Recent Development of QHS and QAS Configurations

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We have made a brief detour in the summer to study quasi-helically symmetric stellarators (QHS) to establish a basis of comparison with QAS.

- In QHS, there are a number of attractive features:
  - good particle drift orbits (magnetic spectrum dominated by single helical component),
  - large rotational transform (large helical motion of the magnetic axis),
  - lower magnitude of bootstrap current,
  - small Shafranov shift (→ higher equilibrium beta limit)

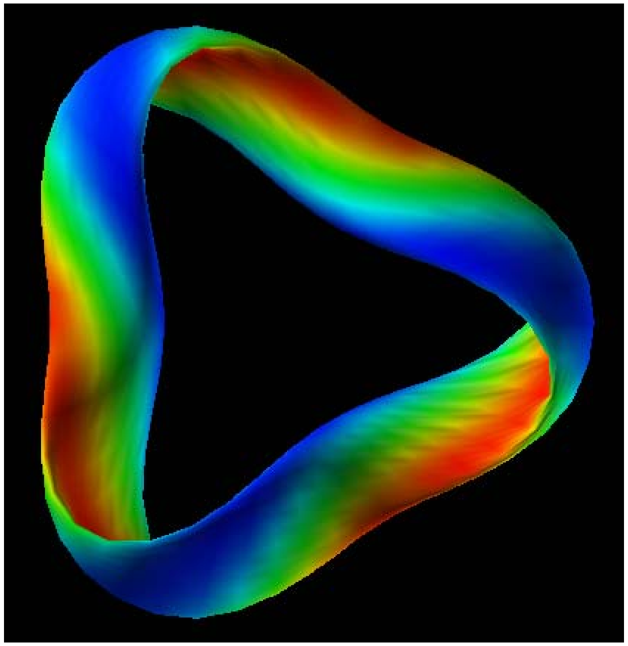
- However, it is generally thought that to have good QH the aspect ratio needs to be large, but it is not clear how low the aspect ratio can go before having good helical symmetry is no longer possible.

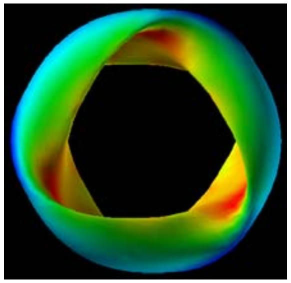
- Our purpose is to find compact configurations with low aspect ratios (A<6) and to compare them with QAS.

In the September meeting, we showed a couple of A=6 QHS configurations with excellent transport properties and listed a number of issues to be addressed:

- ✓ Develop configurations with A<6 with good QH, deeper magnetic well, and fatter waist.
- ✓ Analyze MHD stability and find out beta limit.
- Investigate effects of bootstrap current and iota profiles.
- Examine flux surface integrity and find ways for island avoidance.
- Study coils and Δ_min.

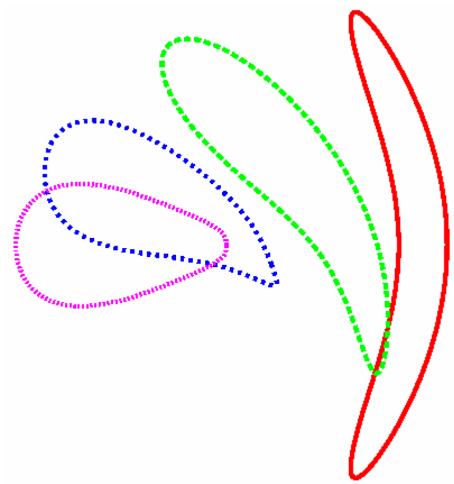
We have found “good” QHS configurations in three field periods having A as low as 4.5 with magnetic well depth in vacuum as much as 4%. We shall discuss two A=6 and two A=4.5 configurations to show their overall transport and interchange stability properties.



