Attractive QAS Configurations for Compact Stellarator Reactors
–
A Review of Progress and Status

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Background

- **We seek to find out the potential of QAS (Quasi-Axisymmetric Stellarator) as power producing reactors.**
  - **How compact QAS can be? Compact in which sense?**
  - **What are high leverage items?**
  - **Critical issues and potential solutions.**

- **Configuration development and optimization constitute one of the major efforts in the ARIES-CS study in order to realize the reactor vision and to find innovative approaches.**
  - **Configuration space is vast and complex for both plasmas and coils.**
  - **Large degrees of freedom in configuration design offer the opportunity to find something better.**

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Background (cont)

- **Good progress has been made since last workshop a year ago.**
  - **Better and more attractive plasma configurations developed.**
  - **Optimized coils designed for the 2 field period configuration with low plasma aspect ratio (~2.5) and low coil aspect ratio (~5.5).**
  - **Better understanding of the alpha loss and ways to minimize the loss.**

Our Approach

- **Broadened the search of configuration space to find good reactor designs.**
  - **Improved NCSX as a reactor**
  - **Developed new QA configurations and corresponding coils**
- **Instead of focusing on a particular configuration, developed various attractive configurations to the extent that the design can be used in the systems/engineering study to understand the respective strengths and shortcomings.**
  - **demonstrated the richness of 3-D QA magnetic topology**
  - **showed the flexibility in configuration optimization**
- **Reactors based on these configurations are compact and competitive with other confinement concepts.**

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Search for something new – our focus

- **Quasi-axisymmetry with biased magnetic spectrum**
  - **Confinement of energetic particles**
  - **Low effective helical ripples**

a NCSX neighbor with enhanced mirror and better fast ion confinement

- **Very compact configurations with compact coils**
  - **Low aspect ratio plasmas**
  - **Large plasma and coil separations**

MHH2 with A~2.5 and R/Δ_{min}~5

- **"Designer's" rotational transform for the integrity of equilibrium flux surfaces**
  - **Avoidance of low order rational surfaces**
  - **Reduced magnetic shear**

SNS/LPS, particularly strong $-\delta\iota/\delta r$ from shaping

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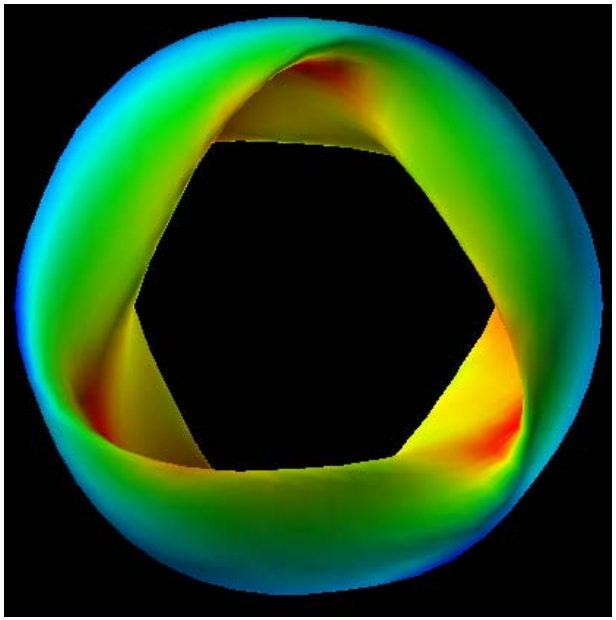
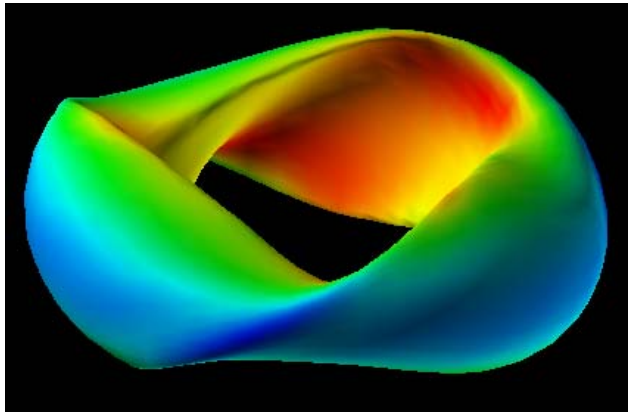
QAS with Biased Magnetic Spectrum

A new class of NCSX-like configurations are found with high magnetic shear, good QA and α confinement, and good MHD stability characteristics. A bias is introduced in the magnetic spectrum in favor of B(0,1).





Plane and perspective views of the last LCMS geometry and |B| in real space.

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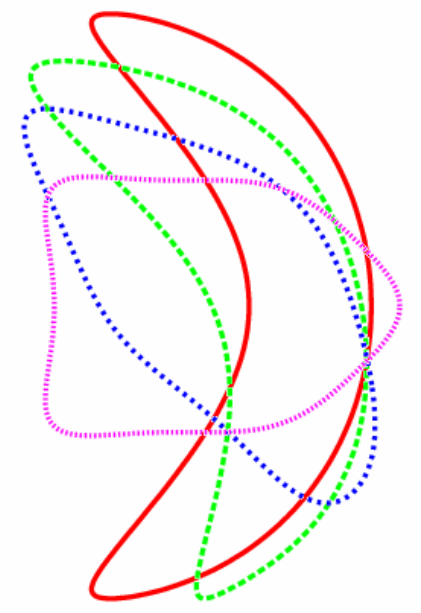
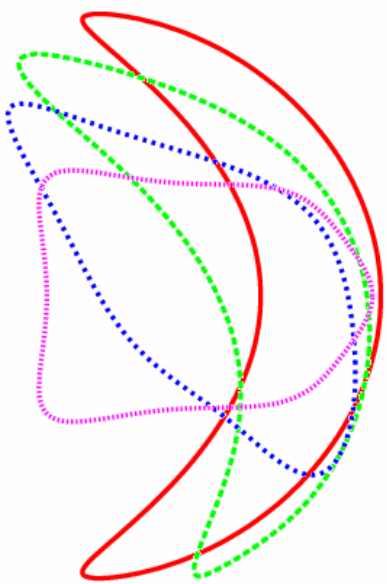
A direct correspondence to NCSX is a configuration named N3ARE which has been the main focus of the systems study.

NCSX

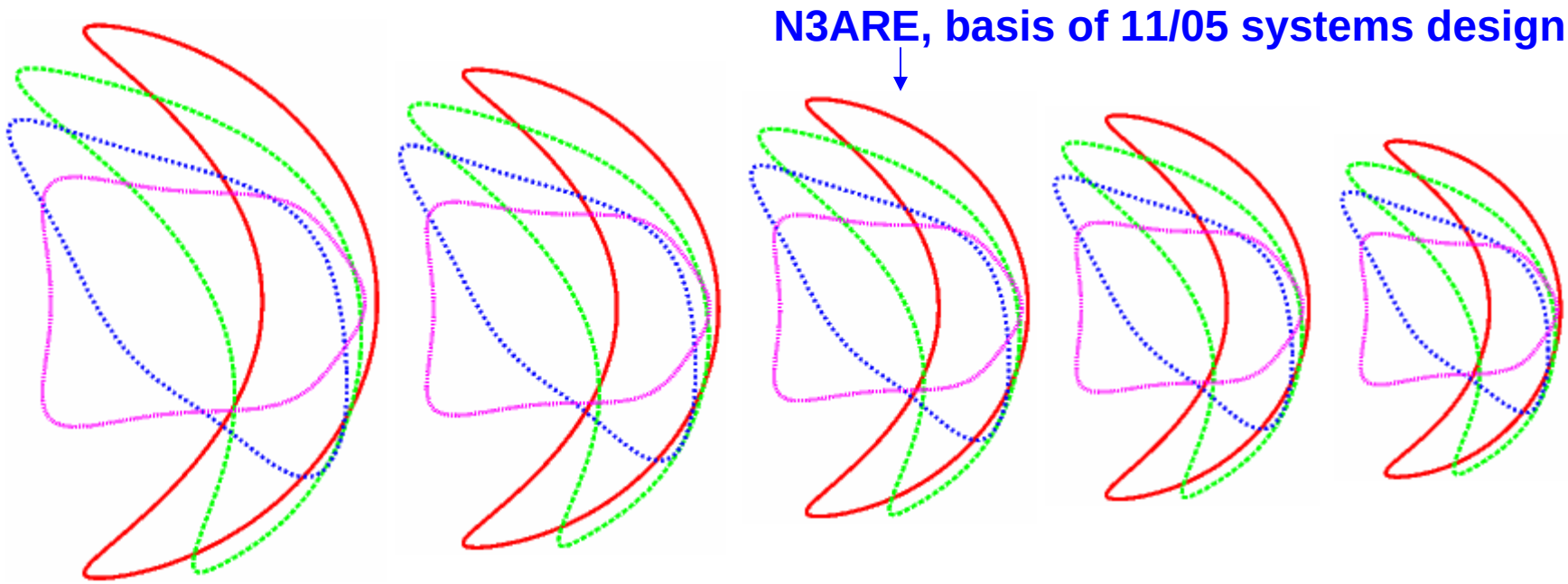


Improve energetic particle confinement while maintaining similar MHD stability/ equilibrium surface characteristics



N3ARE

N3ARE is a member of a family of configurations with the enhanced mirror. Systematic studies indicate that the most attractive plasma aspect ratio is in the neighborhood of A~4.



