PPPL Theory Stellarator Research

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PPPL Theory Review
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PPPL Theory Stellarator Research

- Domestic and international collaboration on design and analysis of stellarator experiments.
- The National Compact Stellarator Experiment (NCSX).

  Development of Attractive NCSX Configuration has Required Key Innovations and Tools Developed by PPPL Theory Group.
- Plans.

PPPL Theory Collaborations on Design and Analysis of Domestic and International Stellarator Experiments

- Collaborative design work on proposed domestic concept exploration experiments: QOS at Oak Ridge, CTH at Auburn.
- Collaboration on LHD:
  - MHD stability analysis.
  - Kinetic stability analysis with FULL code.
  - Magnetic island studies with PIES code.
- Collaborations with other stellarator groups focus on development and applications of PIES code: W7X (Germany), Heliotron-J (Kyoto), TJ-II (Spain), H-1 (Australia).
- NCSX design.

The NCSX Design Team

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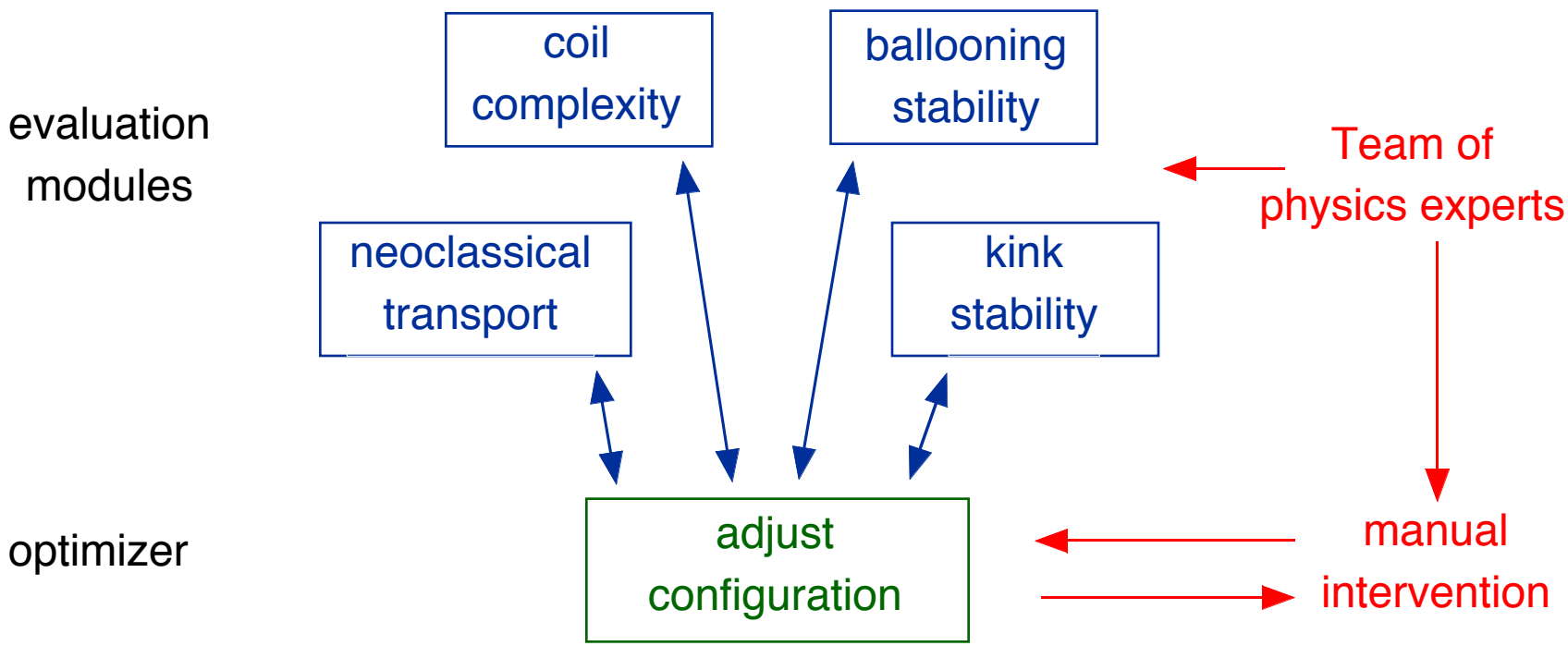
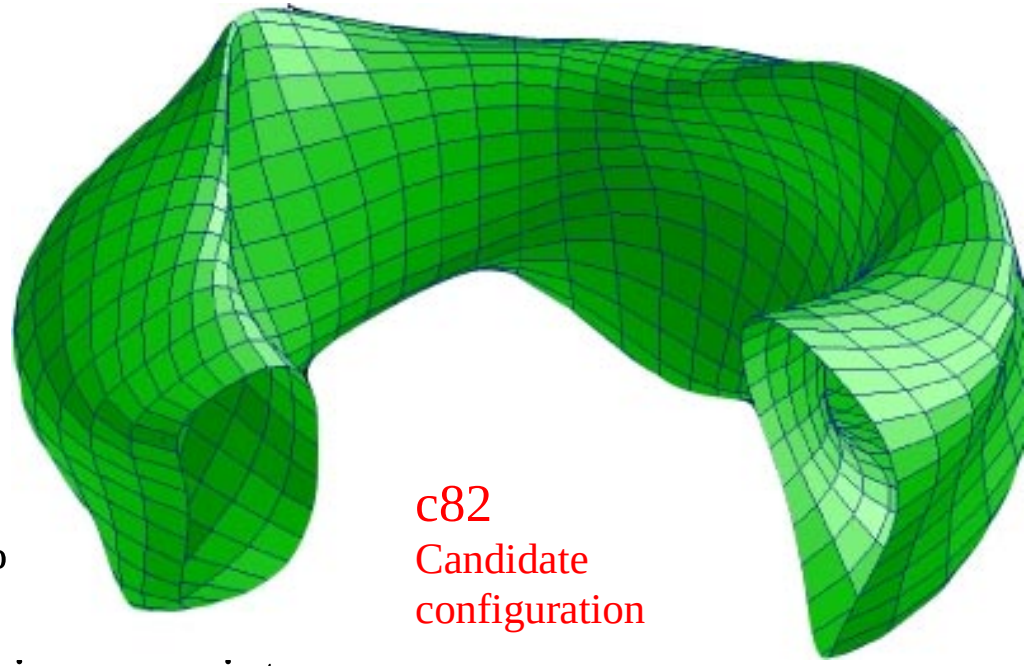
Plasma Configuration Design



