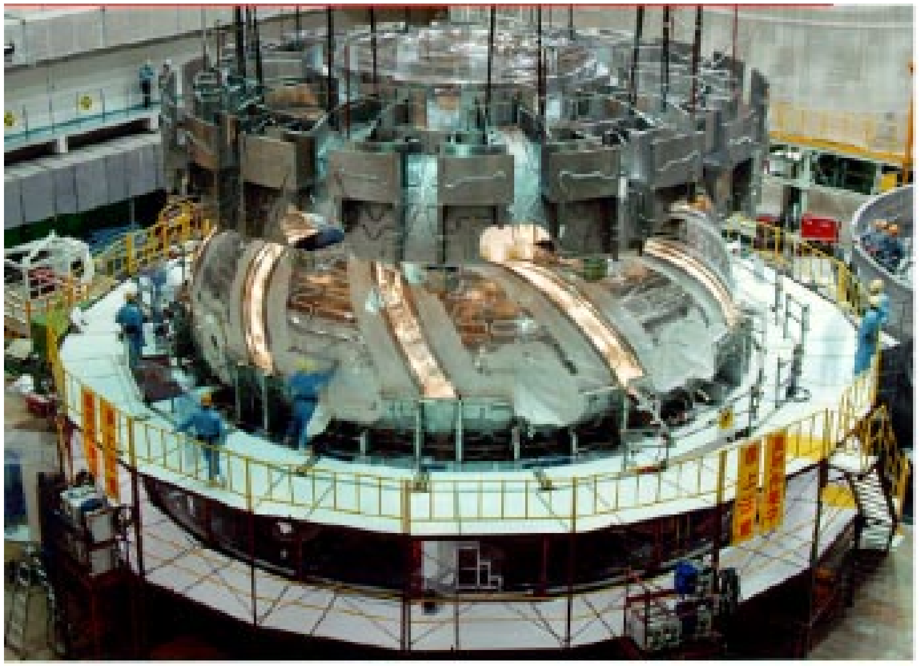
Advancement of 3D plasma physics

- Equilibrium and stability for toroidal systems (islands, stochastic regions, nonlinear MHD and microstability, neoclassical effects).
- Connections to 3D plasma problems in other fields (astrophysics, lasers, accelerators)

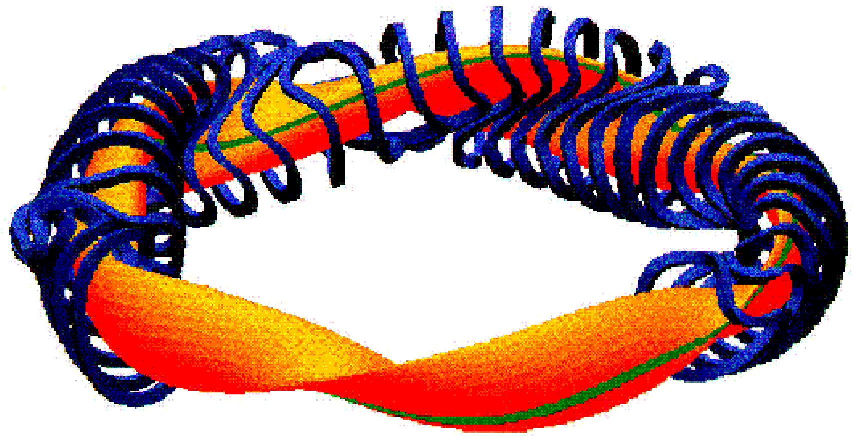
Strong Connection Between Stellarators and Other 3D Plasma Physics Problems

- Many other plasma problems are three-dimensional
  - Magnetosphere; astrophysical plasmas
  - free-electron lasers; accelerators
  - perturbed axisymmetric laboratory configurations
- Development of 3D plasma physics is synergistic, with stellarator research often driving new 3D methods. Examples:
  - methods to reduce orbit chaos in accelerators based on stellarator methods [Chow & Carry, Phys. Rev. Lett. 72, 1196 (1994)]
  - chaotic orbits in the magnetotail analyzed using methods developed for transitioning orbits in stellarators [Chen, J. Geophys. Res. 97, 15011 (1992)]
  - astrophysical electron orbits using drift Hamiltonian techniques and magnetic coordinates developed for stellarators
  - tokamak and RFP resistive wall modes are 3D equilibrium issues
  - transport due to symmetry breaking was developed with stellarators

The World Stellarator Program is Substantial



Large Helical Device (Japan)
Enhanced confinement, high β;
A = 6-7, R = 3.9 m,   B = 3→4 T



Wendelstein 7-X (Germany) (2006)
non-symmetric optimized design:
no current, A = 11, R = 5.4 m,   B = 3 T

- New large international experiments use superconducting coils for steady-state
- Medium-scale experiments (W7-AS, CHS), and
- Exploratory helical-axis experiments in Japan, Spain, Australia.

Large aspect ratios; no symmetry; no current.

Compact Stellarator Opportunity: Combine Attractive Features of Tokamaks and Stellarators

Tokamaks: build on advances in understanding and performance.

- Confirmation of ideal MHD equilibrium & stability theory; neoclassical theory.
- Enhanced confinement modes; transport reduction with flow shear.
- Low aspect ratio.

