Configuration Development
-- High Iota Configurations --

L. P. Ku

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Princeton Plasma Physics Laboratory

Our Task and Accomplishment

- Charge from March project meeting:
  - Develop “high” iota QA configurations having better performance than C82 to feed into the decision point on June 1 for new configuration selection.

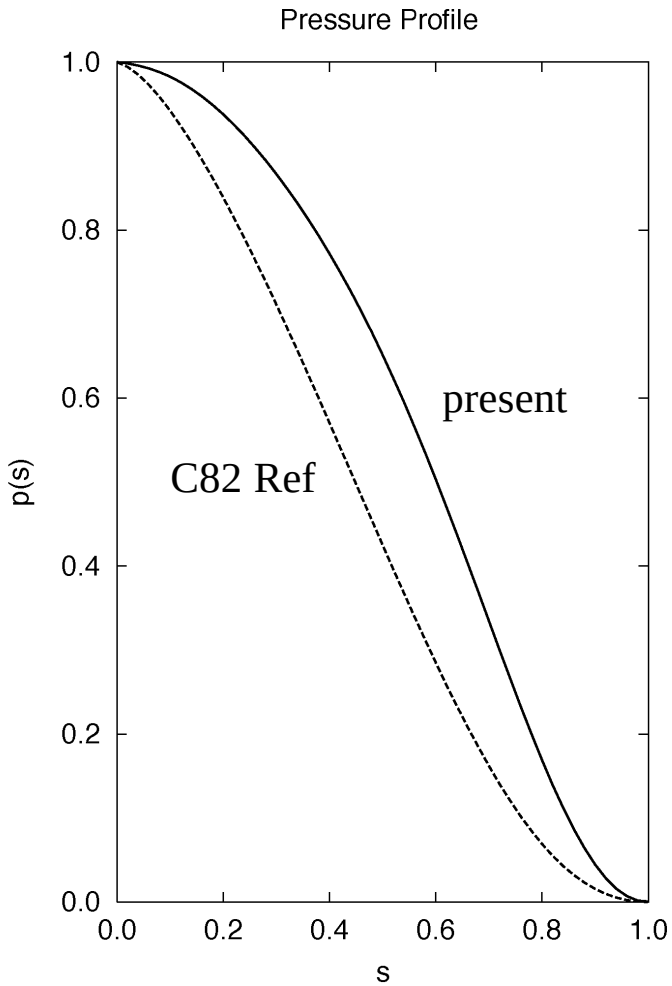
- We have successfully generated a family of QA configurations with
  - external rotational transform in the range of 0.4 to 0.6
  - aspect ratios between 4.5 and 5.5
  - attractive transport properties and coil complexity measures

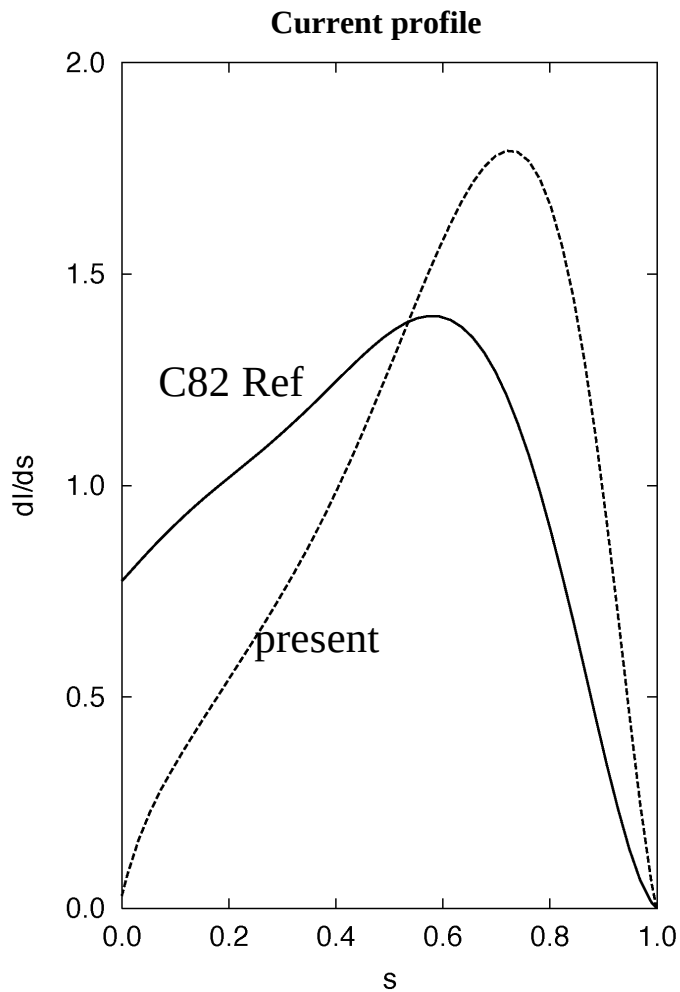
Basic design goals are the same as before and more.

- aimed at satisfying:
  - monotonically increasing ι
  - stable to external kink, vertical, Mercier and infinite-n ideal ballooning modes @ ~4% β.
  - “good” quasi-symmetry, τ (neo-classical)>> τ (ISS95)

