Properties of High β, Quasi-Axisymmetric NCSX Stellarator Configurations

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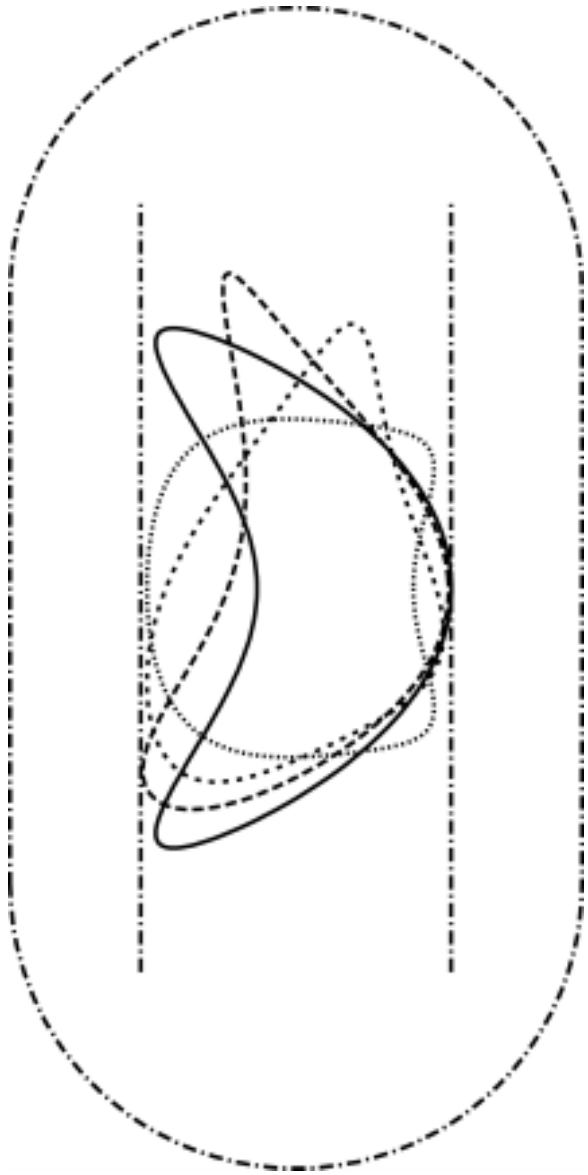
NCSX Stellarator Configurations

- Configurations developed for the National Compact Stellarator Experiment (NCSX) feature:
  - three field periods, R/<a> ~ 3.5
  - stability β ~ 4% (ideal ballooning, external kink and vertical modes)
  - monotonically increasing ι (0.25-0.47), ~50% internal
  - quasi-axisymmetric, largest $B_{m,n}$ ~0.7%, total χ=1.3% at s=0.5

- A typical example: QAS3_C82 in PBX vacuum vessel



R=1.42 m

R_{min}=1.06 m, R_{max}=1.85 m

$\langle a \rangle$=0.41 m, a_{min}=0.25 m

Vol=5.27 m^3

B_{avg}=1.2 T

I_p=200 kA

ι_{ave}=0.35, ι_{ext}/ι=0.45

Φ=0.625 Wb, ψ=0.220 Wb

- Configurations are characterized by
  - strong axisymmetric shaping using Aries reversed-sheared tokamak as the basis to achieve good ballooning stability,
  - strong non-axisymmetric shaping determined by an optimizer to achieve the kink stability,
  - well aligned pressure/current profiles (bootstrap) optimized for the reversed-shear Aries tokamak.

Properties of Configurations Studied in This Paper

- Anatomical study of the interplay of plasma boundary shape, QA and kink stability.

- Sensitivity study of the effects of change in pressure and current profiles on QA and stability.

- Edge rotational transform, its effects on the external kink stability and the implication of plasma currents on configuration robustness.

Boundary Shape, QA and Kink Stability

- We represent the last closed flux surface by*

$$R + iZ = e^{iu} \sum \Delta_{m,n} e^{-imu+inv}$$

- Coefficients, $\Delta_{m,n}$, are ordered by their magnitude and weighted by the poloidal mode number.

- Equilibria were generated using subsets of the coefficients.

- QA and kink stability were calculated and examined.

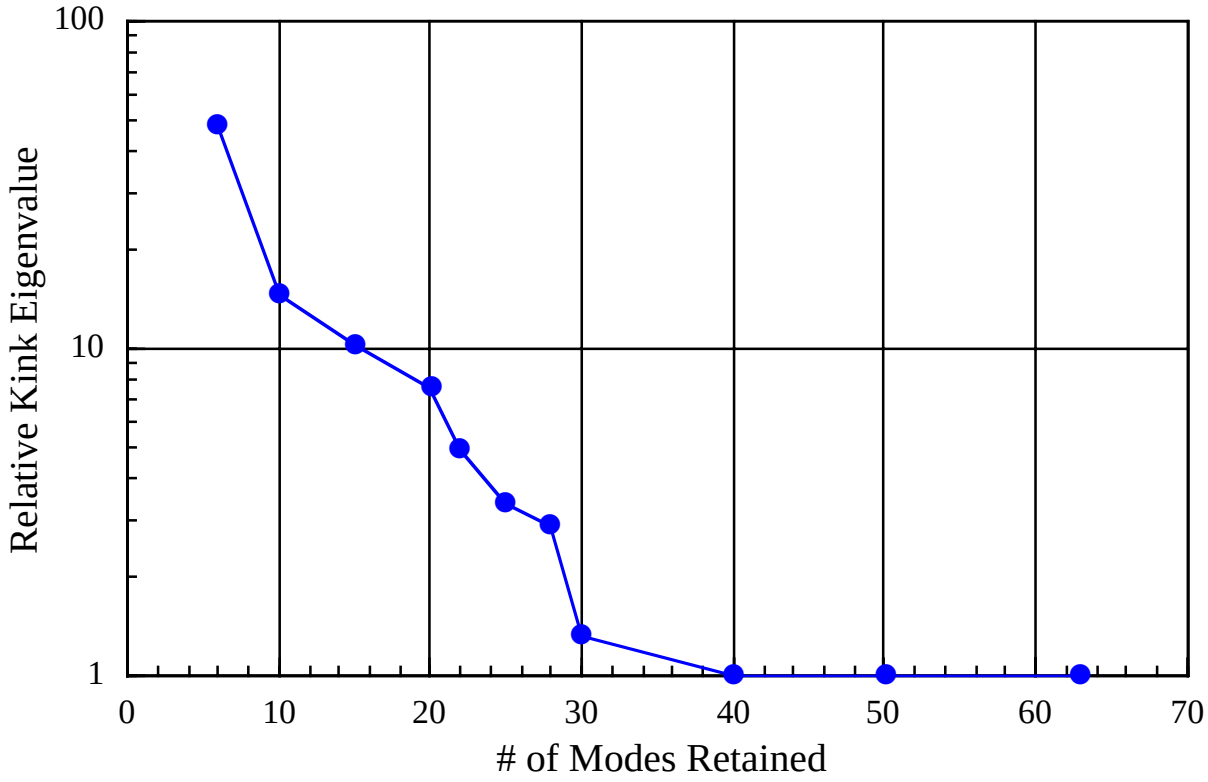
* P. Garabedian and L. P. Ku, Phys. of Plasmas, 6(3), 645 (1999)

$\Delta_{m,n}$ for QAS3_C82 ordered by $|m^* \cdot \Delta_{m,n}|$, where $m^*=\max\{1, |m|\}$. $\Delta_{0,0}$ is normalized to unity.