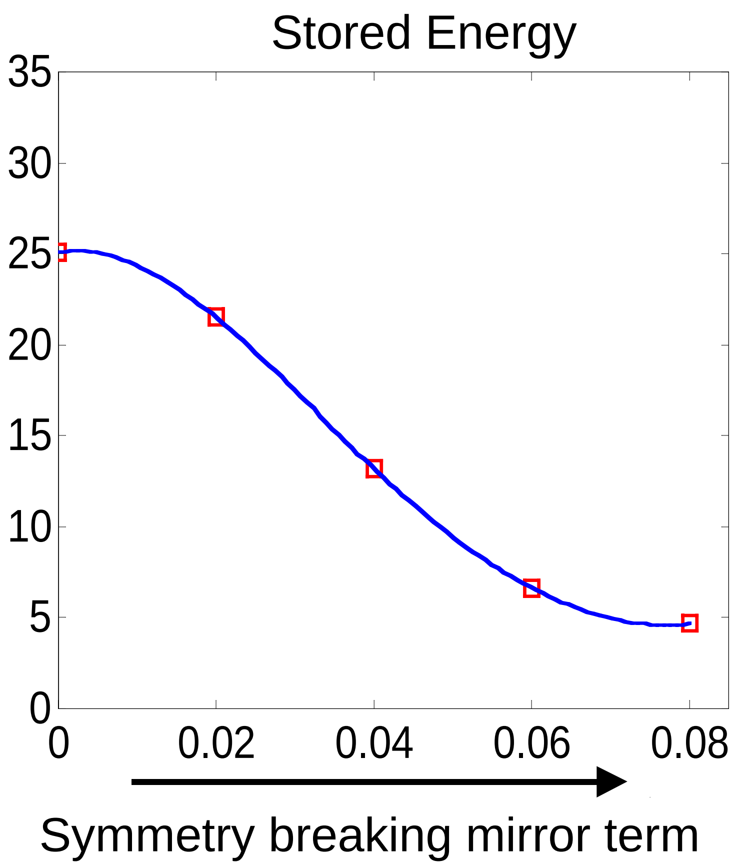
Stellarators: use 3D design freedom to make further gains.

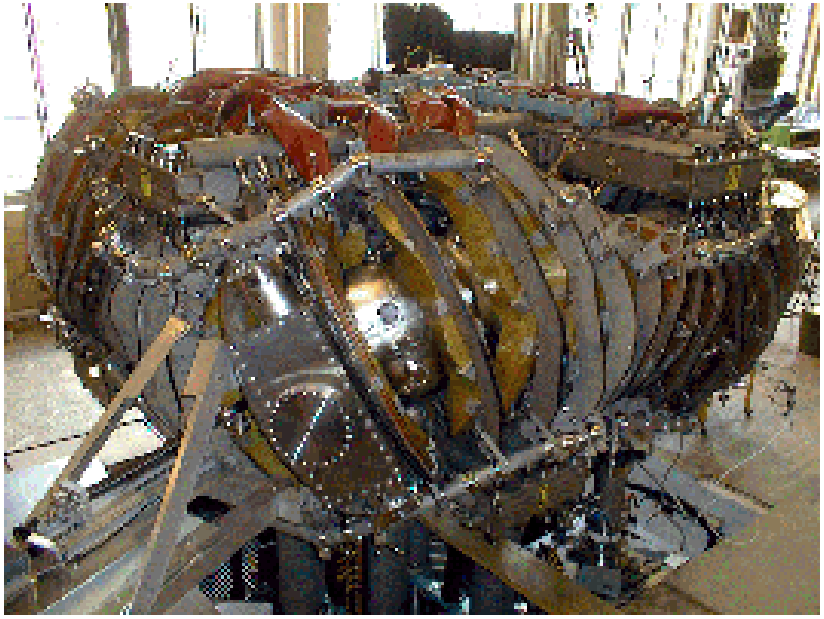
- 3D shaping to stabilize instabilities (kink, vertical, ballooning, Mercier) without conducting wall or feedback. **Prevent disruptions?**
- Externally-generated rotational transform to reduce non-linear coupling. **Easier to control?**
- Magnetic symmetry for well-confined orbits, undamped flows, bootstrap current. **Quasi-axisymmetry ⇒ capture tokamak benefits in 3D?**

Combine in high beta (≥4%), low aspect ratio (<4.4) plasma configurations ⇒ compact stellarators.

Initial Results from HSX: Symmetry Matters!

First Test of Quasi-symmetry





HSX: Helically Symmetric Experiment

- ~50 kW of 2nd harmonic ECH used to produce energetic deeply-trapped electrons (B = 0.5 T, 28 GHz).
- Stored energy drops by a factor ~5 as mirror term is introduced.

- D. Anderson, U. Wisconsin

U.S. Stellarator Program: Understand the Physics that Determines Compact Stellarator Attractiveness

