

Winding surface optimization of QHS46 and ATEN with adjoint REGCOIL

Elizabeth Paul

Ben Cha

Matt Landreman

Overview of REGCOIL parameters

Objective function

$$\chi^2 = \chi_B^2 + \lambda \chi_K^2$$

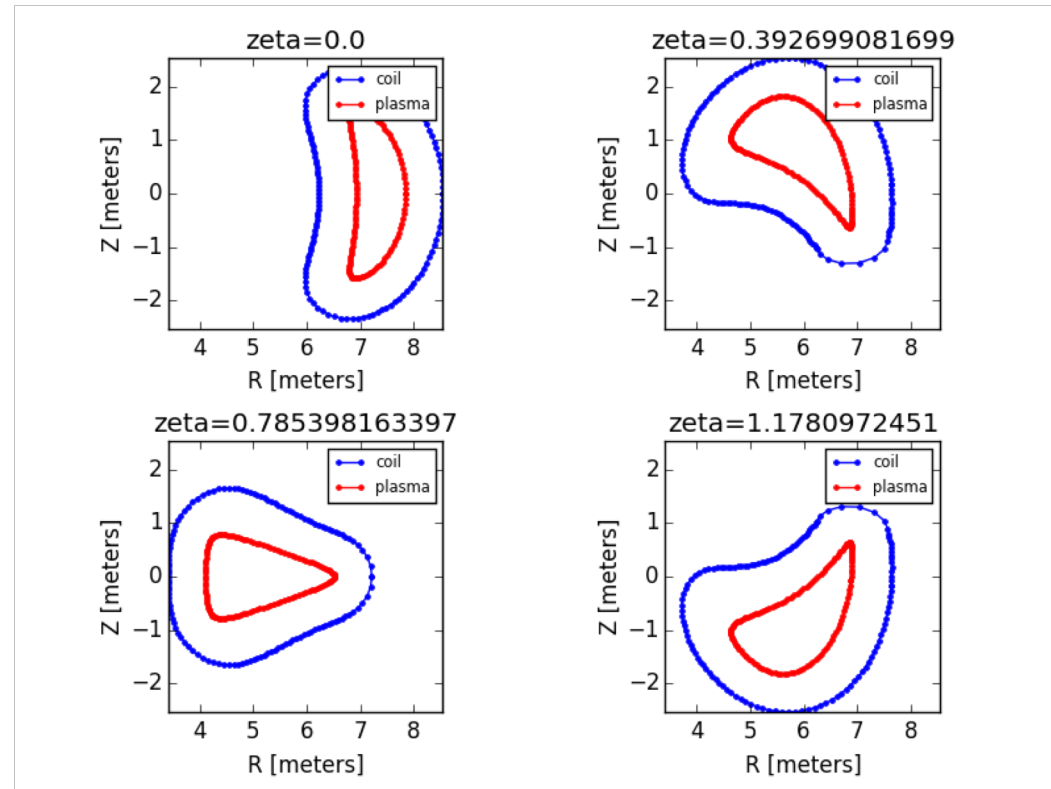
Normal field error Coil complexity

$$\chi_B^2 = \int_{plasma} d^2x B_n^2 \quad \chi_K^2 = \int_{coil} d^2x K^2$$

- λ = regularization parameter
 - Chosen to obtain a given value of K_{max} ($\approx$ min. coil-coil spacing)
- Given fixed plasma and winding surfaces, K chosen to minimize χ^2 subject to fixed K_{max}

QHS46 with offset winding surface

- $R=6.02$ m, $a=0.9$ m
- Offset surface at 0.7 m
- First step – run REGCOIL with different values of K_{max} (λ) and compute coil metrics



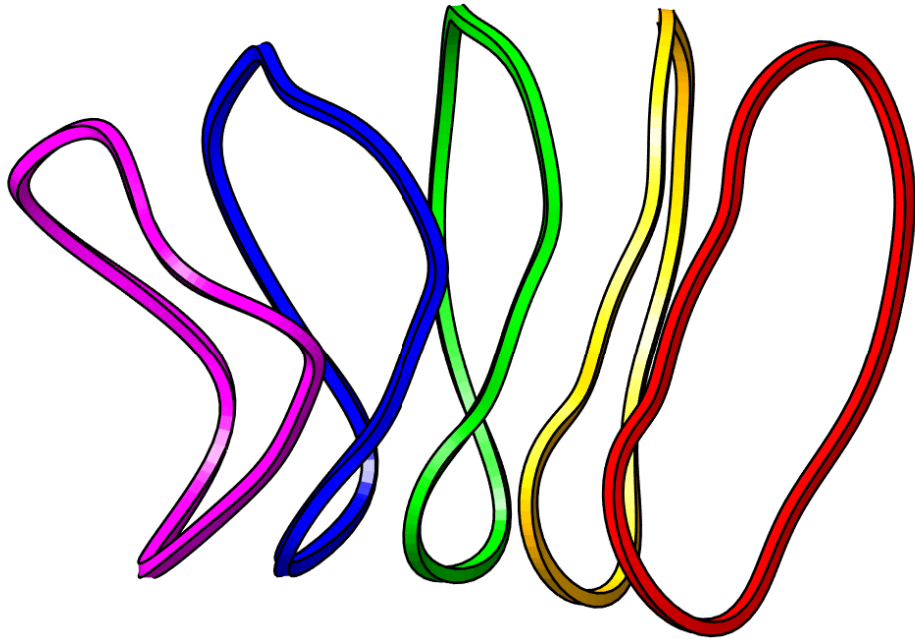
REGCOIL solutions with offset winding surface

