NCSX
Physics Design Development

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OFES PPPL Site Visit
12 September 2000

Outline

- Goals
- Previous status
- New Configurations
  – Characteristics
- Plans

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 $\beta \geq 4\%$
  - prevent disruptions?
- Steady state without current drive.
- Aspect ratio: ~ 4
- Good confinement. Quasi-axisymmetry to close drift-orbits, allow plasma flow

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

The NCSX Design Team

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NCSX Method: Design for High β

- Most stellarator designs have been optimized in the vacuum configuration, then evaluated at high beta

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

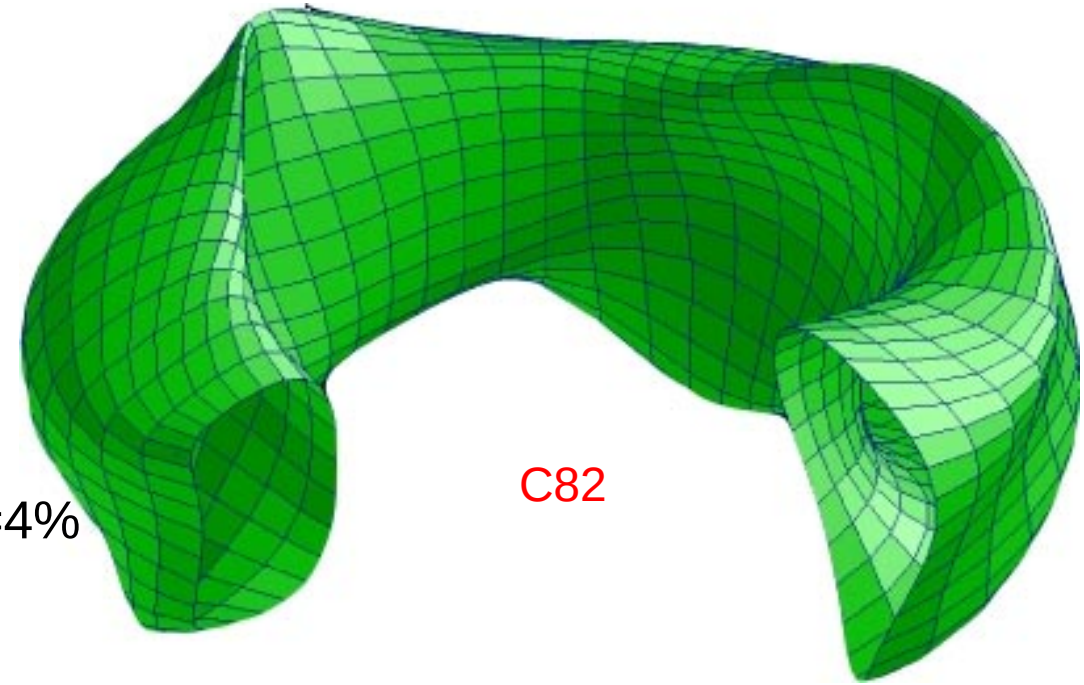
- Required substantial tools development
  - Coil optimization including plasma currents
  - Improved 3D equilibrium codes – PIES and VMEC
  - Kink and ballooning stability calculations inside optimizer
  - Transport and bootstrap calculations inside optimizer
  - Approximate coil design inside optimizer

Previous Configuration Stable at $\langle\beta\rangle$ = 4%

Key Physics Properties

- 3 periods, $\langle A\rangle$=3.4
  Quasi-axisymmetric

- Stable to ballooning, kink, vertical, mercier modes without conducting wall or feedback control at $\langle\beta\rangle$=4% (limited by kink)



- Stellarator shear ($dq/dr < 0$), for neoclassical island stabilization
  – Without need for ECCD feedback

Further detailed analysis indicated:

- Coil current densities relatively large, limiting flexibility
- Flux surface quality – poor at edge for high-beta

Identified Regions of Opportunity Have Been Explored

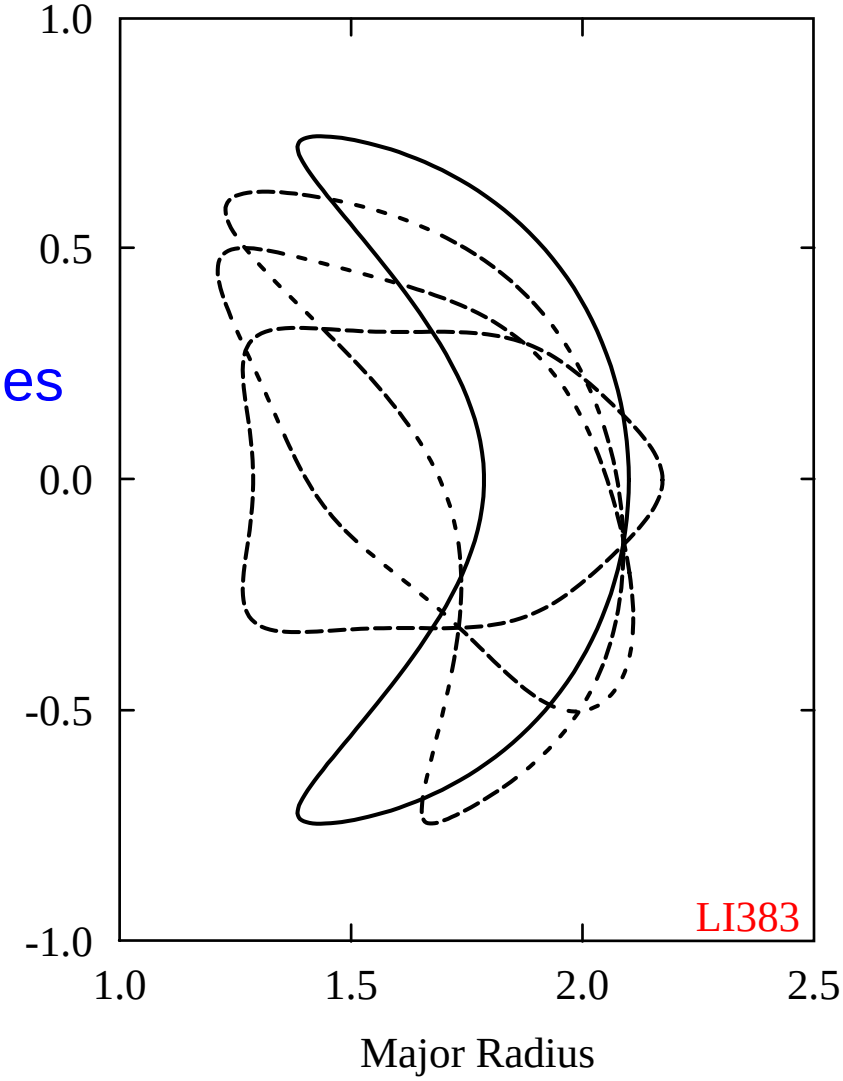
- Aspect ratio, A: 3 – 5 (outside PBX-M constraint)
- Average elongation up to 3 (exploiting robust vertical stability)
- Vacuum magnetic well (suggestions by P. Garabedian)
- Edge iota $\iota(a)$: 0.47 – 0.78
- External transform fractions at β-limit: 50 – 80%
- 2, 3 periods

