Physics Basis for High-Beta, Low-Aspect-Ratio Stellarator Experiments

G. H. Neilson
Princeton Plasma Physics Laboratory

for the National Compact Stellarator Design Team

41st Annual Meeting, APS Division of Plasma Physics
Seattle, WA
November 17, 1999

The Compact Stellarator Team

R. D. Benson, ORNL
L. A. Berry, ORNL
B. Blackwell, ANU
A. H. Boozer, Columbia U.
A. Brooks, PPPL
T. G. Brown, PPPL
M. Cole, ORNL
W. Cooper, CRPP
M. Drevlak, IPP-Greifswald
G. Y. Fu, PPPL
P. Garabedian, NYU
A. Georgievskiy, Raytheon
R. J. Goldston, PPPL
P. Goranson, ORNL
J. Hanson, Auburn U.
P. Heitzenroeder, PPPL
S. P. Hirshman, ORNL
W. Houlberg, ORNL
M. Isaev, Kurchatov

C. E. Kessel, PPPL
L.-P. Ku, PPPL
H. Kugel, PPPL
E. Lazarus, ORNL
Z. Lin, PPPL
J. F. Lyon, ORNL
R. Majeski, PPPL
P. Merkel, IPP-Greifswald
M. Mikhailov, Kurchatov
D. Mikkelsen, PPPL
W. Miner, U. Texas
D. A. Monticello, PPPL
H. Mynick, PPPL
N. Nakajima, NIFS
G. H. Neilson, PPPL
B. E. Nelson, ORNL
C. Neuhrenberg, IPP-G.
M. Okamoto, NIFS

N. Pomphrey, PPPL
M. H. Redi, PPPL
W. T. Reiersen, PPPL
A. H. Reiman, PPPL
G. Rewoldt, PPPL
R. Sanchez, CIEMAT
J. A. Schmidt, PPPL
J. Schultz, MIT
R. T. Simmons, PPPL
D. A. Spong, ORNL
D. Strickler, ORNL
A. Subbotin, Kurchatov
P. Valanju, U. Texas
K. Y. Watanabe, NIFS
R. B. White, PPPL
D. A. Williamson, ORNL
M. C. Zarnstorff, PPPL
I. Zatz, PPPL

Auburn U., Columbia U., ORNL, PPPL, U. Texas-Austin, U. Wisconsin.
Germany, Switzerland, Russia, Japan, Australia

Stellarators Offer Innovative Solutions to Critical Problems of Magnetic Fusion

- Challenge for MFE: Finding a high-beta plasma configuration that can be sustained in steady-state without disrupting.
- Advanced tokamaks:

  Bootstrap current, current profile control, MHD mode control.
  ⇒ Elaborate controls to avoid disruptions; high recirculating power ($Q_{eng} \approx 5$)
- Stellarators:

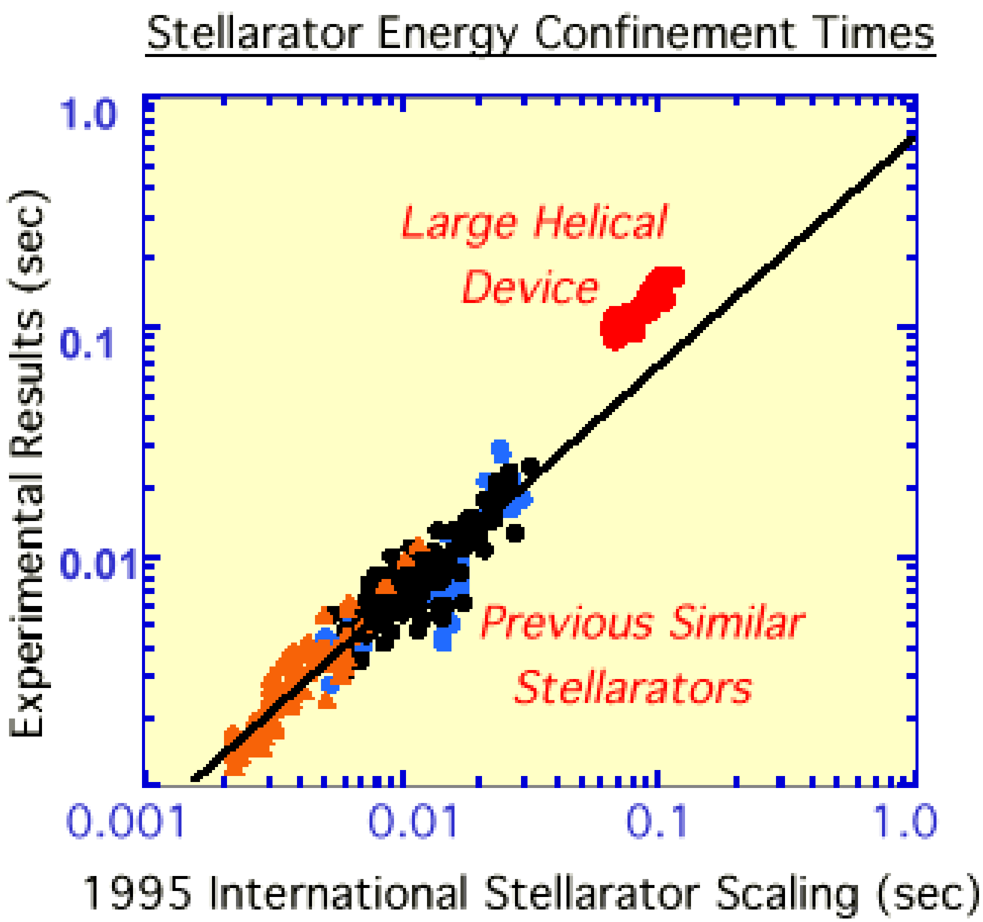
  Externally-generated helical fields, 3D shaping.
  ⇒ High aspect ratio (5-12), low power density ($\leq$1 MW/m^2 neutron wall load)
- Low-aspect-ratio ($\leq$4), high-β ($\geq$5%) stellarators (“Compact Stellarators”).

  Bootstrap current + helical fields & 3D shaping.
  ⇒ Disruption-free operation at tokamak-like performance and aspect ratio.

