Physics Design of NCSX

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Compact stellarators offer novel solutions for confining high-β plasmas for magnetic confinement fusion, combining the advantages of the advanced tokamak with the external control and disruption resilience of the stellarator. The configurations developed for NCSX have a low aspect ratio (3 - 4) and passive stability to the ballooning, low-n external kink, vertical, and neoclassical tearing instabilities, without a conducting wall or active feedback. The plasma shape has high average elongation and triangularity. The 3D shape produces monotonically increasing rotational transform profile and is optimized to produce a quasi-axisymmetric magnetic field for good orbit confinement. A range of such configurations are studied with beta limits as high a 7% and as much as 80% of the magnetic transform generated by the coils. The goal of an experiment using these configurations would be to study the beta limit and disruption resilience. Self-consistent transport simulations of the accessible β range will be presented for both neutral-beam (including fast-ion losses) and ICRF heating.

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Outline

- Motivation
- Configuration Design
- Configuration Characteristics
  – Stability, Transport, Flux surface quality
- Coil Design & Flexibility

Compact Stellarators Offer Innovative Solutions

Can combine the best features of Stellarators and Advanced Tokamaks

- Stellarators: *Externally-generated helical fields, low recirculating power, typically disruption free.*
- Advanced tokamaks: *Excellent confinement, low A – high power density, bootstrap current*
- Compact Stellarators: *Use 3D shaping flexibility to combine best features*

Advances in Theory and Numerical Design Capability ⇒ Compact Stellarators

- 3D shaping to passively stabilize external kink, vertical, neo-tearing, ballooning
  - expand safe operating area to $\beta \geq 4\%$,
    without need for conducting walls or feedback systems
  - prevent disruptions?
- Good confinement. Quasi-axisymmetry to close drift-orbits, allow plasma flow
- Aspect ratio: ~ 4
- Steady state without current drive.

NCSX Physics Opportunities & Goals

- Understand role of external transform & 3D shaping in disruptions
- Understand role of kink- and ballooning modes in beta-limit
  - tokamak-like vs. toroidally localized ballooning
- Test quasi-axisymmetric reduction of neoclassical transport.
  Understand induced flow-damping.
- Understand turbulence in quasi-symmetric configuration.
  Effect of quasi-symmetry and E_r on confinement, ability to induce enhanced confinement
- Understand neoclassical-island stabilization using externally imposed islands
- Understand Alfvenic-modes in 3D geometry
- Understand effect of 3D shaping and flux-surface topology on edge

Method: Design for High β

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

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

- Required substantial tool development
  - Coil optimization including plasma currents
  - Improved 3D equilibrium codes – PIES and VMEC
  - Kink and ballooning stability calculations inside optimizer
  - Transport and bootstrap calculations inside optimizer
  - Approximate coil design inside optimizer

See A. Reiman et al., Invited Talk Thursday, UI1.001

Wide Range of 3D Configurations Has Been Explored

(many useful discussions with P. Garabedian & J. Nuehrenberg)

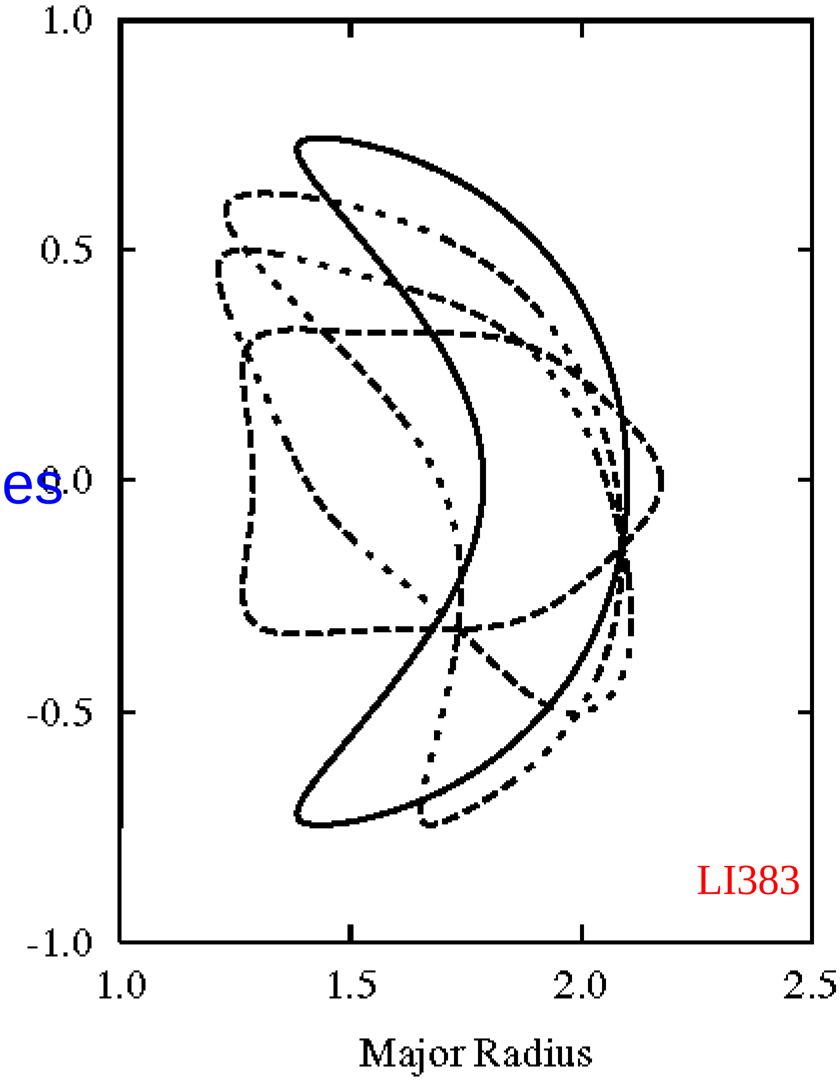
– Aspect ratio, A: 3 – 5
– Average elongation up to 3 (exploiting robust vertical stability)
– Vacuum magnetic well
– Edge iota ι(a): 0.47 – 0.78 (q(a): 1.3 – 2.1)
– External transform fractions at β-limit: 50 – 80%
– 2, 3, 4 periods

- Major distinguishing characteristics:
  flux-surface quality, coil J_{max}, fast ion confinement

- Attractive design configurations have been identified
  → Basis for NCSX Design

