Progress in Configuration Development for Compact Stellarator Reactors

Long-Poe Ku
Princeton Plasma Physics Laboratory

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In March meeting, we introduced a new class of QA configurations featuring:

- strong negative magnetic shear provided by the shaping coils and tailored to match the 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%) in the magnetic spectrum 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 (4% -9%),

- toroidally averaged elongation (>1.8) and triangularity (> 0.7) matching those in advanced, high beta tokamaks and other classes of QA stellarators with good MHD stability properties.

We report today results of further studies of this class of configurations (SNS-QA):

- Additional optimization of α confinement.
  - Configurations with α loss fraction <5% found.

- Modification of rotational transform near boundary for N=2 resonance avoidance.
  - Configurations with robust flux surfaces at 6% β obtained for the three-field period, intermediate and high iota cases.

- Preliminary studies of coil topology.
  - General modular coil characteristics identified,
  - Effects of coil numbers and coil-plasma separation investigated,
  - "Re-constructability" with VMEC in vacuum studied.

Configurations with α loss fraction <5% are found.

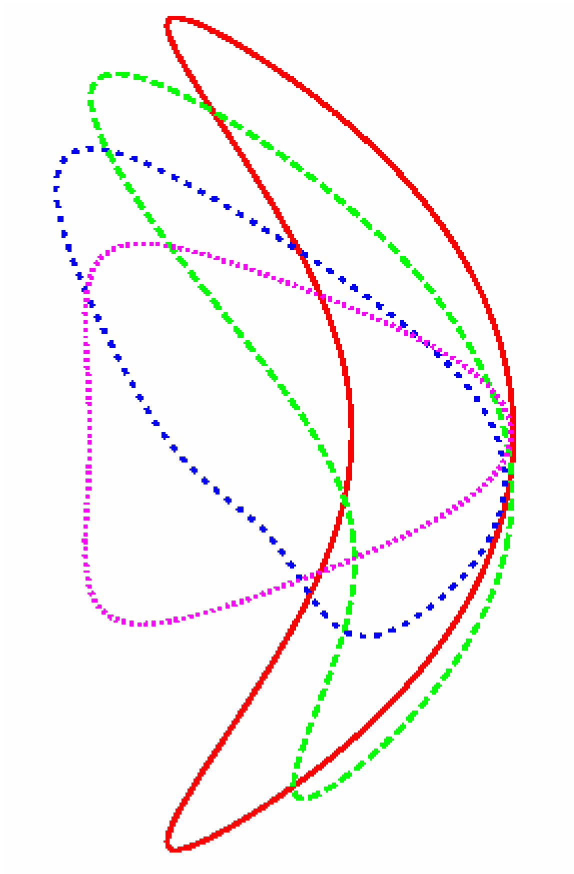
- Configurations reported in March were developed for the vacuum condition.
  - There was no further optimization or improvement at finite β.
  - α losses were calculated at 6% β using assumed pressure and bootstrap current profiles.

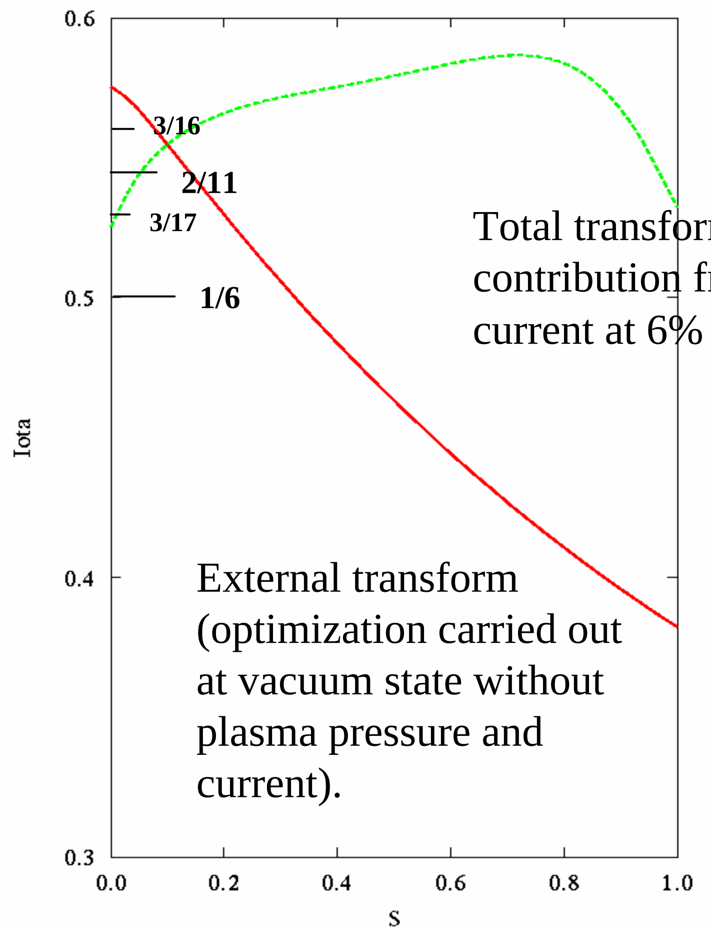
- Better QA and energetic particle loss characteristic may be obtained by further optimization at finite β and current.
  - Pressure driven current will modify QA.
  - Controlling the total rotational transform at finite β gives the external transform more flexibility to shape the plasma.
  - Pressure and current profiles can also be optimized.

- Two case studies were made:
  - KJC167 -- A=6, ι~0.55 at 6% beta, α loss fraction reduced from 6.9% to 4.0% for B=6.5 T, volume=1000 m^3.
  - KKD863-- A=6, ι~0.71 at 6% beta, α loss fraction reduced from 5.3% to 4.8%.

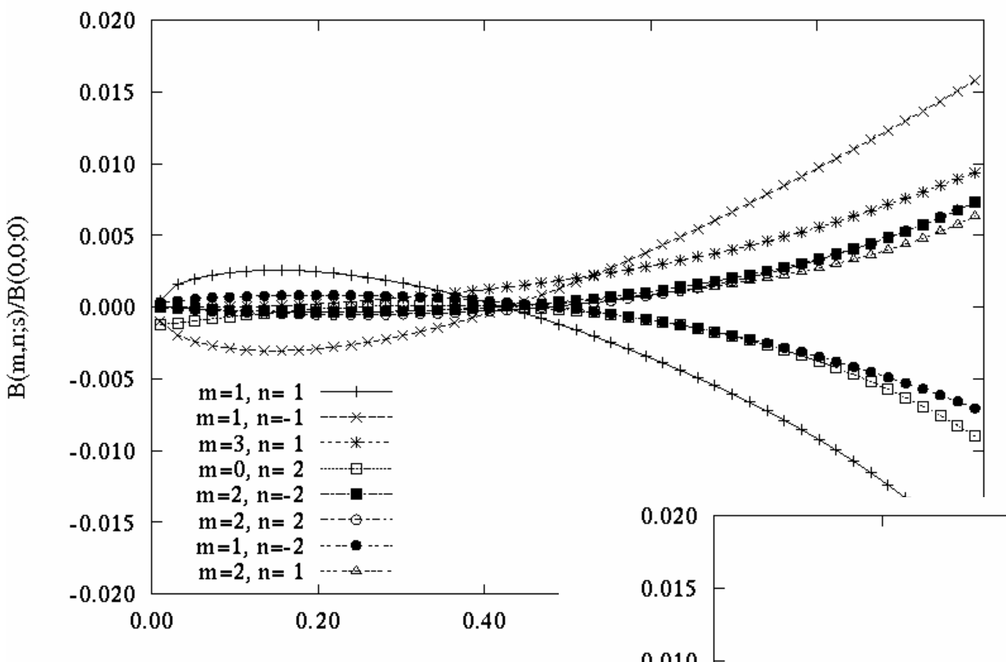
Using KJC167 as an example:
Boundary shape and iota profiles shown in March meeting.

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





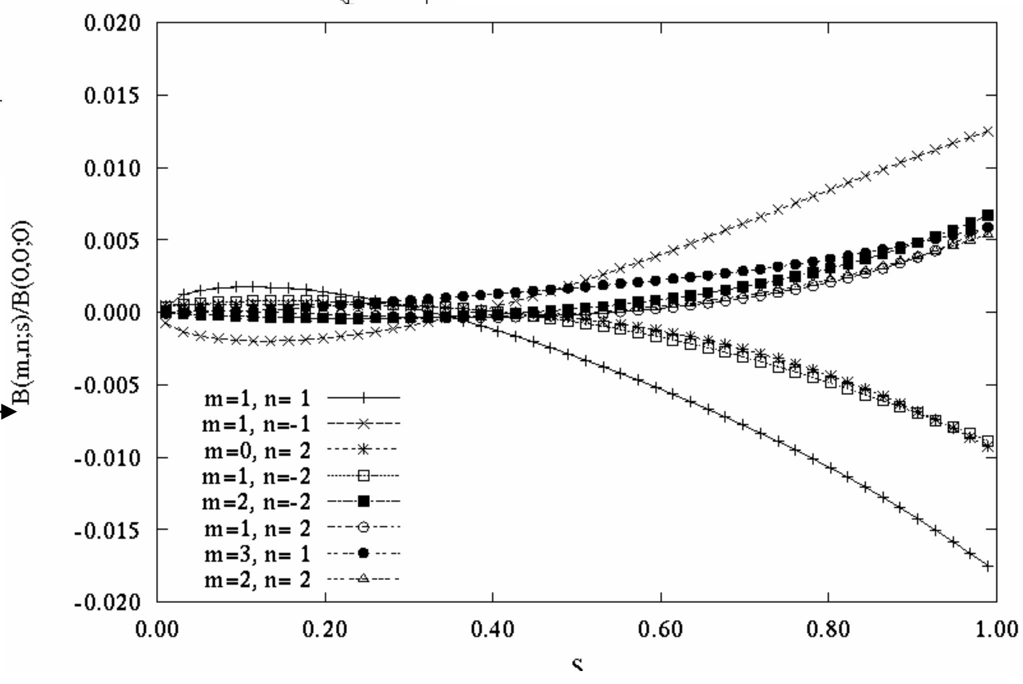
Further optimization at 6% β reduces residues in the magnetic spectrum, particularly in the core. QA is correspondingly improved.



