Physics Design of Compact Stellarators

PSFC Seminar (MIT)

presented by S. P. Hirshman
Oak Ridge National Laboratory
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Germany, Switzerland, Russia, Japan, Australia, Spain

Introduction and Basic Issues

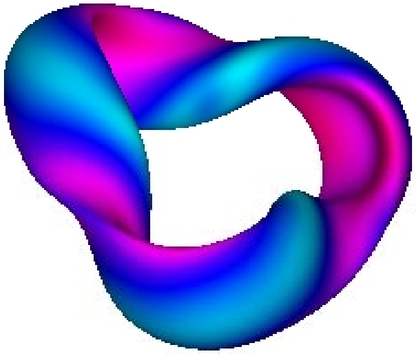
- **Links to US Stellarator program sites related to this talk**
  - www.pppl.gov/ncsx (NCSX Project Info)
  - qos.fed.ornl.gov (QOS Project Info)

Compact Stellarators Combine Best Features of Stellarators and Advanced Tokamaks

- **Traditional Stellarators**
  - Externally-generated helical fields (rotational transform), low recirculating power, large A
  - typically disruption free
- **Advanced tokamaks**
  - Good confinement, low A – high power density, bootstrap current
- **Compact Stellarators**
  - Use 3D shaping flexibility + some plasma current to combine best features

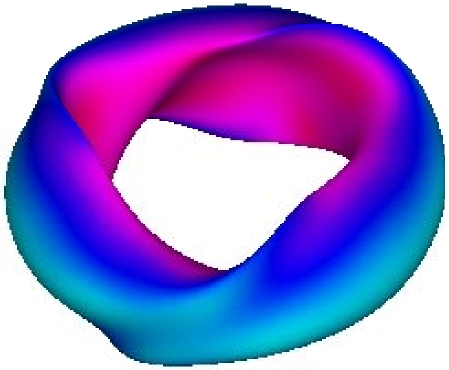
Comparison of Worldwide Stellarators

QOS (Quasi-Omnigenous Stellarator)

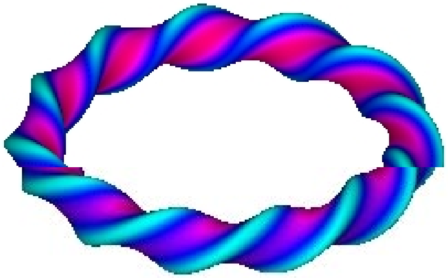


Wendelstein 7-X (Under construction at Griefswald, Germany)

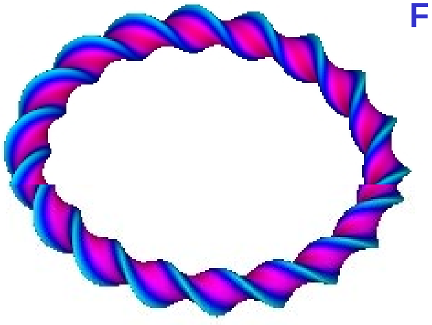
QAS (Quasi-Axisymmetric Stellarator)



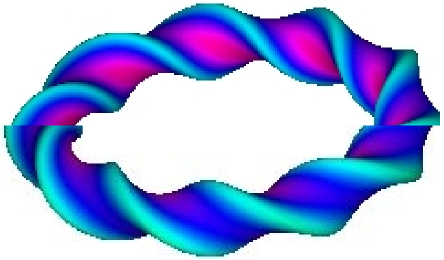
ATF (operated until 1991 at Oak Ridge National Lab)



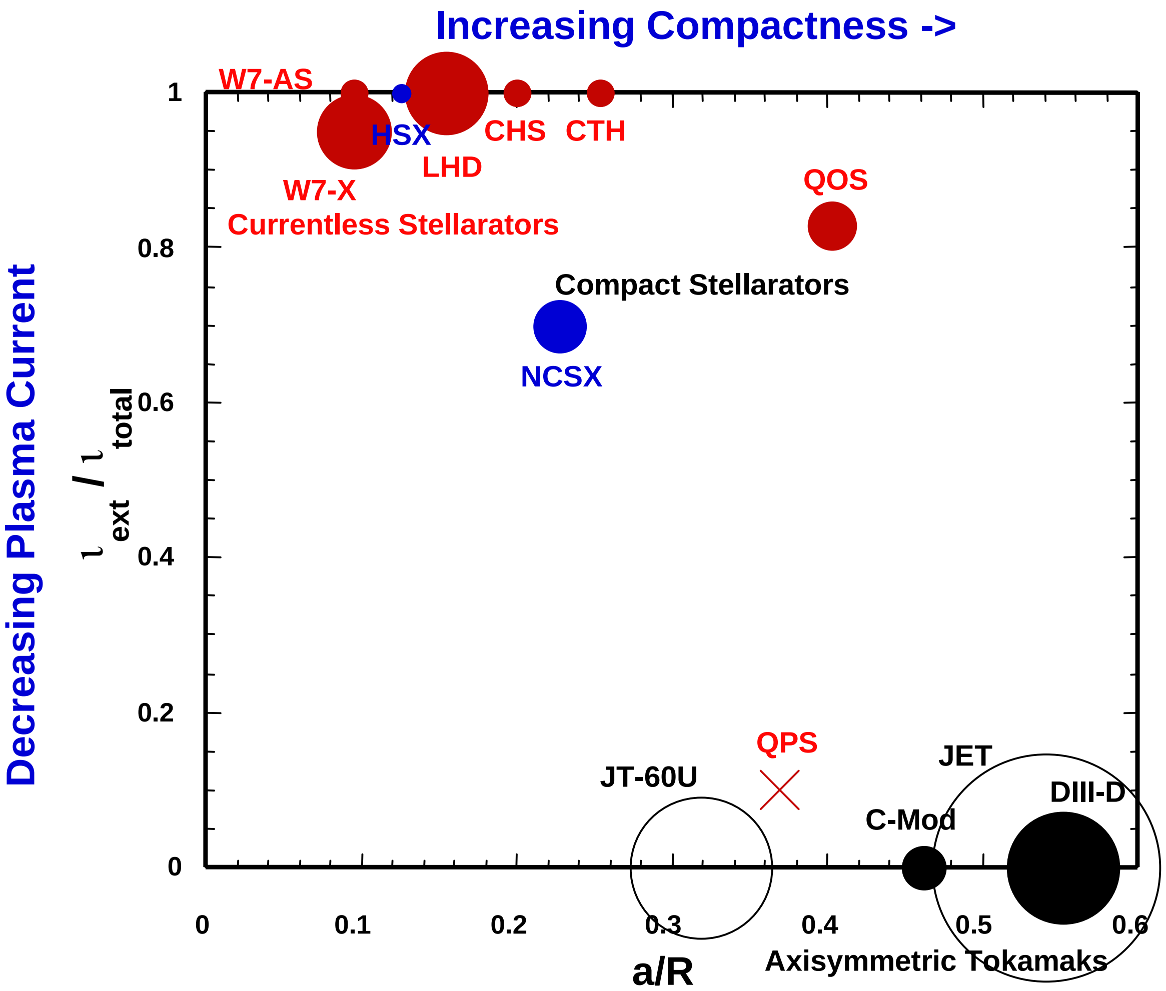
Heliotron (Kyoto Univ. Kyoto, Japan)



LHD (National Institute for Fusion Science, Toki, Japan)



Compact Stellarators - With Some Current - Can Approach A = R/a of Tokamaks



US Compact Stellarator Program

- Physics of compact (low aspect ratio, low N_p) stellarators
  - establish experimental data base for designing low-A, high(er)-β, potentially attractive stellarator reactor
- National Compact Stellarator Experiment (NCSX)
  - experimental "Proof-of-Principle" scale experiment
  - based on "quasi-axisymmetry" design + shaping
- Concept-exploration device
  - explore implications of "quasi-poloidal" symmetry

Challenges for Stellarator Design at Low Aspect Ratio

- **Must Reduce Neoclassical Losses**
  - 3D “ripple” (1/ν) losses enhanced by helical/toroidal coupling unless configuration design is
    - – quasi-symmetric
    - – quasi-omnigeneous

- **Preserve Flux Surface Integrity**
  - increased toroidal/helical coupling at low A=R/a can lead to flux surface fragility (islands, stochasticity)

Challenges for Stellarator Design at Low Aspect Ratios (cont'd)

- Coils are challenging to engineer
  - Less room for "inner" legs of coils
  - Fusion power production ~ $(B_{plasma} / B_{coil})^4$
    - B_{coil} limited by SC technology (< 12T)
    - this ratio decreases at low A
      - 1/R effect (same as for tokamaks)
      - stellarator field complexity
    - optimization goal: *maximize* this ratio - for reactor relevance (P_{fusion}) - while keeping small reactor size

Size (~Cost) of Compact Stellarators

- **Minimum stellarator reactor size determined by maximum plasma-coil separation (Δ) for given R, or minimum $A_\Delta = R/\Delta$**
  - $R_{min} = A_\Delta t$ (t = blanket+shield thickness, fixed)

- **High-N_p stellarators (W7X, LHD, etc) have large $A_\Delta > 12$**
  - coils must be VERY close to plasma (Laplace's equation)

- **Compact stellarators achieve $A_\Delta < 7$: fundamentally different**
  - low $N_p \sim 2$-3, hybrids with net current producing transform
  - potential for smaller ("lower cost") reactors
    - – assuming confinement can be retained

