National Compact Stellarator Experiment

Preparations for NCSX Research

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Preparations for NCSX Research

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Topics

- Mission and Design
- Research Plan
- Summary

Compact Stellarators Have a Crucial Role in Fusion R&D

Stellarators solve critical problems for magnetic fusion.

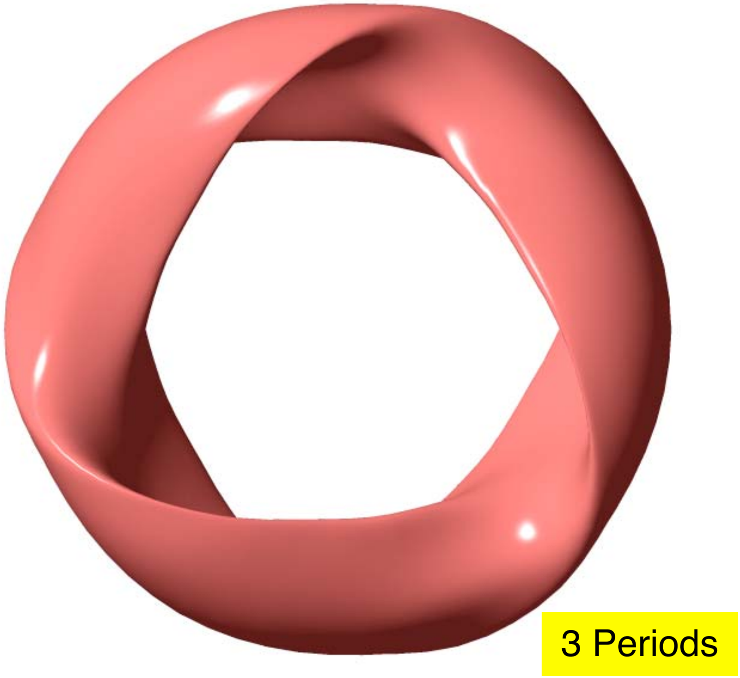
- Steady state without current drive.
- Stable without feedback control or rotation drive. No disruptions.

Compact Stellarators (CS) improve on previous designs.

- Quasi-axisymmetric magnetic field.
- Lower aspect ratio.
  - 4.4 in NCSX *vs.* ~11 in W7-X.

NCSX Mission

- Assess attractiveness of compact stellarators for MFE.
- Advance 3D plasma physics.



NCSX Plasma

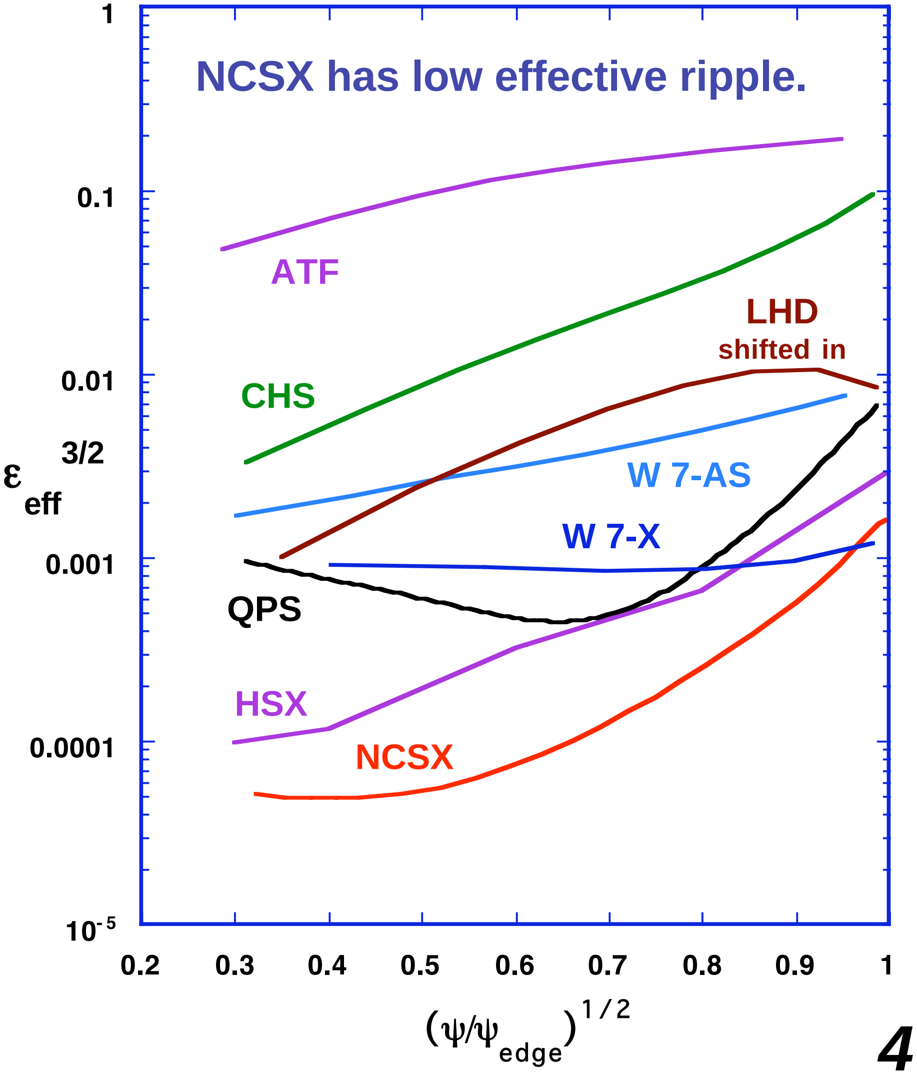
3D geometry has benefits and costs.