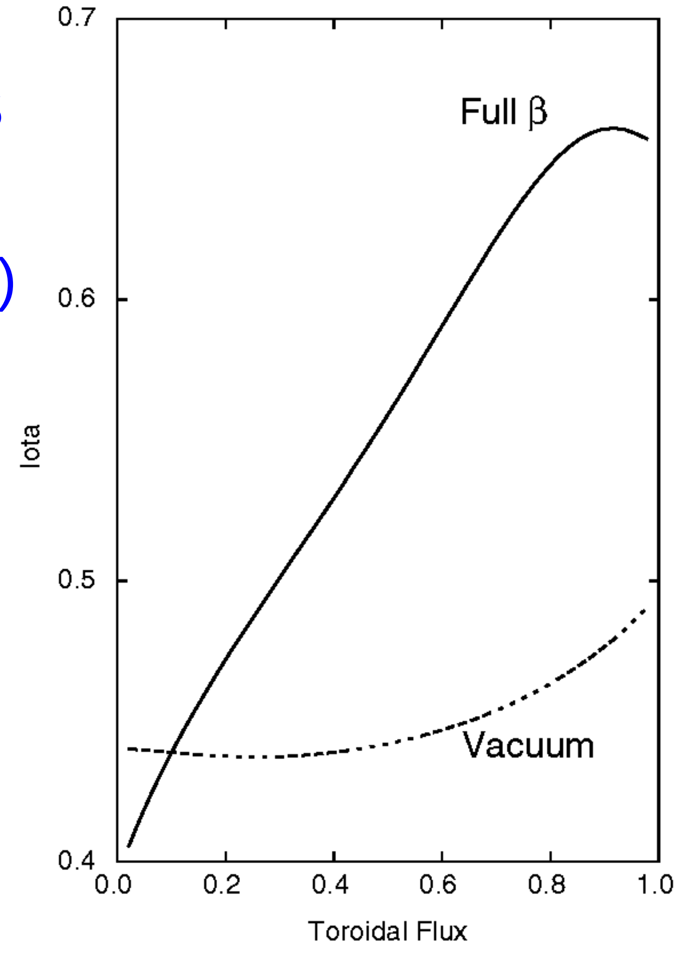
New Attractive Configuration

- 3 periods, ⟨A⟩=4.4, ⟨κ⟩~1.7 ⟨indented⟩
- Stable to ballooning, kink, vertical, Mercier at β=4.1%
- Limited by ballooning, thus should be able to optimize profiles
- Reduced coil complexity
- Iota: 0.4 → 0.65
  ~2/3 from external coils
  neoclassical-tearing stable