- Major distinguishing characteristics:
  flux-surface quality & coil J_{max}

- Attractive new design configuration has been identified

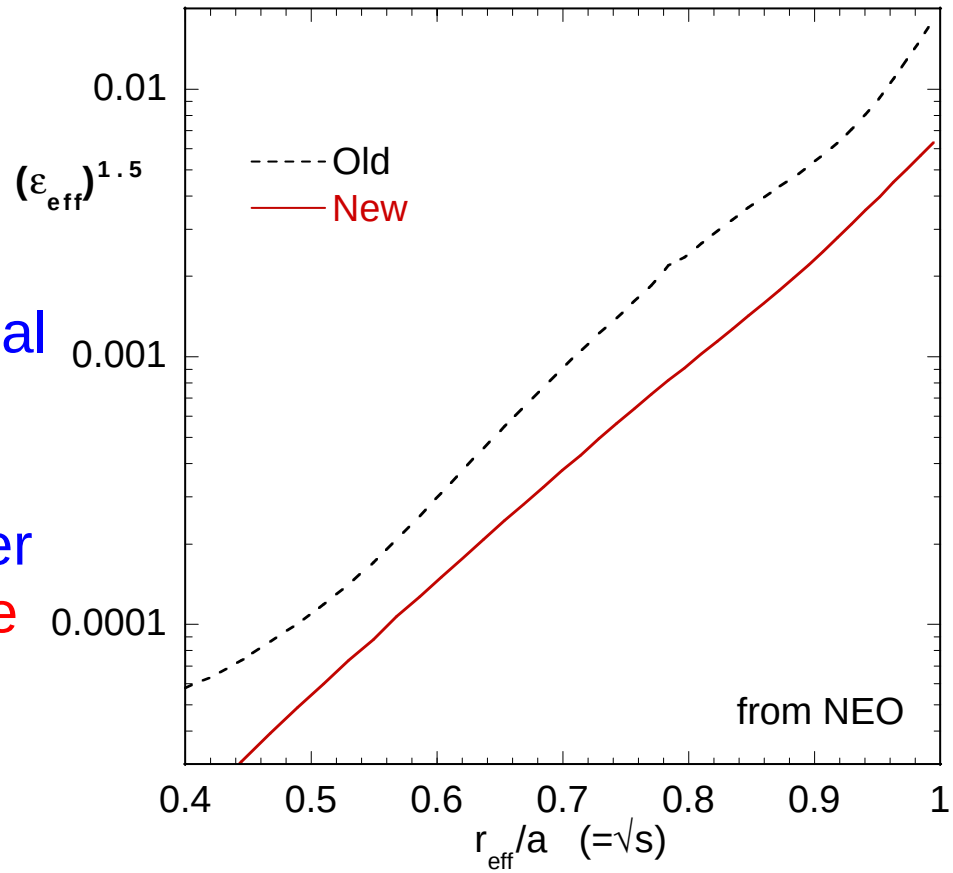
New Attractive Configuration

- 3 periods, $\langle A \rangle$=4.4, $\langle \kappa \rangle$~1.7
- Stable to ballooning, kink, vertical, Mercier at β=4.1%
- Limited by ballooning, thus should be able to optimize profiles
- Good flux surfaces, except one significant island chain
- Saddle-coil current density ~ ½ of C82, less complex



