# NCSX and the Compact Stellarator Opportunity

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**Briefing for Dr. W. Polansky**
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# Stellarators

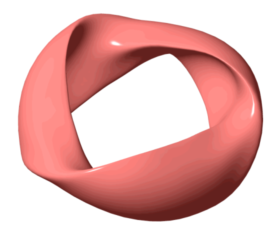
• In toroidal magnetic confinement, need a poloidal component of B (short way around torus), to confine particle orbits.

• Two methods for producing $B_P$ or magnetic rotational transform

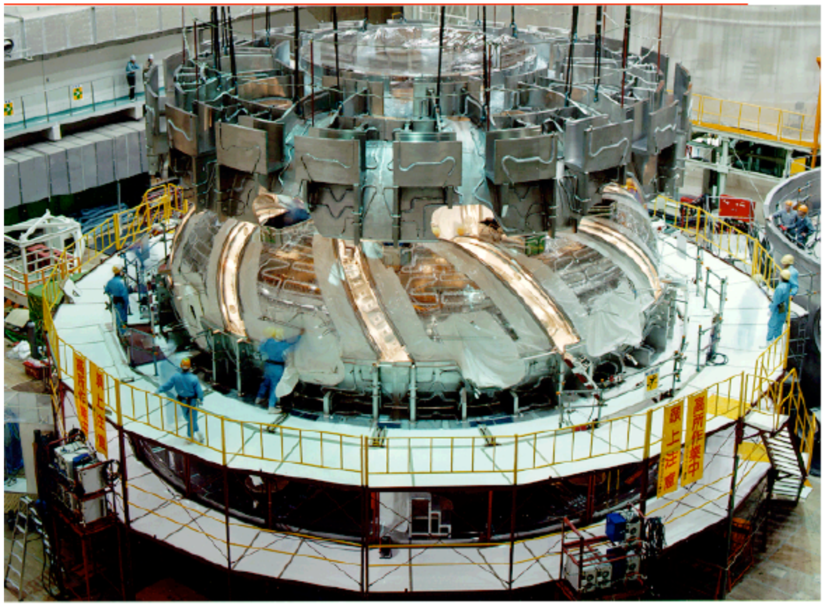
$$□= 1/q \quad B_P / B_T$$

□ current, usually inductive
Tokamaks, STs, spheromaks, FRCs, RFPs…
All axisymmetric configurations

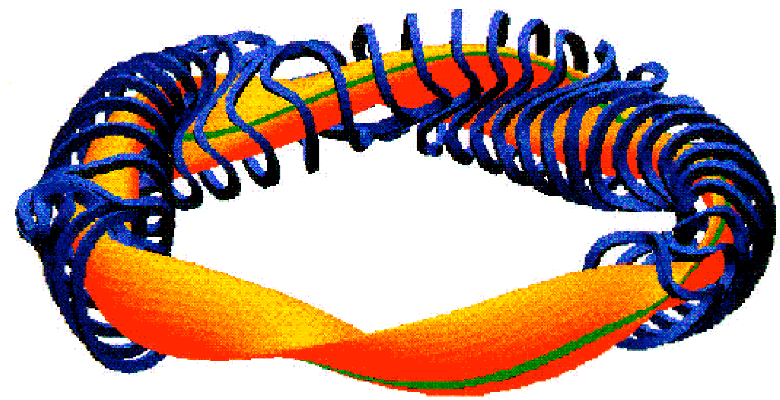
□ 3D helical fields, from external coils: Stellarators
□ intrinsically steady state; external control of configuration
very stable, disruptions not observed



# The World Stellarator Program is Substantial



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



**Wendelstein 7-X (Germany) (2007)**
non-symmetric optimized design:
no current, A□=□11, R=5.4□m, B=3T

- New large international experiments use superconducting coils for steady-state
- Medium-scale experiments (Europe, Japan), and
- Exploratory experiments in US, Japan, Spain, Australia.

