Physics Basis and Configuration Optimization for ARIES Compact Stellarator Power Plants

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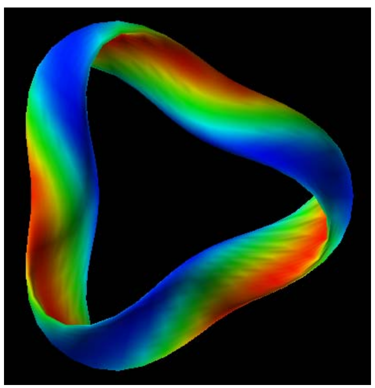
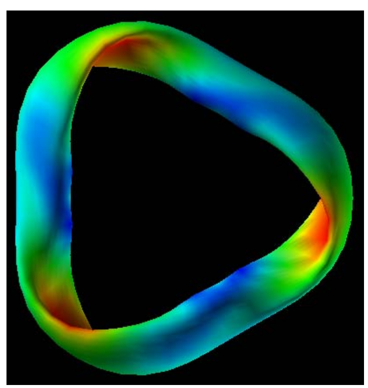
Topics of Discussion

- Physics Basis of QAS Reactors
- Configuration Optimization
  - Needs
  - Optimization systems
- Highlight of Results
  - Overview
  - Details of a specific example (appendix)
- Summary

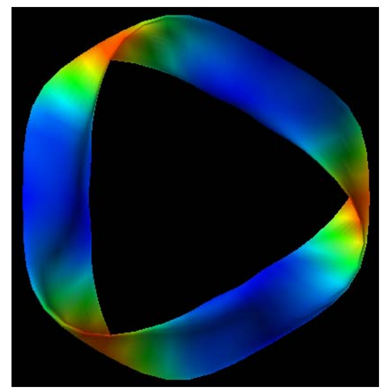
The invention of "Helias" (J. Nührenberg) and the development of drift orbit optimization techniques make stellarator an attractive magnetic confinement concept for fusion reactors.



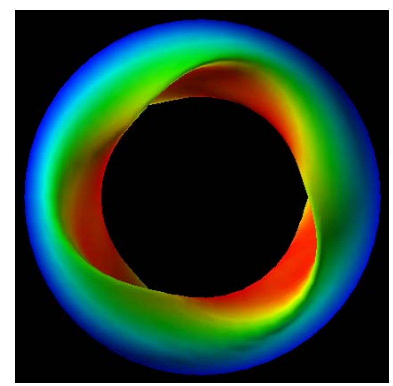
QHS



QOS



QPS



QAS

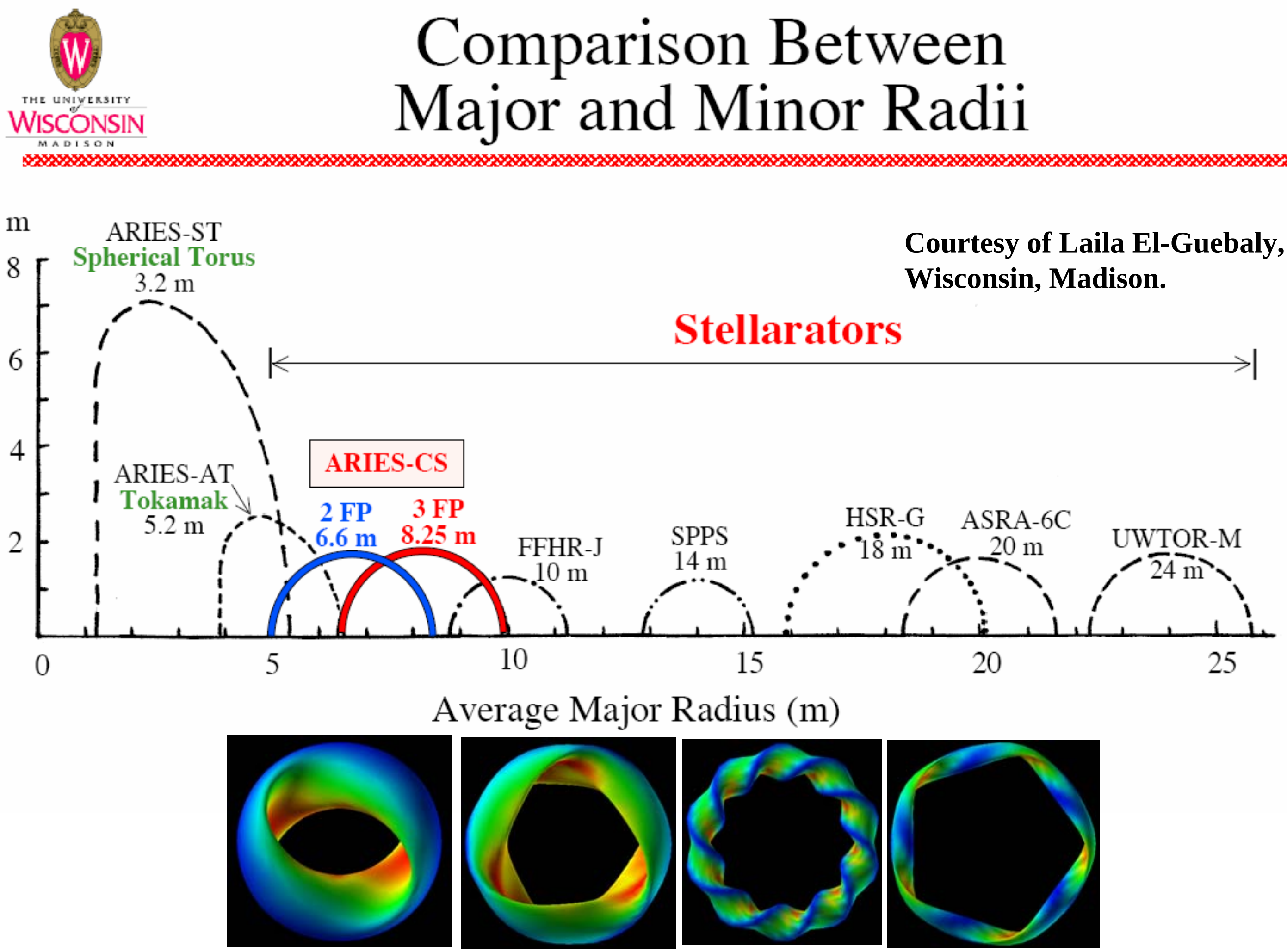
In particular, the discovery of **quasi-axisymmetric (QA)** stellarator configurations opens up the possibility of designing **compact** fusion reactors with **tokamak transport** and **stellarator stability.**

- In 3-D magnetic field topology, particle drift trajectories depend only on the strength of the magnetic field, not on the vector components of the field (or the shape of the magnetic flux surfaces).
  - **QA → tokamak-like field topology → good particle confinement.**
- Stellarators are resilient to plasma disruptions. The performance of existing devices has exceeded stability β limits predicted by linear, ideal MHD theories.

QAS reactors have the potential to deliver economically competitive cost of electricity.

- QA can be achieved at lower aspect ratios with smaller number of field periods.
  - more compact devices
  - bootstrap currents to supplement rotational transform
- Lower aspect ratios typically lead to smaller sized plants.
  - $P \propto \beta^2 B^4 R^3 / A^2$
  - Smaller plant size requires smaller coils aspect ratio, R/Δ_{min}(c-p), as well, however.

QAS power plants maybe designed with major radii less than 10 m (J. Lyon).



Courtesy of Laila El-Guebaly, University of Wisconsin, Madison.

Realizing the potential of QAS as the basis of a power producing reactor is the natural extension of the NCSX project now being actively pursued as part of the US fusion program.

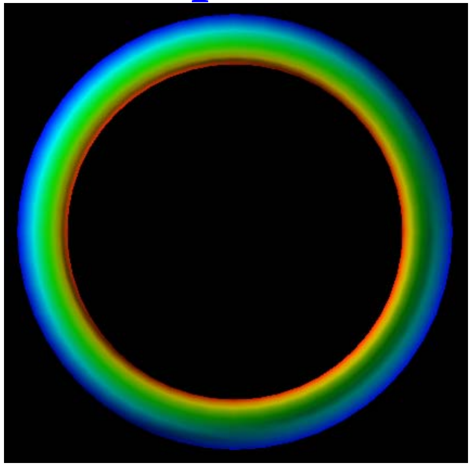
- NCSX is the first generation QAS that will establish the necessary data base to further the development of optimized stellarators.

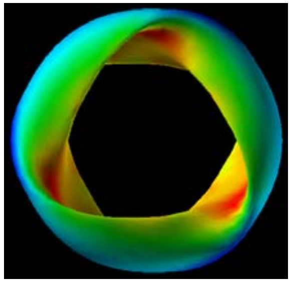
- NCSX is one of the first generation devices designed with modern sophisticated optimization tools that
  - balance the needs for good quasi-symmetry and an MHD stable plasma at high beta based on the present understanding of tokamak physics,
  - assure the complex coils meet the required precision and experimental flexibility.

