PPPL Theory & NCSX

-- Crucial to Achieving Goals

-- Plan Addresses Our Needs

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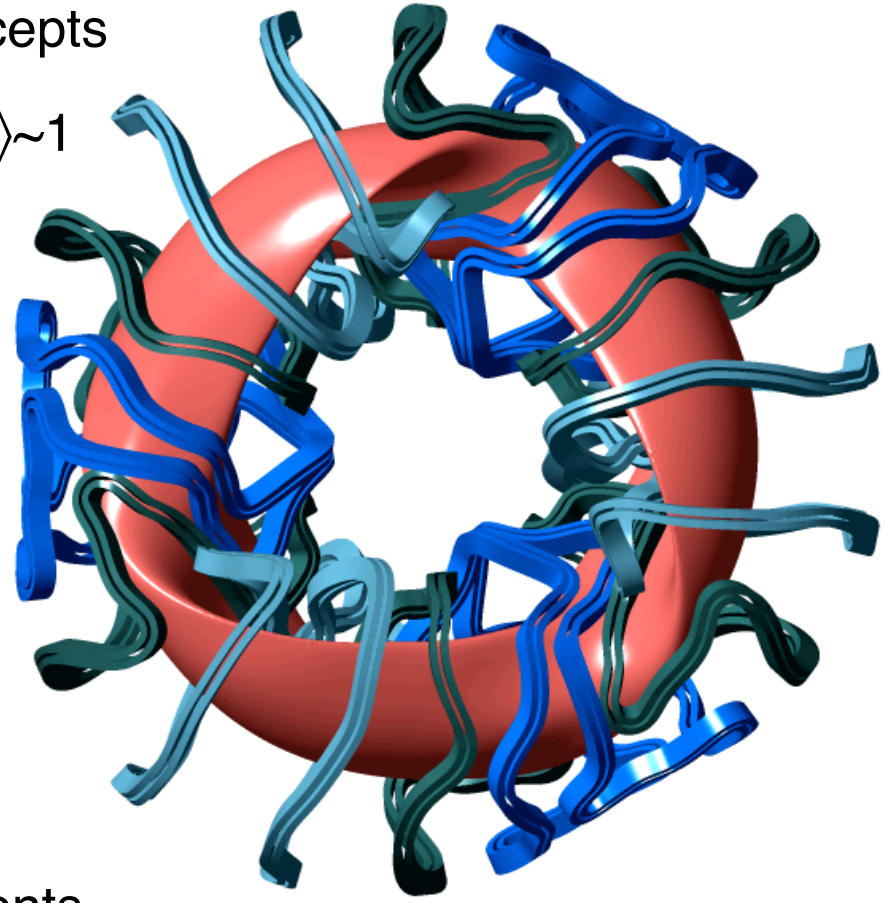
Theory Five Year Review

10 October 2005

PPPL

NCSX Many Unique Physics Properties Guided by our Theoretical Understanding

- Synergy of tokamak and stellarator concepts
- Strong avg. shaping $\langle A \rangle$=4.4, $\langle \kappa \rangle$~1.8, $\langle \delta \rangle$~1
- Quasi-axisymmetric orbit dynamics
- No need for external current drive
- Designed to have good flux surfaces at high- and low-β
- Passively stable at β=4.1% to kink, ballooning, vertical, Mercier, neoclassical-tearing modes
- Stable for $\beta \geq 6\%$ by adjusting coil currents



In combination with ITER: how can we achieve a steady-state high-β burning plasma, and ~5 x the power density of ITER? (like Aries-RS) -- ARIES-CS study

Achieving NCSX Goals
Required Key Contributions from PPPL Theory

G. Fu	MHD stability calculations & optimization
S. Hudson	Flux-surface topology optimizer
J. Lewandowski	Neoclassical transport calculations
Z. Linn	Neoclassical transport calculations
D. Monticello	MHD Equilibrium and stability; bootstrap current
H. Mynick	Neoclassical transport calculations; opt. landscape
N. Pomphrey	Flexibility studies; optimization landscape
A. Reiman	Ballooning stability; flux-surface topology; led fixed boundary equilibrium design
G. Rewoldt	Linear micro-stability
R. White	Fast-ion orbit calculations; boostrap current