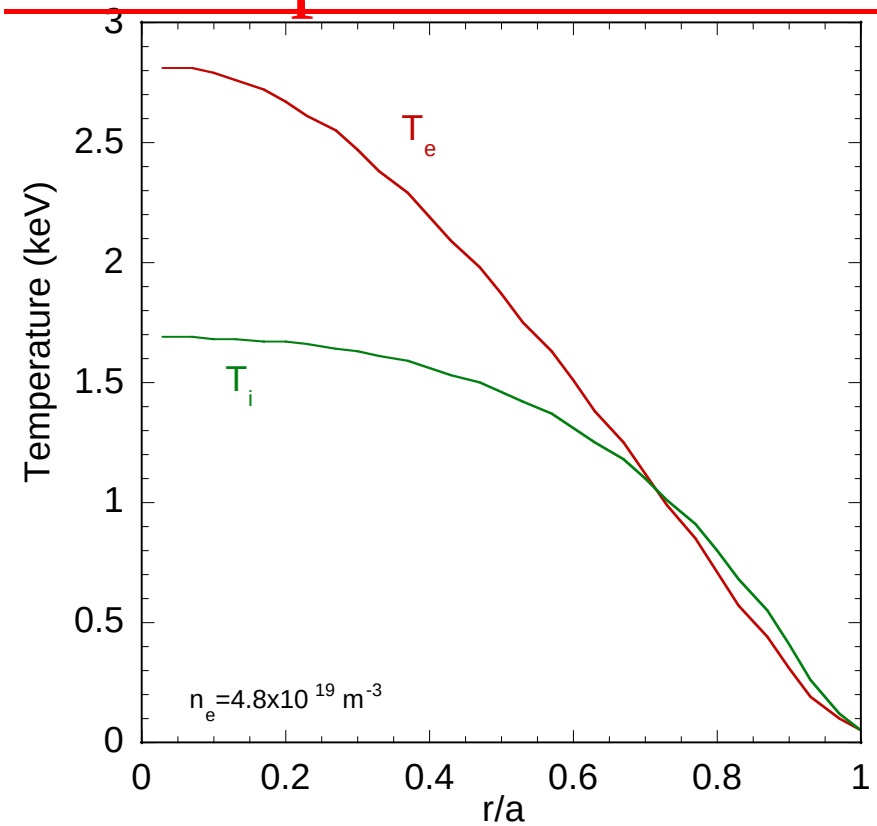
New Configuration: Low effective ripple

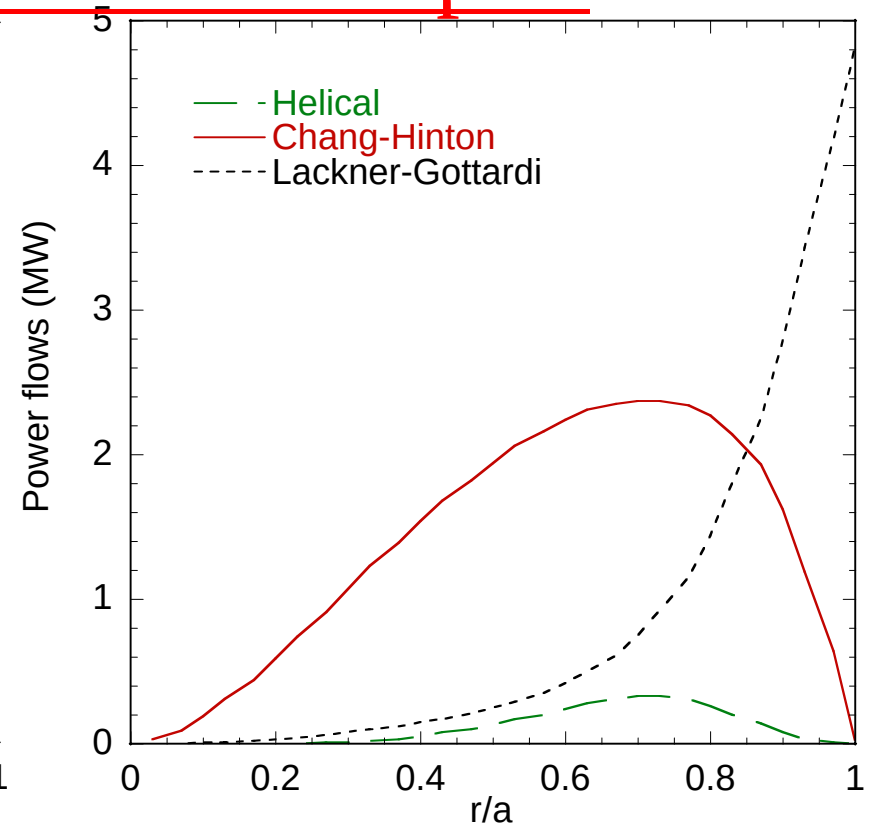
- ε_{eff} from NEO code by Nemov-Kernbichler
- In $1/\nu$ regime, neoclassical transport scales as $\varepsilon_{eff}^{3/2}$
- New configuration is better
  By factor ~2 across profile
- Edge ε_{eff} ~ 3.5%
- Allows counter-inj. NBI



