

Physics Issues in the Design of Low Aspect-Ratio, High- β Quasi-Axisymmetric Stellarators

M. Zarnstorff
Princeton Plasma Physics Laboratory, USA

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The NCSX Design Team

R. D. Benson, ORNL	A. Grossman, UCSD.	J. F. Lyon, ORNL	M. H. Redi, PPPL
L. A. Berry, ORNL	P. Heitzenroeder, PPPL	R. Majeski, PPPL P.	W. T. Reiersen, PPPL A.
A. H. Boozer, Columbia U.	S. P. Hirshman, ORNL	Merkel, IPP-Greifswald	H. Reiman, PPPL
A. Brooks, PPPL	W. Houlberg, ORNL	M. Mikhailov, Kurchatov	P. Rutherford, PPPL
T. G. Brown, PPPL	S. Hudson, PPPL	D. Mikkelsen, PPPL	R. Sanchez, Spain
M. Cole, ORNL	M. Isaev, Kurchatov	W. Miner, U. Texas	J. A. Schmidt, PPPL
W. Cooper, CRPP	W. Kernbichler, Austria	P. Mioduszewski, ORNL	D. A. Spong, ORNL
M. Drevlak, IPP-Greifswald	C. E. Kessel, PPPL	D. A. Monticello, PPPL	P. Strand, ORNL
E. Fredrickson, PPPL	S. Knowlton, Auburn	H. Myrick, PPPL	D. Strickler, ORNL
G. Y. Fu, PPPL	L.-P. Ku, PPPL	G. H. Neilson, PPPL	P. Valanju, U. Texas
A. Georgievskiy	H. Kugel, PPPL	B. E. Nelson, ORNL	R. B. White, PPPL
R. J. Goldston, PPPL	E. Lazarus, ORNL	C. Nührenberg, IPP-G.	D. A. Williamson, ORNL
P. Goranson, ORNL	Z. Lin, PPPL	A. Pletzer, PPPL	M. C. Zarnstorff, PPPL
	J. Lewandowski, PPPL	N. Pomphrey, PPPL	

**In collaboration with Laboratories at
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Wisconsin
Austria, Germany, Switzerland, Russia, Japan, Australia, Spain**

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 \Rightarrow 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 Alfvénic-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

Wide Range of 3D Configurations Has Been Explored

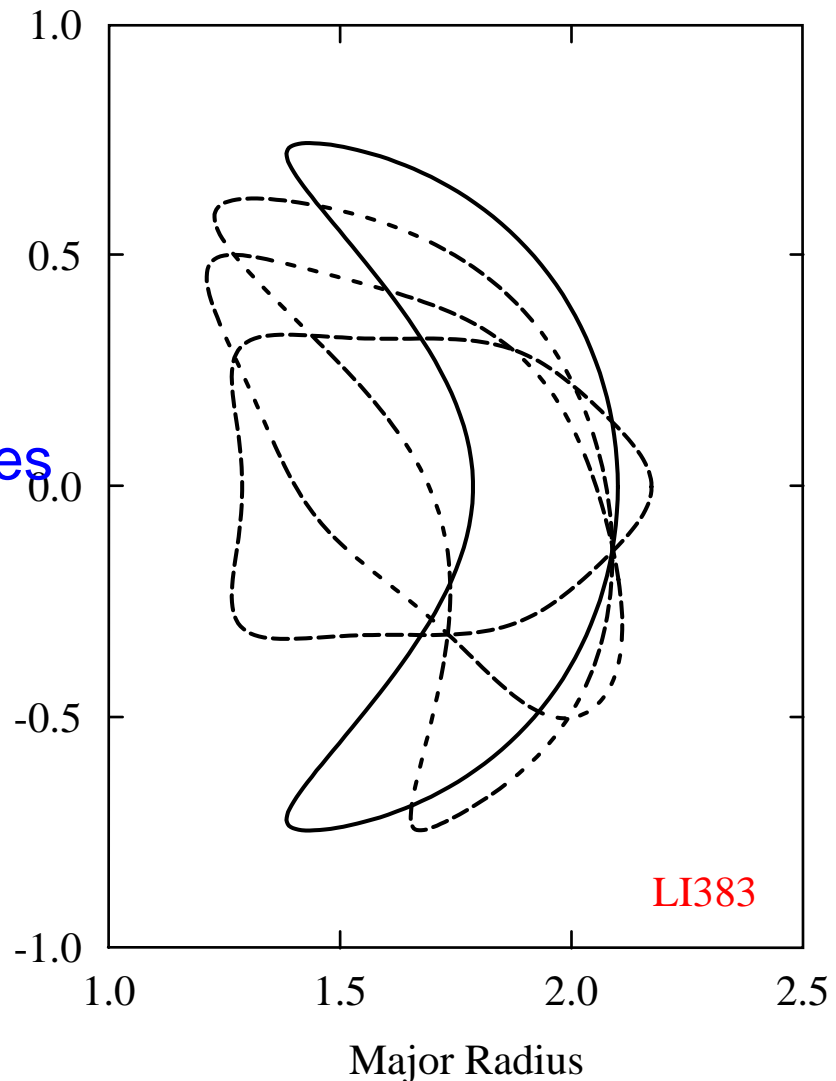
(many useful discussions with P. Garabedian & J. Nuehrenberg)

