Flexibility and Robustness Studies Using the VMEC Free-Boundary Optimizer†

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Introduction

- The coil system for NCSX must be capable of supporting plasmas with a range of current and pressure profiles and of performing a variety of interesting physics experiments.

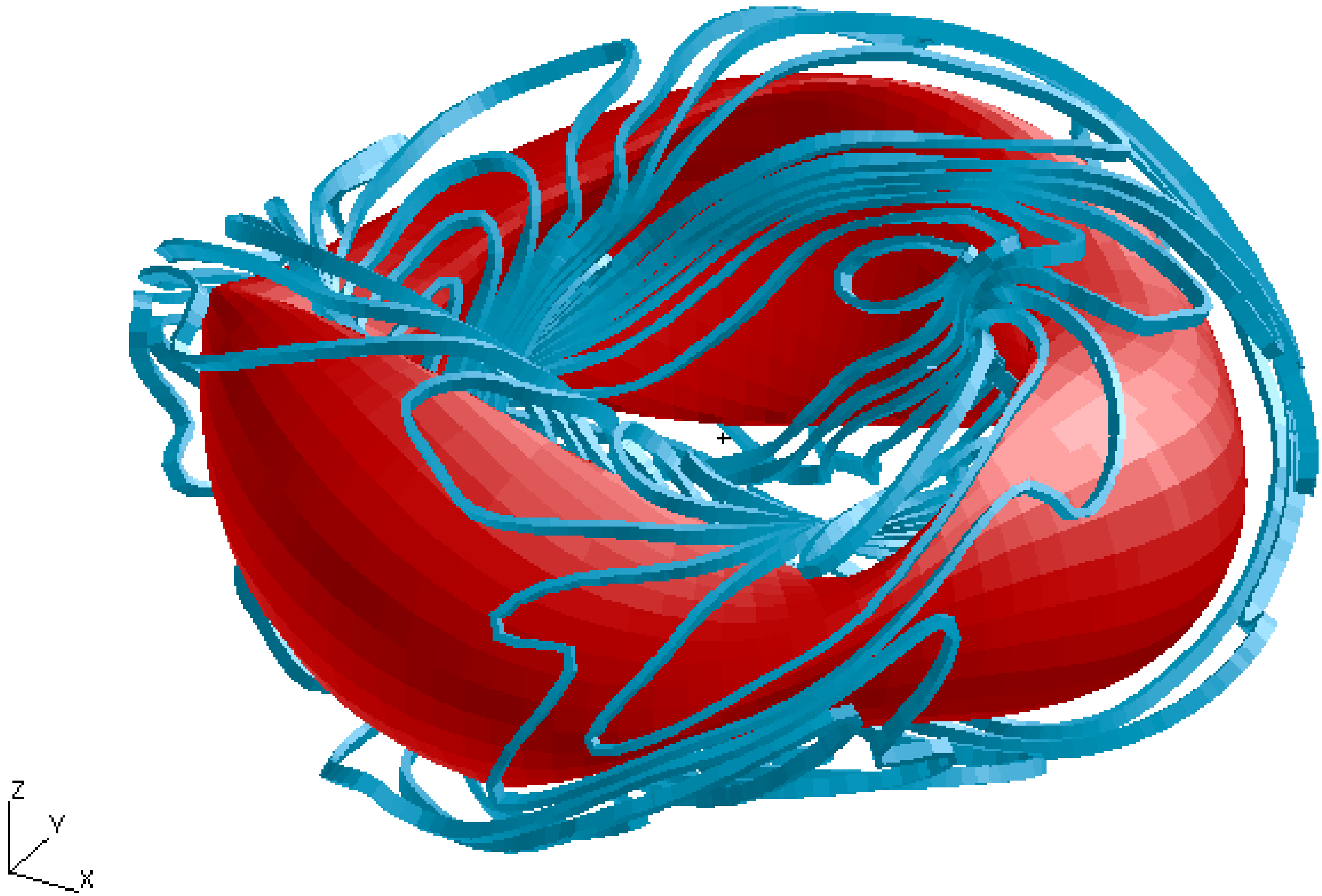
- Using a VMEC based free-boundary optimizer, STELLOPT, we demonstrate the robustness and flexibility of candidate saddle and modular coil designs for NCSX.

Robustness and Flexibility

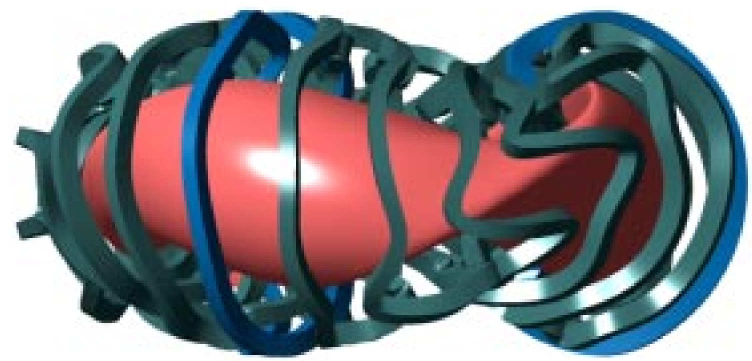
- Robustness – the ability of coils to support equilibria with a wide range of assumed internal profiles (pressure, current).

