NCSX

The Promise and Status of Compact Stellarators

Hutch Neilson

Princeton Plasma Physics Laboratory

Fusion Power Associates Symposium

Gaithersburg, MD

December 13, 2004

Compact Stellarators

NCSX

Promise

- Solve critical problems for MFE.
- Improve on previous stellarator designs.
- Advance fusion science.

Status

- Physics basis for compact stellarator experiments.
- Design.
- Construction of NCSX.

Compact Stellarator Motivation

NCSX

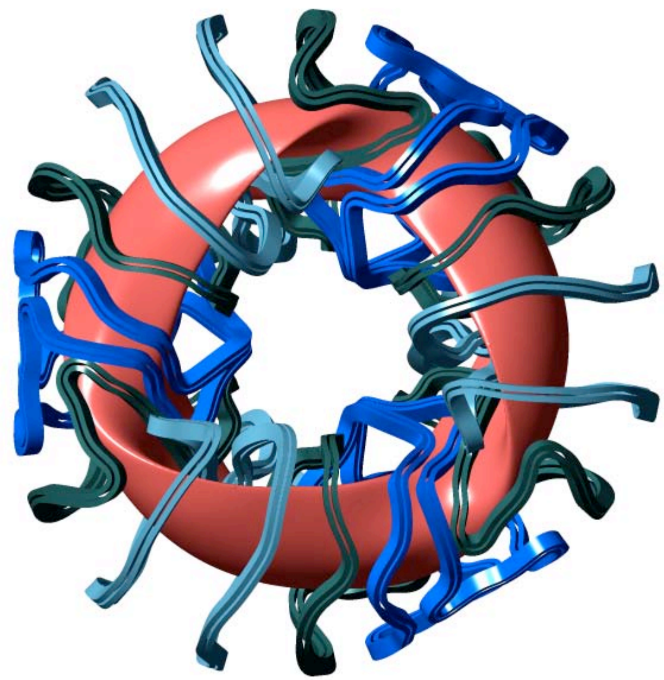
Stellarators solve critical problems for magnetic fusion.

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

Compact Stellarators (CS) improve on previous designs.

- Magnetic quasi-symmetry:
  - good confinement.
  - link to tokamak physics.
- Lower aspect ratio.

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

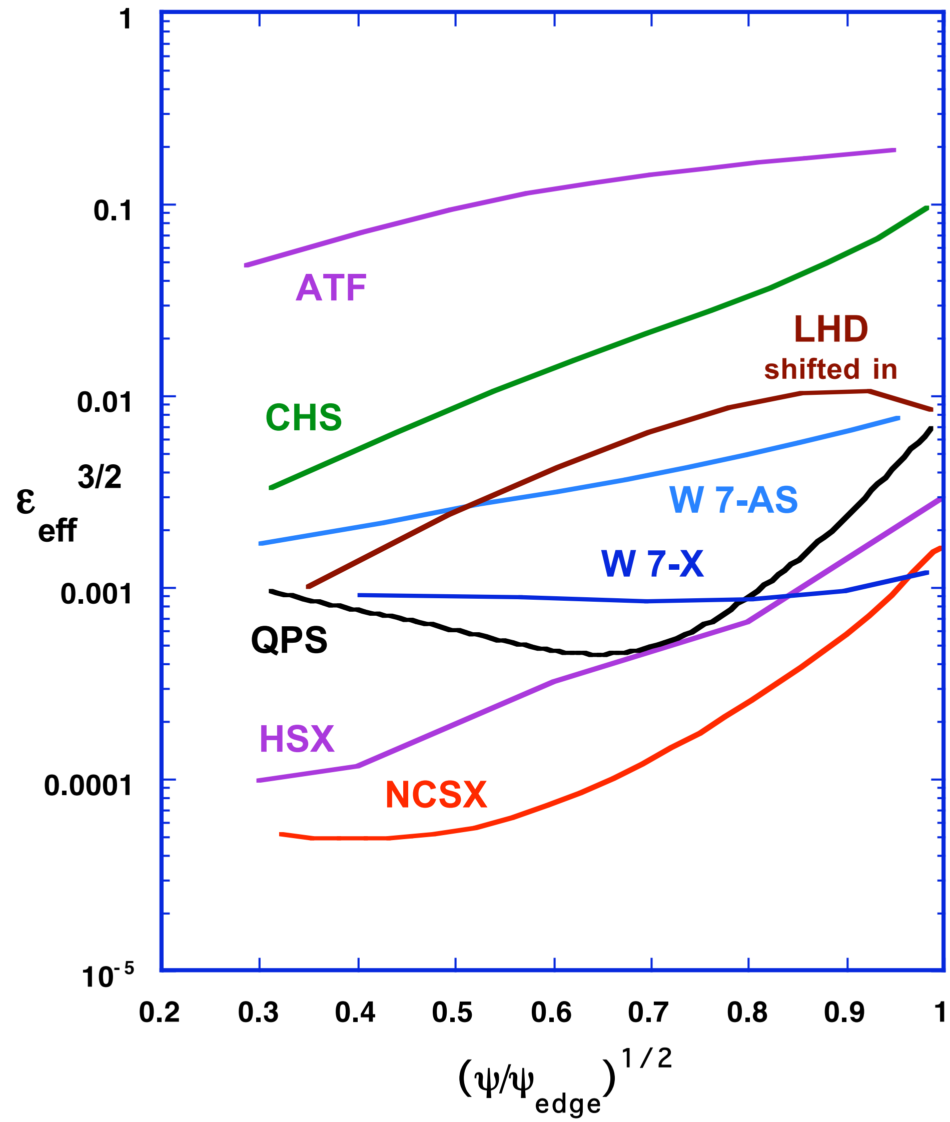


3-Period NCSX Plasma and Coil Design

Quasi-Axisymmetric: Very Low Effective Ripple

NCSX

- In NCSX:
  - ε_{eff} ~ 1.4% at edge, ~ 0.1% in core
- Predicted ripple transport is negligible.
  - neo. transport $\propto \varepsilon_{eff}^{3/2}$ in $1/\nu$ regime.
  - Confinement improves with lower ε_{eff} in experiments.
- Gives low flow-damping.
  - allows manipulation of flows for flow-shear stabilization, control of E_r
- Allows balanced-NBI with acceptable losses (24% at 1.2T).



~ Normalized Minor Radius (r / a)

Stellarator Research Advances Fusion Science

NCSX

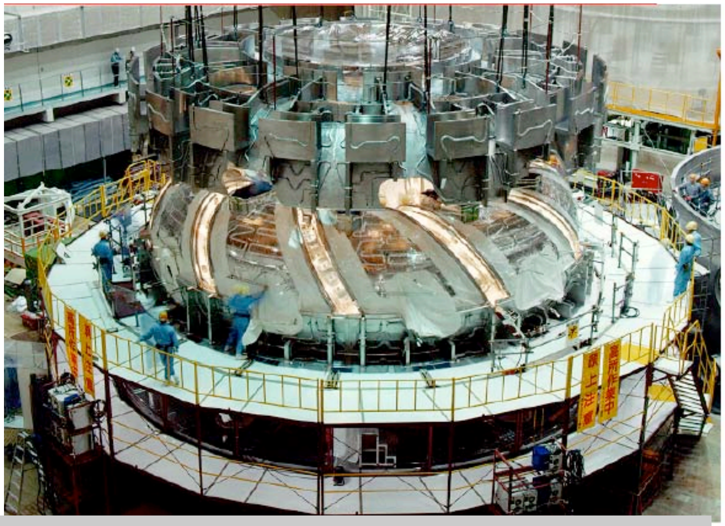
Understanding 3D plasma physics important to all of MFE science

- 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?

