Designing better coils for NCSX

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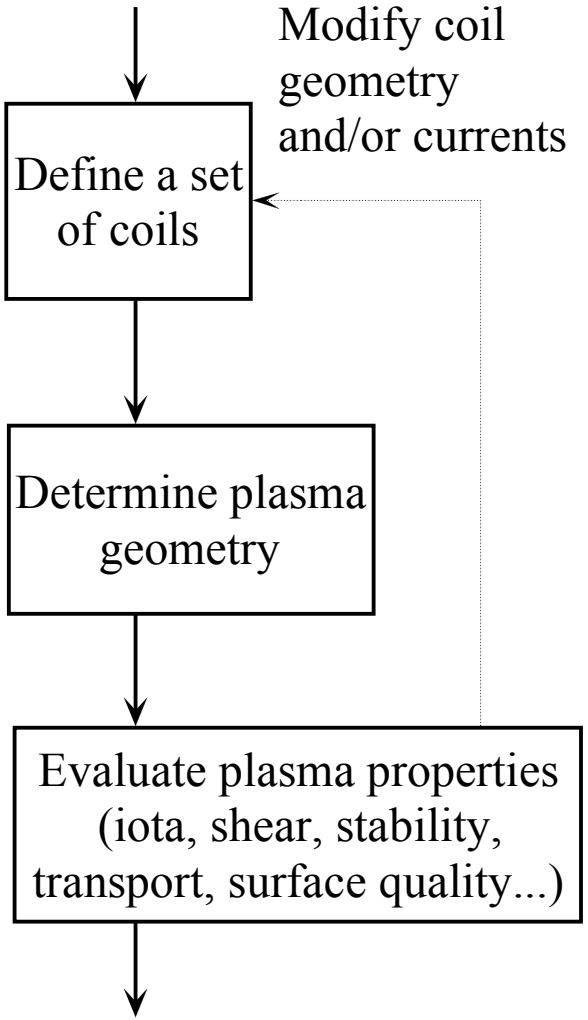
The old paradigm

- Simple coil geometry
  - helical windings on circular toroids, for example
  - circular poloidal field (PF) coils and supplemental toroidal field (TF) coils
- Few free parameters
  - R_h, a_h, n_p, l, α
- No plasma current
- Plasma geometry and properties fall out
- Manual (crude) optimization



CHS

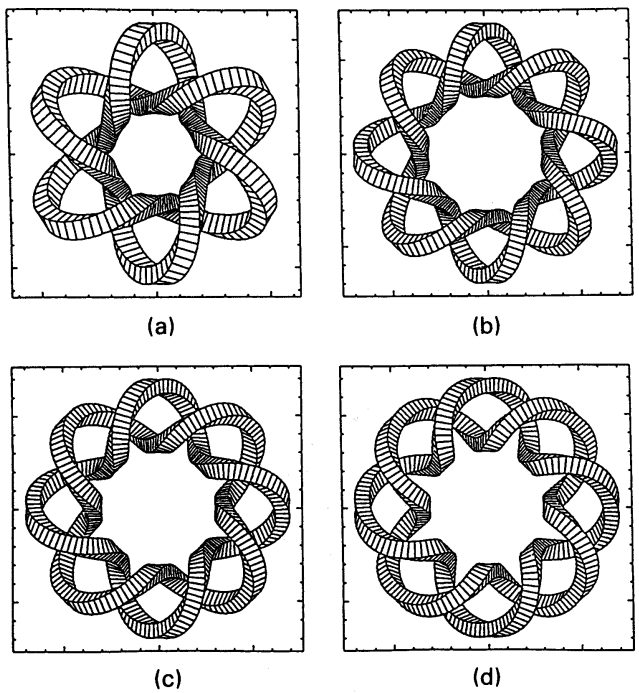


Fig. 3. Top view of the HF coil systems with coil width of 18 cm and coil height of 15 cm: (a) $l = 2$, $m = 6$, $\alpha^* = +0.4$, $R_c = 75$ cm, and $a_c = 32$ cm; (b) $l = 2$, $m = 8$, $\alpha^* = +0.3$, $R_c = 100$ cm, and $a_c = 32$ cm; (c) $l = 2$, $m = 8$, $\alpha^* = 0.0$, $R_c = 100$ cm, and $a_c = 32$ cm; and (d) $l = 2$, $m = 8$, $\alpha^* = -0.3$, $R_c = 100$ cm, and $a_c = 32$ cm.