Coilset	Current Designs		$K_{max} \text{ (A} \cdot \text{m}^{-1}\text{)}$						
	W7-X	HSX	2.55e6	3.07e6	3.51e6	3.92e6	4.28e6	4.68e6	5.04e6
Avg. l (m)	8.69	2.24	10.8	10.8	11	11.2	11.4	11.7	11.9
Max. l (m)	8.74	2.33	10.9	10.9	11.1	11.6	12.2	12.8	13.4
Avg. $\Delta\zeta$ (rad.)	0.198	0.362	0.246	0.315	0.341	0.356	0.368	0.379	0.388
Max. $\Delta\zeta$ (rad.)	0.208	0.478	0.267	0.394	0.449	0.484	0.514	0.542	0.563
Avg. κ (m^{-1})	1.2	5.05	0.773	0.796	0.819	0.851	0.896	0.957	1.02
Max. κ (m^{-1})	2.59	11.7	1.95	1.97	2.1	2.38	2.74	3.07	4.43
Min. coil-coil dist. (m)	0.261	0.093	0.745	0.621	0.559	0.506	0.467	0.433	0.405
Avg. B_n error			0.162	0.081	0.050	0.0310	0.018	0.010	0.006
Max. B_n error			0.313	0.218	0.149	0.0984	0.062	0.038	0.025

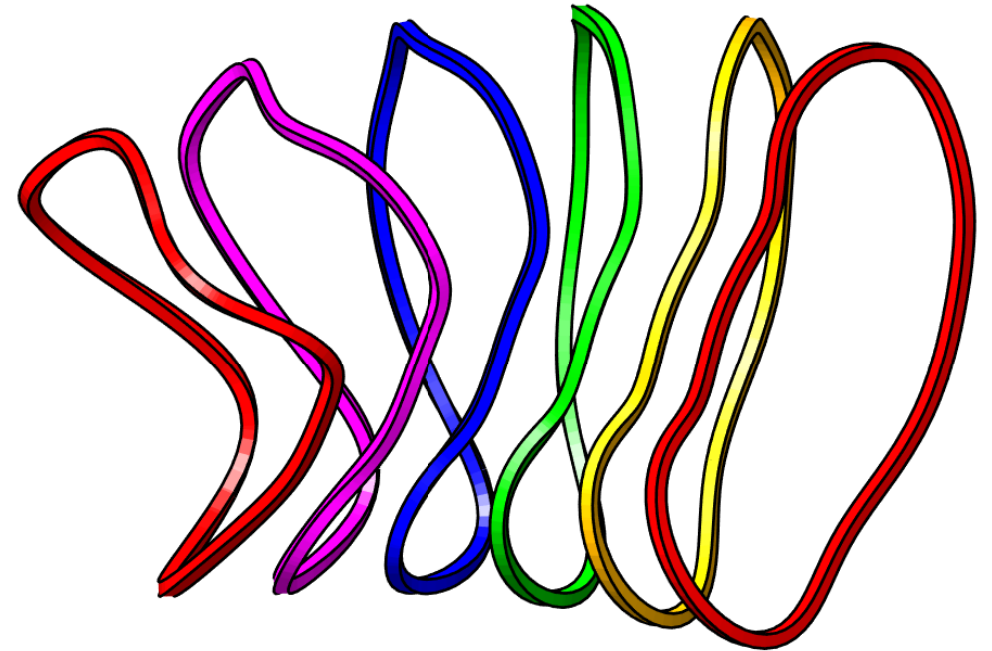
Computed metrics with 5 coils/half period

REGCOIL coils on offset surface ($K_{max} = 3.92e6$)

5 coils/half period



6 coils/half period



- Most coil metrics don't depend strongly on # coils (only coil-coil spacing)

Overview of parameters for WSO

Objective function

$$f = -\alpha_V V_{coil} + \alpha_B \chi_B^2 + \alpha_K K_{rms}$$

Coil-plasma
spacing

Reduce normal
field error

Improve coil
metrics

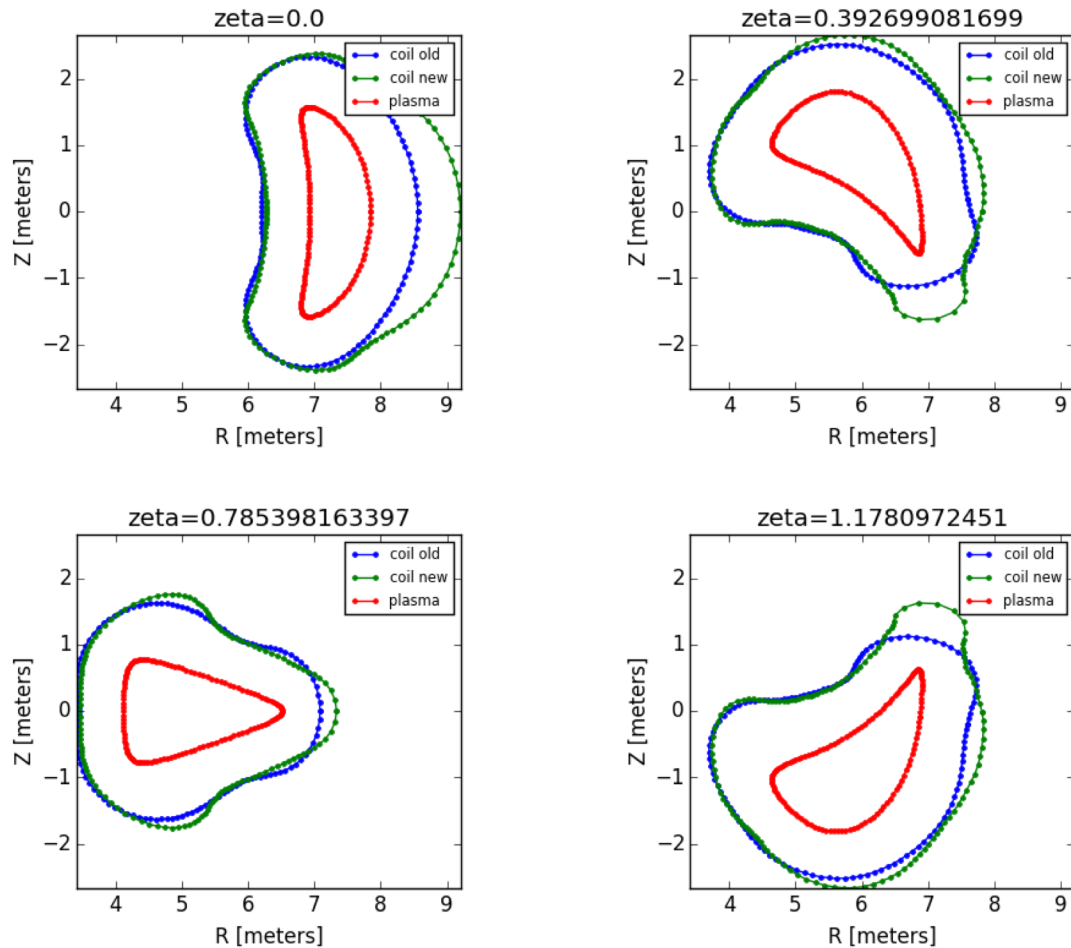
$$\chi_B^2 = \int_{plasma} d^2x B_n^2 \quad K_{rms} = \left(\int_{coil} d^2x K^2 \right)^{1/2}$$