Stellarators Are Making Excellent Progress



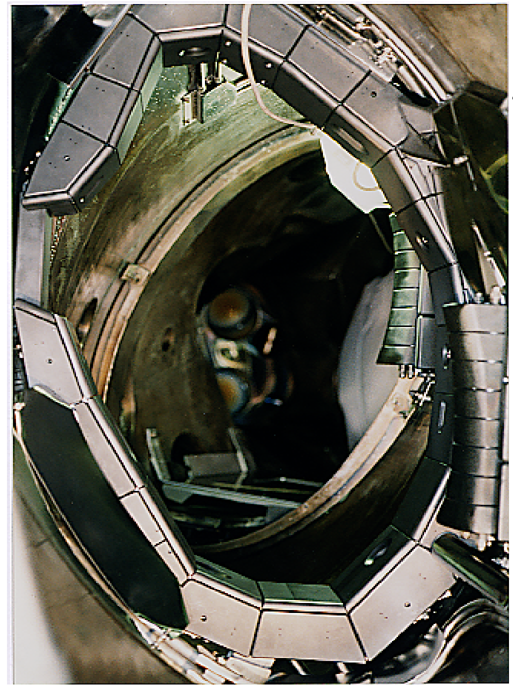
Large Helical Device
(S/C magnets - Japan)

$\beta \sim 4\%$.

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

enhanced confinement.

2-minute pulses.

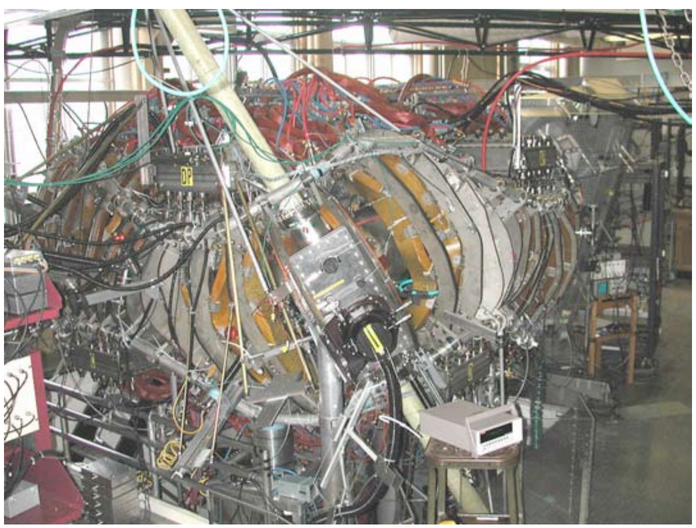


Wendelstein 7-AS
(Germany)

$\beta \sim 3.5\%$.

enhanced confinement.

density control & enhanced performance w/island divertor.



Helically Symmetric Experiment
(U. Wisc.)

- Successful test of quasi-symmetry.

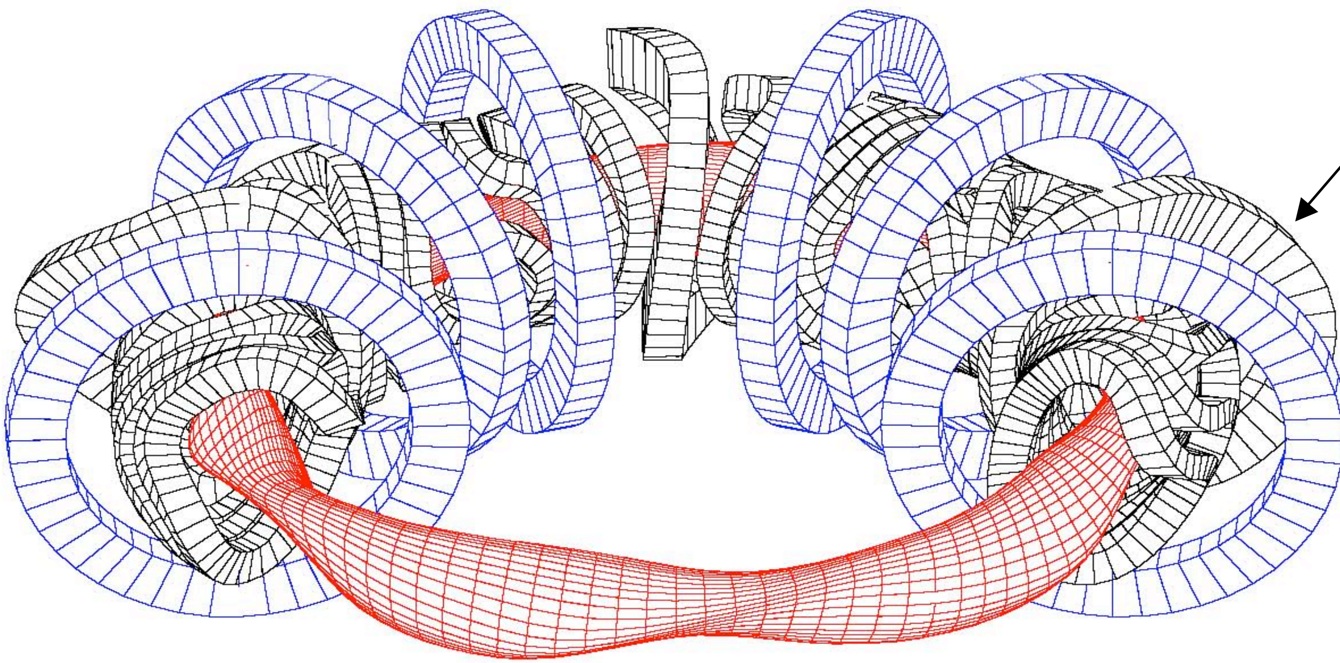
Wendelstein 7-X (Germany)

Optimized Design - S/C magnets

Under construction - Ops. In 2010

W7-AS – a flexible experiment

5 field periods, R = 2 m, minor radius a ≤ 0.16 m, B ≤ 2.5 T,
vacuum rotational transform $0.25 \leq \iota_{ext} \leq 0.6$



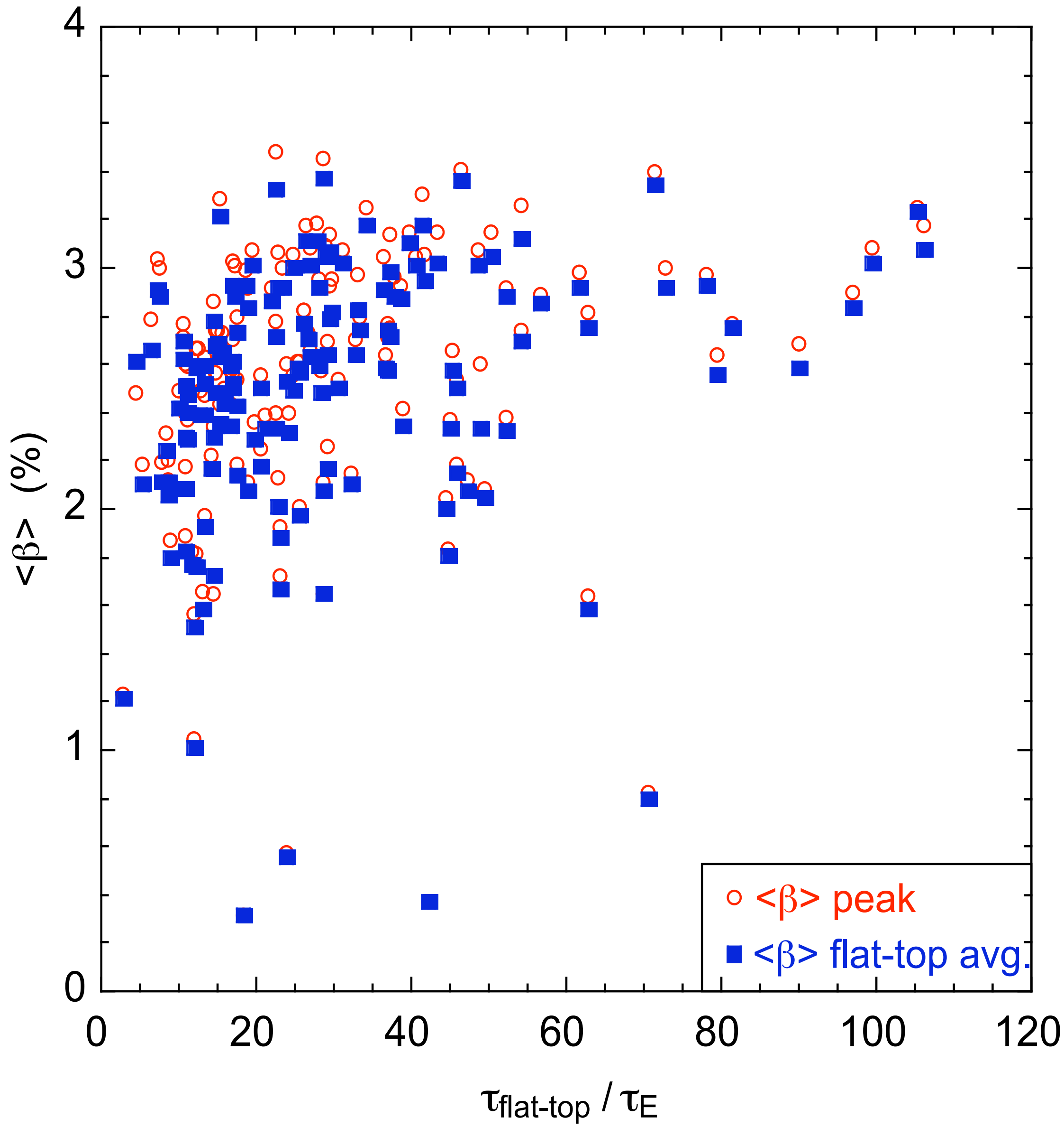
Flexible coilset:

- Modular coils produce helical field
- TF coils, to control rotational transform ι
- Not shown:
  - –divertor control coils
  - –OH Transformer
  - –Vertical field coils

W7-AS

Completed operation in 2002

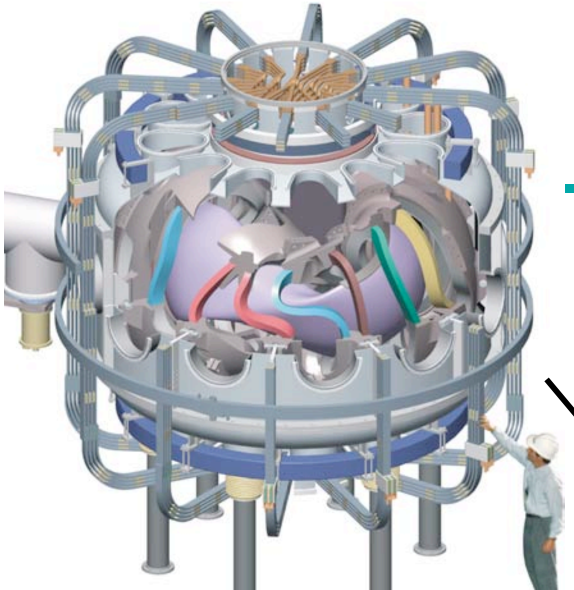
$\langle\beta\rangle$ > 3.2% maintained for > 100 τ_E in W7-AS



- 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.

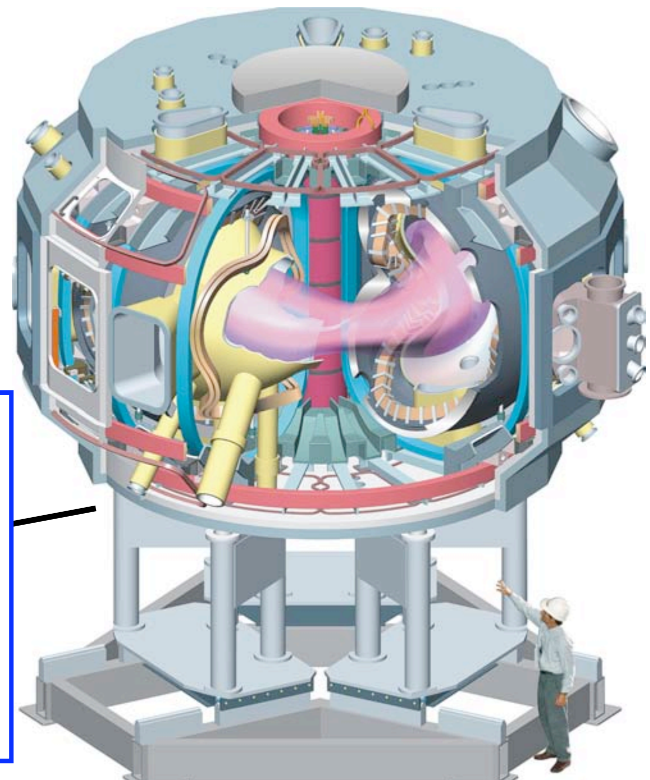
U.S. Stellarator Program Goals: CS Attractiveness, 3D Physics



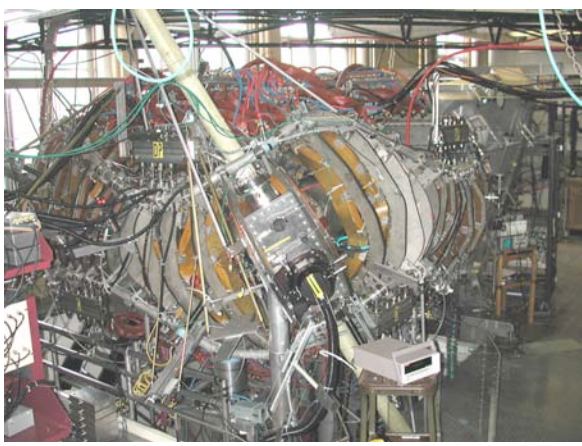
QPS (ORNL)
CD-1 Approved

- International Programs (NIFS, IPP,…)
- Theory & Computation
- ARIES-CS Power Plant Study

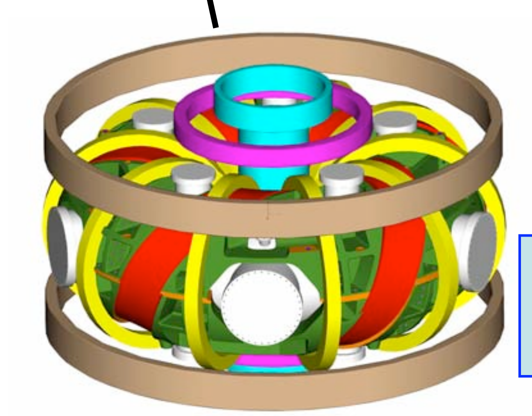
- Test expected CS physics benefits.
- Advance 3D plasma physics.
- Support next-step decisions.



NCSX (PPPL-ORNL)
Under Construction
First Plasma - 2008



HSX (U. Wisconsin)



CTH (Auburn U.)
Ops. in 2005

NCSX Mission: Develop Physics Basis for 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.