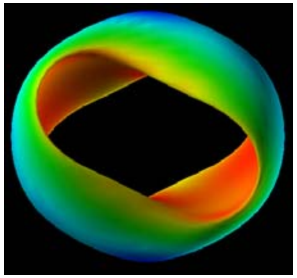
Configuration development and optimization constitute one of the major efforts in the ARIES-CS study in order to realize the reactor vision and to find innovative approaches.

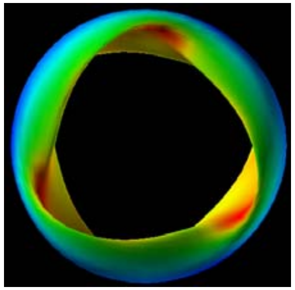
- Configuration space is vast and expansive, its landscape complex.
- Residues in magnetic spectrum cannot be eliminated simultaneously on all surfaces, but may be minimized together with the optimization of other desirable properties (e.g. MHD stability).
- Not all components in magnetic spectrum have equal effects; effective optimization depends on effective targeting.
- While NCSX is a “good” configuration, other equally good or better *reactor* configurations remain to be discovered and developed.

Tokamak-like magnetic field topology can be achieved approximately by a variety of three dimensional shaping of the plasma.









- Because we can only find approximate solutions, configurations are not unique.
- The normally over-determined system allows one to impose further constraints, such as MHD stability to the kink or ballooning modes, the shape and magnitude of rotational transform and so on, in the solution. Optimization of solution is sought once a set of constraints are defined.
- Because of the complexity of equilibrium, transport, and stability calculations and because of the large number of state and dependent variables involved, efficient optimization is possible only in recent years with the advance of computer and computation technology.

A comprehensive system has been developed to aid configuration search.

Plasma Optimization System

Initial “guess”. Plasma boundary represented as Fourier coefficients.

Constraints/weights

1) Select p, J profiles, β, B, FP
2) Iota target
3) MHD stability target (Mercier, ballooning, kink)
4) Transport target (QA, ripple)
5) Coil target (complexity, current density)

ballooning

kink

α loss

transport

shape/position

coil complexity

1) Evaluate equilibrium (VMEC, NSTAB), 2) Jacobian calculations, 3) determine direction of descent, 4) perform functional minimization (Levenberg-Marquardt, GA).

Targets met?

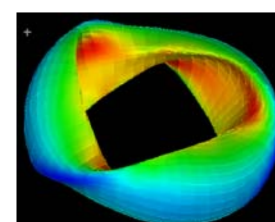
No

Modify weights

Yes

Flux surface quality, islands healing, PIES

Refined calculation and detailed analysis



Minimum requirements in configuration optimization for MHD stable QA plasmas at high β are not well known at present. The following are "acceptance criteria" generally considered§.

- Maximum residues of non-axisymmetry in magnetic spectrum.
  - neo-classical transport << anomalous transport
    - **ovall allowable "noise" content < ~2%.**
    - **effective ripple in 1/ν transport, ε-eff < ~1%**
  - ripple transport and energetic particle loss
    - **α energy loss < ~10%**
  - rotational damping (?)

- Stability beta limits based on linear, ideal MHD theories.
  - vertical modes

$$\iota_{\mathrm{ext}} / \iota \geq \frac{\kappa^2 - \kappa}{\kappa^2 + 1}$$

  - interchange stability
    - **V″~2-4%.**
    - ➢ **LHD, CHS stable while having a hill.**

- ballooning modes
  - **stable to infinite-n modes (eigenvalues calculated by COBRA code).**
  - ➢ **LHD exceeds infinite-n results. High-n calculation typically gives higher β limits.**
- kink modes
  - **stable to n=1 and 2 modes without a conducting wall (eigenvalues calculated by Terpsichore code).**
  - ➢ **W7AS results showed mode (2,1) saturation and plasma remained quiescent.**
- tearing modes
  - **$d\iota/ds > 0$**

- Equilibrium and equilibrium beta limits
  - Shafranov shift

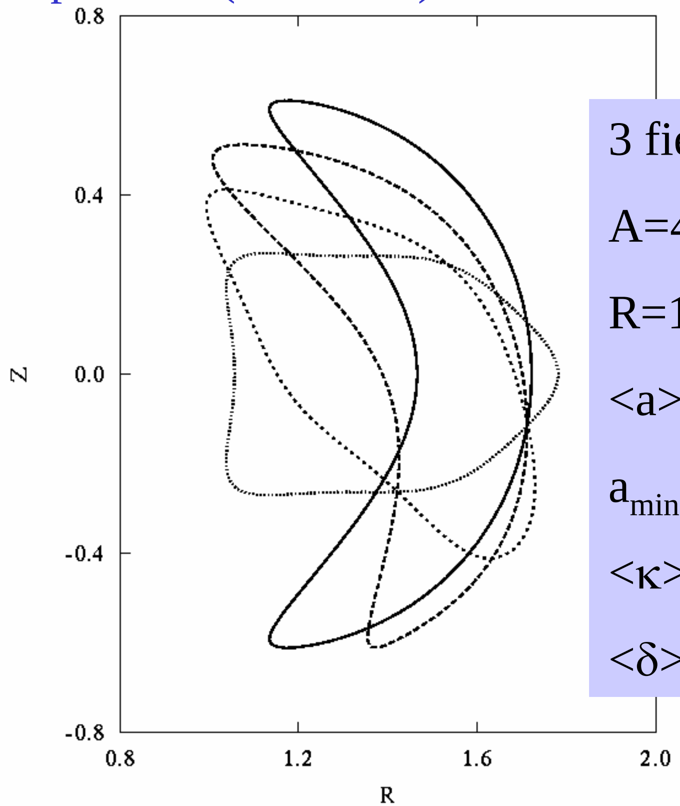
$$\frac{\Delta}{<a>} \approx \frac{<\beta>\cdot A}{2\kappa\iota^2} < 1/2$$

  - large islands associated with low order rational surfaces
    - **flux loss due to all isolated islands < 5%**
  - overlapping of islands due to high shears associated with the bootstrap current
    - **limit $d\iota/ds$**

§The ability to achieve our goals is often compromised by the conflicting demands of various constraints. Typically, we impose different weights depending upon the characteristics of a configuration we are looking for. There is also an issue of convergence and accuracy in numerical calculations.

Physics optimization targets for NCSX class of configurations

The last closed flux surface is optimized to provide fundamental properties of the device: MHD stable at 4% β (no conducting walls), ι(ext)/ι(total)~70%, dι/ds>0 through most of the plasma radius, low residual non-axisymmetric components in magnetic spectrum (ε-eff≤1%) at A~4.5.



3 field periods

A=4.37

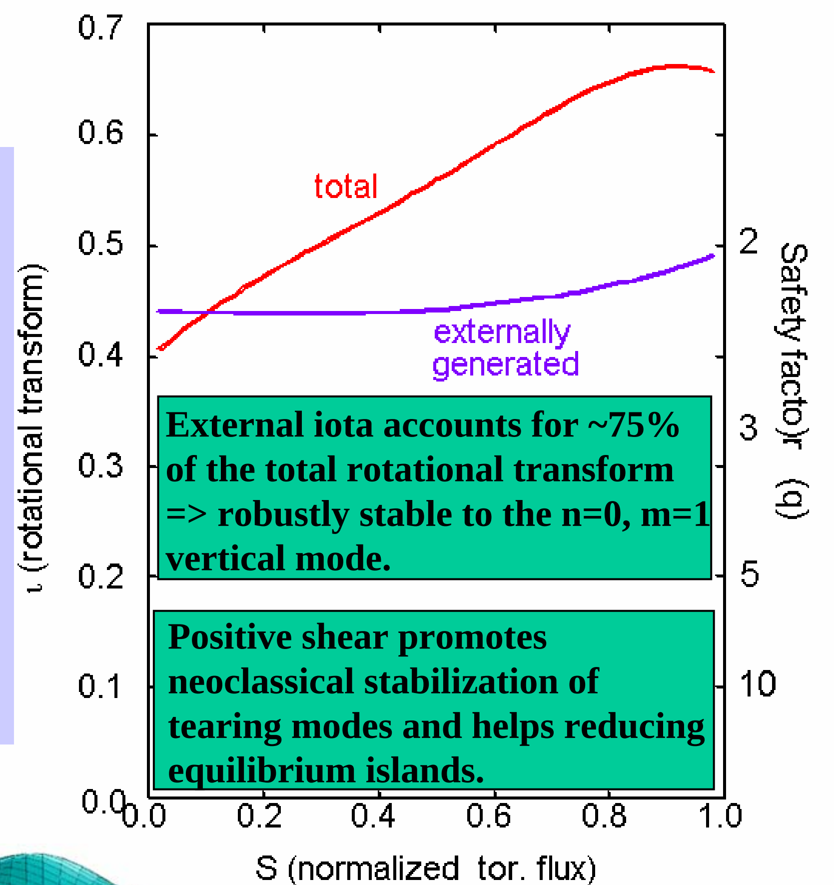
R=1.42 m

<a>=0.33 m

a_{min}=0.26 m

<κ>=1.72

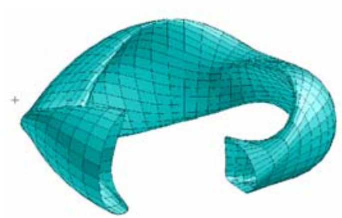
<δ>=0.7



External iota accounts for ~75% of the total rotational transform => robustly stable to the n=0, m=1 vertical mode.