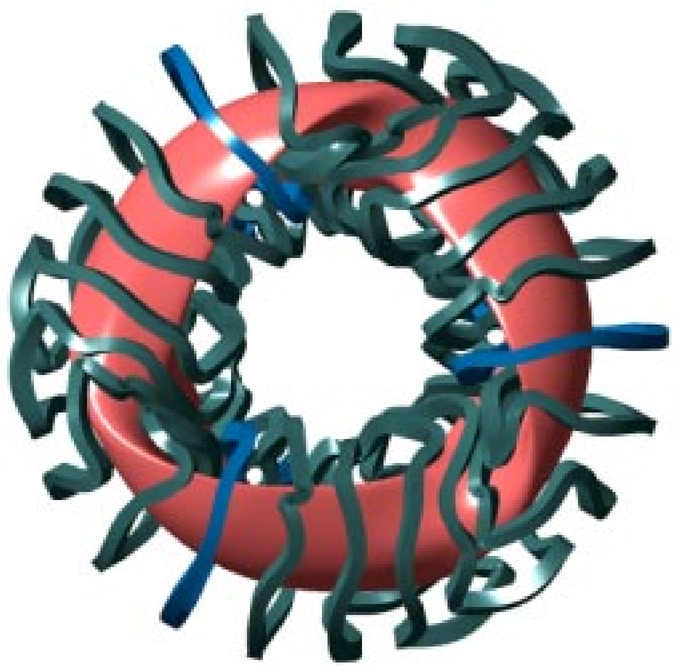
- Flexibility – the ability of coils to produce changes in the plasma configuration which correspond to desired changes in physics properties.

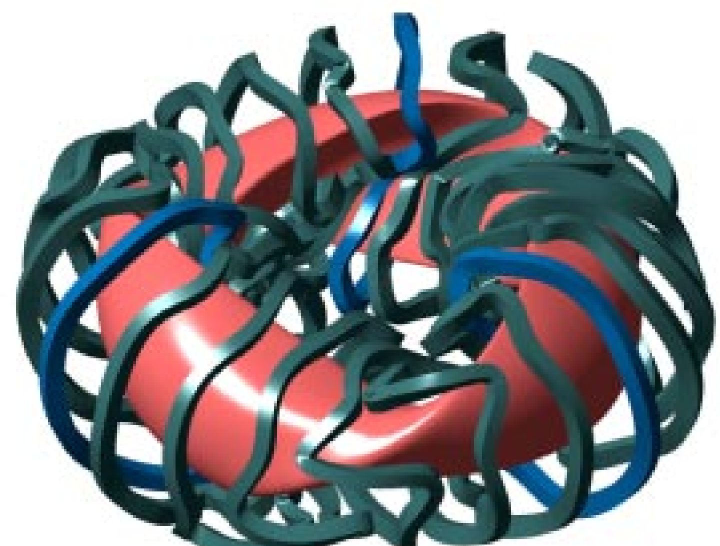
Saddle Coils For LI383



Modular Coils For LI383







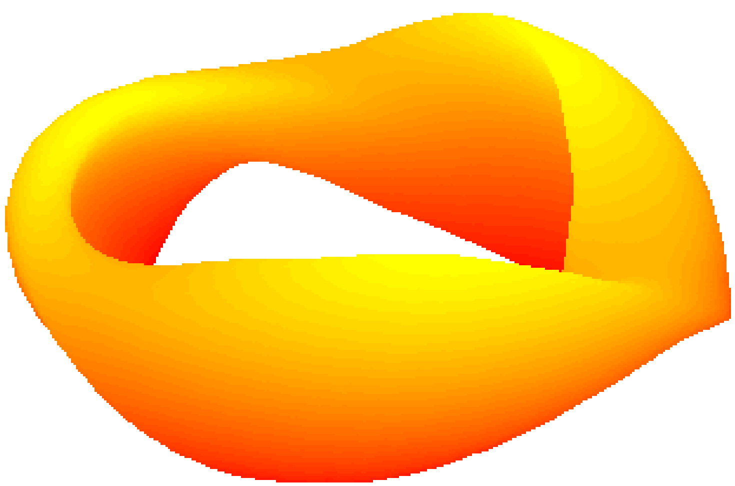
STELLOPT – VMEC Based Free-Boundary Optimizer

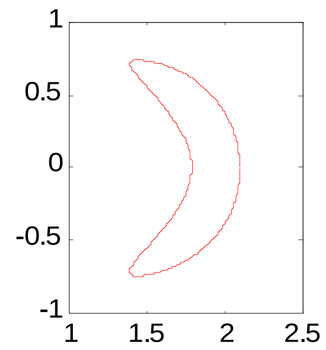
- Levenberg-Marquardt local optimization code
- Multi-processor-capable using UNIX system calls (good portability)
- VMEC 3D - free-boundary equilibrium solver
- TERPSICHORE – evaluates ideal kink stability
- COBRA - evaluates ballooning stability
- SURFSEP – 3D limiter function and plasma boundary constraint
- QAS – Fourier spectrum computed in straight-line (Boozer) coordinates