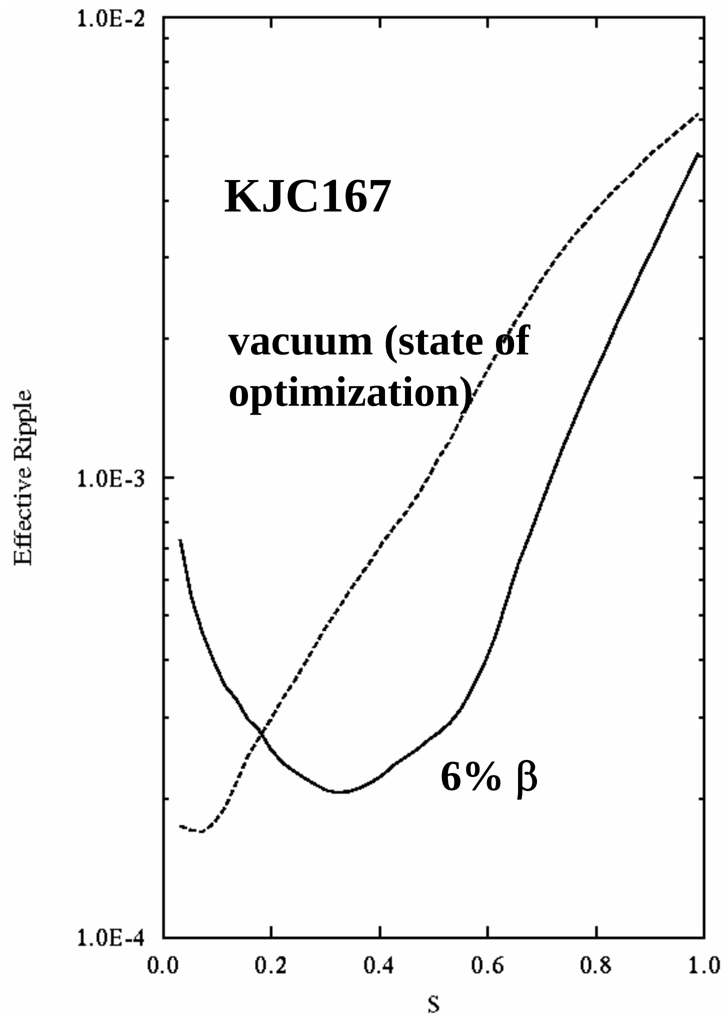
Largest non-axisymmetric components in magnetic spectrum (6% β).

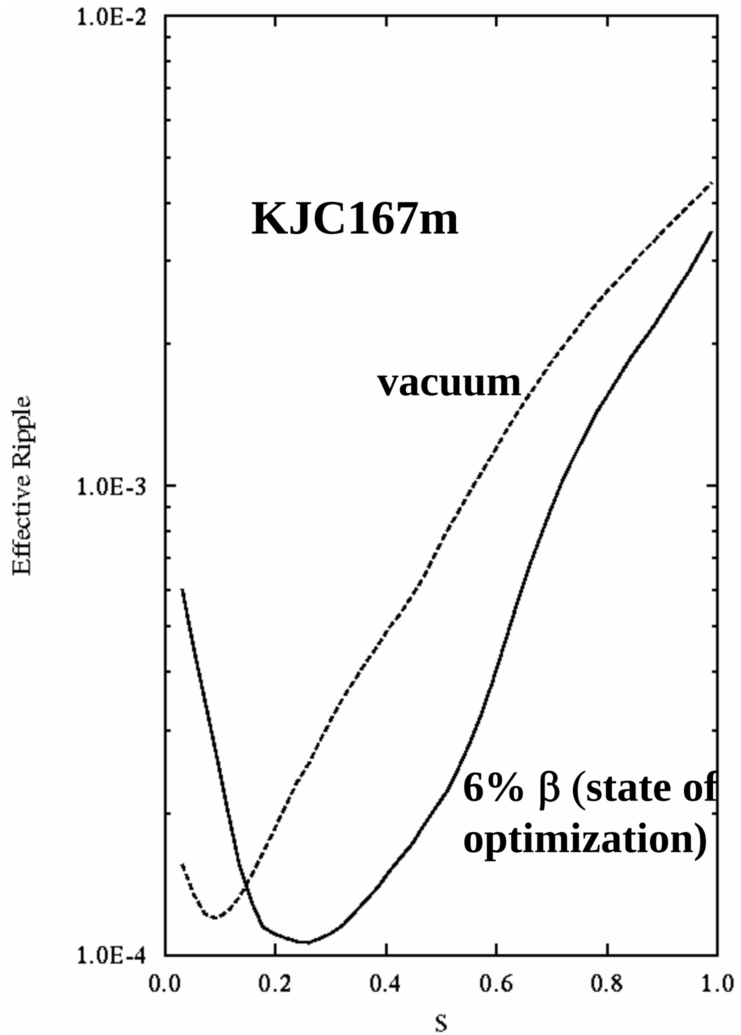
KJC167 (shown in March)

KJC167m (further improved)



Further optimization leads to marked improvement in the effective ripple (1/ν transport) in the core region.



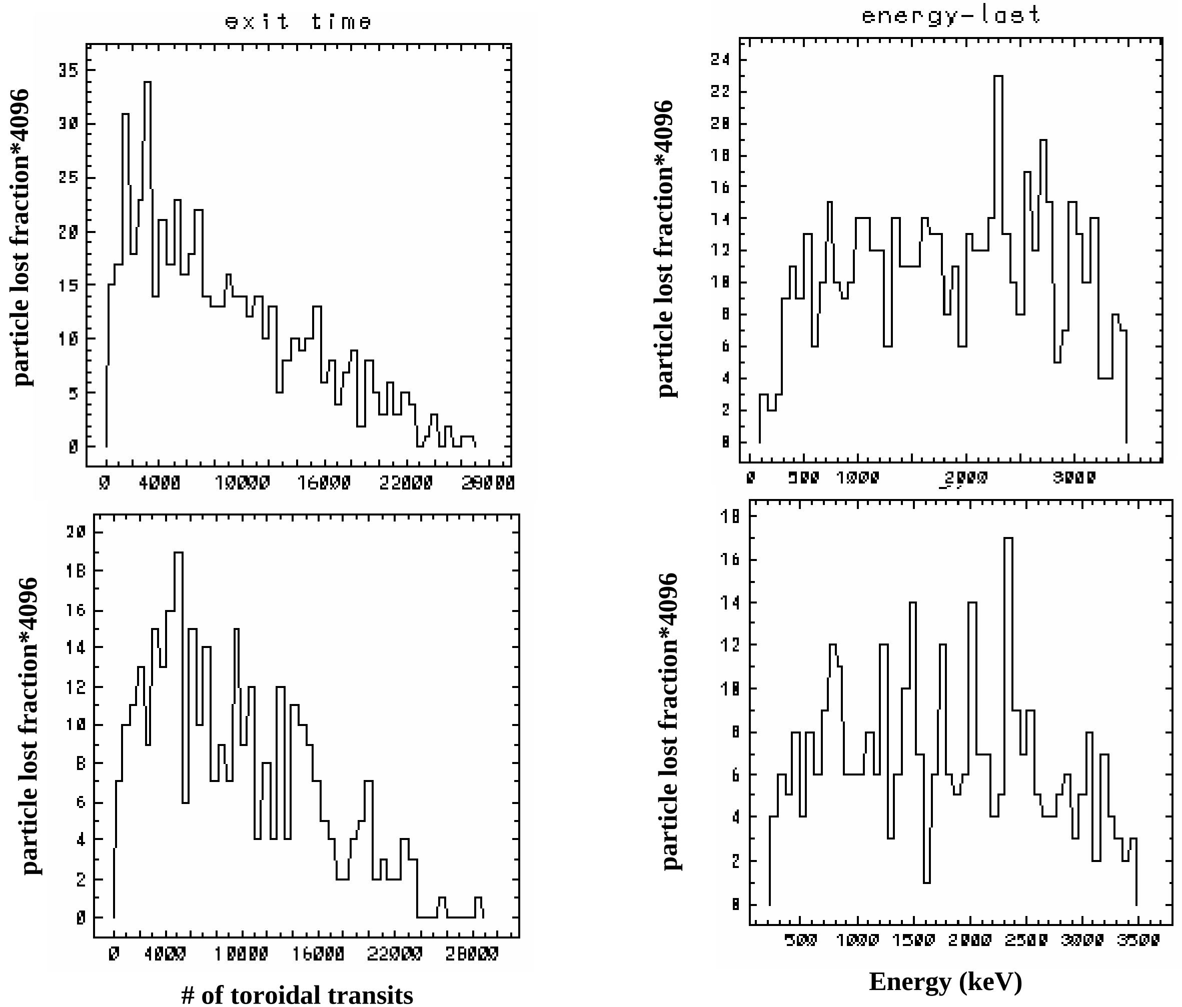


α-loss fraction is reduced correspondingly from 6.9% in KJC167 to 4% in KJC167m in a reactor having volume=1000 m^3 and B=6.5 T.

