Plasma Configuration Development

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Outline of Talk

- Goals of configuration development.
- Methods/Algorithm.
- Evolution of configurations.
- Primary candidate configuration.
- Other candidate configurations.
- Summary and Conclusions.

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Goals of Configuration Development

- **Quasi-axisymmetry for good particle confinement.**
  - **|Bmn| <1% at s=0.5 for n$\neq 0$,**
  - **avoid secondary wells in |B| contours.**

- **Low aspect ratio.**
  - **consistent with siting device in PBX vacuum vessel,**
  - **adequate minimum half width (>0.2 m).**

- **MHD stable at a reasonably high beta.**
  - **plasma current consistent with bootstrap.**

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Goals (cont)

- **Monotonic iota profile at highest achievable beta.**
  - $\iota_e < 0.5$,
  - $\iota_{ext}/\iota > 0.4$,
  - ι_0 consistent with good equilibrium and beam particle confinement (poloidal flux).

- **Realizable coils.**
  - "good" surface curvatures.

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Methods/Algorithm

- **Optimization of configurations at a fixed plasma current and pressure.**
  - **Choose initial n=0 shaping (using Aries as a guide):**
    - » **ε=1.8, δ=0.5, A=R/<a>=3.5.**
  - **Choose pressure and current profiles (using Aries as a guide)**
    - » **high critical ballooning β,**
    - » **good bootstrap alignment without outside current drive,**
    - » **large bootstrap fraction >85%.**

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Methods (cont.)

- Generate external transform by deforming boundary surface.
  - » Use optimizer to seach for quasi-axisymmetric configurations.
  - » n=0 shaping retained in the process.
- Modify boundary geometry to stablize n=1 external kink mode.
  - » outboard surface corrugation,
  - » geometry modification via optimizer.
- Modify boundary or pressure profile to stablize local ballooning modes.
  - » reduce pressure gradient in unstable regions,
  - » geometry modification via optimizer.

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Methods (cont.)

- **Optimization at finite beta and fixed current, while able to identify configurations that meet design goals at the reference operating point, often leads to**
  - » **magnetic hill in vacuum,**
  - » **reduced quasi-symmetry in vacuum and lower beta,**
  - » **lack of control of vacuum shear,**
  - » **a more difficult task for coil design.**

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Methods (cont.)

- **Optimization for configurations in vacuum.**
  - Choose initial n=0 terms with guidance from Aries,
    - » higher ballooning β limit when β is raised.
  - Generate external transform by deforming boundary surface.
    - » Use ‘optimizer’ to seach for quasi-axisymmetric configurations.
    - » n=0 shaping retained in the process.
    - » impose magnetic well and shear constraints.
  - Modify boundary to stabilize MHD modes at finite β.

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A Review of Design Evolution

- **Initial survays of configurations with 2, 3 and 4 field periods and non-monotonic iota profile.**
  - best fit into PBX vacuum vessel: A=3.5,
  - "good" all-around properties with 3 periods,
  - development of qas3_4 for the proposal.

- **Search for configurations with monotonic iota profile at 4% β which are stable to ideal MHD modes.**
  - External n=1 kink mode stablized by high edge shear,
  - Shear required for kink stabilization versus ι_e determined empirically.

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Design Evolution (cont.)

- Low iota in core region (ι_0 ~ 0.1),
- Development of qas3_j5 for the DOE presentation in May.

- **Search for kink stable configurations by using boundary surface modification.**
  - rippling outboard boundary surface,
  - boundary surface modification via optimizer,
  - improvement of Terpsichore,
  - development of qas3_c10.

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QAS3-C10, A Candidate Reference Configuration

- **Parameters at the reference operating point:**
  - **A=3.4**
  - **<a> = 0.4 m, a_{min}=0.26 m**
  - **Vol = 5.3 m^3**
  - **$R*B_{tor}$ = 1.6 (s=0) T-m**
  - **β = 4%**
  - **I_p = 201 kA**
  - **R_{mag} (at ϕ =0) = 1.6 m**
  - **m_{max}=6, n_{max}=3 (per period)**

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Other Candidate Configurations (Work still in progress)

- **QAS3_GK, optimized for vacuum.**
  - quasi-axisymmetry not adequate,
  - external MHD modes yet to be studied.
- **QAS2_J11**
  - quasi-axisymmetry needs improvement,
  - stabilization of MHD modes to be completed.
- **QAS4_C4**
  - quasi-axisymmetry needs improvement,
  - stabilization of MHD modes to be completed.
- **QAS2_H4**
  - stabilization of MHD modes to be completed.

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Summary and Conclusions

- **We have identified a candidate reference configuration that**
  - **has good quasi-symmetry, acceptable particle confinement,**
  - **fits into PBX vacuum vessel,**
  - **is stable to n=1 external kink and ballooning at 4% beta,**
  - **has monotonic iota profile at 4% beta, with ι_{ext}/ι~0.4,**
  - **has good equilibrium at 4% beta,**
  - **produces smooth current potential contours for coil construction.**

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Conclusions (cont.)

- **There are unfinished tasks:**
  - realizablilty with discrete coils,
  - robustness and sensitivity of the configuration to boundary changes,
  - robustness and flexibility to other P and I profiles,
  - goodness of flux surfaces in the presence of islands,
  - self-consistency of bootstrap current,
  - convergence studies of equilibria and stability,
  - stability to other low n modes and vertical displacement,
  - futher configuration improvement (e.g. allow n=0 to vary),
  - access trajectory and startup,
  - adequacy of poloidal flux and hence ι_{ext}.

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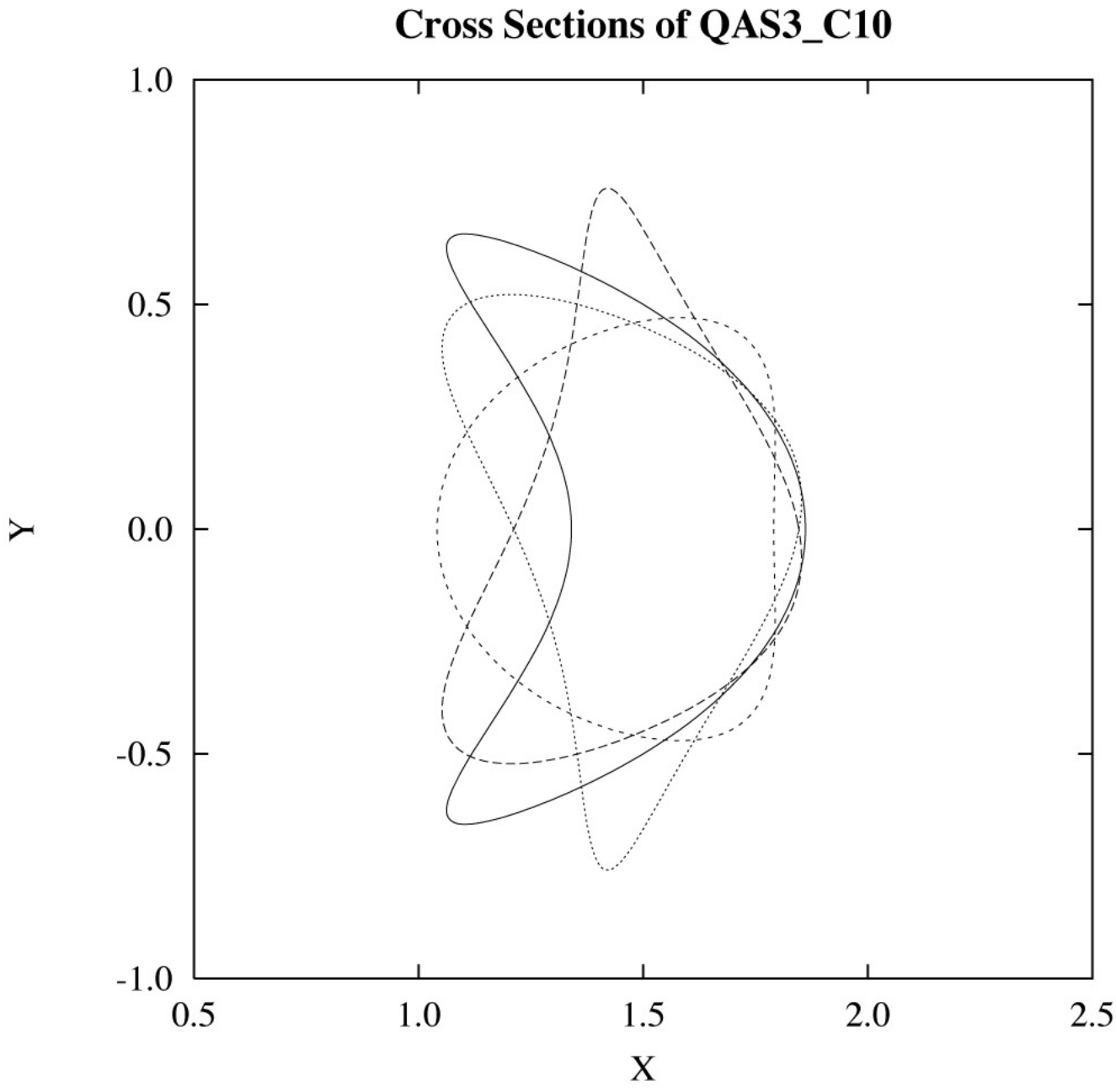
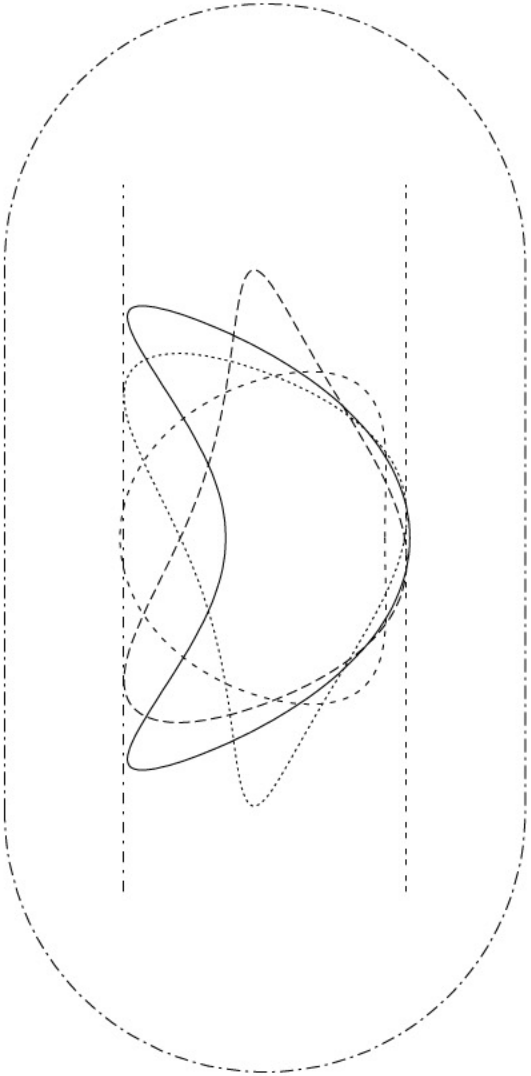
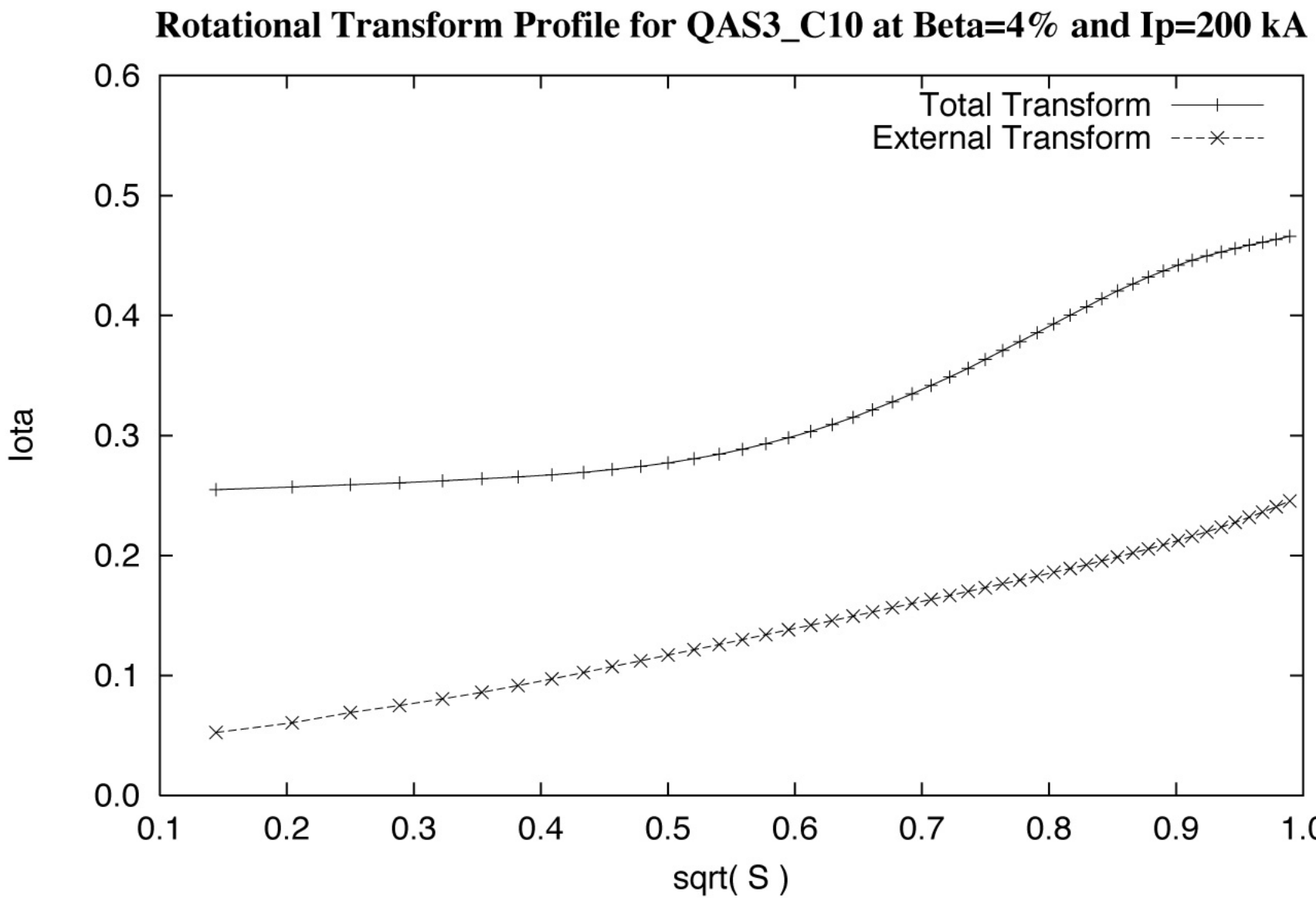
Conclusions (cont.)