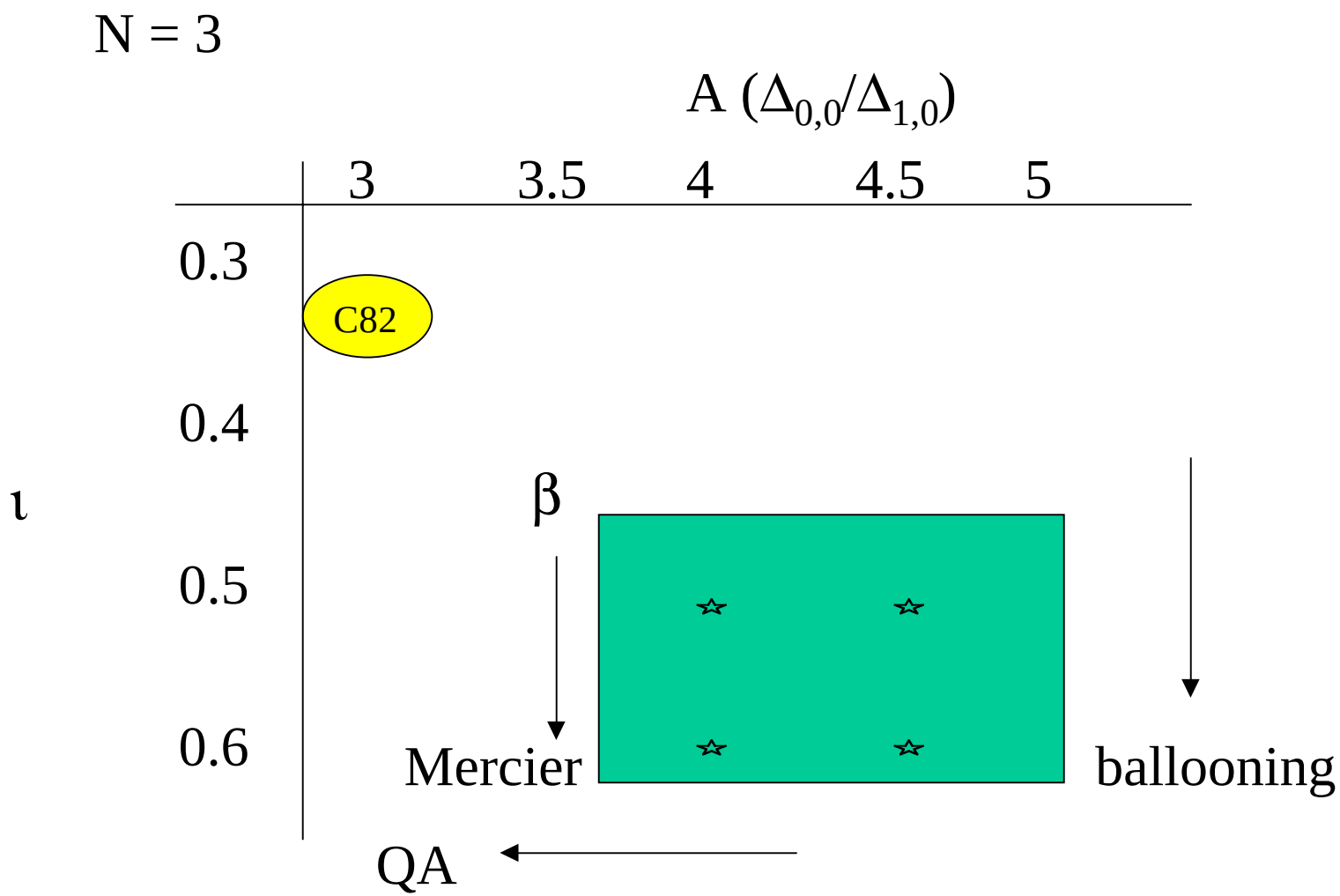
- also with an eye on:
  - less complex surface, hence simple coil topology
  - robustness

A broader pressure profile and consequently a more outward shifted current profile are used as the reference.





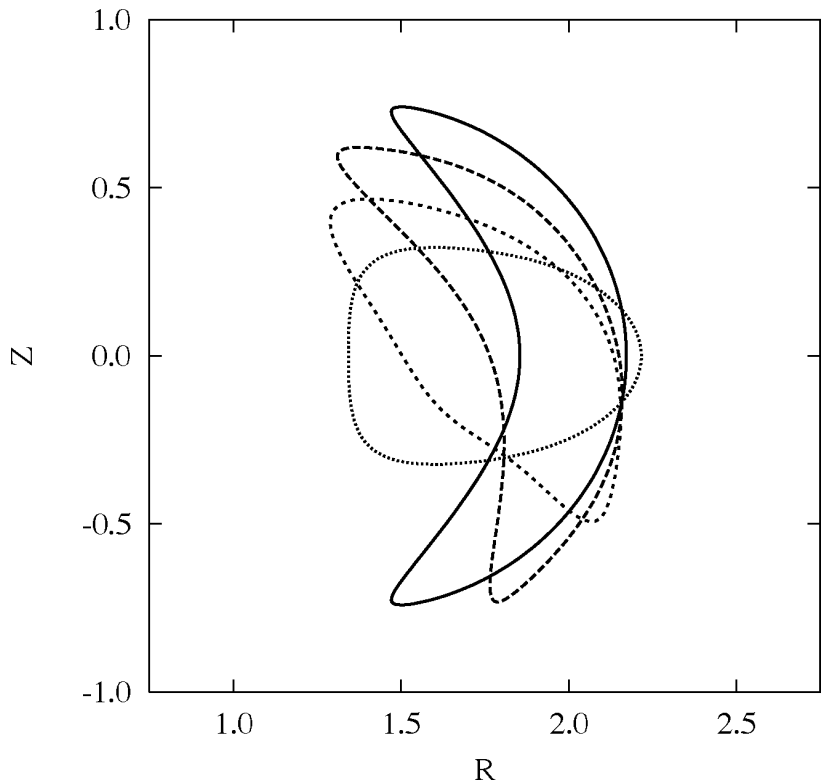
General trend in the configuration space studied



Comparison of Configurations

	II28_253	LI45_200	II75_286	LI65_136	C82
	ι (avg)=0.6 A=5.2 R=1.93 $\langle a \rangle$=0.37	ι (avg)=0.5 A=5.1 R=1.91 $\langle a \rangle$=0.37	ι (avg)=0.6 A=4.76 R=1.82 $\langle a \rangle$=0.38	ι (avg)=0.5 A=4.73 R=1.81 $\langle a \rangle$=0.38	ι (avg)=0.35 A=3.43 R=1.46 $\langle a \rangle$=0.43
MHD stability	ballooning limited β=3.5%	ballooning limited β=4.0%	Mercier limited β=4.0%	Mercier limited β=4.0%	kink limited β=4.0%
Transport	$\chi^2=2.5\cdot10^{-4}$ $\lvert B_{mn}\rvert < 1.5\%$ τ^{NC}=29 ms	$\chi^2=3.8\cdot10^{-4}$ $\lvert B_{mn}\rvert < 2.0\%$ τ^{NC}=24 ms	$\chi^2=1.4\cdot10^{-4}$ $\lvert B_{mn}\rvert < 2.0\%$ τ^{NC}=26 ms (?)	$\chi^2=1.7\cdot10^{-4}$ $\lvert B_{mn}\rvert < 2.0\%$ τ^{NC}=27 ms	$\chi^2=1.9\cdot10^{-4}$ $\lvert B_{mn}\rvert < 3.3\%$ τ^{NC}=18 ms
Coils	$\langle M \rangle$=2.2 J_{max}=0.84 ε_{max}=2.1%	$\langle M \rangle$=3.1 J_{max}=1.7 ε_{max}=2.3%	$\langle M \rangle$=2.0 J_{max}=0.88 ε_{max}=2.2%	$\langle M \rangle$=2.0 J_{max}=0.74 ε_{max}=1.8%	$\langle M \rangle$=3.1 J_{max}=1.2 ε_{max}=3.0%

