Progress investigating alternate coil topologies

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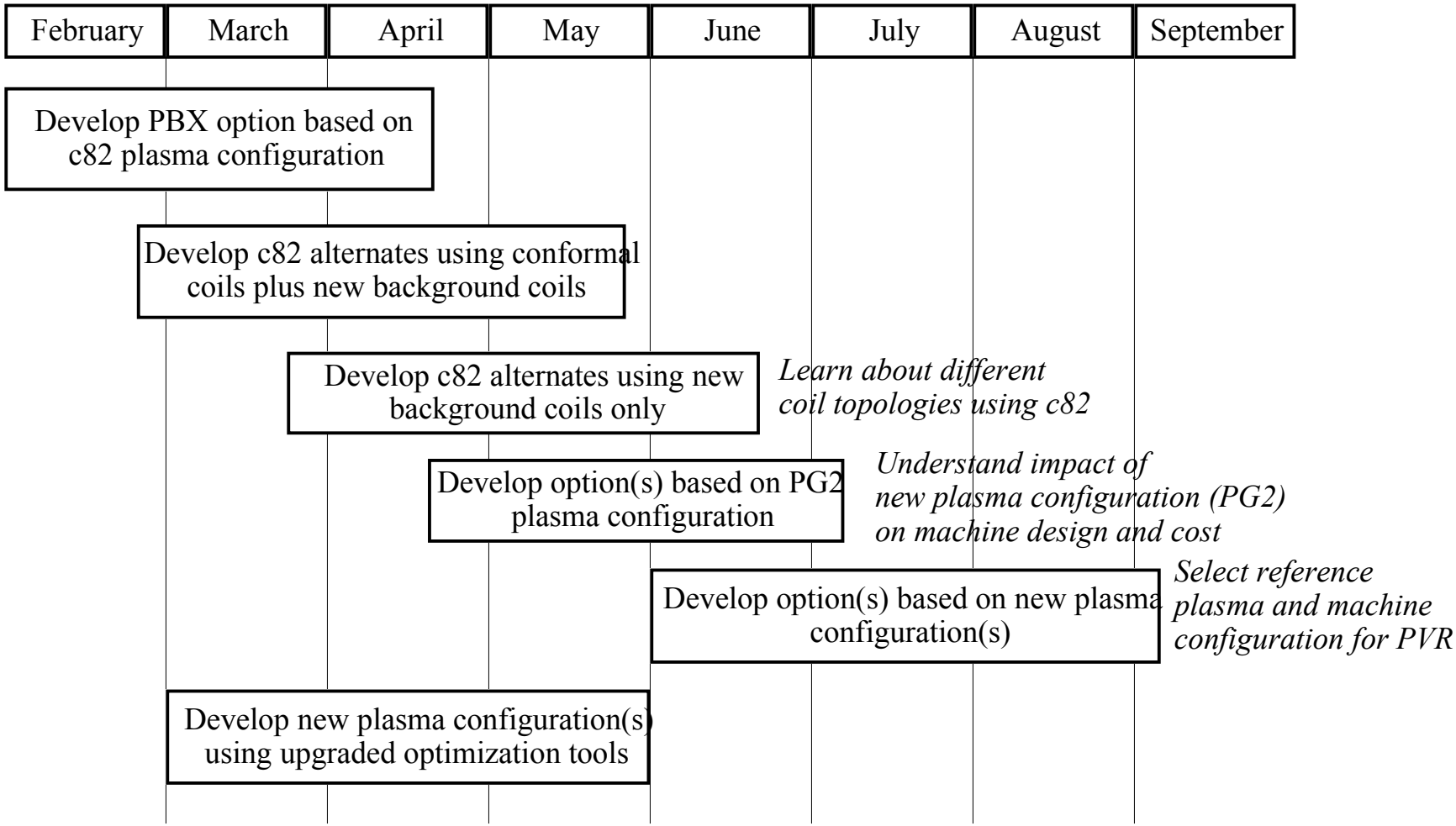
March 24, 2000

NCSX Project Meeting

Goal

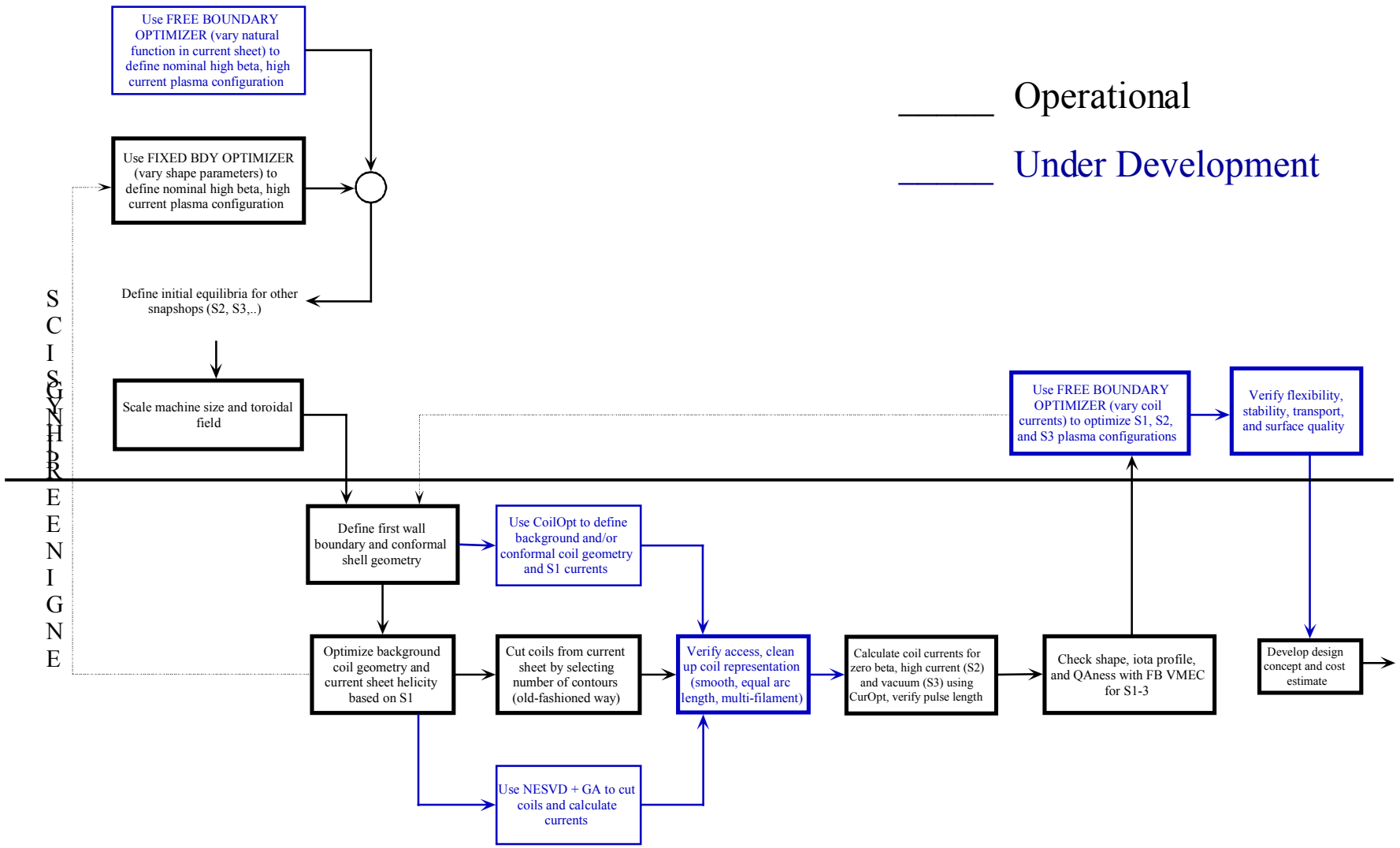
Select reference plasma and machine configuration by 9/1



Engineering effort is planned and on track

- Coil design process defined
- Team in place, responsibilities defined
- Work is proceeding on schedule
- Design development and costing nearing completion for PBX option
  - Conformal coil designs nearly complete for 2 options with new background coils
  - Coil optimization studies underway for “no conformal coil” option

Coil design process is defined

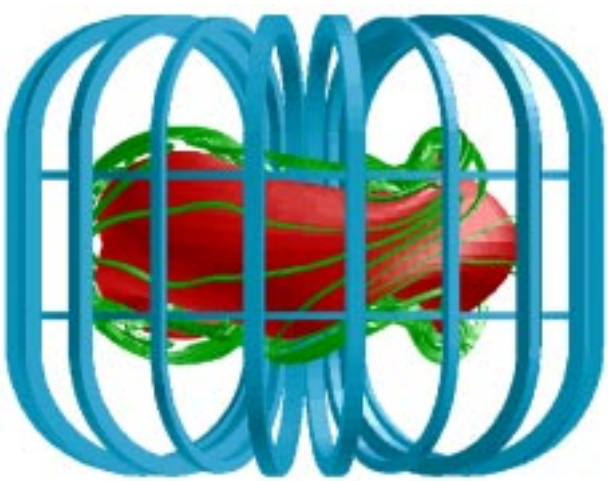


Design development and costing is nearing completion for PBX option

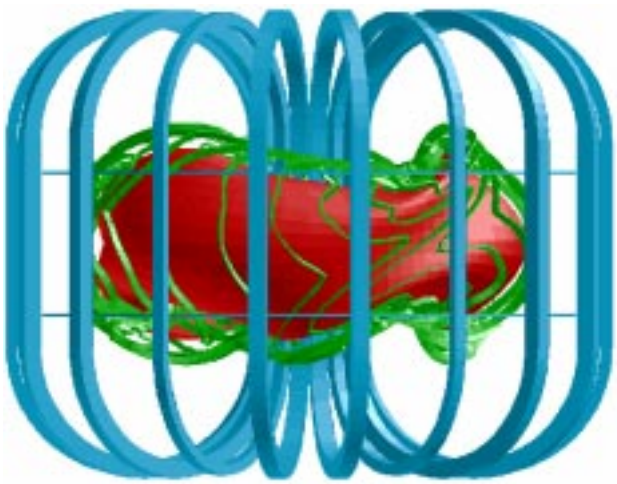
- Saddles (0/0 helicity) seem the best choice for the PBX option
- Highly optimized saddle coil design exists (4064)
- Initial investigation of startup flexibility complete
  - Coil currents and free boundary reconstructions generated for *unoptimized* vacuum and zero beta/full current plasma configurations
  - Initial attempt to check vacuum surface quality with PIES was unsuccessful – no attempts at finite current
- Machine configuration developed (Nelson)
- PFC and VV design concepts developed (Goranson)
- Conformal coil design concept developed (Williamson)
- Access requirements and accommodations investigated (Cole)
- Development of cost algorithms underway

Saddle coils (0/0 helicity) appear the best choice for the PBX option

- Saddles (0/0 helicity) and L=1 (1/1 helicity) were the only ones that reconstructed well
- Saddles appear to provide better access



