# NCSX
# Physics Overview

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# Outline

- Motivation – The Compact Stellarator Opportunity
- Configuration Design, Characteristics
  – Stability, Transport, Flux surface quality
- Coil Design & Flexibility

Definitions:

- $\beta = 2\mu_0 \langle p \rangle / \langle B^2 \rangle$,
- Aspect ratio $A = R/\langle a \rangle$, where $\langle a \rangle$ is the average minor radius,
- Iota ($\iota$) and iota-bar ($\iota\!\!\!-  = 1/q$) are used interchangeably
- s = normalized toroidal flux

# Motivation

- Tremendous advances in understanding of both tokamak and stellarator confinement
- Compact stellarator opportunity: combine best features of both, synergistically, to advance both
  - Stellarators: *Externally-generated helical fields; no need for external current drive; generally disruption free.*
  - Advanced tokamaks: *Excellent confinement; low aspect ratio – affordable, high power density; self-generated bootstrap current*

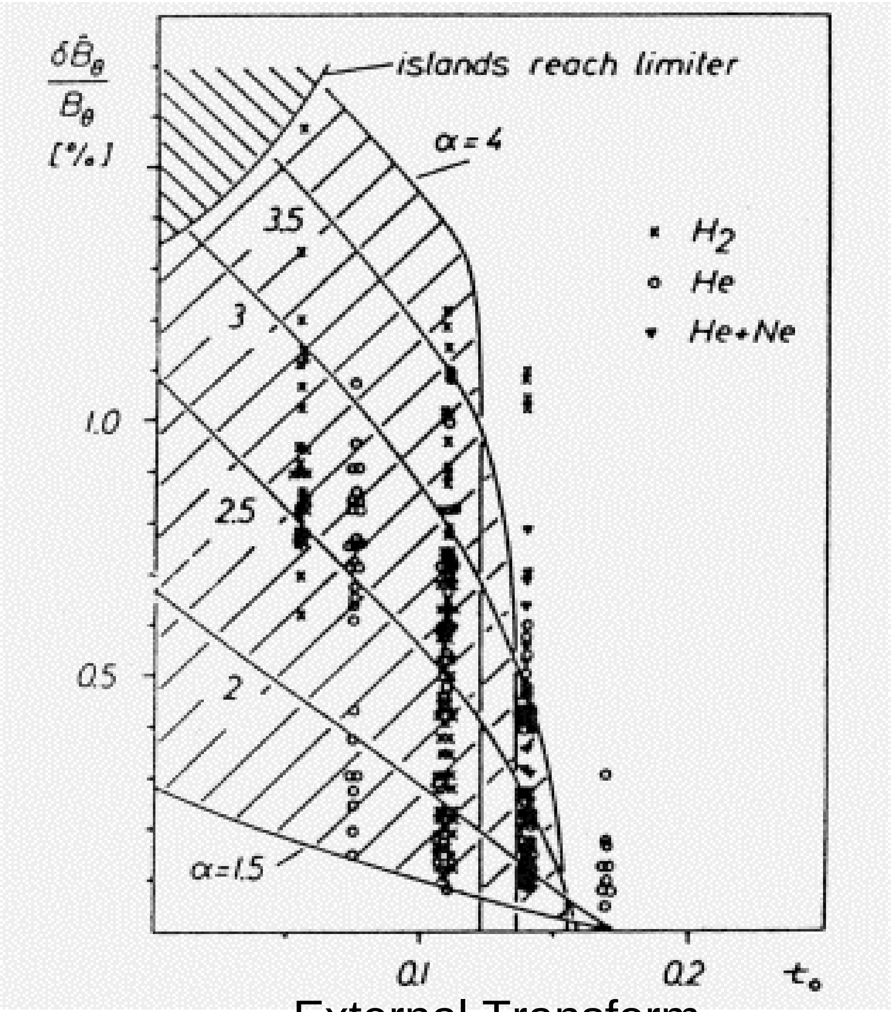
# Stellarator Advances

- Understanding of how to design for orbit confinement, good flux surfaces
- Numerical design to obtain desired physics properties
- Experience in accurately constructing experiments at a range of scales (CE -> PE), with good confinement and stability

Allows effective use of Stellarator Advantages:

- Steady-state compatible, lack of need for external current drive
- Disruptions typically not observed, can be avoided by design.

# Stellarator Fields Can Suppress Disruptions



External Transform

External transform applied to current-carrying stellarator:

- 3-fold increase in density limit.
- q<2 with no disruptions.

total ι(a) = 0.35

Ohmic current, low β, high aspect ratio.

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

**Stellarators typically do not disrupt if stable to global tearing mode. (W VII-A and W7-AS)**

**Experiments are needed to extend to high β, low aspect ratio.**

# LHD Has Obtained Very Good Results

## Confinement

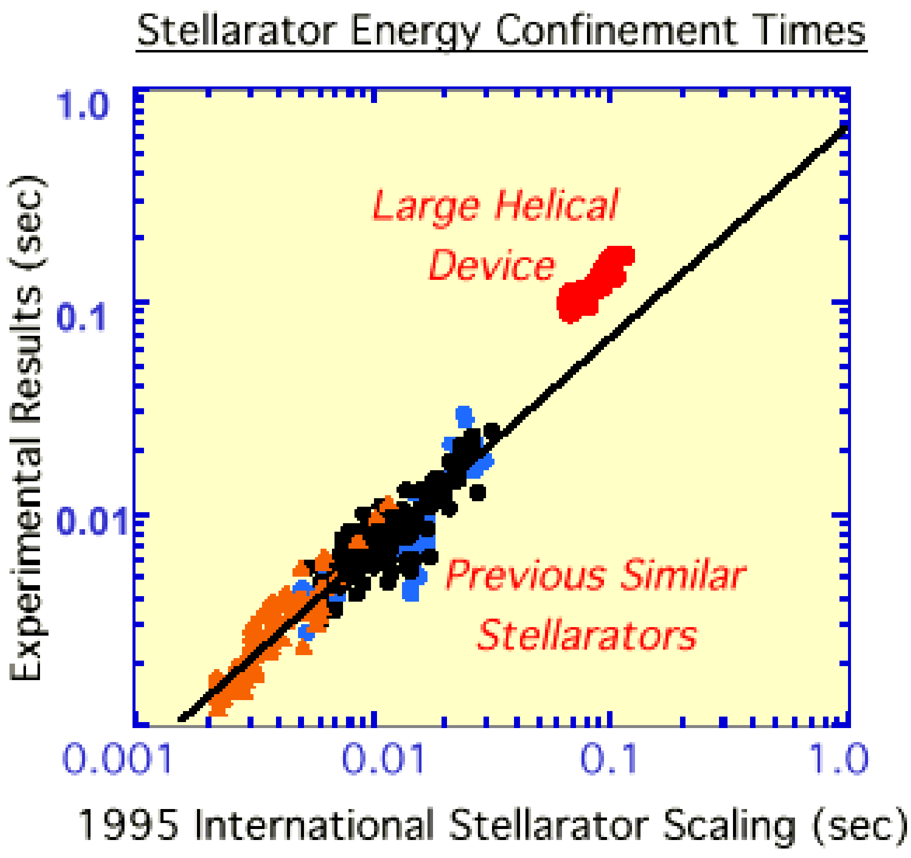
- Enhanced confinement, > 2×ISS95 (multi-device global confinement)
- $\tau_E$ up to 0.3 s.

## Peak Parameters:

- $T_e \leq 4.4$ keV, $T_i \leq 2.7$ keV, $n_e \leq 10^{20}$ m$^{-3}$
- Pulse length over 2 minutes.

## Beta

- $\beta_T$ = 2.4%(IAEA), $B_T$=1.3T with pellet
- $\beta_T$ = 2.2% sustained, $B_T$=0.8T, $T_{e0}$~700 eV
- Exceeds theoretical high-n stability limit. Observe saturated m/n=2/1 mode.
- Now ≳3%, B = 0.5T, $P_{NB}$ = 3.4 MW




Can these good results be extended to low aspect ratio configuration with current and good ion confinement? Can confinement be further improved?

# Two strategies for Orbit Confinement in 3D

3D shape of standard stellarators $\Rightarrow$

orbits can have resonant perturbations, become stochastic $\Rightarrow$ lost

B is bumpy every direction $\Rightarrow$ rotation is strongly damped

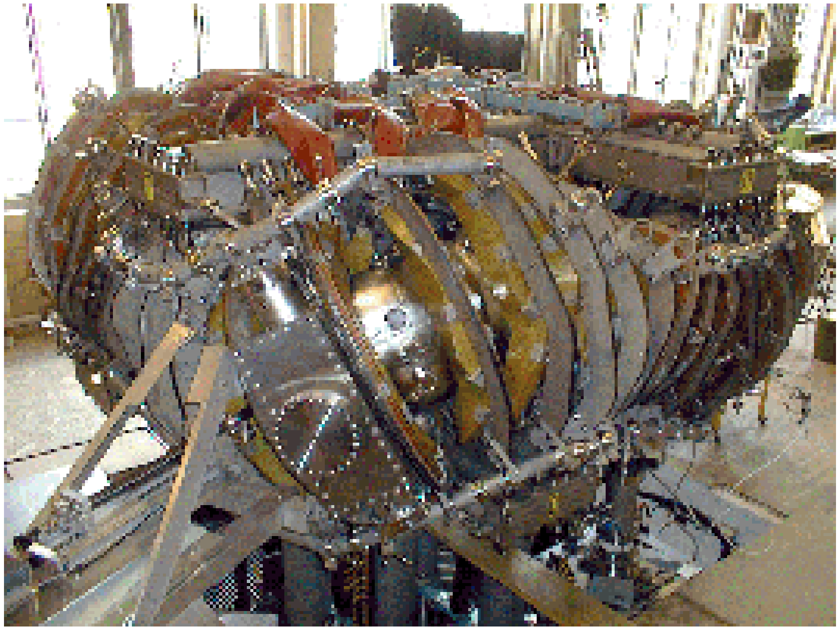
- Non-symmetric drift-orbit omnigeneity
  - Toroidal and helical drifts cancel; align drift orbit with flux surface
  - Principle of W-7X, new German superconducting experiment (A=11)

- 'quasi-symmetric'
  - Boozer (1983) Drift orbits & neoclassical transport depends on variation of |B| within flux surface, not the vector components of B !
  - If |B| is symmetric in "Boozer" coordinates, get confined orbits like tokamak