Positive shear promotes neoclassical stabilization of tearing modes and helps reducing equilibrium islands.

$\propto r^2/a^2$

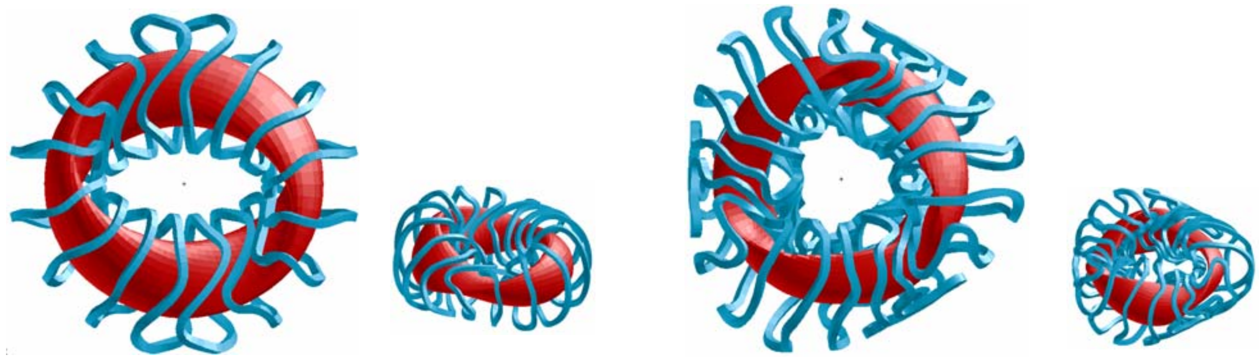


More recent QAS reactor configurations are developed with reduced weights on targets of the calculated linear MHD stability, putting more emphasis on the quasi-axisymmetry and flux surface integrity.

- aspect ratio < 6,
- effective ripple < 1%,
- energy loss of α-particles < 10% (V=1000 m^3, B=6 T)
- rotational transform profile constrained for surface quality,
- magnetic well > 1% @ s=1

- acceptance criteria for MHD stability to infinite-n ballooning and external kinks relaxed – do as much as we can.

Coil design is an integral part of configuration development. Multi-dimensional optimization is again necessary to find coils of low complexity and with good engineering properties that produce the desirable plasma.

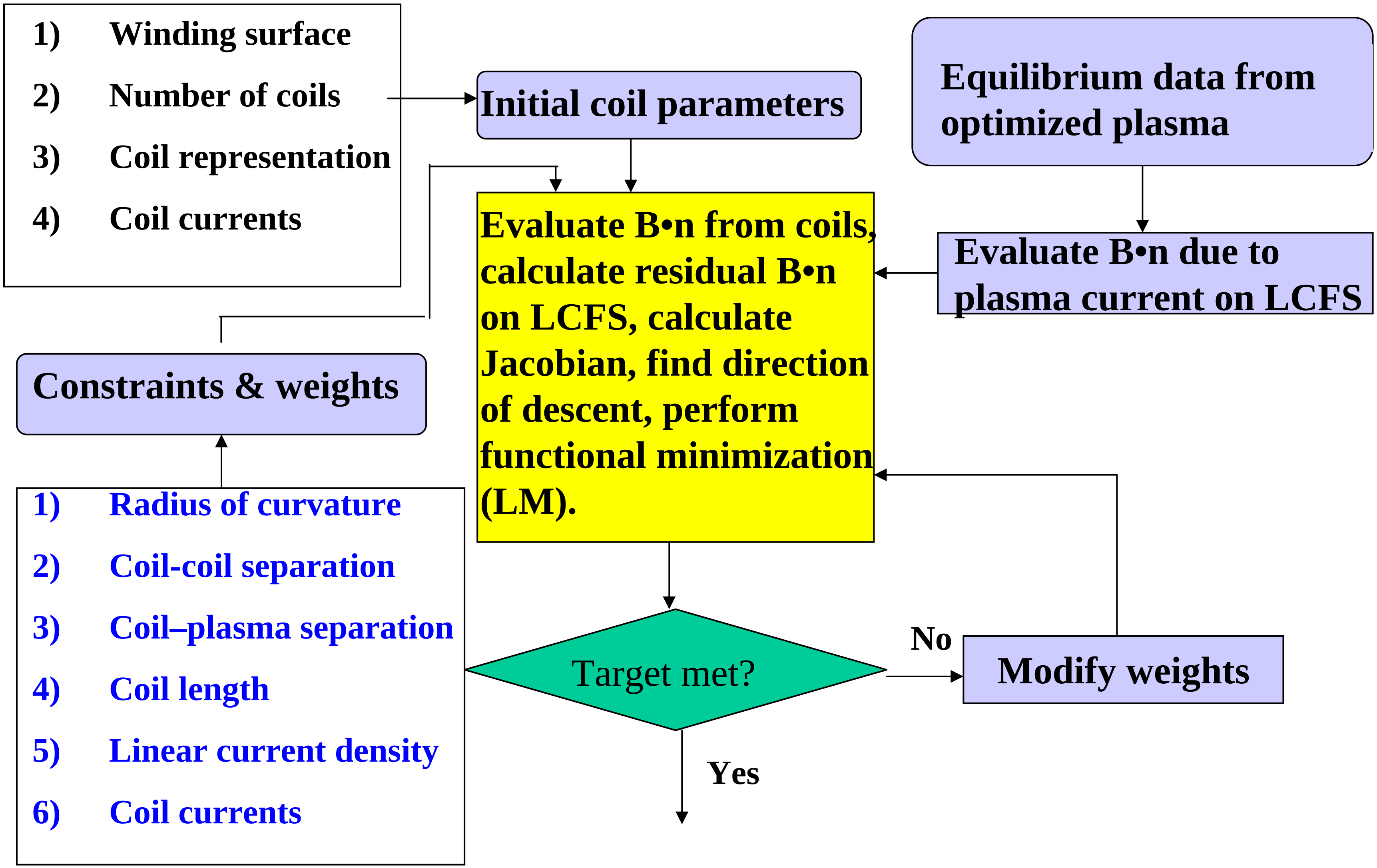


- For coil design, we want, on the last closed magnetic surface,

  B_{norm} (coil) = $-B_{norm}$ (plasma pressure)

  - For discrete coils, we stipulate that, on a computational grid:
    - **Average $|\{B_{norm}$ (coil)+ B_{norm} (plasma pressure)$\}/ B_{norm}$ (plasma pressure)$| < 0.5\%$**
    - **Maximum $|\{B_{norm}$ (coil)+ B_{norm} (plasma pressure)$\}/ B_{norm}$ (plasma pressure)$| < 2.0\%$**
- Direct optimization of plasma properties instead of normal field on LCMS is more complex but offers the opportunity to find improved configurations in the general neighborhood.
- Again, optimization process is invoked since there may involve a large number of independent variables (> 100) as well as constraints.

Coil Design and Optimization System (1)



Coil Design and Optimization System (2)

Evaluate "free boundary" equilibrium, MHD stability and transport

1) Winding surface represented as Fourier harmonics
2) # of coils
3) Coil on winding surface represented as Fourier harmonics
4) Coil currents

Initial condition, coil parameters as independent variables

Constraints/weights

1) Evaluate equilibrium (VMEC), 2) calculate Jacobian, 3) determine direction of descent, 4) perform functional minimization (LM).

eff. ripple

kink

ballooning

dist. to 1st wall

Targets met?

No

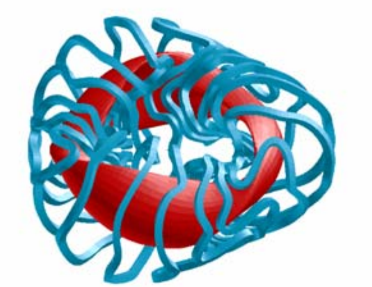
Modify weights

Yes

Islands healing, PIES

Discharge & flexibility (operating space) optimization

1) Iota target
2) MHD stability target (Mercier, ballooning, kink)
3) Transport target (QA)
4) Coil target (κ, Δ's)
5) First wall target



Engineering targets for configurations are well defined, but how to most effectively incorporate them into initial configuration optimization is not clear.