Outline: Developing the Physics Basis for Compact Stellarators

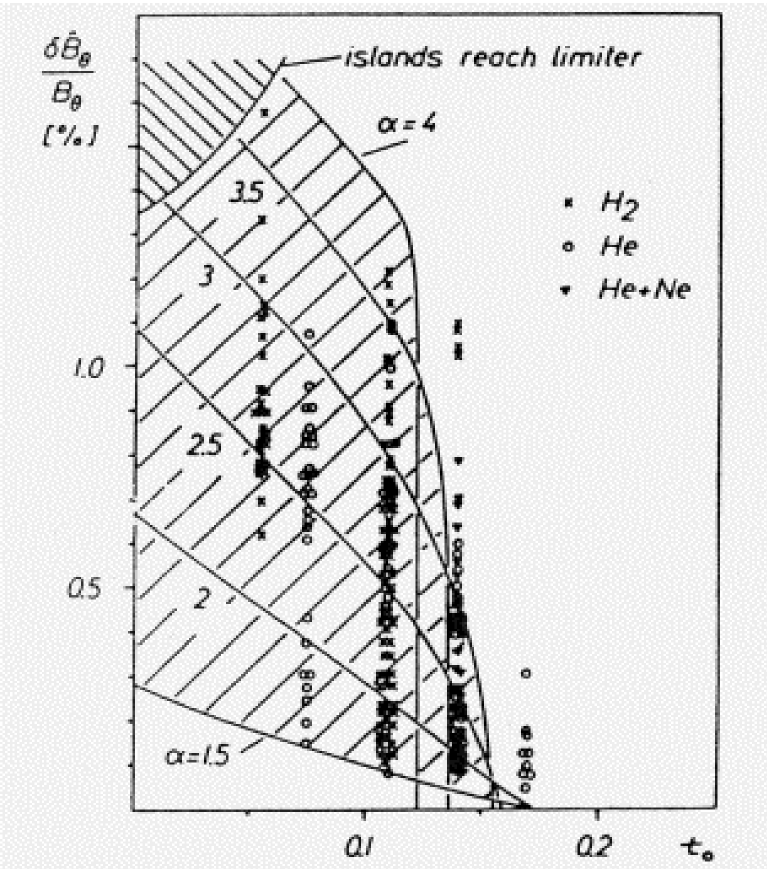
- Toroidal physics knowledge base.
- Compact-stellarator concepts.
- Planned experiments: goals and physics design.

Enhanced Confinement is Obtained in Stellarators



- Similar enhancement (x2.3) seen in low-shear W7-AS.
- ISS95 multi-device empirical scaling similar to tokamak ITER-89P.

Stellarator Fields Can Suppress Disruptions



- Application of external transform:
  - 3-fold increase in density limit.
  - q<2 with no disruptions.
- total ι(a) = 0.35
- Ohmic currents, low β, high aspect ratio.

WVII-A Team, Nucl. Fusion **20** (1980) 1093.

- Disruptions typically not observed in stellarators, if conditions for global tearing stability are satisfied.
- Need experiments to extend to high β, low aspect ratio configurations.

Stellarator Physics Basis- Status and Directions

- Experiments at $T \leq 5$ keV, $n \leq 3 \times 10^{20}$ m^{-3}, $\langle \beta \rangle \leq 2.1\%$, $t_{pulse} \sim 1$ hr.
- Confinement scaling similar to tokamaks, enhanced-confinement regimes.
- Theory-based numerical design capability with computational tools.
- Stellarator research- current directions:
  - New large devices focussed on steady-state, divertor issues.
  - Plasma configurations optimized for high β, well-confined orbits, no current.
  - Large aspect ratios ($R/\langle a \rangle$ = 5-12).
  - Large reactors, e.g. W7-X-based HSR design at R=22 m.
- New direction- broaden the base by adding tokamak-developed physics:
  - Bootstrap current.
  - Transport barrier control via flow shear.

  $\Rightarrow$ Basis for **High Beta, Low-Aspect-Ratio** configurations.

Recent Advances in Theory and Numerical Design Capability ⇒ Compact Stellarators

Apply toroidal physics and 3D shaping to create toroidal magnetic configurations satisfying physics goals.

- Stabilize ballooning, kink, vertical, neo. tearing at high β, even with current.
- Good confinement.
- Steady state without current drive.

Two approaches to CS plasmas with AT-like β (5%) and aspect ratio (<4) will be tested experimentally.

- Quasi-axisymmetry (QA): Hybrid of AT (bootstrap current) + stellarator: **NCSX**
- Quasi-omnigeneity (QO): Low current, advanced-stellarator-like physics: **QOS**

National Compact Stellarator Experiment (NCSX): Develop the Physics of High-Beta QA Stellarators