LI383 Optimized, Fixed-Boundary Properties

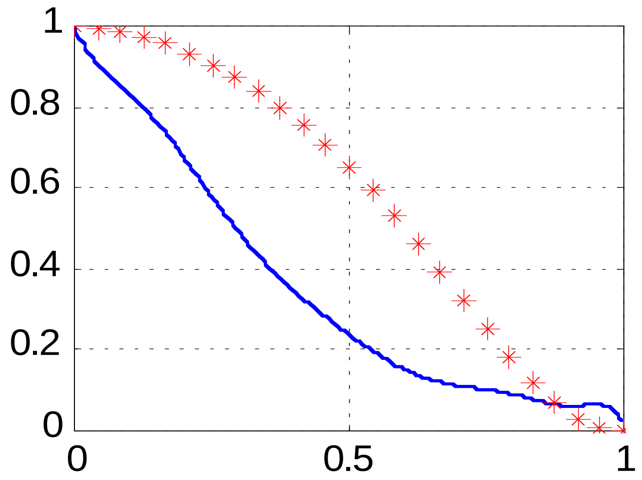
- $A = 4.4$
- $\beta_{max} = 4.1$ % (ballooning limited)
- $I_p = 150$ kA
- $I_p / I_{boot} = 1.12$

- $\iota(0) = 0.40$, $\iota(a) = 0.66$ (full β, full I_p)
- $\iota(0) = 0.45$, $\iota(a) = 0.49$ (vacuum)
- R (fixed volume) = 1.70 m
- <horiz. half-width> = 39.0 cm
- $(\text{horiz. half-width})_{min}$ = 16.0 cm





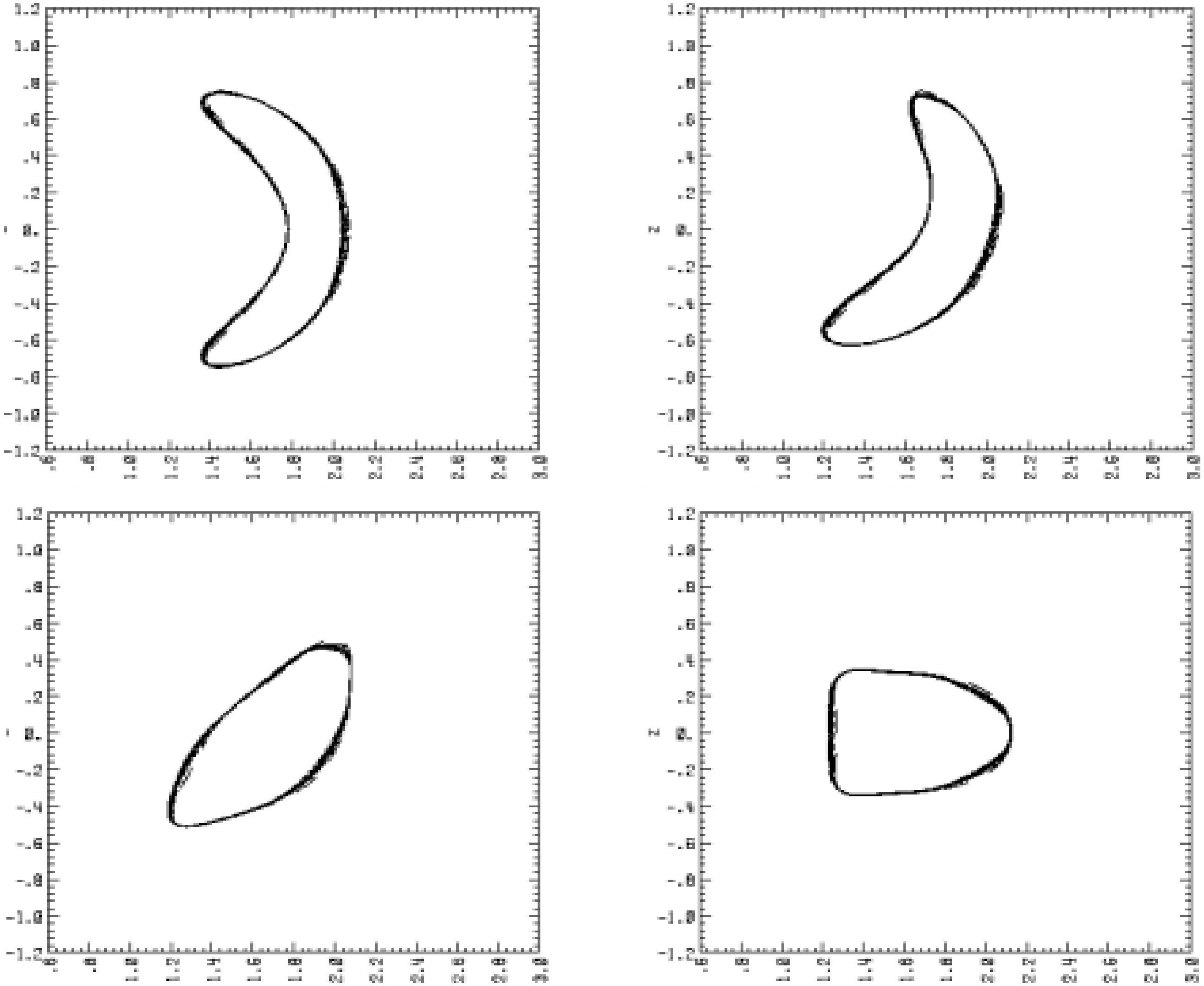
Plasma Profiles for Flexibility and Robustness Studies



Peaked and broad pressure, peaked and hollow current (limiting cases from an experimental database).