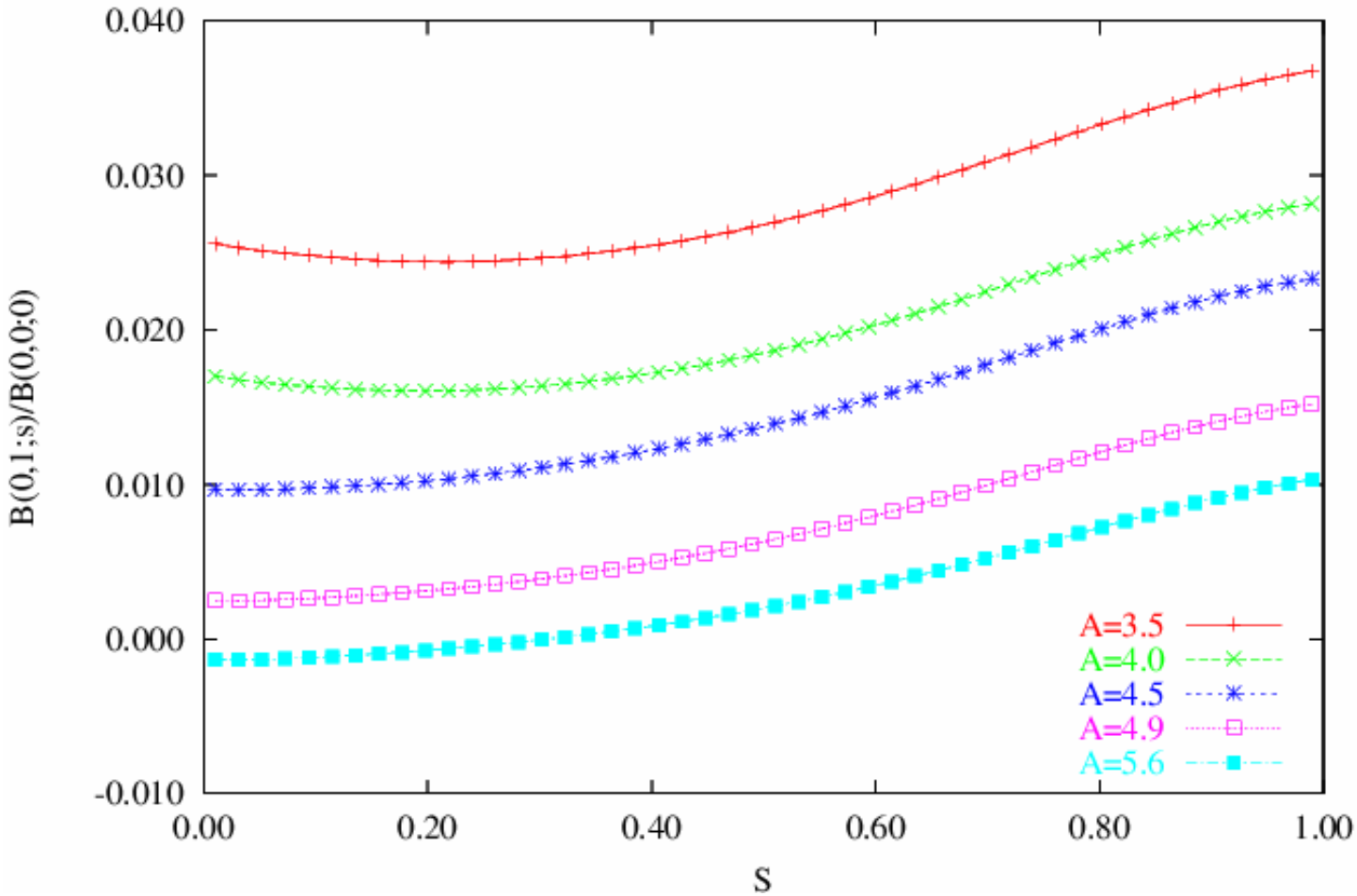
A=3.5 A=4.0 A=4.5 A=5.0 A=5.6

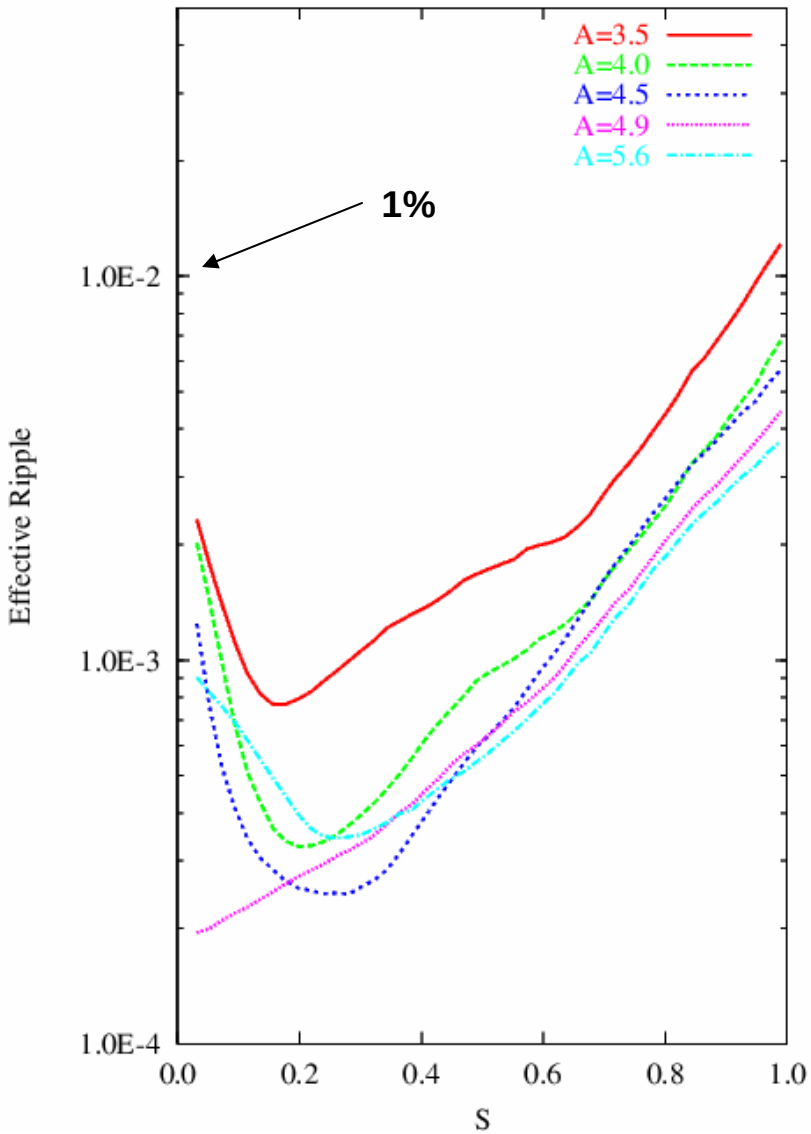
kink stability

QA

ballooning stability

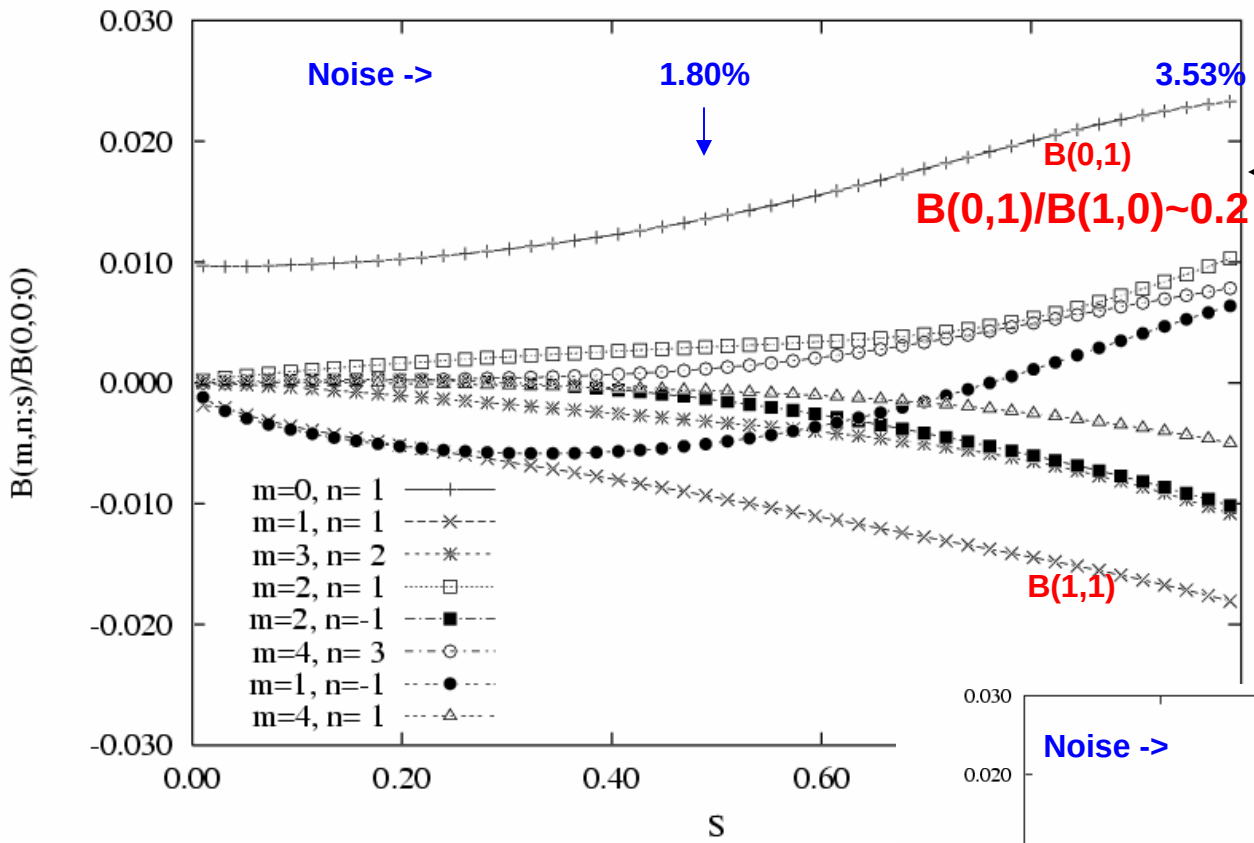
The magnitude of mirror increases consistently as the plasma aspect ratio decreases to maintain the favorable MHD and transport properties. The role of $B_{0,1}$ appears to diminish for A>6 as QA becomes easier to attain.