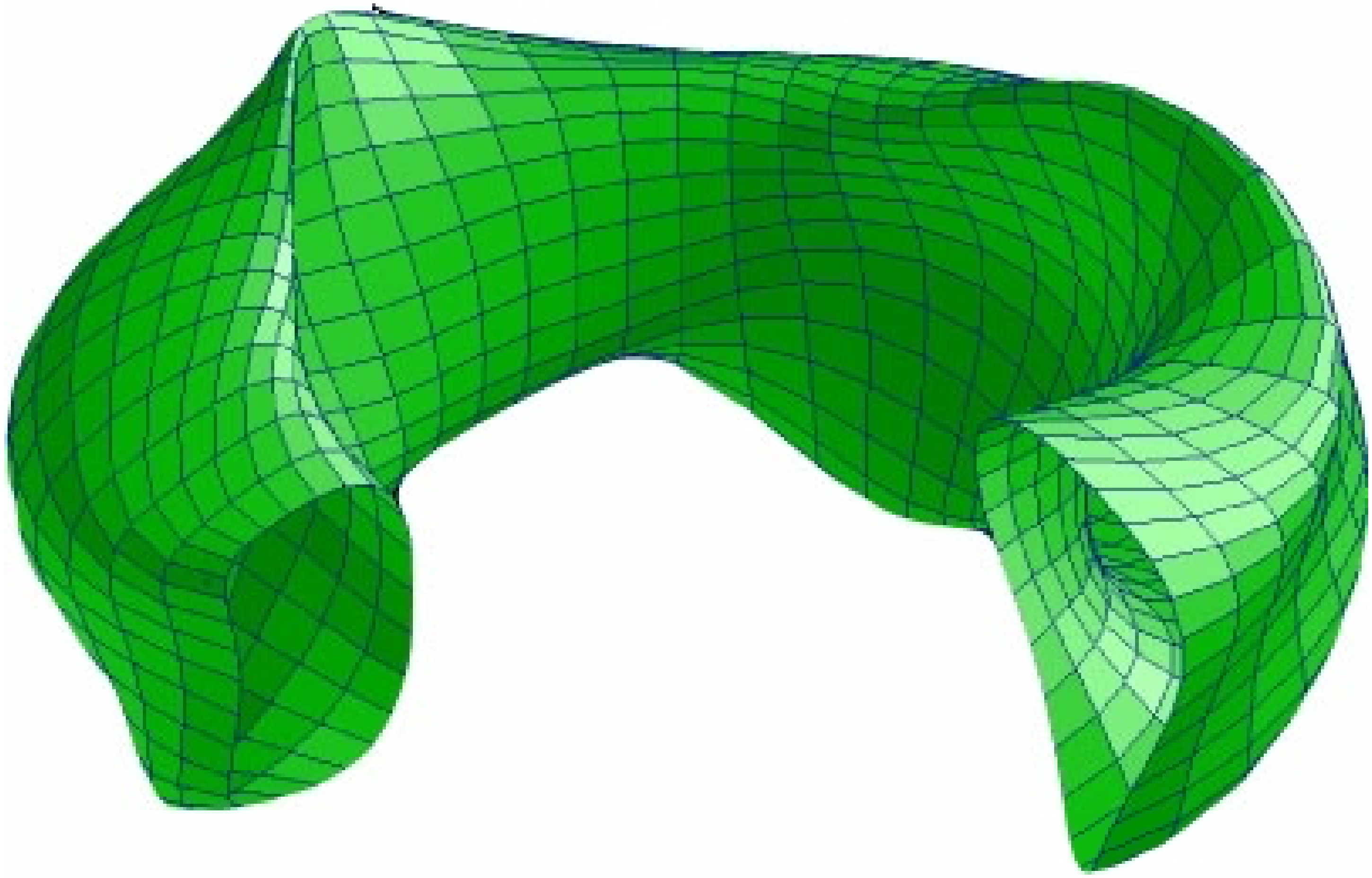
Demonstrate…

- High-beta, disruption-free operation with bootstrap + external transform.

Understand…

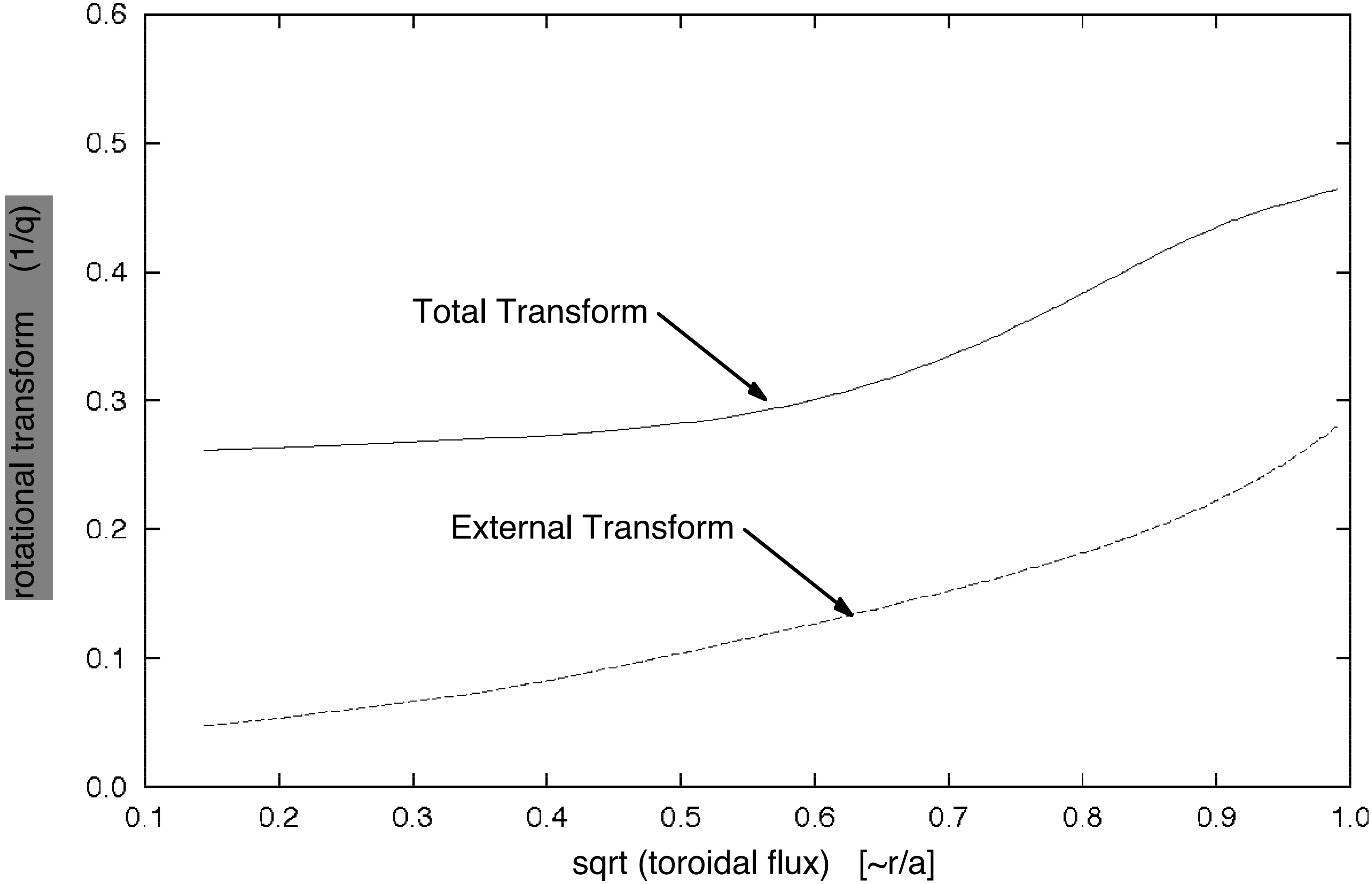
- Beta limits and limiting mechanisms.
- Reduction of neoclassical transport by QA design.
- Confinement scaling; reduction of anomalous transport by flow shear control.
- Equilibrium islands and neoclassical tearing-mode stabilization by choice of magnetic shear.
- Compatibility with power and particle exhaust methods.

