Recent Advances in the Design of Quasi-Axisymmetric Stellarator Plasma Configurations

NCSX: Quasi-axisymmetric stellarator designs combine attractive features of advanced tokamaks and drift-optimized stellarators.

Recent Progress

- Two new approaches to configuration improvement explored.
  Physics properties improved.
- Good equilibrium flux surfaces incorporated as design constraint.
  Configurations with good flux surfaces identified.

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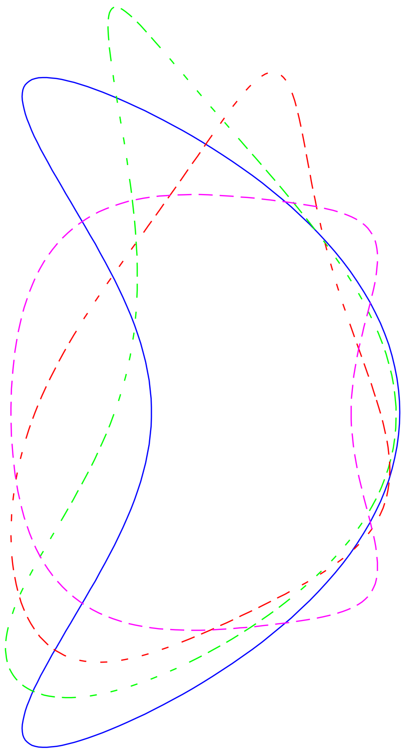
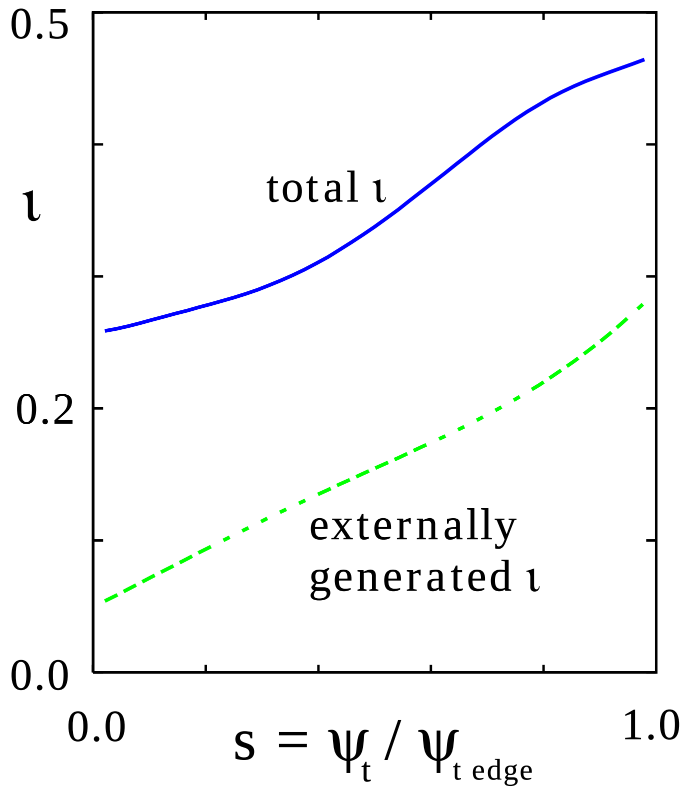
An Earlier Reference Configuration: C82





- Good drift trajectories via quasi-axisymmetry.
- Neoclassical island suppression via $\iota' > 0$.
- MHD stable with bootstrap-like j profile at $\beta = 4\%$.
  - Ballooning stability via $n = 0$ shaping.
  - External kink stabilized without need for conducting wall or feedback. (Externally generated ι' and 3D shaping.)
  - Vertical mode robustly stable without need for wall.

Approaches to Further Configuration Improvement

- Two strategies pursued:
  - Increase ι (poloidal flux) for improved neoclassical confinement, and improve magnetic well properties.
  - Increase axisymmetric elongation to further improve MHD stability.
- Previously precluded by constraint that configuration fit in PBX coils.
- Fueled by code development.
  - VMEC modifications (S. Hirshman) provide:
    - robust convergence over broader range of configurations;
    - improved handling of large numbers of Fourier modes;
    - improved speed.
  - New fast ballooning code (Sanchez and Hirshman) incorporated in automated optimizer.

