VERTICAL STABILITY

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presented at

NCSX Project Meeting
PPPL
March 30-31, 1999

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OUTLINE

* Motivation
* Method
    - CAS3D2MN MHD Stability Code
* Results of Benchmarking
    - Internal mode stability
    - External mode stability
    - Vertical mode stability
* Summary

MOTIVATION:

* Quasi-axially symmetric stellarator (QAS):
  may combine the best features of stellarators and tokamaks.

  - High fusion power tokamak experiments
    often terminated by current and MHD-driven disruptions

  - Candidate configuration must optimize
    QAS MHD stability and particle confinement
    as well as be consistent with practical coil designs

* Classical stellarators, with zero elongation and zero current,
  are vertically stable.

* W7-X stellarator under construction at Greifswald, Germany,
  is elongated, but has zero current.

* National Compact Stellarator Experiment (NCSX) QAS designs

  - Based on TPX and ARIES reversed shear tokamaks

  - Highly elongated and high (~ 200 MA) bootstrap current

  - Kink and vertical instabilities must be calculated
    and control systems devised if necessary

*** For confidence in the vertical instability predictions**

- Benchmark CAS3DMN code against other codes
for axisymmetric and nonaxisymmetric instabilities

* Vertical Instability in Tokamaks

- Neutrally stable in circular geometry
  unstable in the direction of elongation, if elongated

- Stability for field decay index $n = -(R/B_z)(dB_z/dR) > 0$
  depending on the vertical field and the major radius

- With a conducting wall,
  stabilization up to a critical elongation

- With a resistive shell (σ finite), growth rate depends on
  resistive penetration time of the shell, $\gamma \propto 1/\tau_R$

- Toroidal stabilizing effect has been found with
  a higher critical elongation at which the inertial growth
  transitions to growth on a resistive time scale.

*** Consequently stellarator vertical instability**
may be less of a problem than for tokamaks.

* COMPARISONS OF CAS3D WITH TERPSICHORE

* Good overall agreement for fixed boundary

* QAS at 6.73, 6.5 and 6.0% β, for 129 and 48 flux surfaces

  - Same radial profile of the most unstable mode,

  - Same mode numbers for the largest amplitude Fourier components, with few exceptions

  - Reduced λ of most unstable mode as β decreases

* CAS3D takes 31,000 sec and TERPSICHORE takes 95 sec to calculate stability for 129 flux surfaces

  - CAS3D used higher resolution in mapping (1296 vs 264) and a finer flux tube grid (144x144 vs 87x41)

  - CAS3D could resolve unstable modes at 6% beta and do pseudoballooning (high n) stablity

  - TERPSICHORE designed for rapid computation

RESULTS FOR EXTERNAL KINK STABILITY

* Axisymmetric calculations:
 Comparison of external kink calculations for ARIES tokamak

- Stability of eigenvalues and structure of eigenfunctions show agreement between CAS3D, TERPSICHORE and PEST

