Development of A New Class of QA Stellarator Reactor Configurations

Long-Poe Ku
PPPL

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Motivation:

- Flux surface integrity may be an important issue in the design of compact QA stellarator reactors due to
  - significant amount of bootstrap current,
  - existence of low order rational surfaces.

Existence of low order rational surfaces also renders equilibrium solutions based on the nested-flux-surface assumption less certain.

- Difficulty imposed by low order rational surfaces may be dealt with by
  - minimizing the resonance perturbation (healing),
  - choosing iota profiles to minimize the presence of low order resonance.

We proposed to develop configurations with large negative externally generated magnetic shear ($d\iota/ds < 0$) such that at the target β and current the rotational transform will have small but positive shear through most of the plasma, making iota lie in a region devoid of low order rational surfaces.

- The questions are:
    - Island-free regions available? Is there any particular attractive region?
    - QA configurations exist? How good QA can be?
    - MHD stability properties compatible?
    - Coil solutions exist and coil topology consistent with reactor environment?

- To answer these questions, we explored the configuration space for "QA"-ness subject to the constraint of certain magnetic well depth in vacuum. Optimization is done in vacuum but properties are analyzed both at finite β and in vacuum.

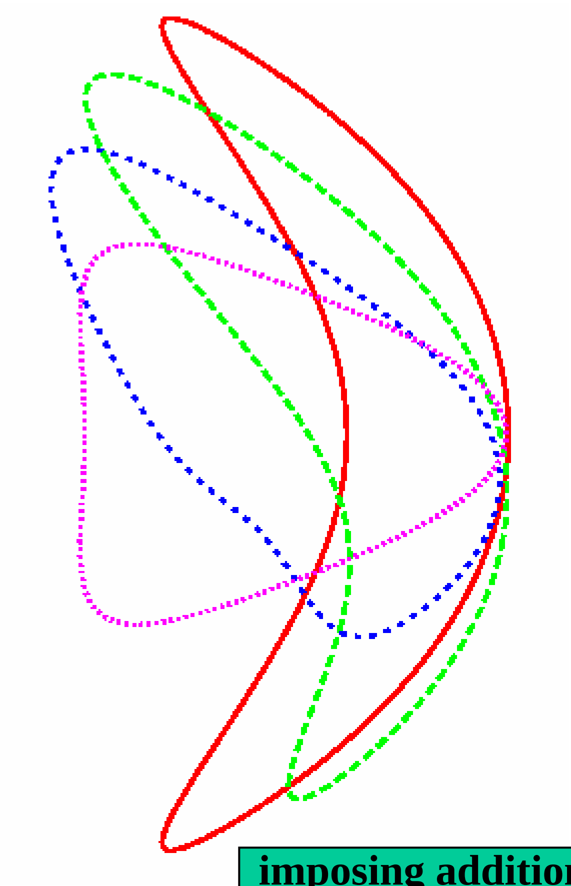
The purpose of this presentation is to show that configurations of the above stated nature do exist, that good QA has been achieved in many of these configurations with α-loss fraction < 10%, and that such configurations have been identified in different regions of rotational transform, and in a number of different aspect ratios and in both 3 and 2 field periods as well.

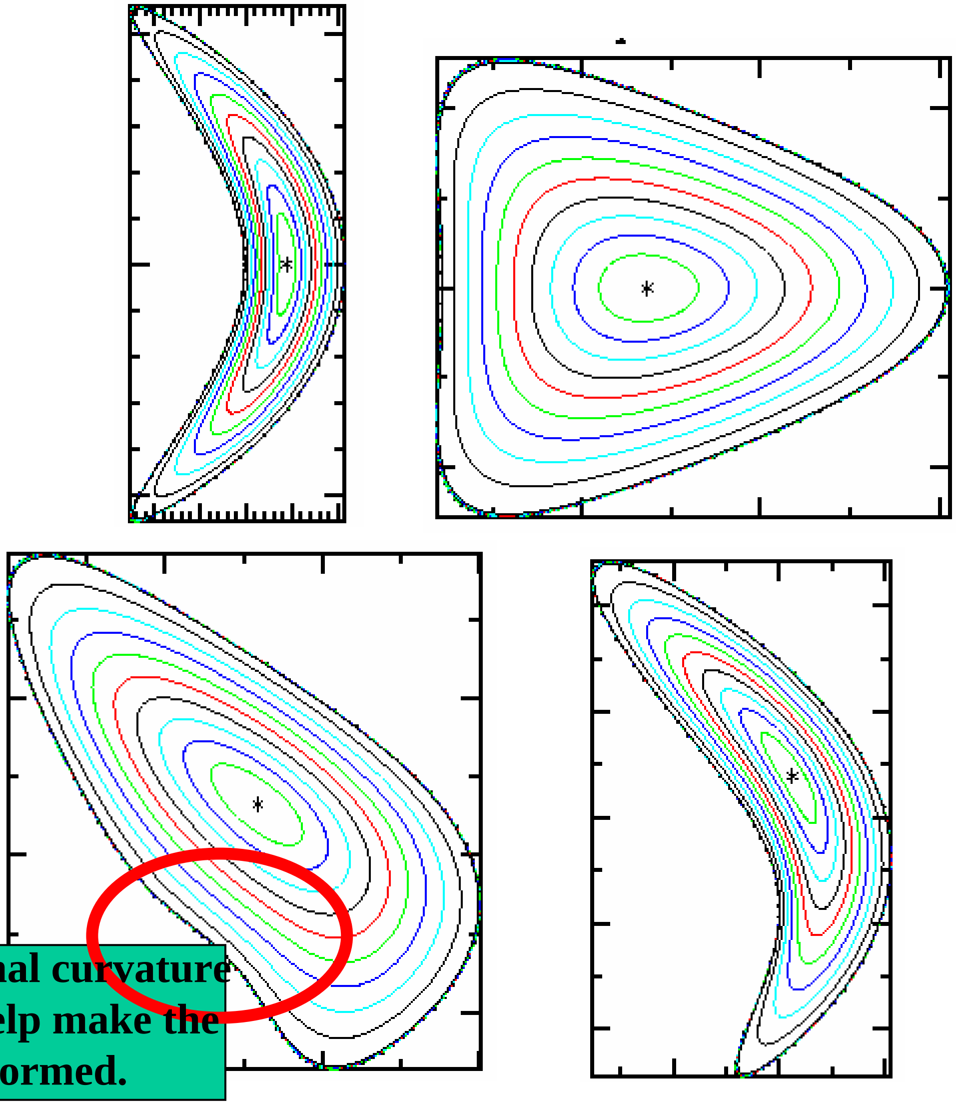
Summary of General Characteristics:

- Negative magnetic shear tailored to match magnitude of the bootstrap current such that the presence of low order resonance is avoided at the target beta (6% in the present study).
- Good QA with low residue non-axisymmetric fields (~1-2%) and low effective ripple (<1%).
- Good α-particle confinement with energy loss fraction in 1000 m^3 reactors at 6.5 T < 10% (confinement proportional to B^2).
- Deep magnetic well in vacuum. Configurations with 4% -9% are found.
- Toroidally averaged elongation (>1.8) and triangularity (> 0.7) match those in advanced, high beta tokamaks and other classes of QA stellarators with good MHD stability properties.
- Reasonably simple shape.

An Example (KJC167): Boundary Shape and VMEC Flux Surfaces.

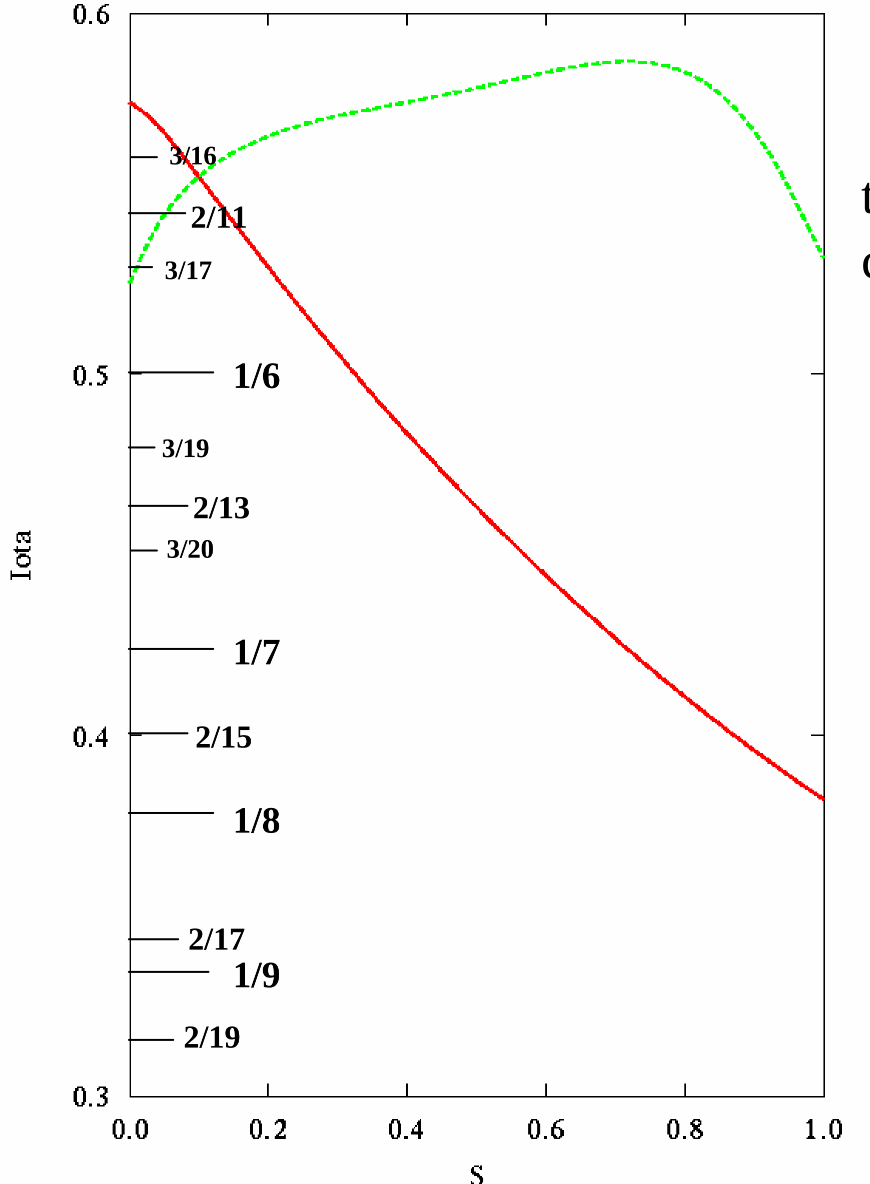
NF=3, A=6.0, ι_{ext}(avg)=0.48, $d\iota_{ext}/ds$=-0.2, β=0.0%





imposing additional curvature constraint may help make the boundary less deformed.

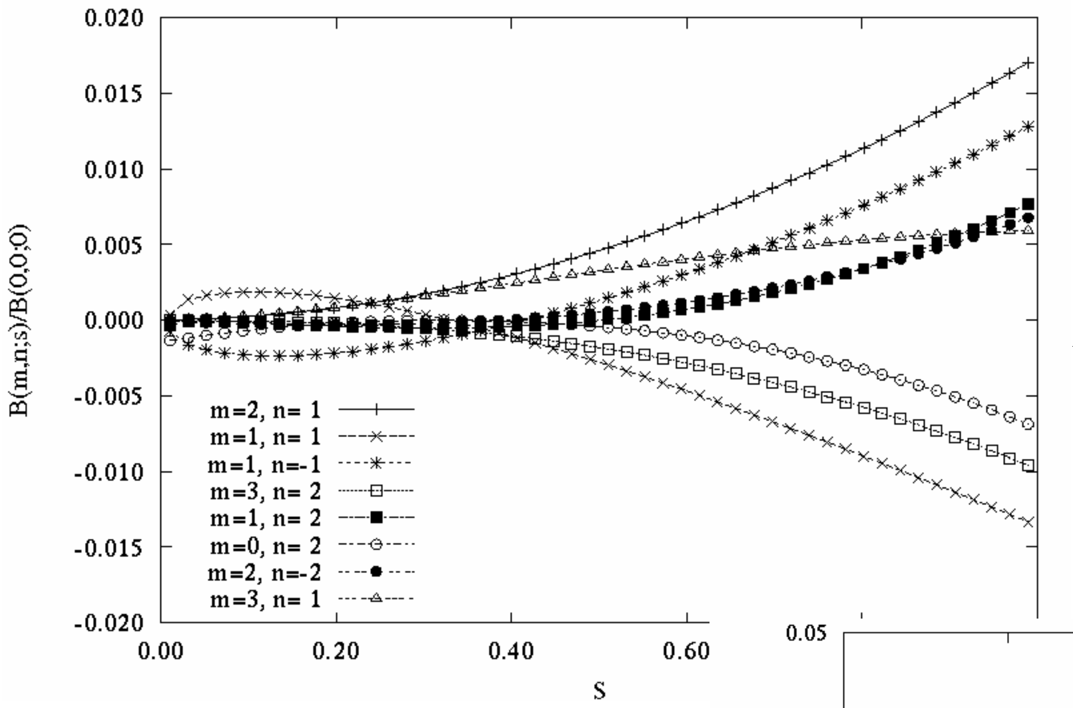
The rotational transform in this example (KJC167) skirts all n=1 resonance at 6% β. (Some refinement near the edge may still be needed to avoid perturbations due to n=2 and n=3 resonance.)



total including bootstrap current expected at 6% β

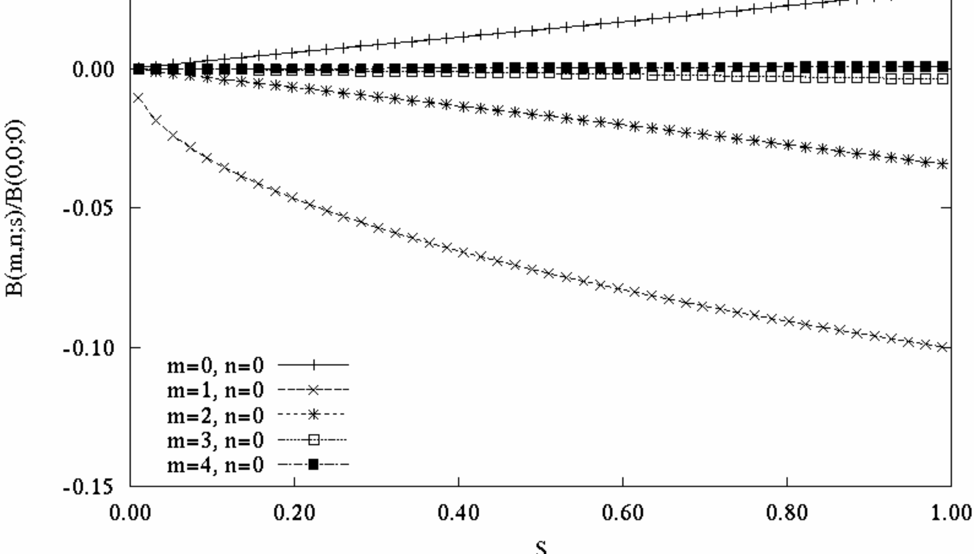
external

Good quasi-axisymmetry is achieved despite the large shear in vacuum iota (KJC167).

