Plasma Equilibrium Flux Surface Quality

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NCSX PAC Meeting #4
Princeton
August 1, 2000

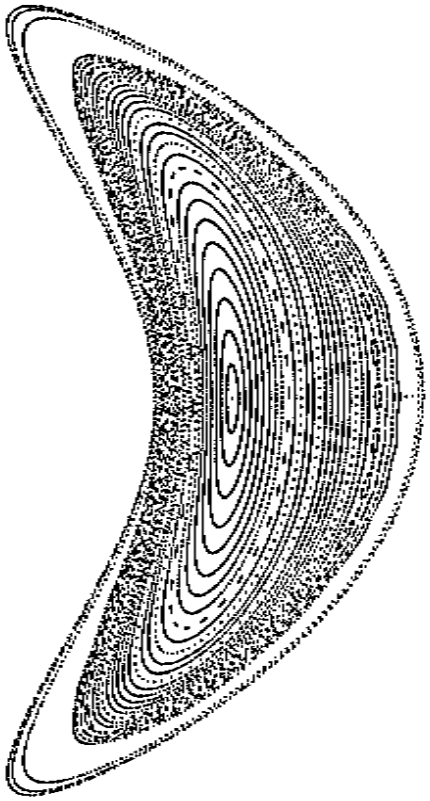
Outline

- Configuration C82: Flux surfaces are a problem at $\beta \approx 3\%$.
- Strategy we adopted for addressing the problem.
- Flux surface calculations for new 3-period configuration show improved flux surfaces.
- Robustness of flux surfaces to changes in profiles.
- Method being implemented to further improve the surfaces.
- Robustness of stability to changes in profiles.

Flux Surfaces are ok for Configuration C82 at $\beta = 0$ (vacuum and full current)