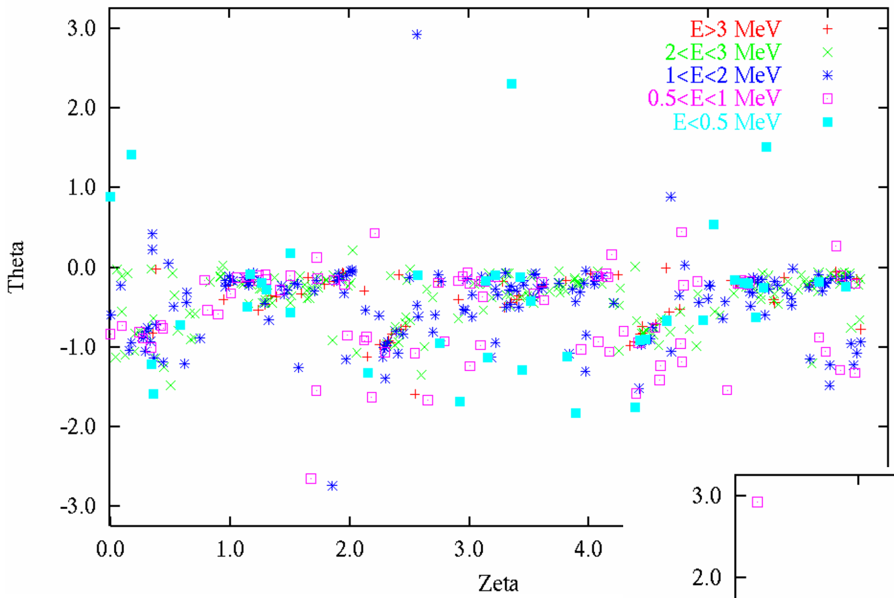
The characteristics of lost particles clearly show more delayed exits and lowered overall exit energy.

KJC167

KJC167m

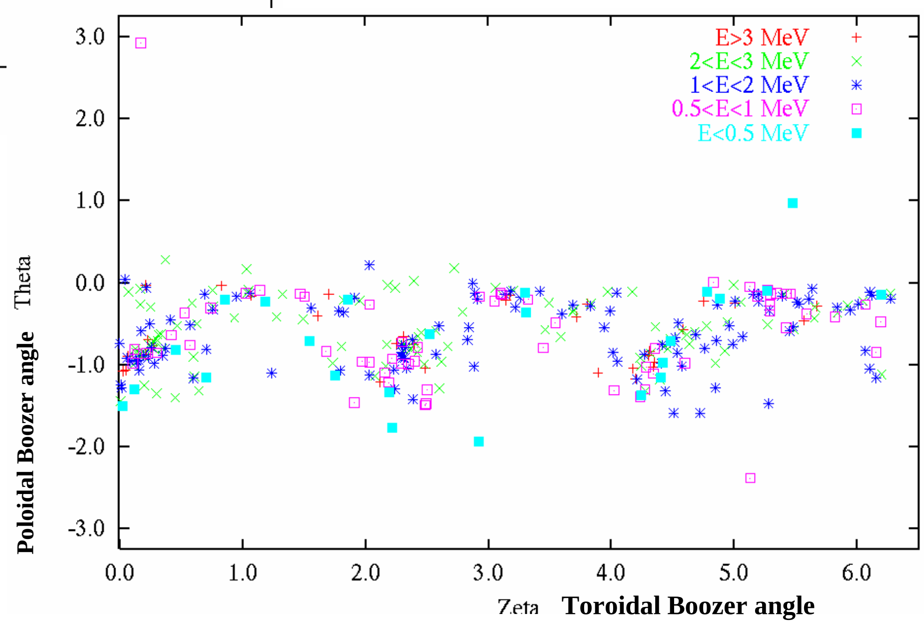


The angular distribution of lost particles in the reduced loss cases appears to show structures with seemingly correlated poloidal and toroidal angles.