Robustness Reconstructions
I_p = 150 kA, β = 4 %, modular coils

- Coil currents held fixed at reference values for optimized baseline profiles
- Little change in plasma position and shape for substantial profile variations
- Similar results were obtained for saddle coils



Flexibility Studies I

- For the four combinations of pressure and current profiles we compare the ability of the modular and saddle coils to optimize the physics (kink stability and QAS).
- STELLOPT varies the coil currents to optimize the β and the QAS.
- The plasma aspect ratio and R^*B_t are constrained to 4.3 and 2.05 respectively.
- The boundary is constrained by a 3D limiting surface.

Flexibility Studies I (cont.)

- The modular and saddle coil designs each have four independent coil groups. A 1/R field is added to simulate the toroidal field in each case.
- For the modular coils we allow the 1/R field to vary to constrain RB_t for a total of five variable currents.
- For the saddle coils the 1/R field is fixed (i.e., there are only 4 variable currents).

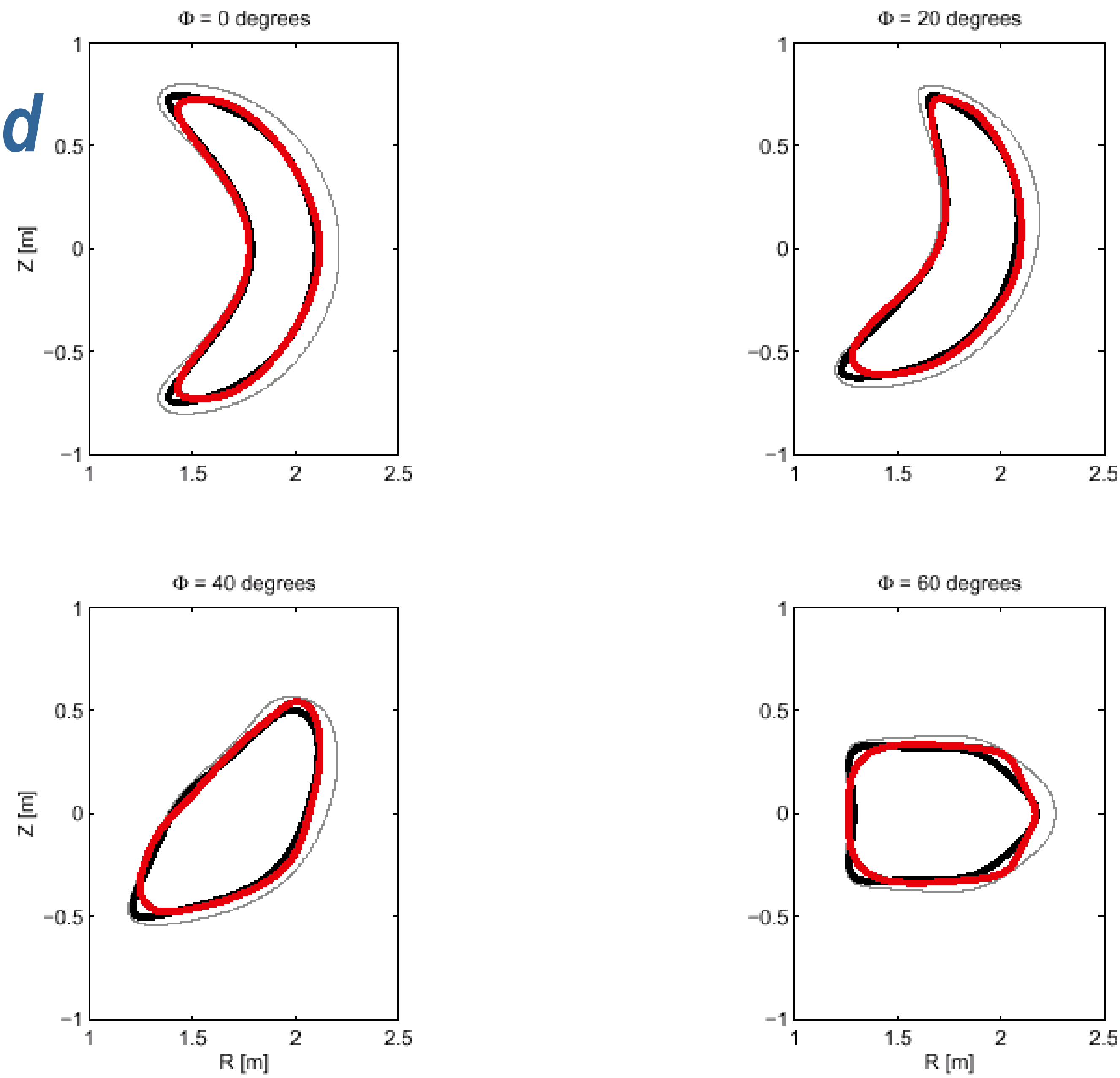
Optimization Results

Pressure /Current	Peaked / Peaked		Peaked / Broad		Broad / Peaked		Broad / Broad	
	Modular	**Saddle**	**Modular**	**Saddle**	**Modular**	**Saddle**	**Modular**	**Saddle**
β [%]	1.0	1.0	2.0	2.0	1.7	1.1	3.7	3.3
$\chi^2(B_{mn})^1$	1.3 (5.4)	2.0 (3.8)	1.9 (4.3)	2.0 (3.0)	1.8	3.8	1.9	2.3
$-\lambda_{Kink}$	1.1e-4 (1.0e-4)	1.3e-4 (9.8e-5)	1.5e-4 (7.0e-4)	1.5e-6 5.4e-4	8.9e-5	8.2e-5	1.9e-6	0
RB_{TOR} [T-m]	2.02	2.04	2.03	2.01	2.00	2.05	2.02	2.02
Dvv [cm]	-2.40	-0.565	-0.800	-0.120	-3.07	-4.79	-1.07	-0.788

$^1\chi^2(B_{mn})$ is normalized to the baseline full current, full β, fixed-boundary values.
The values in parenthesis are initial values before optimization.