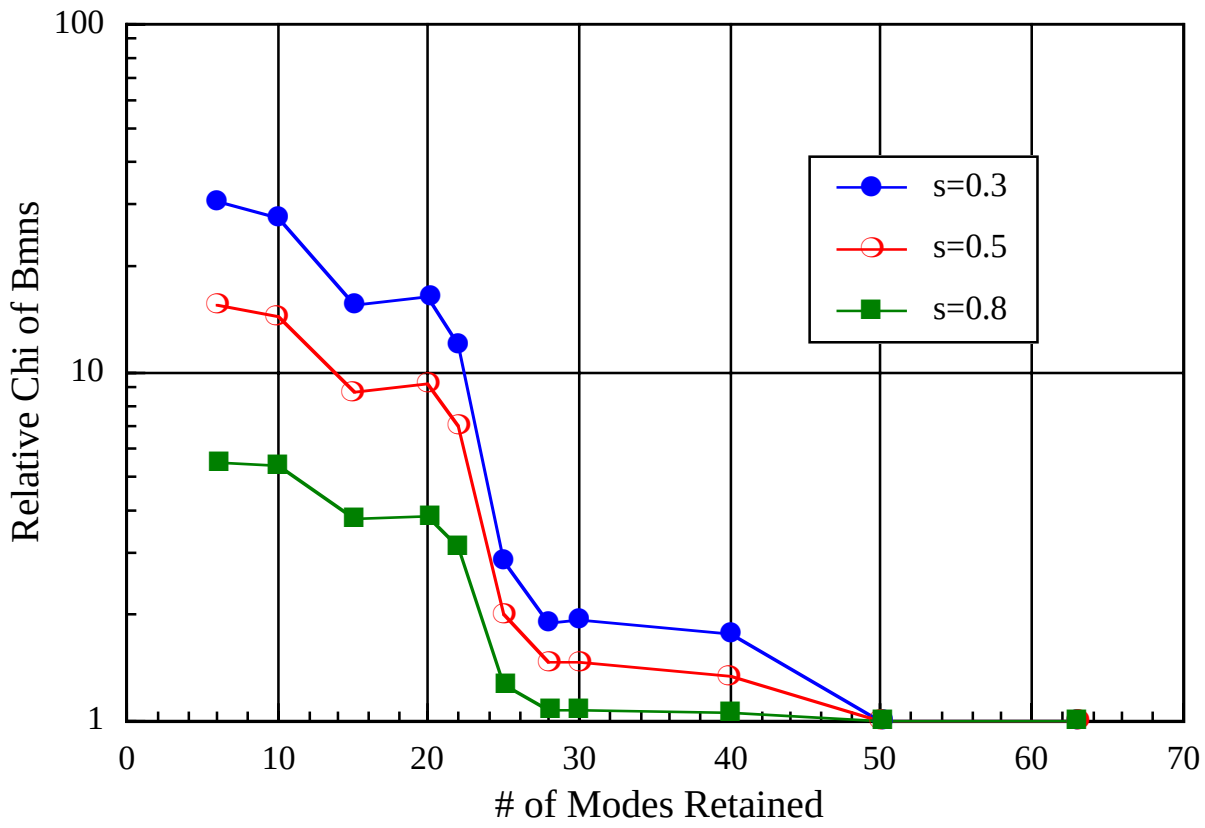
Seq. No.	m	n	$\Delta_{m,n}$	Seq. No.	m	n	$\Delta_{m,n}$
1	1	0	3.098	16	4	0	0.010
2	0	0	1.000	17	3	2	0.012
3	2	0	-0.310	18	4	-1	0.009
4	3	1	0.167	19	-3	-1	0.010
5	2	1	-0.176	20	-4	-2	-0.006
6	3	0	0.071	21	0	1	0.021
7	4	2	-0.044	22	0	-1	0.021
8	1	1	-0.129	23	2	-2	0.009
9	-1	-1	0.107	24	0	-2	0.017
10	-1	1	0.104	25	0	2	0.017
11	4	1	0.026	26	2	-1	-0.009
12	-1	0	0.085	27	1	-2	0.014
13	2	2	0.026	28	4	3	0.003
14	3	-1	-0.014	29	-4	-1	0.003
15	1	-1	-0.041	30	-3	0	0.004

- The following figures show the kink eigenvalue and χ† versus the number of boundary modes retained in the equilibrium construction for QAS3_C82.
  - kink eigenvalue reduces gradually, requiring ever more refined shaping,
  - primary action for QA (measured by χ here) occurs in a small number of terms involving low order modes.

† $\chi = \sqrt{\sum_{n \neq 0} B_{m,n}^2}$



Relative kink eigenvalue versus the retained number of boundary modes in QAS3_C82. Lines are connected between calculated points to aid the eyes.



Relative χ versus the retained number of boundary modes for QAS3_C82. χ is given for three surfaces: s=0.3, 0.5 and 0.8, where s is the toroidal flux label.