Ten-Year Goal

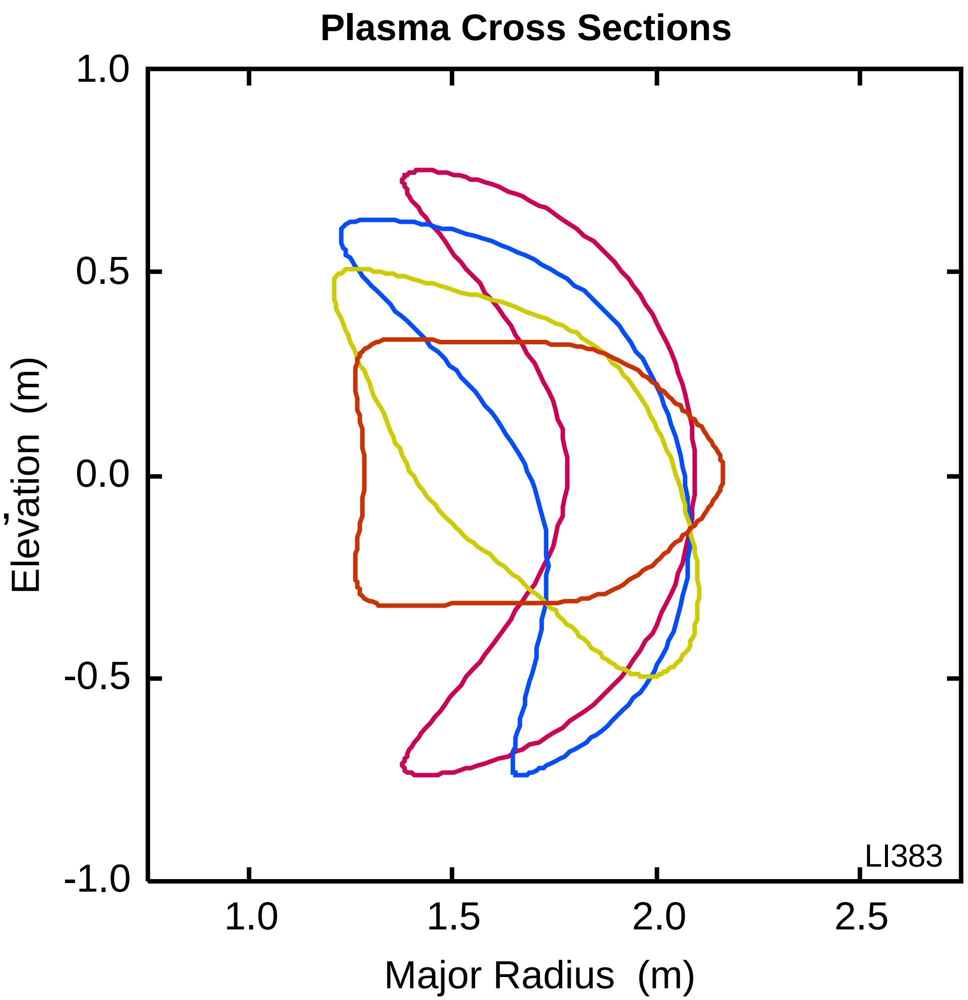
- Evaluate compact stellarator physics benefits and costs, assess attractiveness.

Balanced Program Includes All Needed Elements:

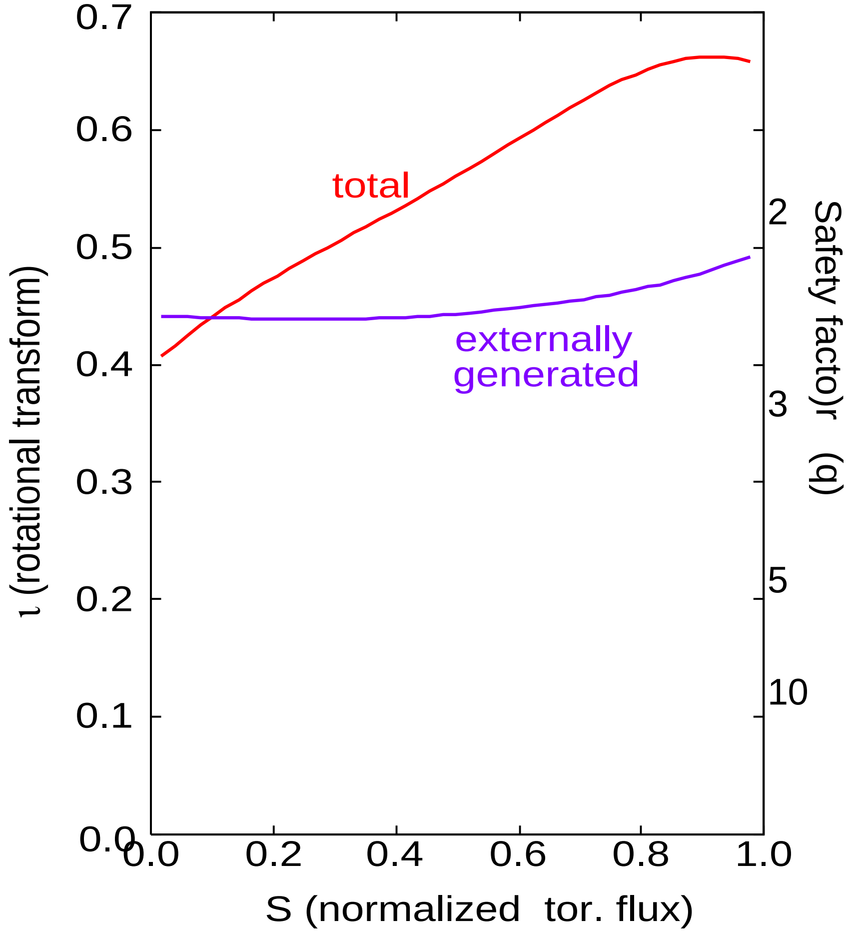
- NCSX: Integrated PoP test of quasi-axisymmetric, high-β, low-R/a design.
  - Stability and disruption resistance at high beta, enhanced confinement at low collisionality, boundary physics.
- QPS: Quasi-poloidal symmetry, very low R/a, CE-scale experiment.
- CE experiments (low beta)
  - HSX - Quasi-helical symmetry.
  - CTH - Kink and tearing stability with current.
- Theory and computation: 3D plasma physics.
- International collaboration on stellarators: LHD, CHS, W7-AS, W7-X, Theory.
- Reactor studies: assess potential for an attractive fusion system.