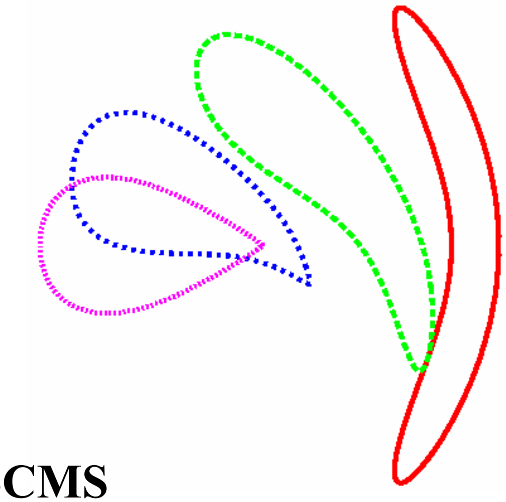


Optimized A=6 configurations

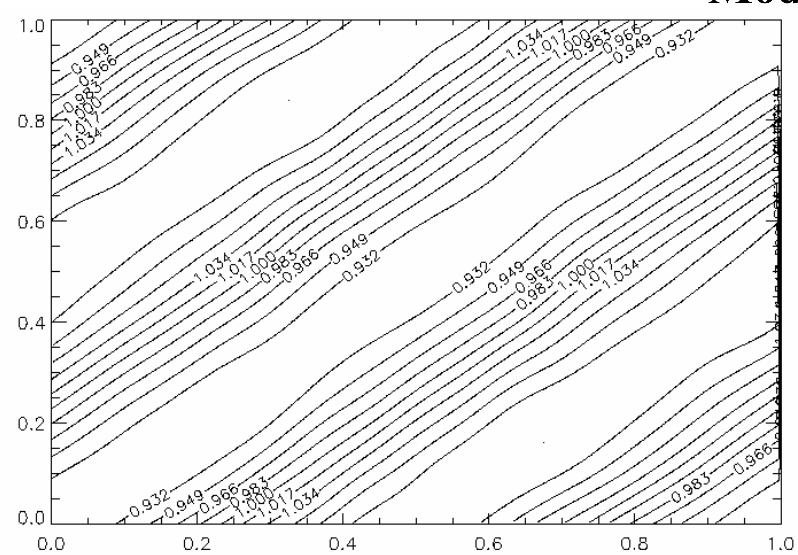
H5B (~1% well)

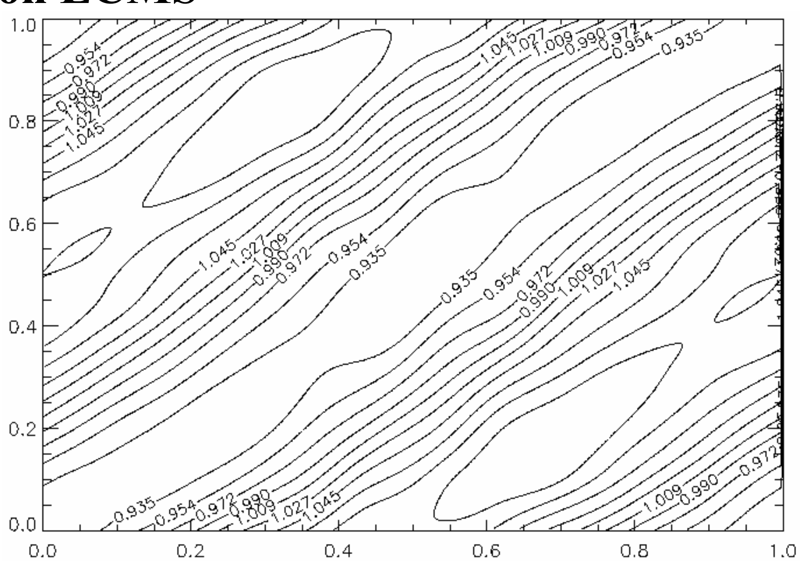


JI6 (~3% well)