Constraints

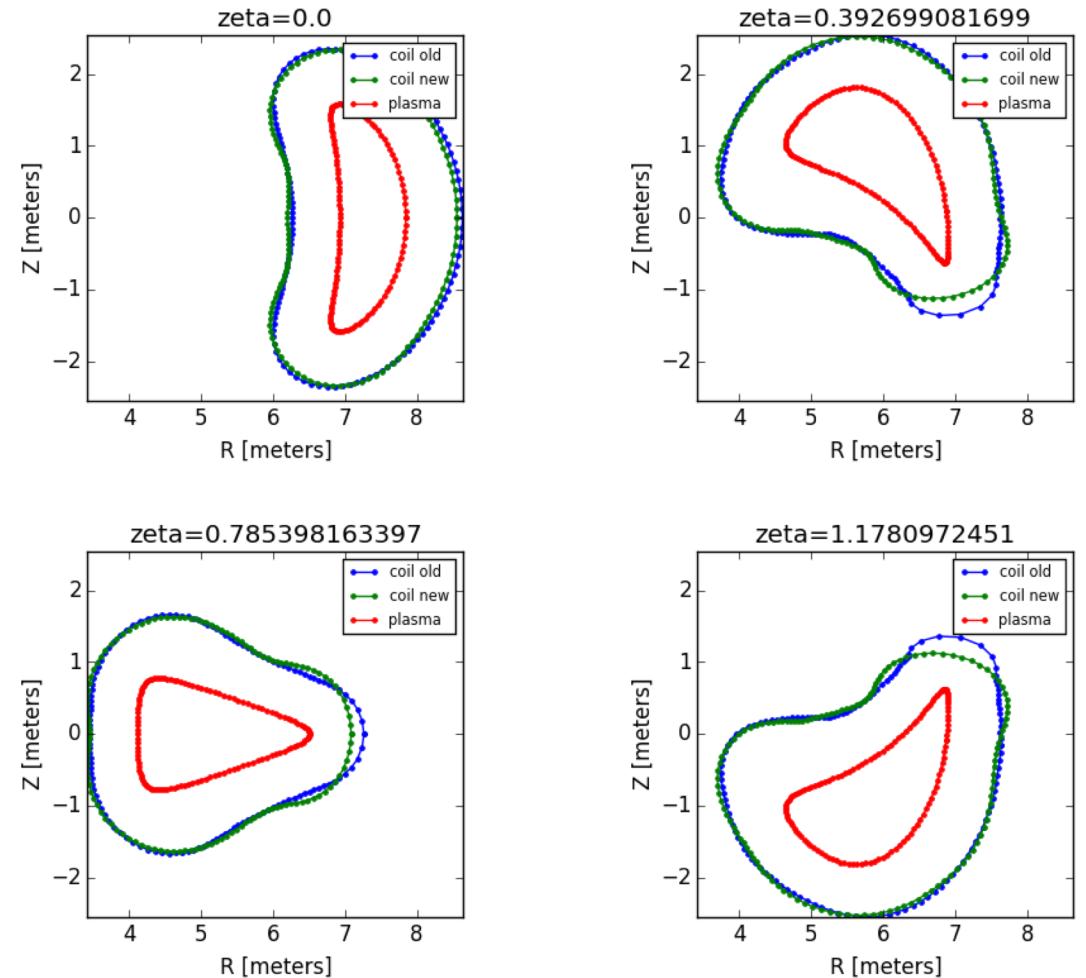
- K_{max} fixed ($\approx$ fixed coil-coil spacing)
- $d_{coil-plasma} \geq d_{coil-plasma}^{target}$ (min. coil-plasma spacing)

Winding surface cross-sections

Run 1



Run 2



Run 1 and Run 2 coil metrics

	α_B			
	W7-X	HSX	7e-4 Run 1	1e-4 Run 2
Avg. l (m)	8.69	2.24	12.83	11.91
Max. l (m)	8.74	2.33	14	13.21
Avg. $\Delta\zeta$ (rad.)	0.198	0.362	0.3971	0.3831
Max. $\Delta\zeta$ (rad.)	0.208	0.478	0.536	0.5418
Avg. κ (m^{-1})	1.2	5.05	0.9953	0.9315
Max. κ (m^{-1})	2.59	11.7	7.889	4.561
Min. coil-coil dist. (m)	0.261	0.093	0.5271	0.5193
Min. coil-plasma dist. (m)			0.6472	0.6491