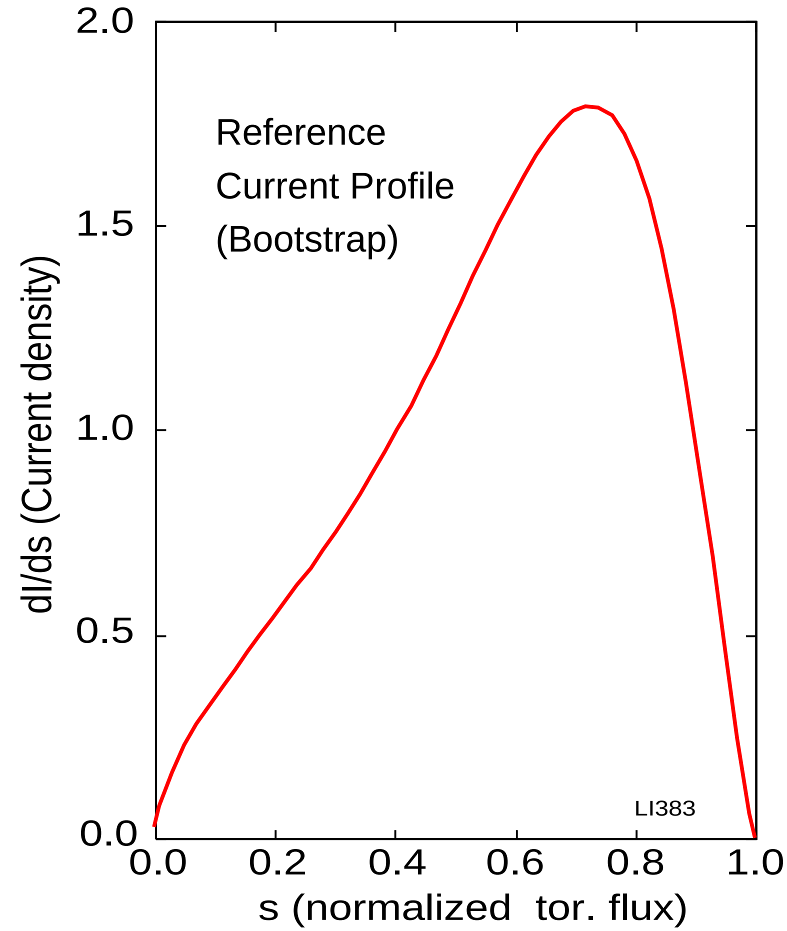
NCSX Plasma Configuration Has Attractive Physics

- 3 periods.
- Aspect ratio R/⟨a⟩ = 4.4
  (compact for stellarators).
- Low helical ripple via QAS design.
- Good magnetic surfaces.
- Stable at β=4.1% to ballooning, kink, vertical, Mercier modes.
- Machine parameters:
  R = 1.4 m, B ≤ 2 T.
- Heating power- upgrades in ( )
  NBI: 3 (6) MW; RF: (6 MW)