In collaboration with UCSD, Columbia U., LLNL, ORNL, PPPL

Auburn, NYU, SNL-A, Texas-Austin, Wisconsin

Australia, Austria, Germany, Japan , Russia, Spain, Switzerland, Ukraine

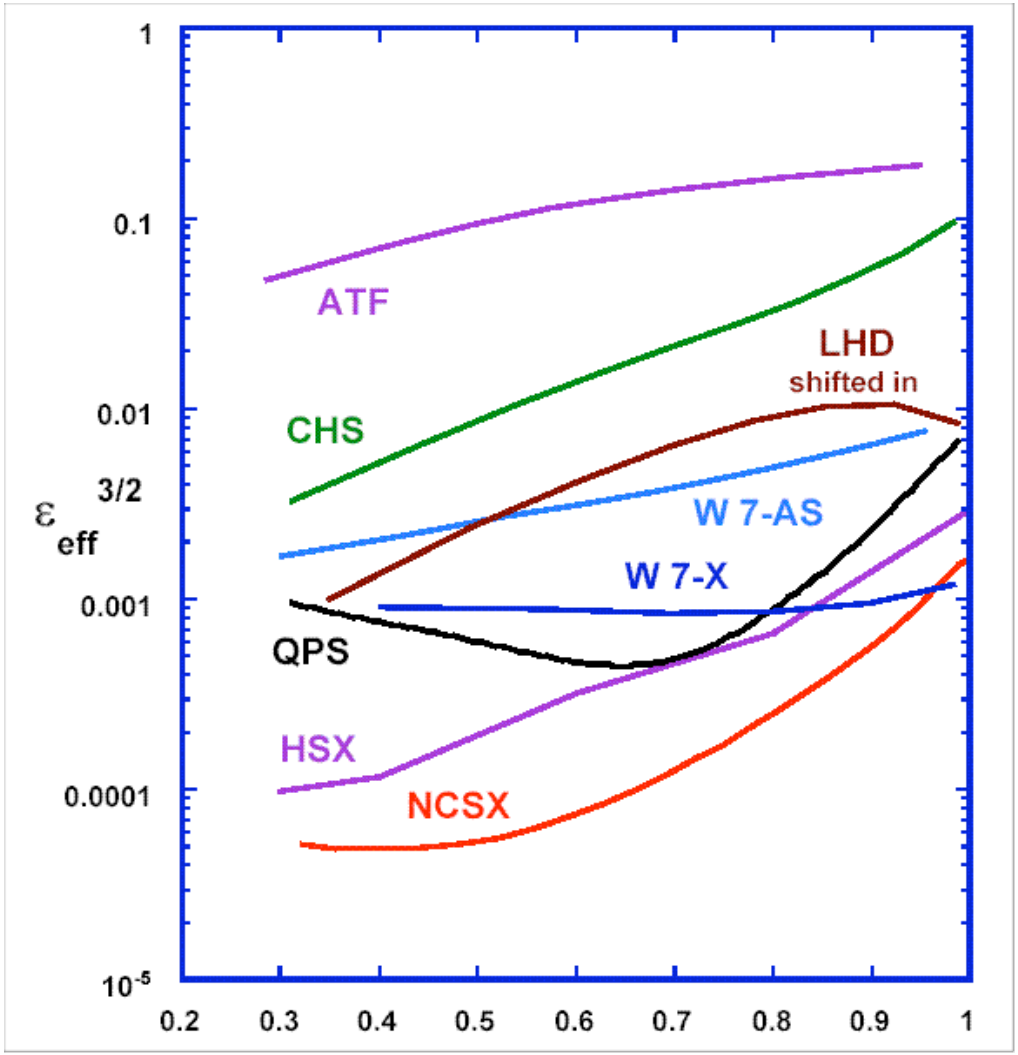
Key for Success: Integrated Team of

Engineers, Experimentalists, Theorists

& Massively parallel computers

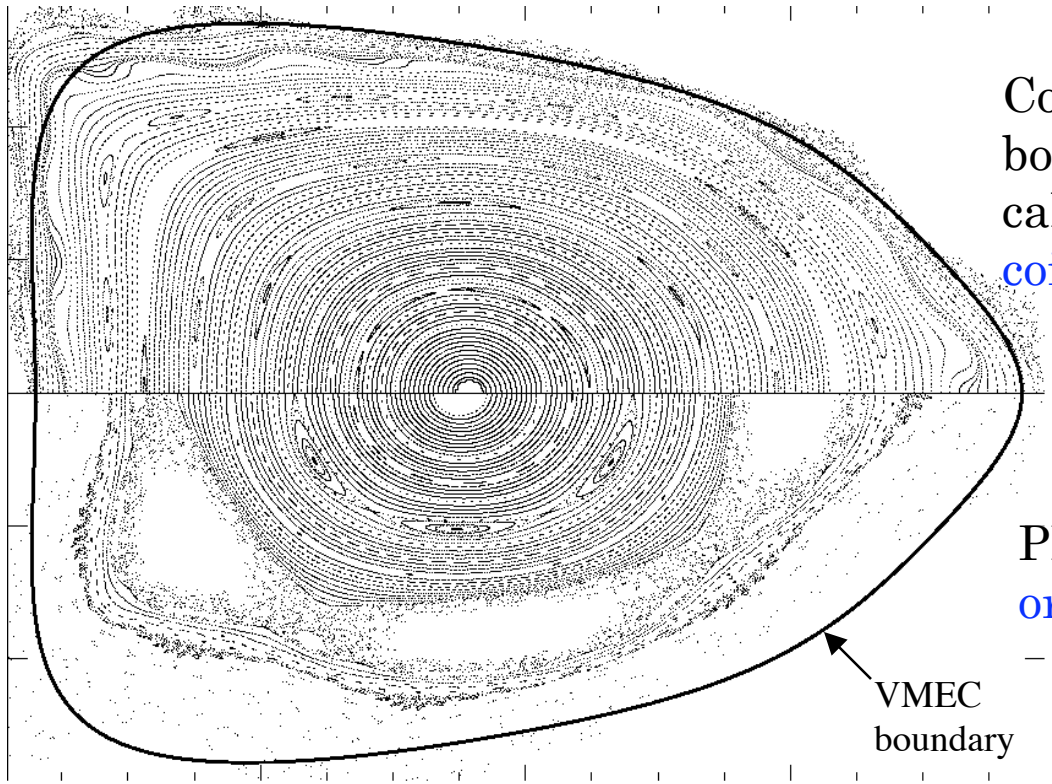
Quasi-Axisymmetric: Very Low effective ripple

- Very low effective helical ripple
  $\varepsilon_{eff} \sim 1.4\%$ at edge
  $\sim 0.1\%$ in core
- Gives low flow-damping
  allow manipulation of flows for flow-shear stabilization, control of E_r
- Reversed shear helps stabilize turbulent transport, via drift precession reversal
- ε_{eff} calculated by NEO (Nemov & Kernbichler)
- Neoclassical transport calculated analytically (Mikkelsen), Monte-Carlo (Lin, White)
- Linear ITG/TEM-stability calculated by FULL (Rewoldt)



Normalized Minor Radius (r / a)

PIES Used to Design for Good Flux Surfaces at High-β with Plasma Current



Converged, free-boundary PIES calculation with healed coils.

$\langle\beta\rangle = 4.1\%$

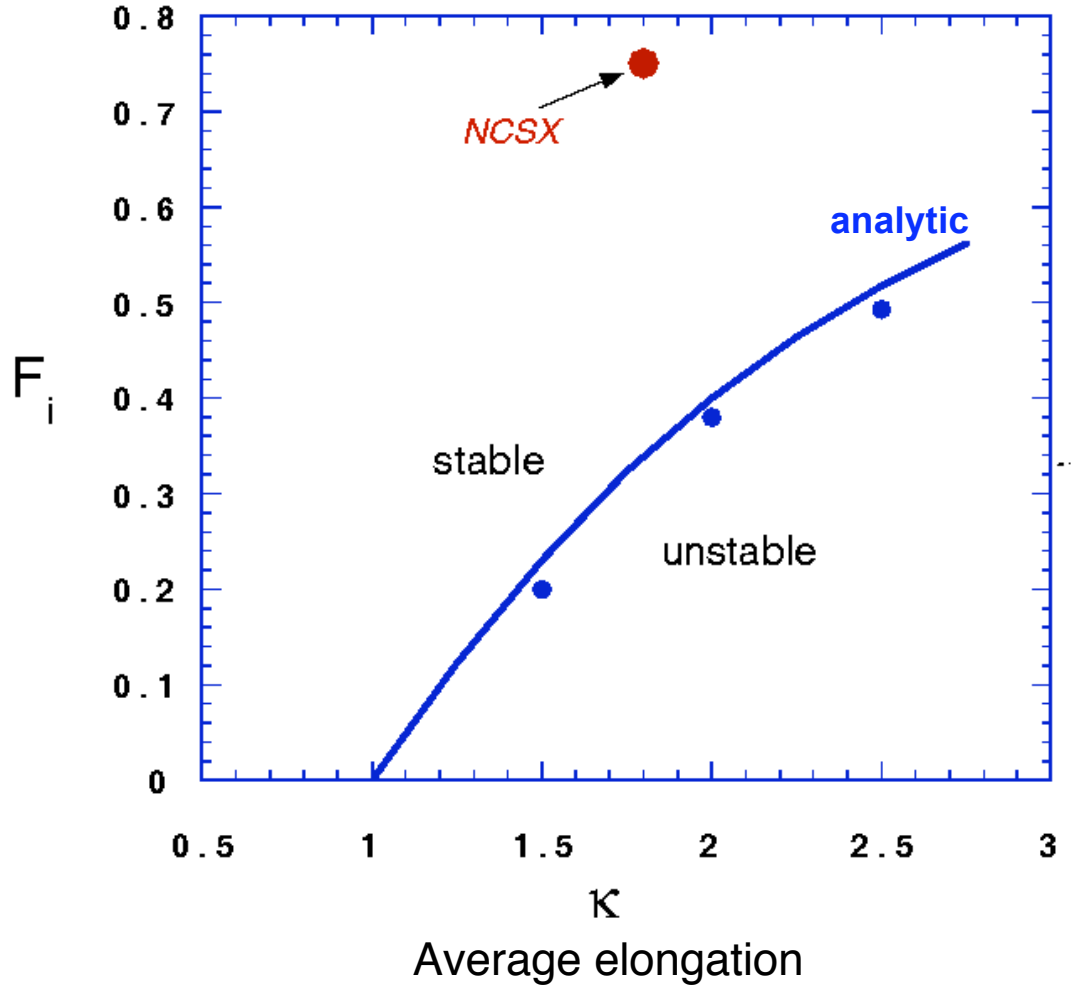
PIES calculation with original coils.