Overview of Design Methodology

Advances in Theory and Numerics Contribute to Design of Compact Stellarators

- **3D Shaping**
  - passively stabilize external kink, vertical displacement, ballooning modes for $\beta \sim 4\%$ with no walls or feedback
    - exceeds tokamak AT limit (~2.5%)
    - ARIES-RS $\beta \sim 5\%$: reactor relevant
- **Specify iota profile**
  - prevent (control?) disruptions
  - neoclassical tearing stabilization: $j_{bs}\,(d \ln \iota)/d\phi > 0$
- **Quasi-symmetry (design Boozer |B|-spectrum)**
  - Good confinement -> closed drift-orbits, allow plasma flow for flow shear stabilization

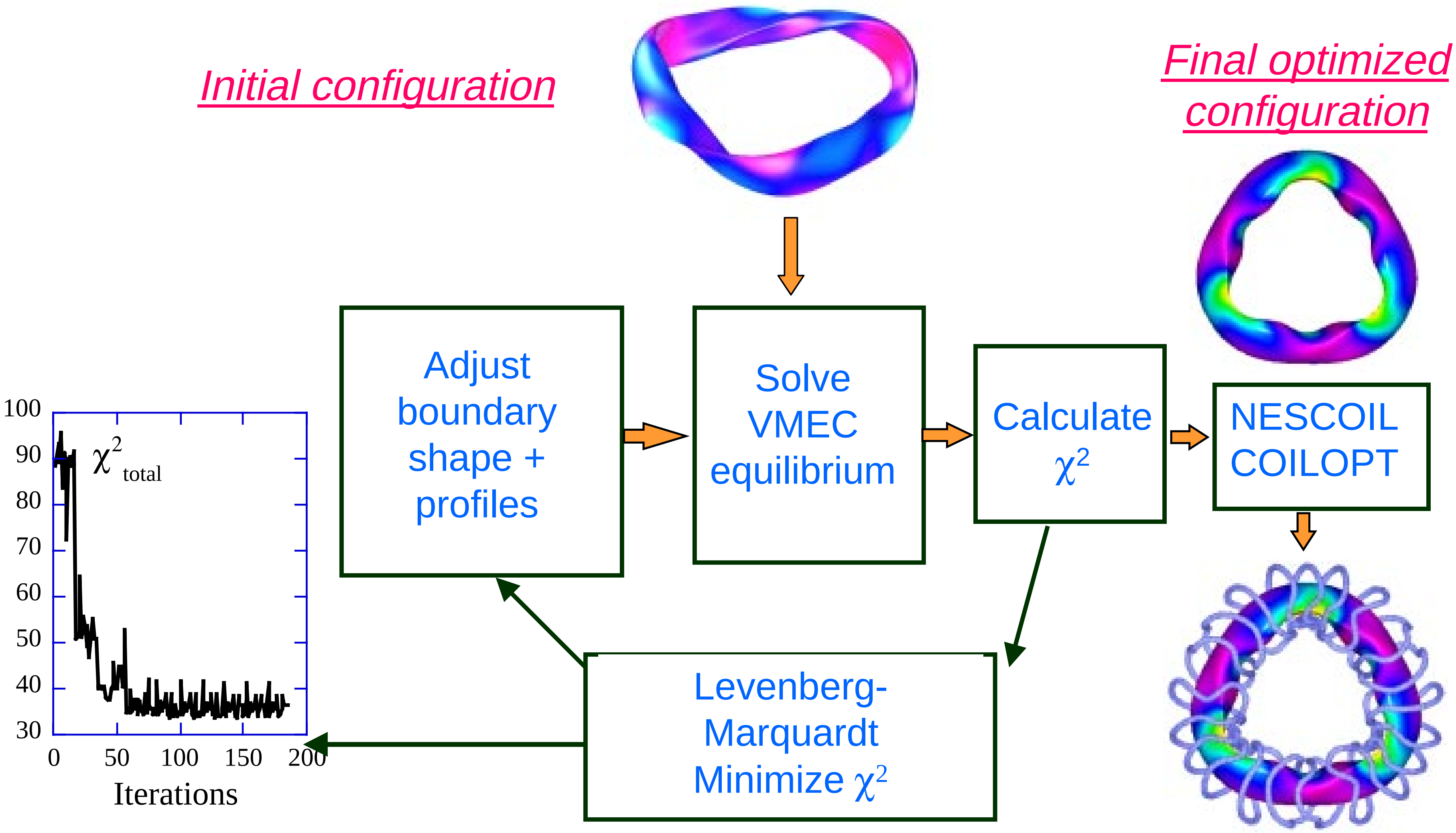
Optimization of Physics and Engineering Properties for Compact Stellarators

- Generalization of numerical method pioneering by J. Nuehrenberg and R. Zille for large A stellarators (originally applied to design Helias - W7X and HSX (QHS))
  - plasma physics properties completely determined by ideal MHD equilibrium, which includes
    - Fourier description of plasma boundary
    - “free functions” $\iota(\Phi)$ (= 1/q) and $p(\Phi)$
  - variation of boundary (and ι, p) - rather than coil topology - to optimize plasma transport, stability, coil “complexity”, beta, etc.

Stellarator Coils Are “Reverse-Engineered”

- Optimized Plasma State
  - Fixed boundary optimization more robust (stable) than “free-boundary”
- Conceptually separates physics from coil optimization
  - Engineering feasible of coils NOT guaranteed by method
  - Innovative methods needed to find coils at low A
    - Singular value decomposition (SVD) of current potentials obtained using NESCOIL (P. Merkel)
    - Genetic Algorithms

Compact Stellarator Optimization Procedure



Initial configuration

Final optimized configuration

Adjust boundary shape + profiles

Solve VMEC equilibrium

Calculate χ^2

NESCOIL COILOPT

Levenberg-Marquardt Minimize χ^2

Optimization Targets (Physics/Engineering)	Example
Aspect ratio	R_0/a - 2.5 to 3.5
Limit outer surface curvature	avoid strong elongation/cusps
Target quasi-symmetries	Minimize B_{mn} if $n \neq 0$ (QA); B_{mn} if $m \neq 0$ (QP); or if $m/n \neq 1$ (QH)
Bounce-average omnigeneity (drift surfaces and flux surfaces aligned)	$B_{min} = B_{min}(\psi)$ $B_{max} = B_{max}(\psi)$ $J = J(\psi)$
Local diffusive transport	D, χ from DKES
Current profile	self-consistent I_{BS}, $I(\psi)$ goes to 0 at edge
Iota profile	Limit low order resonances
Magnetic Well, Mercier (resistive interchange)	$V'' < 0$, $D_M > 0$ over cross section
Ballooning, Kink, and Vertical stability	$\langle\beta\rangle > 2\%$ COBRA and TERPSICHORE

National Compact Stellarator Experiment (NCSX)

NCSX: An Experiment Based on QA to Develop Compact Stellarators

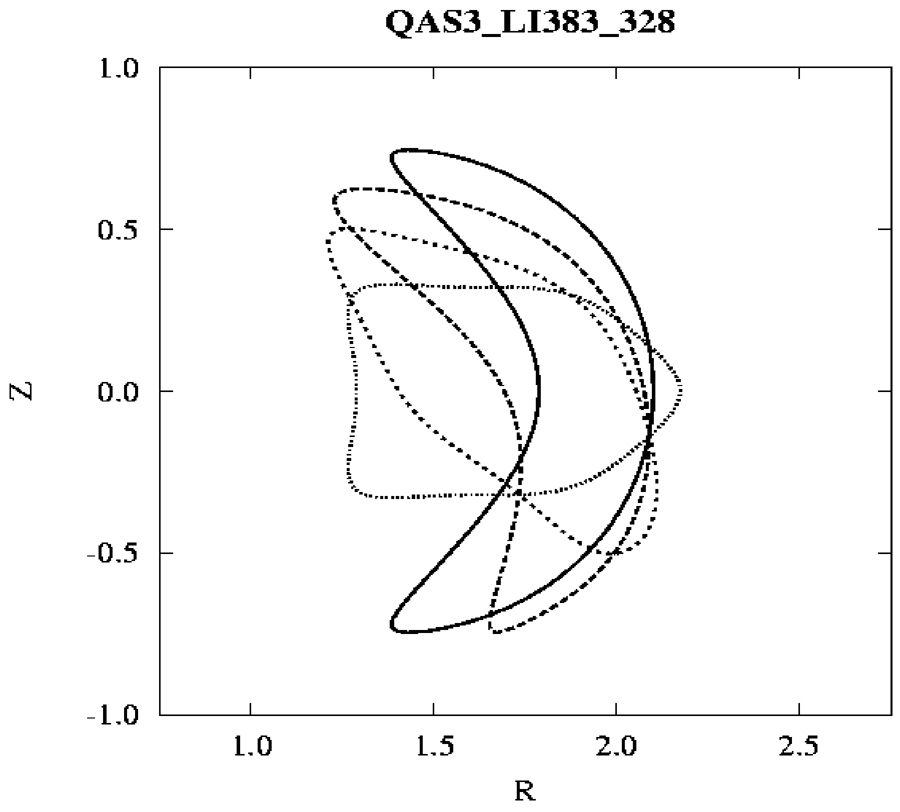
Physics Goals

- Study conditions for high-beta disruption-free operation.
- Determine beta limits (modes) with bootstrap alignment.
- Neoclassical transport reduction by quasi-axisymmetry.
- Anomalous transport reduction by flow-shear control.
- Neoclassical tearing mode stabilization by externally-controlled magnetic shear.