- Basic structure consists of the top six modes. It is a mixture of l=2 and l=3 stellarator. The largest non-axisymmetric magnetic field component is $B_{0,1}$ (~20% at s=0.5)

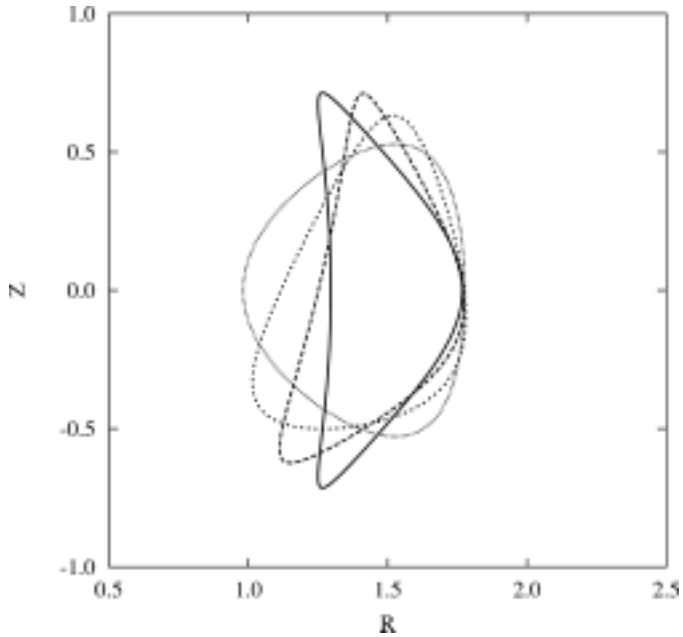
- Using the top 10 modes, the equilibrium having an outboard indentation at the half field period cross section is produced due to the presence of $\Delta_{4,2}$ and $\Delta_{-1,-1}$.

- There is a corresponding large reduction in the kink eigenvalue (~x4). The secondary mirror field, $B_{0,2}$, becomes large (~7% at s=0.5).

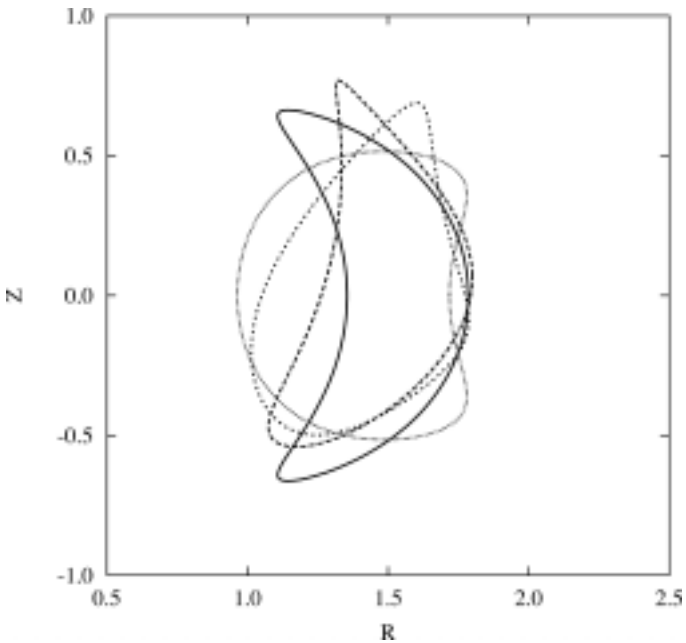
- $B_{0,2}$ and $B_{0,1}$ still dominate the non-axisymmetry with the top 20 modes used to construct the equilibrium, with $B_{1,2}$, $B_{1,-2}$ and $B_{2,-2}$ adding additional 1.5% each at s=0.5. These low order modes are effectively eliminated with the inclusion of $\Delta_{0,\pm 2}$, $\Delta_{0,\pm 1}$ and $\Delta_{2,-2}$ corresponding to terms 21 to 25.

- With the top 30 modes included, the kink eigenvalue and χ are both within ~2 of the corresponding values of the final configuration. The largest non-axisymmetric component, $B_{2,1}$, is now only 0.8% of $B_{0,0}$ at s=0.5.

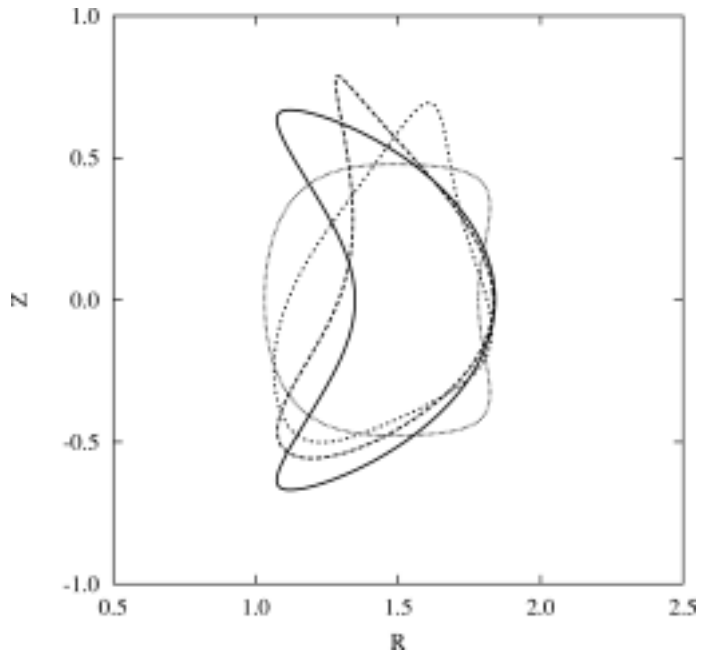
Boundary Evolution of QAS3_C82 with Increasing Number of Modes Included in Equilibrium Calculations.