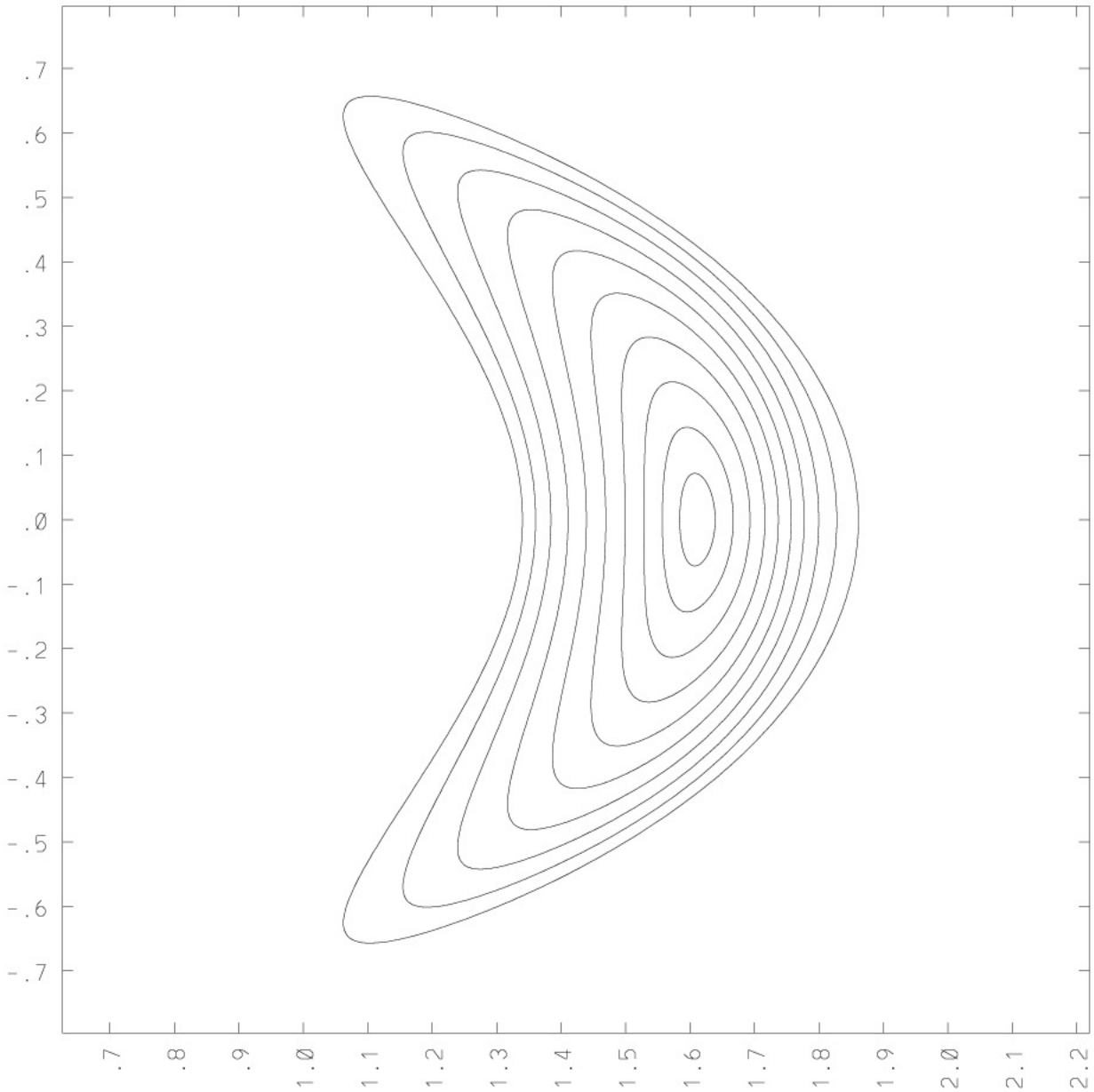
- **It is important to continue developing other potential candidates.**
  - **2 or 4 field periods may be more appropriate for PBX implementation,**
  - **2/4 hybrid may have overall better properties,**
  - **a ‘good’ configuration optimized for the vacuum may provide more flexibility in terms of experiments.**