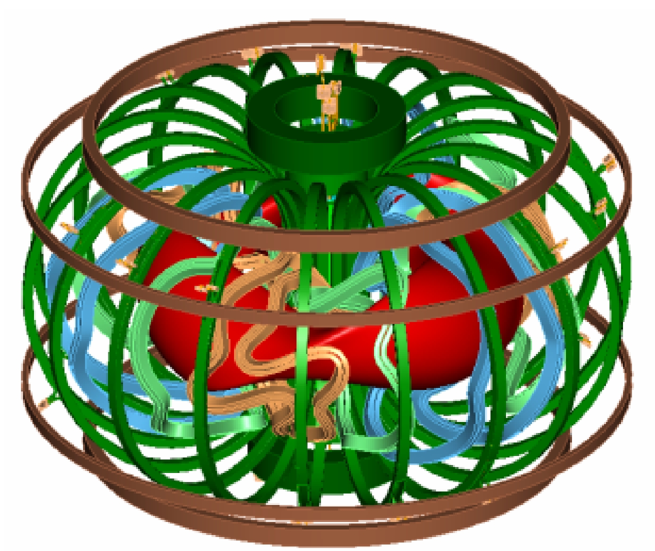
- Coil design
  - recover all desired plasma properties,
  - low complexity and low current density,
  - large coil to coil and coil to plasma separation,
  - low local curvature radius,
  - adequate space for pumping, diagnostics, plasma heating and maintenance.

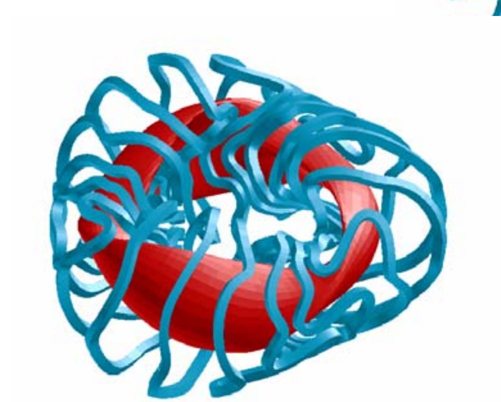
- Magnetic topology of the edge plasma amenable to effective particle and energy exhaust control.

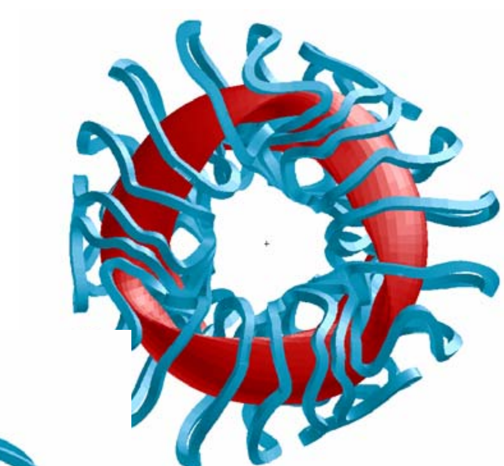
Coil targets optimization in NCSX class of configurations.

Modular Coils are optimized to provide:

1) **good MHD stability and particle transport at the reference state,**
2) **coil build-ability,**
3) **room for first wall, vacuum vessel, and other internal components,**
4) **good flux surface quality (island size <10% plasma volume),**
5) **wide accessible operating region.**





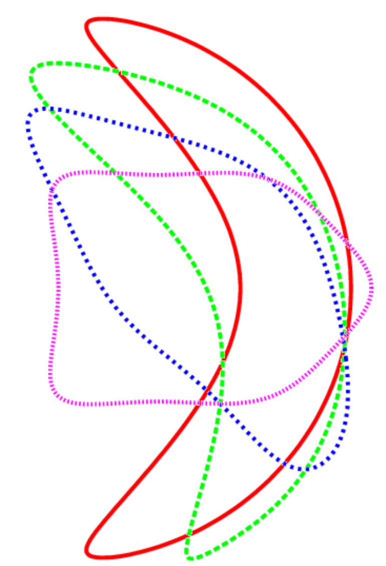


Except for the scale-ups of NCSX, only cursory designs for coils have been carried out so far. Considerable amount of work remains.

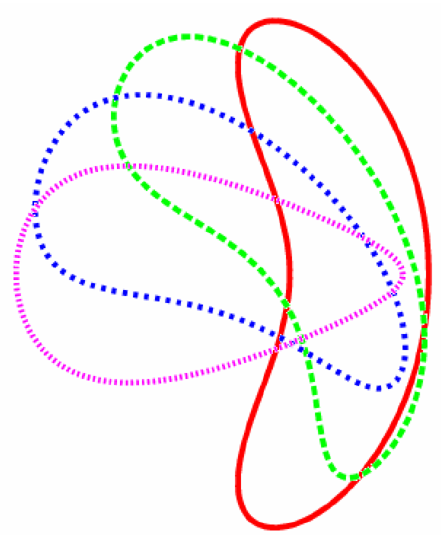
- Only modular coils considered.
- Use only the “NESCOIL” approach (solving for potential on current carrying surface) with the reduced number of modes.
  - to get a “good enough” design as the potential starting point for future optimization
  - to provide sufficient detail to understand the complexity and potential issues (effects of coil aspect ratio, discrete effects, number of coils, etc.)
- Only require good recovery of LCMS and iota profile.

Review of QAS configurations developed in the ARIES project in the past two years.

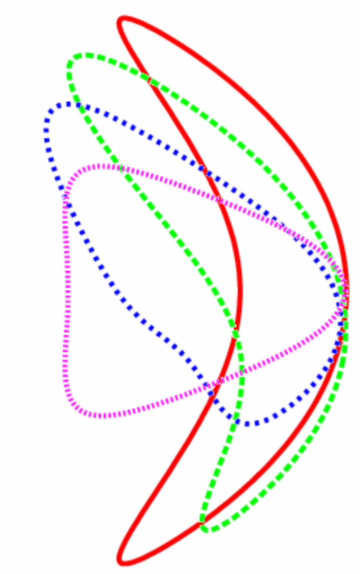
Three lines of development:



NCSX scale-up and upgrade



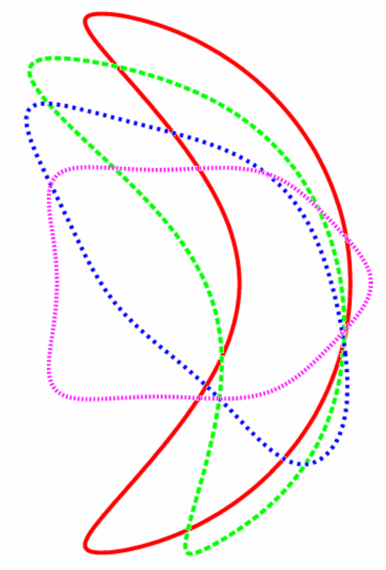
MHH2 with low aspect ratio and simpler shapes

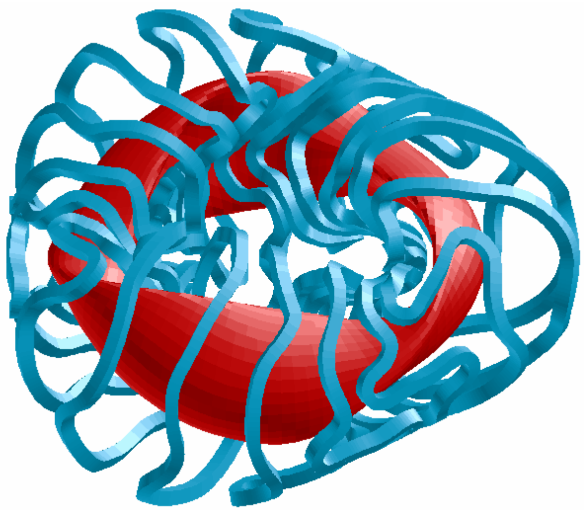


New approaches with emphasis on equilibrium surface quality.

NCSX-Class of Configurations

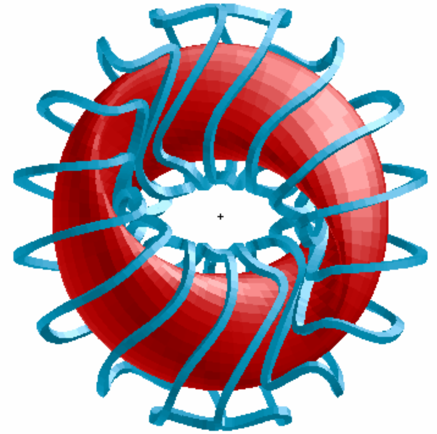
- Maintain basic characteristics of the NCSX M50 plasma and coils.
- Good balance between QA and MHD stability acceptance criteria. α loss < 15% attainable.
- Shown numerically to have high stability β limits.
- Coil designs with aspect ratios as low as 6 feasible to recover all desirable plasma properties.
- Coil “healing” demonstrated.