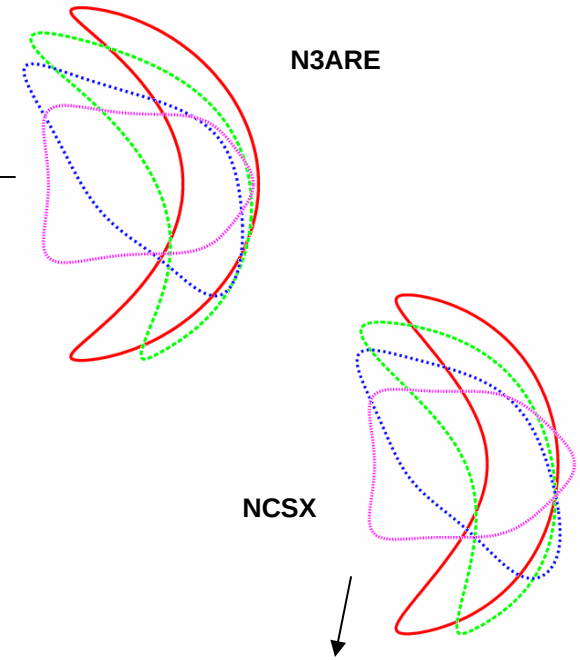


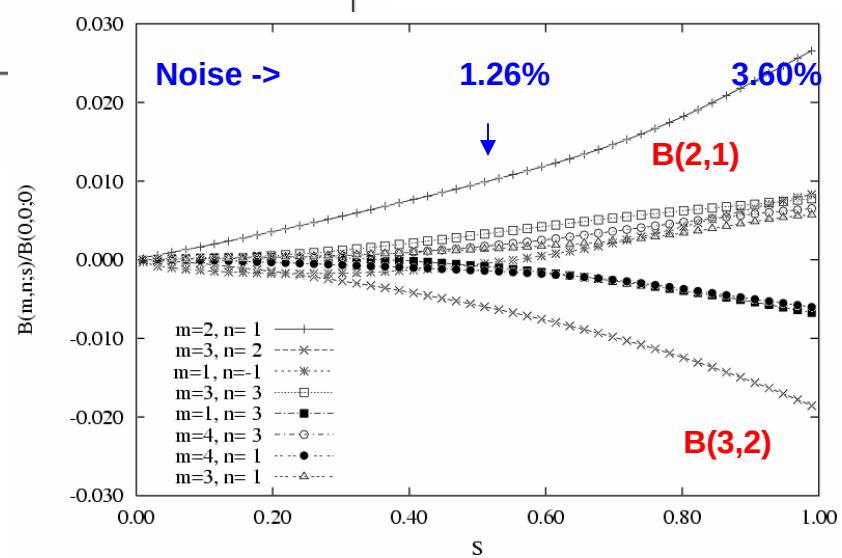


Very low effective ripples (ε–eff) in this class of configurations are found, particularly for A>4, while they maintain favorable MHD stability properties (external kinks, ballooning and Mercier). For example, N3ARE has been "calculated" to be stable at 4-5% β.

The content of the overall non-axisymmetry is still small and comparable to that of NCSX.







$$B = \sum B_{mn} \cos(m\theta - [n - \iota m]\varphi)$$

$$\text{noise} = \sqrt{\frac{\text{magnetic energy, nonsymmetric components}}{\text{magnetic energy, symmetric components}}}$$

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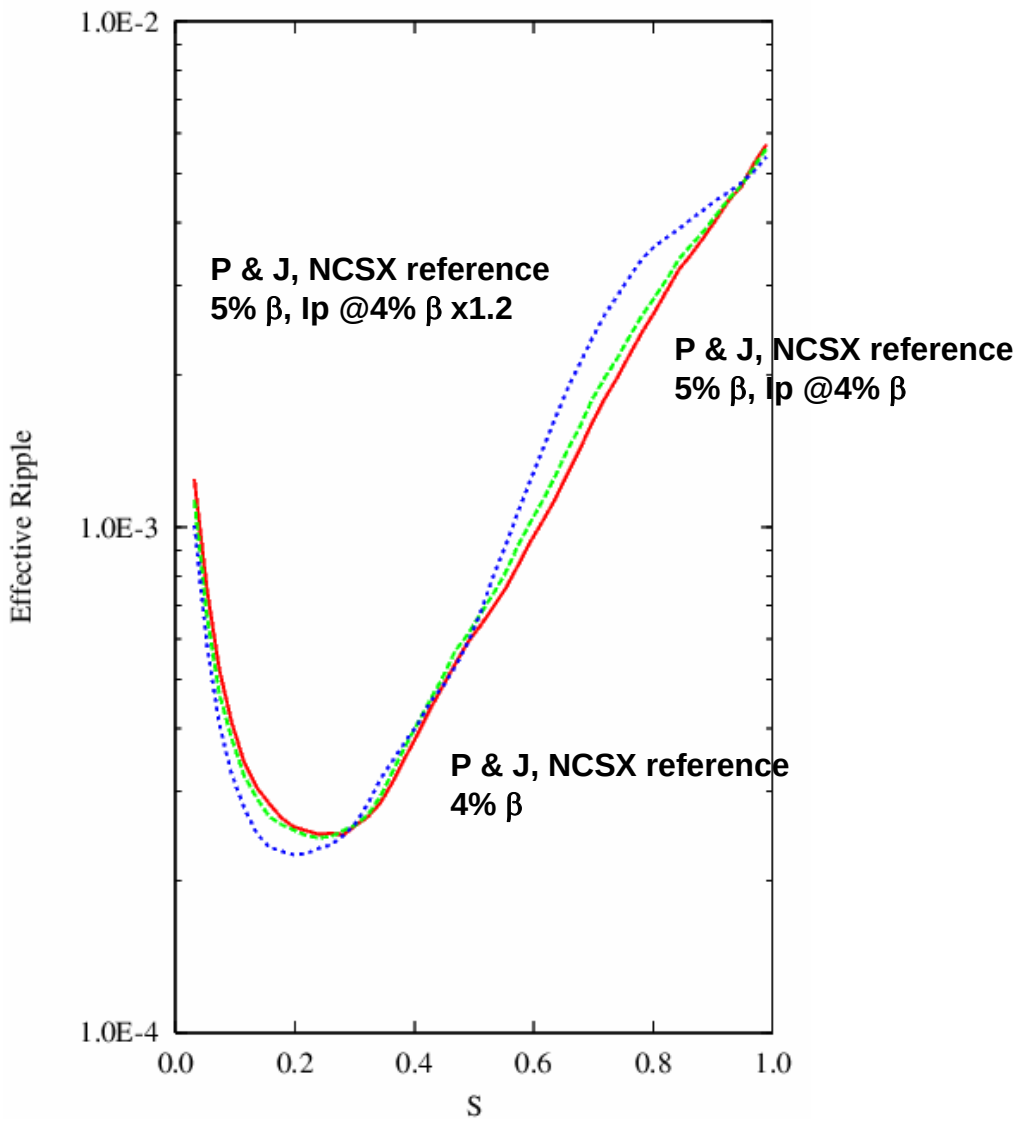
The effective ripple is insensitive to changes in β and levels of plasma current, as shown below due to NEO* calculations for A=4.5 N3ARE.



*V. V. Nemov, S. V. Kasilov, W. Kernbichler and M. f. Heyn, Phys. of Plasma, 6 (12), 4622 (1999)

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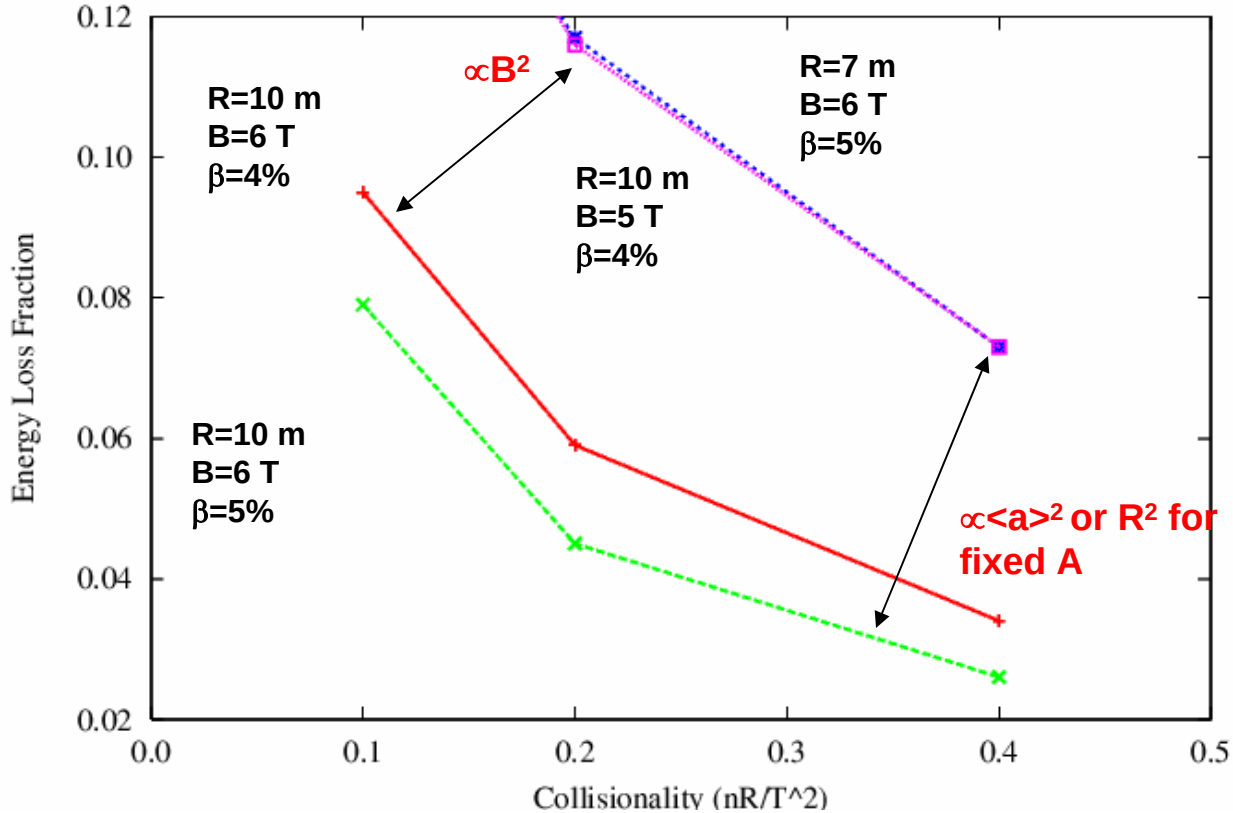
Appropriate bias in the magnetic spectrum helps QAS configurations improve confinement of energetic particles. Here we illustrate survey results of α slowing down calculations by ORBIT3D* for N3ARE.

