The Compact Stellarator Program and NCSX

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for the national team:

UCSD, Columbia U., LLNL, ORNL, PPPL, SNL-A, U. Texas

in collaboration with:

Auburn, NYU, Wisconsin

Australia, Austria, Germany, Japan , Russia, Spain, Switzerland

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Thanks, Reviewers

- Yours is a challenging task.
- Our goal is to help you however we can. Contact

  Stan Mizerski

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  Mike Zarnstorff

  Hutch Neilson

  Rich Hawryluk

  Rob Goldston

  …or any member of the NCSX team.

Compact Stellarators Provide an Exciting Opportunity for the Fusion Program

- Unique science

  unique toroidal configuration controls.

- Innovative solutions for fusion energy

  tokamak+stellarator benefits combined.

- Complement to other toroidal confinement research.
- Robust links to all of fusion science.

- The NCSX is the key element: PoP experiment for broad CS physics studies..
  - Supports fusion goals: plasma physics understanding, concept innovation.
  - High-beta, low-R/⟨a⟩ stellarator-tokamak hybrid via quasi-symmetric design
  - **Sound physics basis.**

Unique Science: Compact Stellarators Address Critical Plasma Physics Questions (*MFE Goal #1*)

- ***Macroscopic stability:*** Can limiting high-β instabilities be stabilized by external transform and 3D shaping? How are disruptions affected?
- ***Turbulence and transport:*** Do anomalous transport reduction mechanisms that work in tokamaks transfer to low-collisionality quasi-axisymmetric stellarators?
- ***Plasma boundary:*** How do stellarator field characteristics such as islands and stochasticity affect the boundary plasma and plasma-material interactions?

Unique controls to understand toroidal confinement fundamentals: rotational transform, shaping, magnetic symmetry.

Innovative Solutions: Compact Stellarators Combine the Best of Tokamaks and Stellarators

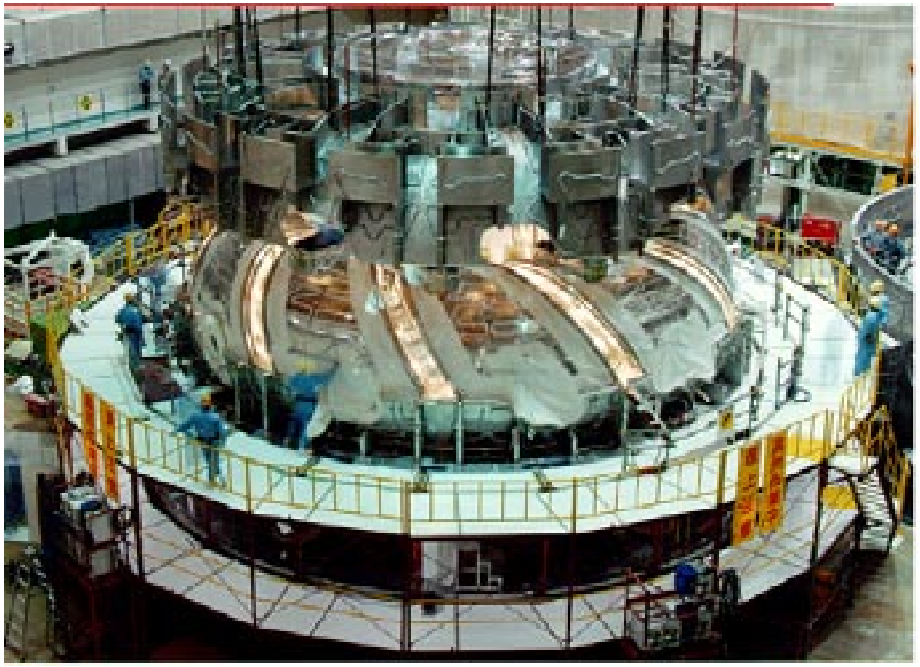
Tokamaks: dramatic advances in performance, physics understanding:

- MHD equilibrium, ideal stability, bootstrap current, transport control.