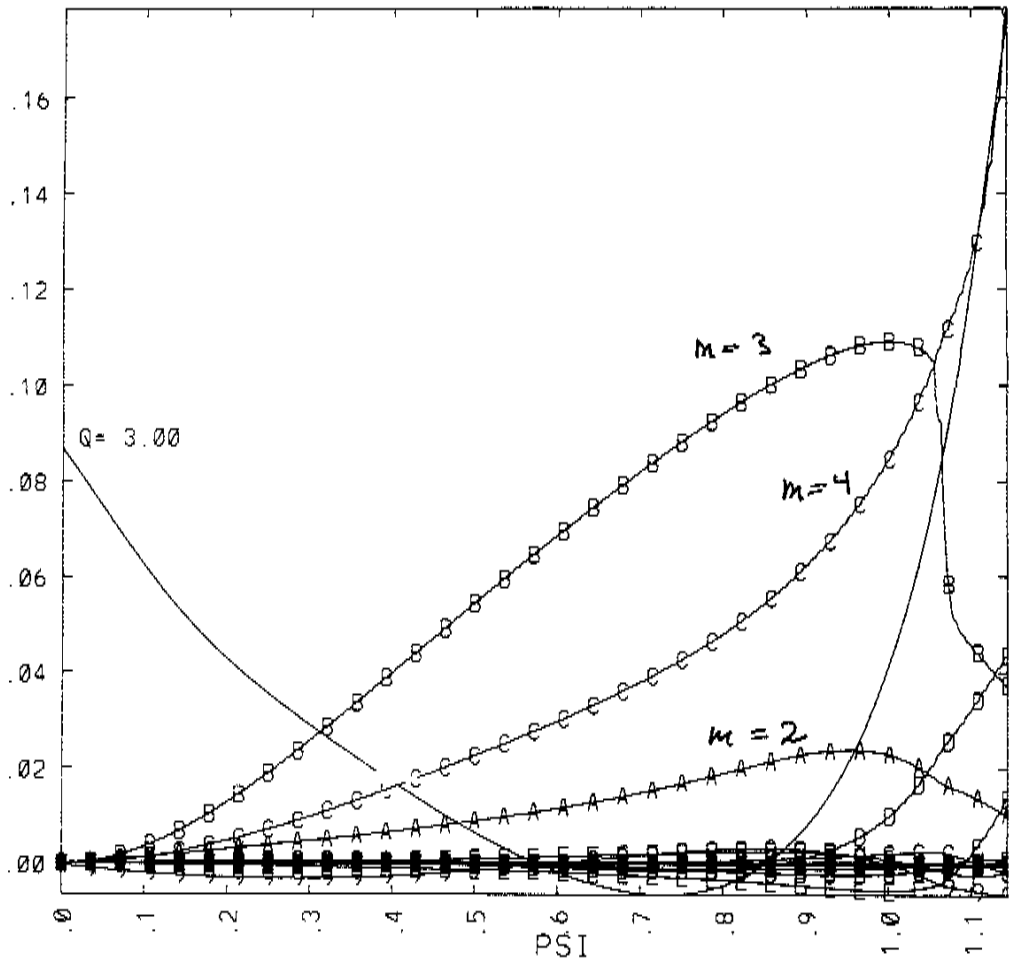
- with stabilization of external kink at ~2% beta

- (C. Neuhrenberg, IPP; Redi, Kessel, Fu, PPPL)

Beta (%)	CAS3D (wall at infinity)	PEST (wall at infinity)	TERPSICHORE (wall at r=2a)	PEST (wall at r=2a)
7.5	unstable	unstable	unstable	unstable
3.6	unstable	unstable	unstable	unstable
2.5	unstable	unstable	stable	stable
2.1	stable	stable	stable	stable

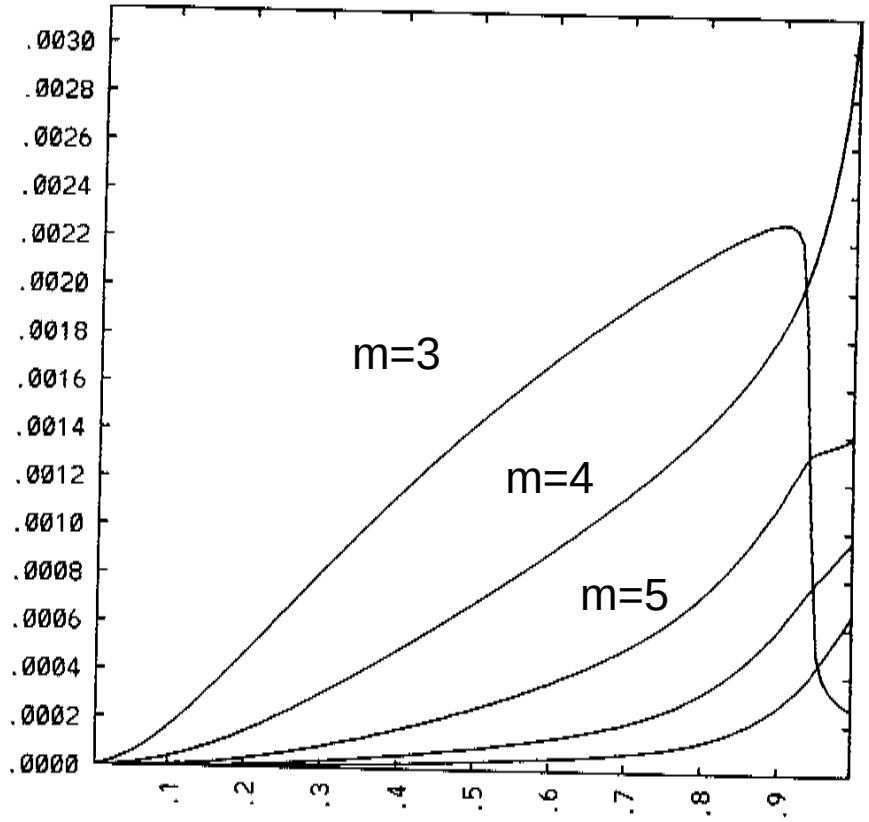
*** QAS3 cases still to be compared to TERPSICHORE for benchmark**