Both must be understood.

Quasi-Axisymmetric Stellarators Can Build on Tokamak Advances

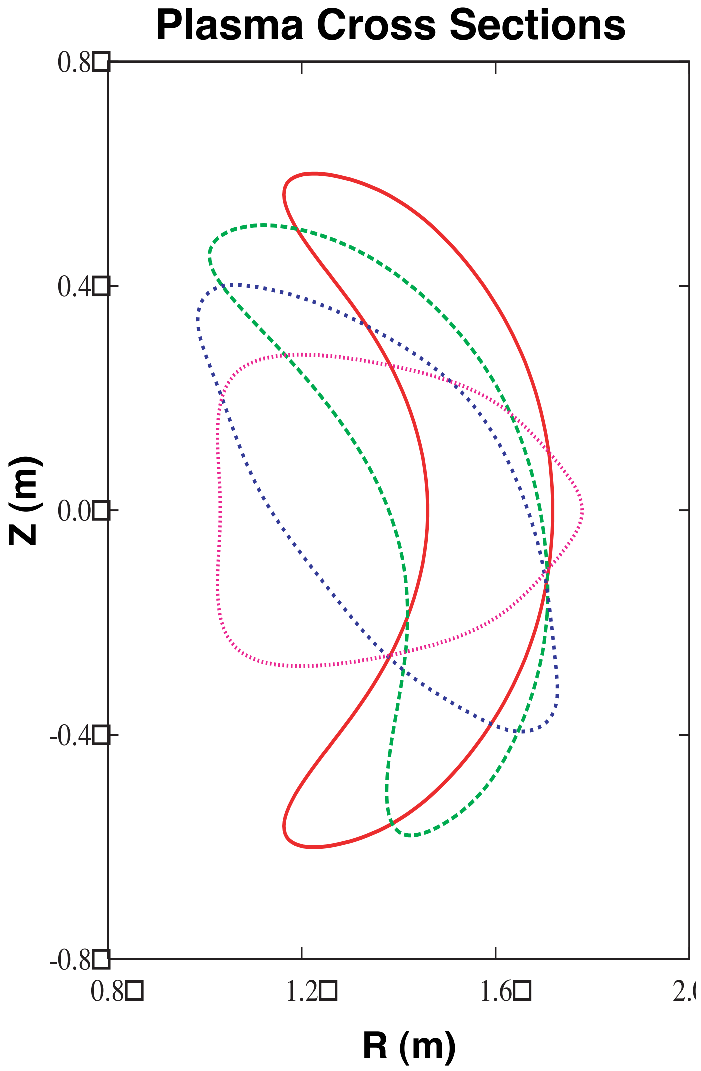
NCSX Will Test a Quasi-Axisymmetric Stellarator Configuration

- Effective ripple <1.5%.
- Low flow damping, tokamak-like orbits ⇒ enhanced confinement.
- Tokamak design tools apply.
  - – e.g., NCSX startup simulations using TRANSP.
- Makes full use of tokamak advances, including ITER burning plasma R&D.
  - Facilitates development.
- Aspect ratio approaching tokamaks.



NCSX Physics Design

Configuration is optimized to realize target physics properties.

