Tilted TF Coil Studies

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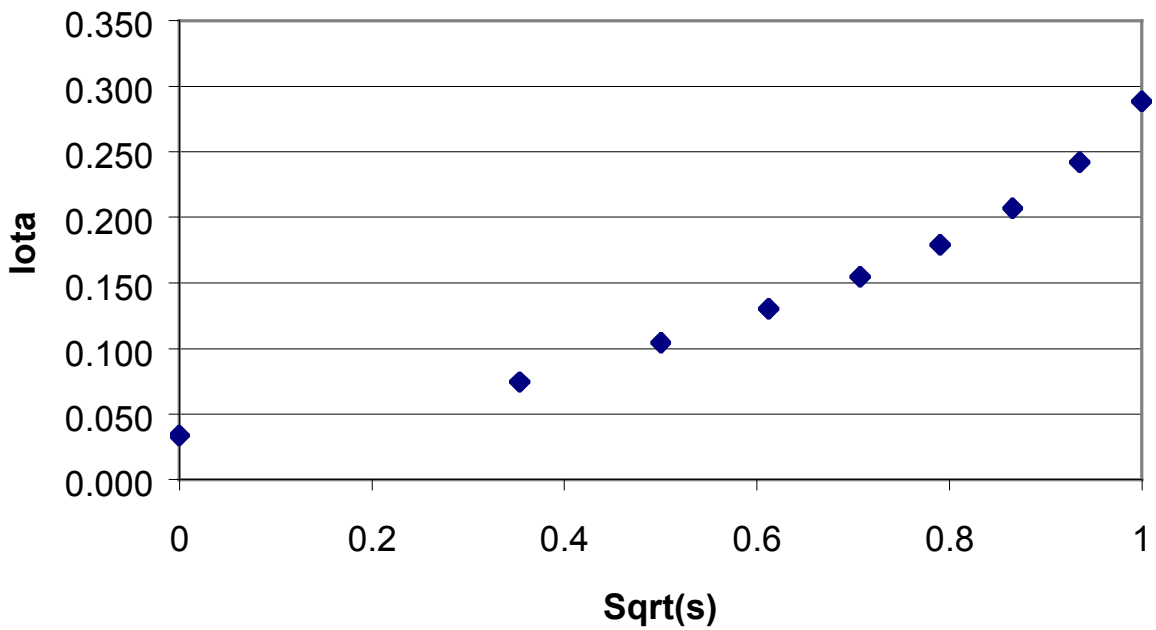
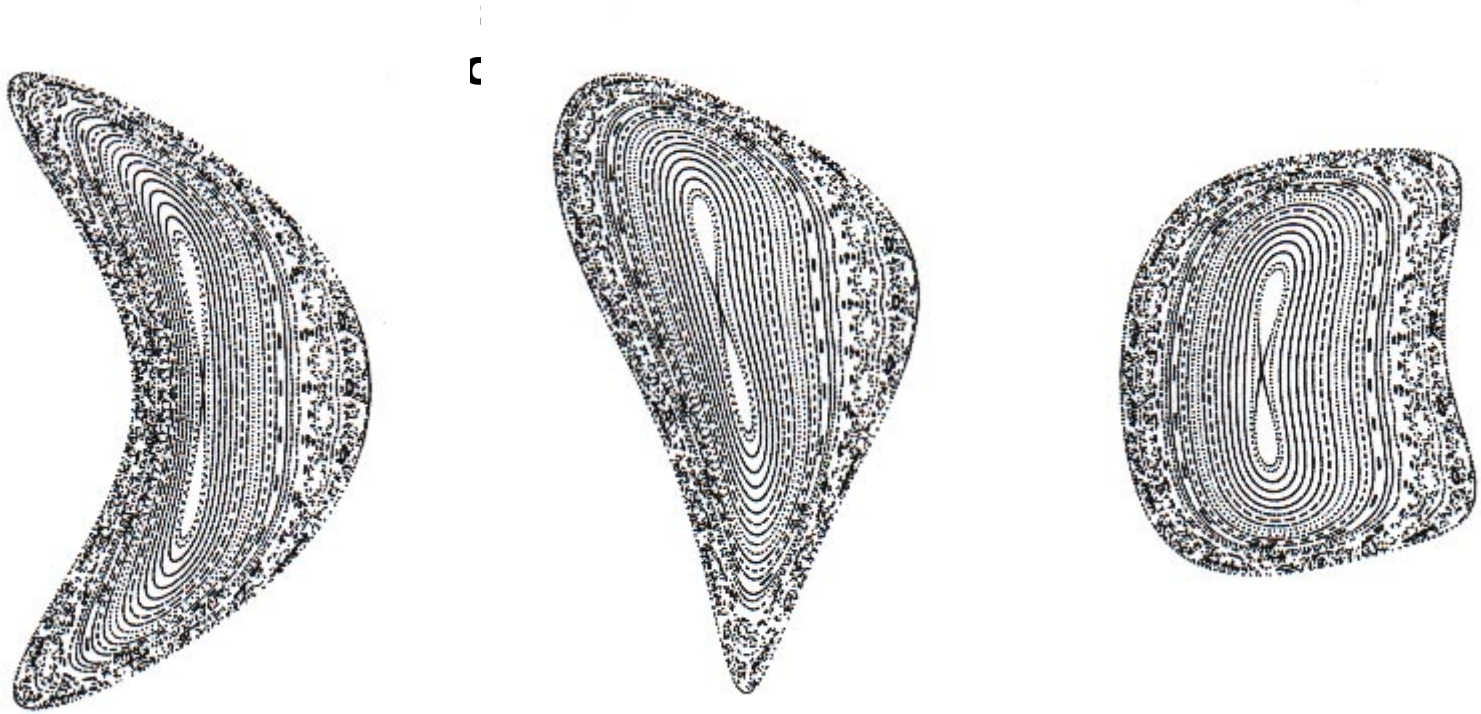
C82 Vacuum Case