**Large aspect ratios; designs without symmetry, no current.**

# 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
- We expect this connection to continue

# Motivation:Combine Best Features of Stellarators and Tokamaks

- Use flexibility of 3D plasma shaping to combine best features of stellarators and tokamaks, synergistically, to advance our understanding of both

   -  Stellarators: *Externally-generated helical fields; steady-state compatible; generally disruption free.*

   -  Tokamaks: *Excellent confinement; low aspect ratio – affordable; self-generated bootstrap current and flows*

The compact stellarator opportunity

# Energy Vision: a More Attractive Reactor

**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/$m^2$)

**Likely configuration features (based on present knowledge)**

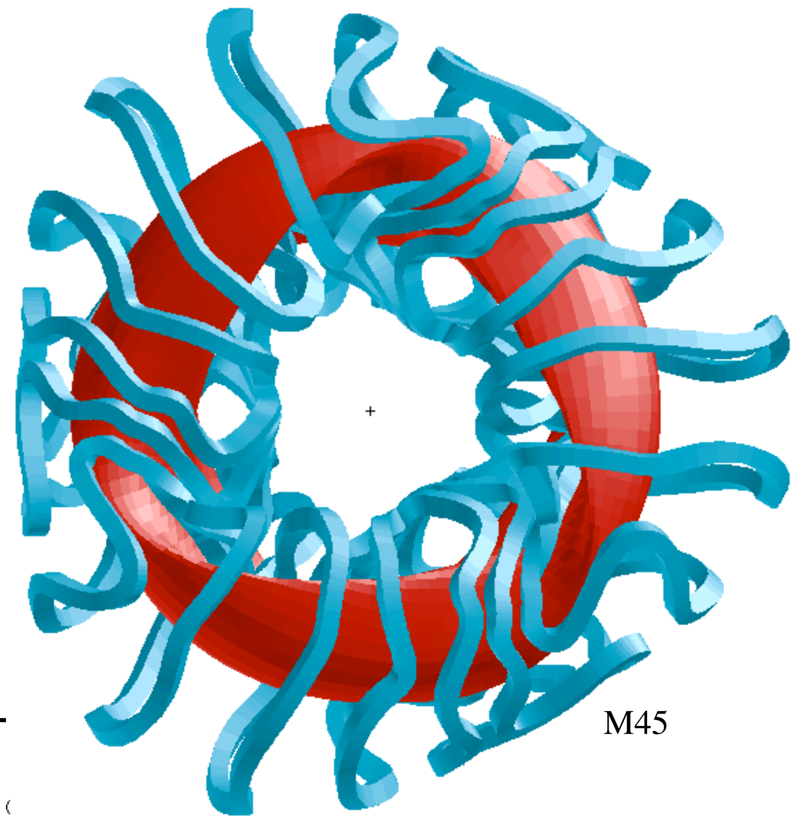
- Rotational transform from a combination of bootstrap and externally-generated (how much of each?)
- 3D plasma shaping to stabilize limiting instabilities (how strong?)
- Quasi-axisymmetric to reduce helical ripple transport, alpha losses, flow damping (how low must ripple be?)
- Power and particle 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 mix, assess attractiveness.**