PEST BENCHMARK
OF ARIES KINK AT 3.5% BETA



TOTAL P.01

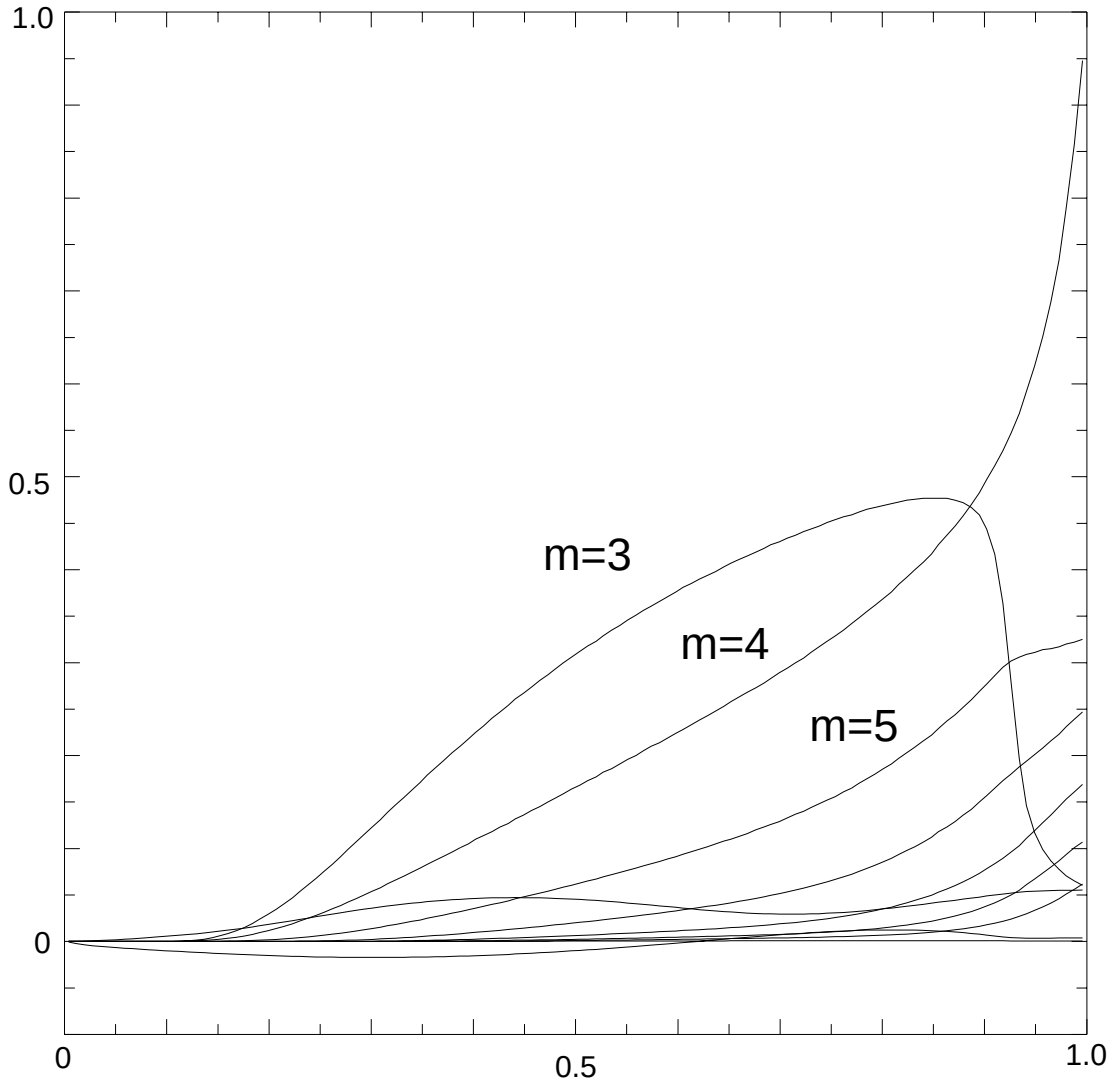
TERPSICHORE BENCHMARK OF ARIES KINK AT 2.46% BETA