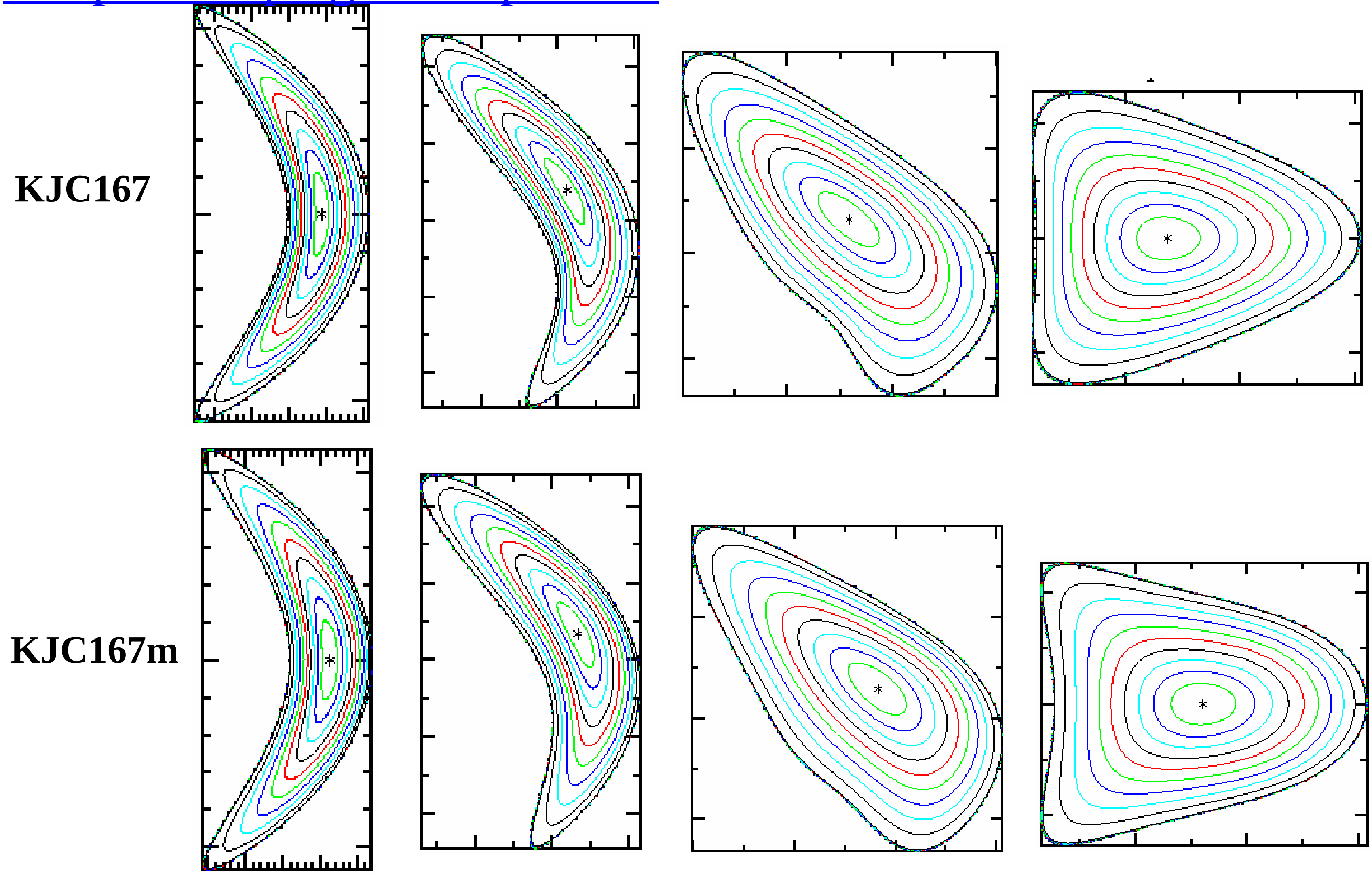


KJC167

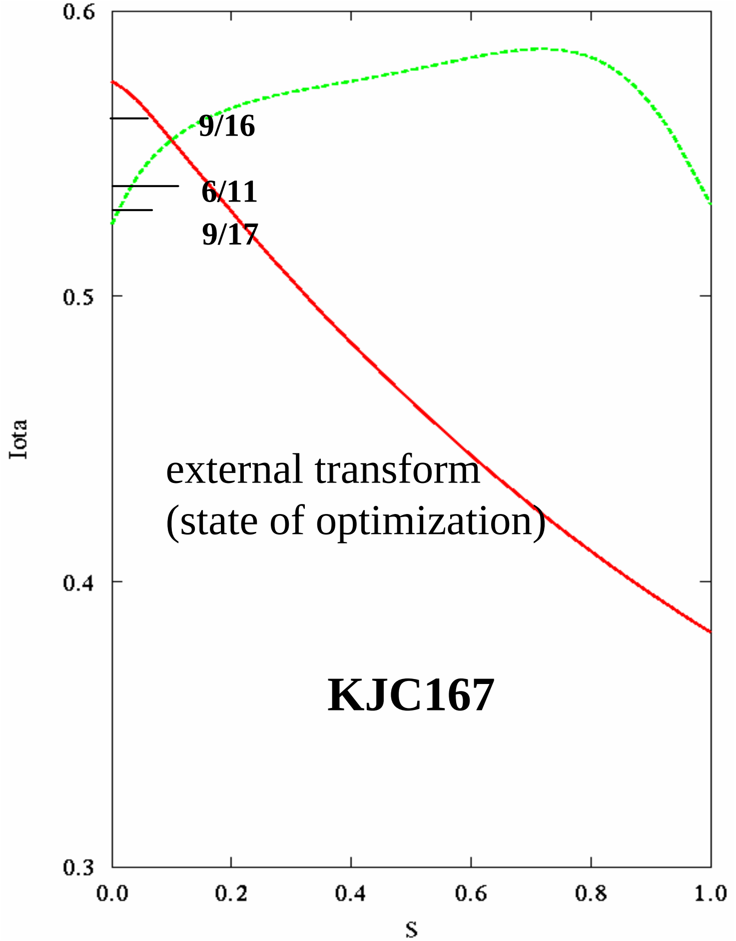
KJC167m

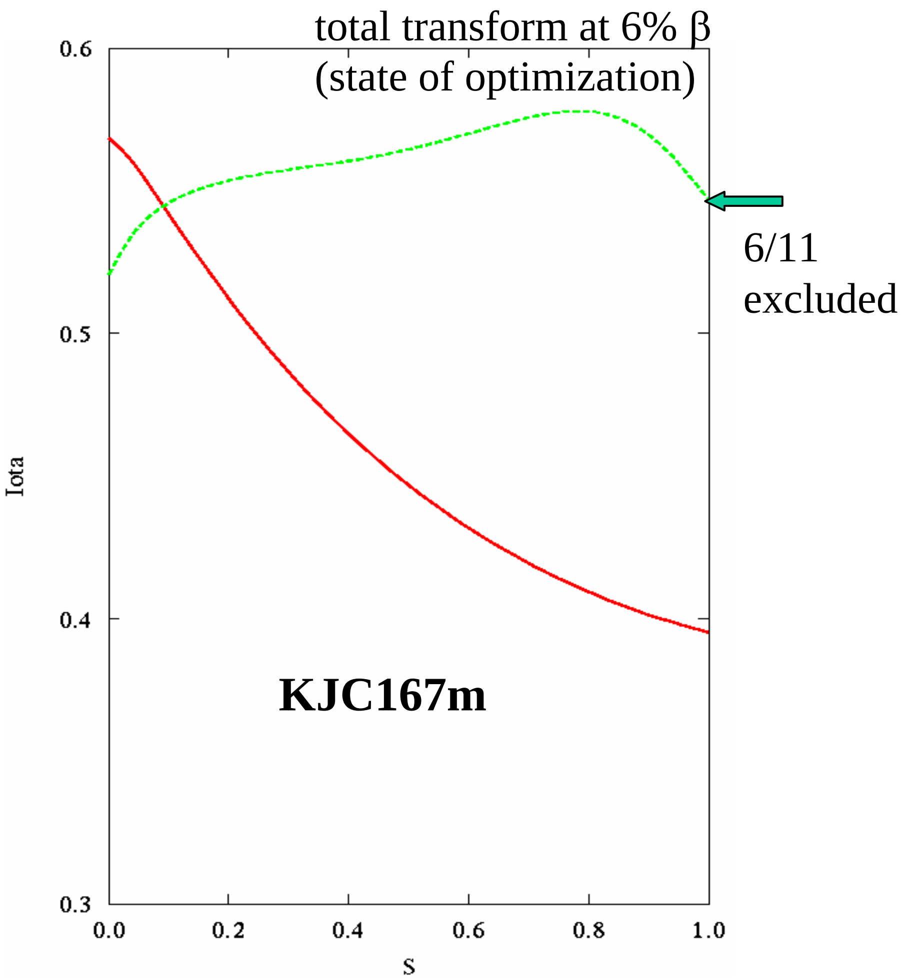


Comparison of vacuum equilibrium surfaces of KJC167 and the further optimized KJC167m shows that better QA requires a more complex shaping of the plasma.

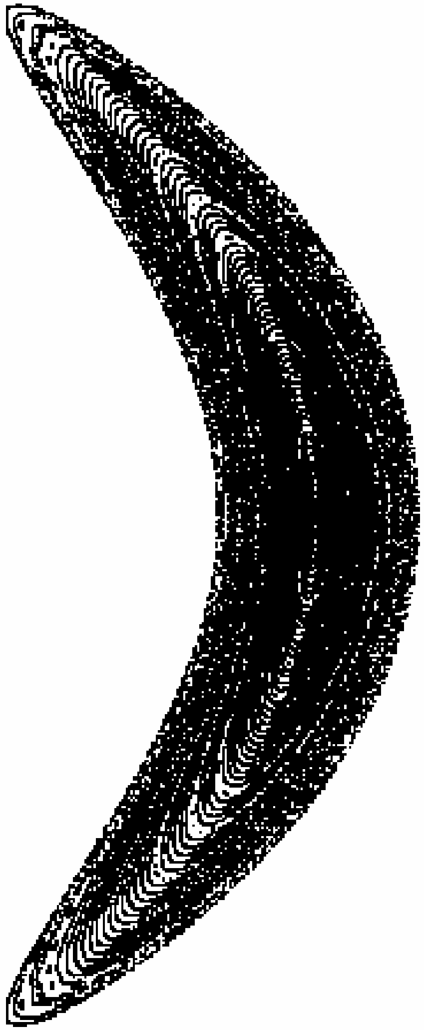


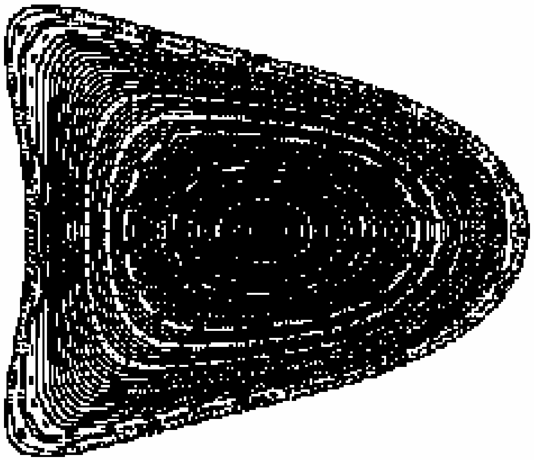
The rotational transform of KJC167 at 6% β crosses the 6/11 resonance near the boundary. KJC167m was simultaneously made to modify the iota to exclude this resonance, leading to the improvement of the overall quality of flux surfaces.

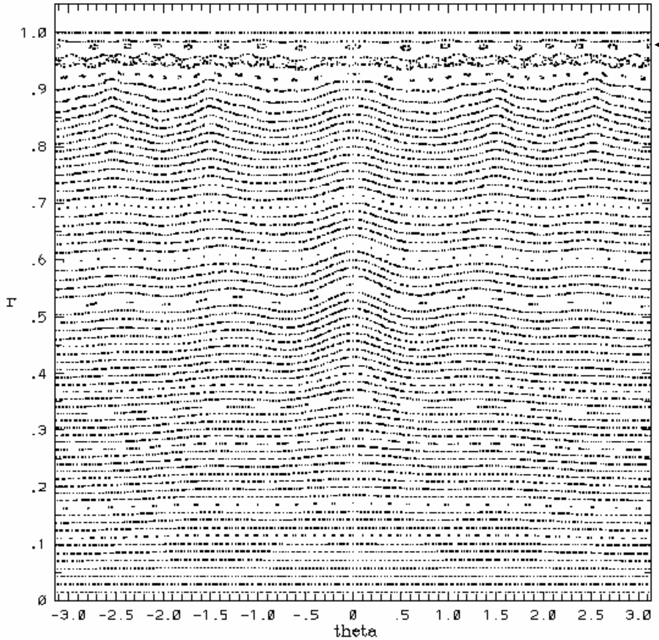




Excellent quality of flux surfaces is observed in most of the plasma for KJC167m at 6% β as seen below based on a PIES calculation.