- Aspect ratio, A : 3 – 5
- Average elongation up to 3 (exploiting robust vertical stability)
- Vacuum magnetic well
- Edge iota $\iota(a)$: 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

New Attractive Configuration

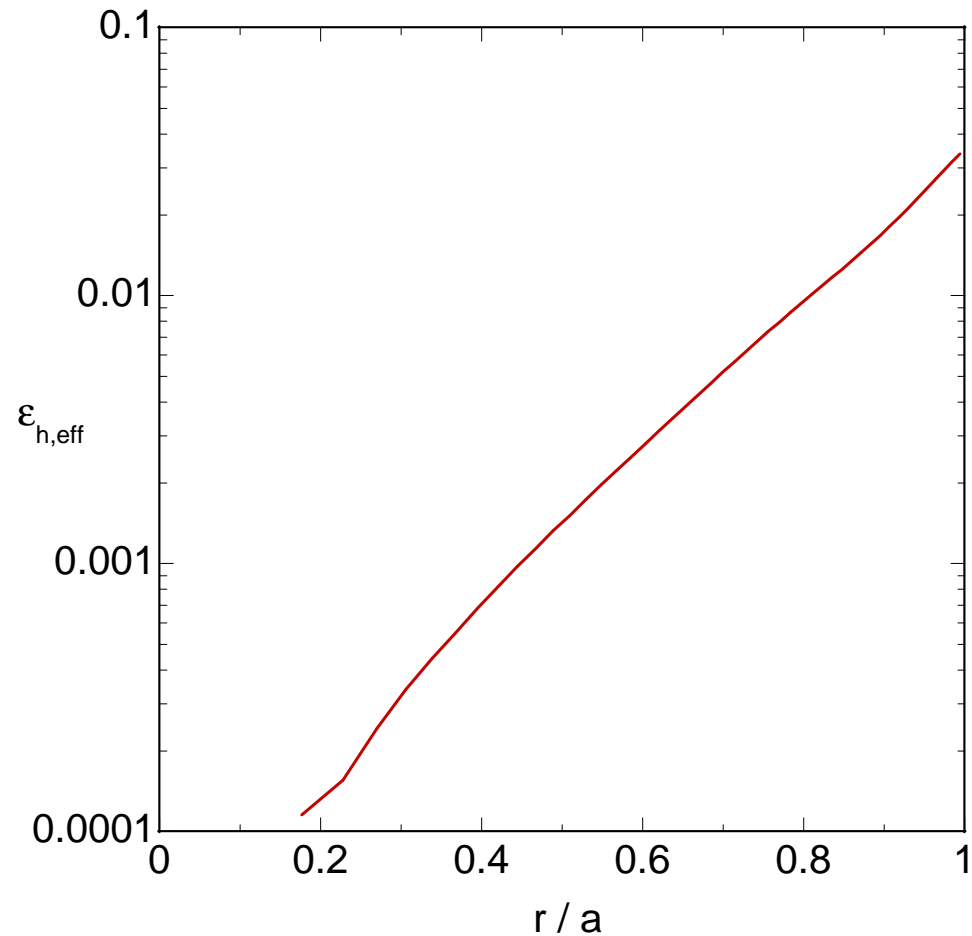
- 3 periods, $\langle A \rangle = 4.4$, $\langle \kappa \rangle \sim 1.7$
 ⟨indented⟩
- Stable to ballooning, kink, vertical, Mercier at $\beta = 4.1\%$
- Limited by ballooning, thus should be able to optimize profiles
- Reduced coil complexity
- Iota: $0.4 \rightarrow 0.65$
 $\sim 2/3$ from external coils
 neoclassical-tearing stable

