Design of Compact Stellarator Experiments

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10th International Toki Conference
Toki City, Japan
January 21, 2000

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U.S. Fusion Researchers Have a Renewed Interest in Stellarators

- Why?
  - Fusion Energy
  - Science

- Design of Planned Experiments
  - Physics
  - Coils
  - Machine Concepts

- Plans and Schedule

Stellarators Offer Innovative Solutions to Critical Problems of Magnetic Fusion

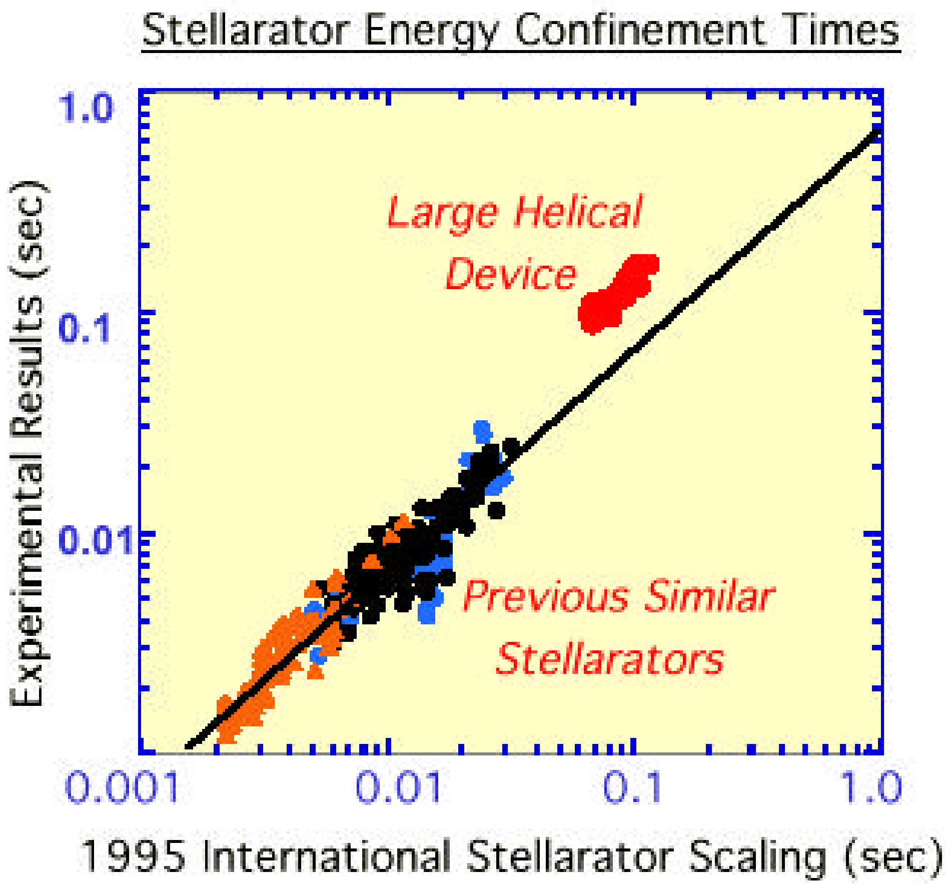
- Challenge for MFE: Finding a high-beta plasma configuration that can be sustained in steady-state without disrupting.
  Difficult task. Must pursue multiple solutions.

- Advanced tokamaks:
  Bootstrap current, current profile control, MHD mode control.
  Elaborate controls to avoid disruptions; high recirculating power (Q_{eng}≈5)

- Stellarators:
  Externally-generated helical fields, 3D shaping.
  High aspect ratio (5-12), low power density (≤1 MW/m^2 neutron wall load)

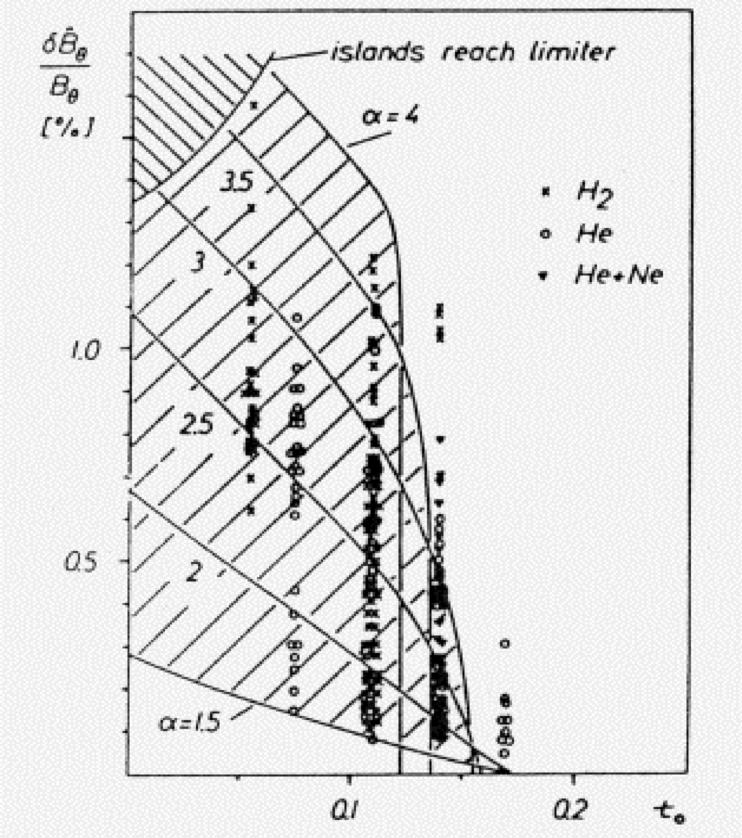
- Low-aspect-ratio (≤4), high-β (≥5%) stellarators ("Compact Stellarators").
  Bootstrap current + helical fields & 3D shaping.
  Disruption-free operation at tokamak-like performance and aspect ratio.

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 Research- Status and Directions

- Strong program world-wide, with $1B-class devices.

Strong knowledge base

- Experiments: confinement scaling similar to tokamaks, enhanced-confinement regimes obtained. Good parameters achieved.
- Theory: numerical design capability with computational tools.
- Engineering: Accurate 3-D coils and structures, at a range of scales.