Radial Structure of Fourier Coefficients of Instability (m,-1)

ARIES Reversed Shear Tokamak External Kink

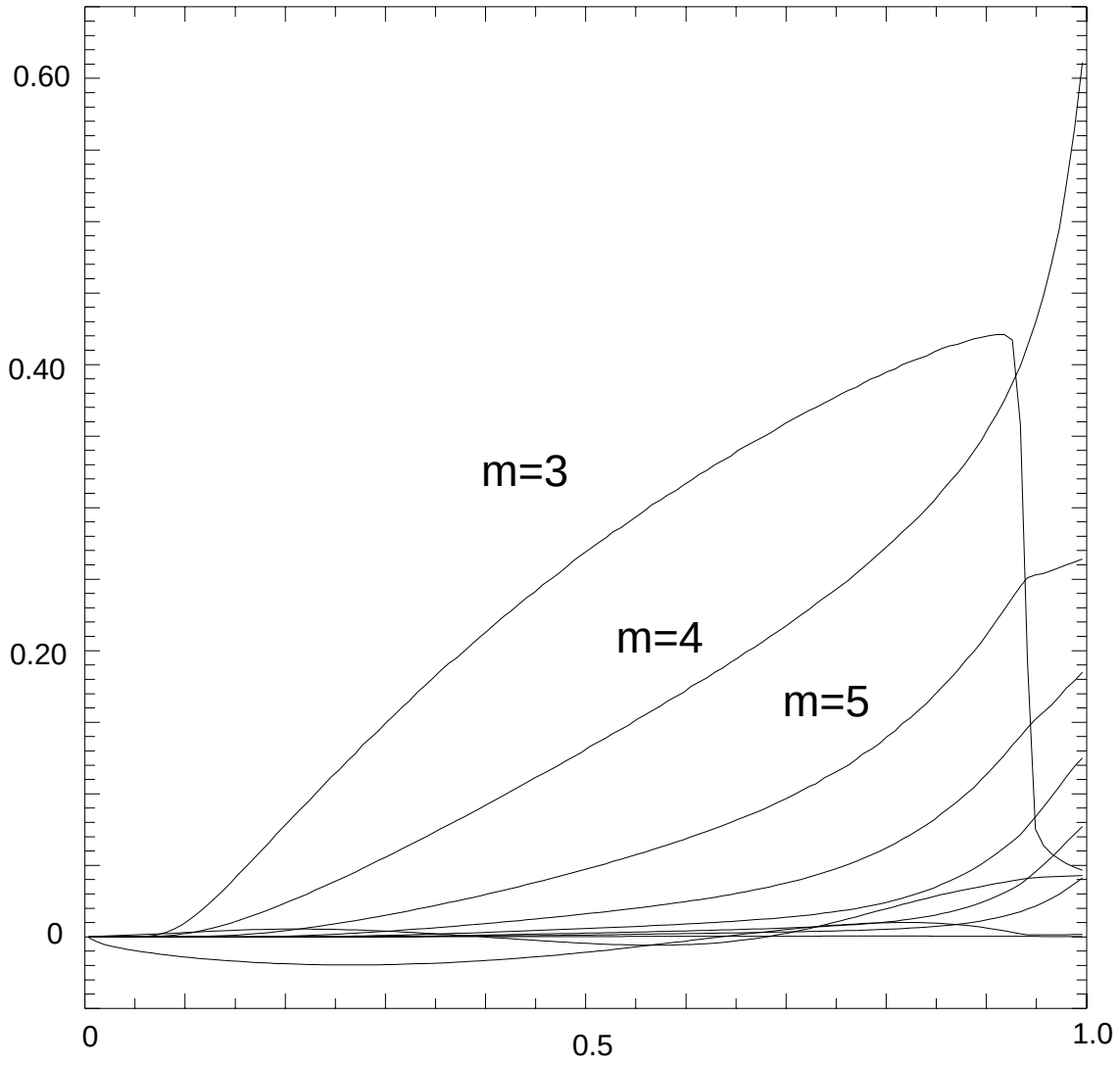
Beta = 3.6%, Eigenvalue = -0.0043



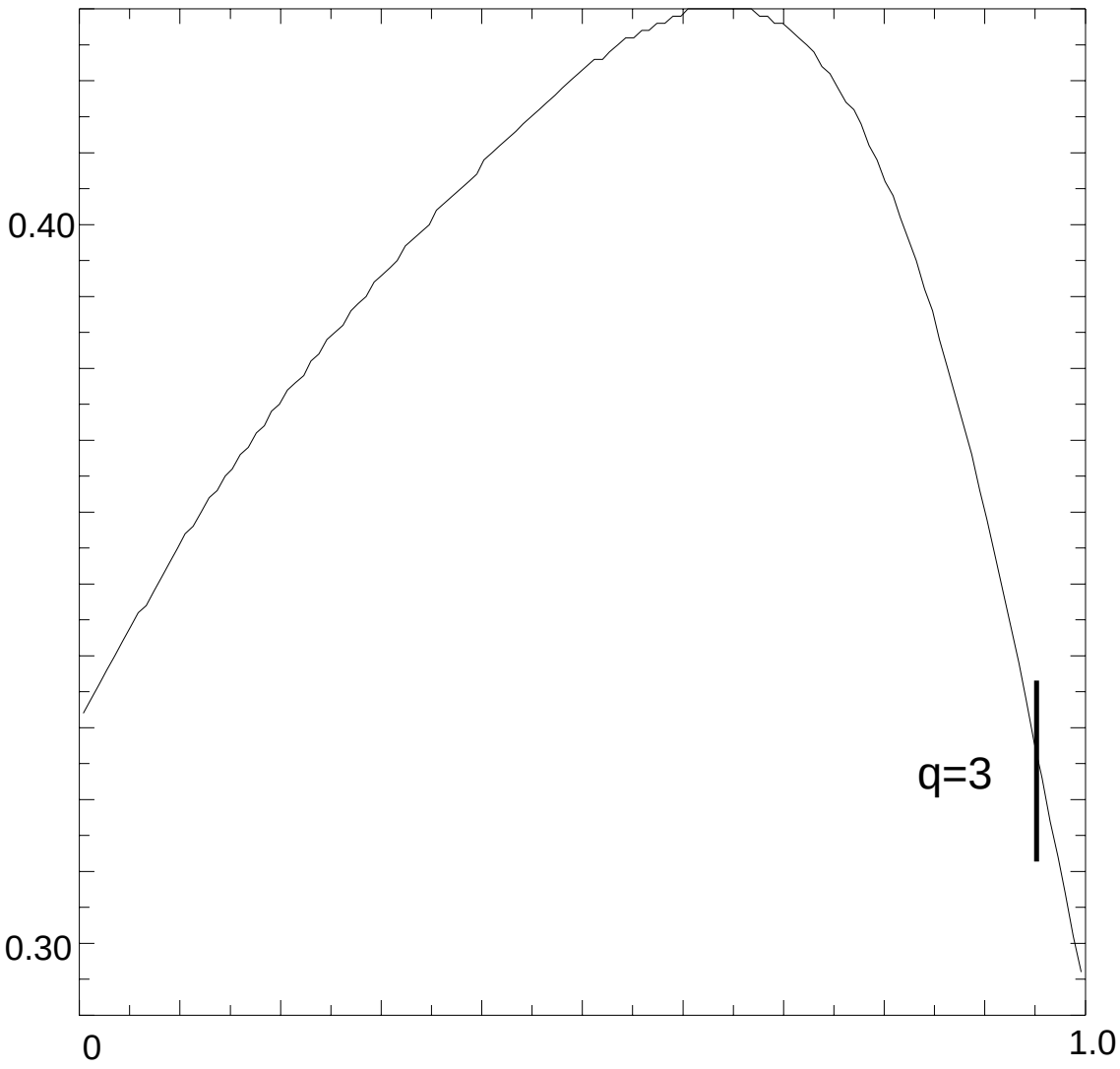
Radial Structure of Fourier Coefficients of Instability (m,-1)

ARIES Reversed Shear Tokamak External Kink

Beta = 2.46%, Eigenvalue = -0.00031



Rotational Transform, Iota, Beta = 2.1%



Mode components close to resonance should be dominant.