- Higher iota improves axisymmetric neoclassical confinement

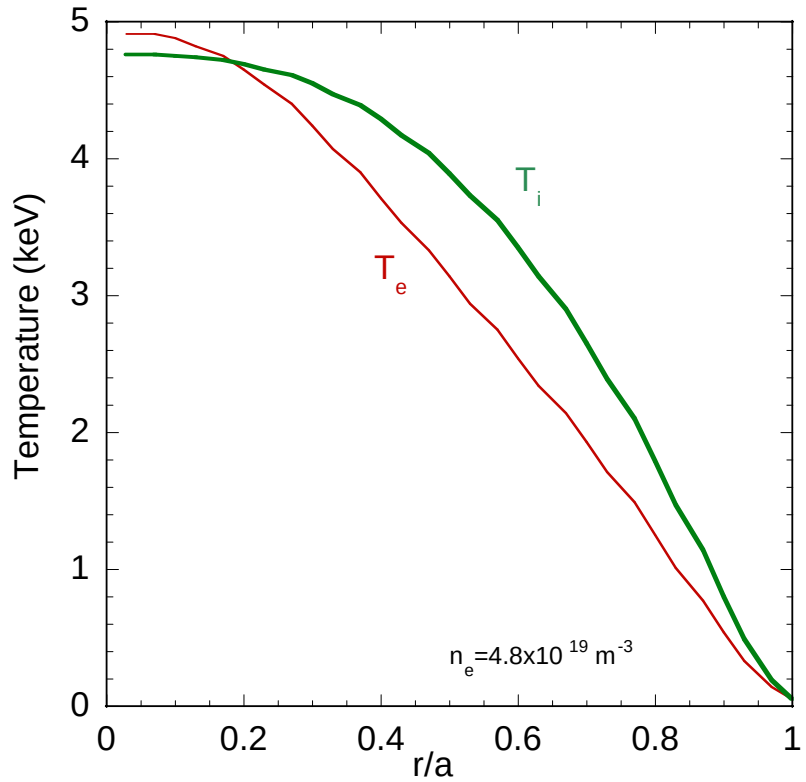
New 3-period: Low Helical transport

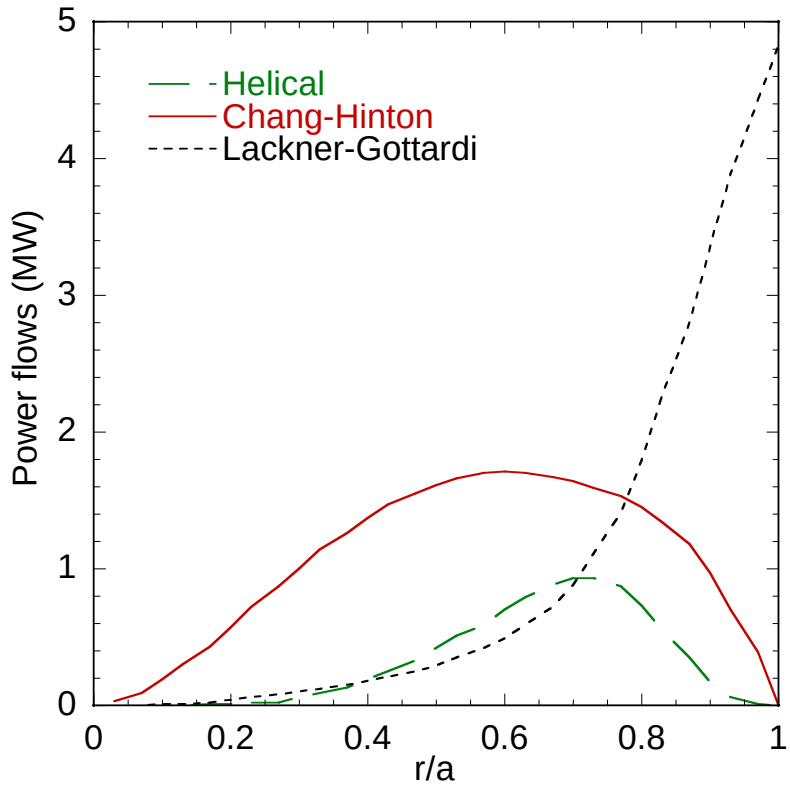




- Helical transport is sub-dominant with self-consistent E_r
- Assume B=1 T, H_{ISS95}=2.6 ($H_{ITER-89P}$=1.1), P_{heat}=5 MW
  $\Rightarrow \beta = 4\%$, $\nu^* \sim 0.25$
- Toroidal neoclassical dominant, due to moderate size and 'reversed shear' $\Rightarrow$ limited poloidal flux

B = 2T Allows Low Collisionality

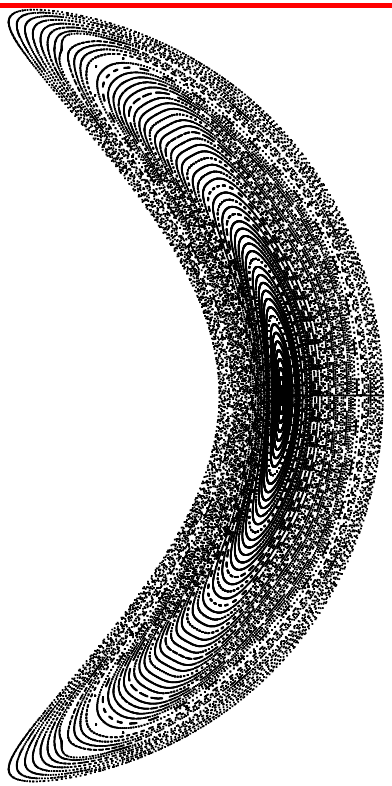




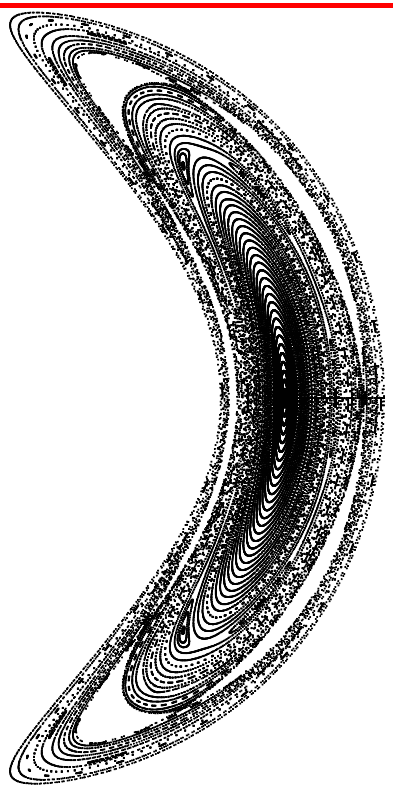
- Helical transport is still sub-dominant
- Assume H_{ISS95} = 2.6, P_{heat} = 5 MW $\Rightarrow \nu^* \sim 0.04$, β = 1.7%
  $H_{ITER\text{-}89P}$ = 0.95