Current directions

- New large devices to study 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: Combine Tokamak and Stellarator Physics $\Rightarrow$ "Compact Stellarators"

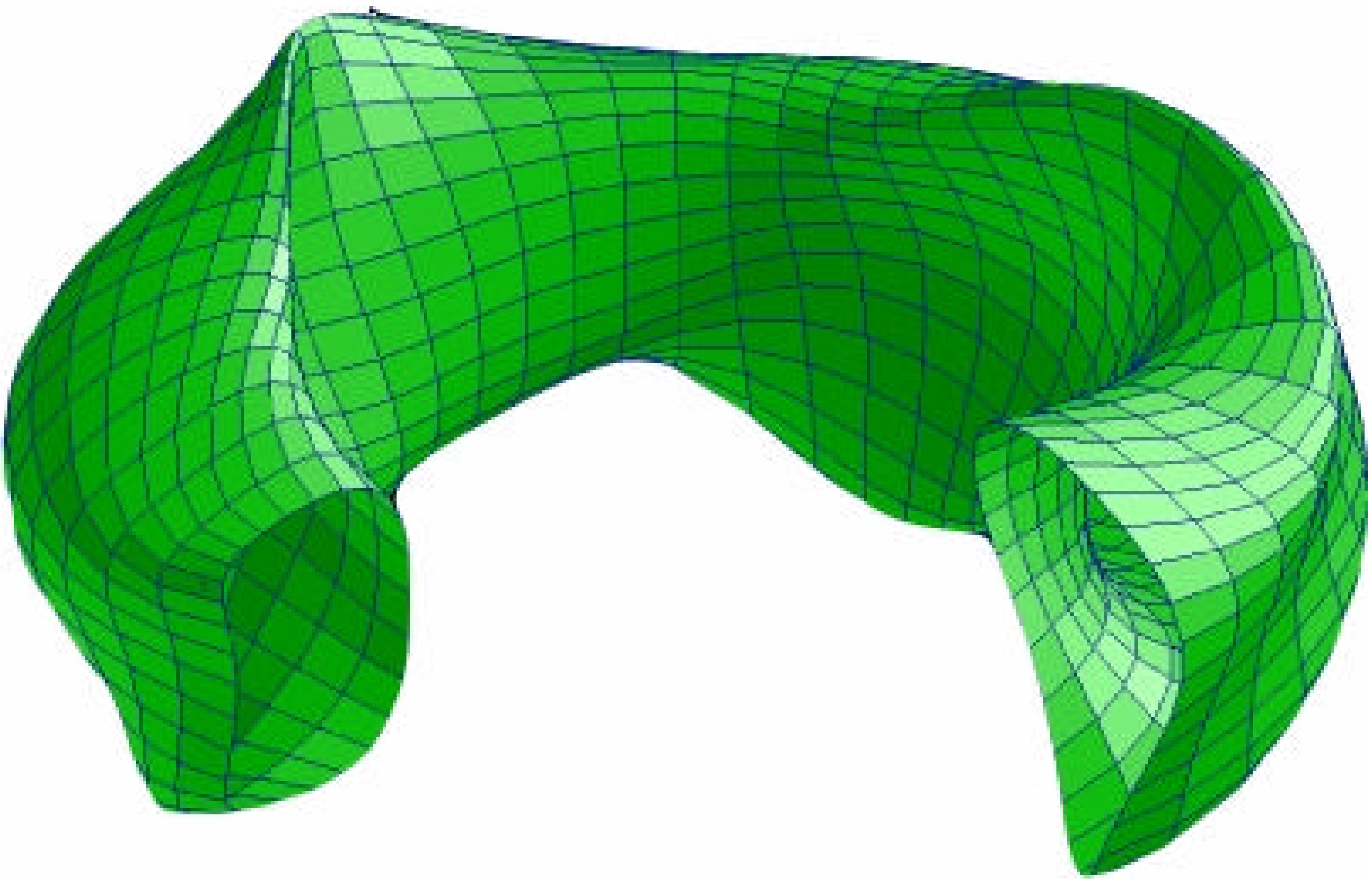
Combine tokamak physics and 3D shaping to create toroidal magnetic configurations satisfying physics goals.

- Bootstrap current.
- Stabilize ballooning, kink, vertical, neo. tearing at high β, even with current.
- Good confinement. Possibility of transport barriers via flow-shear.
- Steady state without current drive.

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

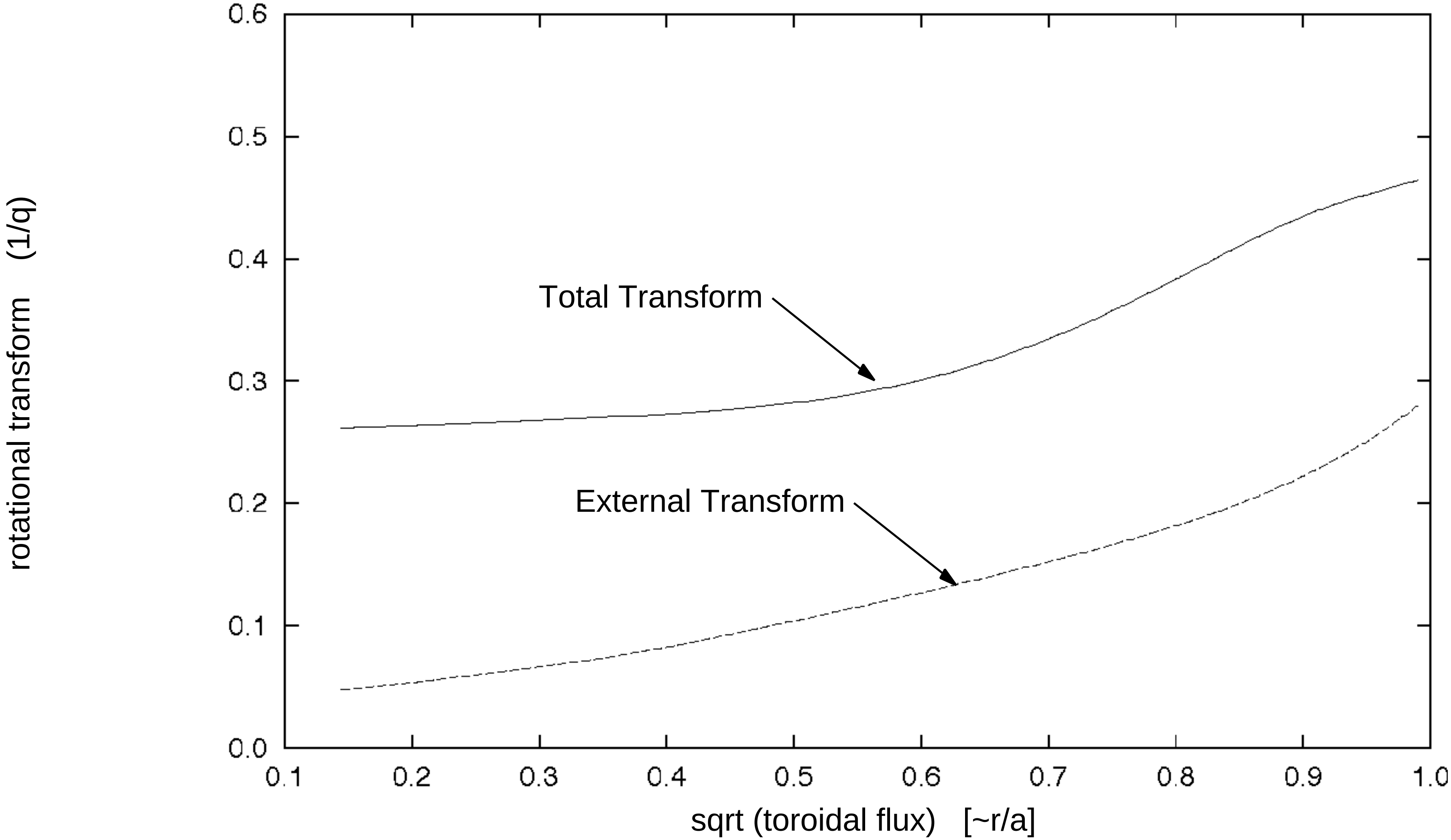
- Quasi-axisymmetry (QA): *Hybrid of AT (bootstrap current) + stellarator:* **NCSX**
- Quasi-omnigeneity (QO): *Low current, advanced-stellarator-like physics:* **QOS**

