Recent Progress in Configuration Development for Compact Stellarator Reactors

Long-Poe Ku
PPPL

Aries Project Meeting, December 3, 2003
Princeton Plasma Physics Laboratory
Princeton, NJ

Our main focus in the last quarter has been the study of flux surface quality --

- Flux surface integrity of the existing configurations.
- Methods of improving surface quality.
- Development of novel approaches to QA configuration design.

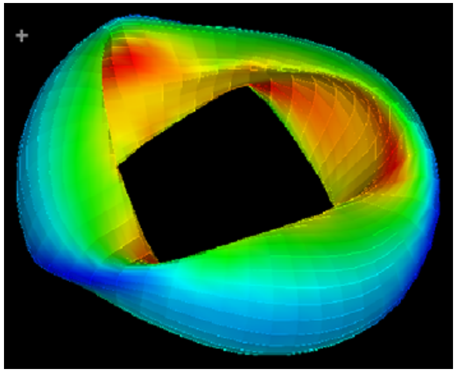
QA reactor configurations are being developed using the knowledge base and the discipline that are used in designing NCSX.

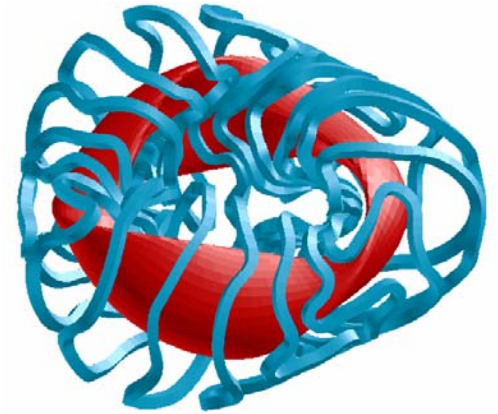
We require plasmas satisfy certain MHD stability acceptance criteria at 4% β with "good" QA:

- MHD stability must be achieved by plasma shaping alone – no conducting walls and no feed-back stabilization coils.
- Measures of plasma stability are the calculated eigenvalues of the linearized ideal MHD stability equation for the external kinks, vertical modes and infinite-n ballooning with some prescribed numerical resolutions and accuracies.
- Nested flux surfaces are assumed to exist in the entire plasma domain.
- Plasma equilibria whose MHD stability measures must satisfy the acceptance criteria are based on a single prescribed pressure profile.
- QA is required to be as "good" as possible ($B_{m,n}$ < a few percent), subject to the satisfaction of MHD stability requirements. Typically, an effective ripple << 1% can be achieved, but it is almost always compromised by the stability requirements.

We require coils be able to produce plasmas that preserve essentially all the above properties under the same conditions and, in addition, have:

- "sufficient" space between plasma and coils,
- "adequate" separation of neighboring coils,
- "large" enough minimum radius of curvature
- minimum coil complexity.





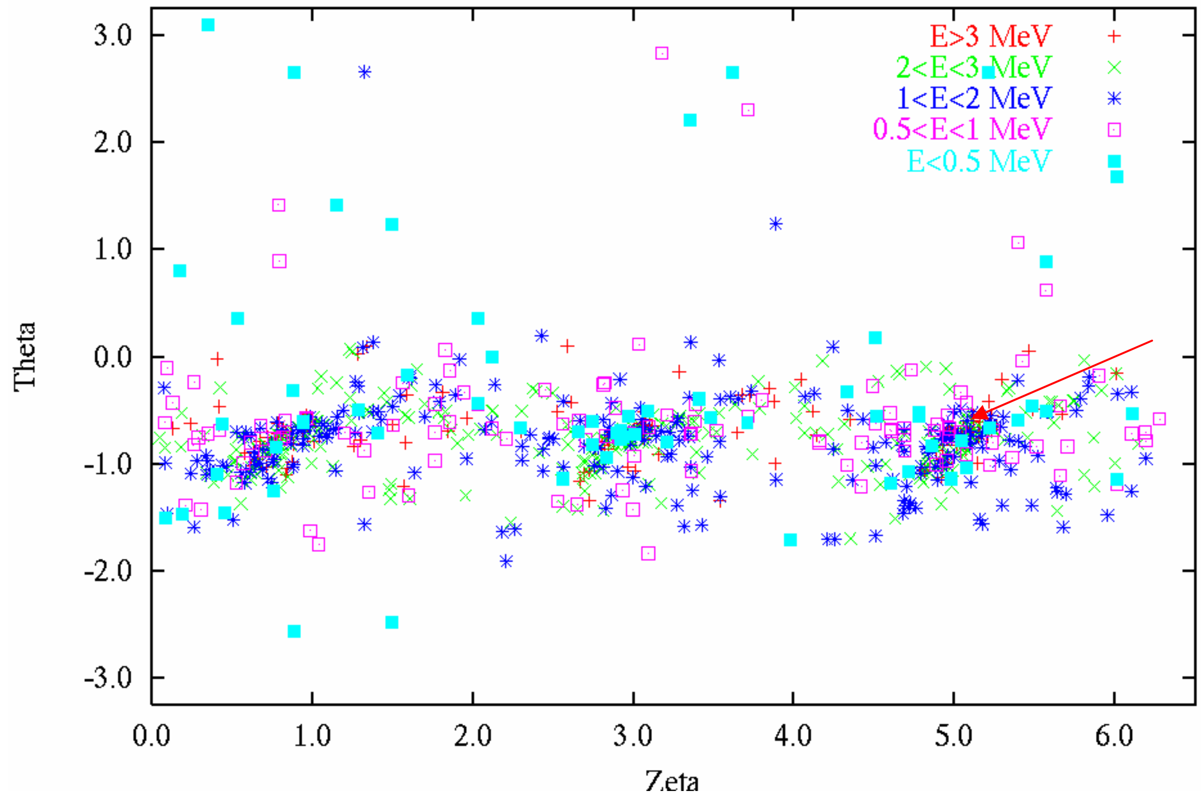
Configurations having "good" plasma, coil and overall reactor performance with R< 8 m (2 GWth) have been identified (J. Lyon's talk).

- For reactors, consideration must also be given to:
  - minimization of α-particle loss,
  - maximization of plasma-coil separation subject to $B_{max} < B_{critical.}$

} Major efforts in FY03

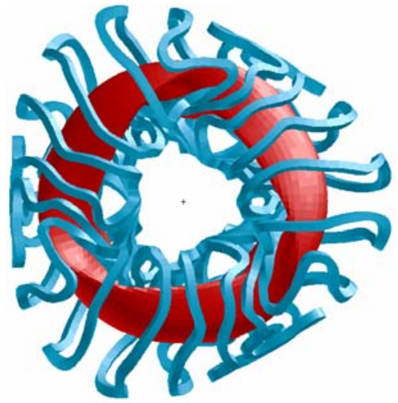
Minimization of α-particle loss is now incorporated into the configuration optimization. Configurations with α energy loss ~ 10% were found. The losses are localized, hence the heat load may be an important engineering issue. Further configuration improvement is needed.

Footprints of escaping α's on LCMS for N3B5D. B=5.5 T, Vol=1000 m³.



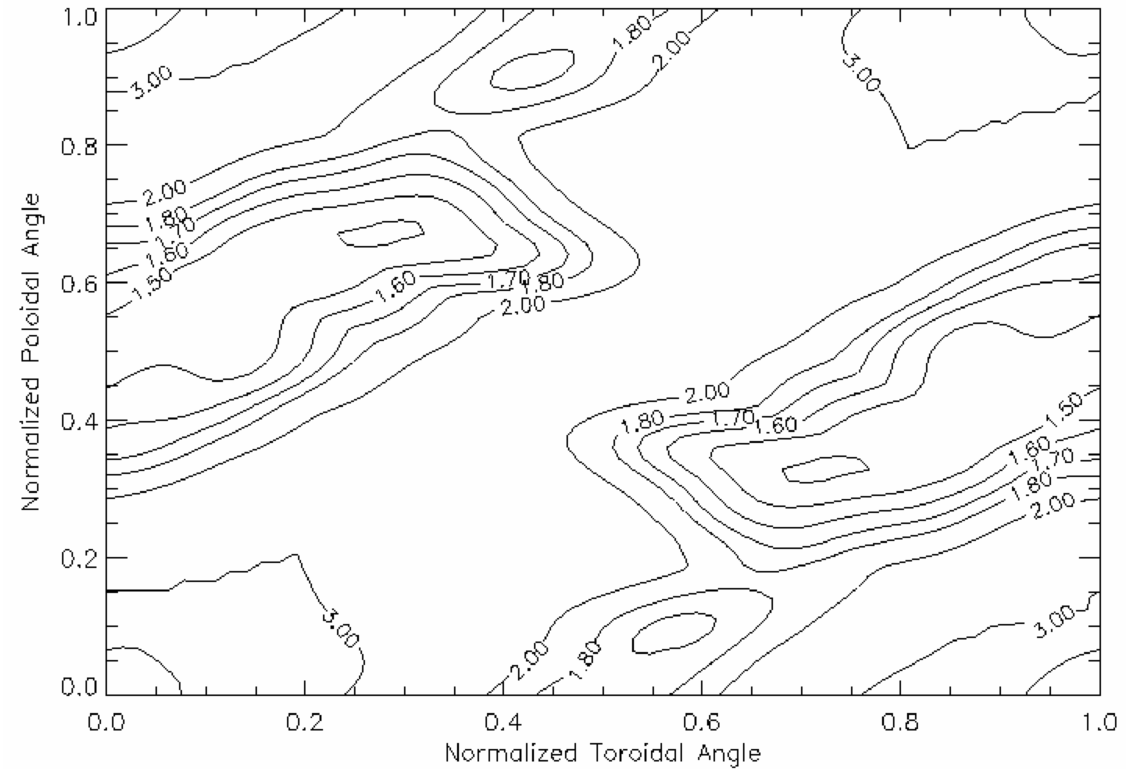
Heat load maybe localized and high (~a few MW/m²)

Optimization of modular coils has led to configurations with coil aspect ratios < 6, hence reactors of smaller sizes are realizable.