S. Hudson, LP Ku, D.Monticello, A. Reiman

- Optimizer built around PIES to heal islands but preserve physics and engineering properties.
- First time this has been done at finite β and/or current
- Tour de force

Extensive Analysis: NCSX Passively Stable

- Stability analyzed and designed for low-n and high-n ideal modes
- Example: Vertical stability found to theoretically depend on elongation and F_i = fraction of rotational transform from external coils
- NCSX assessed to be stable both from analytic treatment and by numerical calculation
- NCSX can and will vary F_i to test theoretical prediction



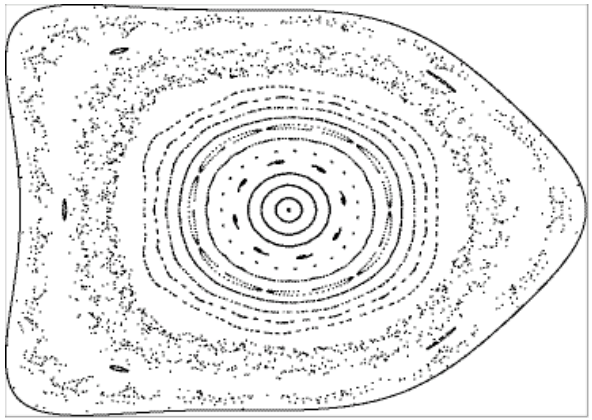
G-Y. Fu

Initial M3D Non-Linear Calculations Indicate Two-Fluid Effects Important

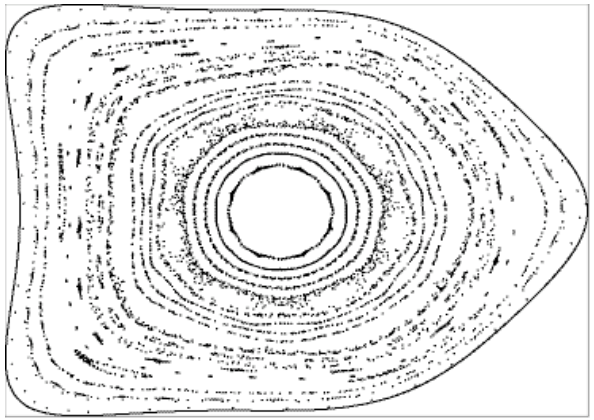
Single Fluid (resis. MHD)

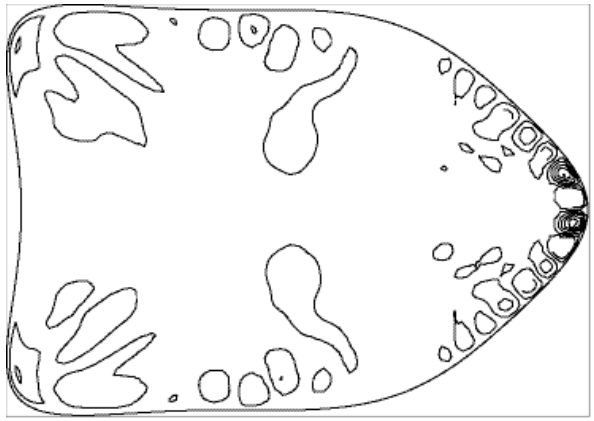
$\langle\beta\rangle = 7\%$

Two Fluid

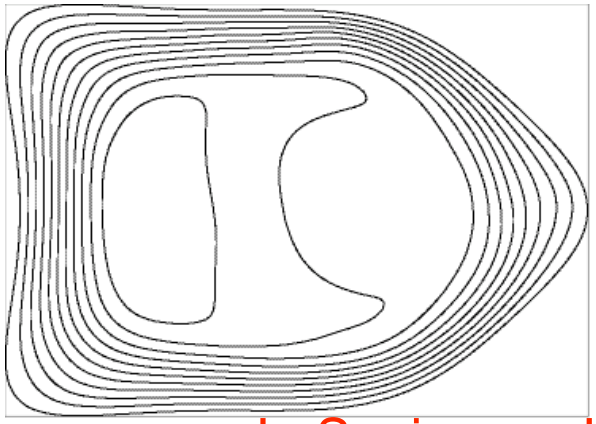


Magnetic Flux Surfaces





ExB Flow Surfaces

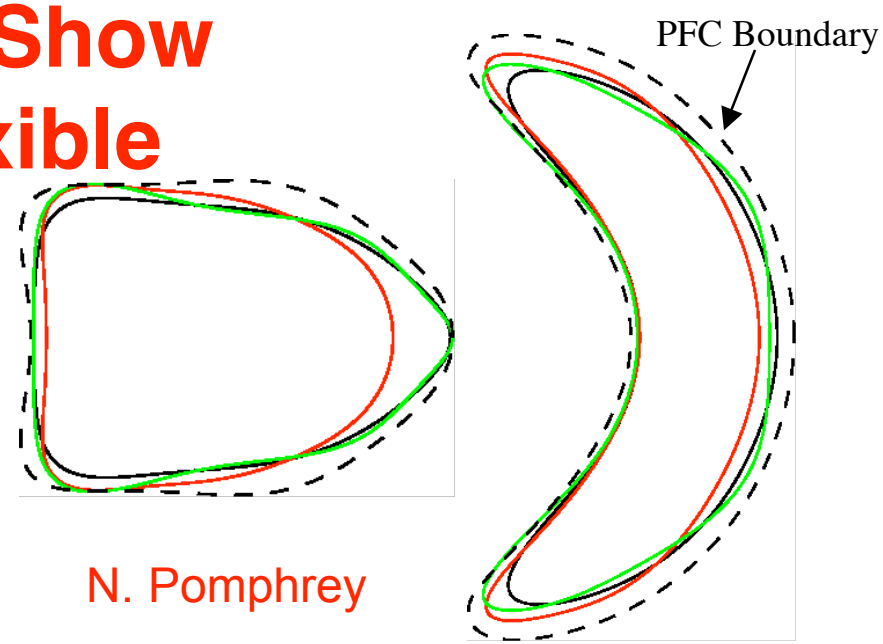


L. Sugiyama, H. Strauss
W. Park

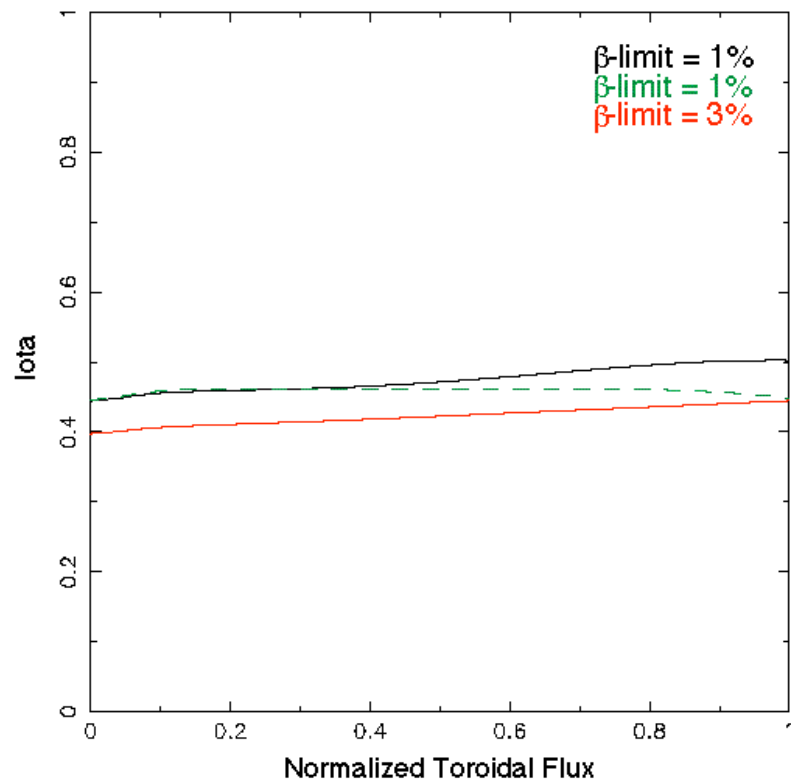
- Preliminary, fixed boundary.
- Two fluid: finite gyro-radius and self-generated flows stabilize equilibrium
- Does not include neoclassical effects yet. Should increase stabilization.