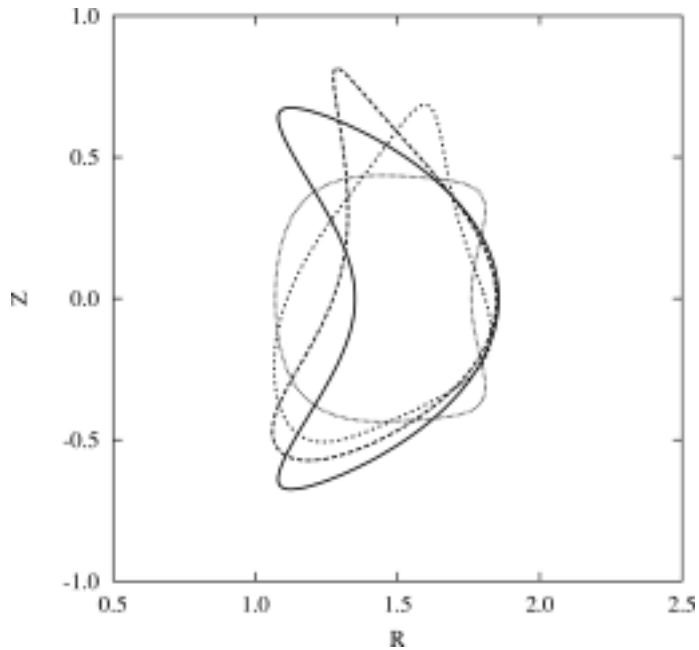
Modes included: 6



Modes included: 10



Modes included: 20



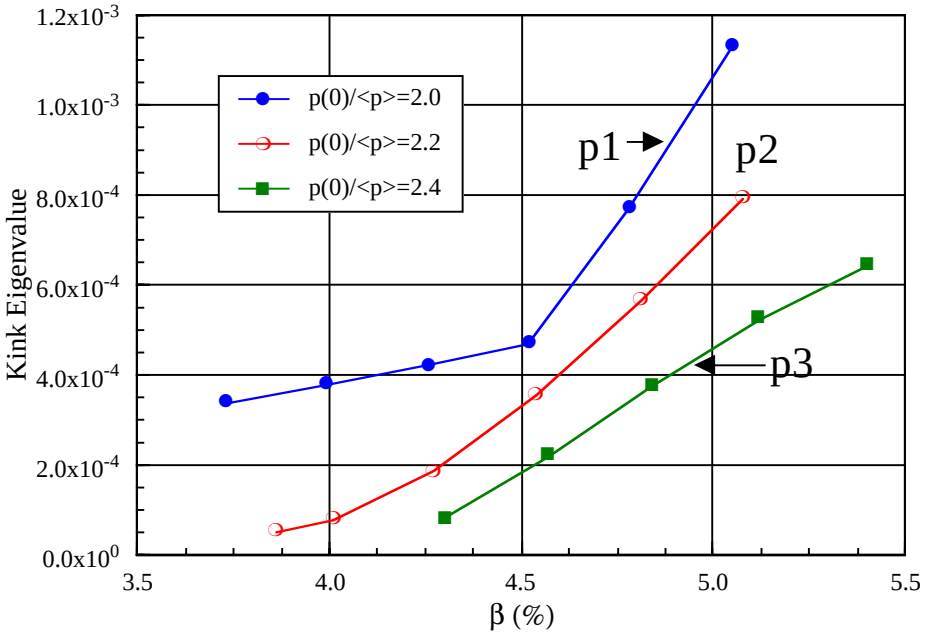
Modes included: 30

Pressure/Current Profiles, QA and Kink Stability

(QAS3_C82 used as an example)

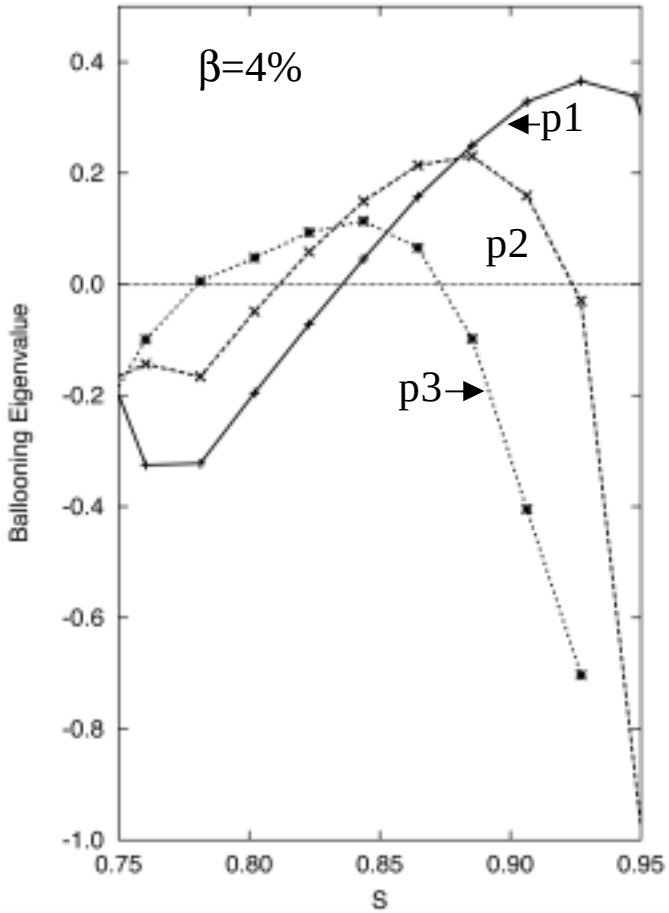
- Kink/ballooning stability may be improved with more peaked pressure profiles for a fixed current profile.

Kink Stability vs β

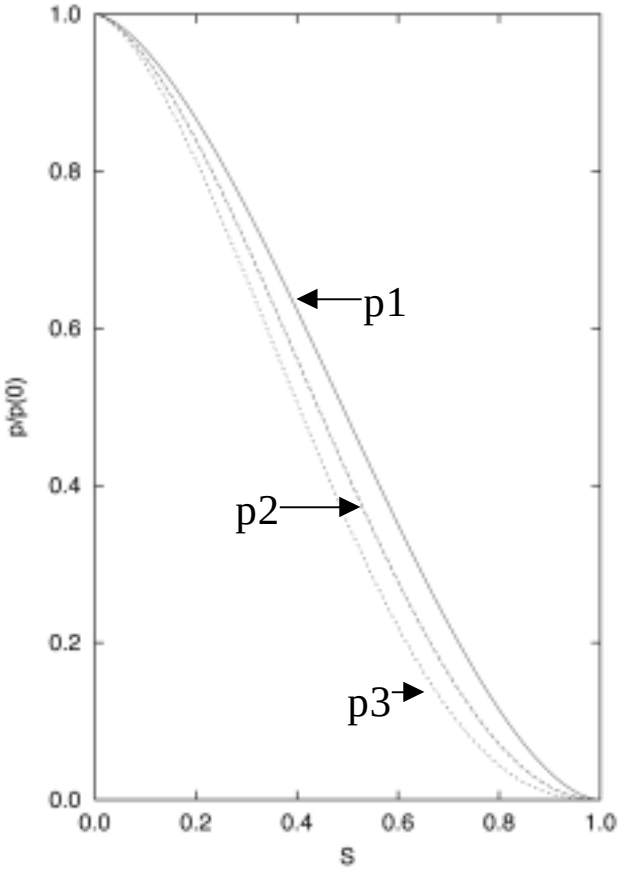


Positive eigenvalue indicates instability

Ballooning Stability vs S



Pressure profiles used in the stability calculation.