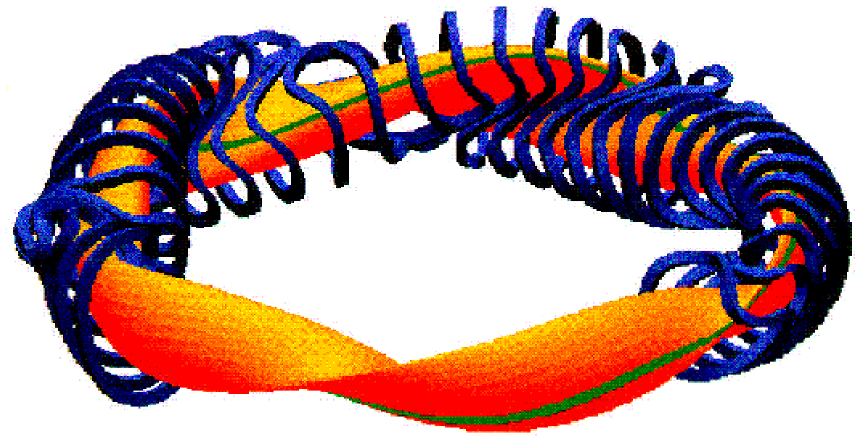
Stellarators: use 3D helical fields from coils to generate rotational transform, shape plasma. Benefits:

- Intrinsically steady-state ⇒ no current drive required.
- Can use 3D shaping to tailor plasma properties. ⇒ **NCSX goals**
  - Stabilize instabilities (kink, vertical, ballooning, Mercier) without conducting wall or feedback. **Prevent disruptions?**
  - Magnetic symmetry. (confined orbits, undamped flows, bootstrap current). . **Quasi-axisymmetry ⇒ capture tokamak benefits in 3D?**
  - High beta (≥4%) and low aspect ratio (<4.4) ⇒ **compact stellarators.**

The World Stellarator Program is Substantial



Large Helical Device (Japan)
Enhanced confinement, high β;
A = 6.



Wendelstein 7-X (Germany)
Physics-optimized design:
no current, A = 11.

- Medium-scale experiments (W7-AS, CHS), and
- Exploratory helical-axis experiments in Japan, Spain, Australia.

Large aspect ratios; physics-optimized designs with no symmetry, no current.

U.S. Stellarator Program Has a Good Foundation

Strong stellarator knowledge base

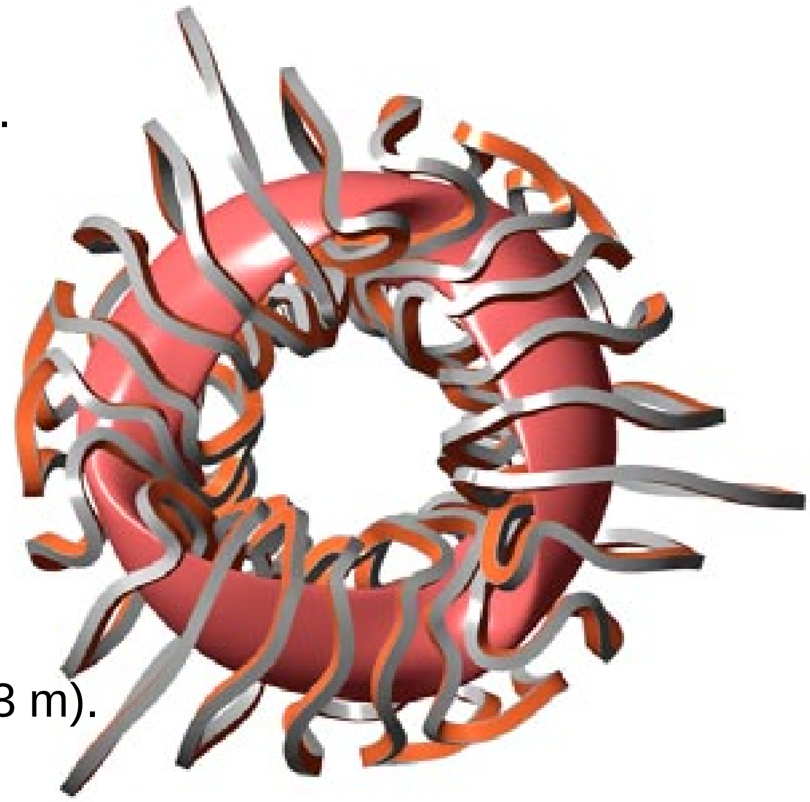
- Experiments: enhanced confinement, high beta, well-heated & diagnosed.
- Theory: physics-based numerical design capability.
- Engineering: accurate 3D coils and structures at a range of scales.