  $\Rightarrow$ neoclassical transport very similar to tokamaks, undamped rotation

Boozer coord: straight field-line coordinates, Jacobian $\propto 1/B^2$

# Helically Symmetric Experiment (HSX): Neoclassical Transport Reduction via Quasi-Helical Symmetry



**R=1.2 m, B=1 T, 4 periods, R/⟨a⟩ = 8**

Univ. of Wisconsin

In Boozer coordinates, magnetic field looks like straight helix

First test of quasi-symmetry

started operation in 2000

# Tremendous Advances in Tokamak Experiments and Understanding

- General confirmation of ideal MHD equilibrium and stabilty theory
- Confirmation of neoclassical transport theory
- Development and understanding of neoclassical tearing
- Stabilization and manipulation of turbulent transport
- Importance for shear-flow stabilization of turbulence, zonal flows
- $\beta_T$~12% achieved with large externally driven currents (incl. Inductive)

Exciting Challenges

– $\beta_T$ ~ 5% steady state without disruptions (e.g. ARIES-RS)
– sustainment of current with minimum recirculating power
  $\rightarrow$ depend on bootstrap current (current driven by pressure gradient)

$\Rightarrow$ Focus of "Advanced Tokamak" and Spherical-Torus Research using conducting walls, feedback stabilization of resistive-wall and neoclassical tearing modes

# Compact Stellarators Offer Innovative Solutions

Compact Stellarators Opportunity $\rightarrow$ **NCSX Goals**

*Use 3D shaping flexibility of stellarators to*

- Passively stabilize external kink, vertical, neo-tearing, ballooning instabilities
  - expand safe operating area to $\beta \geq 4\%$,
    without need for conducting walls or feedback systems
  - prevent disruptions?
- Good confinement. Quasi-axisymmetry to close orbits, allow flow
  Take advantage of tokamak advances; Use bootstrap to raise iota
- Steady state without current drive. Aspect ratio: ~ 4
- Control of iota (q) and shear via coils

Using Advances in Theory and Numerical modeling; parallel computing

# NCSX Mission

**Understand…**

- Beta limits and limiting mechanisms in a low-A current carrying stellarator
- Effect of 3D fields on disruptions
- 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 between power and particle exhaust methods and good core performance in a compact stellarator.
- Explore Alfvenic-mode stability in reversed shear compact stellarator

**Demonstrate…**

- Conditions for high-beta, disruption-free operation

**Acquire the physics data needed to assess the attractiveness of compact stellarators.** (adopted as 10-year goal by FESAC-1999)

# NCSX Design Process Similar to W7-X, HSX

Fixed Boundary
Equilibrium Optimization

In depth analysis
- Flux surface quality (A.Reiman)
- Transport (D.Mikkelsen)
- Stability (G.Fu)

Coil Design
(to reproduced Fixed Bdry
Equilibrium)
(S.Hirshman)

Engineering Analysis (B.Nelson)

Free Boundary Analysis
- Robustness/Flexibility
- Discharge Evolution

(N. Pomphrey, E. Lazarus)

- Transport, stability, flux surface quality
- Engineering
- Edge analysis (P.Mioduszewski)

- Same general process as first developed for W7-X, used on HSX
  - extended to address finite $\beta$, current, and low A

# Method: Design for High $\beta$

- Plasma shape and coils are designed for desired properties at $\langle\beta\rangle \sim 4\%$ including effect of bootstrap current; low aspect ratio

- Most stellarator designs have been optimized without net plasma current, coils designed for vacuum configuration

- Required substantial tool development
  - Improved 3D equilibrium codes – PIES and VMEC
  - Kink & ballooning stability, quasi-symmetry, bootstrap current, coil engineering metrics incorporated into plasma optimizer
  - New coil-design tools to reduce complexity, current density, heal island and preserve good physics properties

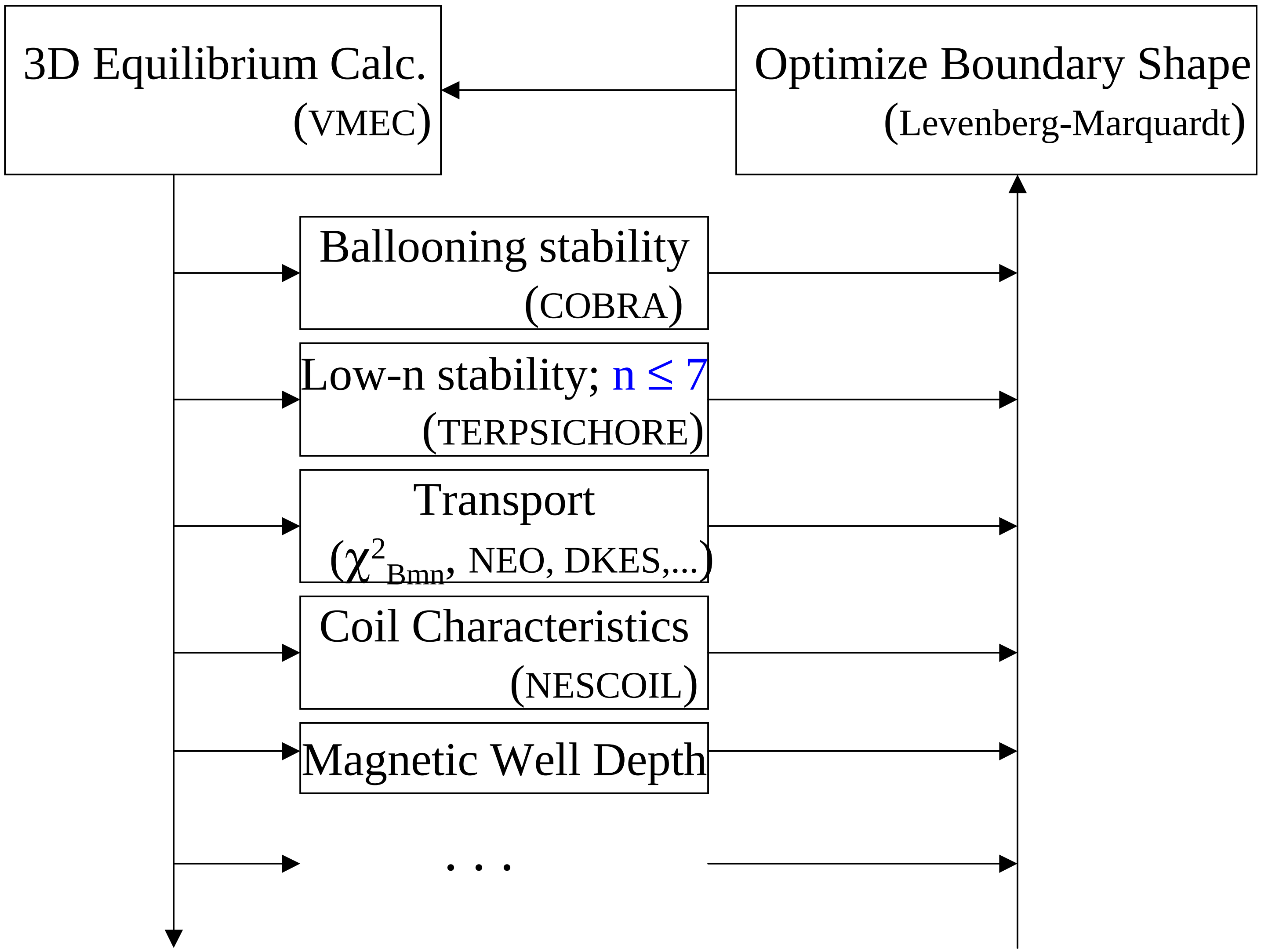
$\rightarrow$ Wide range of configurations explored, evaluated

# Established Codes and Methods used for Analysis

- VMEC - an ‘inverse’ equilibrium solver, which solves directly for the shape of the flux surfaces. Representation presumes that the flux surfaces are simply connected, without islands or stochastic regions. see S. Hirshman
- PIES - is a ‘forward’ equilibrium solver, directly calculating the 3D magnetic field and current distribution, including simulating the effect of islands and stochastic regions by flattening $\nabla p$. Flux surface topology and shape determined by integrating the field-line orbits. see A. Reiman

- TERPSICHORE, CAS-3D - low-n stability codes see G. Fu
- COBRA, VVBAL - infinite-n ballooning codes

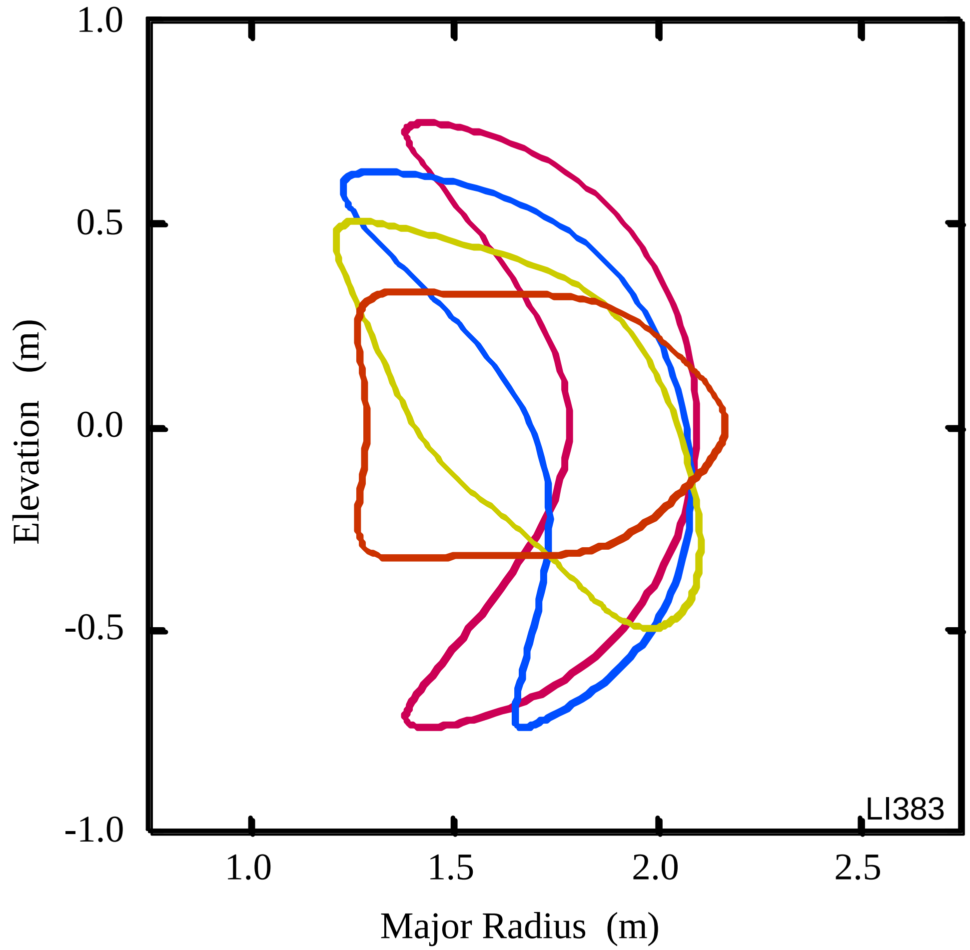
# Fixed Boundary Equilibrium Optimization