- **Why look at vacuum case?**
  - **Vacuum configuration used because we STILL cannot use PIES to do field line tracing of plasma configurations with finite plasma current**
- **Iota profile calculated in fixed boundary VMEC**
- **Ranges from 0.033 on axis to 0.288 on edge**



Fixed boundary PIES results

- B_n identically zero on plasma boundary
- Few good surfaces outside of 3/19 island chain (iota=0.158)



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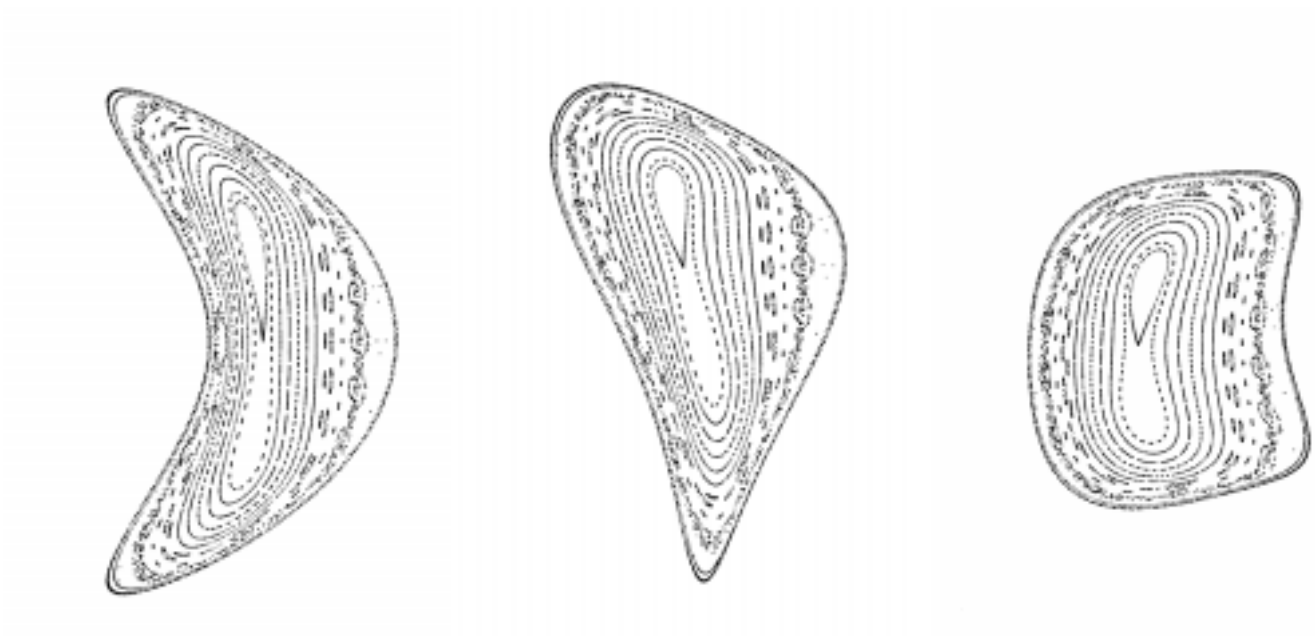
Free boundary PIES results