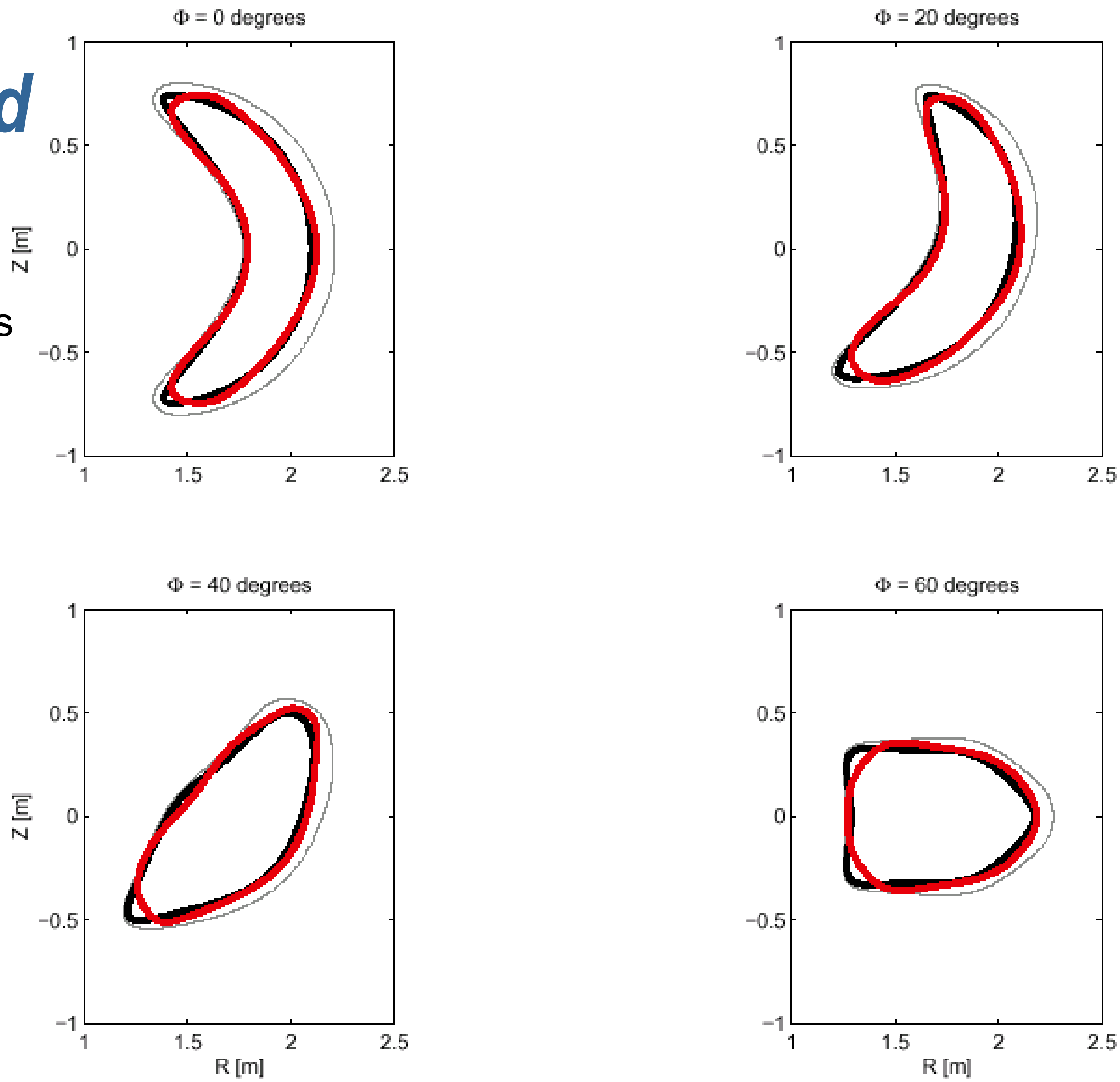
Saddle Coils Peaked / Peaked

- LI383 optimized physics run, β = 1.0 % (4.1 %)
- $\chi^2(B_{mn})$ = 2.0 (3.8)
- λ_{kink} = -1.3e-4 (stable)
- R^*B_t = 2.04 (2.05)
- $|\Delta I_{max}|$ ~ 27 %
- $|\Delta d_{max}|$ = 5.65 cm