NCSX Plasma Configuration Stable at $\langle\beta\rangle$=4%

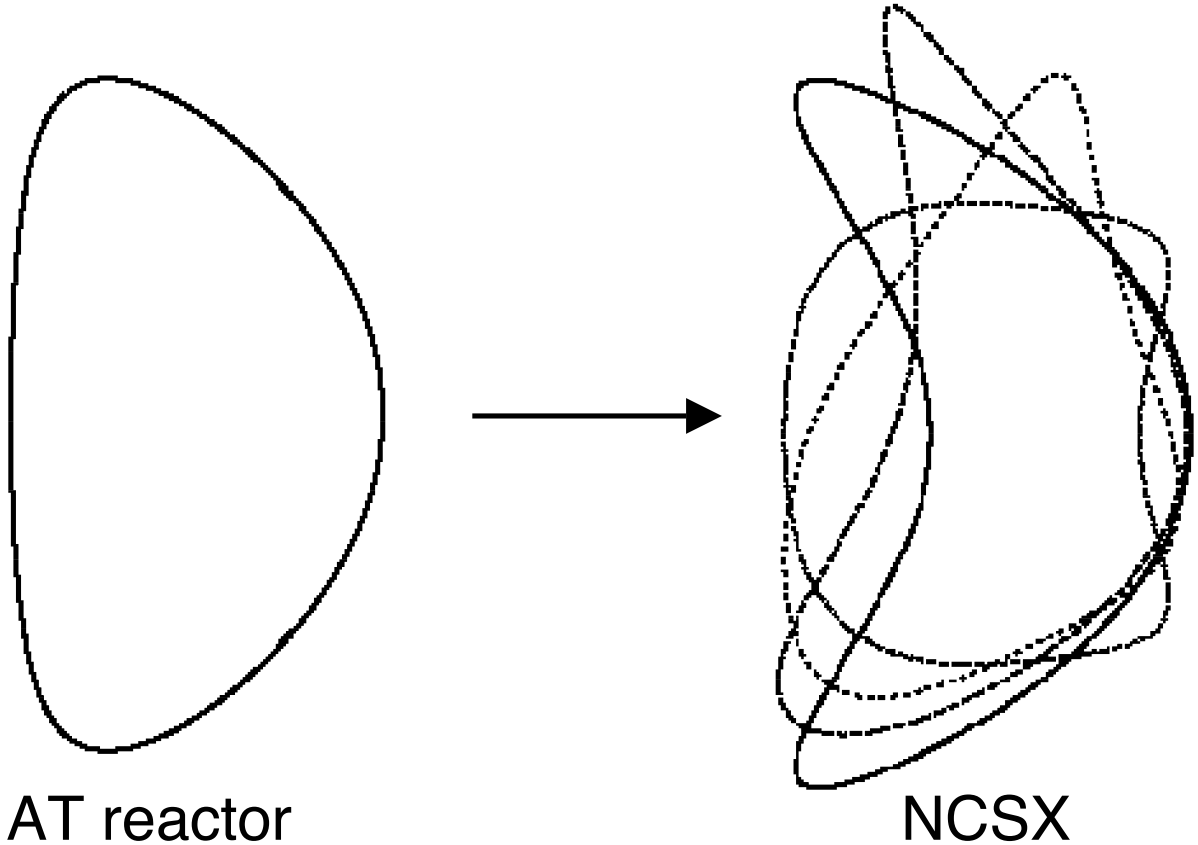


- Aspect ratio 3.4
- 3 field periods
- Assumed bootstrap-like current profile.
- Stable to ballooning, kink, vertical, Mercier modes without nearby conducting structures.