Avg. B_n error

0.001	0.0164
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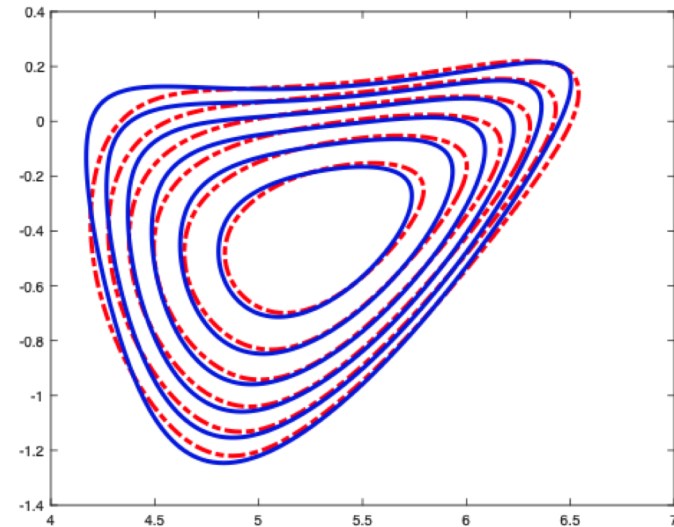
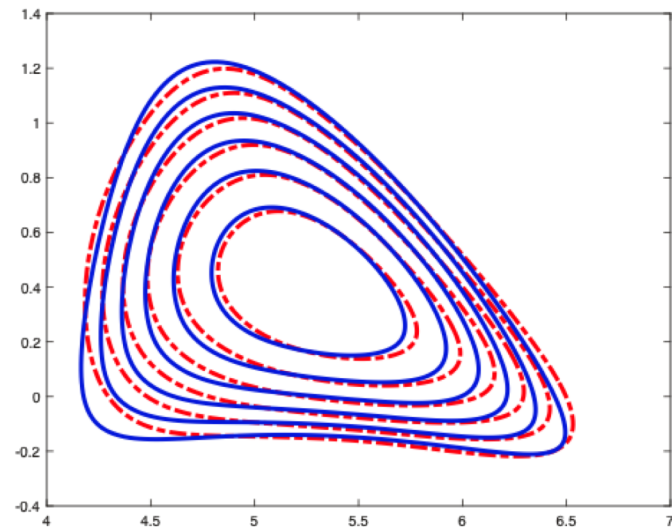
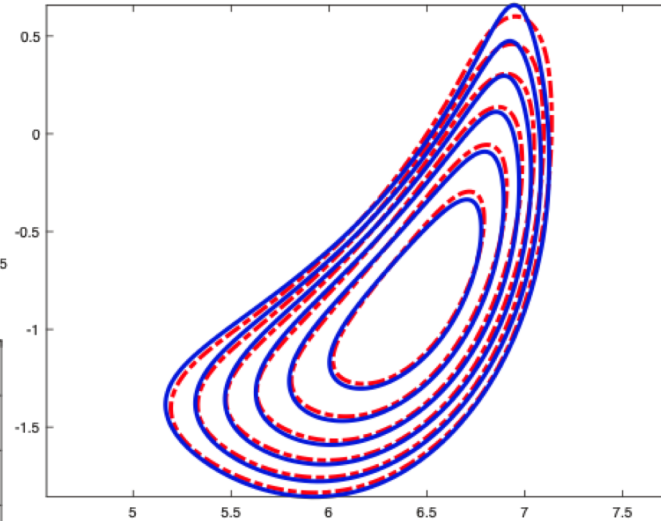
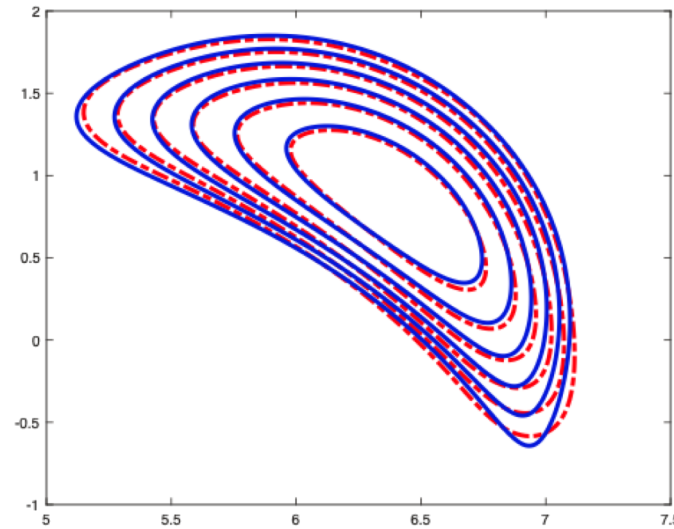
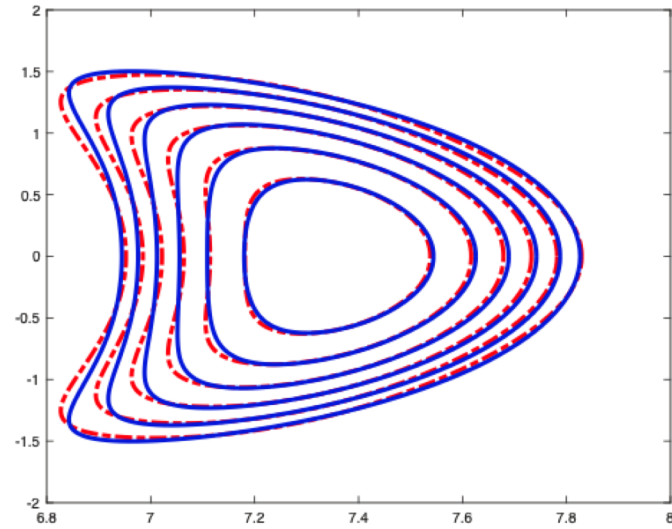
Max. B_n error