0/0 Helicity

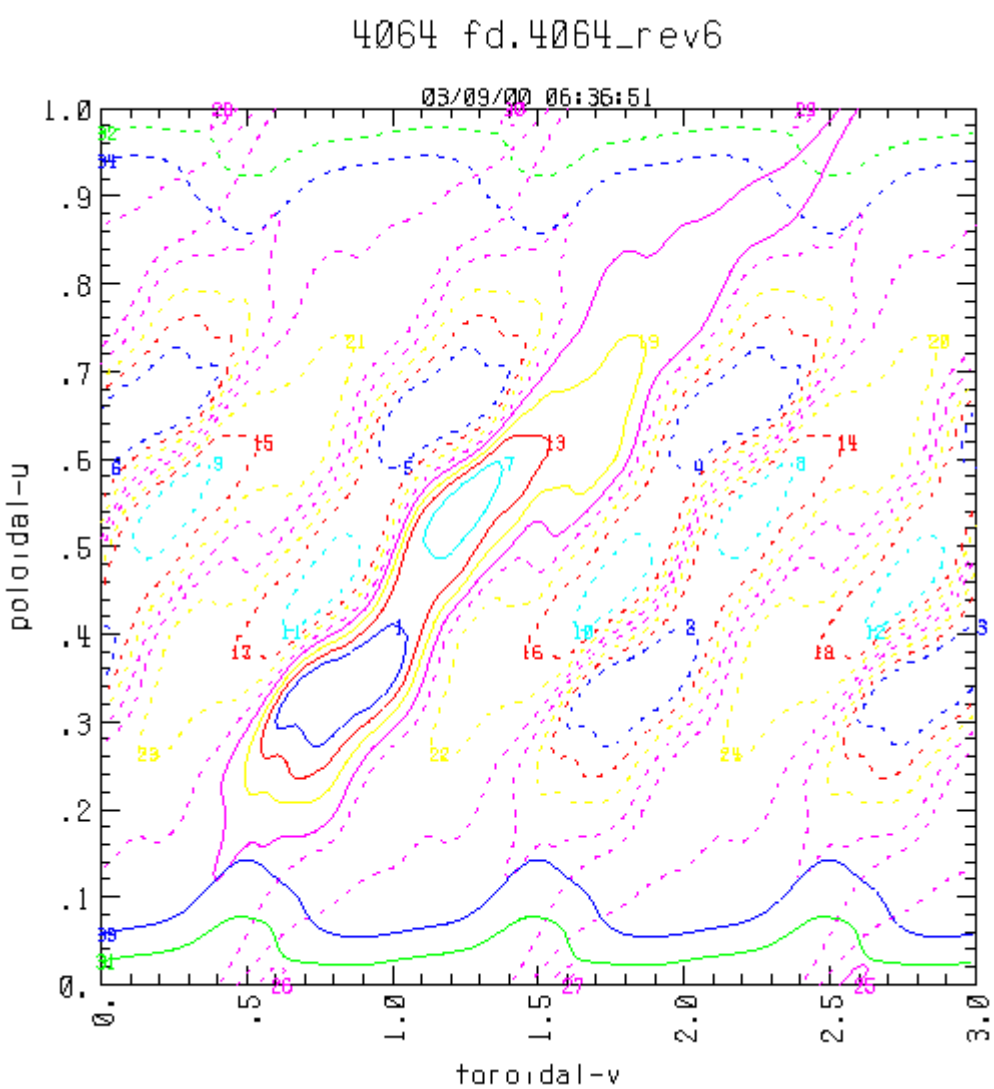


1/1 Helicity

We already have a highly optimized saddle coil design - 4064

- Generated using NESVD plus genetic algorithm (GA) plus a tweak
- Objective was to further reduce J
  - Fewer coils, better access, and lower J
  - Fit to c82 boundary is poor
  - Kink stability restored at the expense of quasi-axisymmetry (χ^2)

4064 conformal coil description

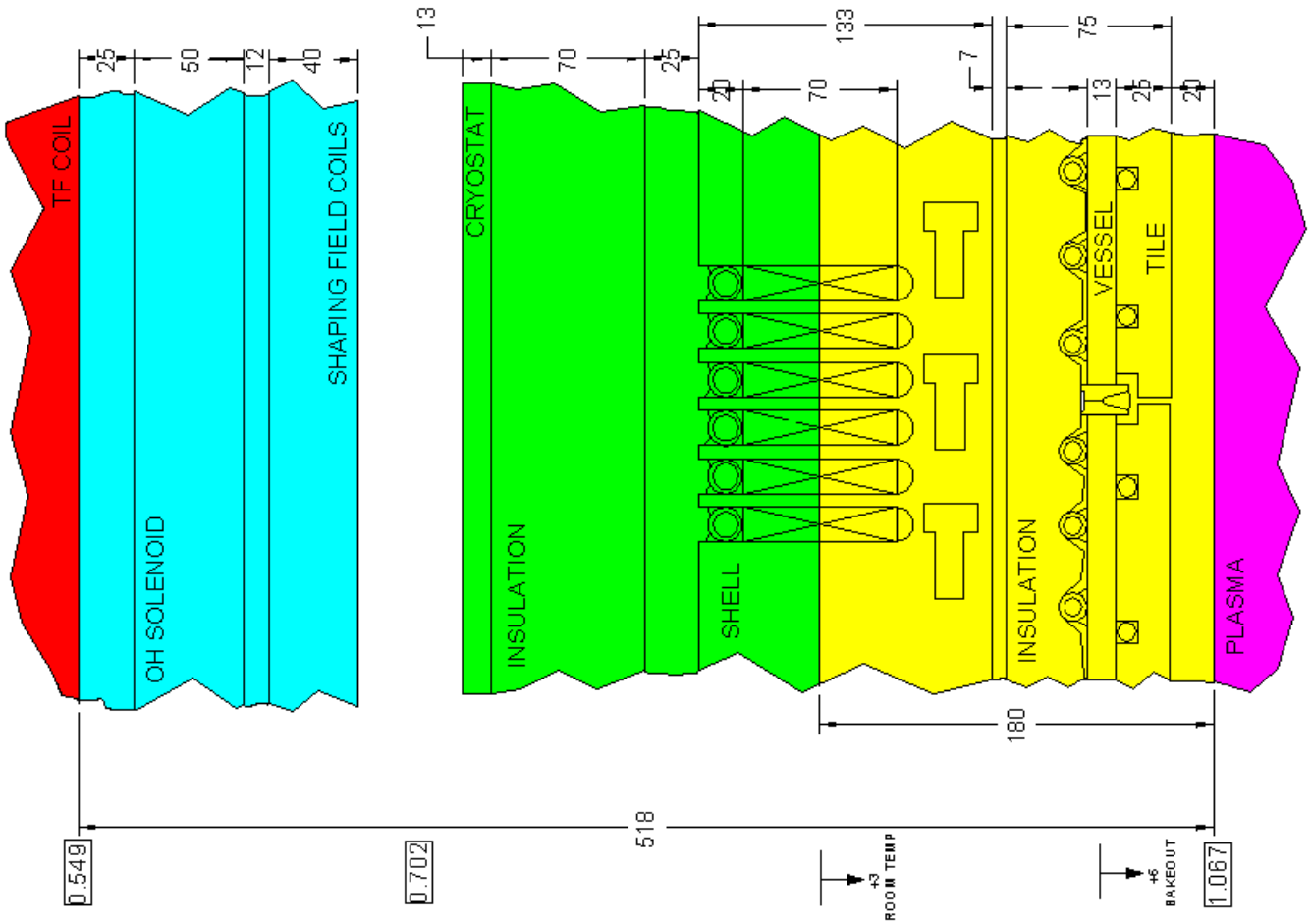


- 30 coils, all >1m
- 214 m total
- 20 MA-m
- Min separation 3.0 cm
- 5 nested saddle coil circuits (30 coils)

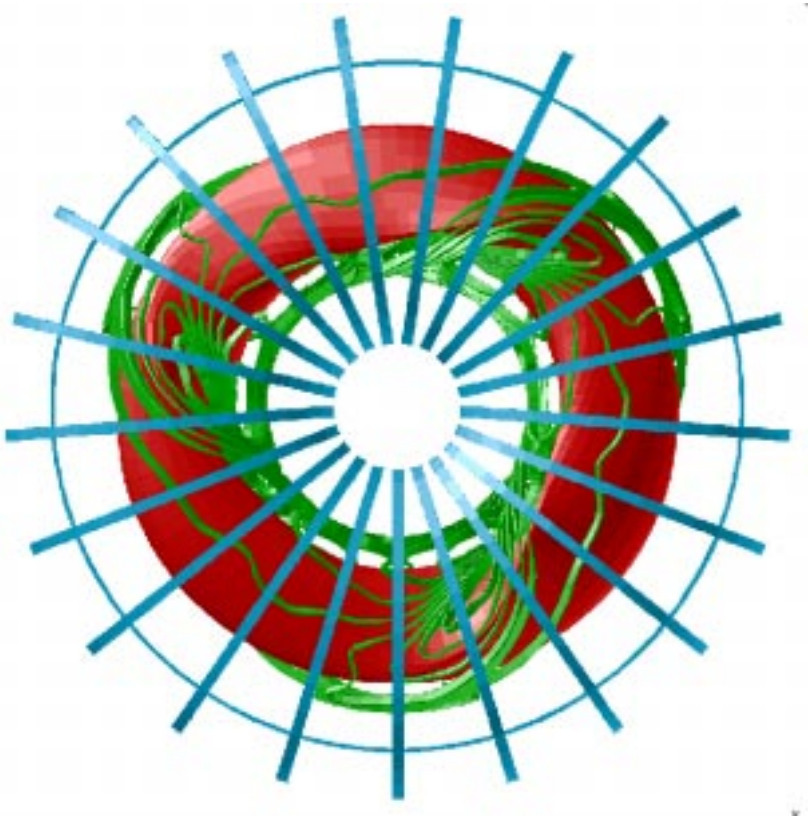
4064 coil set has few extra degrees of freedom (DOF)

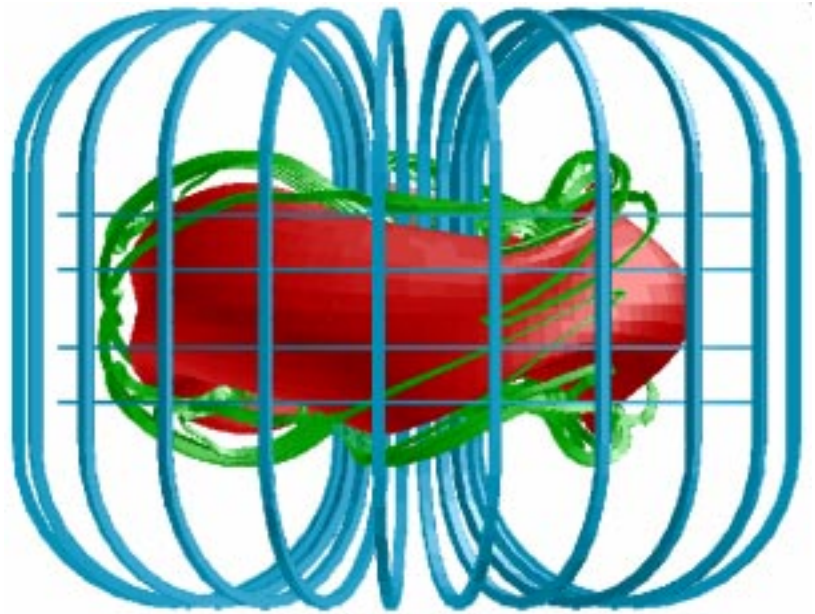
- Saddle coils provide ~2 DOF
  - Total current and skewness of current
  - Nested saddles have similar signatures at plasma
- TF provides 1 DOF, PF provides ~4 DOF
- Elementary controls alone require 4 DOF
  - Toroidal field, plasma current, external transform, radial position
- Extra DOF in PF (2) and saddles (1)