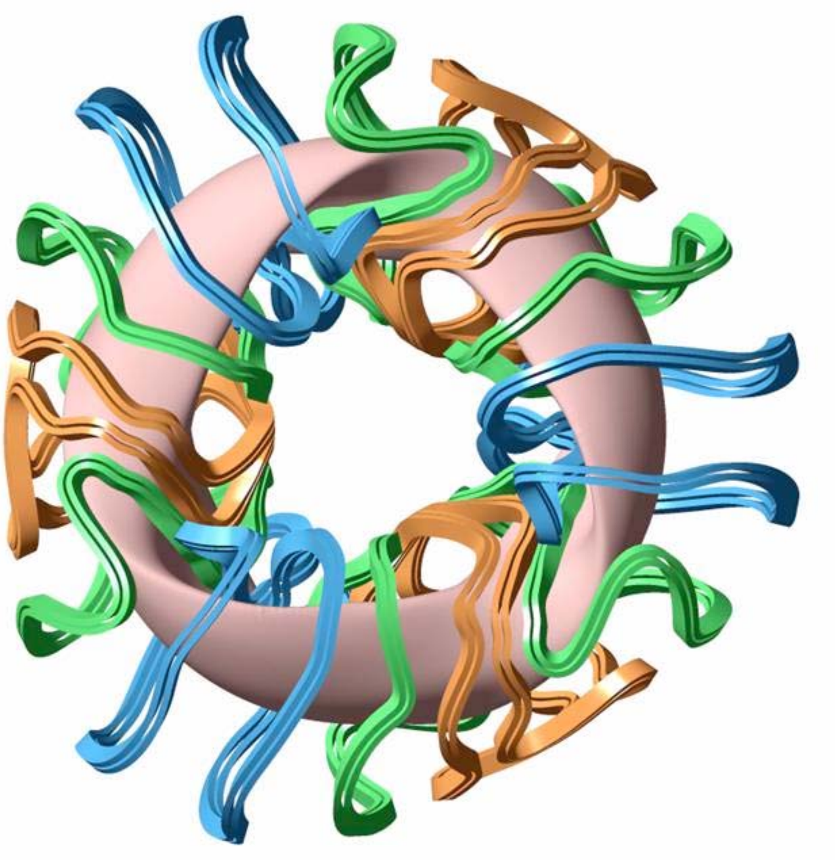


Configuration Properties

- Low R/⟨a⟩ (4.4); 3 periods.
- Quasi-axisymmetric w/ low ripple.
- Stable at β=4.1% to critical MHD instabilities.
- Reverse shear q profile.
- 25% of transform from bootstrap.
- Good magnetic surfaces at high β.
- Constrained by engineering feasibility metrics.

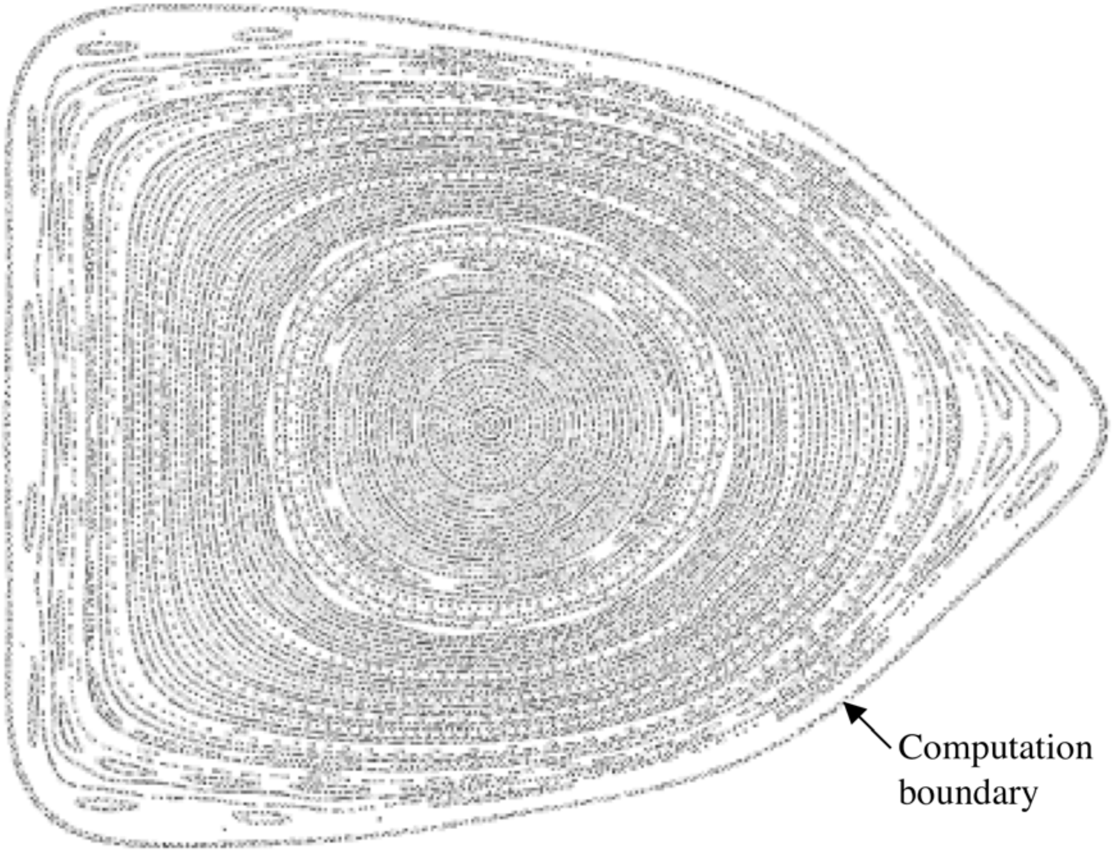
NCSX Design Satisfies Physics and Engineering Criteria