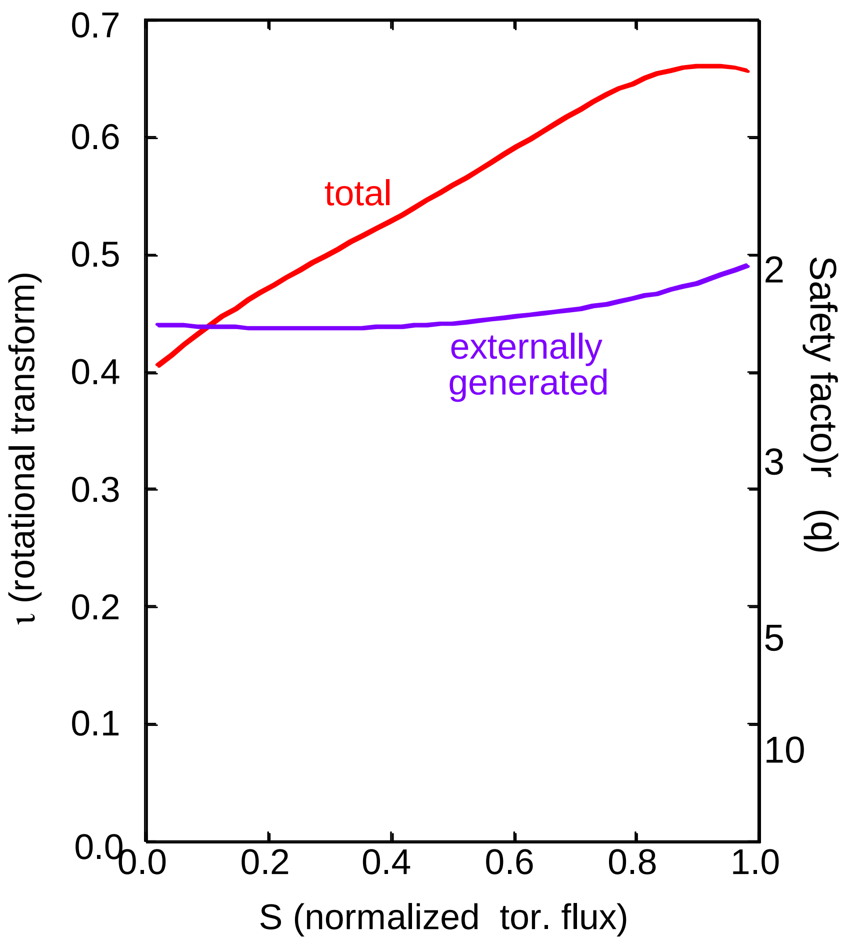
# NCSX Plasma Configuration Has Attractive Physics

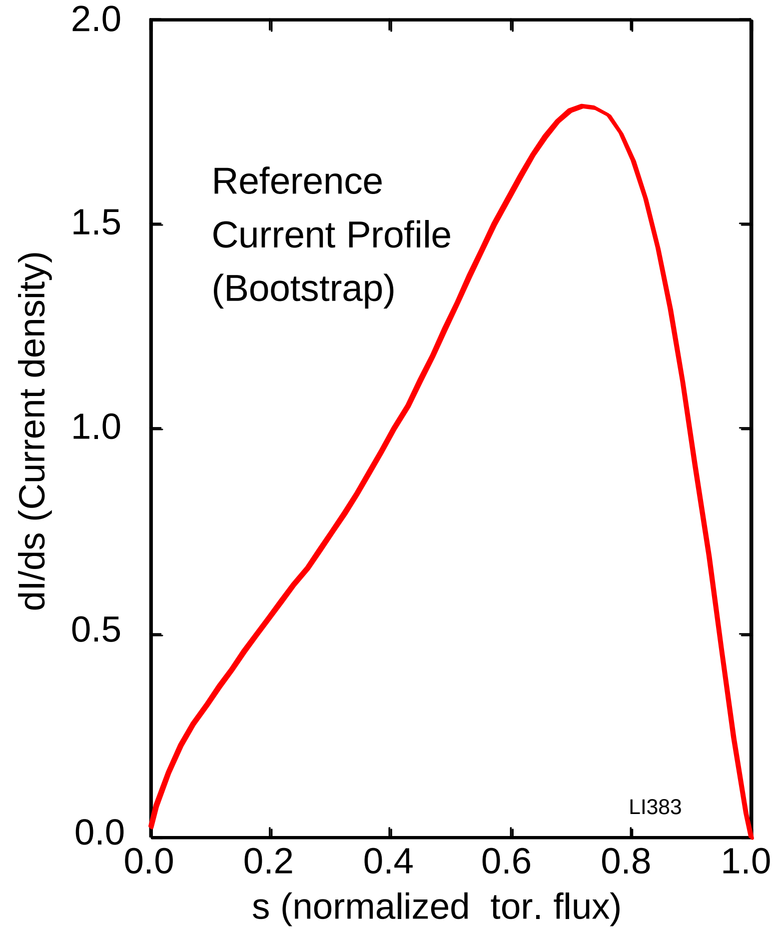
- 3 periods, R/⟨a⟩=4.4, ⟨κ⟩~1.8
  <indented>
- Good magnetic surfaces.
- Quasi-axisymmetric: low helical ripple transport.
- Stable at β=4.1% to kink, ballooning, kink, vertical, Mercier, neoclassical-tearing modes
- Recent study with many more equilibrium & stability modes found an unstable n/m=11/17 edge mode. Can be stabilized with slight shape change. See G. Fu.

**Plasma Cross Sections**



# Hybrid Configuration Combines Externally-Generated Fields with Bootstrap Current




- Quasi-axisymmetry ⇒ tokamak like bootstrap current
- ~3/4 of transform (poloidal-B) from external coils ⇒ externally controllable
- at R=1.4m, B=1.2T, $I_P$ = 125 kA; $I_P^{Equiv}$ = 500kA; $\beta$=4.1% ⇒ $\beta_N^{Equiv}$ = 2.5

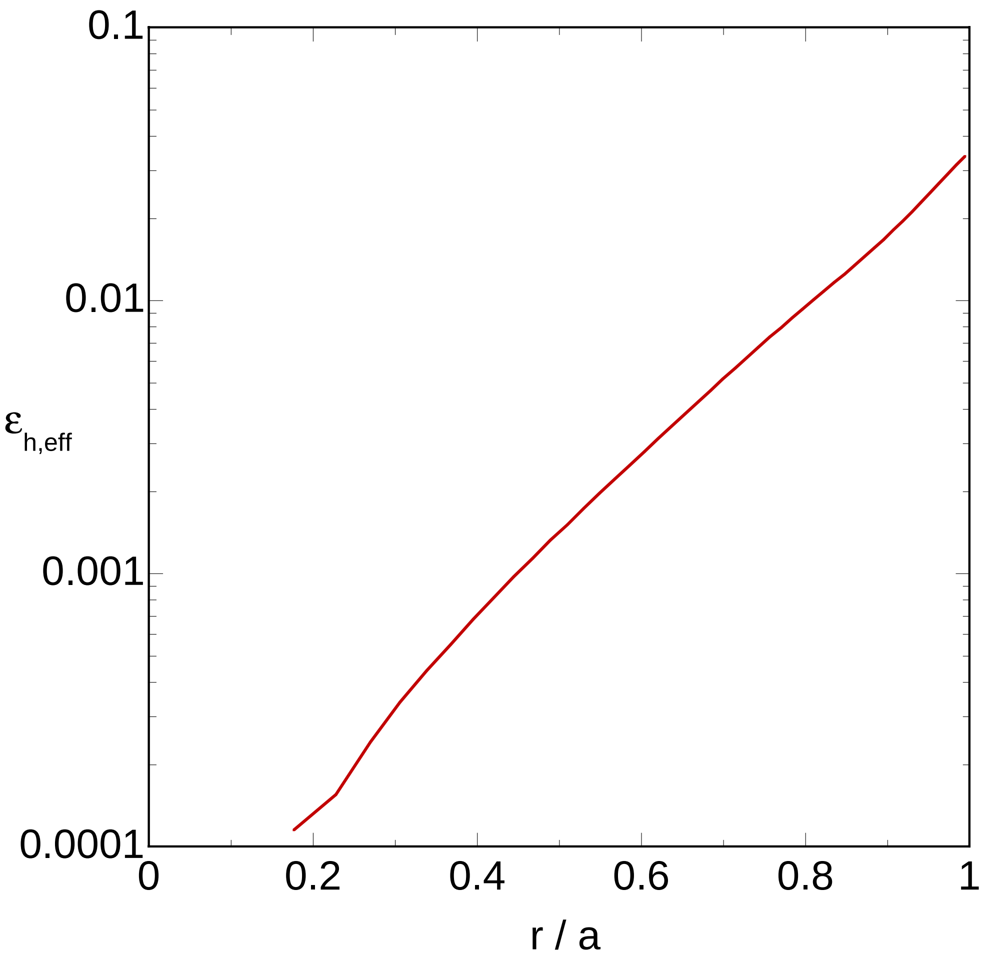
# 3D Shaping Predicted to Stabilize Kink in Several Ways

- Via global shear, similar effect to shear variation in tokamak
  -- but now independent of current, due to external transform
- Large local shear on low-field side increases field-line bending energy
- Depth of magnetic well
- Edge current density is not de-stabilizing (!) (see N. Pomphrey)