Configuration QAS3_LI65_136



A = 4.76

R = 1.8 m

<a> = 0.382 m

a_{min} = 0.16 m

<B> = 1.13 T

Ip = 120 kA

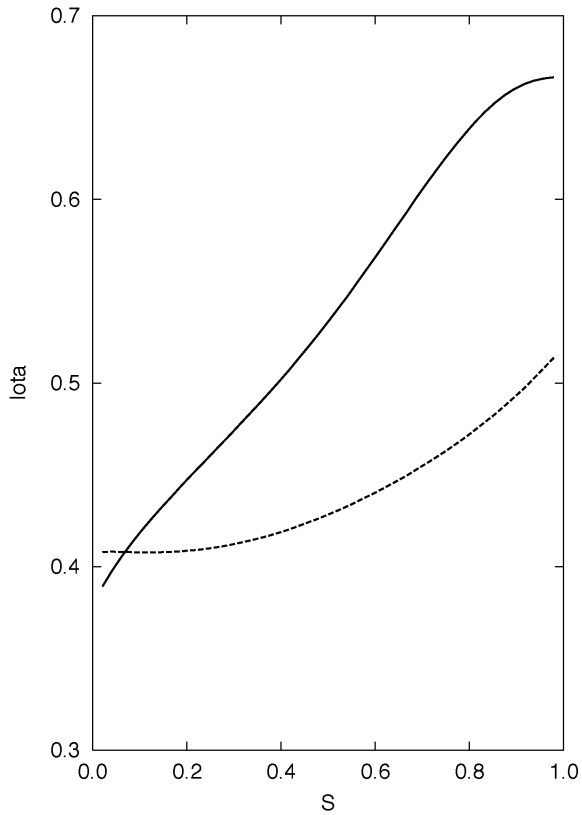
κ_{eff} = 4.3@ ϕ=0

Δ_R/R = 0.127 (ϕ=0, π)

Some important boundary parameters $\Delta_{m,n}$

$\Delta_{0,0} = 1.00$	normalized minor radius
$\Delta_{1,0} = 4.03$	major radius = aspect ratio
$\Delta_{2,0} = -0.26$	axi-symmetric elongation, κ=1.72
$\Delta_{3,0} = 0.10$	axi-symmetric triangularity, δ=0.66
$\Delta_{-1,0} = 0.14$	
$\Delta_{4,0} = 0.04$	axi-symmetric squareness
$\Delta_{2,1} = -0.42$	“helical ellipse”, main component generating transform
$\Delta_{3,1} = 0.12$	
$\Delta_{-1,-1} = 0.13$	crescent, well
$\Delta_{3,2} = 0.08$	shear, well
$\Delta_{0,1} = 0.05$	
$\Delta_{0,-1} = 0.05$	
$\Delta_{4,2} = -0.02$	
$\Delta_{4,3} = -0.02$	

With the reference pressure and current, iota profile is monotonically increasing.



4% β, 120 kA

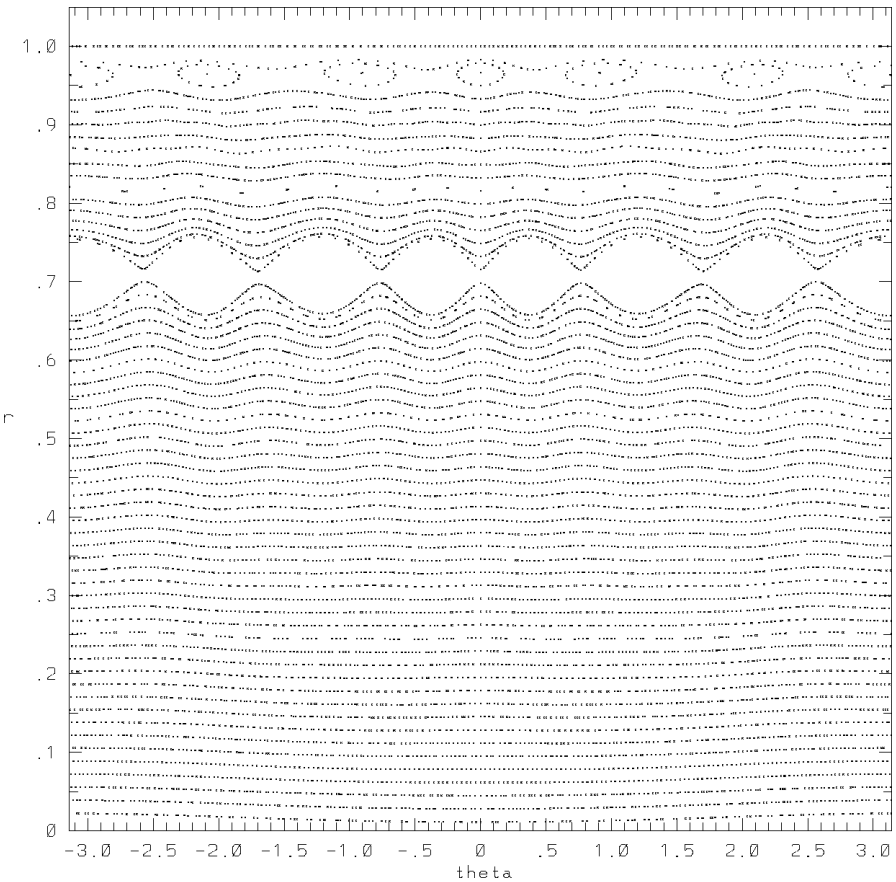
ι crosses 3/7, 3/6 and 3/5 resonances.