For R=8.25 m
Δ_{min}(c-p)=1.4 m
Δ_{min}(c-c)=0.83 m
I_{max}=16.4 MA @6.5 T
B_{max}/B_0~2 for 0.4 m x 0.4 m conductor

Distance between plasma and coil winding surface shown in one field period for a 3-field period, A=4.5 plasma with R=8.25 m and coils with A_c=6.



To make QA reactors more competitive with other confinement concepts, we need to further increase plasma β and simplify coils.

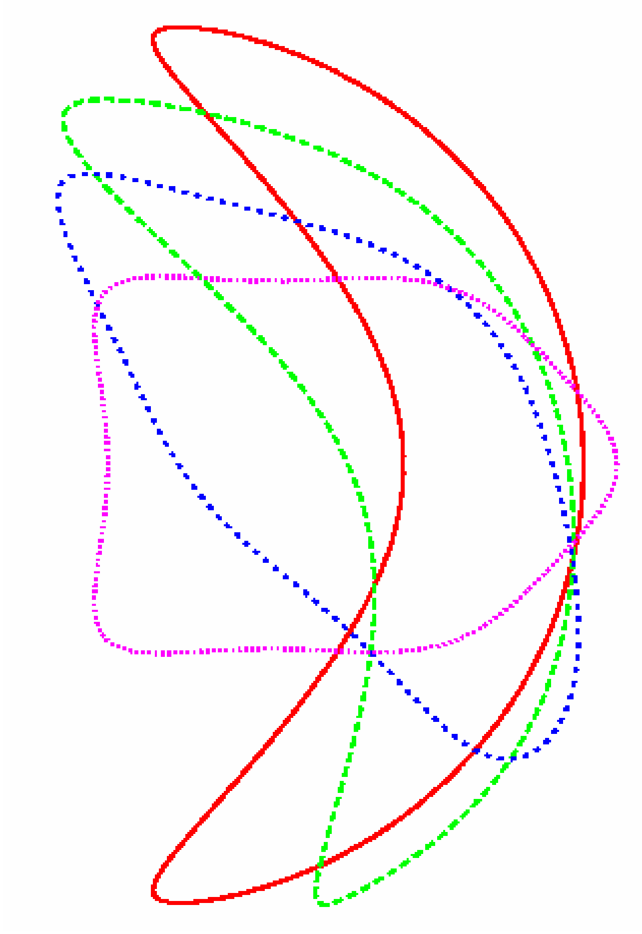
Increasing β raises two issues:

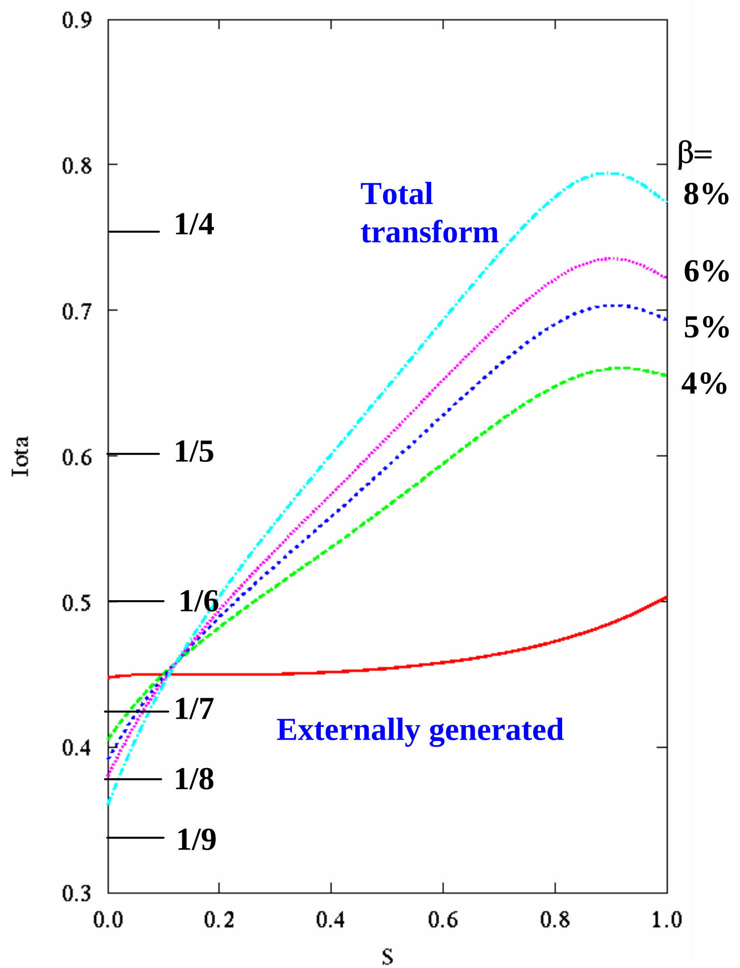
- Integrity of the flux surfaces and the equilibrium β limit,
- Increased demand of plasma shaping for MHD stability (if we approach it business-as-usual) and the consequent increase in coil complexity.
  - Experimental results appear to indicate that stellarator plasmas may be more resilient than the linear theory tells. How should we take advantage of this in configuration development?

The integrity of flux surfaces, along with the MHD stability, set the β limit –

- Shafranov shift: $\frac{\Delta}{<a>} \approx \frac{<\beta>\cdot A}{2\kappa\iota^2}$ < 1/2
- Large islands associated with the low order rational surfaces
  – Flux loss due to all isolated islands < 5%
- Overlapping of islands due to high shears associated with the bootstrap current

We use a three-field period, A=4.5, α-loss optimized configuration to illustrate the effects of β on the flux surface integrity --



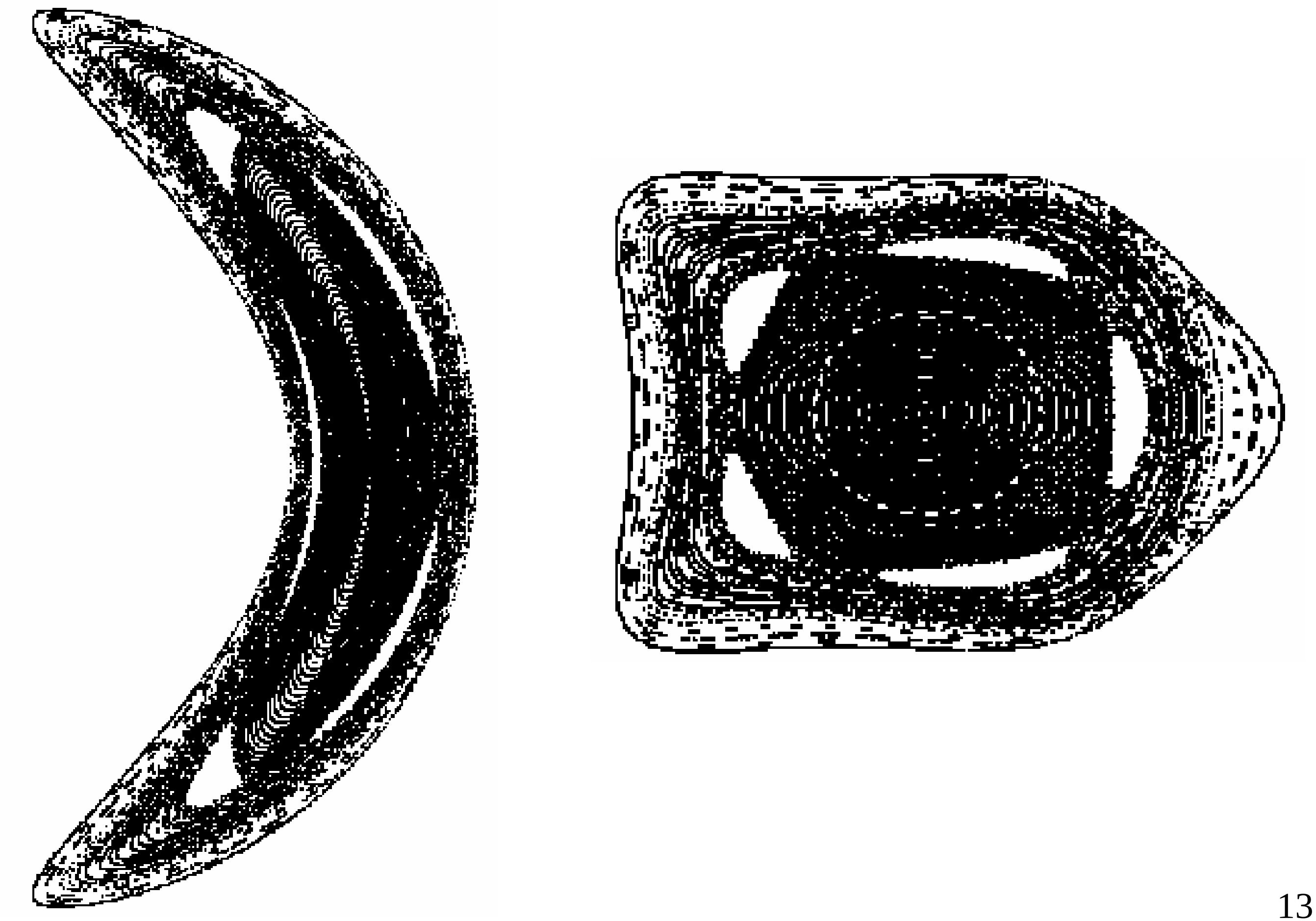


Thanks to the low aspect ratio and relatively high iota, the axis shift is modest even at 8% β, according to VMEC --