Vacuum

free bdry

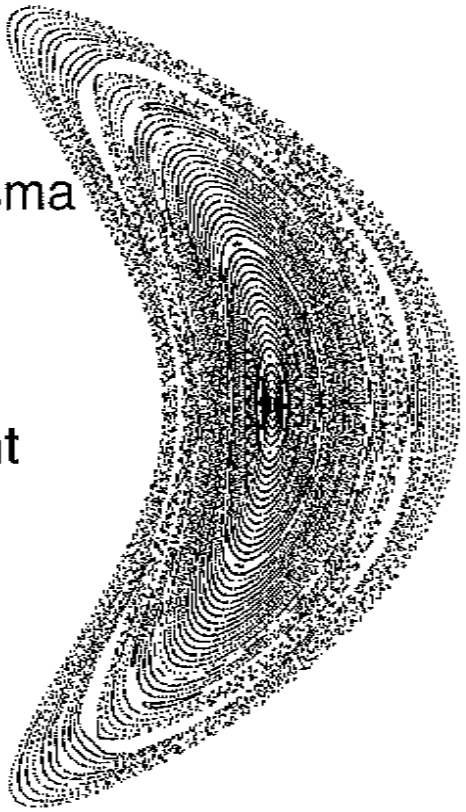


Target Plasma

$\beta = 0$

$\iota(a) = 0.47$
via current

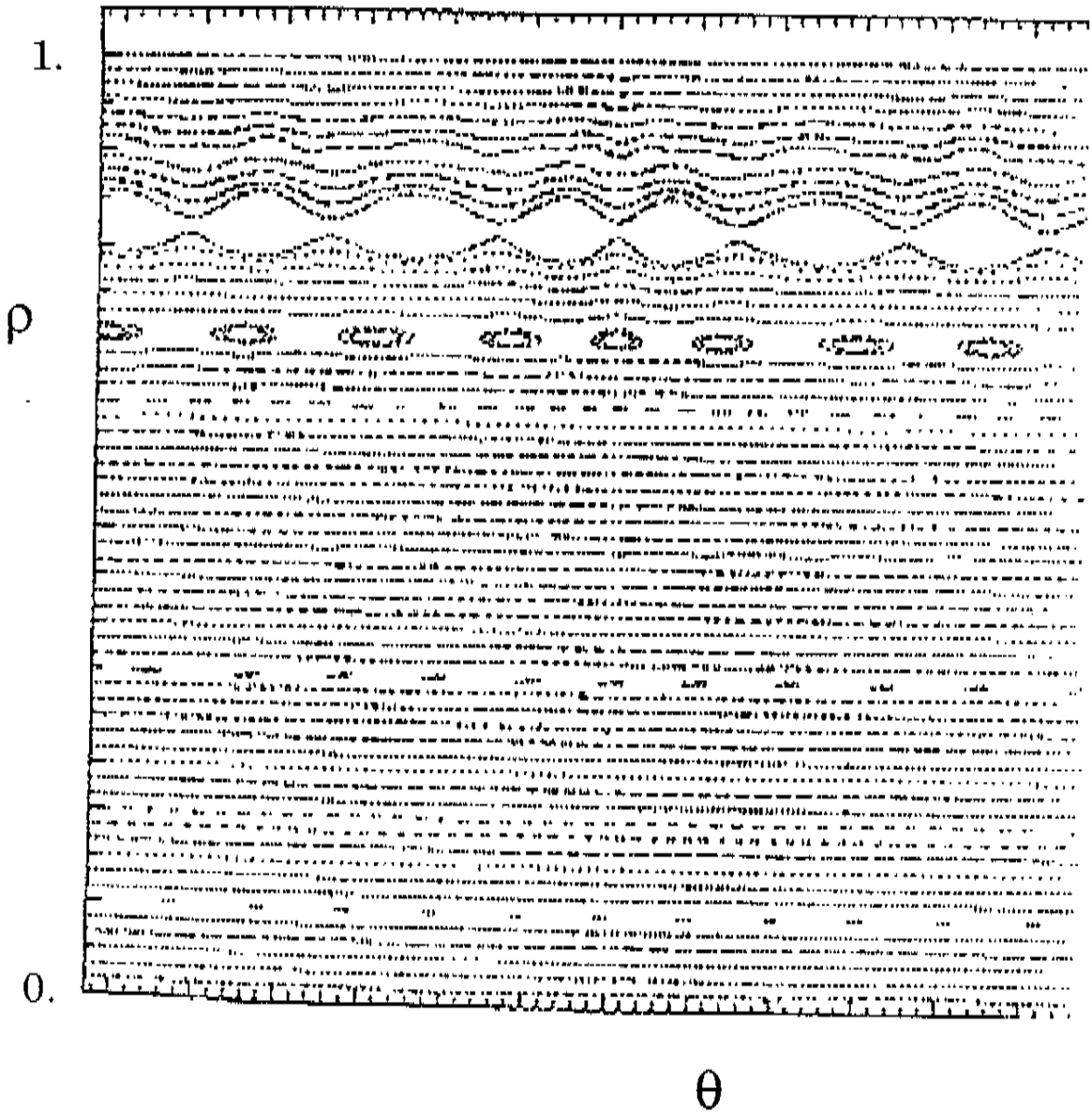
fixed bdry



PIES equilibrium calculations

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

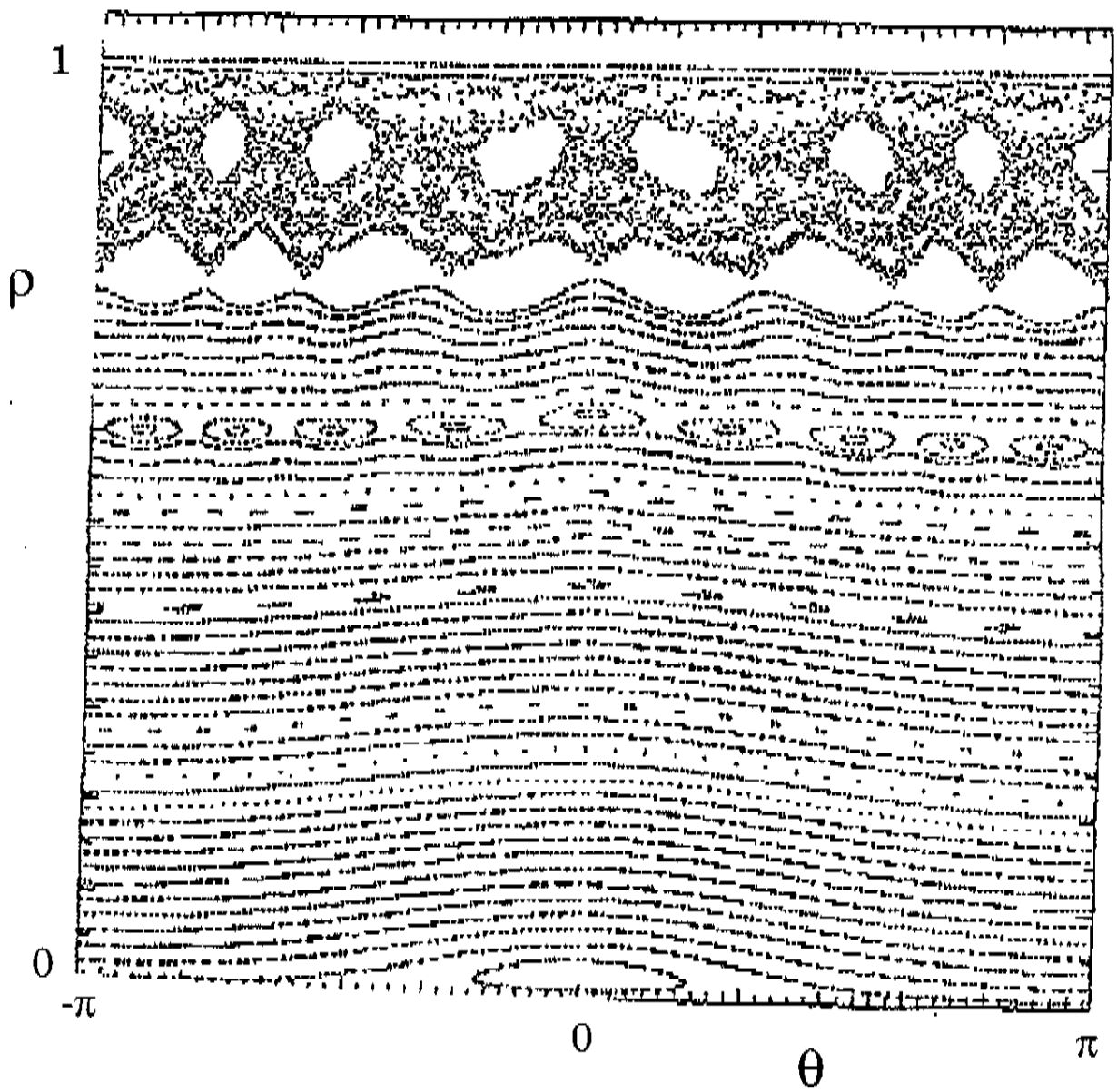
- ρ constant on VMEC flux surfaces. Measures distance from magnetic axis along $\theta = 0$, $\phi = 0$ line.
- θ is VMEC angular coordinate.
- Poincare plot gives straight lines when PIES and VMEC coincide.



C82, $\beta = 0$, full current, replotted

total island width ≈ 10%

C82, $\beta = 3\%$



Substantial fraction of flux surfaces lost.

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

Strategy for Addressing Flux Surface Issue

- Calculate flux surface quality for broader range of configurations. Modifications of PIES and VMEC codes have aided this.
  - Has led to configurations with improved flux surfaces.
- Adjustment of resonant Fourier components of boundary shape to further suppress low order islands.
  - Initial tests of this look promising.
- Neoclassical effect predicted to suppress islands. Being implemented in PIES.
- Develop analytic understanding of physics governing flux surface differences.

A Code Development Effort Has Helped Address the Flux Surface Issue

- VMEC and PIES codes used to calculate 3D equilibria.
  - VMEC: Magnetic field representation assumes good surfaces. Much faster than PIES. Used in optimizer.
  - PIES: General representation of magnetic field can handle islands and stochastic field lines. Used to evaluate flux surfaces outside optimization loop. Initialize with VMEC solution.
- Concerted code development effort in NCSX project has made major improvements to both PIES and VMEC.
- PIES modifications have targeted new physics, algorithm improvement and speed.
  - Improved free-boundary algorithm developed and implemented in collaboration with P. Merkel (Germany).

- Neoclassical model incorporated. Being tested and debugged.
- Improvements in speed.

- PIES speeded up over order of magnitude for typical numbers of Fourier modes, more for larger numbers of modes.

  - Stored matrix inverses for Ampere solve.
  - Conversion to spline representation for field line following.
  - Improved method for PIES initialization with VMEC solution.

  Allows us to routinely evaluate a large number of configurations, and to do higher resolution studies.

- VMEC modifications (S. Hirshman) provide:

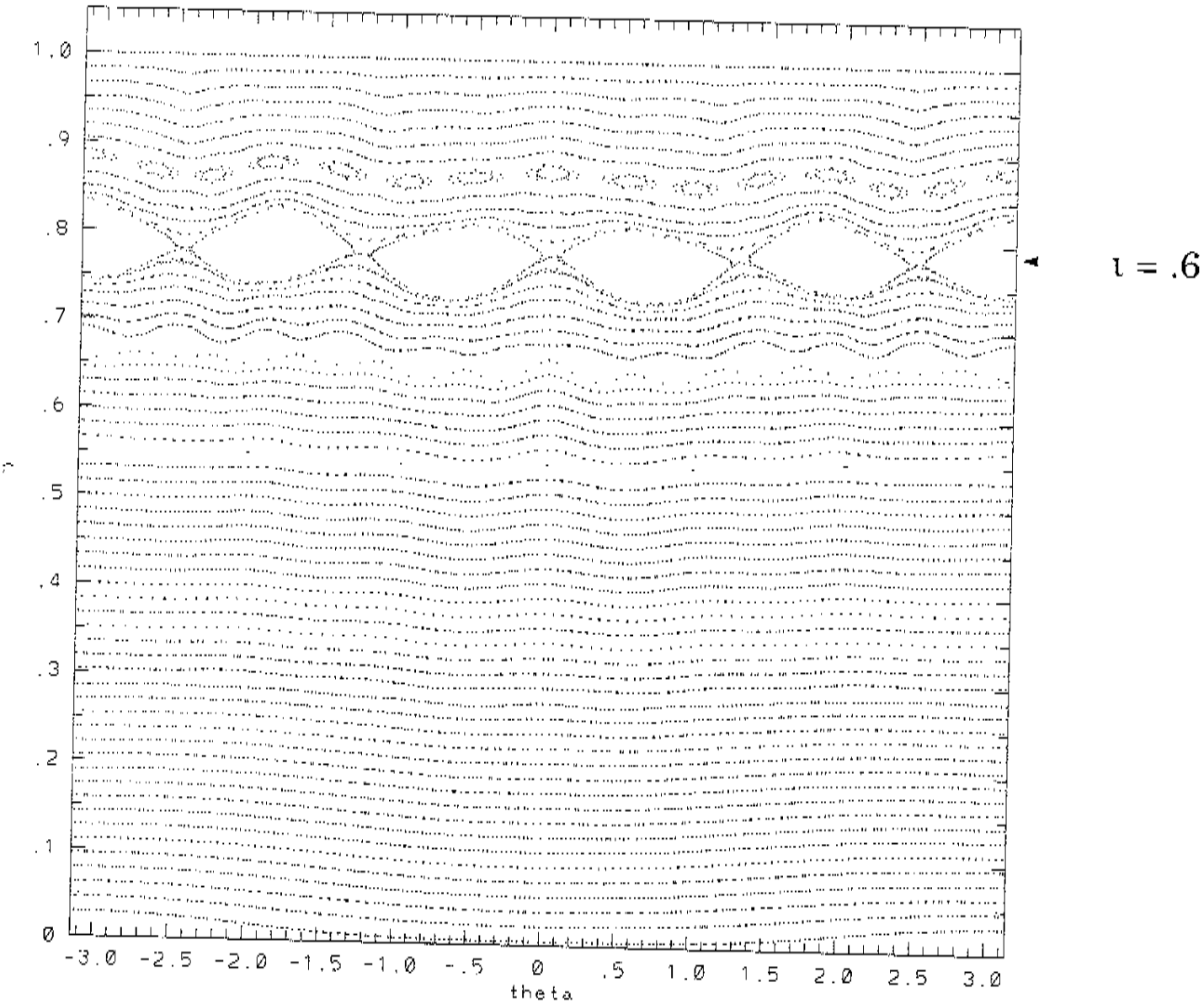
  - robust convergence over broader range of configurations;
  - improved handling of large numbers of Fourier modes;