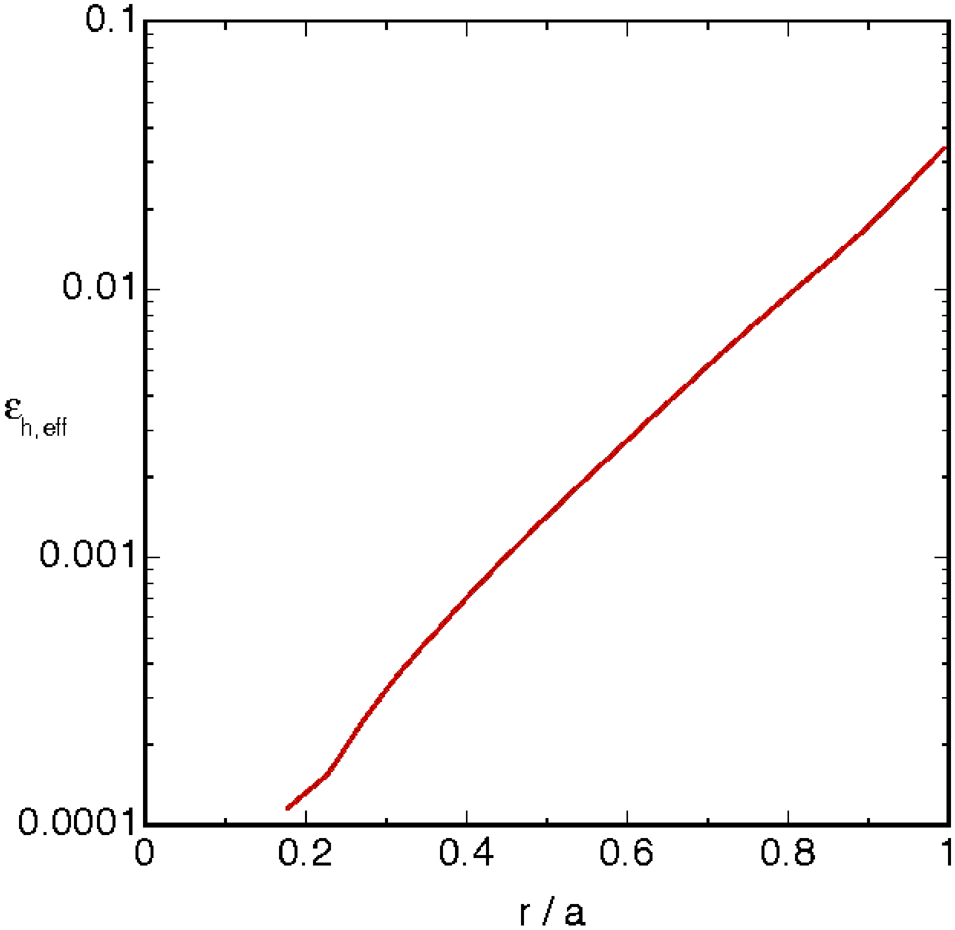
Full β configuration: iota crosses ½

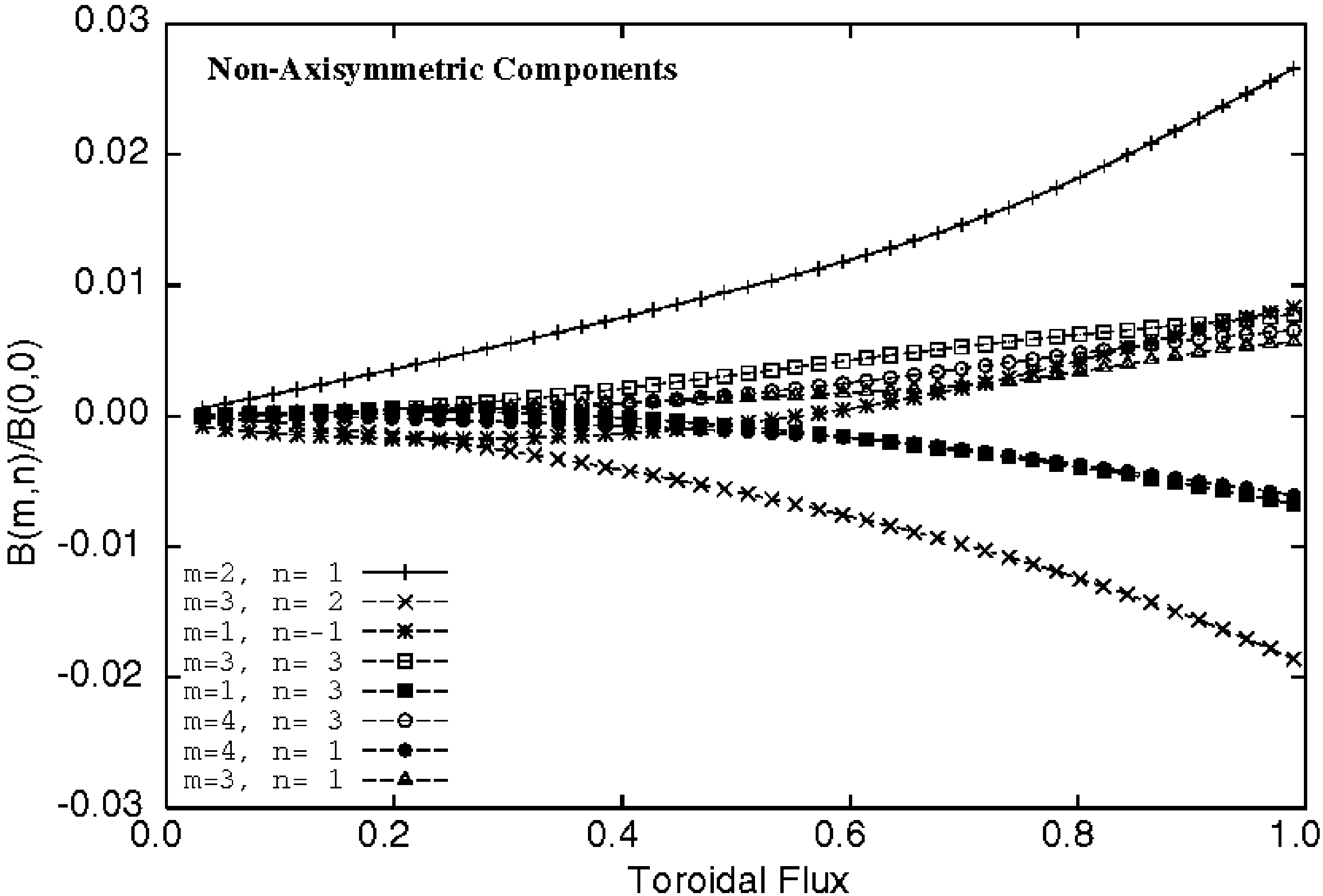
- Full-β, full current iota crosses ½
  - Can produce disruptions in W7-AS when crossing near edge
- Δ′ calculations (Knowlton, Fredrickson) (cylindrical approx.) indicate very small islands could form (3.5% of radius)
- Vacuum iota everywhere below ι = ½ ⇒ edge will pass thru ½ (q=2) during ramp up, may be disruption prone
- Flexibility studies: can avoided this by starting with vacuum iota > 1/2



Quasi-Axisymmetric: Low effective ripple

- ε_{eff} from NEO code by Nemov-Kernbichler
- In 1/ν regime, neoclassical transport scales as $\varepsilon_{eff}^{3/2}$
- Edge ε_{eff} ~ 3.4%
- Allows counter-inj. NBI
- Iota > 0.5 improves axisymmetric-neoclassical confinement




Non-Axisymmetric Components
B(m,n)/B(0,0)
0.03
0.02
0.01
0.00
-0.01
-0.02
-0.03
0.0
0.2
0.4
0.6
0.8
1.0
Toroidal Flux
m=2, n= 1
m=3, n= 2
m=1, n=-1
m=3, n= 3
m=1, n= 3
m=4, n= 3
m=4, n= 1
m=3, n= 1

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Power-Balance Solver (STP)

- Steady-state 1D Power balance solver for T_e and T_i, assumes edge boundary condition and density profile
- Transport model includes full transport matrix, combines
  - 'Shaing-Houlberg' helical neoclassical transport
  - Nemov-Kernbichler calculation of effective helical ripple (correct for $1/\nu$ regime)
  - Axisymmetric (toroidal) neoclassical transport (Chang-Hinton)
  - Anomalous transport models (Lackner-Gottardi, Mixed-shear,…)
- Self-consistent calculation of E_r from helical transport
- Neutral-beam deposition in axisymmetric shape
- Can constrain confinement to global scaling law (with multiplier)
- Benchmarked with Monte-Carlo, including E_r calculation

Monte-Carlo Self-Consistent E_r

J. Lewandowski(PPPL), A.Boozer, J. Williams (Columbia)

- toroidal component of the momentum-balance equation gives

$$\iota \frac{dQ}{dt} - \left\langle \frac{dL_\varphi}{dt} \right\rangle = S(E_r)$$

- where Q is the charge within a surface, L_φ is the canonical toroidal momentum, and S is the toroidal viscous force. In Boozer coordinates,

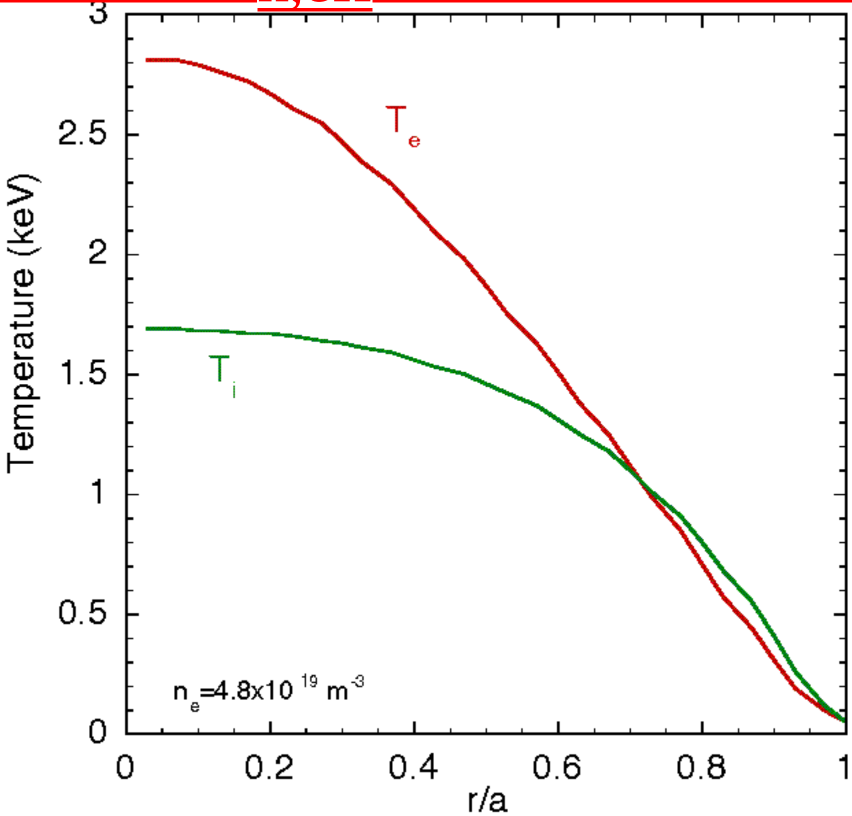
$$S = \tfrac{1}{2} \left\langle \partial_\varphi \left(p_\parallel + p_\perp \right) \right\rangle$$