See G-Y Fu, et al. for detailed discussion of MHD stability

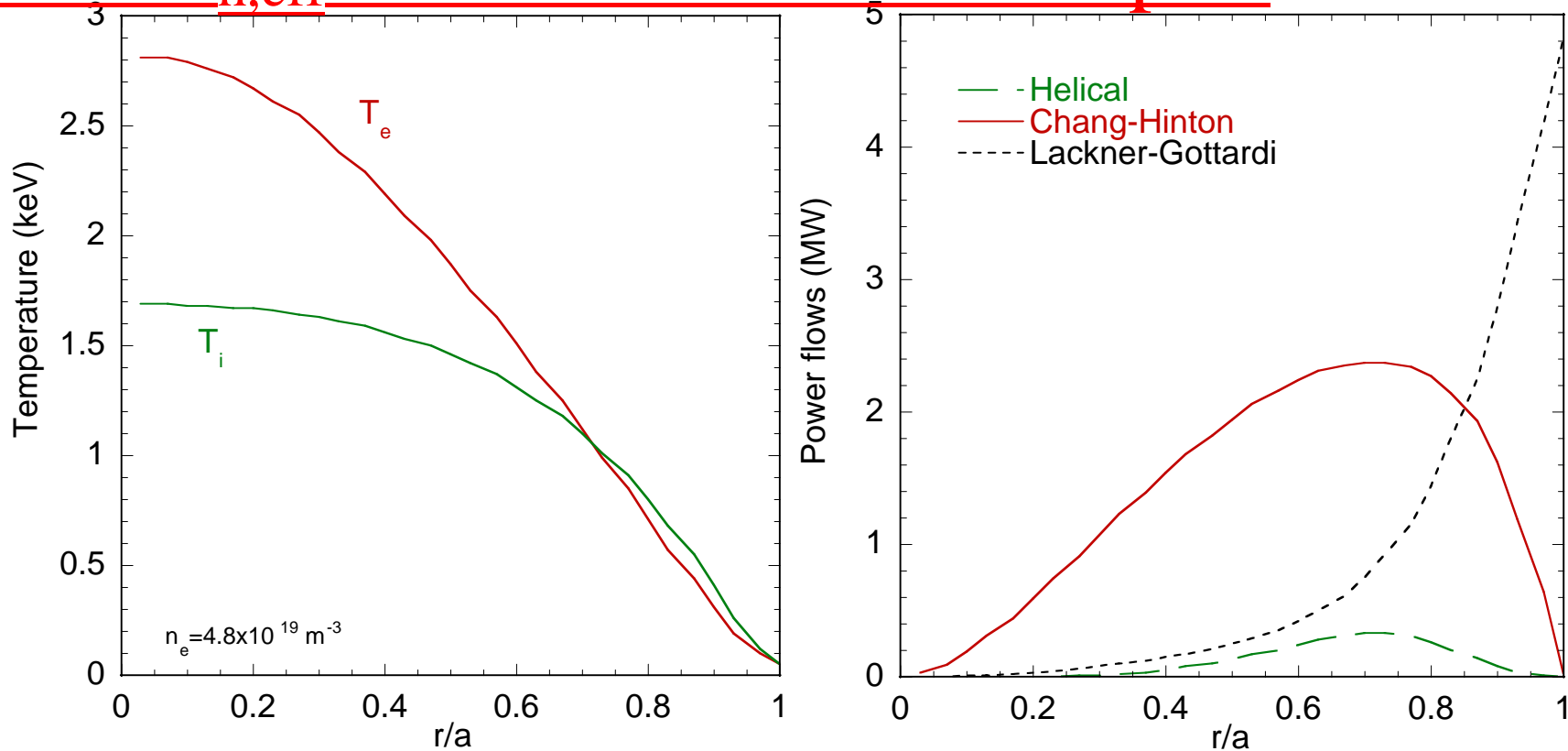


Quasi-Axisymmetric: Low effective ripple

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

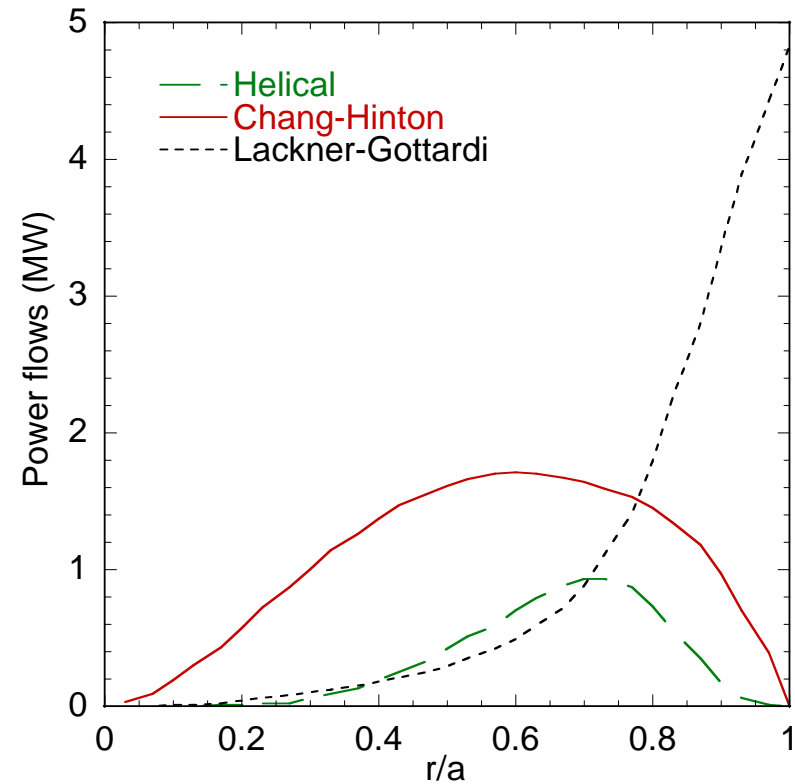
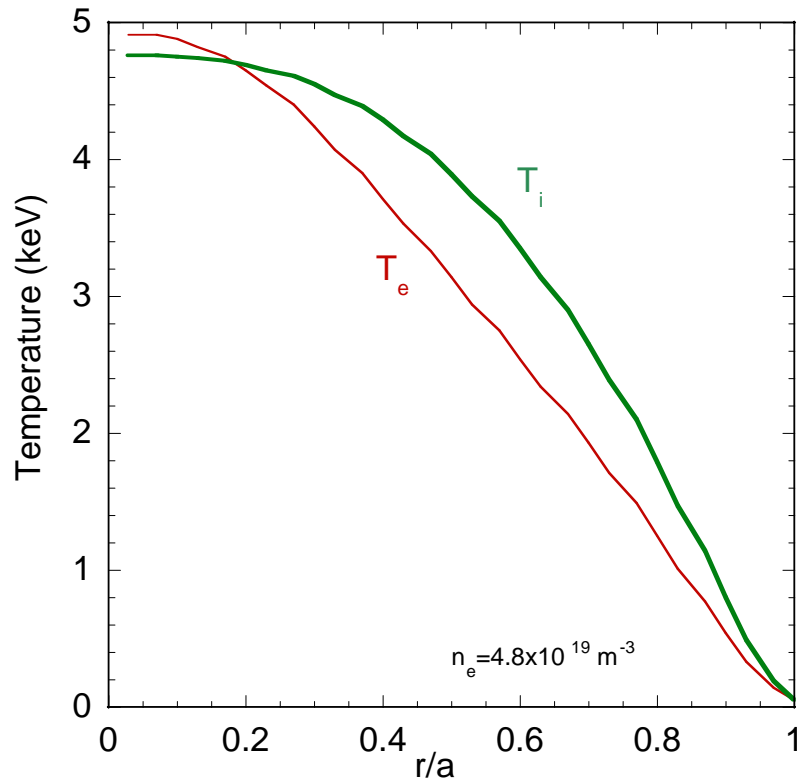


Low $\epsilon_{h,eff} \Rightarrow$ Low Helical transport



- Assume $B=1 \text{ T}$, $P_{heat}=5 \text{ MW}$, $R=1.75\text{m}$, $H_{ISS95}=2.6$ ($H_{ITER-89P}=1.1$)
 $\Rightarrow \beta = 4\%$, $\nu^* \sim 0.25$
- Helical transport is sub-dominant with self-consistent E_r
- Can access $\beta = 4\%$ at high density with $H_{ISS95} = 1.7$
- Shaing-Houlberg for helical transport, benchmarked with Monte-Carlo.
- Can add up to 6MW of ICRF if needed to access high beta.