- improved speed.

A broader range of configurations accessible for optimization and evaluation.

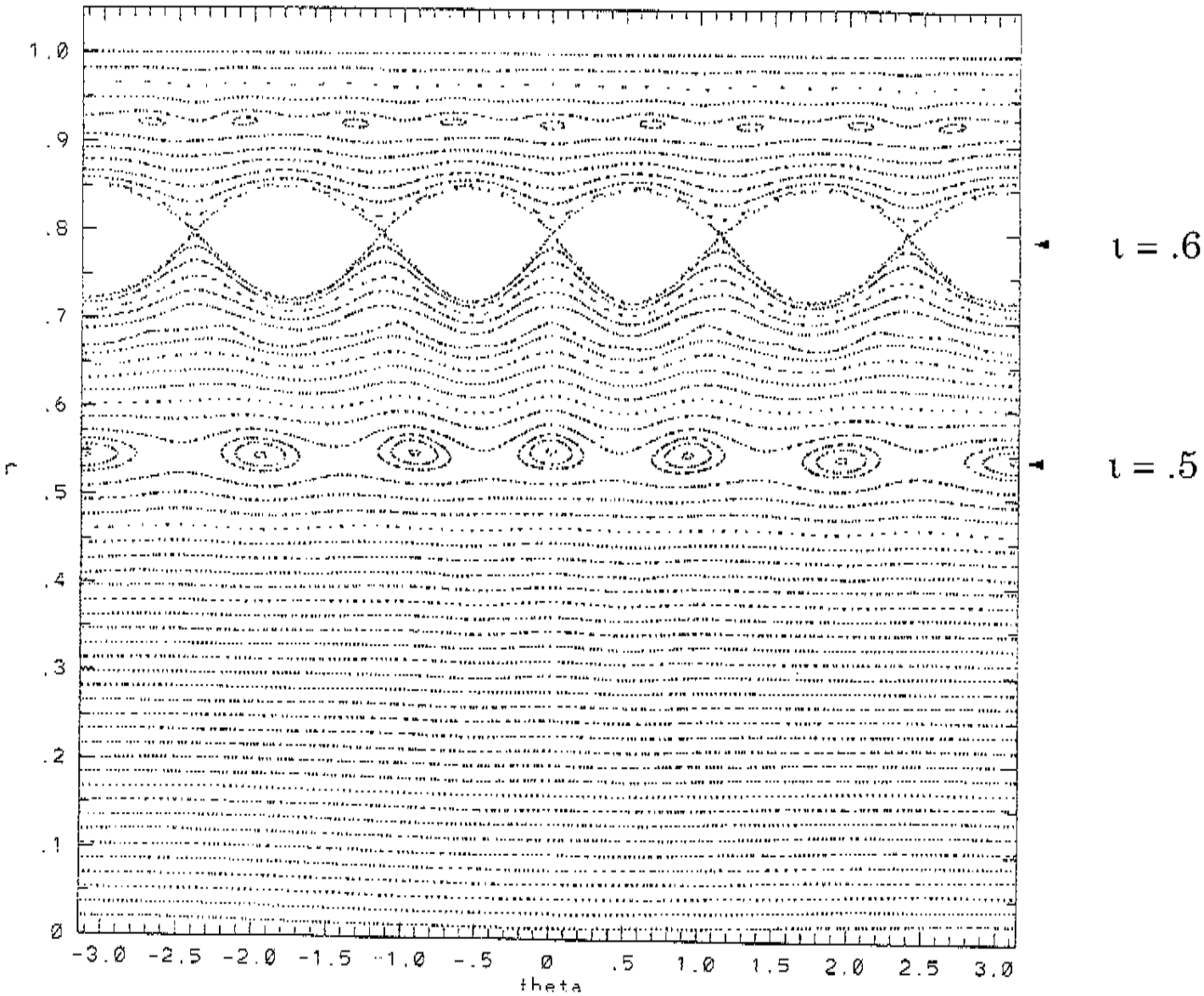
The new 3-period configuration has greatly improved surfaces.

$\beta = 4.2\%$, full current. fixed boundary calculation.



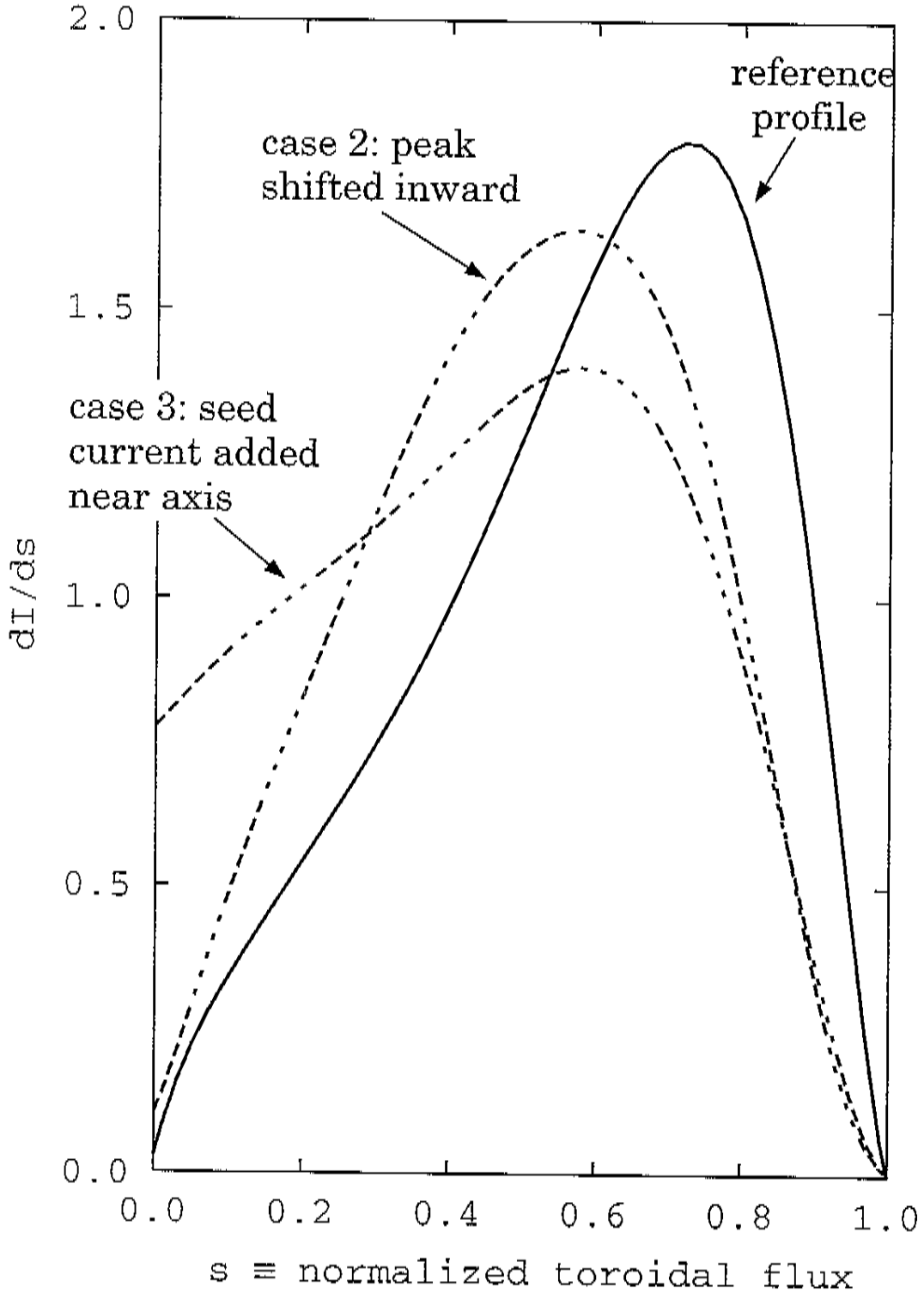
- total island width ≈ 15% (10% regarded as acceptable.)
- Calculation does not include stabilizing neoclassical effect.
- Dominated by single island chain. Can we improve by modifying resonant Fourier component of boundary?