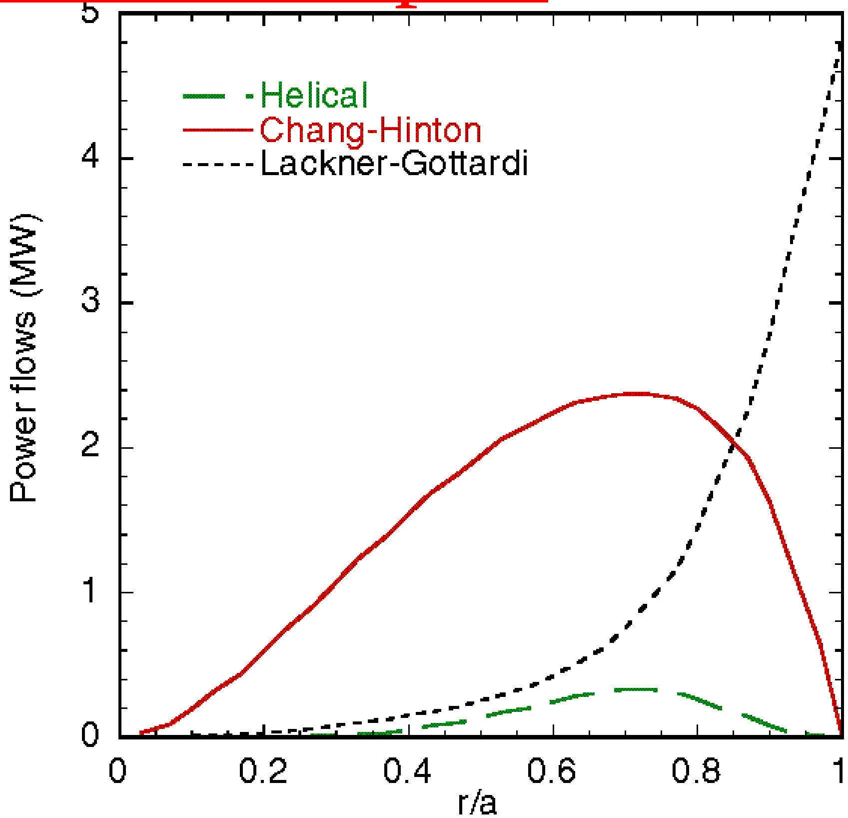
- Directly calculate S in a δf simulation for each species as a function of E_r, solve for where charge fluxes balance.

- Avoids noisy simulated fluxes

See Lewandowski, Poster DP1.133

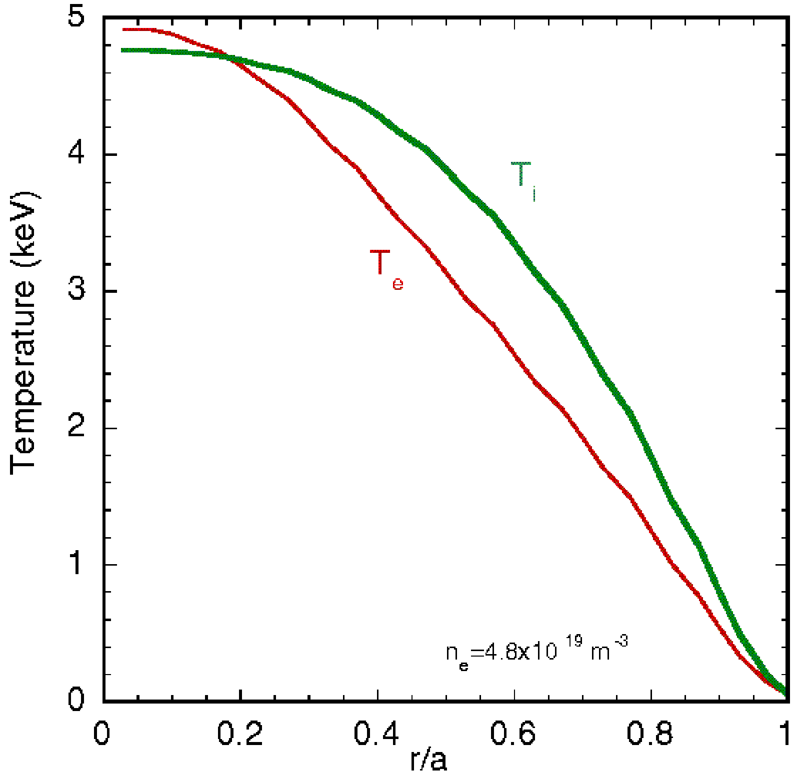
Low $\varepsilon_{h,eff}$ ⇒ Low Helical transport

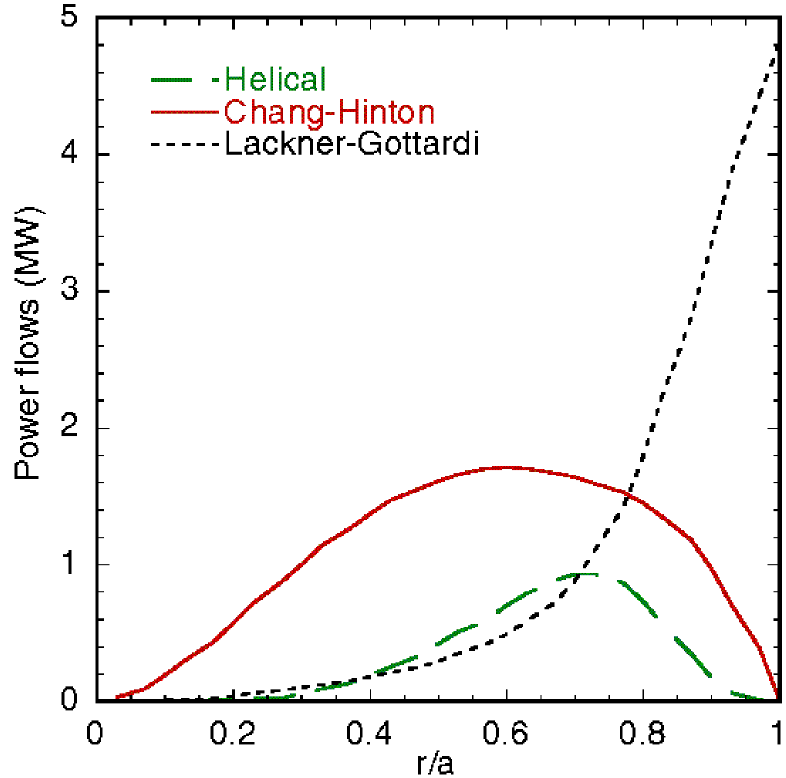




- STP; Assume B=1 T, P_{heat}=5 MW , R=1.75m, H_{ISS95}=2.6 ($H_{ITER-89P}$=1.1) ⇒ β = 4%, ν^* ~ 0.25
- Helical transport is sub-dominant with self-consistent E_r
- Can access β = 4% at high density with H_{ISS95} = 1.7
- Can add up to 6MW of ICRF if needed to access high beta.

