Compact Stellarator Configuration Development Status and Issues

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Review of Tasks for Reactor Configuration Development

- In Oct, 2002 project meeting, we outlined essential tasks for configuration development:
  - Develop effective figures of merit for optimizing α confinement, flux surface quality, and COE;
  - Find means to maximize Δ–min;
  - Explore configuration space for attractive reactor regimes (compactness, good quasi-symmetry, low α losses, robust MHD stability, simple coils)

- We focus first on developing methods to minimize α losses and using the method developed to search for attractive configurations.

  – Implemented method to target directly α losses in configuration optimizer (reported in Jan., 2003 project meeting)

  – Have made extensive efforts to explore the configuration space (aspect ratios, rotational transform, field periods)

Subject of Today's Discussion

Exploration of QA Configuration Space

- We limit the present study to the NCSX (LI383) "class" of configurations

because

- Basic shaping (average elongation, triangularity, etc.) gives good overall quasi-axisymmetry and MHD stability.
- Have shown realizable coils with reasonable coil aspect ratio.

but

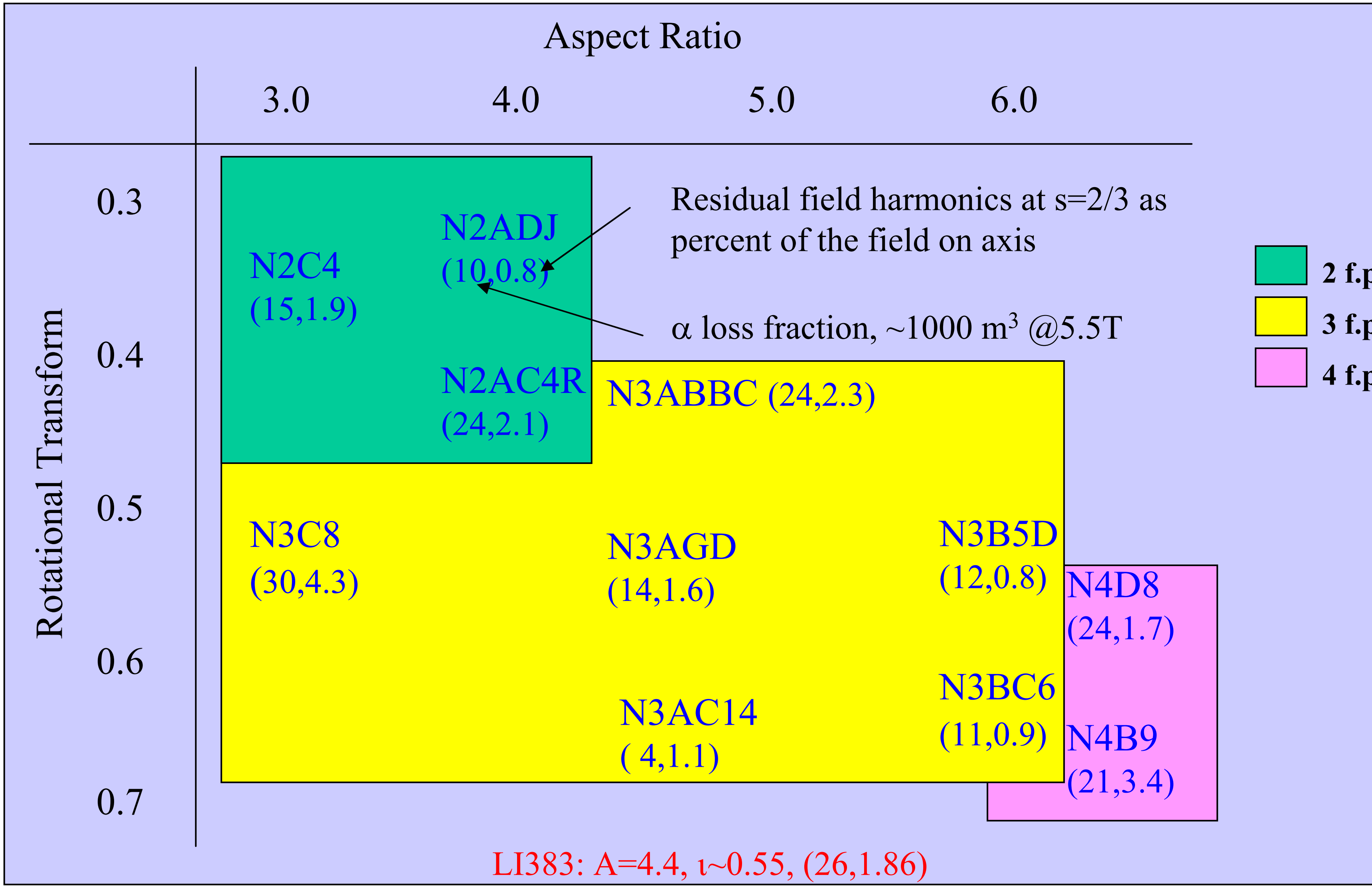
- LI383-like shaping is described by ~60 independent Fourier harmonics. Some high order modes may make required magnetic fields difficult to produce from coils.

- We have explored regions with aspect ratio from 3 to 6.5, rotational transform (@s=0.5) from 0.3 to 0.75.
  - The region is bounded by the consideration:
    - higher iota → difficulty in the kink and Mercier stability and too strong shape deformation
    - higher A → no longer compact
    - lower iota → not enough poloidal flux and difficulty in vertical stability
    - lower A → too difficult to achieve acceptable QA
- Regions of "good" α loss characteristic (~10% energy loss) are found:
  - High q (q-max~5, q-min~2), A~4
  - Low q (q-max~2.5, q-min~1.2), A~5-6.

Significantly improved compared to ~30% loss for most of the QA configurations we had which were not optimized for α losses.

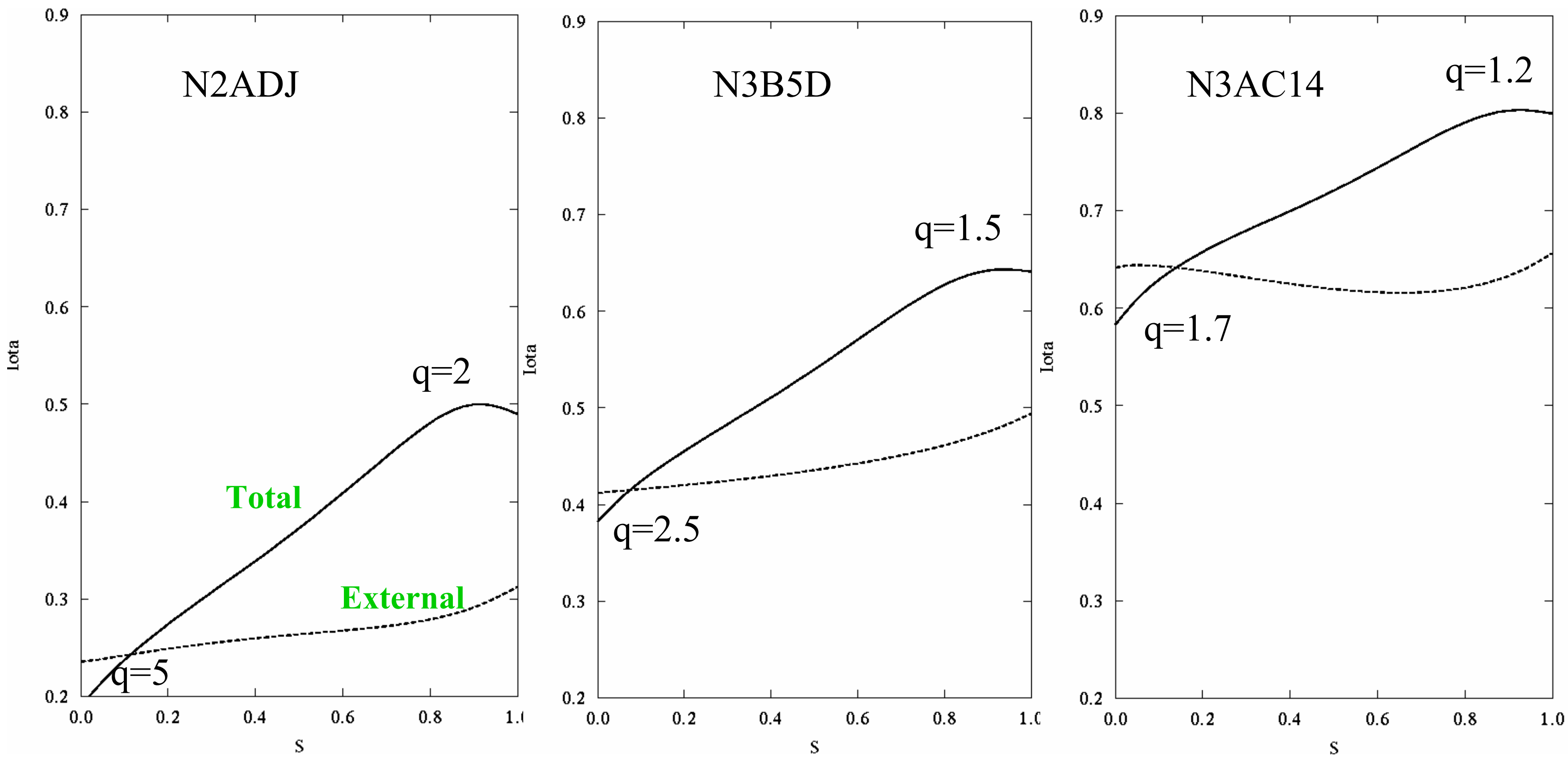
- The search is computation intensive.
  - > 200,000 cpu hours spent on IBM SP (RS-6000, 375 MHz Power3 processors, 1.5 Gflops/sec peak performance) alone.

Representative Configurations in Aspect Ratio-Iota Space

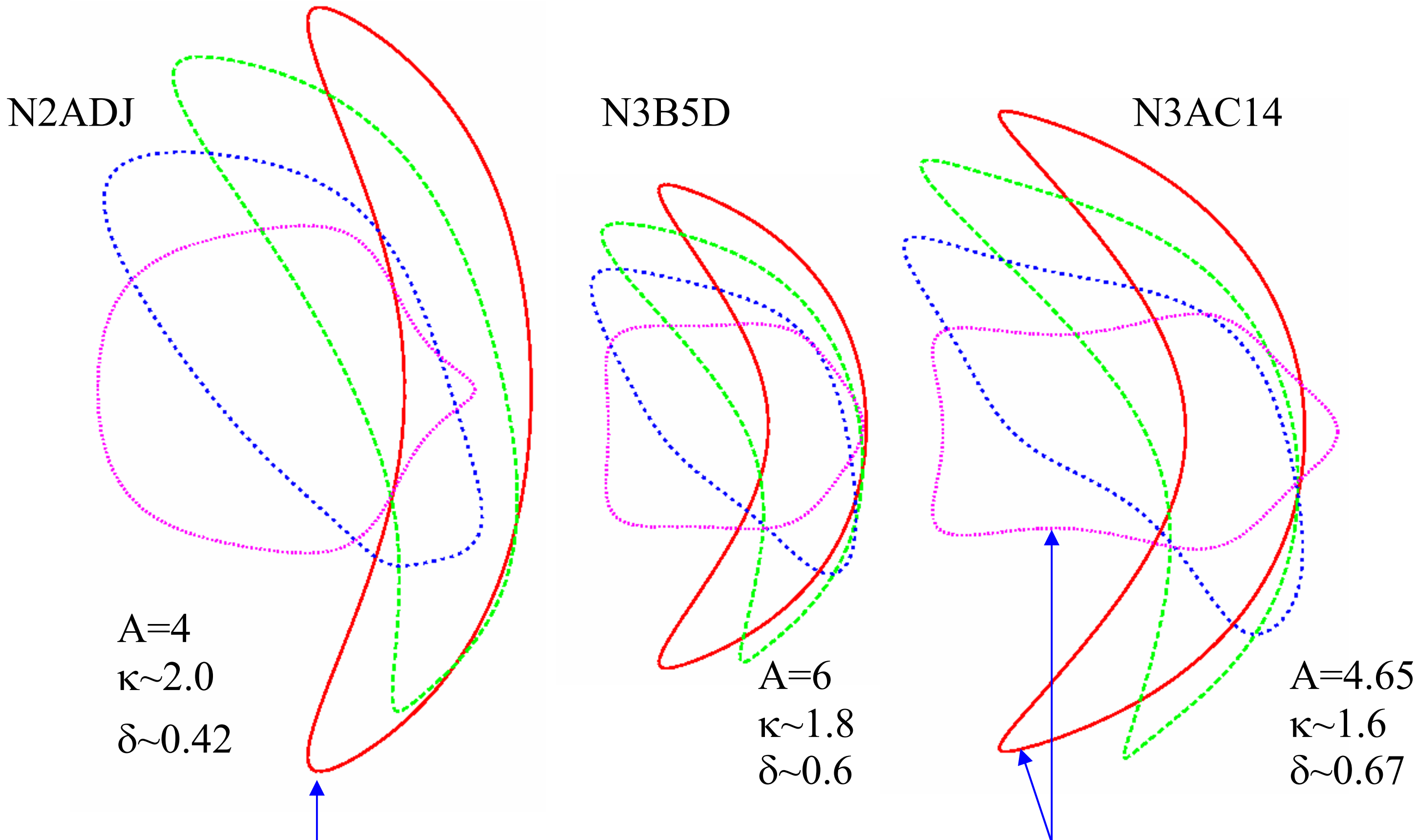


Comparison of properties of three selected configurations: N2ADJ, N3B5D, N3AC14, with increasing rotational transforms and with α loss fraction 10%, 12% and 4%, respectively.

(1) Rotational transform.