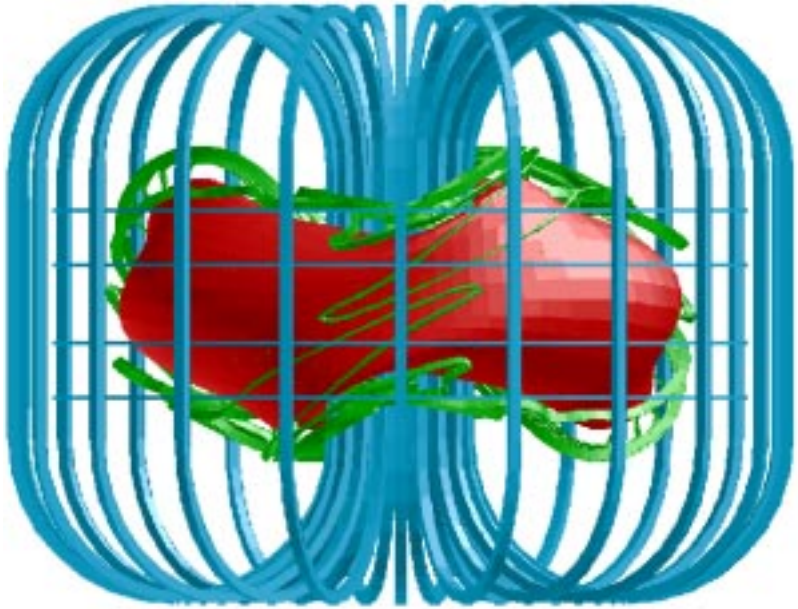
Shape flexibility limited by PBX radial constraints to ~1cm



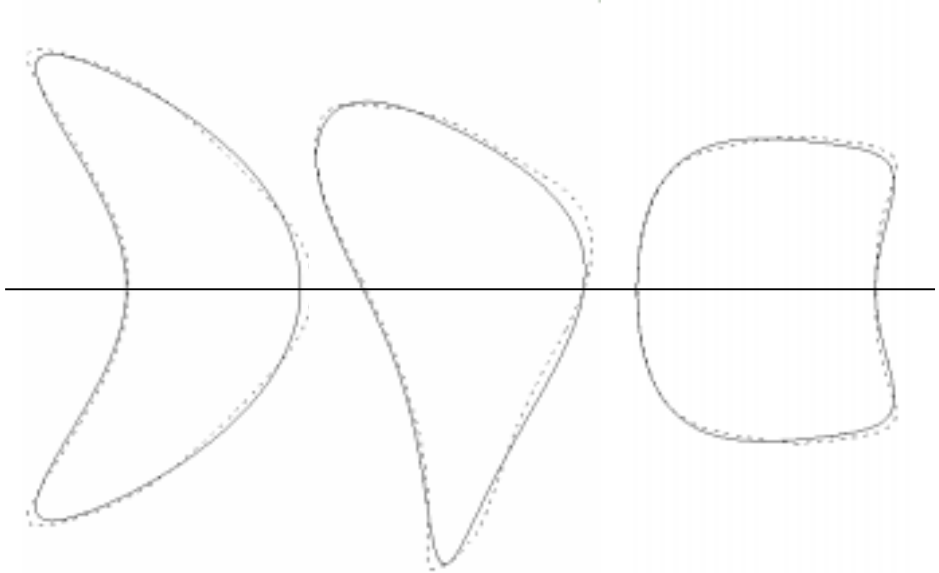
4064 features good outboard access



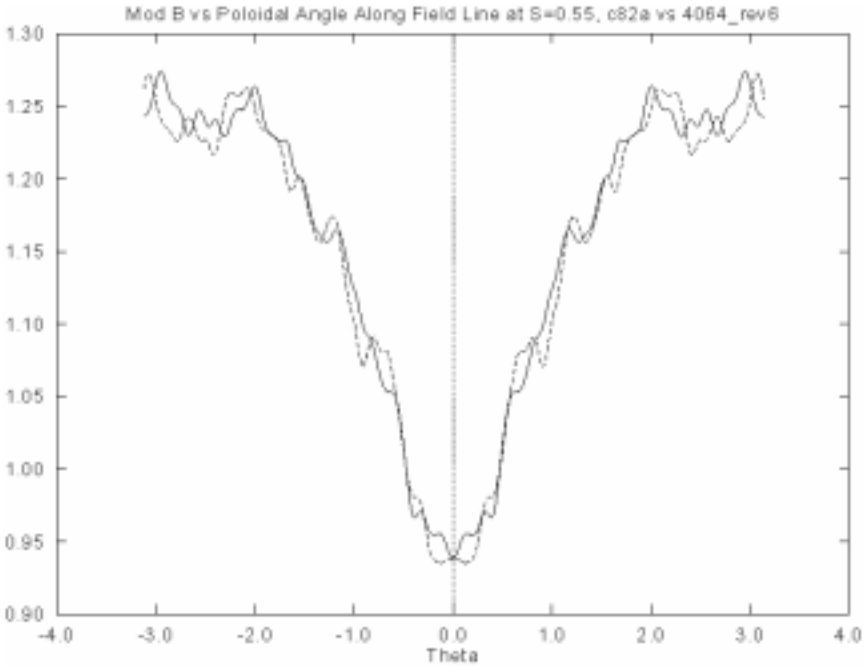


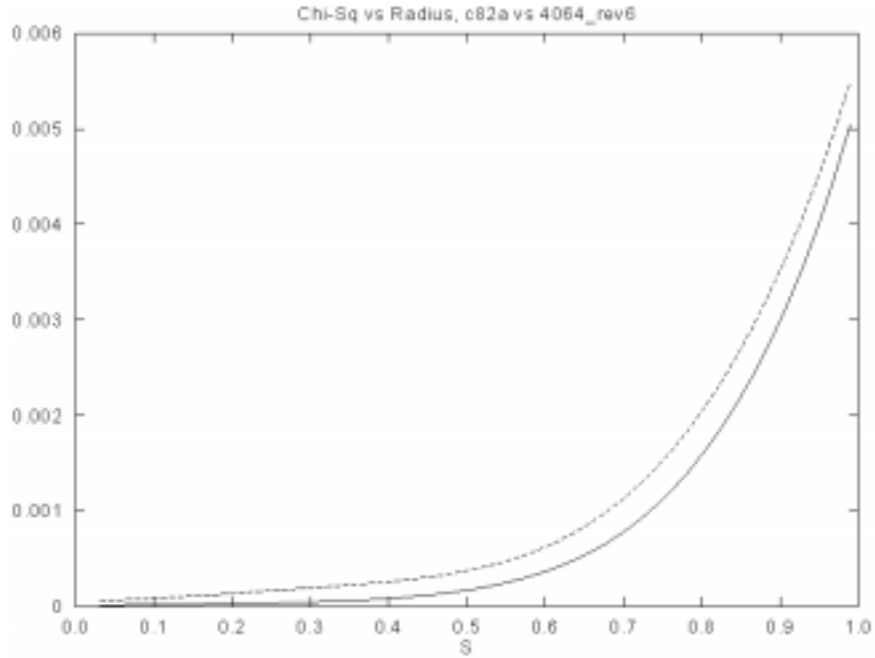


Fit is poor at high beta/full current (S1)
- 7.1% max, 1.5% mean error
- 4.4cm max, 1.2 cm avg separation



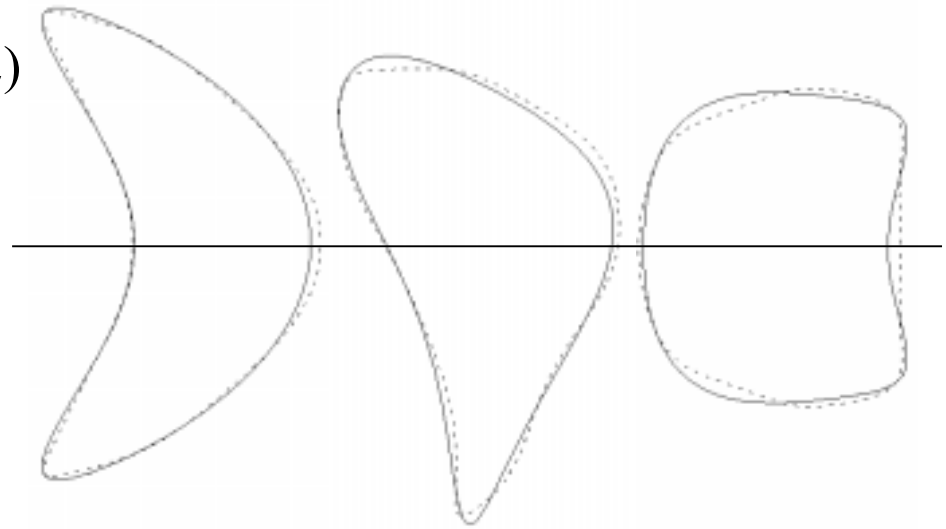
Quasi-symmetry is also poor
- χ^2=1.96 (1.44) at s=0.51 (0.72)
- Transport is TBD
- Kink stable at 3.9% beta!