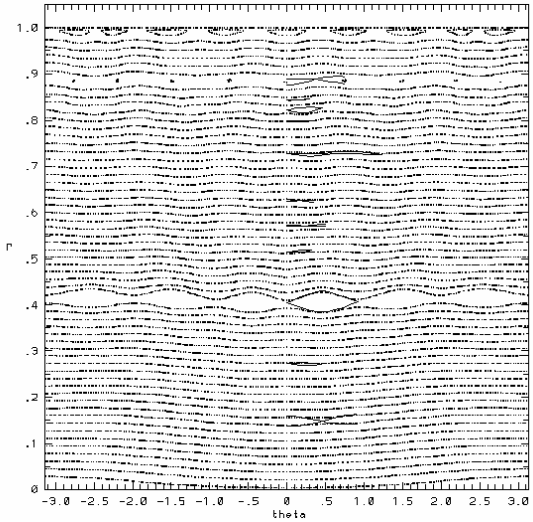
Calculations show loss <10% is achievable, but there is a strong ν, B and R dependence.



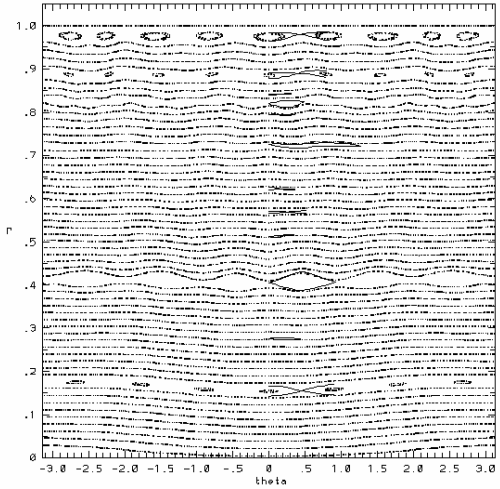
*R. B. White and M. S. Chance, Phys. Fluids 27, 2455 (1984)

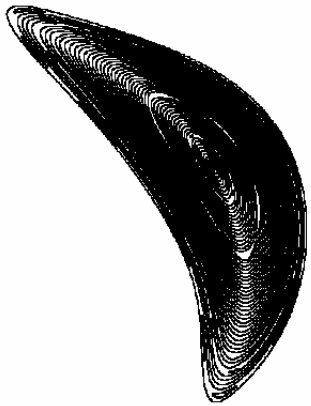
Fixed boundary PIES* calculations indicate that N3ARE is expected to have reasonably good flux surface quality at 5% β.

p & J, NCSX reference
4% β

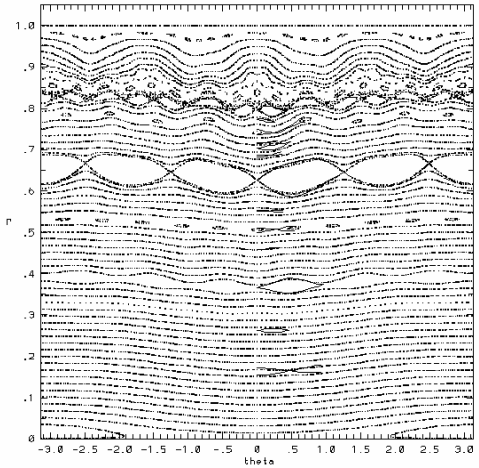


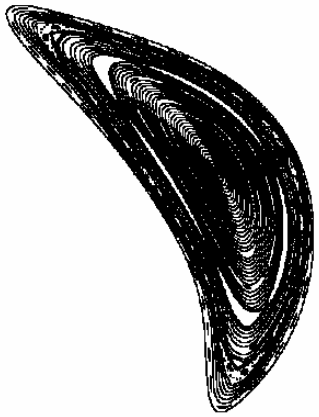
p & J, NCSX reference
5% β, Ip @4% β





p & J, NCSX reference
5% β, Ip @4% β x1.2





*A. Reiman et al., Comp. Phys. Comm., 43, 157 (1986)

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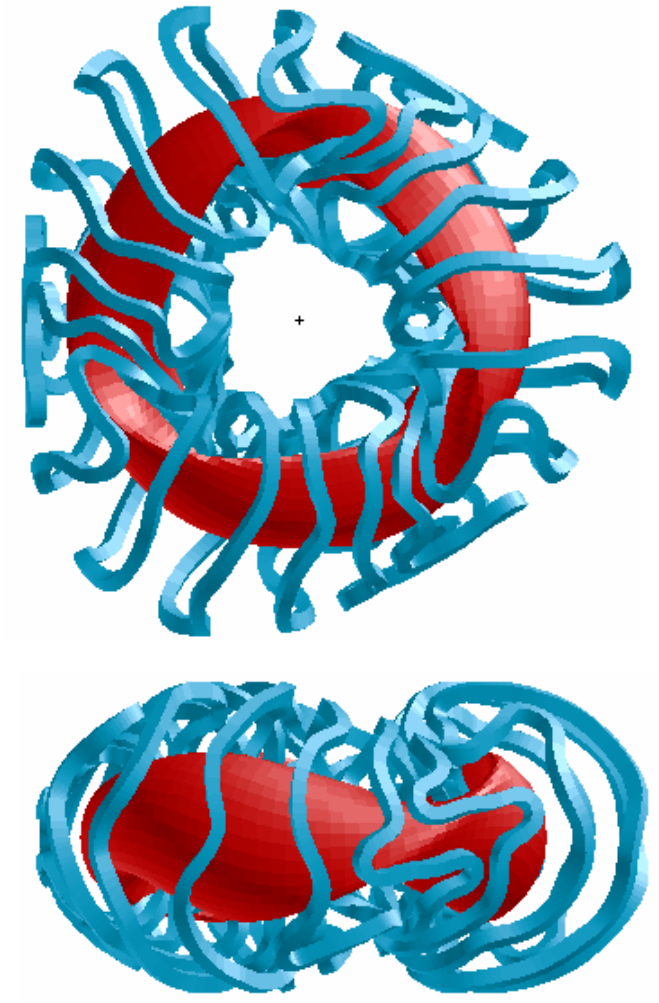
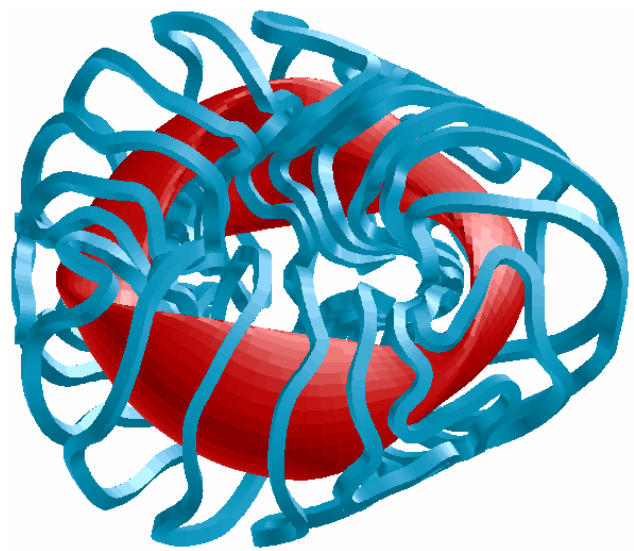
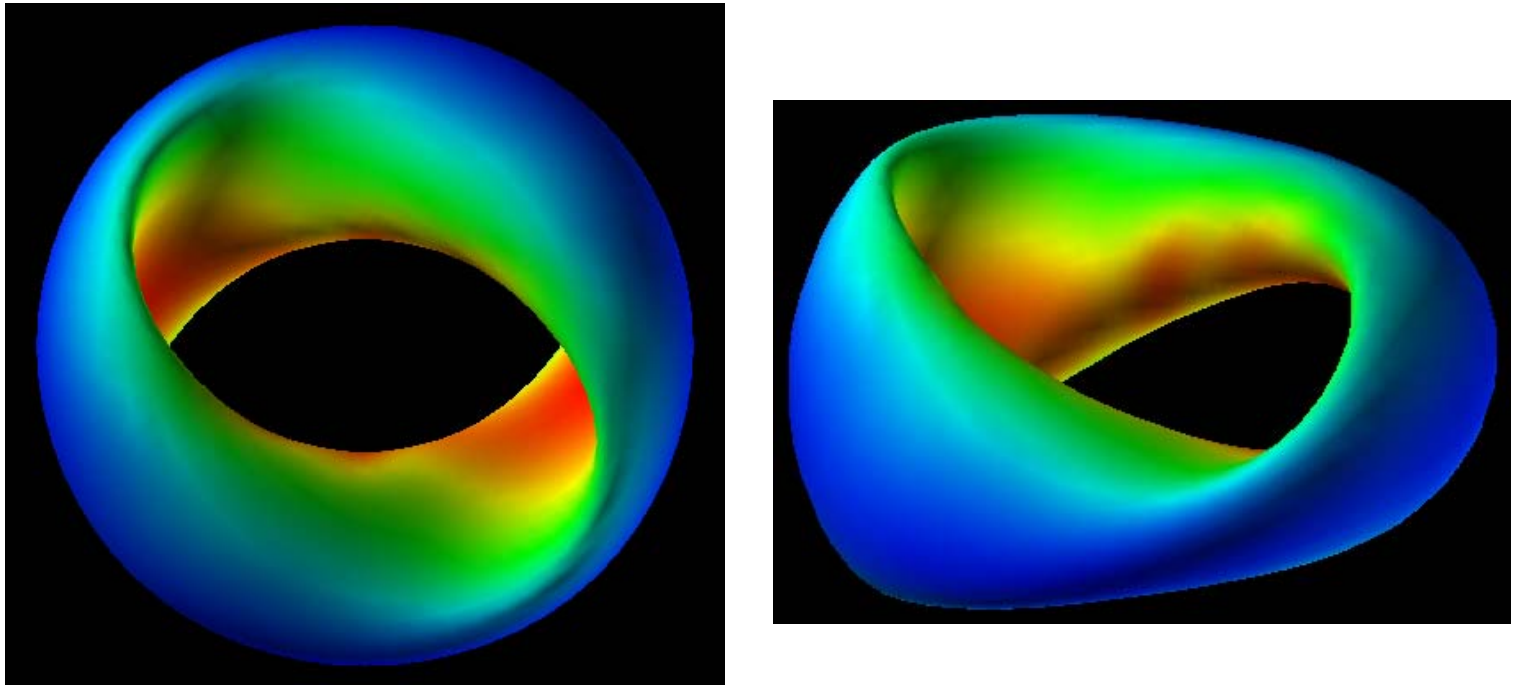
The shape of the plasma indicates that modular coils should have similar degrees of complexity as those of NCSX.