NCSX Coils provide edge shear and ~50% of transform

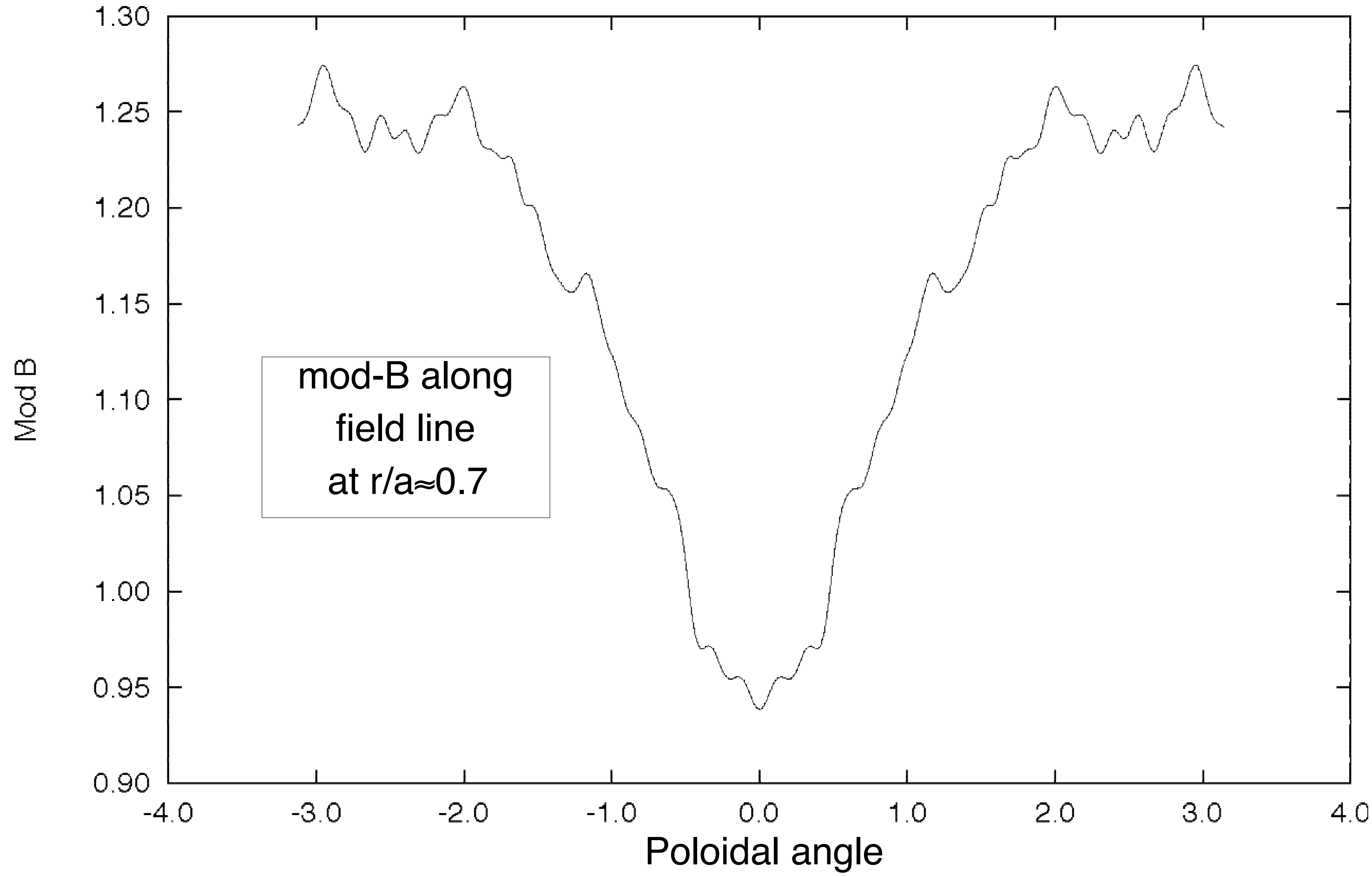


AT→QAS 3D Plasma Deformation for MHD Stability



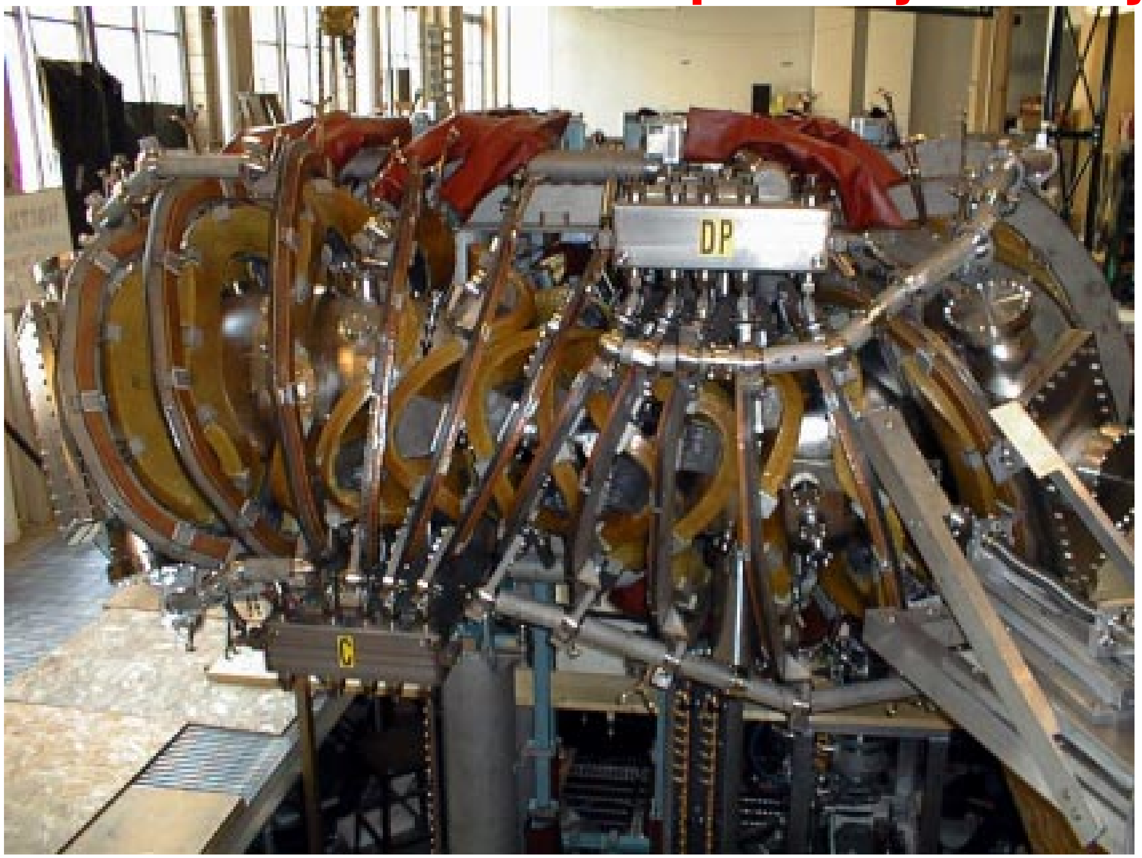
- Ballooning stability (strong axisymmetric shaping).
- Kink stability (edge shear + boundary corrugation).
- Vertical stability (strong external rotational transform).
- Neoclassical tearing stability (stellarator shear everywhere).

IBI Looks Tokamak-Like



- Approximate **quasi-symmetry** (~axisymmetric IBI spectrum in magnetic coordinates) for tokamak-like: neoclassical transport and orbit confinement, bootstrap current, ability to flow.

Helically Symmetric Experiment (HSX) will test transport reduction via quasi-symmetry principles



- R_0=1.2 m
- $\langle a \rangle$=0.15 m
- Aspect ratio 8
- B=1 T

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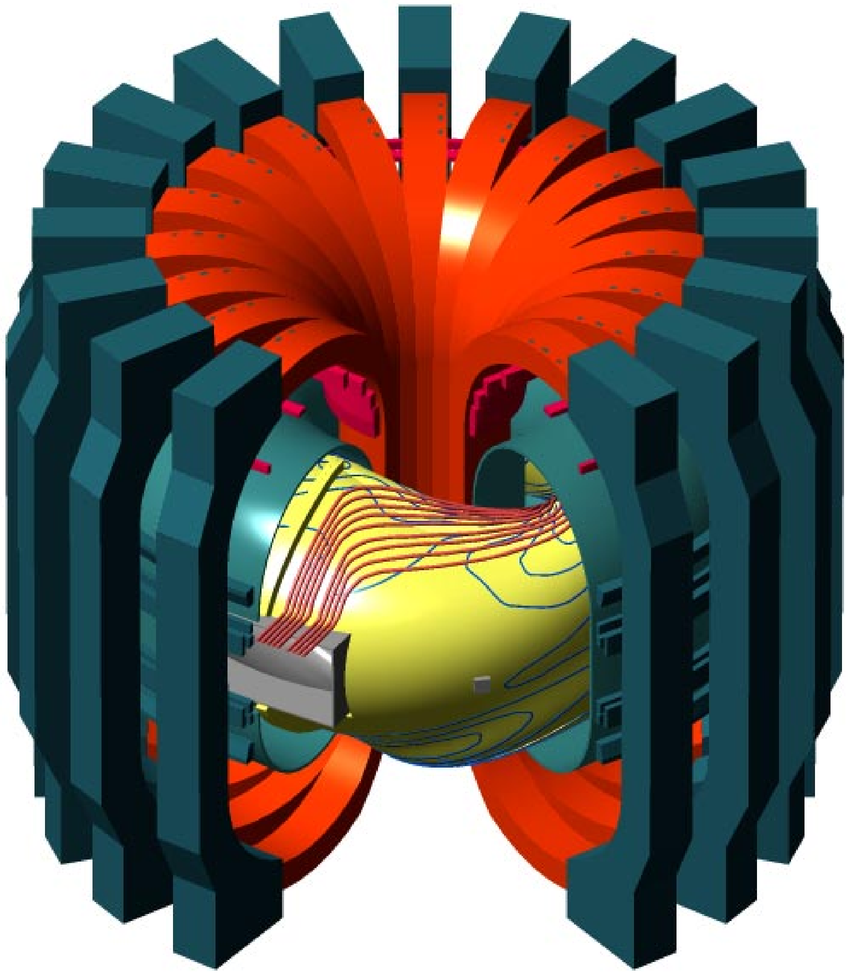
NCSX Coil System Using Existing PBX-M Components