Allows study of plasmas with reactor-like collisionality

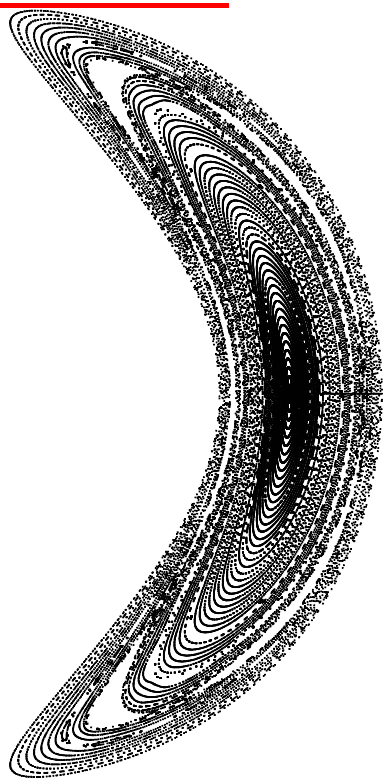
Flux-surface Studies: Startup looks Ok



Vacuum



Full current, β=0 target



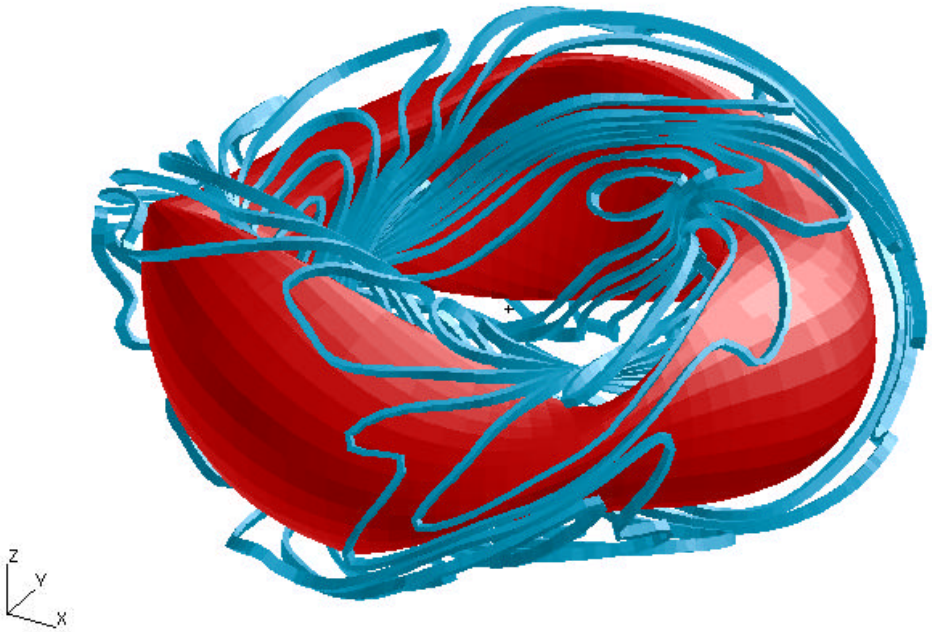
Full current, β=4.2%

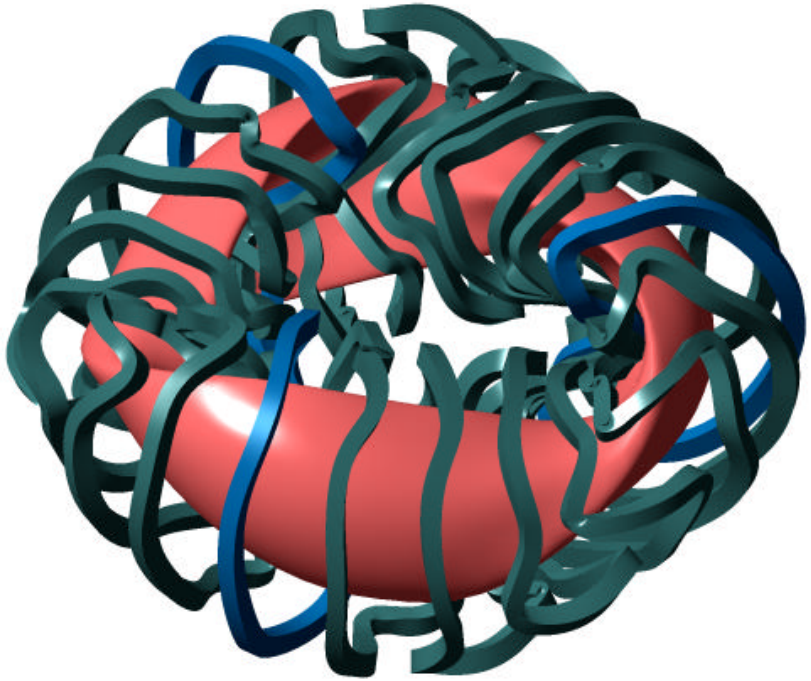
- Fixed boundary PIES equilibrium calculations. Free boundary underway
- Addressing FESAC question of flux-surface robustness
- Large island at ι=0.6, w/a~0.13 for β =0, w/a ~0.1 for β =4.2%
  Neoclassical effects reduce it to effectively < 5% at full β
- Time-dependent startup modeling in progress

Island removal method

- Modify island widths by adjusting resonant Fourier components of plasma boundary shape
- Calculate coupling between plasma boundary shape and island widths using PIES
- Invert coupling matrix to find shape modification to remove islands
- Tested on old configuration: major islands widths reduced a factor of 2 by adjusting two boundary coefficients by ~1.4 mm
- Analysis underway on new configuration