Mod B on LCMS



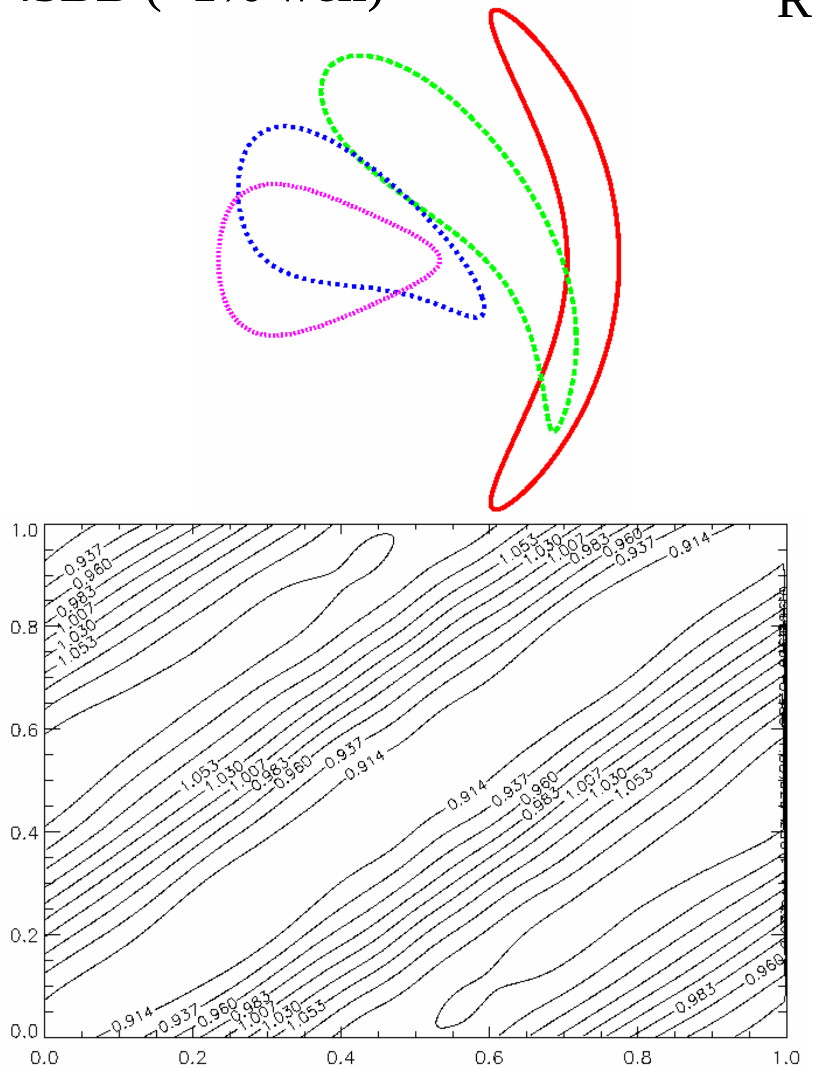


Comparison of some properties:

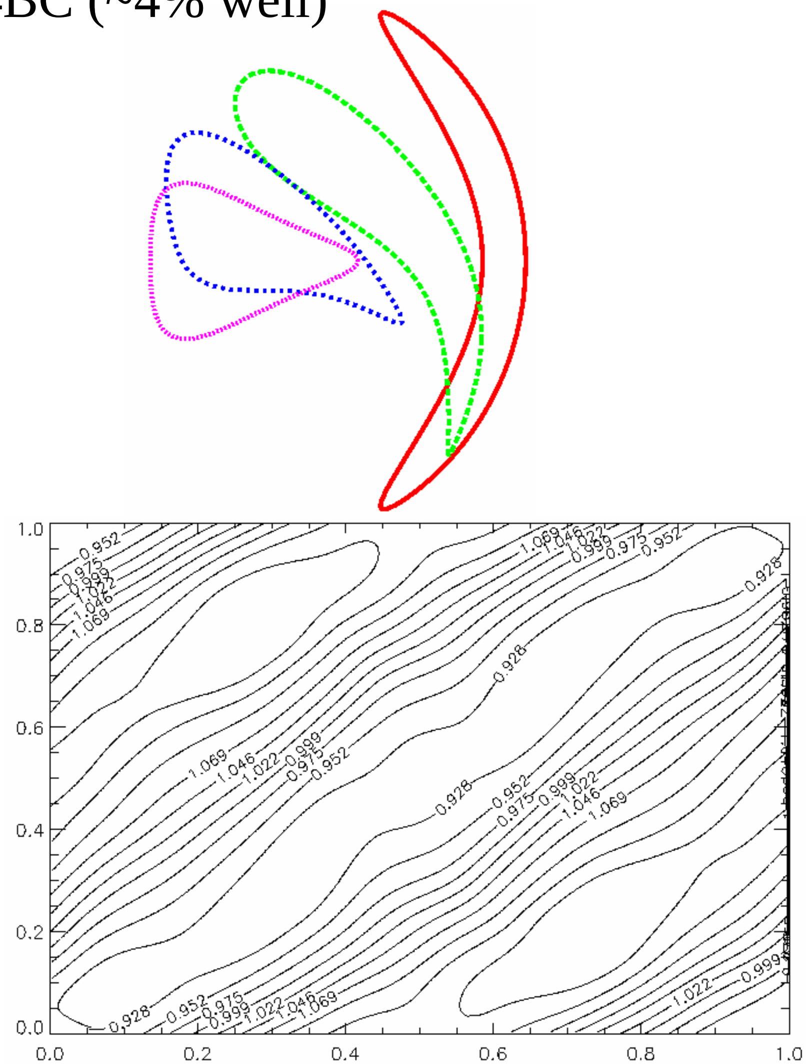
	H5B	JI6
B(1,1)/B(1,0) @s=1	**111**	**42**
B(1,1)/B(m,n) m≠n, max, @s=1	**28**	**8.3**
ε-eff @ s=1	**0.23%**	**0.5%**
α-loss fraction*	**<0.5%**	**~3%**
Magnetic well depth @s=1 w/o plasma pressure	**0.9%**	**3.3%**
Interchange β limit (Mercier & resistive)	**~2%**	**~5%**
Ballooning β limit (infinite-n)§	**~1%**	**~1%**
Rotational transform, ι(0) & ι(1)	**0.80-0.85**	**0.81-0.84**
Waist/R @ ϕ=0	**0.10**	**0.09**

Optimized A=4.5 configurations

P43BB (~1% well)



R74BC (~4% well)



Comparison of some properties:

	P43BB	R74BC
B(1,1)/B(1,0) @s=1	90	16
B(1,1)/B(m,n) m≠n, max, @s=1	19	6.8
ε-eff @ s=1	0.22%	0.36%
α-loss fraction*	~7%	~7%
Magnetic well depth @s=1 w/o plasma pressure	0.7%	4.2%
Interchange β limit (Mercier & resistive)	~1%	~6%
Ballooning β limit (infinite-n)§	~1%	~1.2%
Rotational Transform, ι(0) & ι(1)	0.78-0.82	0.79-0.84
Waist/R @ ϕ=0	0.124	0.11