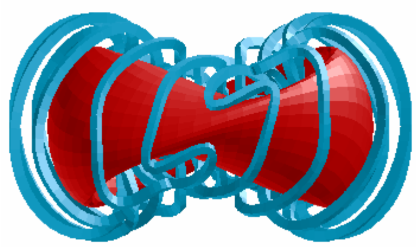




MHH2 (due to P. Garabedian)

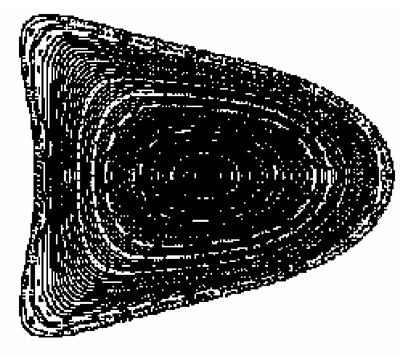
- **Simple shape and "clean" coils embody the vision of reactor attractiveness.**
- **Small plasma aspect ratios (A<3.5) in 2 field periods provide configuration compactness.**
  - **configuration space having ultra low aspect ratio (A~2.5) with good QA, low effective ripple (<<1%), and low α loss recently found.**
  - **configurations of various ι profile possible for the ultra low-A case, indicative of its flexibility in design space.**
- **Reactor compactness can only be realized if coils also have low aspect ratios. Coils are current being designed and optimized.**
- **MHD and equilibrium β limits are being studied.**



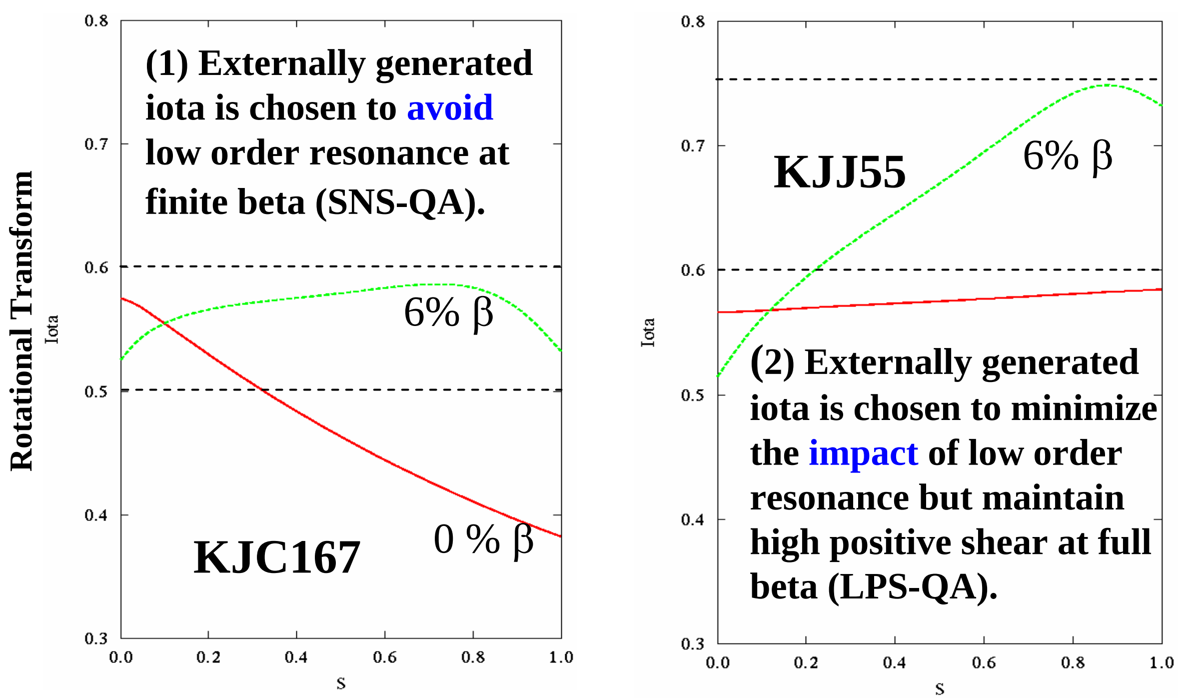


New Approaches : SNS-QA and LPS-QA configurations

- **Improve equilibrium β limit and flux surface quality by judiciously choosing the magnitude and shape of the external rotational transform.**
- **Low effective ripples (<<1%), good quasi-symmetry and low α losses (<<10%).**
- **Two lines of development pursued:**

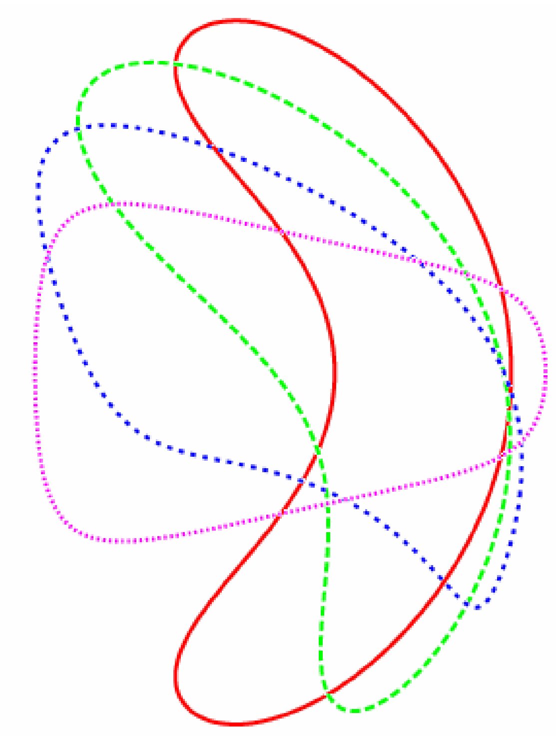


Note: for three periods SNS-QA "good" configuration found so far only for A>5.

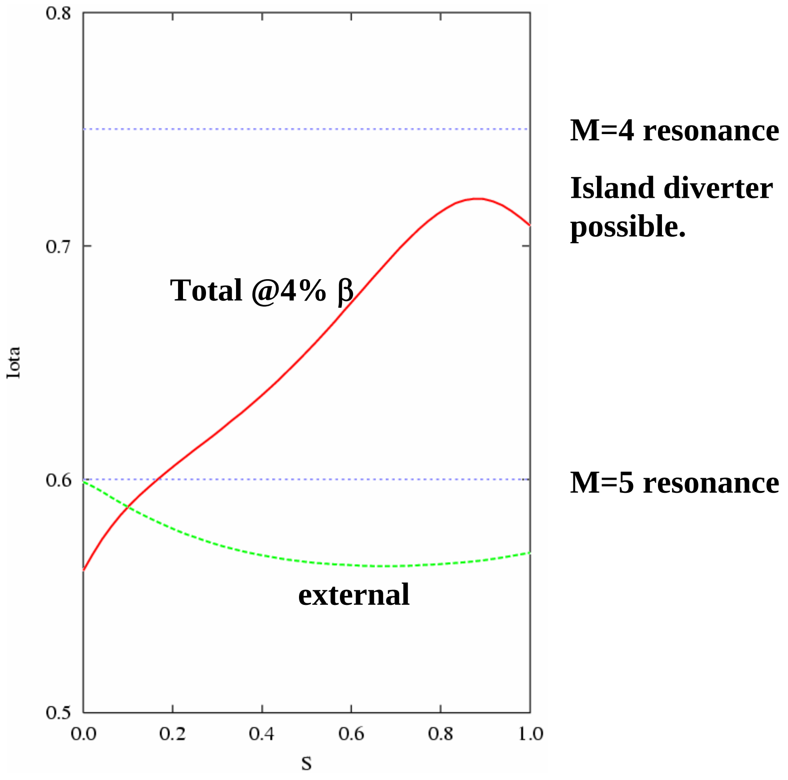


Normalized Toroidal Flux Label

Appendix: Details of KQ26 – A new 3 field-period, aspect ratio 4.5 configuration in the family of LPS-QA illustrated here as an example of design optimization.