TABLE I

Coil Parameters for CHS Design Study

m	6	8		
α^*	+0.4	+0.3	0.0	−0.3
R_c (cm)	75	100	100	100
a_c (cm)	32	32	32	32
Ch (cm)	15	15	15	15
Cw (cm)	18	18	18	18

Ref. K. Nishimura et al, “Compact Helical System Physics and Engineering Design”, Fusion Technology, Vol. 17, January, 1990, 86-100

The innovation

- Merkel pioneered method to calculate current distribution on an enclosing surface that zeroes out the normal field on the plasma surface
- Current sheet is then changed into discrete coils

$$r = \sum_{m=0,n=-n_b}^{m_b,n_b} \hat{r}_{mn} \cos 2\pi(mu + nv)$$

$$z = \sum_{m=0,n=-n_b}^{m_b,n_b} \hat{z}_{mn} \sin 2\pi(mu + nv)$$

$$\phi = \frac{2\pi}{n_p} v$$

$$\vec{j} = \vec{n} \leftrightarrow \Phi(u,v)$$

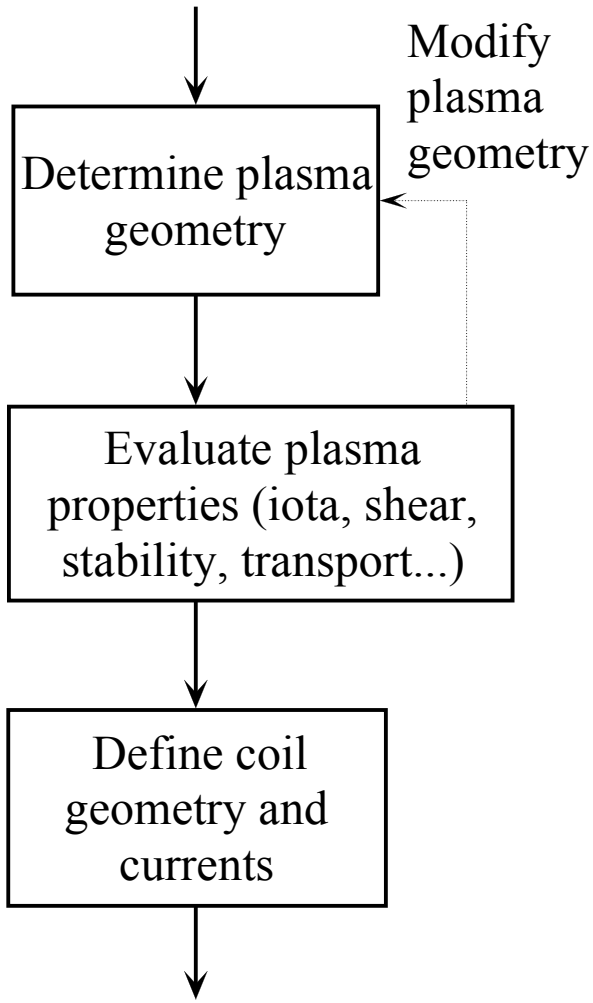
$$\Phi(u,v) = \sum_{m=0,n=-N}^{M,N} \Phi_{m,n} \sin 2\pi(mu + nv) - \frac{I_p}{n_p} v - I_t u$$

$$\oint_{plasma} df\,(\vec{B}\,?\vec{n})^2 = \min$$

Ref. P. Merkel, “Solution of Stellarator Boundary Value Problems with External Currents”, Nuclear Fusion, Vol. 27, No. 5 (1987), 867-871

The new paradigm

- Optimize plasma by varying plasma shape parameters, not coil parameters
- Greater freedom to develop improved plasma configurations
- Sophisticated optimizers constructed to exploit freedom
- Blind with regard to consequences for coil design