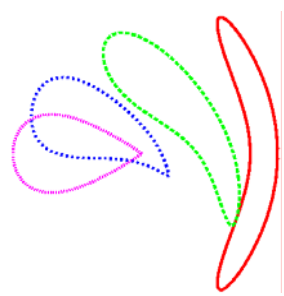
A few comments:

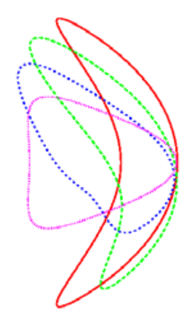
- Excellent confinement properties may be attained for A=6, but confinement of energetic particles is much degraded for A=4.5.
- Ballooning β limit is quite low. Attempt to increase β limit has not been successful. QH is compromised also.
- A few percent vacuum magnetic well would be sufficient to stabilize interchange modes for $\beta>4\%$.
- If confinement is singularly the most important consideration, A=6 QHS is a contender provided that 1) systems tradeoff shows cost competitiveness, 2) “good” coils can be found. If A=6 is not cost competitive, QHS with lower A may not have particular advantages over QAS in terms of energetic particle confinement and MHD stability β limits.

Comparison of QHS and QAS using JI6 and KJC167 as examples

(A=6, NFP=3, same well depth, both optimized with respect to quasi-symmetry)

	JI6	**KJC167**
"noise" energy content‡	**2.4%**	**2.8%**
ε-eff @ s=1	**0.5%**	**0.44%**
α-loss fraction*	**<3%**	**~8%**
Magnetic well depth @s=1 w/o plasma pressure	**3.3%**	**3.0%**
Interchange stability β limit (Mercier & resistive)	**~5%**	**~4%**
Ballooning β limit (infinite-n)§	**~1%**	**~2.5%**
Rotational transform, external, $\iota(0)$ & $\iota(1)$	**0.81-0.84**	**0.57-0.40**
Waist/R @ ϕ=0	**0.09**	**0.14**



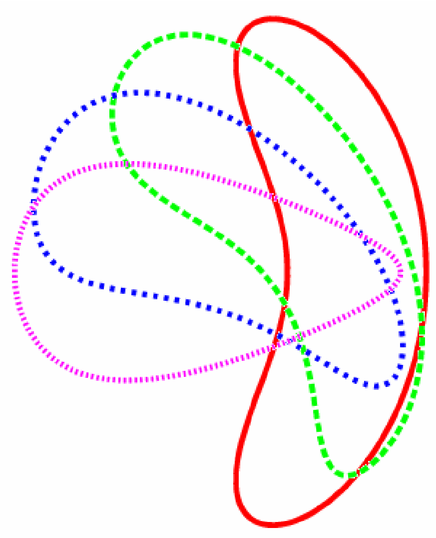


- For 3 field periods and larger aspect ratios (A~6):
  - QHS generally has better confinement, but QAS holds the advantage of having better MHD stability characteristics.
  - The equilibrium beta limit and flux surface quality in QHS may be better if low order islands are excluded in designing the iota profile.
  - Need to look at QHS coils and systems tradeoff in R, β, B

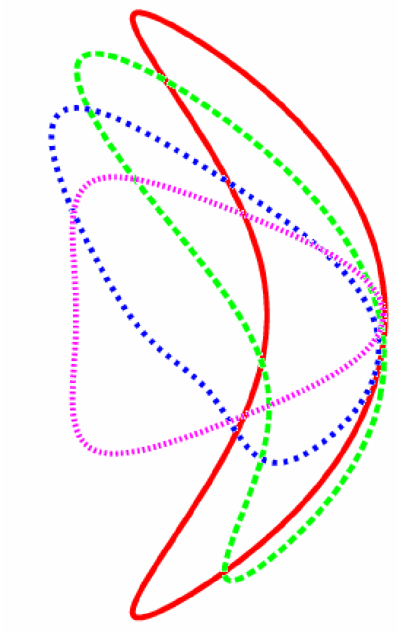
- For lower aspect ratios (as we've done in the systems study so far):
  - For 3 field periods, QAS and QHS are similar in the confinement properties; both are more difficult to optimize, although recent development of LPS-QA for A=4.5 seems encouraging.
  - For A<4, 2 field-period QAS appears more preferable, especially in light of the recently developed ultra low-A MHH2.