- **Best results from coils designed expressly for vacuum**
- **16 contours provided a good fit - 2.95% max error, 0.55% mean error**
- **Qualitatively same as fixed boundary - poor surfaces beyond 3/18 islands**



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Need to fix shape, not coils

- Reverse engineering process based on matching $B_n=0$ on plasma boundary
- If $B_n=0$ does NOT provide good surfaces, neither will finite coils
- Manually tweaking coil currents to fix islands tends to compromise quasi-symmetry (transport) and stability
- Need to incorporate a target function in optimizer to penalize bad surfaces
- The field line Hamiltonian can be used to assess the quality of magnetic surfaces and should be calculable with information in VMEC (Boozer)

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Purpose of this study

- **Are resonant field errors in c82 (in vacuum) are largely due to the 1/R toroidal field?**
- **Can resonant field errors and saddle coil currents and current densities can be reduced by tilting the TF coils?**
- **What next?**

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Saddle coils' job is to null out normal field from TF coils

- Largest Bmn's from TF are n=-1 with low m numbers
- Resonant Bmn's from TF are one order of magnitude smaller
- Saddle coils reduce largest Bmn's by two orders of magnitude

	m	TF Only $B_{m,-1}$	TF + Saddles $B_{m,-1}$	
Non-resonant	1	-4.34E-01	2.38E-03	182
	2	8.02E-01	8.95E-03	90
	3	-6.76E-01		
	4	-2.80E-01	-1.94E-03	144
	5	3.79E-01		
Resonant	11	-5.50E-02	-1.31E-03	42
	12	-3.80E-02	-3.14E-03	12
	13	3.20E-02	5.51E-04	58
	14	1.50E-02	3.12E-03	5
	$\Sigma B_{m,n}^2$	1.89E+00	1.87E-03	1011

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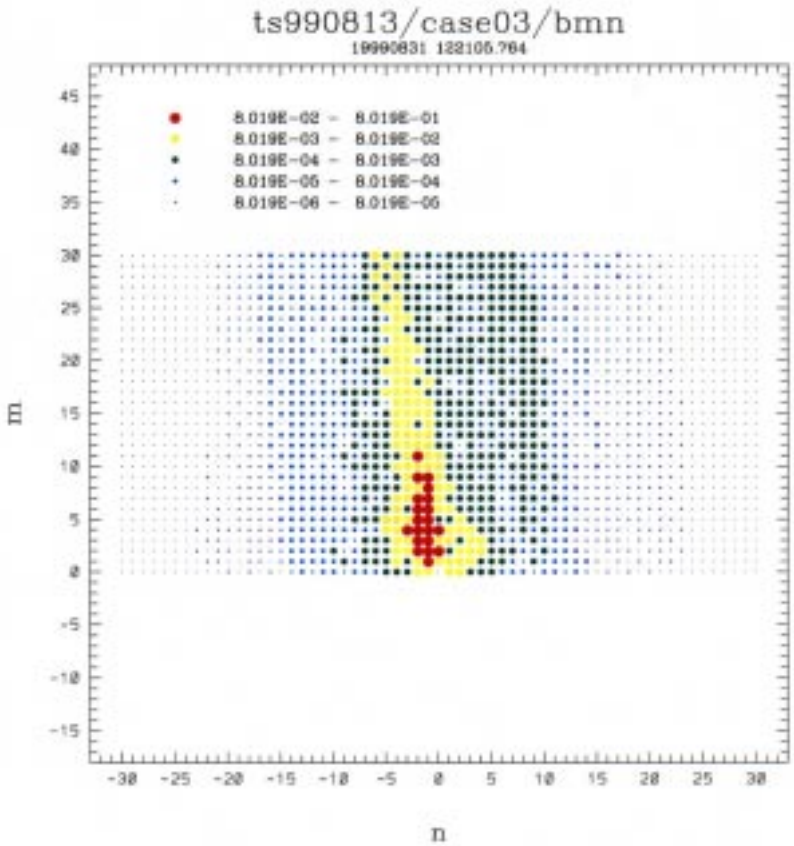
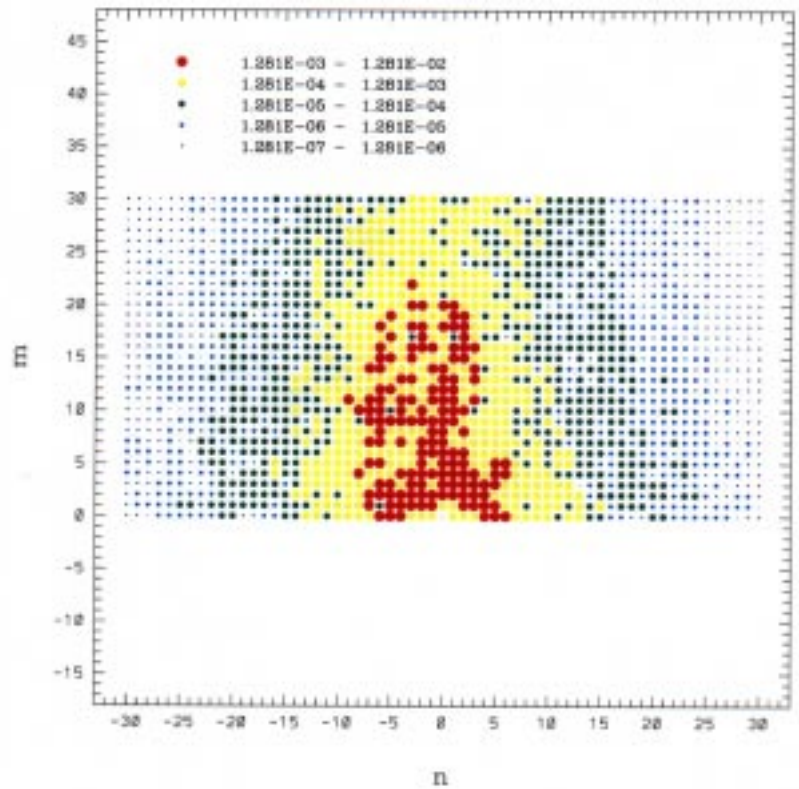
Remaining field errors have broadened spectrum