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



NCSX Plasma and Modular Coils

NCSX Coils Are Designed to Produce Good Surfaces at High β

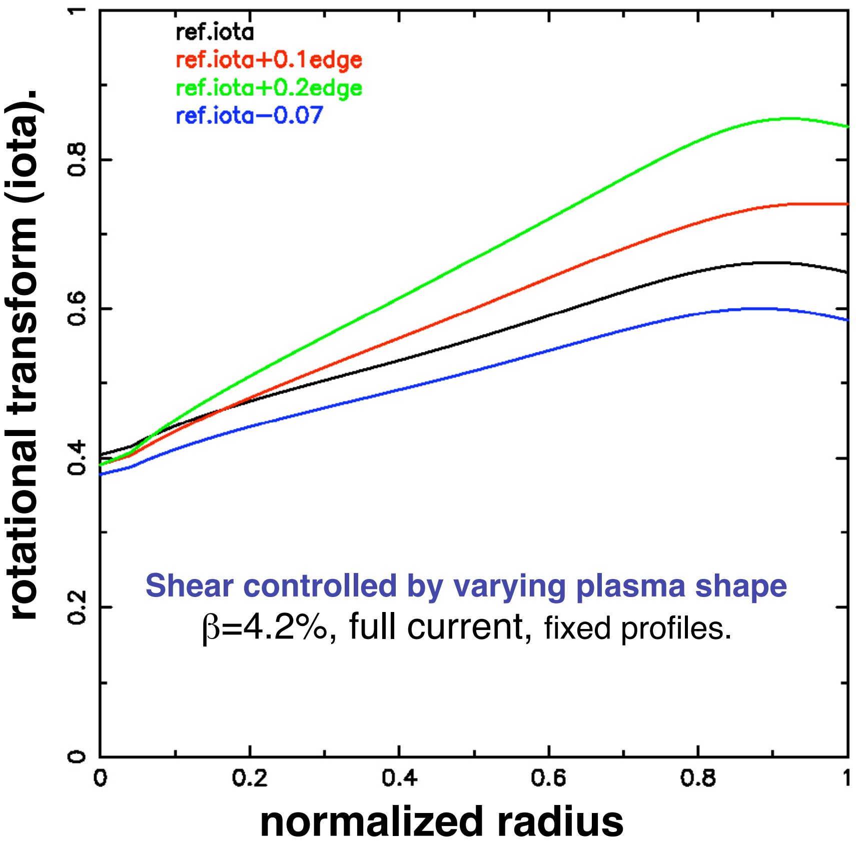


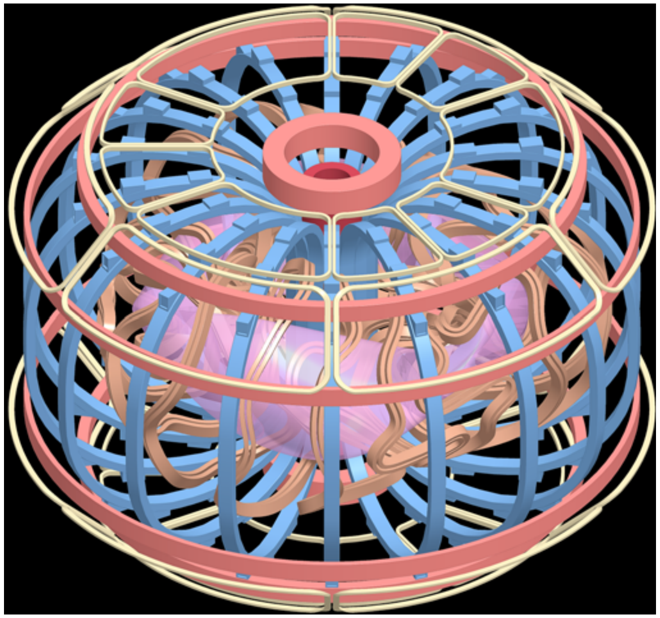
Poincare: PIES, free boundary 3D equilibrium code. β = 4%

< 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)
- Robust: good flux surfaces in vacuum and high beta conditions.

NCSX Coils: Flexibility to Vary Physics Properties





- 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.