Hybrid Configuration Combines Externally-Generated Fields with Bootstrap Current

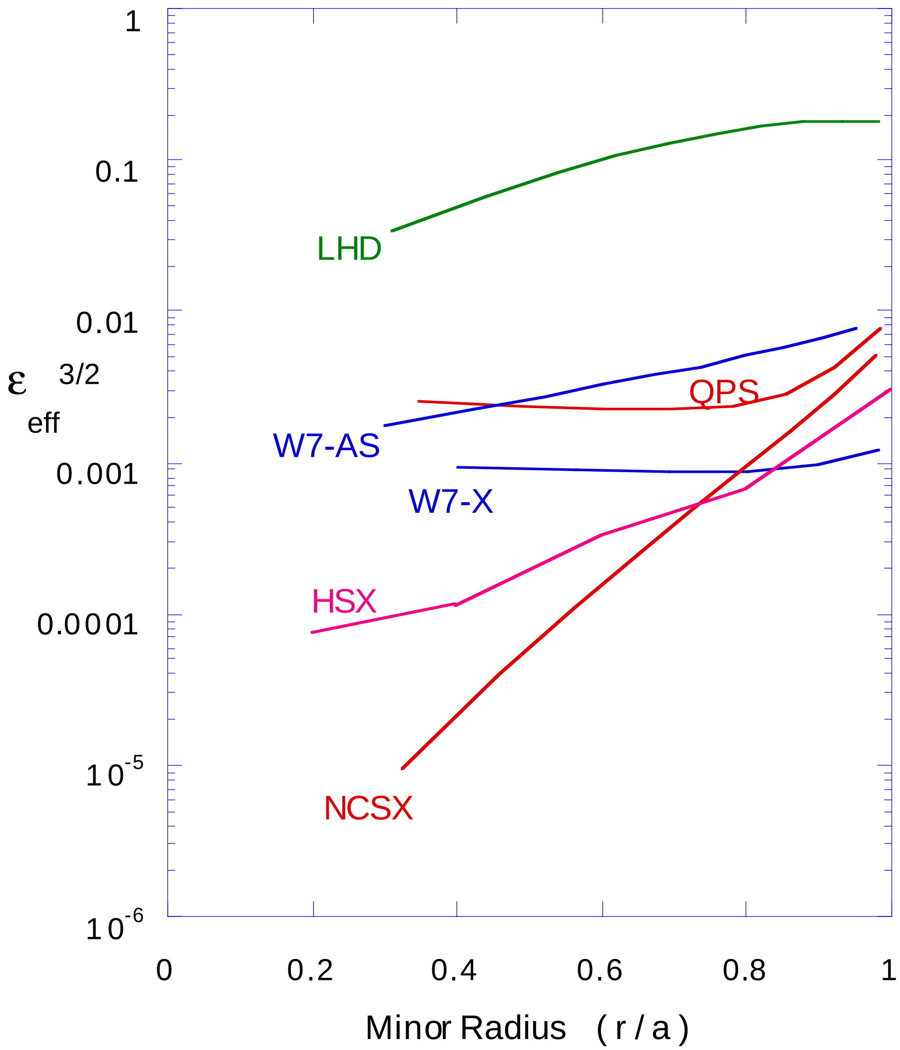




- Quasi-axisymmetry ⇒ tokamak like bootstrap current
- ~3/4 of transform (poloidal-B) from external coils ⇒ externally controllable

Quasi-Axisymmetric: Very Low effective ripple

- ε_{eff} from NEO code by Nemov-Kernbichler
- In $1/\nu$ regime, neoclassical transport scales as $\varepsilon_{eff}^{3/2}$
- Edge ε_{eff} ~ 3.4%, < 0.1% in core
- Allows balanced-NBI in NCSX. 24% loss at 1.2T, drops as B↑
- Should give low flow-damping
  - manipulation of flows for flow-shear stabilization
  - zonal flows like tokamaks
- NCSX: predicted ripple transport is negligible



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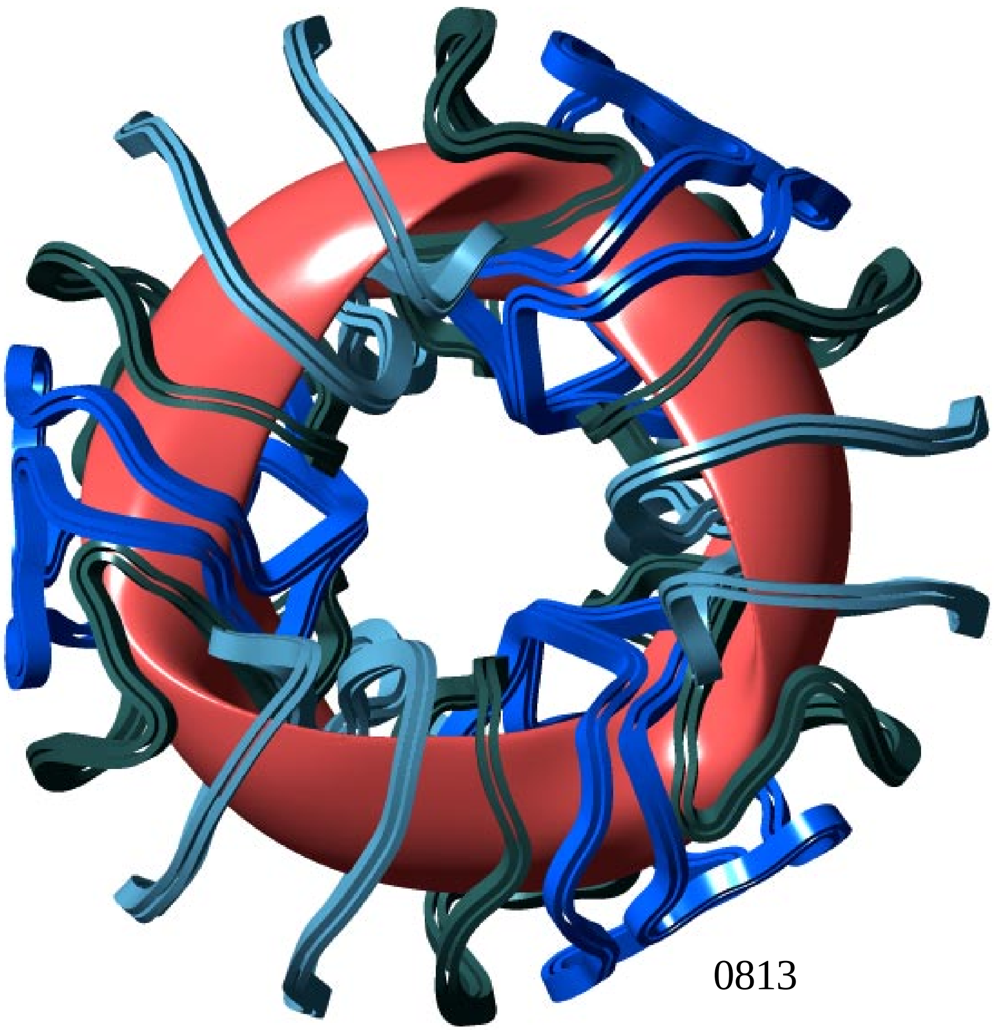
NCSX Modular Coils Provide Good Physics Capability