TF Only



TF + Saddles



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Progression of TF coil configurations studied

- **21 PBX-size racetrack TF coils**
- **3 oversized TF coils**
- **3 oversized TF coils with 45º tilt**
- **3 oversized TF coils with 45º tilt translated 10cm toward plasma**

- ***For the tilted TF coil options, the vertical field from the tilted TF coil was corrected by a single pair of PF coils located outboard of the plasma***

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Tilting and translating the TF coils

- **Should reduce resonant and non-resonant demands on saddle coils**

	m	21 TF coils 0 deg tilt $B_{m,-1}$	3 TF coils 0 deg tilt $B_{m,-1}$	3 TF coils 45 deg tilt $B_{m,-1}$	3 TF coils tilted and translated $B_{m,-1}$	
Non-resonant	1	-0.434	-0.398	-0.507	-0.292	1.5
	2	0.802	0.780	0.352	0.182	4.4
	3	-0.676	0.696	-0.377	-0.389	1.7
	4	-0.280	-0.261	-0.128	-0.068	4.1
	5	0.379	0.391	0.185	0.171	2.2
Resonant	11	-0.055	-0.059	-0.016	-0.010	5.5
	12	-0.038	-0.037	-0.014	-0.008	4.8
	13	0.032	0.034	0.009	0.005	6.4
	14	0.015	0.016	-0.002	-0.001	15.0
	$\Sigma B_{m,n}^2$	1.890	1.900	0.962	0.707	2.7