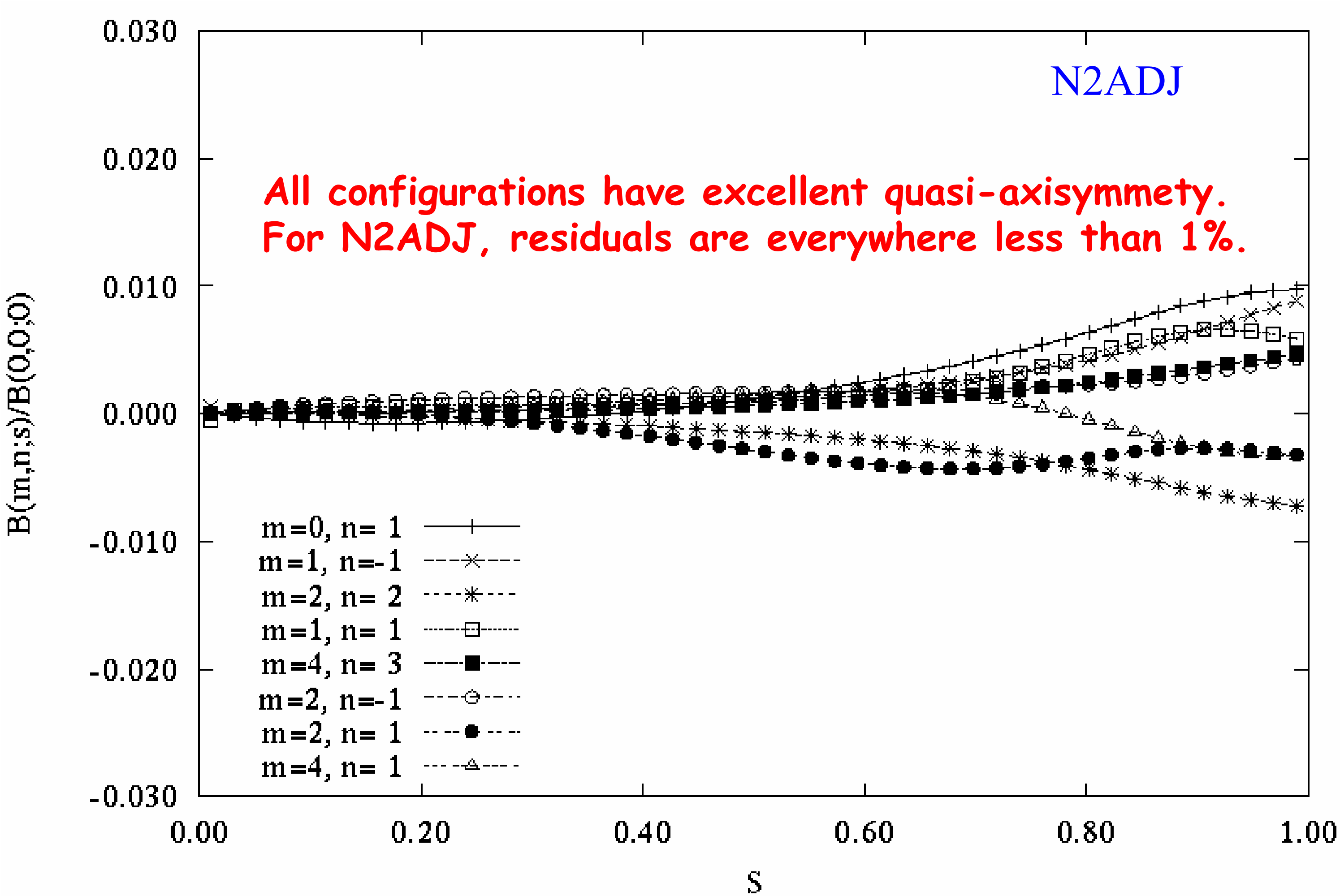
(2) Cross sections equally spaced in half a period (at a fixed major radius).

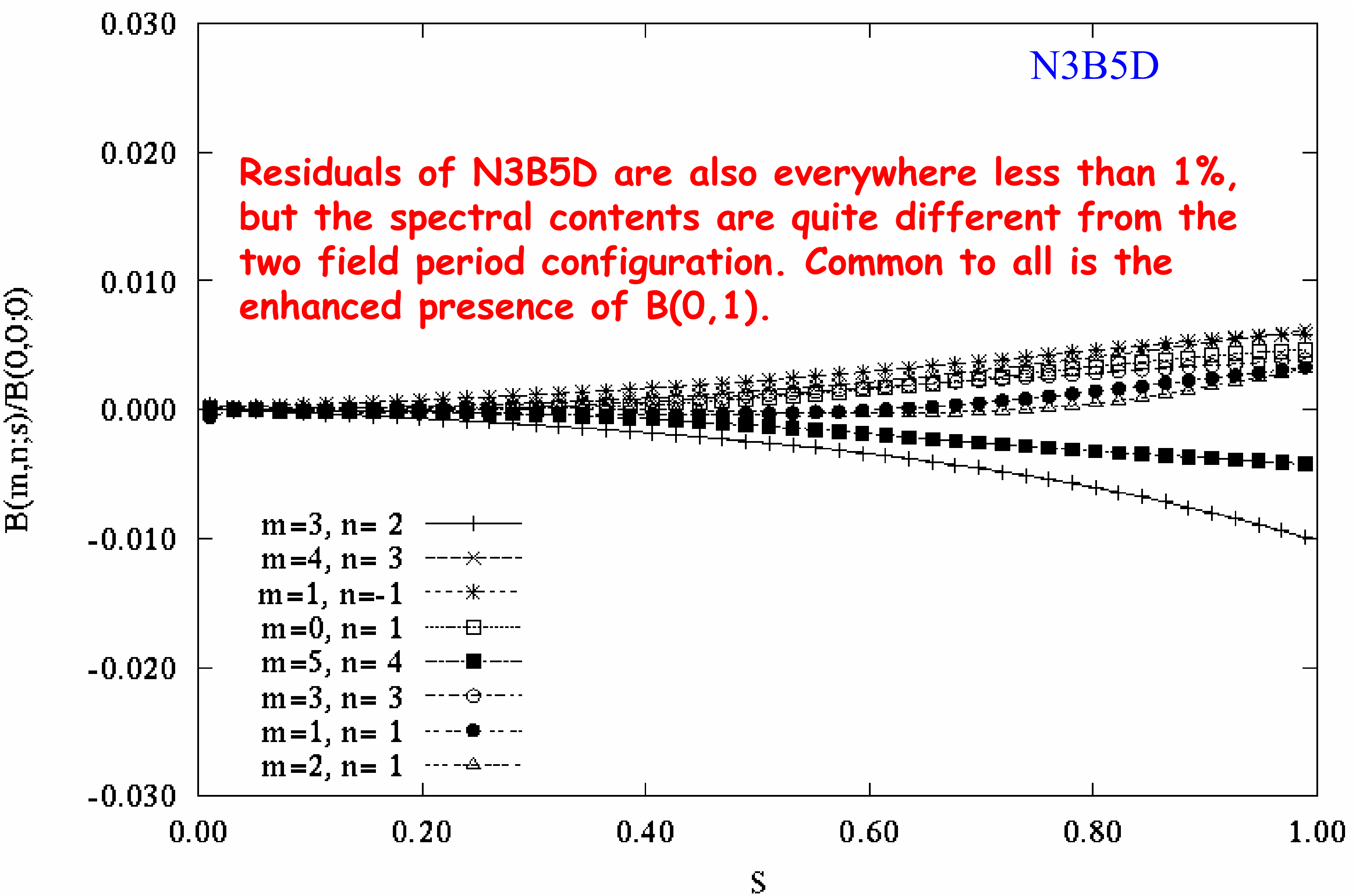


MHD stability optimization results in larger elongation and lesser triangularity.

Shaping to provide higher ι causes stronger deformation.

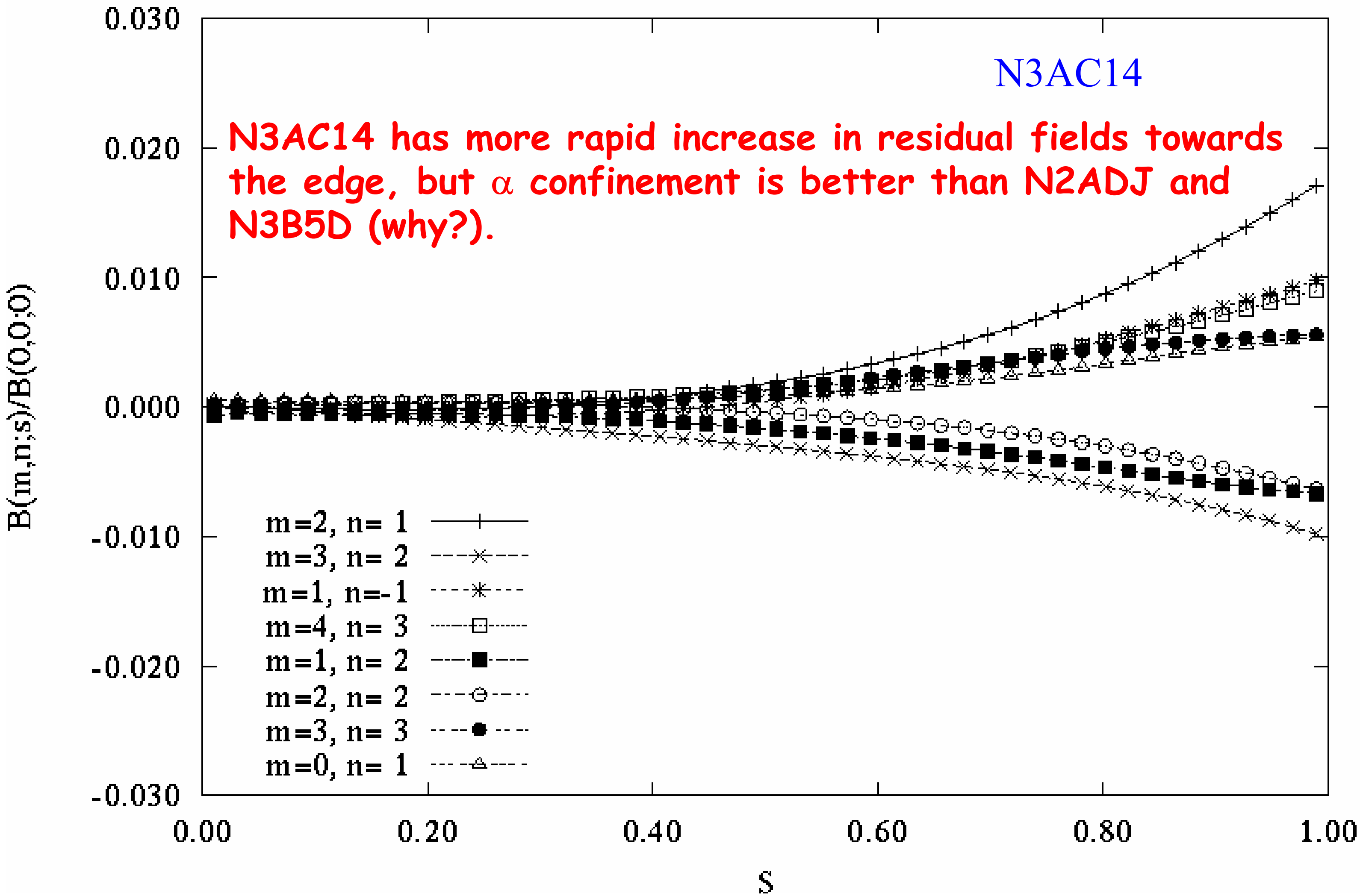
(3) Quasi-axisymmetry measured by residuals in magnetic spectrum.





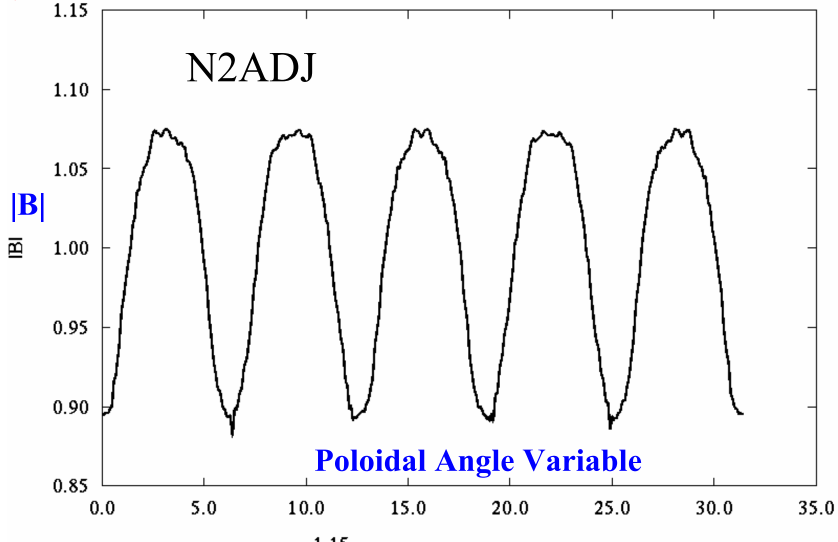
N3B5D
Residuals of N3B5D are also everywhere less than 1%, but the spectral contents are quite different from the two field period configuration. Common to all is the enhanced presence of B(0,1).
B(m,n;s)/B(0,0;0)
S
0.030
0.020
0.010
0.000
-0.010
-0.020
-0.030
0.00
0.20
0.40
0.60
0.80
1.00
m=3, n= 2
m=4, n= 3
m=1, n=-1
m=0, n= 1
m=5, n= 4
m=3, n= 3
m=1, n= 1
m=2, n= 1

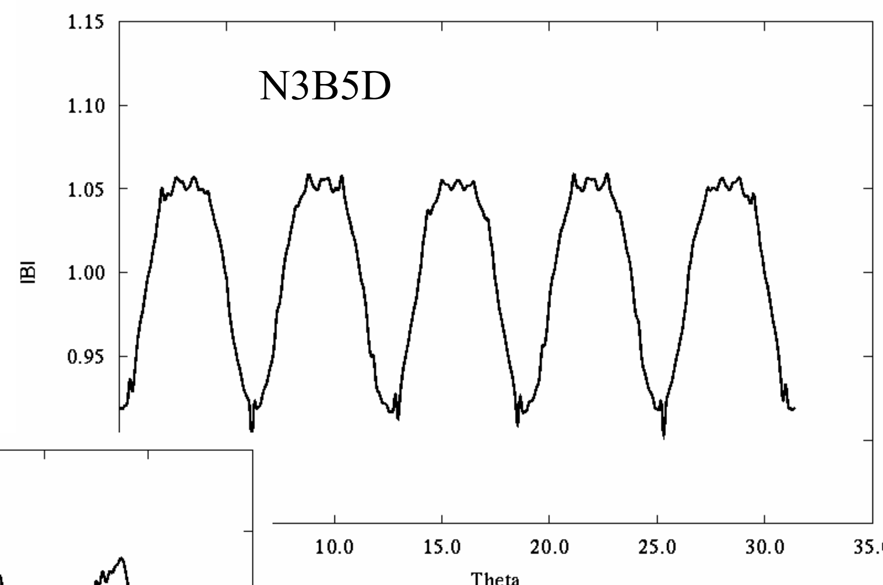
N3AC14 has more rapid increase in residual fields towards the edge, but α confinement is better than N2ADJ and N3B5D (why?).