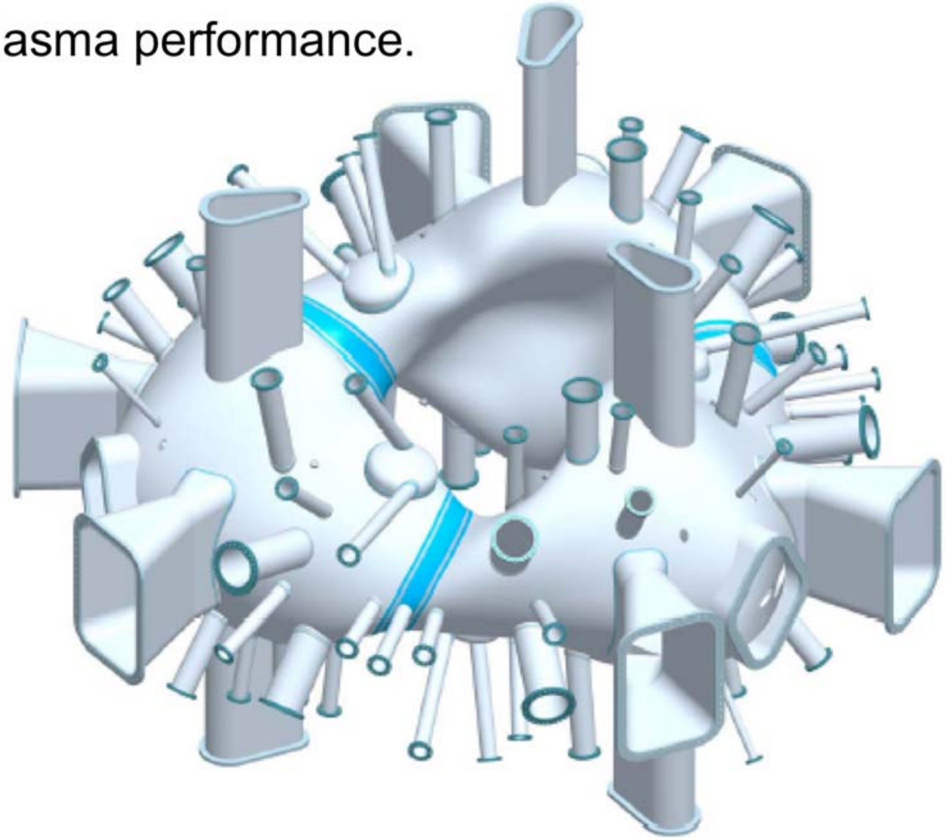
Vacuum Vessel Provides Good Diagnostic Access

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.