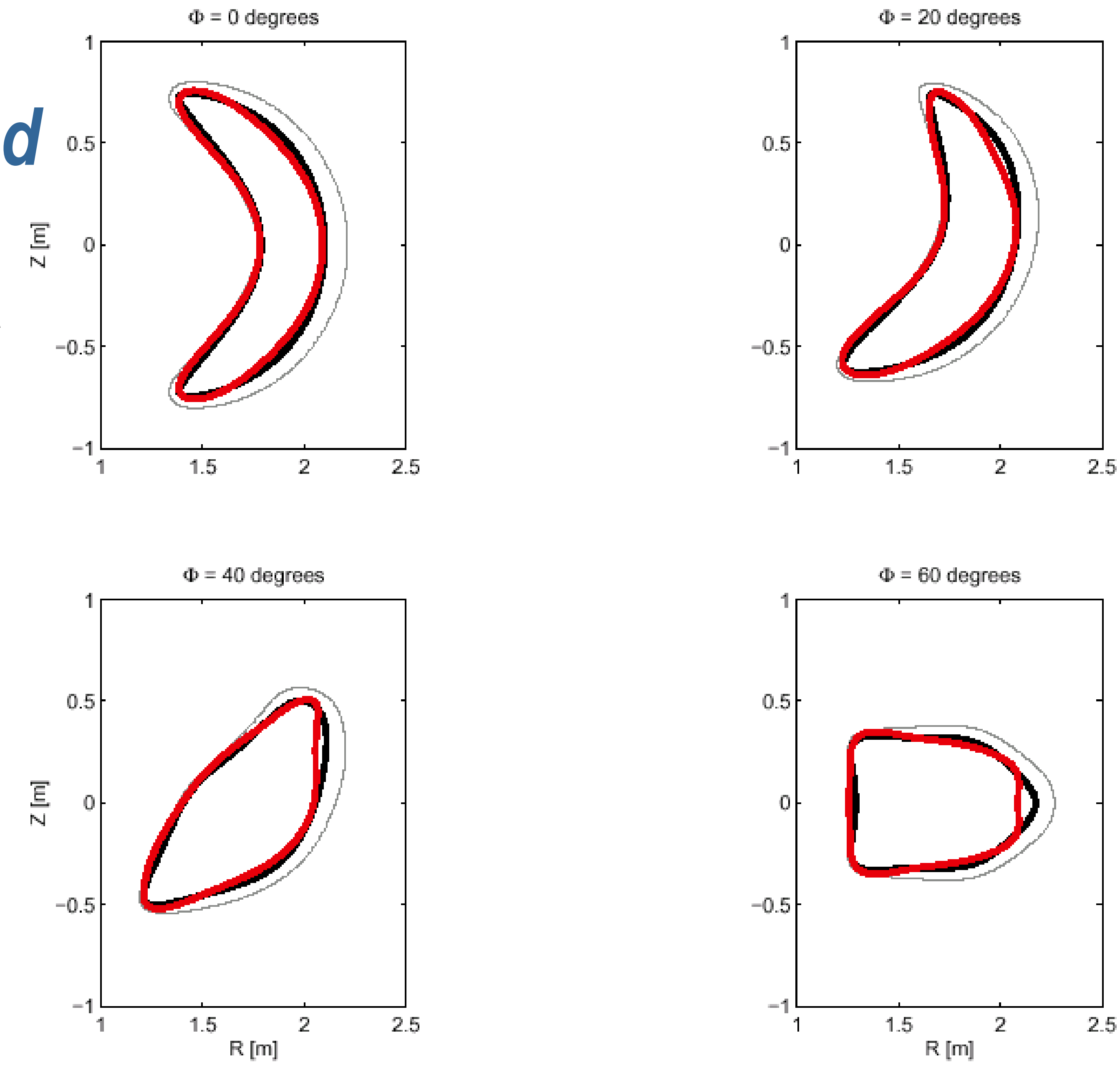
Saddles Coils Peaked / Broad

- LI383 optimized physics run, β = 2.0 % (4.1 %)
- $\chi^2(B_{mn})$ = 1.9 (4.3)
- λ_{kink} = -1.5e-5 (stable)
- R^*B_t = 2.01 (2.05)
- $|\Delta I_{max}|$ ~ 20 %
- $|\Delta d_{max}|$ = 1.2 mm