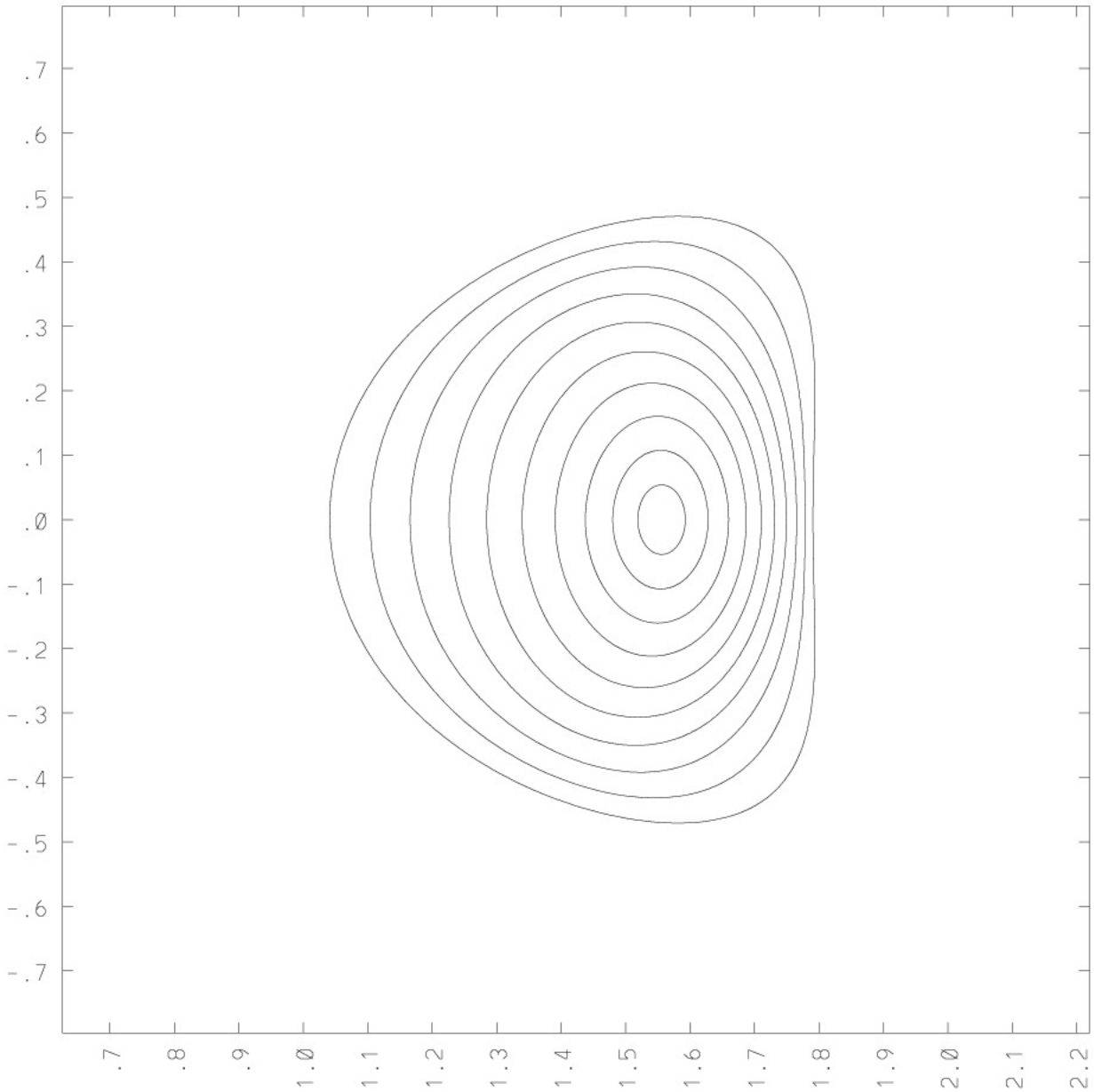

Cross Sections of QAS3_C10
1.0
0.5
0.0
-0.5
-1.0
Y
0.5
1.0
1.5
2.0
2.5
X

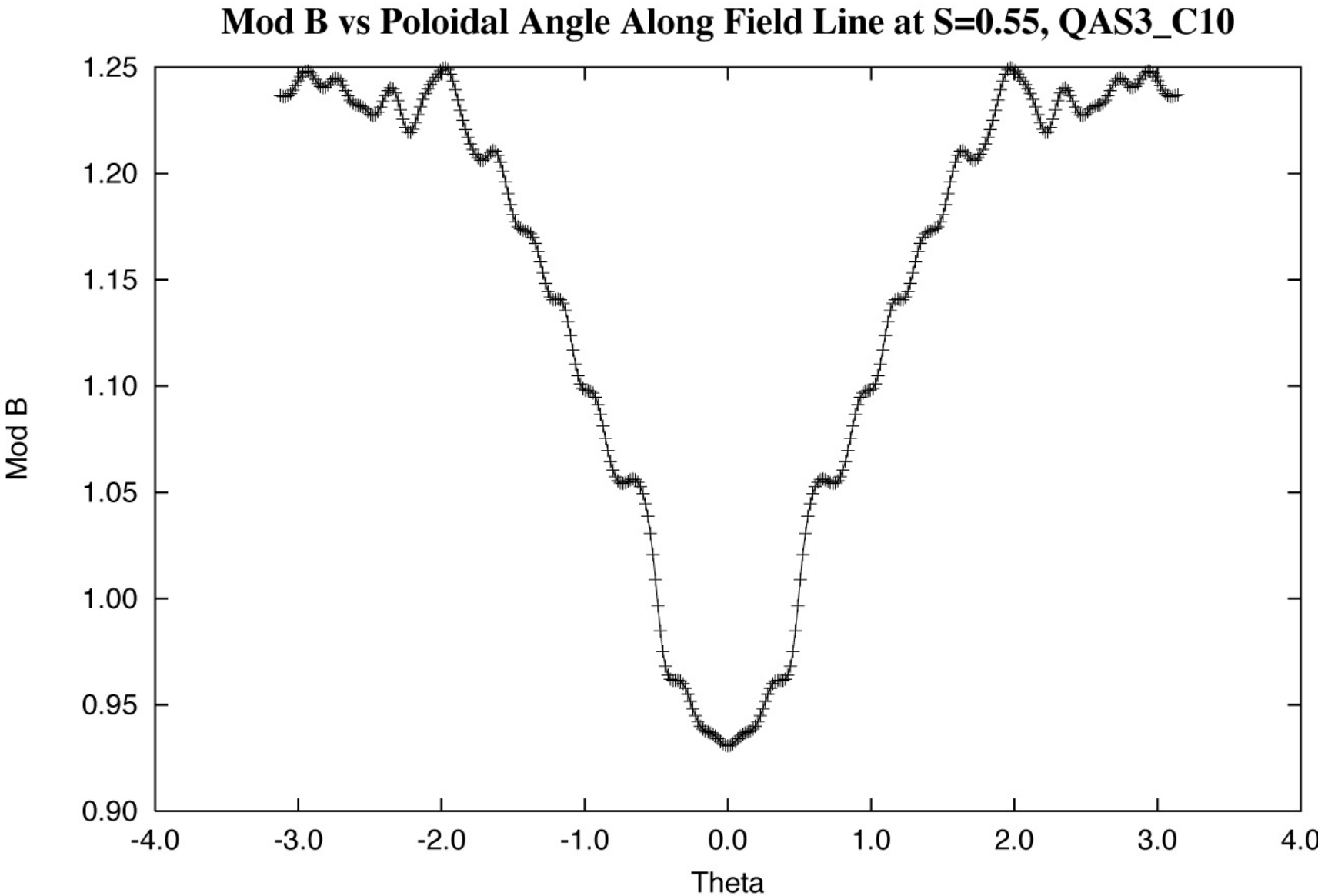
QAS3_C10 in PBX Vacuum Vessel

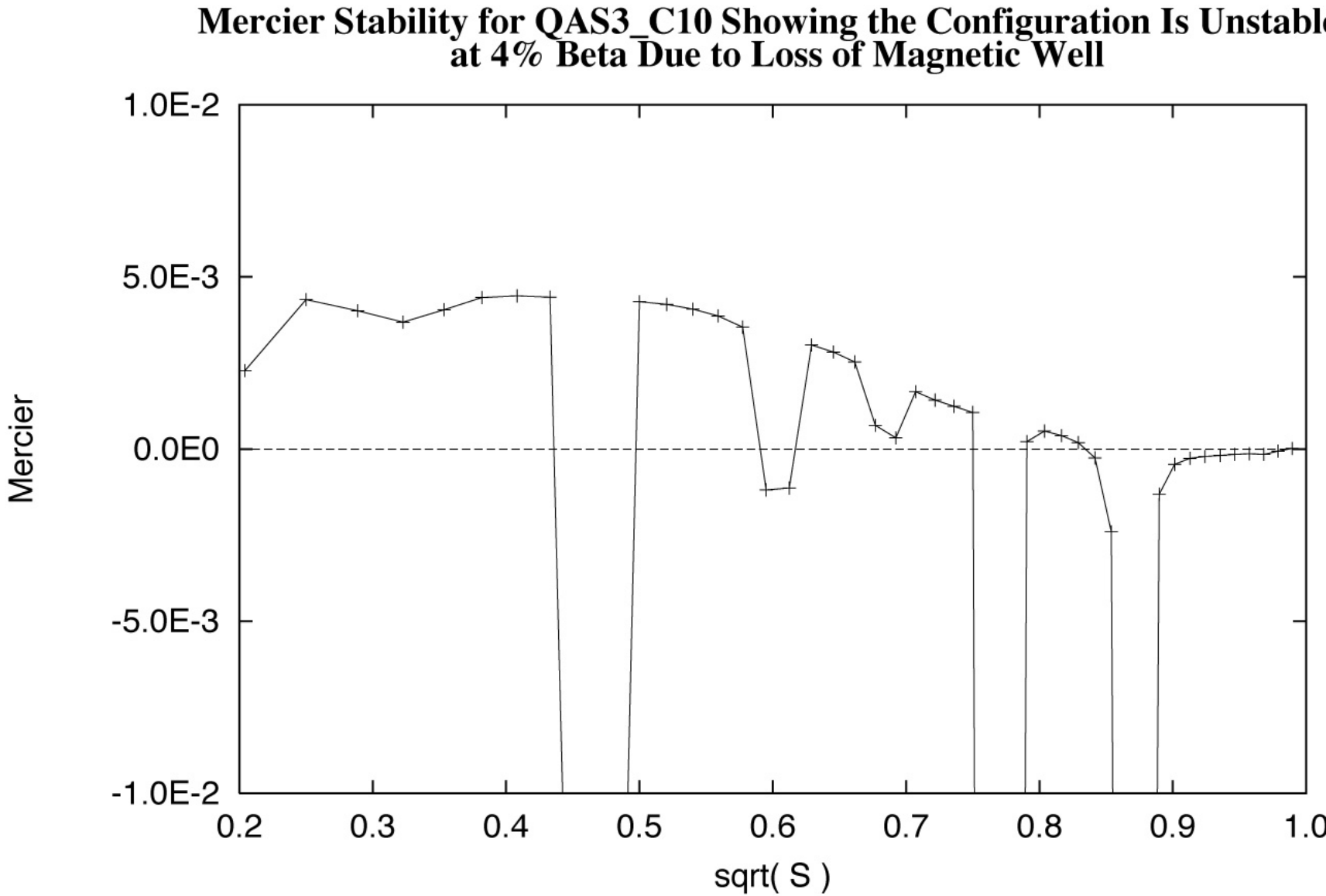


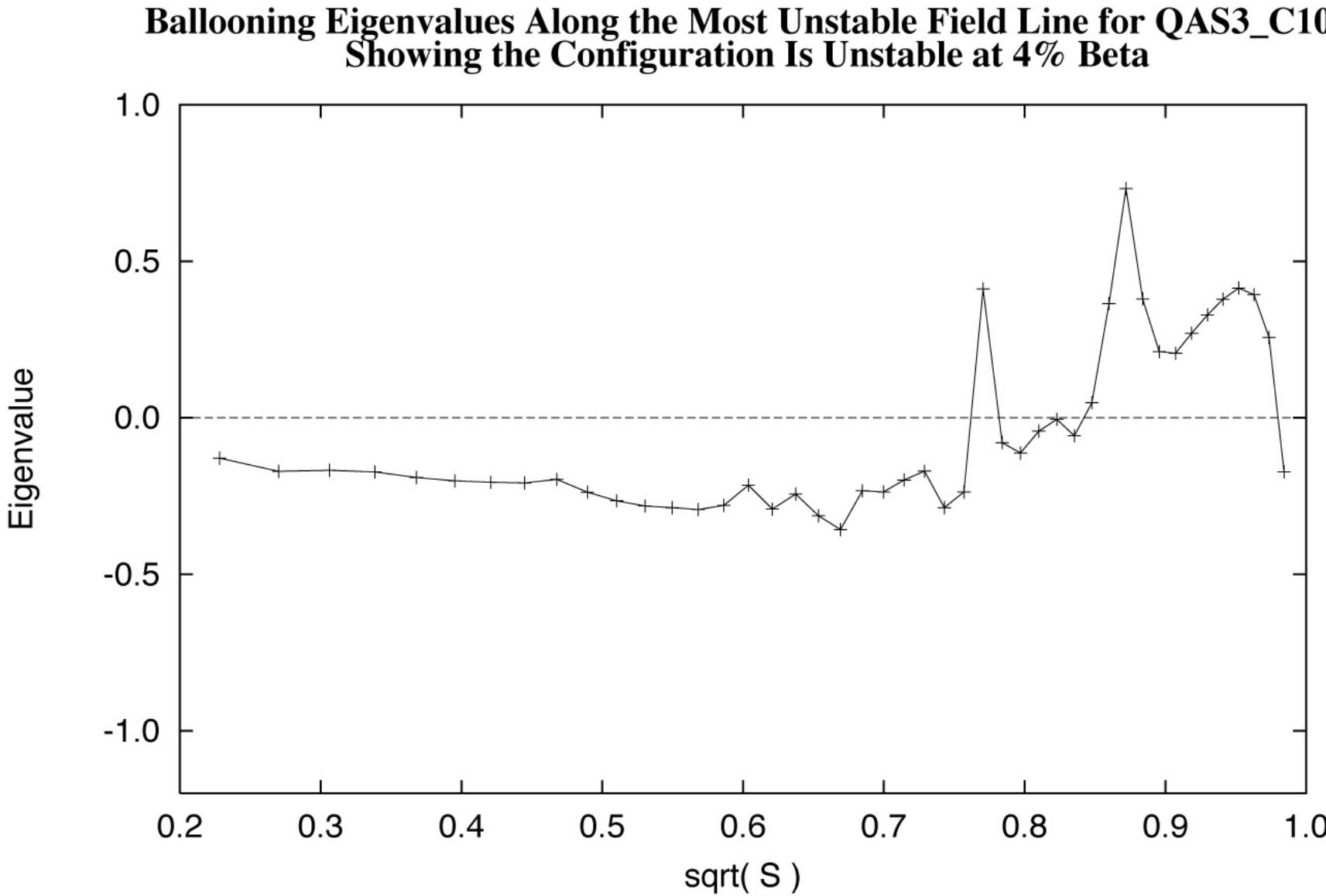

Rotational Transform Profile for QAS3_C10 at Beta=4% and Ip=200 kA
Total Transform
External Transform
Iota
sqrt(S)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

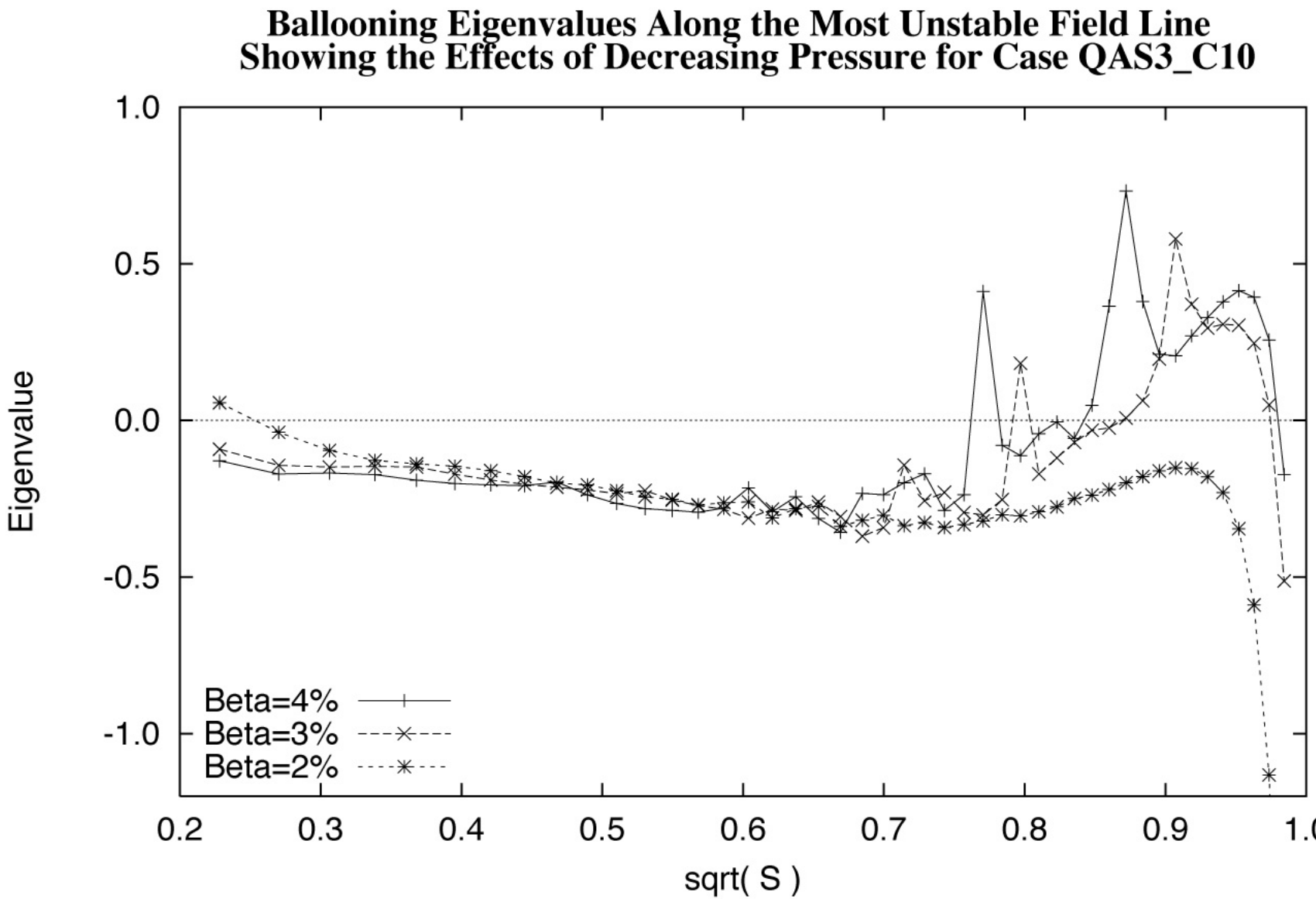

.7
.6
.5
.4
.3
.2
.1
.0
-.1
-.2
-.3
-.4
-.5
-.6
-.7
.7
.8
.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2.1
2.2

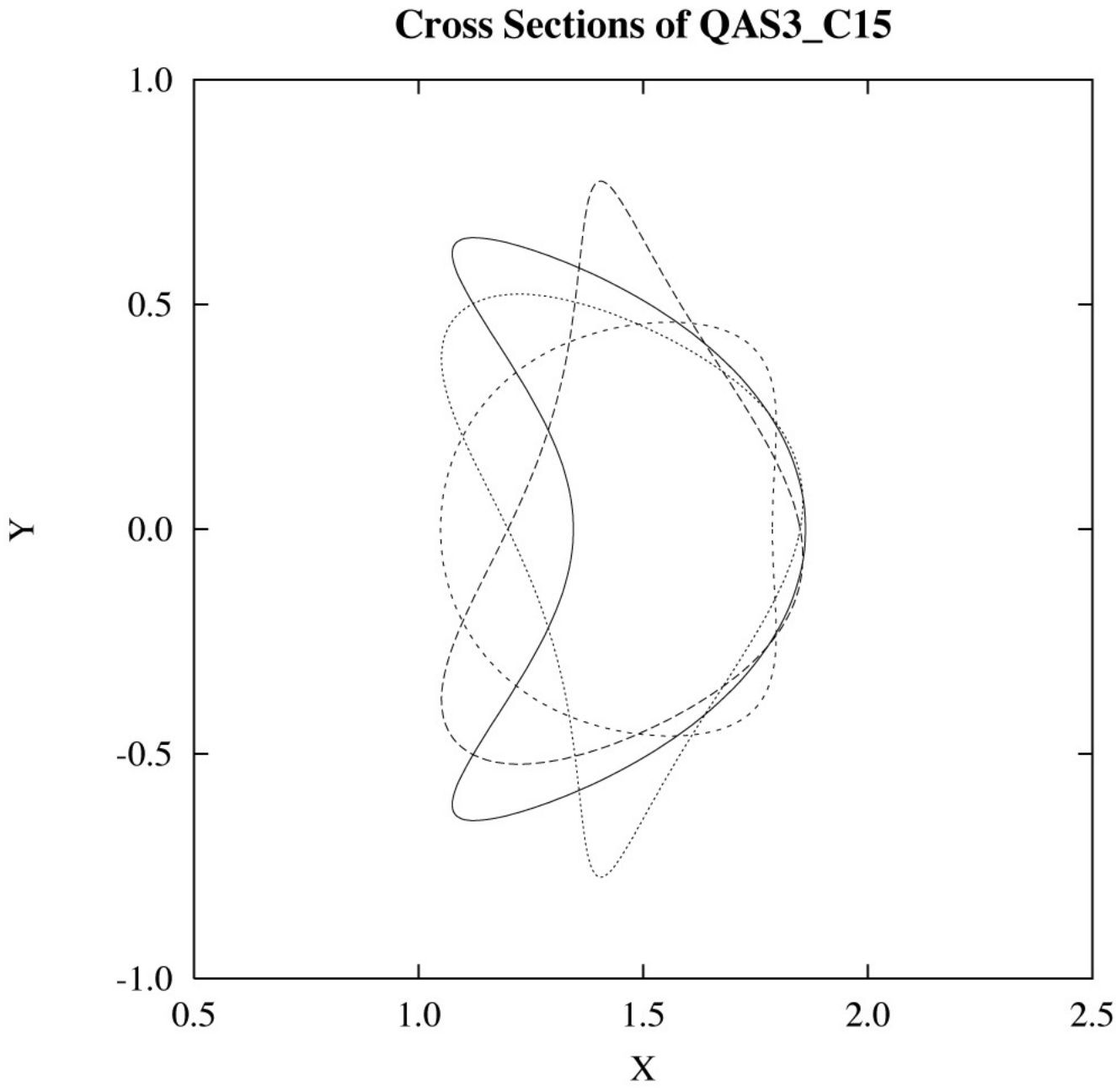

.7
.6
.5
.4
.3
.2
.1
.0
-.1
-.2
-.3
-.4
-.5
-.6
-.7
.7
.8
.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2.1
2.2