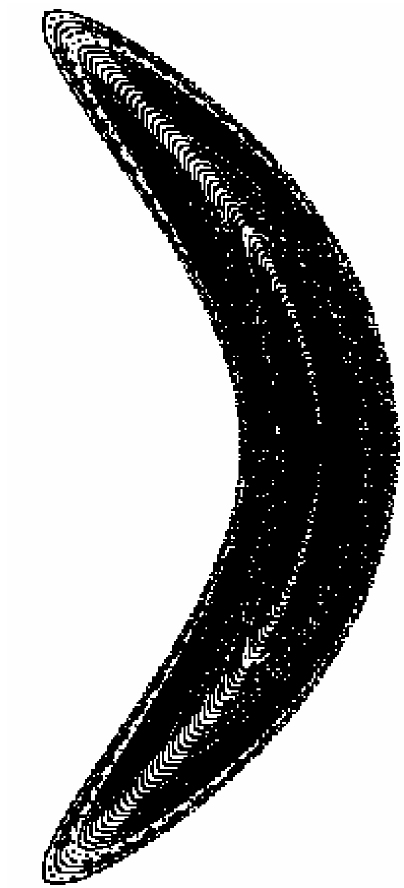


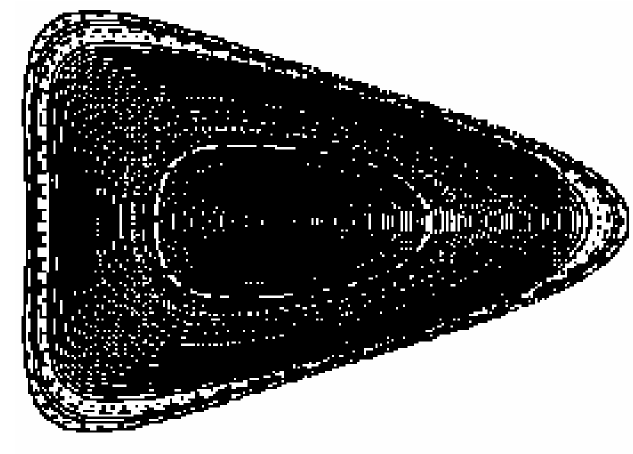


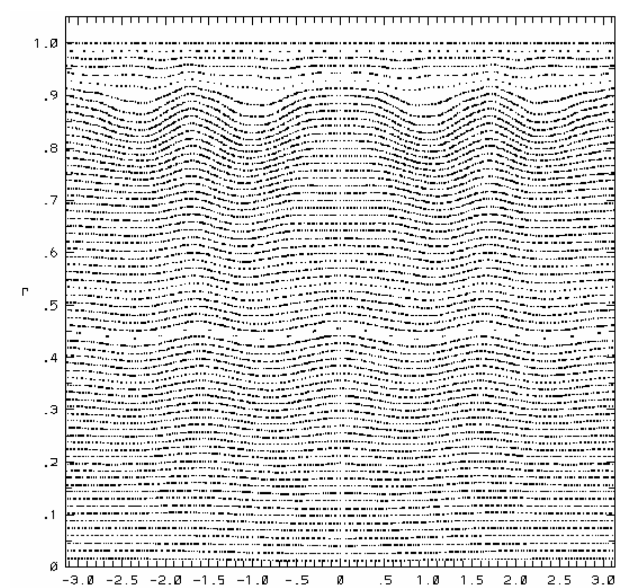
m=16

PIES and VMEC solutions are consistent.

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







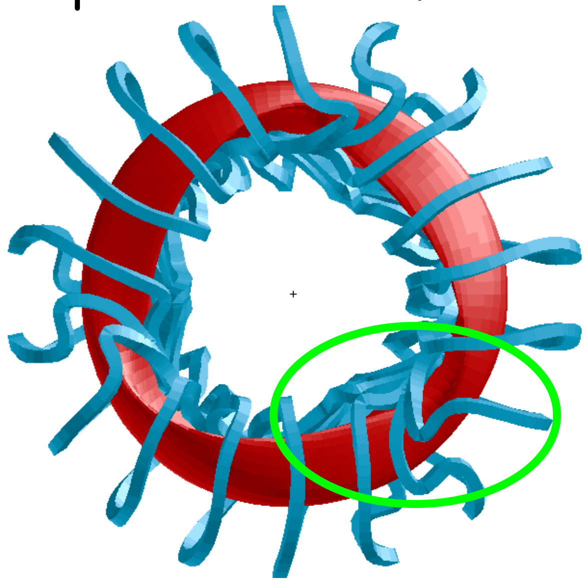
Initial study of coils:

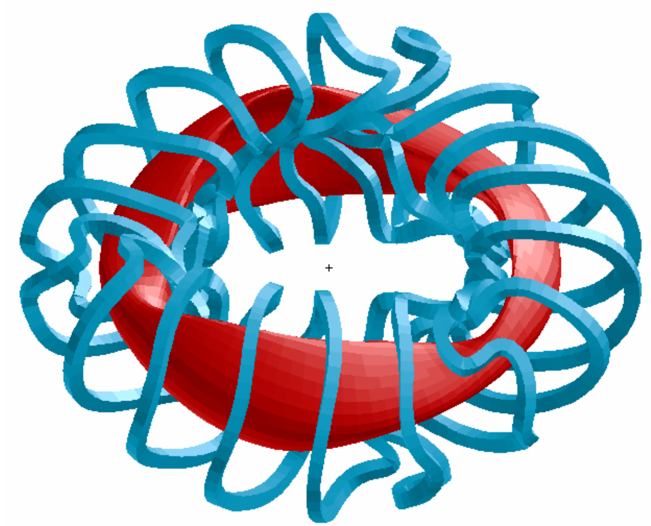
- Purpose
  - Find out if “reasonable” coils exist.
  - Examine conspicuous topological features and their effects on coil designs.
  - Investigate effects of plasma-coil spacing and the number of coils on the design.

- Approach
  - Use “NESCOIL”-type of solutions.
  - Consider mainly modular coils.
  - Choose only the minimum number of Fourier modes in the solution of current potential on the coil winding surface such that the average normal B erorrs ~1%, and the maximum normal B errors <8%.
  - Choose coil winding surfaces “representable” by the minimum number of Fourier modes and with the outboard distance from the plasma chosen to minimize the ripple when solutions are discretized into finite number of coils.
  - Design coils for the vacuum state such that VMEC re-construction would recover rotational transform, aspect ratio, major radius and the magnetic well.

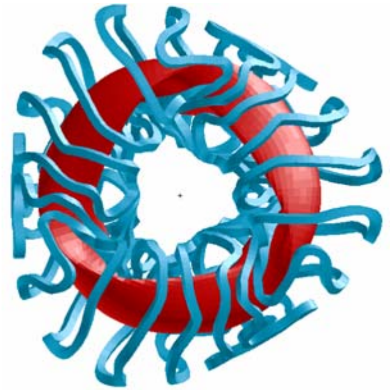
Using one possible design for KJC167m as illustration:

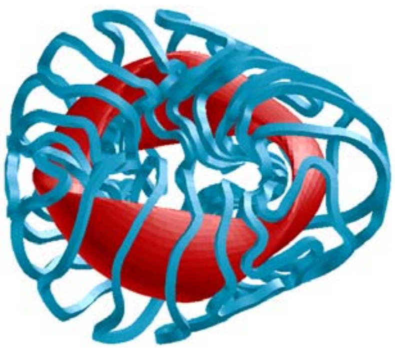
plasma aspect ratio ~ 6; coil aspect ratio ~ 6; number of coils/period=6.