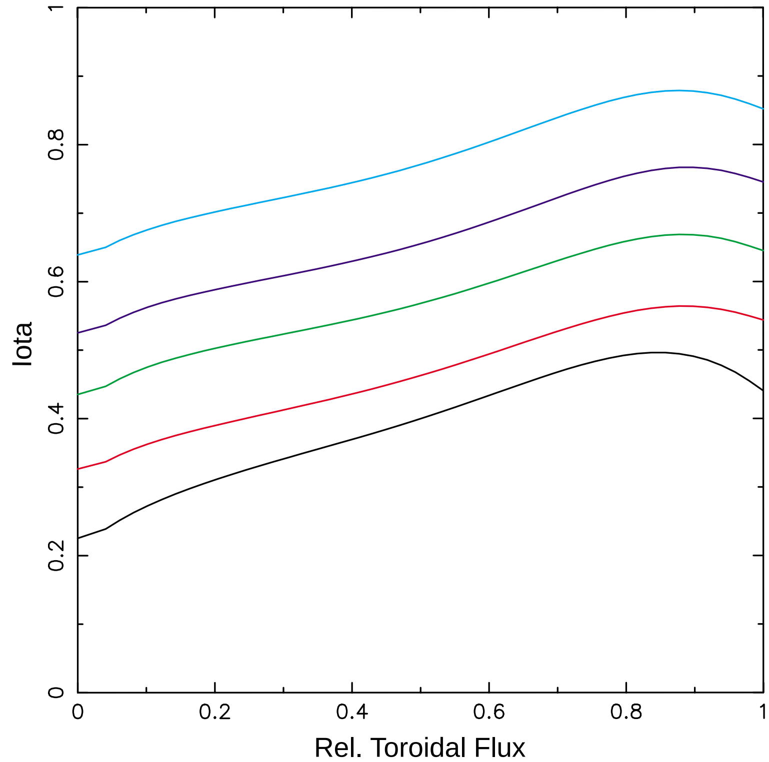
- Modular coils best preserve physics properties of reference plasma:
  - stable at reference β (4%).
  - Good magnetic surfaces.
- Stable to $\beta > 6.5\%$ with some increase in ripple
- Also include Poloidal Field coils and weak Toroidal Field, for flexibility
- Passive disruption stability?

  Equilibrium maintained even with total loss of pressure or current

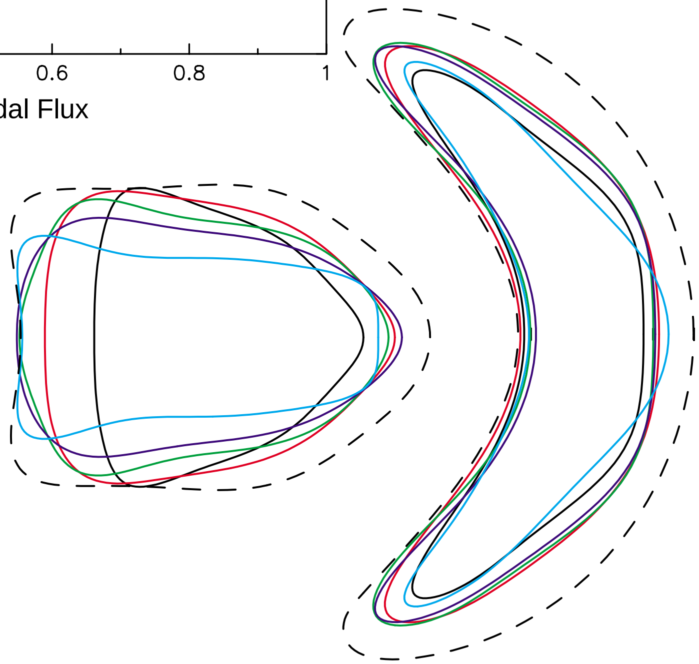


NCSX Modular Coils are Very Flexible

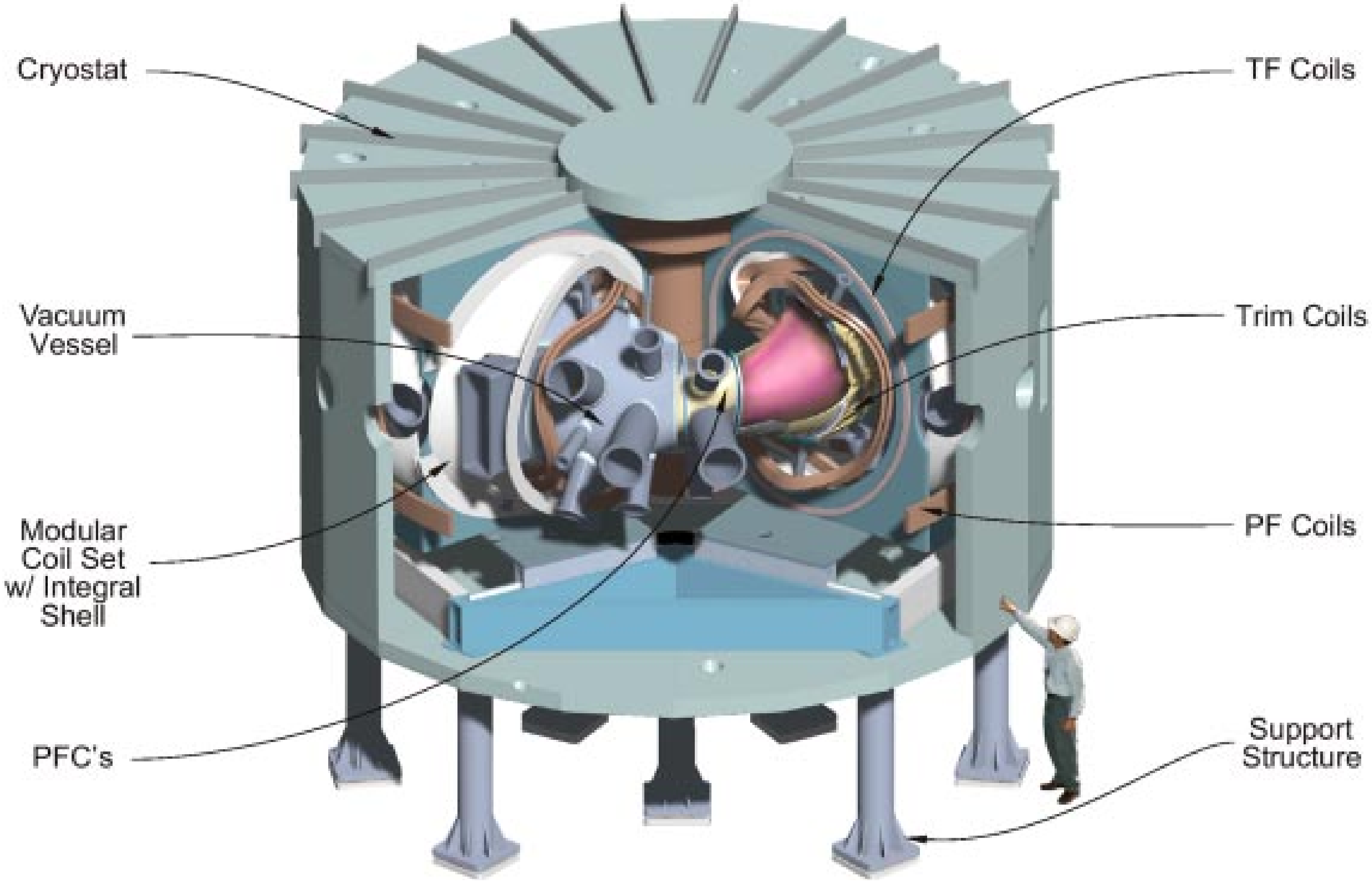
- External rotational transform controlled by plasma shape at fixed plasma current & profile.
- Can adjust to avoid iota=0.5, or hit it.
- Can externally control shear.
- Can vary kink β-limits.
- Can accommodate wide range of p,j profiles.
- Can use to test stability, island effects.