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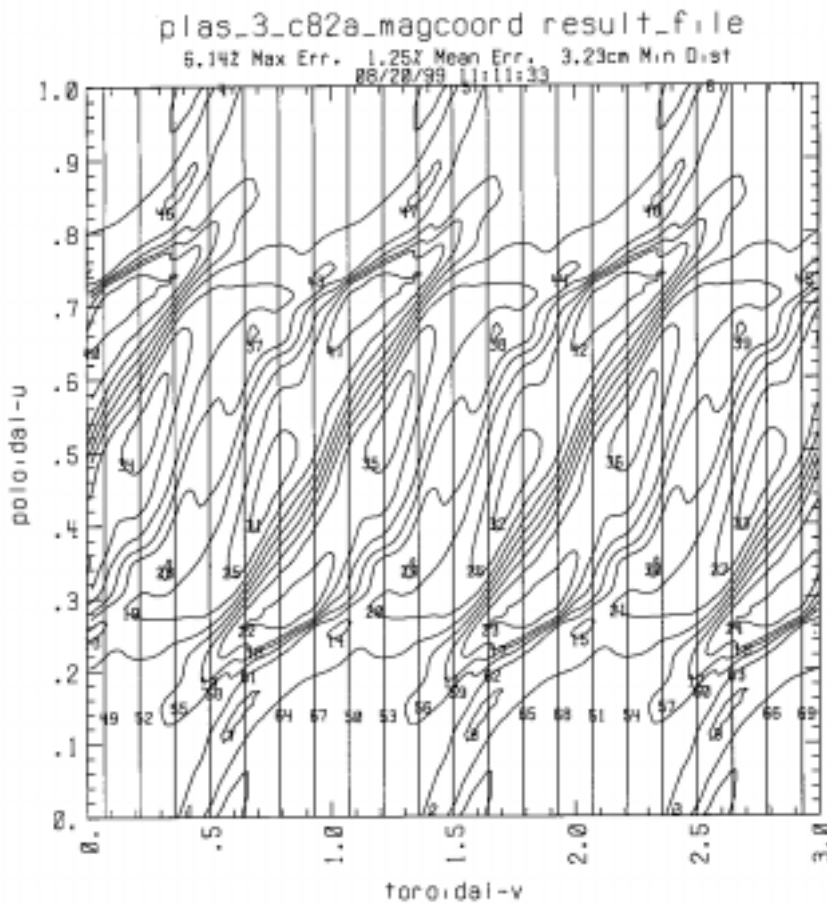
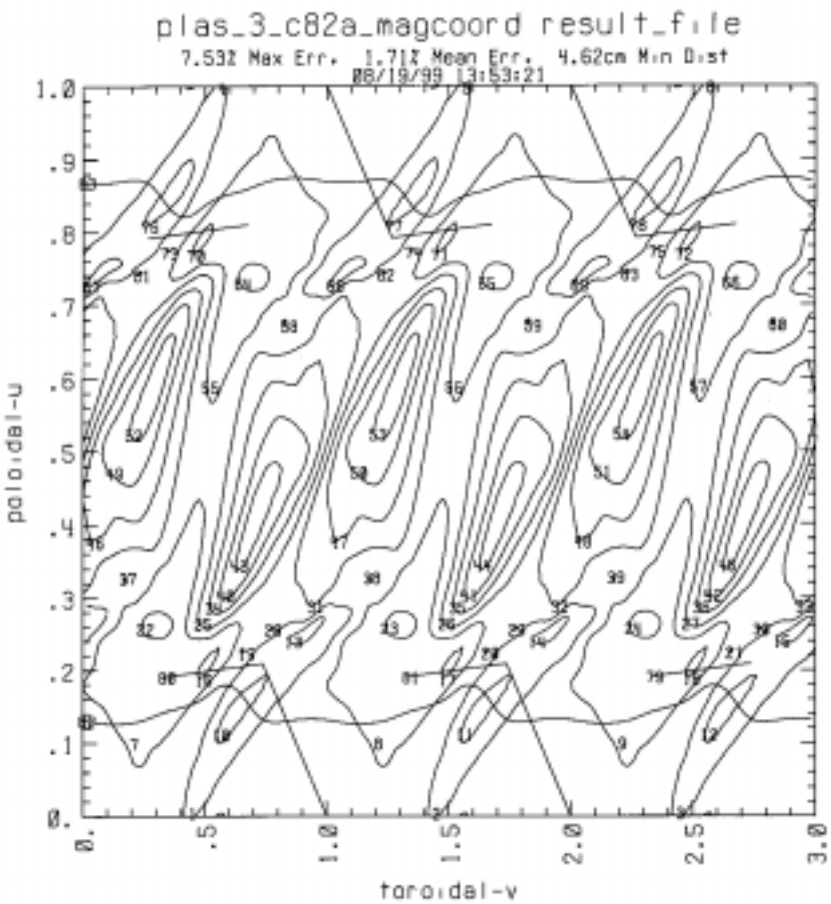
Tilting the TF coils changed the topology of the saddle coils

- **Straight TF coils feature a single set of nested saddles per half period**
- **Tilted TF coils feature 3 sets of nested saddles per half period**
- **Naturally decouples inboard and outboard - flexibility advantage?**





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Tilted TF solutions feature lower saddle coil current density, more coils, and shorter lengths

Number of contours	16	16	8	8
Saddle coils per half period	12	16	8	13
Number of TF coils	21	3	21	3
Tilt angle (deg)	0	45	0	45
Radius of TF inner leg (m)	0.45	0.55	0.45	0.55
Maximum error	3.53%	4.29%	6.14%	7.53%
Mean error	0.63%	0.73%	1.25%	1.17%
Minimum separation (cm)	1.31	1.82	2.72	3.73
Coil current (kA)	52	63	103	126
Coil length (m)	75	60	38	30
Coil current x length (kA-m)	3878	3808	3892	3747
Maximum current density (kA/cm^2)	43.4	19.7	15.5	11.9
Central iota	0.05	0.04	0.05	0.05
Edge iota	0.237	0.219	0.137	0.192
Largest non-resonant $B_{m,n}$ value	(4,-2)	(1,3)	(2,-2)	(1,-1)
	0.013	-0.013	0.018	0.043
Largest resonant $B_{m,-1}$ value	(16,-1)	(11,-1)	(17,-1)	(16,-1)
	-0.0033	0.0035	0.0053	-0.038
$\Sigma B_{m,n}^2$	0.0019	0.0029	0.0066	0.0135