U.S. PoP Program Complements World Stellarator Research.
Unique physics…

- Hybrid concept with some transform from bootstrap current.
- High beta and low aspect ratio together. **"Compact Stellarators"**
- Magnetic quasi-symmetry (confinement, flows).

Quasi-axisymmetric design: also connects to tokamak physics base.
Combined foundation justifies PoP-scale experiment ⇒ NCSX.

National Compact Stellarator Experiment (NCSX)



Broad, In-Depth CS physics program…

- Stability, limiting mechanisms at high β (≥4%).
- Fast ion confinement.
- Enhanced confinement at low collisionality.
- Boundary physics.

⇒ Conditions for disruption-free operations.

Requires PoP Scale Facility

- High-power heating & exhaust (3→12 MW).
- Plasma size like PLT or D-III (R=1.4 m, ⟨a⟩=33 m).
- Wide range in B (1.2 – 2 T).
- Flexible and robust.
- In-depth diagnostics.

Acquire physics data needed to determine compact stellarator attractiveness. (*MFE Goal #2*)

NCSX Has Strong, Robust Linkages to All of Magnetic Fusion Science

Complements ATs and STs.

- Rotational transform: internally generated *vs* hybrid.
- Sustainment: passive *vs* active control.
- Joint experiments with DIII-D, C-Mod, NSTX.

Advances Stellarators Through International Collaboration.

- Sharing of design and analysis tools.
- Collaboration, joint experiments.

Focuses U.S. Compact Stellarator Research.

The U.S. Stellarator PoP Program

Goals

- Develop the physics base for low aspect-ratio, high-β stellarators.
- Assess attractiveness, decide on next steps in ~10 years.

Elements

- NCSX proof-of-principle experiment.
- International collaboration on stellarators.
- Reactor studies.
- Theory: 3D plasma physics.
- CE experiments investigating stellarator physics issues at lower β, higher collisionality.
  - QOS, HSX, CTH

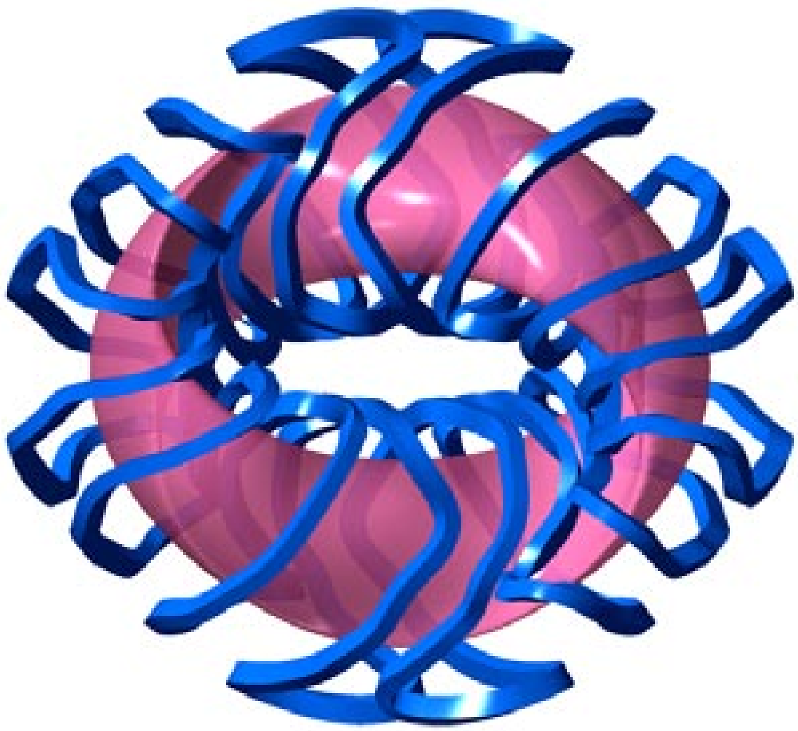
Stellarator Theory and Modeling Advances
3D Plasma Physics Understanding

Important for stellarator design, understanding of experimental results.

- Non-linear MHD stability analysis, including Alfvenic eigenmodes.
- Non-linear micro-stability and turbulence simulation, coupled with neoclassical transport effects.
- Edge 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 magnetic confinement.