A brief review of QAS configurations in our inventory

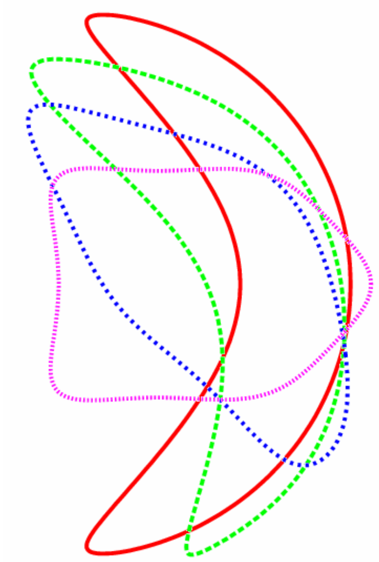
Three lines of development:



MHH2



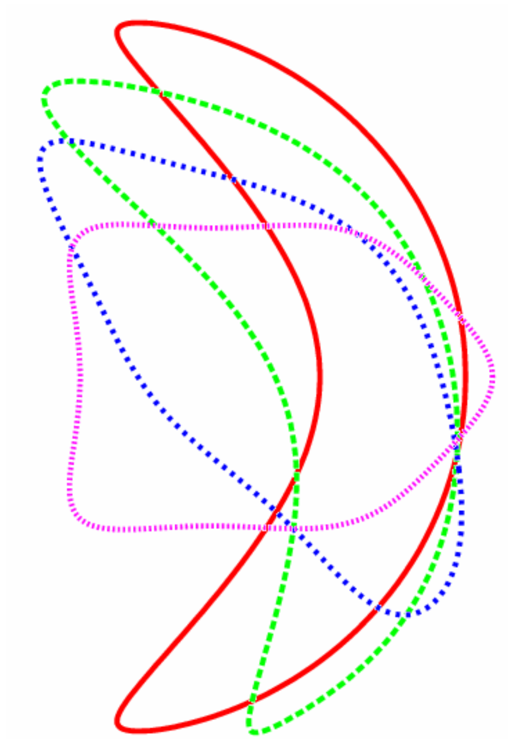
New approaches with emphasis on equilibrium surface quality.

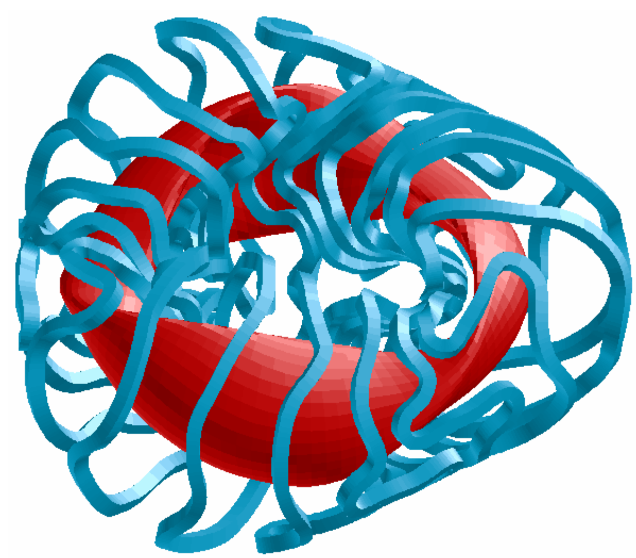


NCSX scale-up and upgrade

NCSX-Class of Configurations

- maintain the basic characteristics of the NCSX M50 plasma and coils.
- balance between QA and MHD stability.
- has shown numerically to have high stability β limits.
- coil designs able to recover all desirable plasma properties.
- coil "healing" has been demonstrated possible.