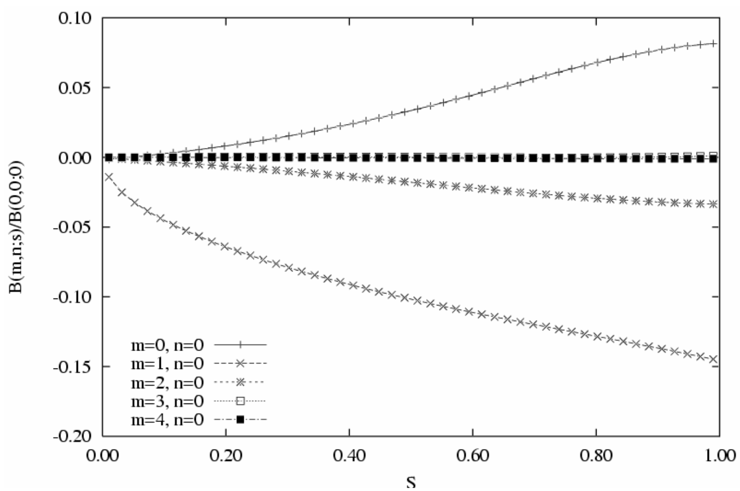


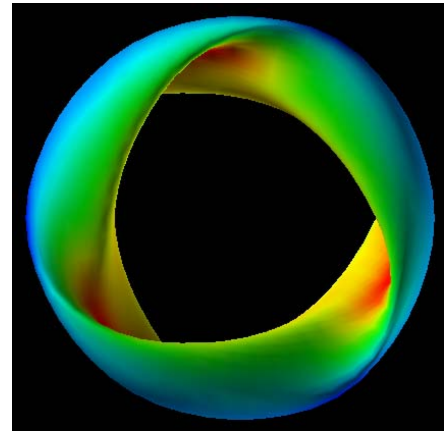
LCMS in four toroidal angles over half period.

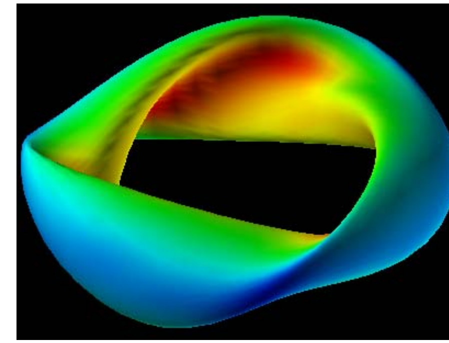


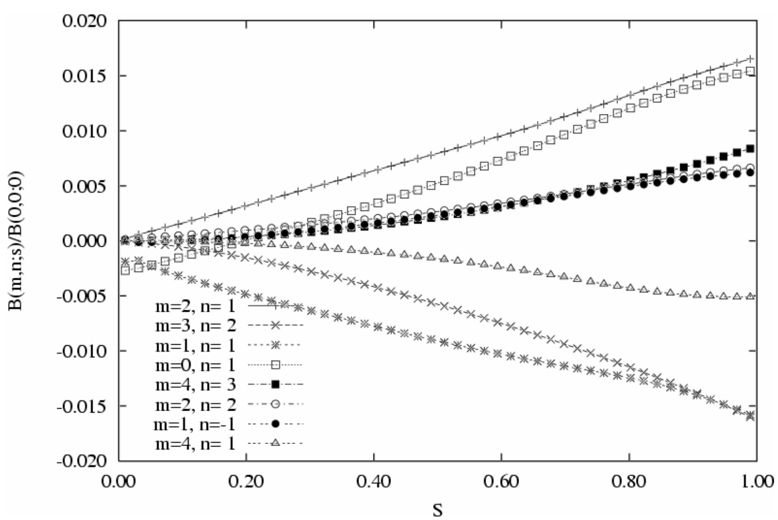
Rotational transform as function of toroidal flux.

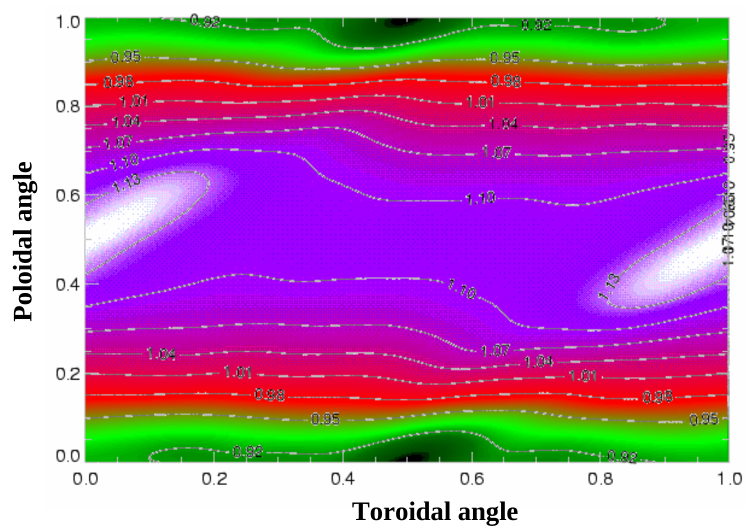
Minimizing non-axisymmetric residues and effective ripples resulted in good quasi-axisymmetry.



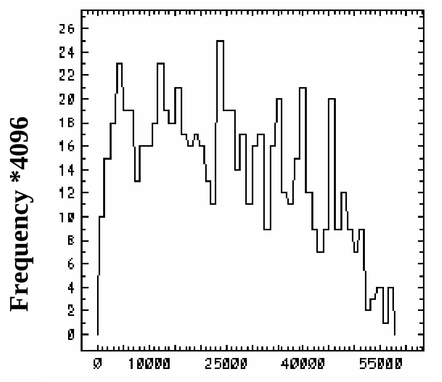






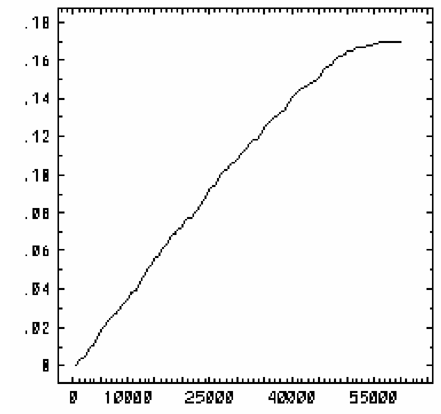


Loss of α energy is ~7% in one slowing down time in our model calculation.



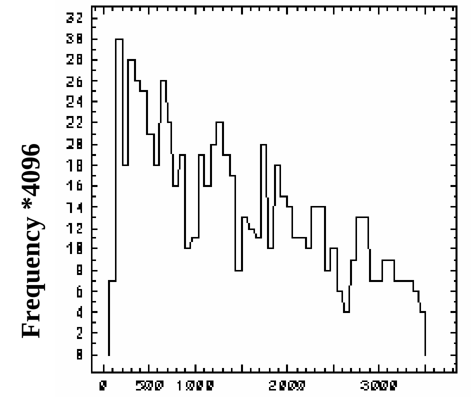
Transit time (in units of 5.27 μs)

Particle loss as function of time.



Transit time (in units of 5.27 μs)

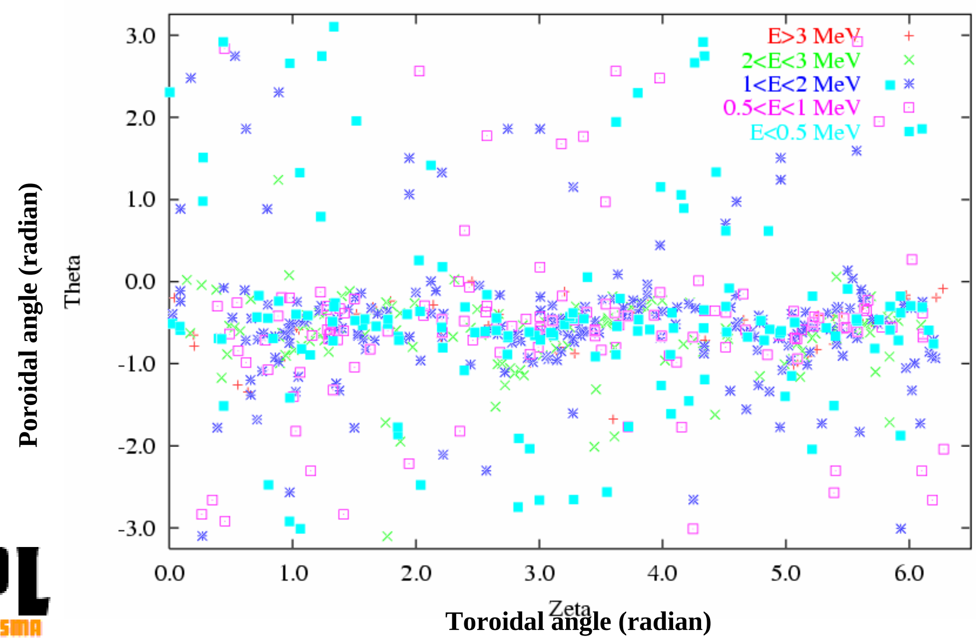
Cumulative particle loss.