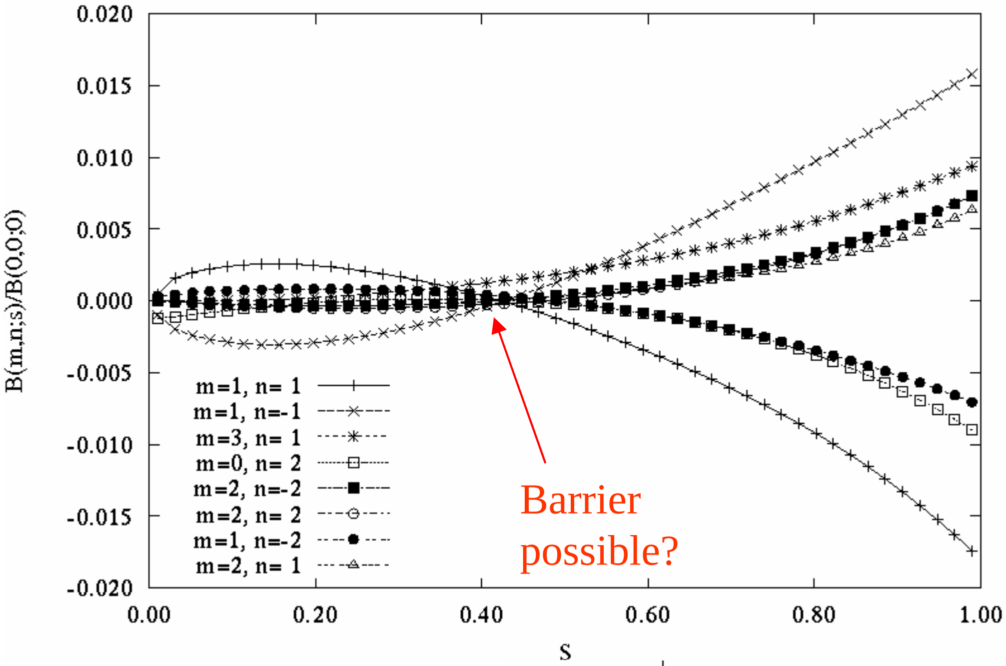


Largest non-axisymmetric components in magnetic spectrum (vacuum) < 1.7%.

Axisymmetric components in magnetic spectrum.

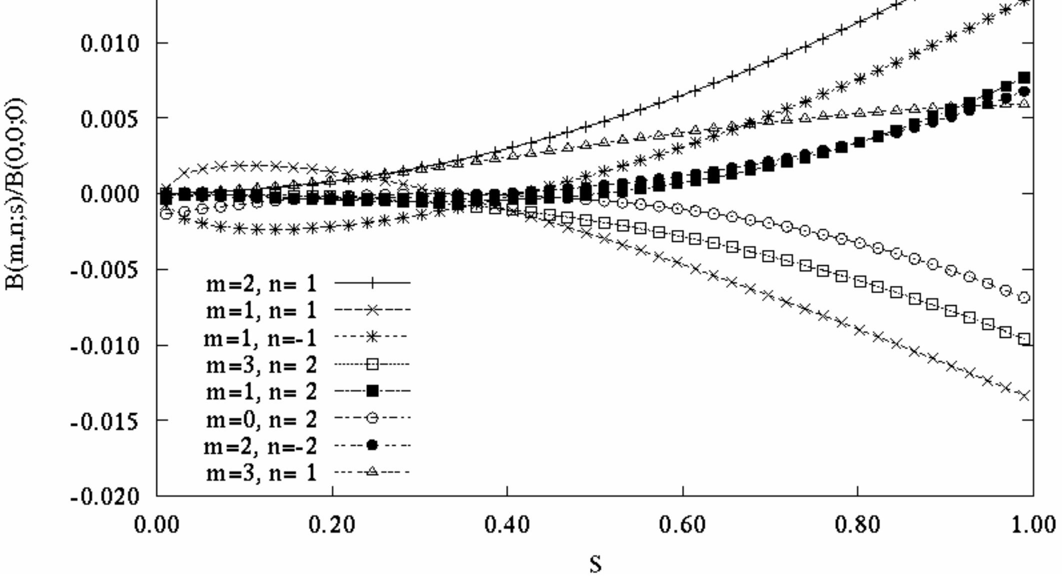


Quasi-axisymmetry is not significantly affected by the plasma pressure (KJC167).



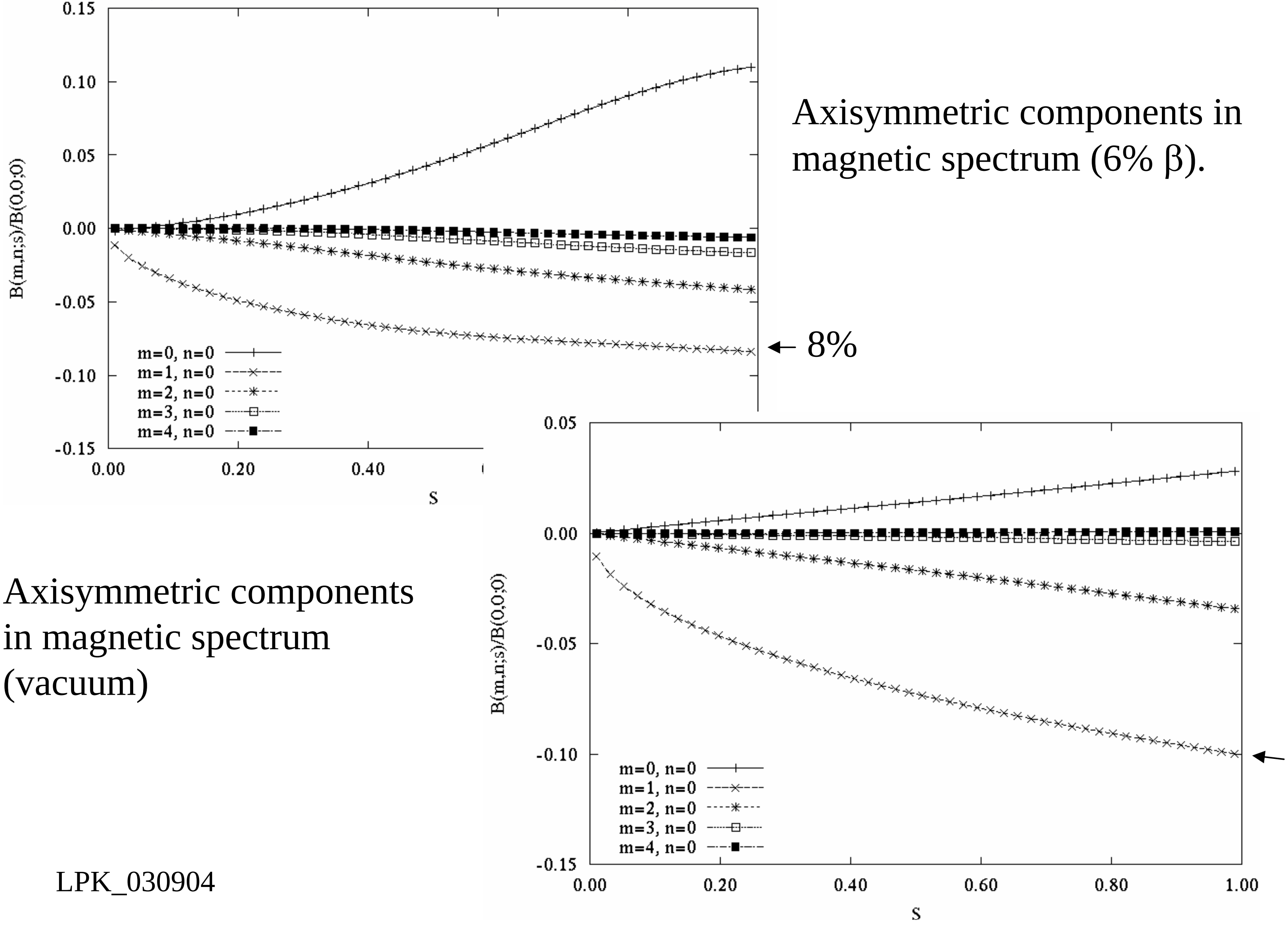
Barrier possible?

Largest non-axisymmetric components in magnetic spectrum (6% β).



Largest non-axisymmetric components in magnetic spectrum (vacuum).

The configuration has relatively smaller B(m=1,n=0). Both the primary axisymmetric ripples along field lines and the amount of bootstrap current will be correspondingly smaller.



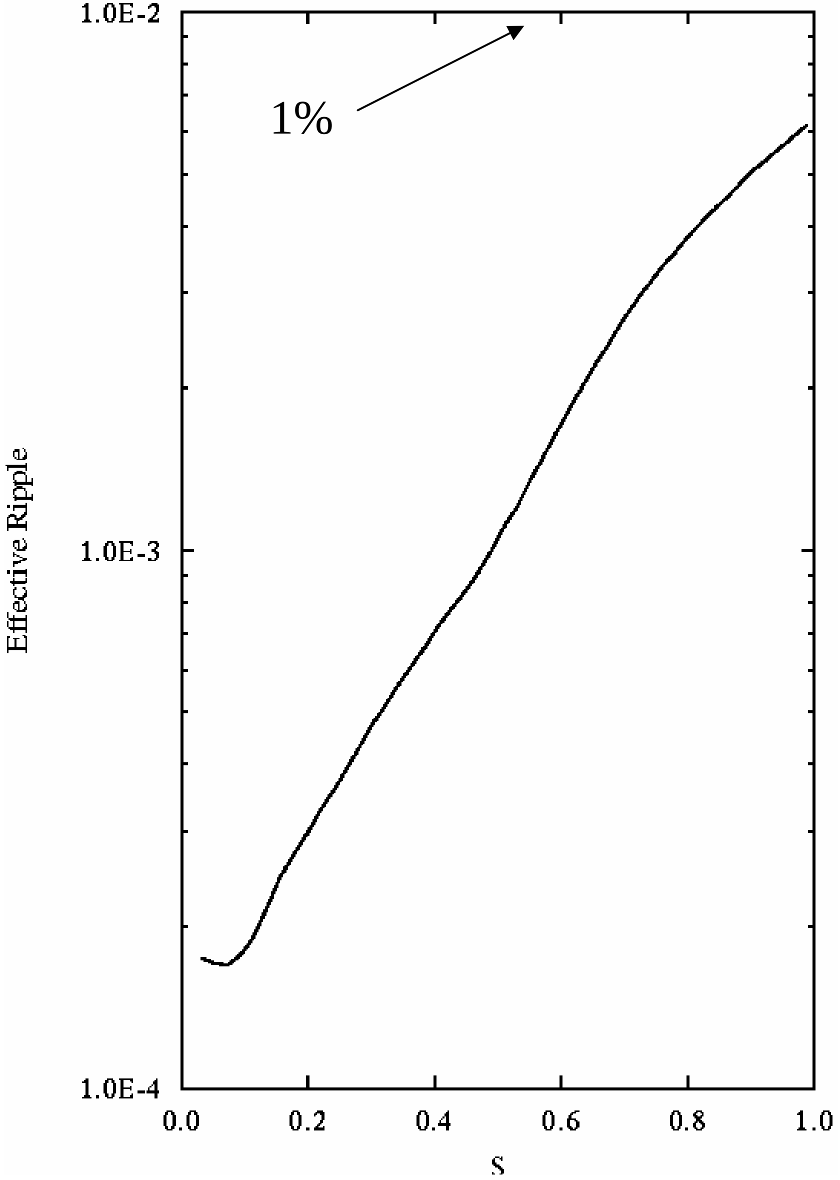
Axisymmetric components in magnetic spectrum (6% β).