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

- 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%



- Bootstrap-like current profile, increases iota.

- Stellarator shear ($dq/dr < 0$), for neoclassical island stabilization.

New configurations being examined.

Configuration looks like hybrid between advanced-tokamak and drift-optimized stellarator.

Development of Attractive NCSX Configuration has Required Key Innovations and Tools Developed by PPPL Theory Group

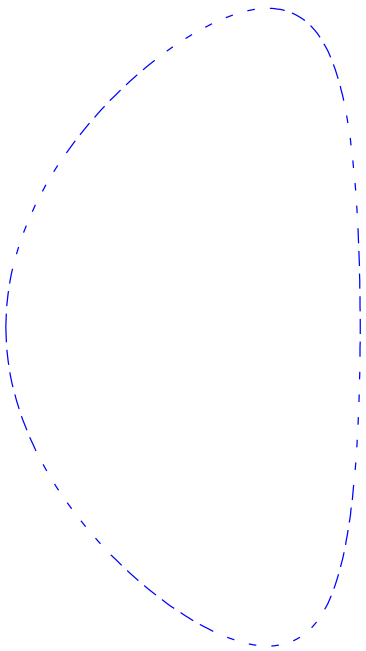
- Strong axisymmetric shaping (a unique feature relative to other stellarators) for ballooning stability.
- Use of externally generated shear and 3D shaping to stabilize kink and vertical modes.
- GTC gyrokinetic code to evaluate neoclassical confinement.
- Contributions to coil design algorithms.
- Evaluation of flux surface integrity with PIES code.