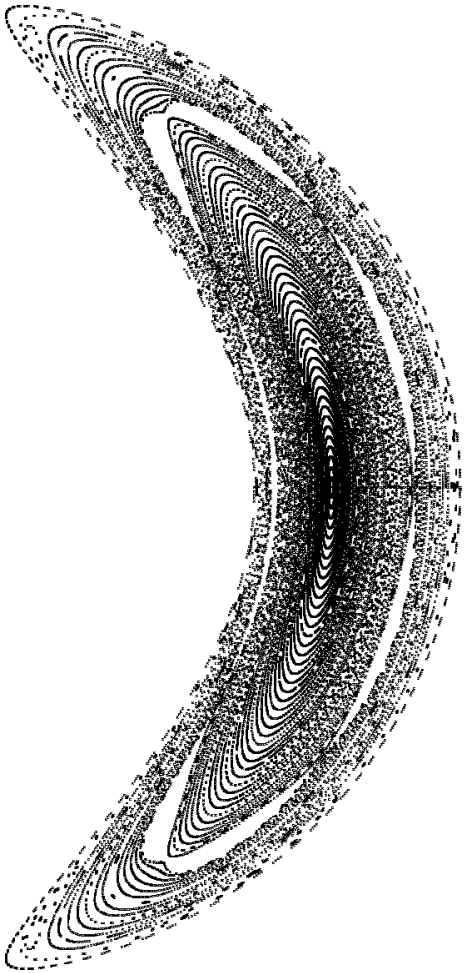
6/9 right at boundary

vacuum

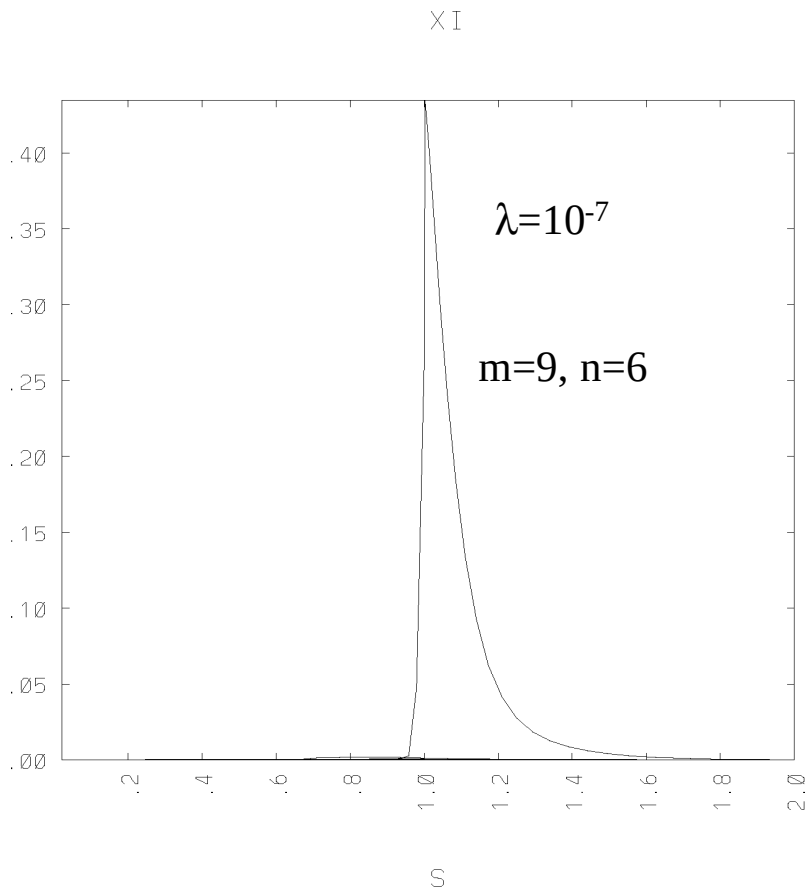
ι crosses 3/7; 3/6 right inside boundary

Fixed-boundary PIES calculation for the vacuum shows that 3/7 resonance is more of a problem than 3/6.