NCSX Configuration Properties

- **Geometry**
  - $N_p = 3$, $A \sim 4.4$, $\langle\kappa\rangle \sim 1.8$, <indented>
- **Stability**
  - ballooning, kink (no wall), vertical, Mercier at β=4.1%
  - limited by ballooning -> profile optimization possible
- **Transport: Low effective ripple (good QA-ness)**
- **Transform**
  - Iota: 0.4 (axis) -> 0.65 (edge) avoid low order resonance
  - ~65% from external coils (at full beta and bootstrap current~150kA at B=1T)
  - neoclassical-tearing stable profile

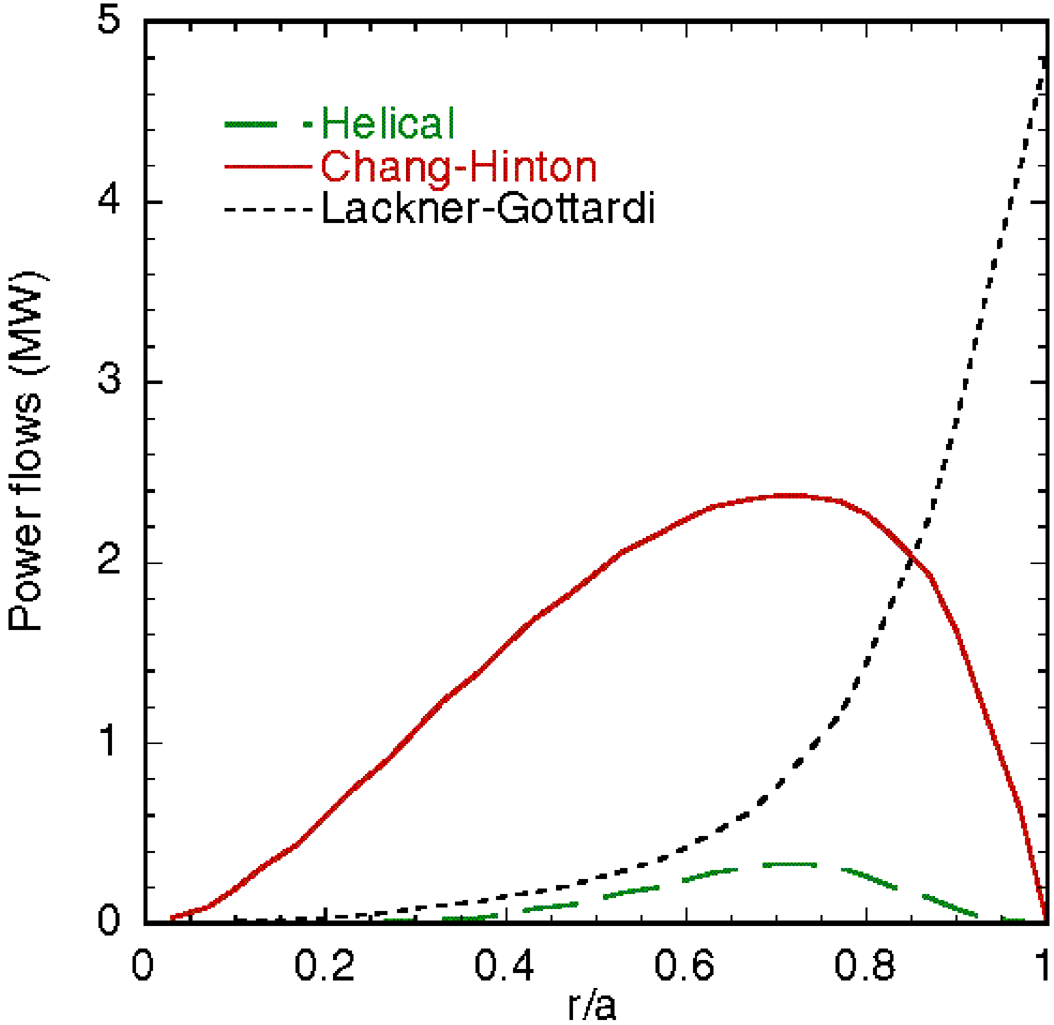
Toroidal Cross Sections of NCSX Plasma



Quasi-Axisymmetry: Low Effective Ripple

- In 1/ν regime, ripple transport scales as $\varepsilon_{eff}^{3/2}/\nu$
- Compute ε_{eff} from NEO (Nemov-Kernbichler) code
  - benchmark against DKES, Monte Carlo, Shaing-Houlberg
- Edge (maximum) ε_{eff} ~ 3.5% (drops exponentially into core)
  - low enough for both co, counter-nbi
  - Helical (ripple) transport sub-dominant to axisymmetric
  - Allows access to high β~4%, ν_* ~0.25, B = 1T, P~5MW

Small Ripple => Low Helical Transport



NCSX Kink and Vertical Stability

- **Finite Currents**
  - concerned with external (low n) kinks
  - 3D shaping: enhanced field bending, stable up to β~4%
- **Large Axisymmetric Elongation and Triangularity (indent)**
  - improves ballooning stability
  - in tokamaks, destabilizes vertical modes for $\kappa > 1$
    - in stellarator, external transform provides robust vertical stability

Analytic Stability Criterion for Vertical Mode

- Assume $R/a >> 1$, $\beta = 0$, $j(r)$ =constant, $\iota(r)$ = constant. (Stellarator expansion)

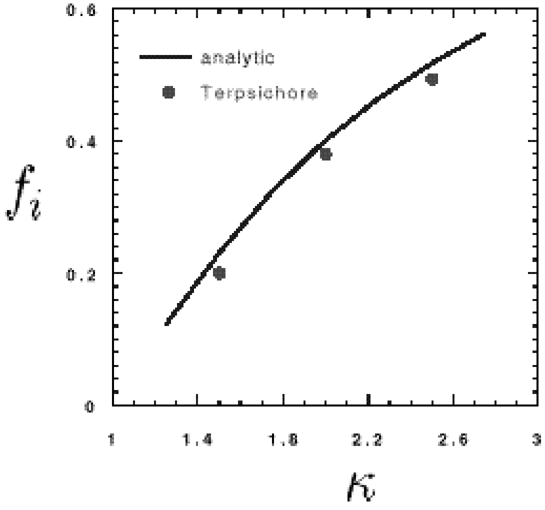
$$\delta W_p + \delta W_{vac} = \frac{1}{2}\int d^3x \quad [\delta \mathbf{B}^2 + \mathbf{j}_{\|} \cdot \xi \times \delta \mathbf{B}]$$

$$\propto \quad [\kappa + 1 - (1 - f_i)(\kappa^2 + 1)]$$

$$f_i = \frac{\kappa^2 - \kappa}{\kappa^2 + 1}$$

f_i : fraction of external transform needed for stabilization

κ : averaged elongation

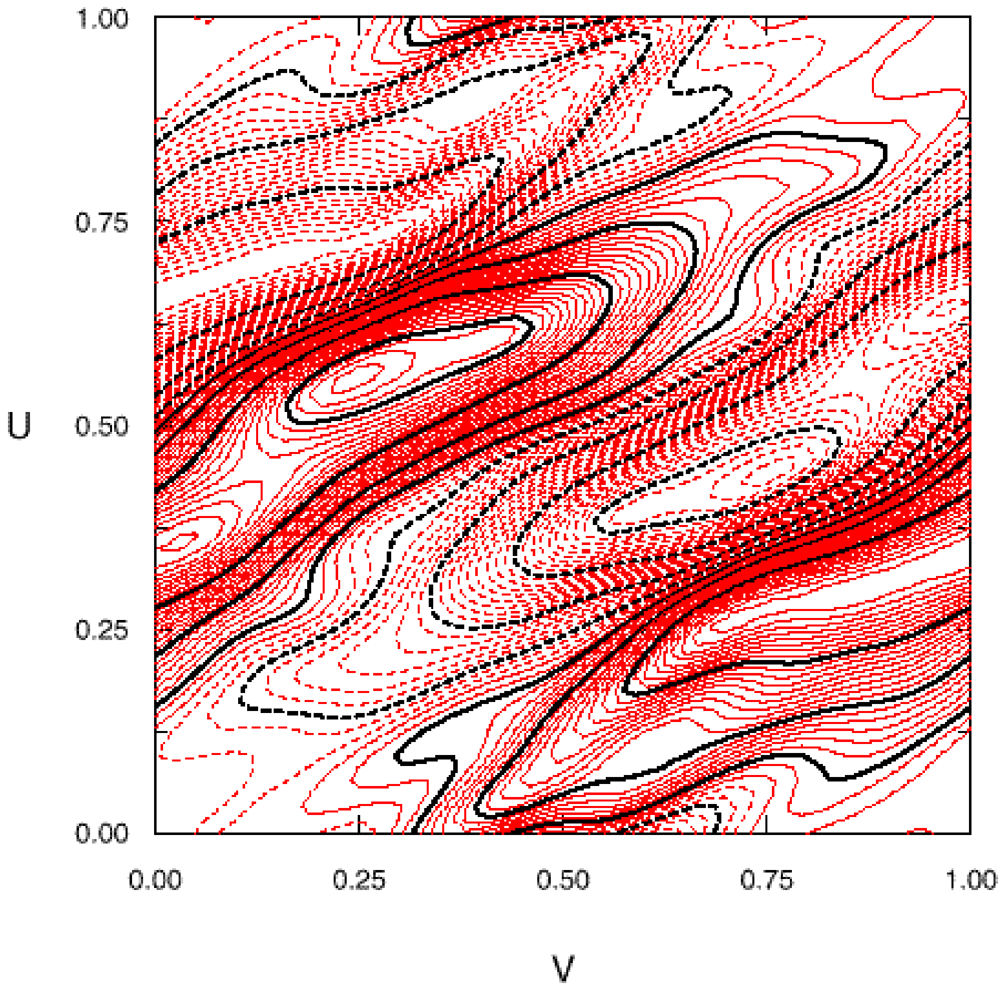


Fu, G. Y. *et al.*, Phys. Plasmas **7**, (2000) 1079.