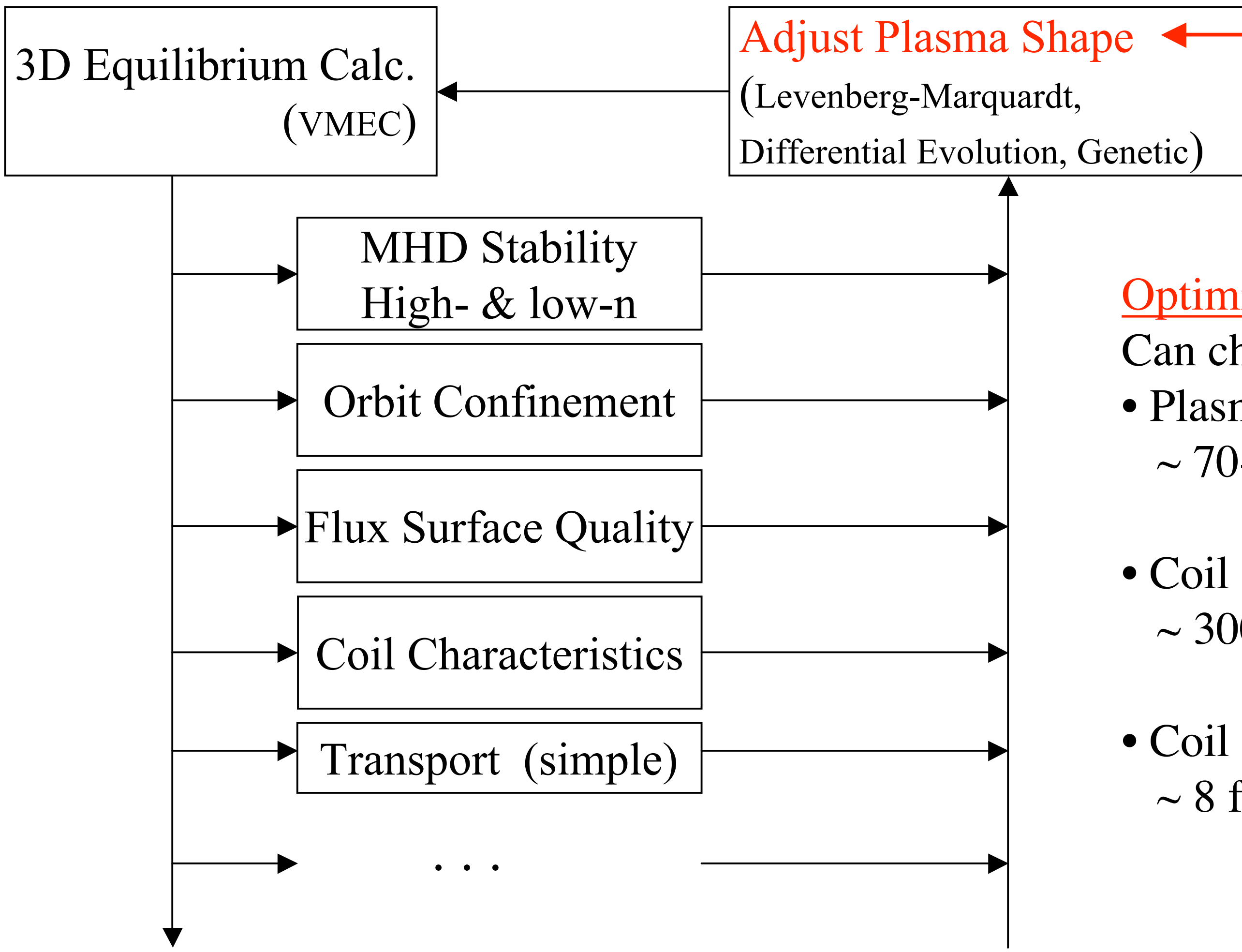
# NCSX Plasma Configuration Has Attractive Physics

- 3 periods, R/□a□=4.4, □□□~1.8
- Quasi-axisymmetric: low helical ripple transport, low flow damping
- Passively stable at □=4.1% to kink, ballooning, vertical, Mercier, neoclassical-tearing modes; without conducting walls or feedback systems.
- Steady state without current-drive
- 18 modular-coils (3 shapes)
  Full coil set includes PF coils & weak T
- Coils meet engineering criteria




Using Advances in Theory and Numerical modeling; parallel computing (NERSC, ACL/LANL, Princeton/PPPL)

# Primary Tool:  Numerical Optimization




Optimization Variables

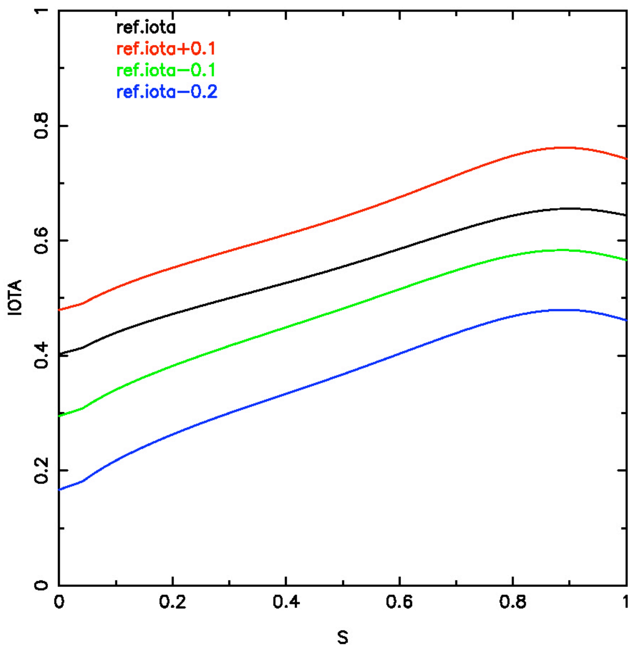
Can choose to vary:

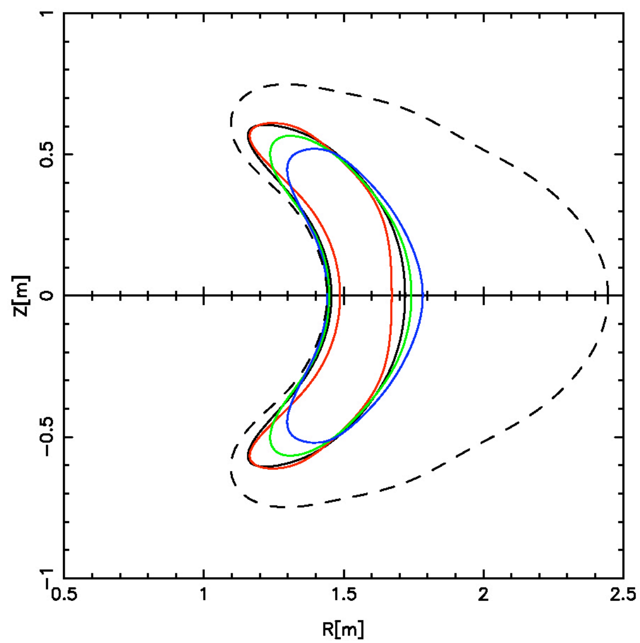
• Plasma Shape
  ~ 70-90 free parameters