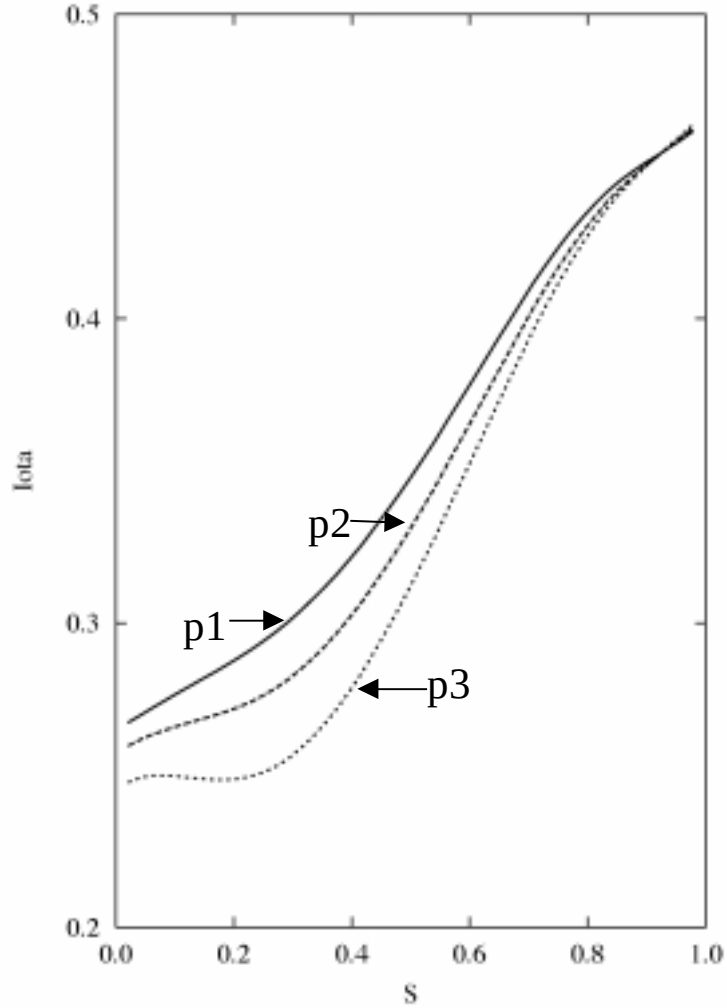
$p(s)/p(0)=(1-s^{\alpha 1})^{\alpha 2}$

P1: $p(0)/\langle p\rangle=2.0$ for $\alpha 1=1.6$, $\alpha 2=1.8$

P2: $p(0)/\langle p\rangle=2.2$ for $\alpha 1=1.6$, $\alpha 2=2.2$

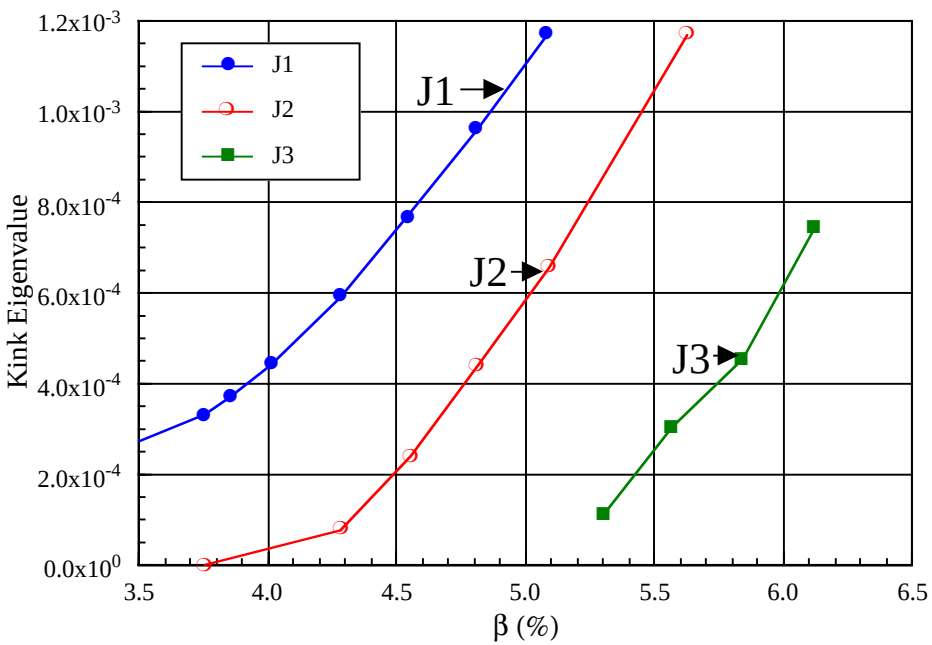
P3: $p(0)/\langle p\rangle=2.4$ for $\alpha 1=1.6$, $\alpha 2=2.6$

Corresponding profiles of rotational transform (ι) at 4% β

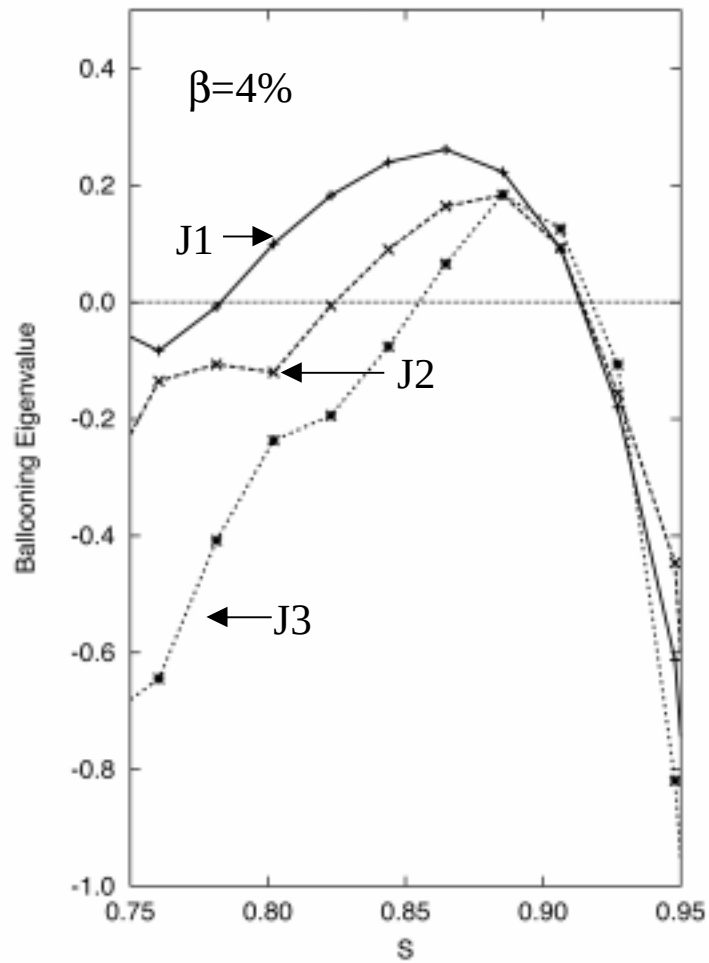


- Kink/ballooning stability may be improved with broader current profiles for a fixed pressure profile