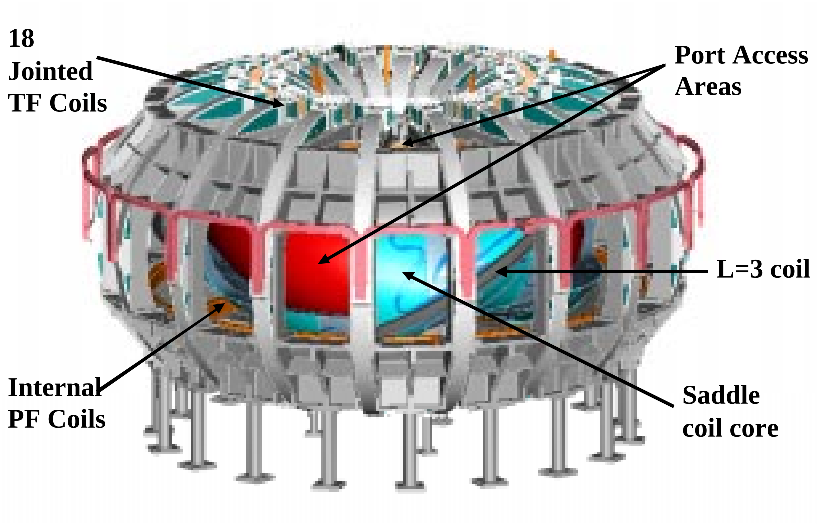
Coil Design for NCSX

- "Infinite" Number of Coil Topologies for Given Stellarator Configurations (opportunity for greater flexibility)
  - Helical coils, modular coils, saddle coils, wavy PF's
- NCSX has focused on two candidates coils
  - Saddle Coils (no net toroidal, poloidal current) + TF
    - use Genetic Algorithm to find optimal set
  - Modular Coils (+small TF for flexibility)
    - COILOPT code moves filaments directly
- Which is better? More flexible? Better engineering? Physics properties? Surfaces?

Using Genetic Algorithm to Select NCSX Saddles



Saddle Coil Option



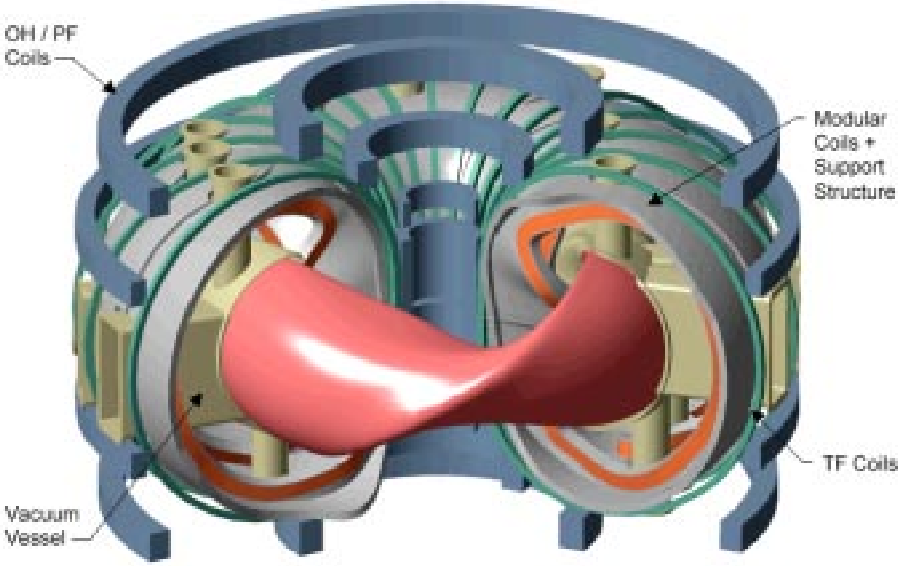
- Demountable TF coil
- Internal PF coil
- Helical field produced by saddle coils: LN-cooled cable in grooves on conformal support shell.
- Conformal vacuum vessel
- Three large openings.

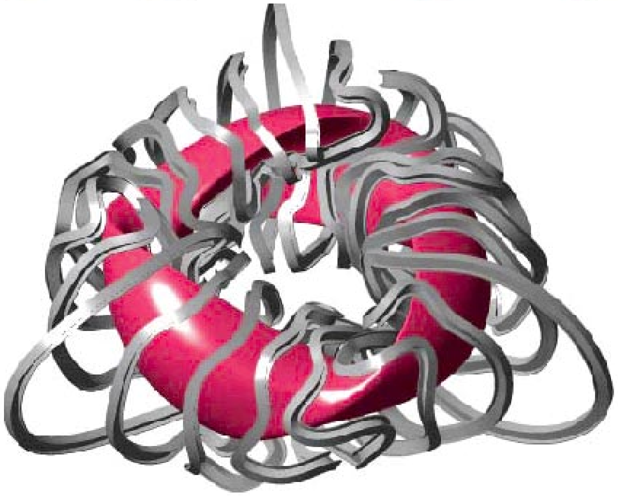
Assessment

- **Good access**
- **Low power requirements**
- **Good constructability**

Coil modifications to improve physics properties being developed.

Modular Coil Option





- LN-cooled cable wound on contoured coil support.
- External PF and supplementary TF.
- Conformal vacuum vessel.

Assessment

- **May provide best physics properties.**

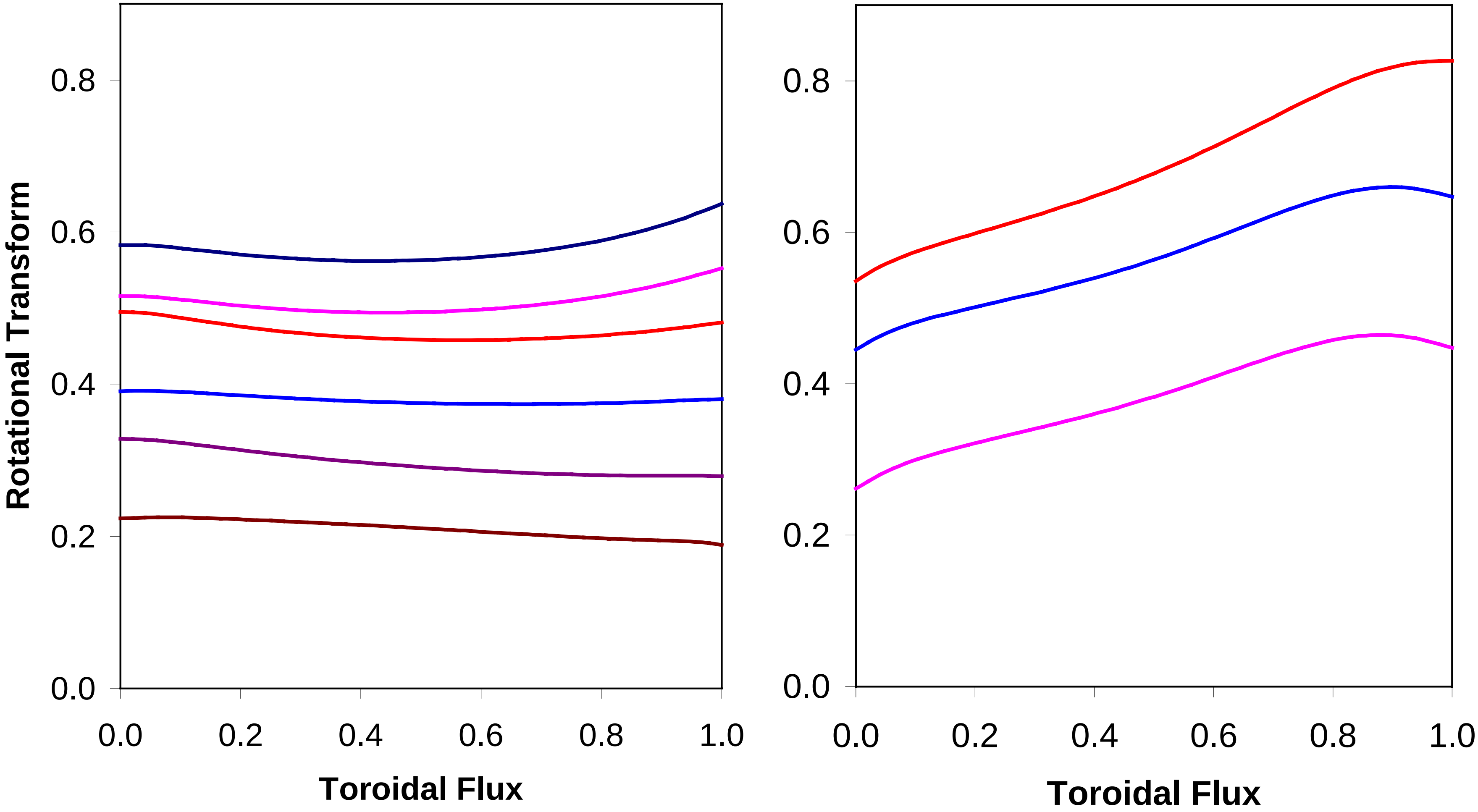
Access-compatible structure concept being developed.