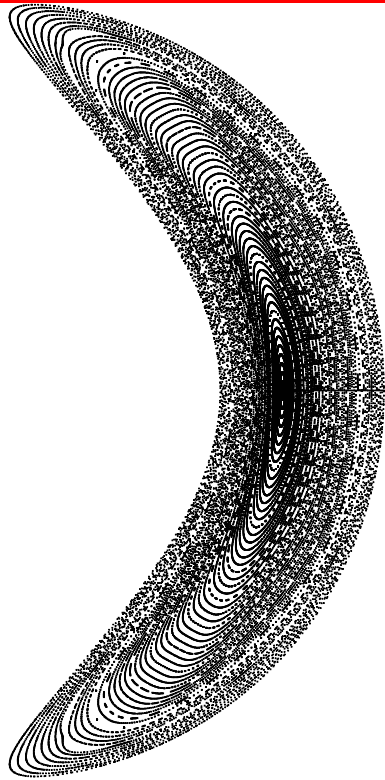
B = 2T Allows Low Collisionality



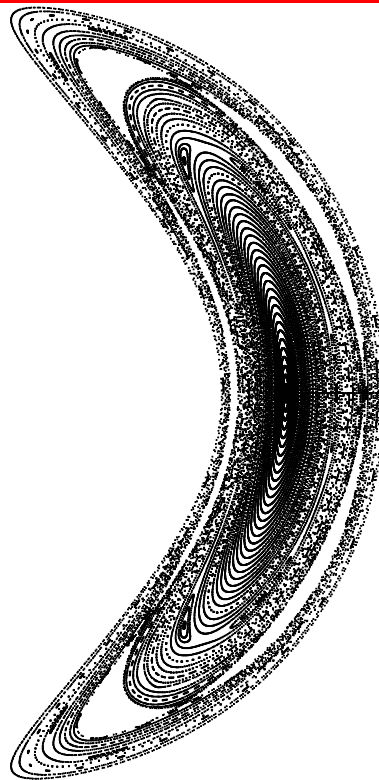
- Helical transport is still sub-dominant
- Assume $H_{ISS95} = 2.6$, $P_{\text{heat}} = 5 \text{ MW} \Rightarrow v^* \sim 0.04$, $\beta = 1.7\%$
 $H_{ITER-89P} = 0.95$