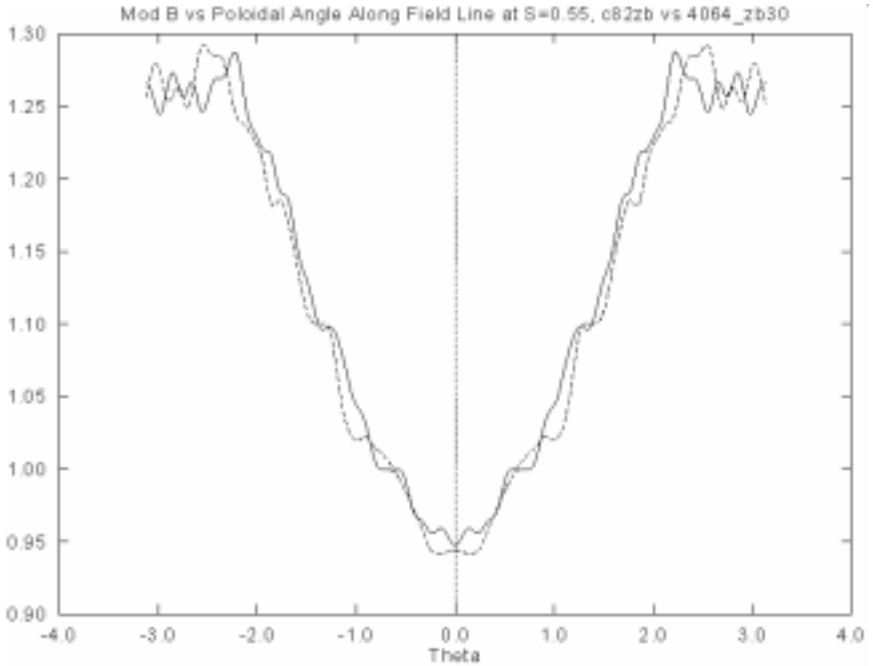


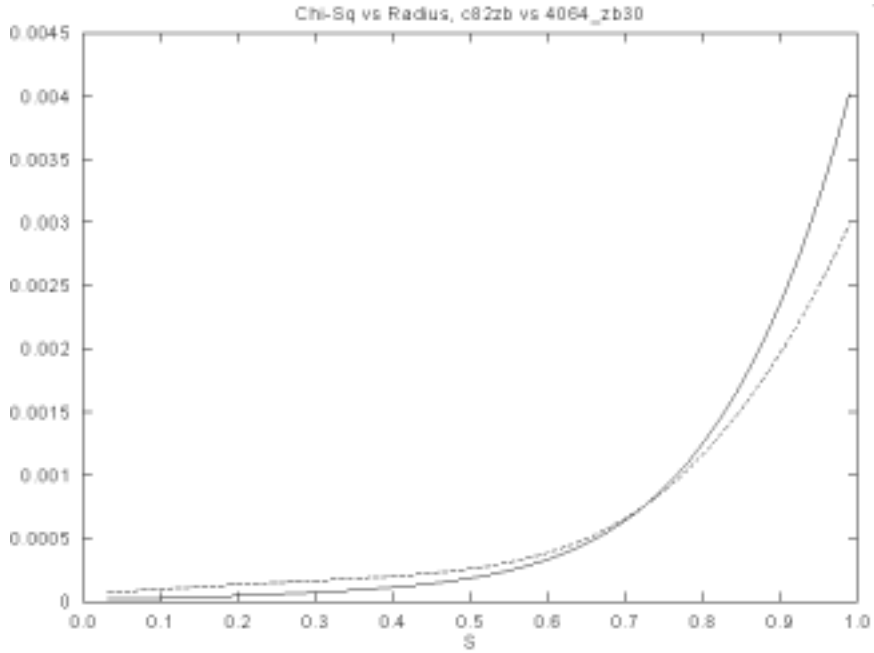


Fit is poor at zero beta/full current (S2)
- 7.4% max, 1.6% mean error
- 4.5cm max, 1.2 cm avg separation

Quasi-symmetry is better
- χ^2=1.3 (0.8) at s=0.51 (0.72)
- Transport is TBD
- Kink stable at zero beta!

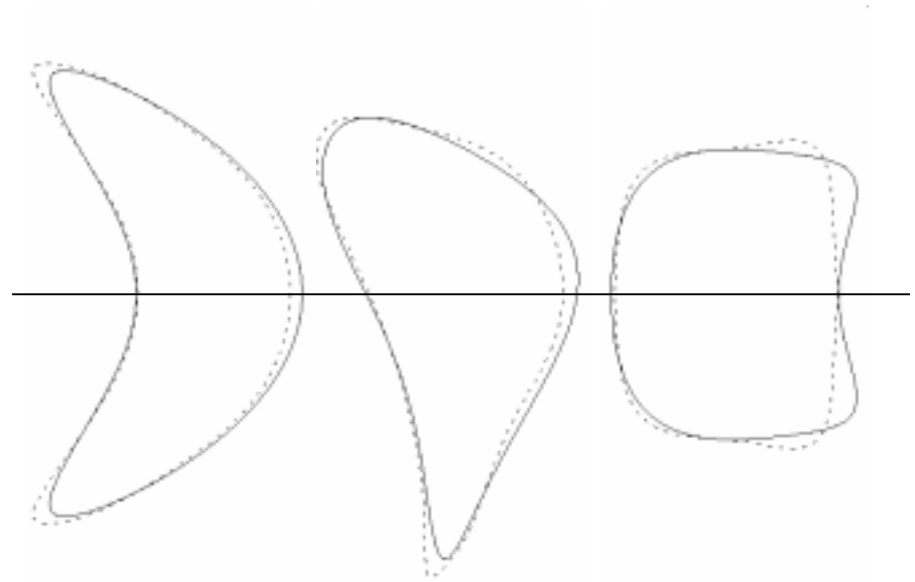


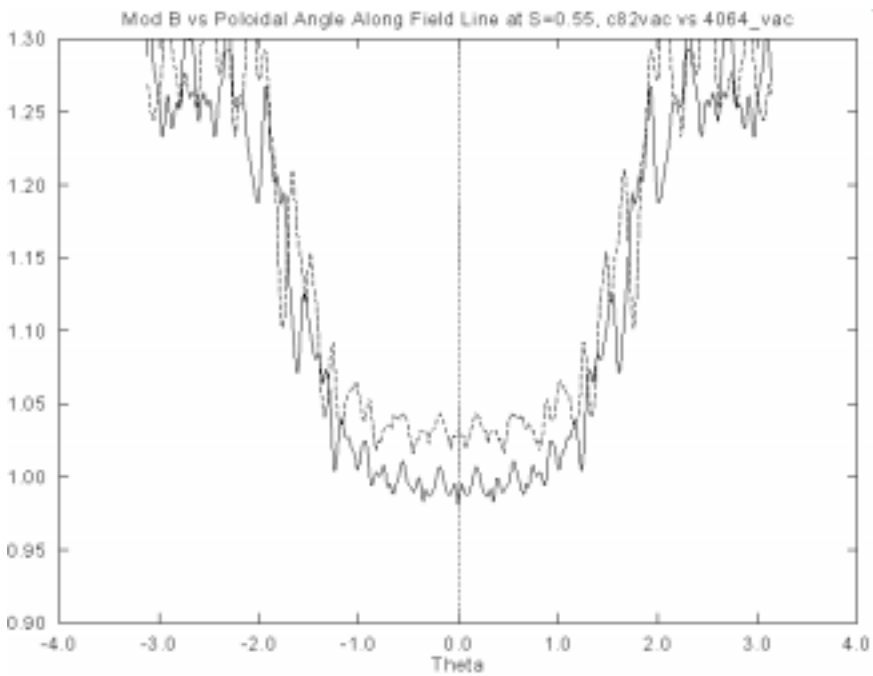


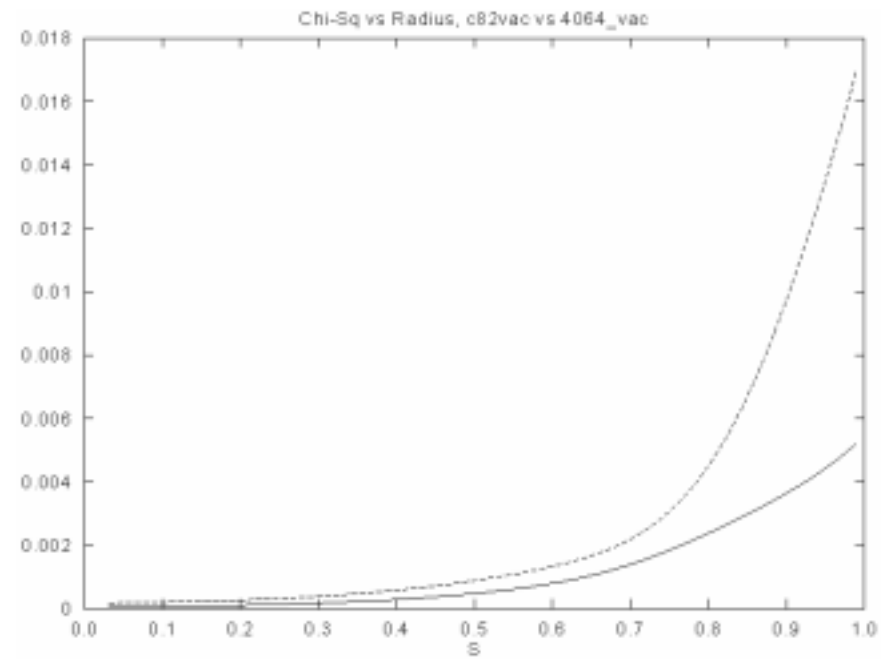


Fit is ugly in vacuum (S3)
- 9.0% max, 1.7% mean error
- 8.1cm max, 1.9 cm avg separation

Ditto for quasi-symmetry
- χ^2=4.0 (2.9) at s=0.51 (0.72)
- Worse at edge
- Transport is TBD





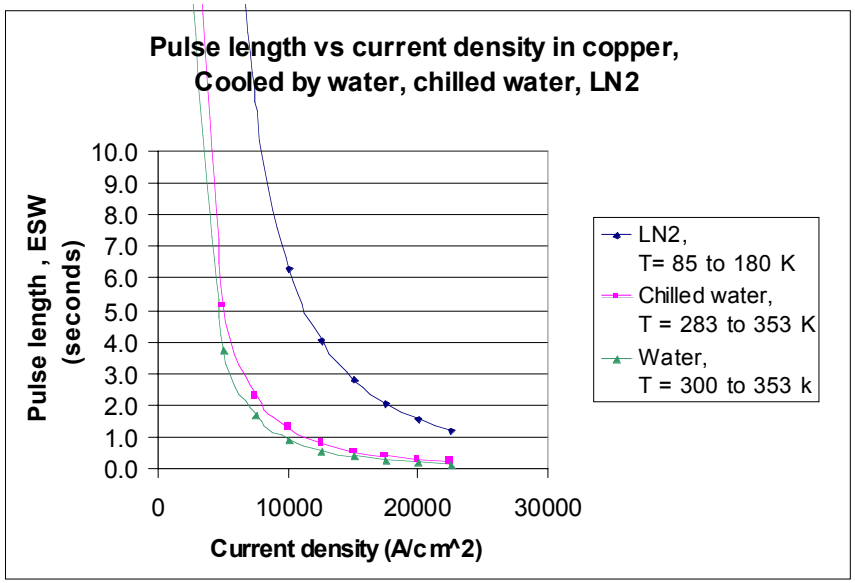


Coil currents vary from 66% to 127% during startup

State		Full Current, Full Beta	Full Current, Zero Beta	Vacuum	Min	Max
Currents (kA)					66%	127%
	Saddle	66.92	80.74	65.02	97%	121%
	Saddle	106.80	118.08	96.77	91%	111%
	Saddle	79.98	68.50	97.11	86%	121%
	Saddle	103.22	97.68	67.89	66%	100%
	Saddle	95.10	93.42	120.37	98%	127%
	EF	-44.35	-7.41	17.76		
	EF	-54.53	-43.84	-44.09		
Field Errors (%)						
	Max	7.13	7.43	8.95		
	Average	1.53	1.62	1.74		
4064_rev6 Coil Currents and Field Errors at R*Btor=1.66						

Current density is high (21 kA/cm^2) at high beta/full current (S1)

- Requires LN2 pre-cooling
- ΔT is ~100K
- Cooldown (temperature ratcheting) is a concern
  - R&D required to quantify
- High current density may limit flexibility
  - During startup alone, coil currents vary from 66% to 127%