0.006	0.003
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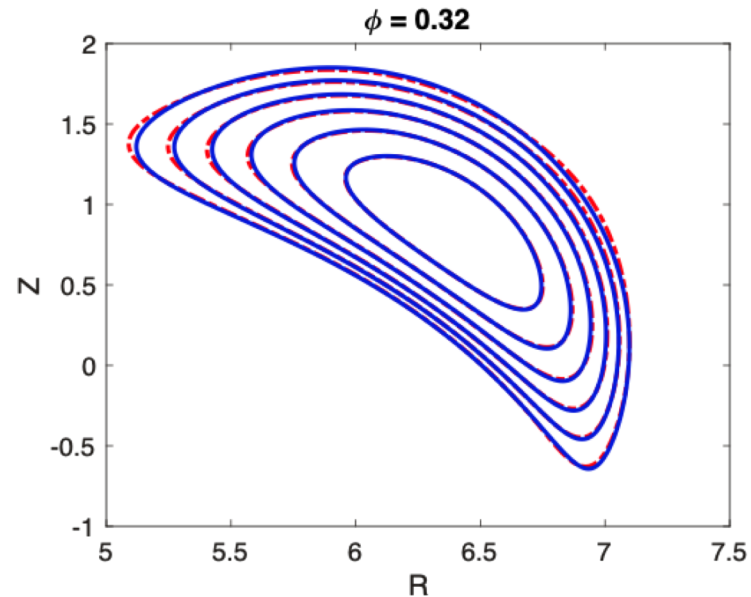
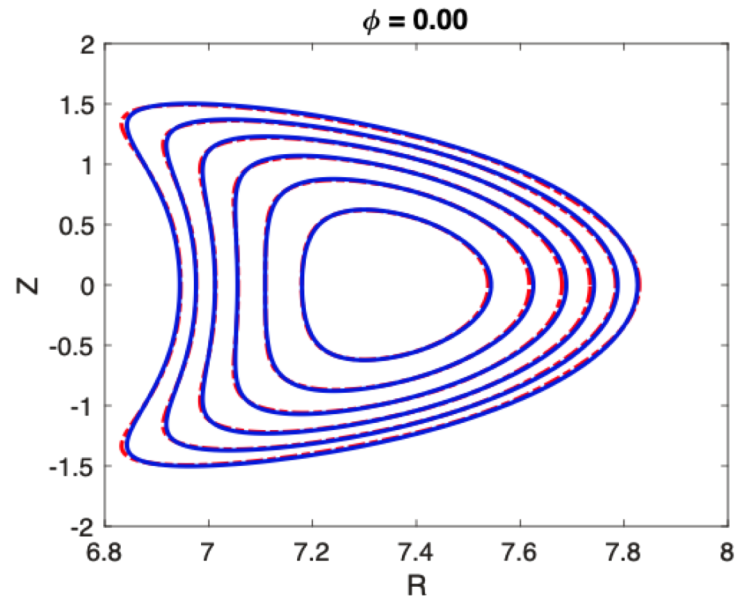
- 5 coils per half period
- $d_{coil-plasma}^{target} = 0.65$ m
- Both show improved normal field error over offset surf
- Run1 - lower normal field error
- Run2 - lower coil complexity

Offset surface Free Boundary VMEC

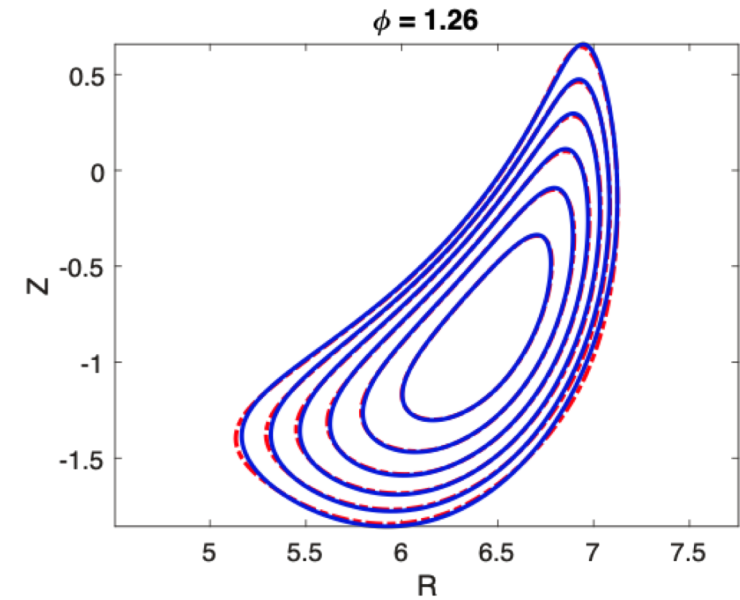
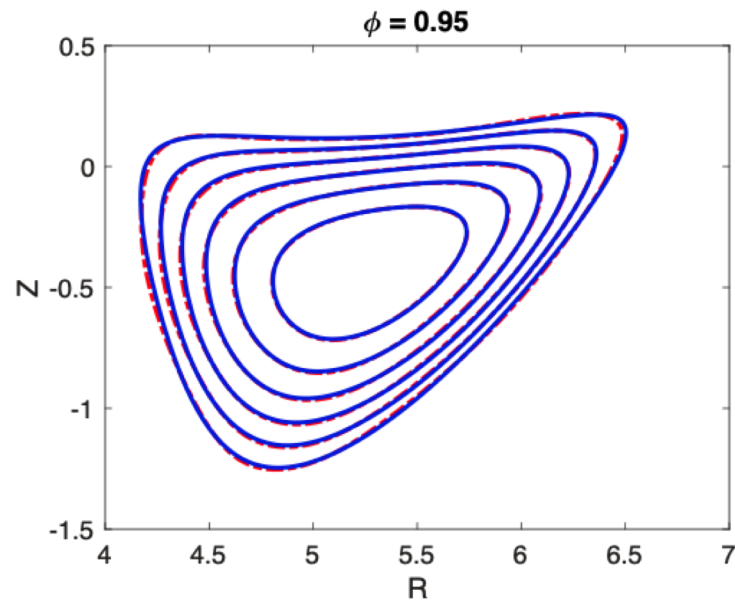
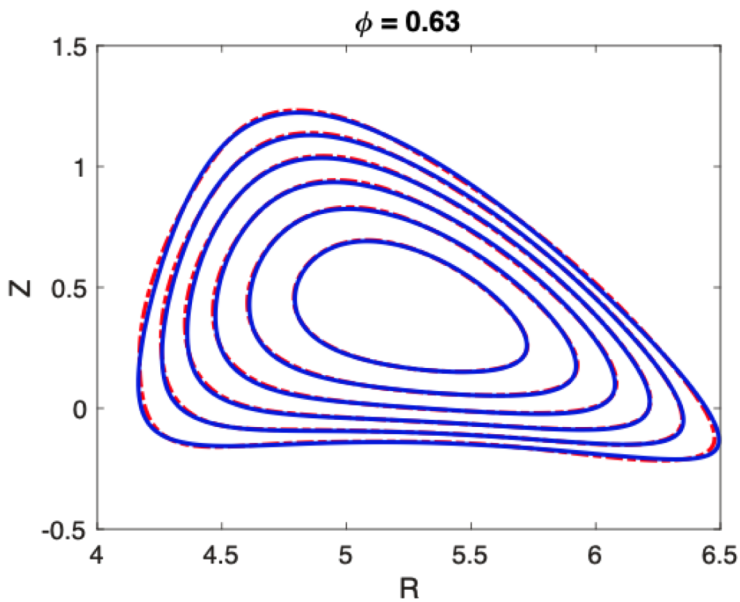
- 5 coils per half period
- Blue = fixed boundary
- Red = free