Allows study of plasmas with reactor-like collisionality

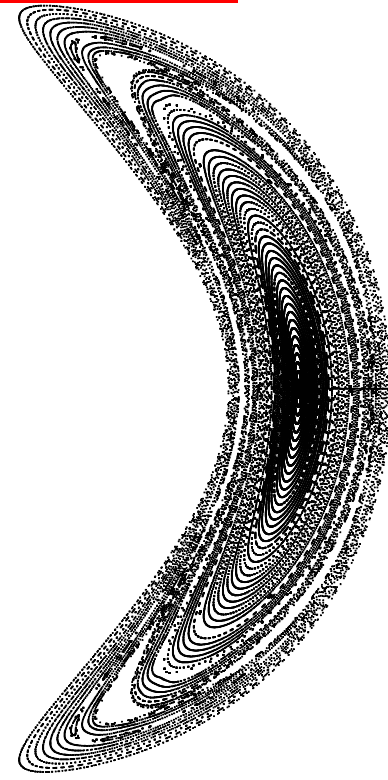
Flux-surface Studies: Startup looks Ok



Vacuum



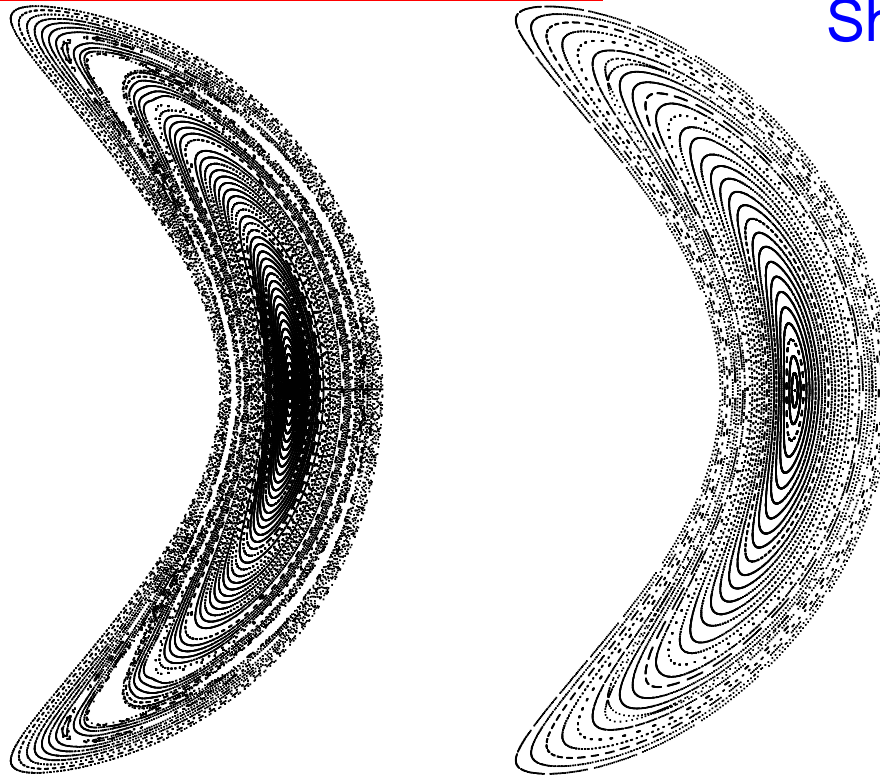
Full current, $\beta=0$ target



Full current, $\beta=4.2\%$

- Fixed boundary PIES equilibrium calculations.
- Large island at $\iota=0.6$, $w/a \sim 0.13$ for $\beta = 0$, $w/a \sim 0.1$ for $\beta = 4.2\%$
Neoclassical effects reduce w/a to effectively < 0.03 at full β
- Time-dependent startup modeling shows kink stability maintained

Island removal method



Shape Perturbations

$\delta r(n,m)$

(3,4) : 4.2 mm

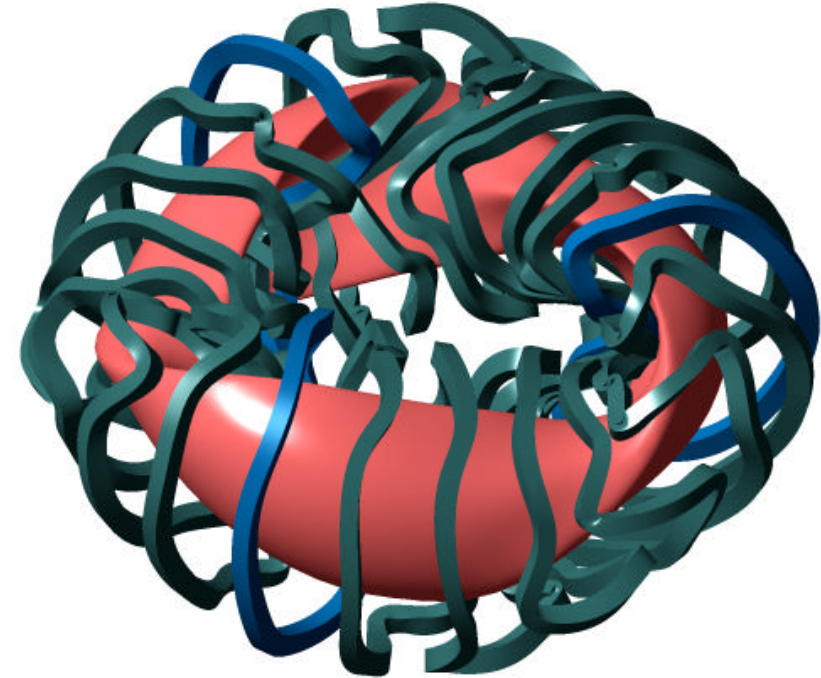
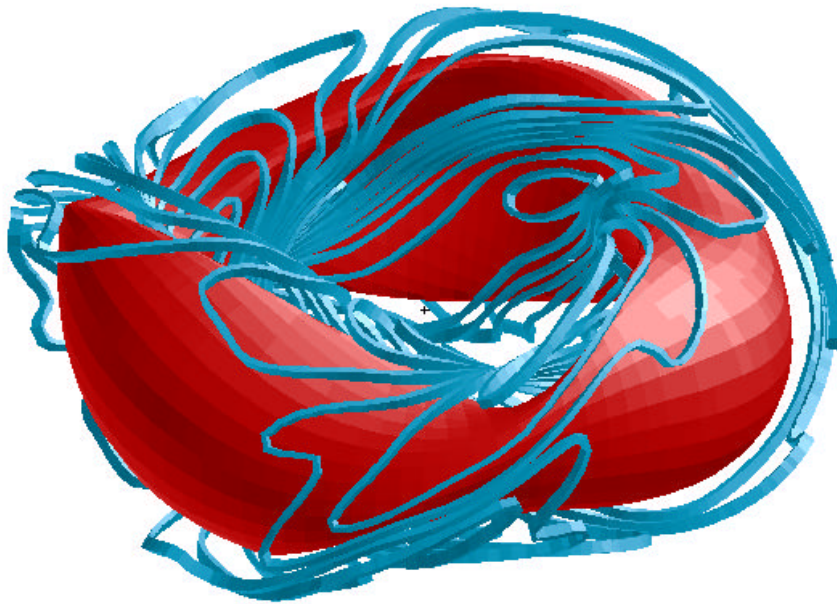
(3,5) : 1.4 mm