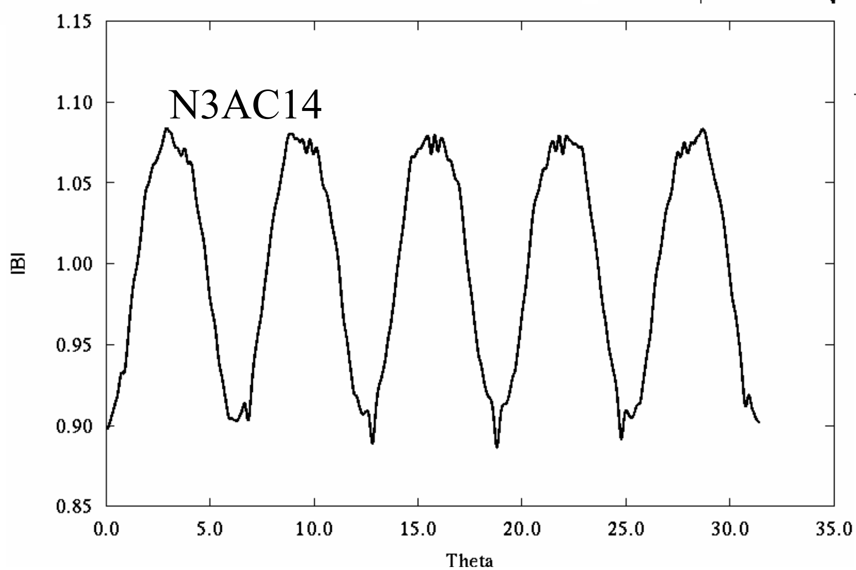


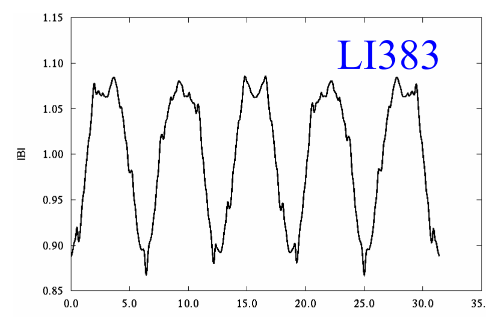
(4) Quasi-axisymmetry measured by ripples along field lines.

These configurations have reduced secondary ripple wells as seen in |B| vs θ plot along a field line on s=0.5 surface. B_{max} align well also.



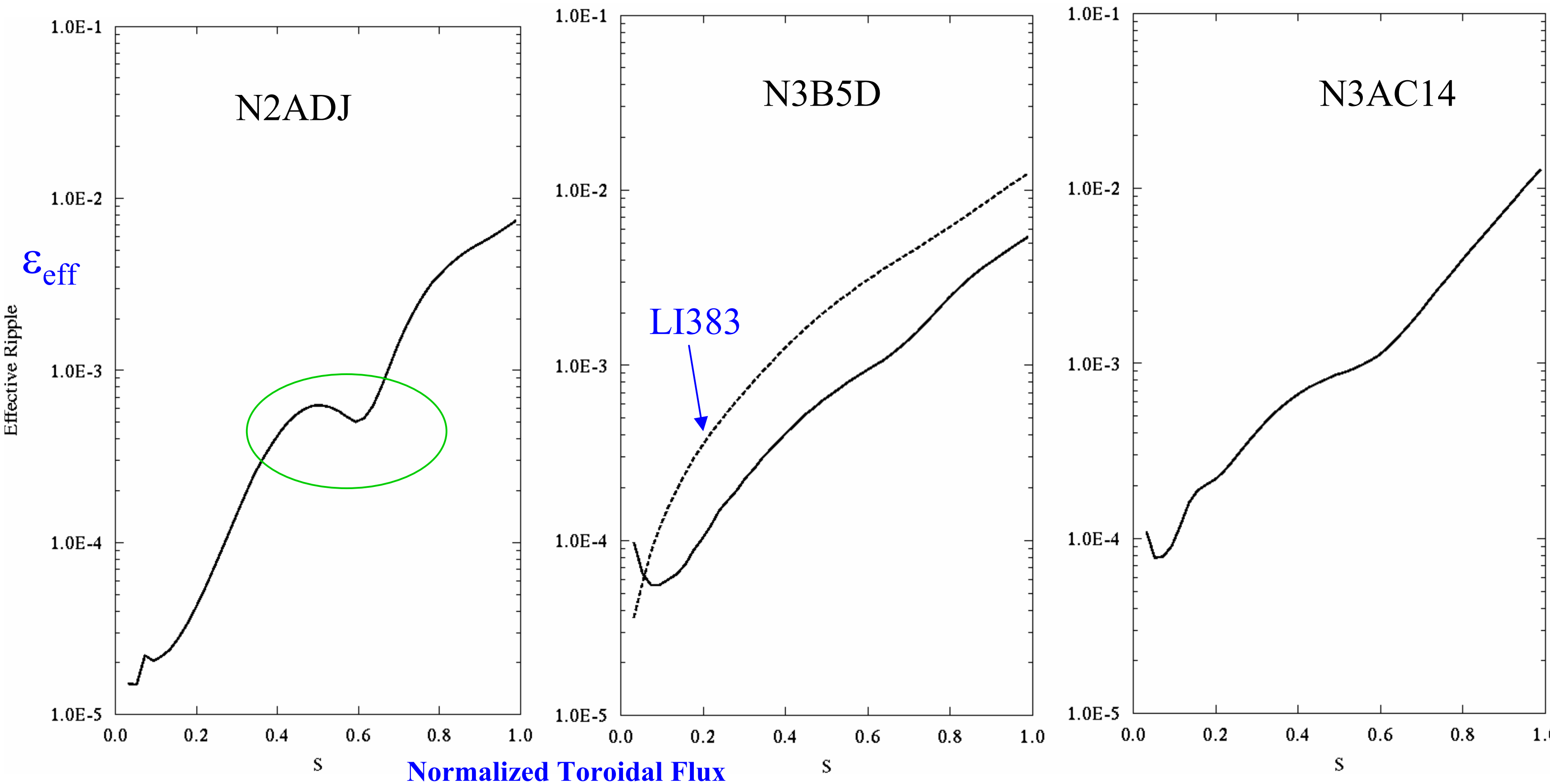






(5) Quasi-axisymmetry measured by the effective ripple, ε_{eff}, in $1/\nu$ transport.

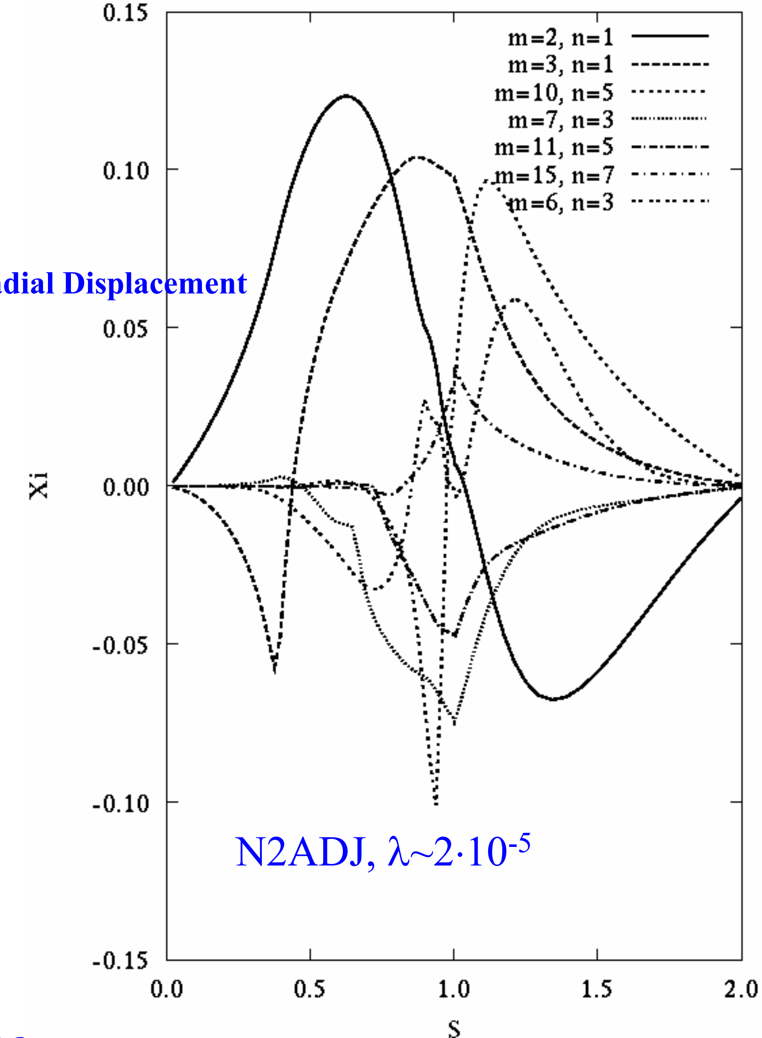
The effective ripples are very small (<1%), so the neo-classical ripple transport will be insignificant relative to the anomalous. Flow damping will also be minimized.

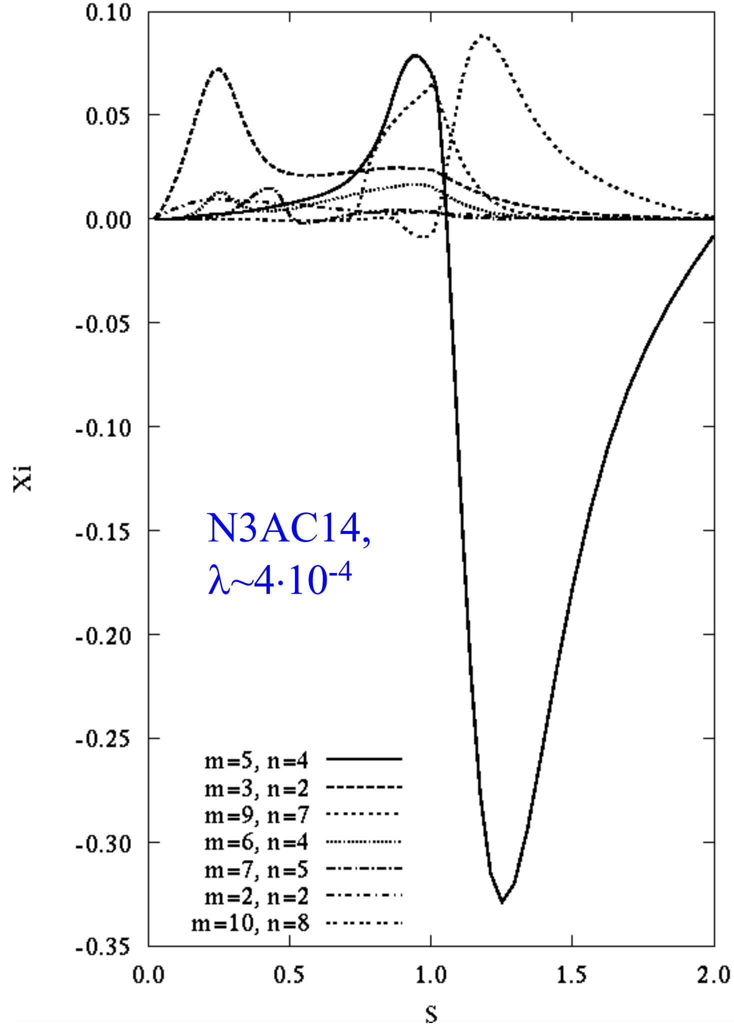


(6) MHD stability: external kinks.

We allow a small residual growth rate in the external kink stability in most calculations. Following are plots of eigenfunctions of some unstable modes for N2ADJ and N3AC14. N3B5D is stable.