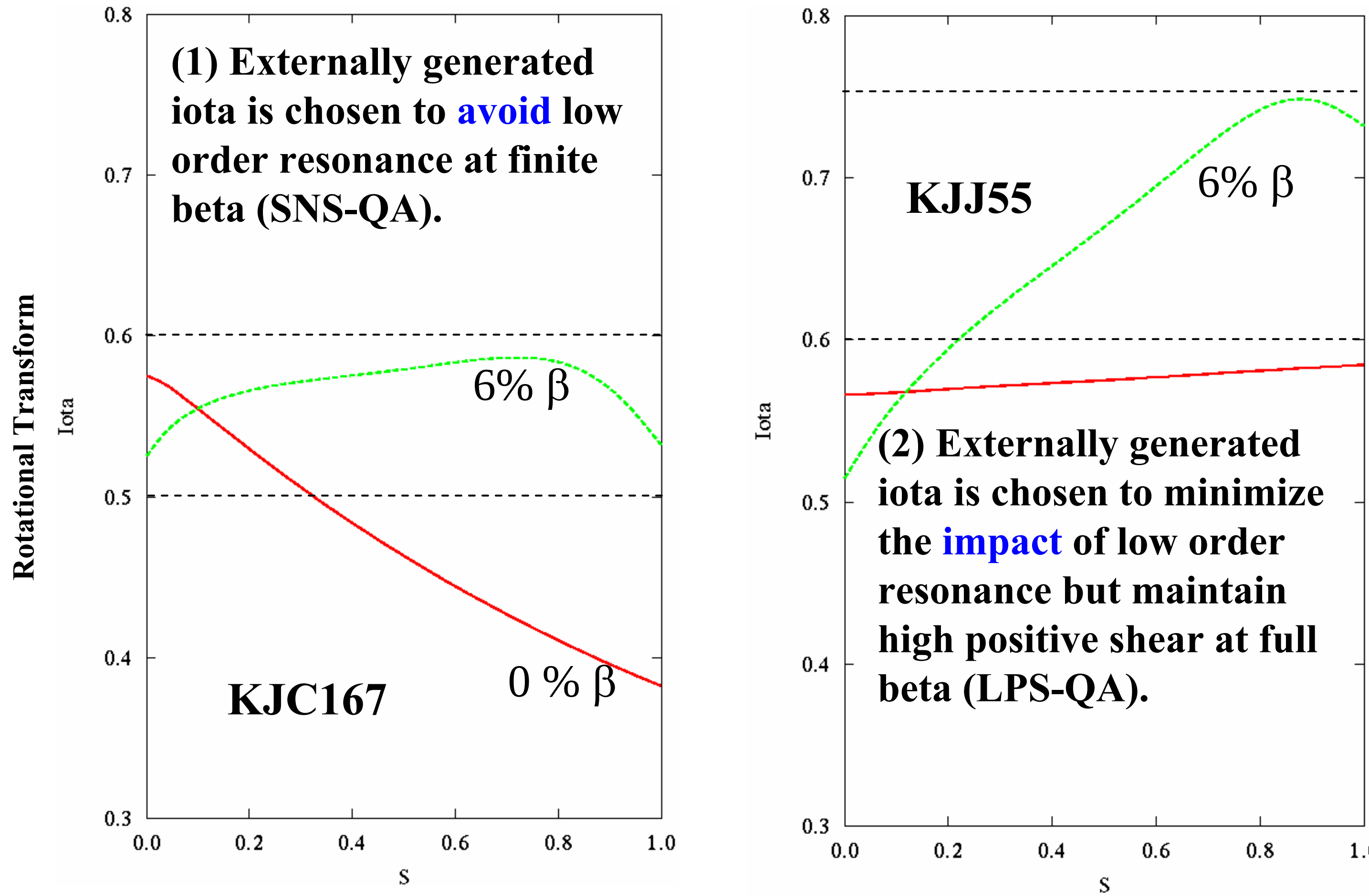
NCSX Class of Configurations

- **Accomplished:**
  - loss of $\alpha \leq 15\%$ achieved with MHD stability to $\beta \geq 4\%$ preserved.
  - configuration space extended to a broader ι region and 2 FP. Better QA for aspect ratio 6 found.
  - good equilibrium up to 8% β demonstrated if size of low order islands can be controlled.
  - coils with coil aspect ratio ~6 feasible without excessive distortion.

- **Issues:**
  - coils for α loss improved configurations not yet designed.
  - alpha loss still high; improvement by relaxing MHD constraints not yet attempted.
  - effective control of low order resonance perturbation to be developed.
  - plasma shape awkward for two-field period configurations.
  - reactor "compactness" for A=6 with trade-off among B, β, R not yet done.

New Approaches : SNS-QA and LPS-QA configurations

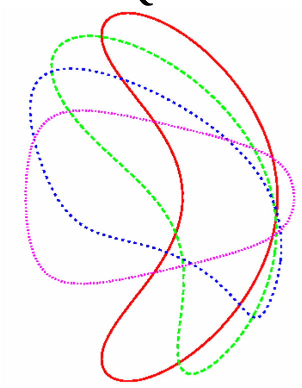
- **Improve equilibrium β limit and flux surface quality by careful tailoring of the external rotational transform.**
- **Two lines of development pursued:**



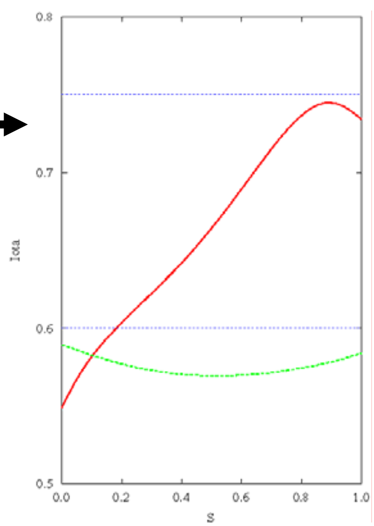
New Approaches : SNS-QA and LPS-QA configurations

- **Accomplished:**
  - good QA and α confinement characteristic (loss ~10%) attainable if MHD stability constraints other then V″ not imposed; effective ripples <<1%.
  - excellent equilibrium with high quality flux surfaces demonstrated for SNS-QA.
  - configurations of similar quality found in both 2 & 3 field periods and in different regions of iota space.