(3,6) : 3.2 mm

(3,7) : -1.1 mm

- 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

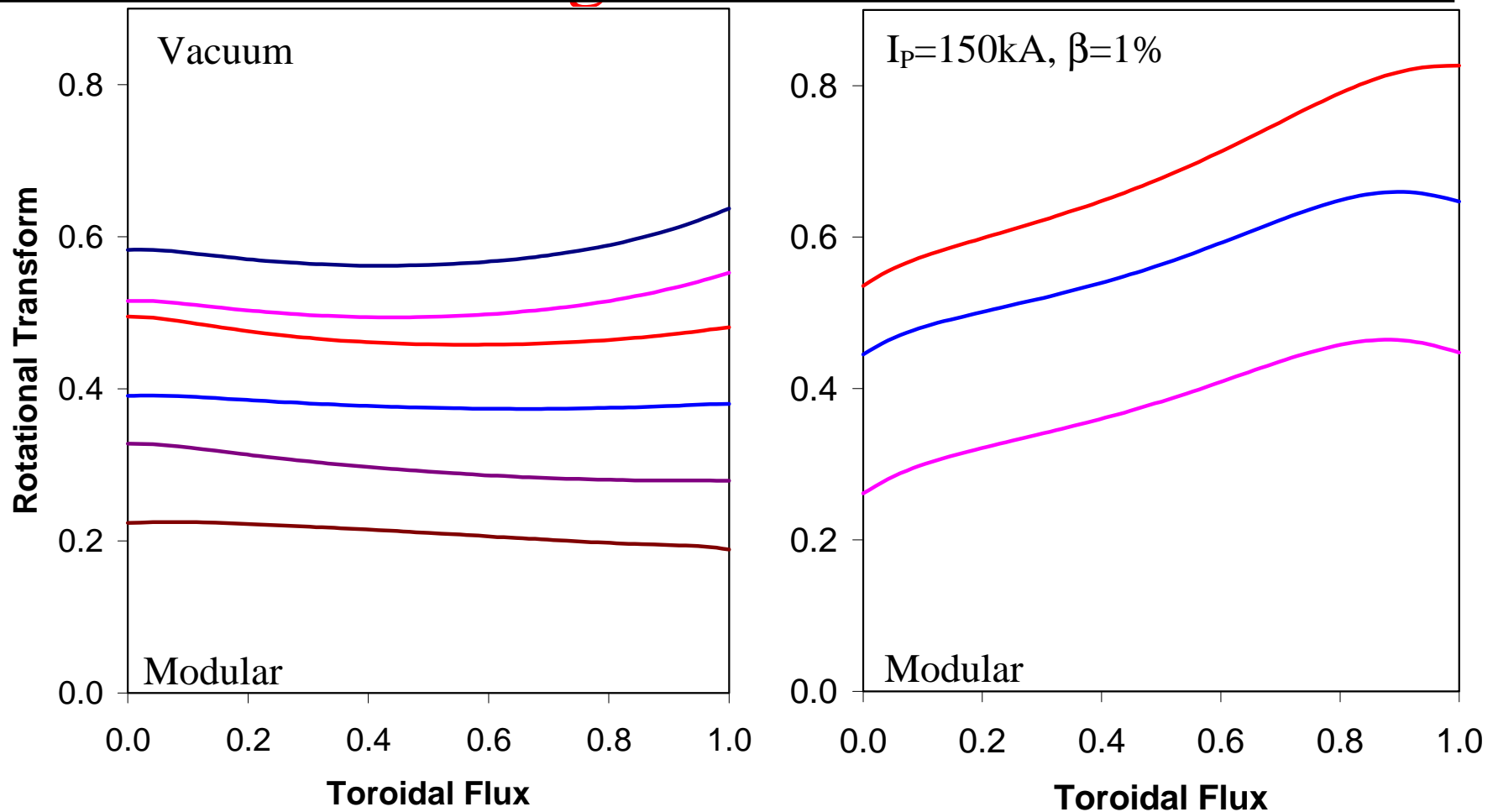


- Optimized saddle coils for 3D field
- + PF + TF coil sets
- See N.Pomphrey, poster for coil optimization
- Which gives better flexibility? Better flux surfaces? Better access? Analysis underway
- Optimized modular coils for 3D field
- + PF + weak TF coil sets