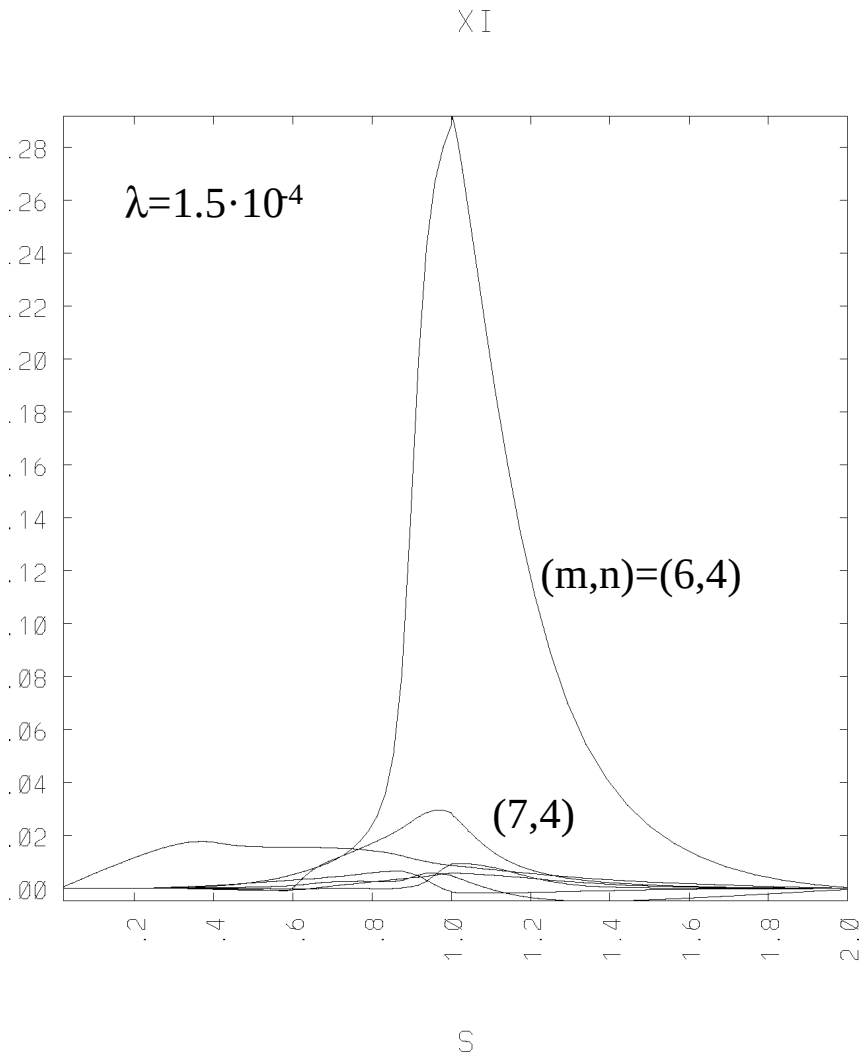




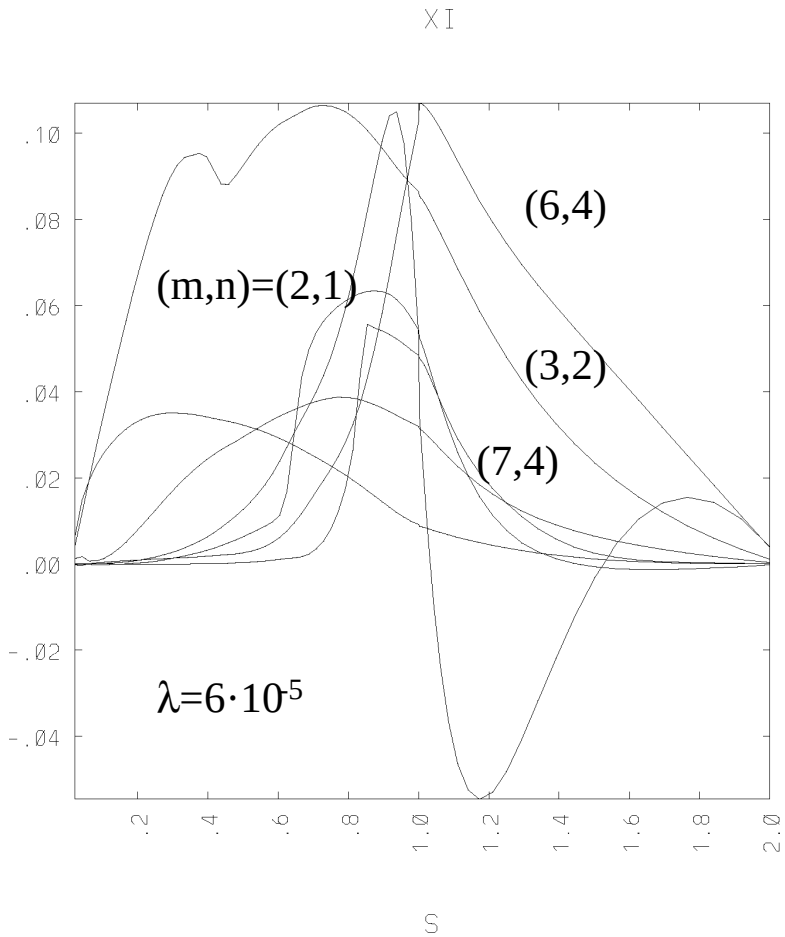
QAS3_LI65_136 is stable to kink modes for Ip < 125 kA and β < 5.5%.



A marginally unstable mode was found under periodicity preserving condition at β=4% and Ip=120 kA

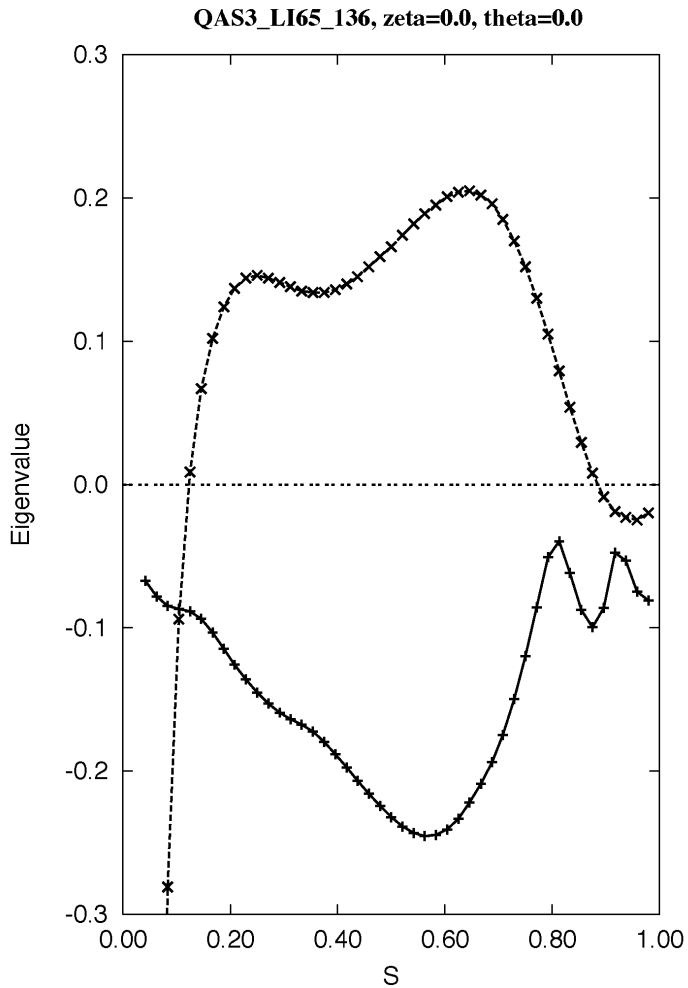


For Ip> 125 kA, external kinks become unstable, dominated by the ι=0.667 resonance. This figure illustrates the eigenfunction from a Terpsichore calculation with β=4%, Ip=125 kA.



For β>5.5% at fixed Ip=120 kA, external kinks again become unstable, dominated by ι=0.5 and 0.667 resonances. This figure illustrates the eignenfunction from a Terpsichore calculation at β=5.5%.

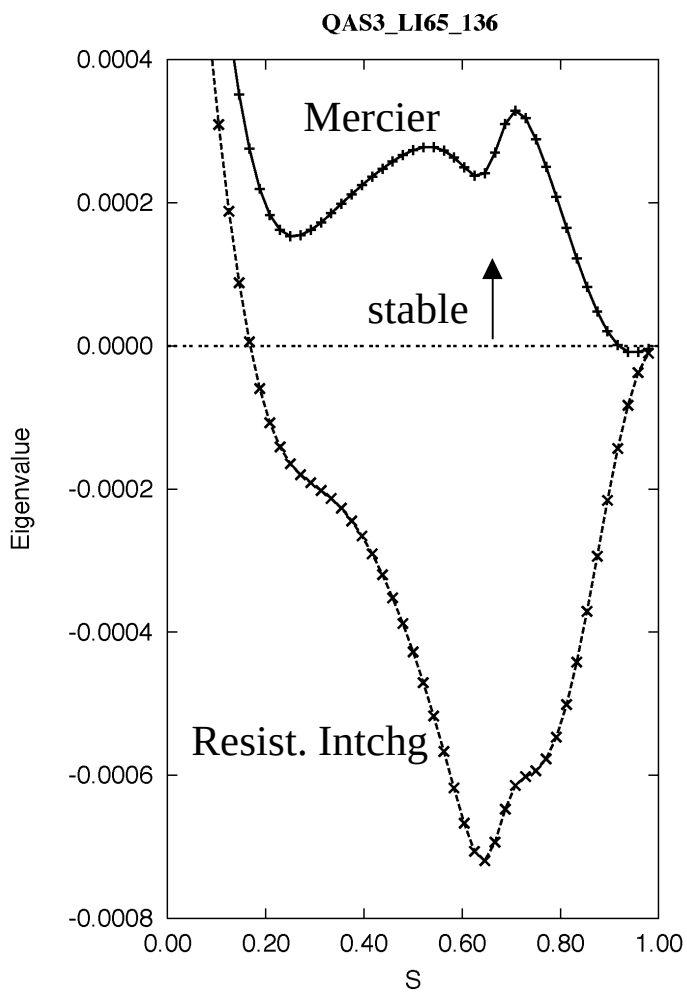
LI65_136 is essentially stable to ballooning and Mercier modes at reference β and Ip.



Mercier stability from a VMEC calculation. The instability for s<0.1 may be numerical since JMC and Terpsichore calculations do not show instability.

Ballooning stability from a Cobra calculation for field line label α=0, θ=0. The ballooning (infinite n) becomes unstable for β >4%.