B = 2T Allows Low Collisionality



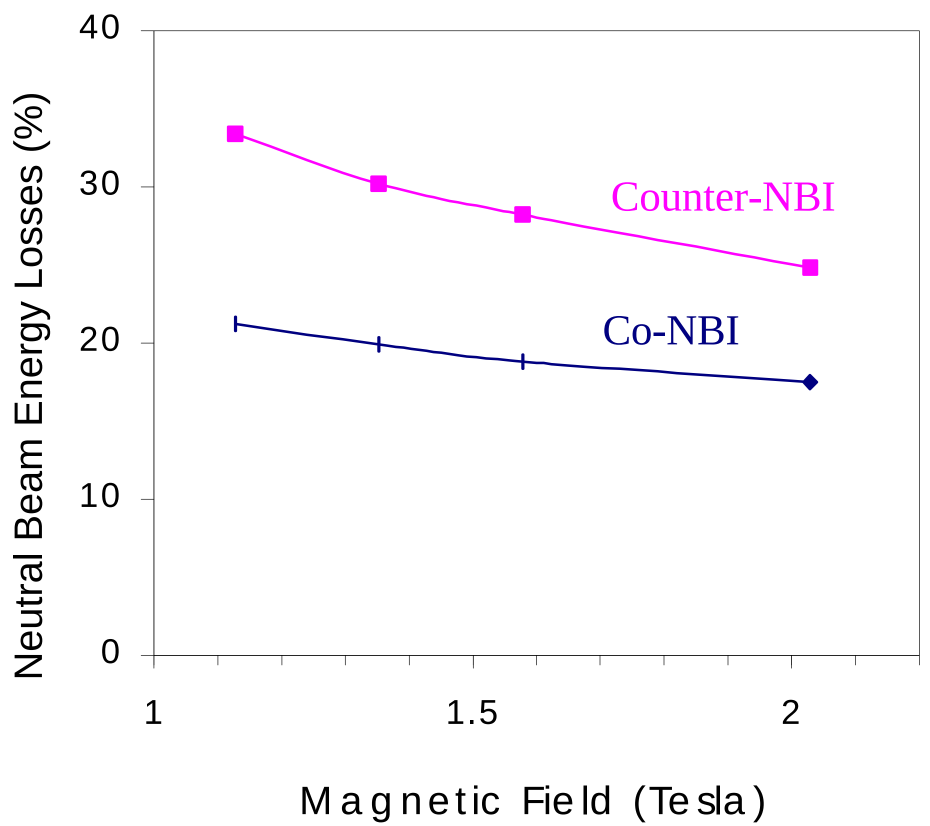


- Helical transport is still sub-dominant
- Assume H_{ISS95} = 2.6, P_{heat} = 5 MW $\Rightarrow \nu^* \sim 0.04$, β = 1.7%
  $H_{ITER\text{-}89P}$ = 0.95

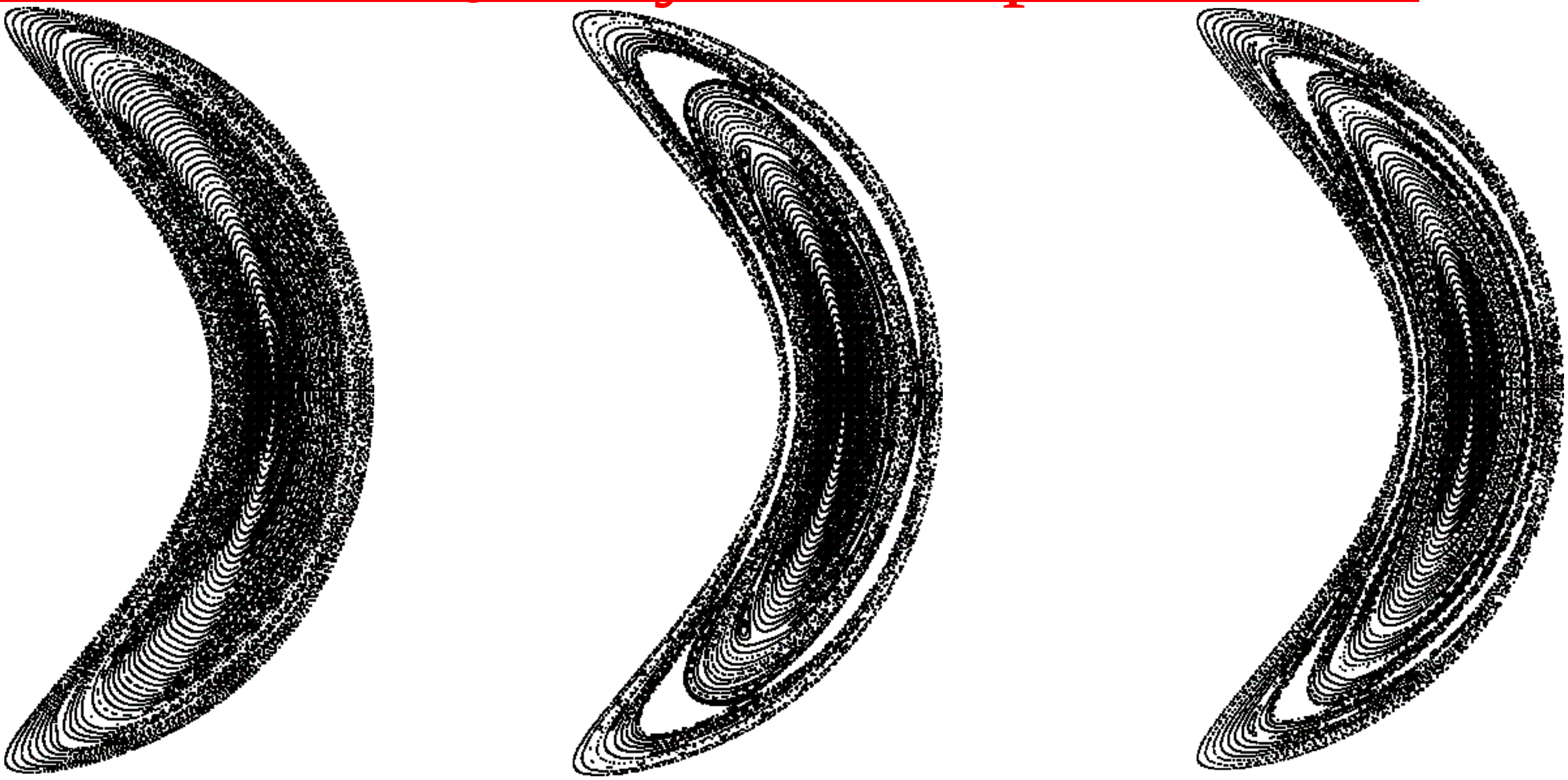
Allows study of plasmas with reactor-like collisionality

New Configurations Allows Counter-NBI

- Gives control of NBCD, Including ability to avoid it
- Mixed co- and counter-NBI would give rotation control
- Assumed tangent to mag.-axis at oblate cross-section