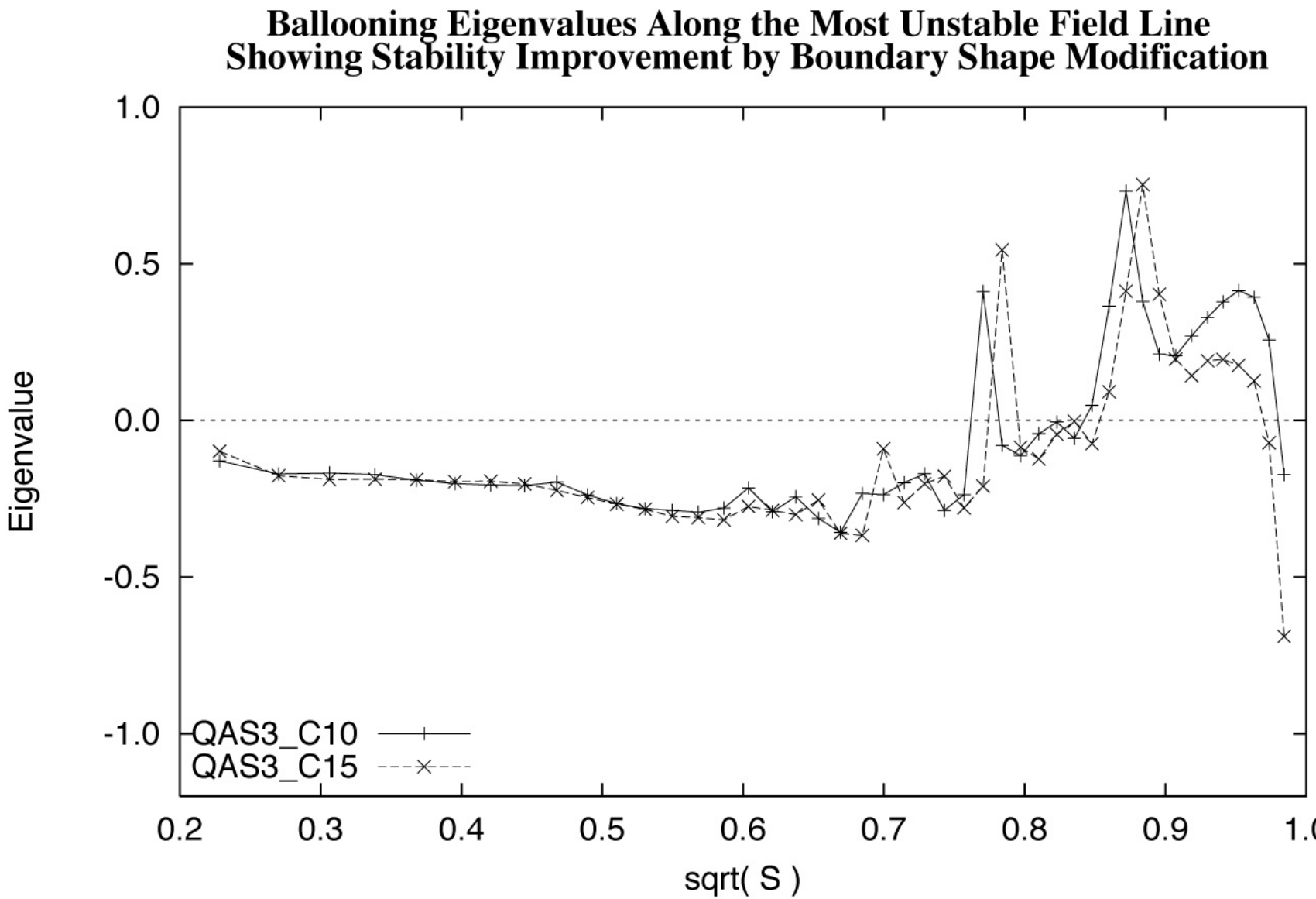

Mod B vs Poloidal Angle Along Field Line at S=0.55, QAS3_C10
Mod B
Theta
1.25
1.20
1.15
1.10
1.05
1.00
0.95
0.90
-4.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0
4.0

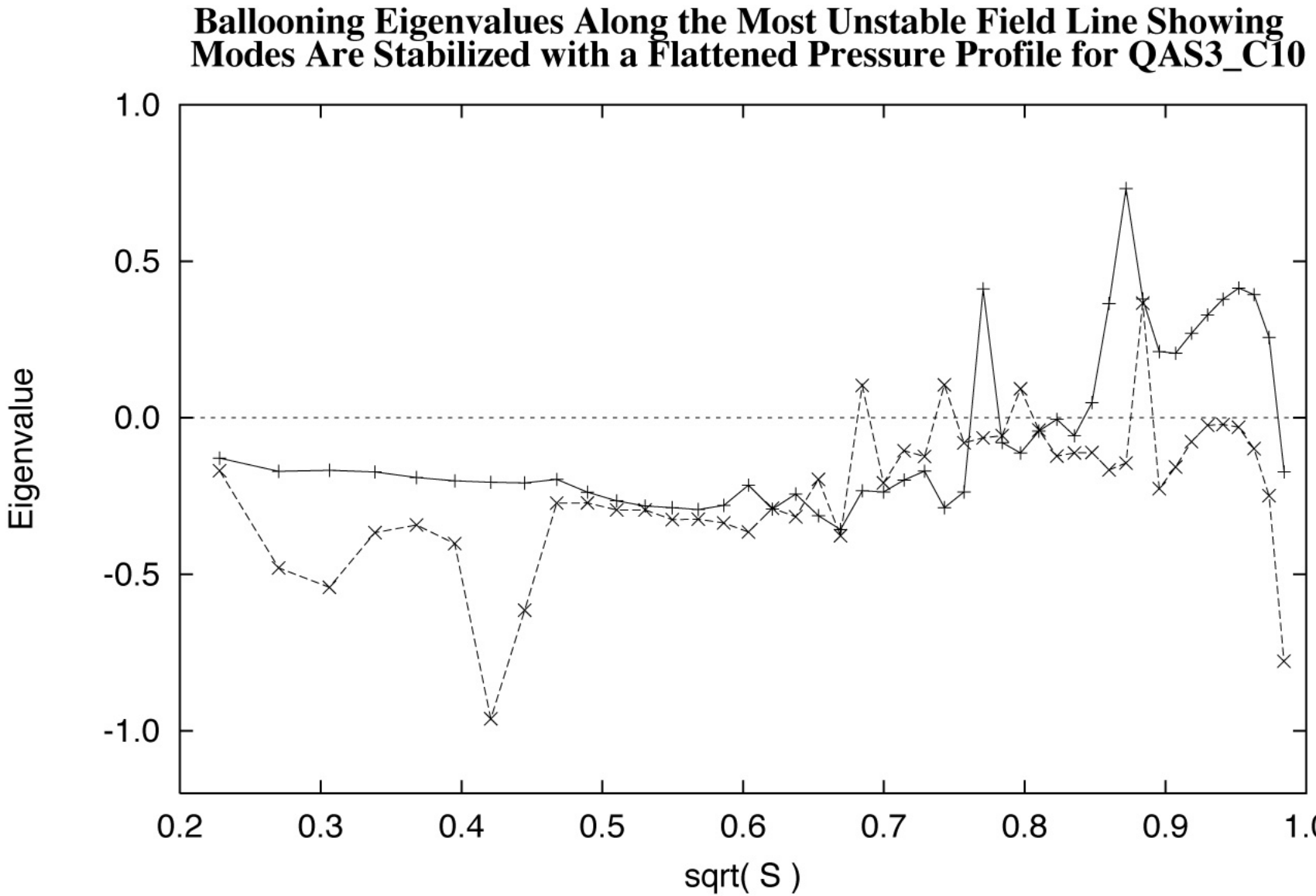

Mercier Stability for QAS3_C10 Showing the Configuration Is Unstable
at 4% Beta Due to Loss of Magnetic Well
1.0E-2
5.0E-3
0.0E0
-5.0E-3
-1.0E-2
Mercier
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
sqrt(S)

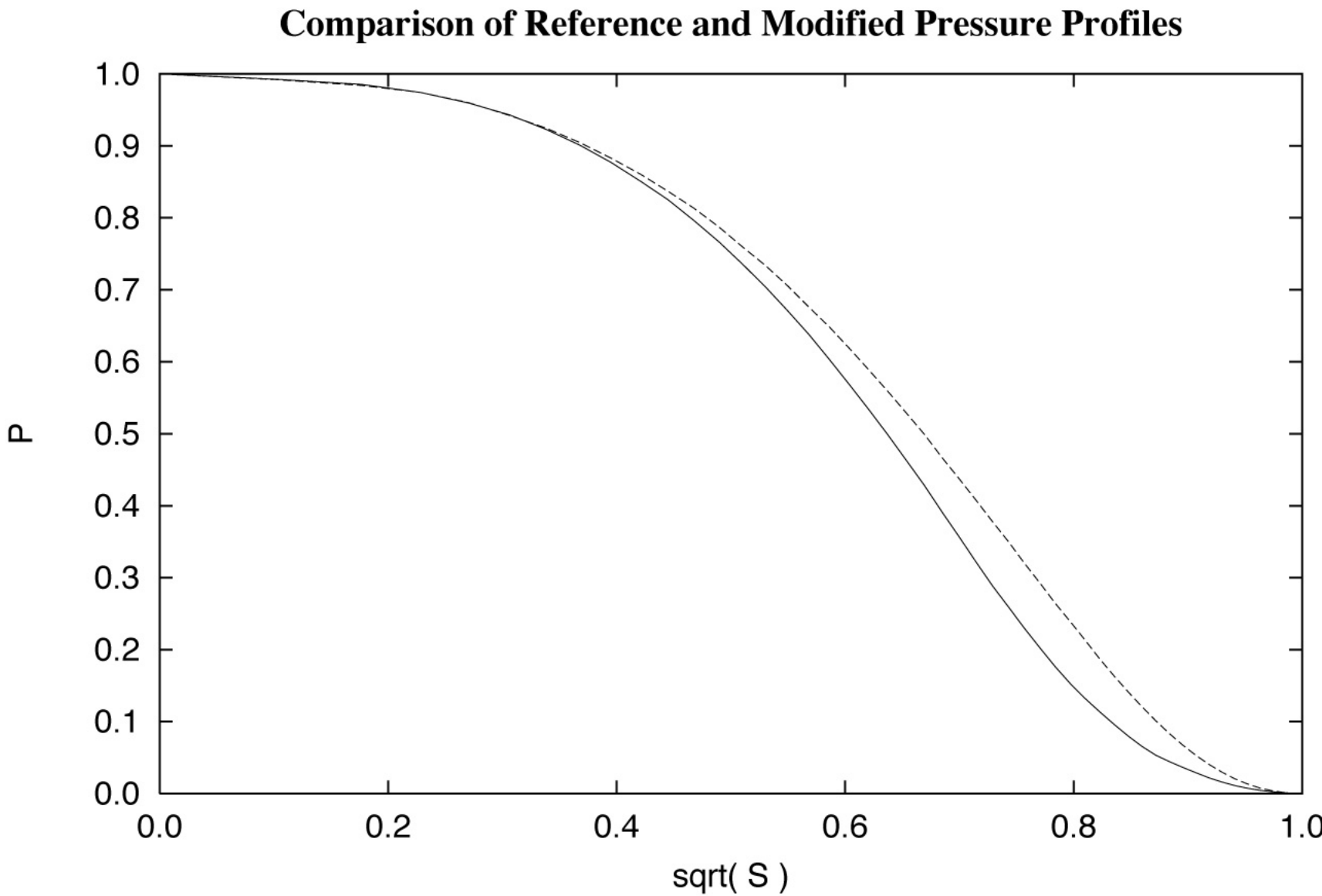

Ballooning Eigenvalues Along the Most Unstable Field Line for QAS3_C10
Showing the Configuration Is Unstable at 4% Beta
Eigenvalue
sqrt(S)
1.0
0.5
0.0
-0.5
-1.0
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

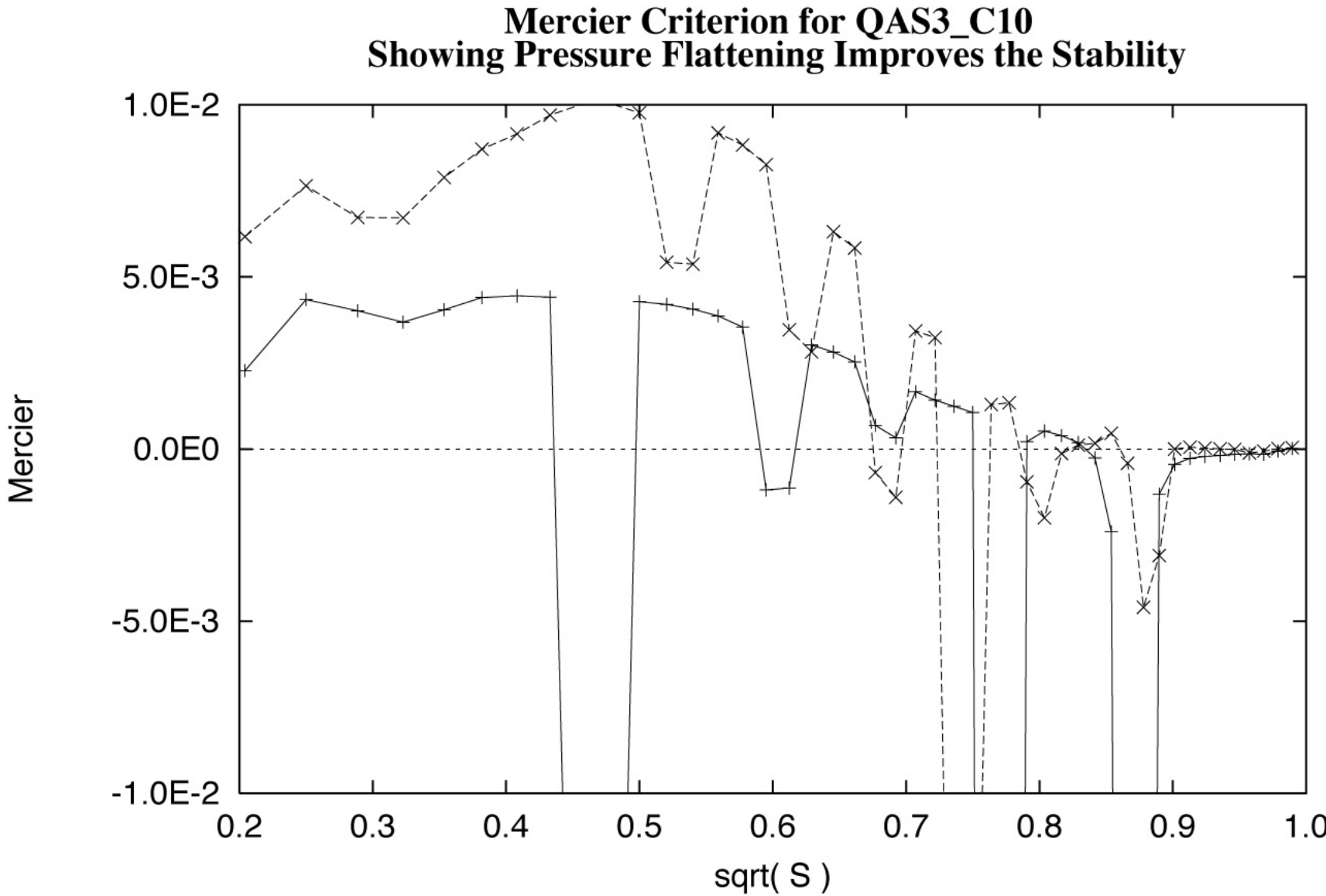

Ballooning Eigenvalues Along the Most Unstable Field Line
Showing the Effects of Decreasing Pressure for Case QAS3_C10
Eigenvalue
sqrt(S)
1.0
0.5
0.0
-0.5
-1.0
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Beta=4%
Beta=3%
Beta=2%