Ballooning Stability

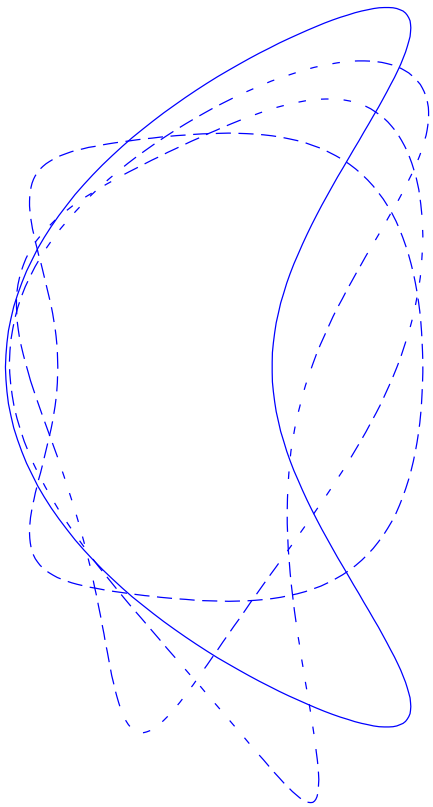
Ballooning β limit an issue for many quasi-symmetric designs, particularly as aspect ratio reduced.

Ballooning modes caused disruptions in TFTR.

Our solution: Strong axisymmetric (tokamak-like) components of shaping. A unique feature relative to other stellarators.



advanced tokamak

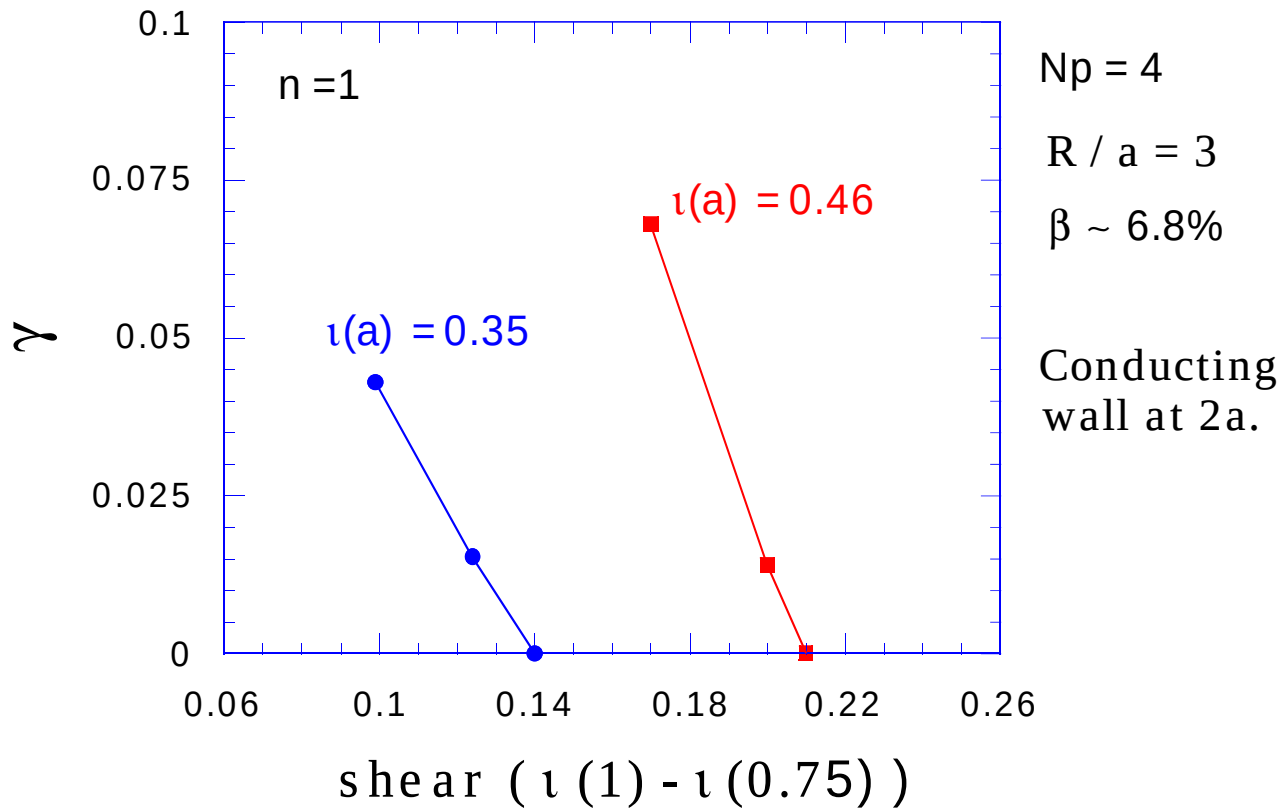


c82 stellarator configuration

Externally generated shear stabilizes external kink mode, even in absence of conducting wall.