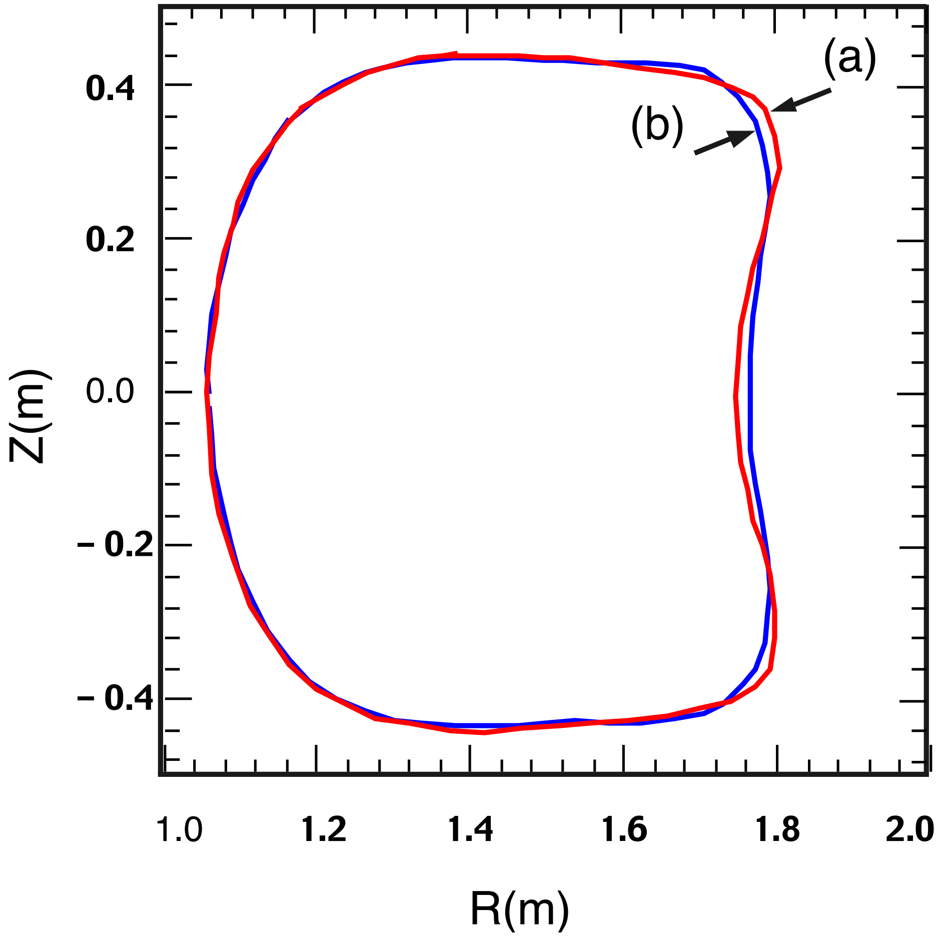
- TF Coils
- PF Coils (not shown)

- New saddle coils (with independent feeds) provide 3D shaping fields, flexibility.

- R=1.45 m, ⟨a⟩=0.42 m
- Aspect ratio 3.5

- NBI heating (6 MW)

Saddle Coils Provide Flexibility to Test Key Physics



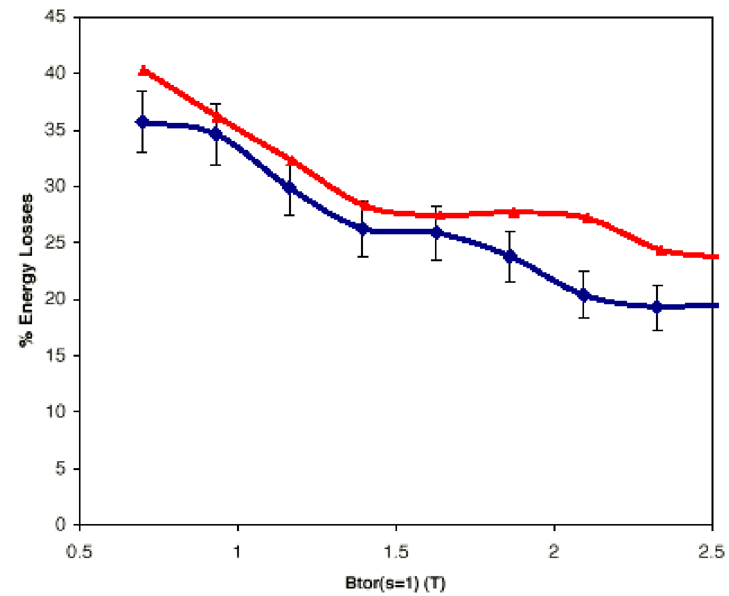
outboard "corrugation" stabilizes kink

(a) marginally stable
(b) kink unstable

- Coils reconstruct plasma boundary (within 1.2 cm avg.) and preserve physics properties– QA and stability.
- Can test kink stabilization with ~10% current adjustment.

NCSX Confinement Projections Using 3D Simulations

Neutral Beam Orbit Loss vs B ⟶



- 3D Monte Carlo orbit-following code with full collision operator.
- Deposition profile from 2D TRANSP simulation.
- Co-injection $H^0 \rightarrow H^+$ favored.