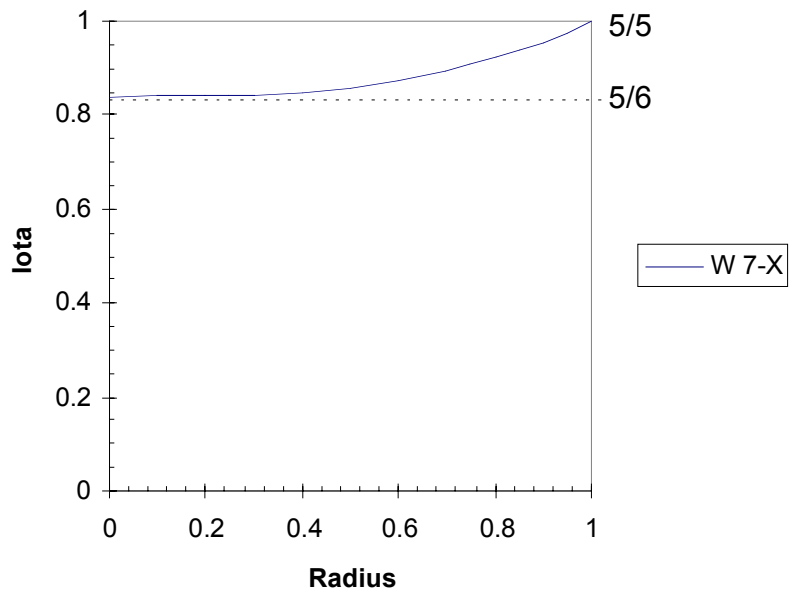
W 7-X optimization principles

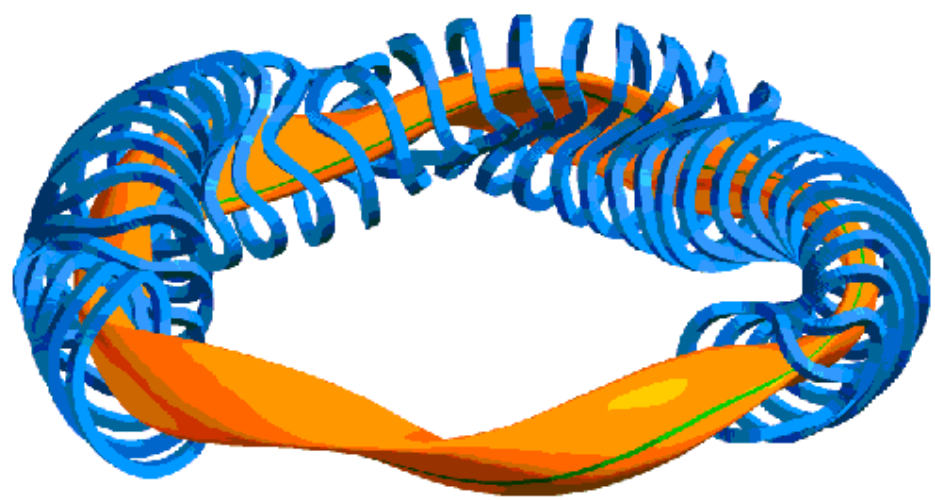
- Provide high-quality magnetic surfaces
  - Pick ι to avoid low order resonances
  - Maintain low shear ($\delta\iota/\iota$=0.1 typical)
  - Minimize bootstrap current (small change in ι with β)
- Provide magnetic well for good MHD stability
- Optimize for reduced neoclassical transport
- Preserve modular coil feasibility by avoiding strong geometrical shaping of plasma boundary

Ref. C. Beidler et al, "Physics and Engineering Design for Wendelstein VII-X", Fusion Technology, Vol. 17, January, 1990, 148-168

W 7-X

- Smooth plasma (21 parameters)
- Smooth modular coils
- Zero net plasma current
- Clean magnetic surfaces
- BUT large A (10)