Radial Displacement

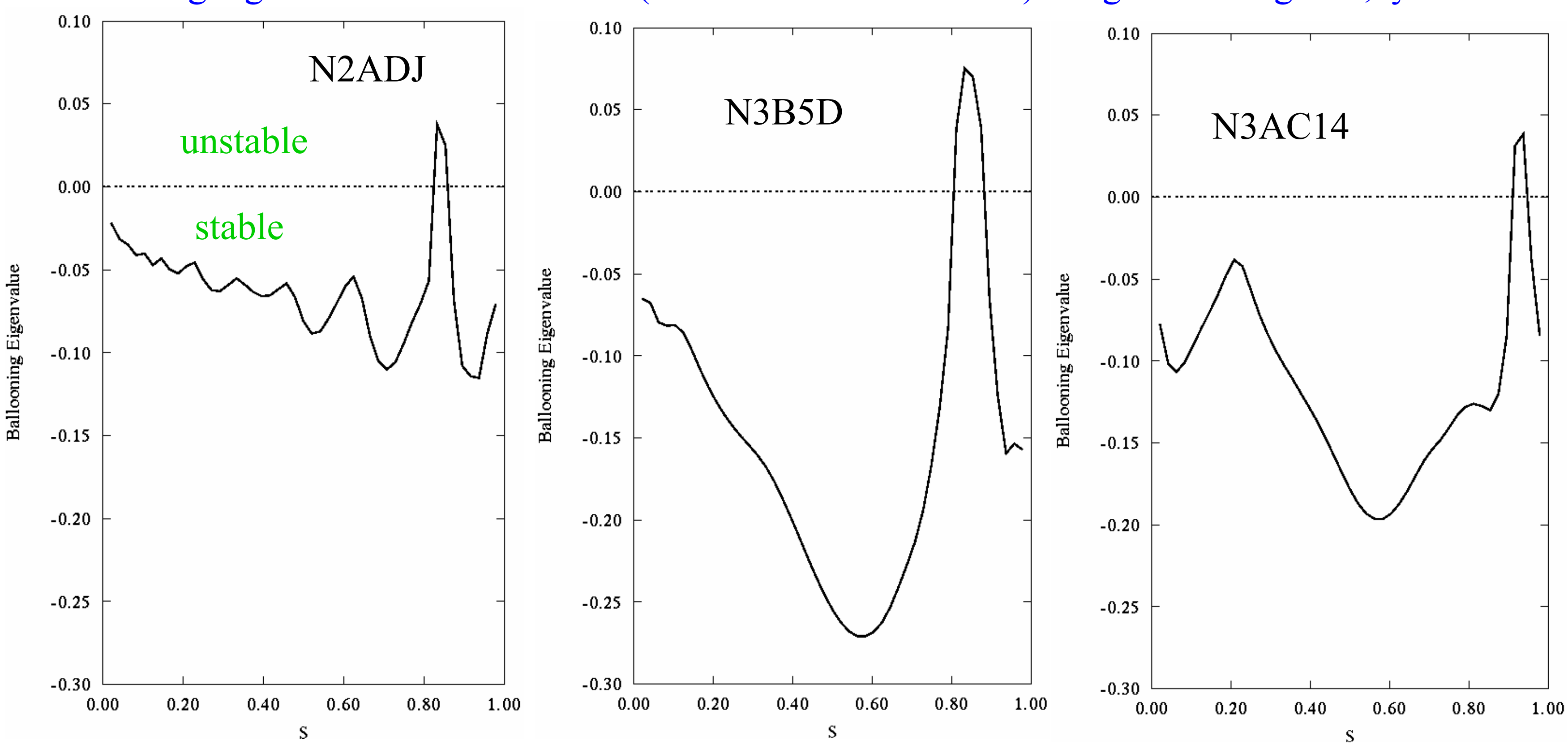




(7) MHD stability: ballooning modes

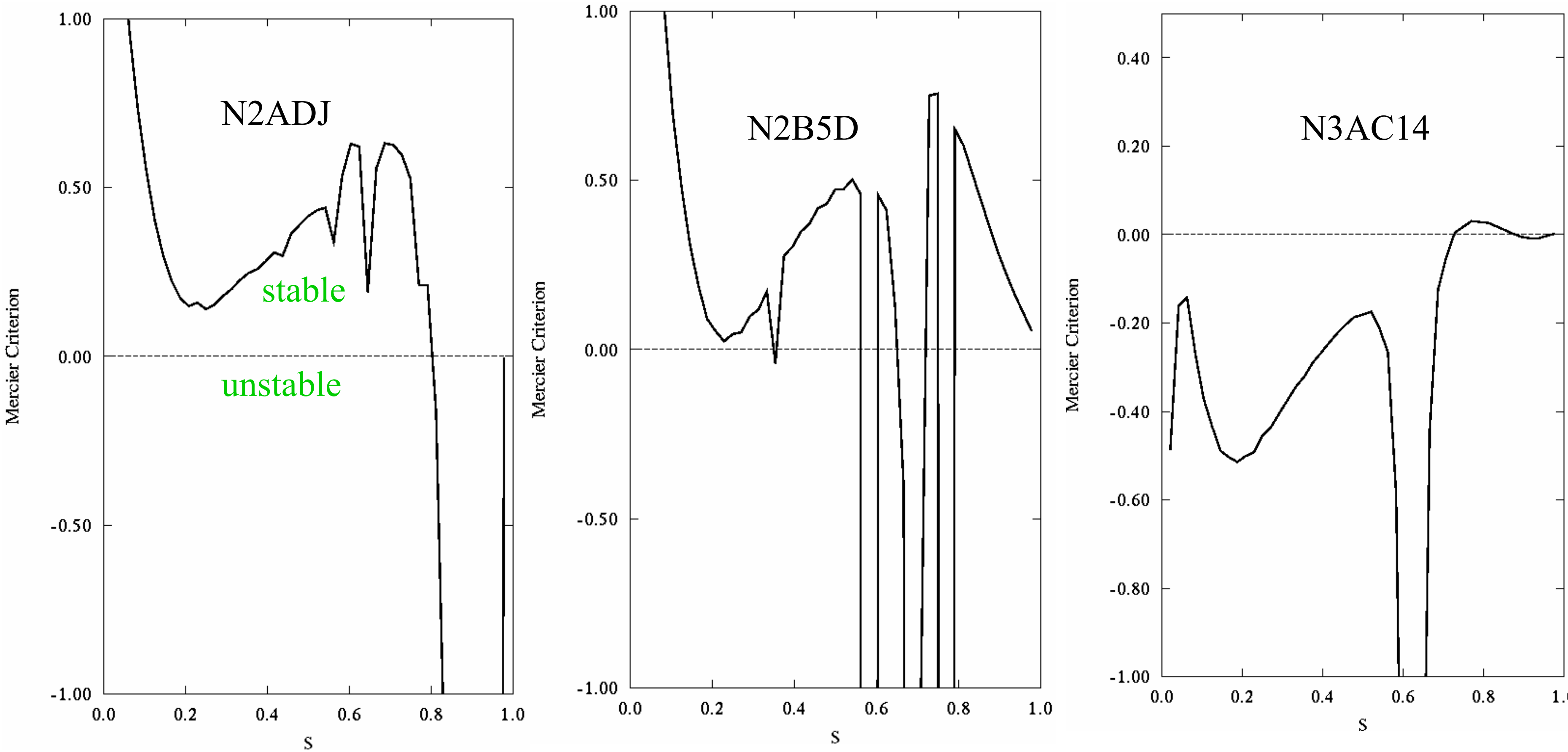
These configurations also have a small region unstable to the infinite-n ideal ballooning modes. Finite-n calculations for NCSX have shown that this is not of concern.

Ballooning eigenvalue as function of s (normalized toroidal flux) integrated along θ=0, ζ=0 field line.



(8) MHD stability: Mercier modes

N3B5D is stable to Mercier except at local resonance surfaces. N2ADJ is unstable to Mercier near the edge, whereas N3AC14 is unstable in the entire interior region due to the weak magnetic well. Do we have to be concerned with this instability?



QA and α confinement may be further improved by allowing less stringent MHD stability constraints.

- Attaining good QA and more stable plasma are frequently not in sync in the optimization calculations.

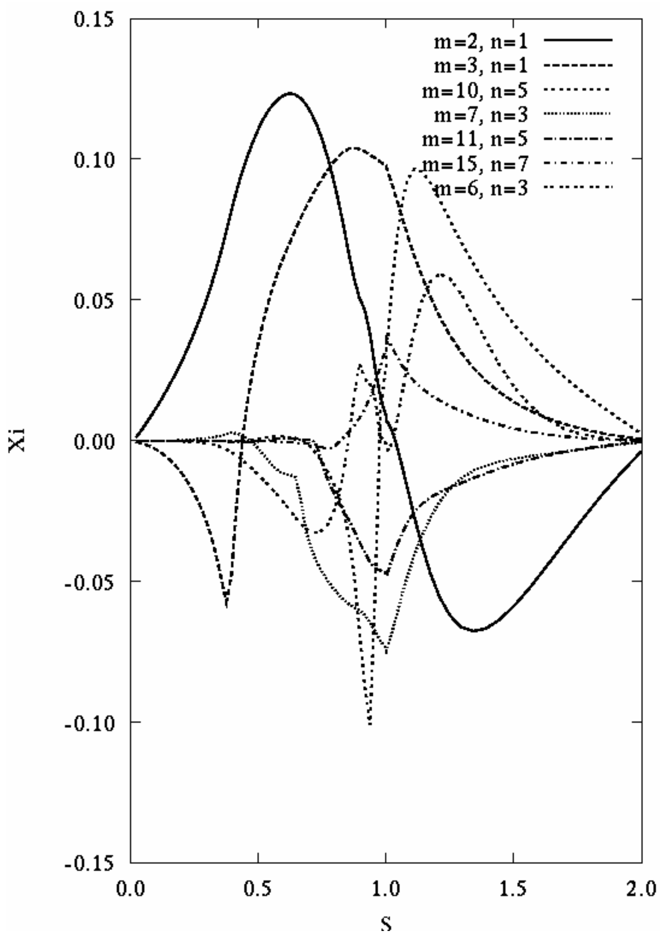
- Recent experimental results raised the issue of designing configurations based solely on ideal MHD and linear stability theories.

- In the present work, we still try to minimize growth rates of the external kinks and ballooning (based on ideal MHD and linear theory) although we do allow some marginal instability.

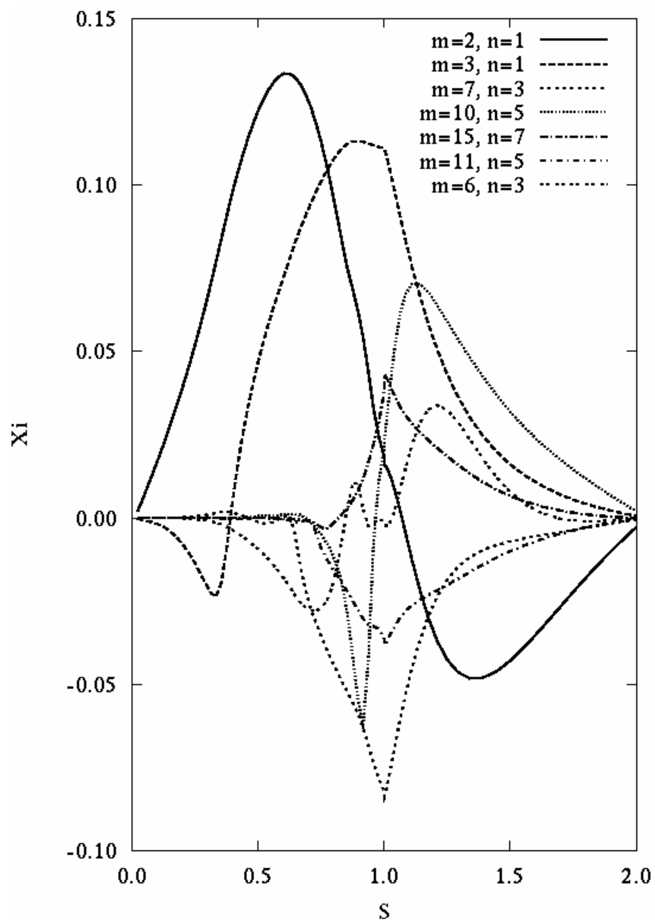
- Here we give an example (N2ADJ versus N2ADR) to show the potential benefit of imposing less stringent stability constraints.

Allowing a larger eigenvalue in external kink calculations, $8.4 \cdot 10^{-5}$ in N2ADR versus $1.7 \cdot 10^{-5}$ in N2ADJ, enables us to find a solution in which α losses are reduced to 6.5% from 10.4%.