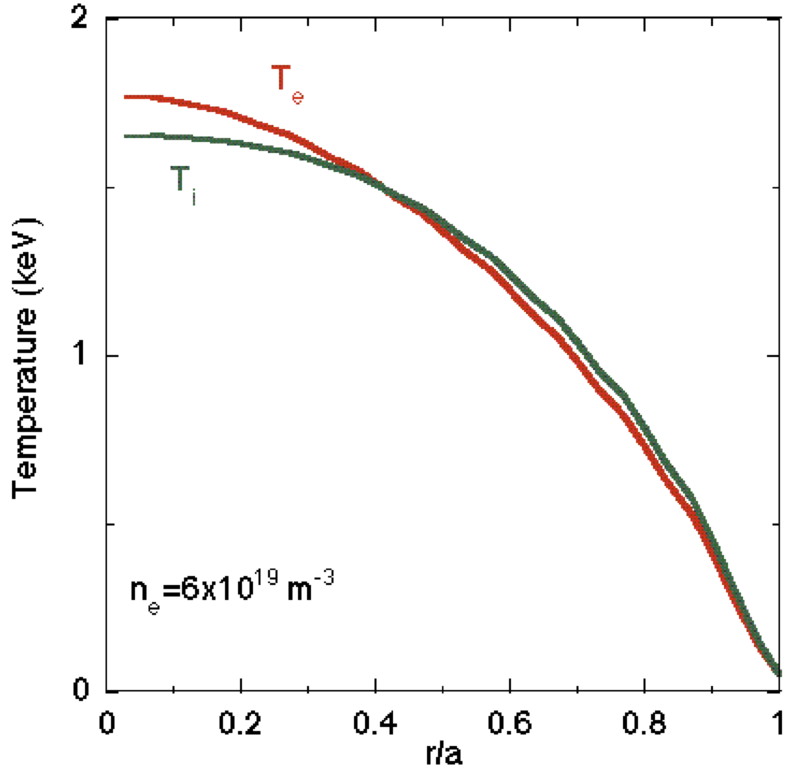
[Mikhailov & Shafranov, NF **30** (1990) 413.]

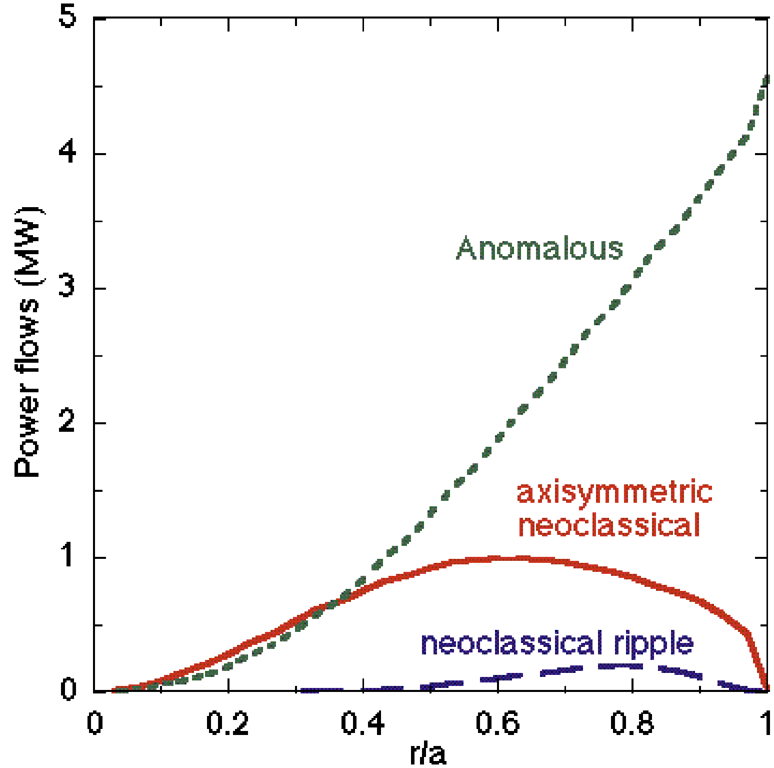
# Quasi-Axisymmetric: Low effective ripple

- $\epsilon_{eff}$ from NEO code by Nemov-Kernbichler
- In 1/ν regime, neoclassical transport scales as $\epsilon_{eff}^{3/2}$
- Edge $\epsilon_{eff}$ ~ 3.4%
- Allows balanced-NBI
  24% loss at 1.2T, drops as B↑
- Should give low flow-damping
  - manipulation of flows for flow-shear stabilization
  - zonal flows like tokamaks
- Linear microstability similar to tokamaks [Rewoldt; Jost et al.]



# Low $\varepsilon_{h,eff}$ $\Rightarrow$ Low Helical transport

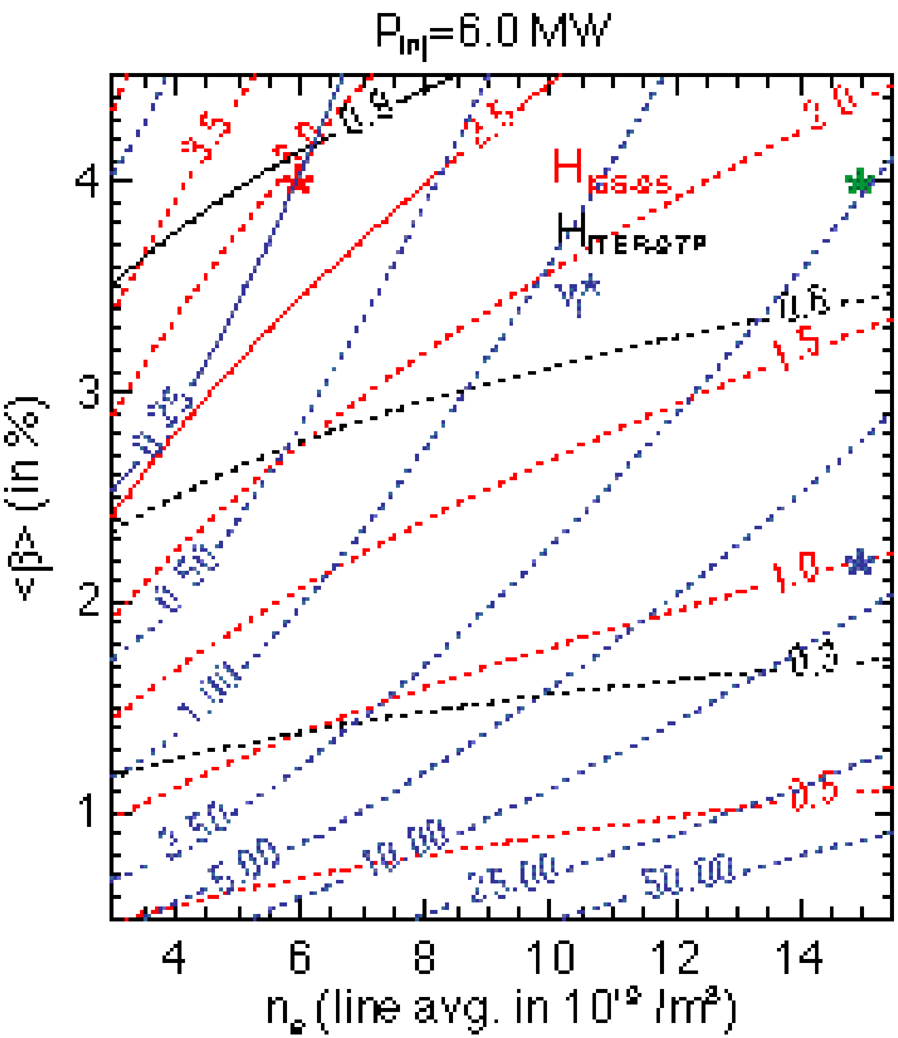



- Helical transport is sub-dominant with self-consistent $E_r$
- Assume B=1.2 T, $P_{inj}$=6 MW , R=1.4m, $H_{ISS95}$=2.9 ($H_{ITER\text{-}97P}$=0.9)
  $\Rightarrow \beta$ = 4%, $\nu^* \sim 0.25$.   B=1.7T gives access to $\nu^* \sim 0.1$, $T_i(0)$~2.3 keV
- Shaing-Houlberg for helical transport, benchmarked with Monte-Carlo.
- Uniform anomalous $\chi$ used.  Similar results obtained with Lackner-Gottardi