3-Period Configuration, $\beta = 0$, full current

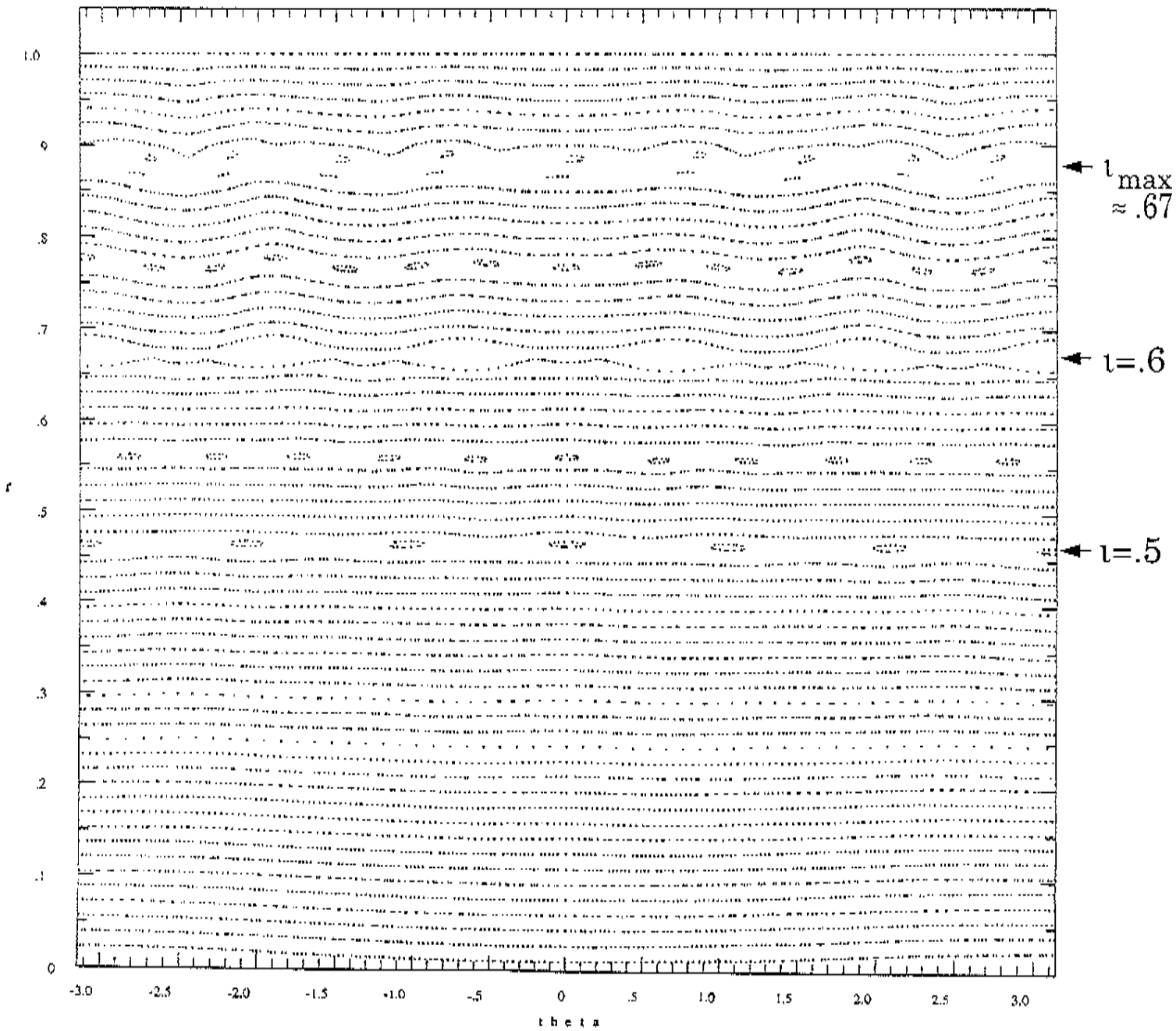


- Total island width ≈ 20%. (slightly larger than $\beta = 4\%$)
- Island produced by resonant Fourier component in shape of boundary? Can be repaired?