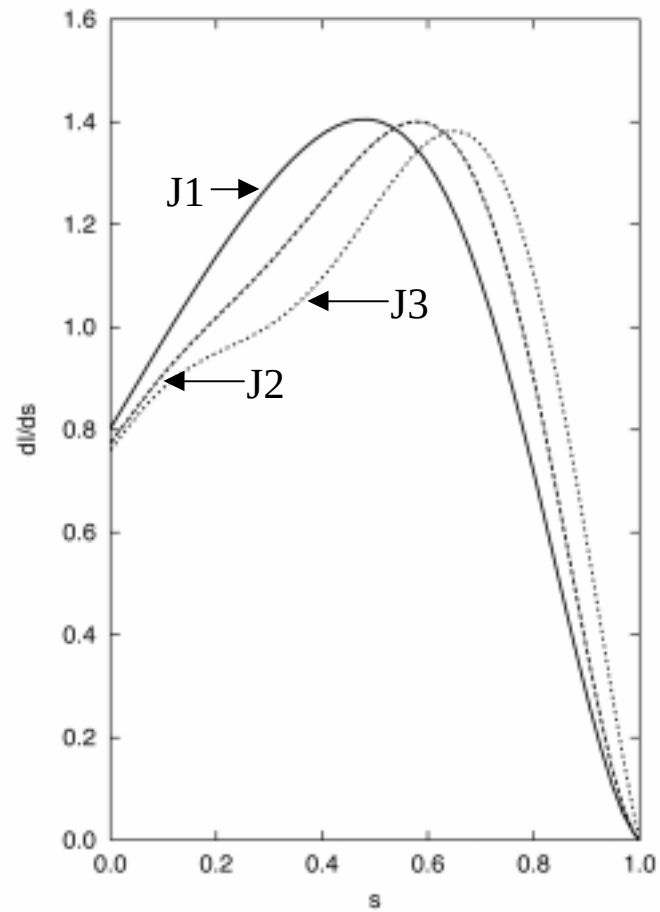
Kink Stability vs β



Ballooning Stability vs S



Current profiles used in the stability calculation



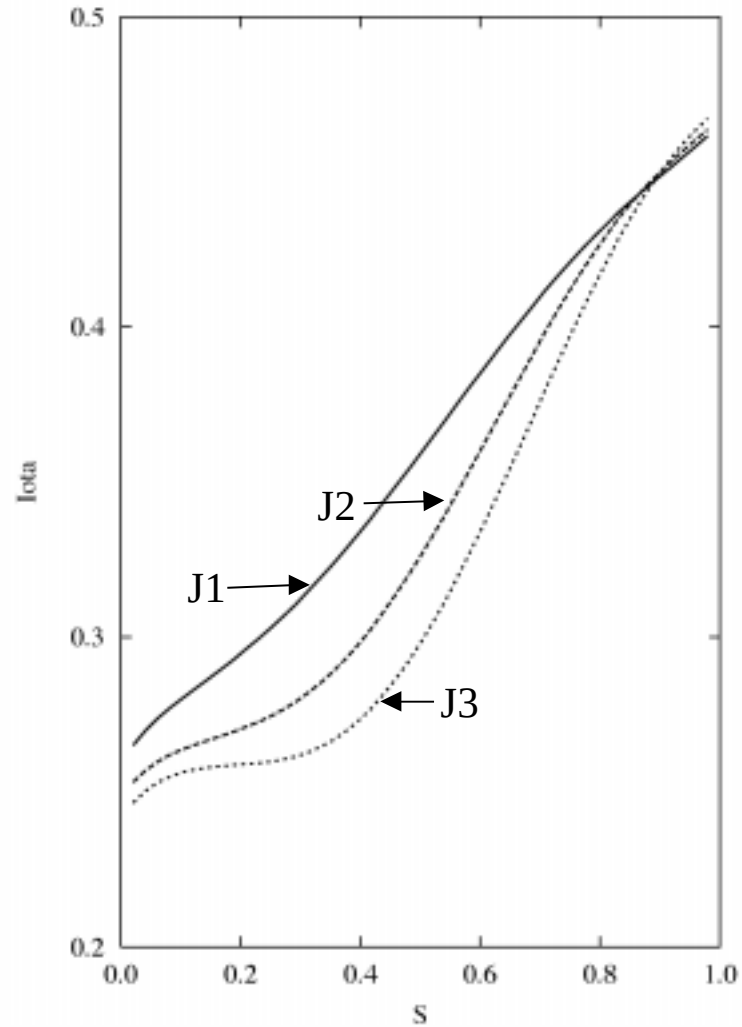
J1: s at peak dI/ds =0.48

J2: s at peak dI/ds =0.58

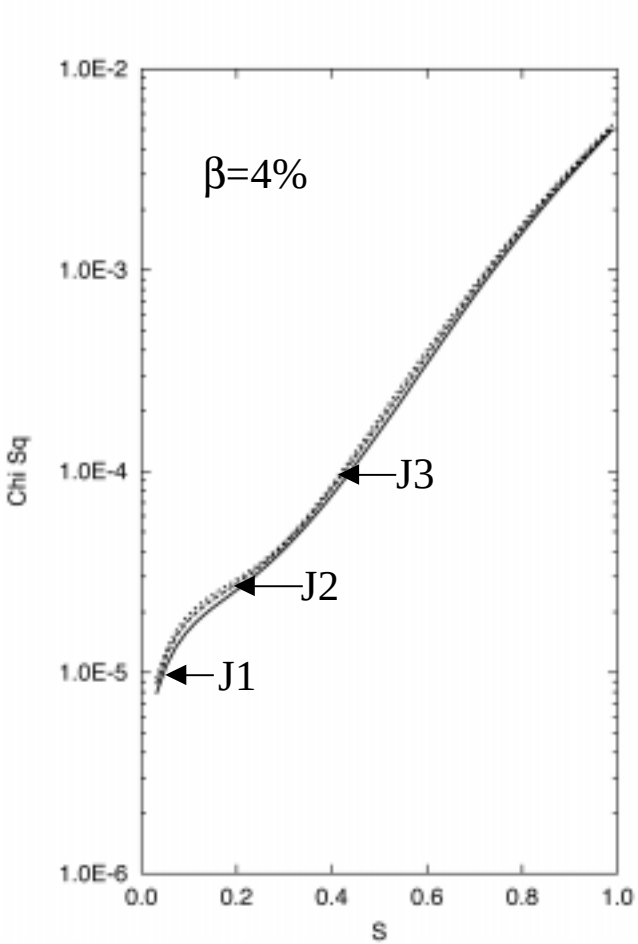
J3: s at peak dI/ds =0.65

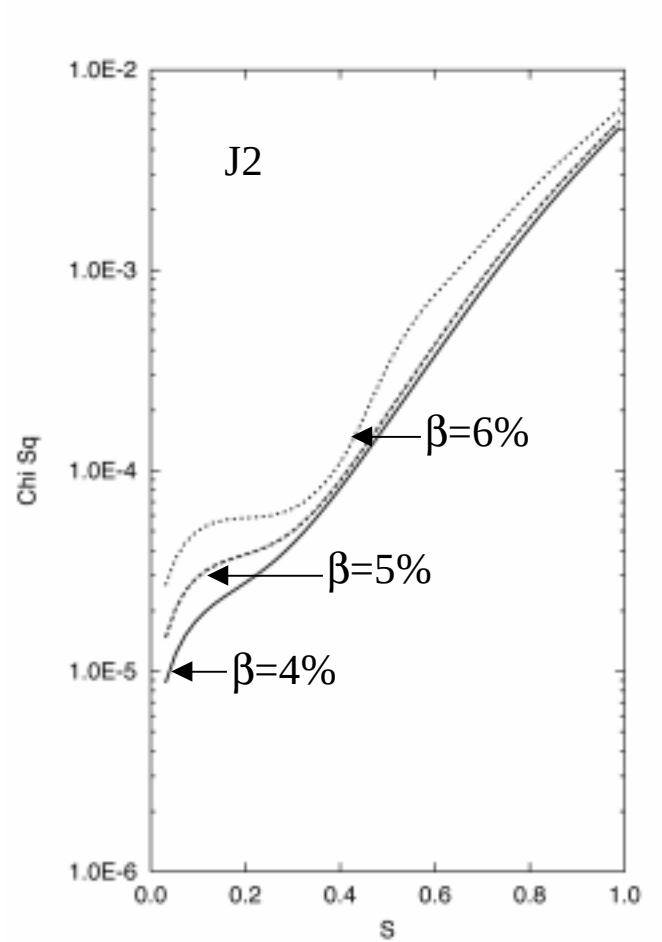