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

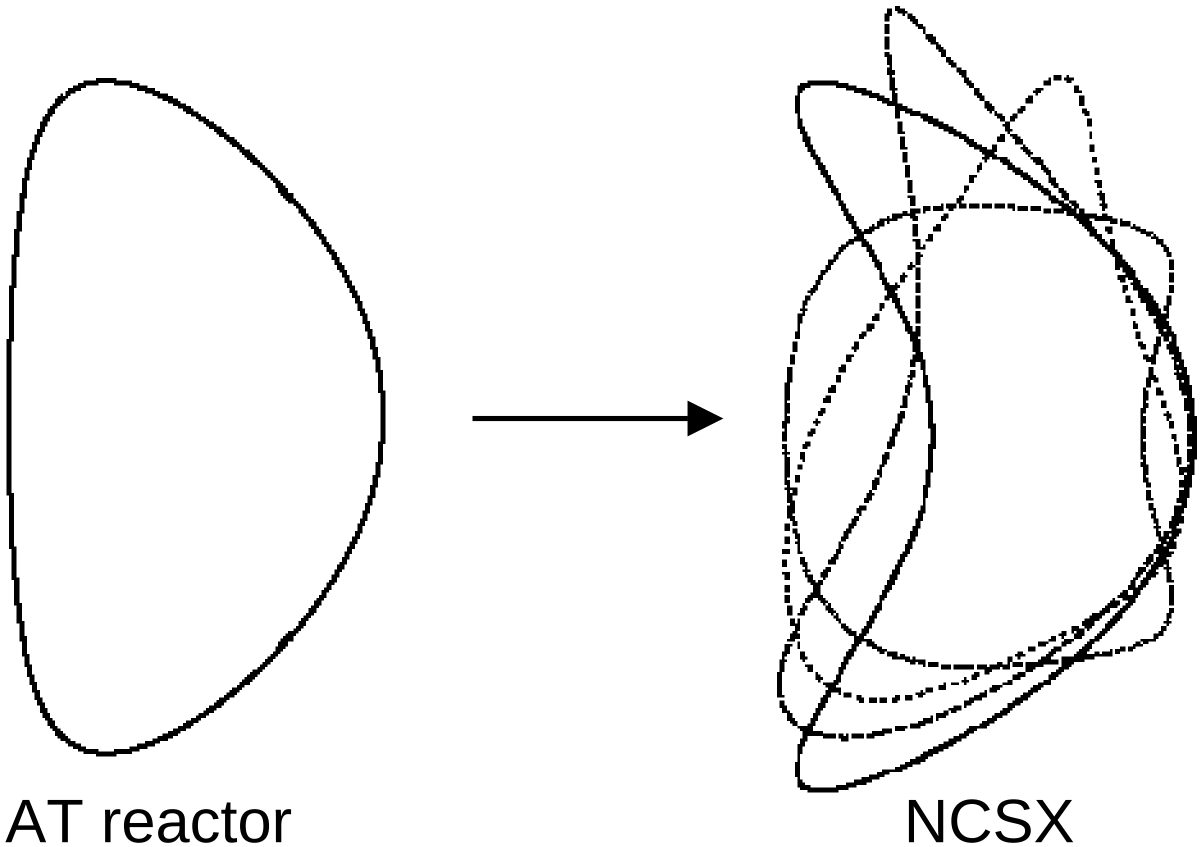


- Aspect ratio 3.4
- 3 field periods
- Assumed bootstrap-like current profile.
- Stable to ballooning, kink, vertical, Mercier modes without nearby conducting structures.

