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.
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-axisymmetric 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.
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.

3D geometry produces benefits and costs. We need to quantify both.
Stellarators Are Making Good Progress

Large Helical Device (S/C magnets - Japan)
\[ \beta \approx 4.5\% \]
\[ T_e \approx 10 \text{ keV}, T_i \approx 10 \text{ keV}. \]
enhanced confinement.
2-minute pulses.

Helically Symmetric Experiment (U. Wisc.)
- Test and understand quasi-symmetry.

Wendelstein 7-AS (Germany)
\[ \beta \approx 3.5\% \]
enhanced confinement.
density control & enhanced performance w/island divertor.

Wendelstein 7-X (Germany)
Optimized Design - S/C magnets
Under construction - Ops. In 2012
\[ \langle \beta \rangle > 3.2\% \text{ maintained for } > 100 \tau_E \text{ in W7-AS} \]

- Peak \( \langle \beta \rangle = 3.5\% \)
- \( \langle \beta \rangle \)-peak \( \approx \) \( \langle \beta \rangle \)-flat-top-avg
  \( \Rightarrow \) very stationary plasmas
- No disruptions
- Duration and \( \beta \) not limited by onset of observable MHD
- High-\( \beta \) maintained as long as heating maintained, up to power handling limit of PFCs.
- \( \beta \) limit may be set by equilibrium degradation.
  \( \Rightarrow \) 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**
$B = 1.2 \, T, \, P = 6 \, MW$
$(\tau_E = 2.9 \times ISS95 \approx L\text{-mode assumed})$
- $n_e = 6 \times 10^{19} \, m^{-3}$
- $T_i(0) = 1.8 \, keV$
- $v_i^* = 0.25$

*coils cooled to cryogenic temperatures, vacuum vessel at room temperature.*
NCSX Physics Design

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

**Plasma Cross Sections**

**Physics Properties**

- 3 periods, low $R/\langle a \rangle$ (4.4).
- Quasi-axisymmetric with low ripple.
- Stable at $\beta=4.1\%$ to specific MHD instabilities.
- Reverse shear q-profile.
- 25% of transform from bootstrap.
- Good magnetic surfaces at high $\beta$.

*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 $\beta$

- Explicit numerical design to eliminate resonant field perturbations
- ‘Reversed shear’ configuration $\Rightarrow$ 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?

Poincare: PIES, free boundary 3D equilibrium code. $\beta = 4\%$

$< 3\%$ flux loss.
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 $\beta$-limit to 1%.
- Can cover wide operating space in $\beta$ (to at least 6%), $I_p$, profile shapes.

Shear controlled by varying plasma shape
$\beta=4.2\%$, full current, fixed profiles.
Properties Are Determined By Plasma Shape

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

\( \beta = 4.2\% \), full current
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?
Ex-Vessel Magnetic Diagnostics Designed for Reconstruction

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

Several strategies being developed for equilibrium reconstruction:
- 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

N. Pomphrey, PPPL
E. Lazarus, ORNL
NCSX Construction is Well Under Way

Vacuum Vessel

Segment #1 of 3
Sealed for Pump-down

Modular Coils

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

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### Key Equipment

1. **Stellarator Acceptance Testing**
   - Verify construction accuracy
   - First Plasma
   - **Stellarator @B = 0.5 T**
   - Ohmic heating, 150 C bake.
   - E-beam & ex-vessel magnetics

2. **Magnetic Configuration Studies**
   - Vacuum flux surface documentation.
   - Magnetic configuration control w/ coils.
   - **Stellarator @B = 0.5 T**
   - **Stellarator @B = 1.2 T**
   - **1.5 MW NBI, NB Armor, 350 C bake**
   - Thomson scattering, in-vessel magnetics, interferometer/polarimeter, SX arrays

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 $|\beta|$ 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

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 of 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 ratio

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/m²)

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