NCSX Plasma Configuration Design

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Configuration Design

Outline of the Talk

- Reformulation of Physics Requirements into Goals of the Design Process.
- The Design Procedure.
- Configurations
  - A Configuration that Fits in PBX (c10).
  - A Lower Aspect Ratio Configuration (work in progress).
- Brief Discussion of Code Benchmarking. (Response to a question from the previous PAC meeting.)

Reformulation of Physics Requirements into

Goals of the Design Process

Compactness. Aspect ratio $R/\langle a \rangle \approx 2 - 3.5$.
$R/\langle a \rangle \approx 3.5$ needed to fit into PBX. Lower preferable for outside PBX option.

Near Quasiaxisymmetry. Want $\sum_{n \neq 0} B_{nm}^2$ small.

Evaluate adequacy using Monte-Carlo codes. Want $\tau_{\text{neoclassical}} \geq 4\tau_{\text{ISS}}$.

Ballooning stability. A problem for other quasisymmetric configurations, except at large aspect ratio.
Our solution: Axisymmetric shaping.

Evaluate using Cooper ballooning code imported from Lausanne.

Adequate poloidal flux. A function of size and ι.
Need axisymmetric contribution to neoclassical transport sufficiently small.

Monotonically increasing ι. Provides neoclassical suppression of magnetic islands across entire cross-section.

Kink stability. Eliminate need for close fitting conducting shell required by reverse shear tokamaks.

Our solution: Can stabilize via externally generated shear or corrugation of boundary. (3D effects.) In practice, need both.

Evaluate external kink stability using Terpsichore code imported from Lausanne.

Substantial external transform. $\iota_{\text{bootstrap}} \leq 60\% \, \iota_{\text{tot}}$ at highest β.

Externally generated transform reduces or eliminates need for externally driven current.

Substantial transform reduces sensitivity to bootstrap current profile, aids robustness.

Previous experiments (W7A, Cleo) found suppression of disruptions when $\iota_{\text{ext}} \geq 15\% \, \iota_{\text{tot}}$.

Bootstrap alignment of current profile. For reactor relevance, configuration must require little or no seed current.

Stellarator bootstrap code imported from NIFS.

Vertical stability. CAS3D bug fixed (collaboration with Carolin Nuehrenberg, Greifswald). Application planned.

Good Flux Surfaces. Issue related to both configuration design and coil design.
Evaluate with free-boundary PIES code.

Robustness and Flexibility. To be addressed when we have a reference design that satisfies our other requirements.

The Design Procedure

- Start with advanced tokamak Aries-RS configuration. Morph to fully three-dimensional stellarator configuration.
  - Retain axisymmetric ($n = 0$) components of shape (at least initially). Endows good ballooning stability properties.
  - Retain current and pressure profiles (initially). Maintains good bootstrap alignment. (With quasi-symmetry, bootstrap controlled by $n = 0$ componenents of B).
- Deformation of shape controlled by optimizer.
  - Evolves through sequence of VMEC equilibria.
  - Levenberg-Marquardt scheme (netlib) evolves Fourier coeffs defining boundary to maximize "objective function".

- Objective function targets retention of quasi-symmetry ($\sum_{n\neq 0} B_{nm}^2$ small) plus desired iota, magnetic well, kink stability, ballooning stability.

- In practice, generating desirable configurations requires manually controlled application of optimizer (Long-poe Ku). (Many local extrema in complicated high-dimensional parameter space.)

  - Adjust relative weights of terms in target function as optimization proceeds. e.g. Helps to add one term at a time to target function.

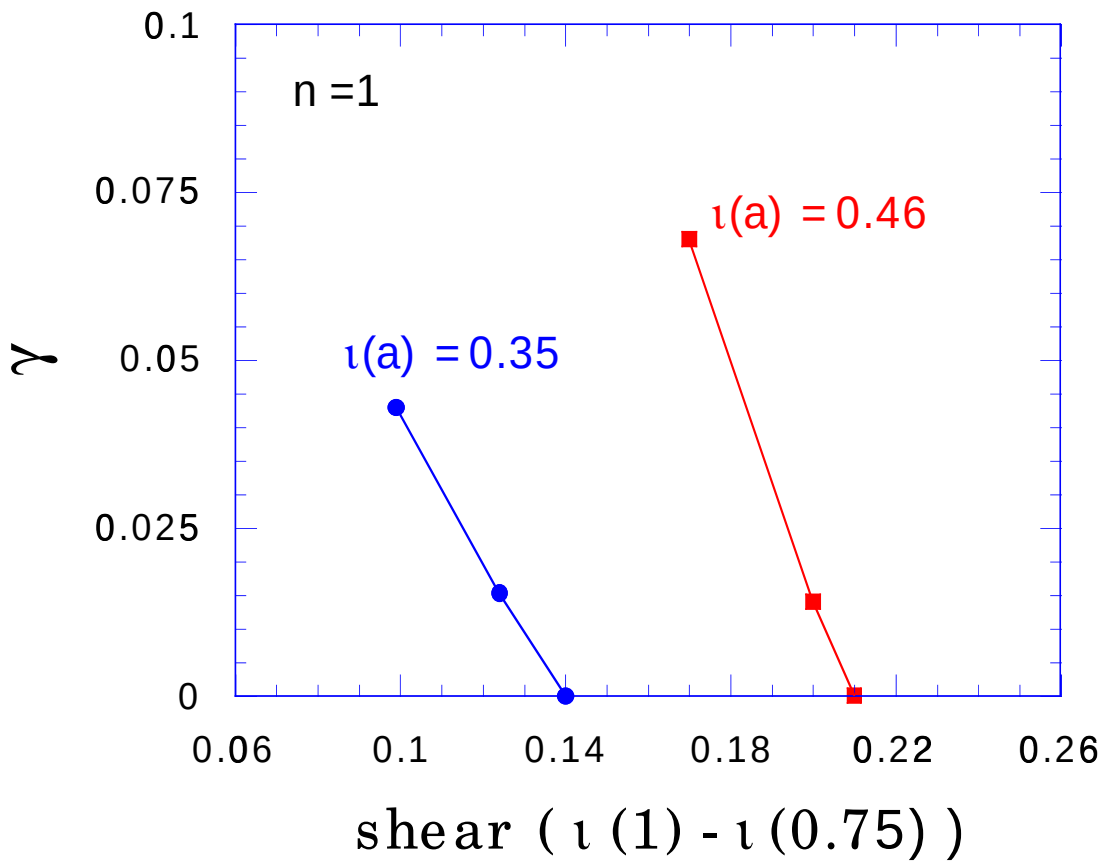
External Kink

Stability calculated using Terpsichore code.

External kink can be stabilized, even in absence of conducting wall, by externally generated shear, or by nonaxisymmetric corrugation of boundary.