NCSX Coils provide edge shear and ~50% of transform

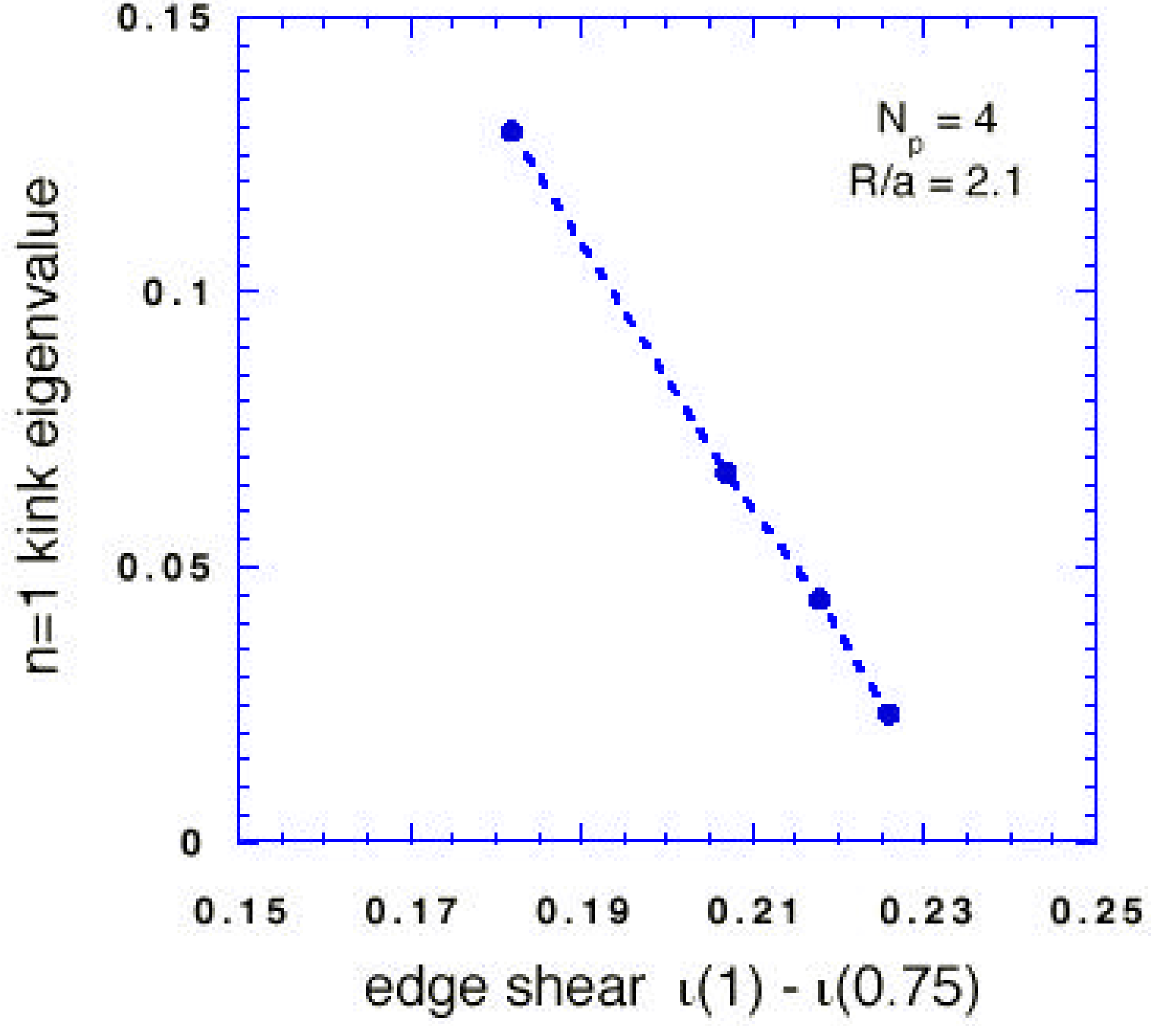


AT→QAS 3D Plasma Deformation for MHD Stability

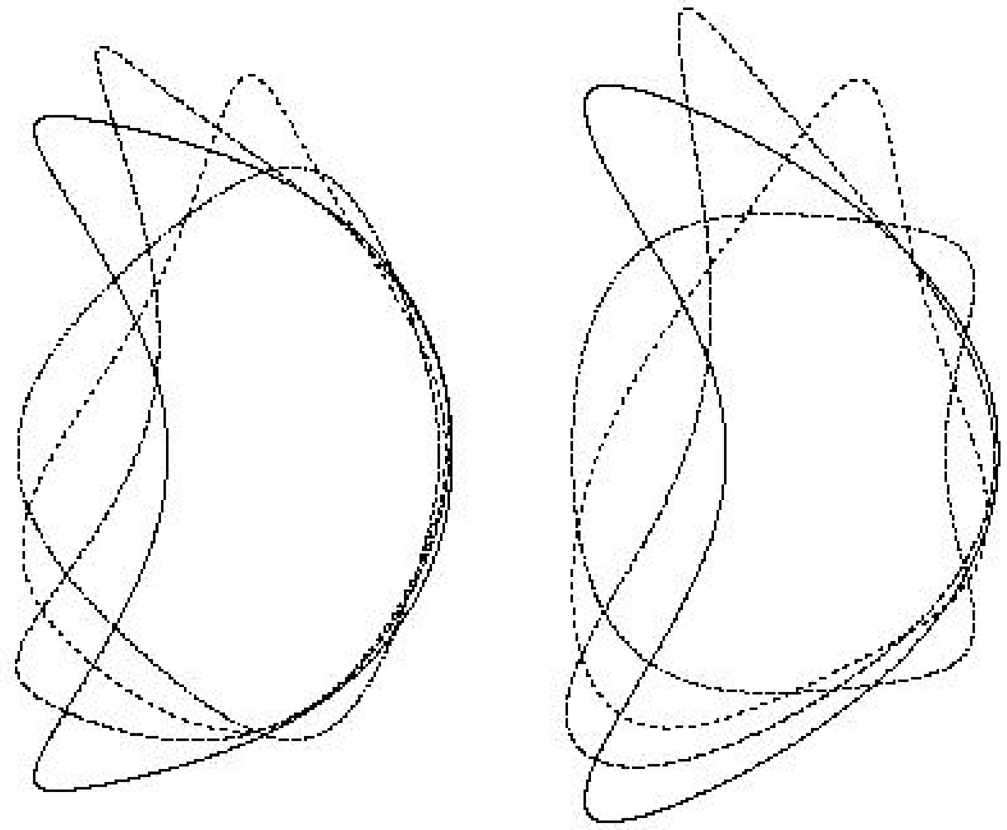


- Neoclassical tearing stability (stellarator shear everywhere).
- Ballooning stability (strong axisymmetric shaping).
- Kink stability (optimum combination of edge shear + boundary deformation).
- Vertical stability (strong external rotational transform).

Stellarator Edge Shear Stabilizes External Kink Mode



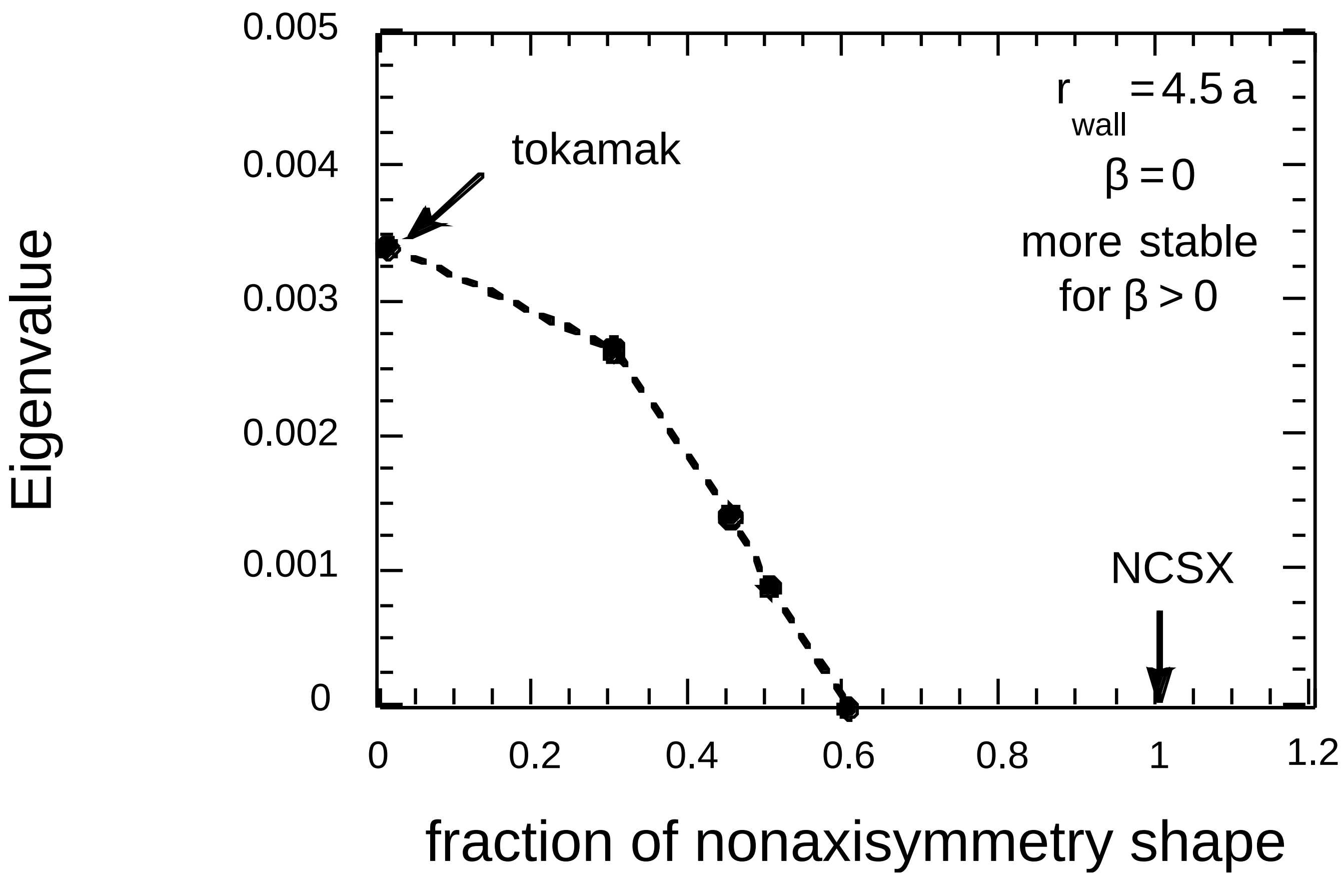
Boundary Deformation To Stabilize External Kink



Unstable Stable

Shape perturbation has little effect on shear and can be controlled with coils.