Theory Calculations Show Coil Set is Very Flexible

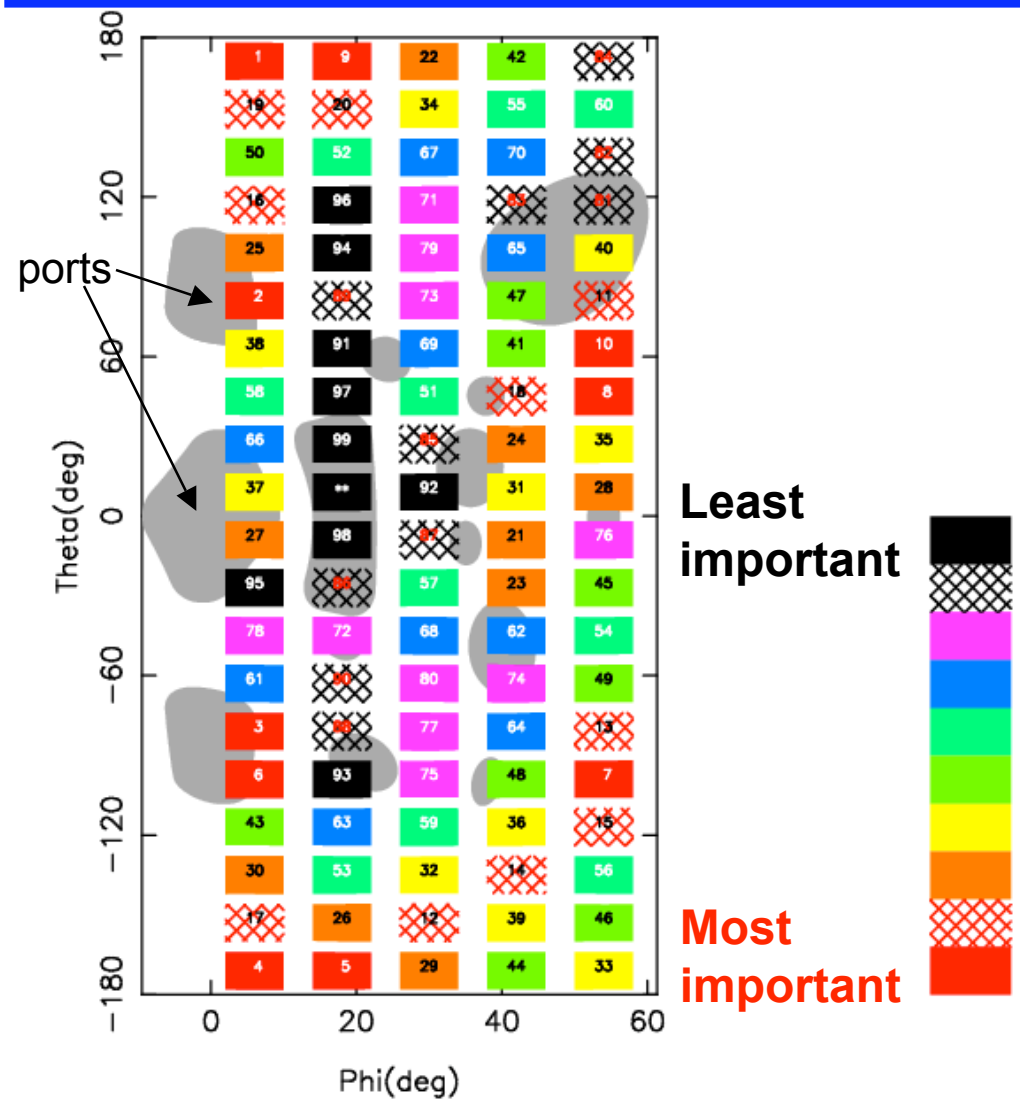
- External-kink marginally stable β changed from 3% to 1% by modifying plasma shape
  - either at fixed shear or fixed edge-iota !
- Useful for testing understanding of 3D effects in theory & determining role of iota-profile
- Similarly, can find stable equilibria with effective ripple varying by factor > 10.
- These types of calculations will be key to targeting our experimental program

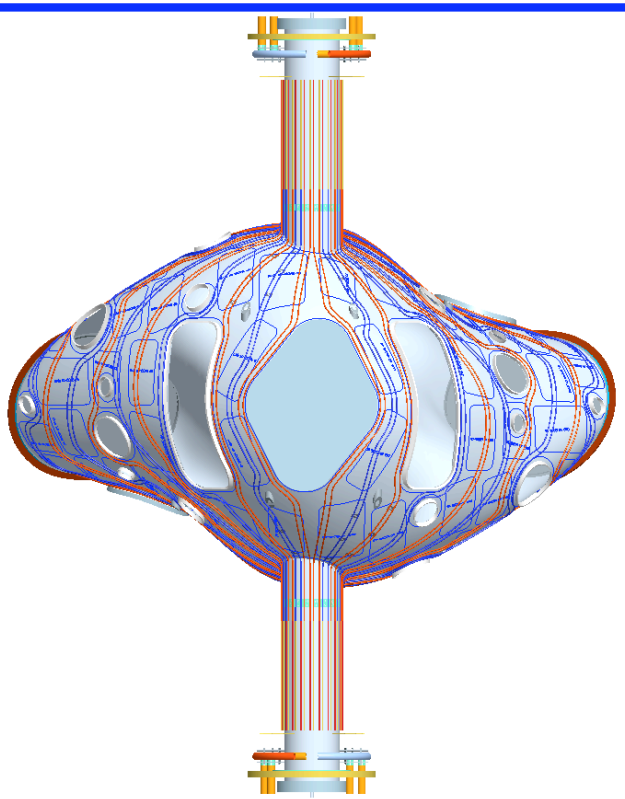


N. Pomphrey



Most Important Saddle Coil Sensors Identified Using SVD Analysis

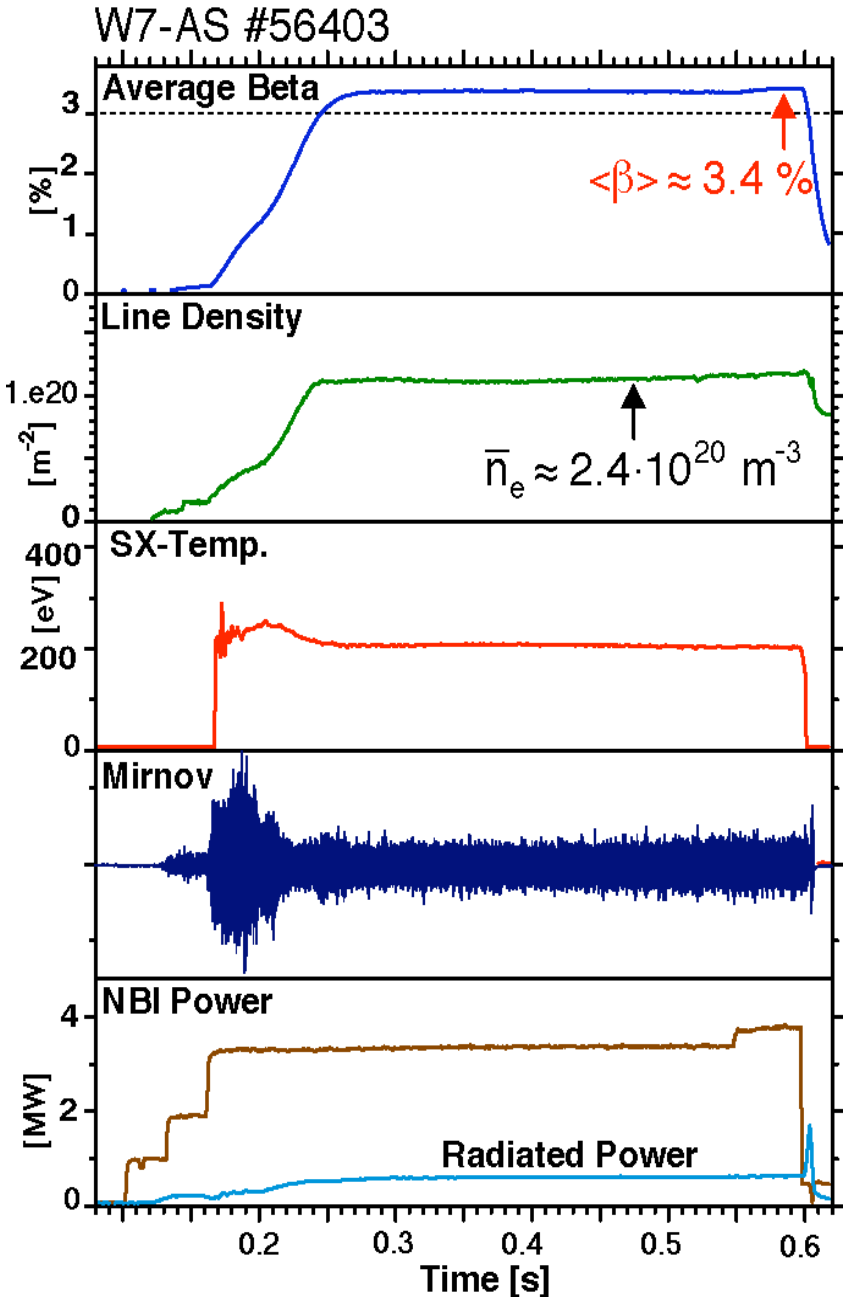




- Ranked by importance for distinguishing numerical database of 2469 equilibria.
- Strong correlation between rank and plasma-loop separation distance.