QOS: CE-level Compact Stellarator Experiment



- $\langle R \rangle$= 0.95 m; $\langle a \rangle$ = 0.37 m
- B = 1 T (0.5 s); P_{RF} = 1-3 MW
- I_{pl} < 60 kA; $\langle \beta \rangle$ limit = 2.5%

proposed by ORNL

- **Quasi-poloidally symmetric stellarator.**
- **Very Low R/a: 2.6**
- **Broaden understanding of toroidal configurations**
  - * stellarator equilibria at low *R/a*
  - * bootstrap current dependence
  - * reduce neoclassical losses
  - * low-*R/a* anomalous transport
  - * β limits
- **Study startup issues for a low-*R/a* quasi-poloidal $\langle \beta \rangle$ = 10-15% compact stellarator concept**

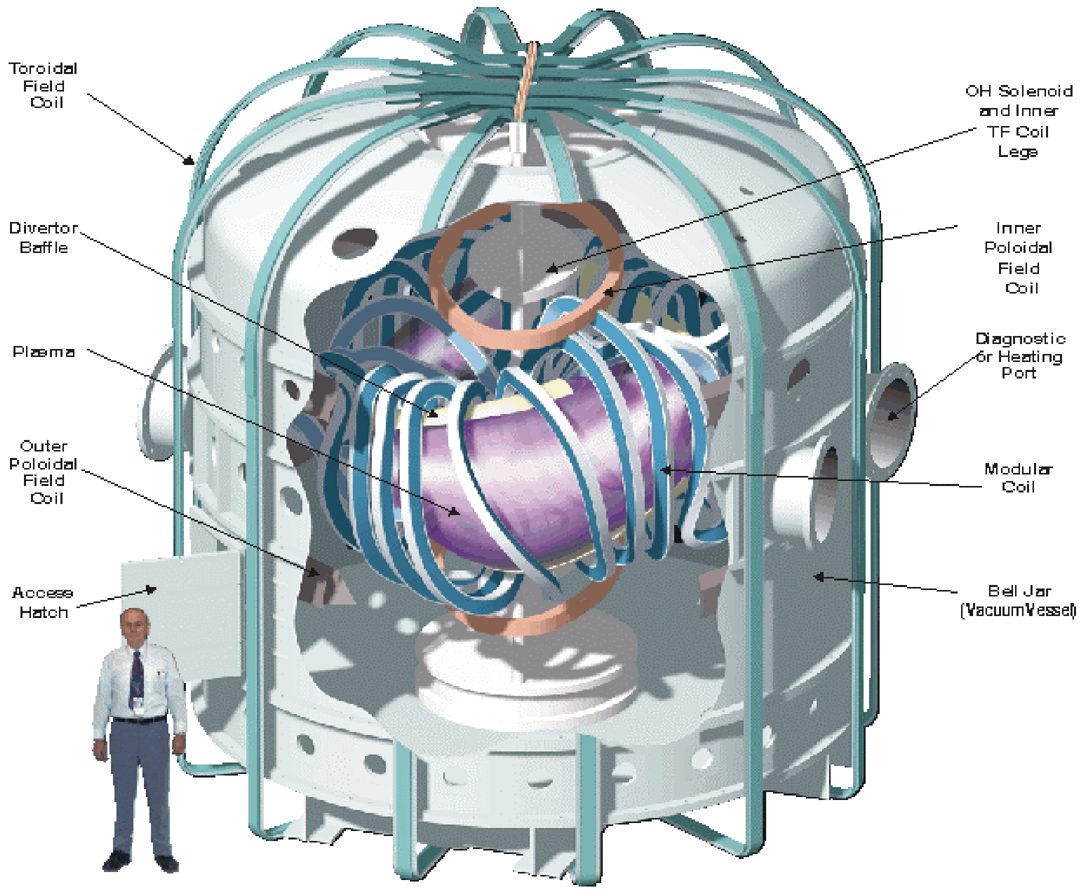
QOS Complements NCSX

Feature	NCSX	QOS
Magnetic Symmetry	Quasi-Axial	Quasi-Poloidal
R/⟨a⟩	4.3	2.6
Key physics issue	Disruption immunity at high-β (4%), low ν*, low-R/⟨a⟩	Toroidal mode coupling effects at very low-R/⟨a⟩, moderate-β (2.5%), high-ν*
Parameters, Capabilities	R = 1.4 m, ⟨a⟩ = 0.33 m, B = 2 T P_{heat} = 3 → 12 MW (NB, IC) extensive diagnostics	R = 0.95 m, ⟨a⟩ = 0.37 m, B = 1 T P_{heat} = → 3 MW (EC, IC) limited diagnostics
Basis (justification for scale)	Theory Stellarator + Tokamak expts.	Theory
Scale of exp't / physics program	Proof-of-principle / in-depth	Concept exploration / exploratory

NCSX: QAS design takes advantage of tokamak physics understanding and performance advances ⇒ PoP.