Corresponding profiles of rotational transform at 4% β

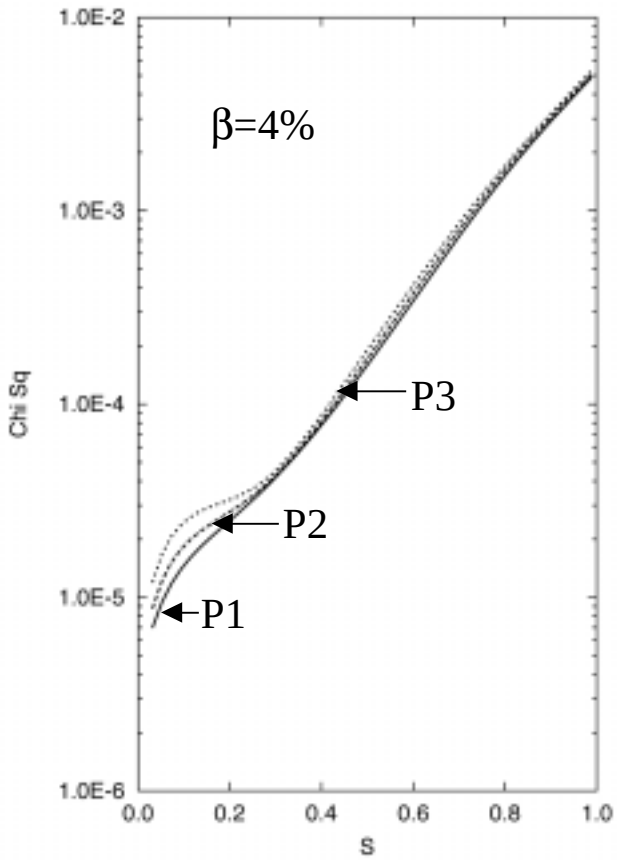
(with fixed total plasma current)

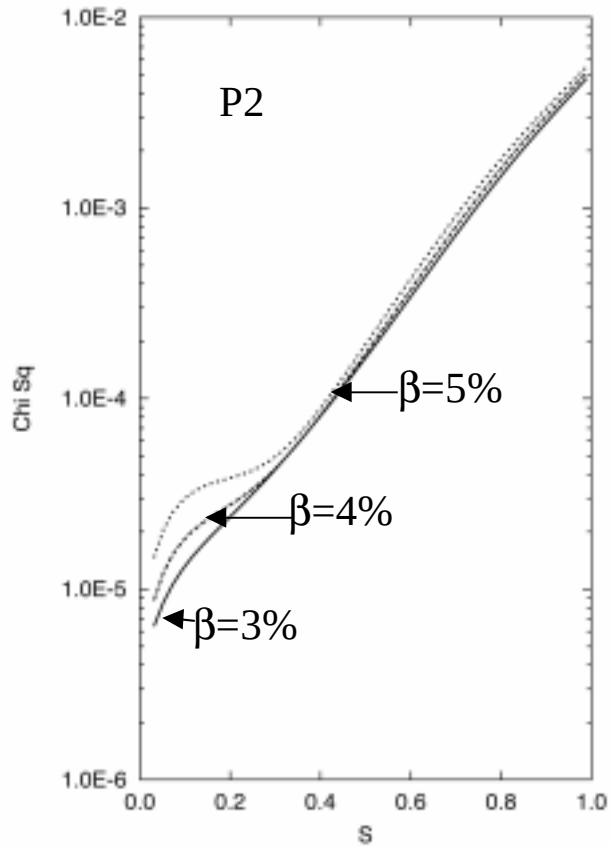


- QA, as measured by χ^2 here, is more sensitive to changes in β (and the magnitude of the total plasma current as well) than to changes in profiles.