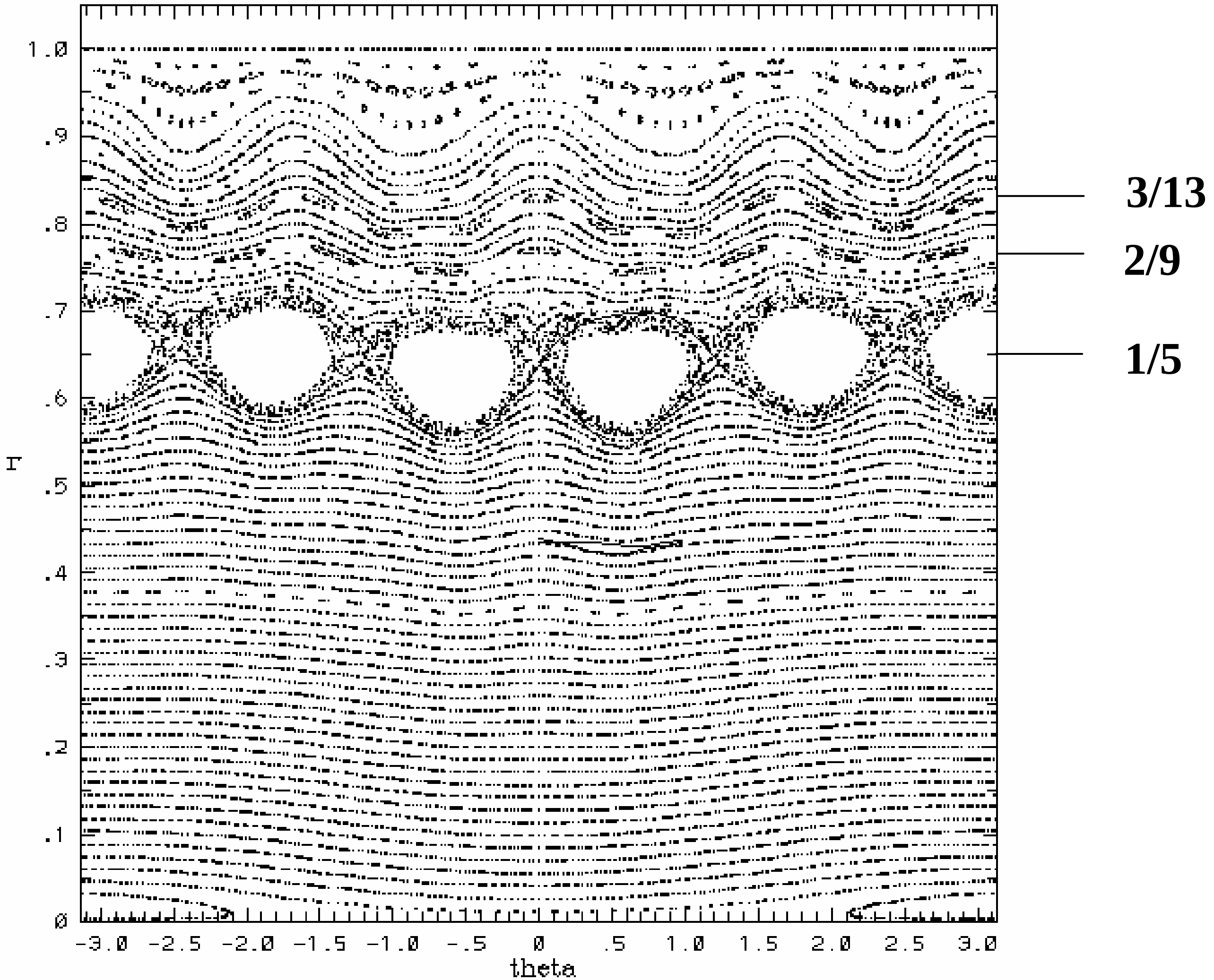
$$\Delta/\langle a\rangle = 7.4\% \ @ \ \beta=4\%,$$
$$= 11.4\% \ @ \ \beta=8\%$$

=> β~30% when $\Delta/\langle a\rangle \sim 0.5$

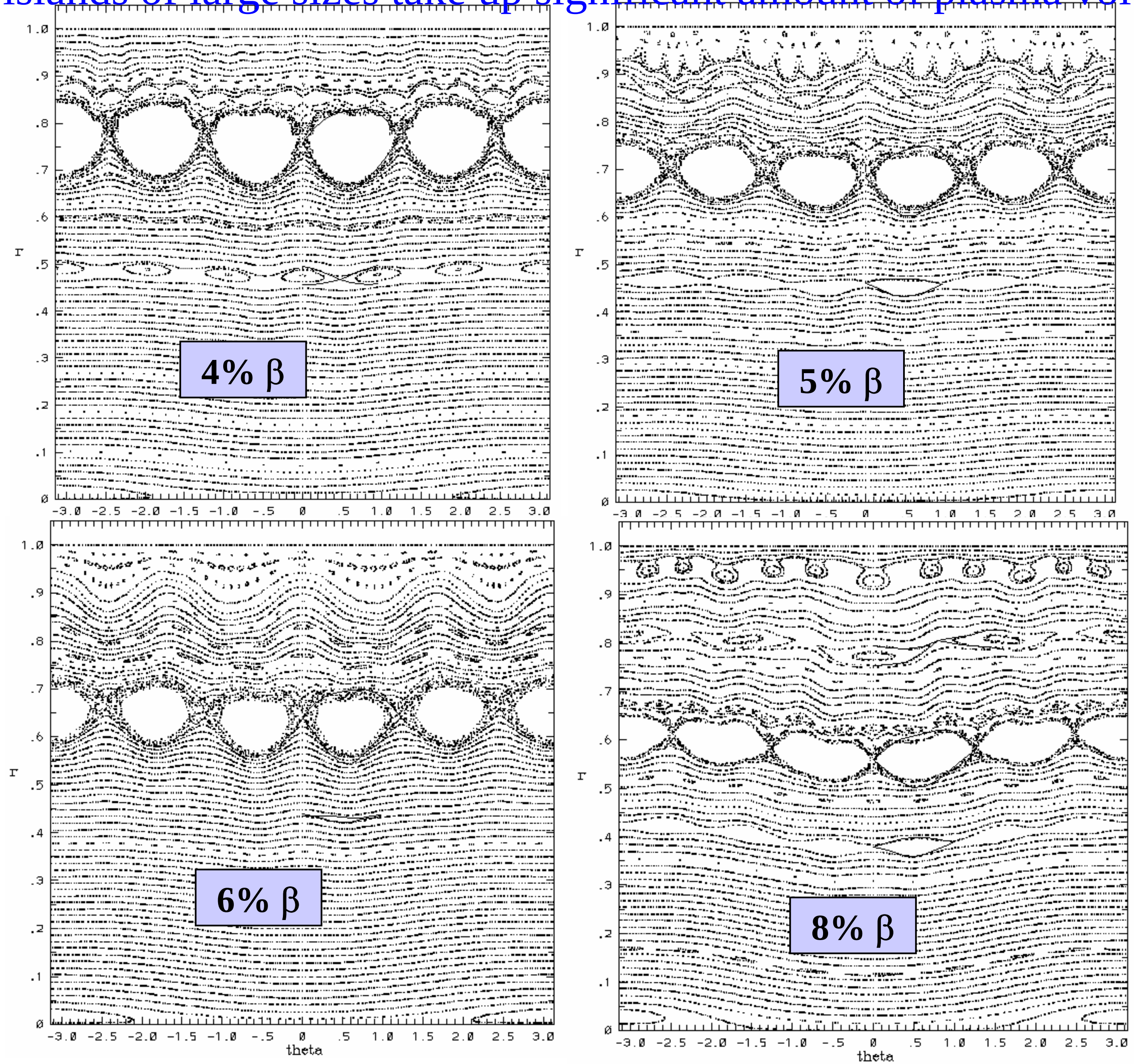
But, due to the presence of low order rational surfaces and high shear, islands of large sizes and regions of poor surfaces exist, as seen in the Poincaré plots from PIES equilibrium calculations. This illustration is for β=6%.