Work in Progress

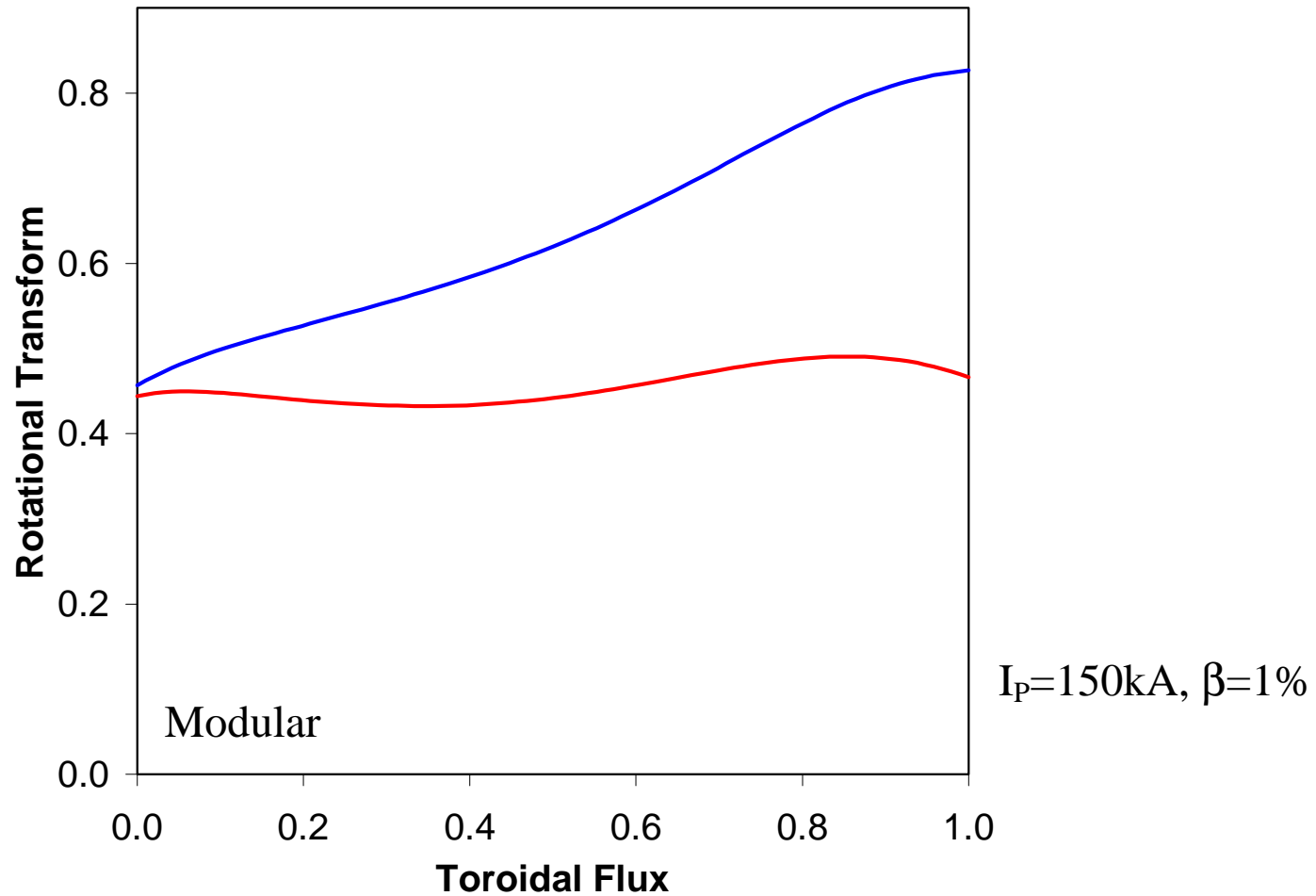
- Reconstruction of good flux surfaces from coils
- Reconstruction of original physics properties from coils
 - Stability and transport
- Flexibility and Robustness of coils
 - Ability to accommodate different pressure and current profiles
 - Ability to vary iota profile and 3D geometry to study 3D plasma physics
- Free-boundary optimizer: vary coil currents to reconstruct plasmas with desired physics properties
- Initial Results indicate good robustness and flexibility

Wide Range of Iota Available



- Can avoid edge $iota = \frac{1}{2}$ resonance

Even Shear can be Varied



Conclusions

- Attractive configuration has been identified
 - passive stability 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