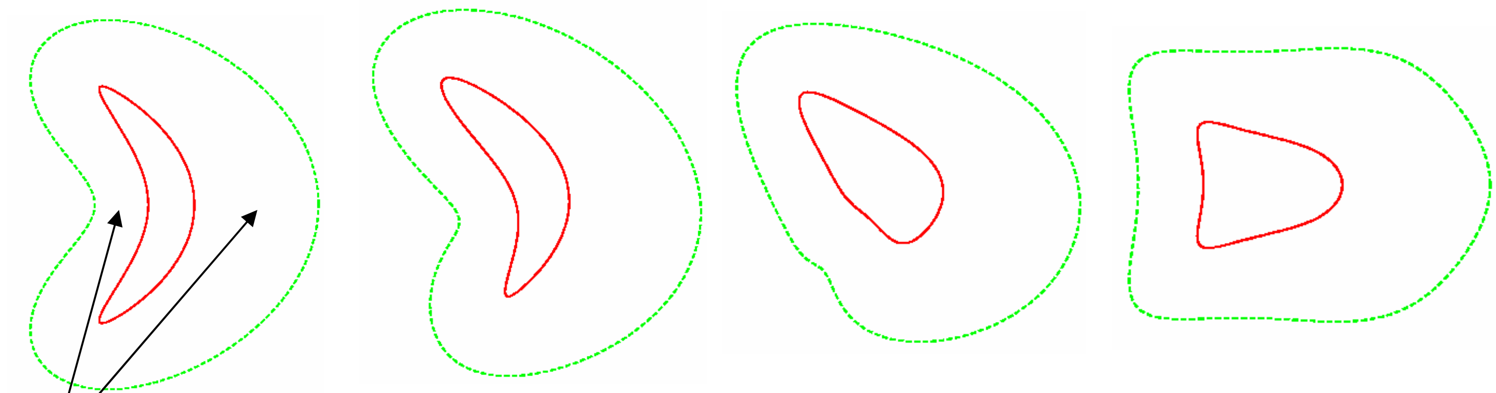


Coils for NCSX-class of configurations shown here for comparison

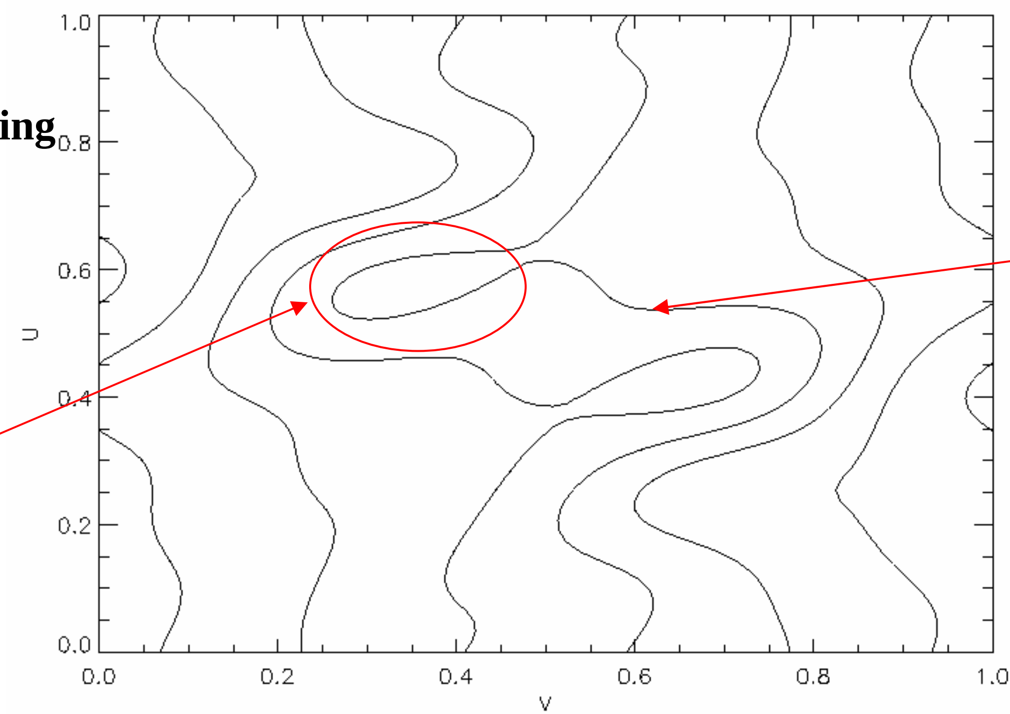




KJC167m -- coil winding surface of the present design and coils viewed on the winding surface.



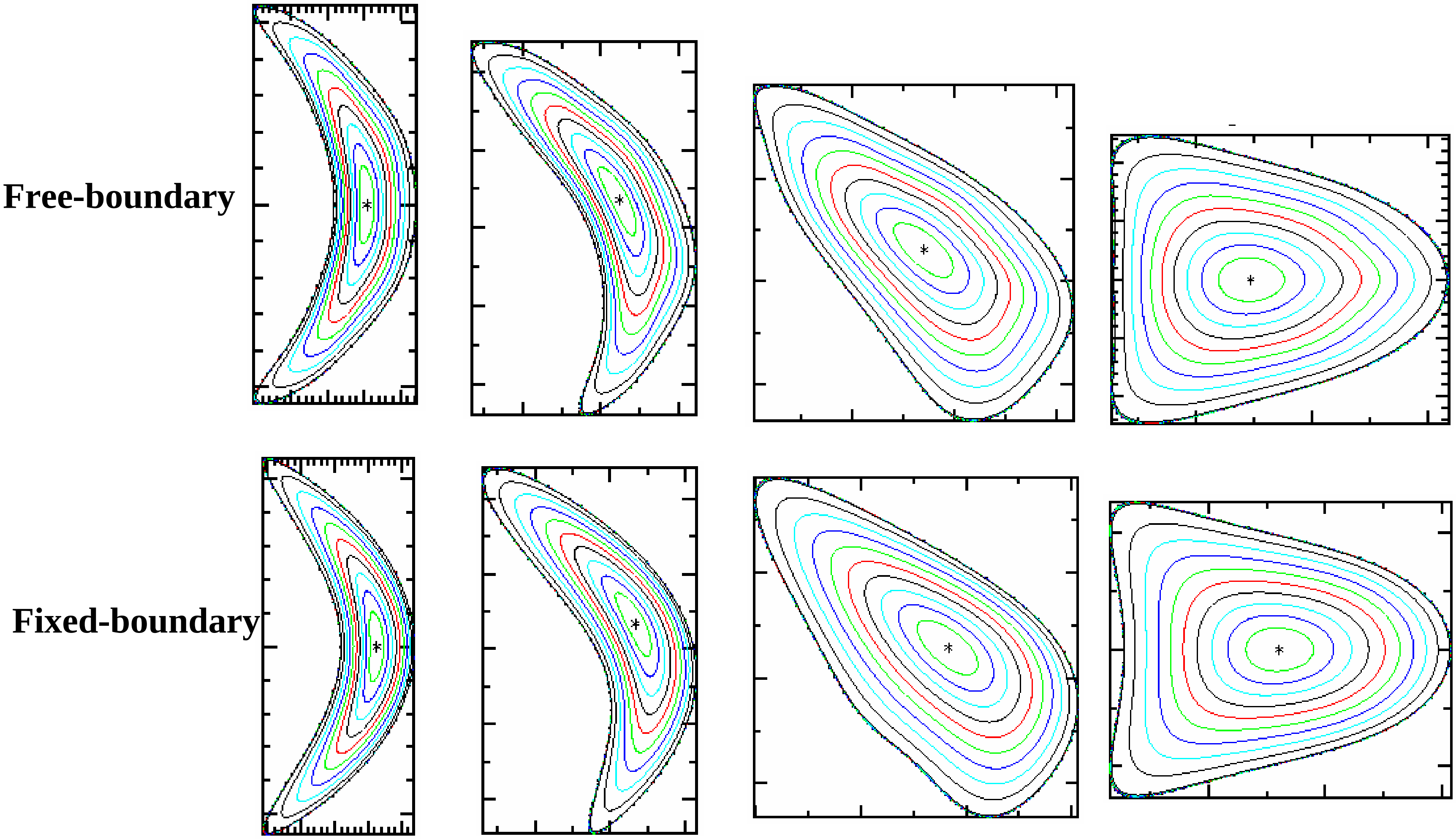
outboard spacing
~2.5x inboard spacing



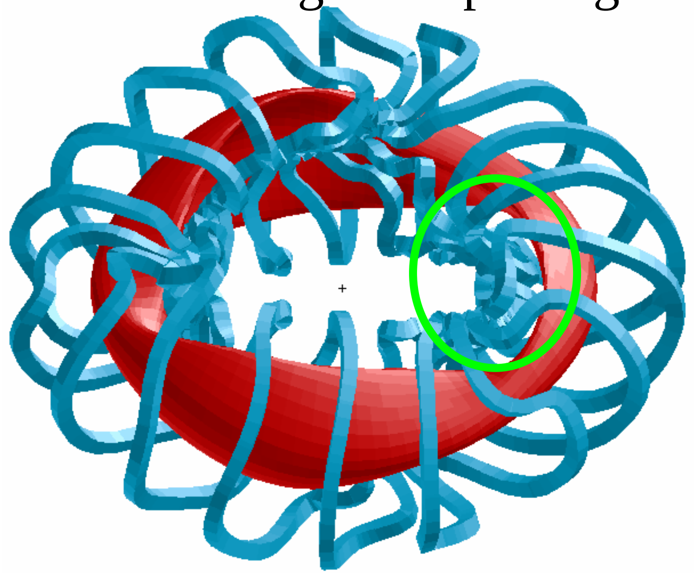
long toroidal winding

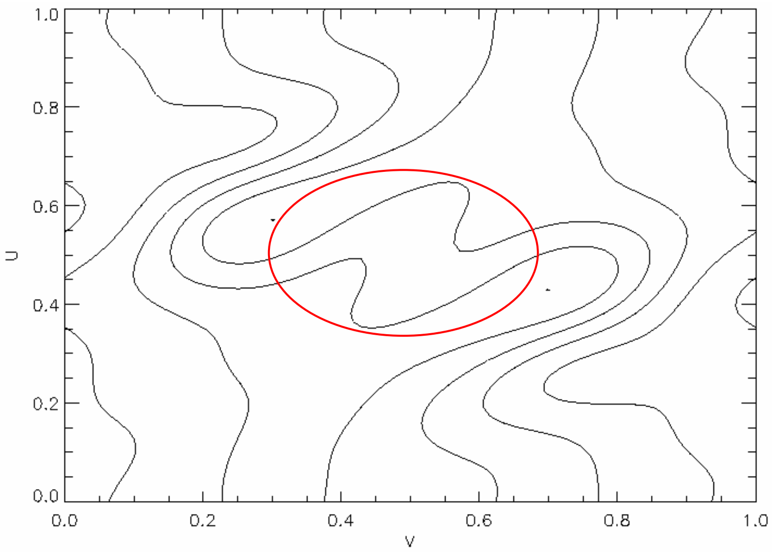
tendency to loop into local saddles

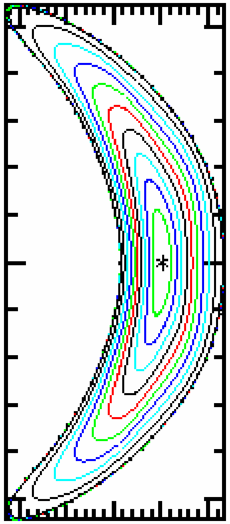
VMEC free boundary solution using the above coils agrees reasonably well with the fixed boundary solution *in vacuo*. Some subtle but important features are missing, however. (e.g. indentation in inboard midplane at half-period)

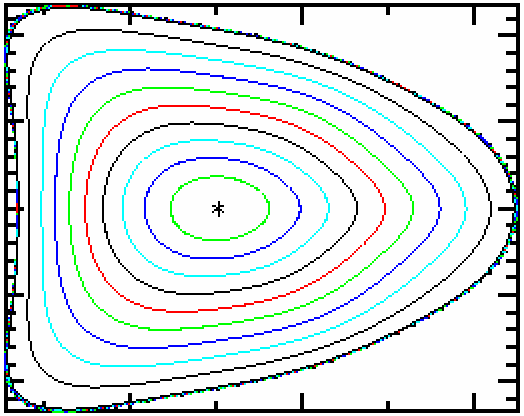


The indentation at inboard midplane may be produced by more twisted coils in that region or placing a coil at half period.