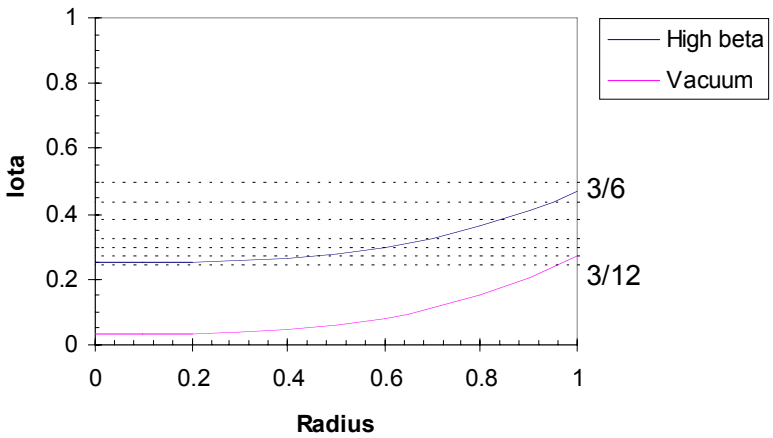


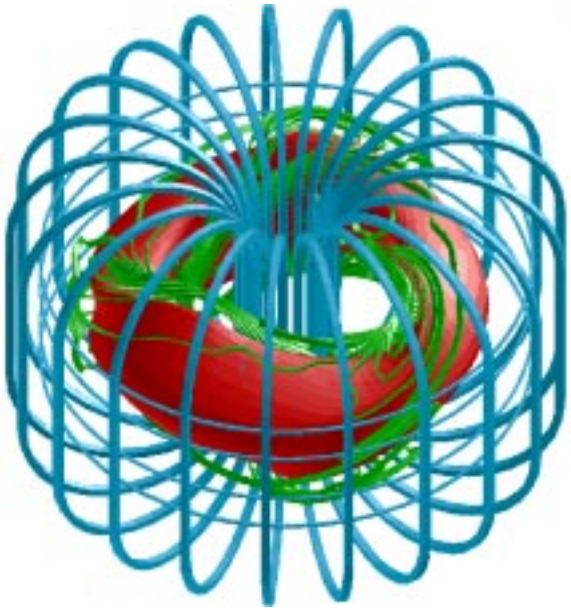
NCSX optimization principles

- Low aspect ratio with good transport and stability properties
  - Current A (3.4 for c82) selected to fit within PBX
- Strong axisymmetric shaping for ballooning stability
- Quasi-axisymmetry for good transport
  - Results in substantial bootstrap current, suppressing magnetic islands and providing a substantial fraction of the total iota
- Externally generated shear and non-axisymmetric corrugation of plasma boundary provide kink stability
- Monotonically increasing iota to avoid shear reversal and stabilize neo-classical tearing modes