Cross Sections of QAS3_C15
1.0
0.5
0.0
-0.5
-1.0
Y
0.5
1.0
1.5
2.0
2.5
X

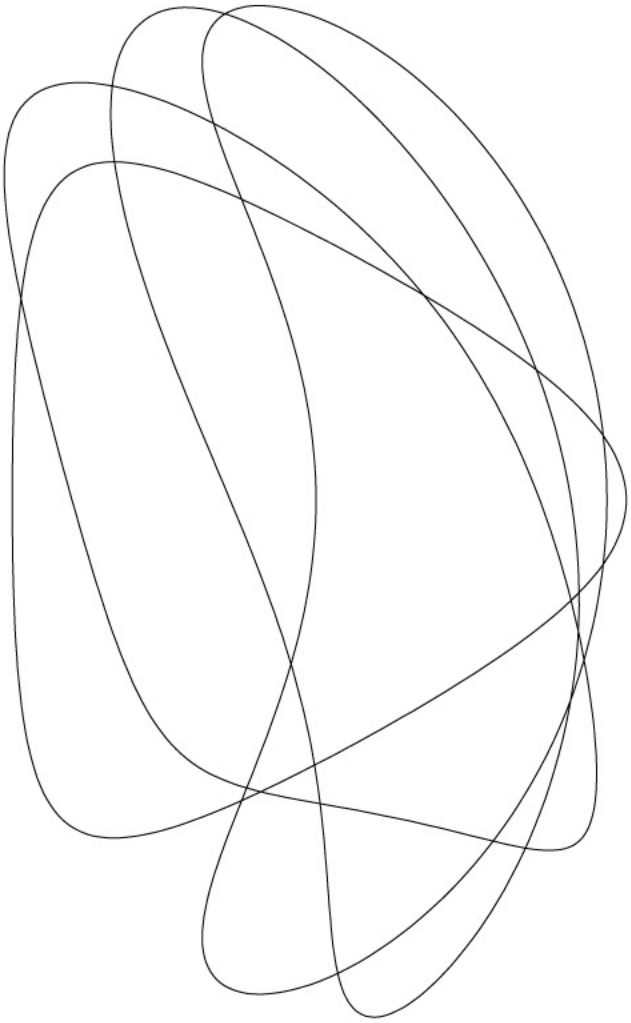

Ballooning Eigenvalues Along the Most Unstable Field Line
Showing Stability Improvement by Boundary Shape Modification
1.0
0.5
0.0
-0.5
-1.0
Eigenvalue
QAS3_C10
QAS3_C15
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
sqrt(S)

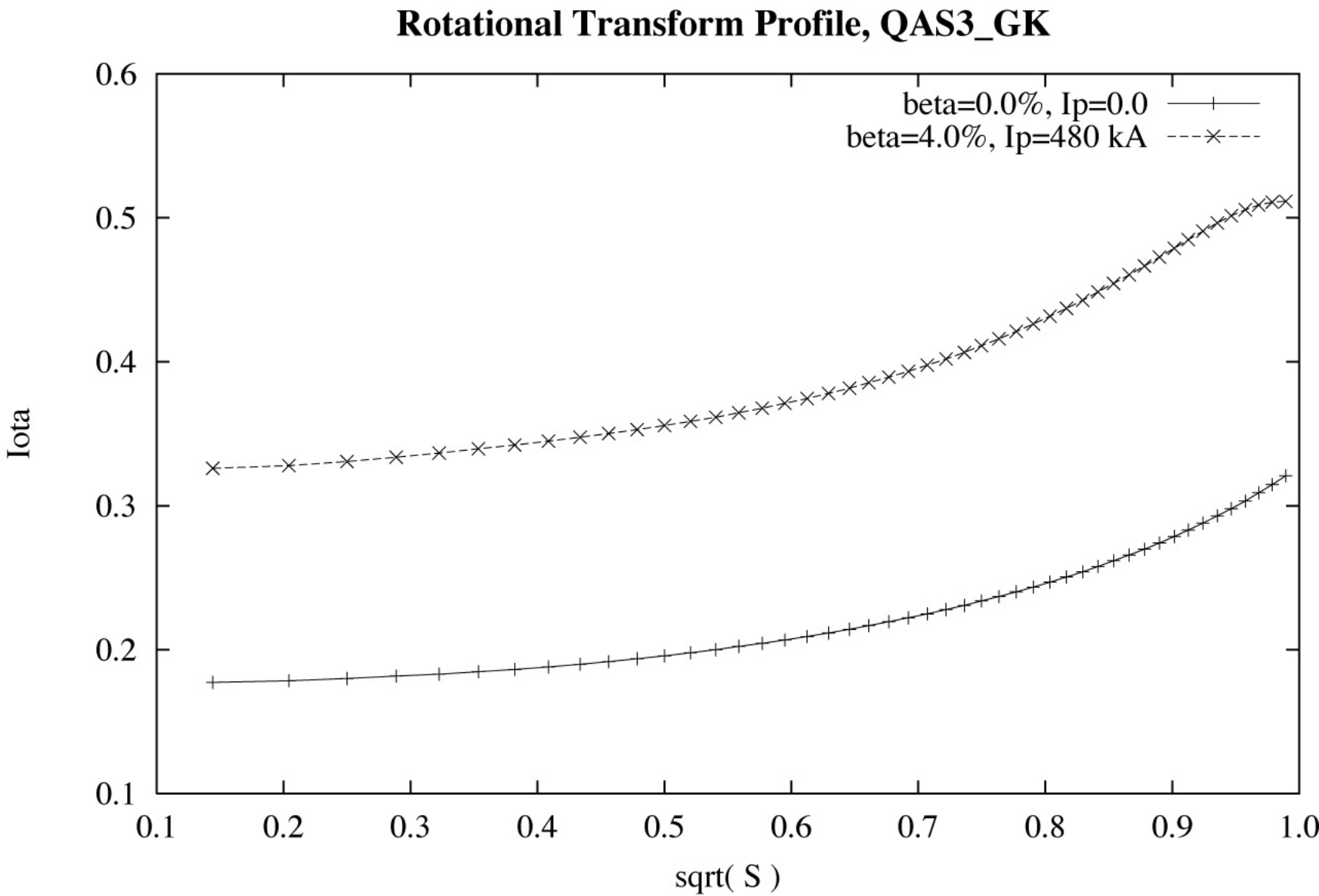

Ballooning Eigenvalues Along the Most Unstable Field Line Showing Modes Are Stabilized with a Flattened Pressure Profile for QAS3_C10
1.0
0.5
0.0
-0.5
-1.0
Eigenvalue
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
sqrt(S)

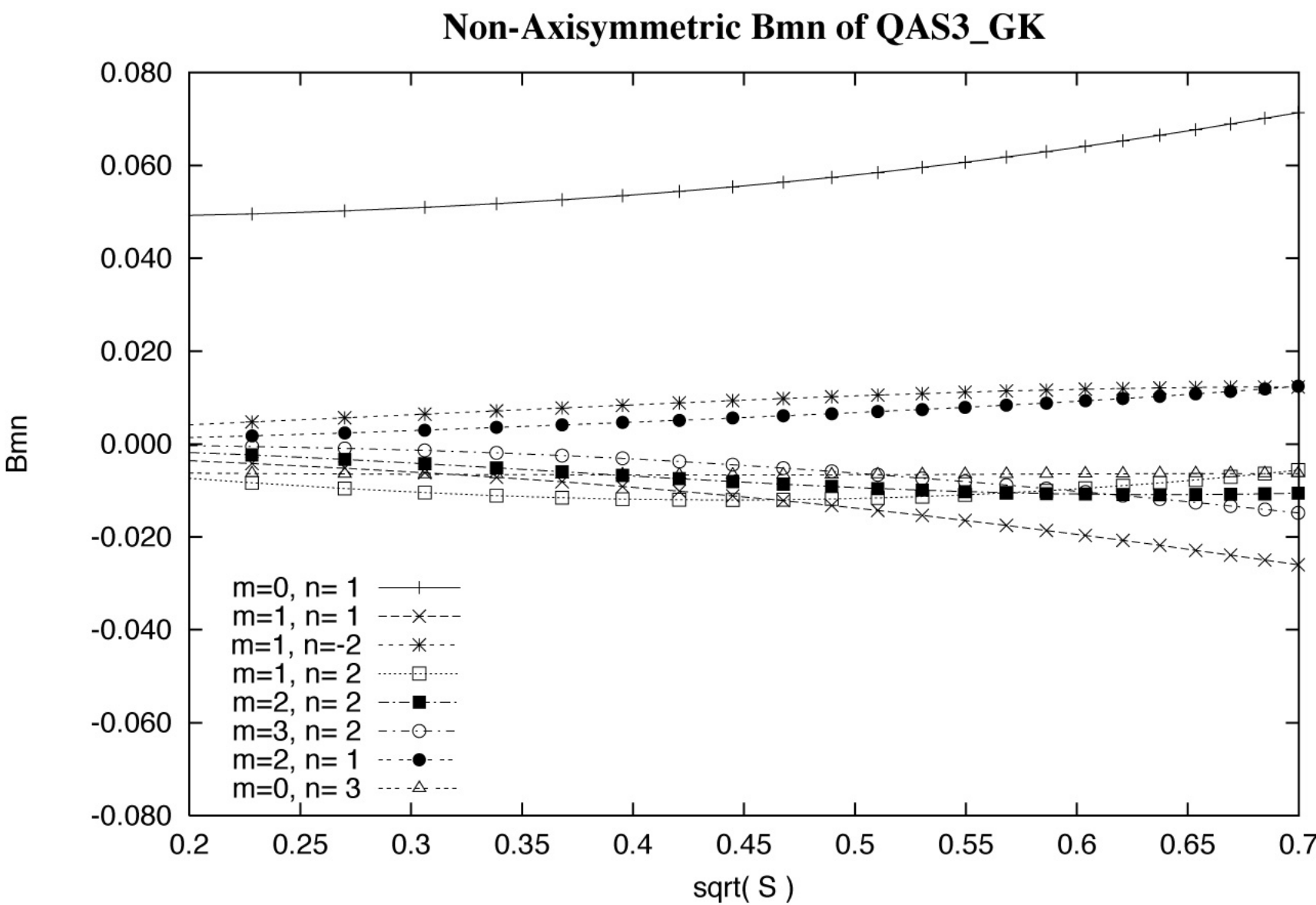

Comparison of Reference and Modified Pressure Profiles
P
sqrt(S)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0
0.2
0.4
0.6
0.8
1.0