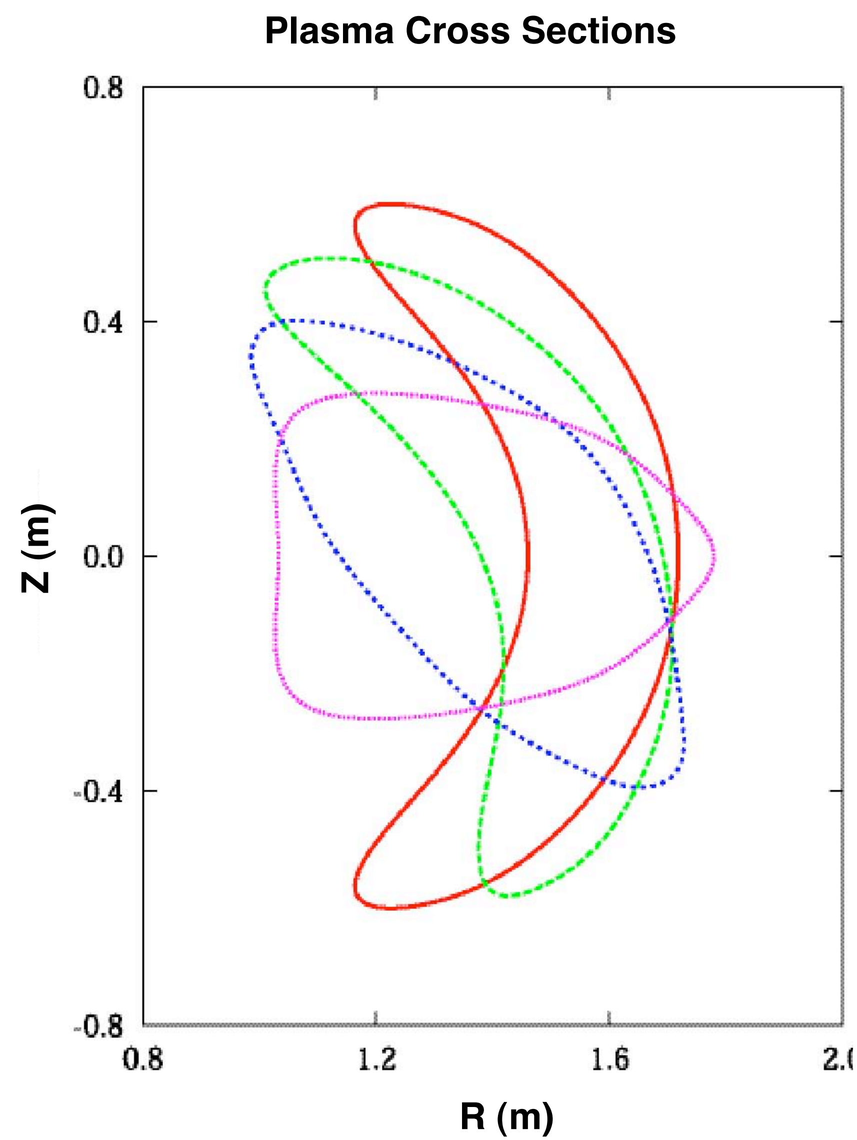
Demonstrate…

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

NCSX Physics Design Target: Attractive Properties

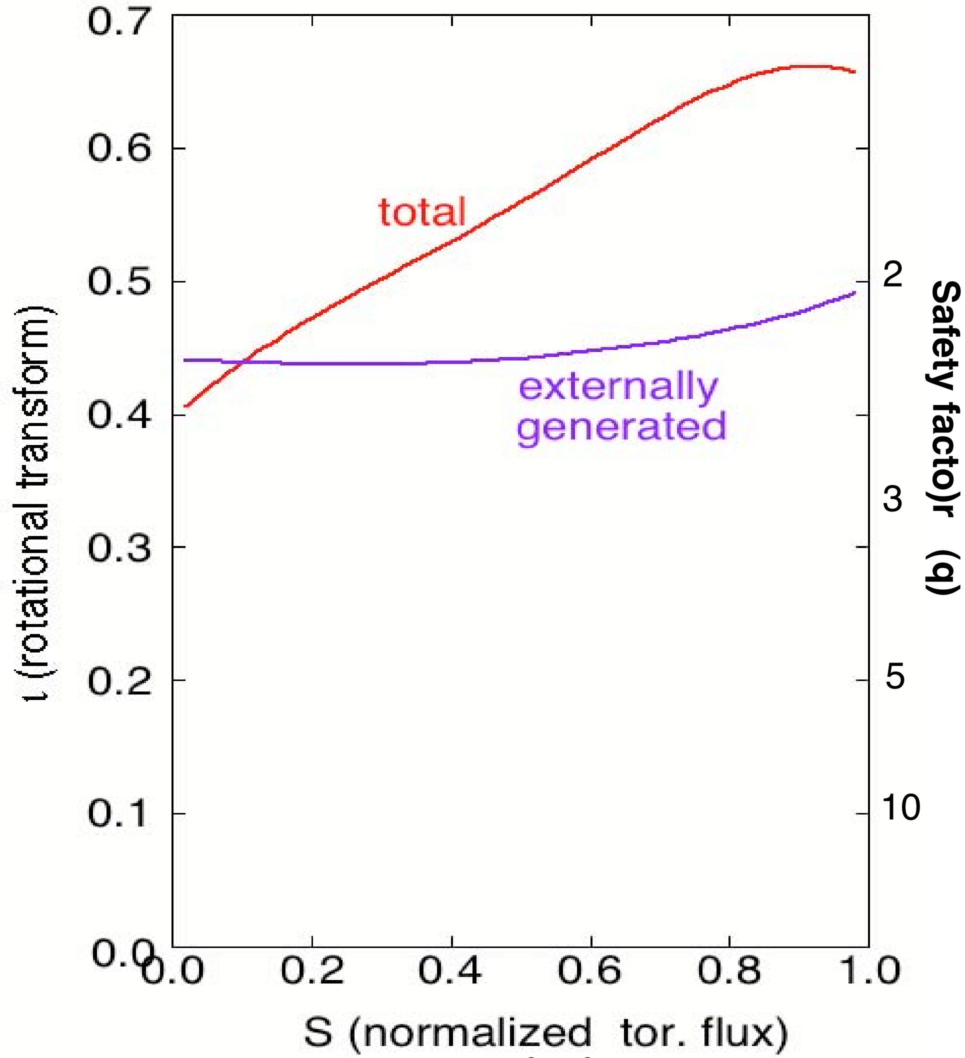
NCSX

- 3 periods, low R/⟨a⟩ (4.4).
- Quasi-axisymmetric w/ low ripple.
- Stable at β=4.1% to ballooning, kink, vertical, Mercier modes, w/out conducting walls or feedback.



Hybrid Configuration Combines Externally-Generated Fields with Bootstrap Current

NCSX

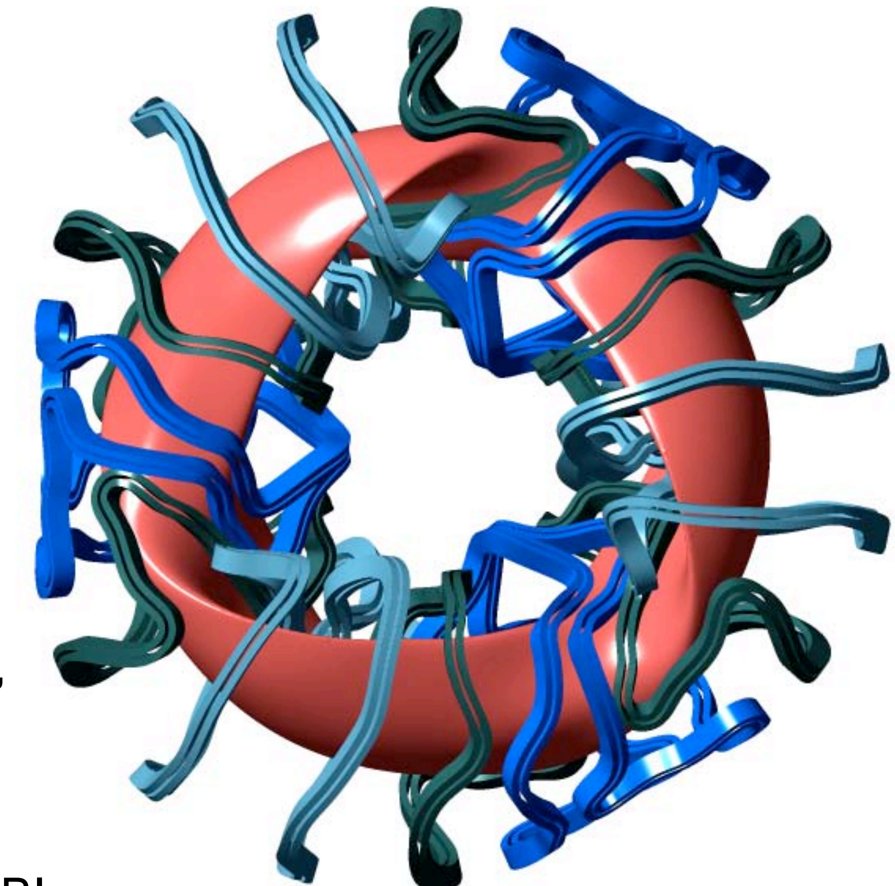


$\propto r^2/a^2$

- Assumed moderately broad pressure profile and consistent bootstrap current profile.
- "Reversed shear" iota profile (0.39–0.65).
  - stabilize neoclassical tearing modes.
- ~3/4 of transform (poloidal-B) from external coils.
- ~1/4 of transform from bootstrap current.