Current Profiles Used in Robustness Study

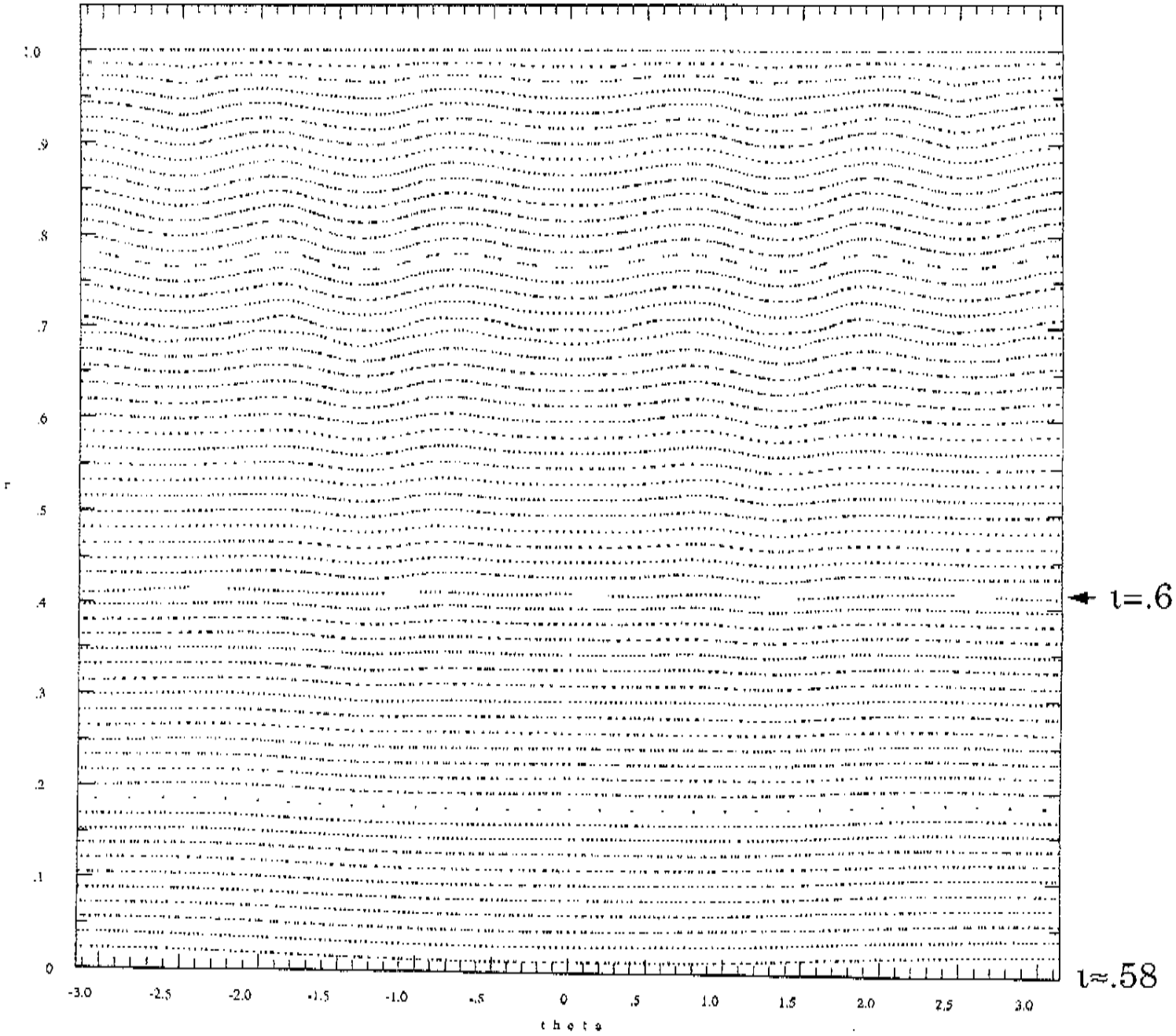


Case 2. 3-Period Configuration with peak of current profile shifted inward. $\beta \approx 4\%$.



Total island width reduced to $\approx 12\%$.

Case 3. 3-Period Configuration with seed current added near axis. $\beta \approx 4\%$.



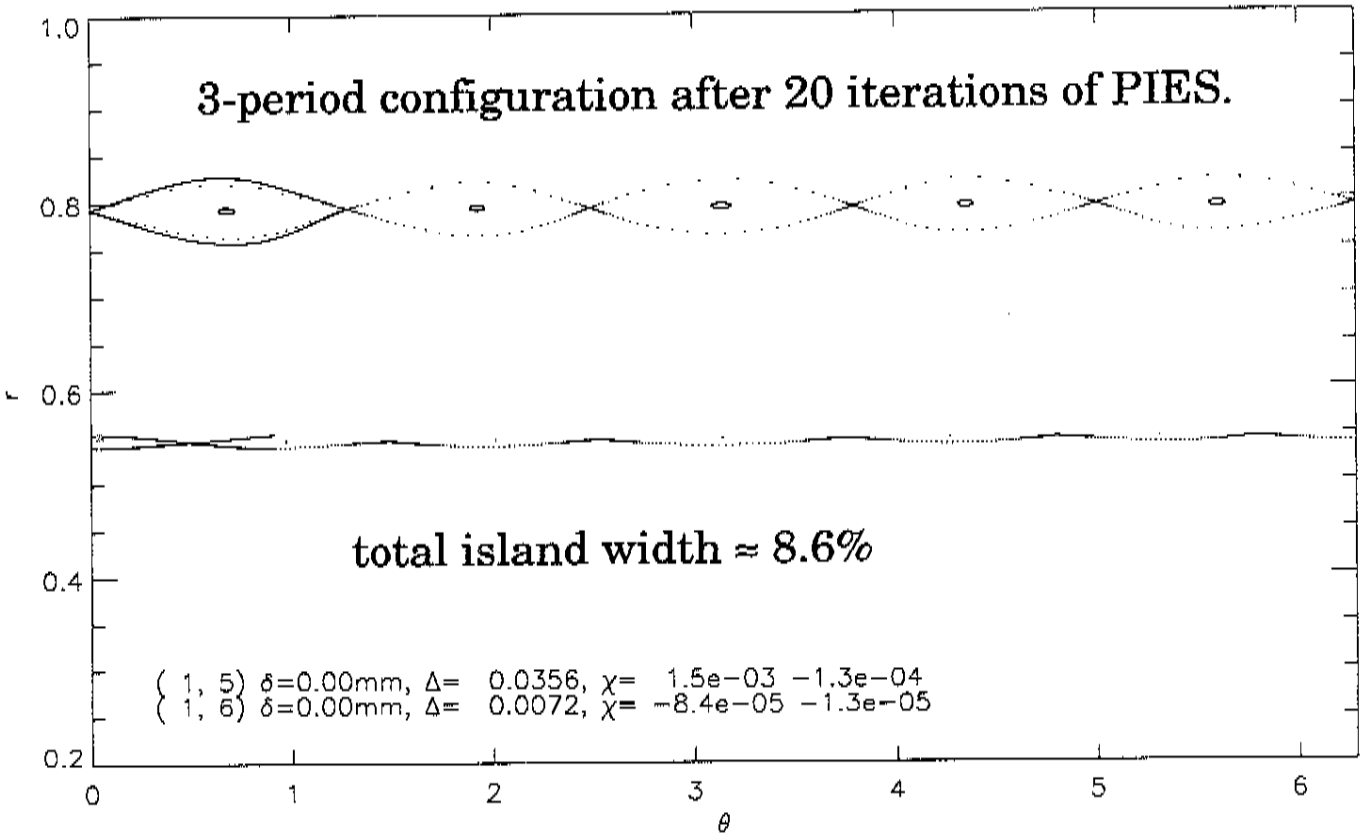
- ι=.6 surface deep in interior relatively unaffected by resonant perturbation at boundary.

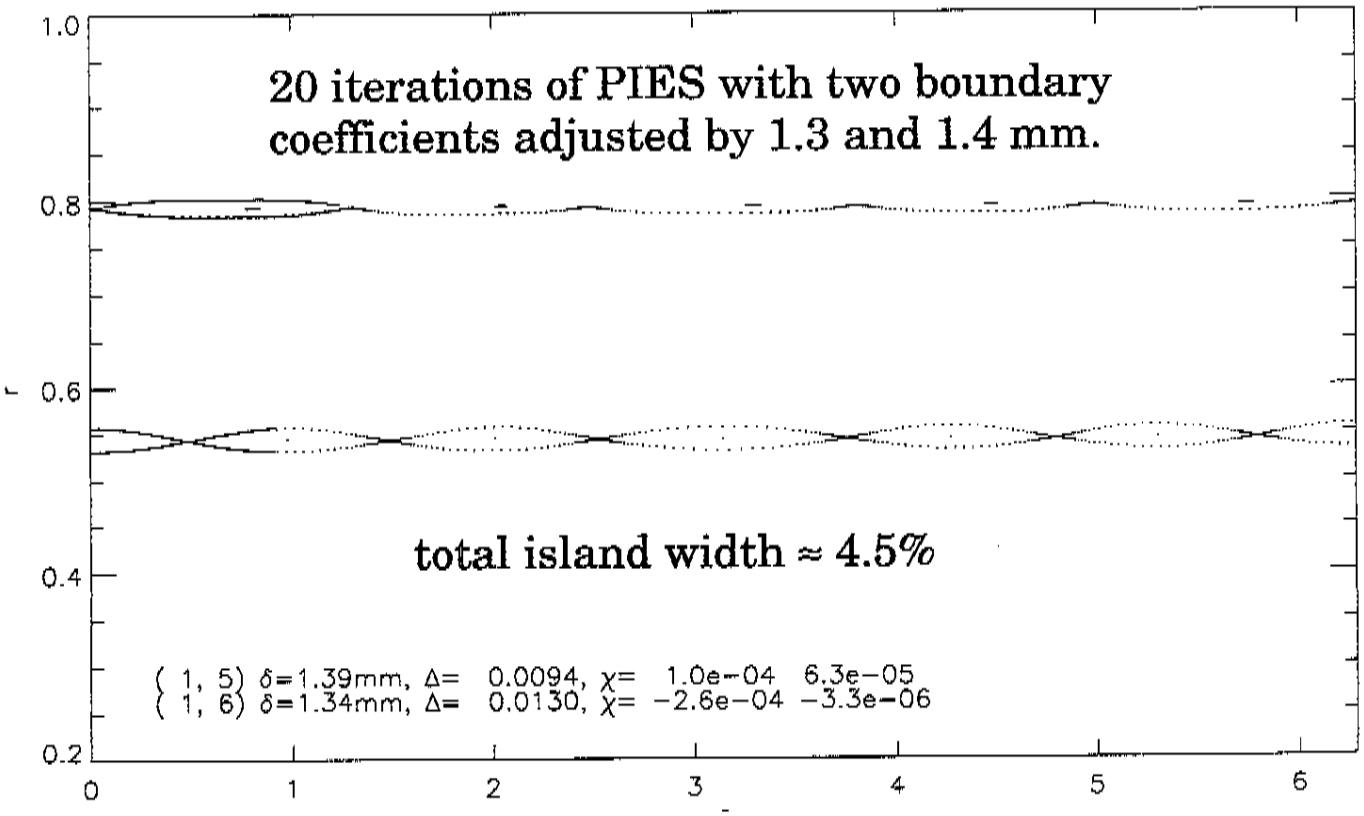
- Good surfaces across entire cross section for this current profile.