← 8%

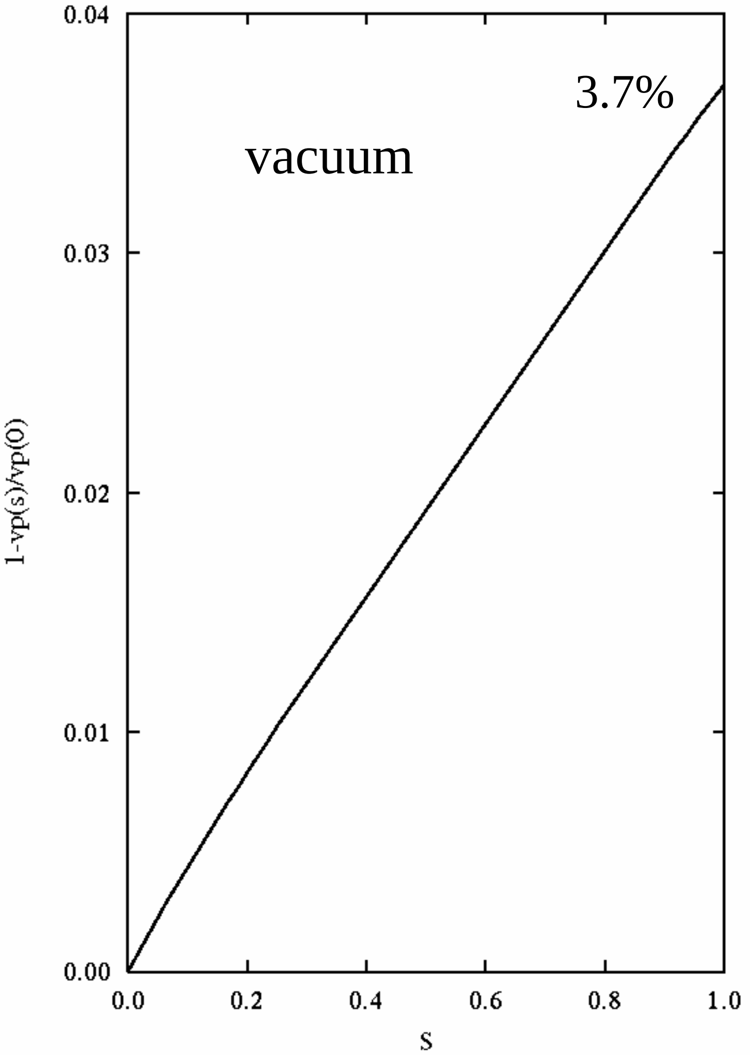
Axisymmetric components in magnetic spectrum (vacuum)

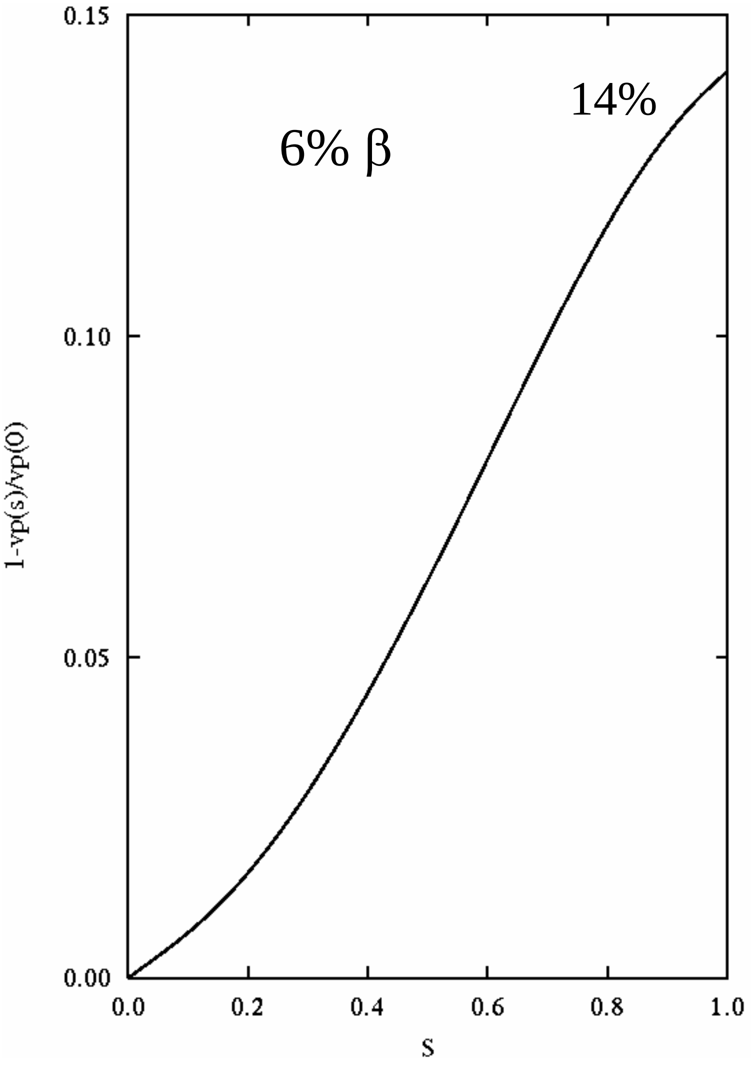
← 10%

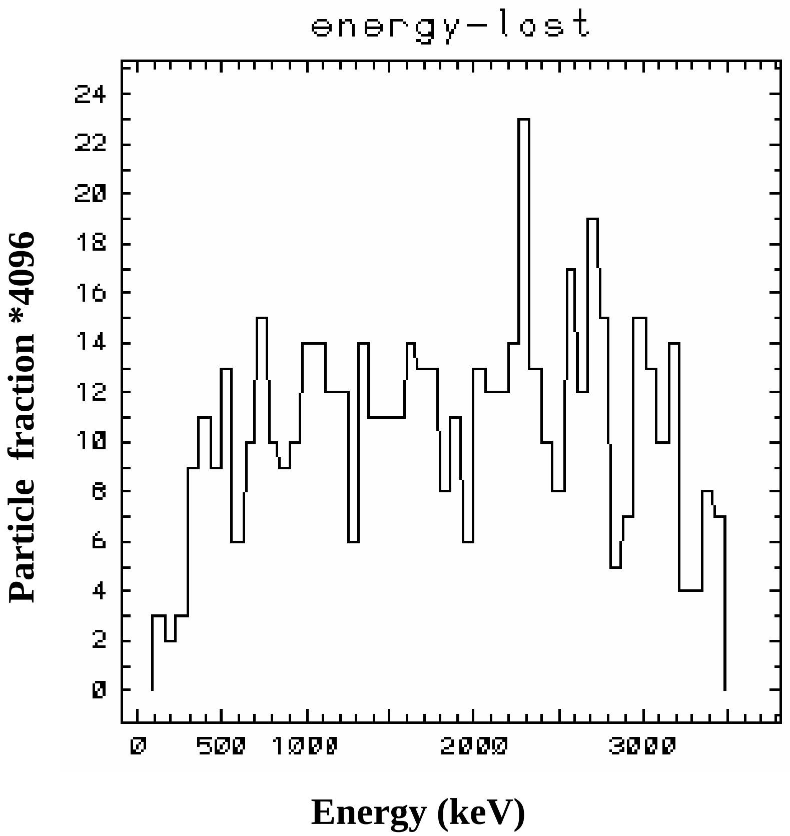
The effective ripple (a goodness measure of transport and confinement in 1/ν regime) is everywhere < 0.6% in KJC167.

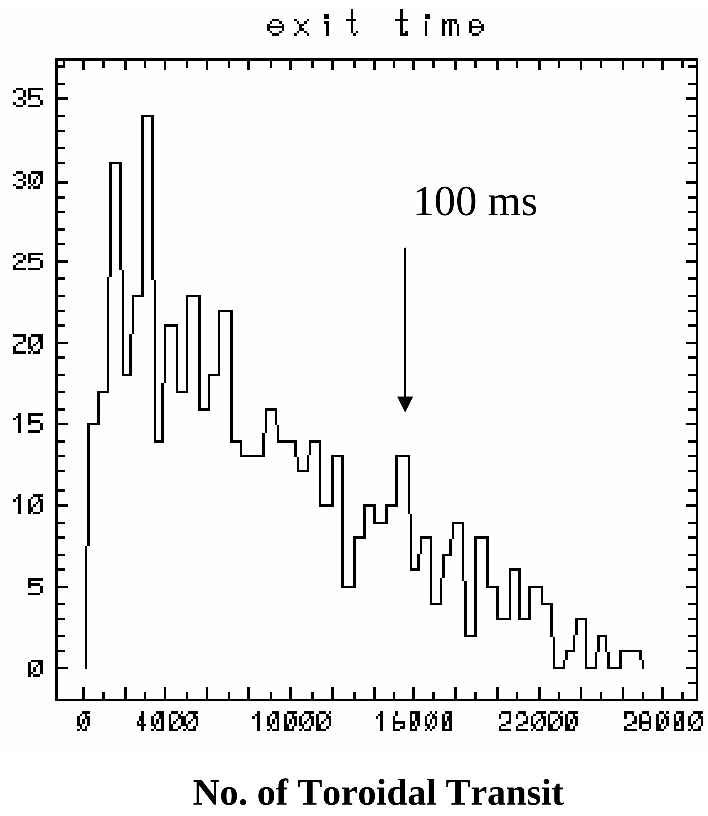


Along with good quasi-axisymmetry. a good magnetic well depth is simultaneously obtained in KJC167.



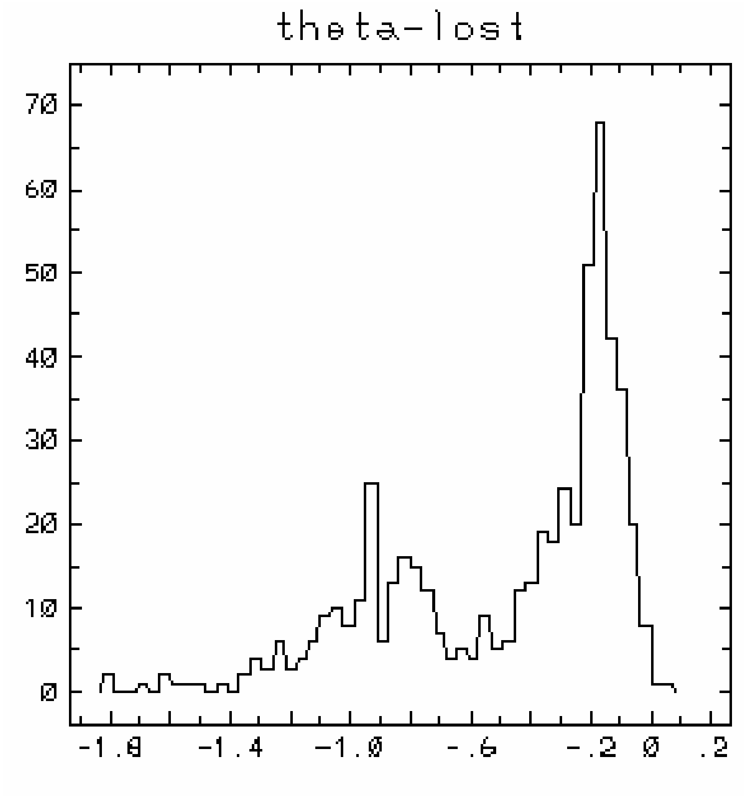




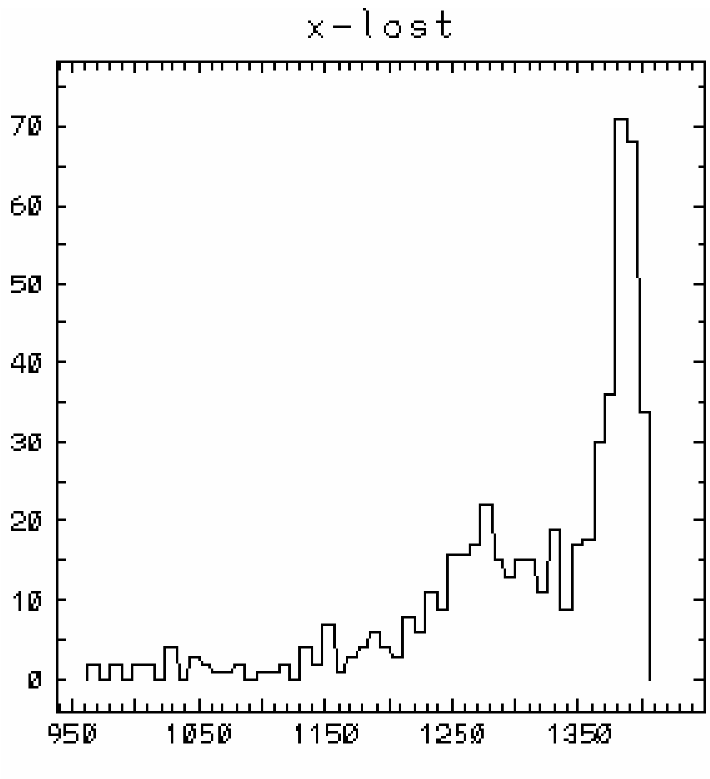


The energy loss fraction of α particles in KJC167 is calculated to be 6.9% for a volume ~1000 m^3 and B=6.5 T. The statistics of the exit particles indicate that a large number of alphas are lost after suffering multiple collisions with an essentially equal distribution in energy between 3 MeV and 0.5 MeV.

Particle fraction *4096



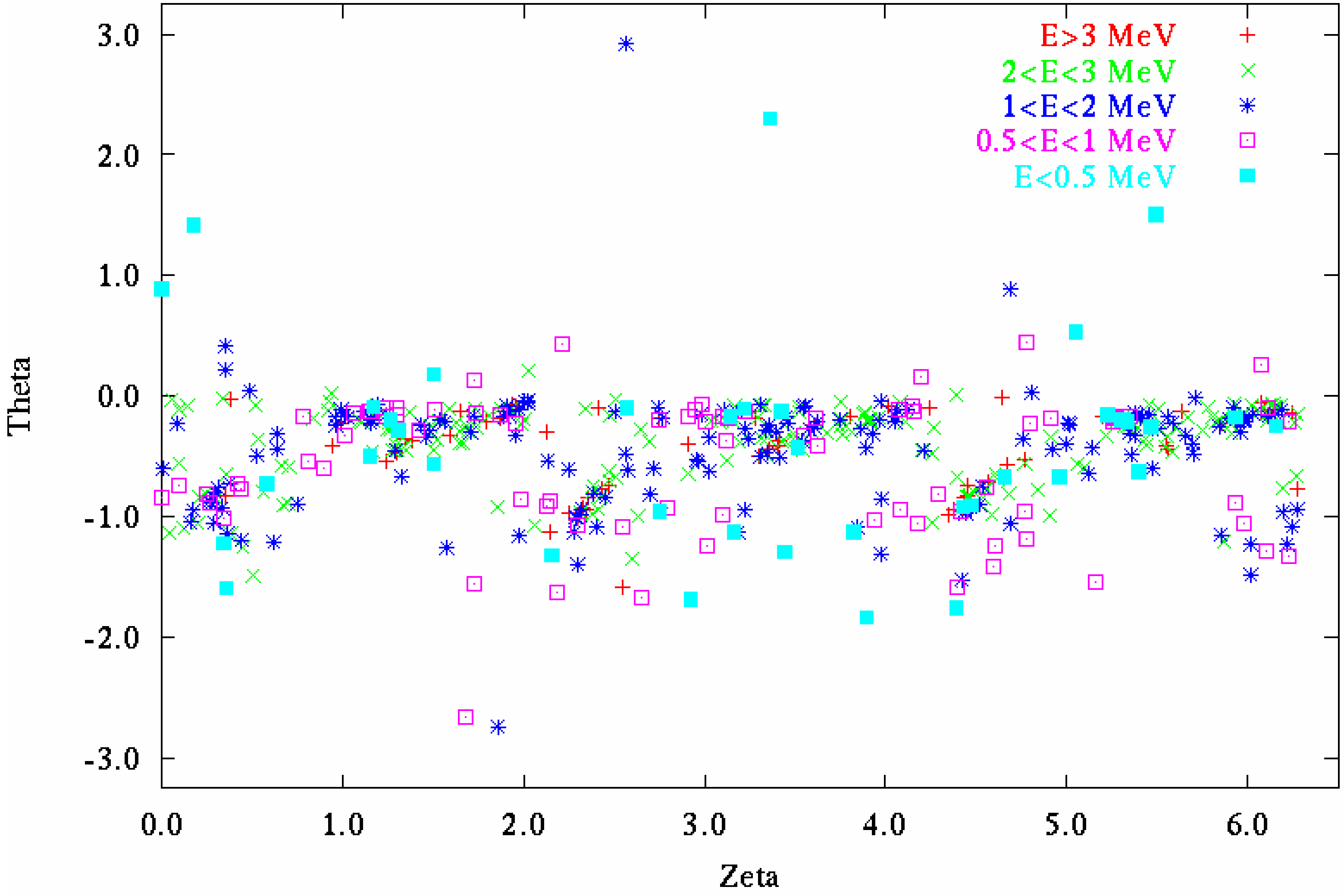
Poloidal Angle (radian)



Major Radius (cm)

The losses are more localized in major radius and poloidal angle than observed in previous cases.