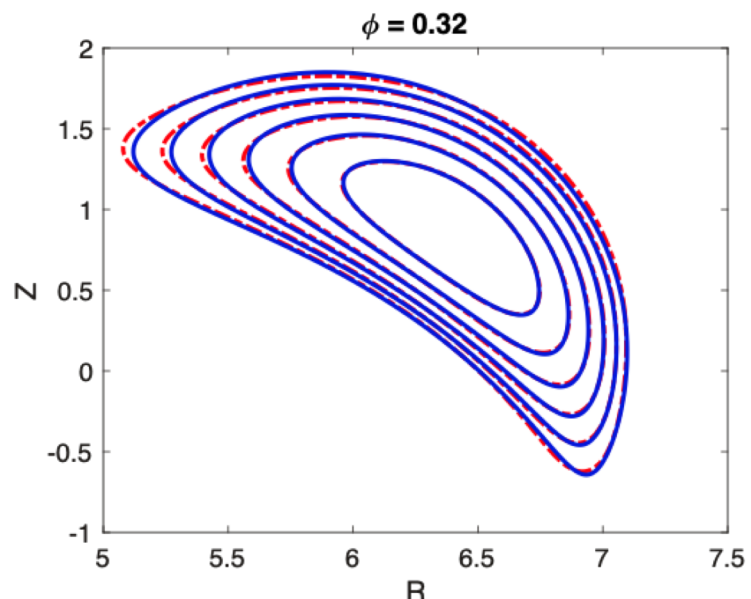
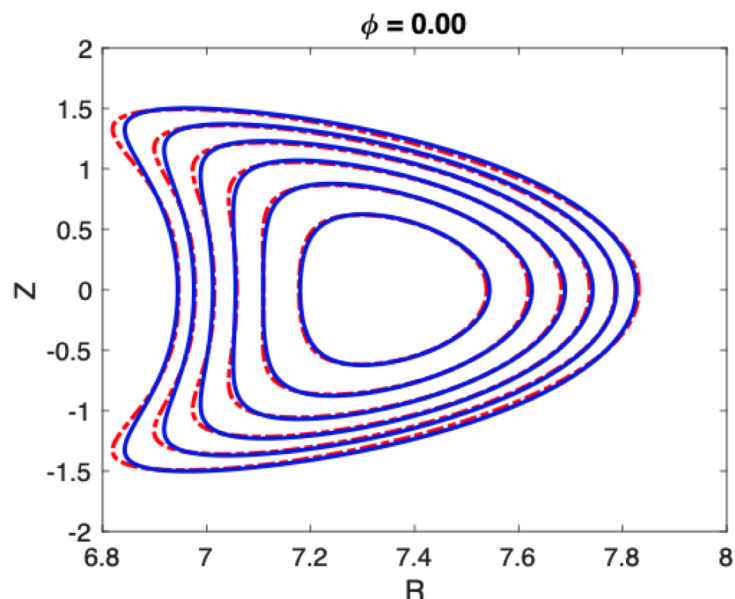
Run 1 Free Boundary VMEC