A Method for Further Improvement of Flux Surfaces

- Island widths adjusted by modifying resonant Fourier components in boundary shape.
  - Island widths tend to be more sensitive to resonant perturbations than are other physics properties, but may still require reoptimization of nonresonant Fourier components.
- Use PIES to monitor island widths.
  - A new diagnostic has been incorporated in PIES for accurate measuremt of island widths. (Hudson) Allows measurement of response of island width to small changes in resonant Fourier components.
- Present status: Testing basic ideas by running PIES a few iterations, adjusting resonant Fourier components, and rerunning PIES from beginning with modified Fourier components.
- Ultimately will want to adjust resonant components as PIES iterates, to maintain minimum possible island widths.

Test demonstrates possibility of reducing island widths through adjustment of resonant Fourier components of boundary.





Rutherford: Analytical calculation of neoclassical effect predicts reduction in NCSX island widths by about a factor of 2.

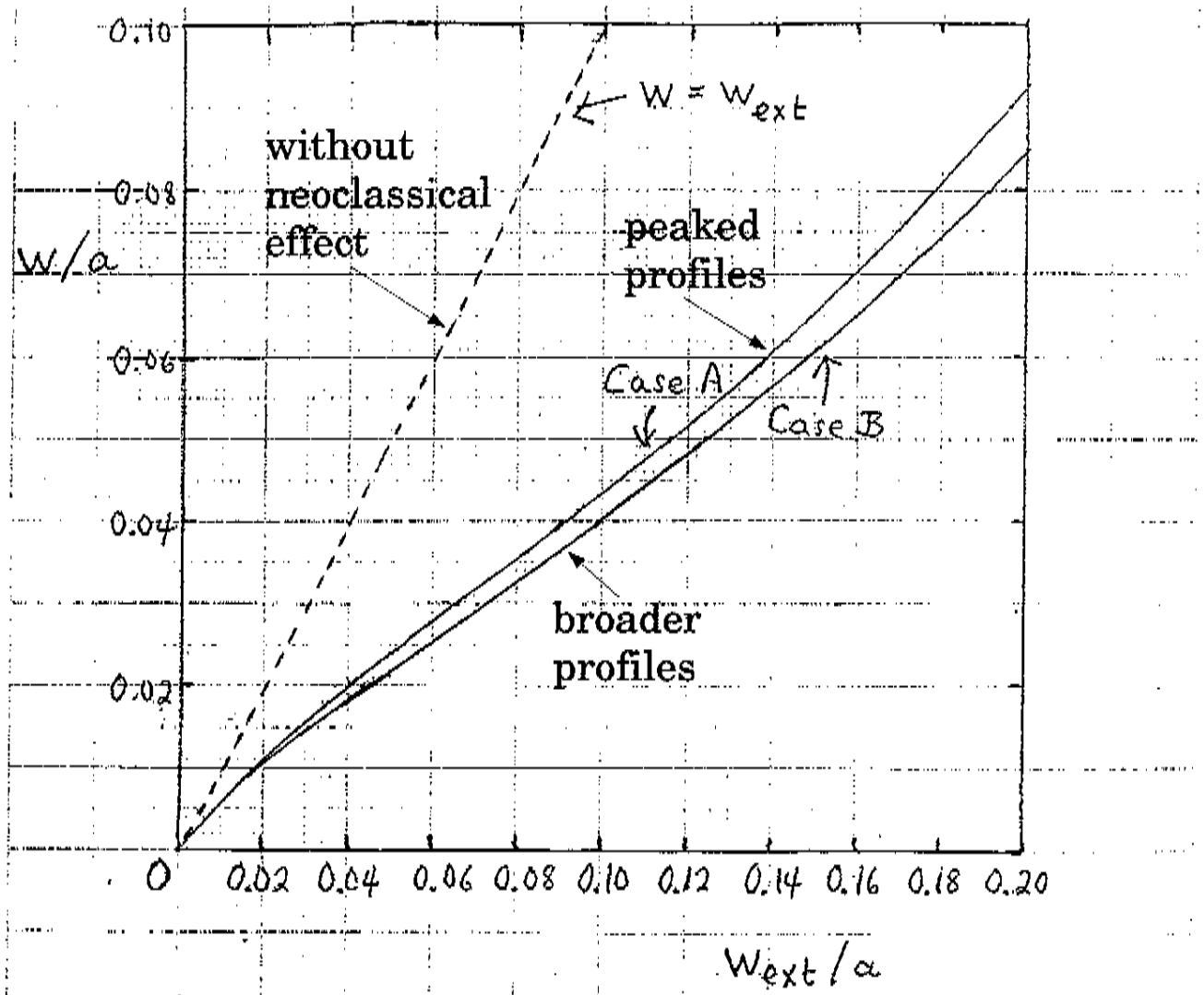


Fig 1: Actual island width W versus width of "vacuum" island W_{ext}. for two profile cases in NCSX

46 1320
K+E 10 X 10 TO ½ INCH 7 X 10 INCHES KEUFFEL & ESSER CO. MADE IN U.S.A.

Ohyabu: LHD

Plasma Changes Island (n/m=1/1) Width Substantially.

- For vacuum configuration, W (island full width) ~ 80mm
  - *Electron beam mapping*
  - *Te-profile during decaying phase.*
- For low n/ high T discharge, the width is generally small.
  - *Clear at low B(1.5T)*
  - *Even with larger vacuum island (LID coil), no change in the plasma stored energy when* $n < 2\times10^{19} m^{-3}$.
- For high density (particularly during pellet shot), the width becomes even wider than W_{ex}.
- Island size sometimes varies even with seemingly the same edge plasma parameters!!!

Tearing Stability

- Equilibrium calculations preserve $N = 3$ or $N = 2$ periodicity.
  - Does not address whether small perturbations that break symmetry can grow to produce large islands (tearing stability).
  - Tearing stability of particular concern at $\iota = .5$ ($q = 2$) surface.
- Preliminary tearing calculation by S. Knowlton finds stability for $\iota = .5$ surface in cylindrical model of 3-period configuration.
- Neoclassical effect predicted to dominate at finite β.