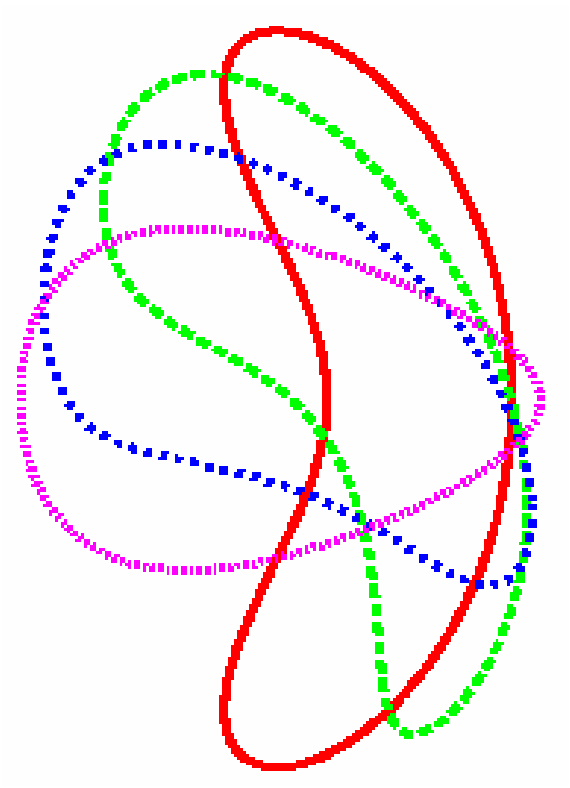
Configurations with "Ultra-low" Aspect Ratios

We have found an MHH2 family of configurations whose aspect ratios are ~2.5. These configurations have low field ripples and excellent confinement of α particles.

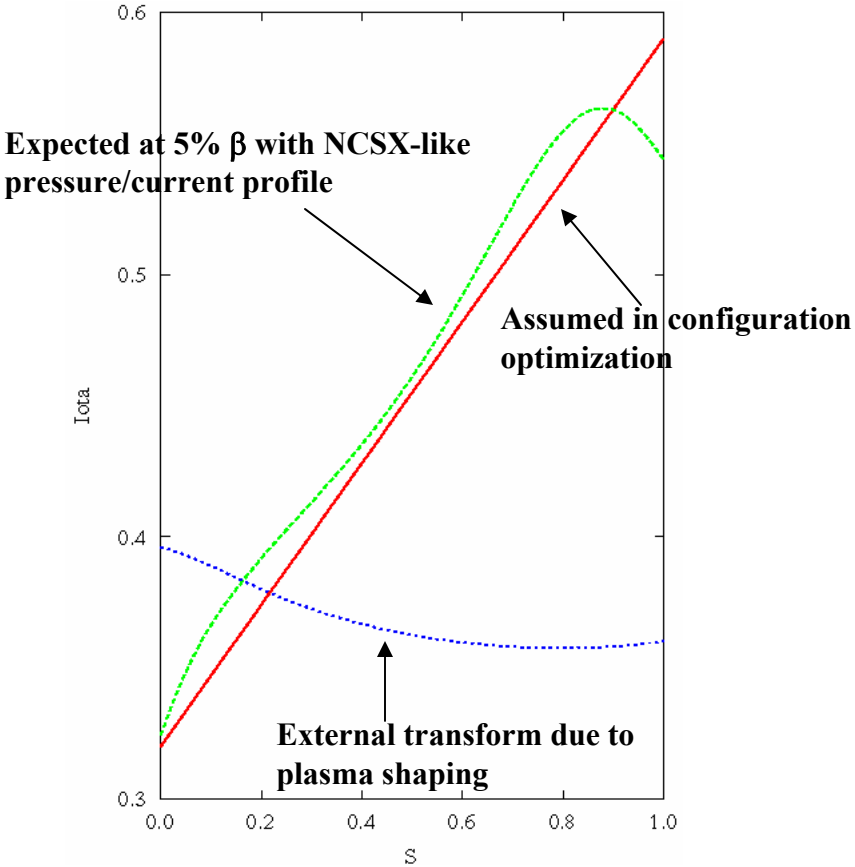


Plane and perspective views of the last LCMS geometry and |B| in real space.

MHH2-K14 is a configuration of the ultra-low A family. The aspect ratio is only ~1.3 per field period but the transform from plasma shaping is of a good magnitude, ~0.19 per field period.

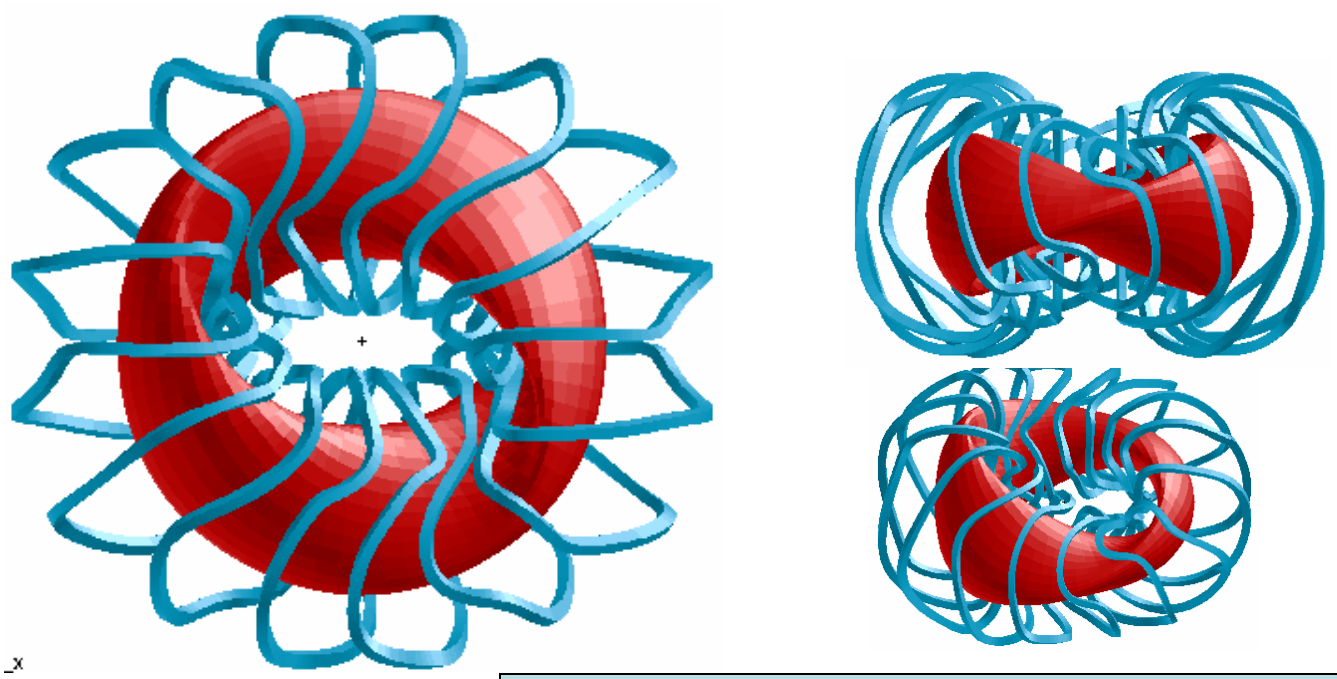


LCMS in four toroidal angles over half period.



Rotational transform as function of toroidal flux.

Modular coils have been carefully designed for MHH2-K14 (K14LA) via three stages of optimization.