External Transform from Stellarator Fields Stabilizes QA Vertical Instability

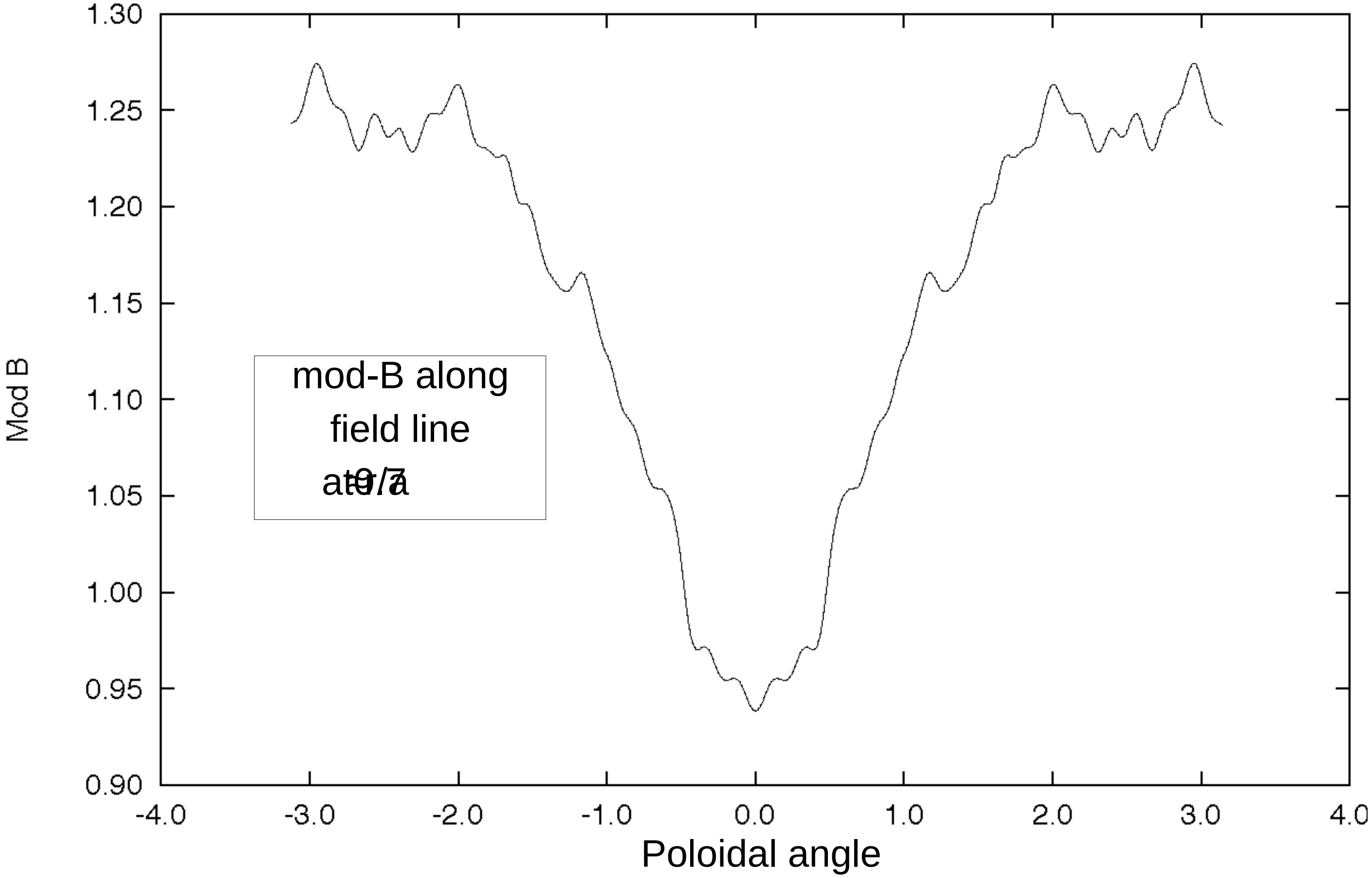


r_{wall}=4.5a

β=0

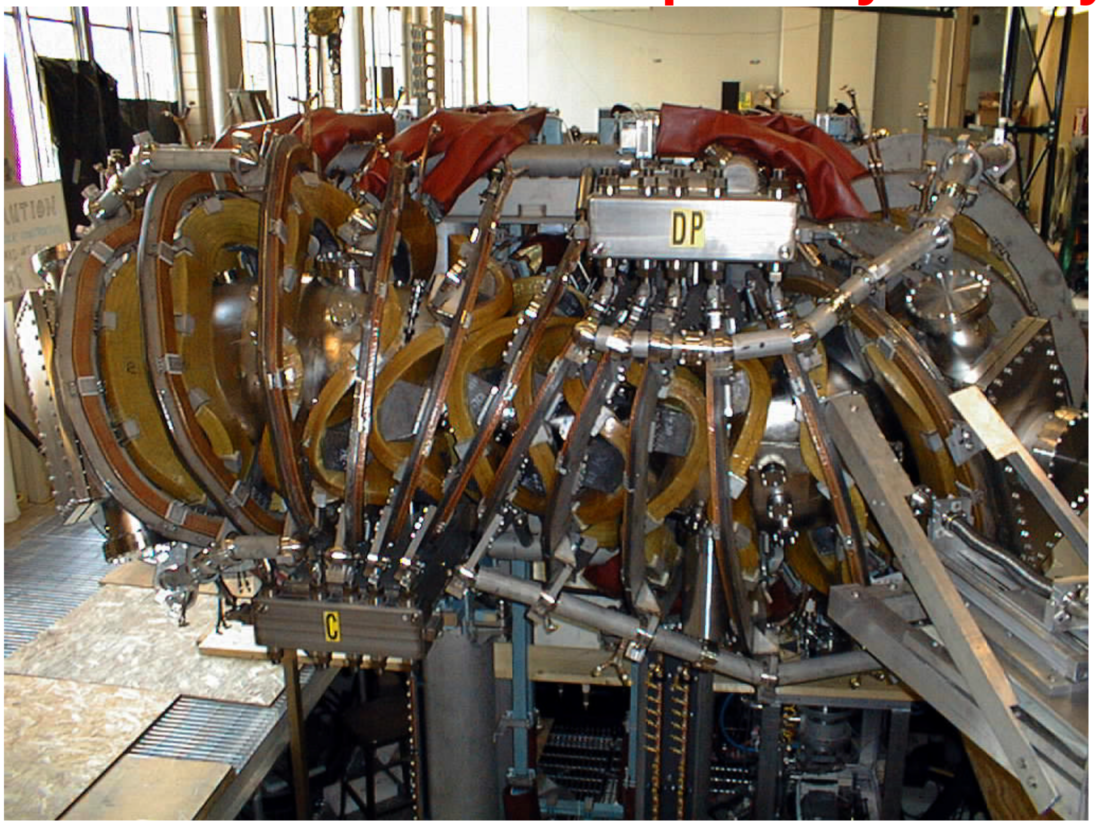
- Required ι_{ext}/ι increases with axisymmetric elongation.