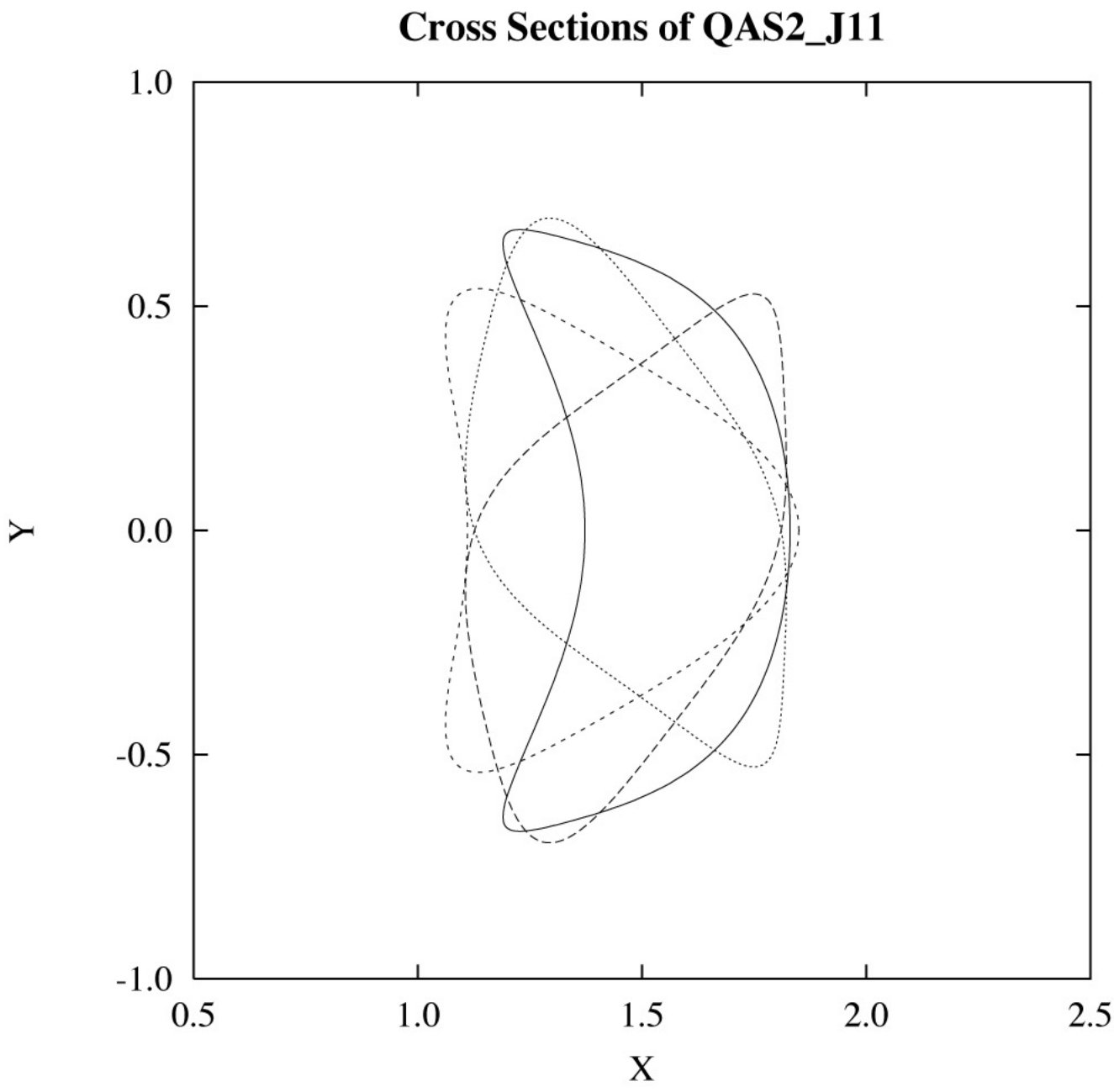

Mercier Criterion for QAS3_C10
Showing Pressure Flattening Improves the Stability
1.0E-2
5.0E-3
0.0E0
-5.0E-3
-1.0E-2
Mercier
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
sqrt(S)

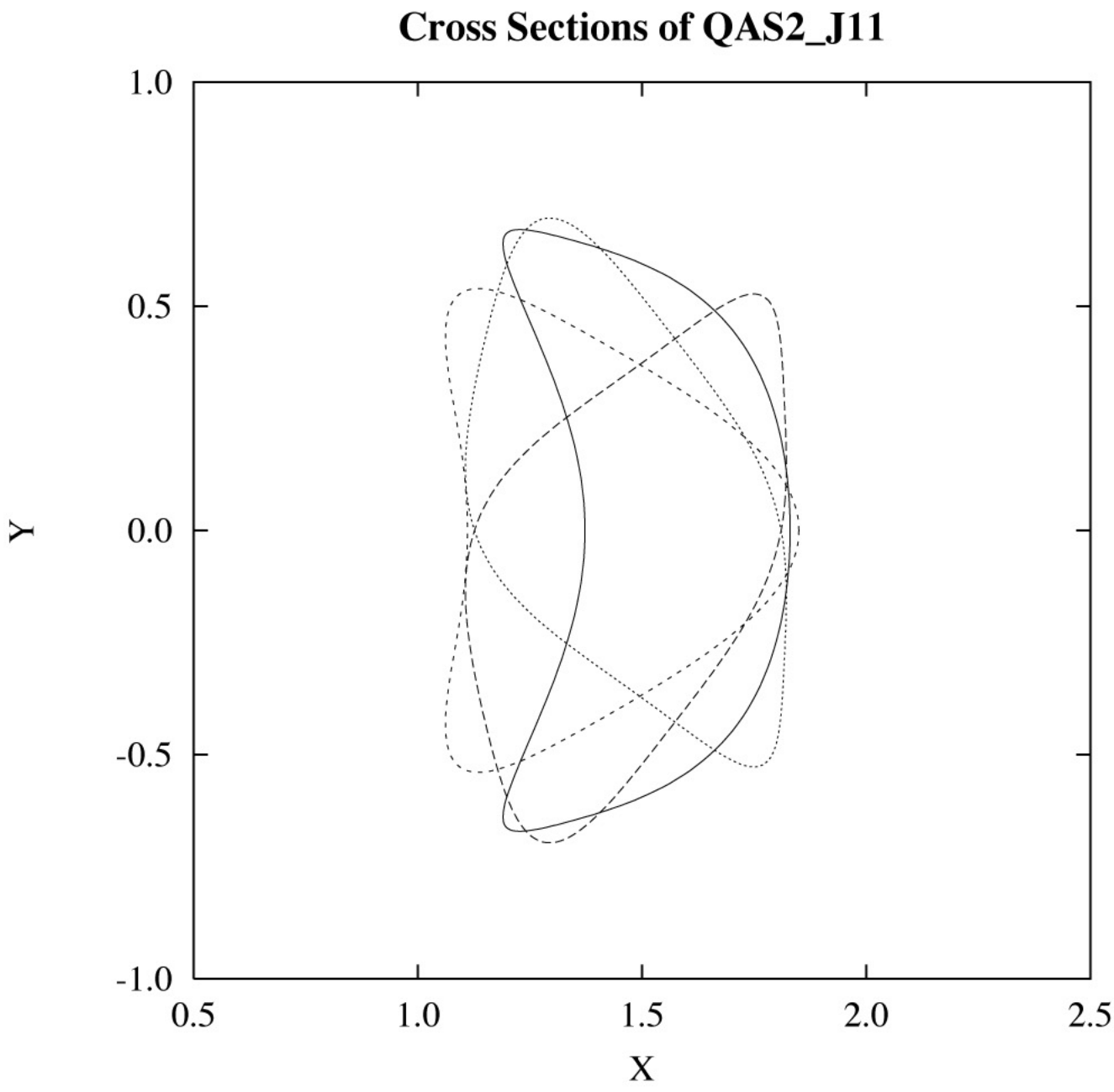
Cross Sections of QAS3_GK

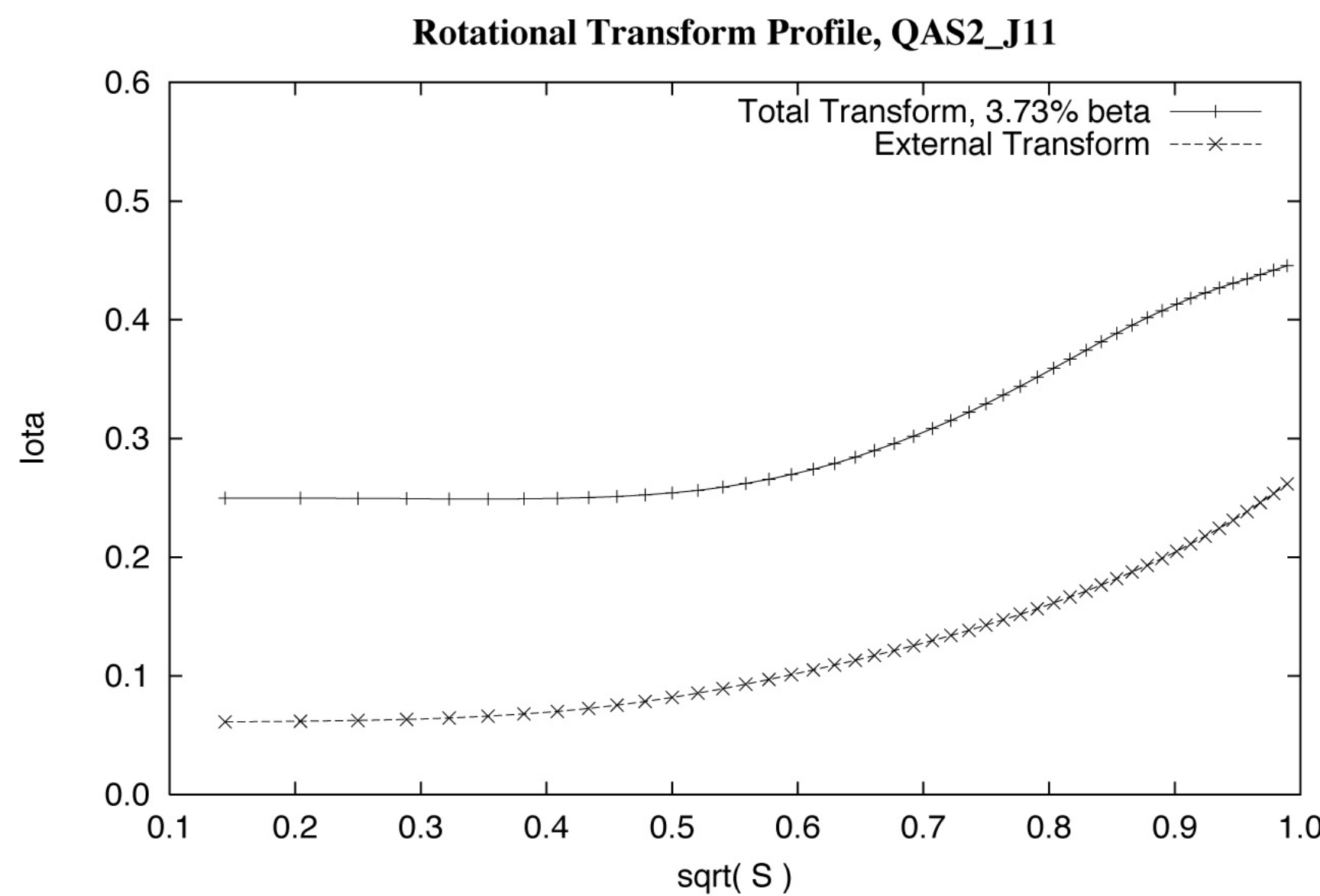


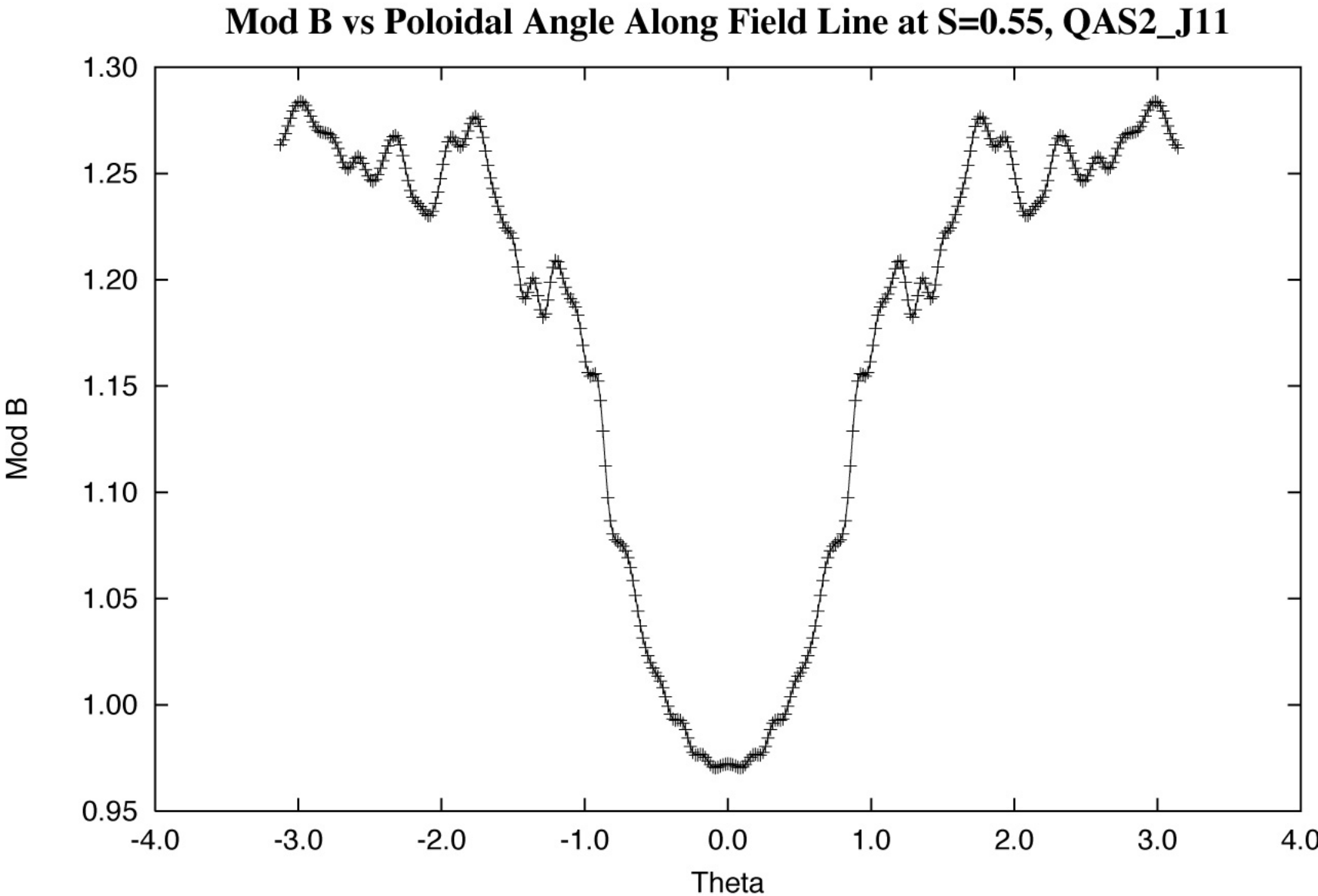

Rotational Transform Profile, QAS3_GK
beta=0.0%, Ip=0.0
beta=4.0%, Ip=480 kA
Iota
sqrt(S)
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