N2ADJ (10.4%)

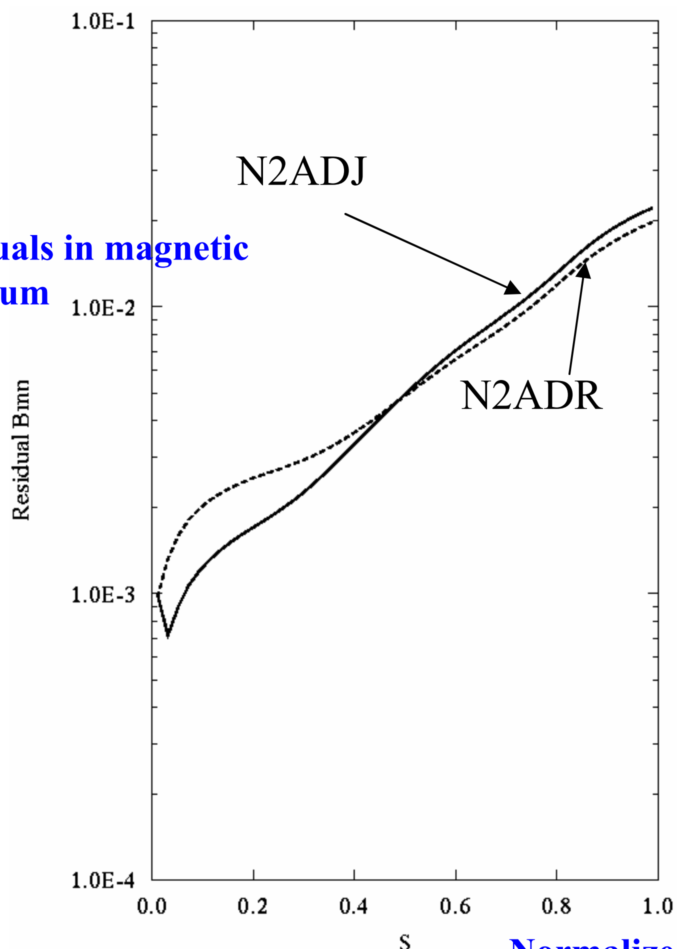


N2ADR (6.5%)

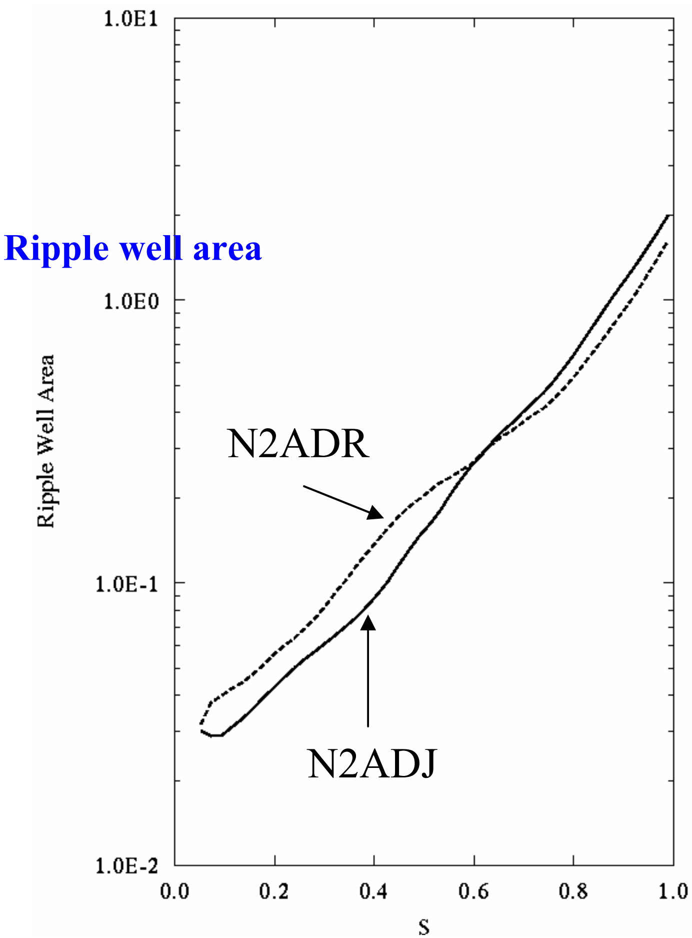


The freedom of lesser kink constraints is used by the optimizer to improve quasi-axisymmetry in the outer region while maintaining good QA in the interior to improve the α loss.

Residuals in magnetic spectrum



Ripple well area



Normalized toroidal flux

The optimization process we used may bring us into local minima !

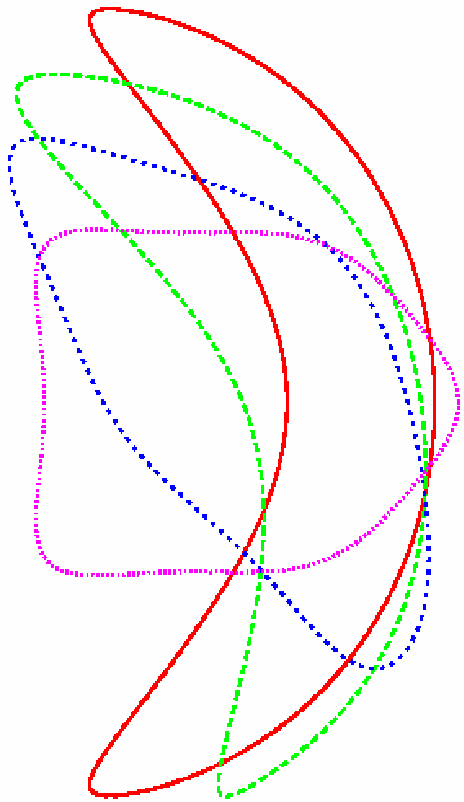
- Presently, we are using a local gradient search algorithm. In a complex terrain, this method requires insight of where the "good" region is and ability to avoid falling into local minima.

- We have implemented global search methods in the configuration optimizer (GA, DE), but have not explore their potential.

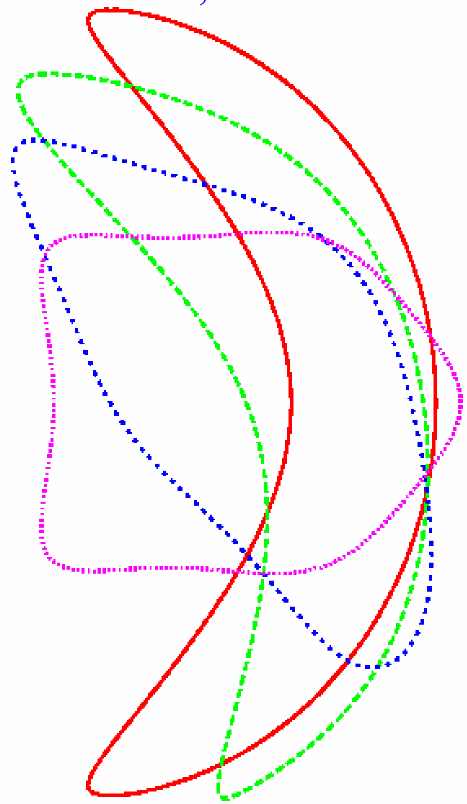
- We made an attempt to "feel" the local topography in the neighborhood of A=4.5, $\iota \sim 0.5$ by giving slightly more freedom to changes in aspect ratio.

These configurations look alike, but differ in QA (next page)

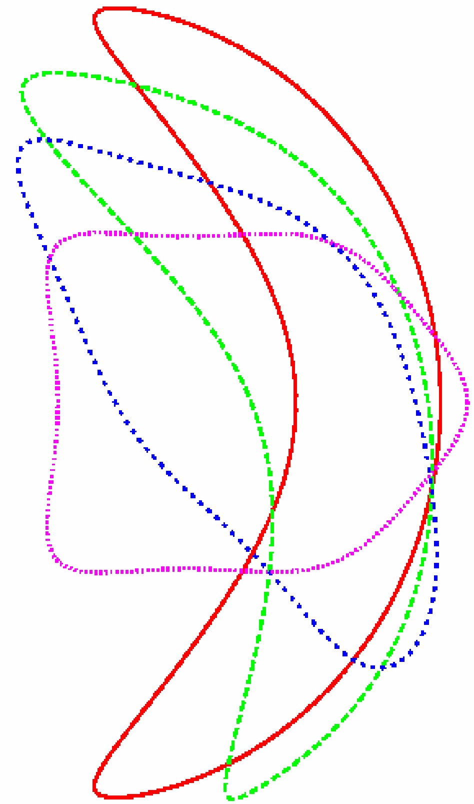
N3AEC, A=4.37



N3AGA, A=4.44

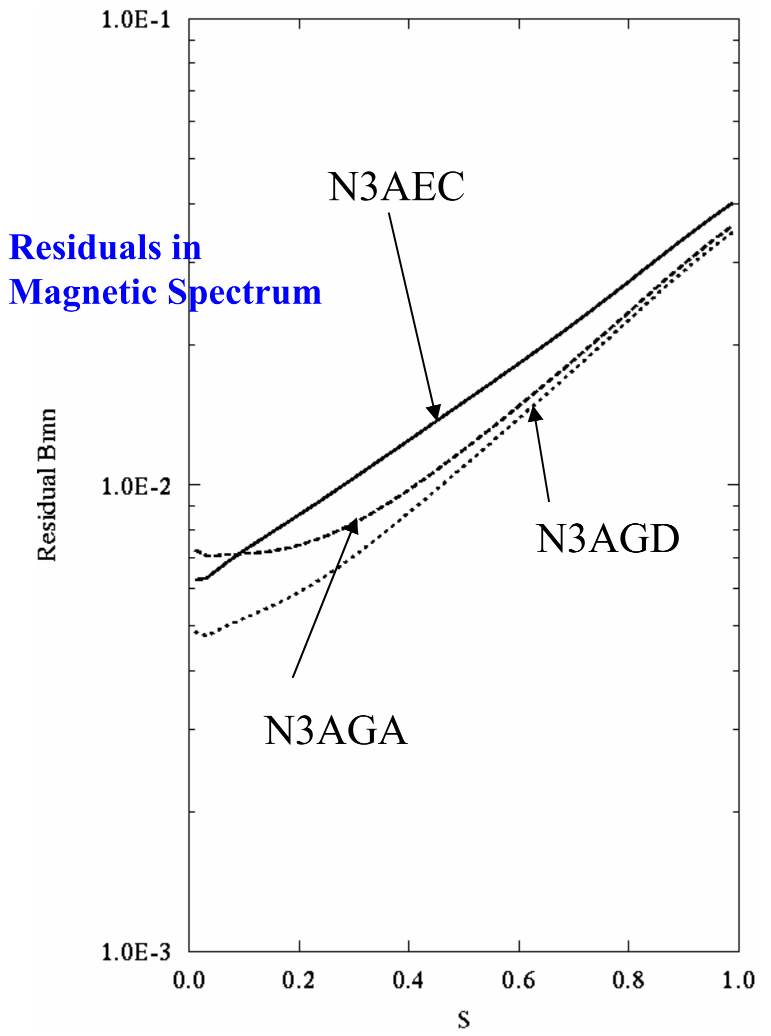


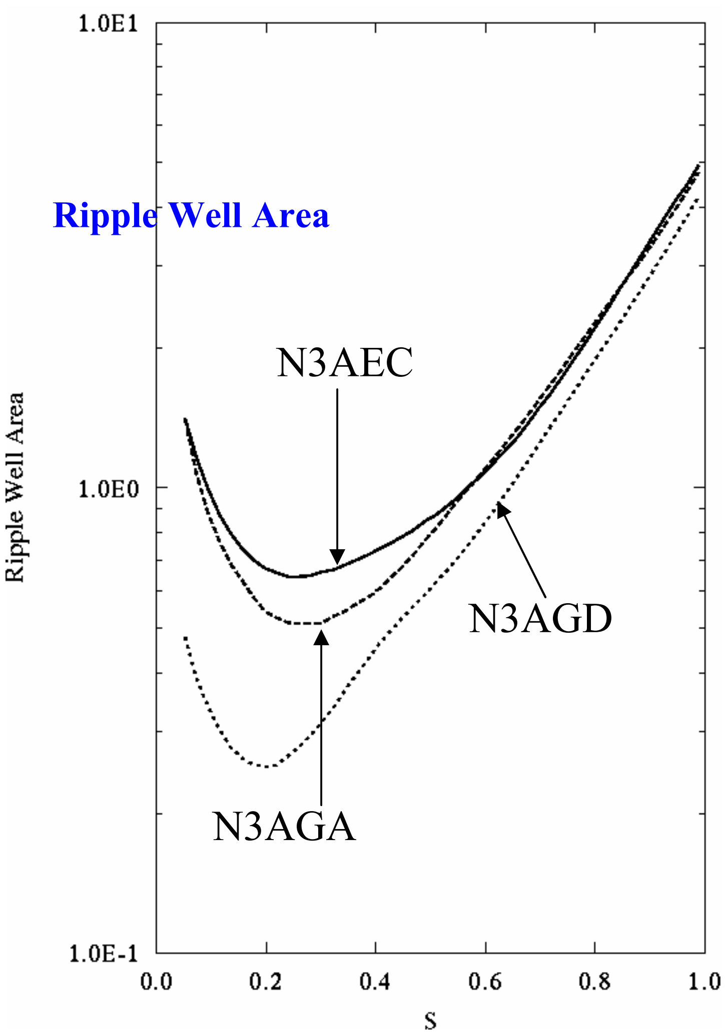
N3AGD, A=4.55



α loss fraction 16.2% 14.2% 14.1%

Clearly, in the neighborhood of N3AEC there are valleys where configurations may have smaller and lesser number of secondary ripple wells and, therefore, better α confinement.





Typical Classes of α Loss Orbits

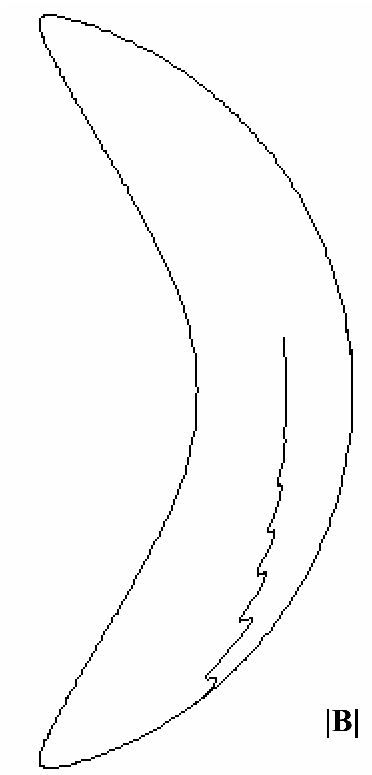
- α's which are collisonlessly lost are typically
  - Helically trapped,
  - Toroidally trapped → helically trapped
    → radial drift
  - Passing → toroidally and helically trapped
    → radial drift

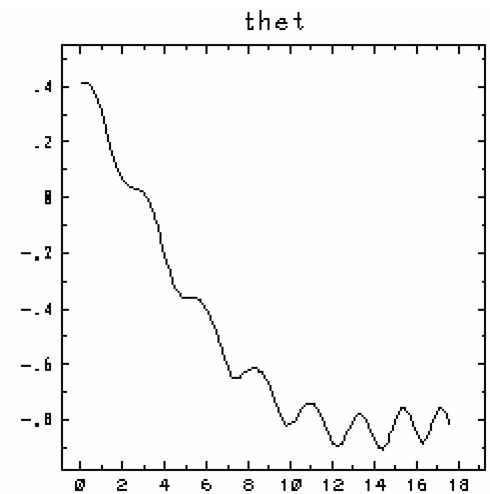
← **Including only trapped particles is not adequate in assessing α losses.**

- What distinguish the loss orbits in confinement improved configurations are the time-delay and frequency of such losses.
  - To further improve losses, QA in outer region needs to be better.