N. Pomphrey, E. Lazarus

W7-AS: $\langle\beta\rangle \approx 3.4$ % : Quiescent, Quasi-stationary



- Highest $\langle\beta\rangle = 3.5\%$

- Duration of high-β phase ~ 75 τ_E
  $\langle\beta\rangle > 3.2\%$ maintained for > 100 τ_E

- No disruptions
- Duration and β not limited by onset of observable MHD

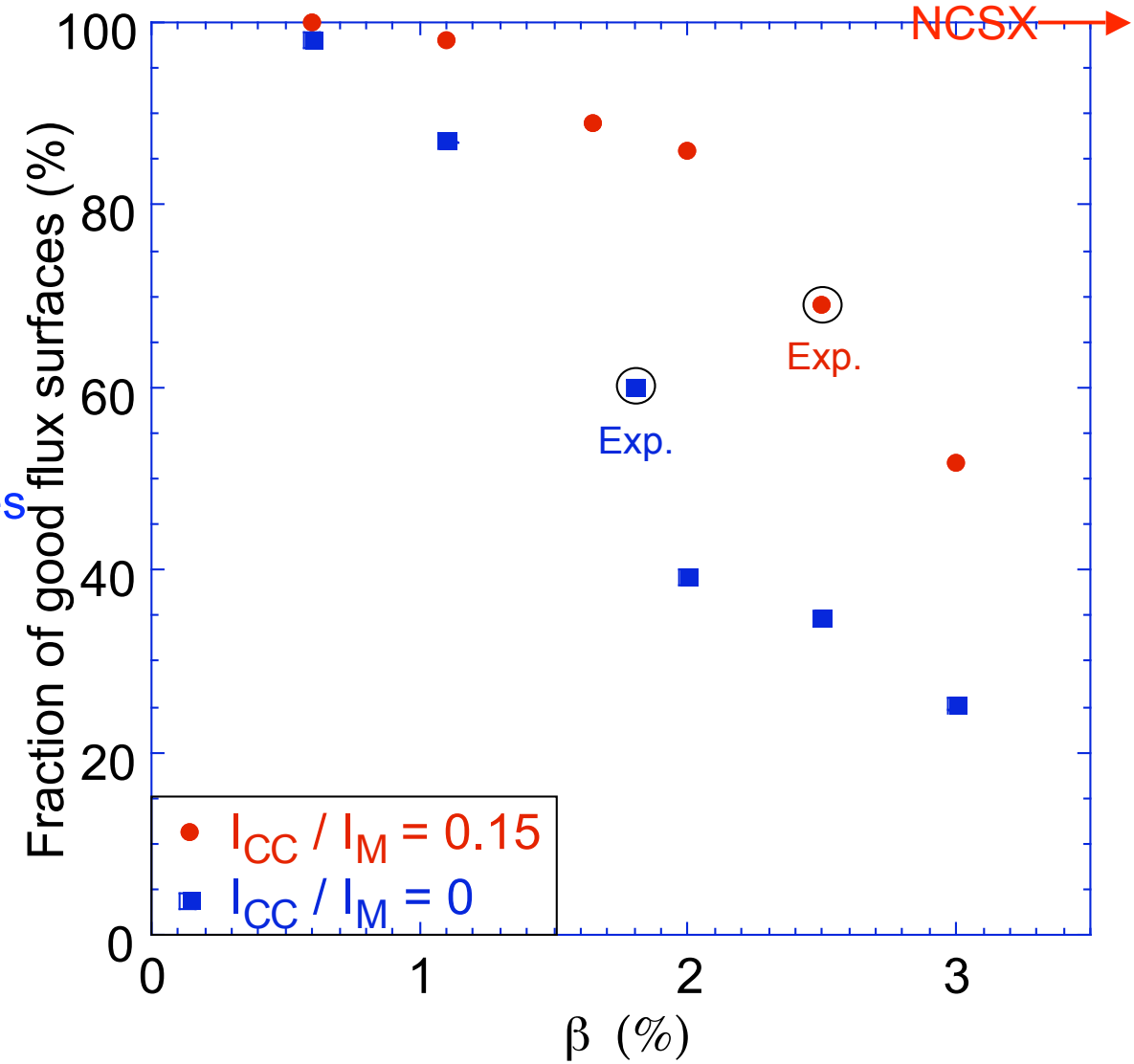
- Well above ideal instability threshold
  $\langle\beta\rangle \sim 1.5 - 2\%$ (Terpsichore)

- **Motivates further theoretical analysis**

What controls the observed β value?

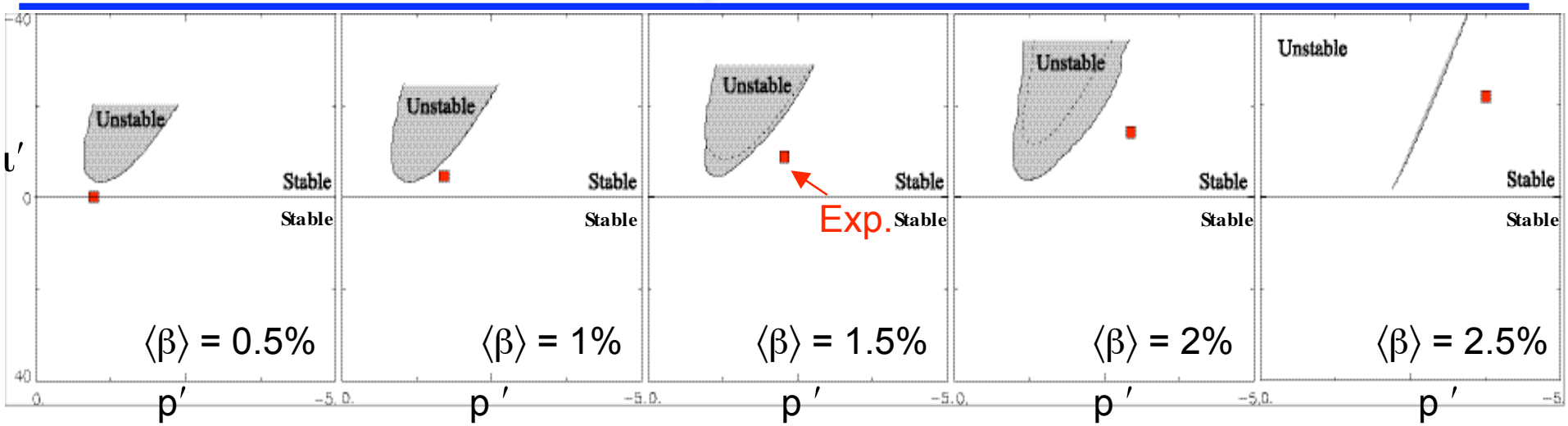
PIES: Degradation of Equilibrium May set β Limit

- PIES equilibrium calculations indicate that fraction of good surfaces drops with β
- Drop occurs at higher β for higher 'control coil current' I_{CC} / I_M
- Experimental β value correlates with loss of ~35% of minor radius to stochastic fields or islands
- PIES modified to impose experimental profiles
- Collaboration starting to apply PIES analysis to DIII-D 3D perturbation experiments



A. Reiman, D. Monticello

New Ballooning Analysis Gives Understanding Access to 2nd Stability in W7AS: Via Stable Path



S. Hudson

- Local stability diagrams for infinite-n ballooning evaluated by Hudson and Hegna. Plots shown for r/a = 0.7
- For $\langle\beta\rangle$ > 2%, plasma is calculated to be in second regime for r/a < 0.8
- From analysis: 2nd stability to ballooning can be accessed on stable path, due to increase of shear with β and deformation of stability boundary.