Robustness of Stability to Changes in Profiles

Robustness studies for configuration C82 presented at PAC #3.

- vertical modes
- kink modes
- ballooning modes

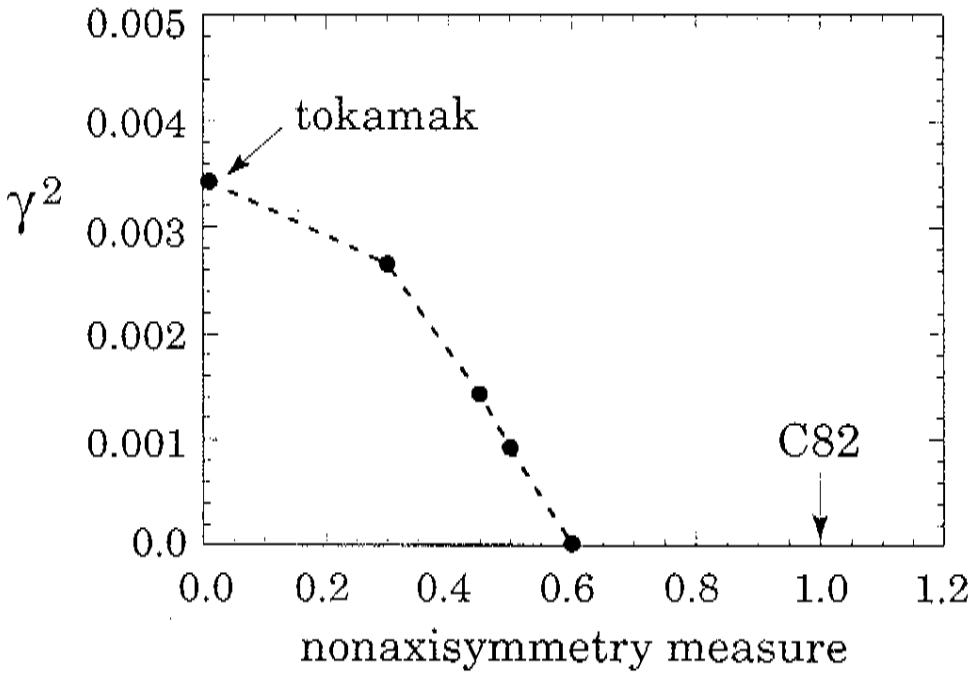
More extensive set of profiles has since been studied by Redi et al.

Similar robustness studies just beginning for new configurations.

Fu, Cooper

Configuration C82 is robustly stable to the vertical mode.

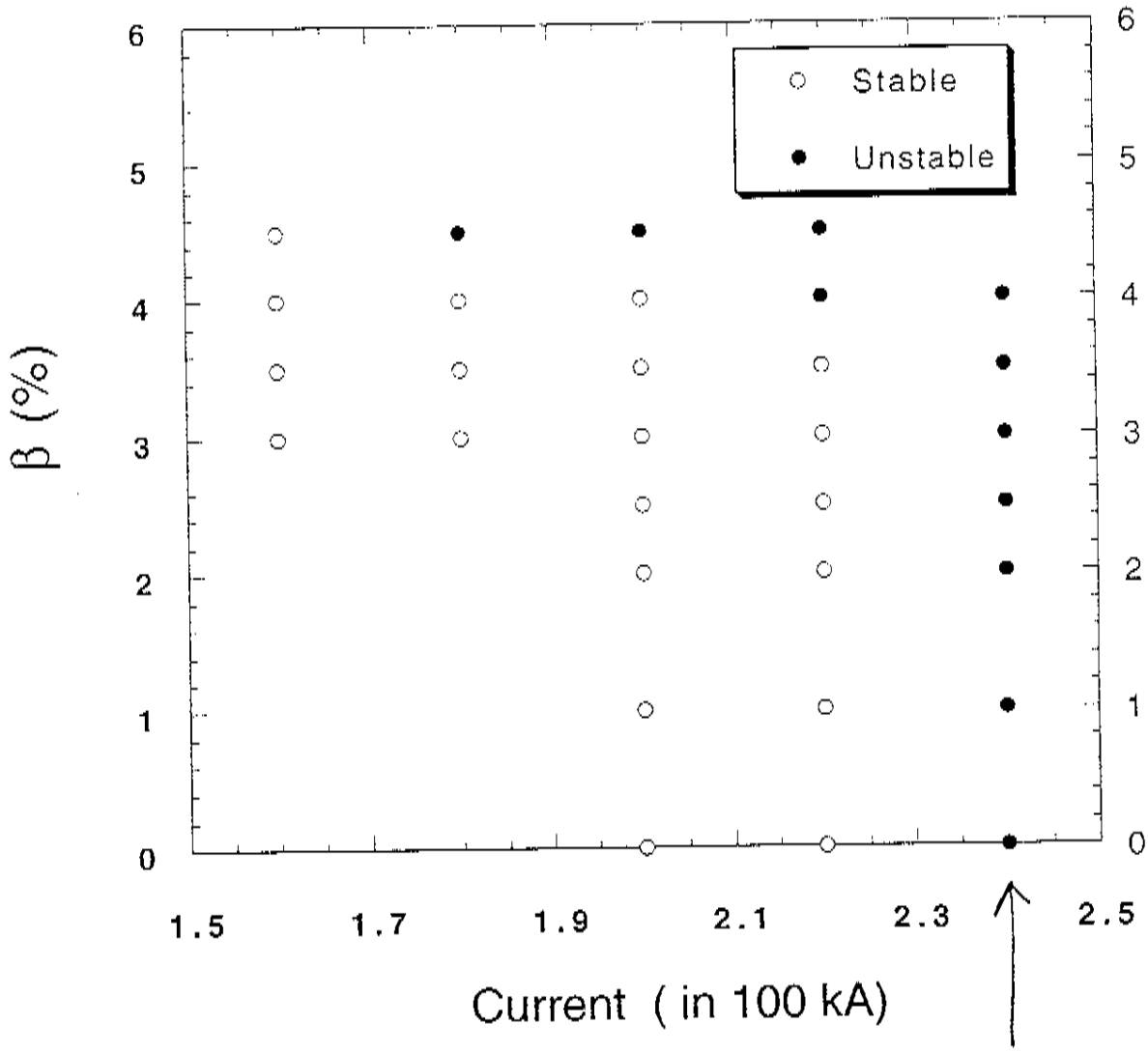
Vertical Stability for a Series of Configurations Interpolated Between C82 and a Tokamak



Increasing C82 elongation finds vertical stability up to elongations of 4.
May be able to improve design by going to higher elongation.