As q=3 is inside the plasma, q=4 is just outside,
m=4,n=1 will increase in magnitude all the way to the plasma edge,
m=5,n=1 will behave the same but not be as large in amplitude
m=3,n=1 will peak near the q=3 surface.

RESULTS FOR VERTICAL STABILITY (AXISYMMETRIC MODE)

* Results for vertical stability

- Axisymmetric calculations confirm ARIES vertical instability with elongation and stability for circular plasma, still to show oblate plasma is stable.

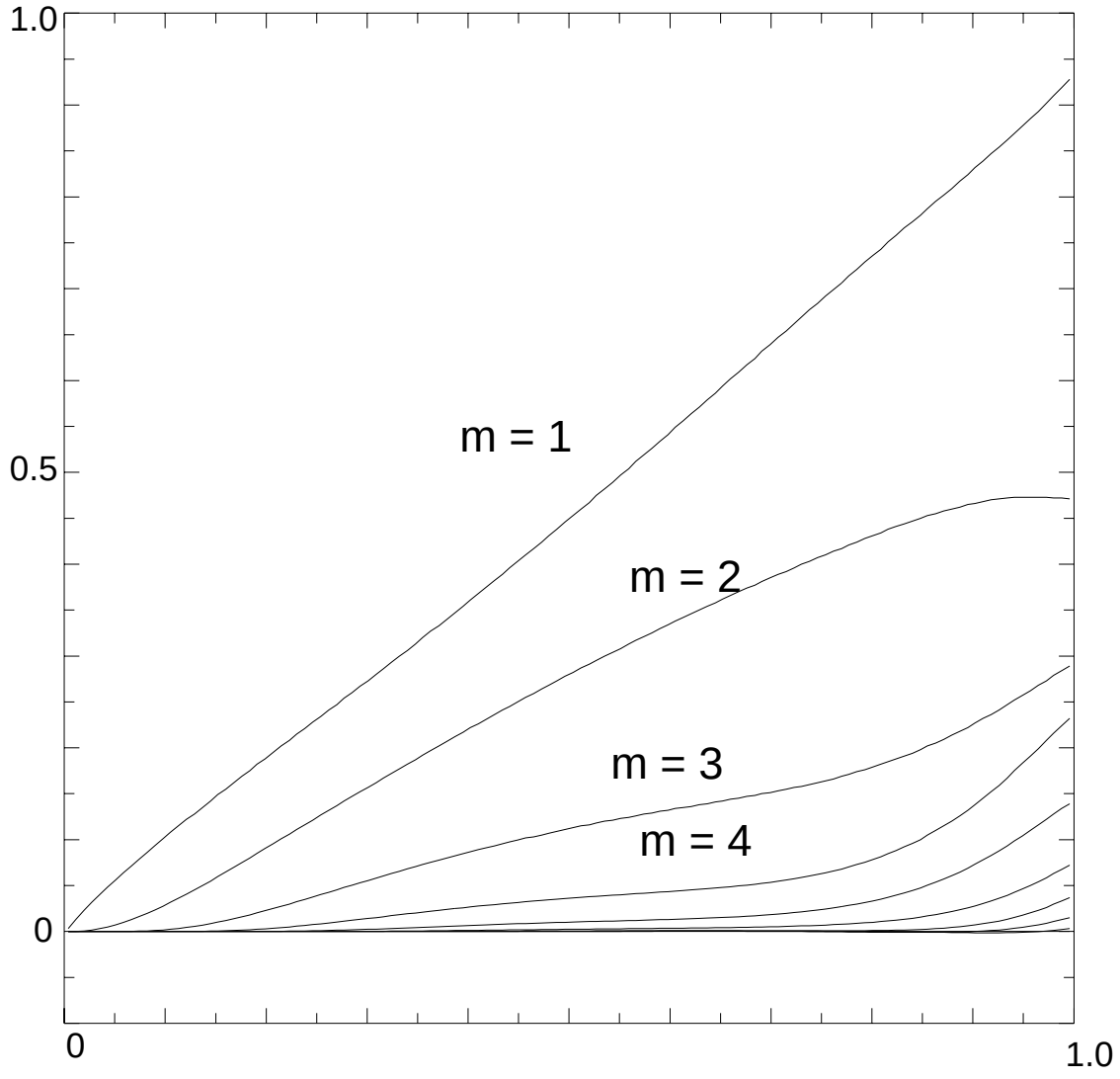
- Axisymmetric calculations also show reduced growth rate at high beta, radial structure of Fourier components and suppression of high poloidal modes at reduced beta.