G. Y. Fu

Effect of Shear



Np = 4

$R / \langle a \rangle \approx 2.1$

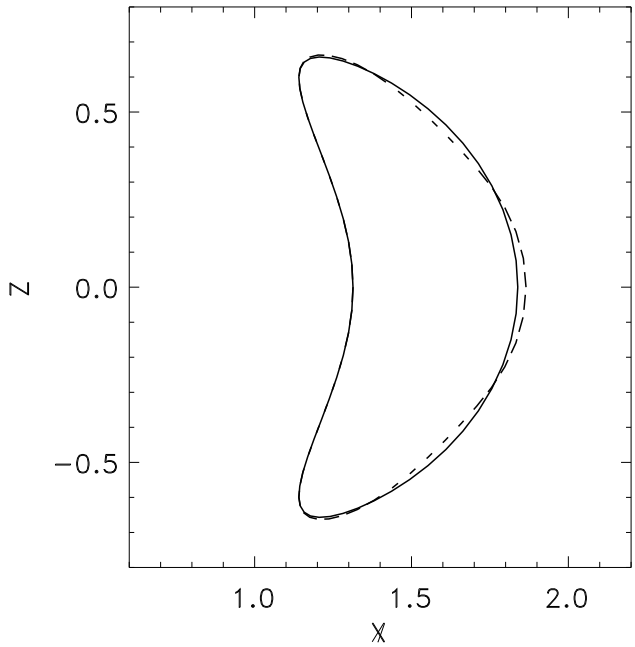
$\beta \approx 6.8\%$

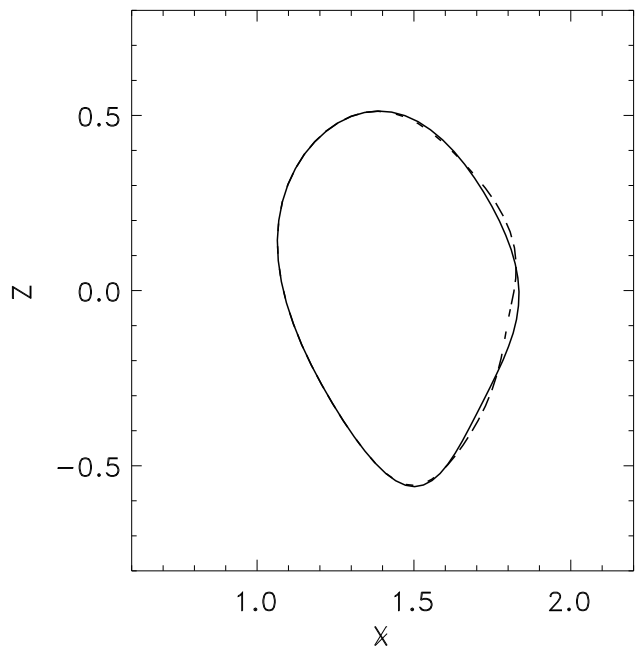
Conducting wall at 2a.

Comparable tokamak has $\beta_c \approx 2.5\%$.

Reverse-shear tokamaks require close-fitting conducting wall for kink stabilization. On L/R time scale of wall, will need to rapidly rotate plasma, with issues of recirculating power, or to provide multi-mode feedback stabilization.