β=4%
J3
J2
J1
Chi Sq
S
1.0E-2
1.0E-3
1.0E-4
1.0E-5
1.0E-6
0.0
0.2
0.4
0.6
0.8
1.0

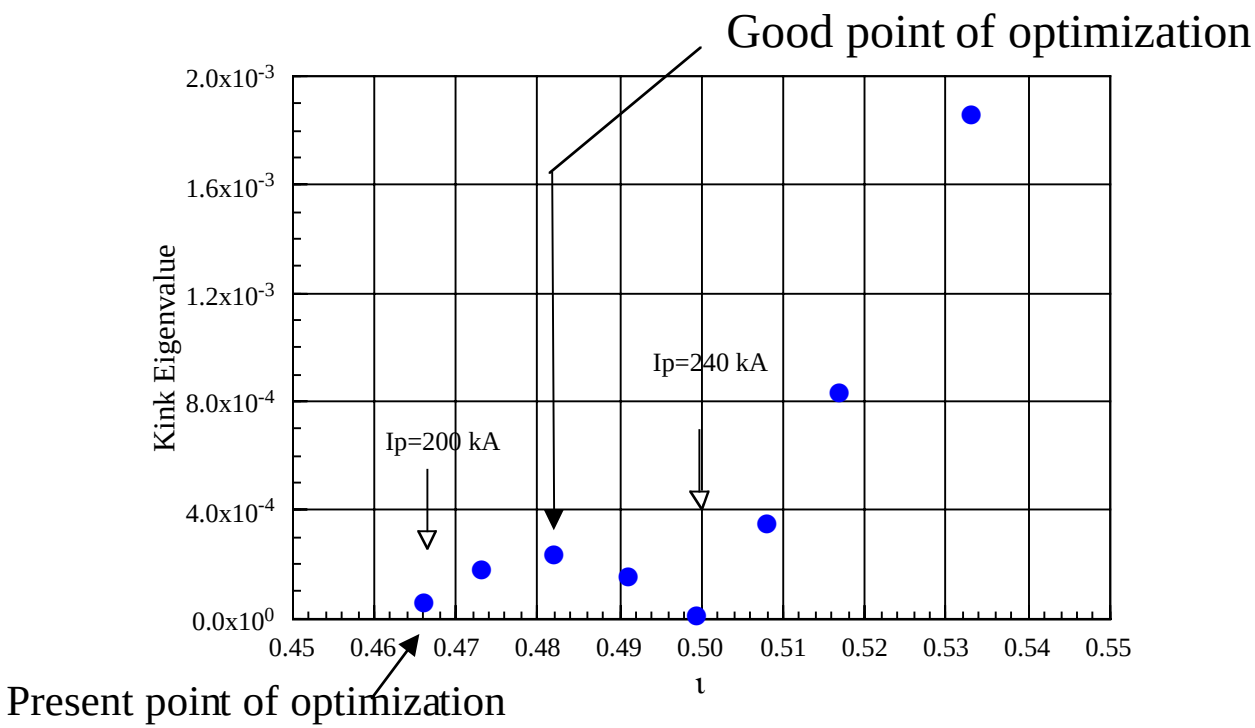

J2
β=6%
β=5%
β=4%
Chi Sq
S
1.0E-2
1.0E-3
1.0E-4
1.0E-5
1.0E-6
0.0
0.2
0.4
0.6
0.8
1.0


β=4%
P3
P2
P1
Chi Sq
S
1.0E-2
1.0E-3
1.0E-4
1.0E-5
1.0E-6
0.0
0.2
0.4
0.6
0.8
1.0

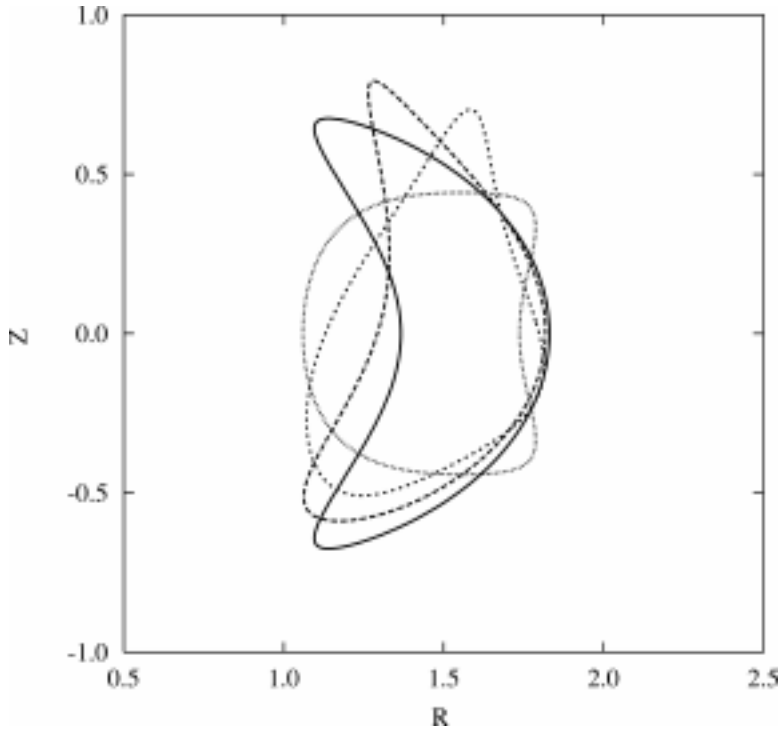

P2
β=5%
β=4%
β=3%
Chi Sq
S
1.0E-2
1.0E-3
1.0E-4
1.0E-5
1.0E-6
0.0
0.2
0.4
0.6
0.8
1.0

Edge Rotational Transform and Kink Stability

- Kink growth rate decreases as the edge rotational transform approaches 0.5 (QAS3_C93).



- This observation suggests that a configuration more robust to current changes may be designed if one optimizes the stability at a current level corresponding to ι=0.48. The following configuration, QAS3_C99, is optimized to be stable for all currents < 240 kA.



Summary and Conclusions

- The physics properties of NCSX configurations were studied with respect to the plasma shaping and the variation in pressure and current profiles.

- The kink stability typical of our configuration favors an outboard indentation at the half field period cross section; the shaping involves detailed refinement, requiring boundary modes of higher poloidal numbers (e.g. m=4).

- Significant QA is achieved in a few low order modes that effectively cancel out the large non-axisymmetric magnetic field components, particularly, $B_{0,2}$, $B_{0,1}$, without compromising the kink stability.

- MHD stability properties may be improved by using more peaked pressure profile or broader current profiles.

- When the plasma current is due to the bootstrap, the stability favors a broader pressure profile since the resulting broader current profile has stronger stabilizing effects that more than compensate for the de-stabilizing effects caused by the broadening of the pressure profile.

- It is important, then, to be able to vary pressure and current profiles independently in experiments. Particularly, if the plasma current arises primary from the bootstrap effects, maintaining current drive capability to allow modification of the current profile will help enhance the plasma performance.

- We demonstrated that it is possible to optimize a configuration that is kink stable to all current levels for which the edge ι is < 0.5.