The scatter plot of the escaping particles on the LCMS of KJC167 shows bands of clustered losses.



Polodal Boozer Angle

Toroidal Boozer Angle

Configurations of similar properties exist in a number of different regions of iota. Configurations with other selected aspect ratios and field periods are also found.

- NP=3, A=6.0
  - $\iota \sim 0.50$
  - $\iota \sim 0.65$

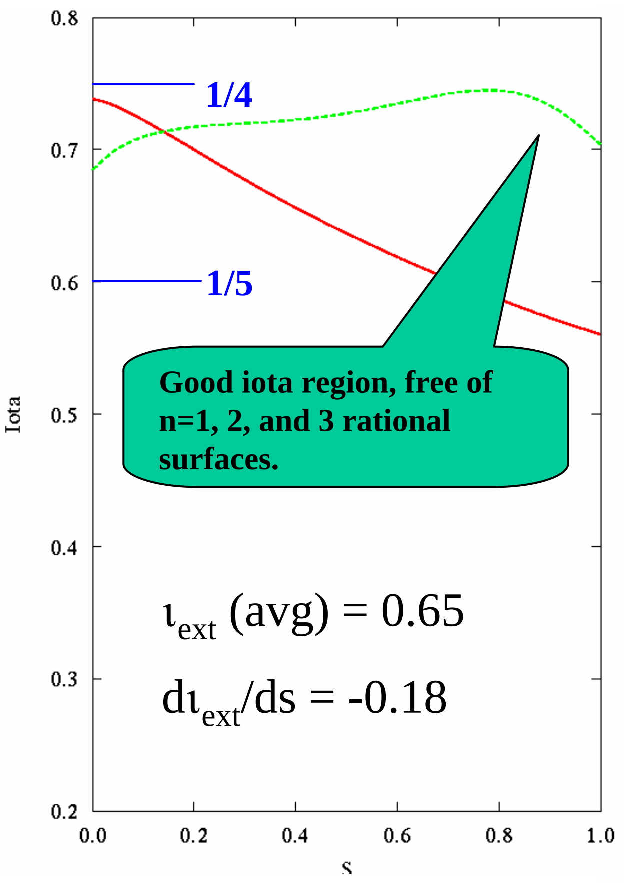
  $\}$ Good QA, good α confinement (loss <7%)

  - $\iota \sim 0.35$ → Good QA, but α confinement not as expected (discussed later). Also, iota range free of low order resonance too narrow.
- NP=3, A=4.5
  - $\iota \sim 0.50$ → Good α confinement (loss ~7%)
  - $\iota \sim 0.65$ → Acceptable QA, α loss ~10%

  $\}$ Need shape improvement.
- NP=2, A=4.0
  - $\iota \sim 0.40$

  Interesting configurations found with ~9% vacuum magnetic well and 7% α loss.

Comparison of configurations with different iota for A=6 and NP=3.

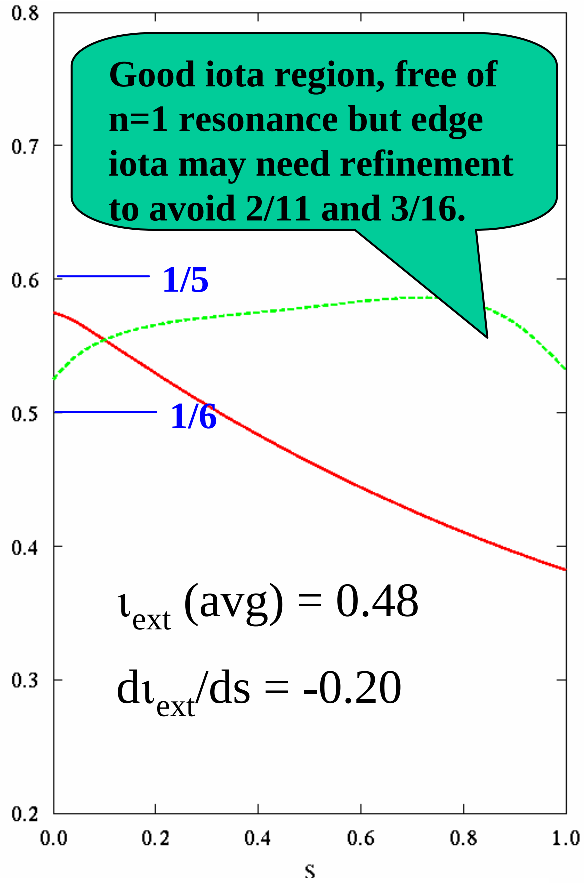


Good iota region, free of n=1, 2, and 3 rational surfaces.

ι_{ext} (avg) = 0.65

$d\iota_{ext}/ds = -0.18$

KKD863

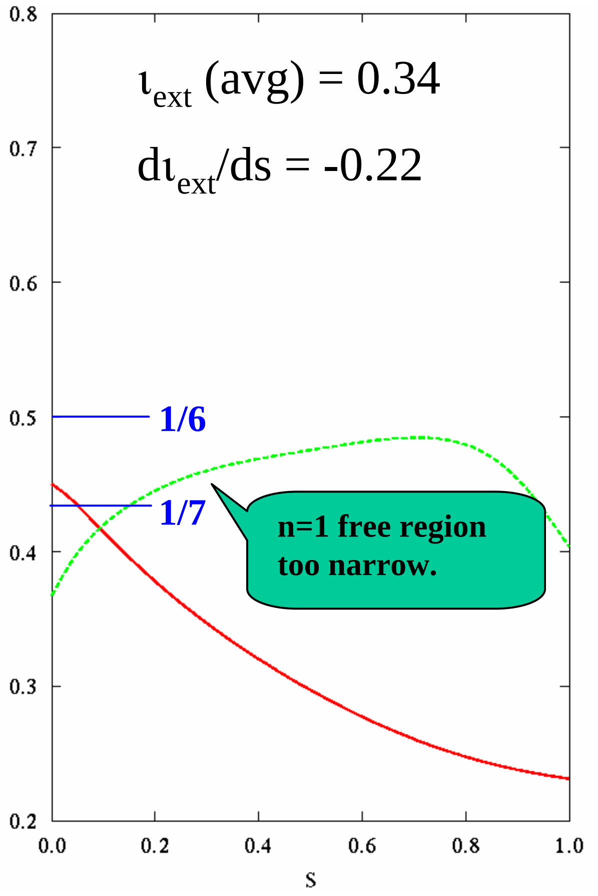


Good iota region, free of n=1 resonance but edge iota may need refinement to avoid 2/11 and 3/16.

ι_{ext} (avg) = 0.48

$d\iota_{ext}/ds = -0.20$

KJC167



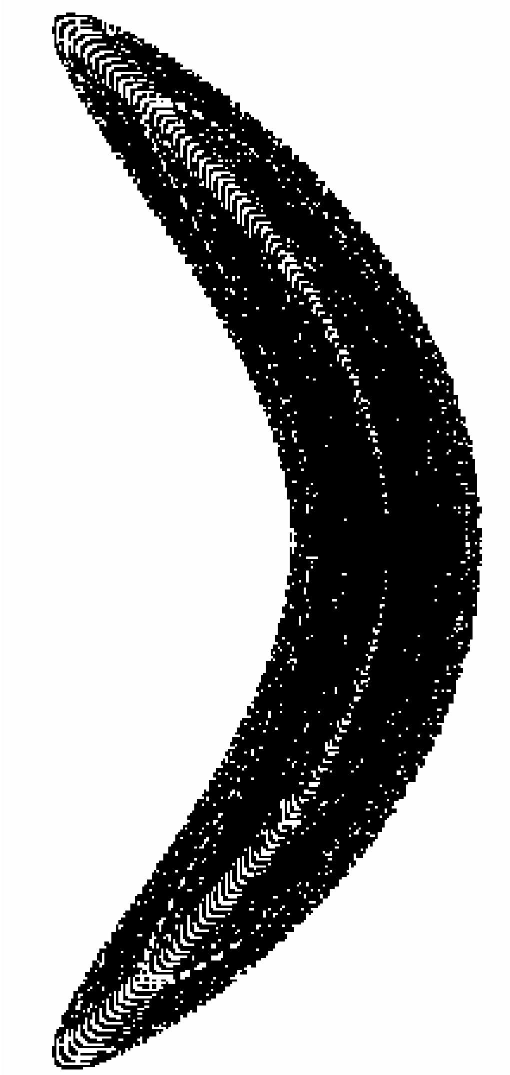
ι_{ext} (avg) = 0.34

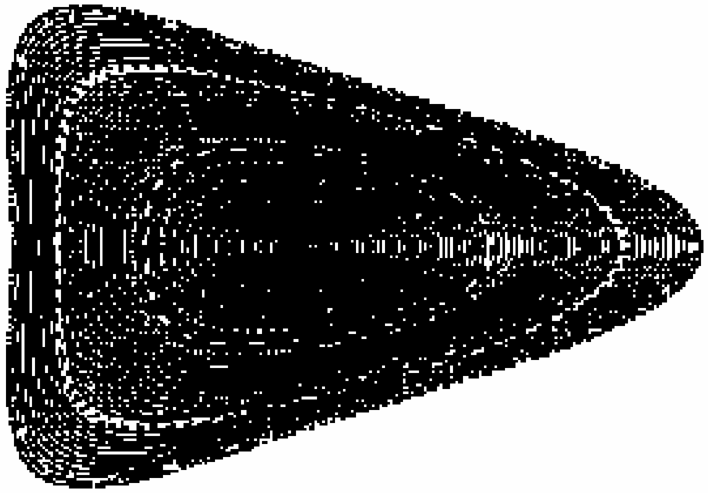
$d\iota_{ext}/ds = -0.22$

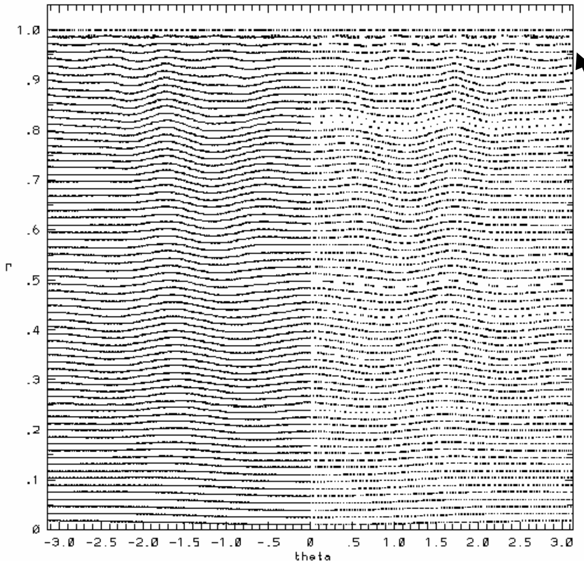
n=1 free region too narrow.

KBF122

Nested flux surfaces cover almost the entire plasma for KKD863 at 6% β as seen below based on a PIES calculation. The iota is in a region free of n=1, 2 and 3 rational surfaces.

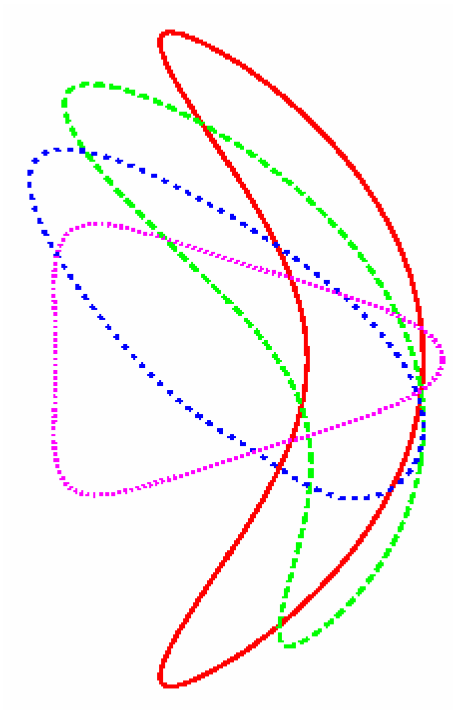




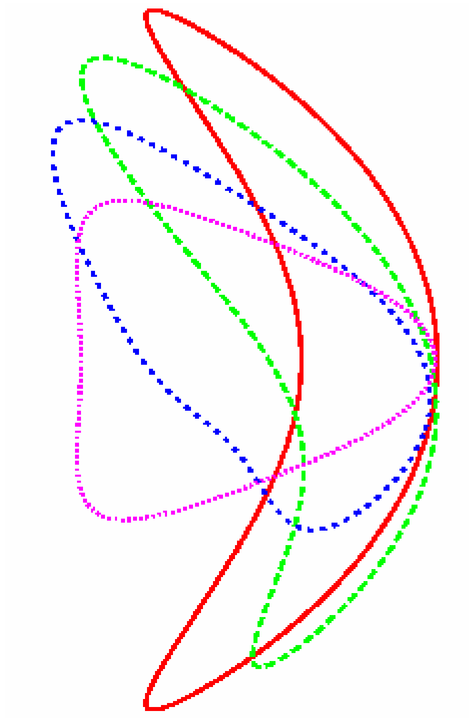


5/21, 6/25

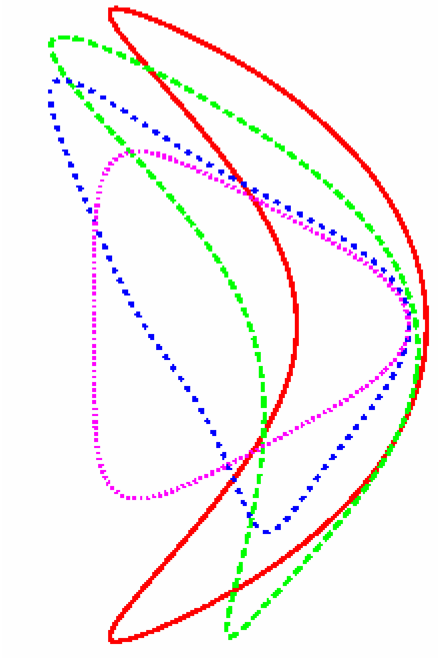
The deformation of the outmost surface becomes stronger as the average iota decreases and Δι increases.