Increased ι and Improved Magnetic Well

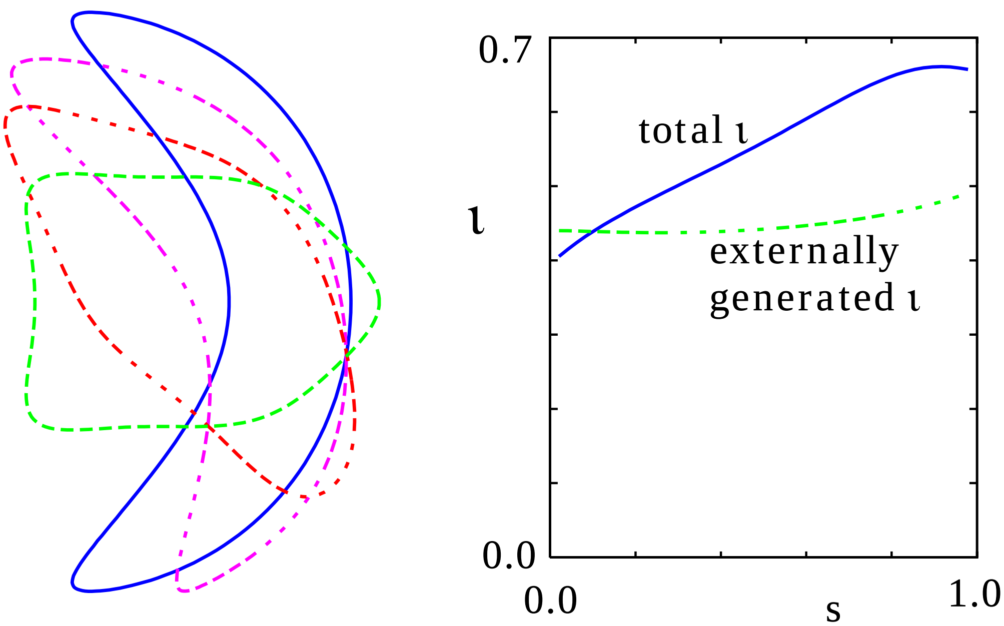
- Increased externally generated ι desired to improve flexibility of experiment.

- Increased $\iota(0)$ and improved vacuum well synergistically lead to a different class of quasi-axisymmetric configurations (Ku):

  – Increasing $\iota(0)$ aids in improving vacuum magnetic well properties.

  – Associated changes in local shear improve stability of external kink (Fu, IAEA).

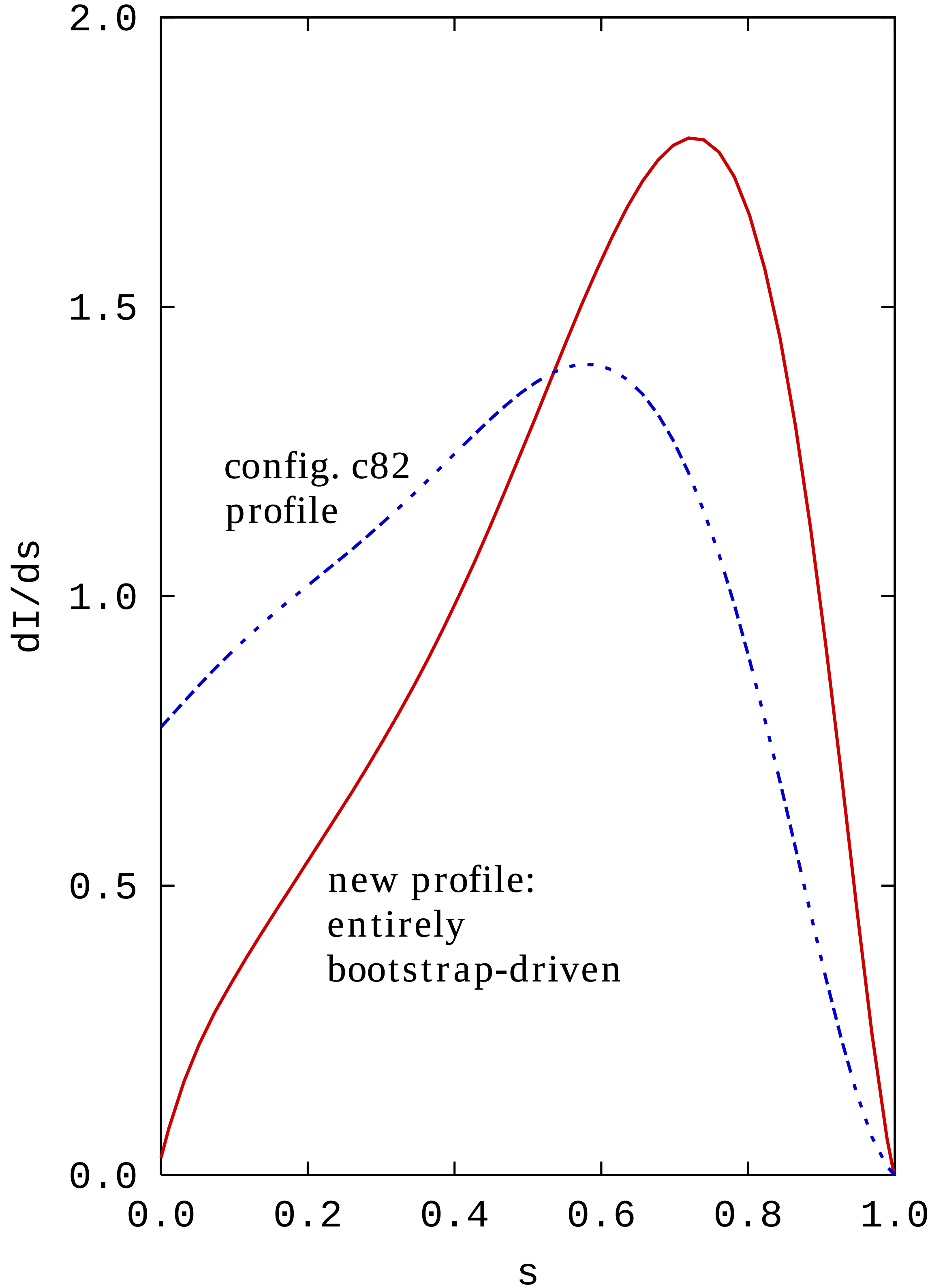
  – Less shear required for kink stabilization, allows higher $\iota(0)$.