Thermal Neoclassical Transport

- 3D gyrokinetic M-C code for electrons, ions.
- Assume $e(\Phi_a - \Phi_0) = T_{i0}$ to approximate ambipolar E_r (ion root); increases confinement by ~30%.
- Neoclassical confinement time $\propto B^2$. Electron transport << ions.

Operating Points, assuming $\tau_E = \min(2.3 \times \tau_E^{ISS95}, \tau_E^{neo}/2)$

- Project $\langle\beta\rangle$=4%, B=1.5 T, P_{inj}=6.9 MW.
- In progress: improved confinement-optimization; RF heating scenarios.

Low-R/a Quasi-Omnigeneous Stellarators

- Approximately aligns bounce-averaged drift orbits and magnetic surfaces to reduce neoclassical transport and orbit loss.

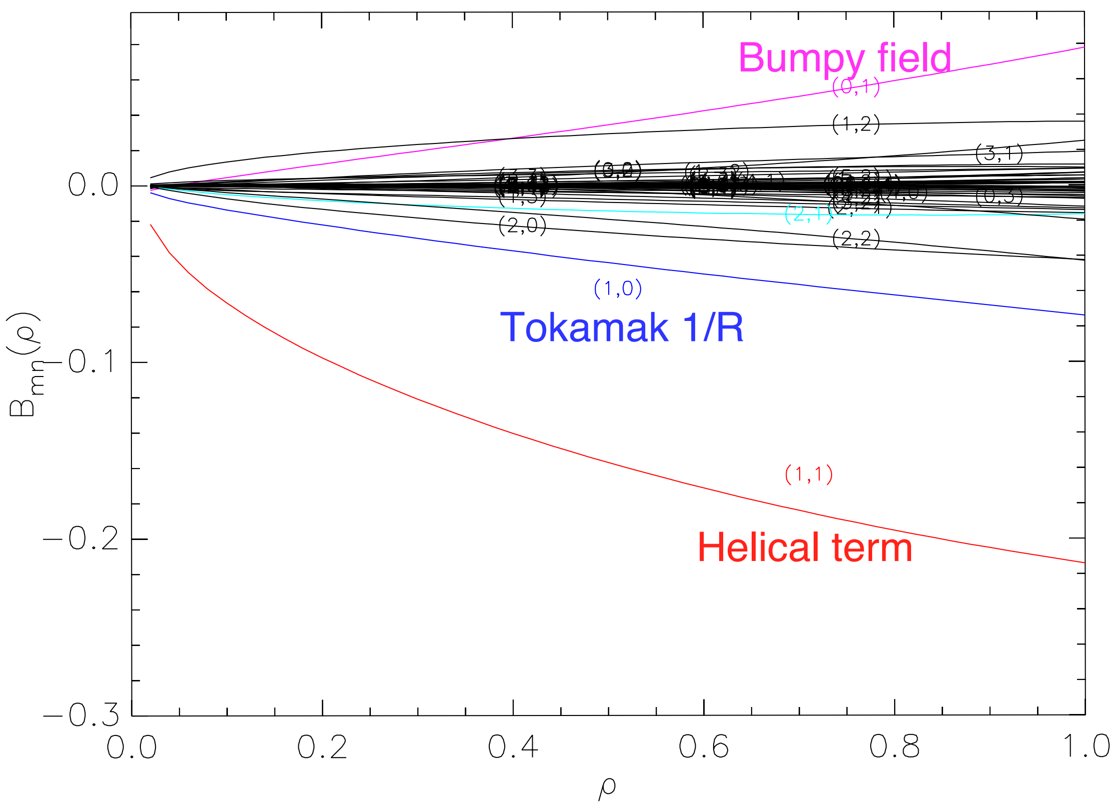
- Magnetic well and stellarator shear out to edge.

- Low bootstrap current (~1/10 of tokamak) makes configuration insensitive to β.
  - magnetic shift $<0.1\langle a\rangle$ as β varies $2\rightarrow6\%$.
  - iota reduced <8% in reference QOS configuration (β=2%)

QOS Experiment will test

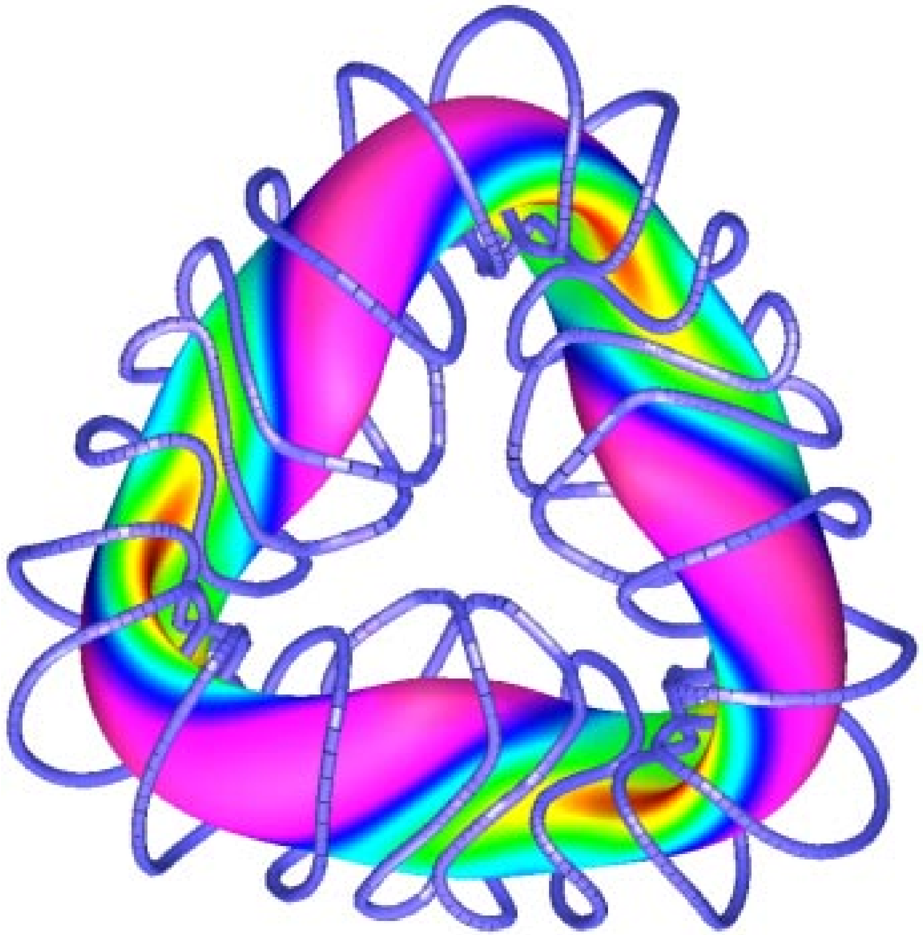
- Reduction of orbit loss and neoclassical transport
- Reduction of bootstrap current
- Configuration invariance with beta.