See D. Mikkelsen

# Wide Range of Plasmas Accessible

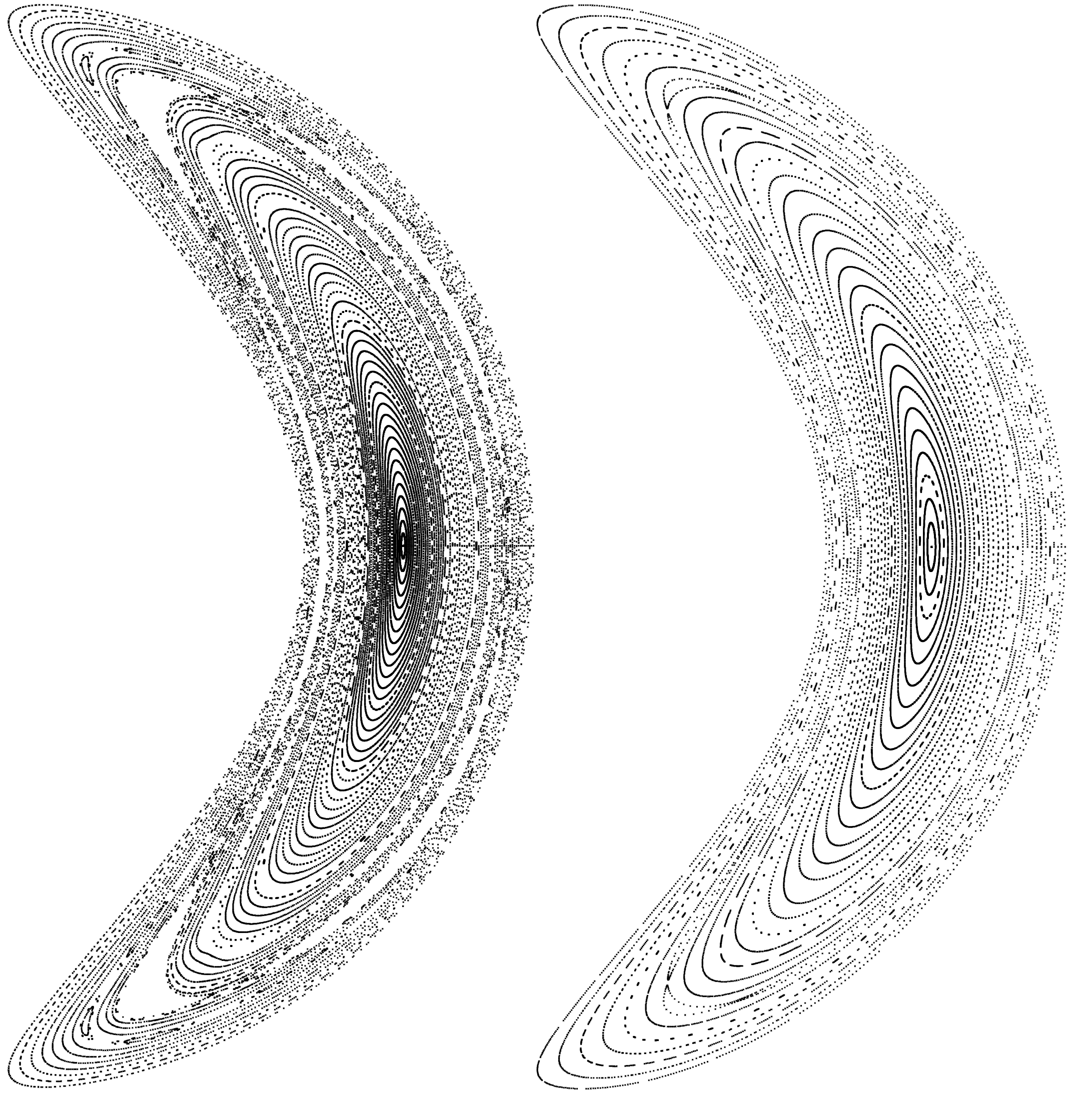



B = 1.2 T

- Contours of H-ISS95, H-ITER-97P, and min $\nu_{*I}$
- $\beta$=4%, $\nu_{*I}$ =0.25 requires $H_{ISS95}$=2.9, $H_{ITER-89P}$=0.9
- $\beta$=4% at Sudo 'density-limit' requires $H_{ISS95}$=1.8
- $H_{ISS95}$=1.0 gives $\beta$=2.2% sufficient to test stability theory

- 3MW gives $\beta$=2.7%, $\nu_{*I}$ =0.25 with $H_{ISS95}$=2.9;
  $\beta$=1.4% with $H_{ISS95}$=1.0 sufficient to test stability theory

# Island Removal Method

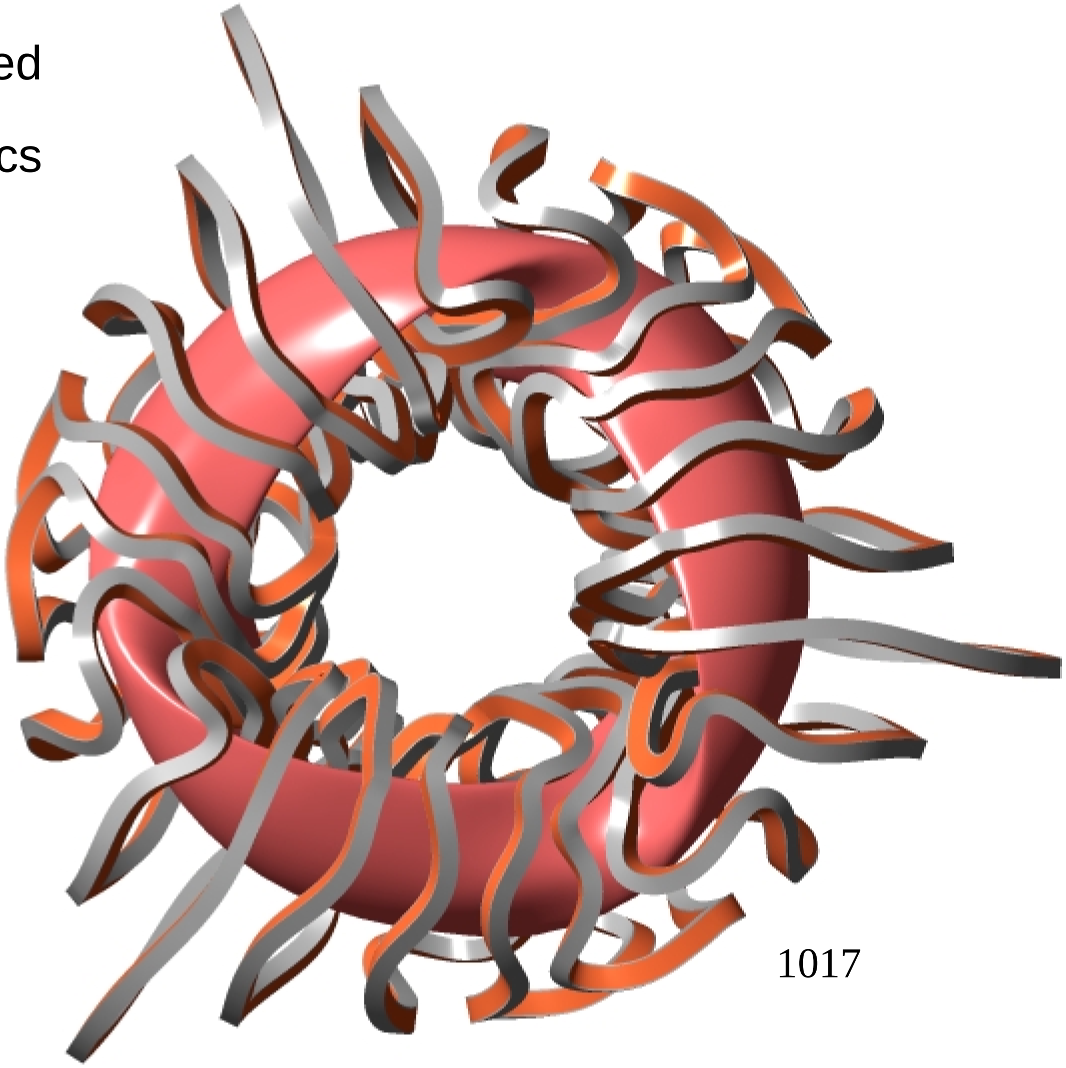


- Calculate coupling between plasma boundary shape and island widths by perturbation, using PIES
- Invert coupling matrix to find (small) shape modification to remove islands
- Modification had no effect on calculated stability or transport
- In experiment, neoclassical effects should heal islands

(see A. Reiman)

# NCSX Modular Coils Provide Good Physics Capability

- Wide range of coil designs explored
- Modular coils best preserve physics properties of reference plasma:
  - stable at reference $\beta$ (4%).
  - Good magnetic surfaces.
  - A=4.1,  modest increase in ripple.
- Also include Poloidal Field coils and weak Toroidal Field, for flexibility
- Outer coil-leg displaced for tangential NBI and diagnostics
- Stable to $\beta$ > 6.5% with some increase in ripple



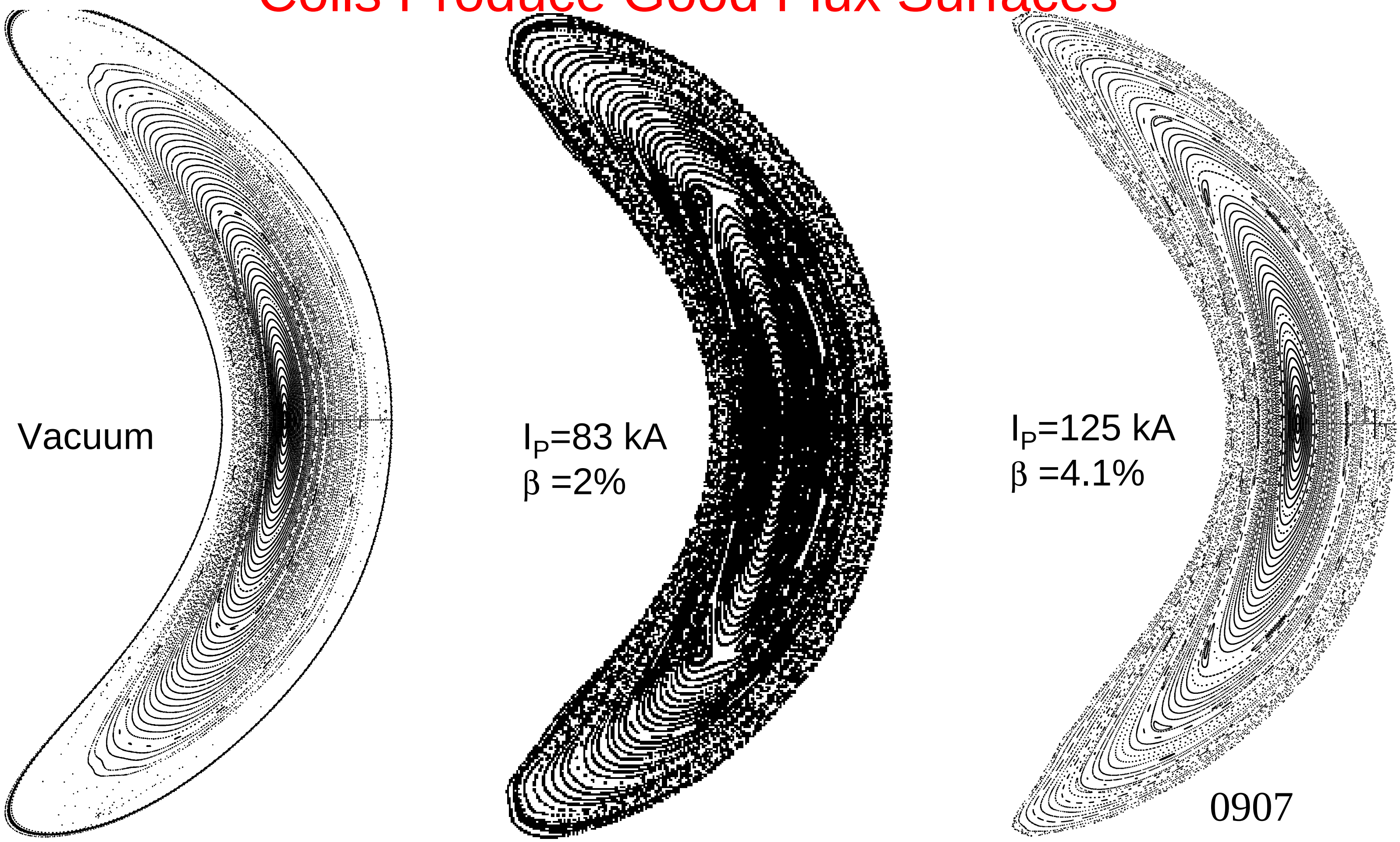

see S. Hirshman

# A Number of Coil Designs are Being Considered

| Coil ID | Ref. LI383 | 0907 (m2) | 1017 (m3) | 0105 (m8) |
|---|---|---|---|---|
| Extended for NB Access | | No | Yes | Yes |
| A | 4.36 | 4.25 | 4.16 | 4.17 |
| $\beta$ | 4.19 | 4.24 | 4.10 | 4.09 |
| $\lambda$, Kink (x$10^4$) upto n=11 | Stable | Stable | Stable | Stable |
| $\lambda$, Ballooning, $\zeta$=60 | 0.91-0.96 | 0.92-0.96 | Stable | Stable |
| $\varepsilon_{h,eff}$ (%) | | | | |
| s=0.3 | 0.22 | 0.36 | 0.45 | 0.30 |
| s=0.5 | 0.68 | 0.89 | 1.1 | 0.79 |
| s=0.8 | 2.2 | 2.6 | 3.4 | 2.5 |
| $f_{NB}$ (%), 40KeV NBI, 2T, H | 14.4 | 17.7 | 17.2 | 15.4 |