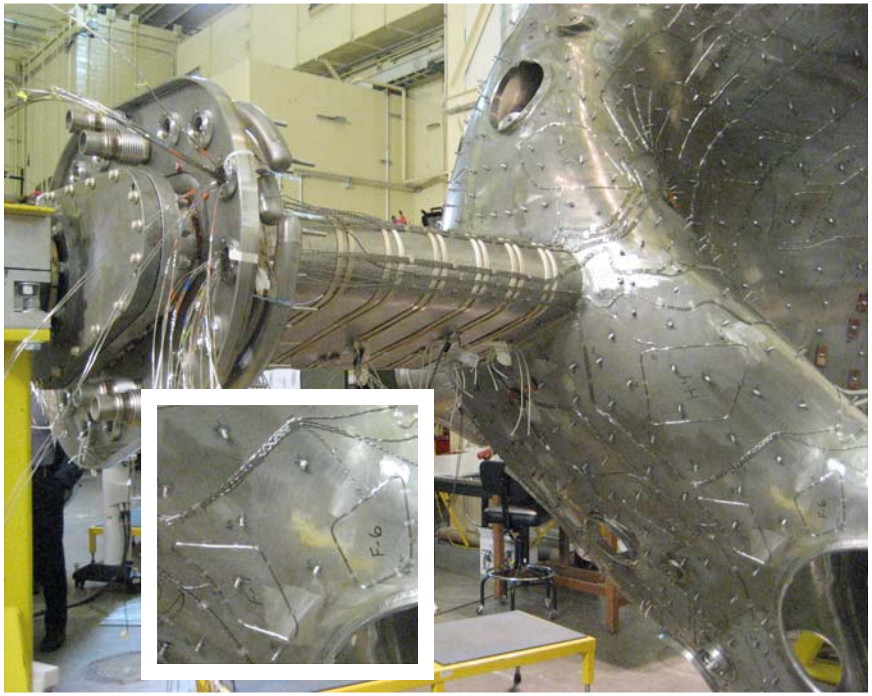
Design

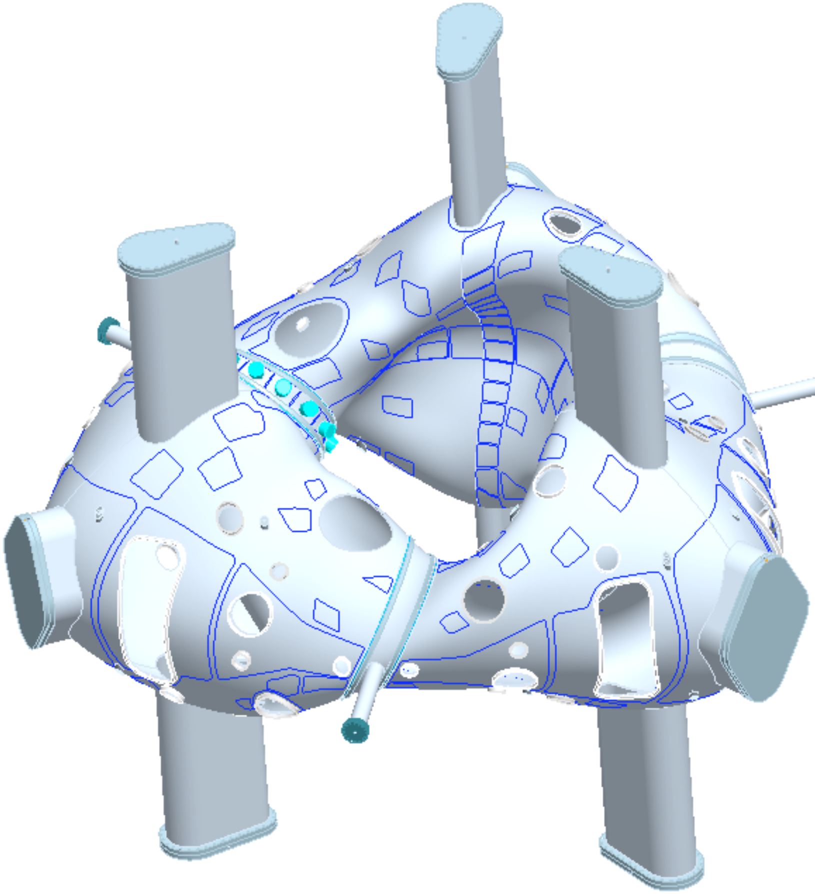
- About 100 ports, filling all available openings in surrounding magnets.
- Vacuum boundary inside coils.
  - Shell geometry similar to plasma's. Tolerance ±5 mm.
- Bakeable to 350 C.
- Inconel material.



Innovative Magnetic Diagnostic Loop Array for Plasma Reconstruction

- Designed using free-boundary VMEC equilibrium data base.
  - 2,500 cases
- Locations on VV ranked for reconstruction effectiveness using SVD algorithms.



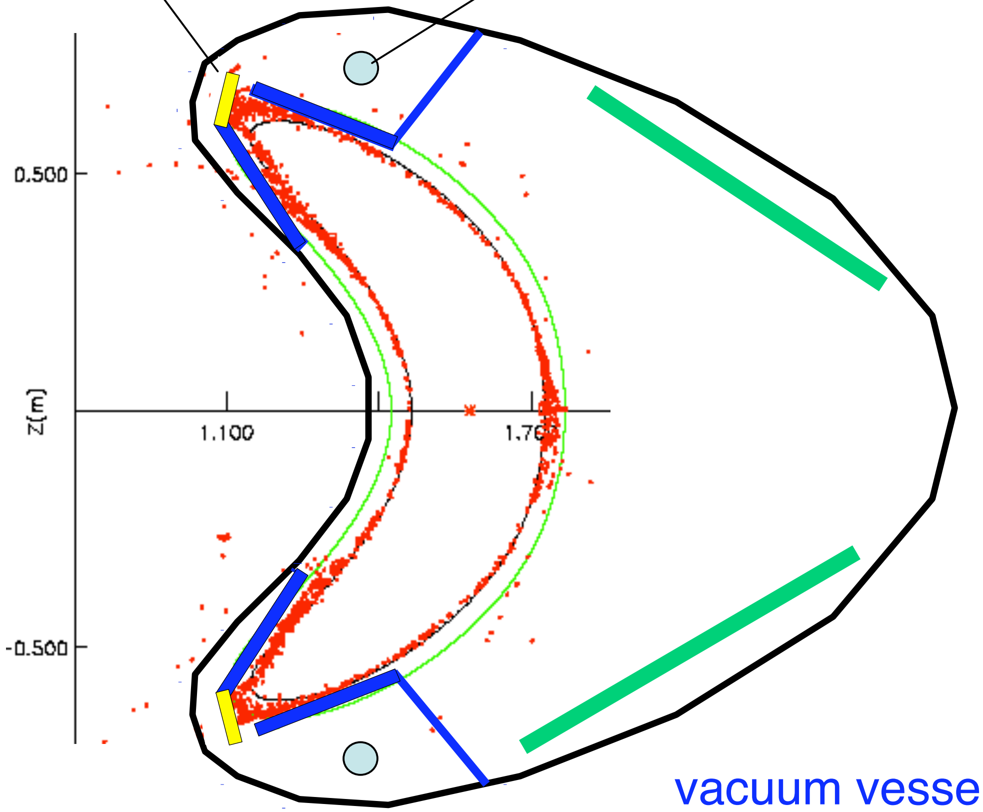


- 227 loops / 151 distinct locations/shapes.