Configuration 383

Increasing ι(0) eliminates need for seed current on axis.

Pressure also broadened somewhat from Aries profile.



Configuration 383 Has Improved Properties Relative to C82

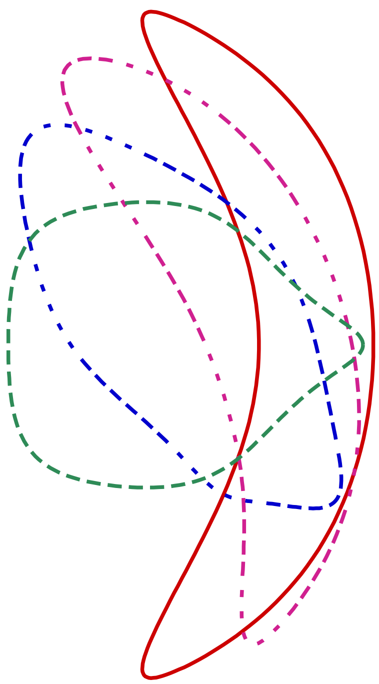
	C82	383
No. Periods	3	3
$R/\langle a \rangle$	3.4	4.4
R (meters)	1.46	1.73
I_p (kA) at $B = 1$ T	200	150
β	4.0%	4.1%
limiting instability	kink	ballooning
$\iota(0)$	.26	.4
$\iota(a)$	.47	.66
$\iota(0)$ vacuum	.05	.45
$\iota(a)$ vacuum	.29	.49
ion confinement (ms)	18	28
NBI loss	23%	19%
coil complexity	3.11	2.05
max coil current density ($\mathrm{kA/cm^2}$)	35.8	17.8

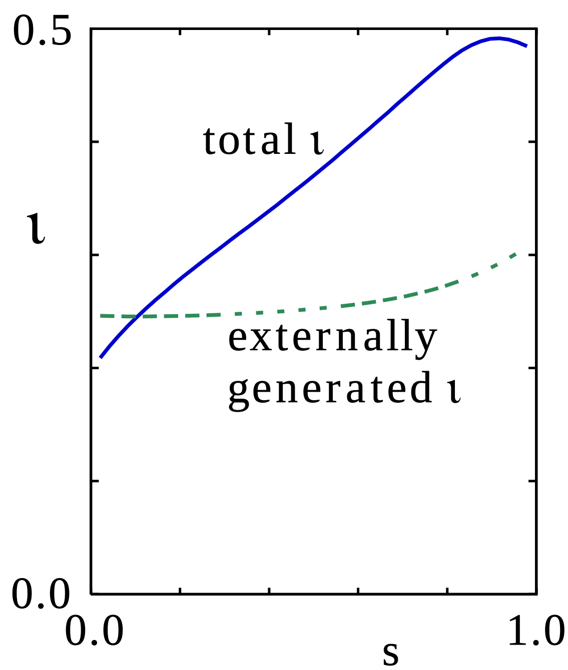
- Ion confinement calculated by GTC code with model potential $e\Phi/T_{i0} = s$.
- 383 also has improved flux surfaces (PIES).

Have studied a range of configurations of this type, with $R/\langle a\rangle \approx 3-5$, $2-4$ periods, $\iota(a) < .75$.

Configuration 2121, A 2-Period Configuration

Has good physics properties but some difficulties in recovering physics properties from coils.