|B| Looks Tokamak-Like



- Approximate **quasi-symmetry** (~axisymmetric |B| 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
- a =0.15 m
- Aspect ratio 8
- B=1 T

Univ. of Wisconsin

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

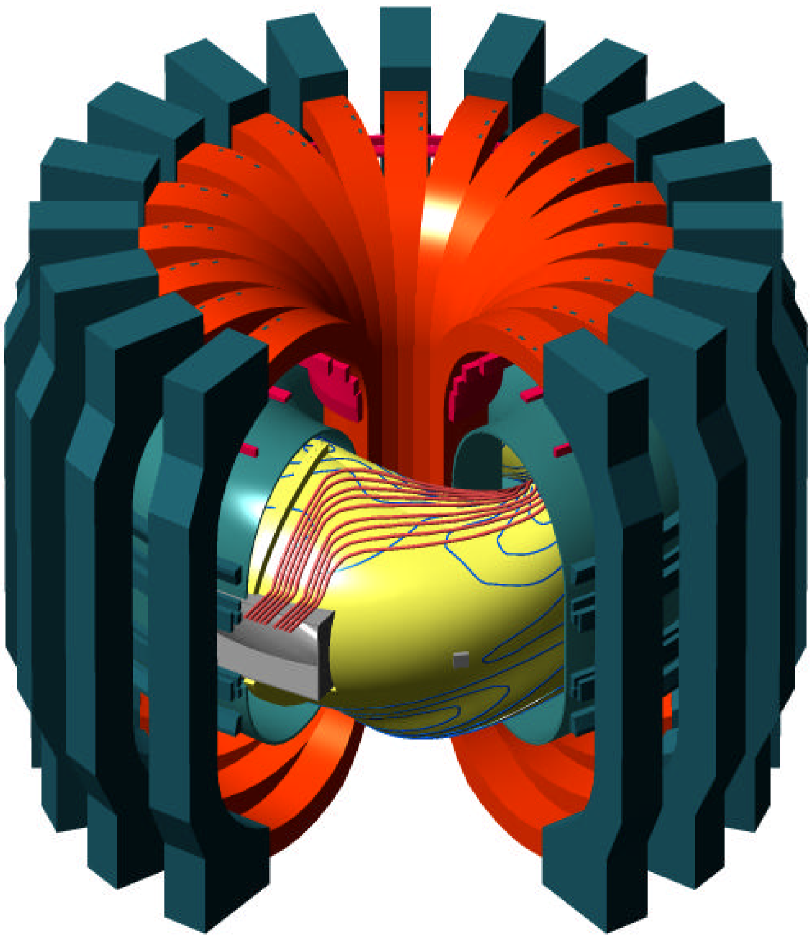
Demonstrate…

- 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 Coil Option Using Existing PBX-M Components



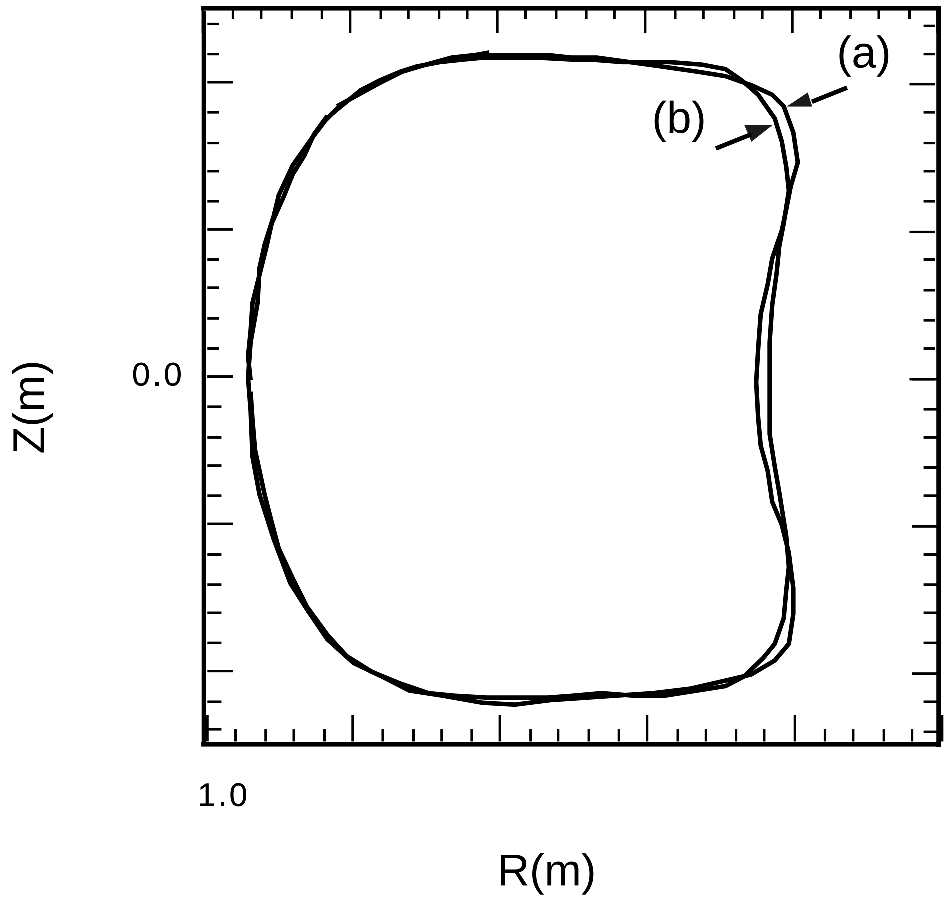
- TF Coils
- PF Coils

- 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



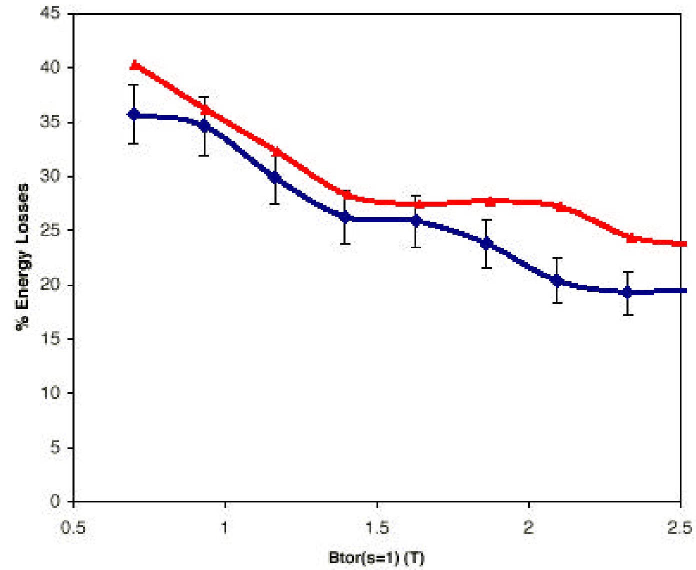
outboard "corrugation" stabilizes kink

(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 B^2. Electron transport << ions.