QOS: explore less-developed QPS physics and very low R/⟨a⟩ ⇒ higher risk, potentially high payoff ⇒ CE.

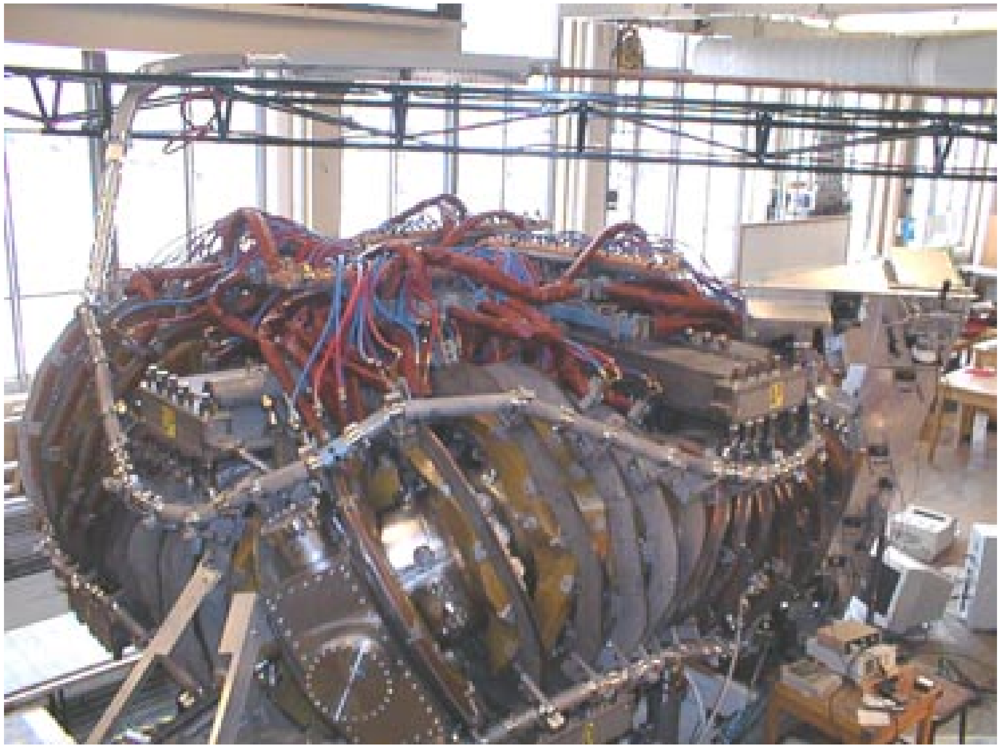
QOS Status



Designed using tools and experience of multi-lab NCSX-QOS team

- **PVR scheduled for April 24-25**
- **Design, Cost & Schedule Review in April 2002**
- **Design and construction in parallel with NCSX proposed**

Helically Symmetric Experiment (HSX)