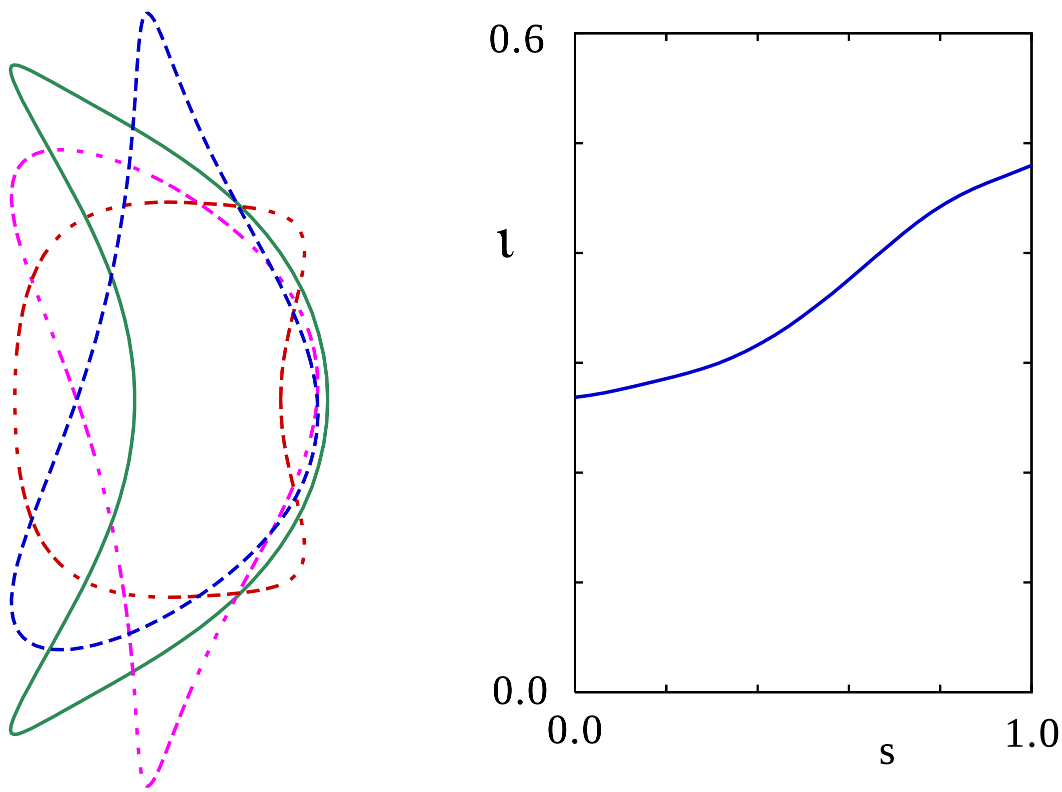
	C82	383	2121
No. Periods	3	3	2
$R/\langle a\rangle$	3.4	4.4	3.16
ion confinement (ms)	18	28	25
NBI loss	23%	19%	18%
coil complexity	3.11	2.05	1.71
max coil current density ($\mathrm{kA/cm^2}$)	35.8	17.8	16.5

An Alternative Strategy: Take advantage of robust vertical stability to increase $n = 0$ elongation.

- Increasing elongation improves stability to ballooning and kink.

A Configuration with $\kappa = 2.45$ (vs 1.9 for c82)

(Kessel)



Configuration 3k245

Equilibrium Flux Surfaces are an Issue for Stellarators (Monticello et al, HP1.027)

- 3D equilibrium fields in general have magnetic islands and regions of chaotic field line trajectories.

- Stellarators generally designed to have good vacuum flux surfaces.
  - Not adequate when current produces substantial ι.
  - Pressure-driven currents can break surfaces.

- VMEC equilibrium code: Magnetic field representation assumes good surfaces.

- PIES code: Solves 3D equilibrium equation using general representation of magnetic field.

3k245 Has Good MHD Stability but Poor Flux Surfaces

	C82	383	3k245
No. Periods	3	3	3
$R/\langle a \rangle$	3.4	4.4	3.0
β	4.0%	4.1%	5.5%*
ion confinement (ms)	18	28	18
NBI loss	23%	19%	27%
coil complexity	3.11	2.05	2.79
max coil current density ($\mathrm{kA/cm^2}$)	35.8	17.8	21.

*Stable at $\beta = 7\%$ after reoptimization.

The PIES Code

- General representation of field greatly slows algorithm relative to VMEC.
  Use VMEC solution to initialize PIES.

- Initial step:

$$\mathbf{j}_\perp = \mathbf{B}_{\text{vmec}} \times \nabla p / B^2_{\text{vmec}},$$