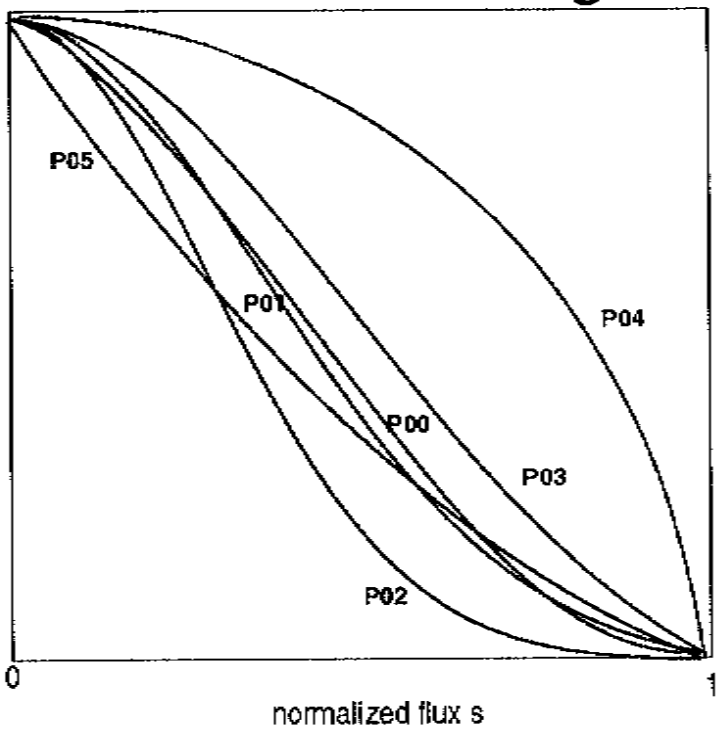
Fu

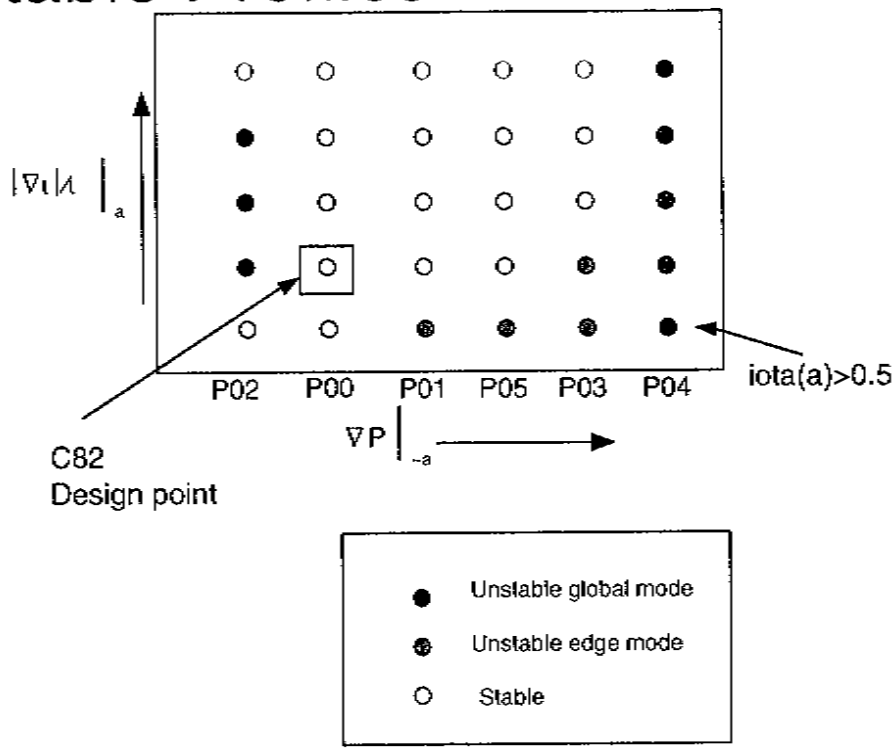
Kink Beta Limit Goes Up at Lower Current



ι = .5 surface moves into plasma

Initial Flexibility Study Indicates Range of Stable Profiles

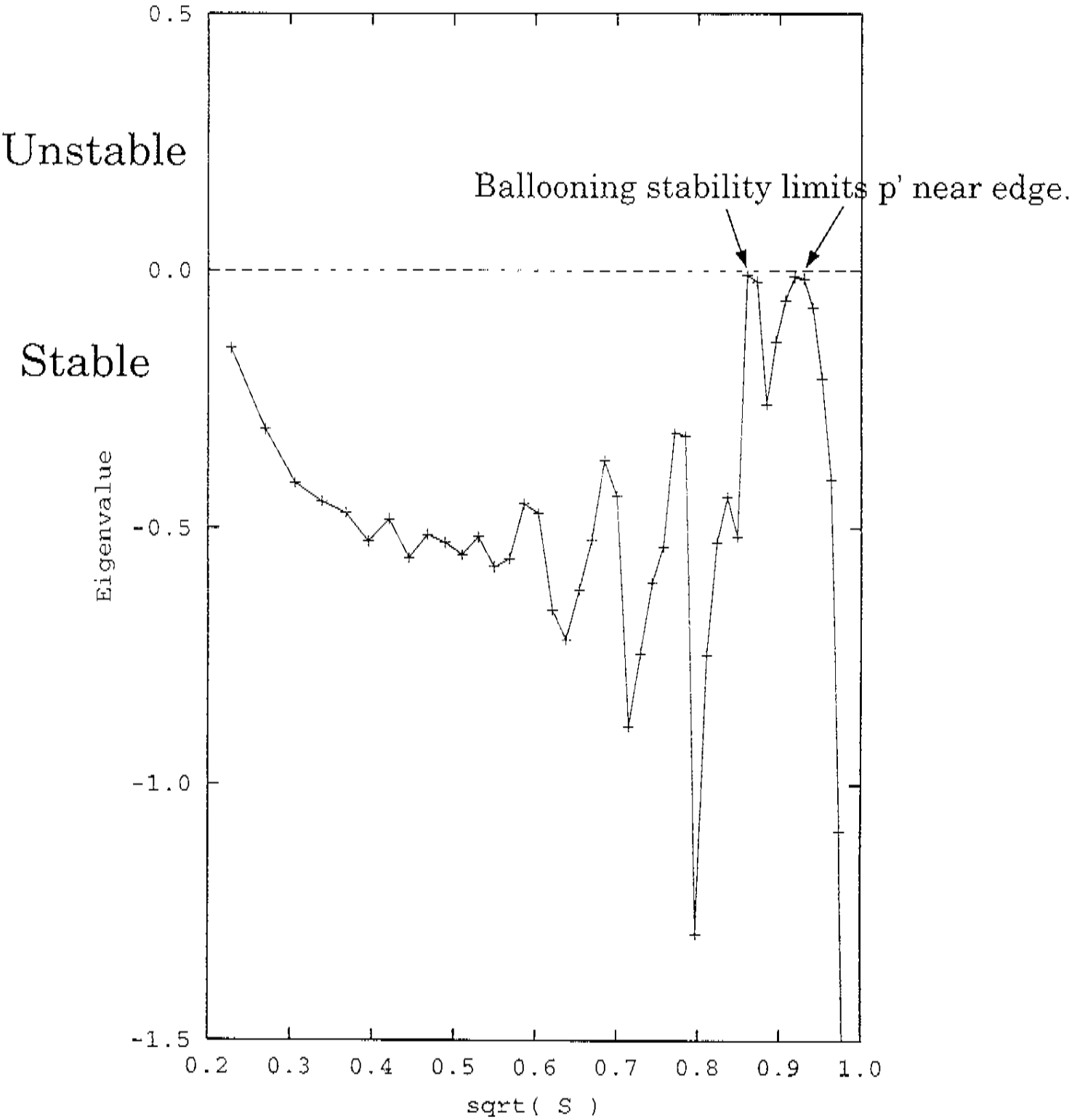




β~4%, parametric profiles, fixed boundary shape

Ku, Cooper, Monticello

Ballooning is robustly stable in C82 through most of cross-section.



Plans for Flux Surface Studies

- Further improvement of fixed boundary surfaces via control of resonant Fourier components of boundary shape.
- Develop analytic understanding of physics governing flux surface differences.
- Free-boundary calculations of equilibrium flux surfaces.
- Robustness of free-boundary flux surfaces, including a startup sequence.
- Tearing calculations. (Knowlton finds stability at $\iota = .5$ surface in cylindrical model of 3-period configuration.)

Conclusions

- Recent configurations have greatly improved fixed boundary surfaces relative to configuration C82. Fixed boundary flux surfaces close to adequate.
- Neoclassical effects predicted to further improve flux surfaces. To be calculated with PIES code.
- Further improvement of fixed boundary flux surfaces being pursued through control of resonant Fourier components of boundary shape.
- Free-boundary issues remain to be addressed.