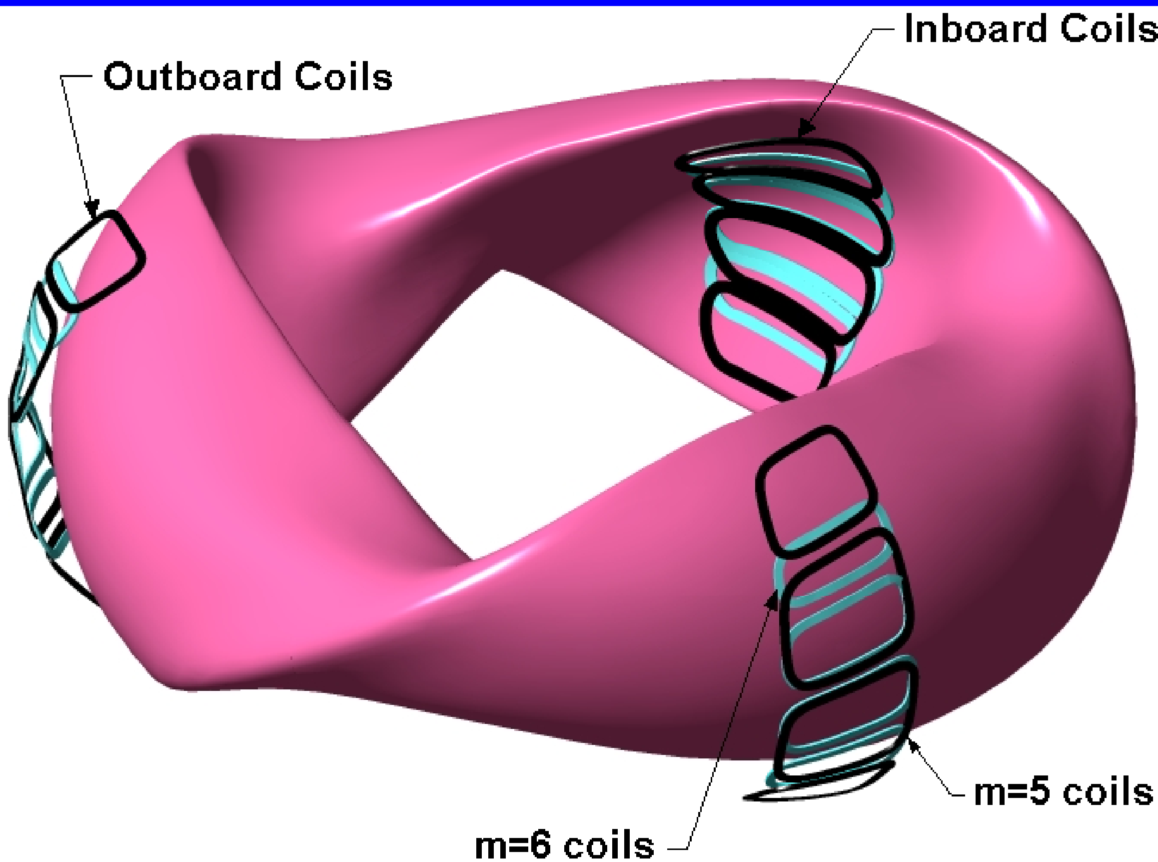
- Analysis to date has concentrated on 0907 and 1017 coils
- 1017 produces higher ripple than desired for baseline
- 0105 and later improved designs appear favorable.
  Will be analyzed in depth after PVR.

# Coils Produce Good Flux Surfaces



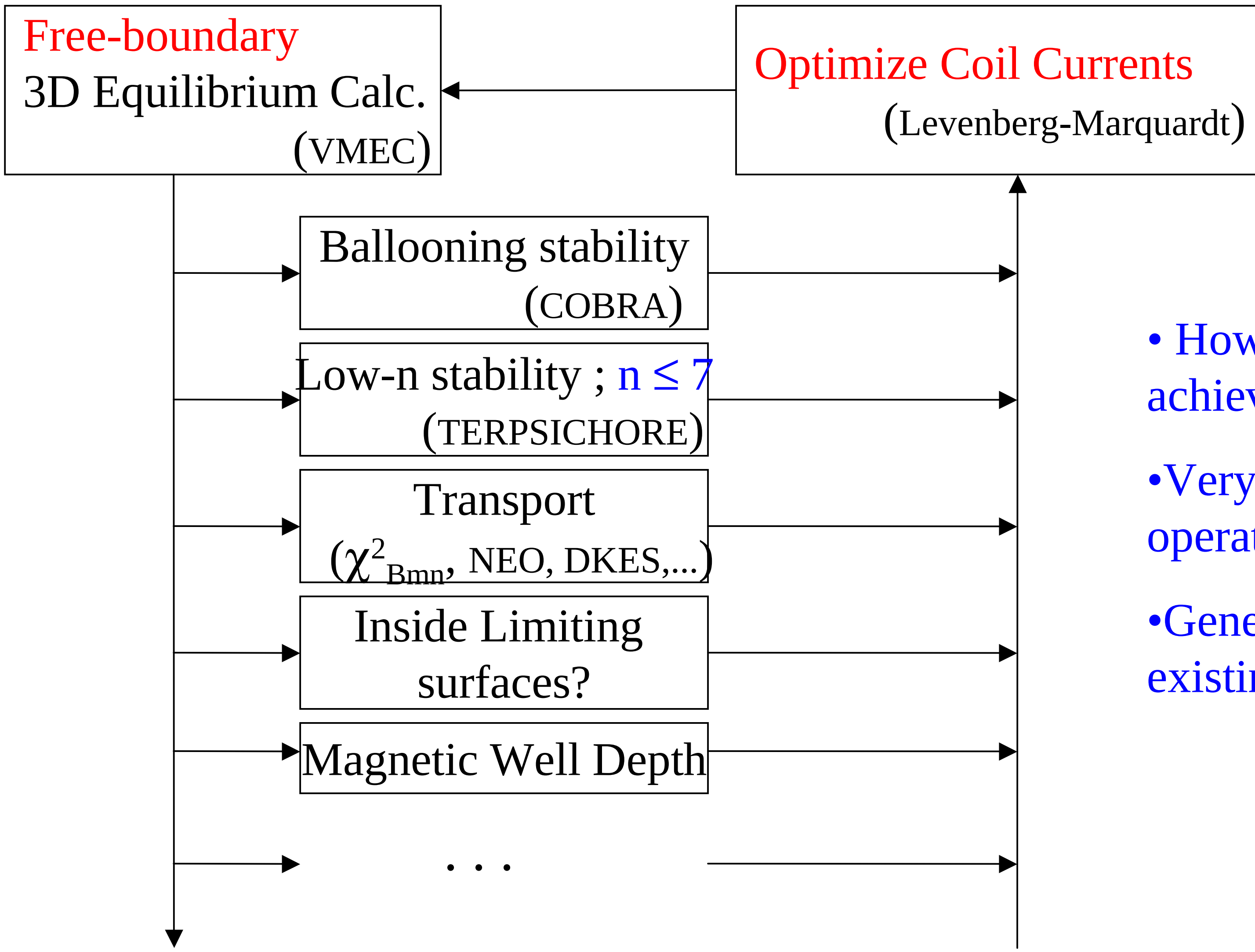

- Free-boundary equilibria (PIES)
- $I_P$ values for $B_T$=1.2 T
- Coils designed to produce good surfaces at full current. Island in middle case can be eliminated with trim coils. See A. Reiman

# Trim Coil Array Controls m=5 and 6 Resonances




- For supression of equilibrium islands over wide range of iota and shear profiles
- Tested on vacuum and finite β configurations.  More underway.

# Free-Boundary Optimizer used to Assess Flexibility

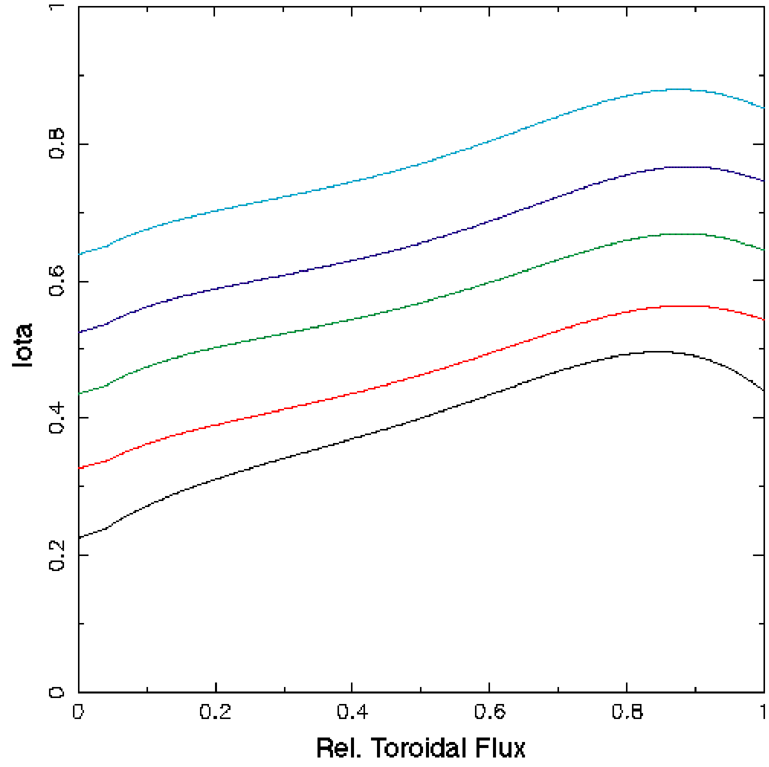



- How to use coils to achieve physics goals?
- Very similar to how one operates an experiment
- General tool, useful on existing experiments