LI65_136 is unstable to resistive interchange at all beta and current levels.

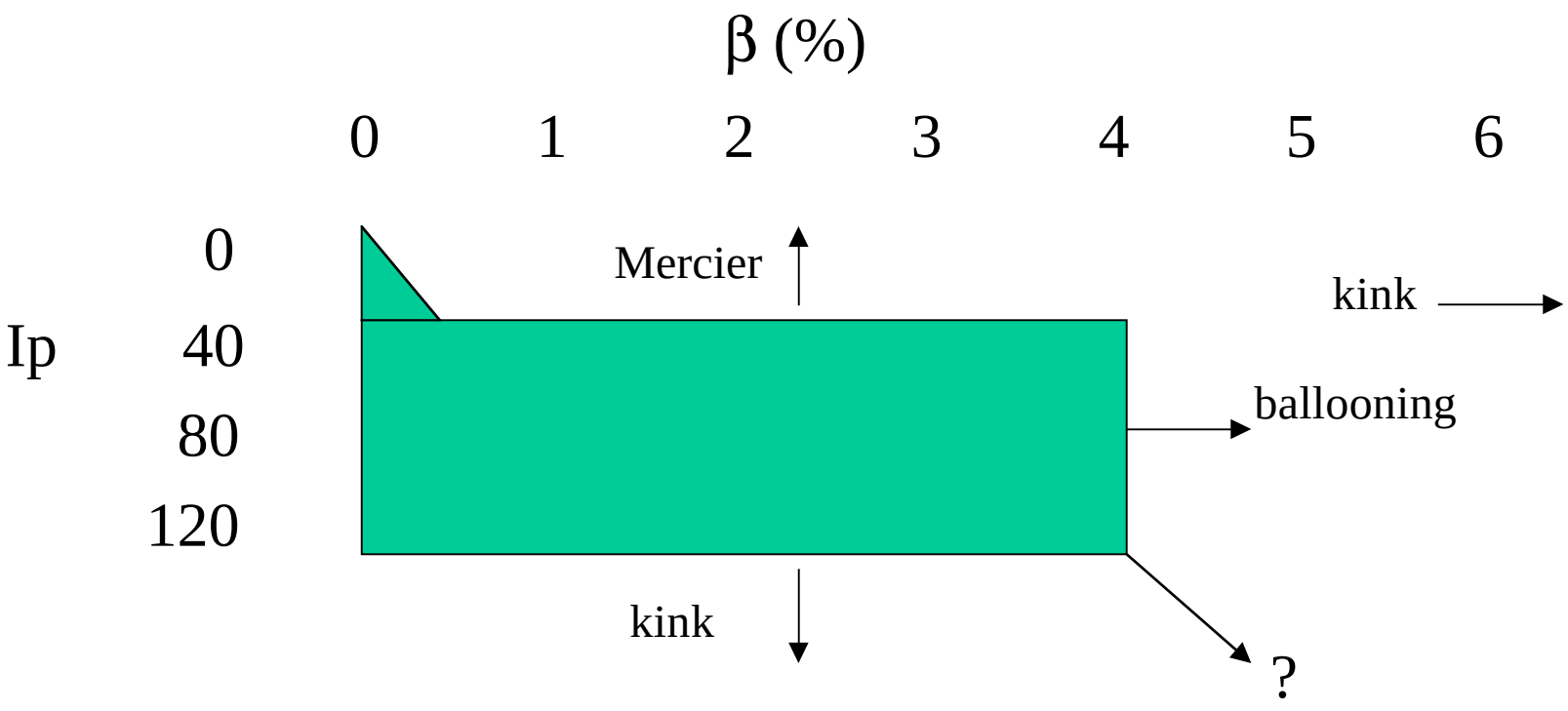


JMC calculation (with detuning) at β = 4% and Ip=120 kA.

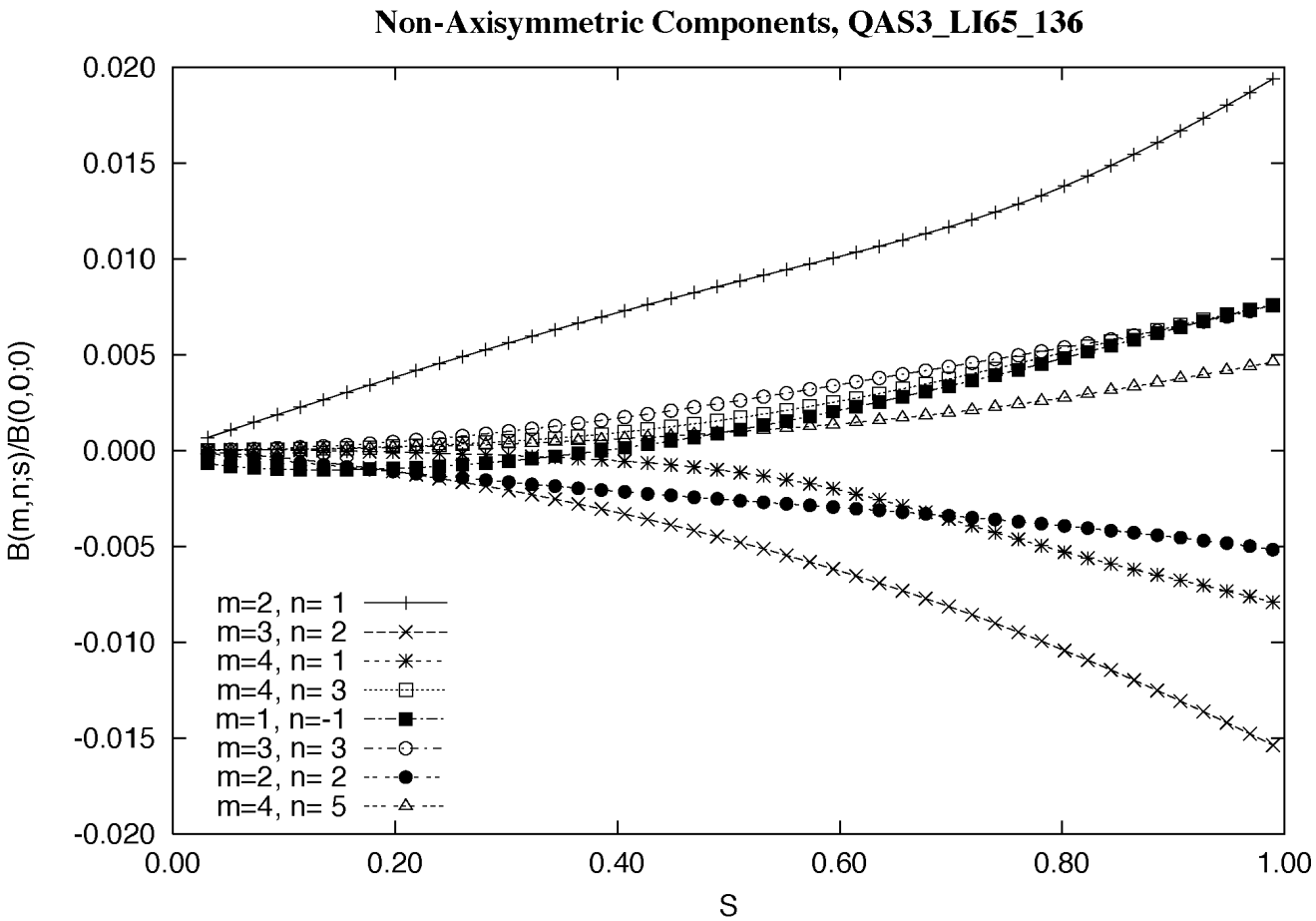
Mercier is unstable without currents for β as low as 1%. To be Mercier stable, Ip>40 kA.