No. of Coils: 8/period

Different Types of Coils: 4

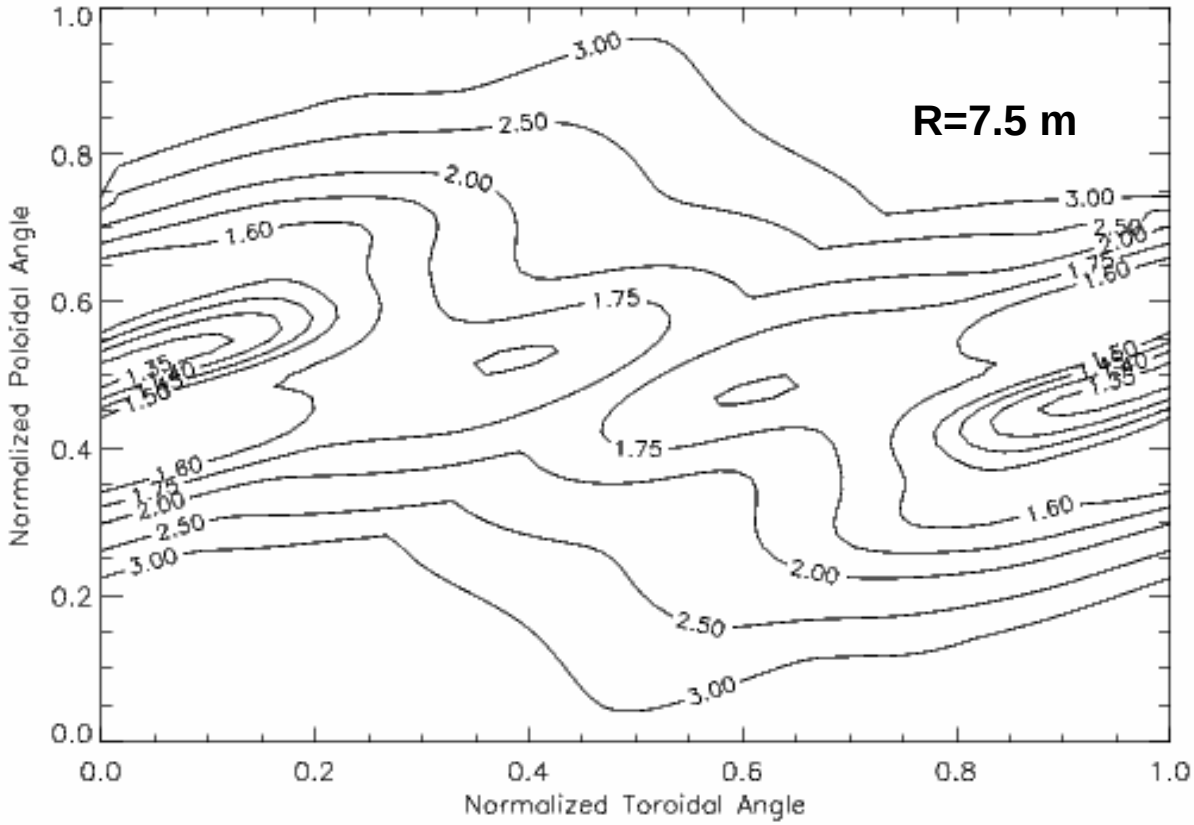
R/Δ_{min} (coil-plasma) = 5.5

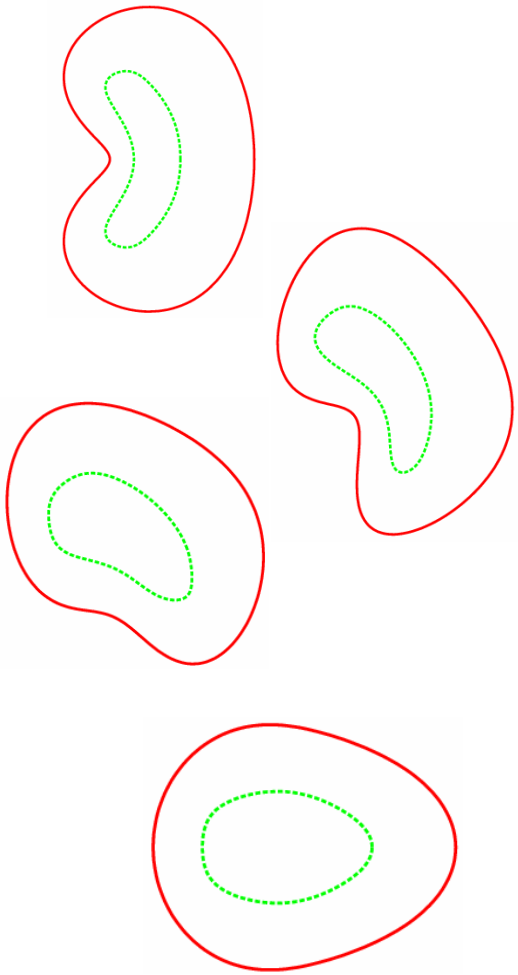
R/Δ_{min} (coil-coil) = 10.3

I /R-B (max) = 0.32 MA/m-T

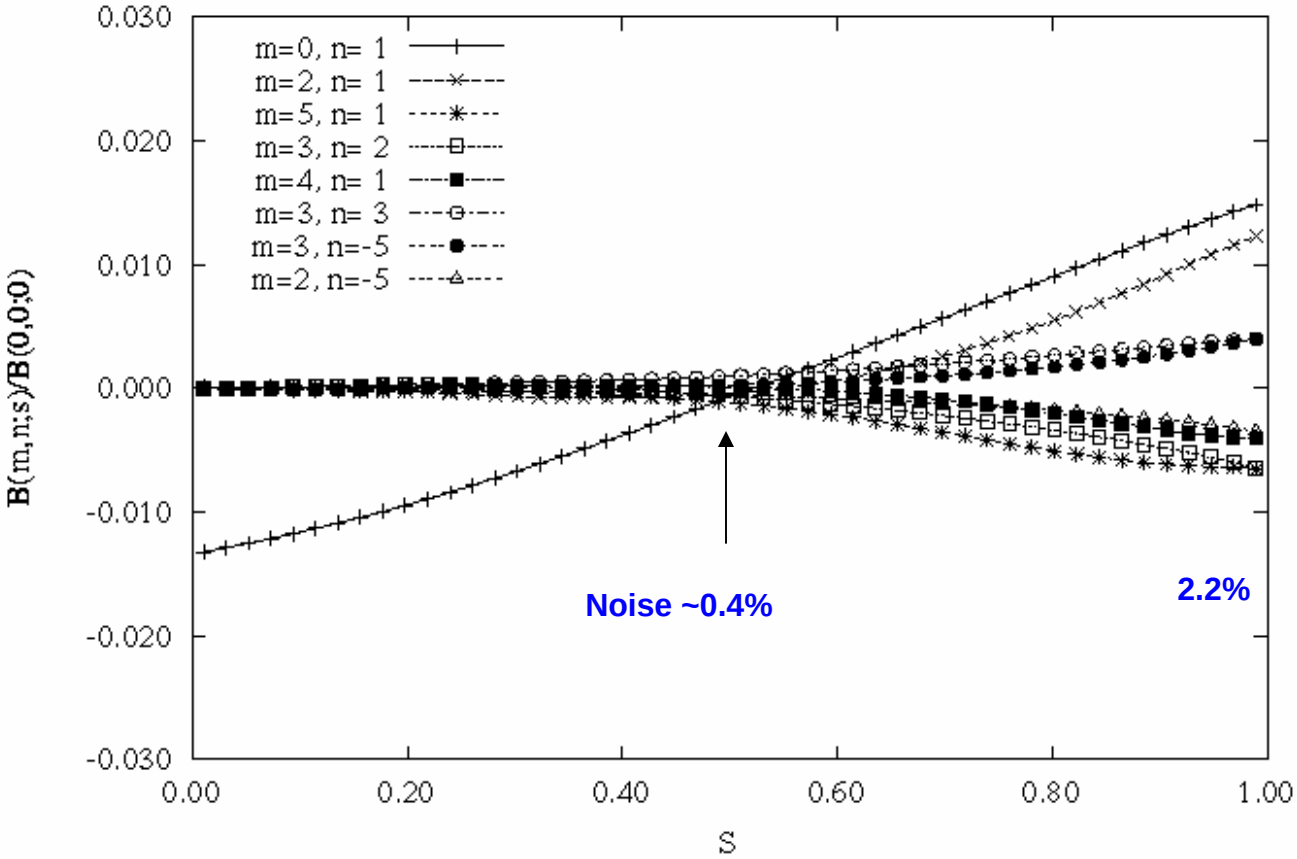
B(max)/B(0) = 2.5 for 0.4 m x 0.4 m conductor

Calculation of plasma to coil distance shows a good all around separation for the placement of blanket and shield modules.





Very small non-axisymmetric residues in the magnetic spectrum are seen based on the free-boundary equilibrium constructed by VMEC*, showing the superior QA of K14LA.



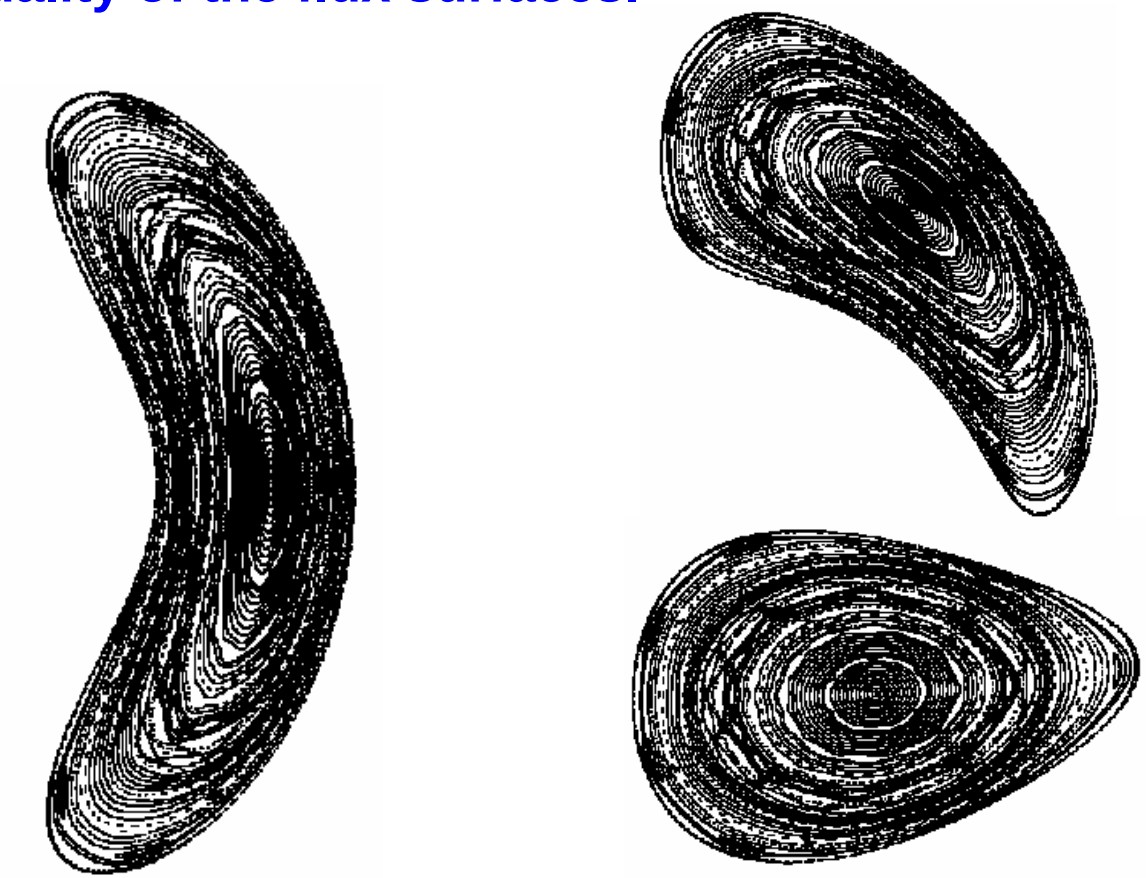
Free–boundary plasma, K14LA coils:

Effective ripple <0.8%

α energy loss in model calculation ~ 5%

*S. P. Hirshman, W. I. van Rij, P. Merkel, Comp. Phys. Commun., 43, 143 (1986)

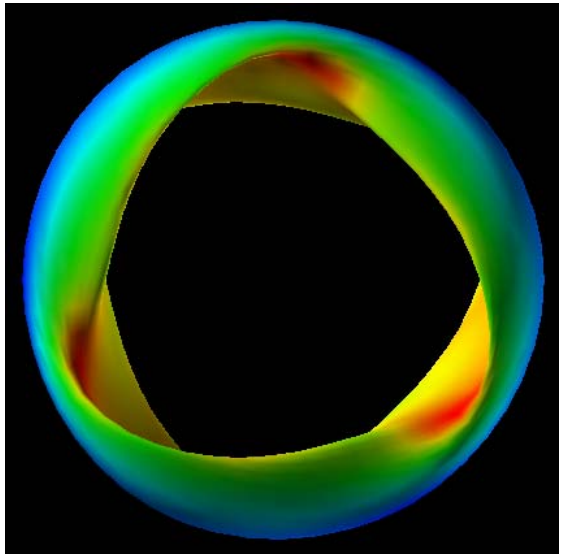
MHH2-K14 has reasonably good flux surface integrity. While islands of the lowest orders, m=4, 5, 6, do not contribute to significant flux loss, the proximity of islands of intermediate mode numbers degrades the quality of the flux surfaces.