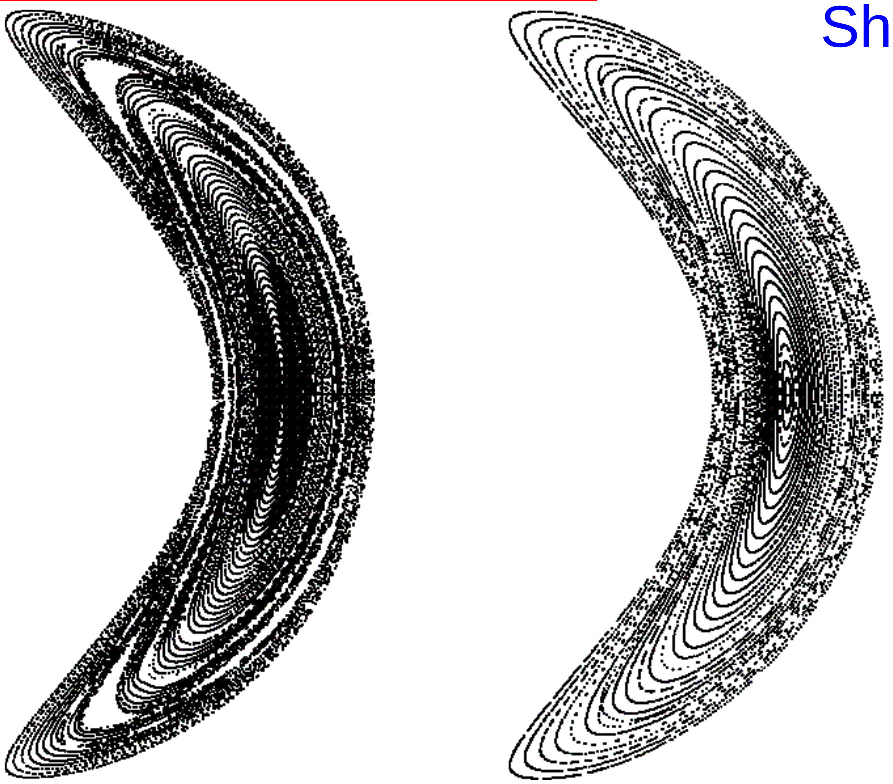
Flux-surface Quality: Startup looks Ok



Vacuum | Full current, β=0 target | Full current, β=4.2%

- Fixed boundary PIES equilibria. See Monticello et al, Poster HP1.027
- Large island at ι=0.6, w/a~0.13 for β =0, w/a ~0.1 for β =4.2%
  Neoclassical effects reduce it to effectively < 3% at full β
- Time-dependent startup modeling: See Lazarus et al. Poster HP1.031

Island removal method



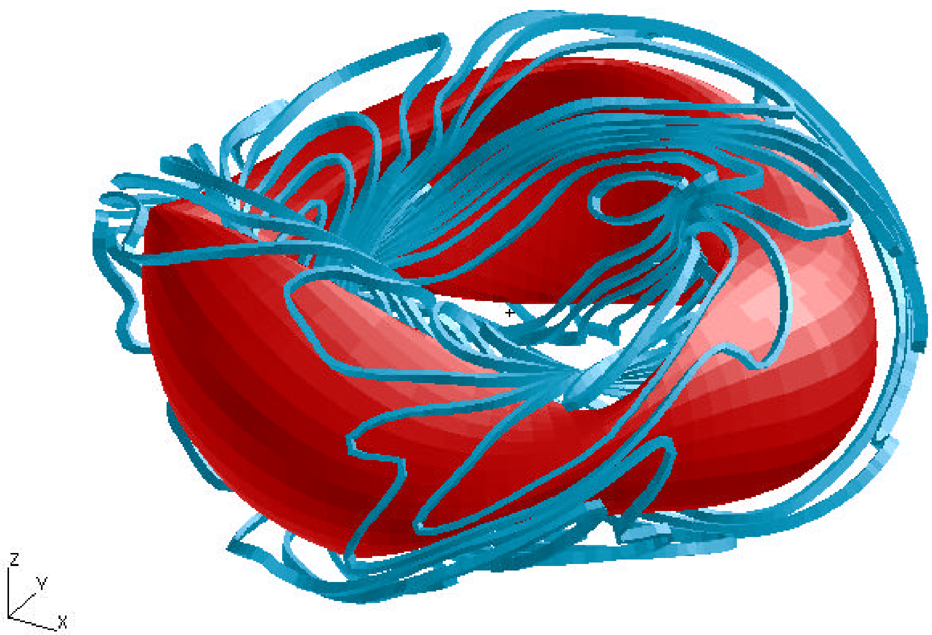
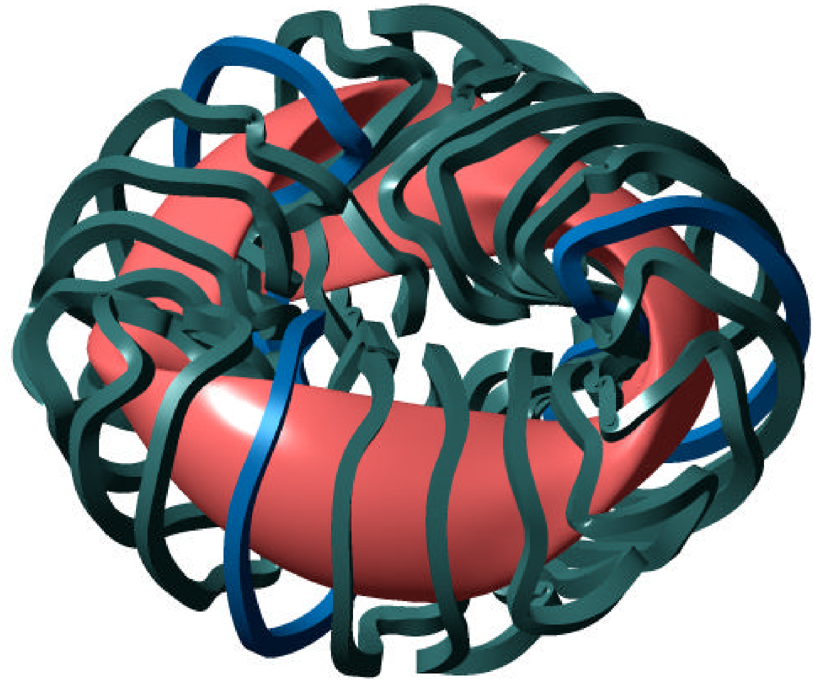
Shape Perturbations

$\delta r(n,m)$
(3,4) : 4.2 mm
(3,5) : 1.4 mm
(3,6) : 3.2 mm
(3,7) : -1.1 mm

See Hudson et al.
Poster HP1.028

- Calculate coupling between plasma boundary shape and island widths by perturbation, using PIES
- Invert coupling matrix to find shape modification to remove islands
- Modification has no effect on calculated stability or transport

Multiple Coil Designs Offer Opportunity

- Optimized saddle coils for 3D field
- + PF + TF coil sets

- Optimized modular coils for 3D field
- + PF + weak TF coil sets

- Which gives better flexibility? Better flux surfaces? Better access?   Analysis underway

See Valanju et al, Poster HP1.034 & Berry et al, Poster HP1.035

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Coil Flexibility Analysis

- Reconstruction of good flux surfaces from coils
- Reconstruction of original physics properties from coils
  - Stability and transport