Using External Coils To Reconstruct the Physics Properties of NCSX

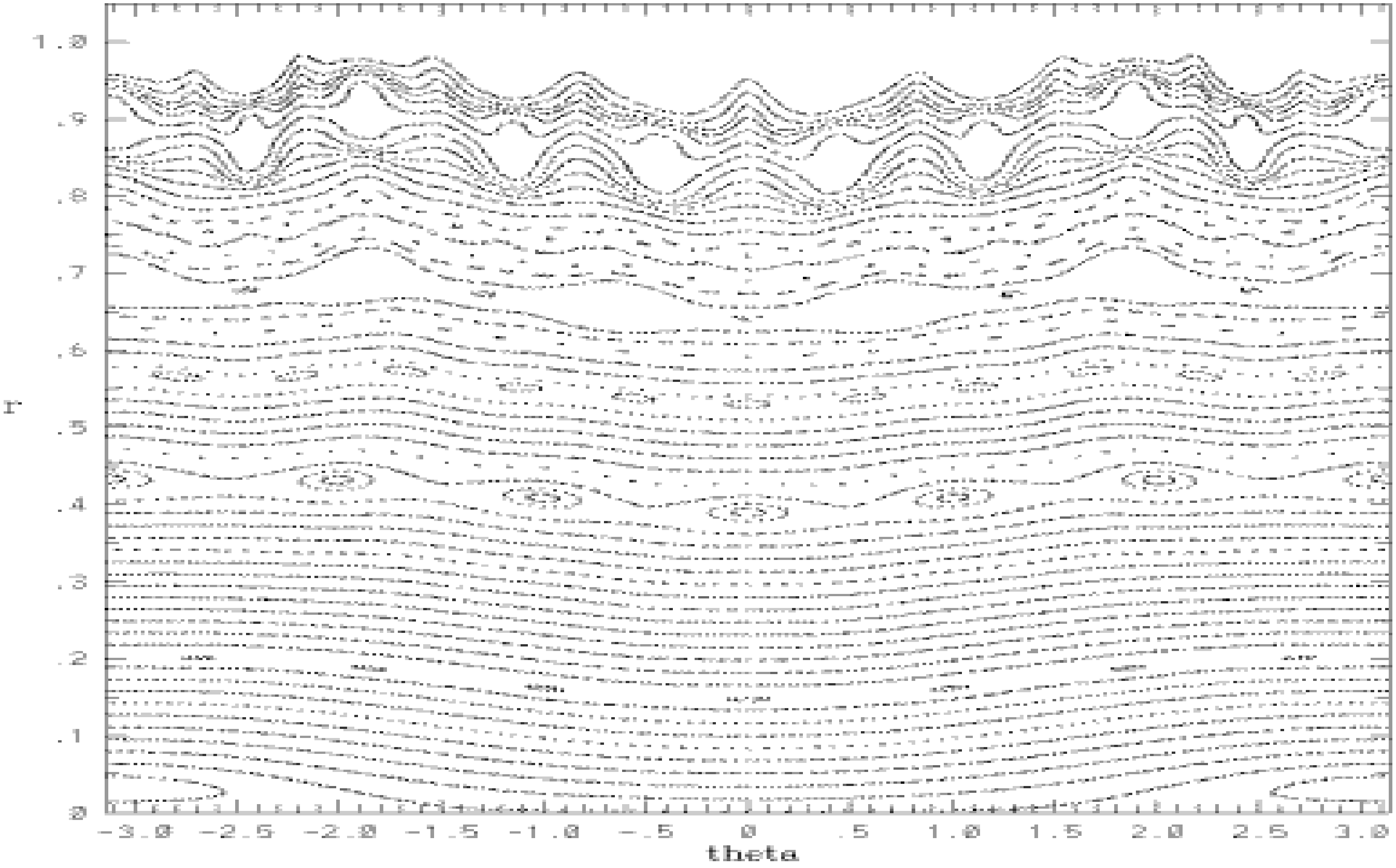
- **Free-boundary (VMEC) calculations**
  - determine how close free-bdy plasma shape is to that required for physics preservation
  - re-evaluate physics “targets” (stability, transport, etc.)
  - generally “acceptable” for modulars. Saddles (?)

- **Evaluate (and suppress) effects due to possible “resonant” field perturbations**
  - use free-bdy PIES code (equilibrium with islands)
  - develop trim coils to cancel islands as ι varies

Range of ι Available with Modular Coils



PIES Free-Boundary Reconstruction of NCSX
(full β, current, modular coils only)



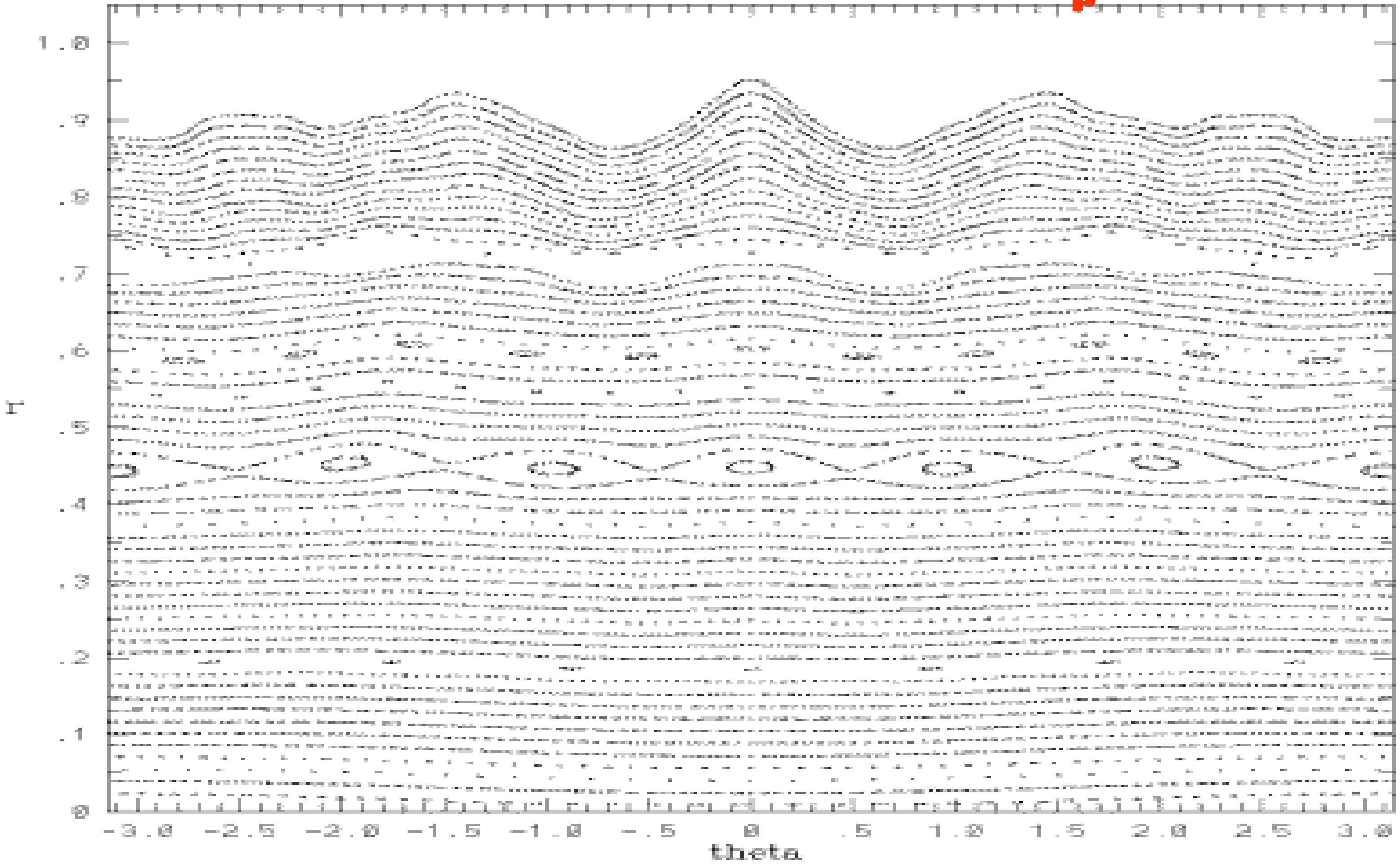
Island Removal Method
(Generalize Cary-Hanson to finite β, I_{plasma})

- Compute coupling matrix relating plasma boundary shape to internal island widths
  - use PIES rather than vacuum field line tracings

- Invert matrix
  - boundary modifications to eliminate resonant islands

- Resultant boundary changes are small (~0.01<a>)
  - do not adversely effect stability or transport

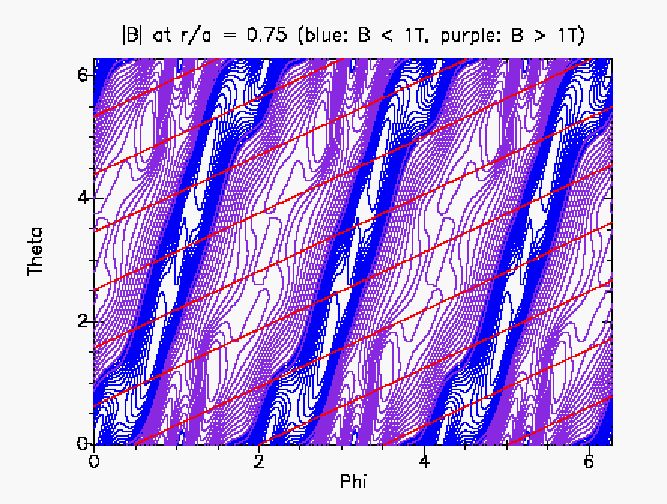
PIES Free-Boundary Reconstruction of NCSX (modular coils + helical m=5,n=N_p trim coils)



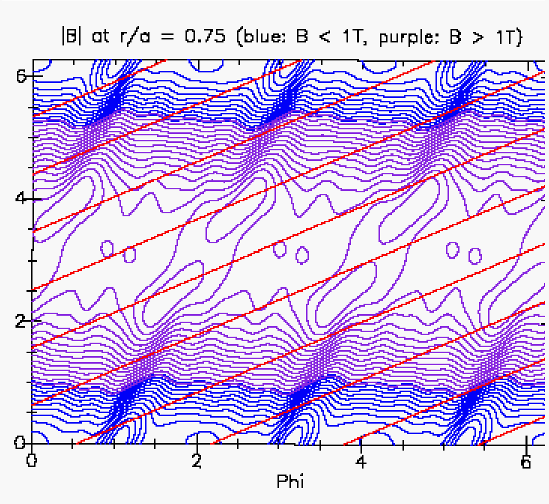
Quasi-Poloidal and Quasi-Omnigenous Stellarators:
Concept Exploration Experiment