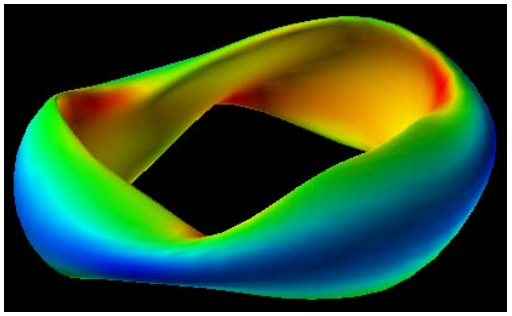


Poincaré plots in Cartesian coordinates at three different toroidal angles.

Configurations with "Designer's" Rotational Transform

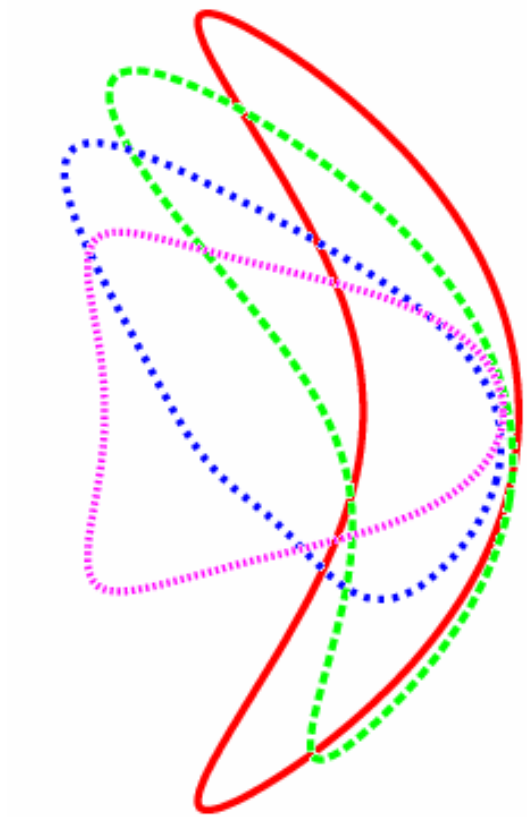
Configurations (SNS/LPS) are found whose iota profile is essentially flat, showcasing the existence of excellent flux surface integrity in QAS.

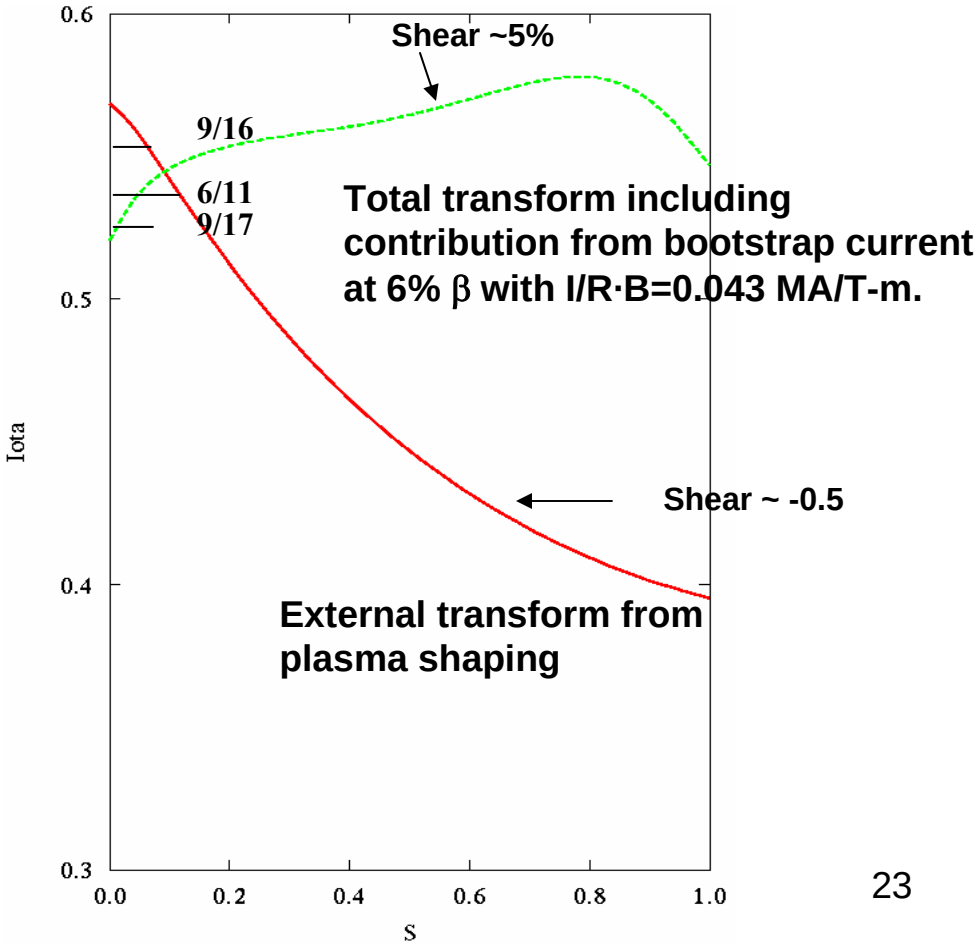




Plane and perspective views of last LCMS geometry and |B| in real space.

KJC167 is a 3 field-period, aspect ratio 6 configuration in which the iota profile is selected to minimize the impact of low order resonance on the flux surface integrity. In this case, the external iota has a strong negative shear, but the iota at operating β is expected to have a small but positive shear in most of the plasma volume.





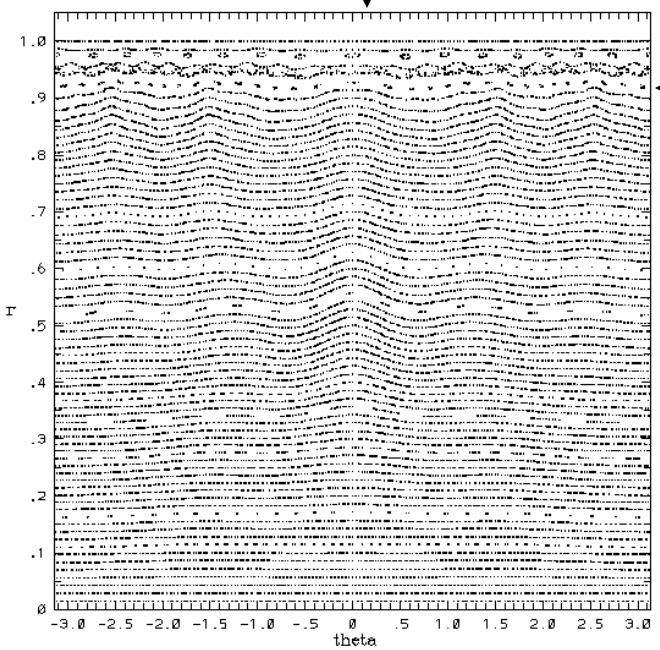
Excellent quality of flux surfaces is observed in most of the plasma for KJC167 at 6% β as seen below based on a PIES* calculation.

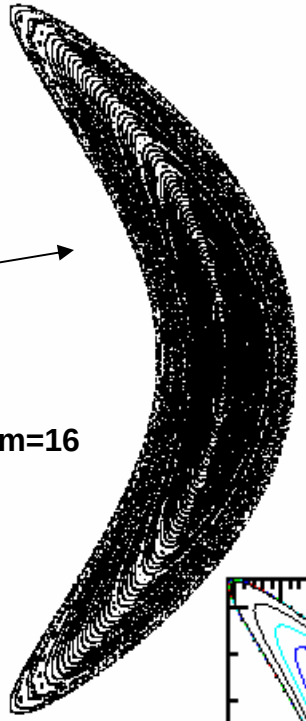
Equilibrium calculated by PIES @6% β.

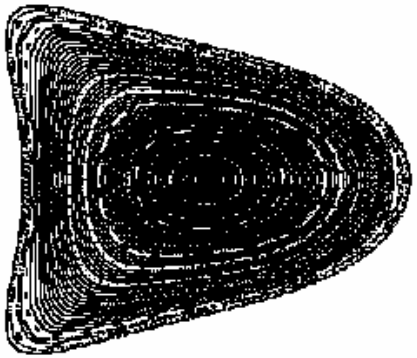
Poincaré plot in r-θ at φ=0.

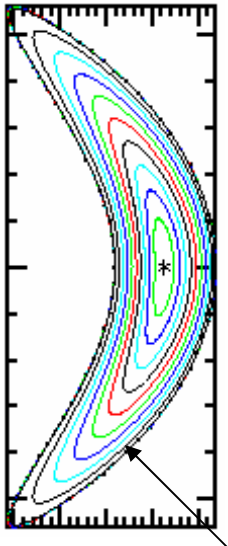
In Cartesian

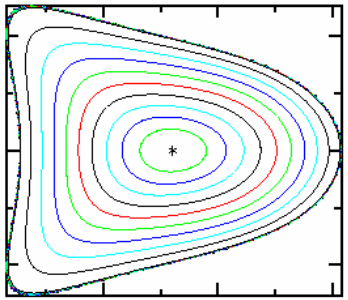
m=16











PIES and VMEC solutions are consistent.