Coil Design Satisfies Physics and Engineering Criteria

- NCSX design uses 18 modular coils (3 shapes)
  - Also TF, PF, and helical trim coils.
- Free-boundary method was used to optimize coils for target properties.
  - VMEC and PIES 3D equilibrium codes.
- Required properties are realized:
  - Free-boundary equilibrium with the required physics properties (R/⟨a⟩, QA, stability at β = 4%, iota profile).
  - Engineering feasibility metrics: coil-coil spacing, min. bend radius, tangential NBI access, coil-plasma spacing.
  - Good magnetic surfaces at high β.



NCSX Plasma and Modular Coils

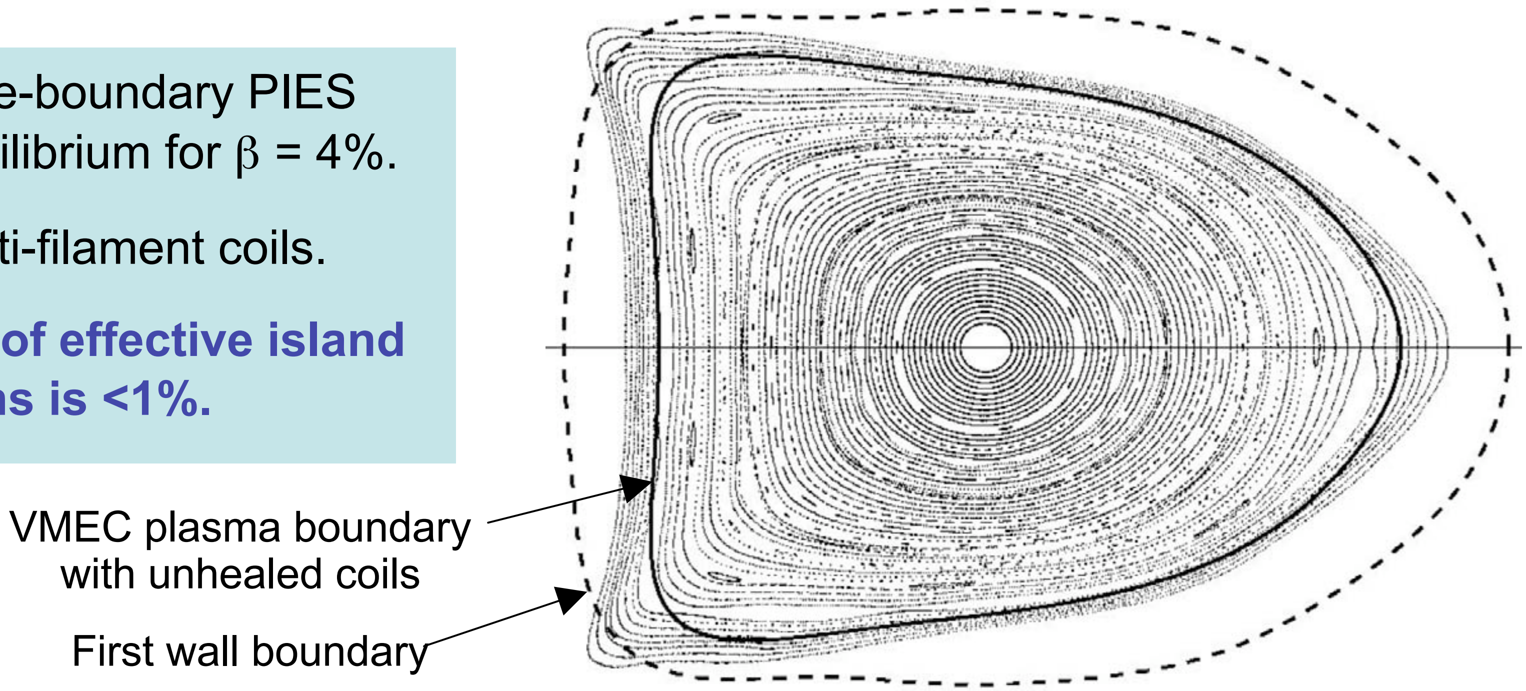
NCSX Coil Design Produces Good Surfaces at High β

NCSX

- Coil geometry adjusted to “heal” islands (measured with PIES code) while preserving physics and engineering properties.
- Corrections for neoclassical and finite $\chi_{\perp}/\chi_{||}$ effects (not included in PIES calculation) reduce effective island width by factor 2-3.

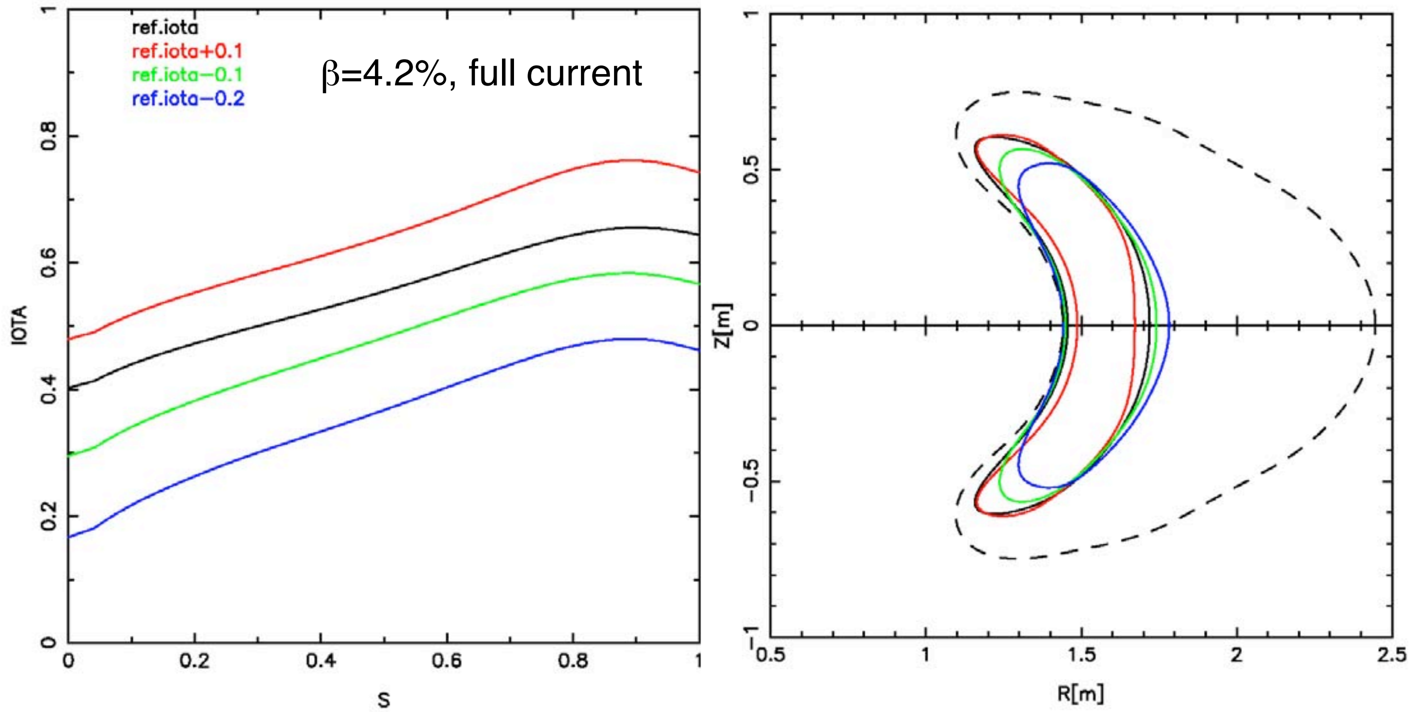
- Free-boundary PIES equilibrium for β = 4%.
- Multi-filament coils.