Symmetries of |B| in Boozer-coordinates Needed for Good Confinement in Stellarators

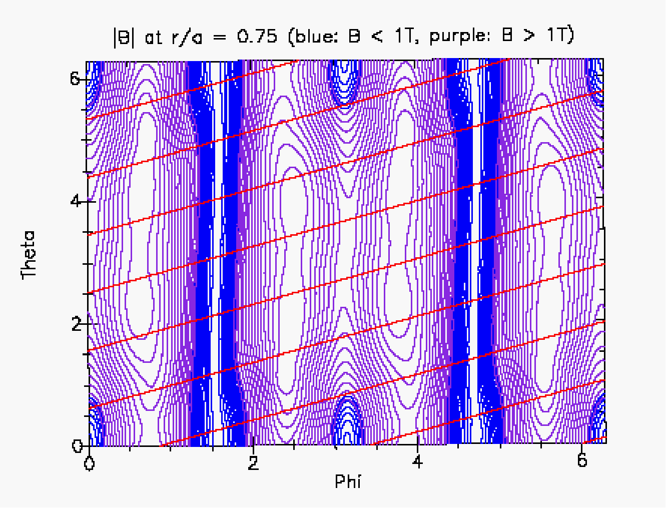
Quasi-Helical



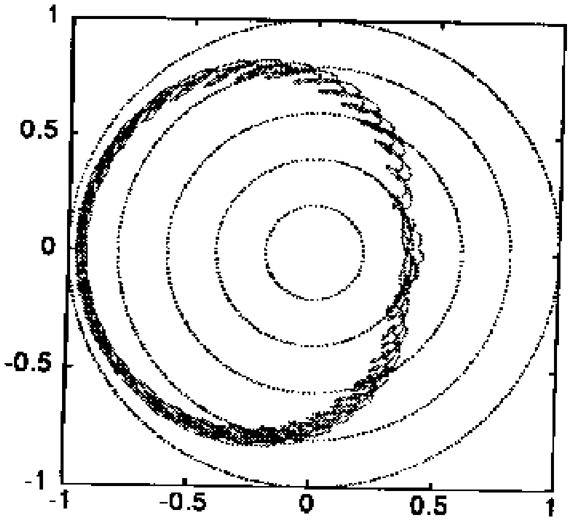
Quasi-Axisymmetric



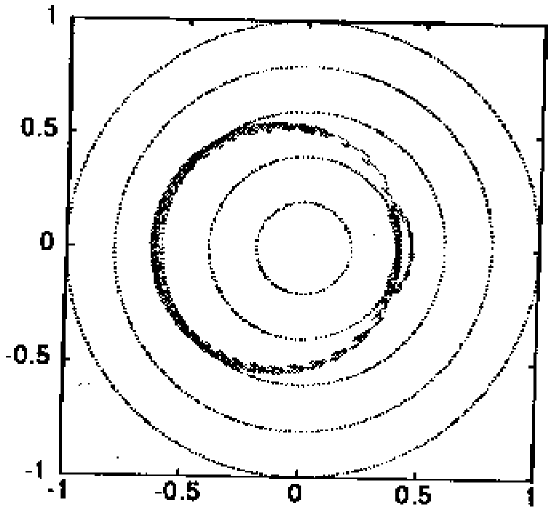
Quasi-Poloidal



Example of Quasi-Omnigeneous Orbits: Trapped Particles in LHD - $J \sim J(\Phi)$



R = 3.75 m



R = 3.60 m

QOS Mission

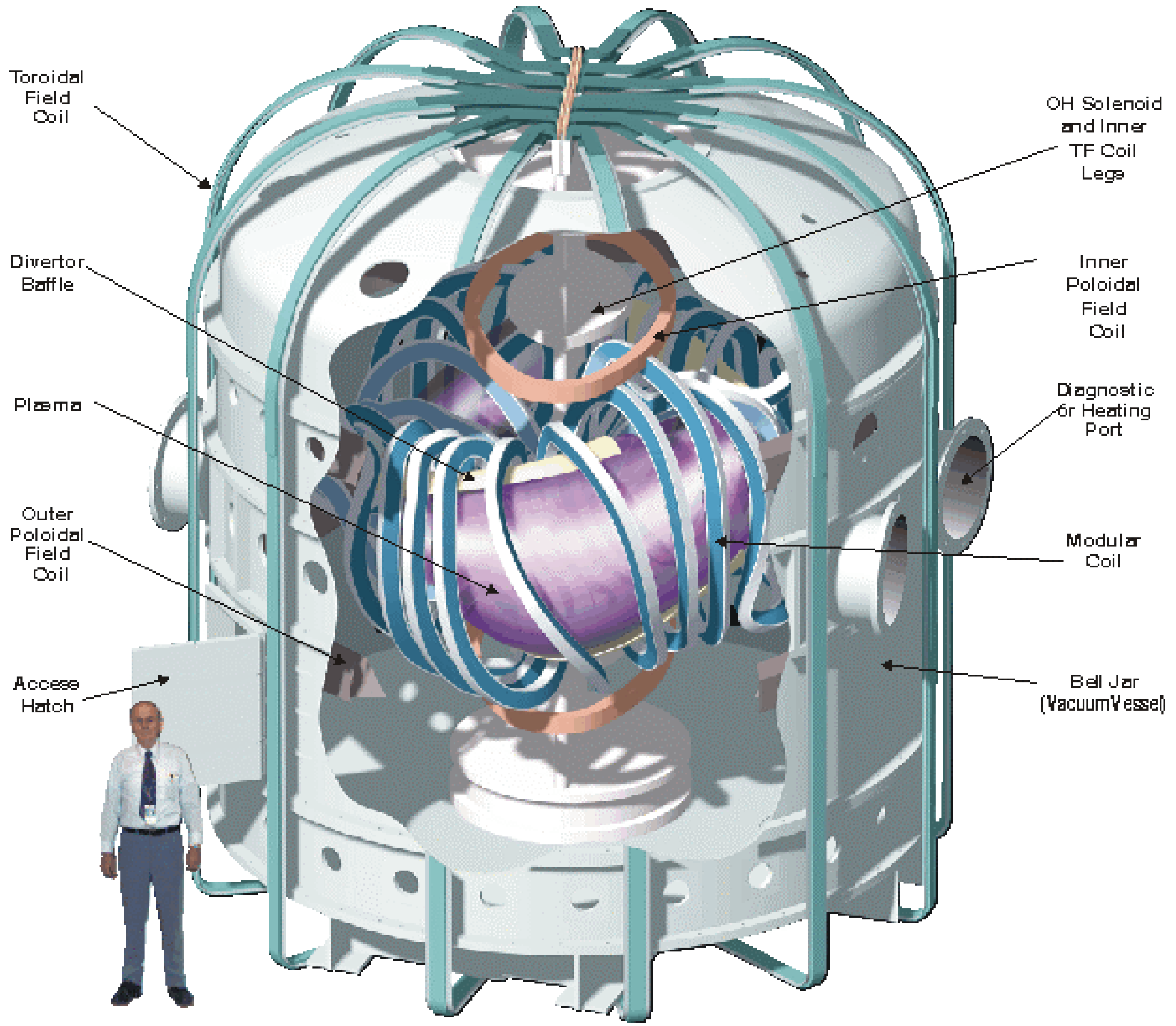
- Explore physics of quasi-poloidal stellarators to support high-β (10-15%) reactor concept
  - demonstrate neocl'al transport reduction
  - study equilibrium quality at very low A
  - bootstrap current scaling - vary $|B|_{mn}$
  - E-field control => barrier formation
    - low A, QPS (large toroidal viscosity)

QOS Relationship to NCSX

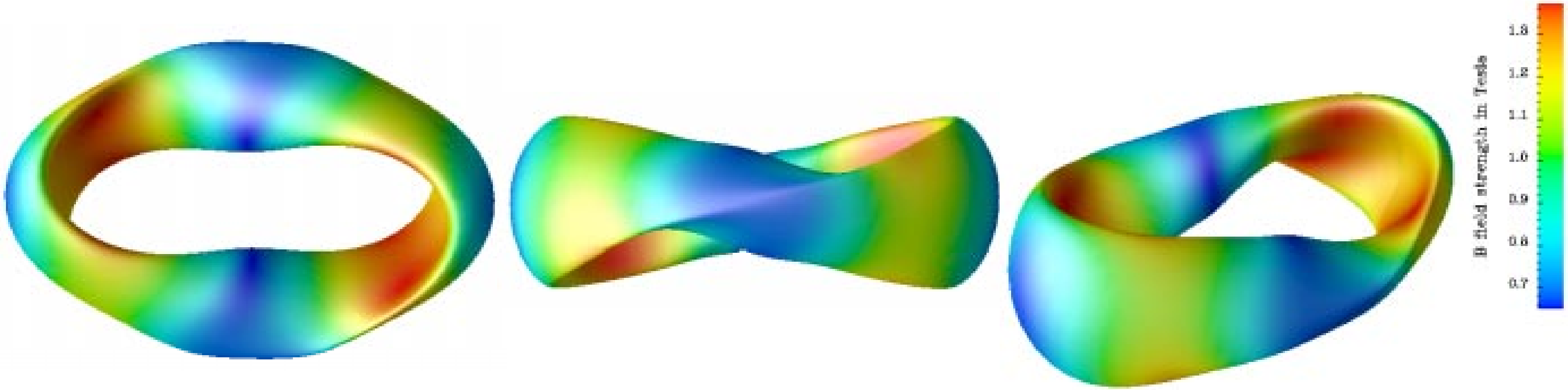
- Complements NCSX (QA) to broaden knowledge base for compact stellarators
  - Explore new quasi-poloidal magnetic configuration
  - low bootstrap, very low *A* regime
  - low $\beta \sim 2\%$ limit design (no nbi)
    - due to low available power and $\beta \sim P^2$