R/a=3.6 QO Spectrum Has Unique Characteristics



- Large helical term (~3×W7X) increases vacuum iota (~0.6)
- 1/R term ~1/4×tokamak reduces toroidal curvature drift.
- Radially-varying mirror ("bumpy") term produces poloidal grad-B drift.

QOS Plasma Configuration and Modular Coils



R_0 = 1 m, $\langle a \rangle$ = 0.28 m

$R_0/\langle a \rangle$ = 3.6

B_0 = 1 T

ɫ(0) = 0.56, ɫ(a) = 0.65 (monotonic)

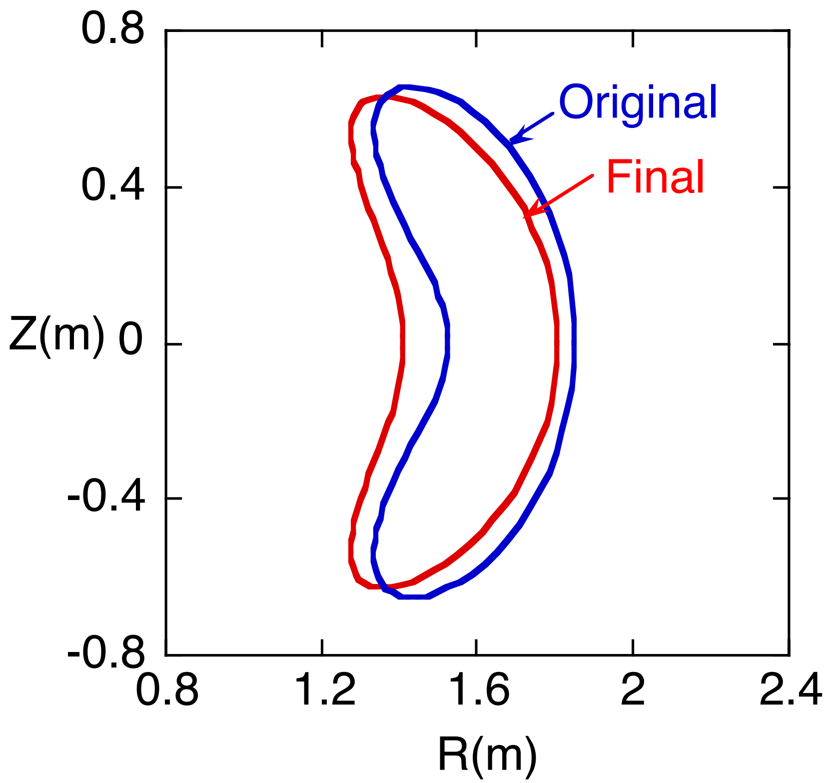
vacuum well

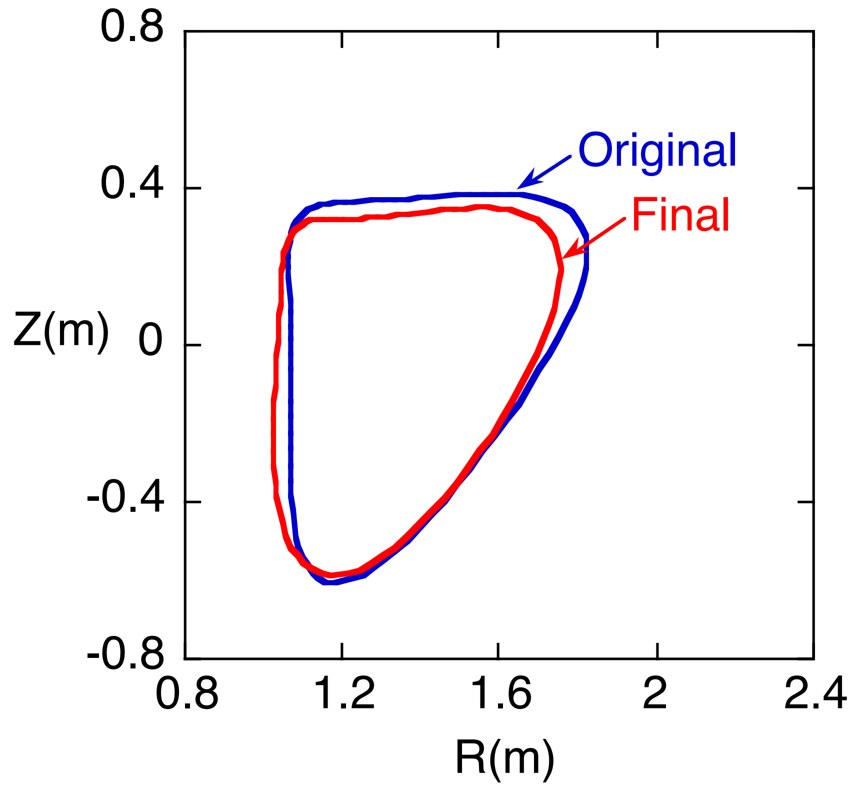
neoclassical $\tau_E \approx 3\text{-}5 \times$ISS95 scaling

(Monte Carlo loss rate calculation)

- Large helical deformation distinguishes from QA shape.

QOS Ballooning Beta Limit Increased by 3D Reshaping





β = 2% (“original”) → β > 4% (“final).

Summary

Compact stellarators combine the best of stellarators and advanced tokamaks: Steady-state disruption-free operation at tokamak-like performance and aspect ratio.

Dramatic progress in physics development for compact stellarators has strengthened the basis:

- Stability to ballooning modes through shaping.
- Stellarator shear for neoclassical tearing stability.
- Equilibrium reconstruction from practical coils preserving key physics properties.
- NCSX: Kink and vertical stability in high-bootstrap, advanced-tokamak-like QA configuration.
- QOS: Good neoclassical confinement in low-aspect-ratio, advanced-stellarator-like QO configuration.

Next Physics Development Steps

NCSX

- Magnetic surface robustness throughout plasma evolution.
- Optimization of coils and transport.
- Access for full diagnostic and heating complement.

QOS

- Plasma configuration and modular coils optimized for experiment.
- Assessment of performance and flexibility.