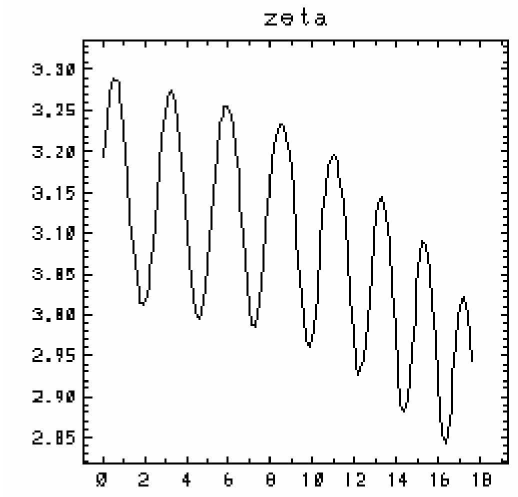
An example of helically trapped and lost particle orbit

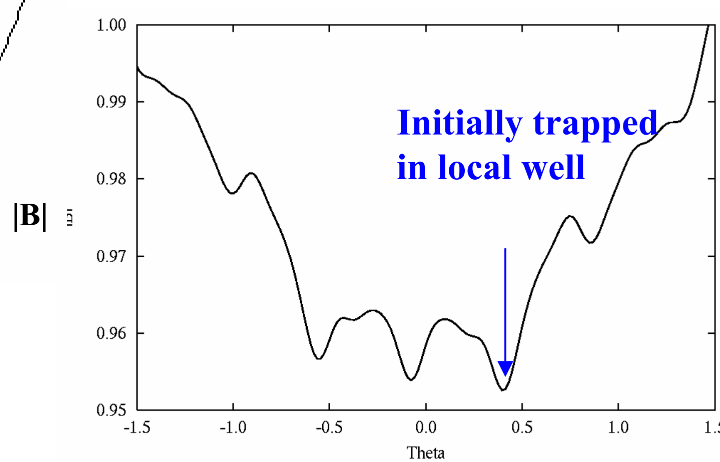
N3AEC (530)



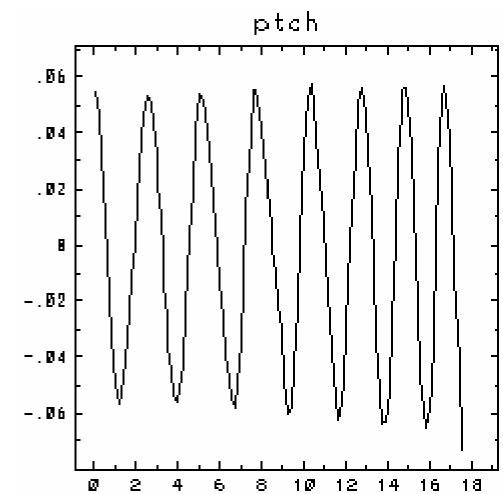


Transit Time



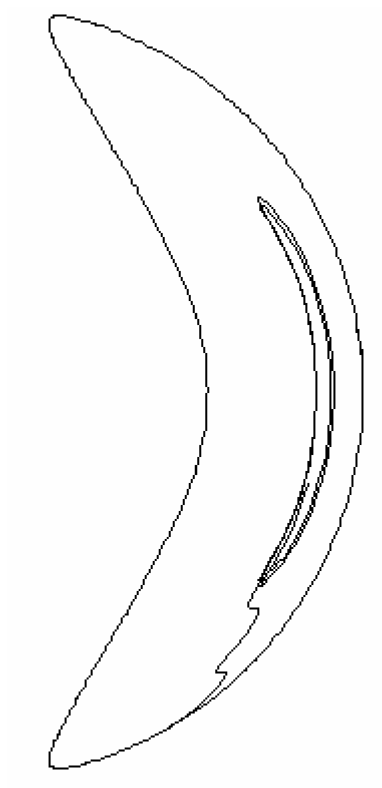


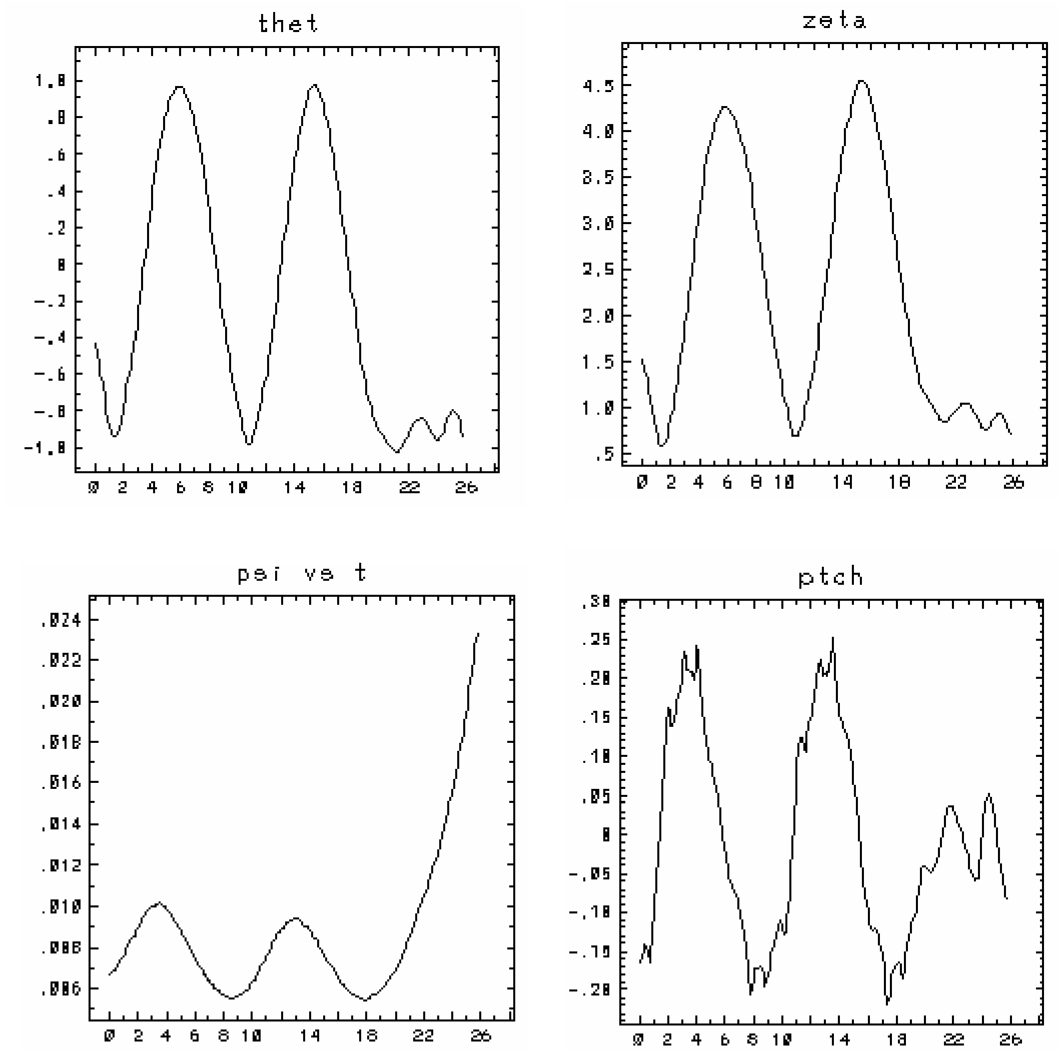
Poloidal Angle



An example of toroidally trapped particle which is lost after being helically trapped.

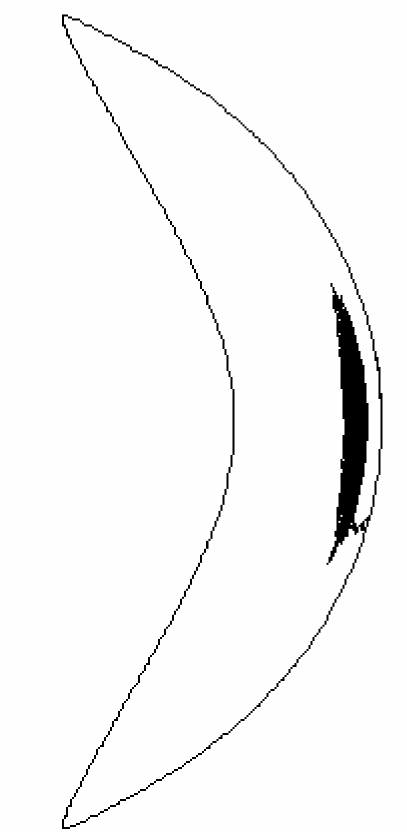
N3AEC (715)

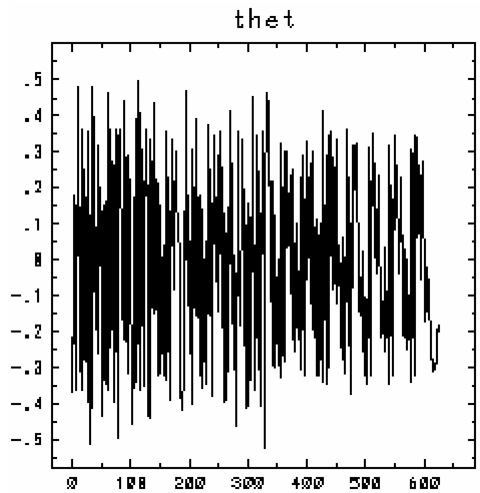


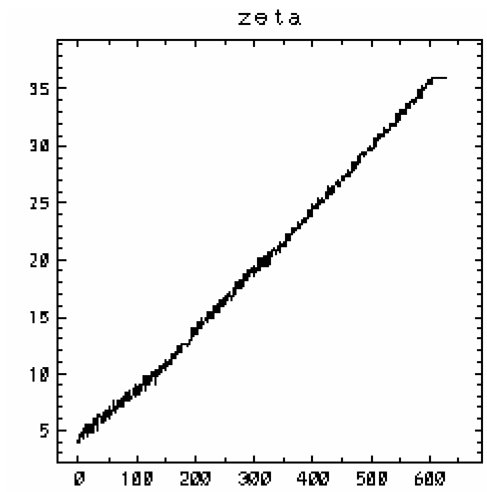


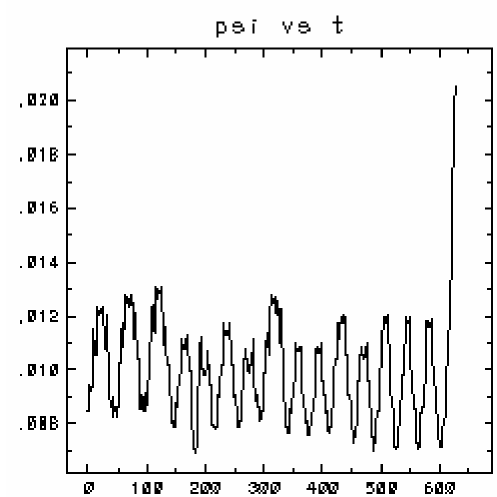
An example of toroidally trapped particle which is lost after being helically trapped in a configuration with smaller magnetic perturbation amplitude and frequency.