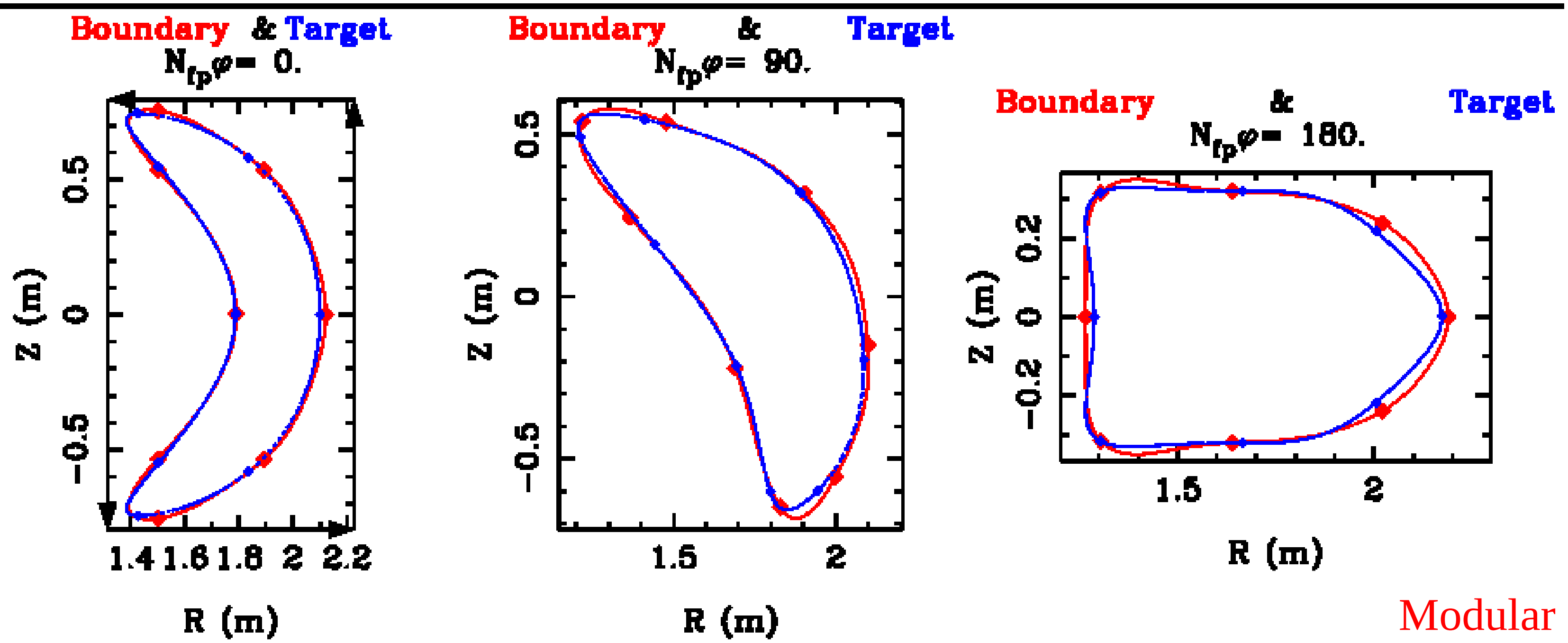
- Flexibility and Robustness of coils
  - Ability to accommodate different pressure and current profiles
  - Ability to vary iota profile and 3D geometry to study 3D plasma physics

$\longrightarrow$ Free-boundary optimizer: vary coil currents to reconstruct plasmas with desired physics properties

See Hatcher et al, Poster HP1.031

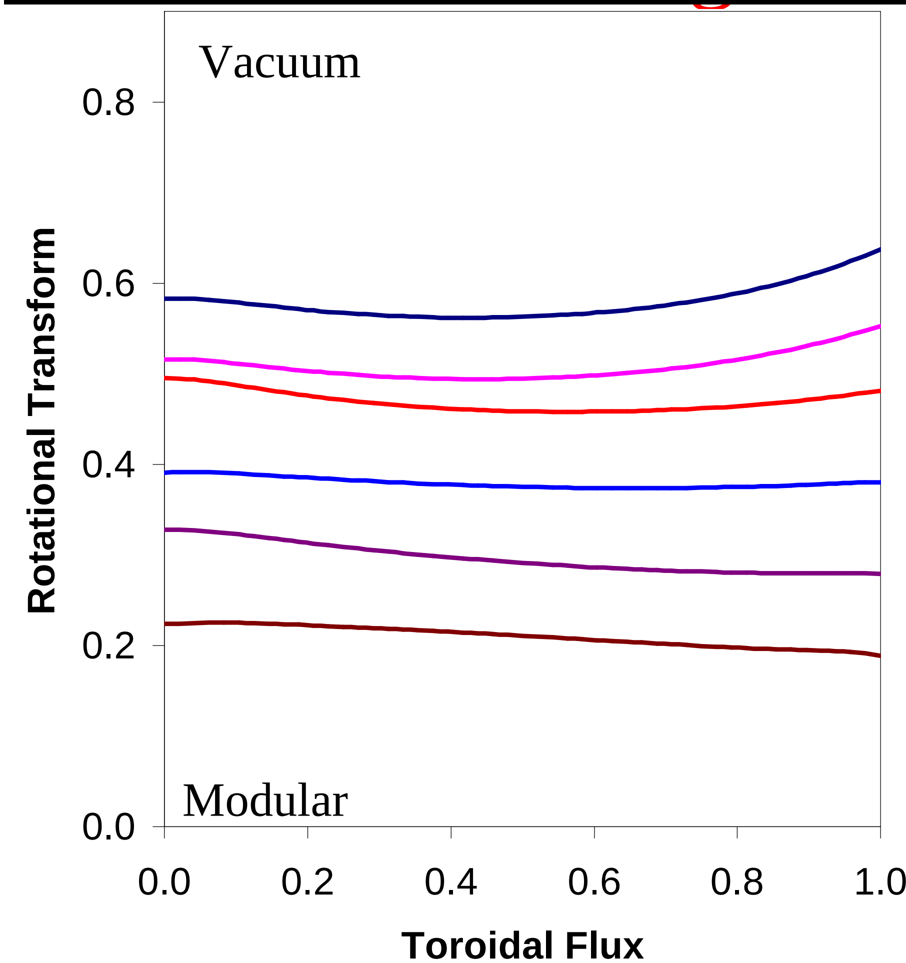
- Initial Results indicate good robustness and flexibility