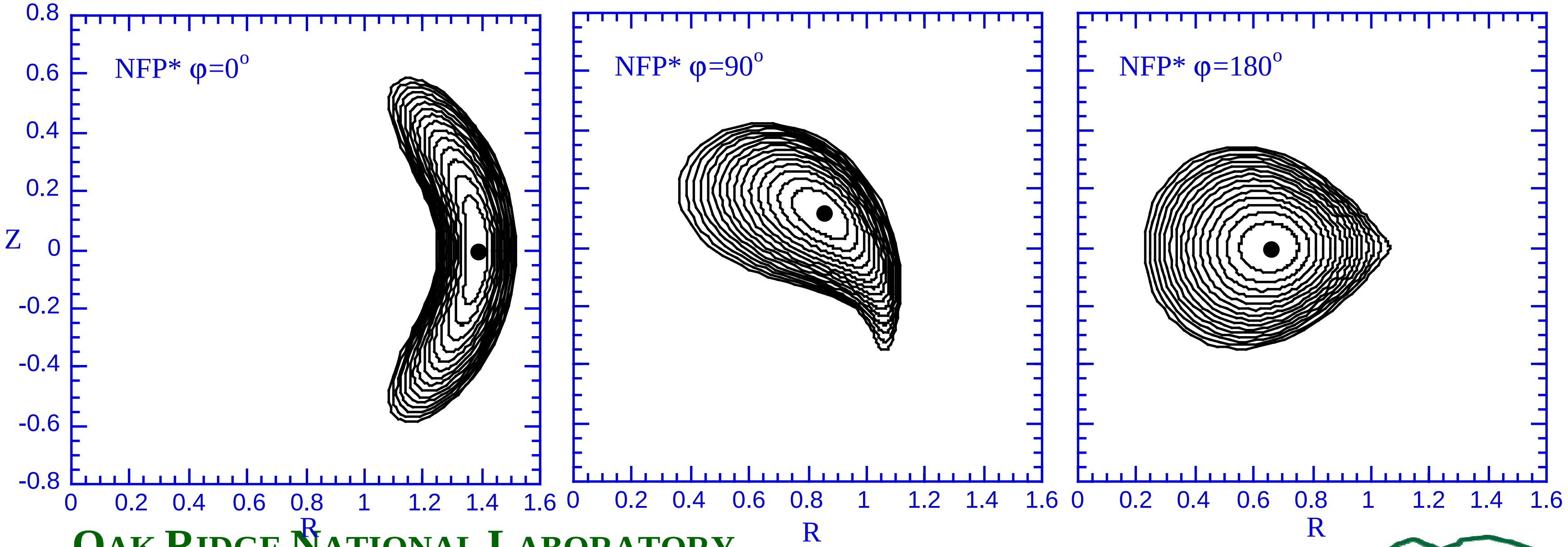
QOS: N_p=2 Quasi-Poloidal Stellarator Concept Exploration Experiment

- **Geometry**
  - $\langle R_0 \rangle = 0.86$ m, $\langle a_p \rangle = 0.34$ m, $\langle A \rangle \sim 2.5$
- **Parameters**
  - $\langle B_0 \rangle = 1$ T for 1 s
  - $P_{ECH} = 0.6–1.2$ MW
  - $P_{ICRF} = 1–3$ MW


Toroidal Field Coil
Divertor Baffle
Plasma
Outer Poloidal Field Coil
Access Hatch
OH Solenoid and Inner TF Coil Legs
Inner Poloidal Field Coil
Diagnostic or Heating Port
Modular Coil
Bell Jar (VacuumVessel)

QOS CE, $N_p = 2$, $\beta = 1.3\%$





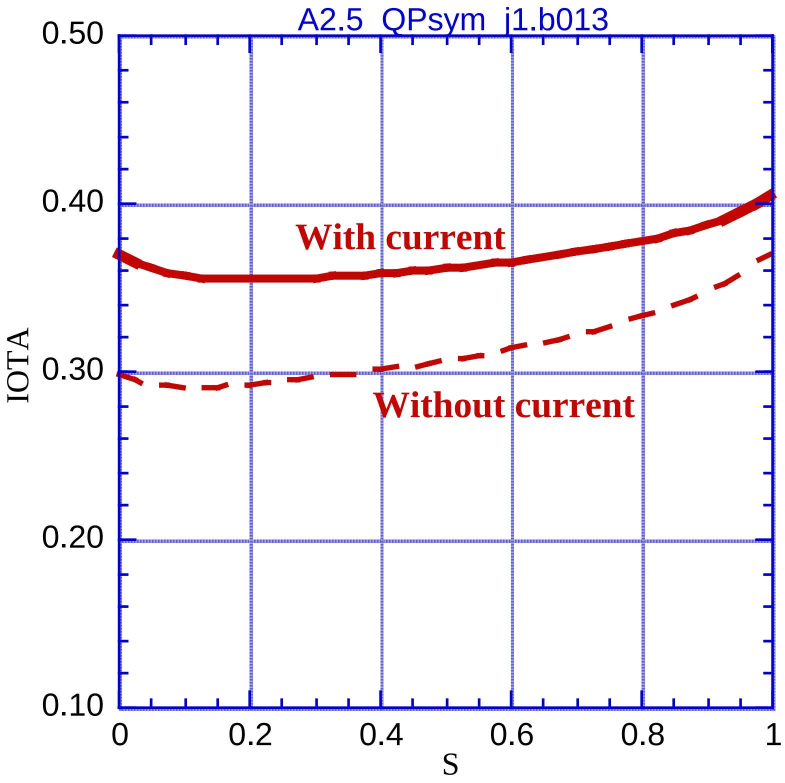
QOS-CE Physics Parameters

- ι ~ 0.3 to 0.4 in vacuum

- I_{plasma} ~ 25 kA for B = 1T (at β = 1%)
  - transform from current *adds* only a small amount (~0.07-0.03) to external transform (neoclassical-tearing stable profile)
  - lower current (3-5) compared to tokamak with same ι

- τ^{nc}/τ^{ISS95} ~ 2-4 for B = 1T (further increase possible)
  - nc confinement *sub*-dominant transport mechanism