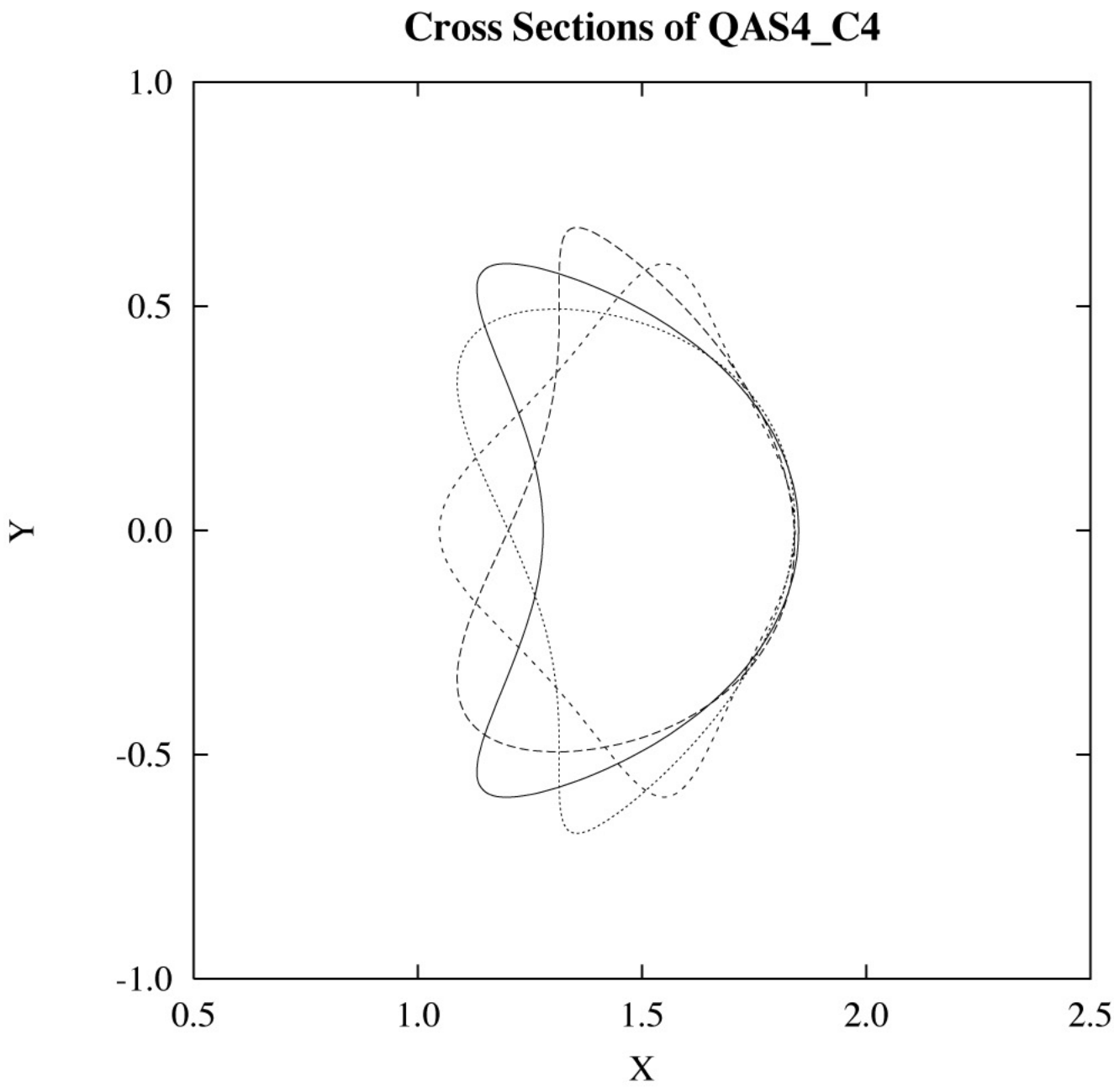

Non-Axisymmetric Bmn of QAS3_GK
Bmn
sqrt(S)
0.080
0.060
0.040
0.020
0.000
-0.020
-0.040
-0.060
-0.080
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
m=0, n= 1
m=1, n= 1
m=1, n=-2
m=1, n= 2
m=2, n= 2
m=3, n= 2
m=2, n= 1
m=0, n= 3

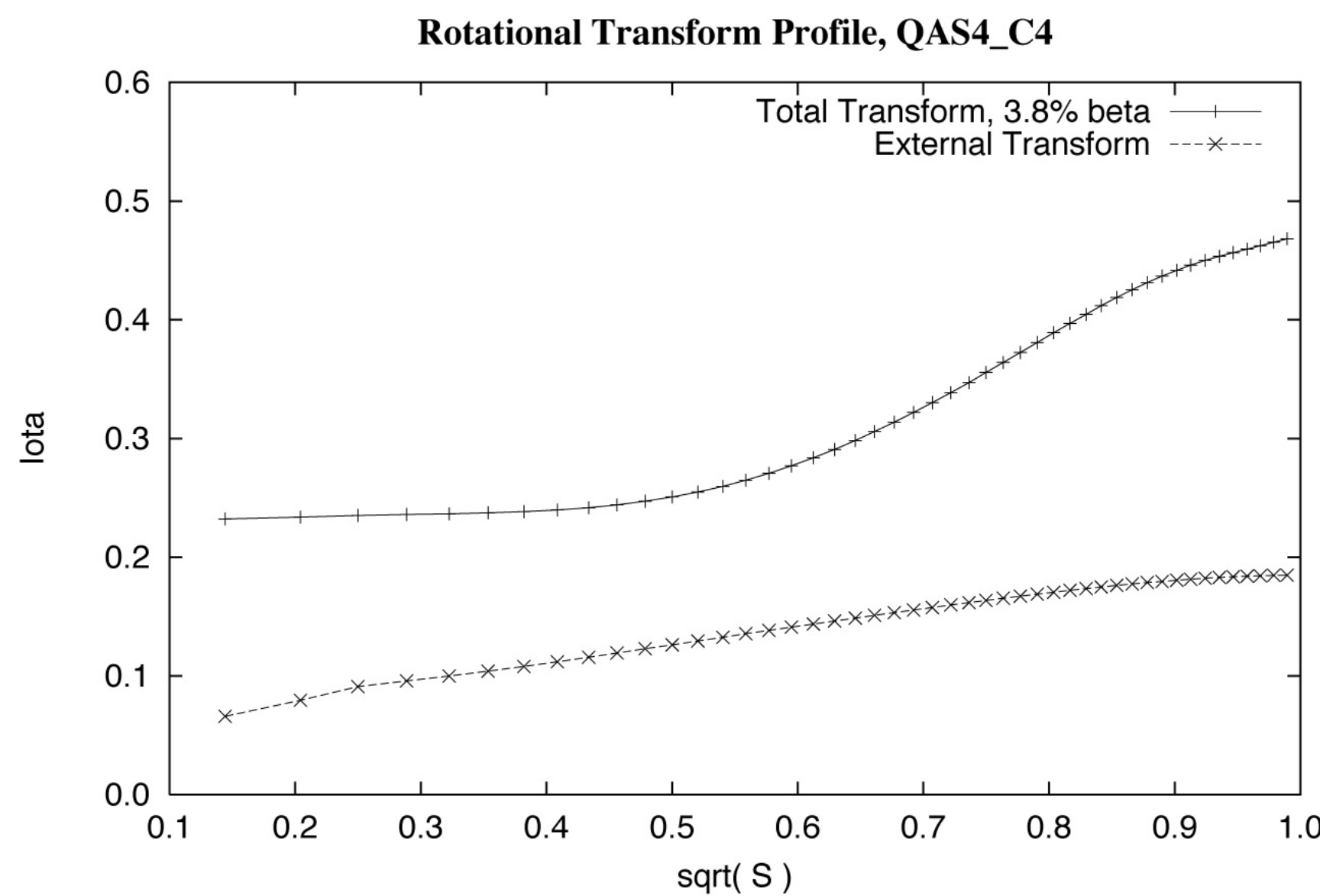

Cross Sections of QAS2_J11
1.0
0.5
0.0
-0.5
-1.0
Y
0.5
1.0
1.5
2.0
2.5
X

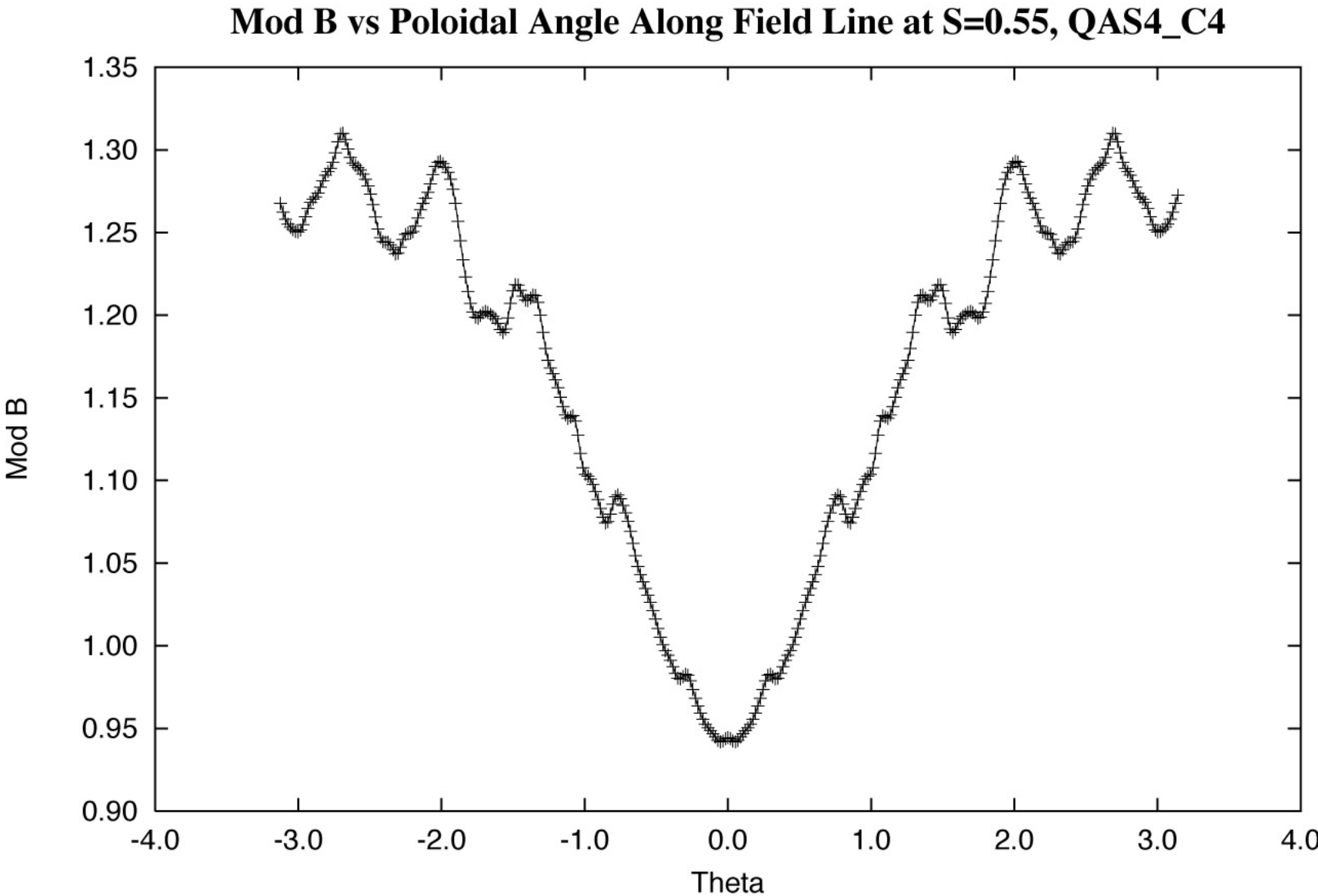

Cross Sections of QAS2_J11
1.0
0.5
0.0
-0.5
-1.0
Y
0.5
1.0
1.5
2.0
2.5
X

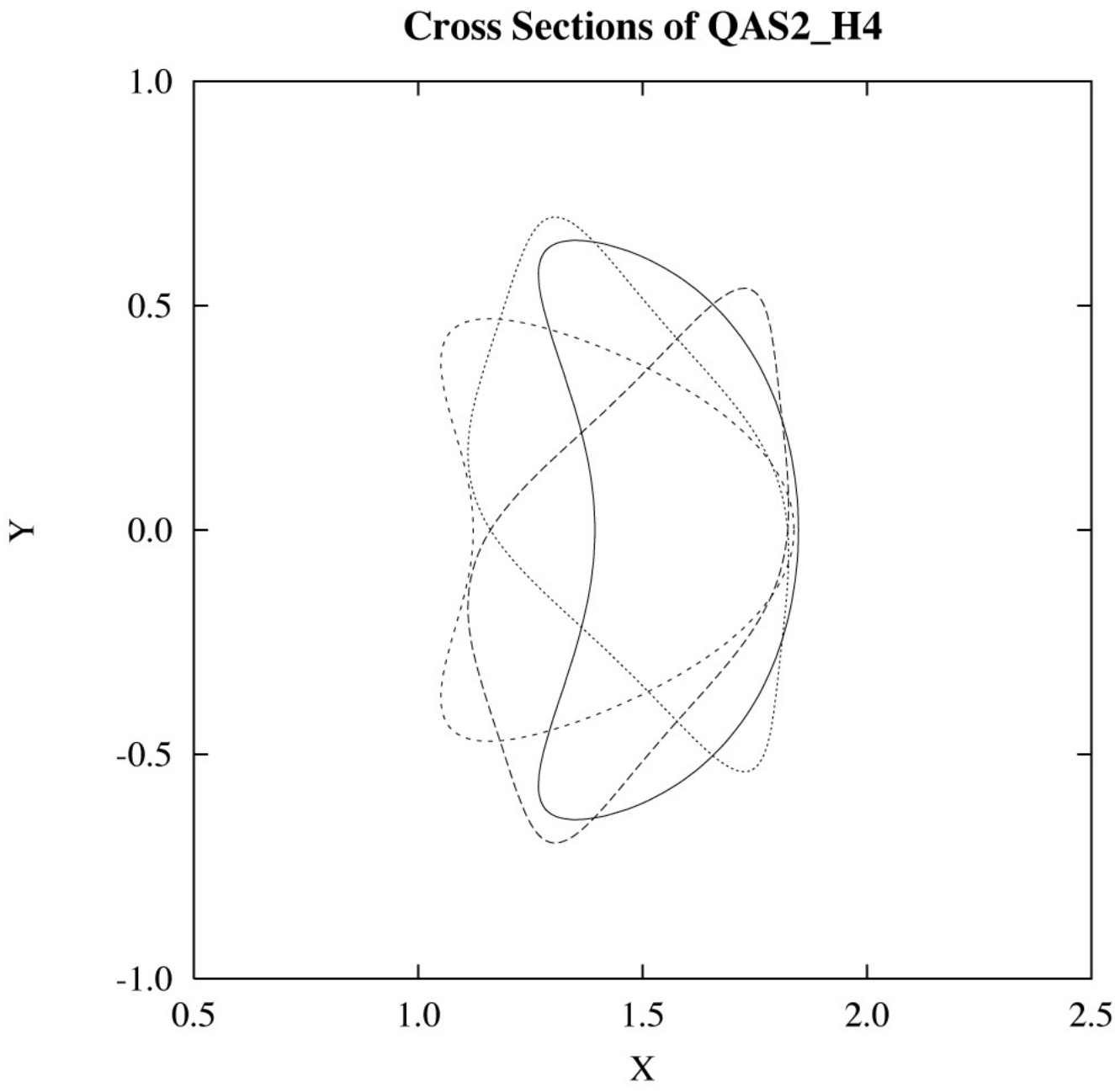

Rotational Transform Profile, QAS2_J11
Total Transform, 3.73% beta
External Transform
Iota
sqrt(S)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