Beta	**Eigenvalue**
7.6%	-0.041
3.5%	-0.076
2.5%	-0.089
2.1%	-0.094
Circular	
0.7%	-3.10^{-12}

* Eigenvalue will change with beta since the vertical field of each configuration will be different and the derivative of the vertical field determines stability.

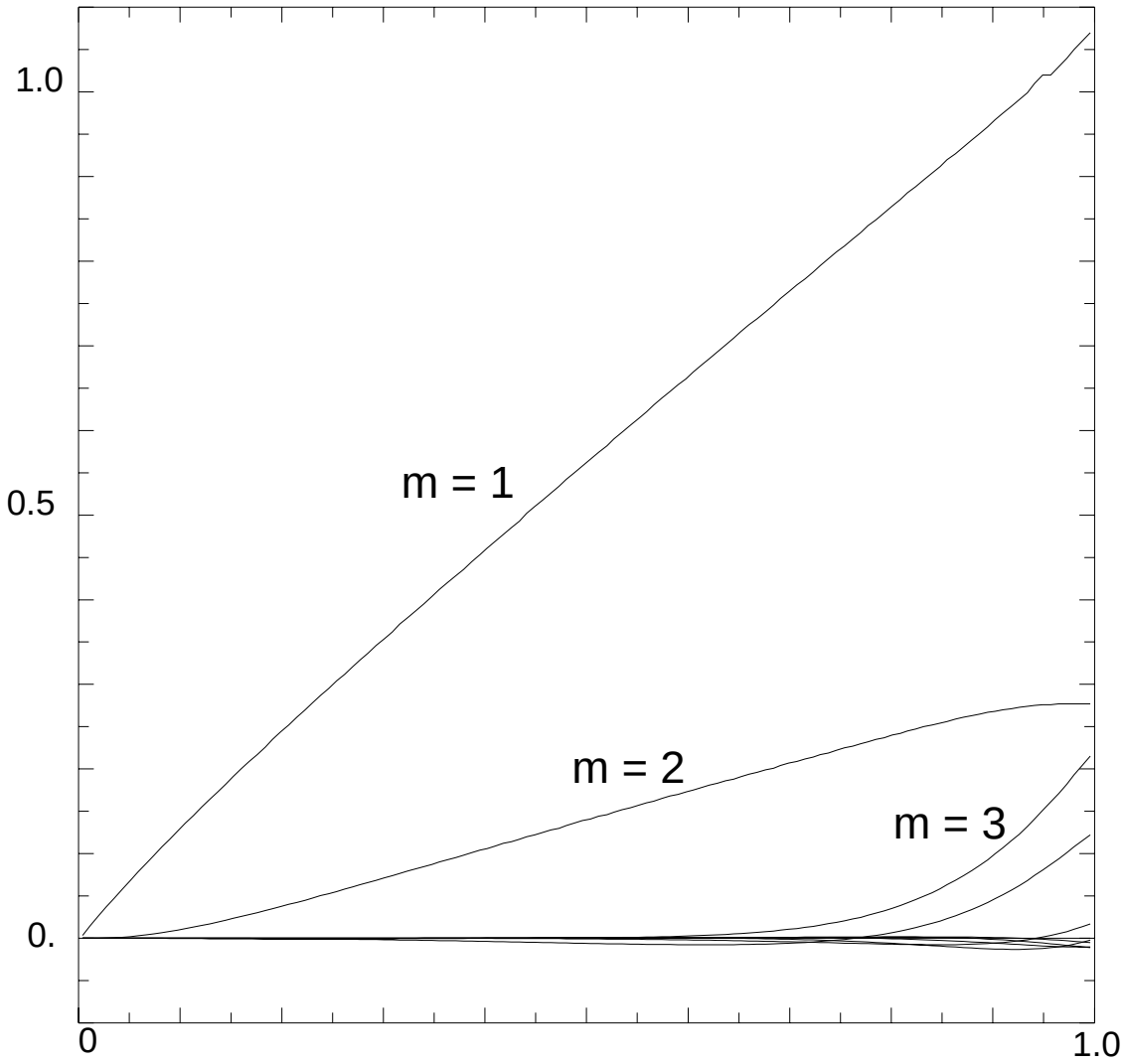
*** QAS3 vertical instability predictions in progress.**
- No other 3D MHD code can predict this instability so benchmarking against other codes
for axisymmetric and kink, low n mhd instability is required