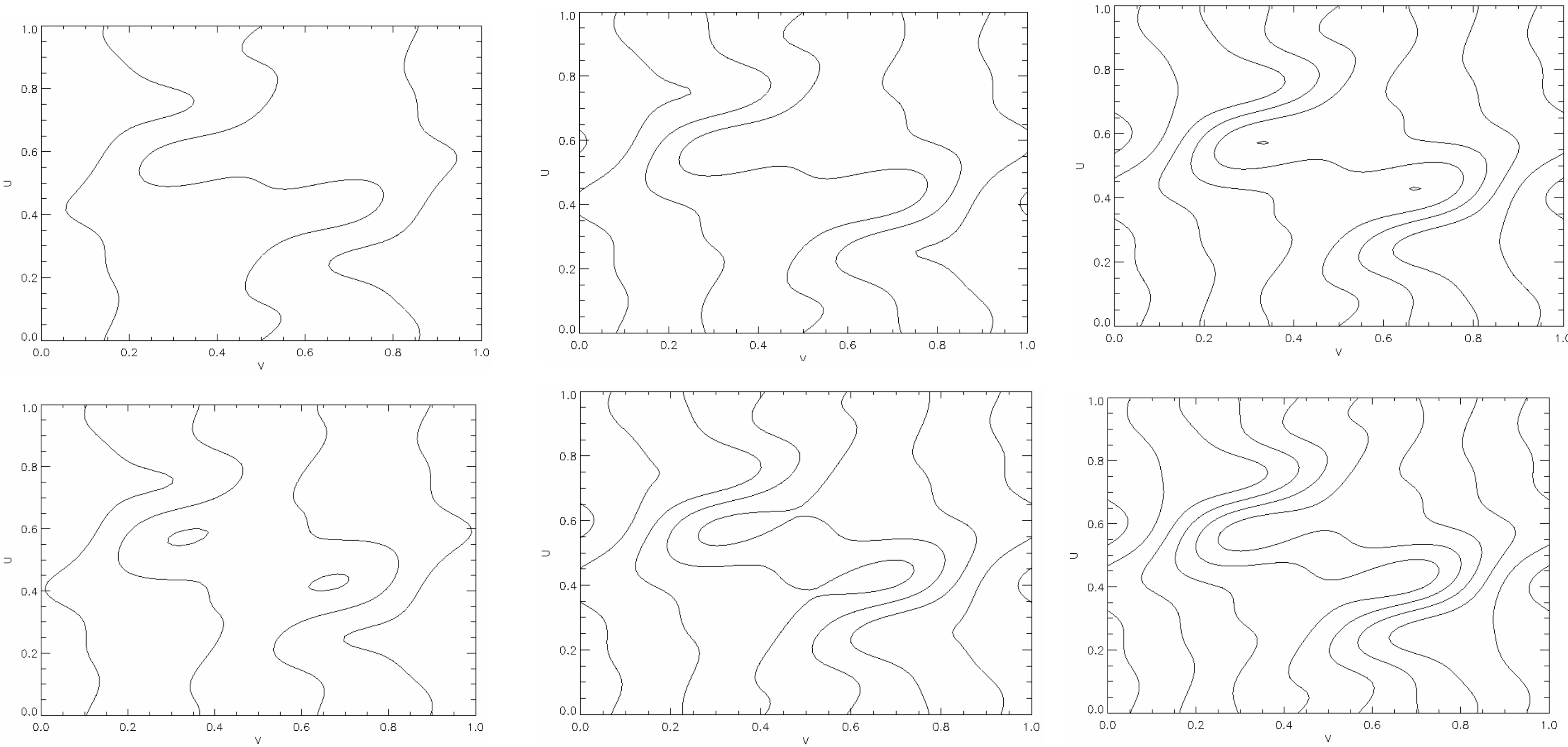






The awkward coil winding at inboard half-period may be made better by placing a coil at half period or by breaking the long toroidal winding with the help of local saddle coils.

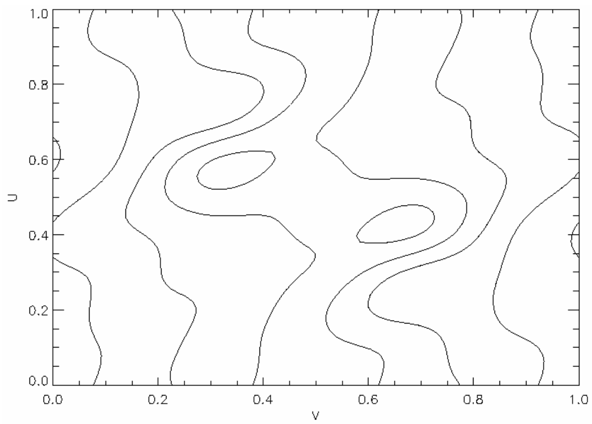
KJC167m: different number of coils viewed on the winding surface



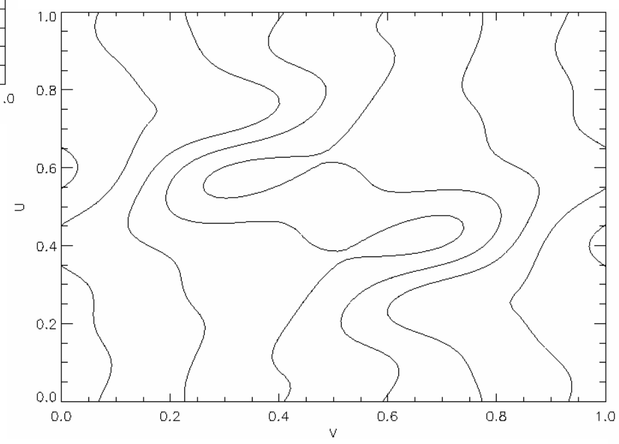
← **reconstruction poorer**

Maintaining the same plasma-coil spacing in the outboard but changing the spacing in the inboard (hence the coil aspect ratio) alters local topology and B_{max}/B_0 that one may want to consider in the design tradeoff.

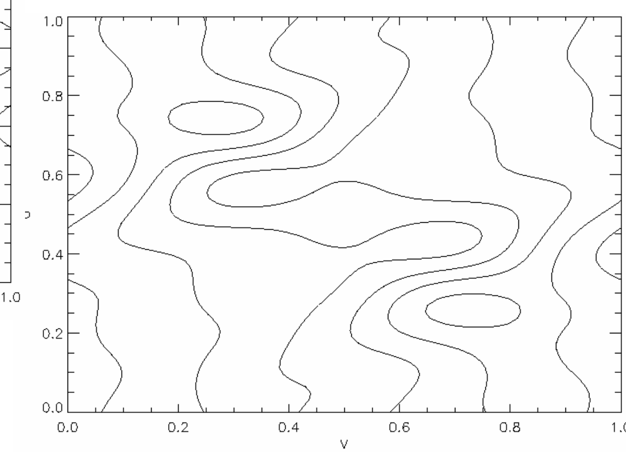
complexity increases



Ac~7

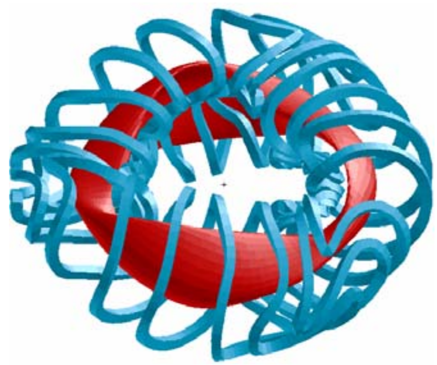


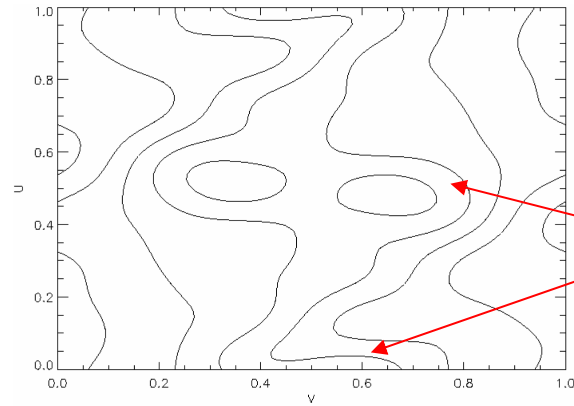
Ac~6



Ac~5

KKD863 (average rotational transform ~0.7): **higher rotational transform demands more complex coils, but this coil set provides a reasonably good solution.**