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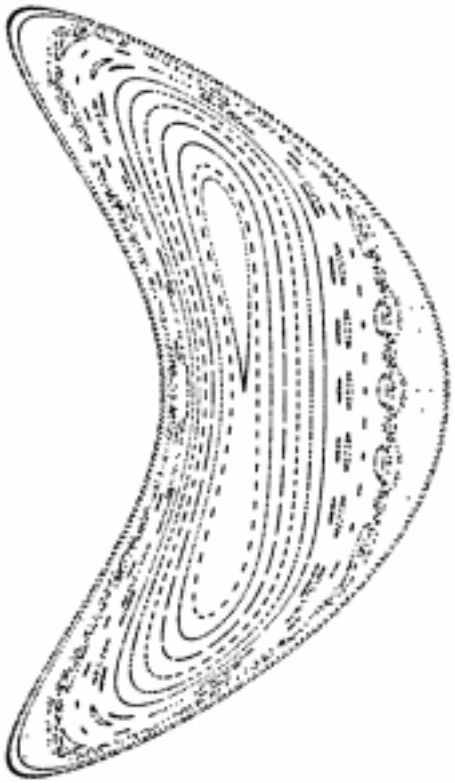
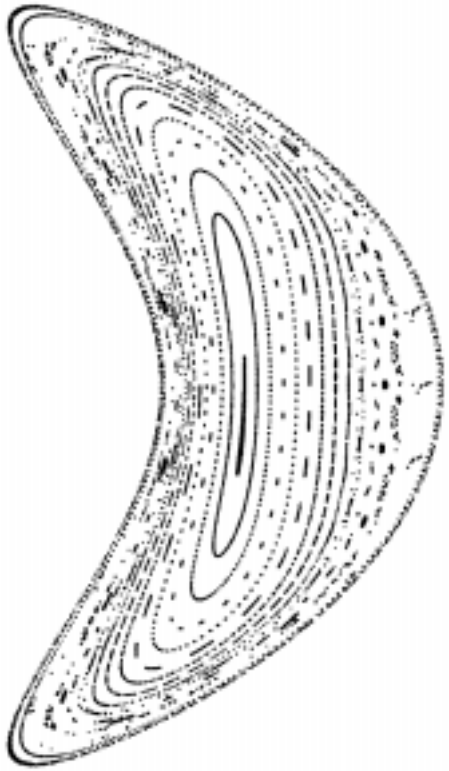
16 contour (unoptimized) solutions had similar reconstructions for straight and tilted TF coils