ι_avg~0.65, Δι=0.18

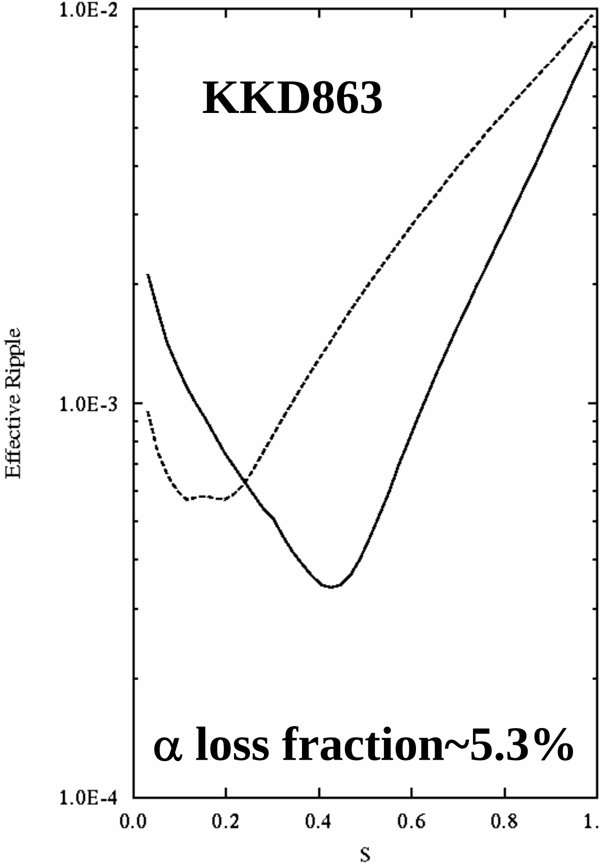


ι_avg~0.5, Δι=0.20



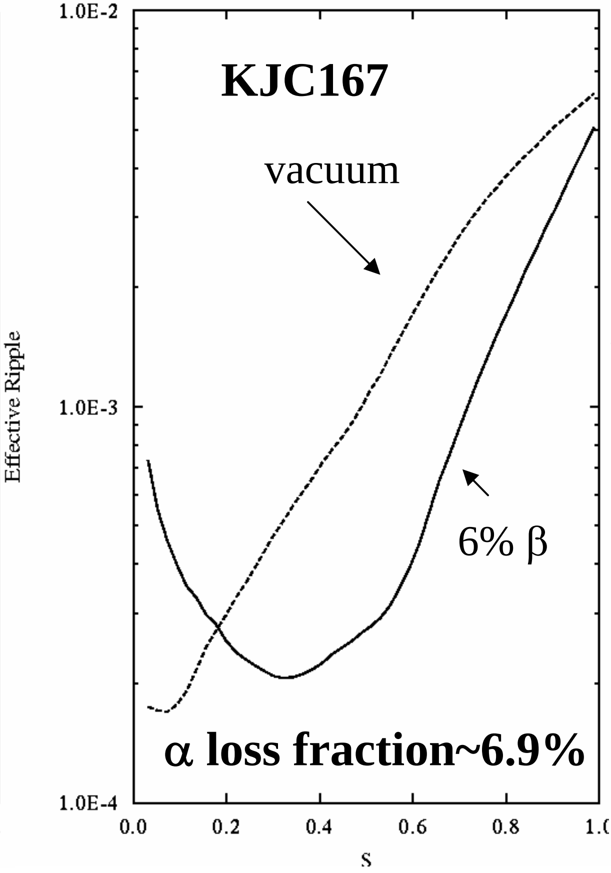
ι_avg~0.35, Δι=0.22

While they all have good QA as seen in the calculated effective ripples in the absence of plasma pressure, the α confinement at finite β is different due to the stronger Shafranov shift in the lower iota configurations and the larger amount of poloidal flux in the higher iota configurations. Note that QA is optimized for vacuum. The increase in ε-eff at higher β relative to that in vacuum in the plasma core due to pressure induced effects can be reduced by re-optimizing the configurations at finite β.



KKD863

α loss fraction~5.3%

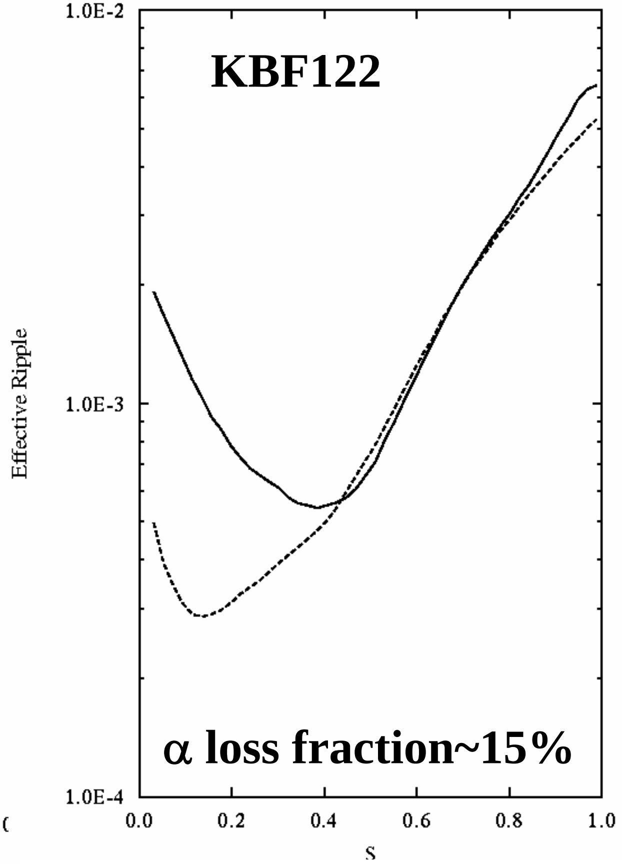


KJC167

vacuum

6% β

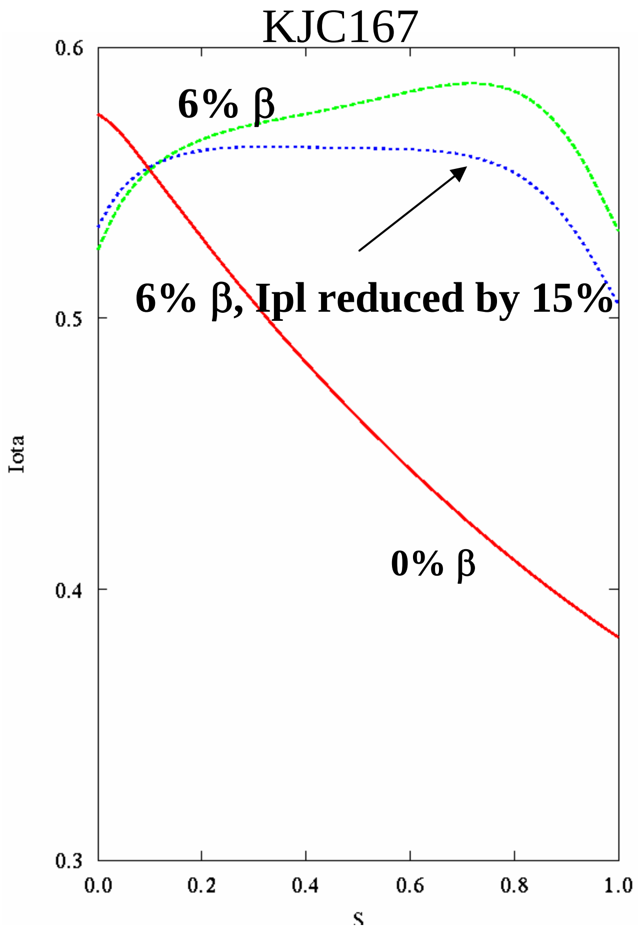
α loss fraction~6.9%



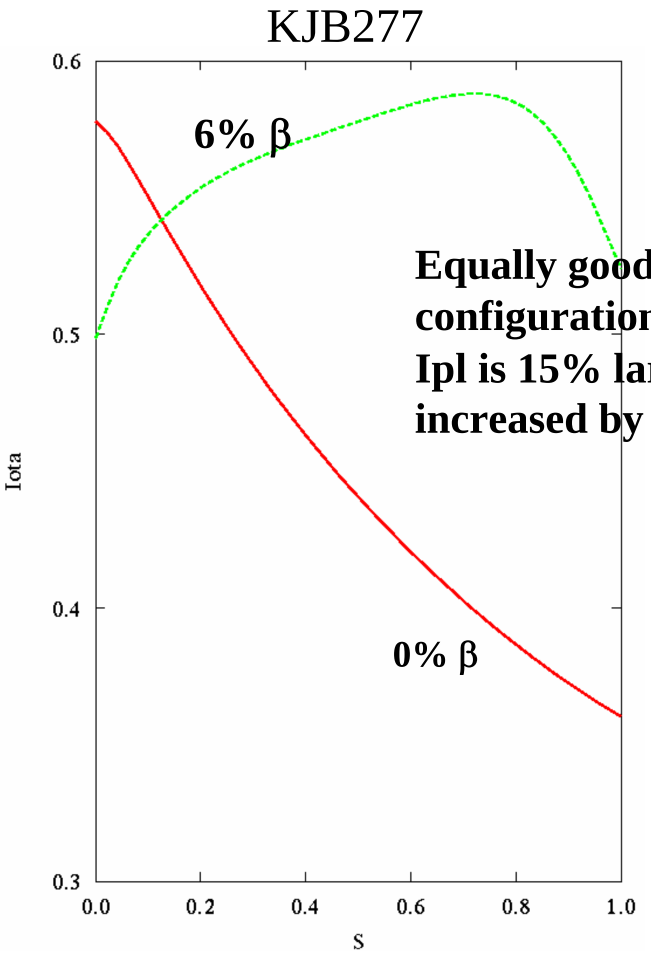
KBF122

α loss fraction~15%

Comparison of configurations with different degree of magnetic shear – robustness to levels of bootstrap current.



KJC167

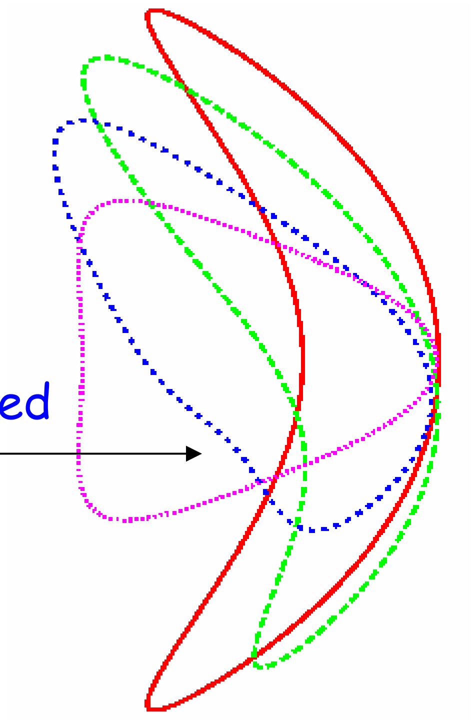


KJB277

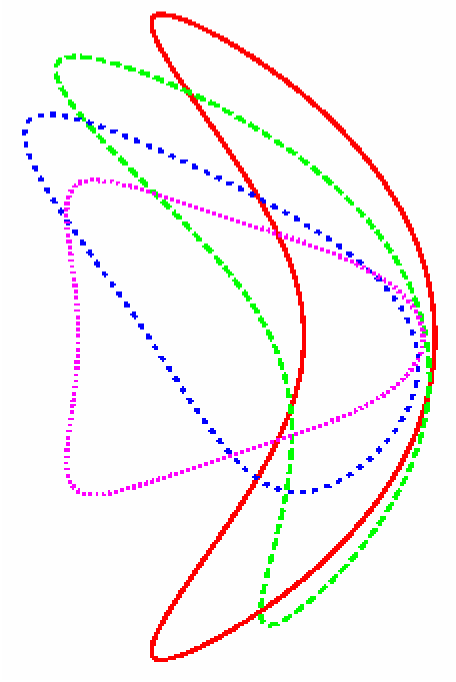
Equally good QA configuration obtained if Ipl is 15% larger. $\Delta\iota_{ext}$ increased by 0.02.

Boundary shapes for these two configurations are similar- the increased $\Delta\iota$ resulted in only a small increase in deformation.

The local boundary deformation may be due to numerical artifact in the search for optimal rather than physical needs, but need to be investigated.