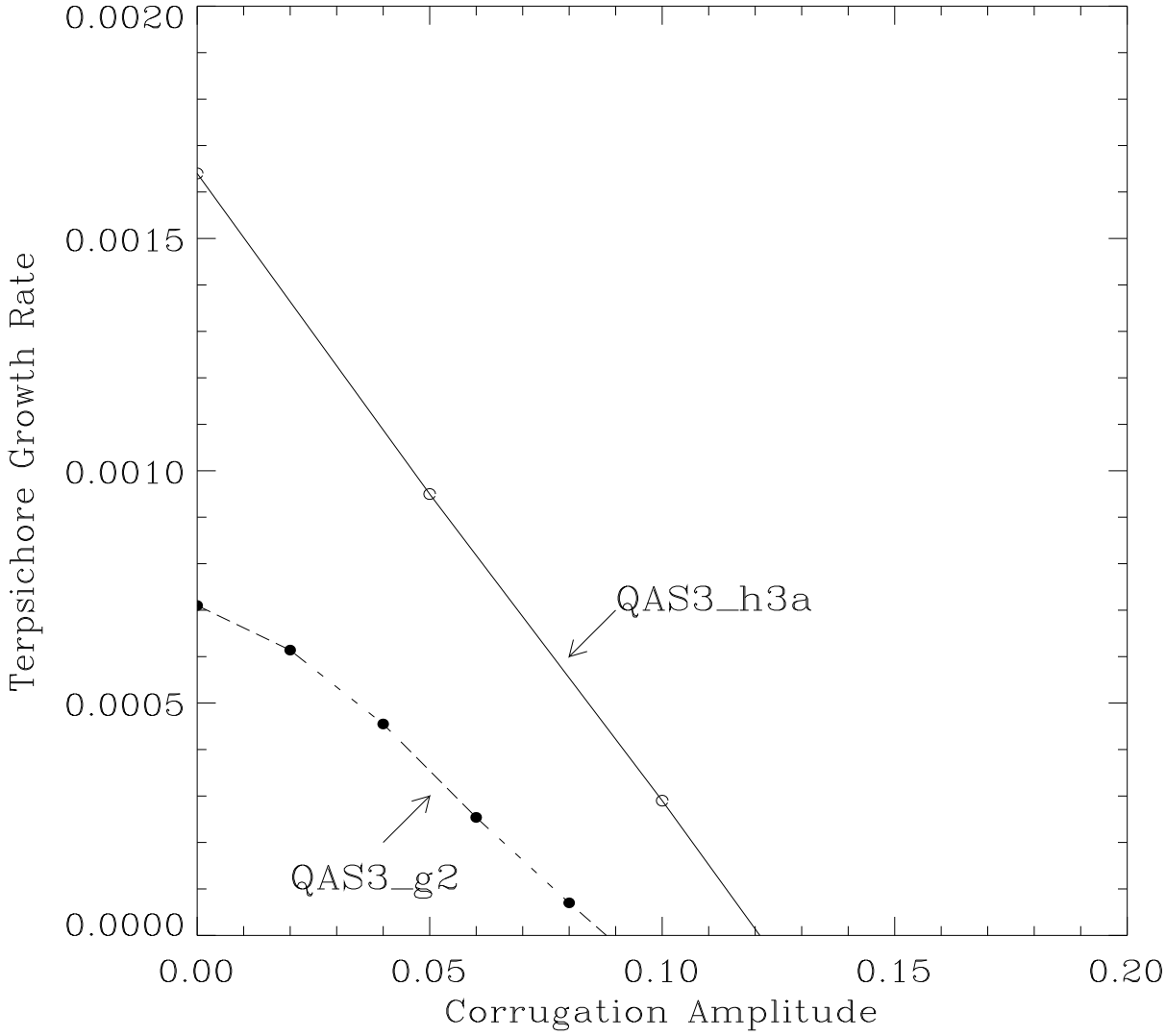
Pomphrey and Fu





Stabilizing Effect of Corrugation

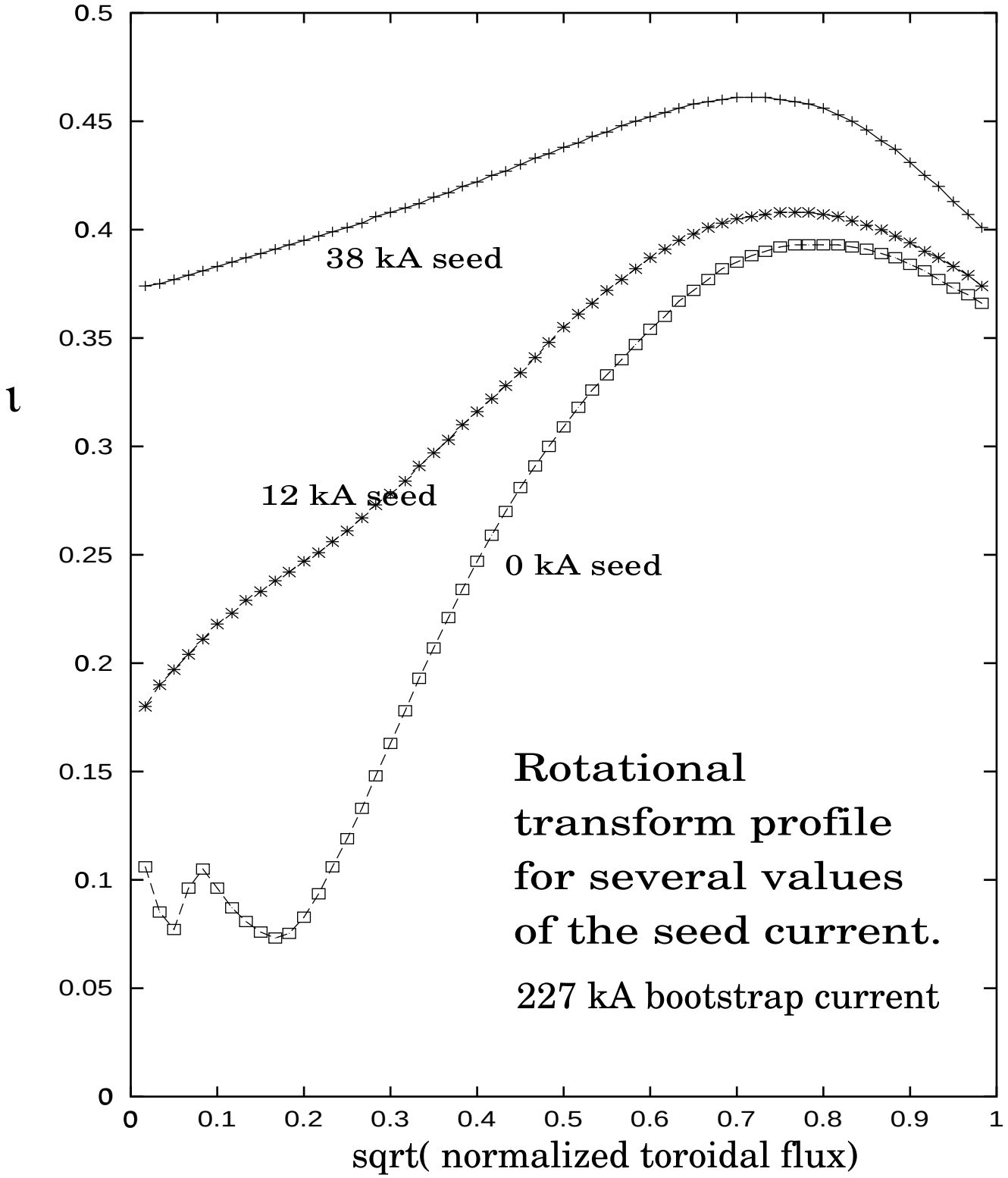
(Corrugation similar to that produced by Furth-Hartman coils.)