Sum of effective island widths is <1%.



Also, good surfaces in a range of vacuum configurations.

NCSX Coils: Flexibility to Vary Physics Properties



External iota controlled by plasma shape at fixed profiles.

Also

- Can externally control shear.
- 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.

NCSX Machine Parameters

NCSX

Stellarator

Major radius: 1.4 m

Performance:

Magnetic Field Strength (B)

@ 0.2 s pulse: 2.0 T

@ 1.7 s pulse: 1.2 T

Vac. base pressure: 2×10^{-8} torr

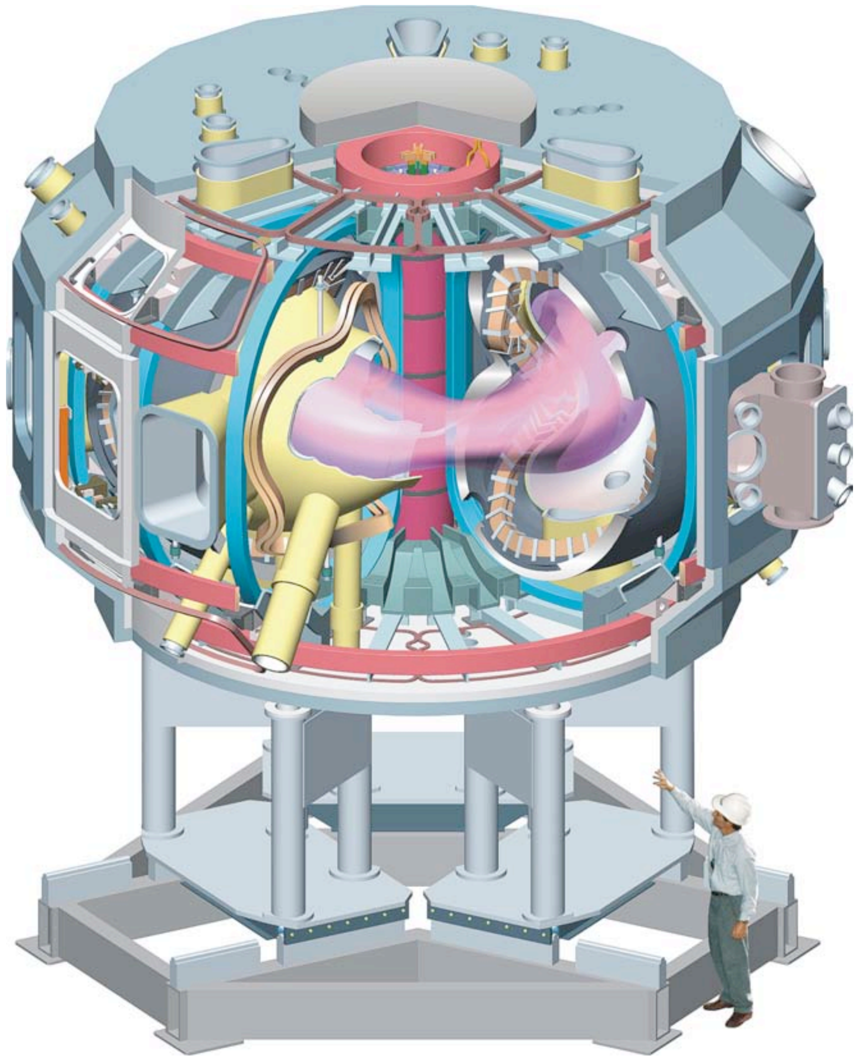
Vessel bakeable to 350 C.

Plasma Heating planned

NBI: 6 MW (tangential)

ICH: 6 MW (high-field launch)

ECH: 3 MW



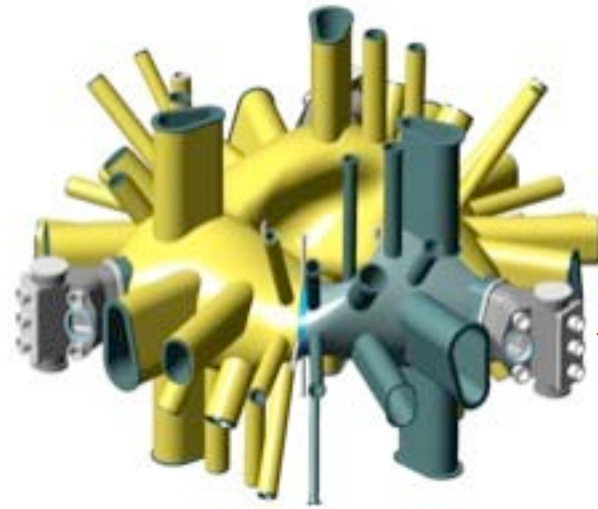
coils cooled to cryogenic temperatures, vacuum vessel at room temperature.

NCSX Engineering is Based on a Robust Concept

NCSX

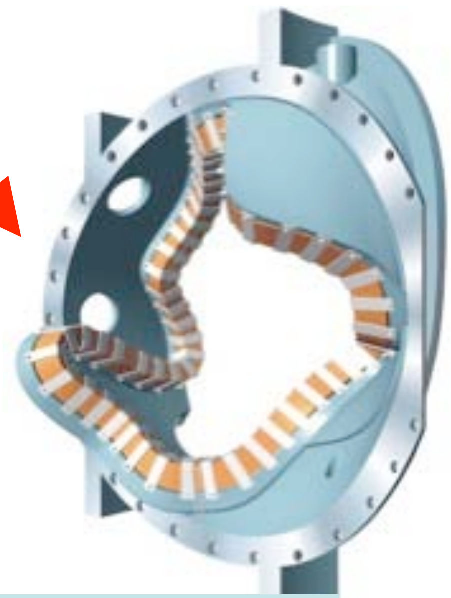
Modular Coil Winding Forms

(MCWF)

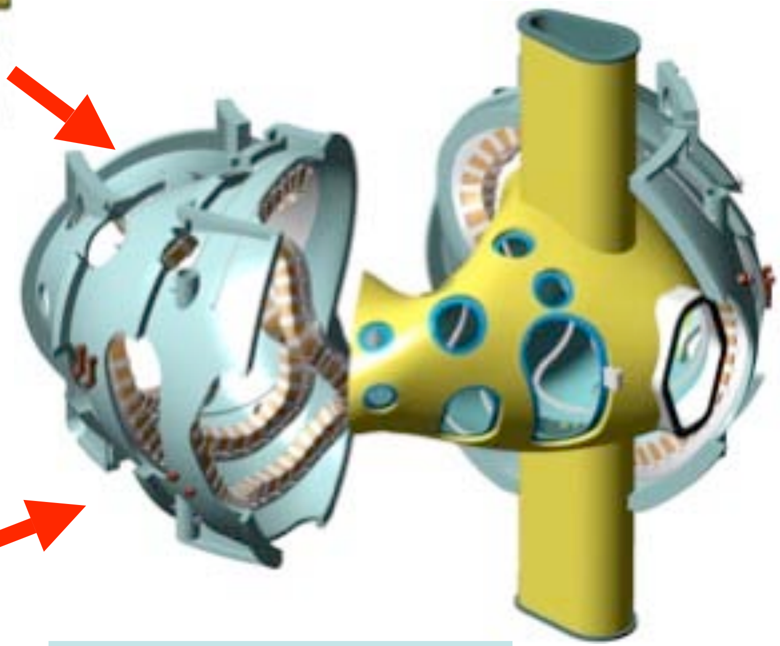


Vacuum Vessel

(shown with insulation)