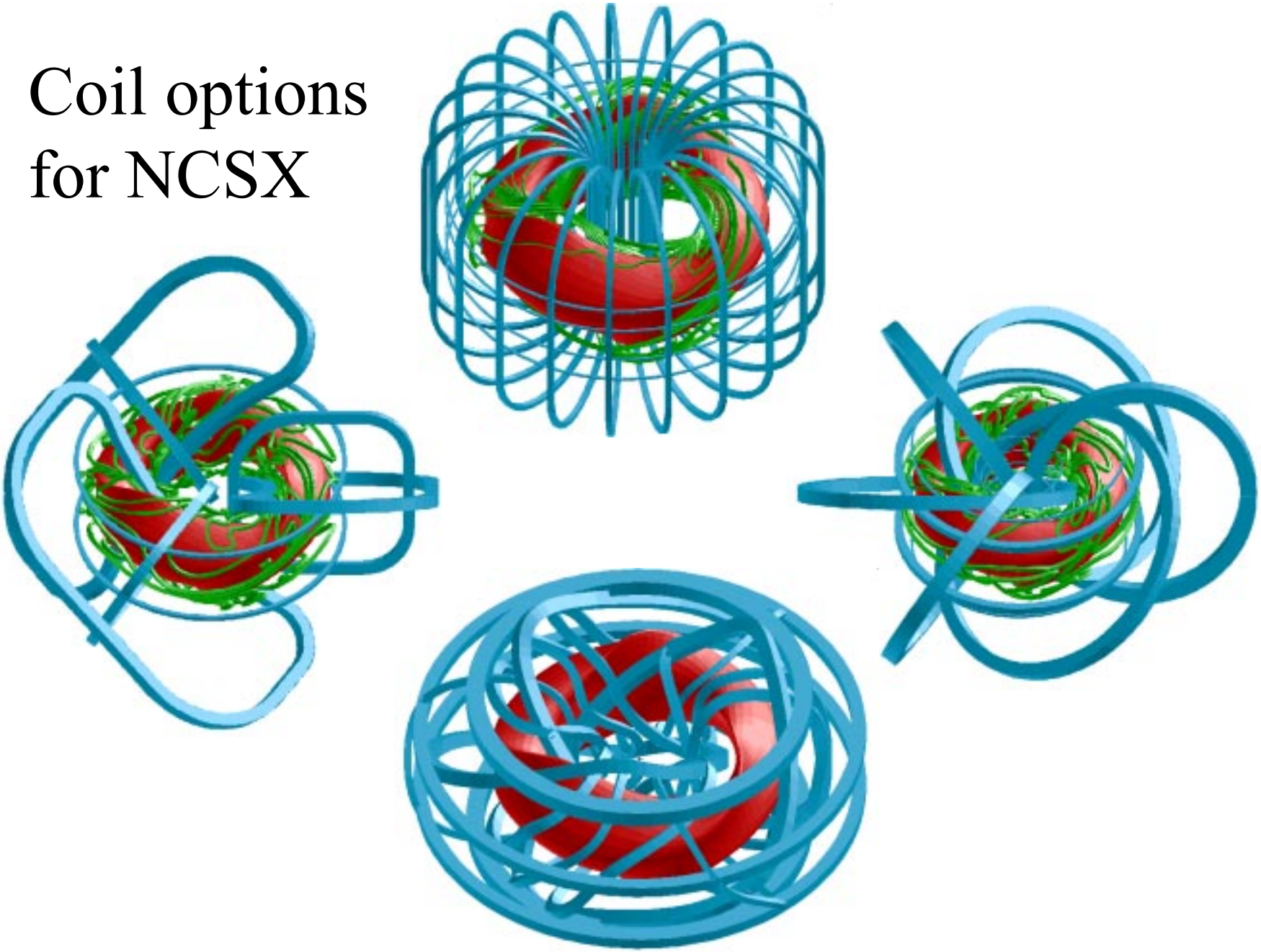
NCSX

- Attractive solutions at low A (3.4 for c82) BUT
- Strong shaping (39 parameters)
- No attractive modular coil solution found to date
- Plasma current provides half the total transform
- Magnetic surfaces TBD





Coil options for NCSX

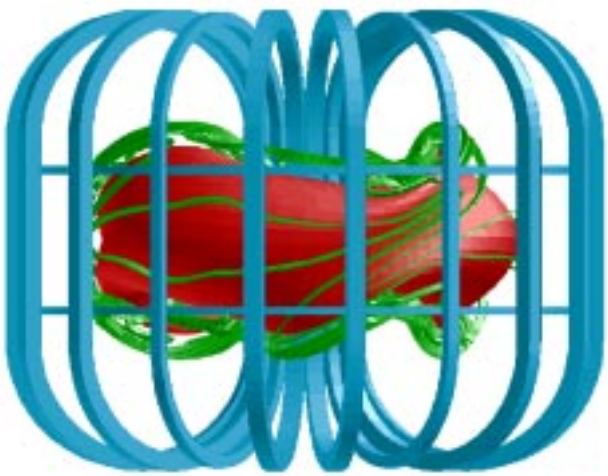


PBX option

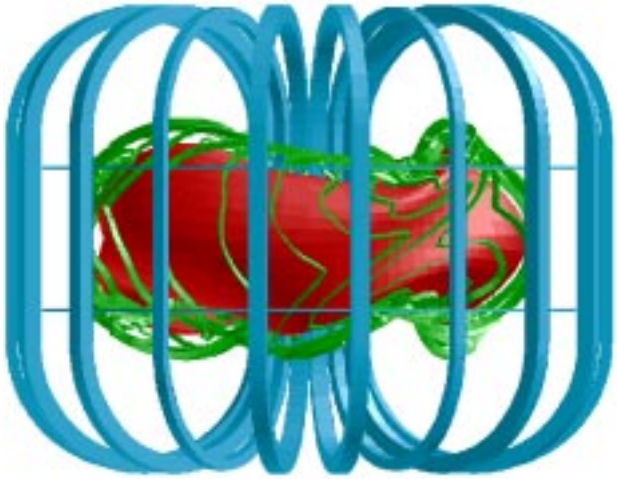
- Design development and costing nearly complete
- Saddles (0/0 helicity) seem the best choice
- Highly optimized saddle coil design exists (4064)
- Initial investigation of startup flexibility complete