Initial assessment of PBX option (4064) is nearly complete

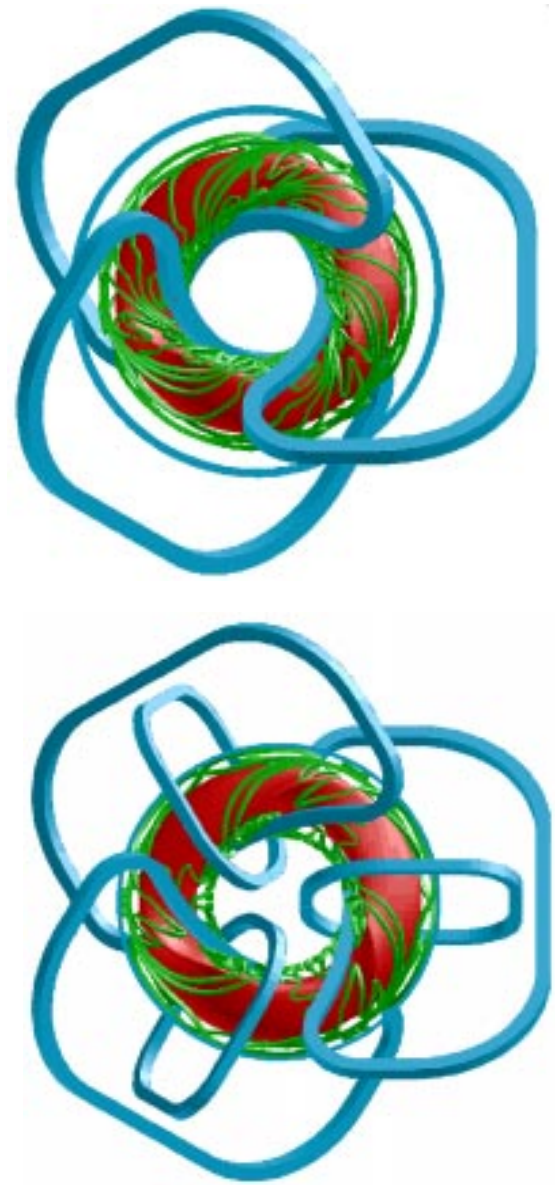
- Current density high but marginally OK for 1s ESW, may limit flexibility
- Access appears adequate for NB and RF, diagnostic access is TBD
- 4064 coil set has few (~3) extra degrees of freedom (DOF) beyond those required for elementary controls (B_t, I_p, R_p, $iota_{ext}$)
- Shape flexibility limited by PBX radial constraints to ~1cm
- Results of initial investigation of startup flexibility:
  - 4064 coil set cannot match c82 boundary during startup
    - Plasma does not fit within present first wall boundary
    - Would need to modify FW and winding surface or shrink plasma
  - χ^2 doubled (relative to fixed boundary value) for high beta/full current, impact on transport is TBD
  - Surface quality is unknown
- No other flexibility points defined or evaluated
- Design concept developed, cost assessment underway

2 classes of new background coils explored – tilted TF and L=3 coils

- Both have the potential to relieve apparent problems in the PBX option
  - Better conformal coils (reduced J, lower cost, reduced technical risk, enhanced flexibility)
  - Improved access and shape flexibility by relaxing constraints imposed by PBX coils
  - Complete freedom in optimizing plasma configuration re aspect ratio, elongation, and helical axis excursion

Tilted TF Coil Options

- Tilted TF coils fit in the groove on the inboard side
- Replacing the PBX TF set with 3 tilted TF coils reduces the maximum current density (J) in the conformal coils by more than 50%
- Adding 3 more tilted TF coils does not further reduce J_{max} but reduces total amp-m by 25%

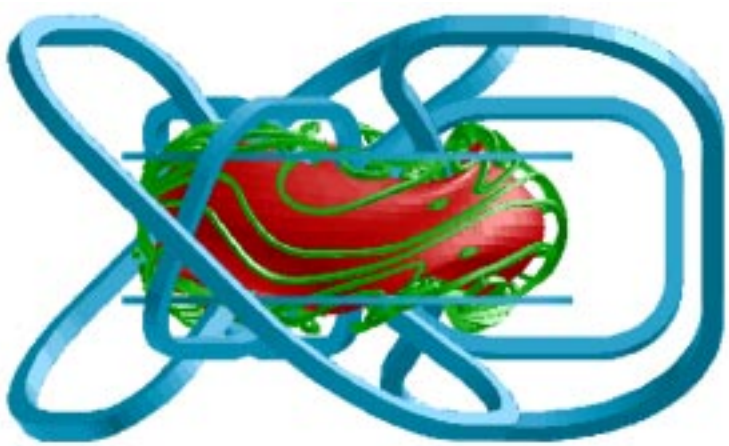


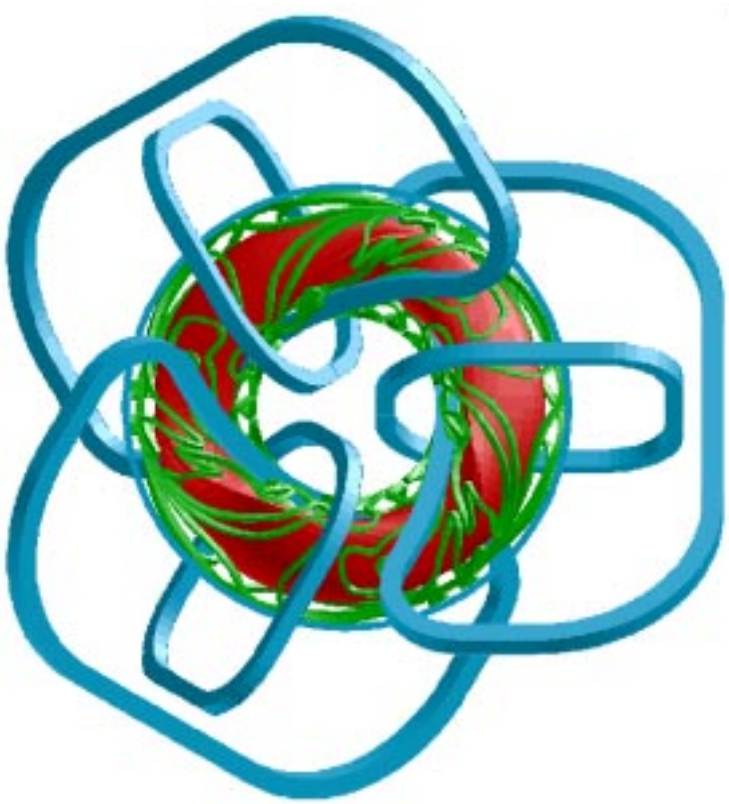
The best CS helicity for the tilted TF option appears to be 0/1 (wavy PF coils)

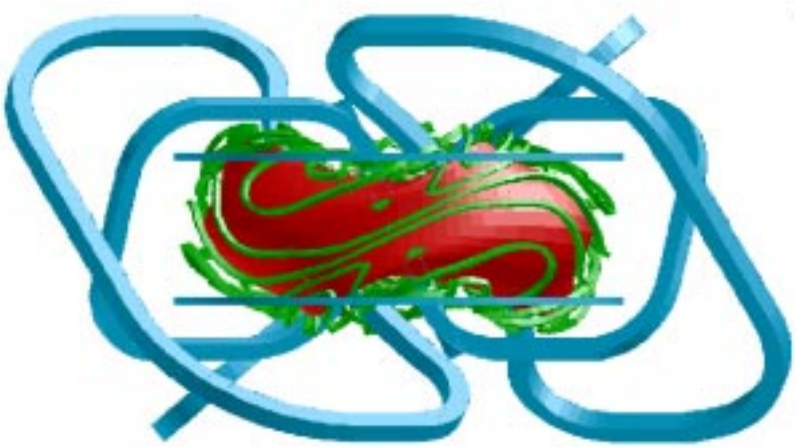
Current sheet helicity		0/0	1/1	1/2	0/1
Case		526a.7	510a.2	528a.3	536.3
Max error	%	6.5	4.3	4.4	4.8
Avg error	%	1.0	1.1	0.5	1.1
Number of coils (>1m)		24	8	21	23
Independent circuits (with coils >1m)		6	2	5	6
Total length	m	196	157	254	169
MA-m	MA-m	18	16	17	18
Min separation	cm	4.2	4.6	3	5.2
J in Cu at 2T	kA/cm^2	12.7	12.3	15	11
Access		Limited	Good	Most Limited	Good
Reconstruction data					
Maximum separation	cm	4.1	3.5	2.2	2.6
Average separation	cm	0.6	0.7	0.4	0.7
Quasi-symmetry		Good	Good	Good	Good

Case 536.3

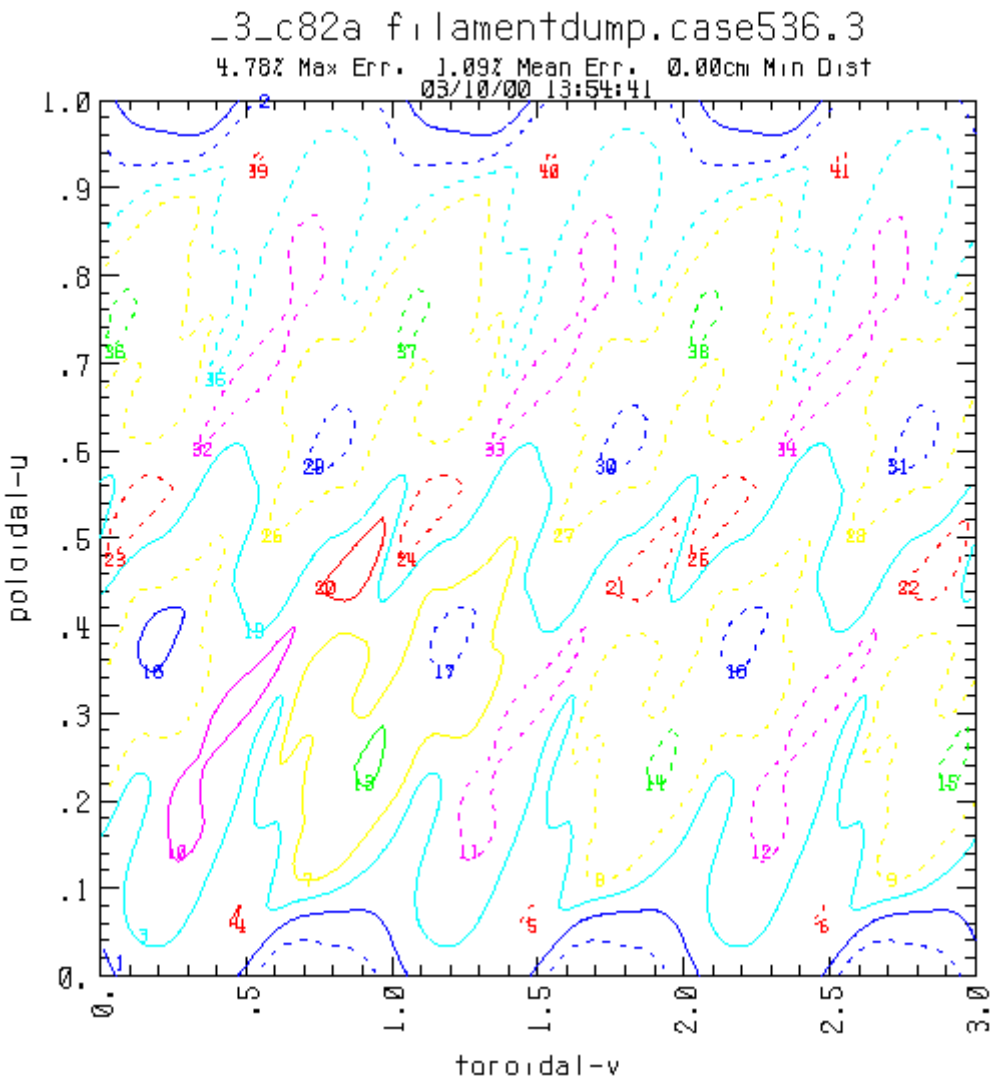
- 6 tilted TF coils with 0/1 helicity
- Current density is 11.0 kA/cm^2, marginally OK for water cooling
- Access appears good if tiny saddles can be eliminated