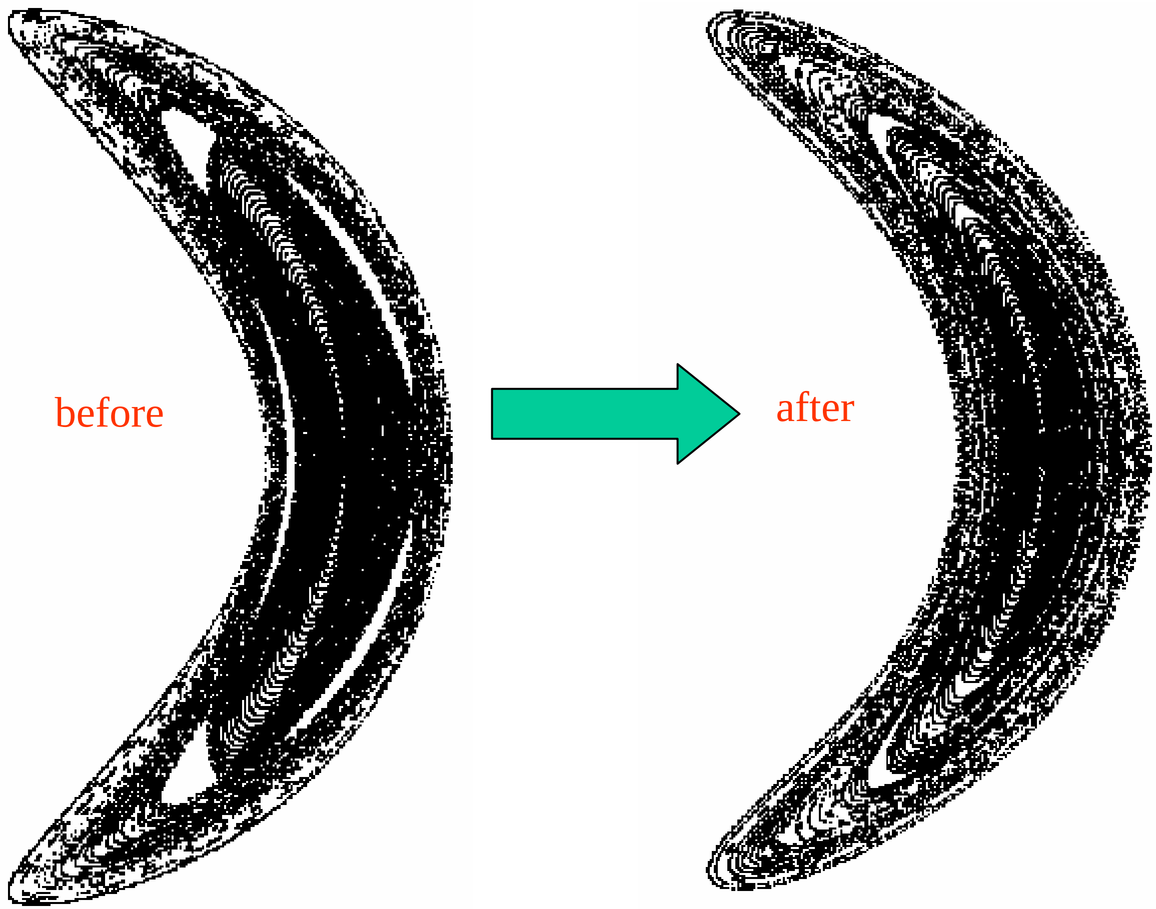
The quality of flux surfaces maybe easier to compare with if we look at the Poincaré plot in the polar coordinates, as illustrated below:

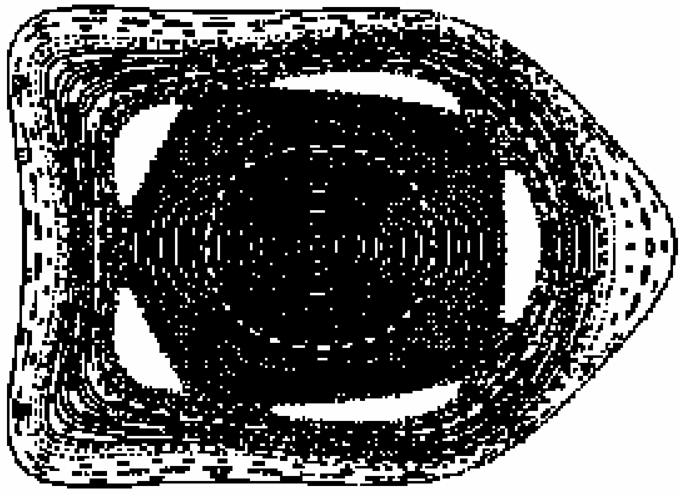


PIES results show that most surfaces are of reasonably good quality between 4% and 8% β, but islands of large sizes take up significant amount of plasma volume.

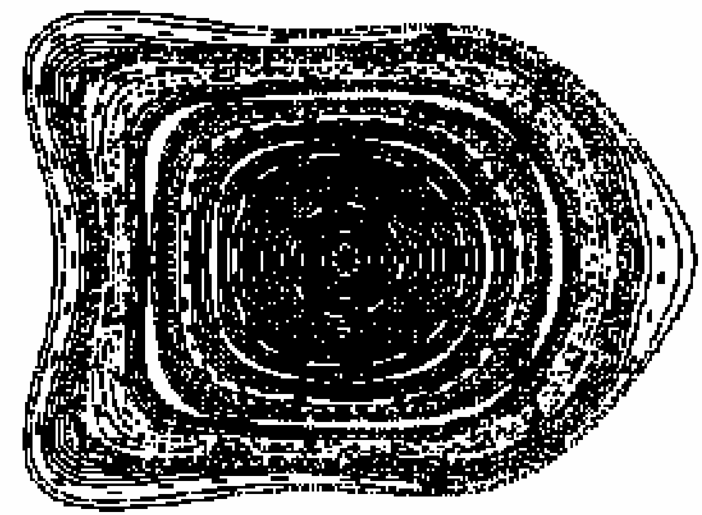


Large, isolated islands can be "healed" by zeroing out the resonant perturbations. An algorithm that calculates the resonant normal fields by constructing the quadratic flux minimizing surfaces has been implemented in PIES (S. Hudson) and has been extensively used in the design of NCSX. Here we illustrate that by simply hand adjusting boundary shaping harmonics, we are able to almost "heal" the m=5 island.

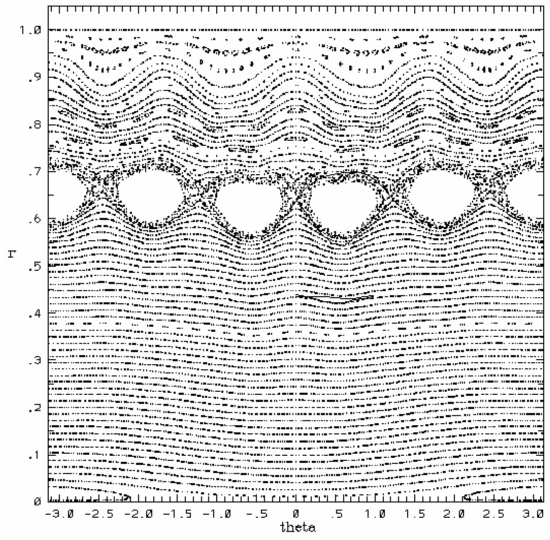


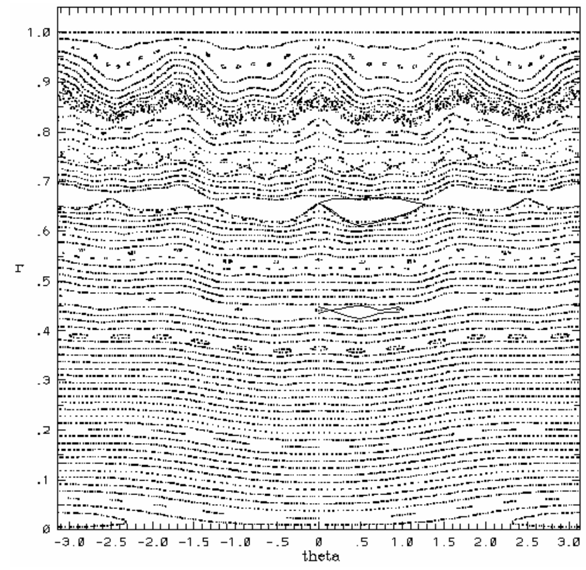


before



after





PIES healing and PIES equilibrium calculations demand considerable computer resources. Are there simpler methods that can be integrated into the configuration optimization to minimize the island size, as we did by adjusting the plasma boundary?

- One possible approach is to take advantage of results from the analytic theory, for instance, solution to the island size for non-overlapping, single harmonic, narrow island in large aspect ratio, low beta plasmas, due to C. Hagna, as a guide:

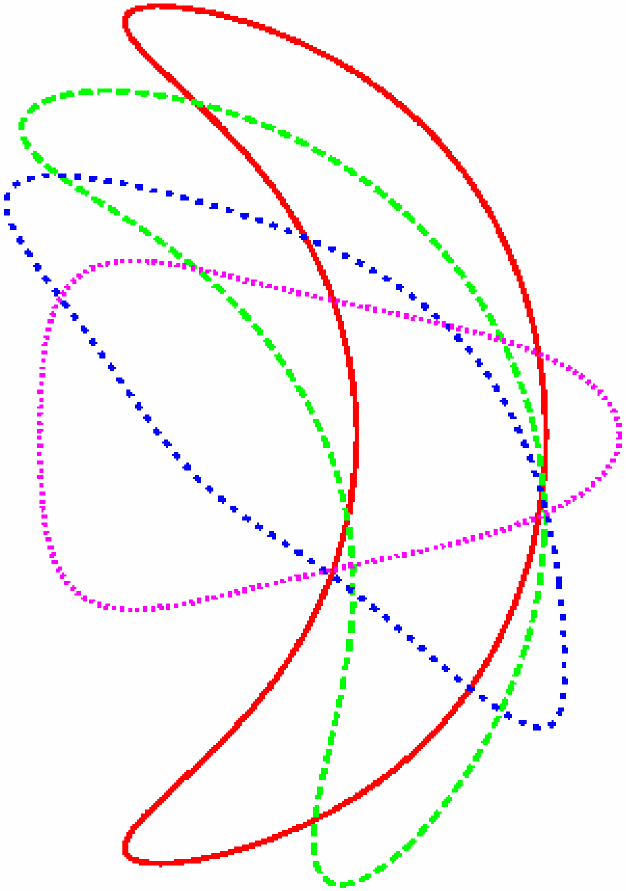
$$D \propto \frac{D_{NC} + D_R}{-\Delta'}$$