β=0, full current



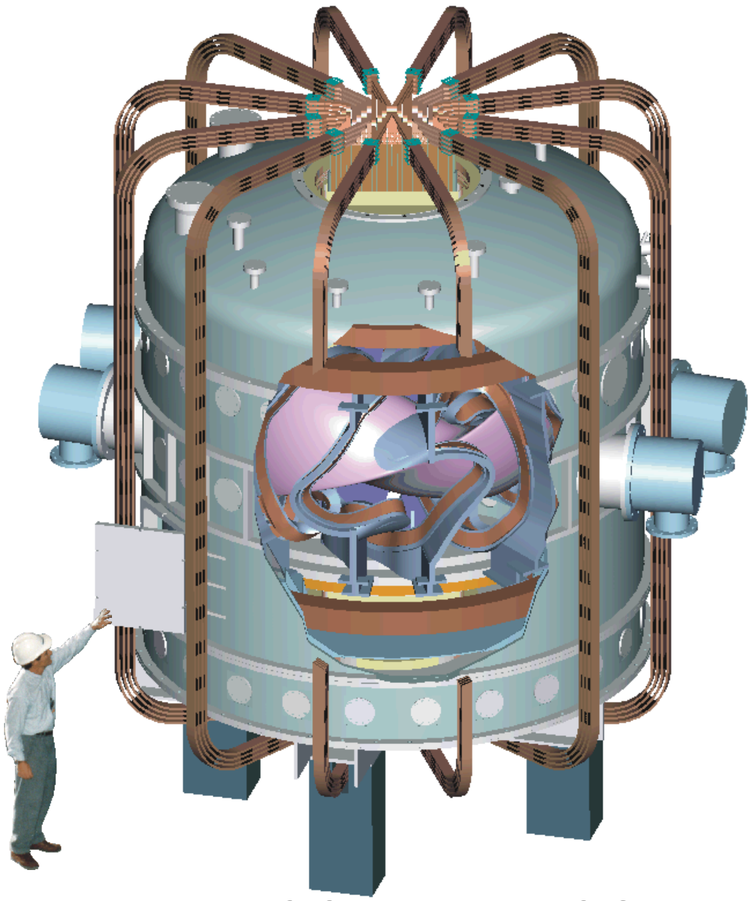
NCSX Stellarator Core Concept



Sited at PPPL; uses existing ancillary equipment and infrastructure.

Project cost ~$65M (FY2003-06).