Case 536.3 conformal coil description

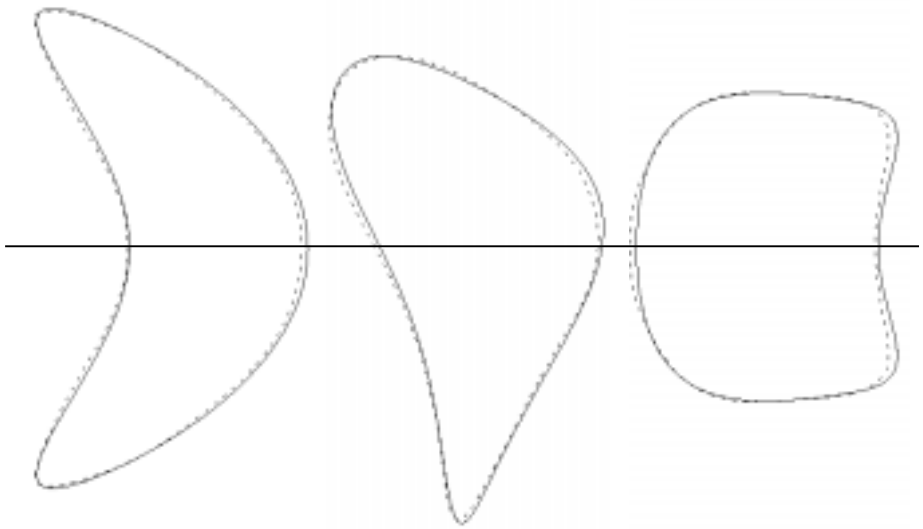


- 41 coils, 23 coils >1m
- 169 m total
- 18 MA-m
- Min separation 5.2 cm
- 1 wavy PF coil circuits inboard, 2 wavy PF coil circuits outboard (5 coils)
  - Provide separate in-out control
- 3 large (>1m) saddle coil circuits (18 coils)
- Some of the 3 smaller saddles (<1m) would likely be eliminated or lumped into one circuit (18 coils)

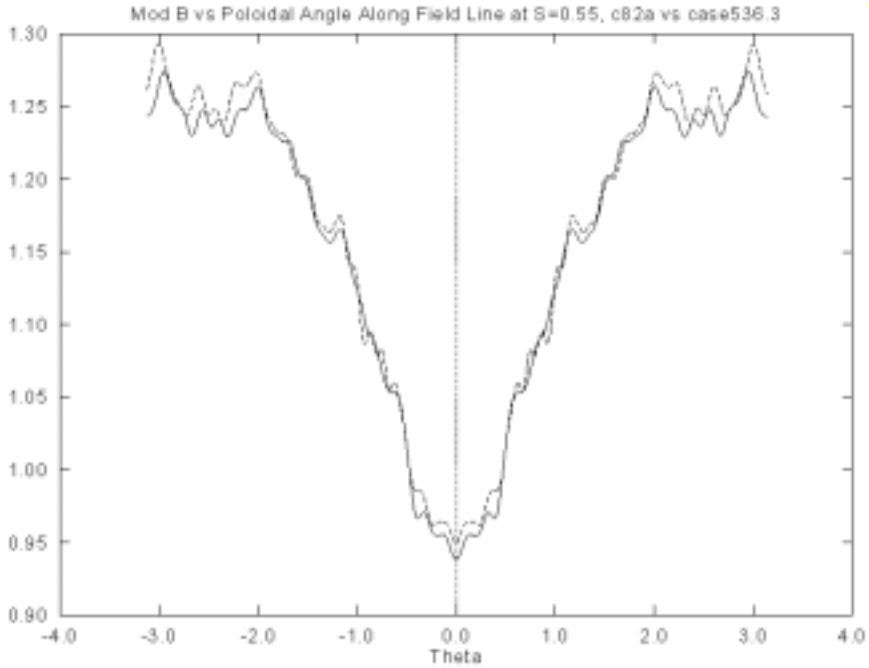
Case 536.3 coil set has more degrees of freedom (DOF) than 4064

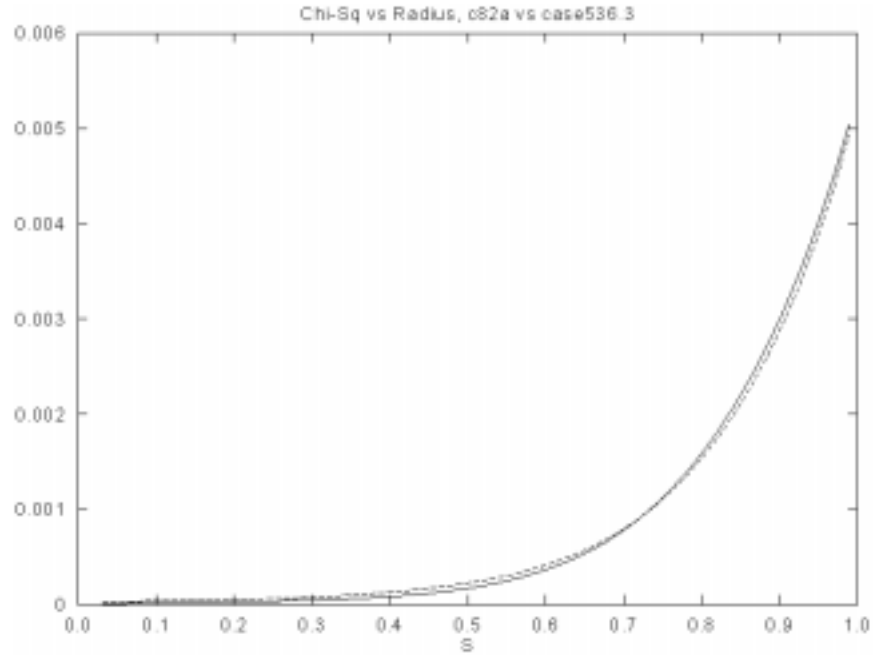
- Conformal coils provide 5+ DOF (v. 2 DOF)
  - Different coil geometries should have different signatures at plasma, unlike tightly nested saddles
- TF provides 2 DOF, PF provides ~4 DOF
- Elementary controls alone require 4 DOF
  - Toroidal field, plasma current, external transform, radial position
- Extra DOF in TF (1), PF (2) and conformal coils (4+)

Fit is better than for 4064
- 4.8% max, 1.1% mean error
- 2.6cm max, 0.7 cm avg separation



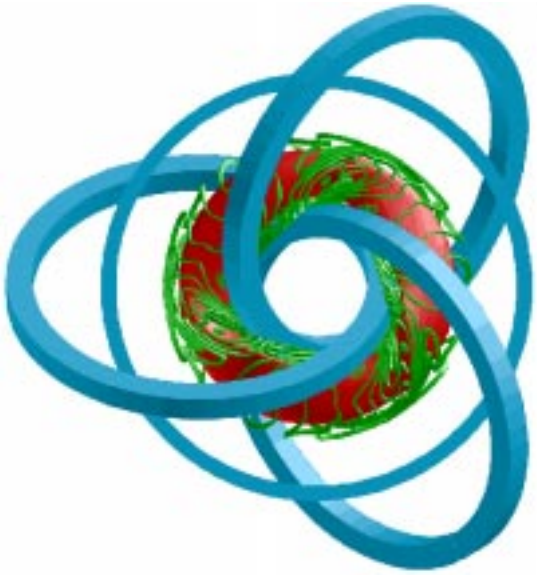
Quasi-symmetry is also better
- χ^2=1.2 (1.0) at s=0.51 (0.72)
- Transport is TBD
- Kink stability is TBD

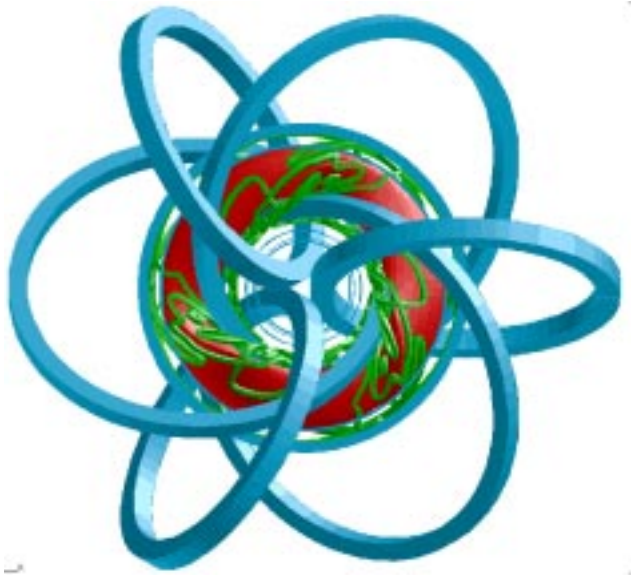




L=3 Coil Options

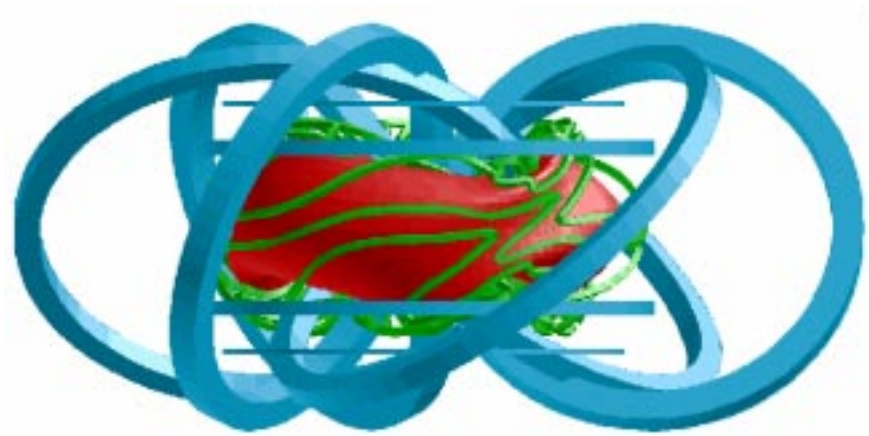
- L=3 coils close on themselves after one poloidal and one toroidal revolution
- Circular planar coils were studied for use with conformal coils – simple, can be wound
- Replacing the TF set with 3 circular L=3 coils reduces the current density (J) in the conformal coils by 30%
- Adding 3 circular TF coils to the 3 circular L=3 coils further reduces J by 40%