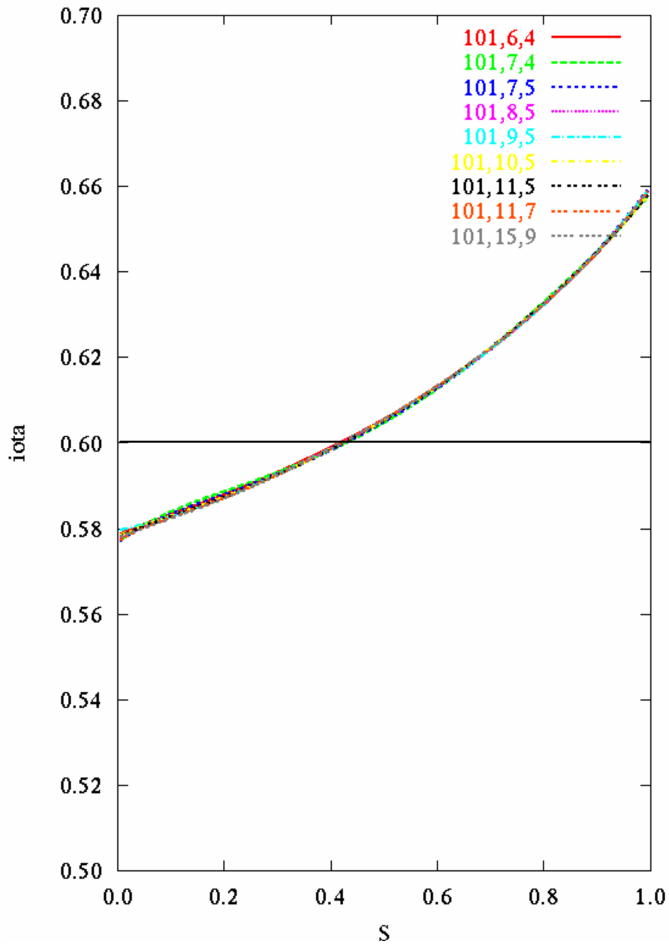
$$w = \frac{D}{2} + \sqrt{\frac{D^2}{4} + | w_p^2 + \varphi \cdot w_v^2 |}$$

$$w_p^2 \propto \frac{p'}{B^2} \cdot \frac{\varepsilon_{m,n}}{m\iota'^2} \cdot \frac{A_l^2}{-\Delta'}$$

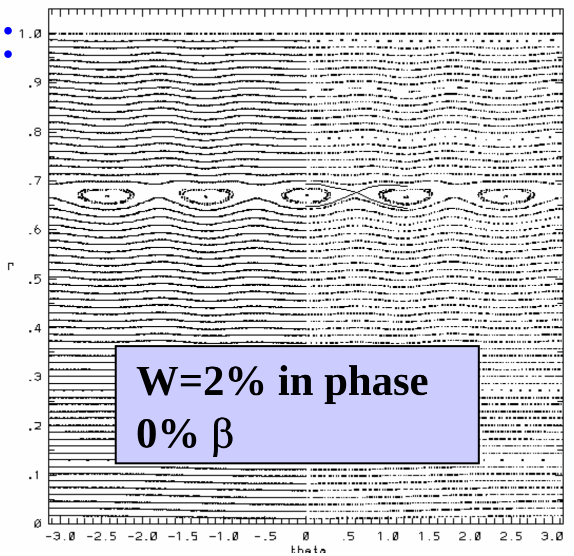
$$w_v^2 \propto \frac{B^{\rho}_{m,n}}{m \cdot i'}$$

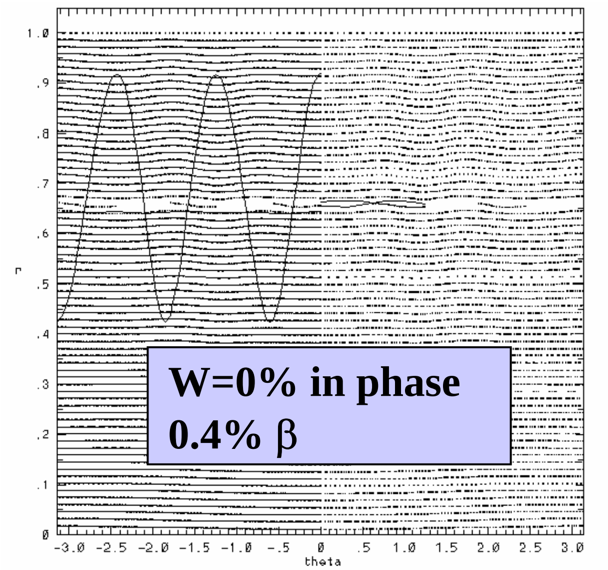
To test the theory and to find the scaling constants for the highly shaped plasmas, we devised a three-field period, A=6 configuration with one "tunable" term for adjusting the size of the vacuum island. The configuration has only one major resonance and is assumed to have no imposed plasma current. It also has a magnetic well of 4%.

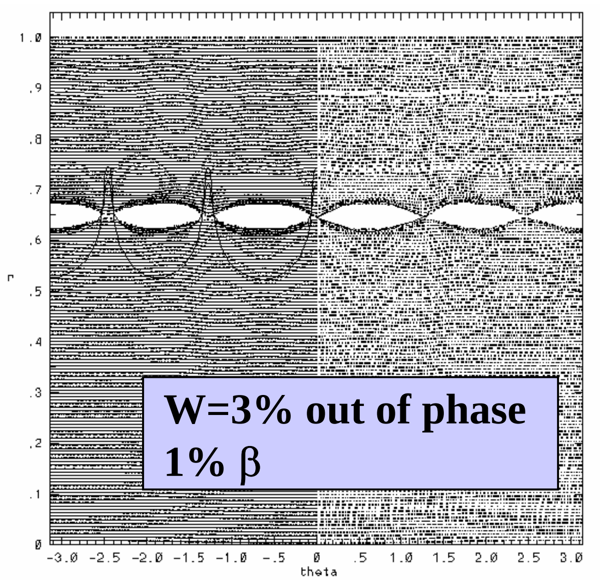


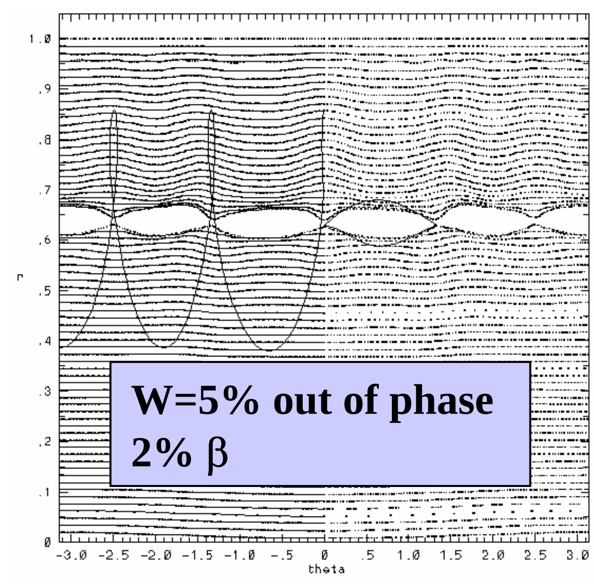


Poincaré plots showing the effects of pressure on the island size (notice the cancellation of vacuum and pressure driven islands at 0.4% β):