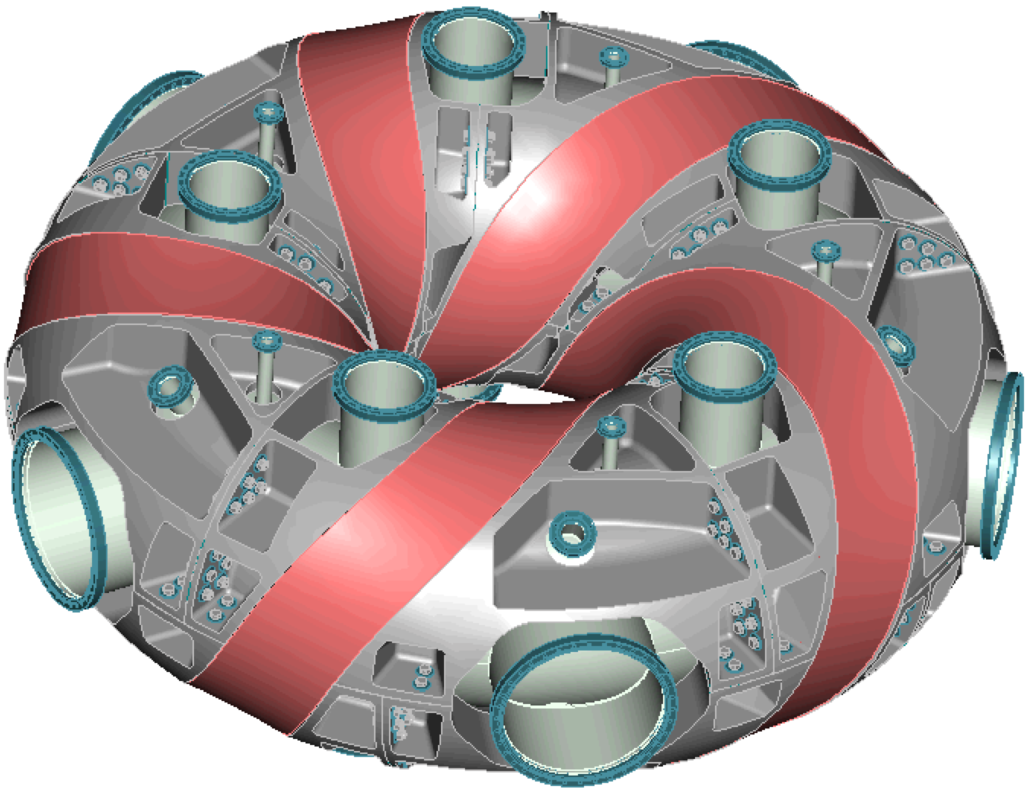
QPS Will Pioneer Good Confinement in Very Low Aspect Ratio Stellarators



<*R*> = 0.9 m; <a> = 0.35 m
B = 1 T (0.5 s); P_{RF} = 1-3 MW
Sited at ORNL.

- **R / ⟨a⟩ = 2.6.**
- **Consequences of poloidal symmetry**
  - **lower parallel bootstrap current compared to quasi-axisymmetry leads to robust equilibrium with β**
- **Can study fundamental issues common to low-β and high-β quasi-poloidal configurations**
  - **flux surface robustness**
  - **reduction of neoclassical transport**
  - **scaling of the bootstrap current with β, magnetics**
  - **ballooning instability character & limits**

Compact Toroidal Hybrid (CTH) Targets Current-Driven Disruptions at Low Aspect Ratio



Auburn University
R=0.75m, <a> =0.18m, B=0.5T, I_p=50 kA
Approved Sept. 2000; Operations planned in FY03

Under what conditions are current-driven disruptions suppressed by helical field?
- Variable vacuum rotational transform & shape

How do we measure 3-D magnetic equilibrium of current-driven stellarator?
- Measurement of rotational transform by novel MSE/LIF

How do magnetic stochasticity & islands influence stability?
- External control of magnetic errors, measurement of islands in plasma

Stellarator Theory and Modeling Advances
3D Plasma Physics Understanding

Important for stellarator design, understanding of experimental results.

- Non-linear MHD stability analysis, including Alfvenic eigenmodes.
- 3D tearing mode theory and computation.
- Non-linear micro-stability and turbulence simulation, coupled with neoclassical transport effects.
- 3D edge plasma and neutrals modeling.
- Integrated discharge analysis and simulation.
- Faster 3D equilibrium calculations including islands, stochastic regions, and neoclassical effects.
- 3D equilibrium reconstruction and analysis, coupled to coil design.
- RF wave propagation and damping.

Topics are of broad importance for fusion science, basic plasma physics.

Program Status: Strong DOE Support

- HSX has been operating since 1999.
- CTH was approved in 2000; to operate in 2003.
- NCSX and QPS
  - Scientific peer reviews (March-April, 2001) confirmed physics basis and design approaches.
  - "Mission Need" approved by DOE.
  - Conceptual design reviews planned for April, 2002.
  - Construction planned for FY2003-06
- Fusion Energy Sciences Advisory Committee [FESAC] endorsed NCSX as a "Proof-of-Principle" experiment and affirmed support for the program (May-August, 2001):

  FESAC: The "gains earn for the compact stellarator an important place in the portfolio of confinement concepts being pursued by the US Fusion Energy Sciences program."

Compact Stellarator Research Advances the Toroidal Physics Frontier in Unique Ways

- Can limiting instabilities (e.g., external kinks, neoclassical tearing modes) be stabilized by external transform and 3D shaping? How are disruptions affected?

- Can the collisionless orbit losses traditionally associated with 3D fields be reduced by designing the magnetic field to be quasi-axisymmetric? (Nuehrenberg, Garabedian)

- Do anomalous transport reduction mechanisms that work in tokamaks transfer to quasi-axisymmetric stellarators? Do mechanisms that work in currentless stellarators transfer to hybrids?

- How do stellarator field characteristics such as islands and stochasticity affect the boundary plasma and plasma-material interactions?

CS provides unique controls to understand toroidal confinement fundamentals: rotational transform, shaping, magnetic symmetry.

Conclusions

- Compact Stellarators are an exciting opportunity for unique fusion science.
  - Stabilize high-β instabilities with 3D shaping; understand 3D effects
  - Transport in low-collisionality quasi-axisymmetric system.
- They provide innovative solutions to make magnetic fusion more attractive.
  - Combine best characteristics of stellarators and tokamaks.
  - Possibly eliminate disruptions; intrinsically steady state
- Strong linkages with all of magnetic fusion science, complementing other toroidal confinement research programs.
- Lead experiment NCSX has sound physics basis, attractive configuration.
  - passive stability to kink, ballooning, vertical, Mercier, neoclassical tearing with $\beta > 4\%$
  - very good quasi-axisymmetry
  - ability to study disruptive processes in 3D
  - flexible coil system