KQ26F

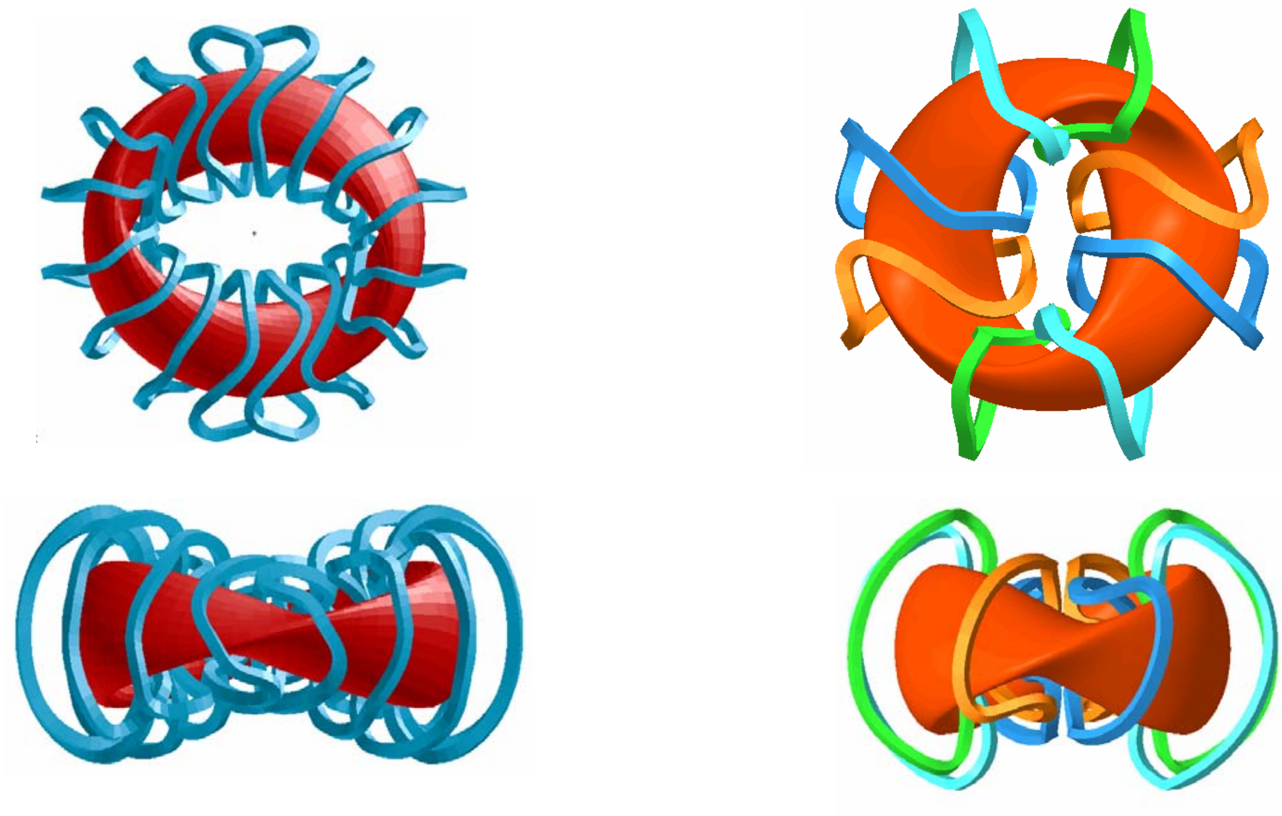


- **Issues:**
  - LPS-QA not adequately developed. QA strongly depends on V″. (Recent development for A=4.5 seems very encouraging.)
  - not yet able to get "nice" boundary shape for A=4.5 SNS-QA in three field periods.
  - potential of 2 field period configuration not fully explored.
  - difficult to stabilize MHD modes (in calculation) without compromising QA, particularly with respect to the infinite-n ballooning in SNS-QA.
  - coil designs only at cursory level.



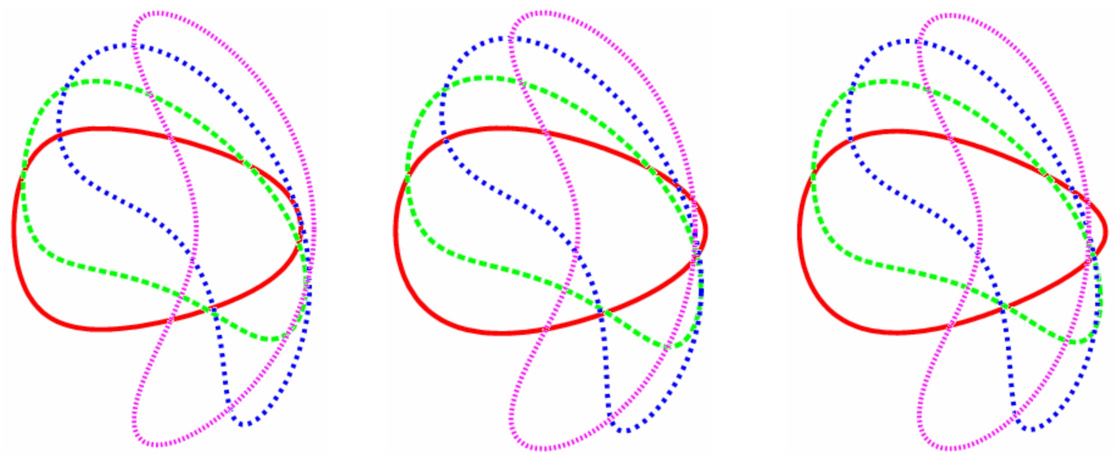
MHH2 (P. Garabedian)