VERTICAL INSTABILITY OF ARIES TOKAMAK AT 7.5% BETA SHOWS RADIAL BEHAVIOR



Eigenvalue = -0.041

VERTICAL INSTABILITY OF ARIES TOKAMAK IS STILL UNSTABLE AT 2.1% BETA WHERE KINK IS STABLE. WEAKER RADIAL STRUCTURE THAN AT 7.5%



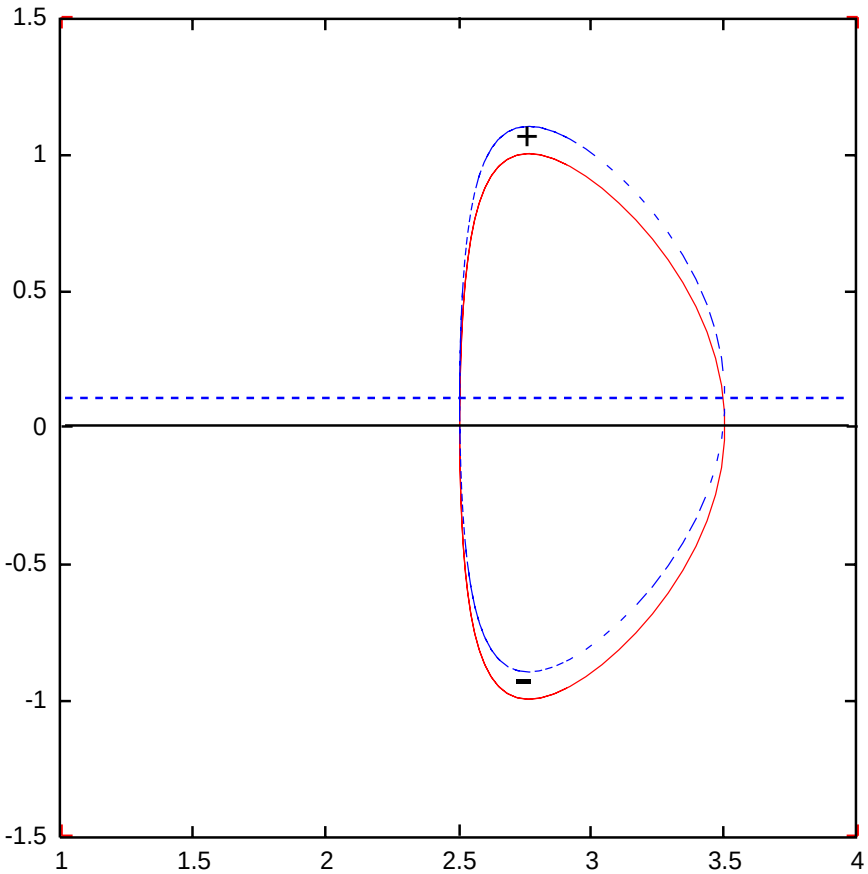
Eigenvalue = - 0.094

WHAT CAUSES the POLOIDAL and RADIAL STRUCTURE of the VERTICAL SHIFT INSTABILITY?

Perturbed current has mostly m=1 character

Since the change from + to - does not occur at Z=0,
other m components must be present.

The plasma instability is not assumed to be a rigid deformation
so that the Fourier components have nonlinear radial behavior



vertical shift

BENCHMARKING SUMMARY

* Low n MHD: for QAS2_20 design CAS3D predicts stability

  - Only numerical modes found for $\beta \leq 5\%$.

  - Very high toroidal mode number simulations at 6.73% beta
    - show increased $|\lambda|$ and narrowed radial extent

  - Comparisons with TERPSICHORE show good agreement for fixed boundary

2) External kink

  - CAS3D, PEST and TERPSICHORE in agreement for axisymmetric ARIES case

  - CAS3D and TERPSICHORE comparisons of QAS3 designs are in progress

3) Vertical Instability

  - CAS3D axisymmetric benchmark for ARIES confirms elongation instability, shows expected radial behavior

  - QAS3 calculations are in progress