R=1.2 m, B=1 T, 4 periods, R/⟨a⟩ = 8

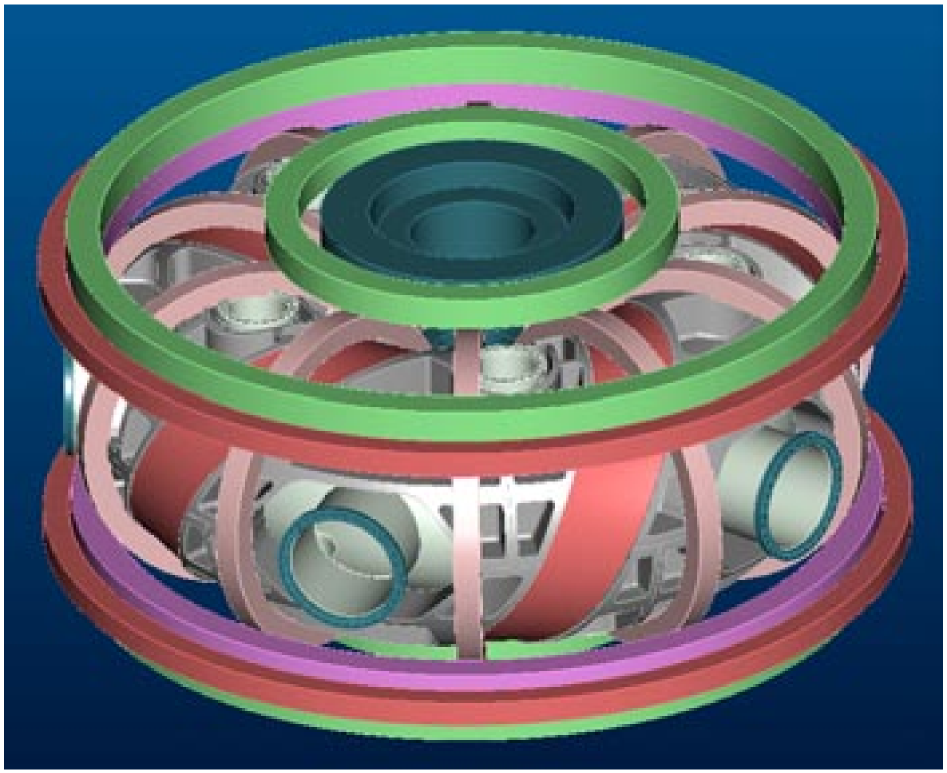
Operating since 2000.

University of Wisconsin

- **Supports NCSX:**
  - **First test of quasi-symmetry.**
  - **Developed method to map magnetic field spectral content.**
- **Complements NCSX via unique properties and physics issues:**
  - **High effective transform (q=1/3).**
  - **Low parallel viscosity in helical direction.**
  - **Mercier and ballooning limits accessible at low-β via flexible auxiliary coils.**

Compact Toroidal Hybrid

Auburn University



- **Flexible, Ohmic current, low R/⟨a⟩.**
- **Contributes to NCSX through improved understanding of kink and tearing modes in current-carrying stellarators.**
- **Operation to begin in 03.**

R=0.75m, <a> =0.18m, B=0.5T, I_p=50 kA

Compact Stellarator Design Program Has Already Advanced Stellarator Science

Capable tools have been developed…

- Improved 3D equilibrium codes- PIES and VMEC.
- Plasma currents, high β incorporated into configuration optimization.
- Free-boundary optimizer- new tool for flexibility evaluation.
- Stability, transport, bootstrap current, and coil engineering metrics integrated to target design objectives.
- Coil design innovations to reduce complexity and current density, heal islands, preserve good physics properties.

Results have been delivered…

- 20+ publications.
- Plasma and coil configurations: hundreds evaluated.
- **A sound physics basis for NCSX design.**

The "Robustness" Issue Identified in 1999 Has Been Resolved

- New NCSX plasma design has dramatically improved magnetic surfaces. Edge stochasticity problem of 1999 design has been overcome.
- NCSX modular coils are designed to produce good magnetic surfaces in vacuum and high beta states; neoclassical effects are calculated to further reduce islands.
- Multi-helicity trim coils are included in the design to maintain good surfaces in other configurations.
- Coils produce QA equilibria over wide range of β's and I_P's.
- Coils are robust to profile variations $\Rightarrow$ design is not "optimized on the head of a pin."
- Coils can vary beta limit $\Rightarrow$ stability mission is robust.
- Stable startup pathway from vacuum to high-beta state has been demonstrated.

Summary

- **Compact stellarators make unique contributions to stellarator physics.**
  - Magnetic symmetry, high β / low-R/$\langle a \rangle$ together, hybrid optimization.
- **Complementary to the AT & ST programs.**
  - Effects of 3D shaping, external rotational transform, quasi-symmetry on stability and transport.
  - Effects of stellarator field structures in the edge.
- **National stellarator program provides breadth of science.**
  - Theory of 3D plasma physics
  - CE experiments exploring compact stellarator physics issues.

  $\Rightarrow$ **NCSX** proof-of-principle experiment for broad, in-depth CS physics studies to determine concept attractiveness.
- **A sound physics basis for NCSX design has been established.**