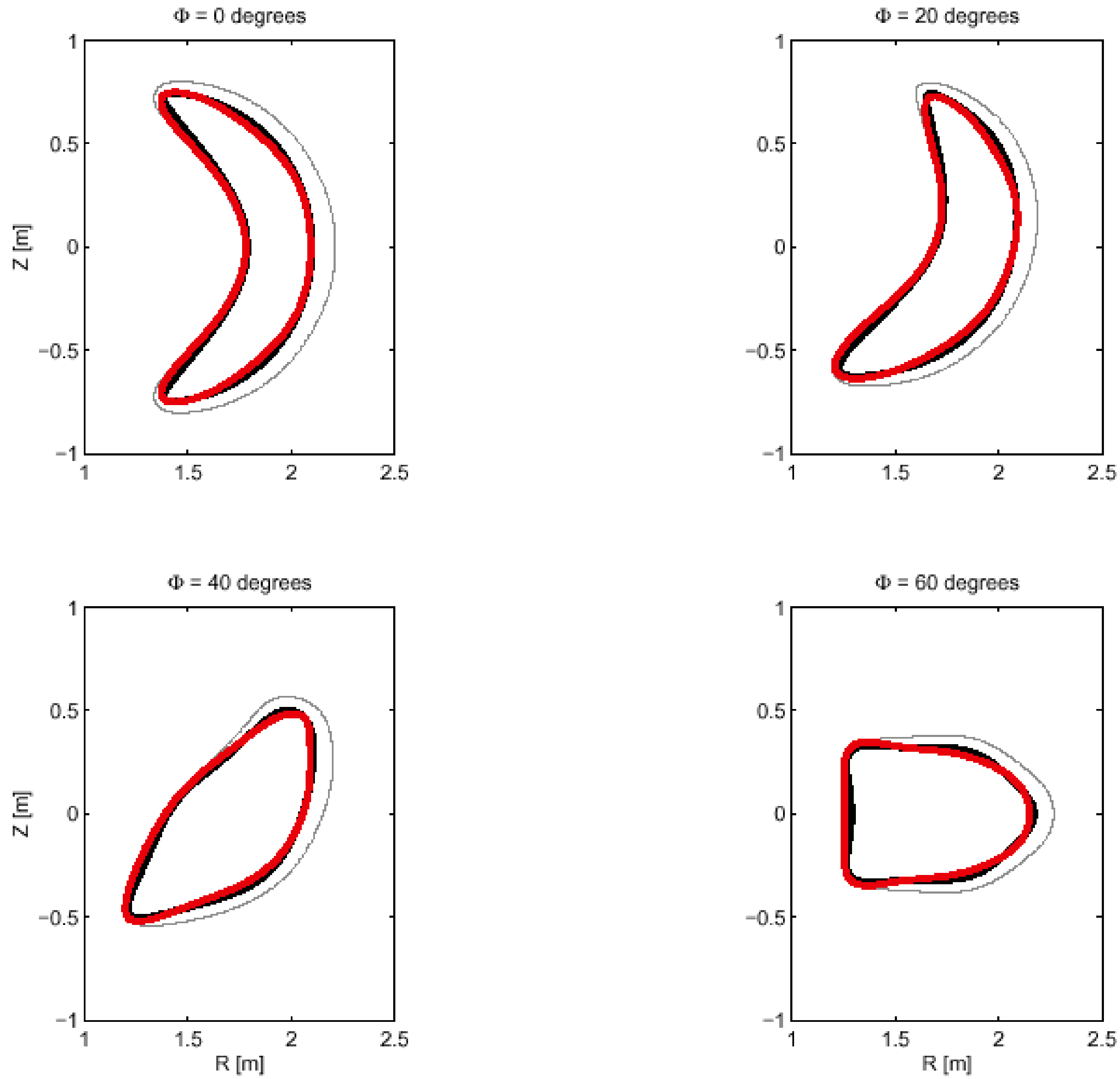
Modular Coils Broad / Peaked

- LI383 optimized β limit run, β = 1.7 % (4.1 %)
- $\chi^2(B_{mn})$ = 1.8
- λ_{kink} = -8.9e-5 (stable)
- R^*B_t = 2.00 (2.05)
- $|\Delta I_{max}|$ < 5 %
- $|\Delta d_{max}|$ = 3.07 cm



Modular Coils
Broad / Broad

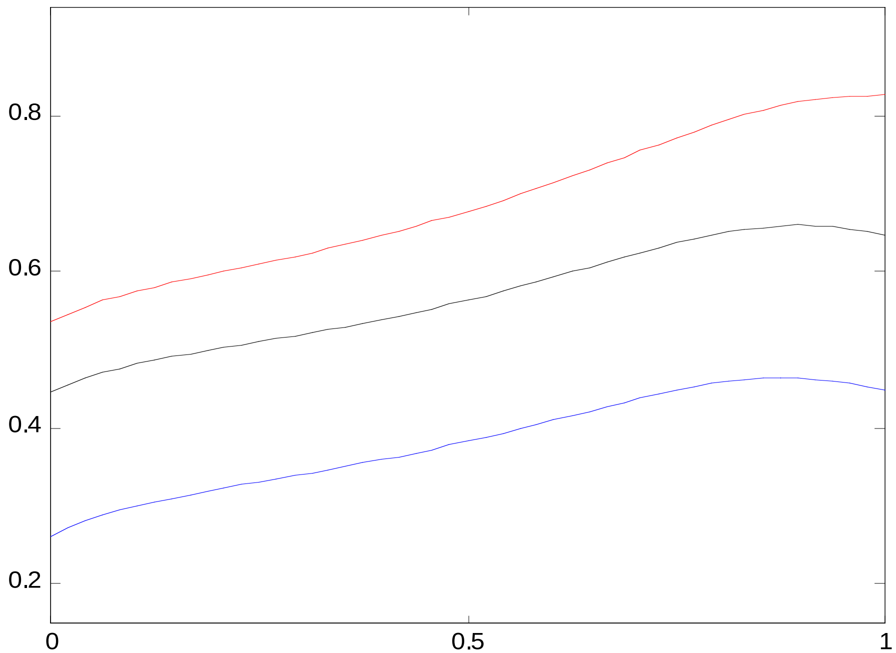
- LI383 optimized β limit run, β = 3.7 % (4.1 %)
- $\chi^2(B_{mn})$ = 1.9
- λ_{kink} = -1.9e-6 (stable)
- R^*B_t = 2.02 (2.05)
- $|\Delta I_{max}|$ < 5 %
- $|\Delta d_{max}|$ = 1.07 cm