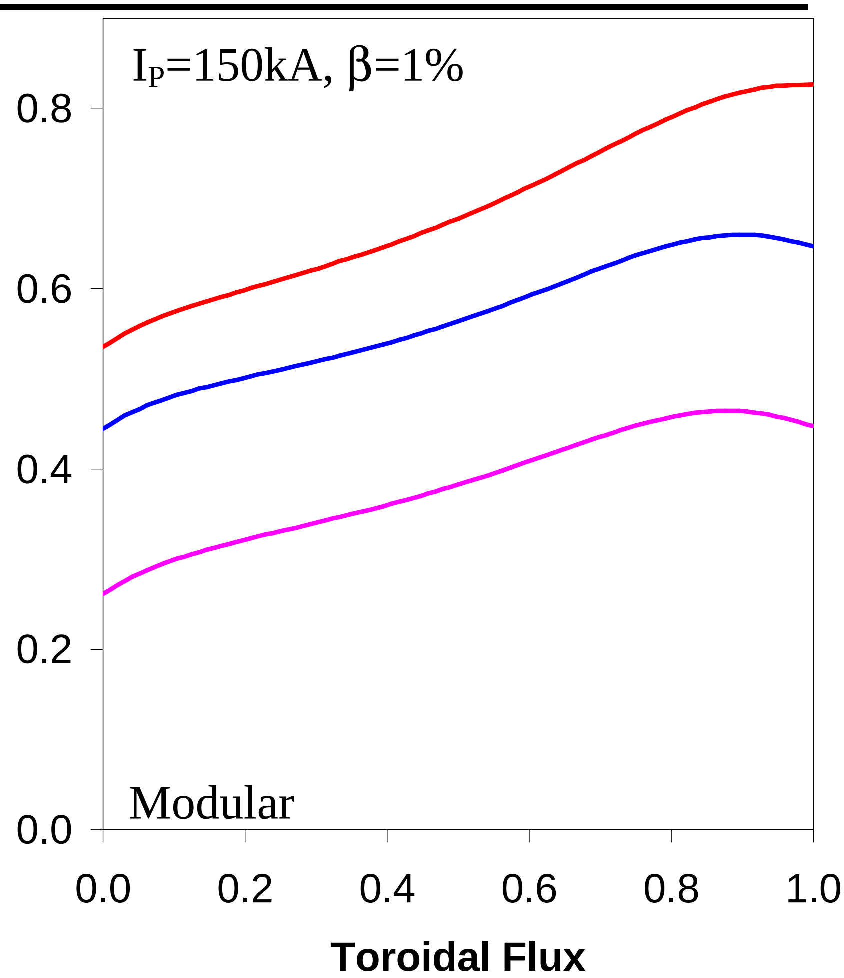
Modular Coils Reconstruct Target Physics



- Discrete coils cannot reproduce original shape precisely, due to engineering constraints
- Free-boundary optimization adjusts coil currents (and thus plasma shape) to recover physics properties
  - Reconstructed plasma is kink, ballooning, vertical, neo-tearing stable. Mercier is marginally stable (unstable at edge, not targeted in optimization)
  - $\varepsilon_{h\ eff}$ is higher than fixed-boundary by ~30%
- Stable saddle coil reconstructions have B(m,n≠0) components higher by factor 2 – 3, so far.

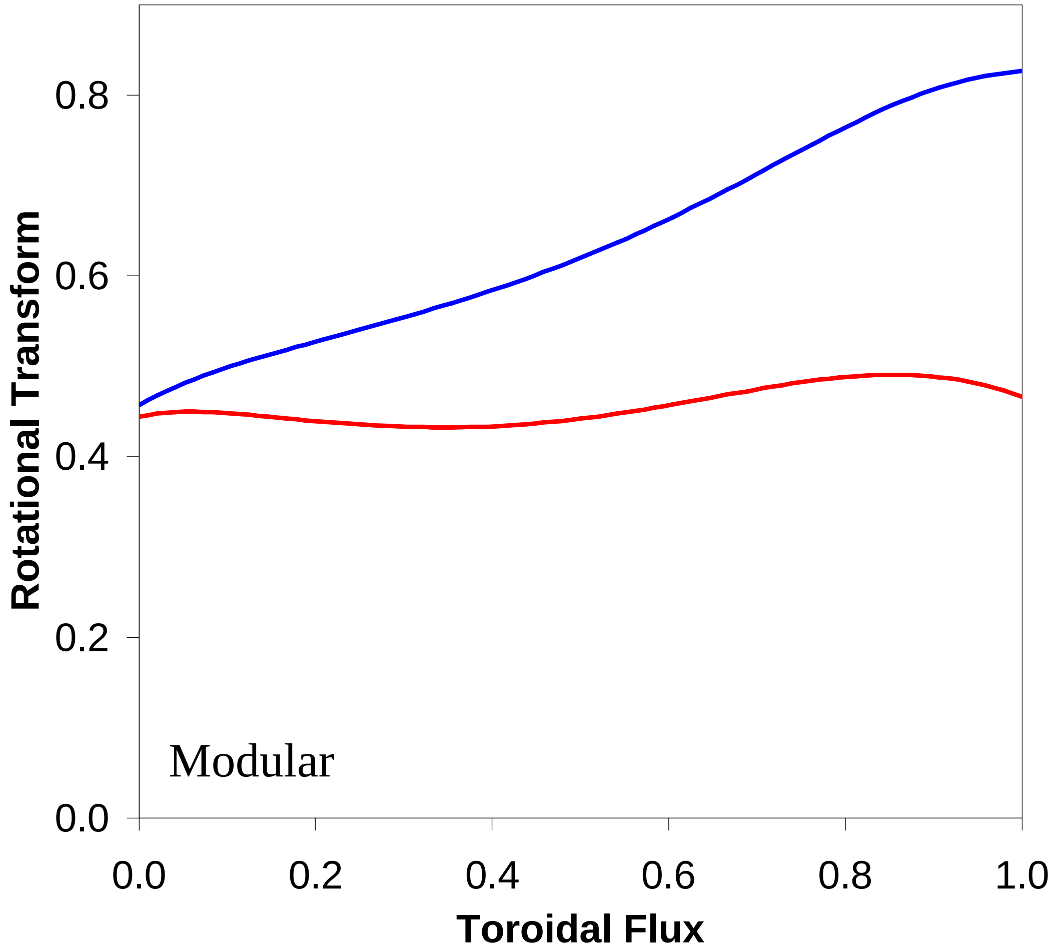
Wide Range of Iota Available





- Can avoid edge iota = ½ resonance

Even Shear can be Varied



I_P=150kA, β=1%

Divertor/Limiter Investigation Begun

- Working group formed (LLNL, ORNL, PPPL, UCSD, IPP-Garching)
- Initial requirements for divertor/limiter established
- MFBE code (E. Strumberger) has been imported from Garching, operating at NERSC, maps field lines outside VMEC equilibrium
- Plan:
  - Use MFBE to establish magnetic topology of edge region
  - Develop range of limiter/divertor options
  - Integrate a range of options into configuration

See A. Grossman et al, Poster HP1.033

Conclusions

- Attractive configuration has been identified
  - passive stabilty to kink, ballooning, vertical, Mercier, neoclassical tearing to $\beta > 4\%$
  - no need for conducting walls or feedback systems
  - very good quasi-axisymmetry
- Coil designs appear flexible, can reproduce physics goals
- Basis for exciting and flexible experiment
  Test our understanding of compact 3D confinement