Theory Plan Addresses NCSX Needs

To prepare for the coming experiments

- Routine equilibrium analysis, including islands, neoclassical & rotation effects, …
- Comprehensive analysis/modeling, including diagnostic simulation (ala Transp)
- Control strategies and algorithms, including flux surface quality
- Turbulence simulations, including self-generated flows
- Non-linear macro-stability, including kinetic effects
- Alfvenic-mode stability, including fast ion kinetic effects
- SOL & divertor modeling

PPPL Theory will play a key role in future success,
in continued collaboration with the entire theory program.

Conclusion: PPPL Theory Crucial to Achieve our Goals

- Provided key developments for NCSX design
  - Stabilize high-β instabilities with 3D shaping with $\beta > 4\%$
  - Tokamak-like transport using quasi-axisymmetry. Low rotation damping.
  - Good flux surface quality at high and low-β
  - Flexible coil system

  Stimulated substantial advances in theory and modeling
- PPPL Theory plan prepares for NCSX Experimental Needs
  - Addressing full range of key topics
  - Engaged now in collaborations on 3D physics to build understanding and guide developments, e.g. W7AS & DIII-D experiments
- Stellarator theory and NCSX have broad scientific impact;

  provide innovative solutions to make magnetic fusion more attractive.
  - Build upon characteristics and understanding of stellarators and tokamaks; ITER.
  - Use 3D shaping to investigate stability & transport, and improve them.
- Theory plan needs to be supported

NCSX and Stellarator Theory Have Broad Impact

Strong contributions to the Priorities Panel's Topical Questions:

- T1.How does magnetic structure impact confinement? What is the effect of 3D shaping on confinement? Shear? Is quasi-axisymmetry effective? How does it differ from axisymmetry?
- T2.What limits maximum pressure? Can 3D shaping increase the β limit? Is reversed shear beneficial? What are the limiting mechanisms with 3D fields and how can they be controlled?
- T3.External control and self organization How does 3D shaping affect self-organization of profiles? How high a bootstrap fraction is controllable? Under what conditions are disruptions eliminated?
- T4.Turbulent transport How is turbulent transport affected by 3D shaping? Does reversed shear help stabilize turbulence in 3D? How does electron transport depend on local shear and curvature?
- T5 Electromagnetic fields and mass flow generation How does flow damping affect zonal flows and turbulence stabilization? Can transport barriers be accessed with quasi-symmetry?
- T6.Magnetic field rearrange and dissipate How do shear, pressure, seed perturbations, and ion kinetics affect NTM onset and saturation,in detail?
- T9.How to interface to room temperature surroundings? How is the SOL and interface affected by stochasticity and 3D shaping? Can the interface and exhaust be improved using 3D effects?
- T11.Electromagnetic waves interacting with plasma How do RF waves interact with plasma in 3D?
- T12.High-energy particles interacting with plasma How does 3D shaping affect energetic-ion instabilities? Can they be stabilized? Can orbit losses of energetic ions be controlled in 3D?
- T15.How to heat, fuel, confine steady-state or pulsed plasmas? How can we control and fuel a 3D plasma? How much control is required? How can we diagnose the plasma state in 3D?

NCSX Research Mission

Acquire the physics data needed to assess the attractiveness of compact stellarators; advance understanding of 3D fusion science.
(FESAC-99 Goal)

Understand…

- Pressure limits and limiting mechanisms in a low-A current carrying stellarator
- Effect of 3D magnetic fields on disruptions
- Reduction of neoclassical transport by quasi-axisymmetric design.
- Confinement scaling; reduction of turbulent transport by flow shear control.
- Equilibrium islands and tearing-mode stabilization by design of magnetic shear.
- Compatibility between power and particle exhaust methods and good core performance in a compact stellarator.
- Energetic-ion stability in compact stellarators

Demonstrate…

- Conditions for high normalized pressure disruption-free operation
- High pressure, good confinement, compatible with steady state

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 ($\Rightarrow$ minimal recirculating power)
- High power density (~3 MW/m^2)

Likely configuration features (based on present knowledge)

- Rotational transform from coils and self-generated bootstrap current (how much of each?)
- 3D plasma shaping to stabilize instabilities (how strong?)
- Quasi-axisymmetry to reduce 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.

Motivation: Build Upon Recent Advances in Understanding

Stellarators:

- Design for orbit confinement, good flux surfaces
- Numerical design to obtain desired physics properties
- Accurate construction of experiments with good properties

(e.g. W7AS, HSX, and superconducting LHD)

Tokamaks:

- Confirmation of ideal MHD equilibrium & stability theory; neoclassical theory; neoclassical tearing theory
- Importance of shear-flow & zonal (self-generated) flows for turbulence stabilization

Challenges:

– $\beta_T \sim 5\%$ steady state, good confinement without disruptions (~ARIES-RS)

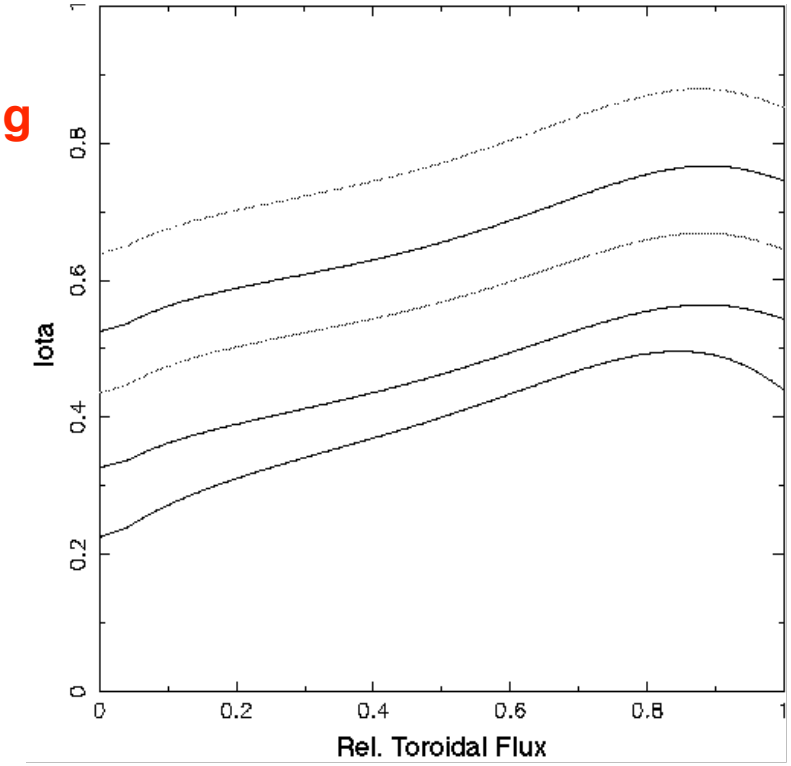
– sustainment of current with minimum recirculating power

($\Rightarrow$ ~80% self-generated current boostrap)

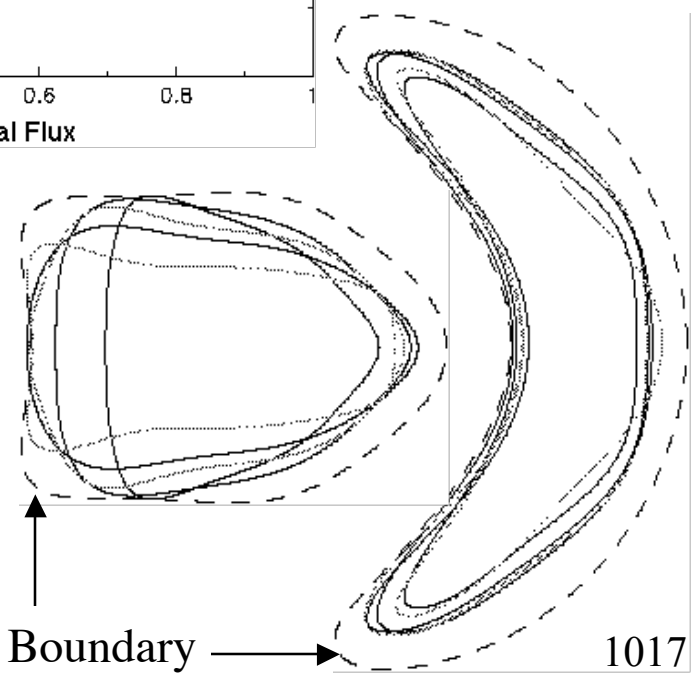
Modular Coils are Flexible

By varying coil currents, control iota profile by varying plasma shape at fixed parameters.