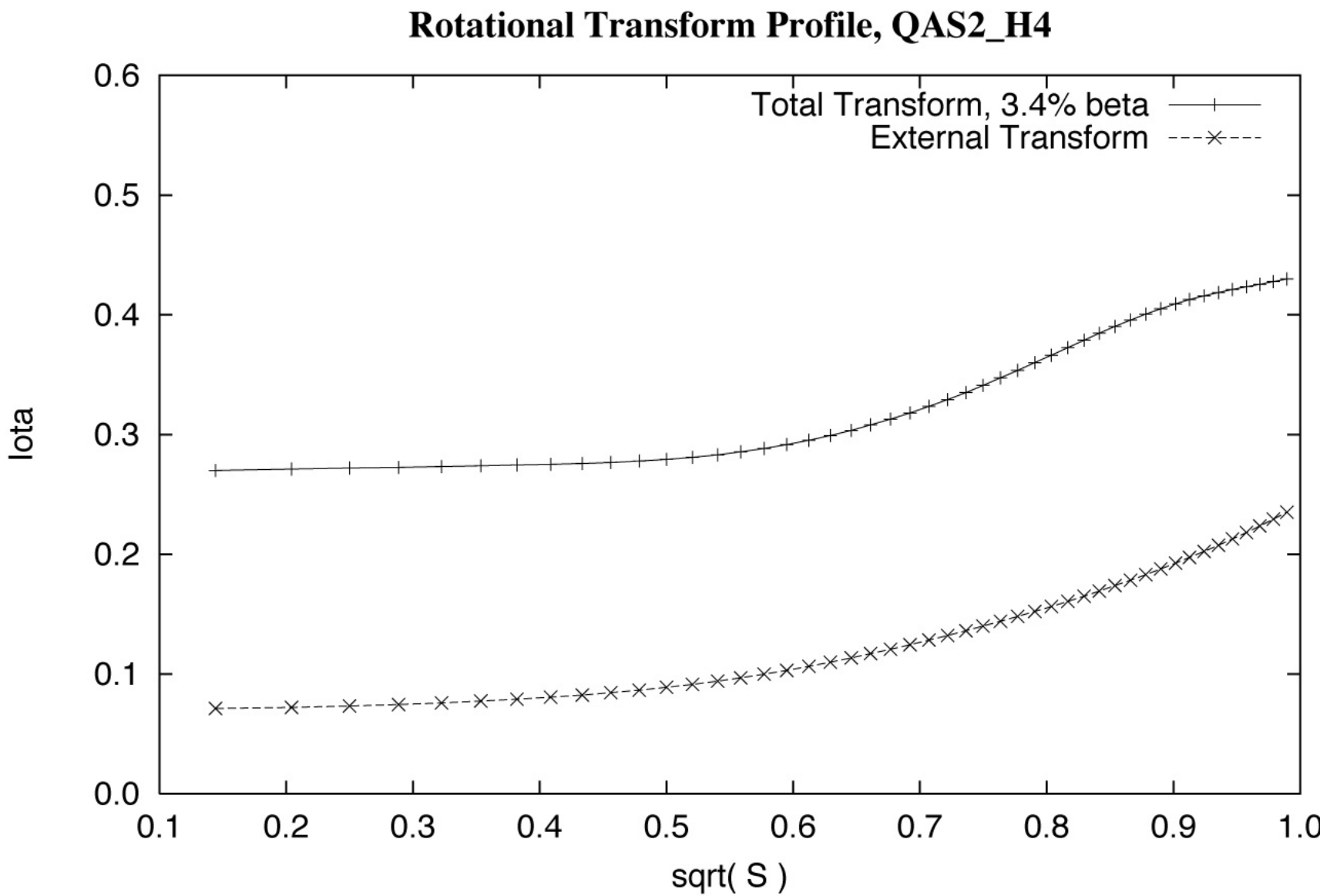

Mod B vs Poloidal Angle Along Field Line at S=0.55, QAS2_J11
Mod B
Theta
1.30
1.25
1.20
1.15
1.10
1.05
1.00
0.95
-4.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0
4.0

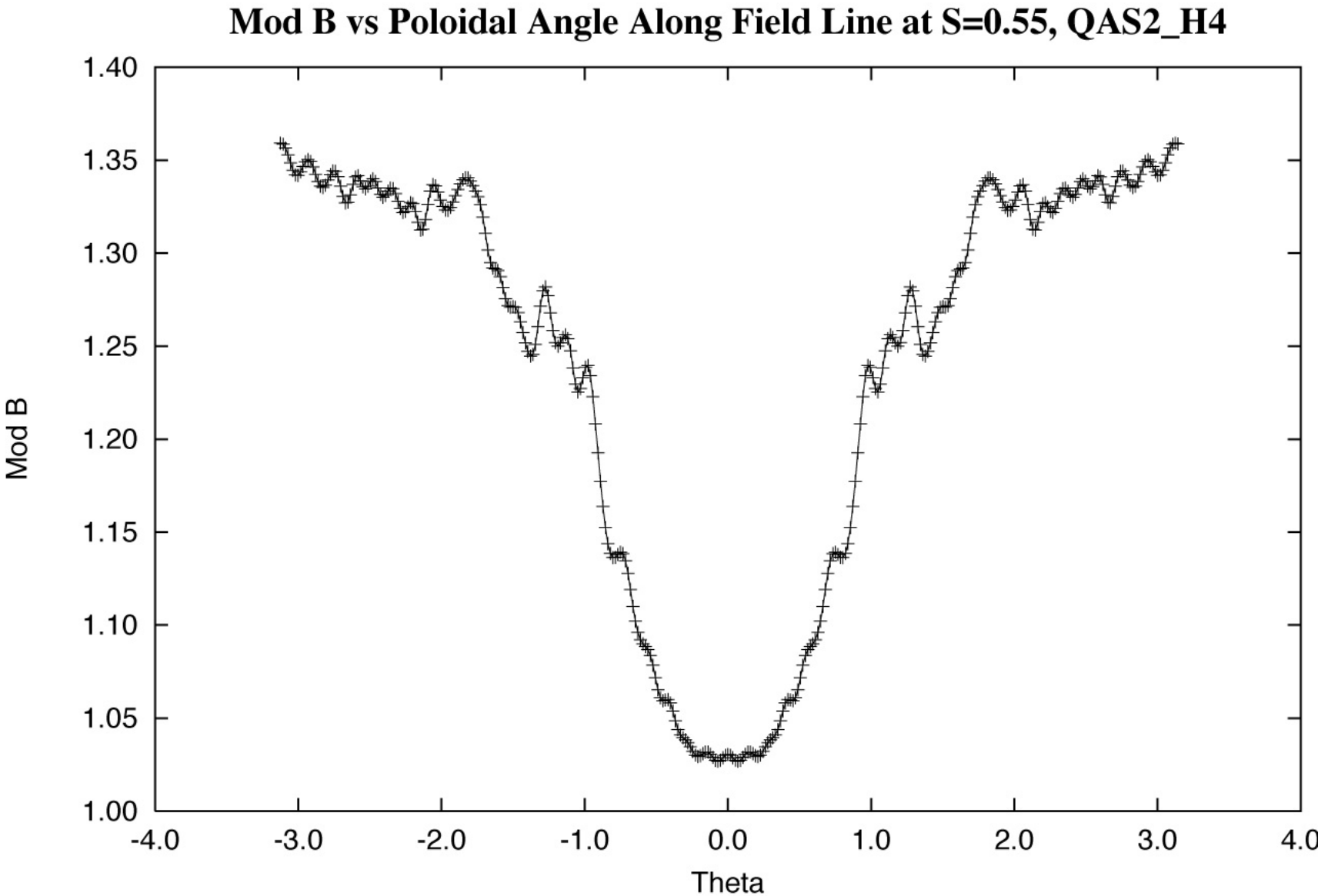

Cross Sections of QAS4_C4
1.0
0.5
0.0
-0.5
-1.0
Y
0.5
1.0
1.5
2.0
2.5
X

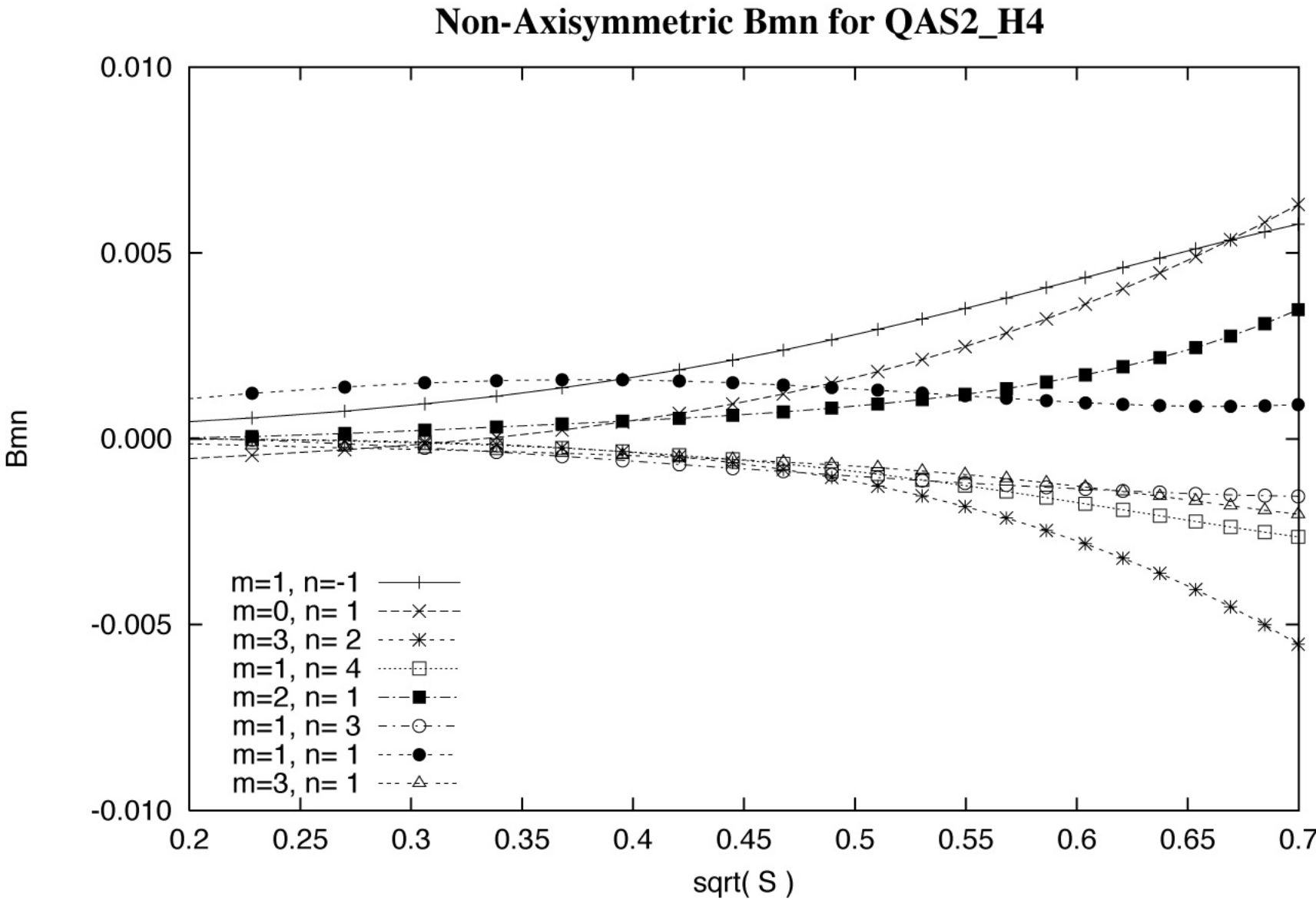

Rotational Transform Profile, QAS4_C4
Total Transform, 3.8% beta
External Transform
Iota
sqrt(S)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0


Mod B vs Poloidal Angle Along Field Line at S=0.55, QAS4_C4
Mod B
Theta
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


Cross Sections of QAS2_H4
1.0
0.5
0.0
-0.5
-1.0
Y
0.5
1.0
1.5
2.0
2.5
X


Rotational Transform Profile, QAS2_H4
Total Transform, 3.4% beta
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


Mod B vs Poloidal Angle Along Field Line at S=0.55, QAS2_H4
Mod B
Theta
1.40
1.35
1.30
1.25
1.20
1.15
1.10
1.05
1.00
-4.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0
4.0


Non-Axisymmetric Bmn for QAS2_H4
0.010
0.005
0.000
-0.005
-0.010
Bmn
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
sqrt(S)
m=1, n=-1
m=0, n= 1
m=3, n= 2
m=1, n= 4
m=2, n= 1
m=1, n= 3
m=1, n= 1
m=3, n= 1