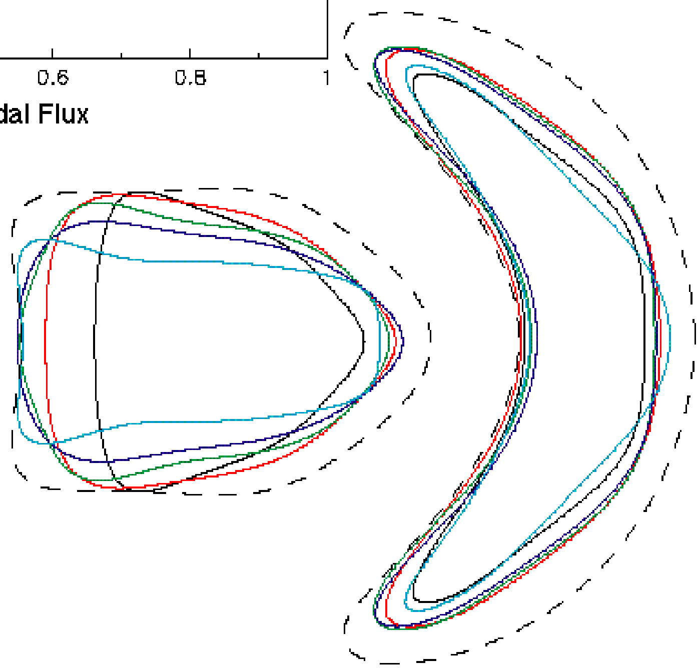
# Modular Coils are Flexibile

- External rotational transform controlled by plasma shape at fixed plasma current & profile.
- Can adjust to avoid iota=0.5, or hit it
- 1017 coils shown.

  Similar results for 0907 coils
- Can externally control shear
- Can accommodate wide range of p,j profiles
- Can use to test stability, island effects




$\beta$=0, full current

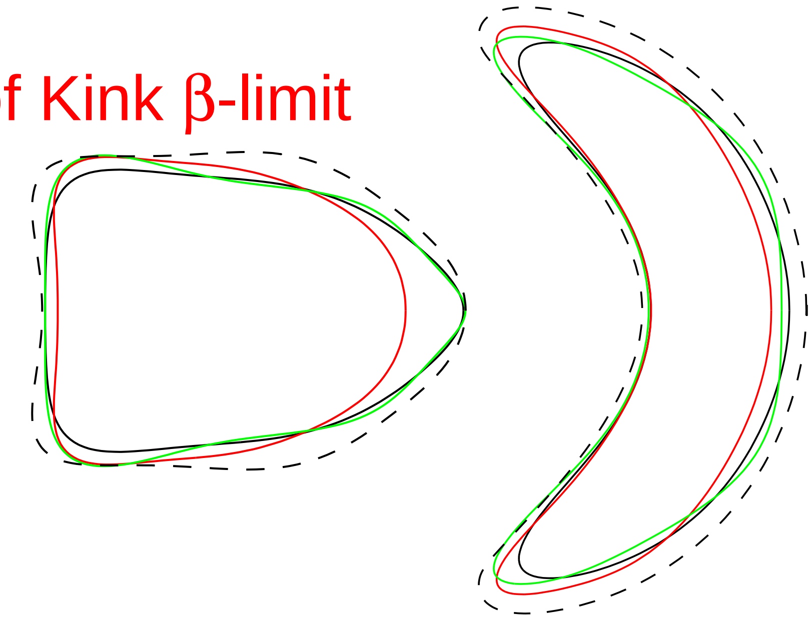


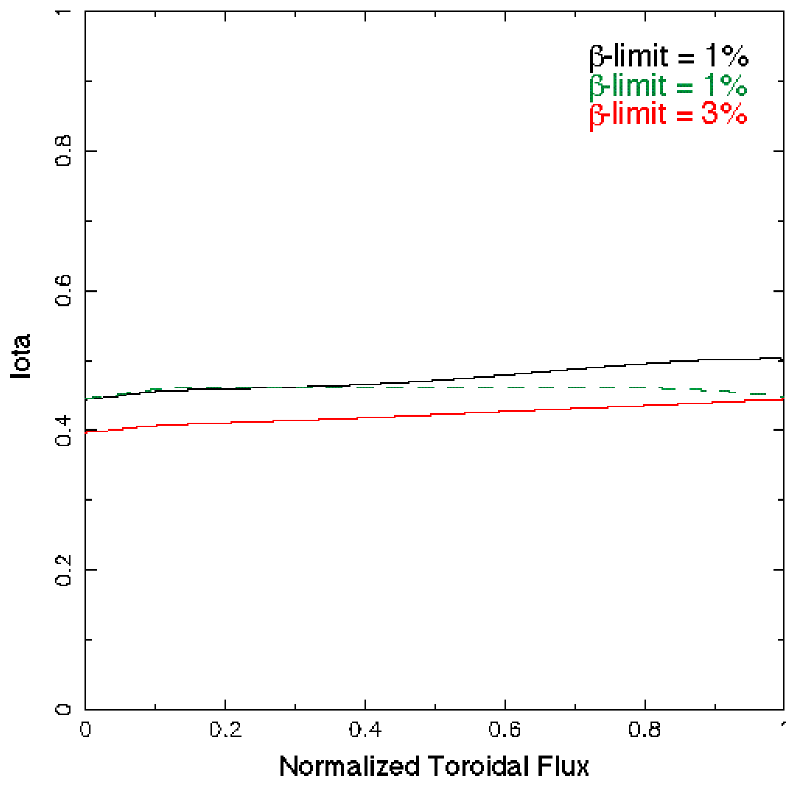
See N. Pomphrey

# Coil Flexibility Gives Control of Kink β-limit

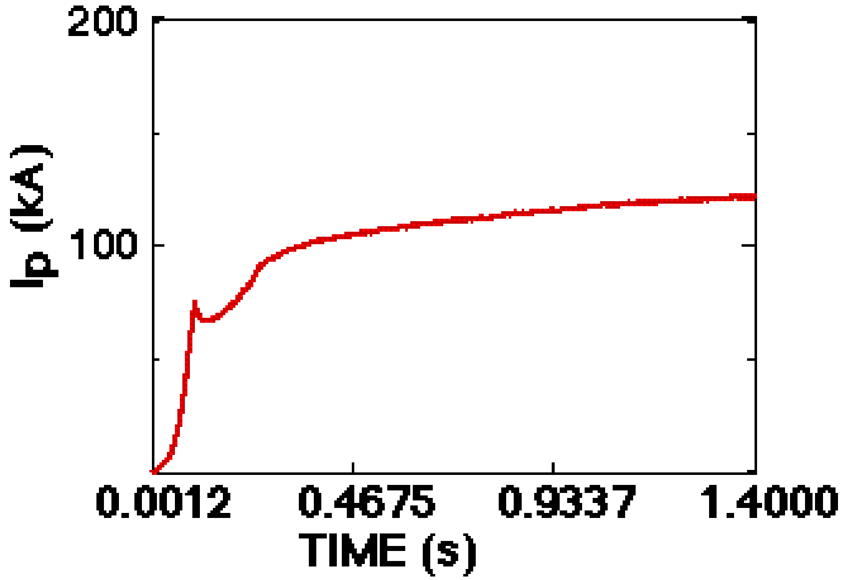
- External-kink marginally stable β changed from 3% to 1% by modifying plasma shape
  - either at fixed shear or fixed edge-iota !
- Free-boundary equilibria, fixed pressure and current profiles
- Useful for testing understanding of 3D effects in theory & determining role of iota-profile

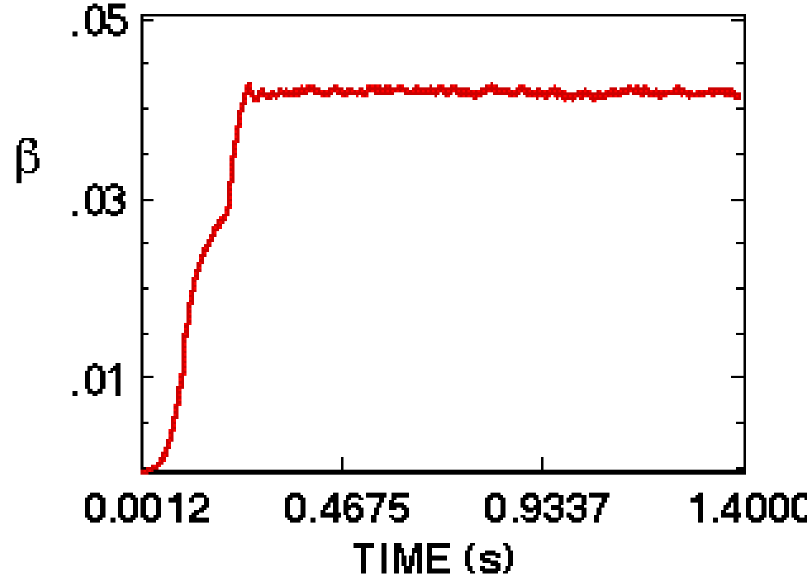
- Similarly, can find stable equilibria with effective ripple varying by factor ~ 5. For testing transport optimization & flow damping

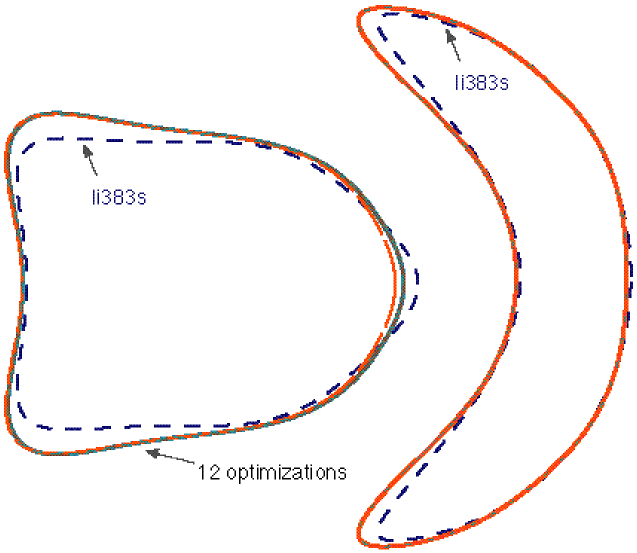




# Modeling of Discharge Evolution Shows Stable Access




0907

- Stable evolutions calculated for high and low temperatures (confinement)
- Stable evolution with
  - iota(a) crossing 1/2
  - iota(a) always > 1/2