- Use 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

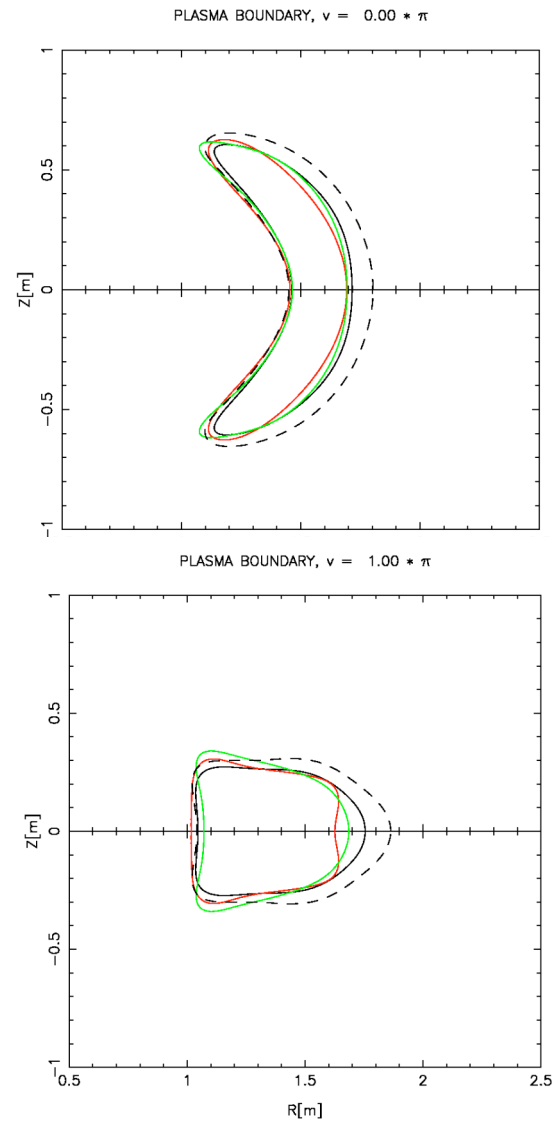


β=0, full current



Equilibrium Maintained even with Loss of I_P or β

- Total loss of I_P or β 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!



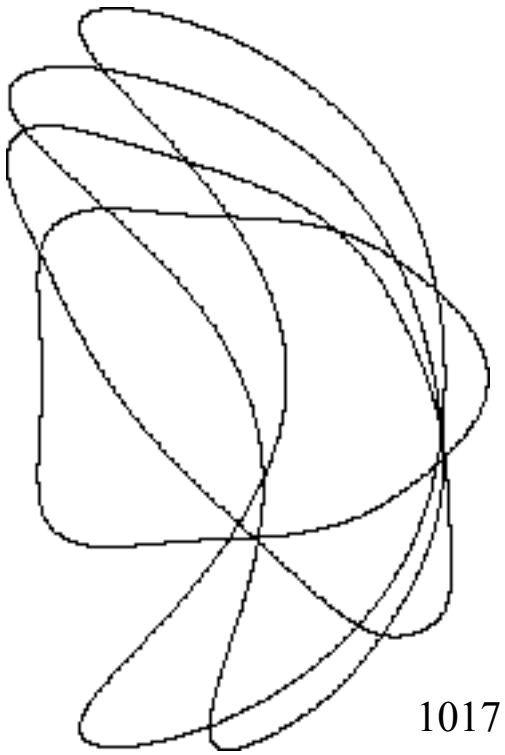
β-limit is Very High for Free-boundary

- By modifying coil currents, have found $\beta \geq 6.5\%$ no-wall stable free-boundary equilibria. Limit not yet found.

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

- Effective ripple increase by factor of 2.8

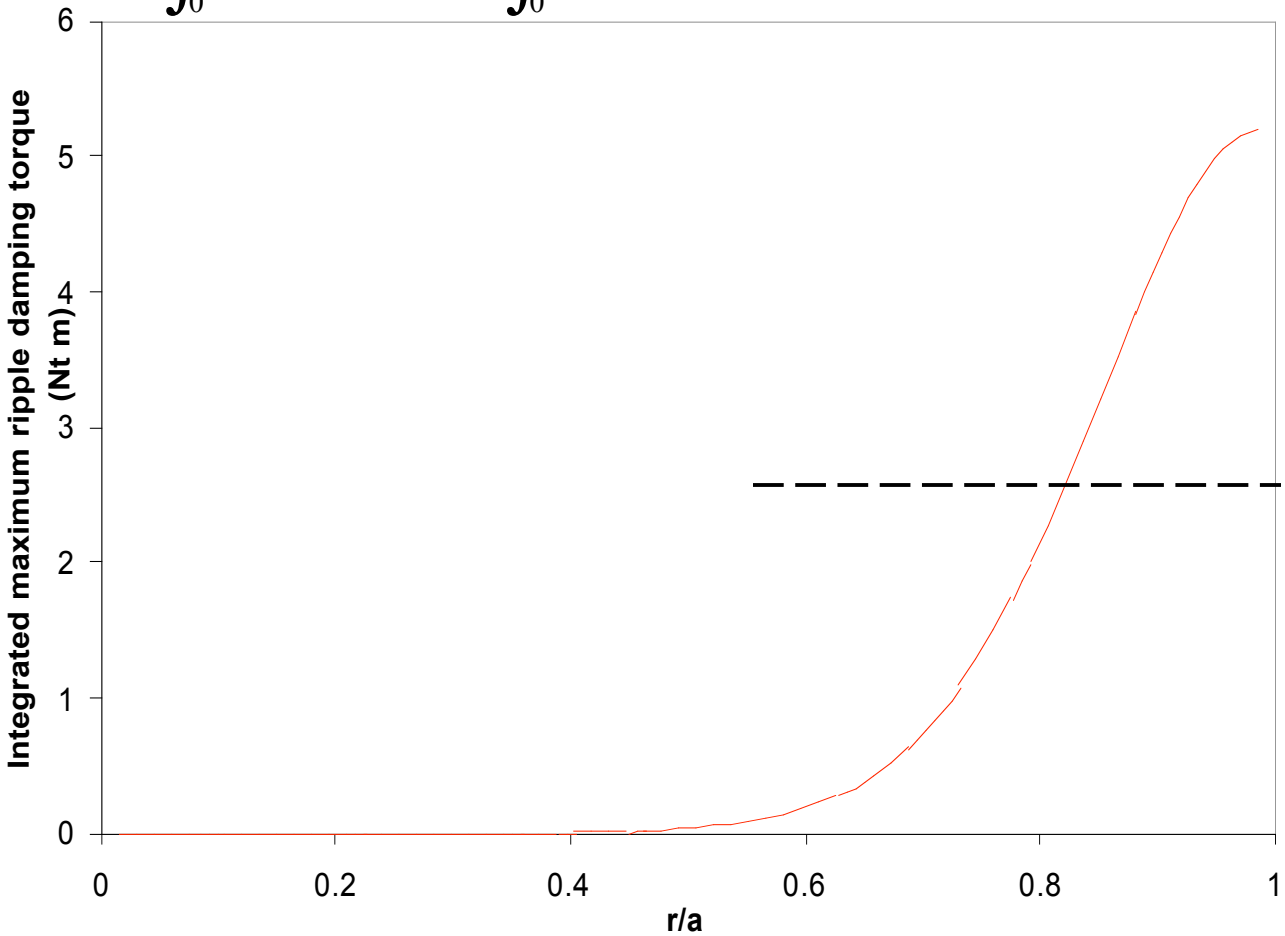
- Access needs 2.3 x tokamak L-mode with P_{inj} = 6MW