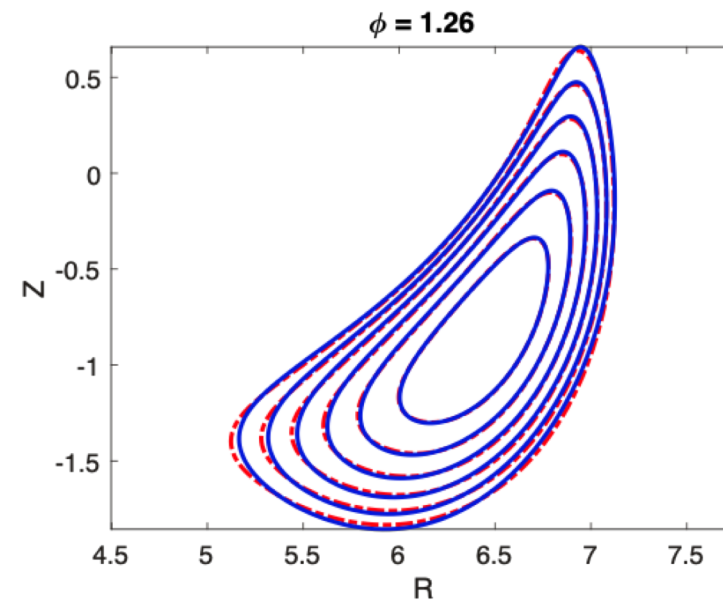
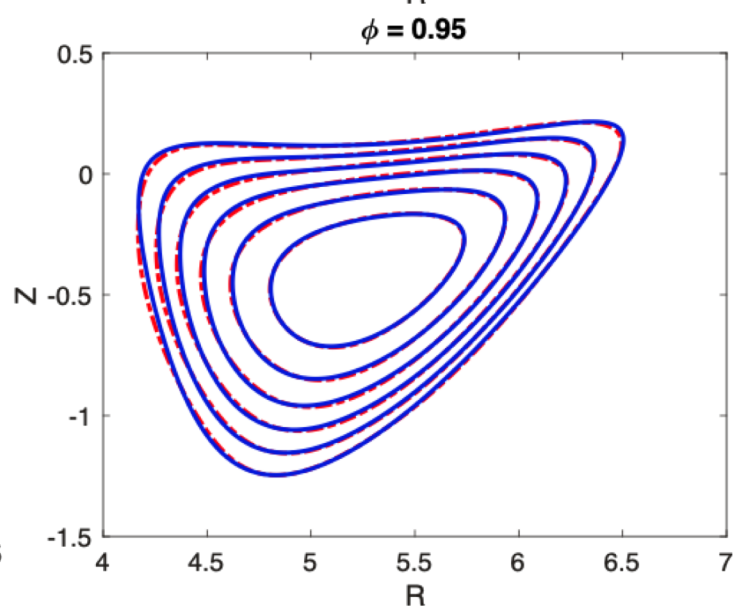
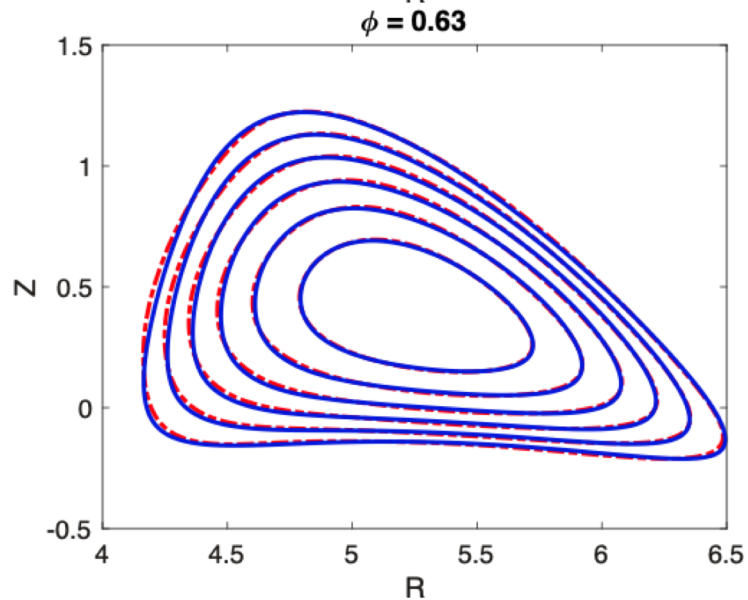
- 5 coils per half period
- Blue = fixed boundary
- Red = free