$$\nabla \cdot \mathbf{j}_\| = -\nabla \cdot \mathbf{j}_\perp,$$

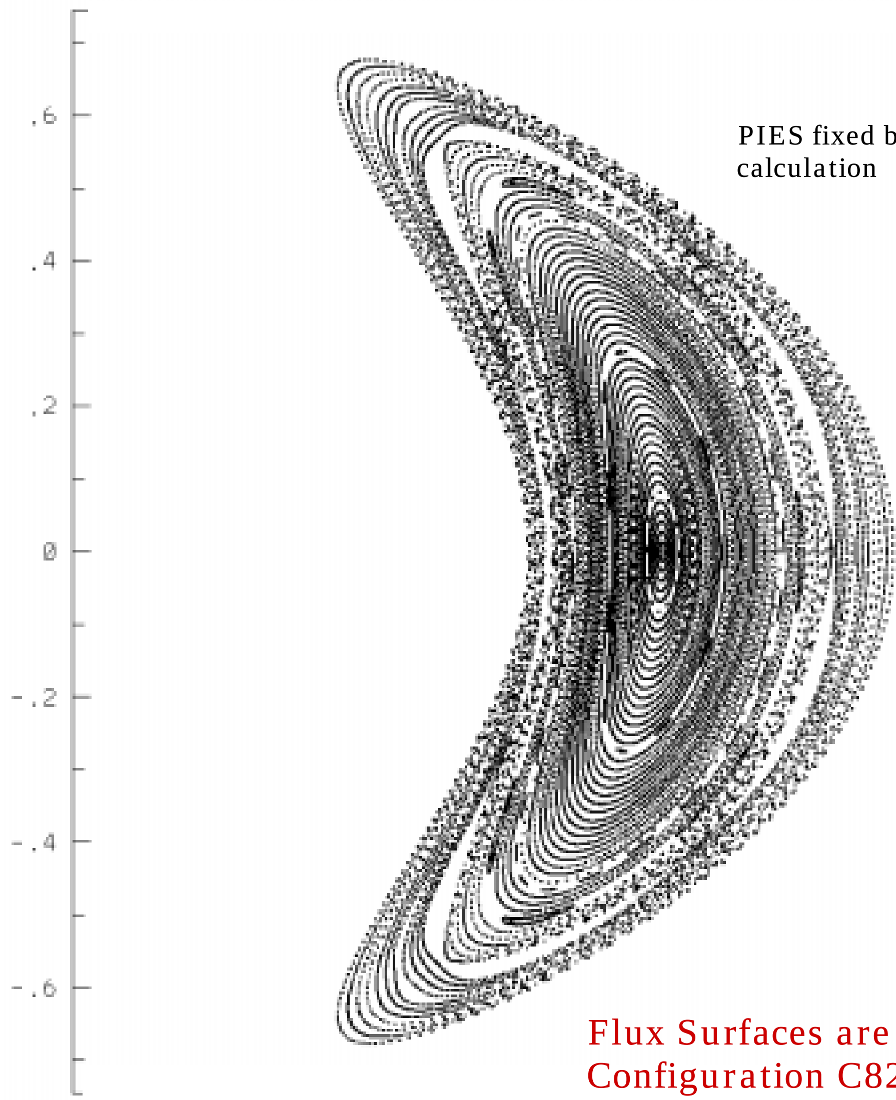
$$\nabla \times \mathbf{B} = \mathbf{j}.$$

  Updated $\mathbf{B}$ has islands.
  Iterate to convergence with underrelaxation scheme.

- PIES modifications in past year have speeded up code over order of magnitude for typical numbers of Fourier modes, more for larger numbers of modes. (Monticello, Reiman, Jun, Pletzer)

  – Stored matrix inverses for Ampere solve.
  – Conversion to spline representation for field line following.
  – Modification of underrelaxation scheme to improve coupling to VMEC.

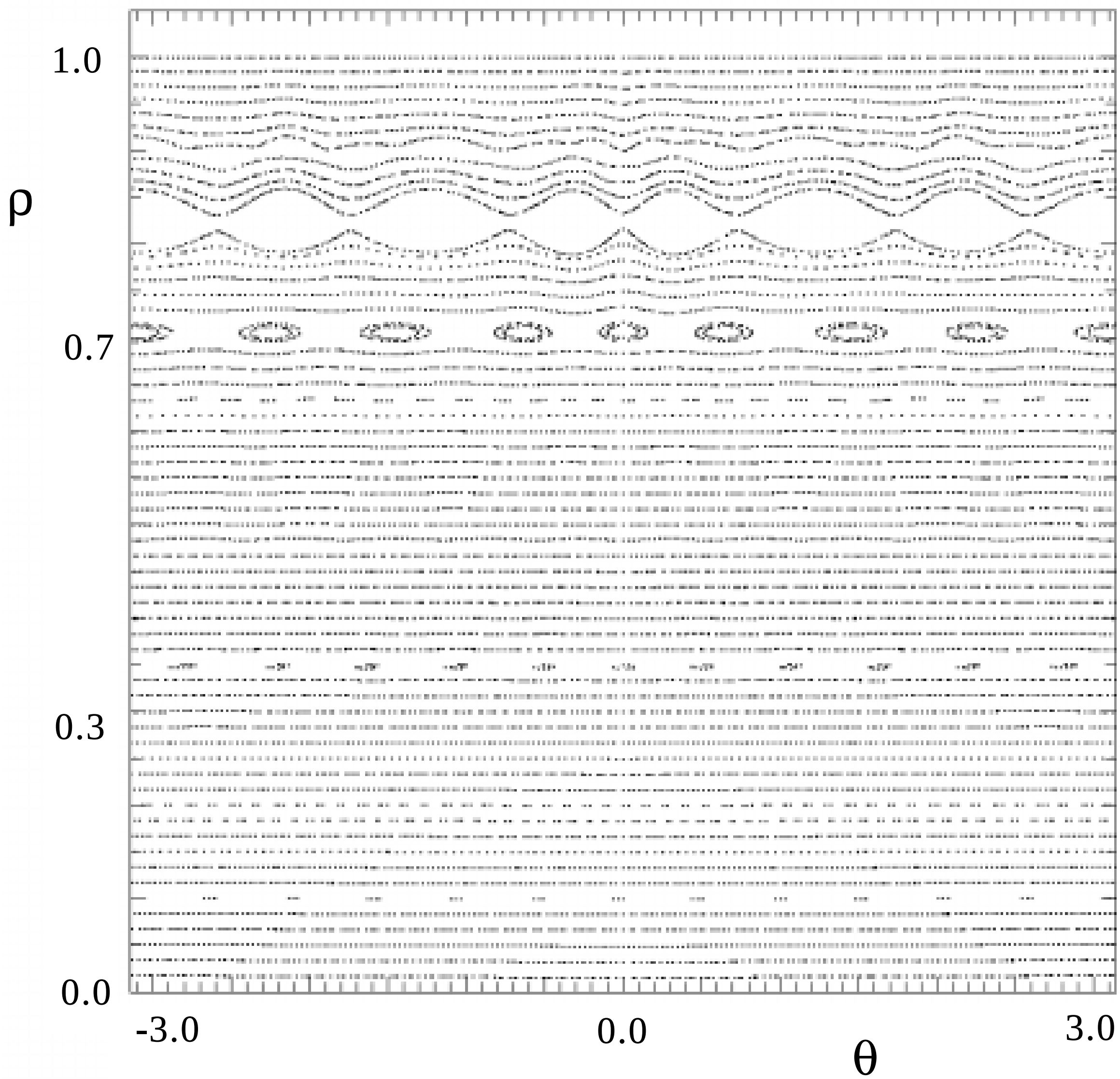
  Has allowed routine evaluation of candidate configurations and higher resolution studies.