21 straight TF coils



3 tilted TF coils



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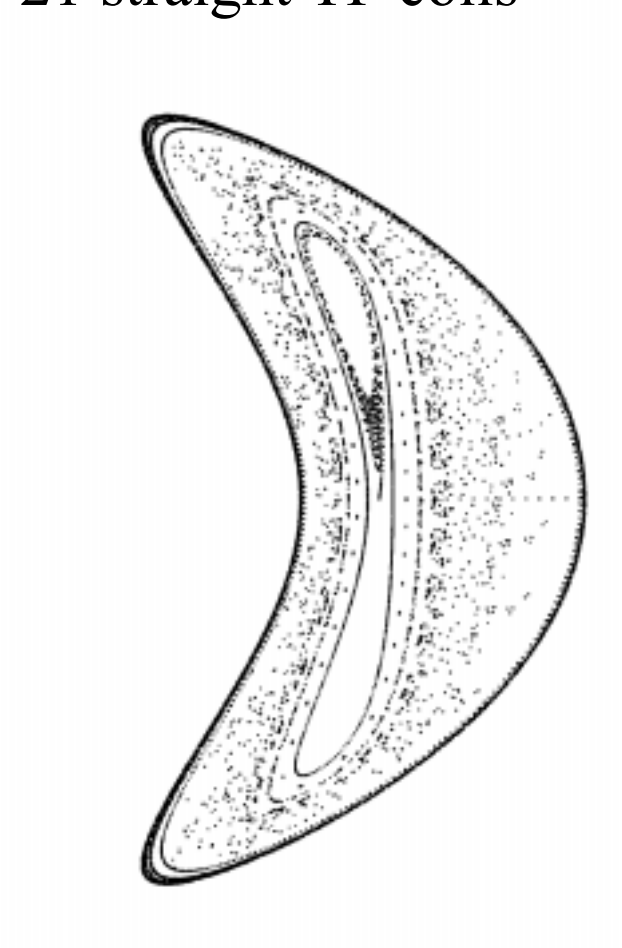
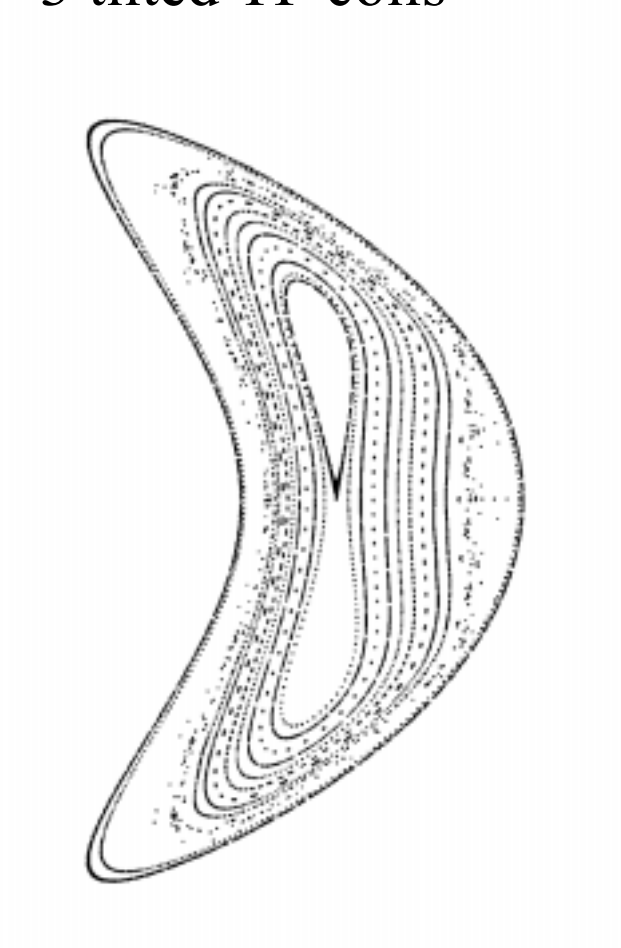
8 contour solutions had better reconstructions for tilted TF

21 straight TF coils



3 tilted TF coils



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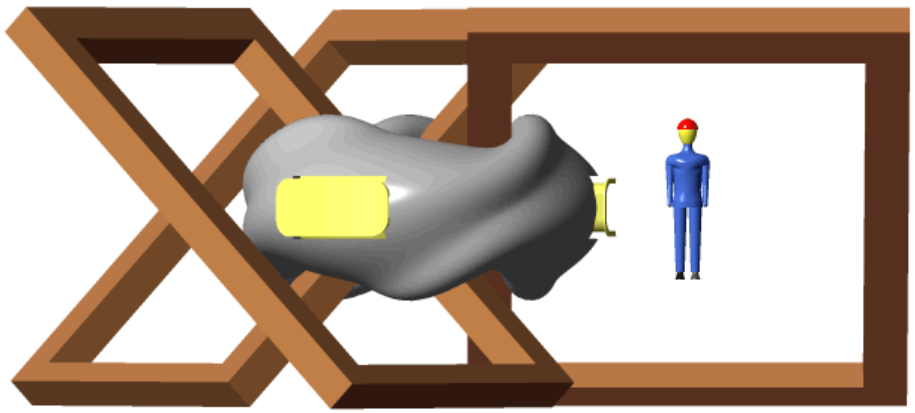
Tilted TF coils provide much improved access



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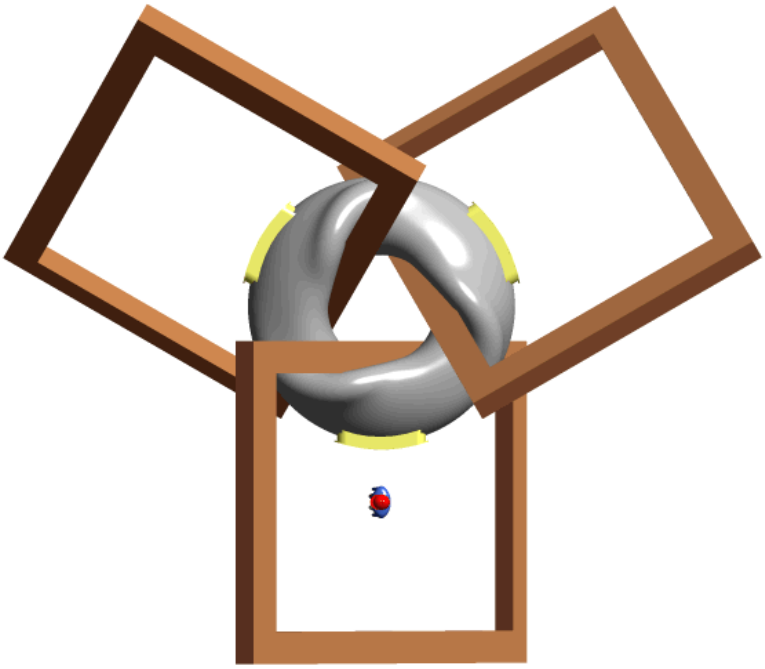