NCSX Offers a Robust Divertor Concept

- Strong flux-expansion (> 10:1) always observed in bean-shaped cross-section. Allows isolation of PFC interaction.

- Possible divertor plate and liner geometries being studied.



NCSX Machine Design

Major radius: 1.4 m

Performance:

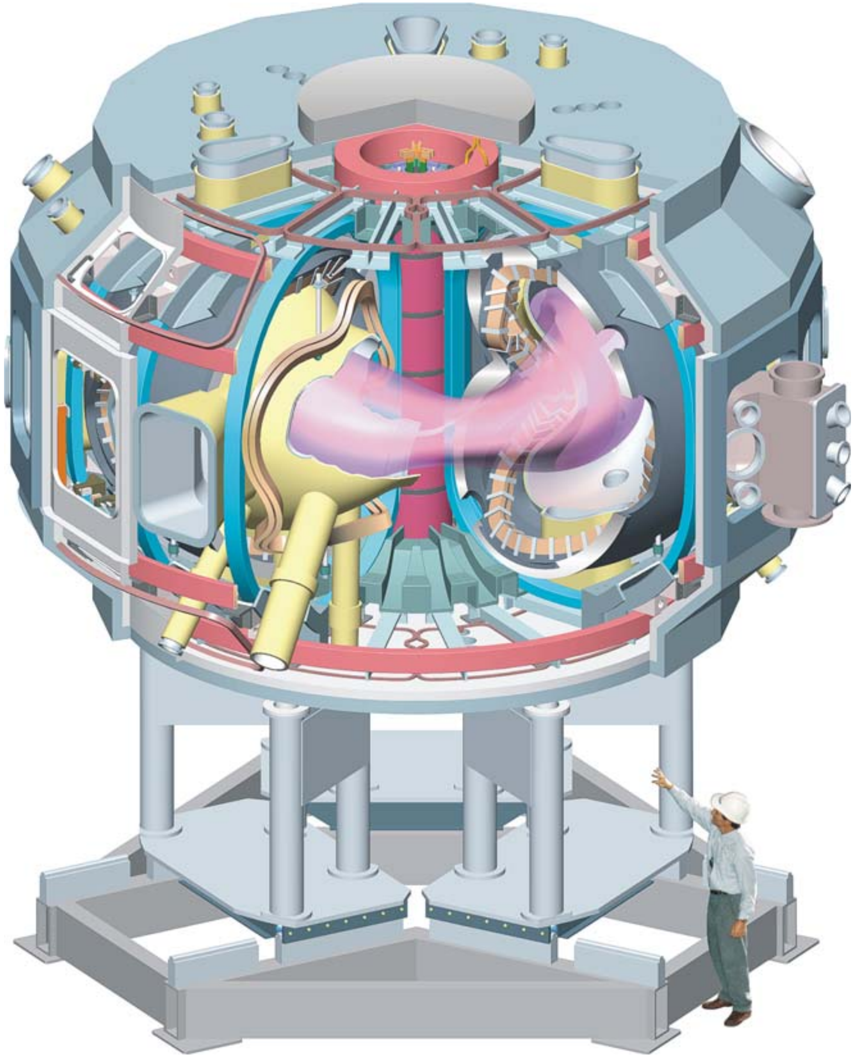
Magnetic Field Strength (B)

@ 0.2 s pulse: 2.0 T

@ 1.7 s pulse: 1.2 T

Construction Progress:

W. Reiersen, next paper



NCSX Experimental Research

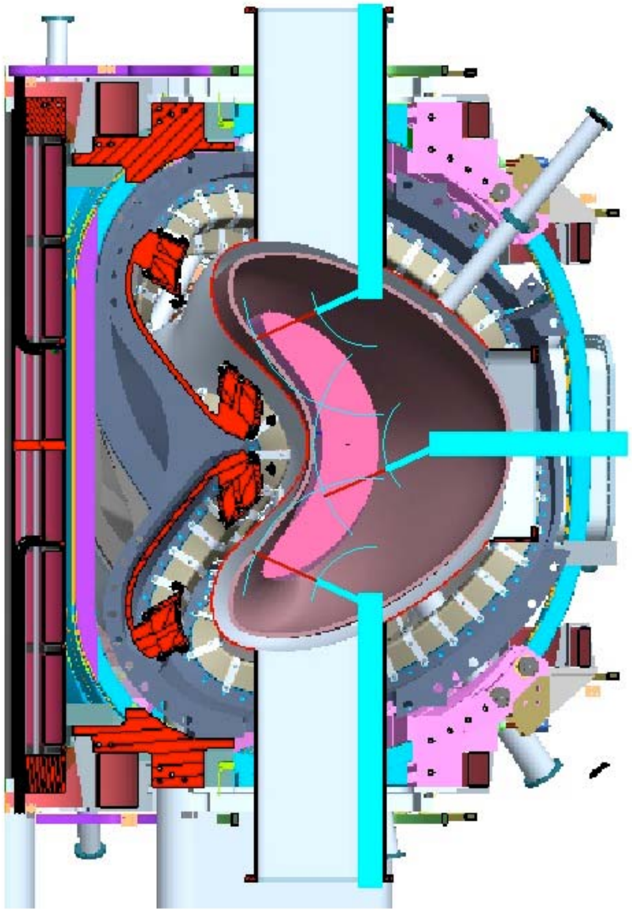
Planned as a series of campaigns, starting with…

1. Stellarator Acceptance Testing & First Plasma
2. Magnetic configuration studies
   - electron-beam mapping studies
3. Initial Heating Experiment
   - 1 - 3 MW neutral beam heating, partial PFC coverage
   - B ≥ 1.2T, full flexibility
   - Initial diagnostics, magnetics, profiles (n_e, T_e, T_i, v_ϕ, P_{rad}) & SOL
4. High Beta Experiments
   - ≥3 MW heating (NBI, ECH)
   - B = 2T; divertor
   - Improved diagnostics

Magnetic Configuration Studies

Document key characteristics:

- Vacuum flux surface characteristics
- Control of vacuum field characteristics using coil current
  - Good surfaces over wide range of configurations (e.g., iota-scan)
  - Verify rotational transform
- Numerically model as-measured magnetic field.



Auburn University will collaborate and loan equipment.

Initial Heating Campaign

Research Goals:

- Demonstrate basic real-time plasma control
- Characterize confinement and stability
- Characterize SOL properties for first divertor design.
- Investigate momentum transport, effects of quasi-symmetry
- Test MHD stability at moderate β, dependence on 3D shape
- Explore transport barriers, enhanced confinement regimes.
- Investigate local transport and effects of quasi-symmetry.

Equipment and diagnostic upgrades are currently being planned and estimated.

Key Equipment Upgrades for Initial Heating Campaign

- Coil and power systems (B ≥ 1.2T, full flexibility)
  - Modular coils and TF powered from D-site, PF coils from C-site
  - Central solenoid upgrade.

- Heating systems
  - 3 MW NBI refurbishment and installation
  - 600 kW 70GHz ECH heating via collaboration with IPP (Germany)

- Plasma facing components and NB armor
  - partial liner inside vacuum vessel (~1/3 coverage)
  - 350 C bakeout, wall conditioning, boronization

- Data acquisition and control systems
  - diagnostic control; initial plasma feedback control

  Plan: PC-based acquisition; MDS+ organized similar to NSTX.

Key Diagnostic Upgrades for Initial Heating Campaign

- In-vessel magnetic diagnostics + instrument external magnetics diags.
- Thomson-scattering profile (T_e, n_e)
- X-ray crystal spectroscopy. (T_i)
- UV spectrometer
- PFC-mounted probes
- Filtered 1D and 2D cameras. Filterscopes.
- Infrared cameras
- Bolometer array
- Soft x-ray camera
- Diagnostic neutral beam and toroidal CHERS profile (v_ϕ, T_i, n_C)
- Motional stark effect
- Heavy ion beam probe (possible collaboration with NIFS, Japan)

Compact Stellarators Provide Unique Opportunities for Fusion Science

Understanding 3D plasma physics important to all of MFE science

- Rotational transform sources (int., ext.): effect on stability, disruptions?
- 3D plasma shaping: stabilize without conducting walls or feedback?
- Magnetic quasi-symmetry: tokamak-like fundamental transport properties?
- Effects of 3-D fast ion resonant modes & Alfvénic modes in 3-D?
- 3D divertors: effects on boundary plasma, plasma-material interactions?

Answering critical fusion science questions, e.g.

- How does magnetic field structure impact plasma confinement?
  - plasma shaping? internal structure? self-generated currents?
- How much external control *vs.* self-organization will a fusion plasma require?

Energy Vision: an 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)

Configuration features

- 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?)
- $R/\langle a \rangle \sim 4$ (how low?) and $\beta \sim 4\%$ (how high?)

Design involves tradeoffs.

Need experimental data to quantify, assess attractiveness.

Summary

- NCSX will provide 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.

- Compact stellarators provide unique opportunities for fusion science and an attractive reactor vision.