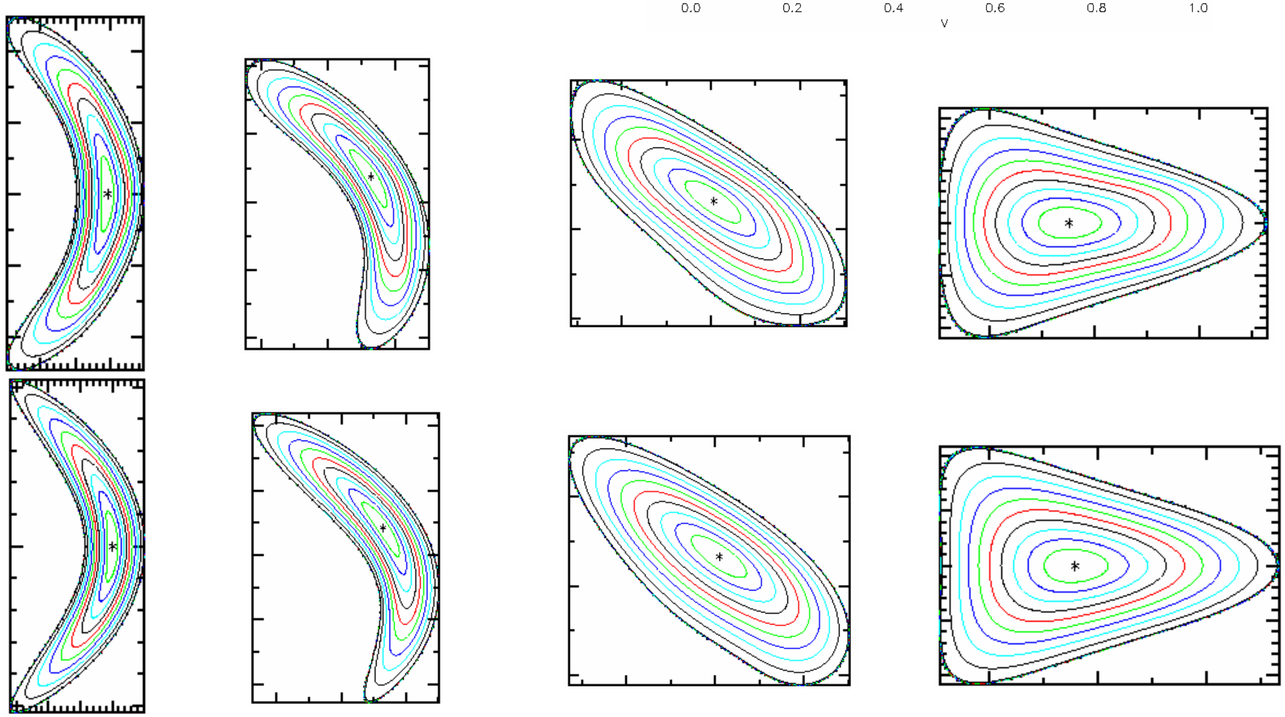




Strong toroidal excursion at the outboard and saddle formation at the inboard.

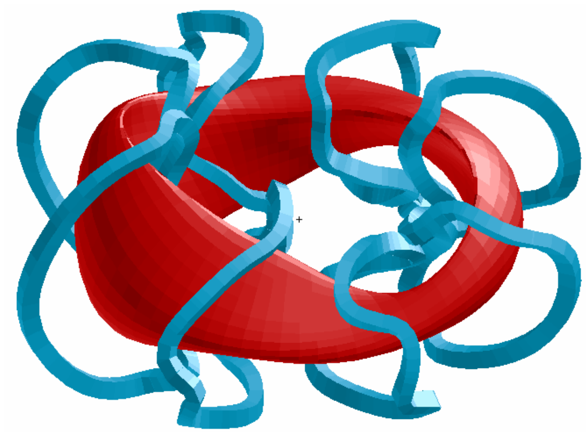
Free-boundary

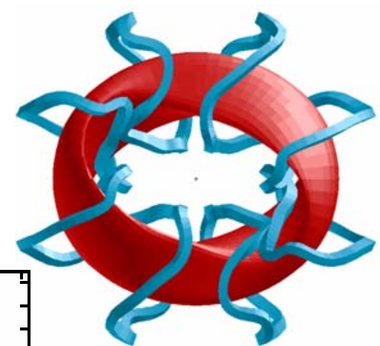
Fixed-boundary

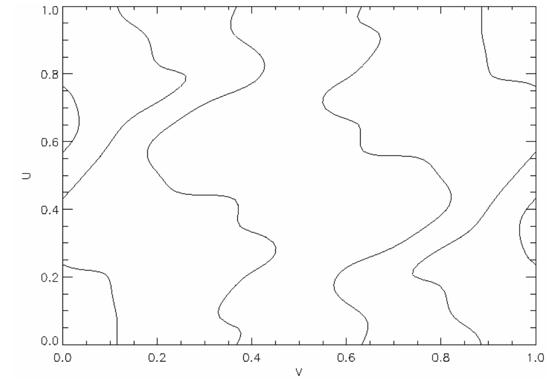


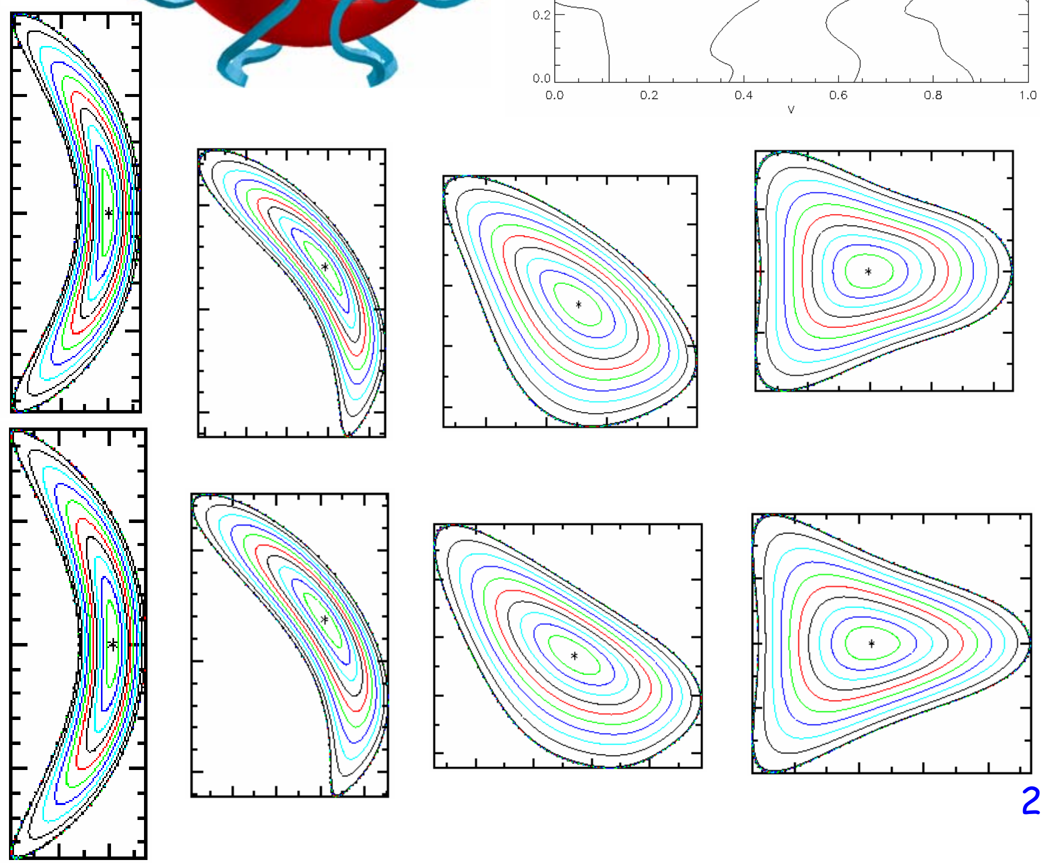
An interesting design for the two-field period configuration KDB124 (average ι~0.42, α loss fraction~7.3%).

Plasma aspect ratio ~4, coil aspect ratio ~4, 4 coils/period.









Free-boundary

Fixed-boundary

Summary and Future Work

- We have made further progress in developing the SNS-QA configurations discussed in the March meeting:
  - shown by further optimizing QA that the α-loss may be reduced to <5% for B=6.5 T and volume=1000 m^3 reactors.
  - shown that the rotational transform may be modified to avoid having higher order rational surfaces in the outer region without affecting other essential properties.
  - shown the characteristics of modular coils and some possible design approaches.

- We plan to address the following topics for SNS-QA in the near future:
  - Improvement of coil topology and coil design optimization.
  - Further configuration refinement and improvement in:
    - stability to MHD modes based on code calculations using ideal, linear theories (optimization for external kinks and ballooning at full β with iota constraint) and non-linear formulations as in NSTAB.
    - shape optimization by altering number of modes describing plasma to seek for further improvement in all properties.
- We also plan to re-examine methodology/strategy for improving flux surface quality in the NCSX-type (MPS-QA) of compact stellarators.