Run 2 Free Boundary VMEC

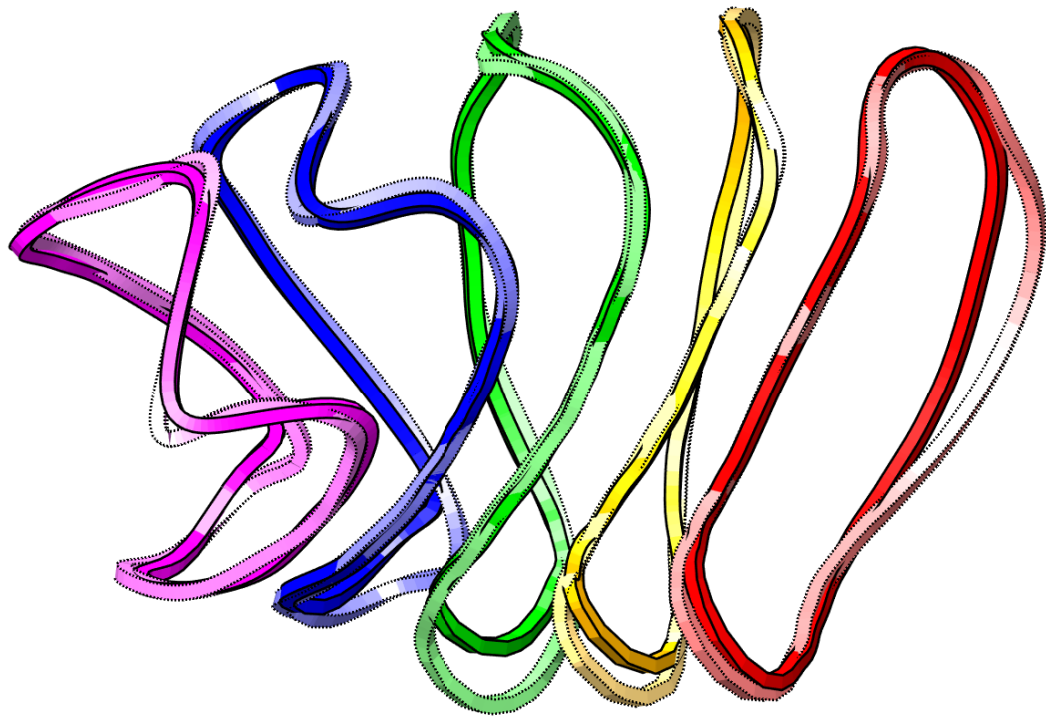


- 5 coils per half period
- Blue = fixed boundary
- Red = free

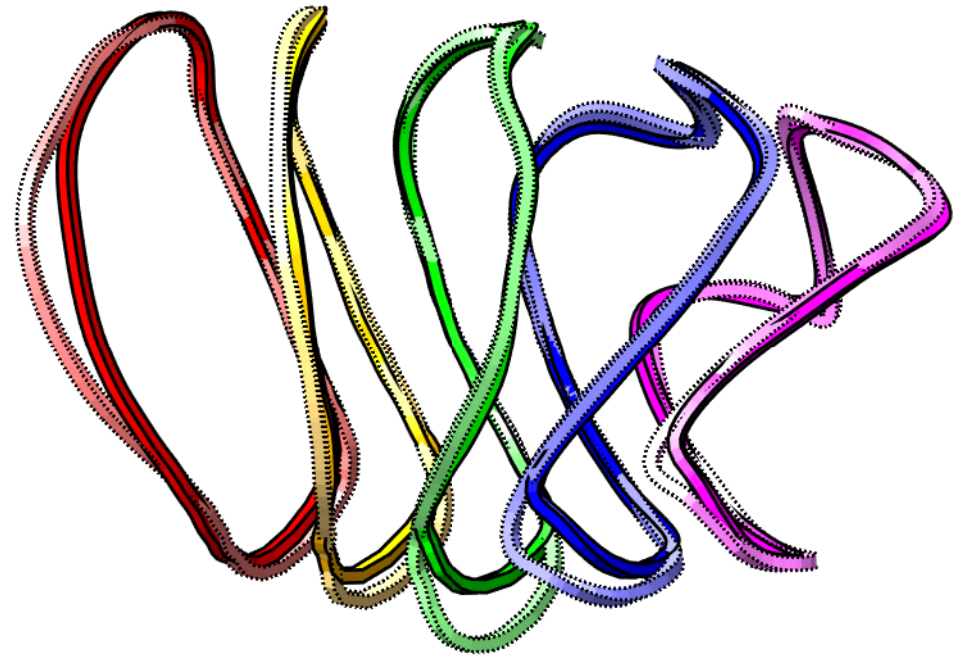


Run1 vs. Run 2 Coils

- Run1 = light
- Run2 = dark



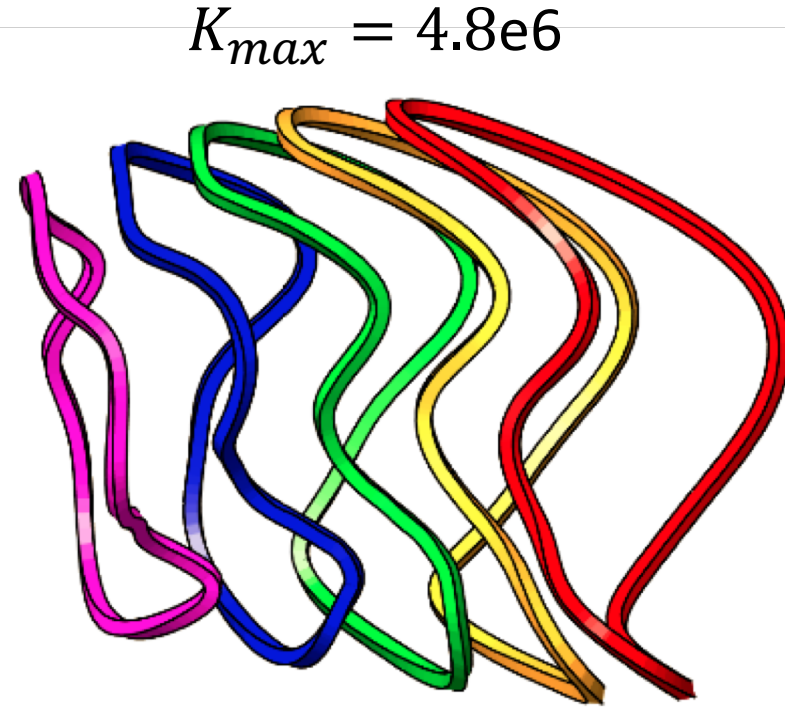
Front view



Rear view

Initial ATEN Results – offset surface

- $R=2$ m, $a=0.3$ m
- $d_{coil-plasma}^{target} = 0.25$ m
- Difficult to achieve similar normal field error without significantly increasing coil complexity



Coilset	Avg. I (m)	Max I (m)	Avg. $\Delta\zeta$ (rad)	Max $\Delta\zeta$ (rad)	Avg. κ (m^{-1})	Max κ (m^{-1})	Min coil-coil (m)	Avg. B_n error	Max. B_n error
HSX	2.24	2.33	0.362	0.478	5.05	11.7	0.0930		
ATEN	4.94	5.63	0.274	0.301	2.93	12.9	0.127	0.171	0.59

Concluding thoughts

- QHS46
 - Run1 coils reproduce desired surfaces well, but coil metrics may not be desirable
 - Run2 coils reproduces desired surfaces slightly worse, slight improvement in coil metrics
- ATEN equilibria appears to require much more coil complexity
- How to choose target metrics?
 - Eg. curvature, coil-plasma spacing, coil-coil spacing