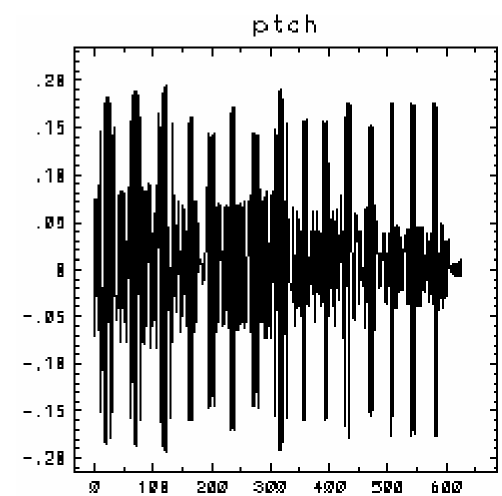
N3AC14 (2654)





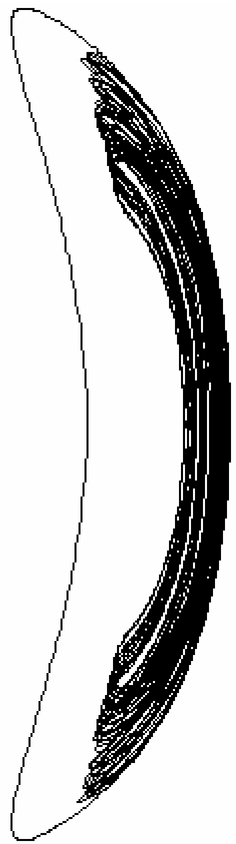


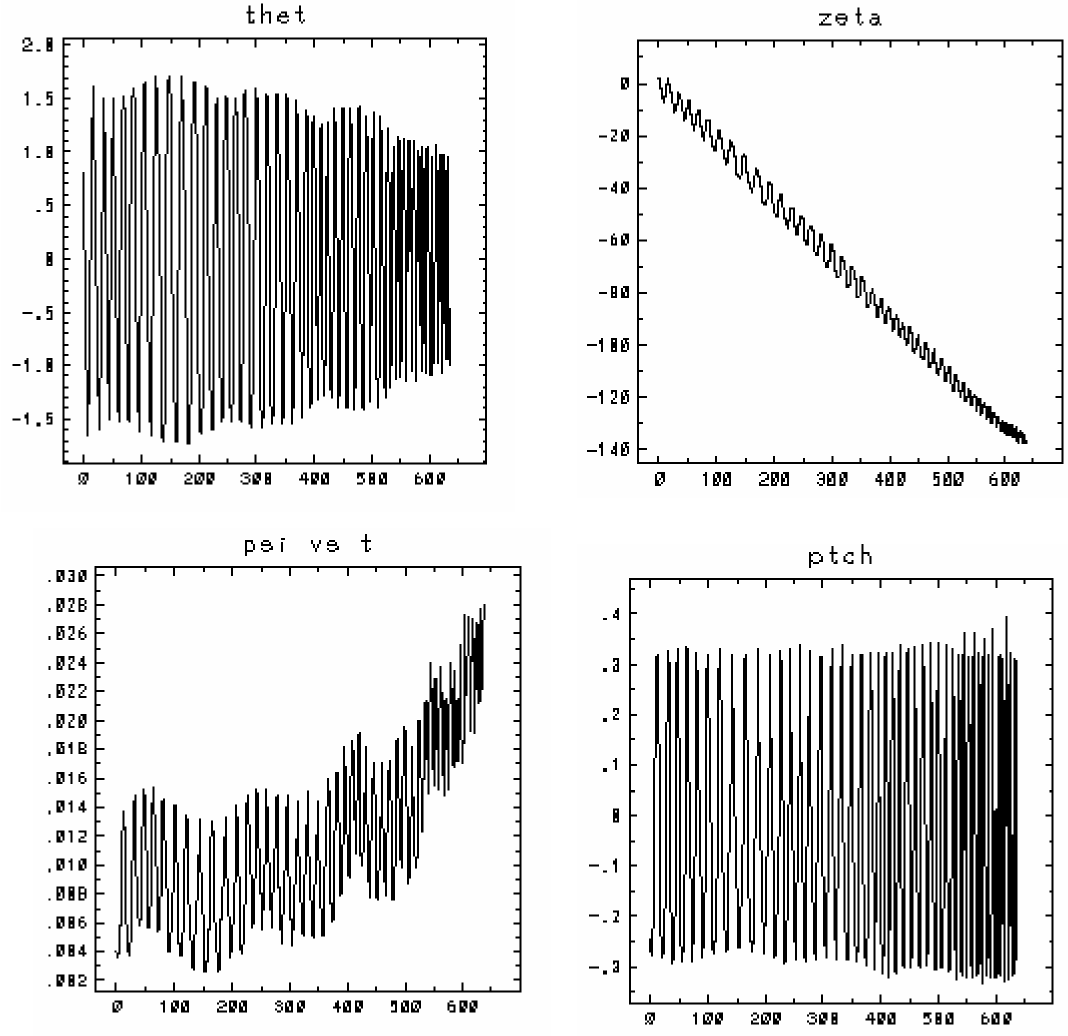




An example of toroidally trapped particle which is lost due to radial drift in a configuration with small magnetic perturbation amplitude and frequency and low iota.

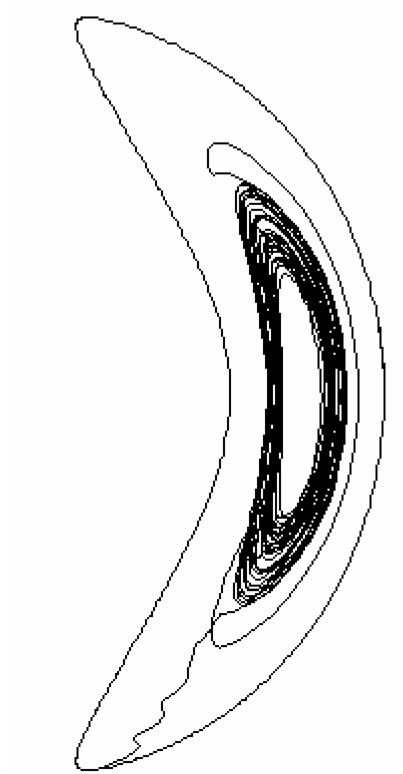
N2ADJ (950)

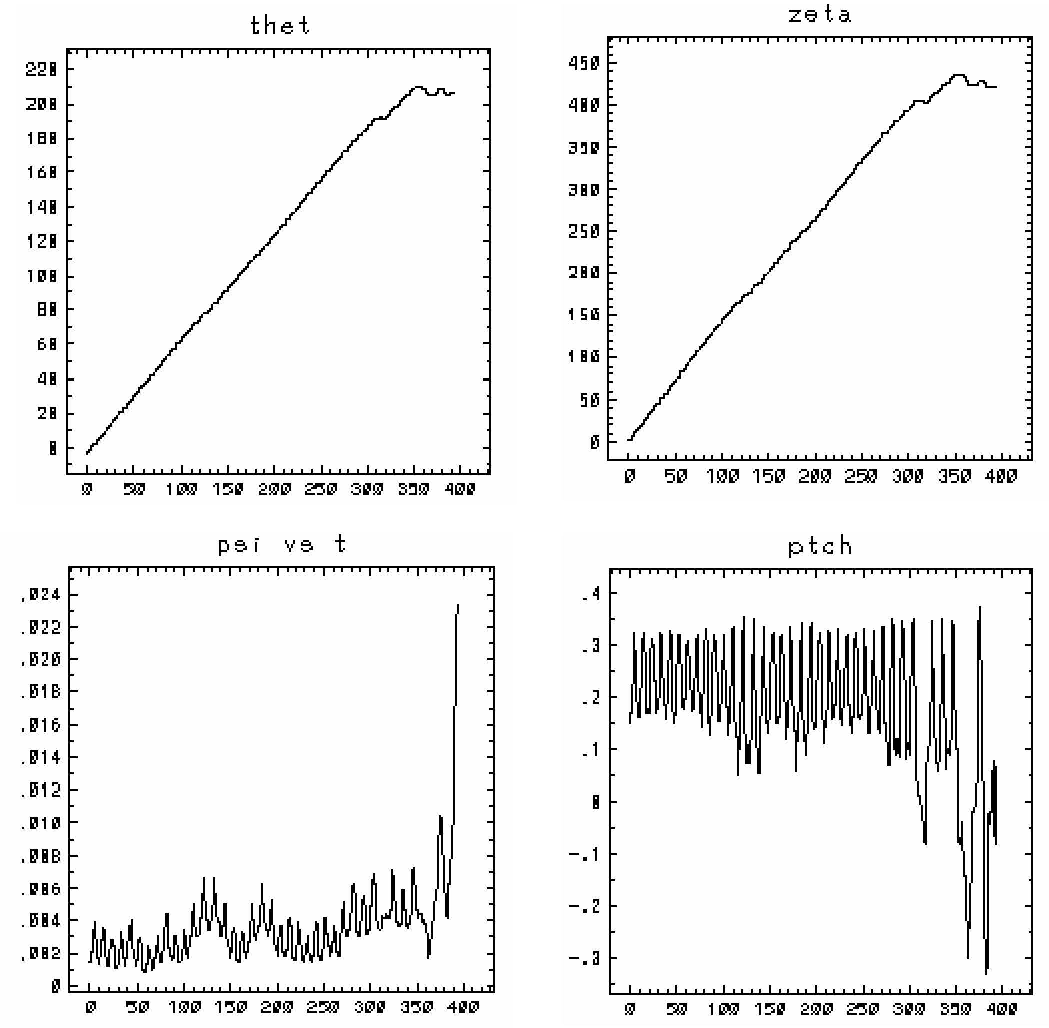




An example of an initially passing orbit which is lost after being helically trapped.

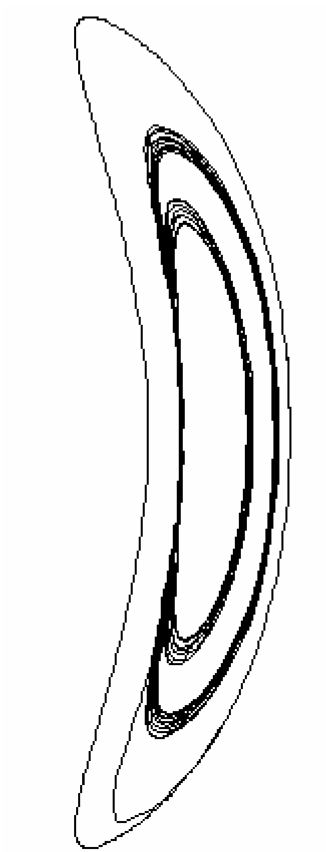
LI383 (25)

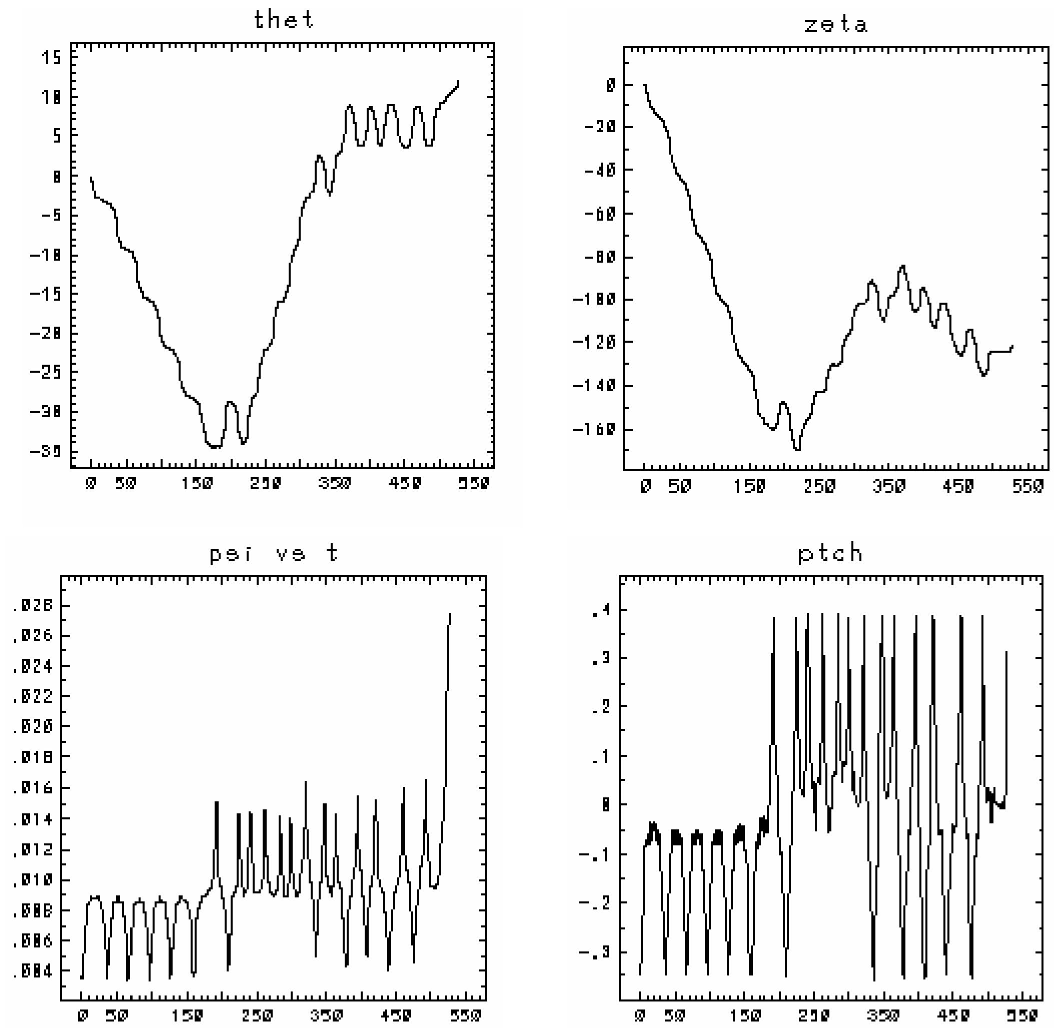




An example of an initially passing orbit which is toroidal trapped and de-trapped, and lost after being helically trapped.