Flux Surfaces are ok for
Configuration C82 at $\beta = 0$.

We find it helpful to look at Poincare plots in polar (ρ,θ) coordinates.

- ρ constant on VMEC flux surfaces. Measures distance from magnetic axis along θ = 0, ϕ = 0 line.
- θ is VMEC angular coordinate.
- Poincare plot gives straight lines when PIES and VMEC coincide.

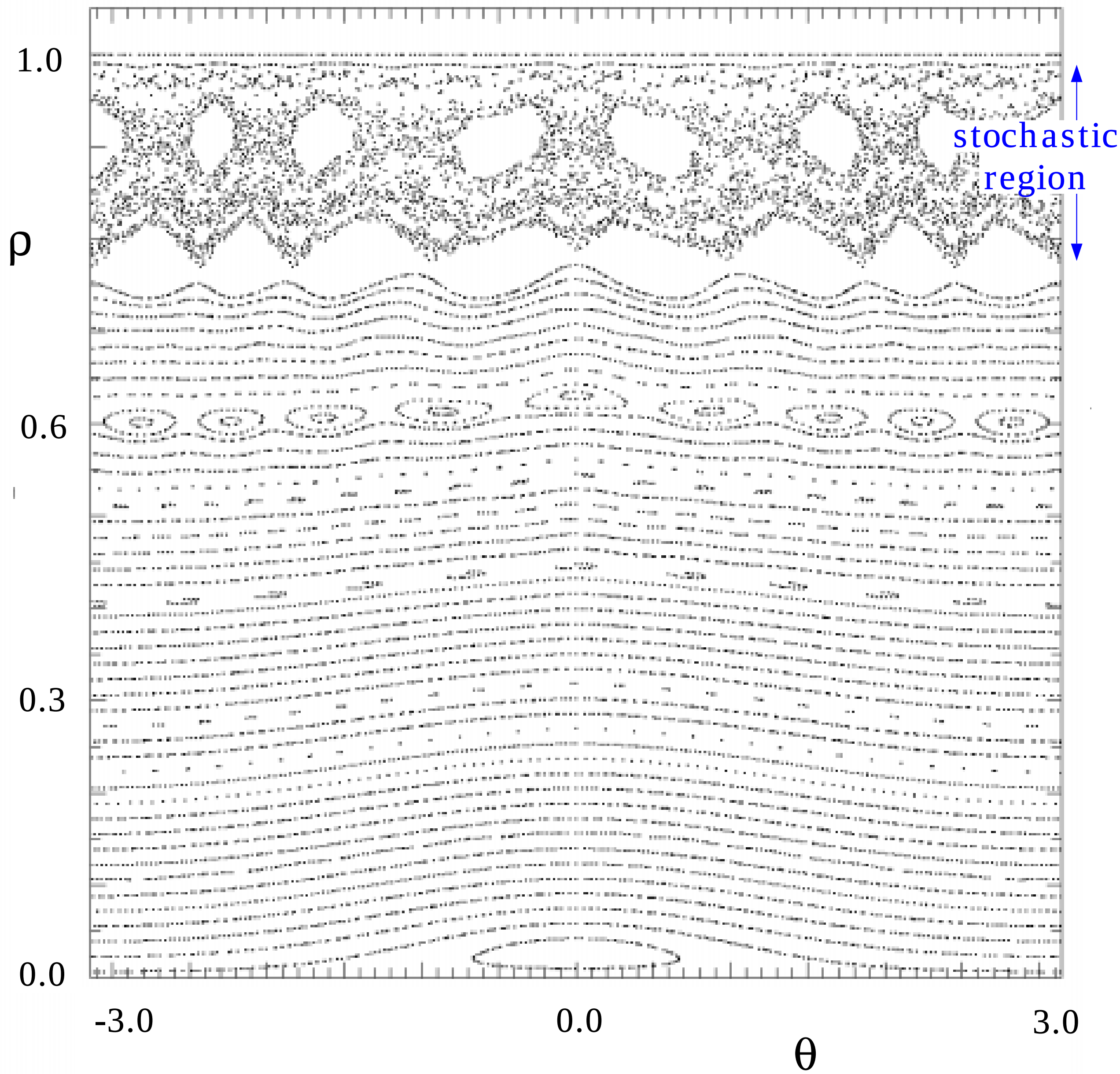


fixed boundary calculation