• Coil Shapes
  ~ 300 – 400 f.parameters

• Coil Currents
  ~ 8 free parameters

# Modular Coils are Flexibile

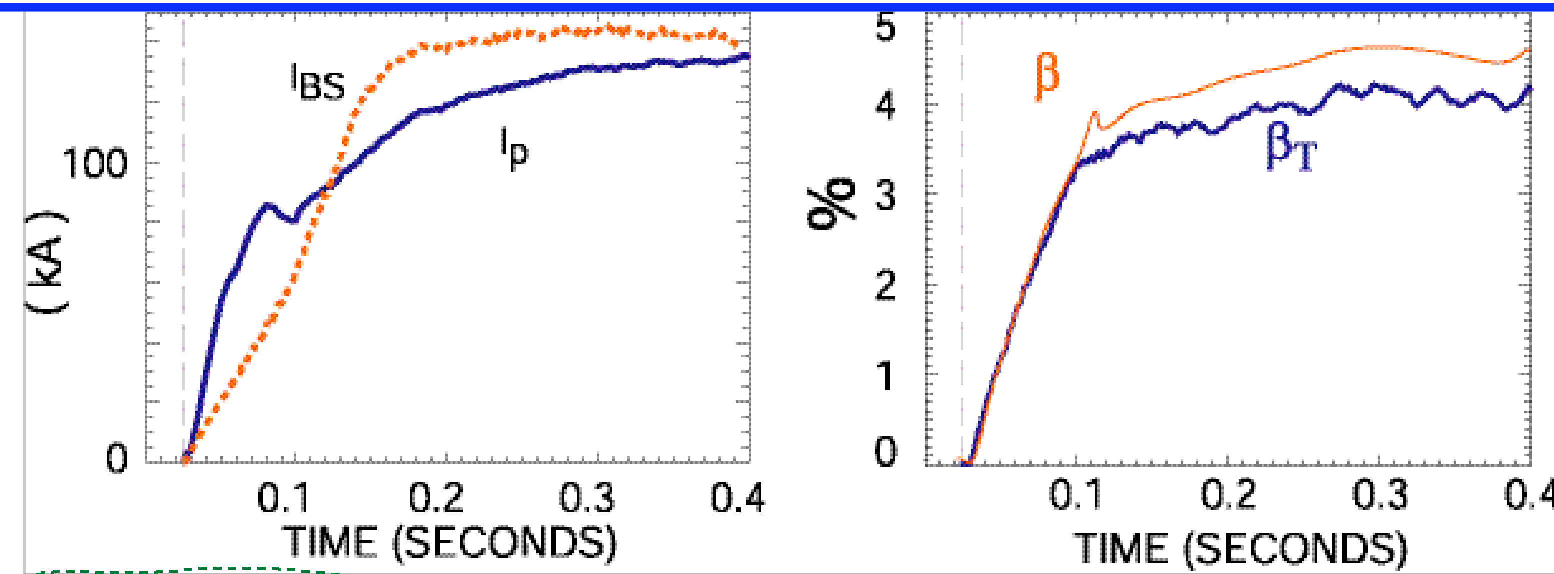


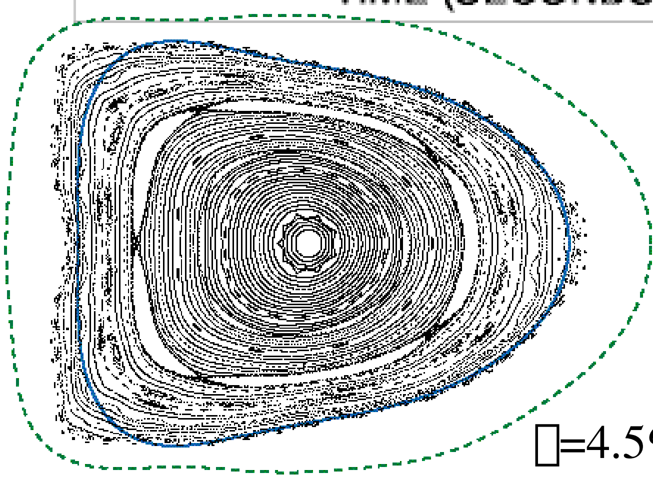




β=4.2%, full current

- 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 accommodate wide range of p,j profiles
- Can use to test stability, island effects. Can lower theoretical β-limit to 1%

# Modeling of Discharge Evolution Shows Stable Access



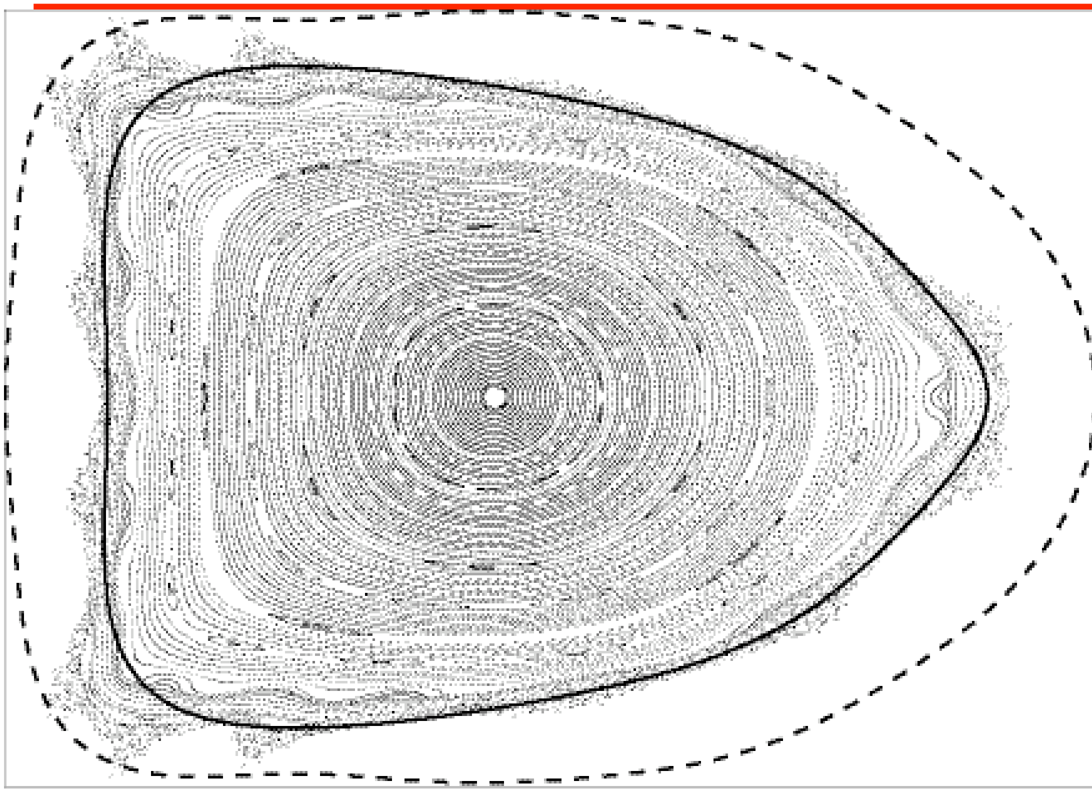



□=4.5%

2.5% effective surface loss

- Profiles modeled using predictive transport model, self-consistent bootstrap current
- Calculated: stable evolution
- Calculations indicate acceptable flux surfaces, including neoclassical effects