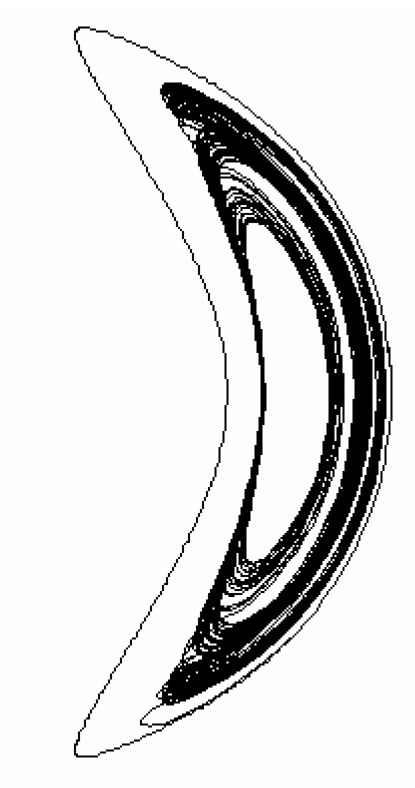
N2ADR (3224)

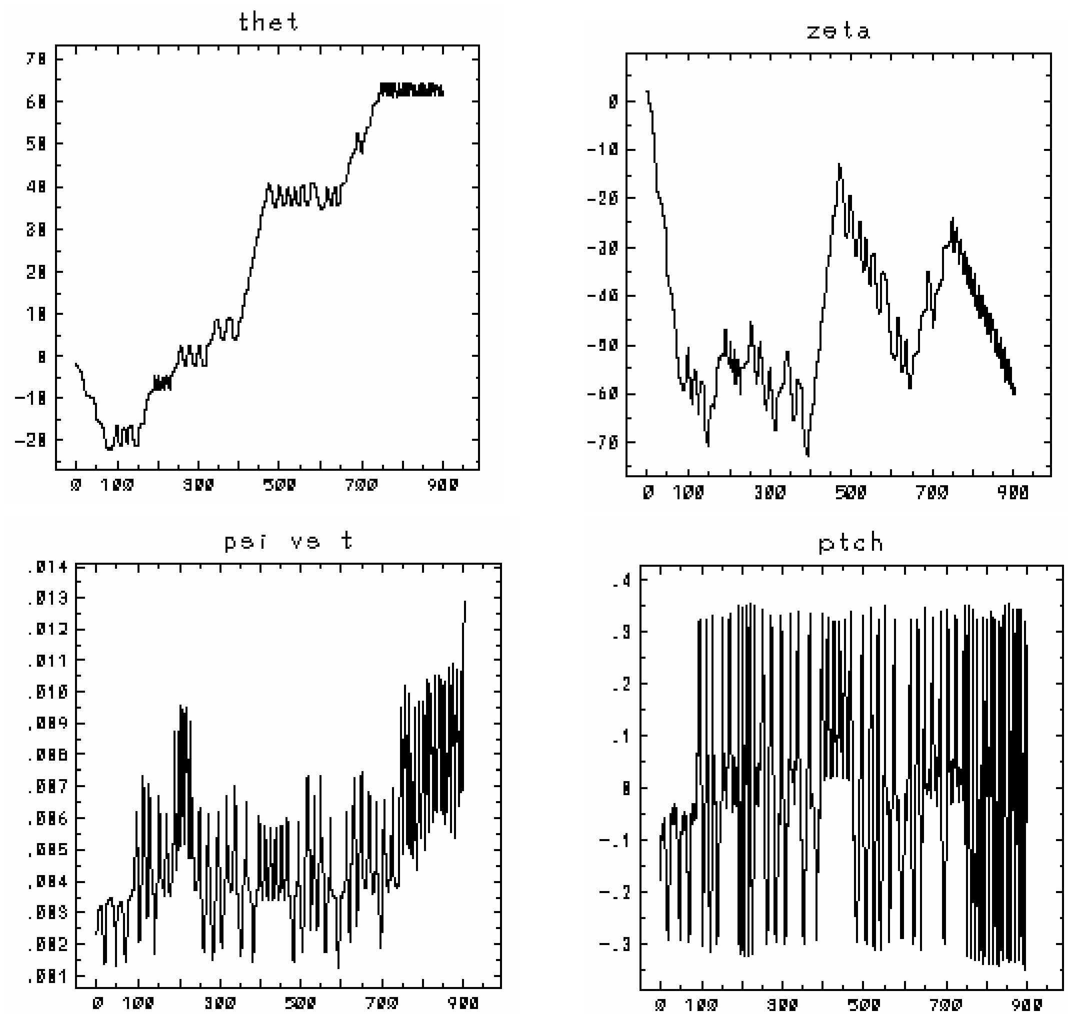




An example of an initially passing orbit which is toroidal trapped and de-trapped many times before being helically trapped and lost in a configuration with small magnetic perturbation amplitude and frequency.

N3B5D (114)





For compact QA reactors, impact of α energy loss ~10% should be examined in both power balance and engineering studies.

- QA has to be compromised by the requirement of MHD stability, magnetic shear, and desired amount of external rotational transform.
  - It will be very difficult (may not even be possible) to eliminate entirely the secondary ripple wells.

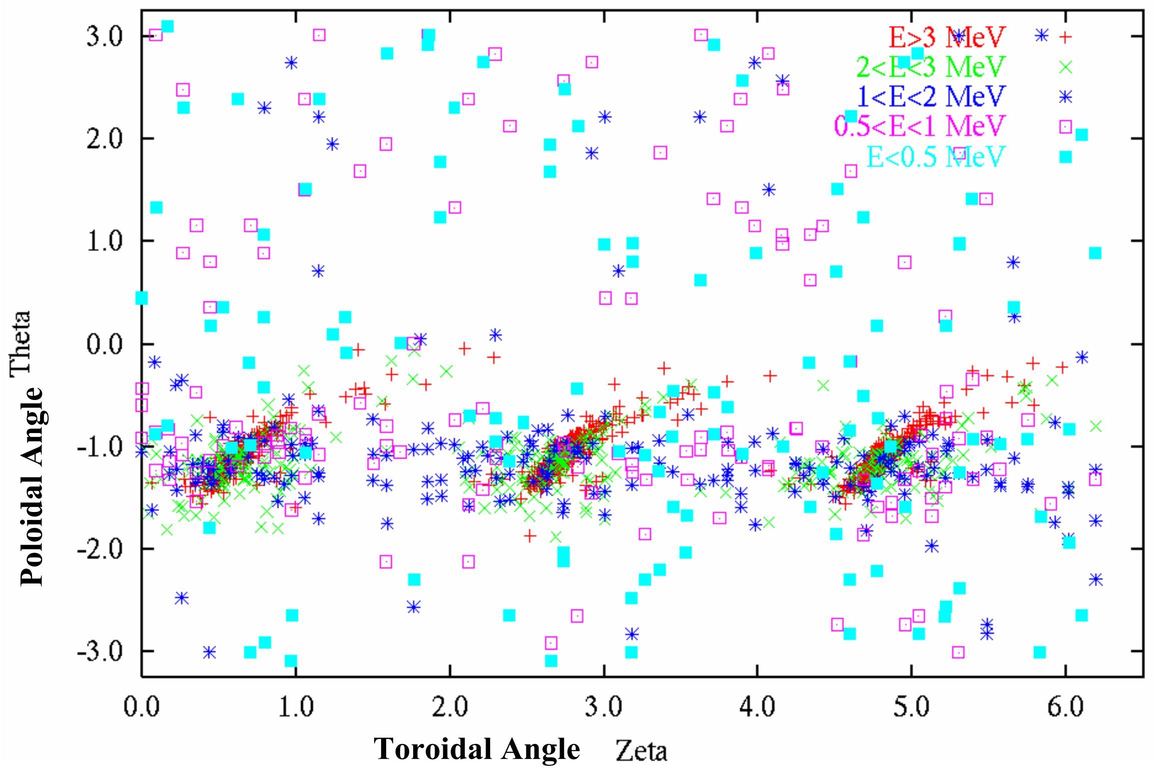
- α loss can be further reduced by using higher fields and larger sizes.
  - Higher fields also improve the power density and larger sizes make more room for blanket/shield/RH.

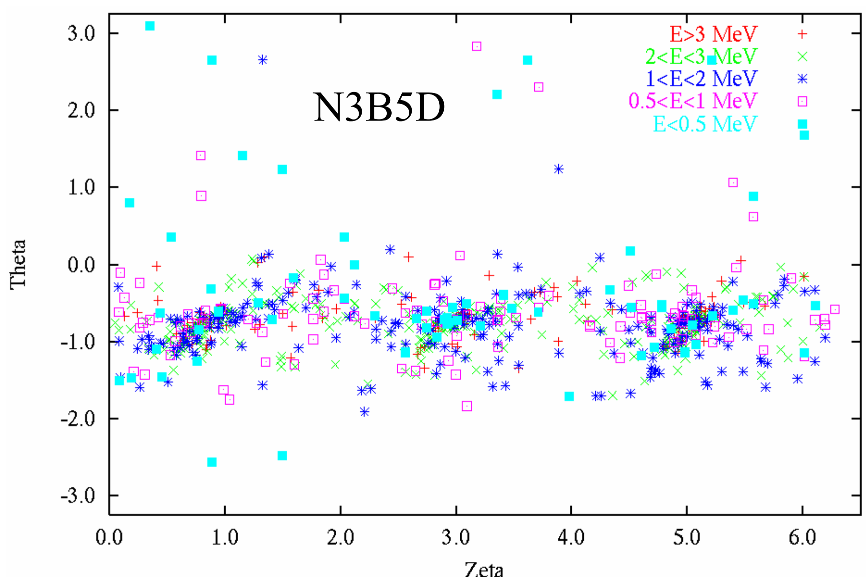
- It would be useful to examine up-front the "engineering" cost of allowing certain α losses as well as higher fields and reactor sizes.

As a first step, we have examined the footprint of lost α's.

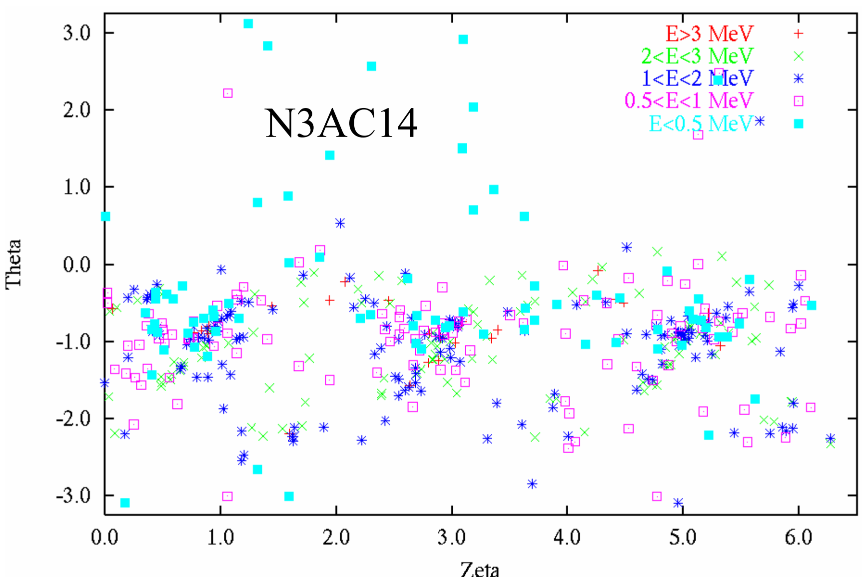
For LI383 (α un-optimized), most lost energy is concentrated in narrow helical bands centered around θ_b~-60° and ζ_b ~ 120° in each field period.

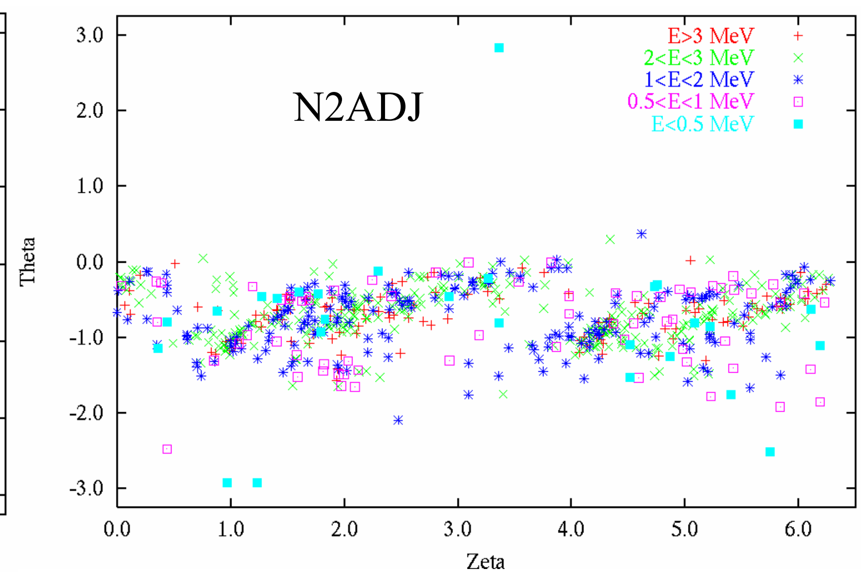
(θ_b,ζ_b) where α's leave the last closed flux surface.





For lower loss configurations, the energy loss band tends to be broader, its average poloidal angle smaller (closer to midplane) and toroidal angle closer to half a field period. We note that (1) footprints on 1st wall may be different, (2) flux expansion for diverter may not coincide with the most intense loss zone.





Summary

- We have carried out an extensive search of configurations for good QA, good α confinement and MHD stability at 4% β.

- Attractive configurations in low aspect ratio, low ι region and larger aspect ratio, higher ι region have been found. This is made possible by targeting directly α losses along with other QA and MHD stability properties in configuration optimization.

Issues and Plans for Next Step

- Critical issues remain to be addressed for the present repertoire of configurations:
  - Existence of good flux surfaces
  - The impact of higher β
  - The ability to design coils with reasonable coil aspect ratios
  - Trade-off among B, β, A, R in cost and systems space.
- We plan to study the quality of flux surfaces and effects of higher β, as well as to carry out initial coil designs, all in parallel, for the remainder of this year.

But, we should also keep in mind …

- Configuration space is vast and complex; what we have may not be the best (may not even be close to the best). This is equally true for coil designs.
  - Keep some efforts to continue optimizing and searching
    - particularly, with respect to simplifying shapes and,
    - finding realizable yet "better" pressure/current profiles.

- QA is not the only approach to CS reactors.
  - Keep some efforts to examine QH and drift-orbit optimized configurations.

PG configurations