Hughes and Monticello

Self-Consistent Bootstrap Current Calculations

with NIFS bootstrap current code

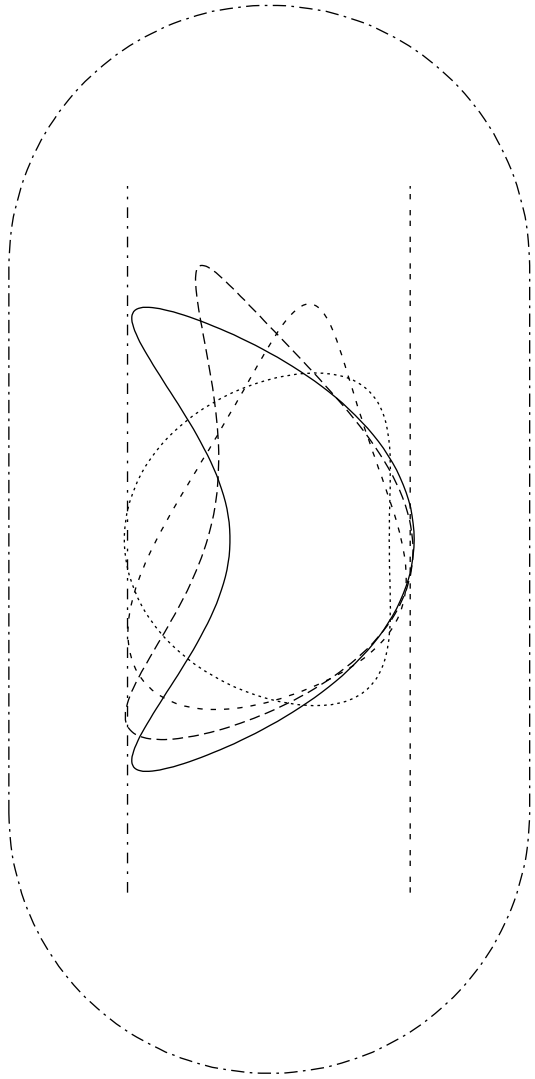


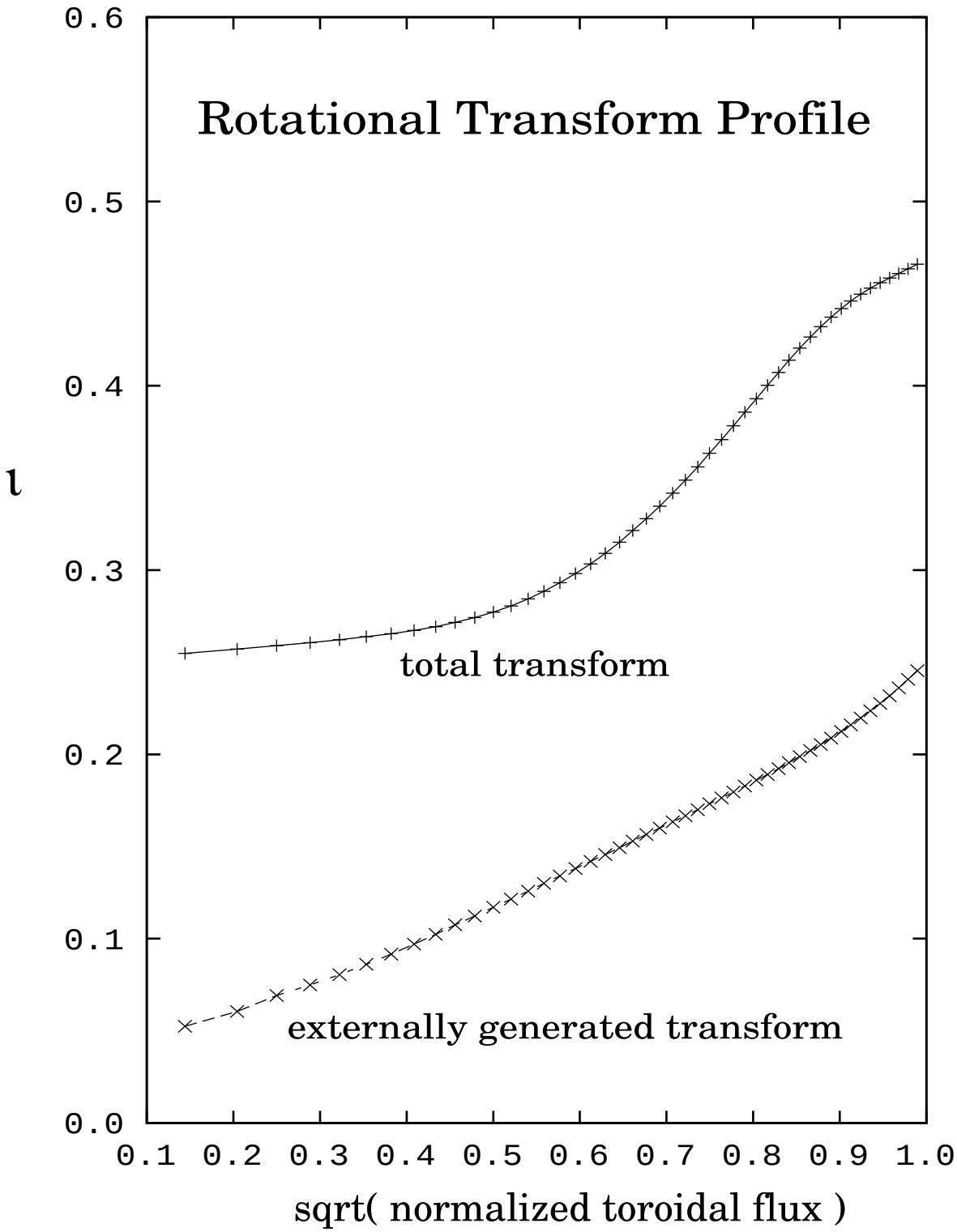
- Externally generated transform reduces or eliminates need for rf current drive, with its recirculating power, restrictions on operating density, etc.
- Seed current drive gives ι flexibility knob.

Review of Status as of PAC 1

- Presented set of configurations with $R/\langle a \rangle \approx 2.1$.
- Ballooning stable at β as high as 11%. Typically 5 – 7%.
- Kink and ballooning stable at β as high as 7%.
- Did not make use of corrugation in kink stabilization.
- ι and ι_{ext} typically smaller than we now demand.
- Design studies since that time have focused primarily on configurations fitting in PBX. Recent effort on lower aspect ratio for outside PBX option.

QAS3_C10 in PBX Vacuum Vessel



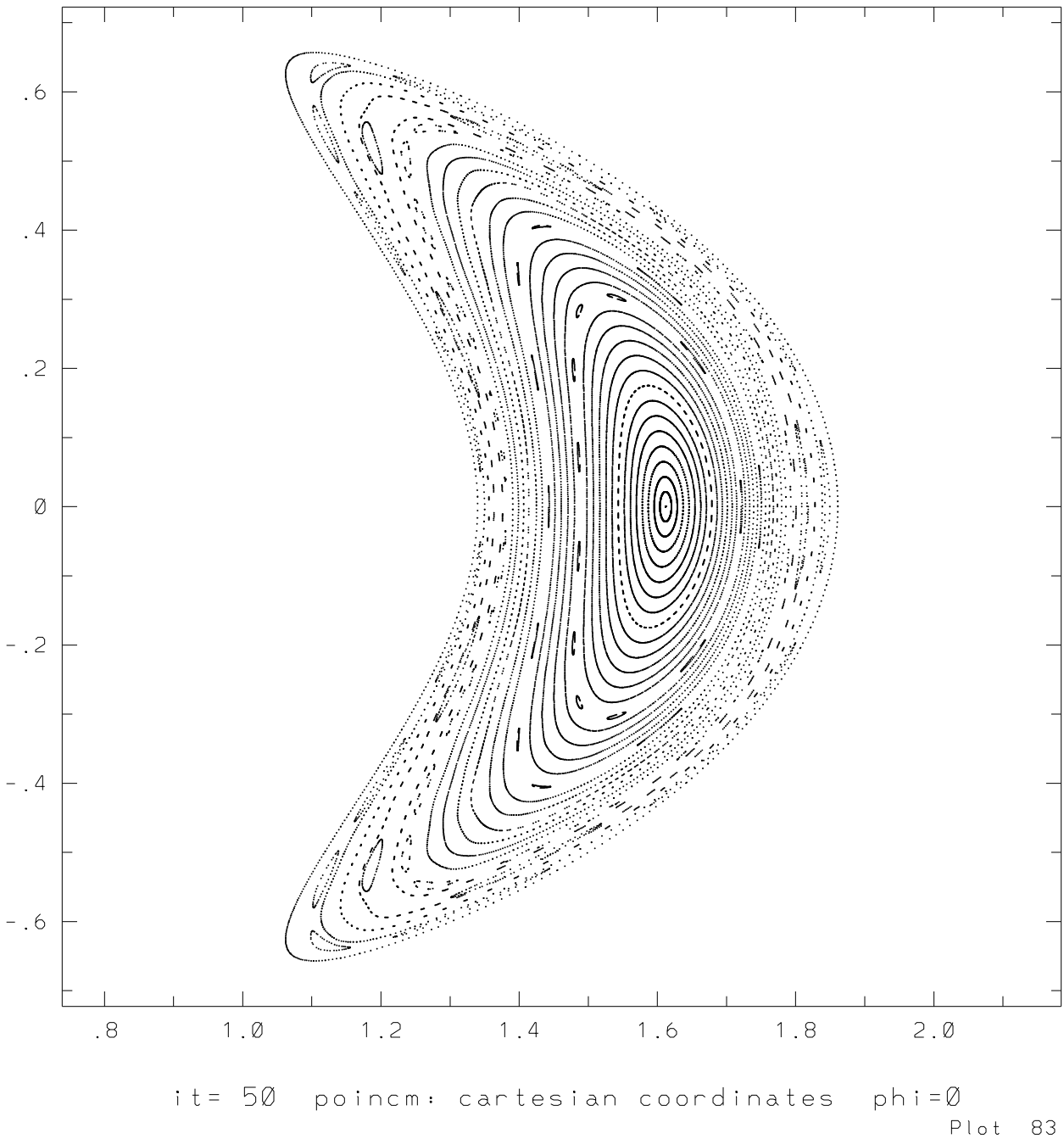


Monotonically increasing ι. (Monotonically decreasing q.)