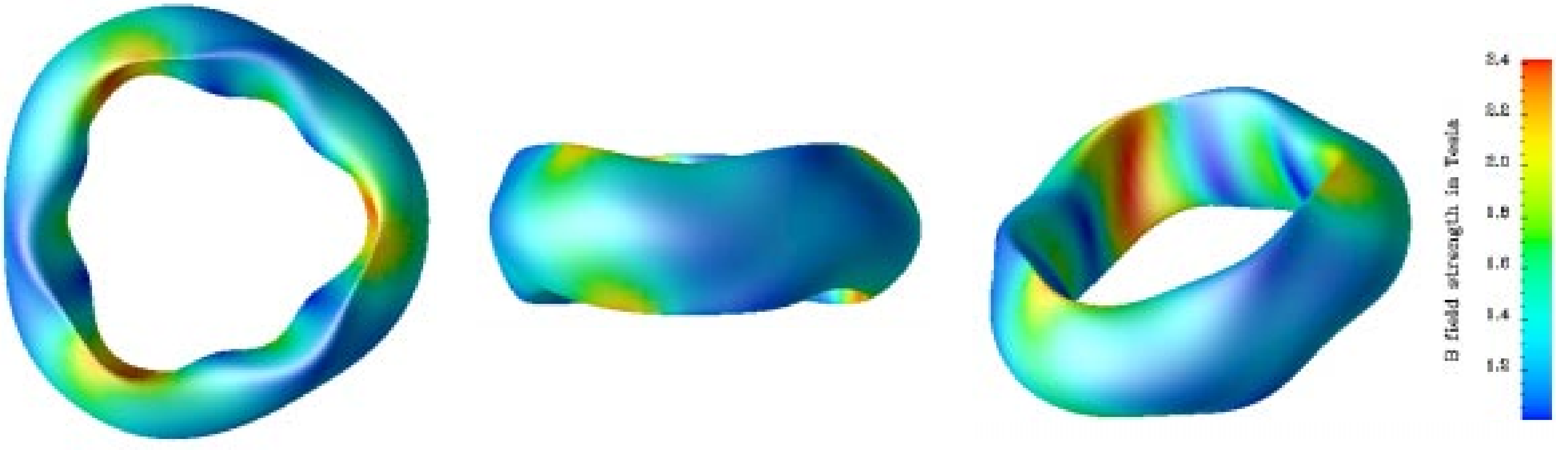
CE Configuration “Invariance” At Low β

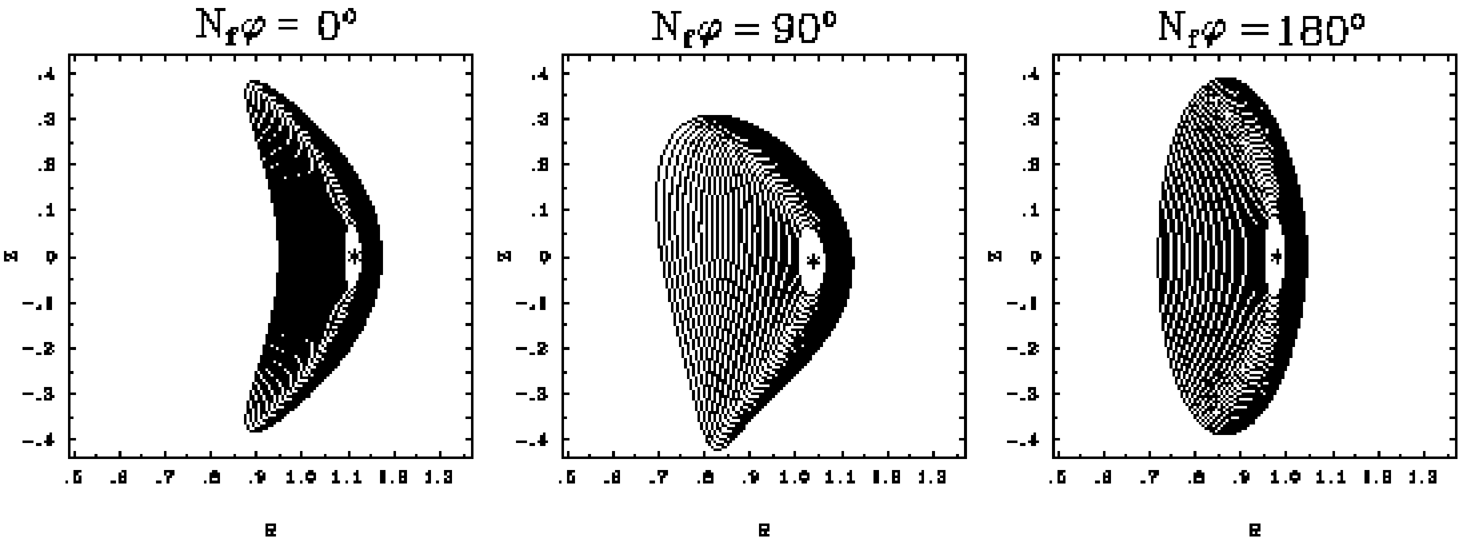


High-β QOS (QPS) Configuration

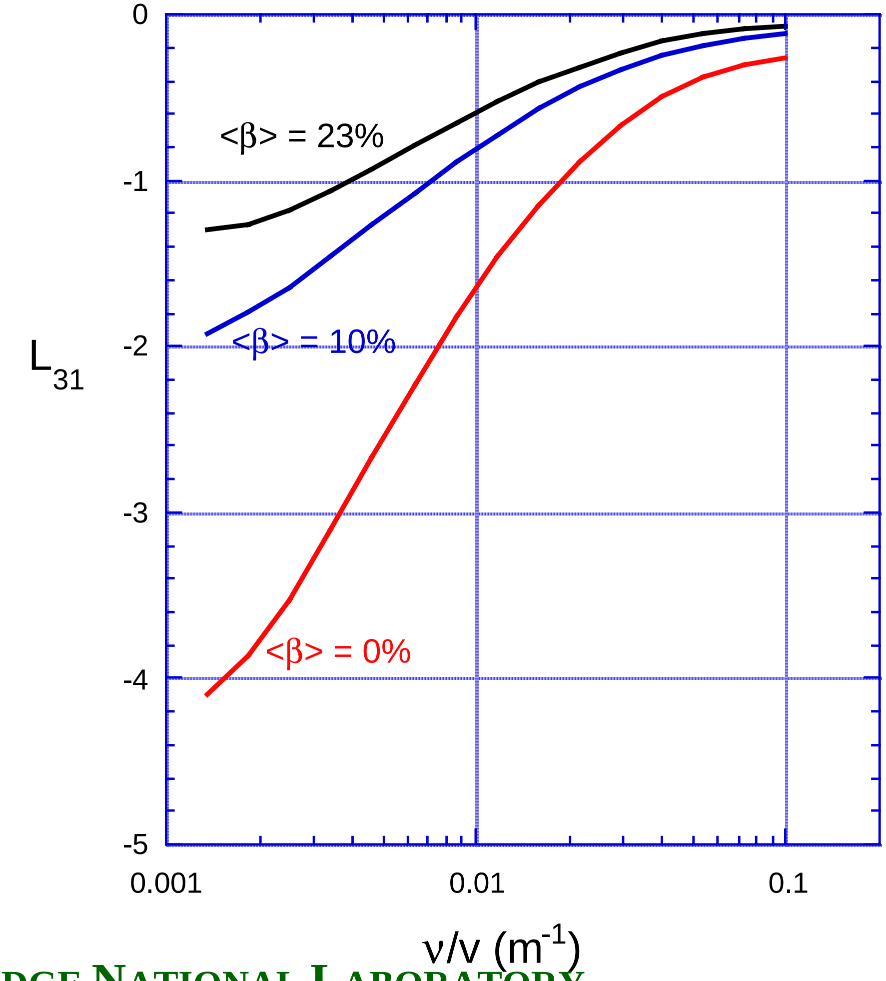
- Closely related to Advanced Tokamak concept
  - 100% bootstrap current
    - at edge, $\iota_{ext} \sim \iota_{plasma}$; tokamak-like profile
  - bootstrap current alignment (self-consistency)
    - $f_{trap} \neq 0$ on axis (toroidal bumps) - no seed needed
  - "high-q" : q(0) ~ 2.5, q(edge) ~ 8
    - small poloidal flux NOT problem as for axisymmetry
  - 2nd Ballooning, Mercier stable for $\beta \sim 15\%$
    - kink and vertical stability for small boundary change
      - due to reduction in $j_{bs} \sim 3$, finite edge ι_{ext}
    - high Tryon factor, $\beta_N \sim 20\text{-}30$

Surfaces for High-β (15%) QOS (N_p = 3, A = 3.5)





Approximate Bootstrap Constancy With β (configuration invariance)



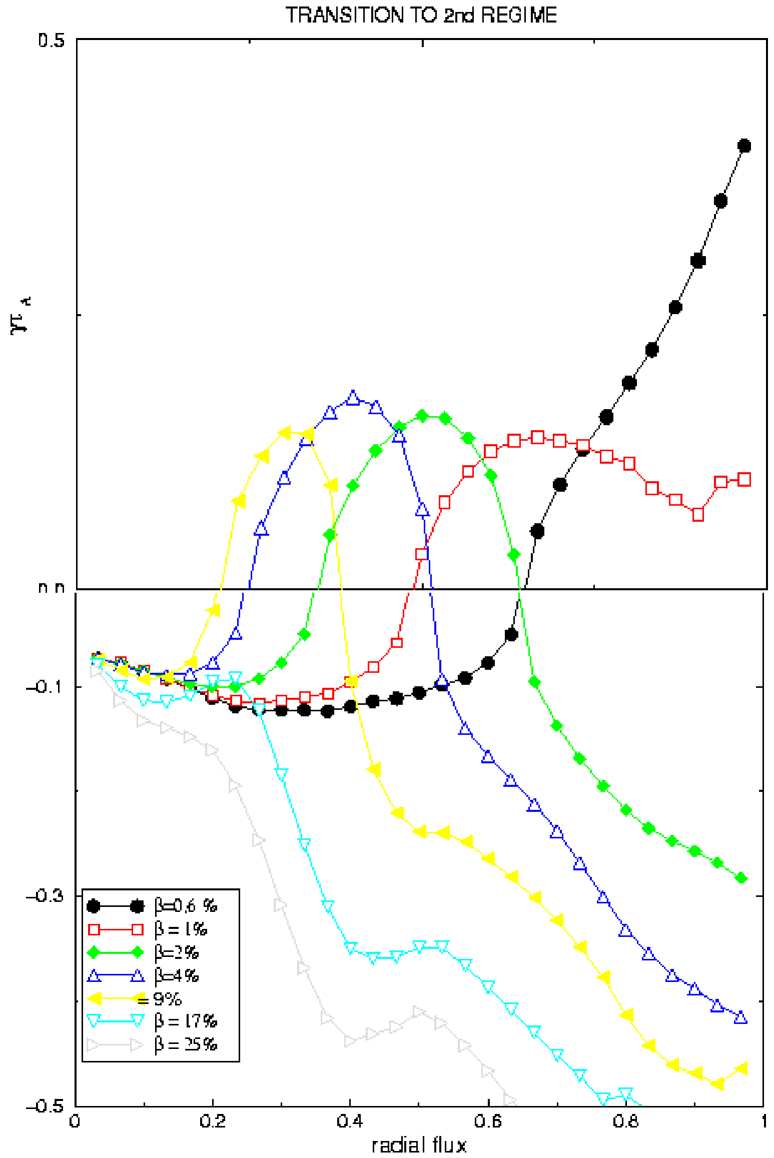
For low ν_*

$\beta * L_{31} \sim \beta^k$

k << 1

qp symmetry improves with β

Edge Becomes 2nd Stability at Low β



Summary

- Reference NCSX plasma configuration has been selected
  - passive stability to kink, ballooning, vertical, Mercier, neoclassical tearing to $\beta \sim 4\%$
    - eliminates need for feedback or conducting walls
  - high degree of quasi-axisymmetry achieved
    - good thermal, energetic particle confinement
  - two coil designs are under development
    - reproduce targeted physics goals
    - flexible to achieve startup, transitional plasmas
    - resonance suppression capabilities

Summary (cont'd)

- QOS Concept Exploration Experiment has been designed
  - orthogonal symmetry to QAS
    - good quasi-poloidal symmetry
    - low bootstrap current - complements NCSX
    - low parallel flow (high parallel viscosity)
      - complementary scheme for E X B shear control
  - foundation for high-β, QPS vision
    - shares many features with Advanced Tokamak, except |B| spectrum has "orthogonal" symmetry

These configurations were made possible by advances in the physics and numerics of low aspect ratio, 3-D systems. They form the basis for exciting experiments to test our understanding of compact stellarator plasmas.