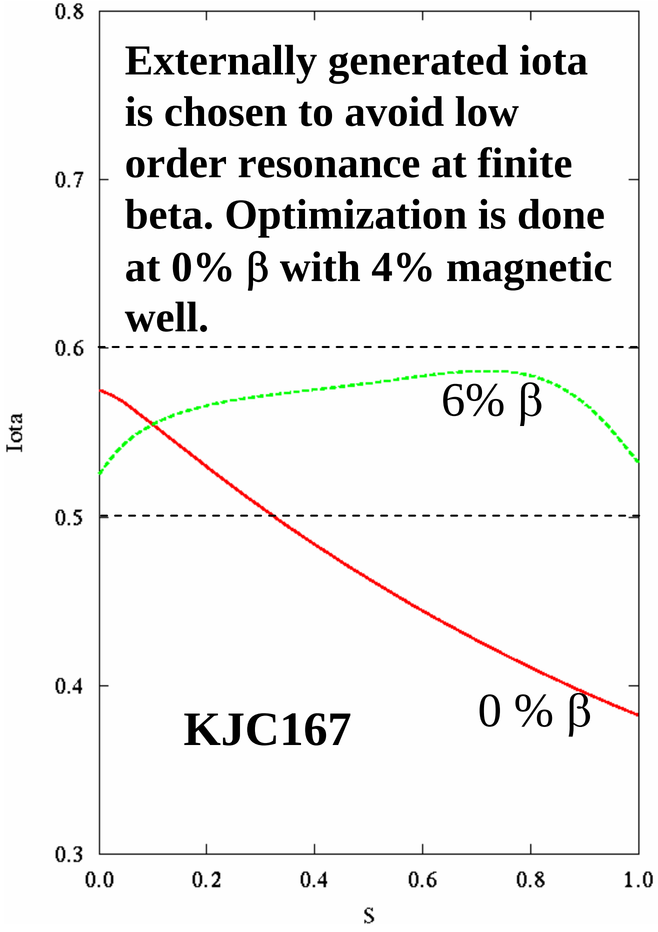


KJC167

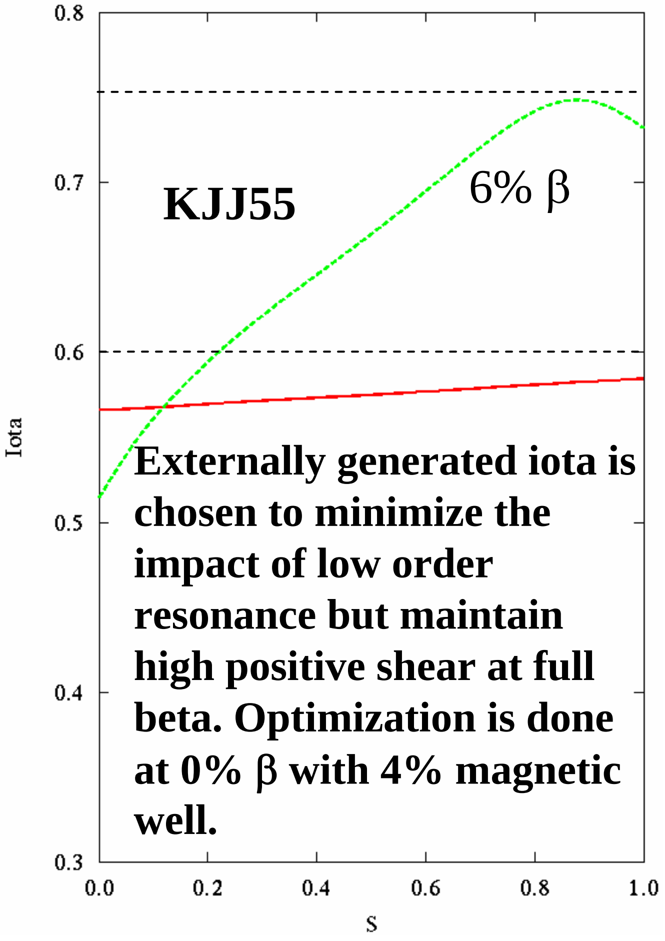


KJB277

Comparison with another set of QA configurations with monotonically increasing iota profiles currently being developed.

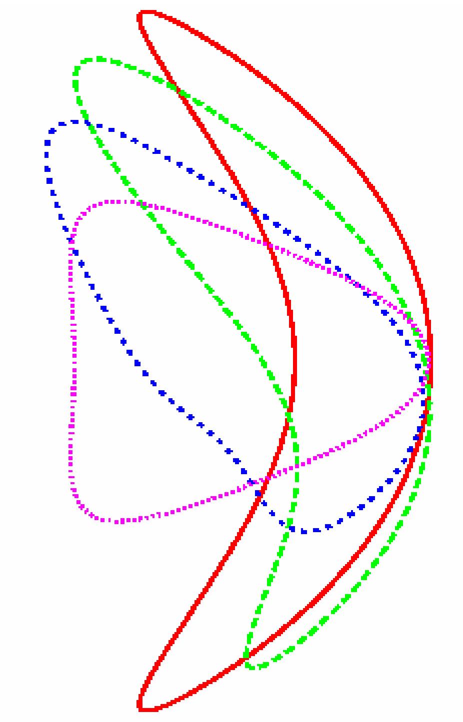


Externally generated iota is chosen to avoid low order resonance at finite beta. Optimization is done at 0% β with 4% magnetic well.

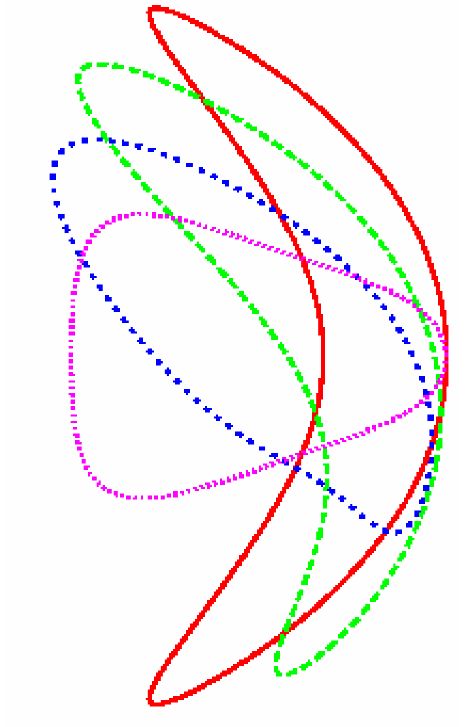


Externally generated iota is chosen to minimize the impact of low order resonance but maintain high positive shear at full beta. Optimization is done at 0% β with 4% magnetic well.

The complexity of boundary shape are similar for two classes of configurations if similar degree of QA and vacuum magnetic well depth are imposed.

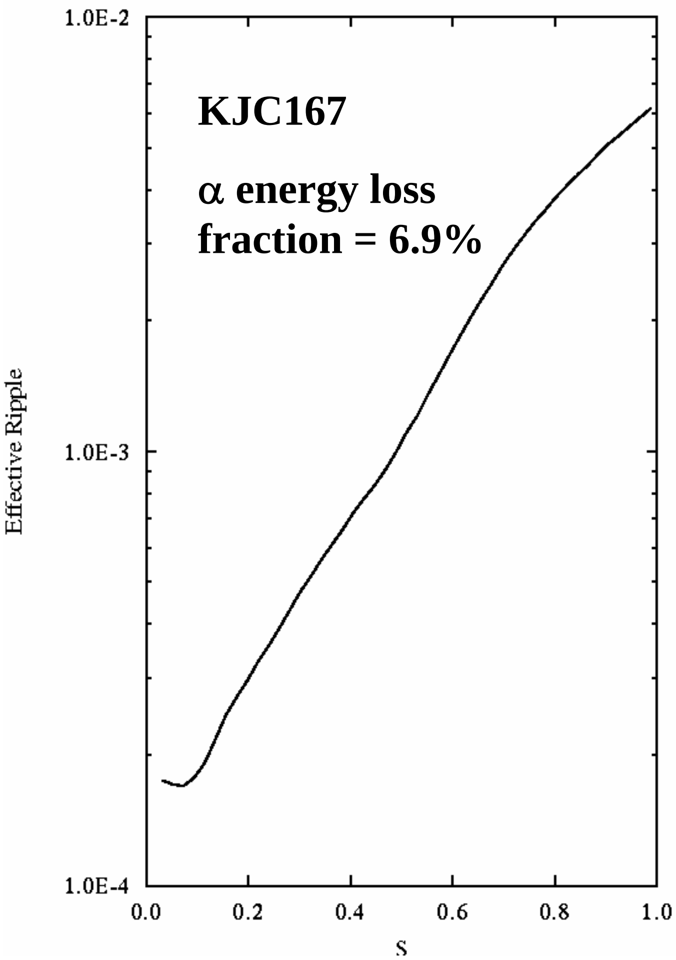


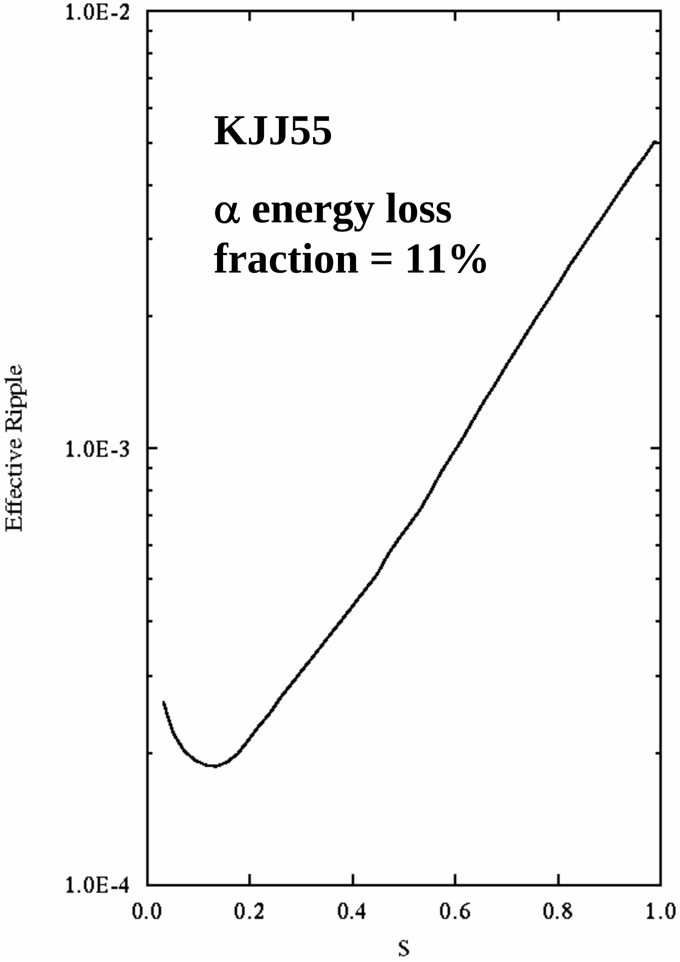
KJC167



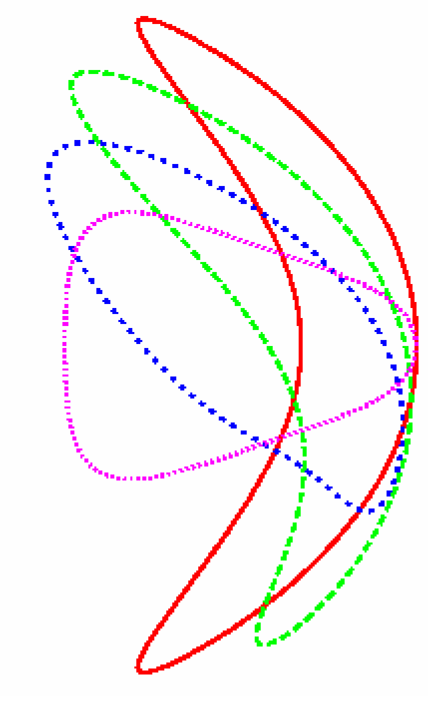
KJJ55

Although both configurations have similar QA, as shown below for the effective ripple (in vacuum), KJJ55 has poorer α confinement at 6% β.



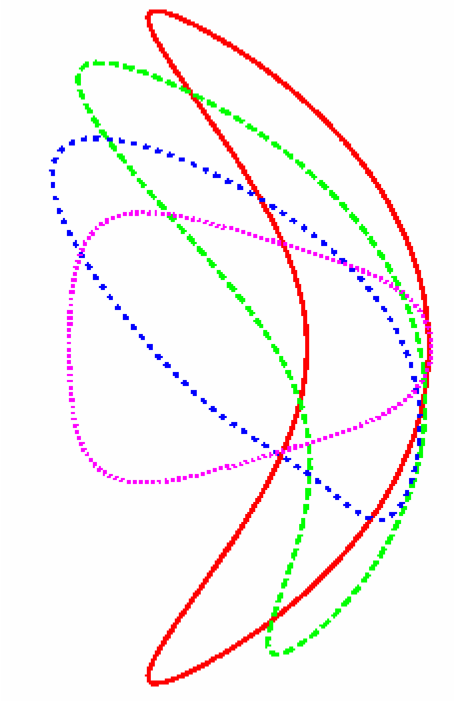


QA and α confinement for configurations with externally generated monotonically increasing iota profile are more sensitive to the constraint of the magnetic well.