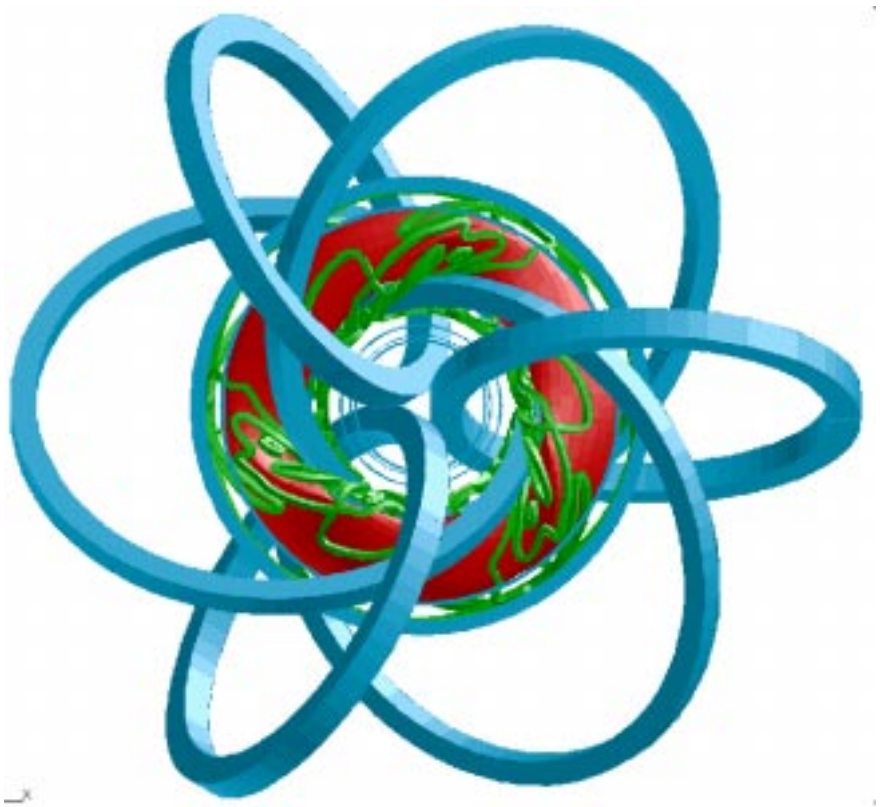


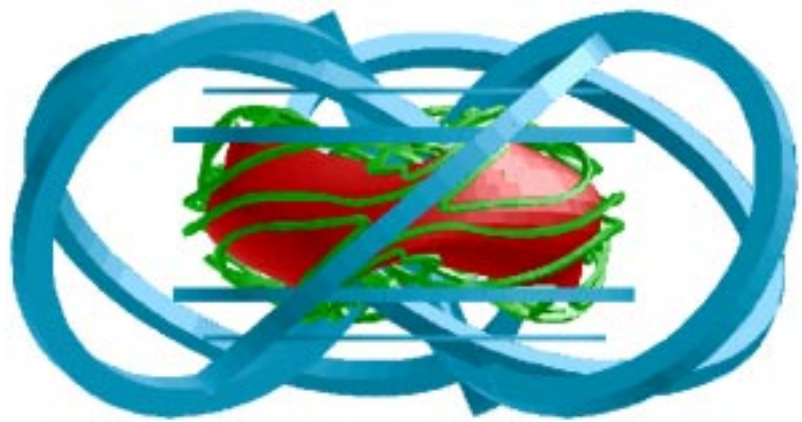


Case 393j.7

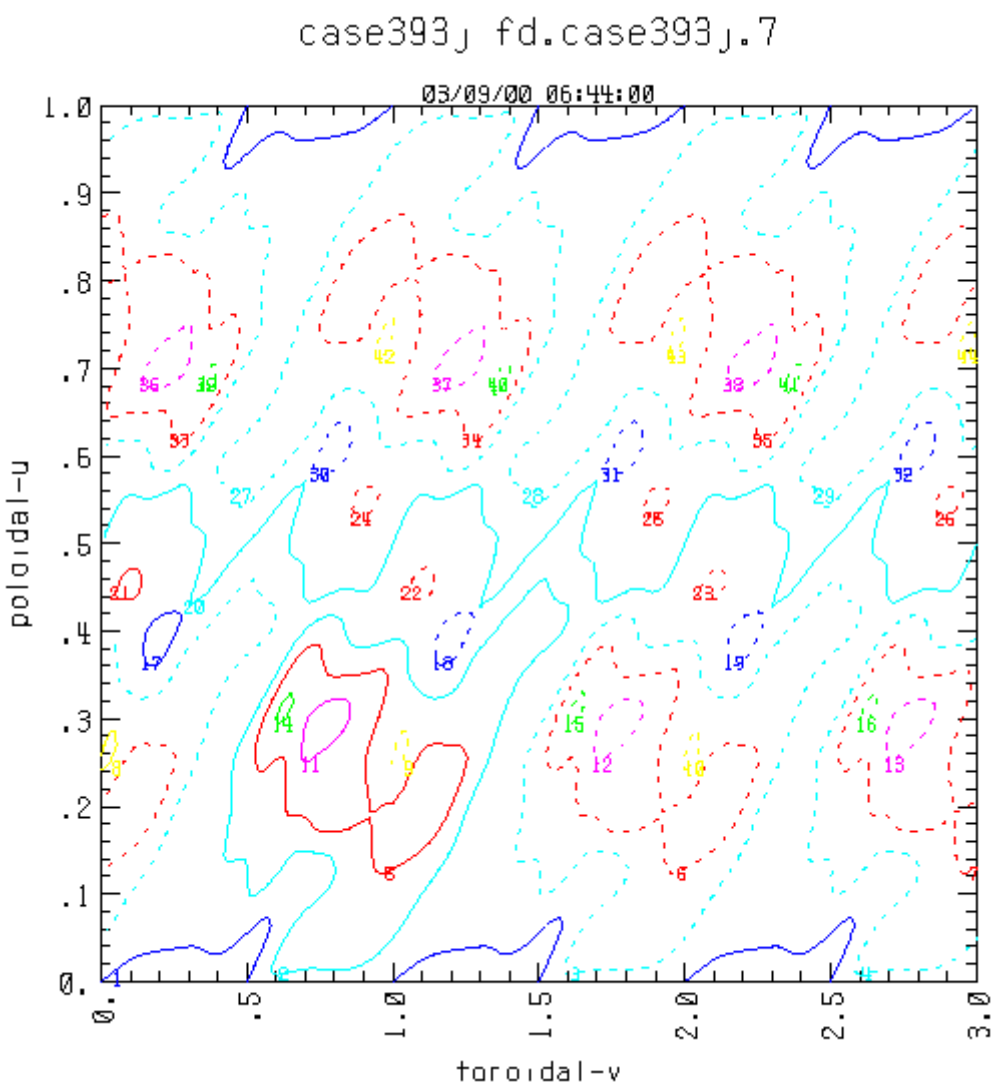
- 3 L=3 coils with 3 tilted TF coils (all circular)
- 0/0 helicity (unoptimized)
- 8.7 kA/cm^2
- Access needs improvement
- Transport and kink stability are TBD







Case 393j.7 conformal coil description

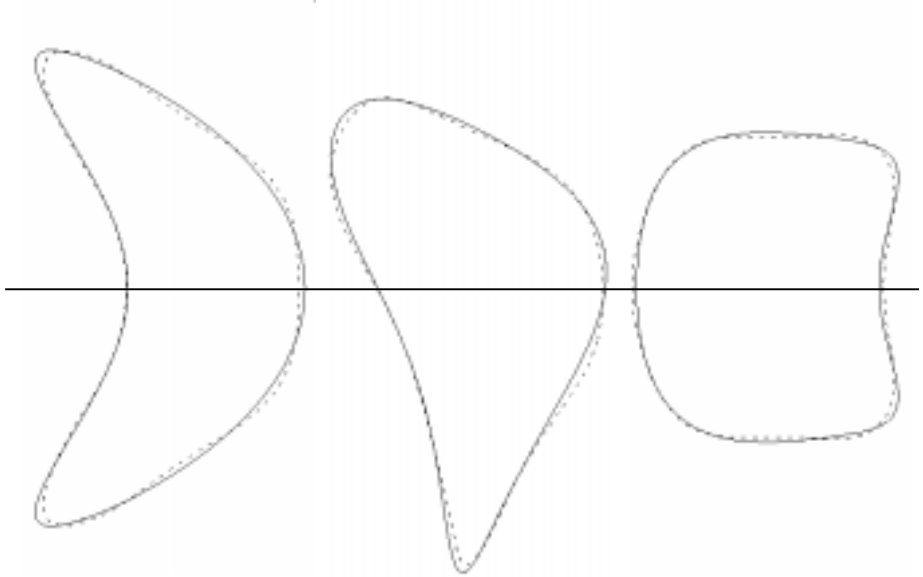


- 44 coils, 20 coils >1m
- 154 m total
- 17 MA-m
- Min separation 6.8 cm
- 1 wavy PF coil circuits inboard, 1 wavy PF coil circuits outboard (2 coils)
  - Provide separate in-out control
- 1 large saddle coil circuit with 2 nested saddles inside, 1 outside (18 coils)
- 4 smaller saddles (<1m) would likely be eliminated or lumped into fewer circuits (24 coils)

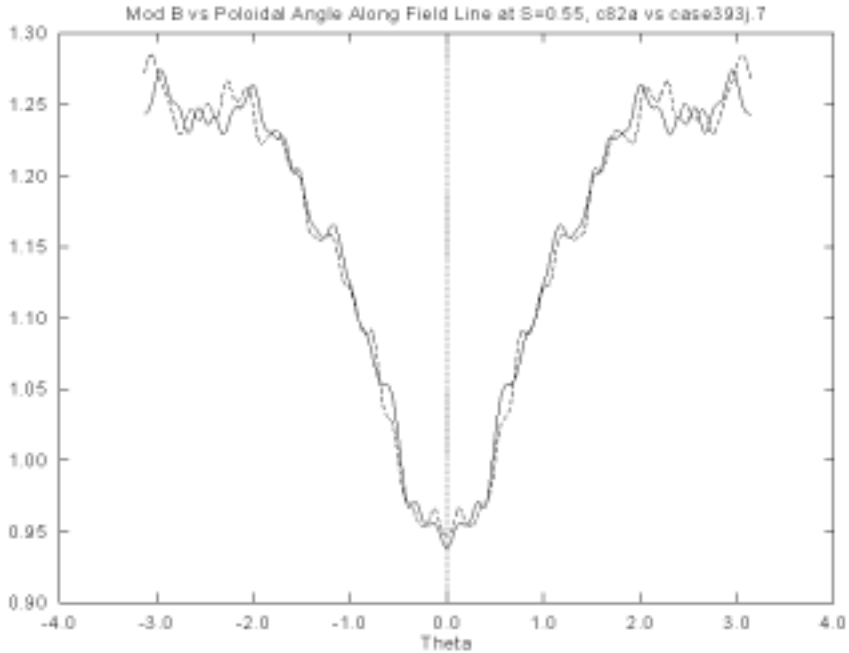
Case 393j.7 coil set also has more degrees of freedom (DOF) than 4064