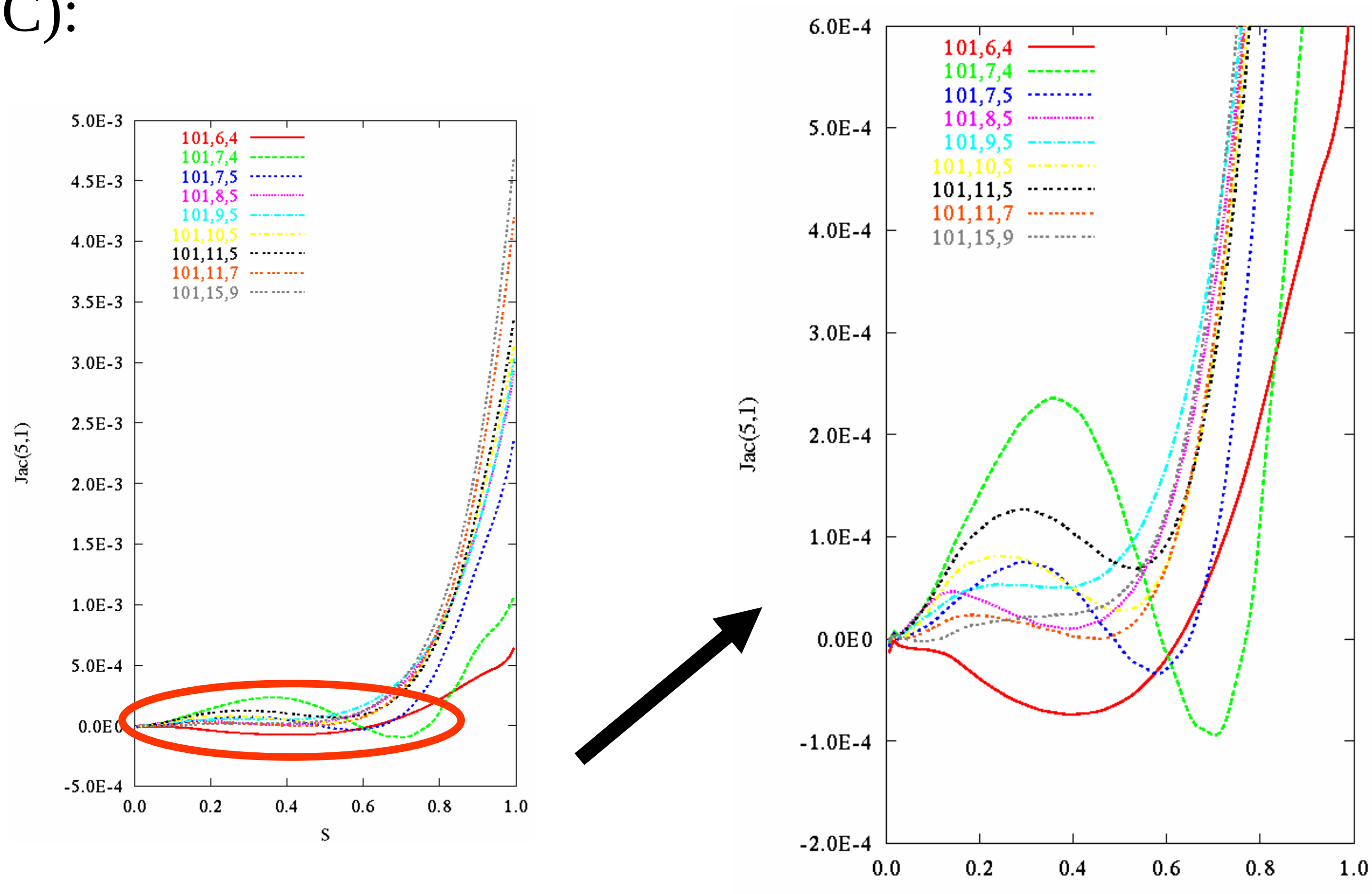








To correlate with the analytic solution, we need to know the resonance Jacobian, but it is very sensitive to the details of the calculation (VMEC):



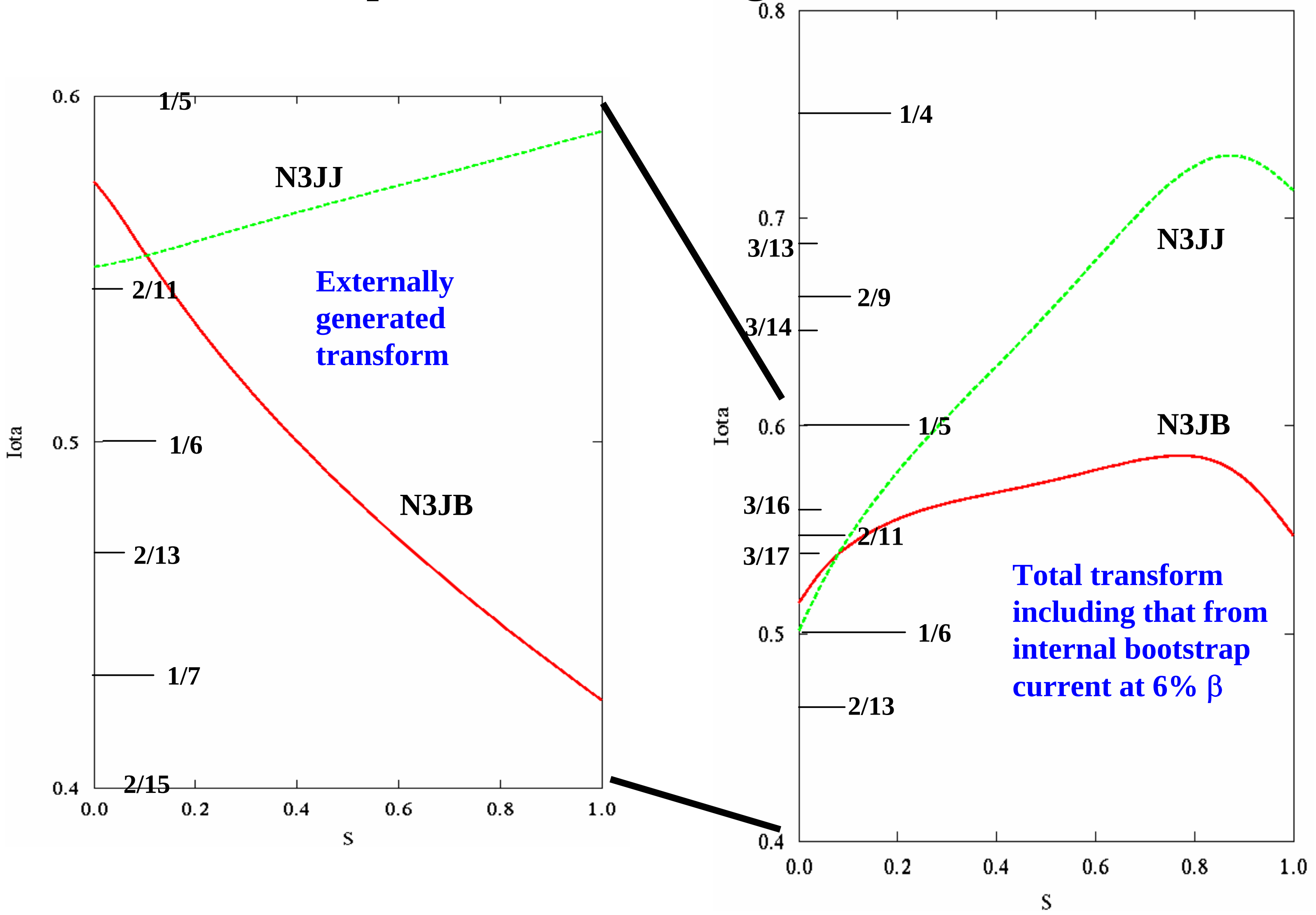
We need to resolve the sensitivity issue before we can move forward to devise a “useable” figure-of-merit in the configuration optimization.

Instead of confronting issues posed by islands, an alternative would be to avoid having low order rational surfaces in the plasma to the degree possible in the design of configurations --

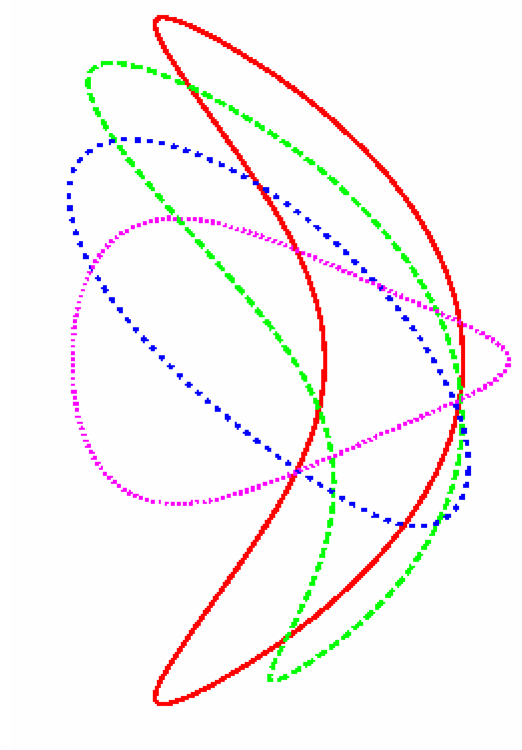
- A novel approach – configurations with steep, negative magnetic shear in vacuum (externally generated) and low, positive shear at full β and full current.

  – QA configurations exist?
  – Island-free regions available?
  – MHD stability properties compatible?
  – Coil solutions exist and coil topology consistent with reactor environment?