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…

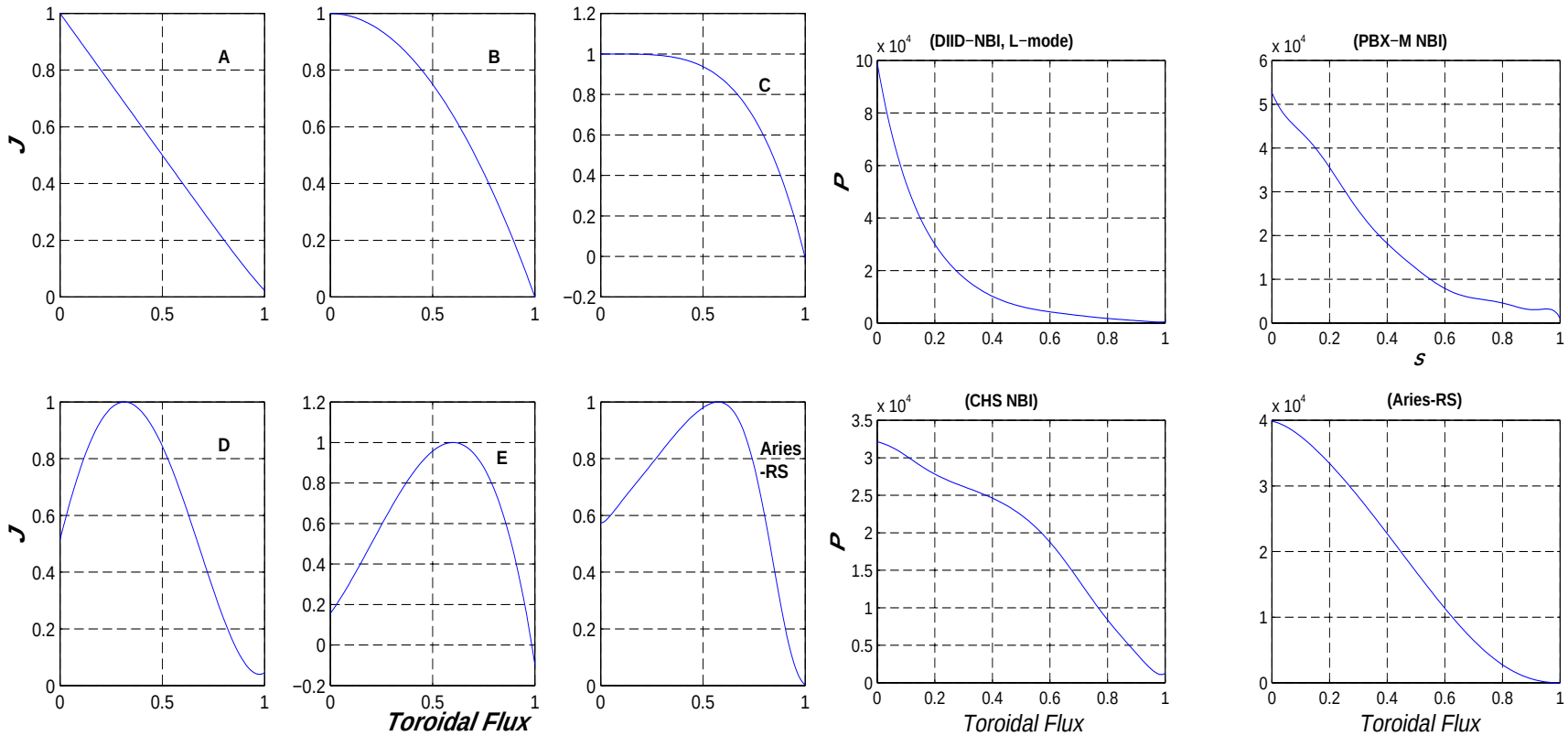
Flexibility and Robustness Studies

- Robustness
  - Vary profiles for fixed total current and b
  - Vary total current and b for fixed profiles

- Flexibility
  - Vary coil currents to change external-iota
    for fixed current and beta while optimizing quasi-symmetry
    (e.g. for transport and stability studies,
    or avoiding resonances)