Modular Coils



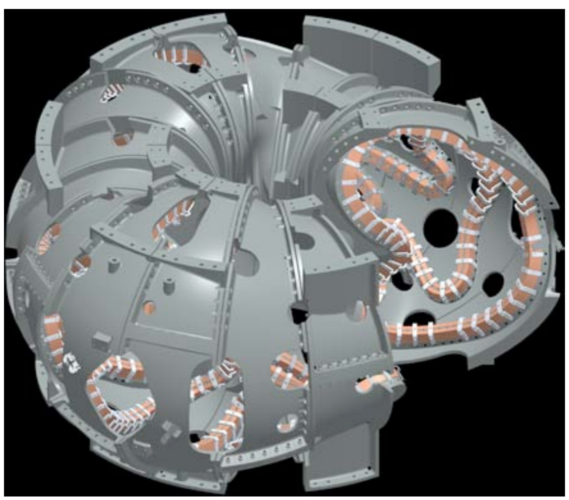
Field Period Sub-Assembly

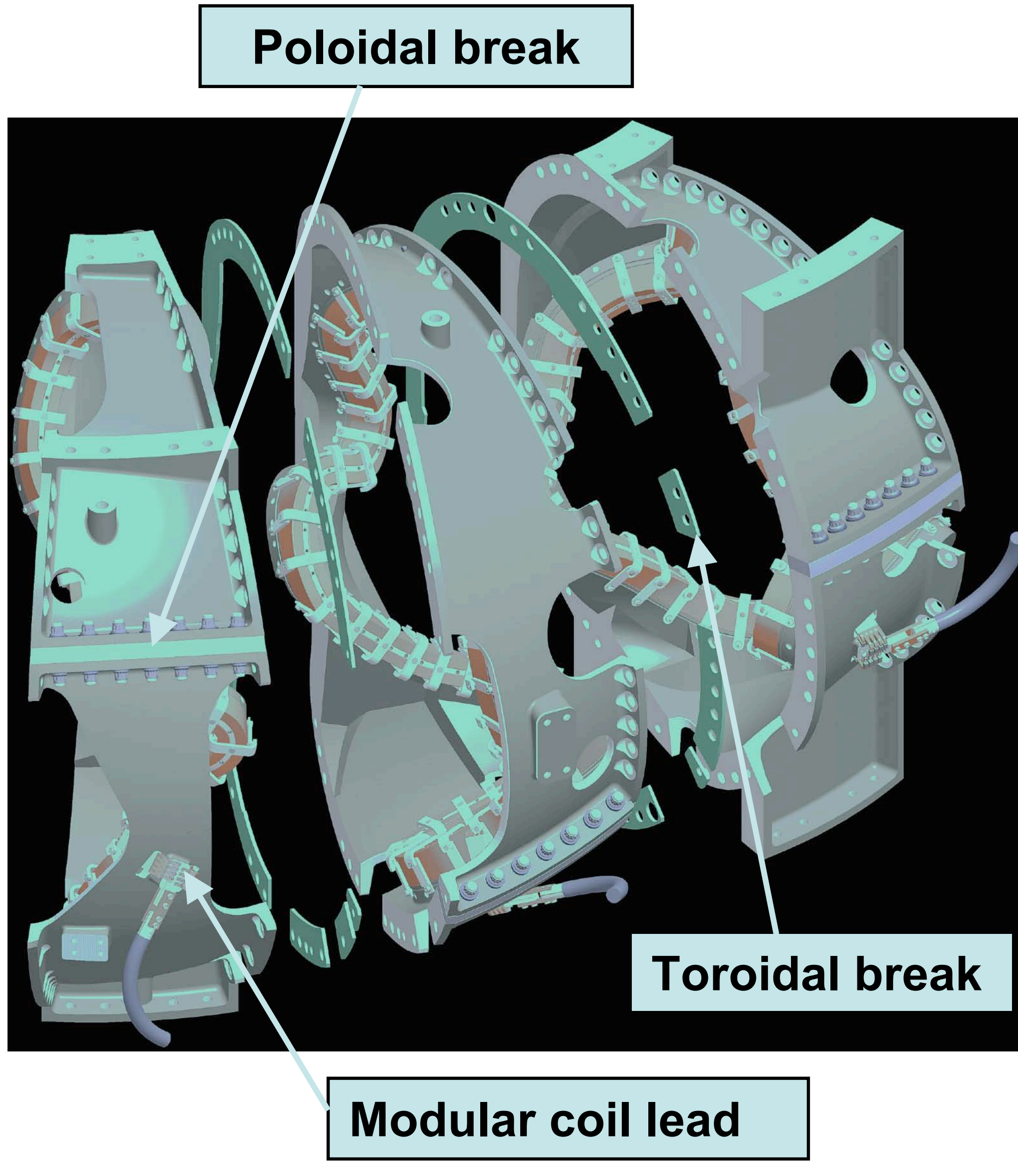
Coil form stays with the coil as part of the machine structure.

Winding Forms Make a Continuous Shell

NCSX

- Shell consists of individual modular coil winding forms that are bolted together
- Insulating breaks reduce eddy currents.
- *Shell concept also attractive for reactors. –ARIES-CS.*





Vacuum Vessel Has Good Access

- Interior space maximized for SOL and divertor flexibility, consistent with assembly of coils over vessel.
- Port configuration maximizes diagnostic access.
- Vacuum vessel bakeable to 350C means future PFCs can be simpler, more reliable, take up less space.

- **Shell material - - - - - - -Inconel 625**
- **Thickness - - - - - - -- - 0.375 inch**
- **Time constant - - - - - - -5.3 ms**

MCWF and VV Manufacture Have Started!

NCSX

- Industry teams developed solutions to fabrication challenges through R&D.
  - Geometries, tolerances, materials.
- Fabricated prototypes.
  - Using product data close to final design specs.
  - Gained experience, reduced production risks.
- **We have placed contracts for the production components**
  - VV: Major Tool & Machine, Inc., Indianapolis, IN
  - MCWF: Energy Industries of Ohio, Inc., Cleveland, OH, with:
    - C.A. Lawton Co. (pattern)
    - Metaltek International (casting)
    - Major Tool & Machine (machining)