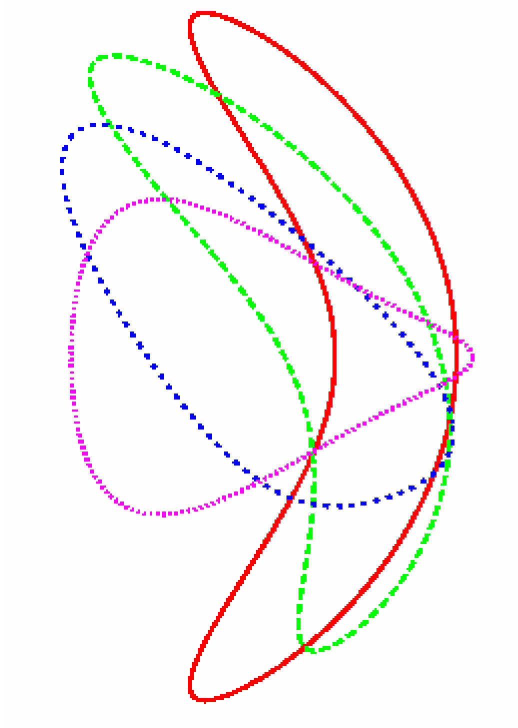
Consider 3-field period, A=6 configurations:



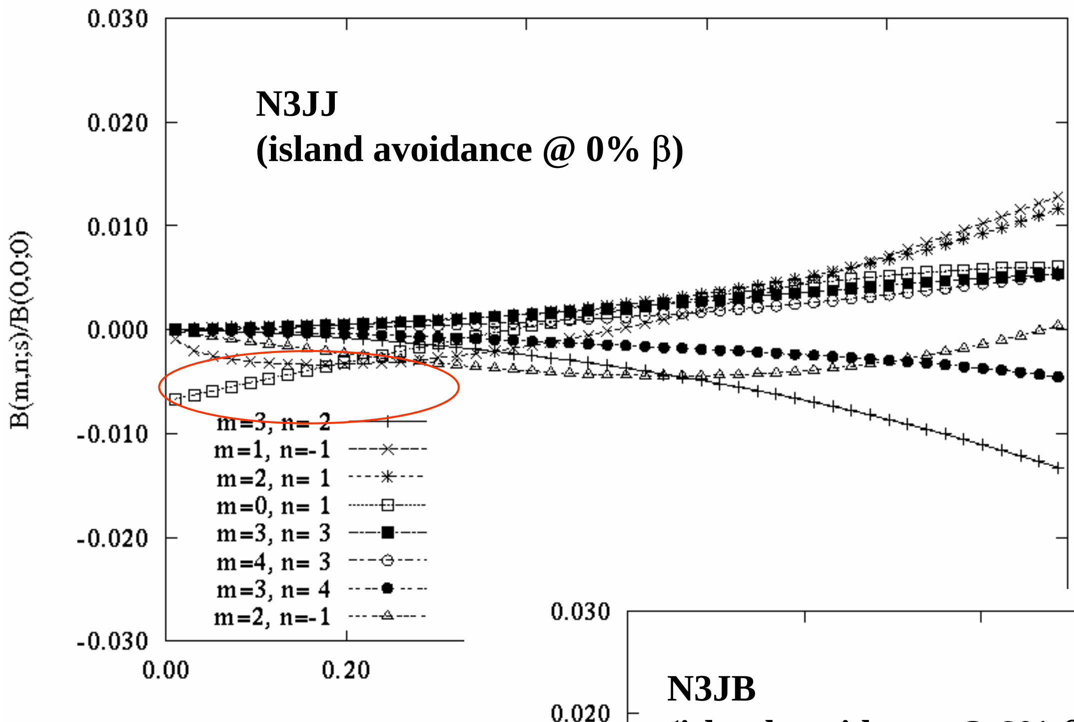
N3JJ
(island avoidance @ 0% β)



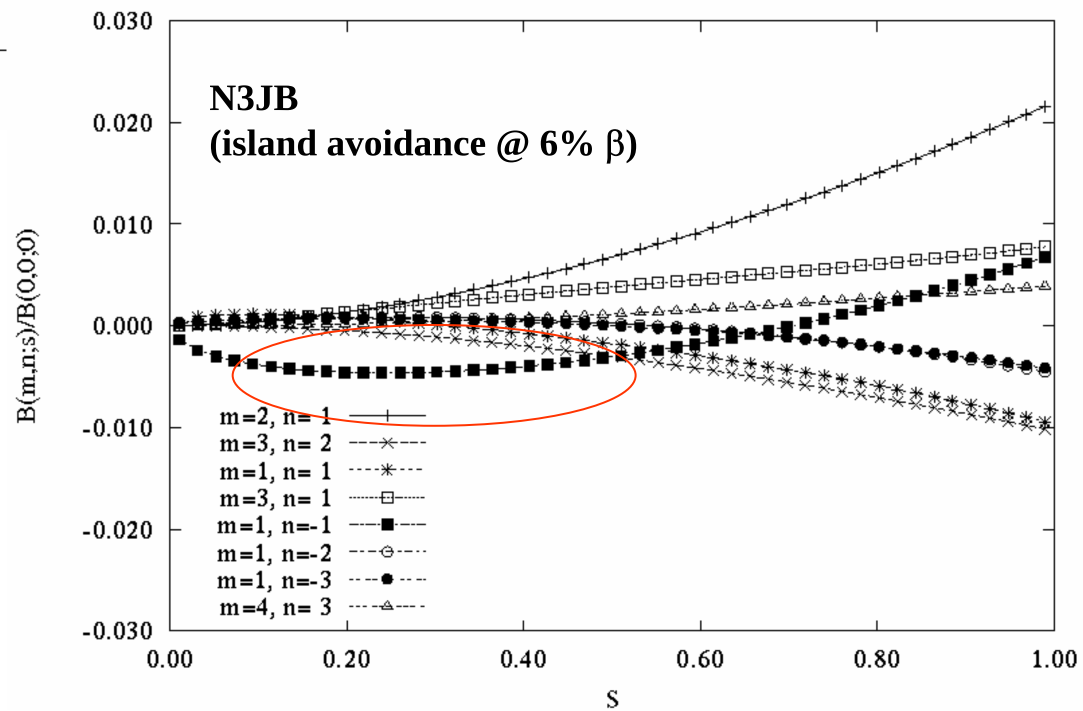
N3JB
(island avoidance @ 6% β)



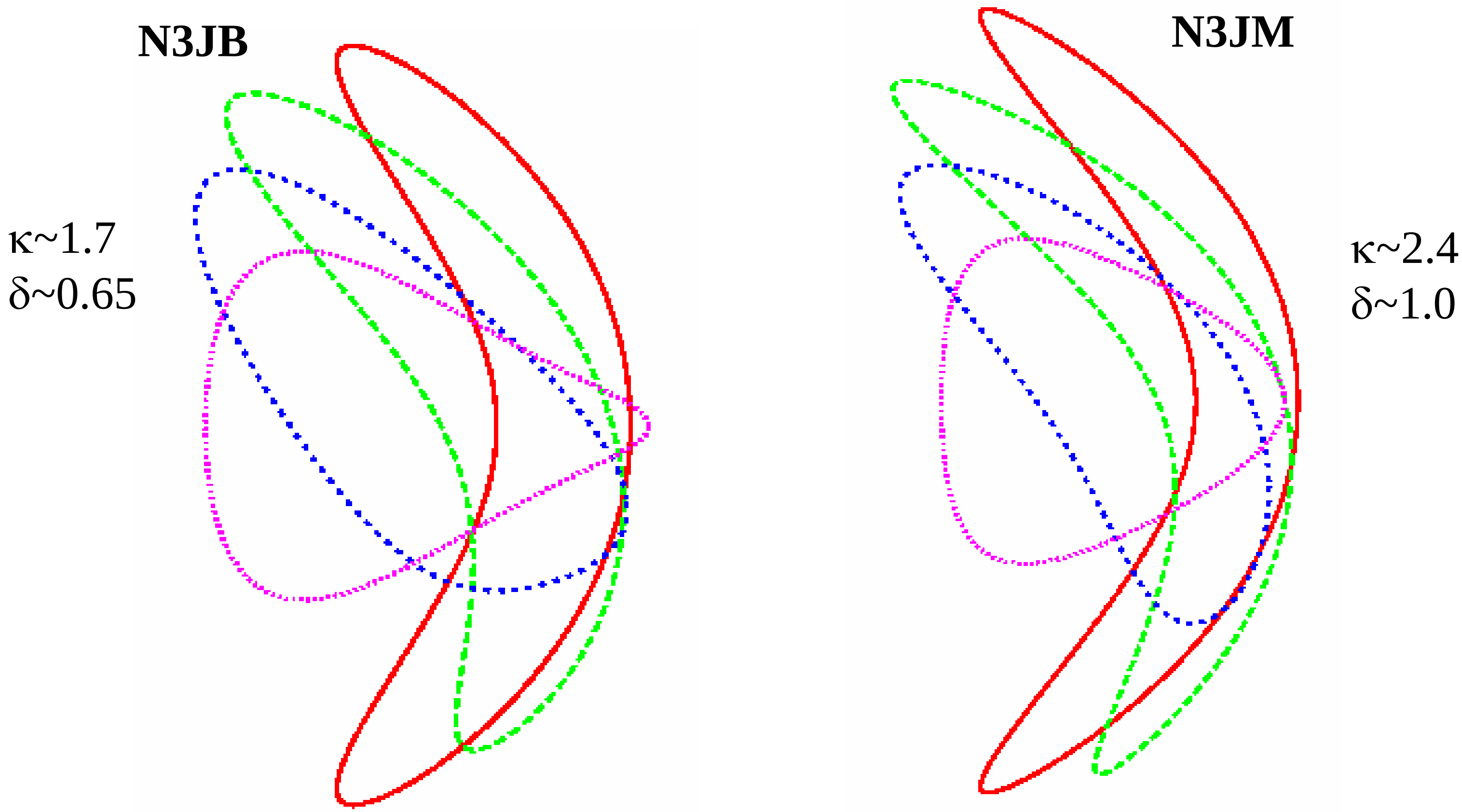
Both are partially optimized with respect to QA with 5% magnetic well at 0% β.