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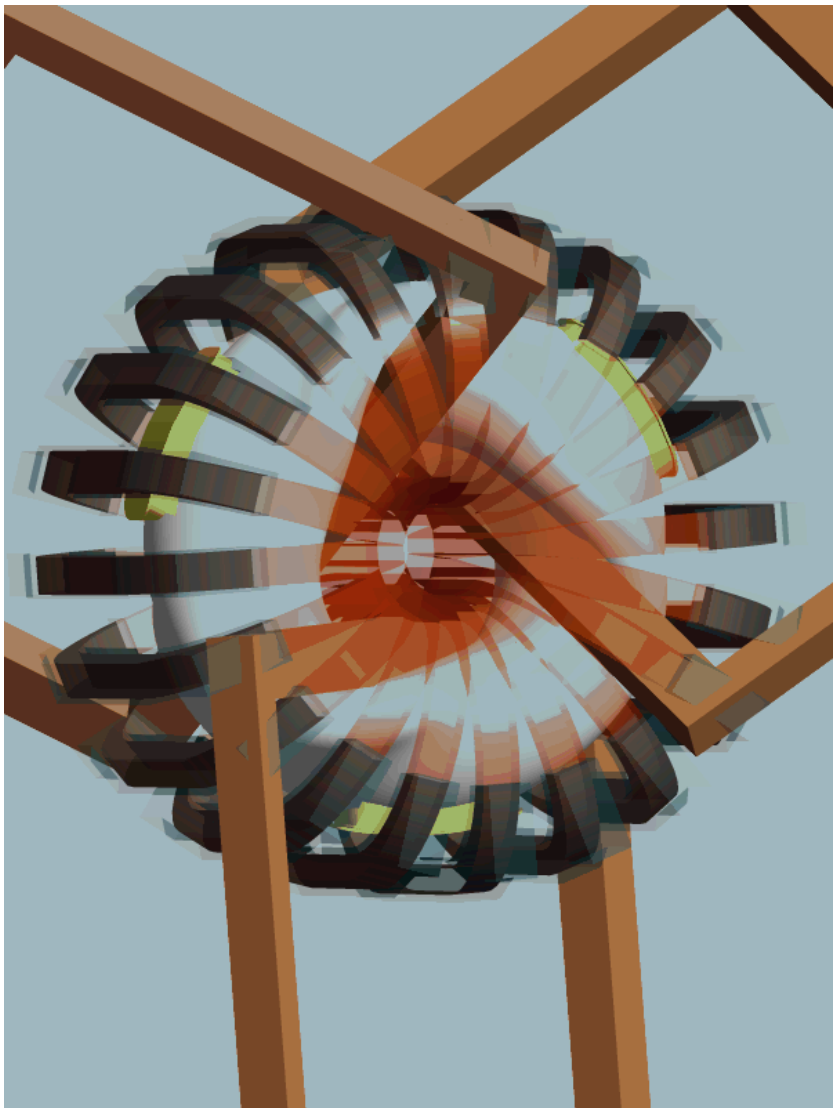

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Tilted TF coils are an interesting option

- Lower resonant and non-resonant field errors to be corrected
- Decouples inboard and outboard saddles - better flexibility?
- Saddle coil current density is substantially less
- Total length of saddle coils is reduced
- Much better access
- Cost and quasi-symmetry are TBD

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What next?

- Develop tools to assess quality of magnetic surfaces
  - Field line Hamiltonian technique with VMEC
  - Field line tracing with VMEC
- Develop true optimization tools for coil design
  - Need to vary parameters such as TF tilt angle
  - Need to constrain coil currents based on current density
  - Need to gauge quasi-symmetry and magnetic surface quality
- Develop reliable cost algorithms to compare candidate coil configurations
  - Incorporate in a systems code?
- Develop a plan for addressing flexibility
  - Meet shaping requirements for alternate configurations or provide flexibility in low order harmonics?
- Complete trade studies of candidate coil topologies
  - Including tilted v. straight TF coil options
  - Make recommendation to project