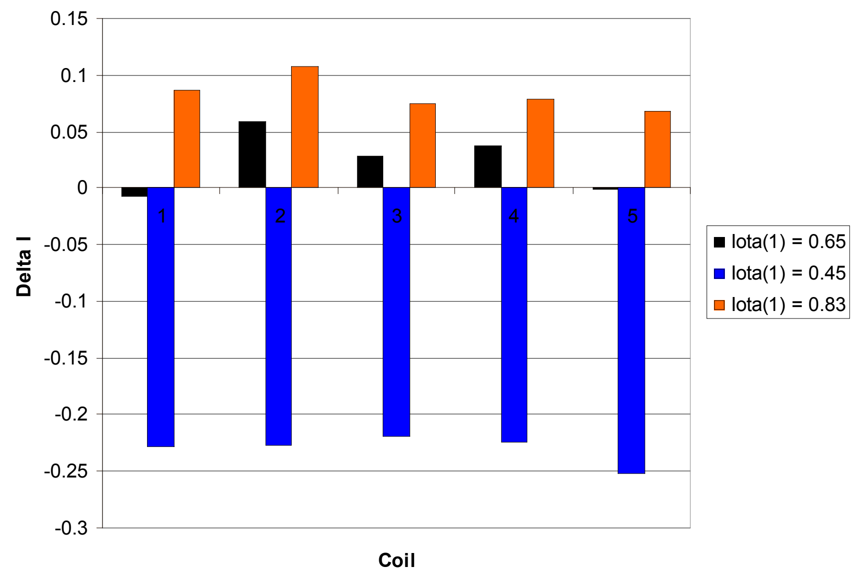


Flexibility Studies II

- Using the baseline pressure and current profiles at β = 1 %, STELLOPT varies the coil currents to shift the iota profile relative to the baseline.

- Results shown for modular coils, saddles do equally well.

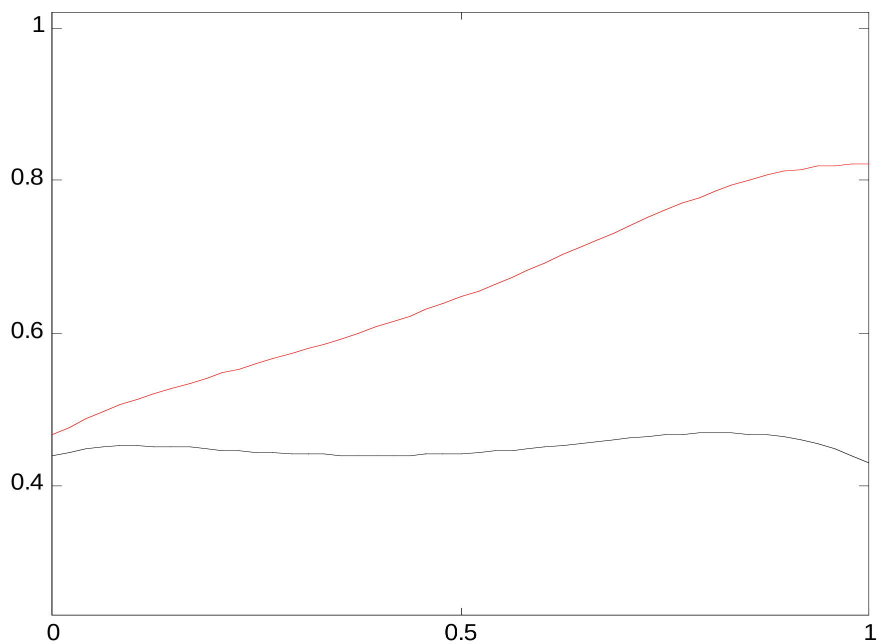


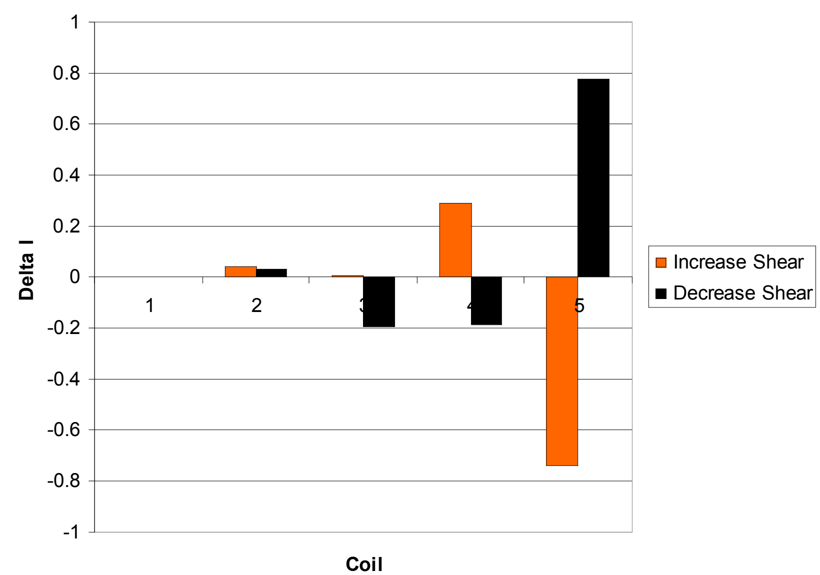


Flexibility Studies III

- Using the baseline pressure and current profiles at β = 1 %, STELLOPT varies the coil currents to change the shear.

- Results for saddle coils shown, modulars do equally well.





Conclusions

- A number of numerical experiments were performed to evaluate the robustness and flexibility of the primary coil set for NCSX.
- Both modular and saddle coils show considerable flexibility for performing physics experiments.
- From these results both show comparable flexibility. Additional flexibility may be achieved by adding other “trim” coils to the primary set.