C82, β = 0, full current, replotted

total island width ≈ 10%

C82 (Previous Configuration), β = 3%



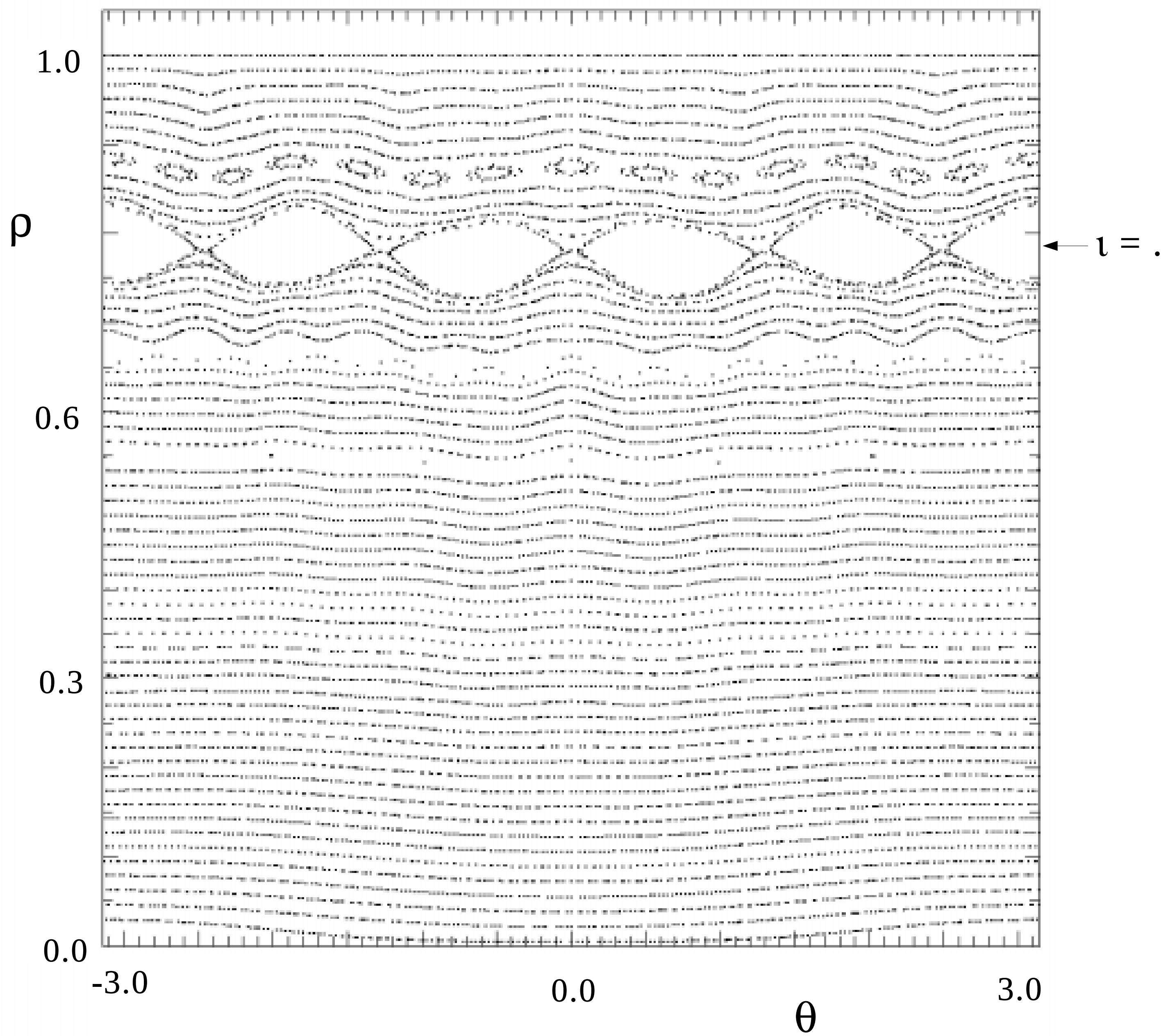
fixed boundary calculation.

Substantial fraction of flux surfaces lost.

Calculation does not include neoclassical effects, predicted to suppress islands.

Configuration 383 has greatly improved surfaces.

β = 4.2%, full current. fixed boundary calculation.