Resistive interchange may be stabilized with a vacuum magnetic well > 3%.

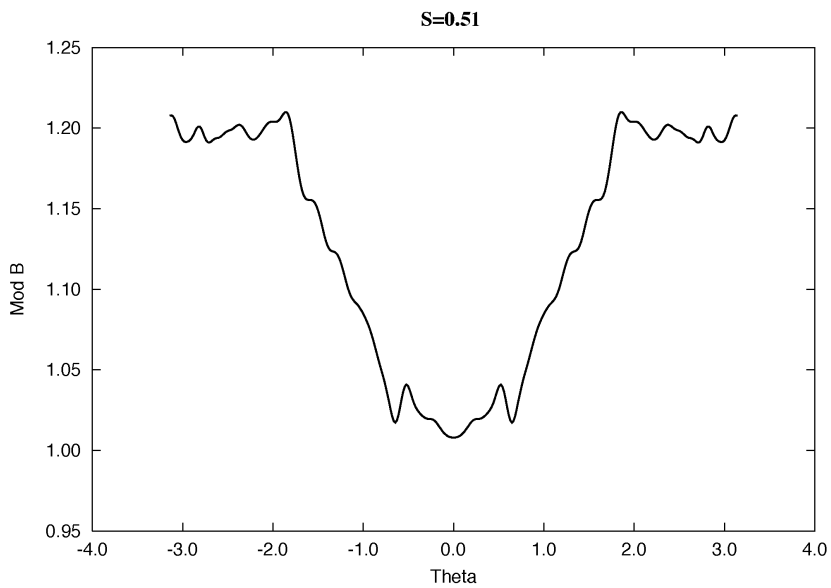
Stability boundary for LI65_136 (resistive interchange not included)

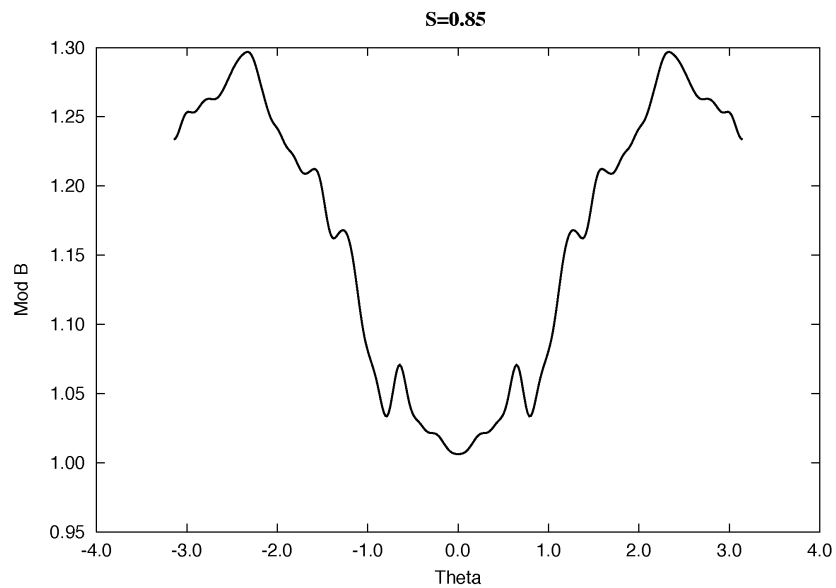


LI65_136 has excellent quasi-symmetry. The largest n≠0 harmonic in the magnetic spectrum is < 2%.



Mod B along field lines are smooth with few secondary ripple wells even for s~0.8.





LI65_136 thus has comparably better thermal and energetic particle energy confinement.

- GTC neo-classical confinement calculations for D at 4% β with fixed n_0R/T_0^2 , n, T profiles, and B:

  – LI65_136: R=1.9 m, T_0=2.3 keV, n_0=0.625·10^{20} m^{-3},
  <a>=0.382 m, ι_e=0.67
  » τ_{Ei} = 27 ms

  – C82: R=1.5 m, T_0=2.14 keV, n_0=0.673·10^{20} m^{-3},
  <a>=0.426 m, ι_e=0.47
  » τ_{Ei} = 18 ms

LI65_136 has more margin for neo-classical transport relative to ISS95 than C82.

$$\frac{\tau_{\mathrm{Ei}}^{\mathrm{NC}}(\mathrm{LI65_136})}{\tau_{\mathrm{Ei}}^{\mathrm{NC}}(\mathrm{C82})} = 1.5 \qquad \frac{\tau_{\mathrm{E}}^{\mathrm{ISS95}}(\mathrm{LI65_136})}{\tau_{\mathrm{E}}^{\mathrm{ISS95}}(\mathrm{C82})} = 1.02$$

$$\frac{\tau_{\mathrm{Ei}}^{\mathrm{NC}}}{\tau_{\mathrm{E}}^{\mathrm{ISS95}}}(\mathrm{LI65_136}) = 1.47\ \frac{\tau_{\mathrm{Ei}}^{\mathrm{NC}}}{\tau_{\mathrm{E}}^{\mathrm{ISS95}}}(\mathrm{C82})$$