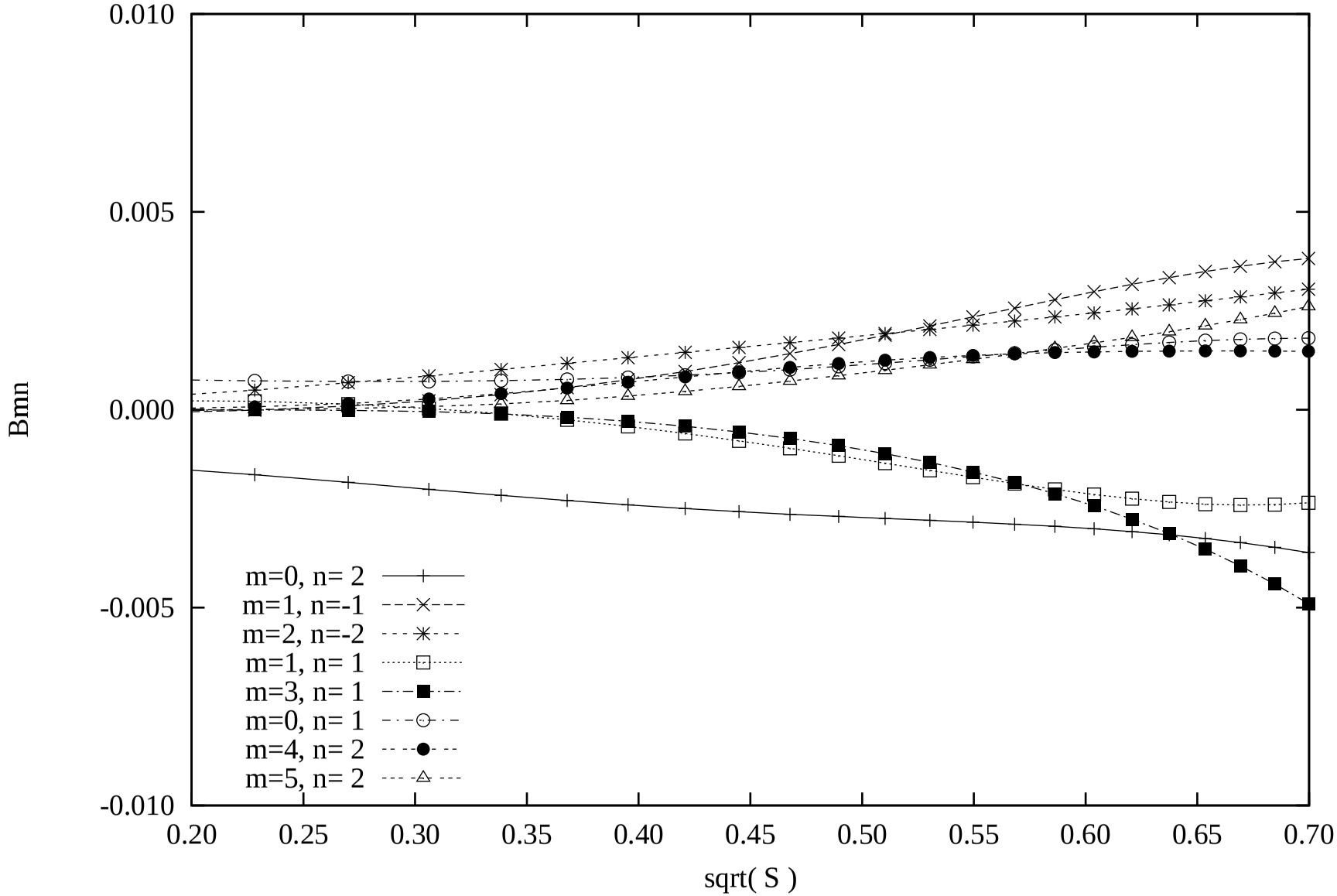
Not possible in an axisymmetric device such as a tokamak. Reversed-shear tokamaks have shear reversal layer with associated MHD stability issues, neoclassical tearing instability in exterior.