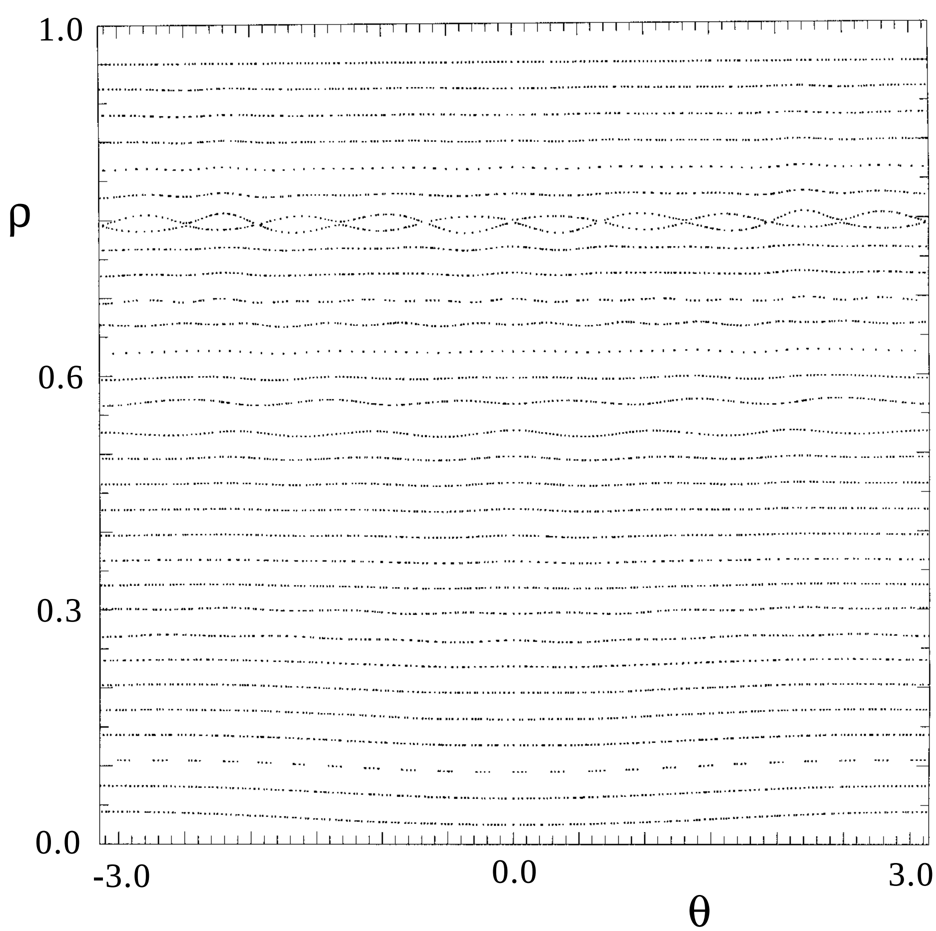


- total island width ≈ 15% (10% regarded as acceptable.)
- Calculation does not include stabilizing neoclassical effect.
- No broad stochastic region.
  Dominated by single island chain. Can improve by modifying resonant Fourier component of boundary.

Improvement of Equilibrium Flux Surfaces

(Hudson et al, HP1.028)

- Series of PIES runs measure effect of a set of boundary perturbations. (New diagnostic in code accurately measures small changes in island width.)
- Response matrix determines desirable boundary shape to minimize island widths.
- Configuration 383: 5 boundary harmonics modified to target 9 interior resonances. Largest adjustment ≈ 4 mm.
  Quasi-axisymmetry and MHD stability preserved.



Further Assessments of Configuration 383 are Promising

- Transport assessments with self-consistent ambipolar potential indicate available power adequate to reach 4% β.

  - Assessments done with new 1D transport solver (Mikkelsen, Zarnstorff).
    Solver benchmarked against GTC Monte Carlo code in which ambipolar electric field recently incorporated (Lewandowski, Lin, Boozer).
  - Require 1.7 ISS95 to get $\beta = 4\%$ for $R = 1.75$ m, $B = 1$ T, $P = 5$ MW (high collisionality).
  - ITER-89P more optimistic than ISS95 in this regime. (dependence on elongation, etc.)
    $H_{\mathrm{ITER-89P}} = 1.1$ gives $\beta = 4\%$ at $\nu* \approx .25$. (vs 2.6 ISS95).
  - Predict reactor-like collisionality at $B = 2$ T.

- Higher externally generated transform in configuration 383 provides increased flexibility. (Hatcher et al, HP1.030)

  - Externally generated ι varied from .2 to .6 with ripple $< 2.3 \times$ original.

  - Magnetic shear varied to approximately shearless at full plasma current. (ripple $6.5 \times$ original)

- Initial startup simulations indicate reasonable coil current requirements, kink stability throughout evolution. (Lazarus et al, HP1.031)

Summary

- Two new approaches to configuration improvement explored.
- Good equilibrium flux surfaces incorporated as design objective.
- New NCSX reference configuration: 383.
  - Neoclassical confinement time $\approx 50\%$ longer.
  - Coils are simpler and have lower current density.
  - Improved flux surface quality.
- Small adjustment of boundary shape suppresses residual island chain.
- Initial studies indicate flexibility to study range of configurations.
- Preliminary studies of startup promising.