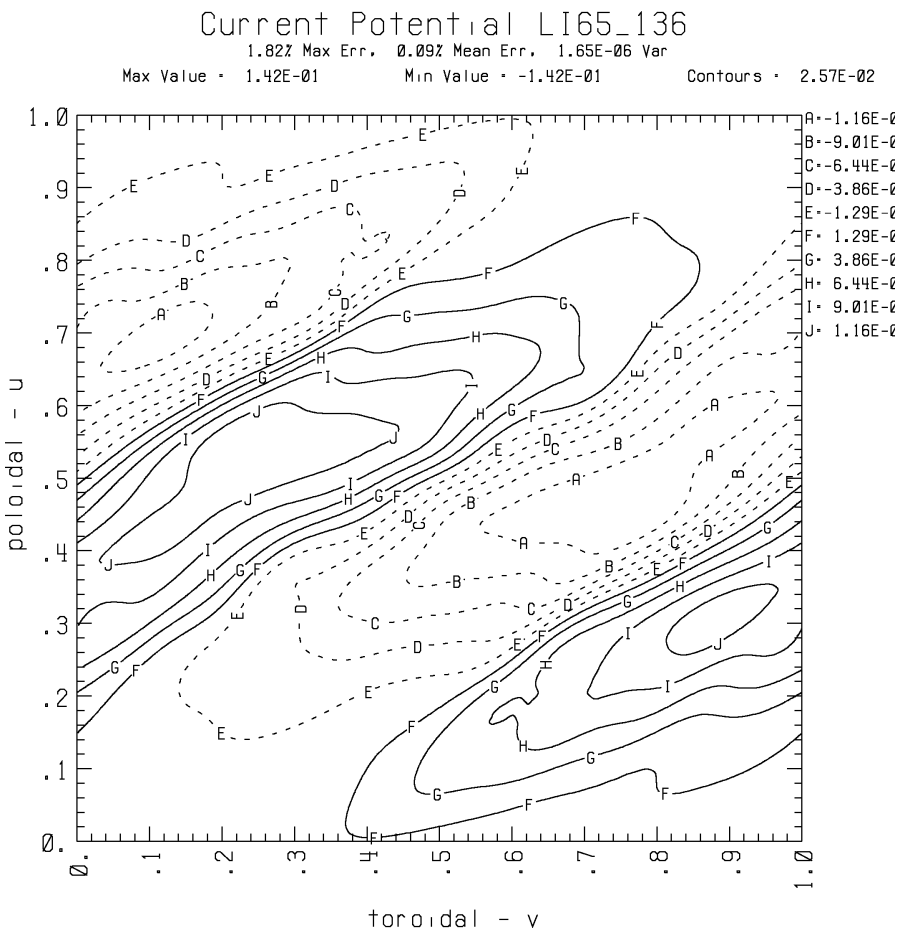
LI65_136 also has better confinement for energetic particles from NBI

- ORBIT3d calculations using 40 keV H with the same deposition profile as that for C82 calculation:
  - Energy loss fraction = 17% (R_t=1.67 m, R_0=1.87 m) for LI65_136

    vs

  - Energy loss fraction = 25% (R_t=1.30 m, R_0=1.50 m) for C82

LI65_136 has less complex current potential contours, lower peak current density, and better fitting errors for coils.



Saddle coils:

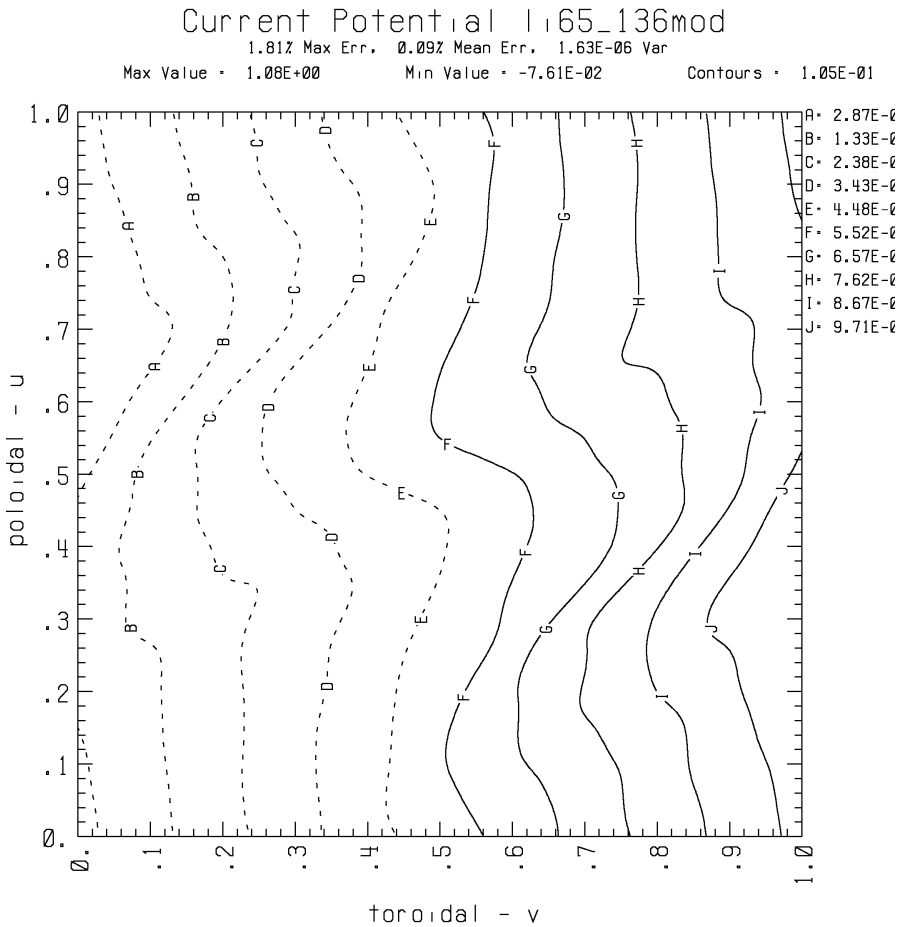
A. Conformal surface, 0.18 m displacement

B. 1/R background field

Current sheet solution:

$\langle m \rangle = 1.98$, $J_{max}/I_{pol} = 0.74$

$\varepsilon_{max} = 1.8\%$, $\varepsilon_{mean} = 0.09\%$



Modular coils:

A. Conformal surface, 0.18 m displacement

Current sheet solution:

$\langle m \rangle = 2.06$, $J_{max}/I_{pol} = 0.72$

$\varepsilon_{max} = 1.8\%$, $\varepsilon_{mean} = 0.09\%$

Work Plans for Next Step

- Complete characterizing present configurations
  - Flux surfaces: PIES calculations at reference β and Ip
  - Bootstrap current: KBSC calculations with axi-symmetric fields
  - Reconstructability: coil cutting and free boundary VMEC analysis
- Improve present configurations
  - MHD stability
    - vacuum magnetic well
    - pressure profile optimization for ballooning

    - external transform modification (edge and center iota, shear) for kink instability avoidance and island size mitigation
  - Transport
    - Optimization using NEO, DKES, ORBIT

- Expand the boundary of present configuration subspace (e.g. number of field periods. aspect ratio, iota)

- Explore other regions of configuration space with different characteristics