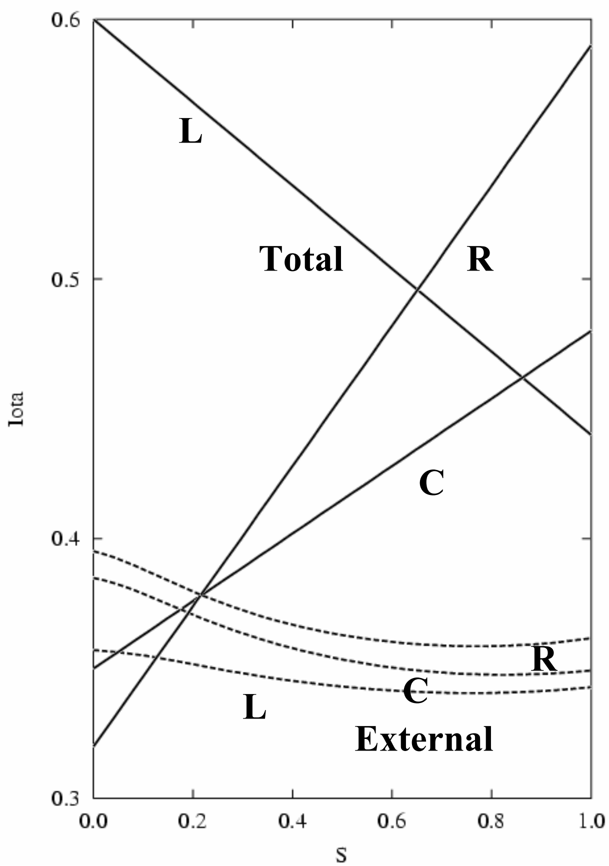
- **Small plasma aspect ratio ($A<3.5$) in 2 field periods provides configuration compactness.**
- **Simple shape and “clean” coils provide reactor attractiveness.**



MHH2

- **Accomplished:**
  - configuration space having ultra low aspect ratio (A~2.5) with good QA, low effective ripple (<<1%), and low α loss recently found.
  - configurations of various ι profile possible for the ultra low-A case, indicative of its flexibility in design space.
- **Issues:**
  - equilibrium and stability β limits yet to be analyzed.
  - coils for new A=2.5 configuration need to be designed and optimized.
  - consistency with reactor compactness need to be studied.





Summary

The physics basis of QAS and QHS as candidate for compact stellarator reactors has been assessed. New configurations have been developed, others refined and improved, all aimed at low plasma aspect ratios, hence compact sizes at a given fusion power.

- Configurations with excellent quasi-symmetry have been found with $A \leq 6$. Configurations with both 2 and 3 field periods possible.
- Progress has been made to reduce loss of α particles. Losses ~10% and lower have been achieved. The loss is still higher than desirable in many QAS configurations.
- Numerical calculations using codes based on linear, ideal MHD theories show that stability to the external kink, ballooning, and Mercier modes may be attained in most cases but at the expense of the reduced quasi-symmetry and increased complexity of plasma shape. Recent experimental results indicated that linear, ideal MHD stability theories may be too pessimistic, however.
- The ultra low A, 2 field-period MHH2 has unique features in the design flexibility and the simpler, "gentler" geometry increases its reactor attractiveness. Further development should follow.
- Configurations of LPS-QA/SNS-QA or NCSX classes are of interests particularly if flux surface quality and/or MHD stability are considered important.

FY05 Work Scope and Activities Envisioned

- Preparation for the selection of preferred cases for power plant studies.
  - 2 field periods:
    - ✓ **Further improve physics attractiveness of low A MHH2.**
    - ✓ **Design and optimize coils for MHH2.**
    - ✓ **Complete the study of the properties of SNS-QA.**
  - 3 field periods:
    - ✓ **Systems tradeoff of R, B, β for A=6 cases and compare with A=4.5**
    - ✓ **Study intermediate cases to find best compromise among QA, MHD stability, energetic particle loss, and coil complexity (particularly the study of the potential of LPS-QA).**
    - ✓ **Take second look of coils and look for better designs.**

- Preparation of basic information needed to compare various symmetry approaches to compact stellarator reactors.
  - Cursory studies of QHS, (QPS ?) with low A to find strengths and weaknesses.

- Continue to investigate methods for improving α loss, surface quality, and coil geometry, and continue to search attractive regions in configuration space.
  - J invariant, local transport barrier, aspect ratio and size scaling, resonance perturbation reduction, etc.