Energy (keV)

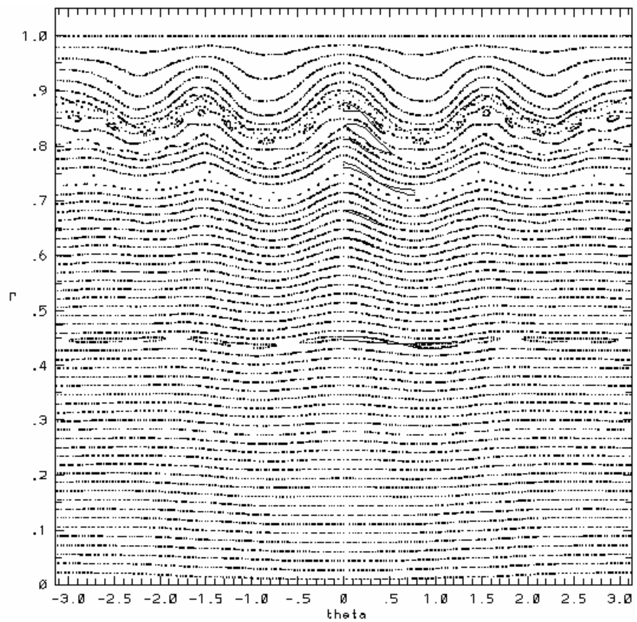
Energy loss distribution

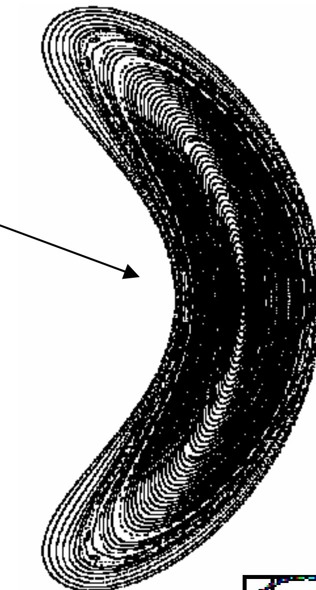
Scatter diagram showing distribution of lost particles in energy, toroidal and poloidal angular space on LCMS.

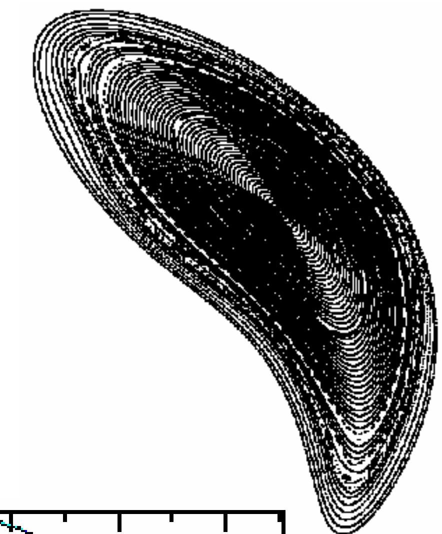


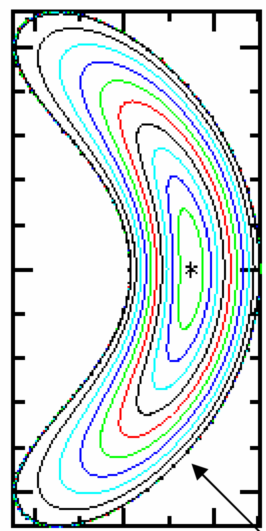
KQ26 has good equilibrium flux surface quality.

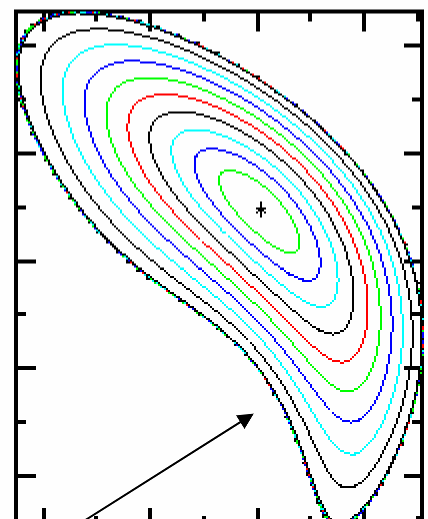
Equilibrium calculated by PIES
@4% β





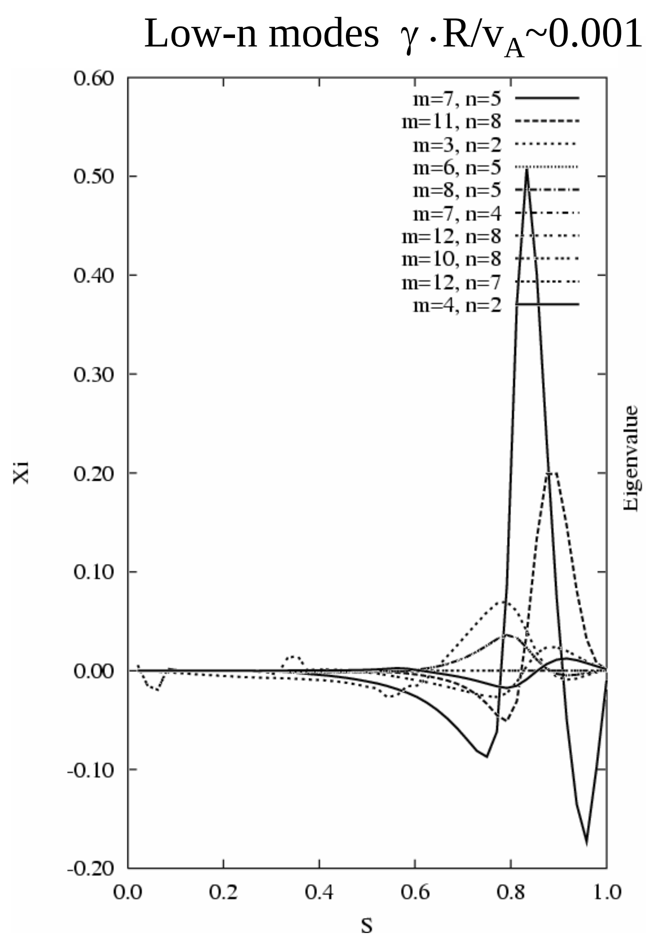


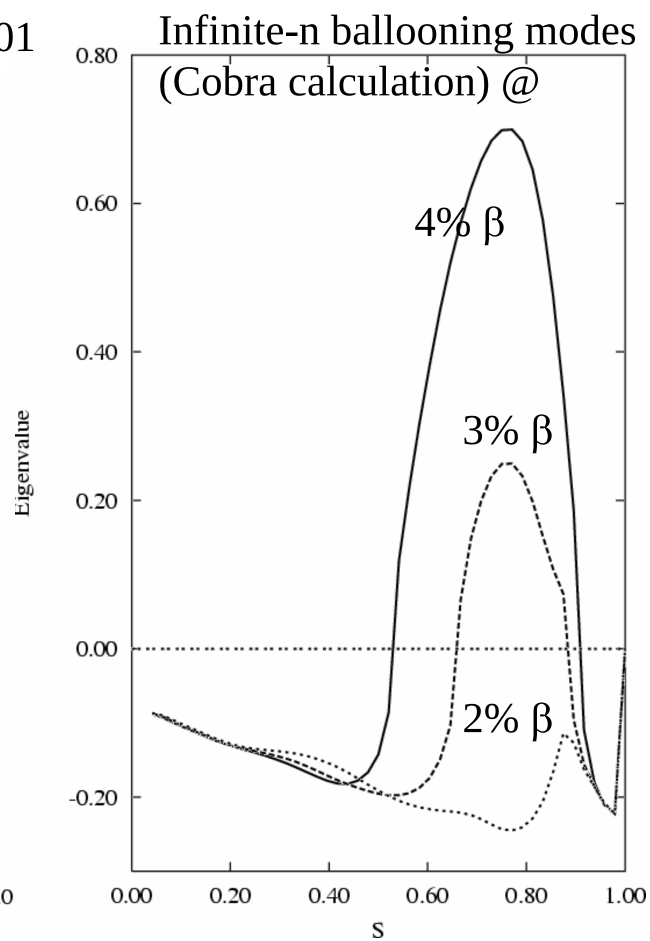


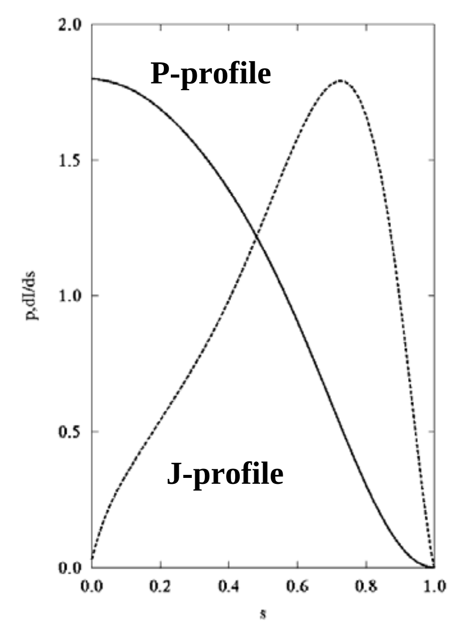


Equilibrium calculated by VMEC

KQ26 is stable to the m=1, n=0 vertical mode according to the Terpsichore calculation (no feedback control necessary) and is slightly unstable to both low and high-n internal modes at β=4%.