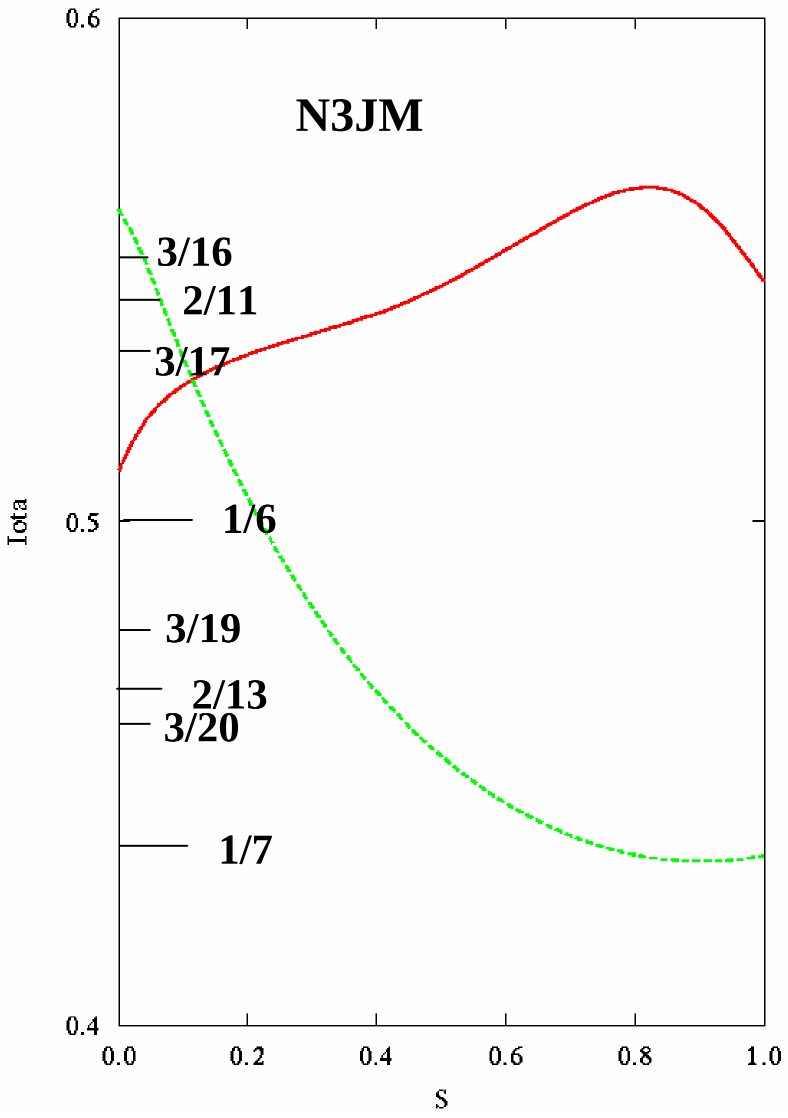


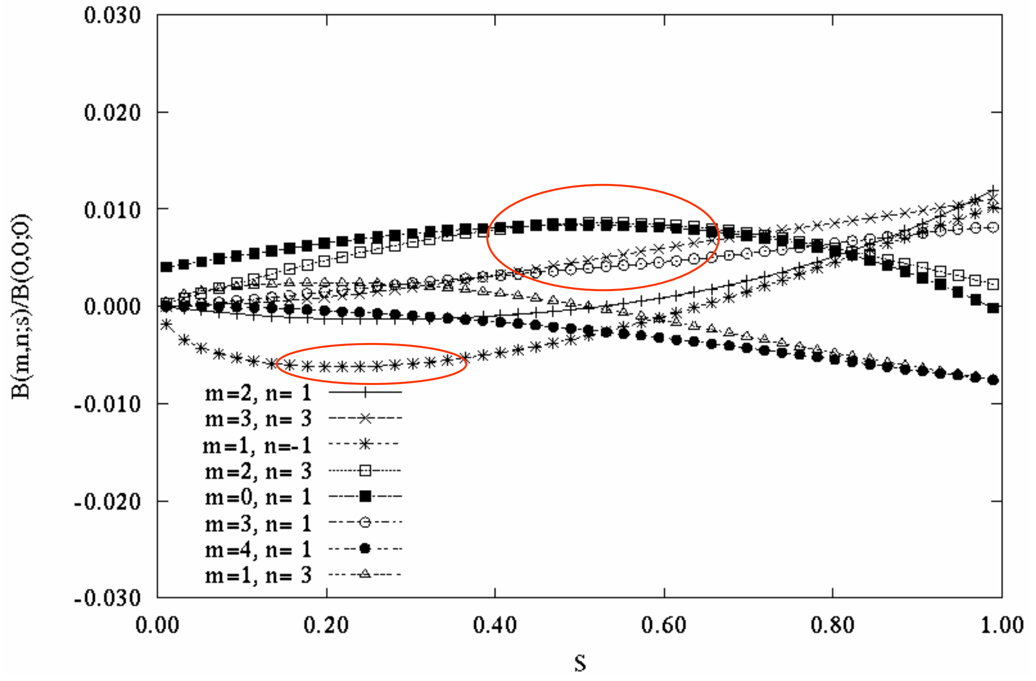
Both have reasonably good QA, but improvements probably will be needed. Typically, QA is harder to achieve for an iota with steeper slope.



Further improvement of N3JB (avoidance of major islands at 6% β) with respect to QA and MHD stability leads to increased elongation and triangularity (without introducing high order terms in plasma shaping).

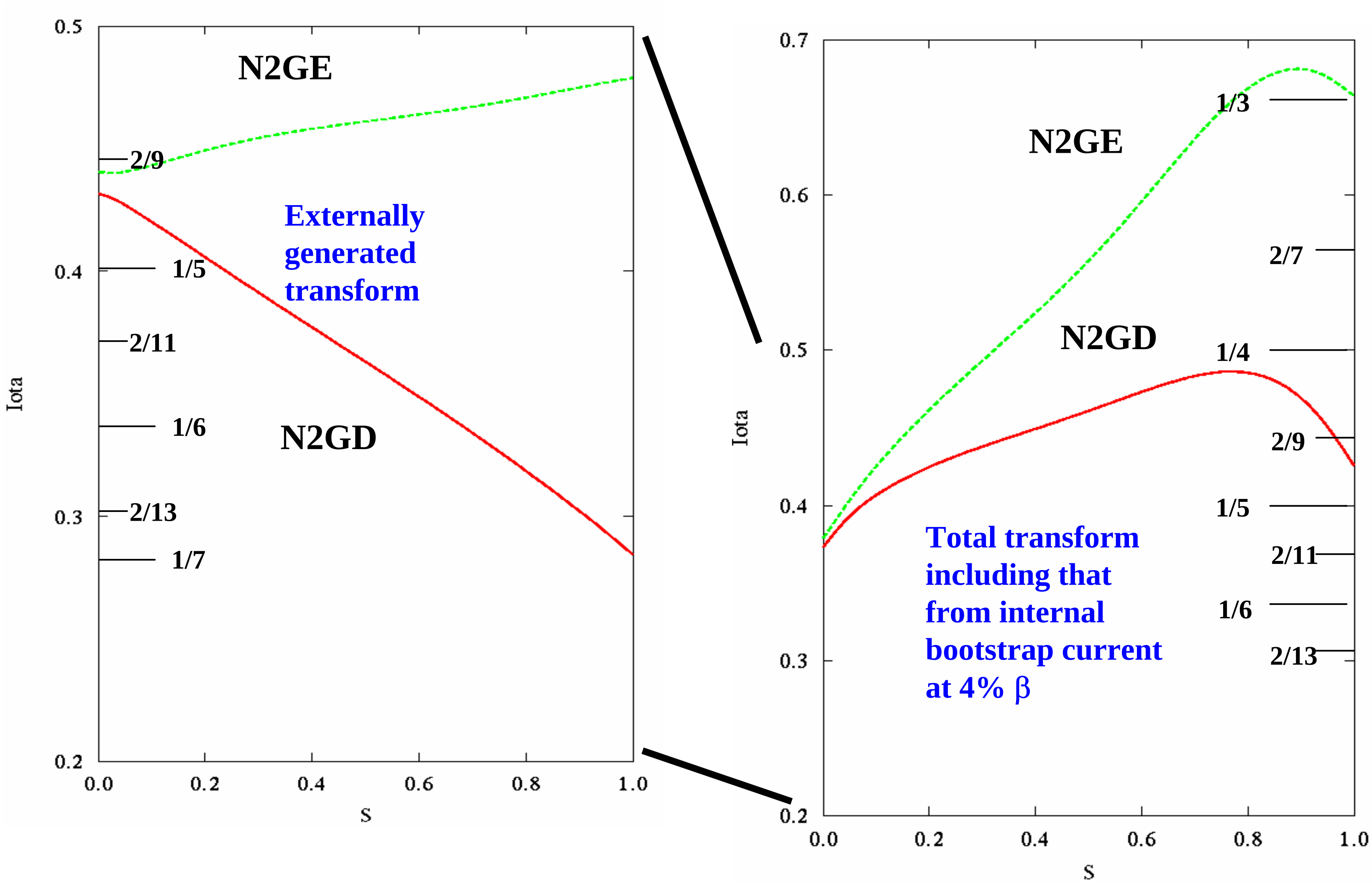






Minimization of negative shear at full current, full beta results in a nearly “up-turn” vacuum iota near the edge. QA clearly needs more work.

Two-field period configurations with similar characteristics may exist for ι≤0.5, but the width of regions free of low order rational surfaces may be too narrow to make good configurations hard to come by.



Summary and future work

- Equilibrium β limit for the 3-field period configurations under consideration appears to be quite high, even with the presence of n=1 islands.

- To minimize the deleterious effects of islands, the sizes of large islands need to be controlled in configuration development. Implementation of an effective figure-of-merit is being considered.

- We propose to examine a new class of QA configurations which attempts to avoid as much as possible the low order rational surfaces at full beta and full current. Initial results are encouraging, but in-depth analyses and further configuration development are needed.