- Initial Results indicate good robustness and flexibility

Plasma Profiles for Robustness Studies

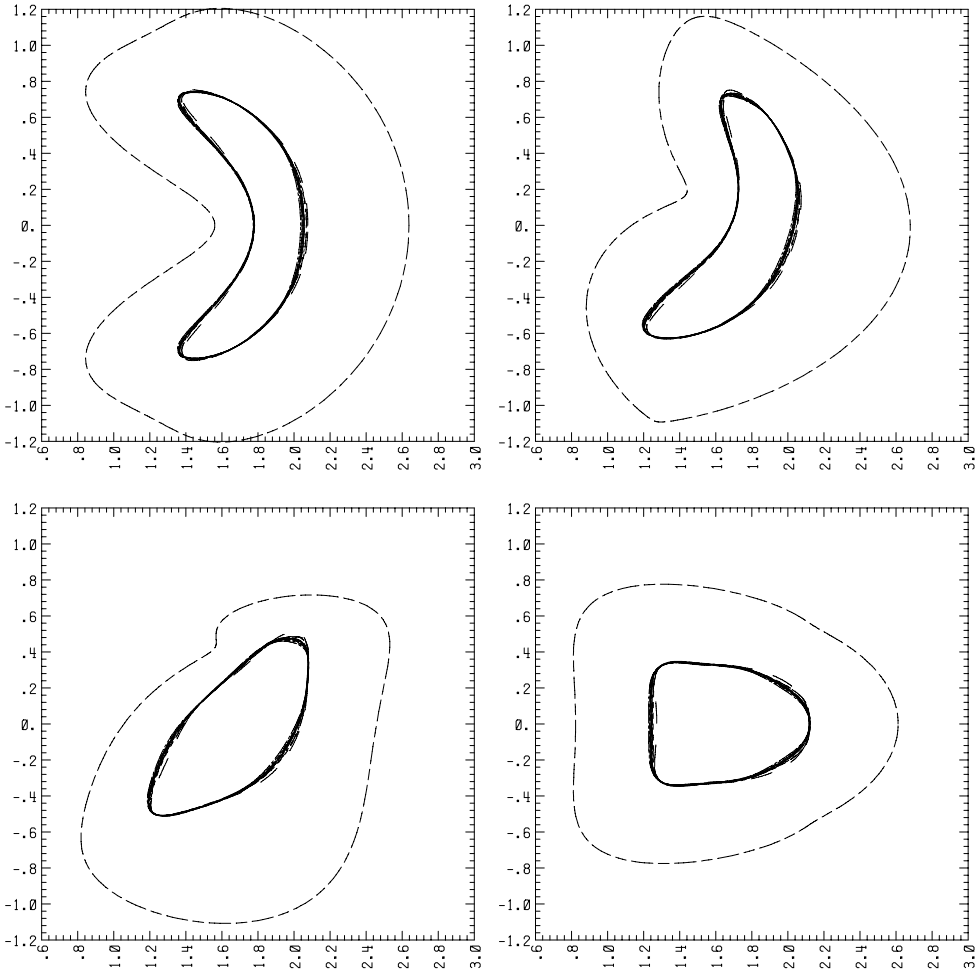


current

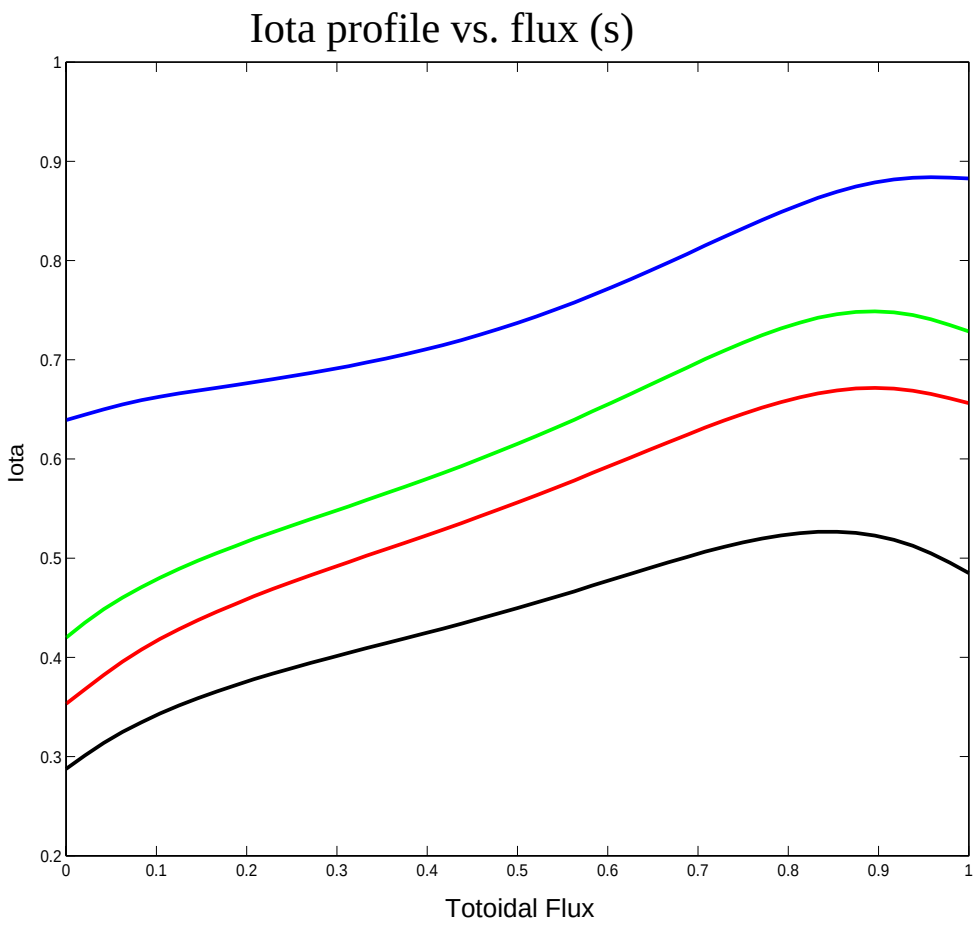
pressure

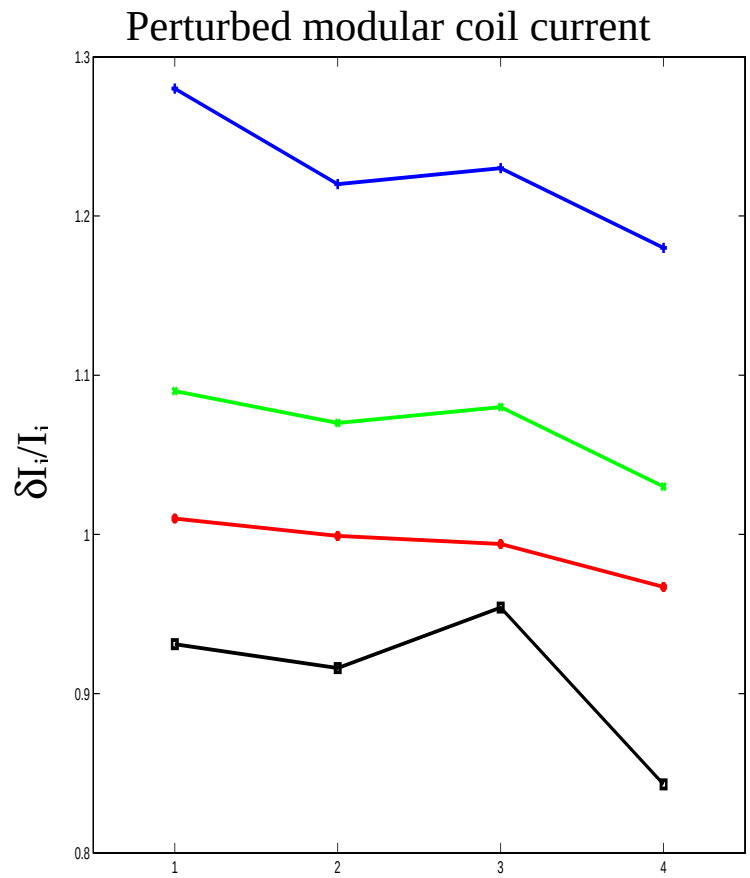
Robustness Reconstructions

- I_P = 150 kA, β = 4%
- all combination of profiles
- Modular coil currents held fixed, PF currents varied
- Being used to characterize variation of physics characteristics vs profiles



Wide Range of Iota Available



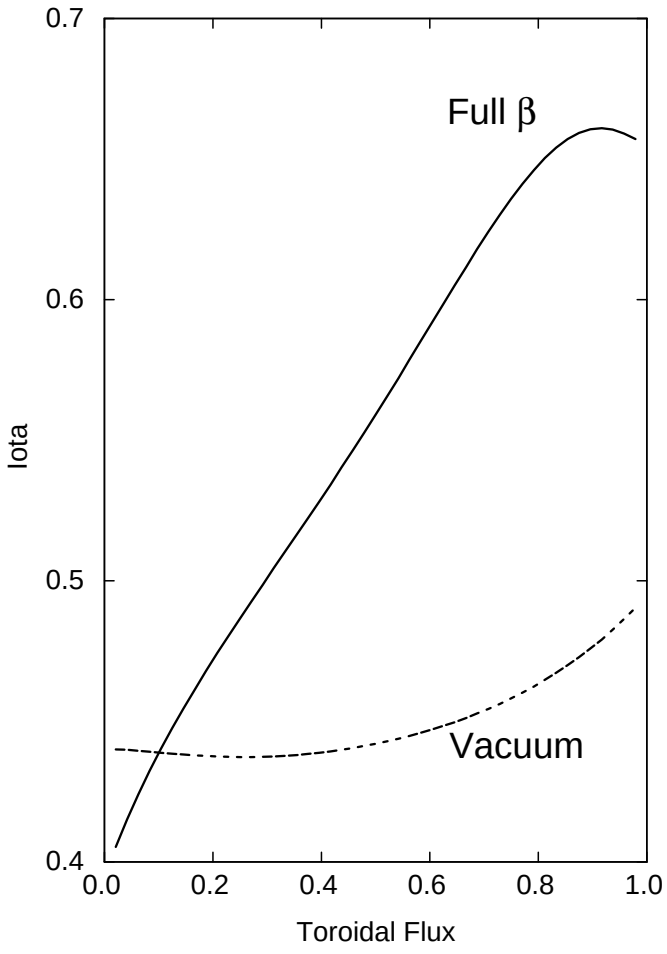


I_P = 150kA, β ~ 1%

- Can avoid edge iota = ½ resonance

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 indicate this can be avoided



Preparations for Physics Validation Review

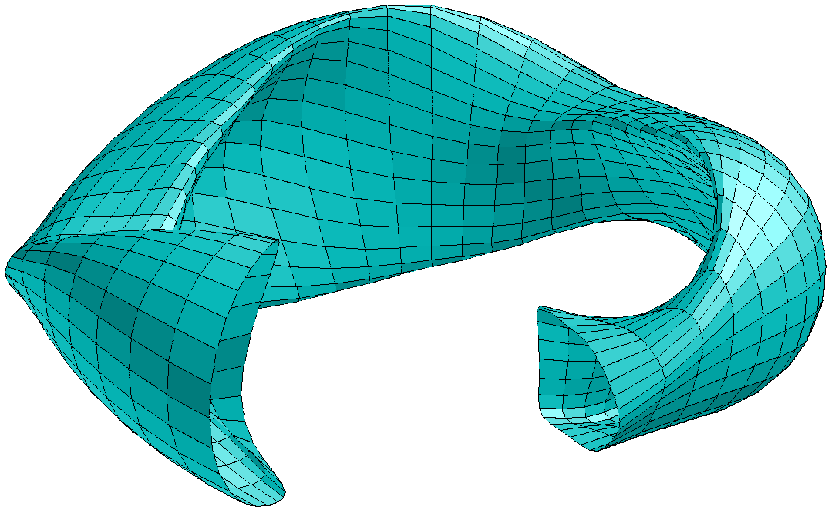
- Remove remaining islands in configurations
  – Check effect on physics and coils

- Free-boundary PIES reconstruction from coils
  – Flux surface quality and robustness

- Flexibility & robustness assessment of coil designs
  – Ability to support our physics goals and program
  – Demonstration discharge scenarios

- Develop divertor/limiter physics design

– Decide between different coil topologies

Conclusions

- Exciting new configuration has been identified
  - 3 period: higher iota, low coil current density
- All of the issues with the old configuration have been addressed
  - Flux-surface quality, coil currents, transport optimization
- Analyzing coil designs, free-boundary flux-surface quality, and flexibility and robustness to prepare for PVR.