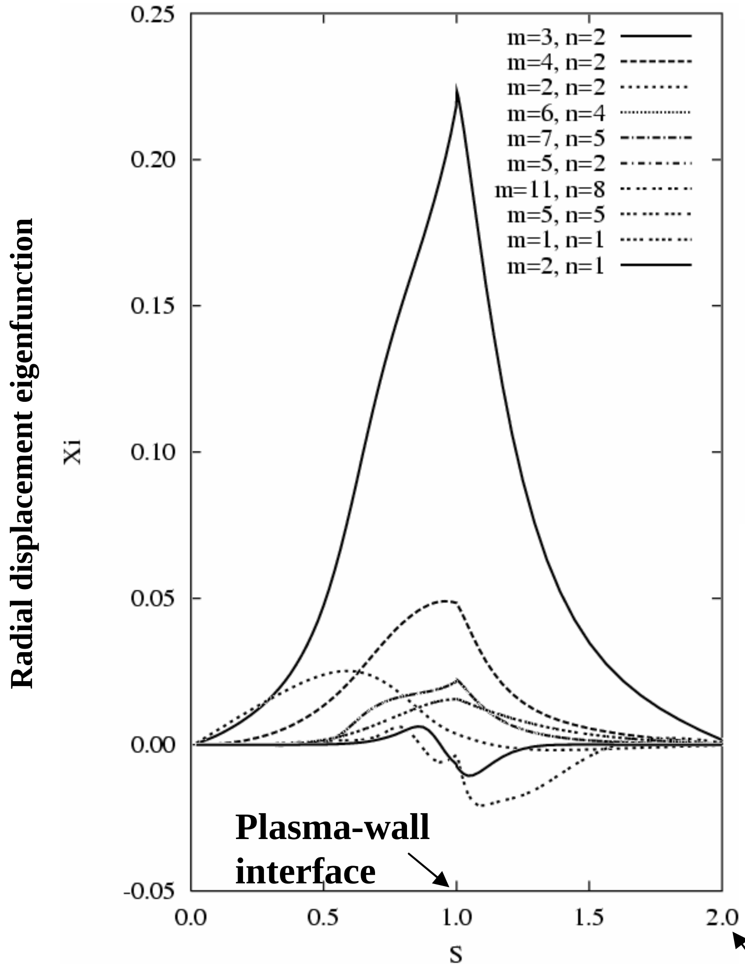


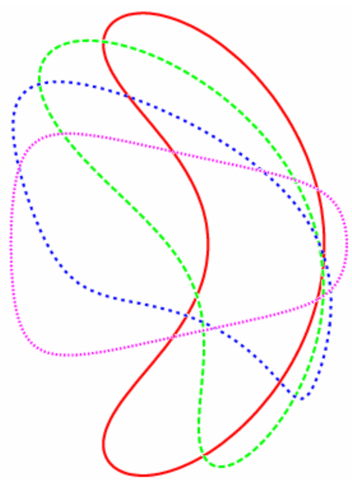




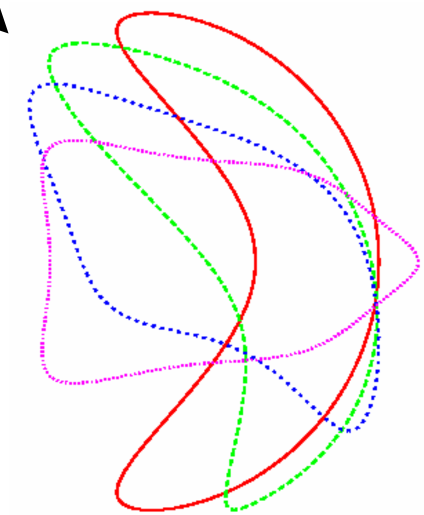
KQ26 may be unstable to free-boundary modes for β>4% according to the Terpsichore calculation primarily due to current driven forces at the m=3, n=2 resonance, but it could be made stable with more flux surface shaping to improve the local shear.

$\gamma \bullet R/v_A \sim 0.036$



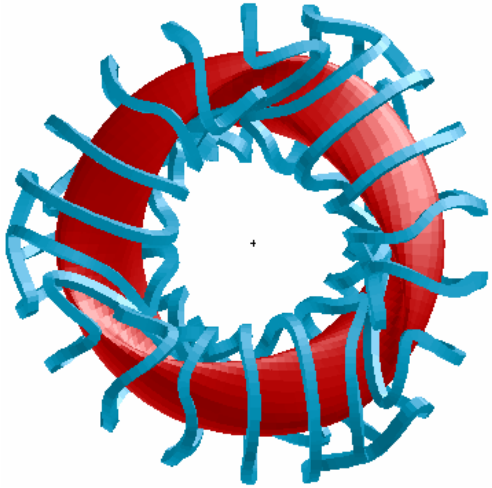


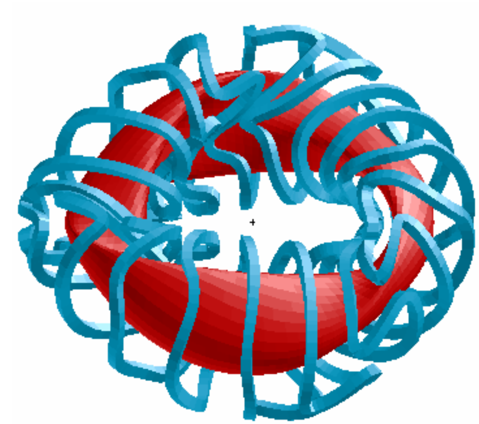
These modes may be stabilized by further shaping.

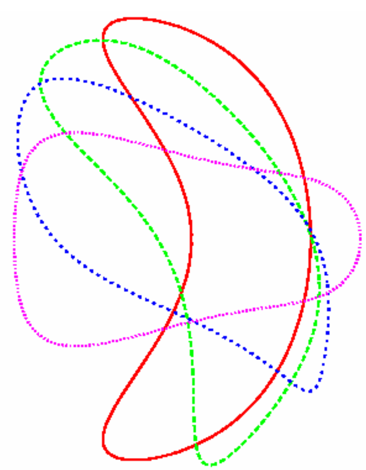


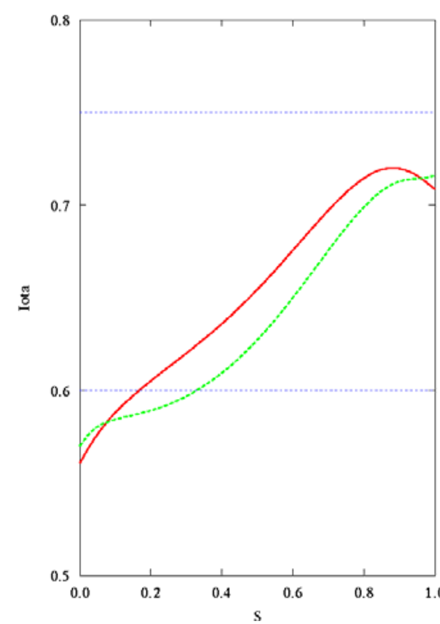
Wall @3.5x plasma-vacuum interface

An initial coil design with coil aspect ratio 6.6 showed a reasonable recovery of LCMS and iota profile, but coils are quite complex and the coil-to-coil spacing too small. Further optimization is necessary.









Summary

- We have revised and upgraded NCSX-type of configurations and developed new classes of QAS during the course of the ARIES studies.
  - Configurations with excellent QA have been found with A≤6. Configurations with both 2 and 3 field periods possible.
  - Progress has been made to reduce loss of α particles and to improve magnetic flux surface integrity. Losses ~10% have been achieved (This may still be high, however). Novel configurations were also discovered with excellent flux surface quality attainable.
- Modular coils have been designed to examine the geometric complexity and the constraints due to the maximum allowable fields, desirable coil-plasma spacing and coil-coil spacing, and other coil parameters.
  - Adequate space in general exists to accommodate blanket/shield (low coil aspect ratio), consistent with the low plasma aspect ratio feature of QAS.
  - The general characteristic of B_{max}/B_0 indicates that field on axis ~7 T may be possible in view of recent Nb_3Sn development.
  - There is a strong incentive to simplify coils for the purpose of remote maintenance without compromising the fundamental requirement of yielding plasmas with all the essential quality.

→ Considerable amount of coil design and optimization work remains to be done.