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

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

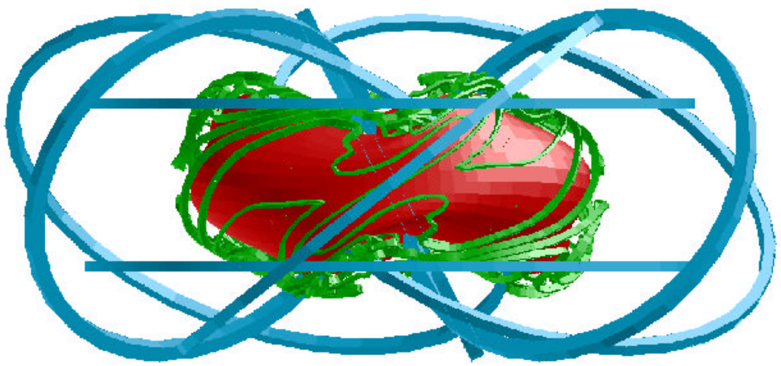
$\langle\beta\rangle$=4% Operating Point in NCSX

R=1.45 m, a =0.42 m, Z_{eff}=2

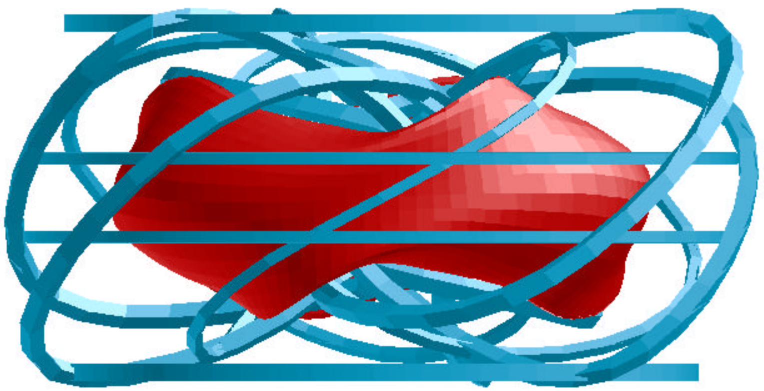
Magnetic field, B (T)	1.5
Injected power, P (MW)	6.9
Volume-avg. beta β (%)	4.0
Volume-avg. density, n (10^{19} m^{-3})	11.3
Central temperature, T_0 (keV)	2.0
Collisionality parameter (nR/T^2)	4.2
τ_{Ei} (ms)	53

- $\tau_E^{assumed} = \min(2.3\times\tau_E^{ISS95}, \tau_E^{neo}/2)$
- NBI orbit losses per Monte Carlo calculations
- Neoclassical confinement times per gyrokinetic simulations.
- Density less than Sudo limit, by constraint.
- Includes 10% beam beta.

Optimized Coil Options Are Being Studied for NCSX



Planar circular coils
Conformal saddles



Optimally-shaped coils
No saddles

Benefits

- Heating and diagnostic access.
- Reduce or eliminate saddle coil requirements.

Low-R/a Quasi-Omnigeneous Stellarators

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

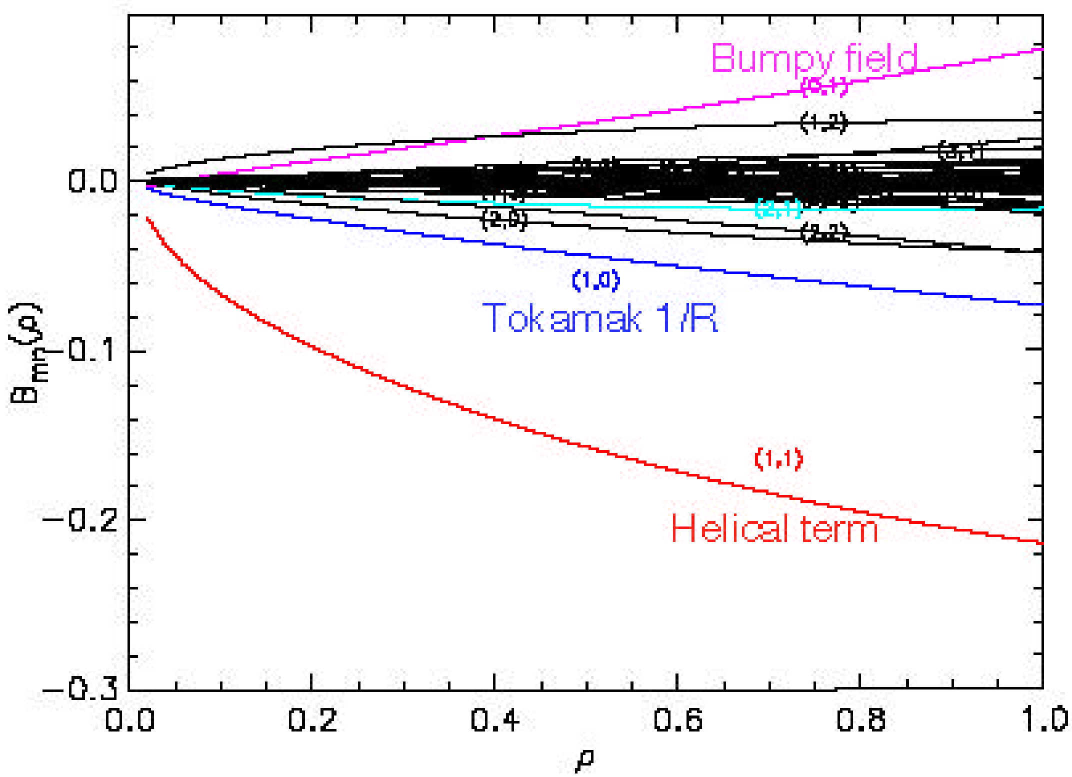
- Magnetic well and stellarator shear out to edge.