Fu and Cooper. Calculations with Terpsichore code.

Effect of Shear

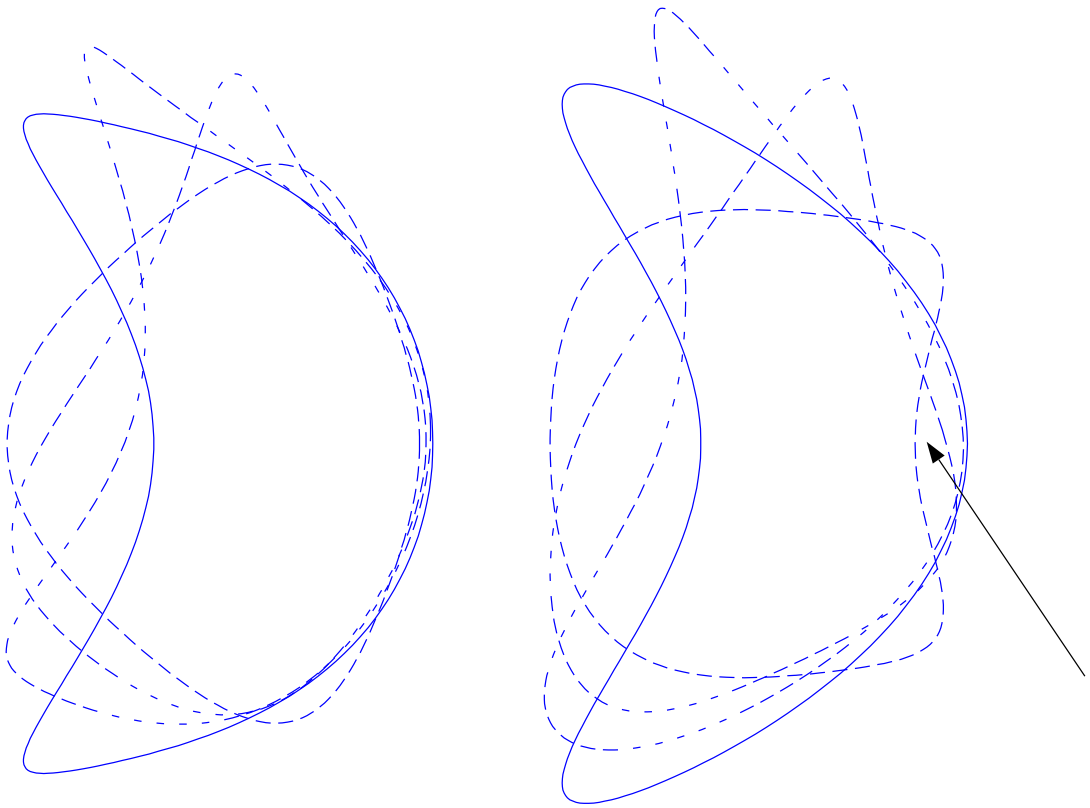


- Comparable tokamak has $\beta_c \approx 2.5\%$.
- Advanced tokamaks rely on close-fitting conducting wall to stabilize external kink.