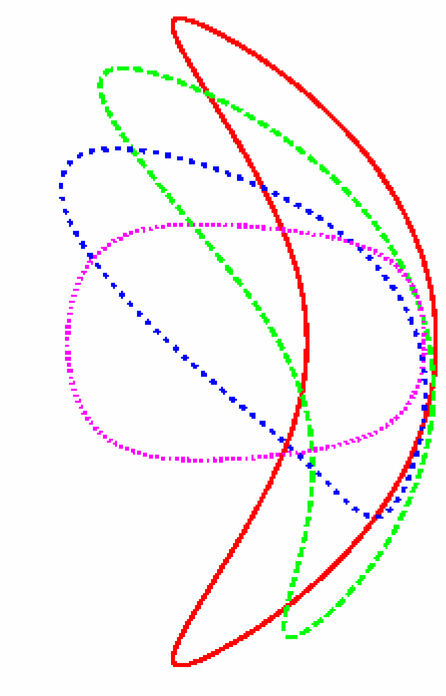
Well depth = 4%

α loss =11%



Well depth = 3%

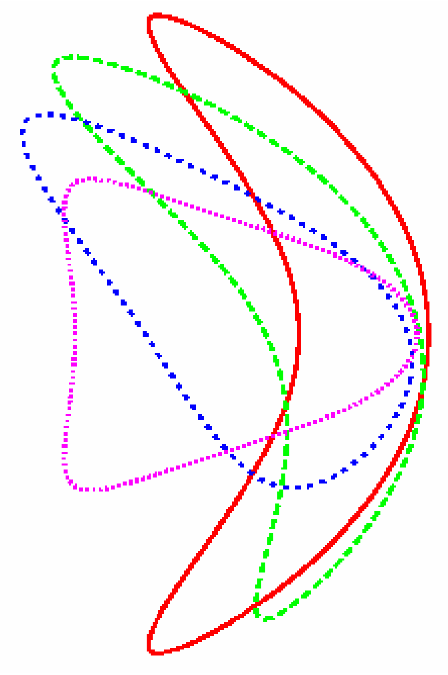
α loss =8.5%



Well depth = -1%

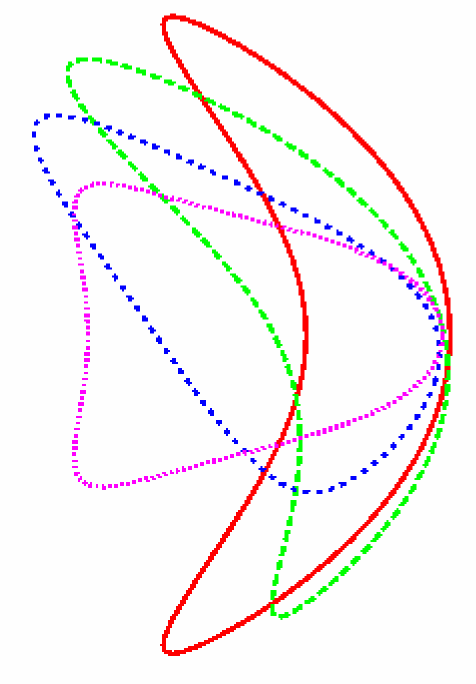
α loss =2.6%

Similar trend also observed for configurations with monotonically decreasing iota but it is not as sensitive. However, we have observed that local minima in this configuration subspace are even more numerous and deeper, making it more difficult to escape local trapping. It is difficult to ascertain this sensitivity.



KJB277: well depth 4%

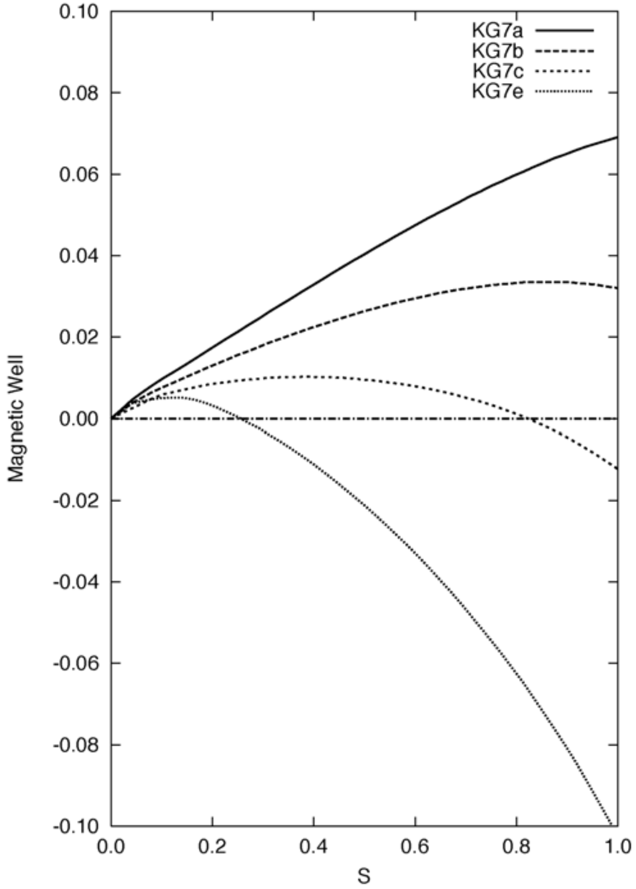
α loss =8.8%

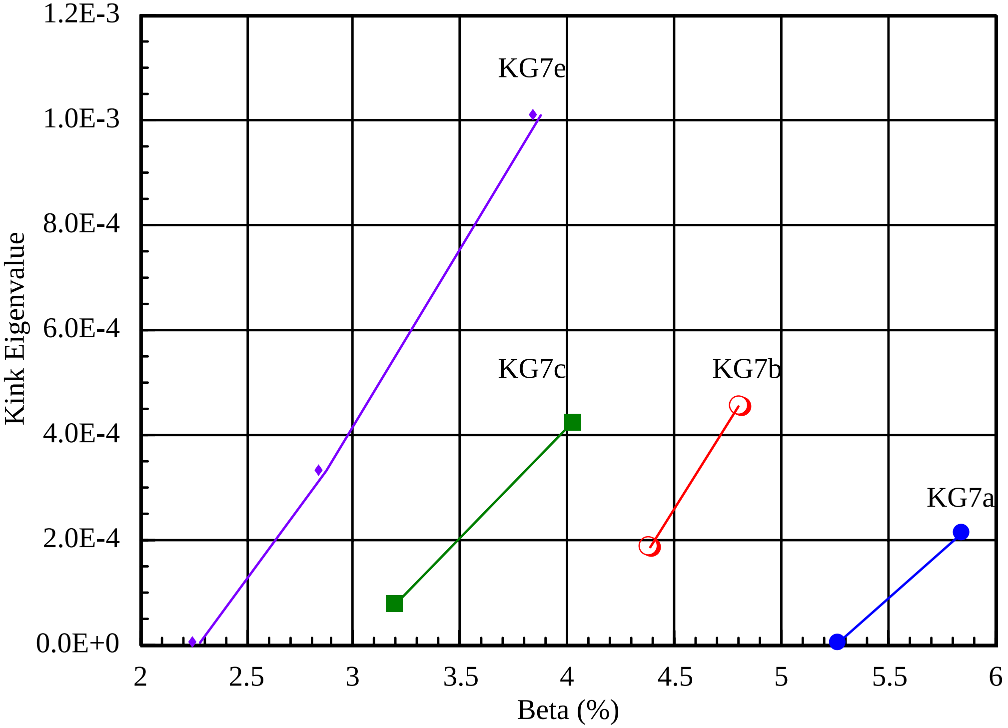


KJB277w: well depth 2%

α loss =7.2%

How does MHD stability and magnetic well interplay? With plasma pressure, the well will deepen so that the role of initial vacuum well is not clear. Previous studies (using Terpsichore) for kink stability based on the linear, ideal MHD theory did show a positive correlation with the critical beta.





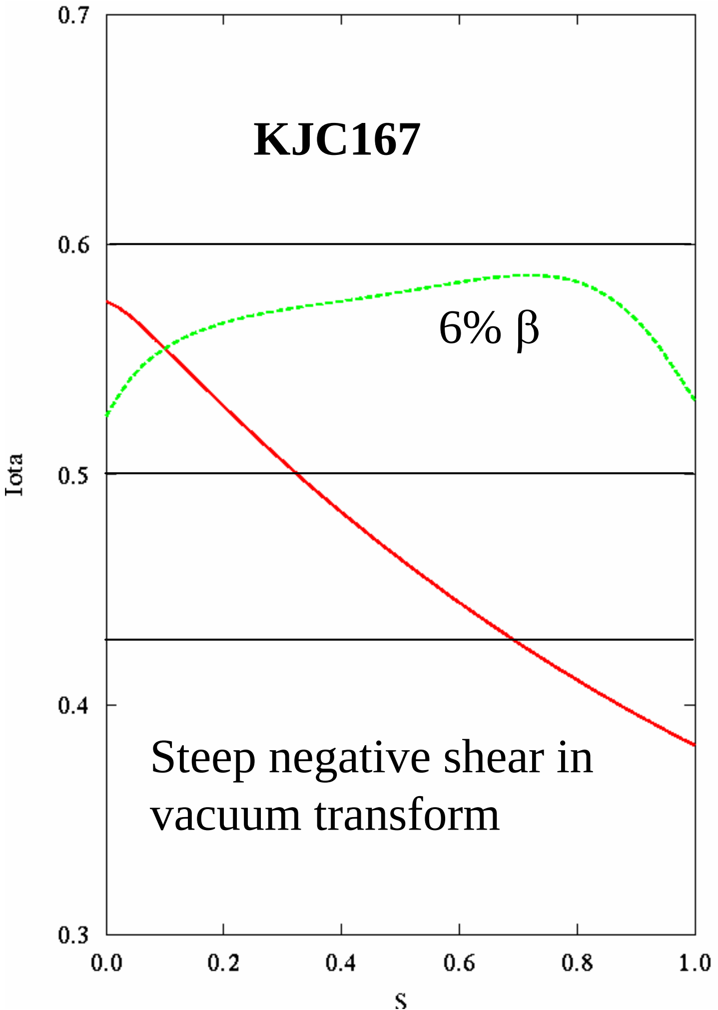
For the present configurations, what is the beta limit according to the linear theory?

- External kink modes: pressure driven contribute ~50% of the instability at 6% β (eigenvalue is on the order of 10^{-3}). For fixed current, unstable even at 0% β due to current driven force. ← value in terms of growth rate being assessed

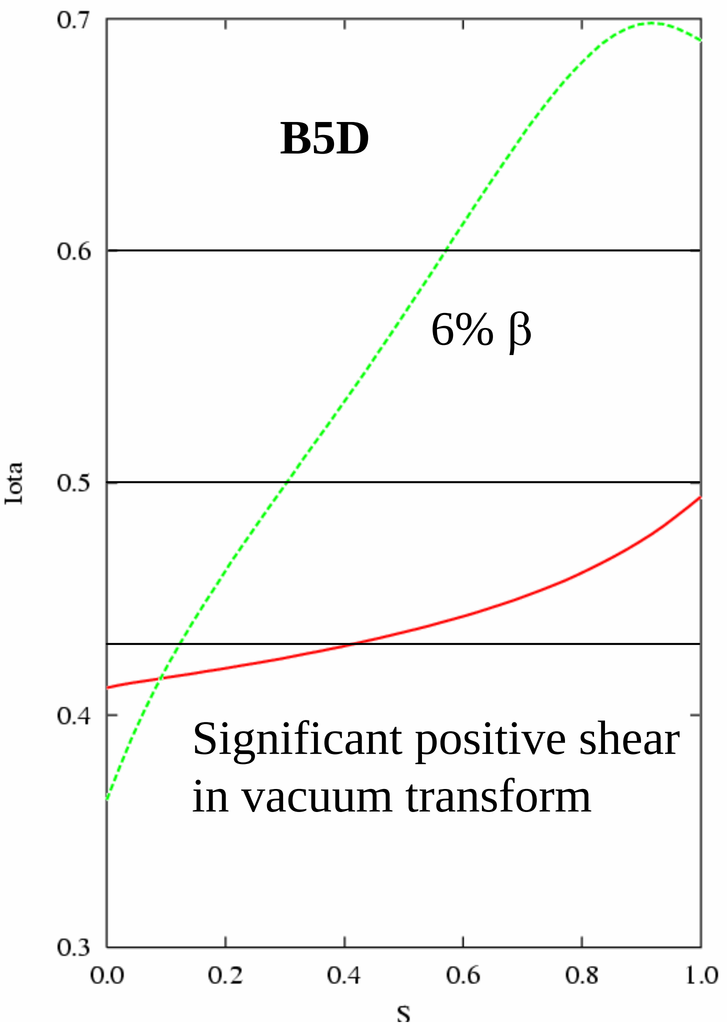
- Infinite-n ballooning generally stabilized at ~2-3% β. ← finite intermediate n being studied.

Comparison with NCSX-class of configurations -distinctive profiles of rotational transform.

NP=3, A=6

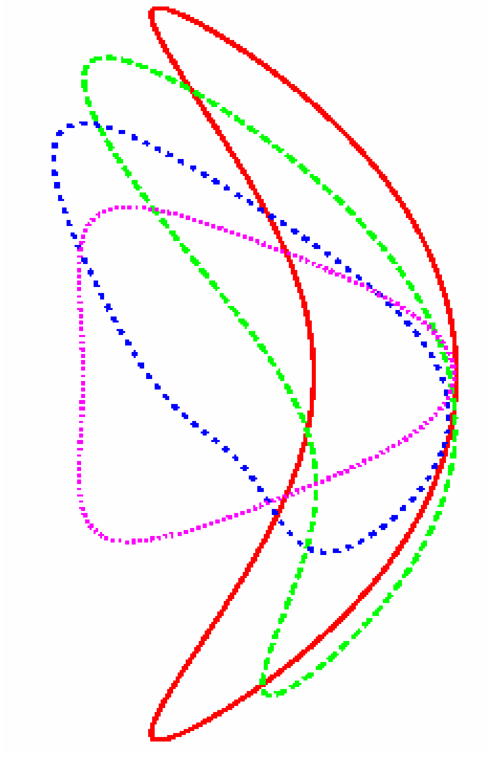


Steep negative shear in vacuum transform

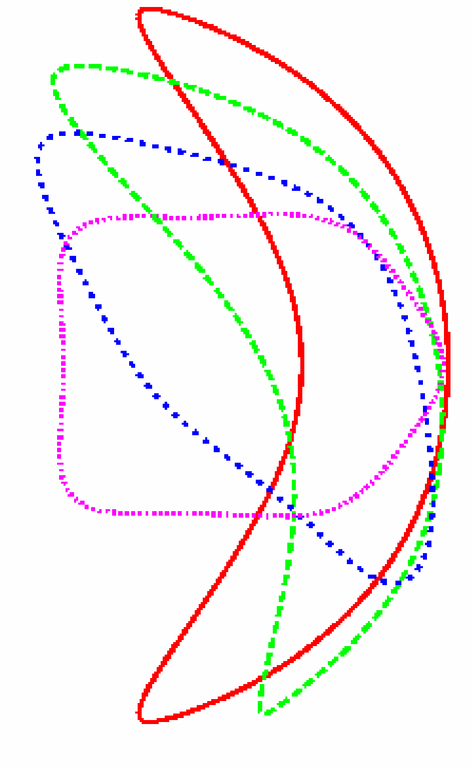


Significant positive shear in vacuum transform

Comparison of plasma boundary shape: KJC167 was optimized for QA in vacuum with a magnetic well constraint, whereas B5D was optimized at 4% beta subject to N=1 kink stability and infinite-n ballooning stability constraints. Both the toroidal and poloidal mode numbers for shaping in B5D were allowed to be one degree higher.