- Low bootstrap current (~1/10 of tokamak) makes configuration insensitive to β.
  - magnetic shift <0.1 a as β varies 2 → 6%.
  - iota reduced <8% in reference QOS configuration (β=2%)

QOS Experiment will test selected physics properties

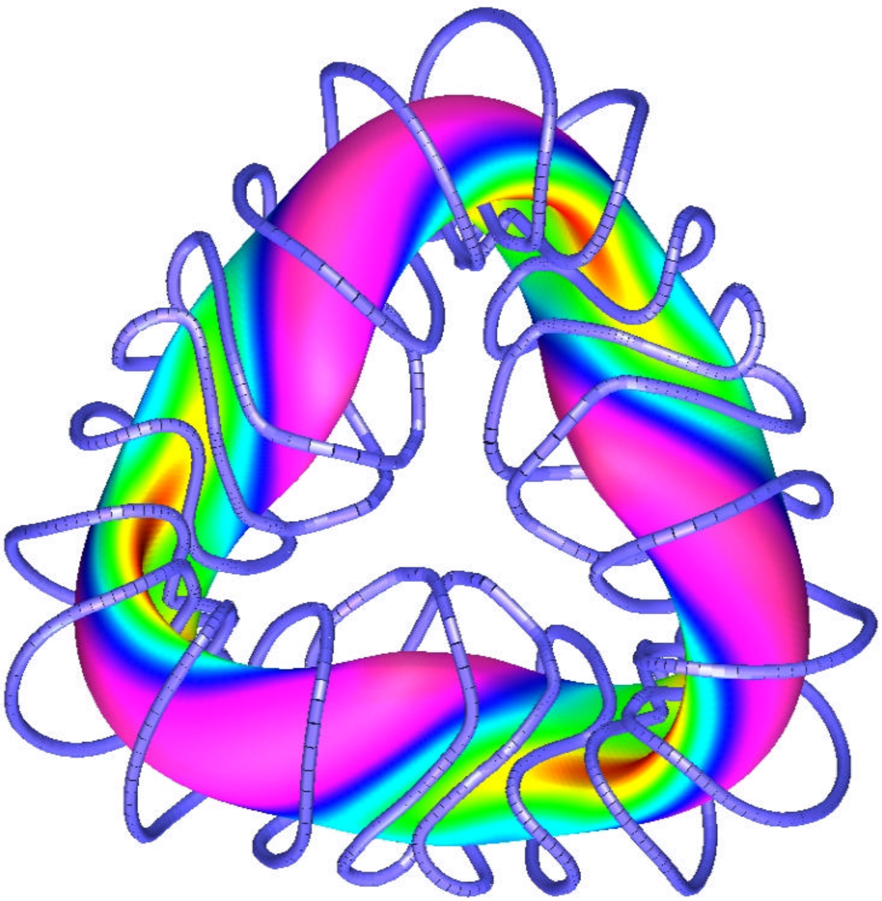
- Reduction of orbit loss and neoclassical transport
- Reduction of bootstrap current
- Configuration invariance with beta.

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, a = 0.28 m

R_0/ a = 3.6

B_0 = 1 T

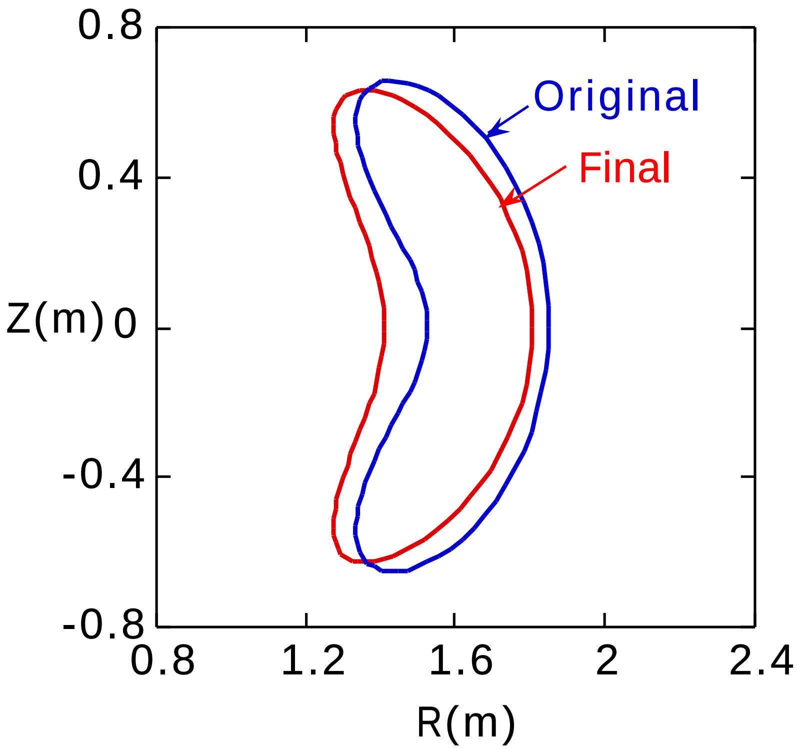
$\iota(0) = 0.56$, $\iota(a) = 0.65$ (monotonic)

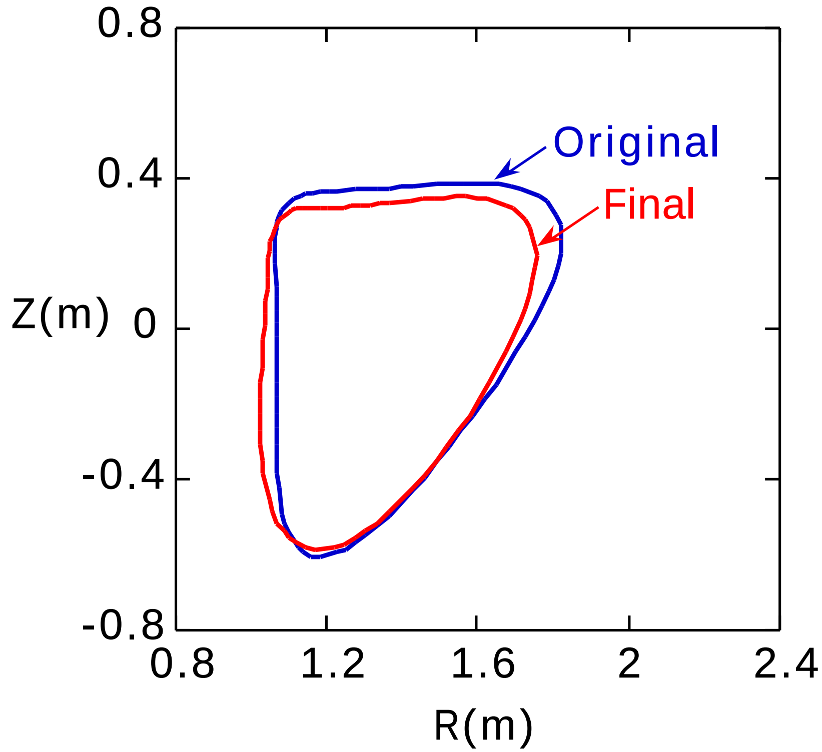
vacuum well

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).

Plans

NCSX: Develop design to fully satisfy physics requirements

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

Submit proposal in 2001

QOS: Physics development

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

Timing similar to NCSX

Summary

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

Physics development has made dramatic progress:

- 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.

A range of interesting coil and machine options exists. Physics benefits are being evaluated.