C. Nuehrenberg and M. Redi, using CAS3D code, have verified stabilization in absence of conducting wall.

Ku, Fu, Cooper, C. Nuehrenberg, Redi

External Kink stabilized without need for wall stabilization by combination of externally generated shear and corrugation of boundary. C82 stable with reference profiles at $\beta \approx 4\%$.



c3
unstabilized

c82
stabilized

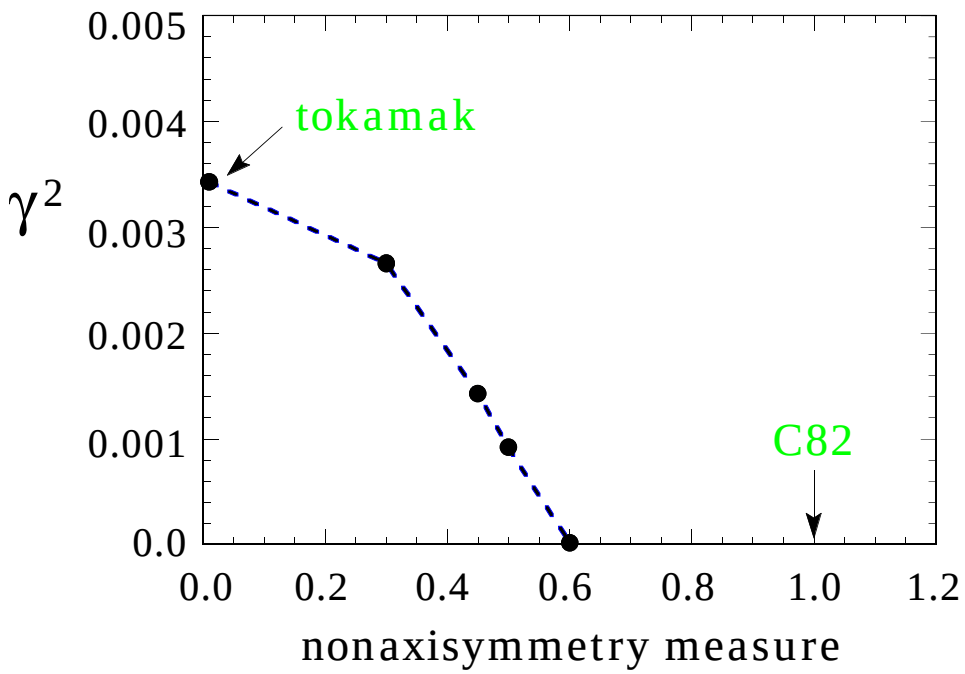
Stabilizing Corrugation with little effect on shear

Indentation controllable with outside pusher coil.

Fu, Cooper, C. Nuehrenberg, Redi

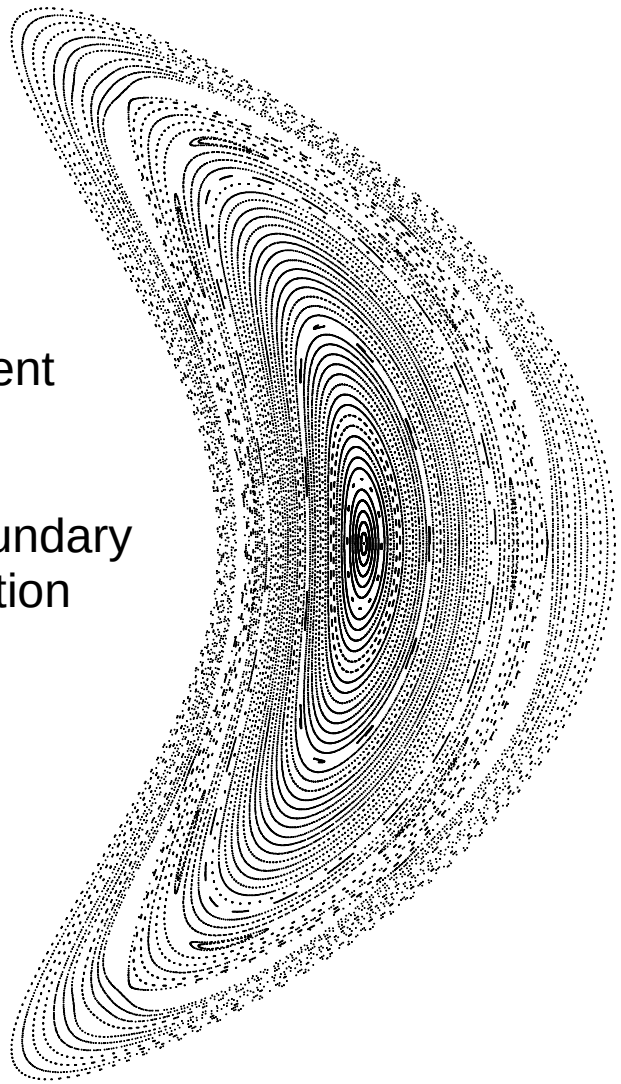
Configuration C82 is robustly stable to the vertical mode. (no conducting wall)

Vertical Stability for a Series of Configurations Interpolated Between C82 and a Tokamak



Can further improve design by going to higher elongation.