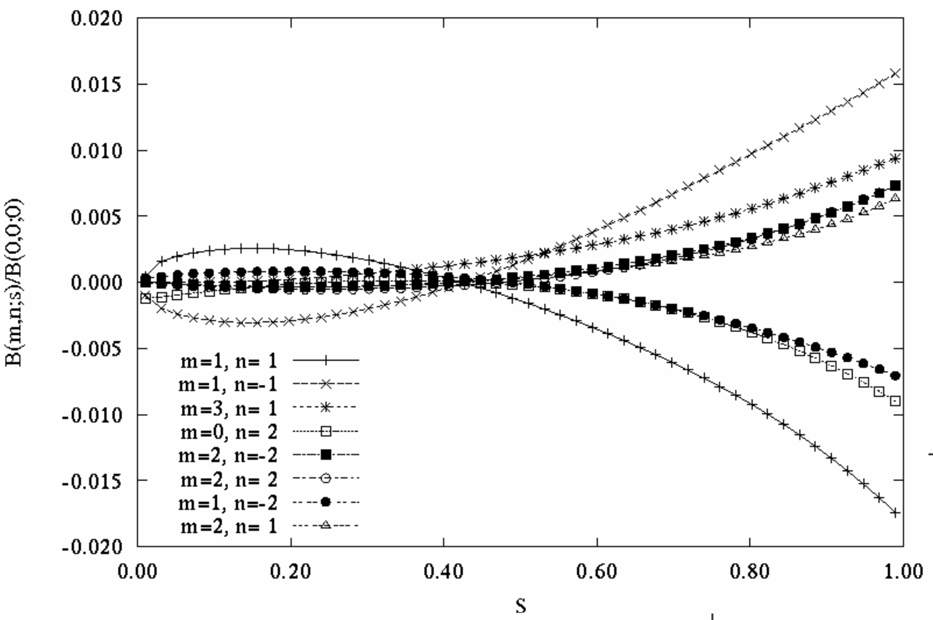


KJC167



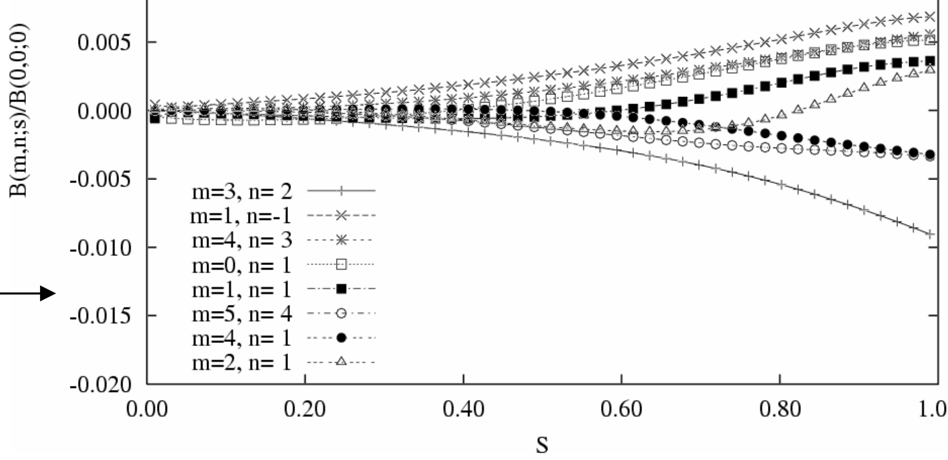
B5D

Comparison of non-axisymmetric components in magnetic spectrum: NCSX-like configurations achieve better QA perhaps due to the increased degree of freedom in shaping and the relaxation of the magnetic well constraint.



KJC167 at 6% β

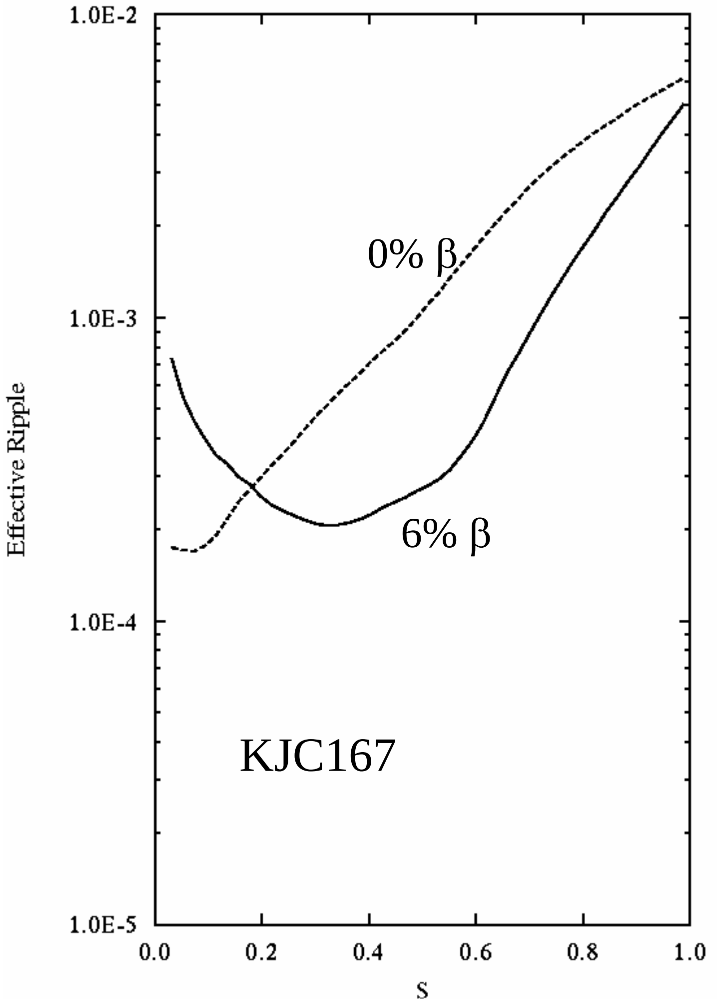
<1.7%

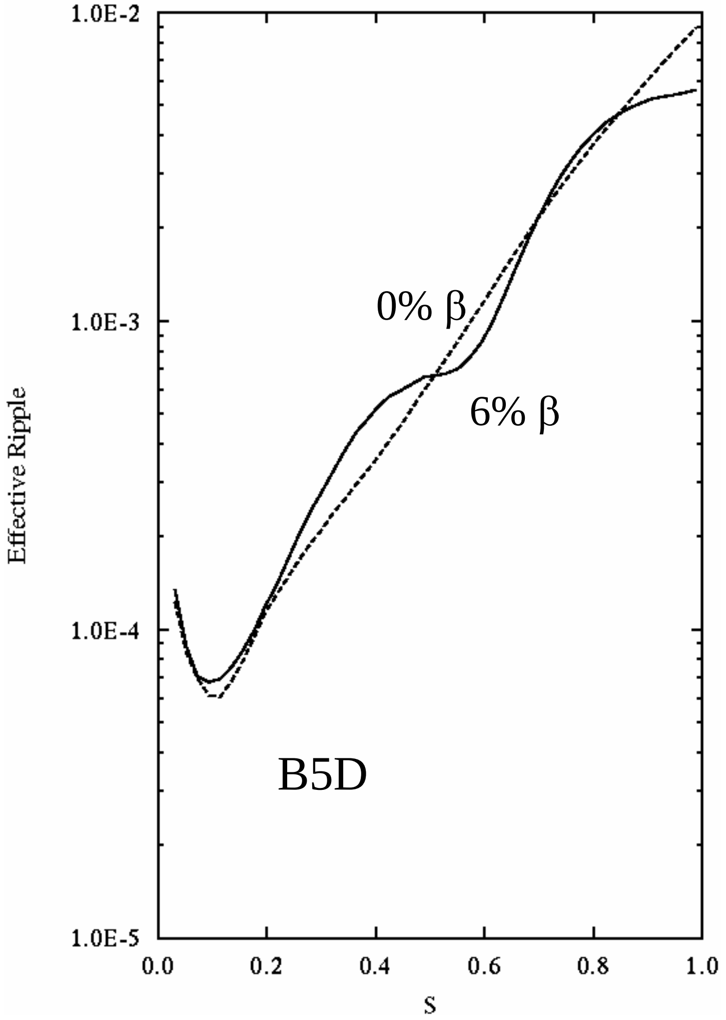


<0.9%

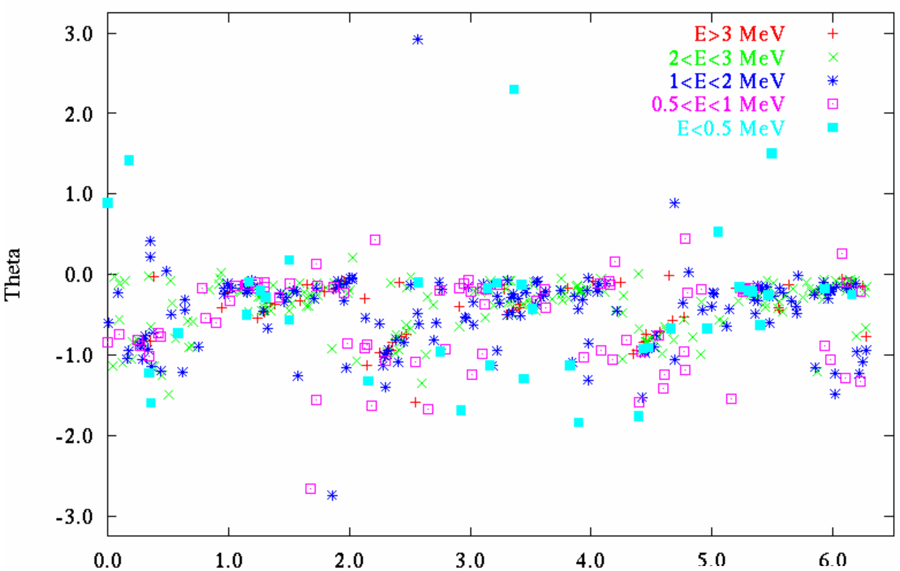
B5D at 6% β

NCSX-like B5D has a superior ε-eff characteristic in the core region, but presumably the ε-eff of KJC167 in the core can be further optimized at finite β.

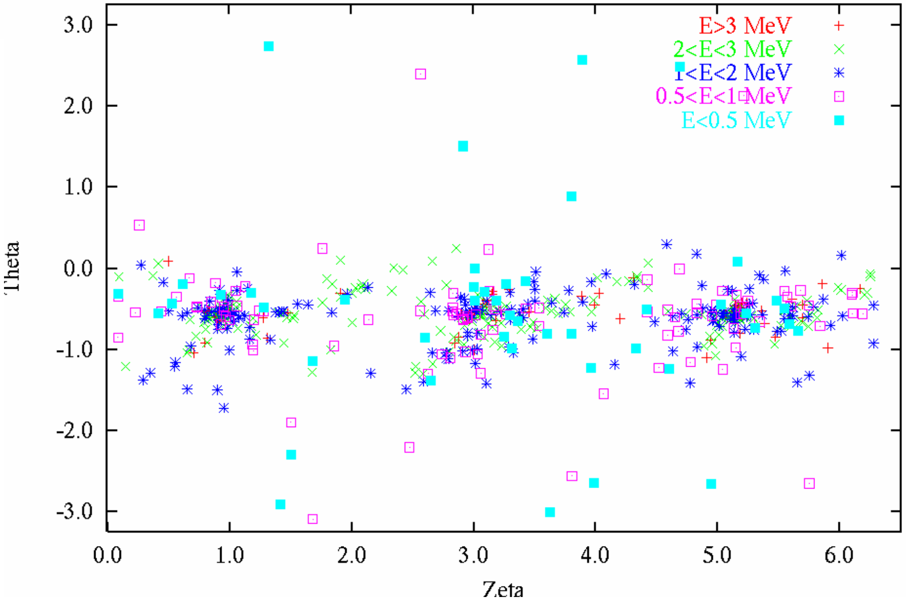




α confinement of both cases are similar; larger residues in KJC167 do not hurt.



KJC167, α energy loss fraction = 6.9% (1000 m^3, B=6.5 T , 6% β)



B5D, α energy loss fraction = 7.7% (1000 m^3, B=6.5 T, 6% β)

Comparison of MHD Stability:

- B5D stable to N=1 external kinks and infinite-n ballooning modes at 4% β based on calculations using ideal, linear MHD theories. It has a very shallow vacuum magnetic well, ~0.8%. It is unstable at 6% β, with a Terpsichore calculated eigenvalue $1.5\cdot10^{-3}$ for the N=1 kinks.

- KJC167 unstable to external kinks and infinite-n ballooning using the same types of calculations at 4% β. It is ballooning stable at β ~2% and has ~4% vacuum magnetic well. At 6% β, it has a Terpsichore calculated eigenvalue $6.0\cdot10^{-3}$ for the N=1 kinks.

Can further optimization be able to improve these ?

Summary and Future work

- An initial set of new QA configurations aimed at having good flux surface quality at high β has been developed.
  - Preliminary assessment indicates that these configurations have good quasi-axisymmetry, good α confinement characteristic and deep magnetic well.
  - The configuration space also appears to be broad enough to encompass various iota regions, aspect ratios and field periods.

- We plan to address the following for this new class of configurations in the near future:
  - Coil topology and its design optimization.
  - Further refinement and improvement in:
    - alpha confinement (improvement of QA in core at full β).
    - stability to MHD modes calculated by codes based on ideal, linear theories (optimization for external kinks and ballooning at full β with iota constraint).
    - shape optimization (imposing curvature constraint).
    - iota refinement to avoid 2nd or 3rd order resonance near plasma edge (imposing iota profile constraint).
- We also plan to re-examine the island-healing methodology in the configuration optimization for NCSX-type of compact stellarators.