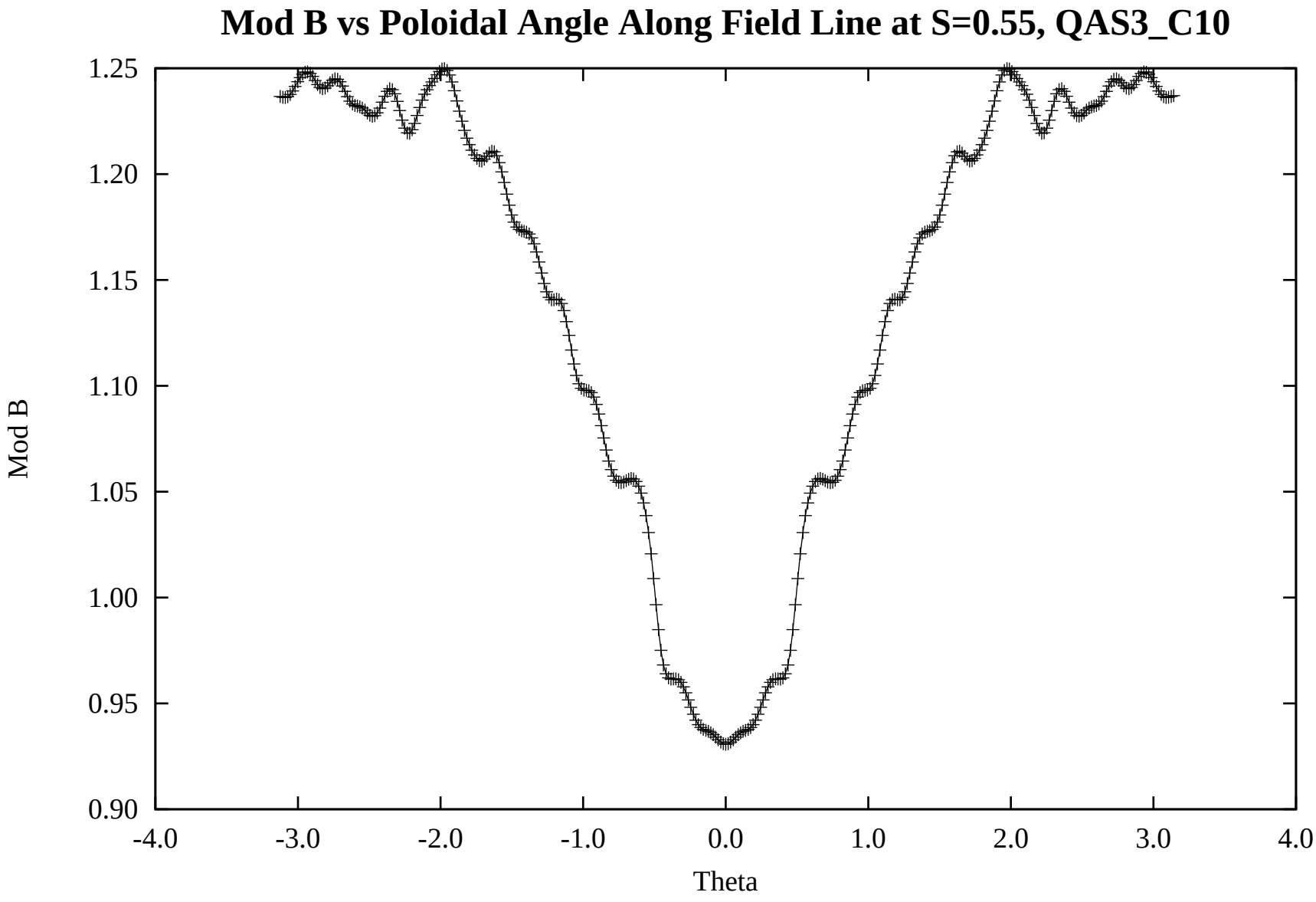
D. Monticello

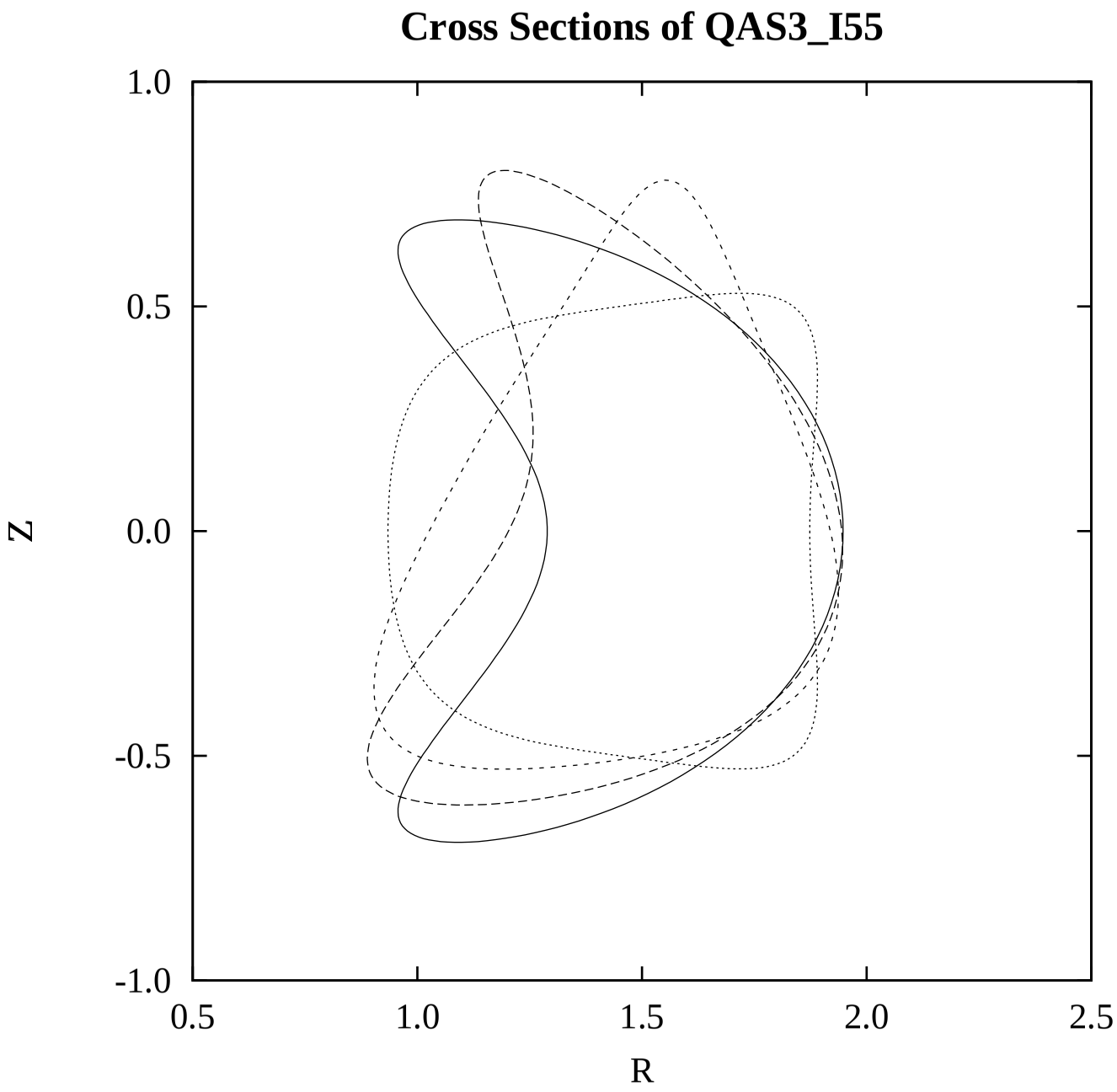
Fixed Boundary PIES Calculation for c10