The PIES Code



C82
full current
$\beta = 0$

fixed boundary
calculation

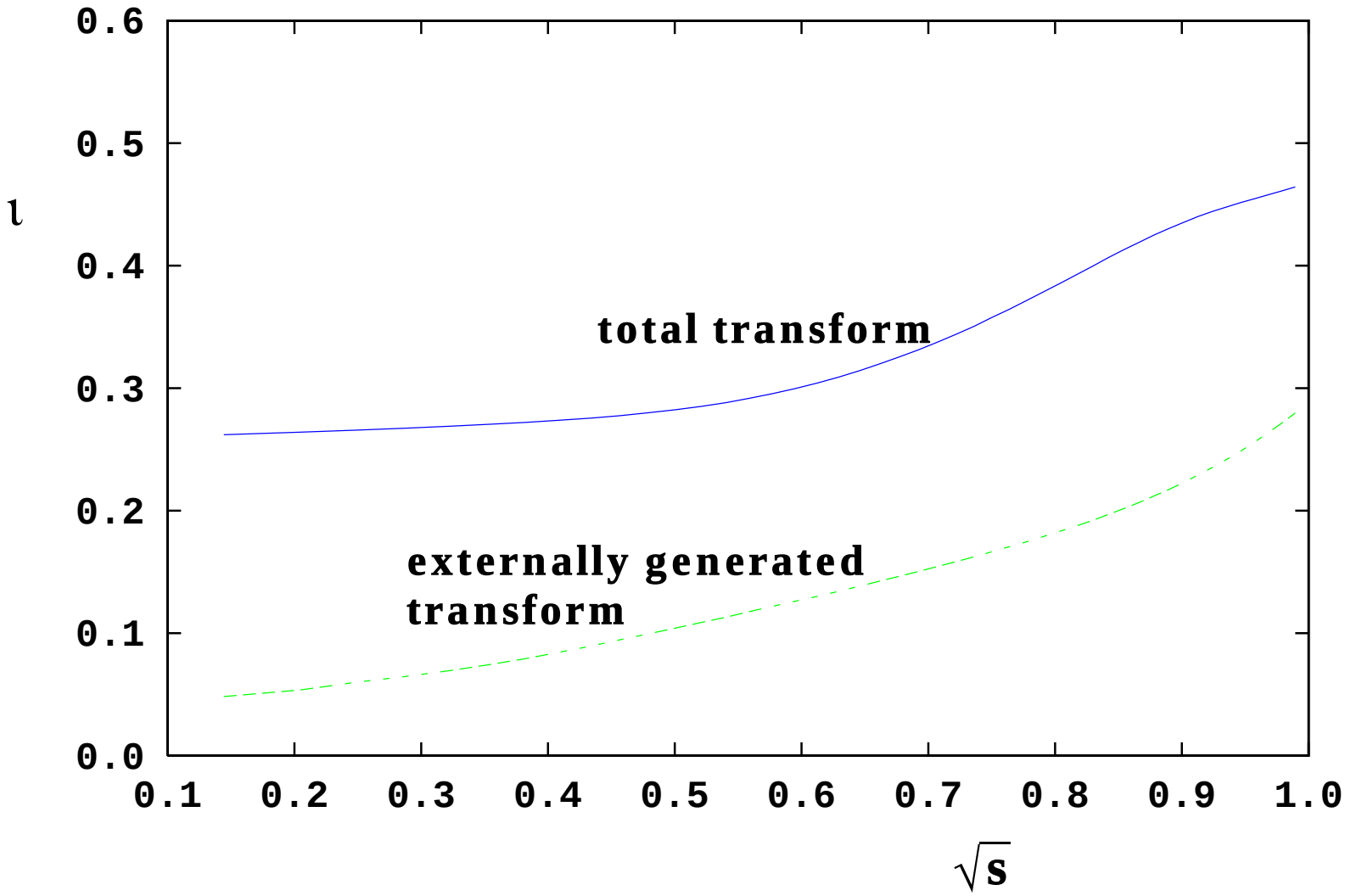
- Field line trajectories can define nested flux surfaces, or islands, or can be chaotic.