Equilibrium calculated by VMEC

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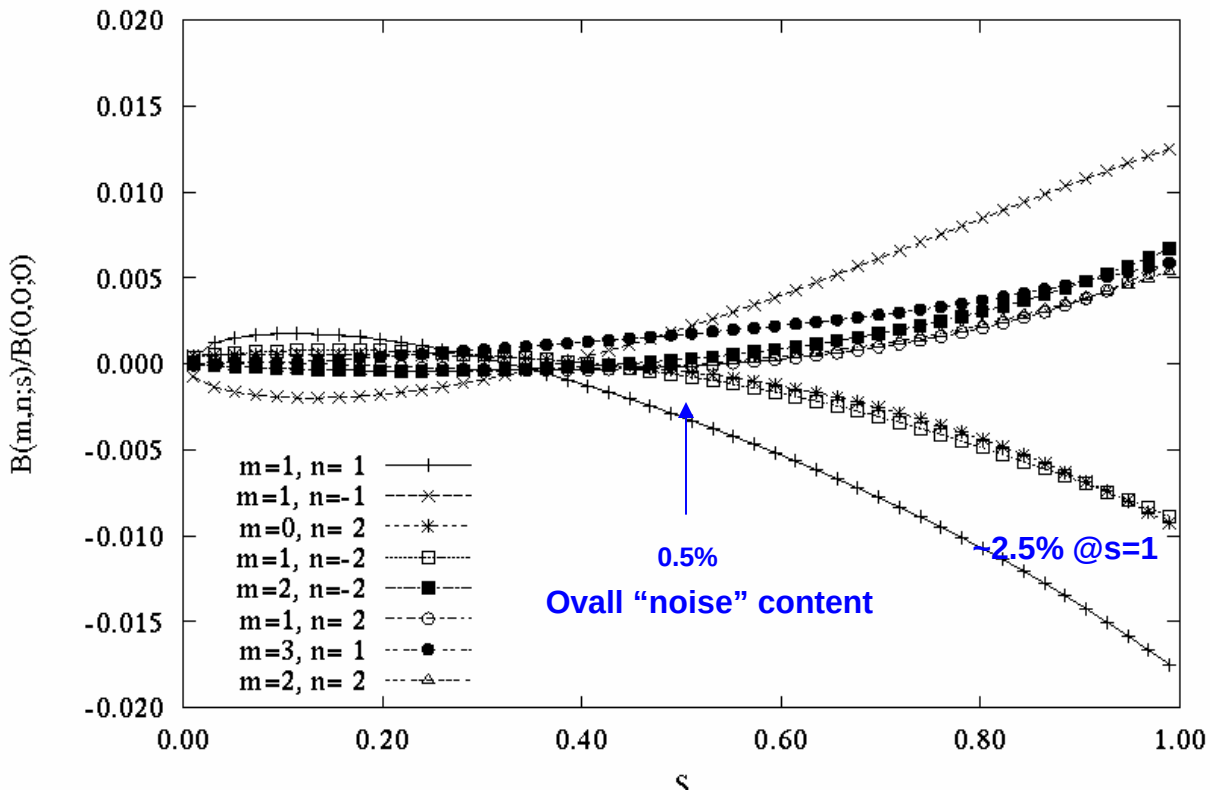
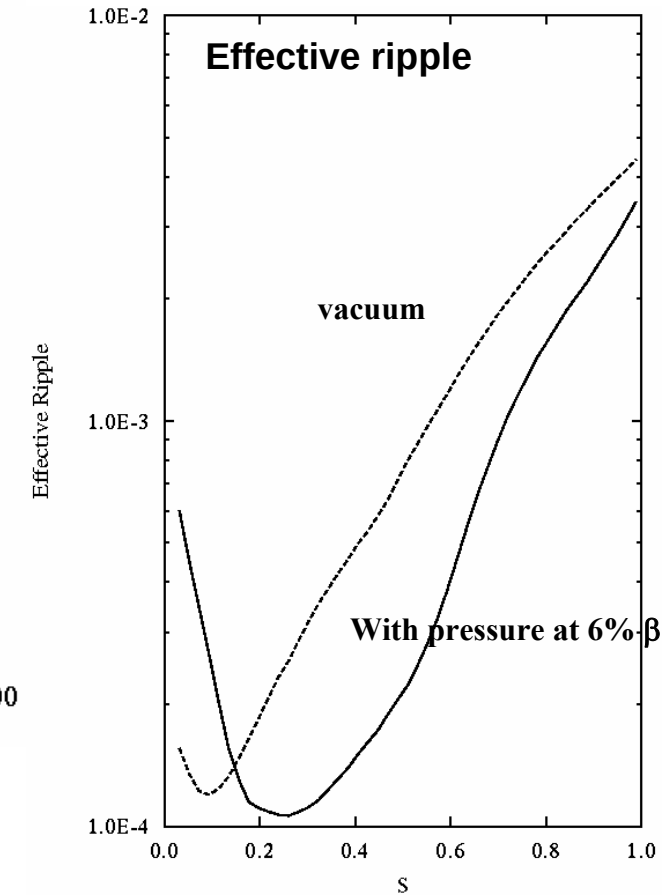
* A. Reiman and H. Greenside, Comp. Phys. Commun. 43, 157 (1986)

The configuration has good quasi-axisymmetry. The effective ripple @s=1 is only 0.35% at 6% β and the overall "noise" is <2.5%. Loss of α energy is ~8% in one slowing down time in our model calculation.



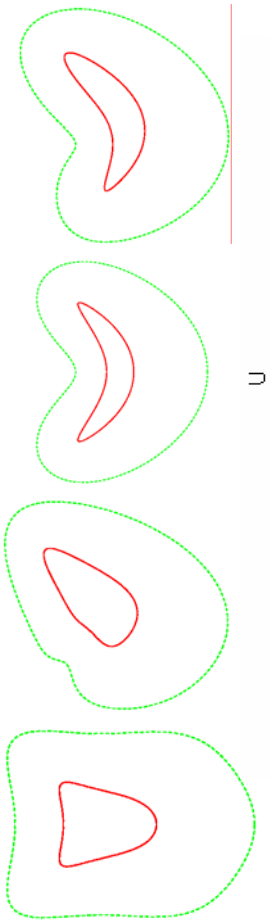
Eight major non-symmetric components in the magnetic spectrum plotted as function of normalized toroidal flux.

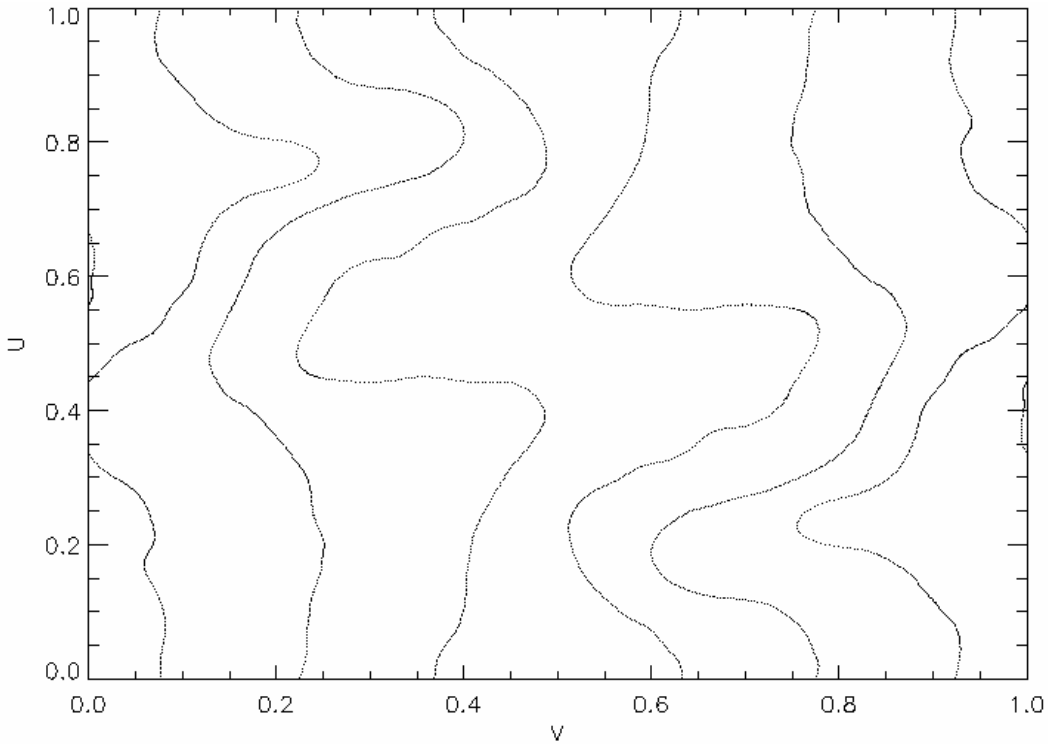


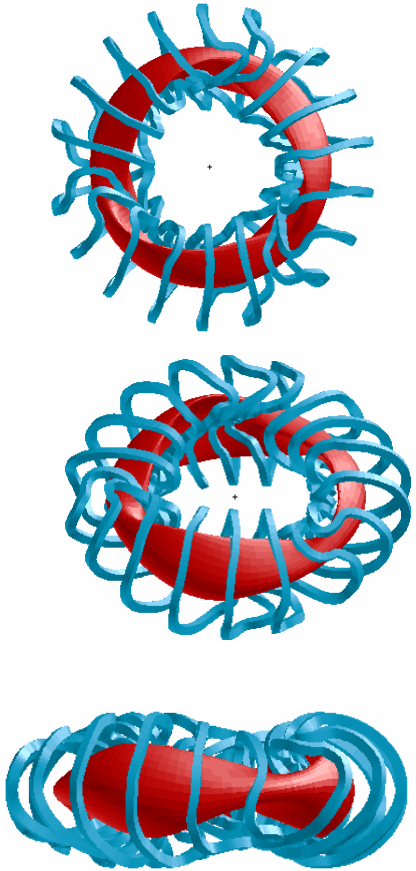
$$B = \sum B_{mn} \cos(m\theta - [n - \iota m]\varphi)$$

$$\text{noise} = \sqrt{\frac{\text{magnetic energy, nonsymmetric components}}{\text{magnetic energy, symmetric components}}}$$

A proposed design for the modular coils is to have 6 coils/period with coil aspect ratio R/Δ_{min}(C-P)~6. The example given here, KJC167-M05, based on equal coil currents, has smooth contours with small toroidal excursion.







Coil contours viewed on "U-V" plane of the winding surface in one field period.

Summary & Conclusions

- **We have**
  - **expanded the NCSX-class of configurations to include those with better alpha confinement and surface integrity.**
  - **identified and developed new classes of configurations with smaller aspect ratios, better QA and more robust surface quality.**
  - **shown a reasonably large separation between plasma and coils is achievable and coil ripples may be controlled with as small as 16 coils.**
- **Hopefully, we have demonstrated the richness of the QA magnetic topology and the flexibility in configuration optimization.**
- **The most attractive configuration will ultimately be determined by our understanding of the physics of QAS and the results of systems optimization and constraints arising from engineering designs.**

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