# Multiple Methods used to Produce Good Flux Surfaces

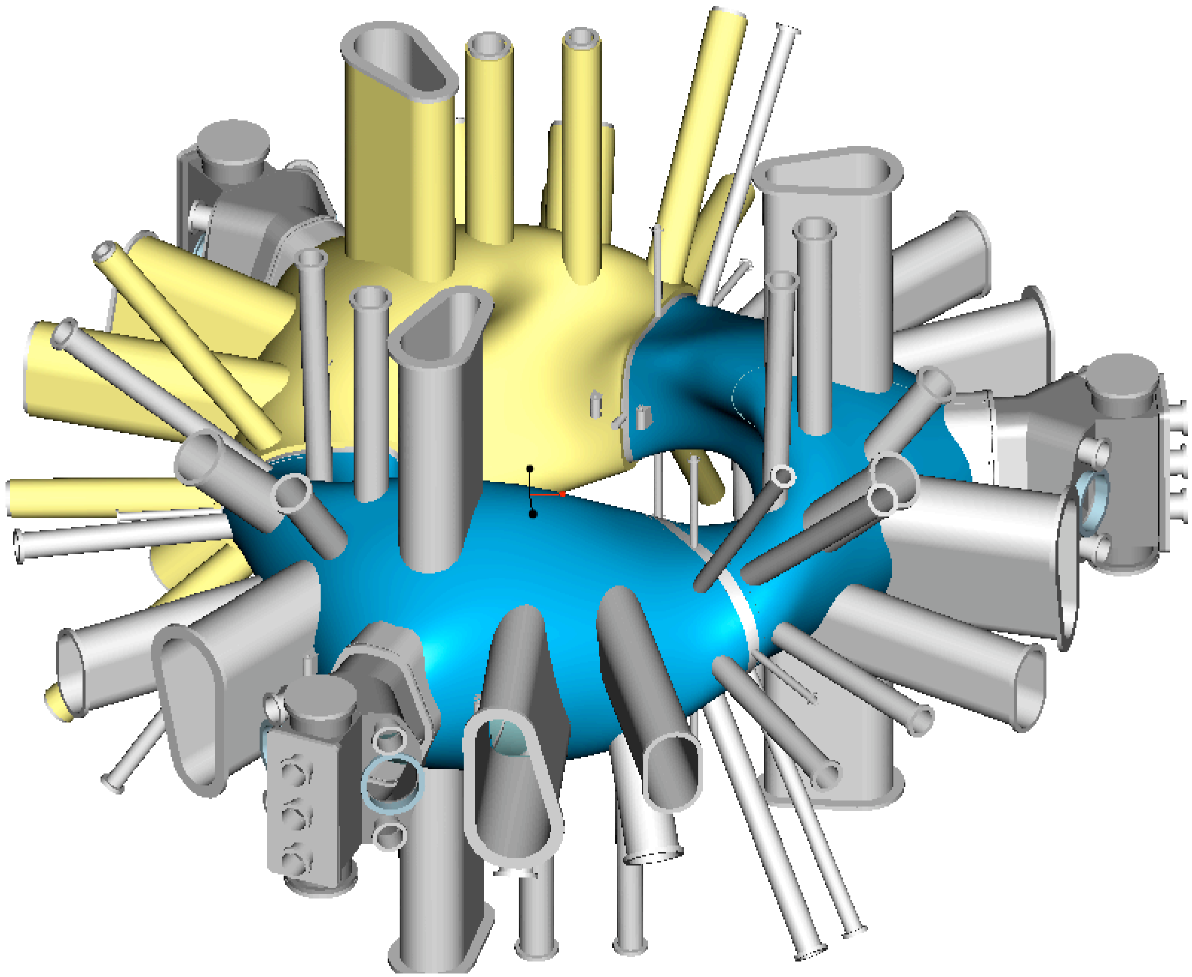


β=4.1% reference
Poincare: PIES
Dashed: first wall
Solid: VMEC boundary

'Healed' coils:
- Infinite-n ballooning unstable on 5/49 surfaces for reference profiles.
- Finite-n ballooning stable thru n=45
- Ok for simulated profiles, flexibility studies.

- Explicit design to eliminate resonant fields, in both fixed boundary target plasma, and in coil designs.
- 'Reversed shear' configuration ⇒ neoclassical healing of equilibrium islands and stabilization of tearing modes
- Trim coil arrays targeting low-order resonances (upgrade)

# 3D Engineering:  Also Computationally Intensive



## Conclusions

**A sound physics design has been established for NCSX**

- Attractive configuration has been designed
  - Builds upon what we have learned from tokamaks and stellarator research
  - Projects to an attractive reactor vision
- Robust, flexible coil system for testing understanding and exploring
- Coils meet physics and engineering criteria

**NCSX will be a valuable national facility for the fusion science program.**

**Demonstration of the capabilities of integrated modeling and design optimization**