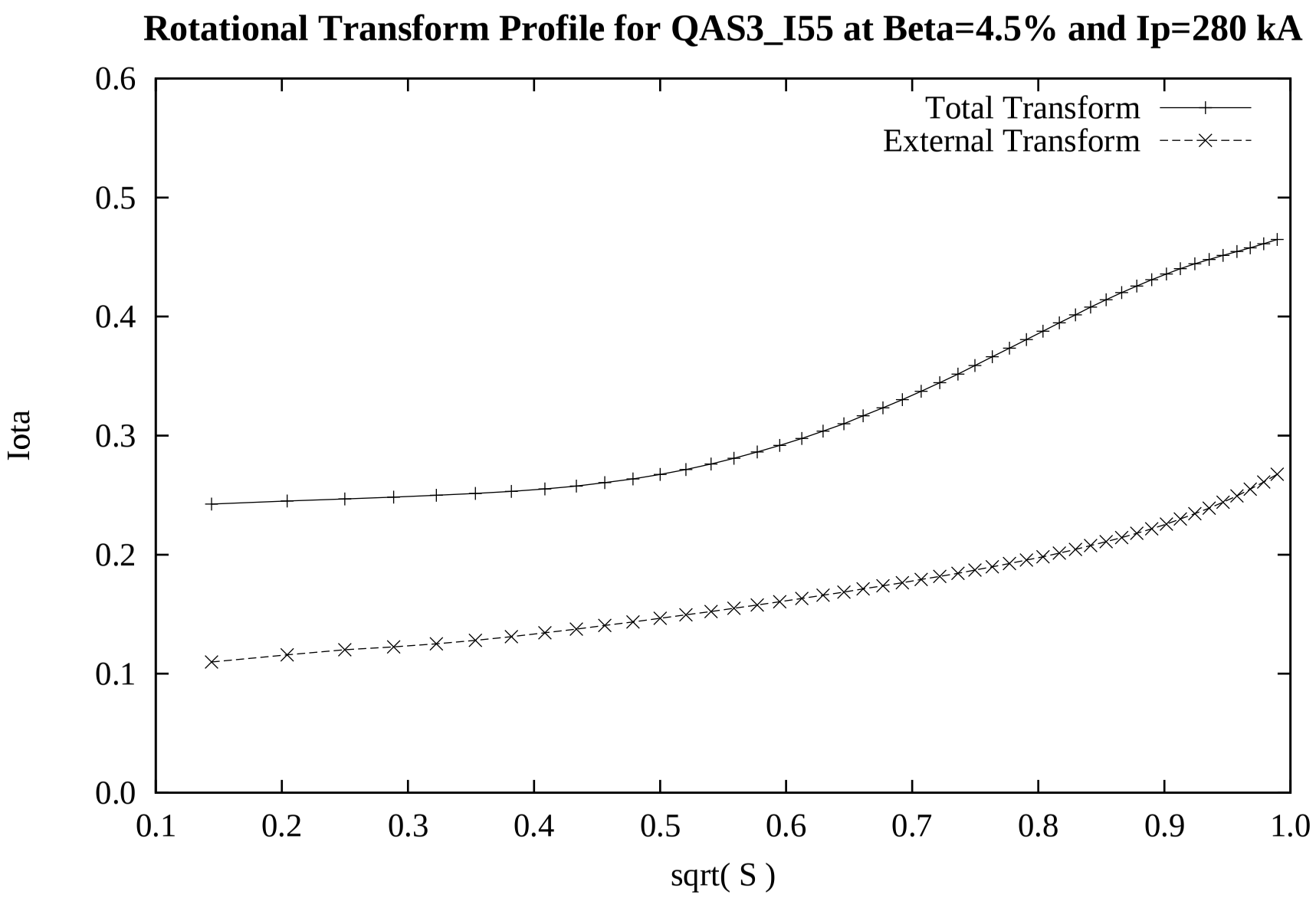


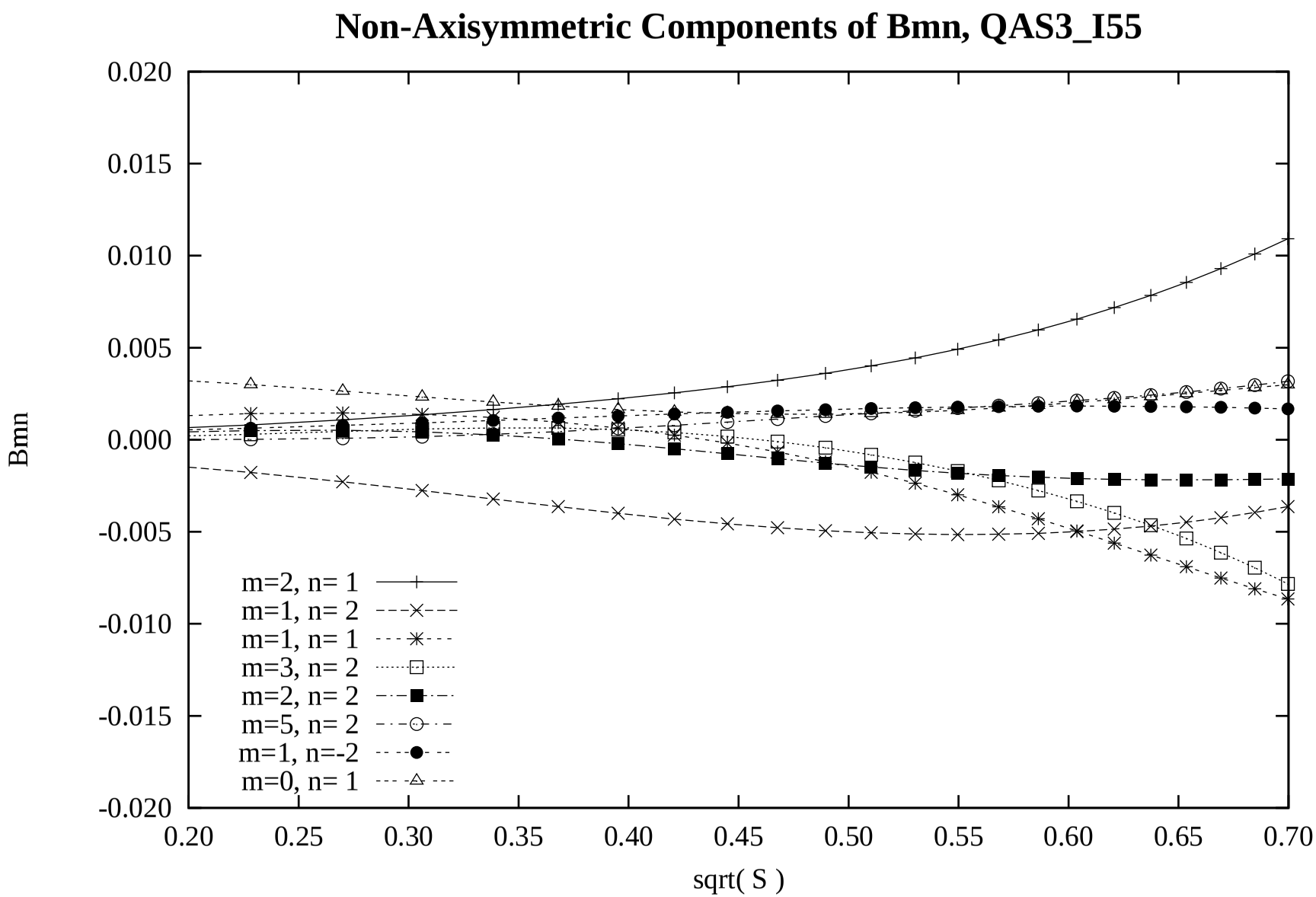
Does not yet include effect of neoclassical suppression of islands.