- Flux surfaces broken by pressure-driven currents, giving β limit.

- PIES: self-consistent equilibrium for 3D field. (Also addressed by HINT code in Japan.)

- PIES free-boundary capability unique. Developed in collaboration with Germans.

- Implementing bootstrap (neoclassical) effect.



Sign of ι (relative to direction of bootstrap current) gives neoclassical effect that opposes magnetic island formation.

Recent Design Progress

- Higher elongation ($\kappa = 2.5$), $R/\langle a \rangle = 4$.
  - Neoclassical thermal confinement time about 50% higher.
  - β limit raised to 5.75%
- Configurations with vacuum magnetic well (advocated by Garabedian), $R/\langle a \rangle = 4.75$, and larger externally generated transform.
  - Simpler coils.
  - Neoclassical thermal confinement time 50% higher.
  - Energetic particle losses reduced 30%.
  - ι at edge raised to .7 (from .5).
  - Larger fraction of transform generated externally (80% rather than 40%.)
  - No seed current required. (Current entirely bootstrap driven.)

Stellarator Theory Plans

- Continued near term focus on NCSX.
  - Complete implementation of bootstrap current model in PIES.
  - Select new reference configuration from improved designs.
  - Self consistent radial electric field and neoclassical flow damping in GTC.
- Reactor studies.
- Long term: Increased focus on international and domestic collaboration.
- Increased emphasis on code development and fundamental studies during NCSX construction phase:
  - GTC: Turbulent transport in stellarators.
  - PIES: Stability and plasma evolution in presence of islands.
  - M3D: Nonlinear MHD instabilities in stellarators.
  - Linear MHD instabilities: Improved understanding of 3D stabilization mechanisms.
  - Transport calculations: Generalization of $\mathbf{E}\times\mathbf{B}$ shearing rate calculations to 3D geometry.

Summary

- The PPPL theory group has been leading the plasma configuration design for the National Compact Stellarator Experiment (NCSX).
  - Key innovations and tool development by the theory group have been required to develop an attractive configuration.
  - Design process continuing, with further improvements in configurations and computational tools.
- The theory group is providing key tools and expertise to international and domestic stellarator collaborations.
  Non-NCSX collaborative work will increase when NCSX moves into an engineering design phase.

Codes and Benchmarking

The computational tools used in the design of NCSX are mature codes that have been carefully validated by their authors. We have also benchmarked these codes ourselves.

Ballooning Our main tool to calculate 3D ballooning has been a Swiss ballooning code that is part of the Terpsichore suite. We have benchmarked this against a German 3D ballooning code (part of the CAS3D suite). More recently, we are moving to the new COBRA code developed by Sanchez and Hirshman at Oak Ridge. Have benchmarked it against the Terpsichore ballooning code.

Kink Have used both Terpsichore (Swiss) and CAS3D (German), and have benchmarked them against each other. We have benchmarked both codes against PEST for tokamak external kink modes.

Neoclassical confinement. GTC (developed at Princeton) has been the main tool. Benchmarked against GC3 Monte Carlo code (also developed at Princeton) for 3D transport. Recently have been using DKES (developed by Hirshman at Oak Ridge, mod-

ified by German group at Garching) in our optimizer. We have benchmarked it against GTC.

Flux surfaces. Using PIES code (developed at Princeton). Has been benchmarked against analytical solutions for narrow islands, and against other analytical models. Benchmarked against VMEC for configurations with good surfaces. Benchmarked against linear resistive stability code for tokamak tearing mode calculations in TFTR. Presently being benchmarked against HINT (as part of LHD collaboration) and against M3D (Princeton nonlinear resistive evolution code).