Core rotation is un-damped

Integrated maximum (E_r = 0) ripple-damping toroidal-torque from axis to given radius

$$\int_0^r J_r\, B_P\, R\, d\underline{v}' \sim \int_0^r \bar{J}_r(r')\, \bar{B}_P(r')\, R_0\, d\underline{v}'$$



- 6MW balanced NBI planned
- 3MW unidirectional NBI ~ 2.7 Nt-m

Edge velocity will probably be constrained to counter-rotation

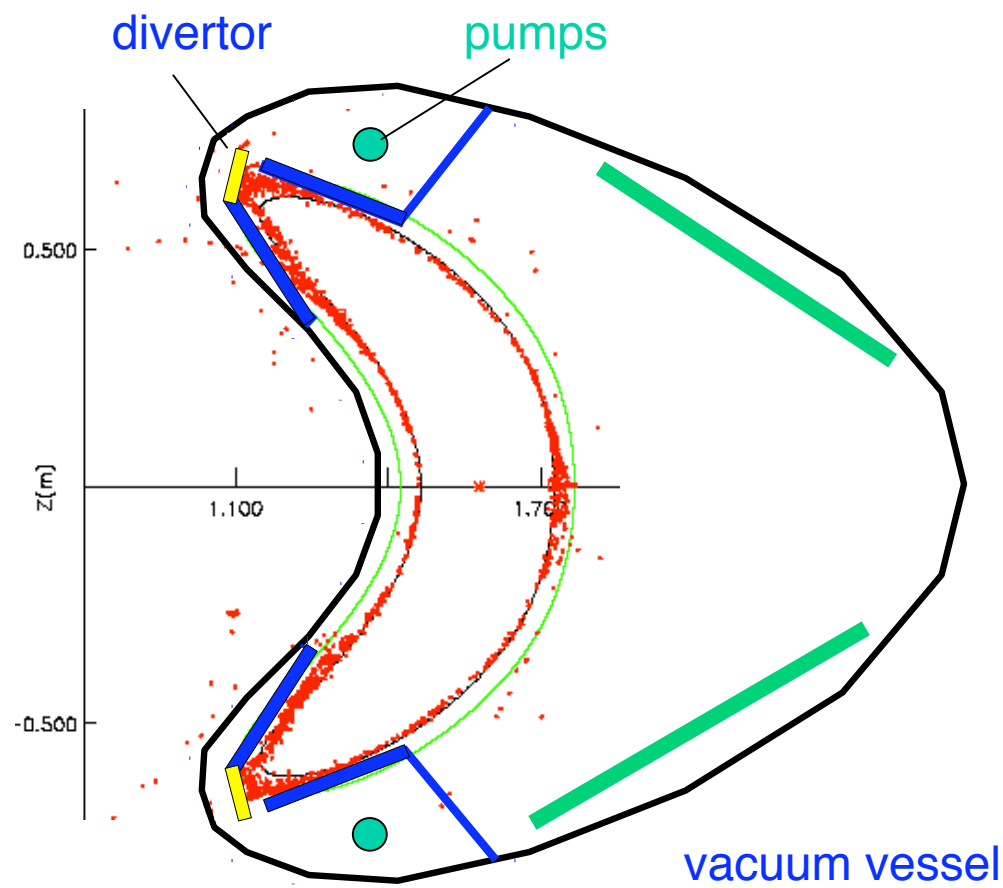
Divertors in Bean-tips

- Strong flux-expansion always observed in bean-shaped cross-section. Allows isolation of PFC interaction.

- Similar to expanded boundary shaped-tokamak configurations

- Connection length in SOL $L_C \sim 180$m for > 80% of field lines good isolation of contact

- Kolmogorov length > 50m Field weakly stochastic



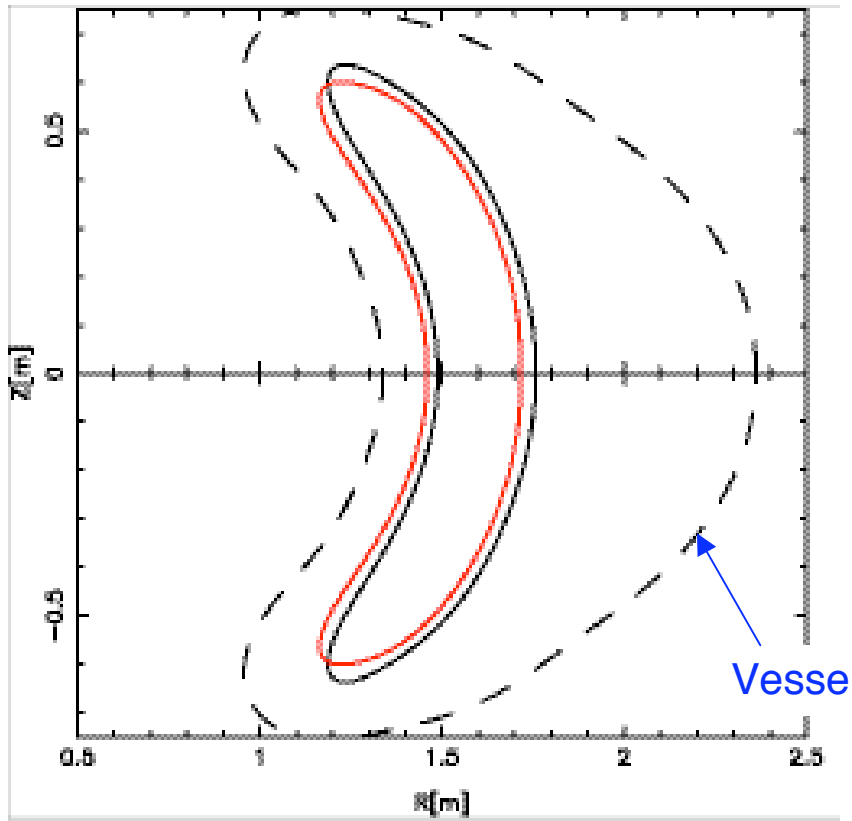
MFBE field-line tracing

A. Grossman
P. Mioduszewski

Coils Redesigned in 2002 to Increase Plasma-Wall Separation

- Goal: increase plasma-vessel separation to improve divertor design; improve ICRF antenna design
- Goal: SOL connection length

  > 100m
- Plasma-coil separation Δ increased by ~14%
- $A_{\Delta} = \langle R \rangle / \Delta$ decreased to 6.7
- Also improved coil manufacturability



β=4.2%,
full current

- Designed to accommodate up to 6MW of NBI; 6MW of ICRH; ECH

Two strategies for Orbit Confinement in 3D

3D shape of standard stellarators ⇒ no conserved canonical momenta

orbits can have resonant perturbations, become stochastic ⇒ lost

B is bumpy every direction ⇒ rotation is strongly damped

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

  ⇒ neoclassical transport very similar to tokamaks, undamped rotation

- Non-symmetric drift-orbit omnigeneity; "linked mirror" configurations
  - reduce: ∇BxB drift ⇒ orbit width, Pfirsch-Schluter & bootstrap currents
  - Principle of W-7X, new German superconducting experiment (A=11)
  - Being explored at low aspect ratio in the design of QPS (ORNL)

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