Preparing to Wind the Modular Coils

NCSX

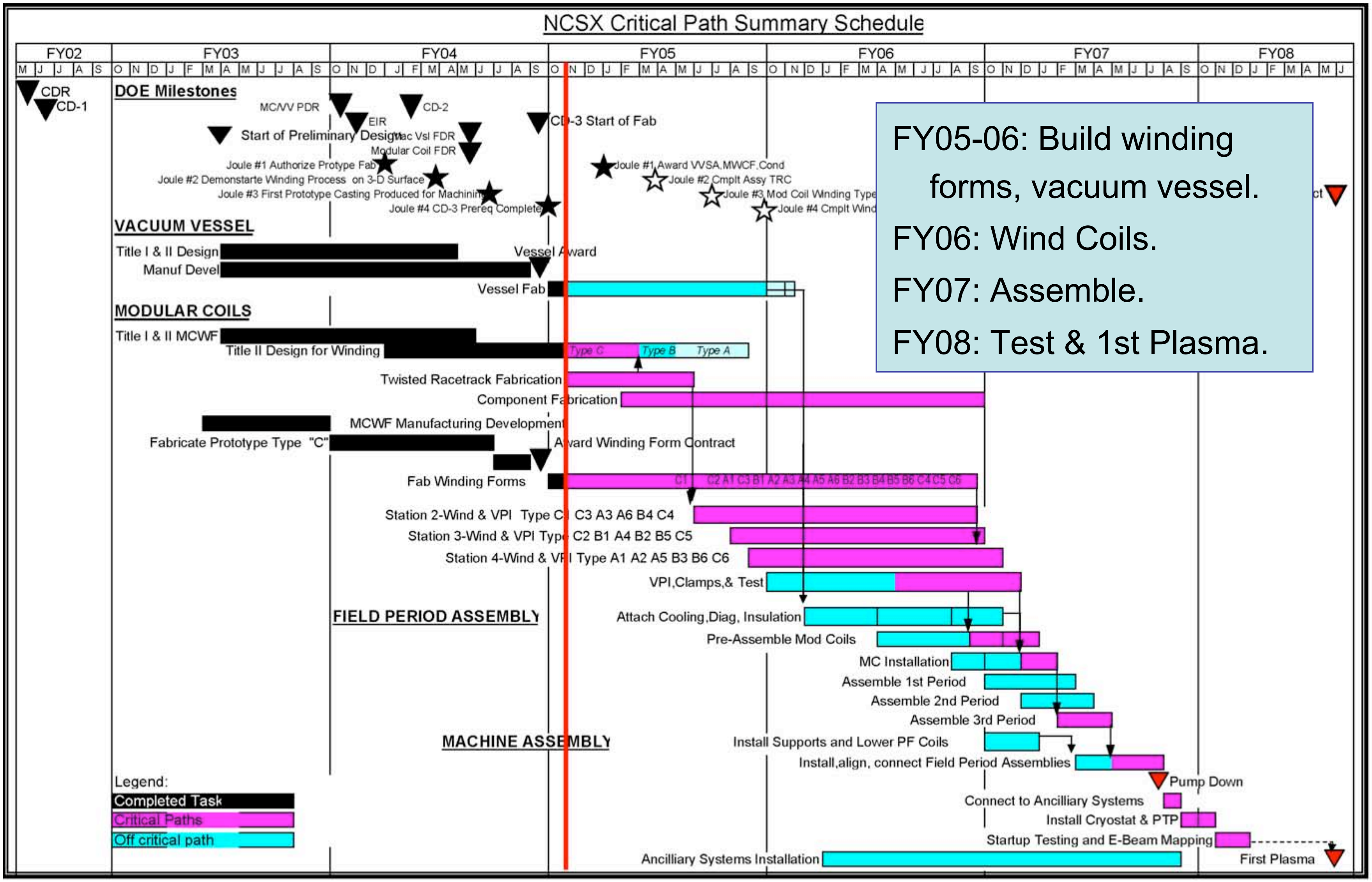
- Manufacturing facility is operating.
- Process steps have been developed by R&D.
  - Conductor placement on 3D surface.
  - Conductor deformation during winding.
  - Tooling & fixture optimization.
  - Epoxy impregnation.
- Twisted racetrack will provide integrated demonstration.
- All coils will be cryogenically and electrically tested.

Modular Coil Manufacturing Facility

Twisted Racetrack Being Wound

NCSX is on Schedule

NCSX



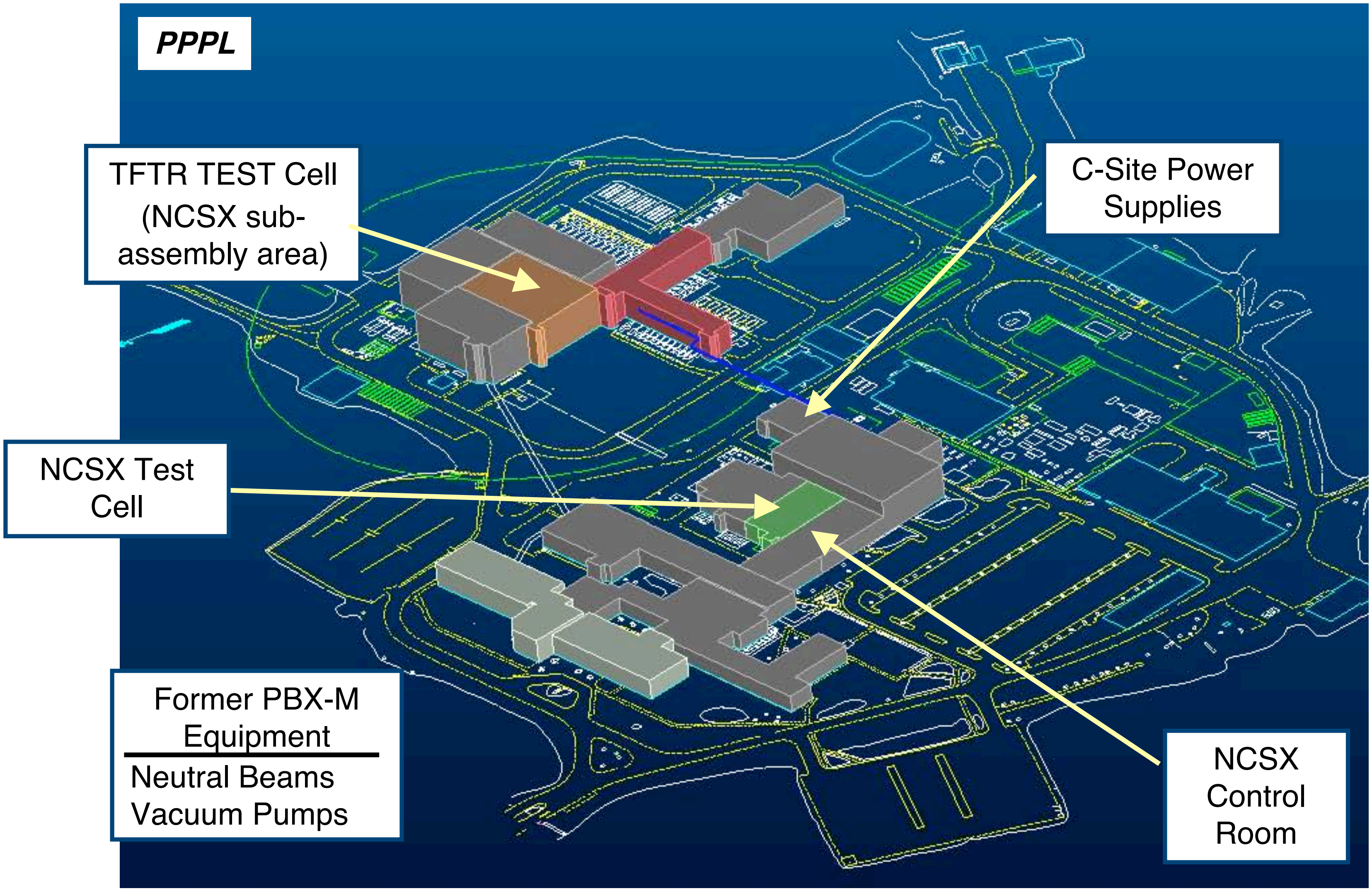
FY05-06: Build winding forms, vacuum vessel.

FY06: Wind Coils.

FY07: Assemble.

FY08: Test & 1st Plasma.

NCSX Will Use Existing Fusion Program Infrastructure to Reduce Costs



Research Preparations Are Under Way

NCSX

- Developing requirements for magnetic sensors, first wall design, diagnostics.
- Developing analytical tools.
- Collaborating on stellarator experiments.
- Planning the experimental program.
- Program Advisory Committee meets annually.
- Research forum in late 2006.

NCSX research will be a national and international collaboration led by PPPL-ORNL partnership.

Summary

NCSX

- Stellarators advance fusion science and provide solutions to magnetic fusion challenges:
  - Steady state, high-beta operation.
  - Understanding of 3D plasma physics for all MFE

- The NCSX is designed around a low-R/⟨a⟩, high-beta, quasi-axisymmetric stellarator plasma and a flexible coil set.

- Construction of major components has started.

- First Plasma in May, 2008.

- Research to be a national / international collaboration.