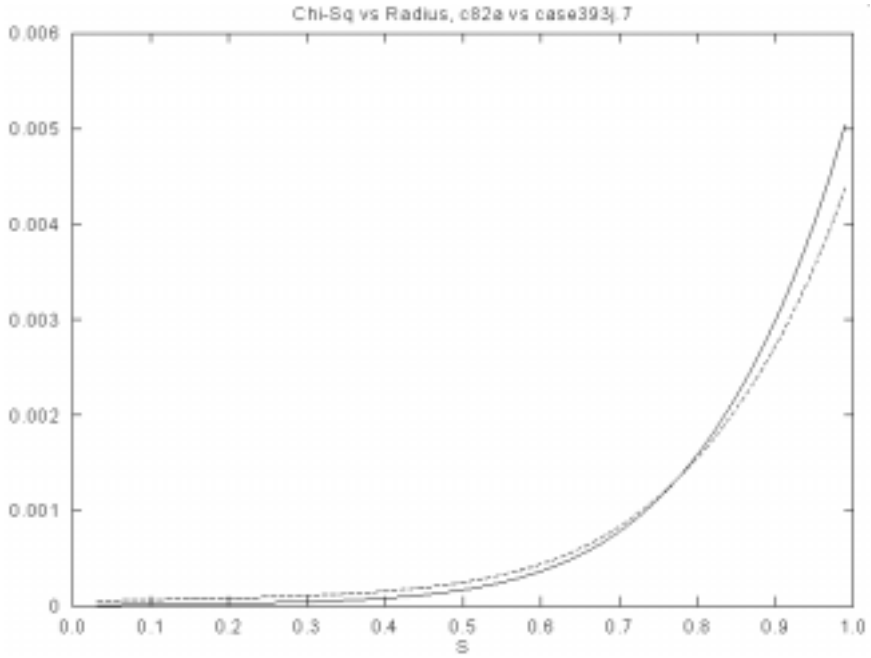
- Conformal coils provide 4+ DOF (v. 2 DOF)
  - Different coil geometries should have different signatures at plasma, unlike tightly nested saddles
- TF provides 2 DOF, PF provides ~4 DOF
- Elementary controls alone require 4 DOF
  - Toroidal field, plasma current, external transform, radial position
- Extra DOF in TF (1), PF (2) and conformal coils (3+)

Fit is better than for 4064
- 5.2% max, 1.2% mean error
- 4.6 cm max, 0.7 cm avg separation



Quasi-symmetry is also better
- χ^2=1.3 (1.0) at s=0.51 (0.72)
- Transport is TBD
- Kink stability is TBD





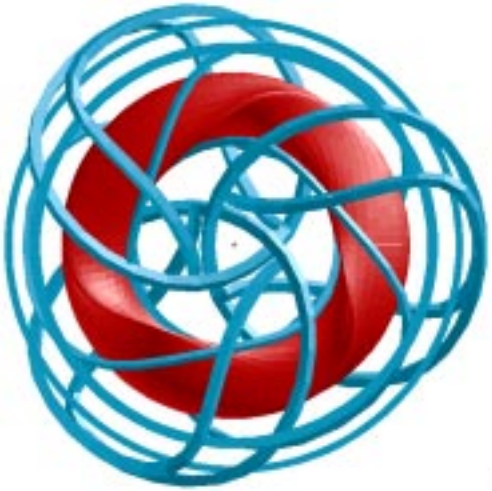
New background coil options showing promise relieving PBX option deficiencies

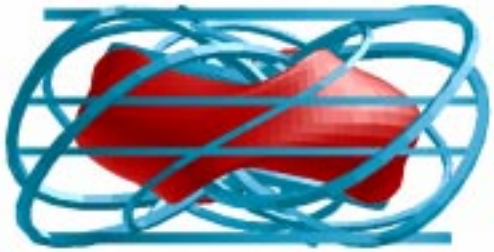
Background Field Coils		20 PBX TFCs	6 Tilted TFCs	3 L=3 plus 3 Tilted TFCs
Case		4064	536.3	393j.7
Current sheet helicity		0/0	0/1	0/0
Max error	%	7.1	4.8	5.2
Avg error	%	1.5	1.1	1.2
Number of coils (>1m)		30	23	20
Total length	m	214	169	154
MA-m	MA-m	20	18	17
Min separation	cm	3.0	5.2	6.8
J in Cu at 2T	kA/cm^2	21	11	8.7
Access		OK (?)	Better	Needs improvement
DOF in TF and conformal coils		1, 2	2, 5+	2, 4+
Reconstruction data				
Maximum separation	cm	4.4	2.6	4.6
Average separation	cm	1.2	0.7	0.7
Chi-squared [a]		1.9	1.2	1.3
Kink stable		Yes	TBD	TBD

[a] Ratio to fixed boundary value at s=0.55

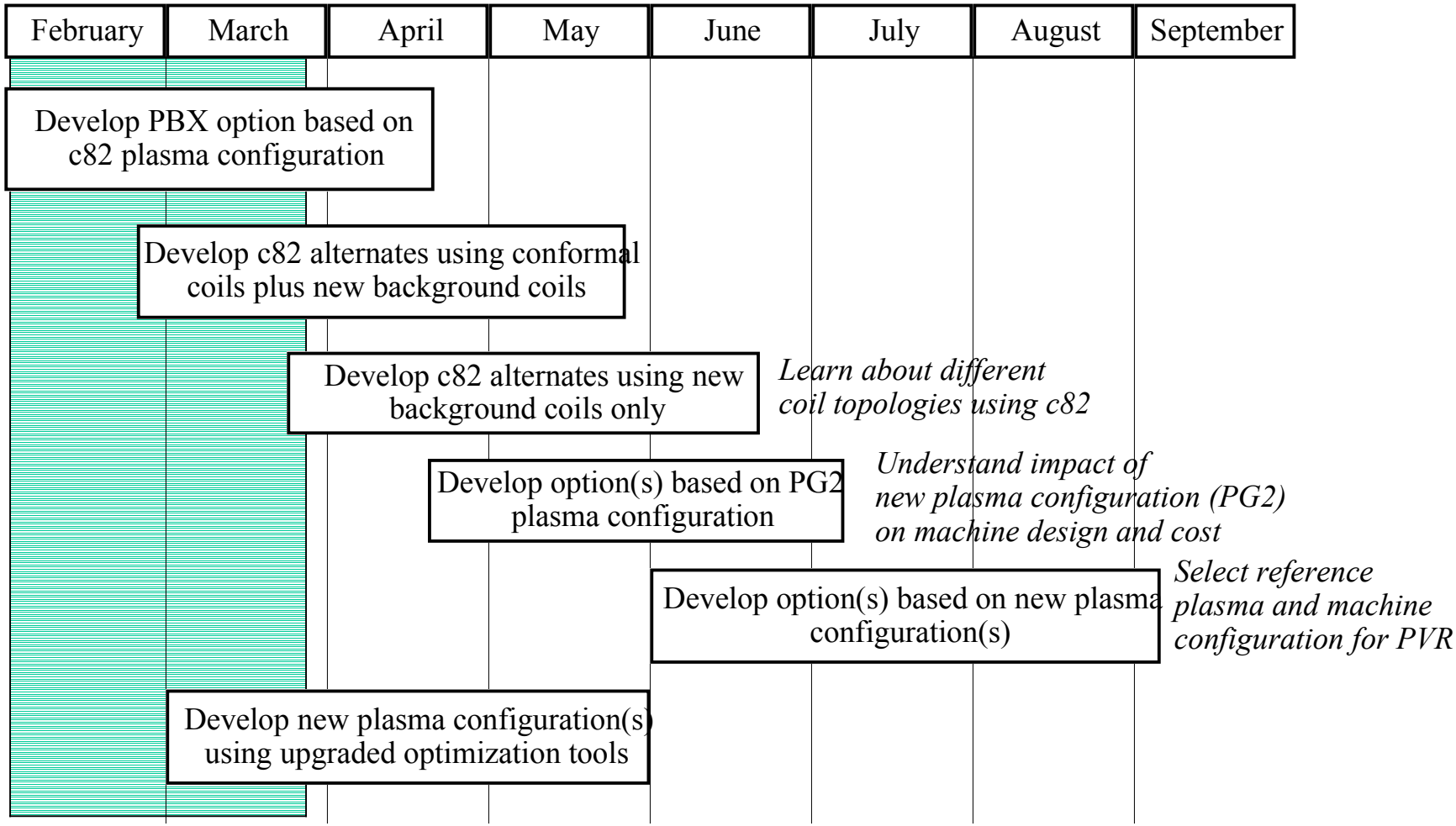
Coil optimization studies underway for “no conformal coil” option

- New coil parameterization generated since January project meeting
- No breakthroughs yet
- Plan is to use free-boundary optimizer to find acceptable plasma rather than match c82 exactly



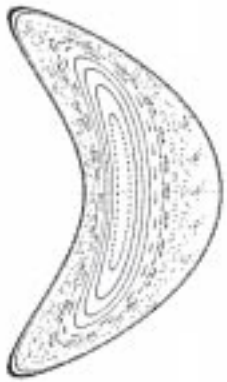


What next?

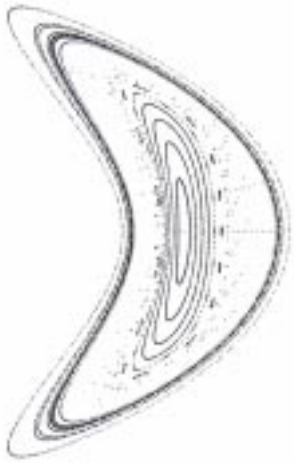

February
March
April
May
June
July
August
September
Develop PBX option based on c82 plasma configuration
Develop c82 alternates using conformal coils plus new background coils
Develop c82 alternates using new background coils only
Learn about different coil topologies using c82
Develop option(s) based on PG2 plasma configuration
Understand impact of new plasma configuration (PG2) on machine design and cost
Develop option(s) based on new plasma configuration(s)
Select reference plasma and machine configuration for PVR
Develop new plasma configuration(s) using upgraded optimization tools

The biggest risk?

- A rude awakening when we calculate physics properties based on the plasma geometry and volume defined by the region of good surfaces
  - Plasmas whose properties rely on high shear need full volume (to be near coils) with clean edges
  - Edge-limiting islands and stochastic regions might lead to smaller plasmas with uninteresting properties
  - Much different than reverse-engineered experiments with flat iota profiles (W7X, HSX)
  - Our *best* vacuum reconstructions are ~70% volume
  - Raising iota (adding current) may shrink plasma
  - Few extra DOF in representative coil designs
    - Radically different design concept for coils required?
  - No calculations yet on magnitude of problem
  - No demonstrated ability to do anything about it



100% TF
Iota(a)=0.158



80% TF
Iota(a)=0.208