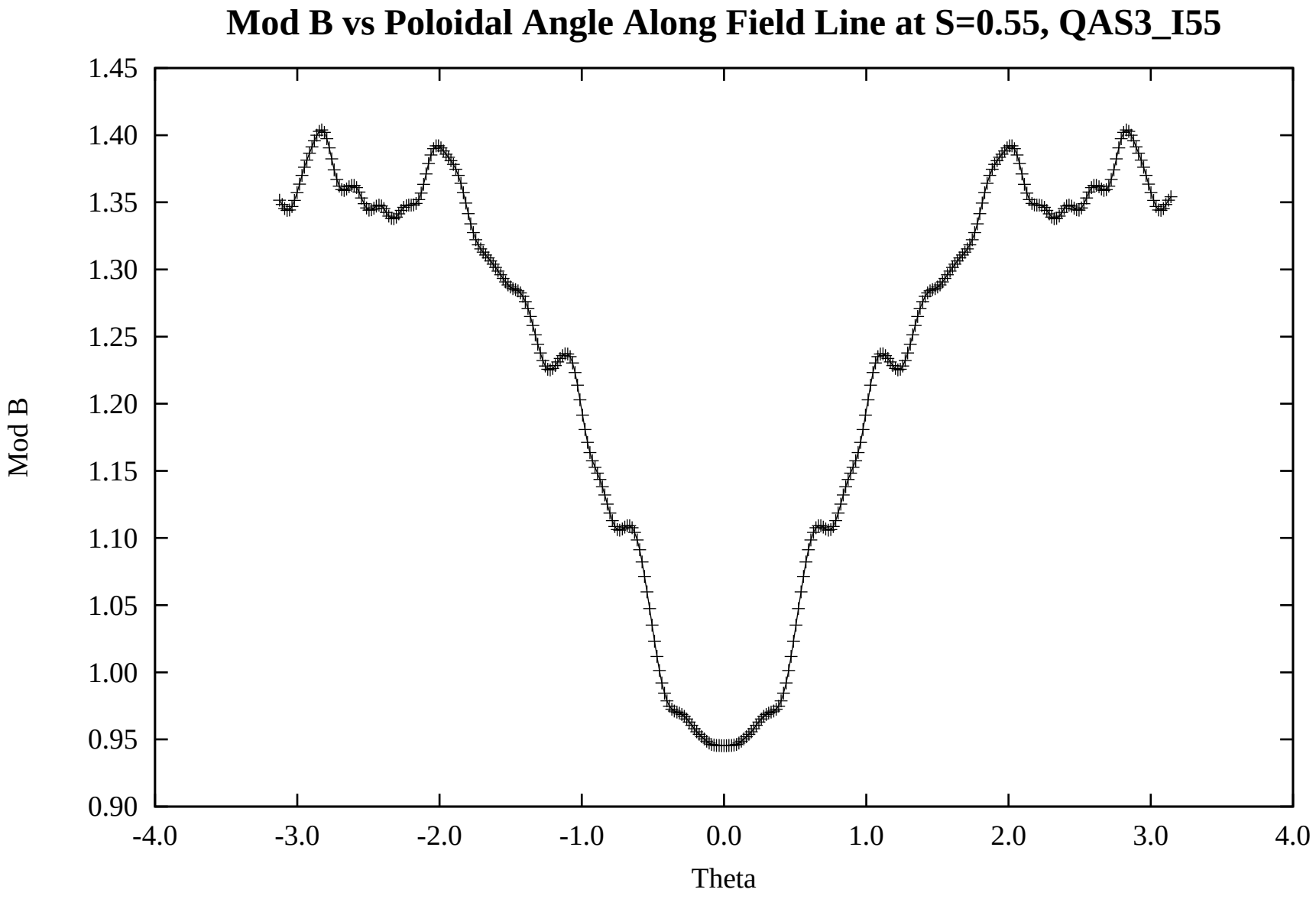

0.010
0.005
0.000
-0.005
-0.010
Bmn
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
0.70
sqrt(S)
m=0, n= 2
m=1, n=-1
m=2, n=-2
m=1, n= 1
m=3, n= 1
m=0, n= 1
m=4, n= 2
m=5, n= 2


Mod B vs Poloidal Angle Along Field Line at S=0.55, QAS3_C10
1.25
1.20
1.15
1.10
1.05
1.00
0.95
0.90
Mod B
-4.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0
4.0
Theta


Cross Sections of QAS3_I55
1.0
0.5
0.0
-0.5
-1.0
Z
0.5
1.0
1.5
2.0
2.5
R


Rotational Transform Profile for QAS3_I55 at Beta=4.5% and Ip=280 kA
Total Transform
External Transform
Iota
sqrt(S)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0


Non-Axisymmetric Components of Bmn, QAS3_I55
Bmn
sqrt(S)
0.020
0.015
0.010
0.005
0.000
-0.005
-0.010
-0.015
-0.020
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
0.70
m=2, n= 1
m=1, n= 2
m=1, n= 1
m=3, n= 2
m=2, n= 2
m=5, n= 2
m=1, n=-2
m=0, n= 1


Mod B vs Poloidal Angle Along Field Line at S=0.55, QAS3_I55
Mod B
Theta
1.45
1.40
1.35
1.30
1.25
1.20
1.15
1.10
1.05
1.00
0.95
0.90
-4.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0
4.0

Continuing Work on Configuration Design

- Further improve neoclassical confinement in c10.
- Additional configurations with $R/\langle a \rangle \approx 2.8$ and lower being studied. Will also look at higher ι.
- Will investigate further improvement of neoclassical confinement via pseudosymmetry and J^* alignment with flux surfaces.
- Other transport studies: to be discussed by Harry Mynick.
- Fully bootstrap self-consistent profiles.
- PIES calculation of free-boundary equilibria with magnetic islands.
- Vertical stability calculations.
- Startup, robustness, and flexibility, after a satisfactory baseline configuration identified.

Code Benchmarking

(Response to a question from the previous PAC meeting.)

Ballooning. Benchmarked Lausanne code against German code. Helped us to learn to run codes properly. (e.g. adequate resolution in different coordinate systems used in different parts of code.)

Kink. Compared with PEST tokamak external kink calculations.

- Good agreement with Terpsichore pseudoplasma method.
- Problems identified in Green's function calculations in CAS3D and Terpsichore. (Codes not previously used with finite net currents.)
  CAS3D has been fixed by Carolin Nuehrenberg.

Bootstrap code interpolates between analytical results in different collisionality regimes. We have compared with Monte Carlo.

- Problem identified in standard analytical physics model near rational surfaces.
- Corrected code now agrees well with Monte Carlo.

Neoclassical confinement calculations to be described by Harry Mynick.

Summary

A configuration that fits in PBX (c10):

- $d\iota/dr > 0$ across entire cross-section.
  - Bootstrap suppression of magnetic islands.
  - Avoids MHD problems seen at shear-reversal layer in tokamaks.
- Ballooning mode stabilized at $\langle\beta\rangle = 4\%$ by axisymmetric shaping.
- Kink mode stabilized at $\langle\beta\rangle = 4\%$ with wall at $2a$ by combined effects of externally generated shear and nonaxisymmetric corrugation of plasma boundary.
- Neoclassical confinement marginal for c10. More work needed.

Exploring lower aspect ratio configurations that do not fit in PBX. Larger $\langle a\rangle$. Higher β limits.