See E.Lazarus; E. Fredrickson

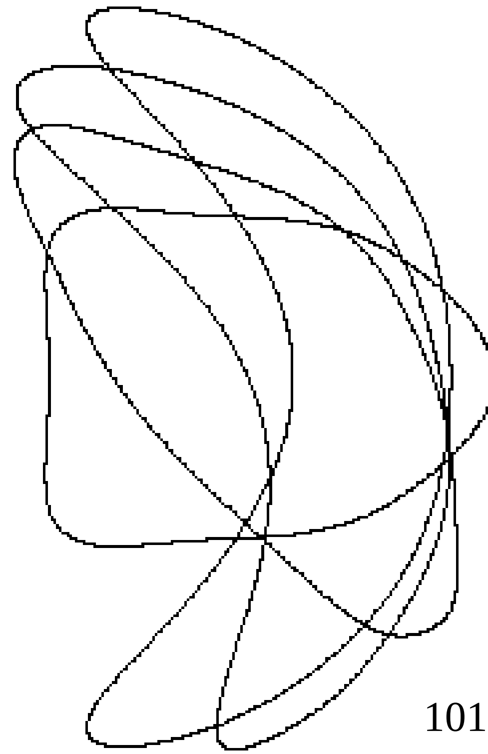
# β-limit is Very High for Free-boundary

- For both 0907 and 1017 coils, free-boundary equilibria have been found for β ≥ 6.5%. Limit not yet found.

- Case shown has had pressure locally flattened near edge to stabilize high-order 11/17 mode. See G. Fu

- Effective ripple increase by factor of 2.8
  Requires $H_{ITER\text{-}97P}$=2.3 with 6MW

- No systematic profile optimization has been attempted. Presumably, would further increase β-limit.

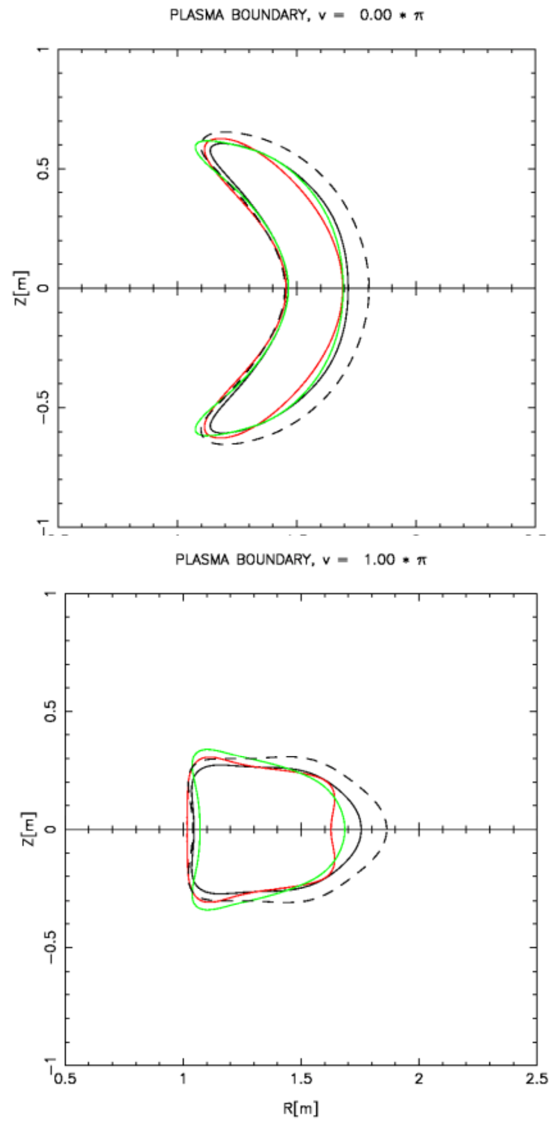


1017

# Equilibrium Maintained even with Loss of $I_P$ or $\beta$

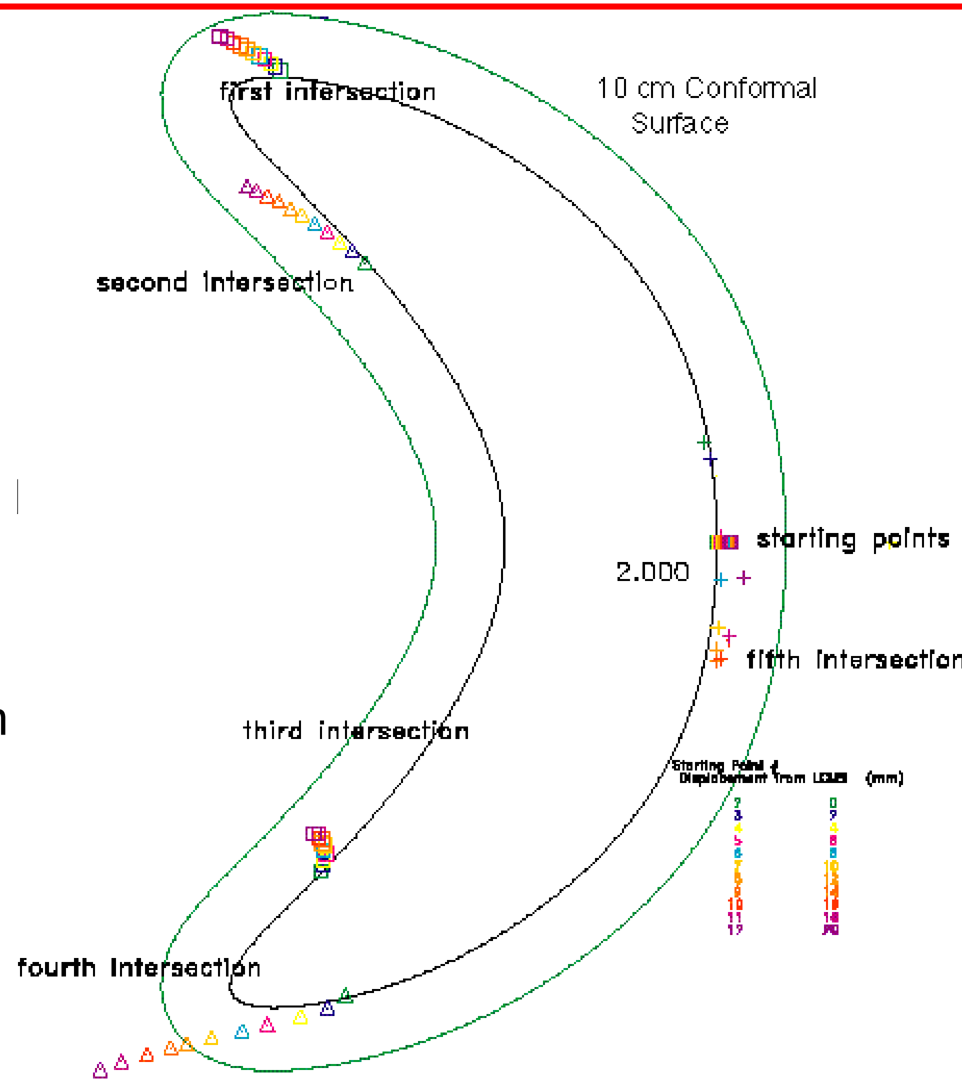
- Total loss of $I_P$ or $\beta$ only causes a small shift in equilibrium (few cm), for fixed coil currents.
- For comparable tokamak,

  loss of $\beta \Rightarrow$ radial shift of ~ 30cm.
  Similar shift for ~ 20% drop in $I_P$.
- Any NCSX disruptions will not lose radial equilibrium, should give unique insight into tokamak disruption dynamics.
- Possibility of passive disruption stability!



# Edge shows Large Flux Expansion Near Tips

- 11 Field lines in scrape-off launched across 2 cm at outer midplane of elongated cross-section
- Followed through 2 toroidal transits (5 more crossings)
- Flux expansion in the tips ~ 10:1
  Maximum flux expansion appears to
  slightly away from tips
- No separatrix observed
- May allow divertor-like solutions with neutral baffling in tips
- May facilitate H-mode transitions, similar to JET




See P. Mioduszewski

# NCSX Research Advances Fusion Science in Unique Ways

- Can limiting instabilities, such as external kinks and neoclassical tearing modes, be stabilized by external transform and 3D shaping? How are disruptions affected? How much external transform is enough?

- Can the collisionless orbit losses from 3D fields be reduced by designing the magnetic field to be quasi-axisymmetric? Is flow damping reduced?

- Do anomalous transport reduction mechanisms that work in tokamaks transfer to quasi-axisymmetric stellarators? How much effective-ripple is too much?

- How do stellarator characteristics such as 3D shape, islands and stochasticity affect the boundary plasma and plasma-material interactions?

**NCSX provides unique knobs to understand toroidal confinement fundamentals: rotational transform, shaping, magnetic symmetry.**

# NCSX Proposed Design

upgrades in ( )

- Major radius 1.4 m., Magnetic field 1.2 $\rightarrow$1.7 T (1.24s ; 0.46s flattop)
  > 2T at reduced $\iota_{external}$
- Flexible coil set: modular, poloidal, toroidal, trim.
- Plasma heating:
  - OH, $I_P$ up to 420 kA
  - Neutral beam: 3 MW ($\rightarrow$6 MW) tangential co- & ctr-; from PBX-M
  - (Ion cyclotron RF: 6 MW; mode conversion or high-harmonic).
- Heating pulse length 0.3 s ($\rightarrow$ 1s)
- Carbon plasma facing components, bakeable to 350 C.

# Conclusions

**Compact Stellarators provide both interesting science and solutions for the physics challenges of magnetic fusion energy.**

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

- Attractive configuration has been identified
  - passive stability to kink, ballooning, vertical, Mercier, neoclassical tearing with $\beta > 4\%$
  - very good quasi-axisymmetry
- Robust, flexible coil system for testing understanding and exploring

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

**Ready for the next phase: conceptual design.**