Saddle coils seem 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

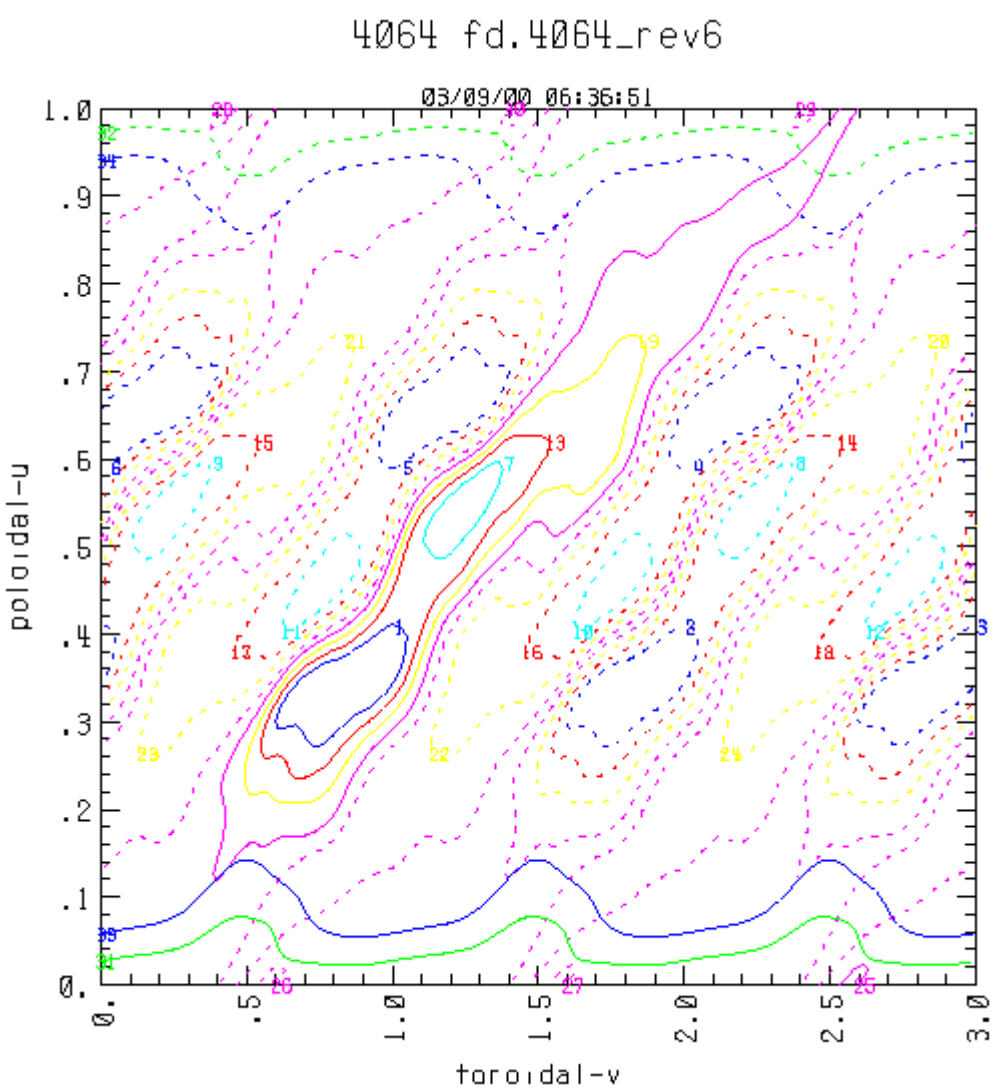


0/0 Helicity



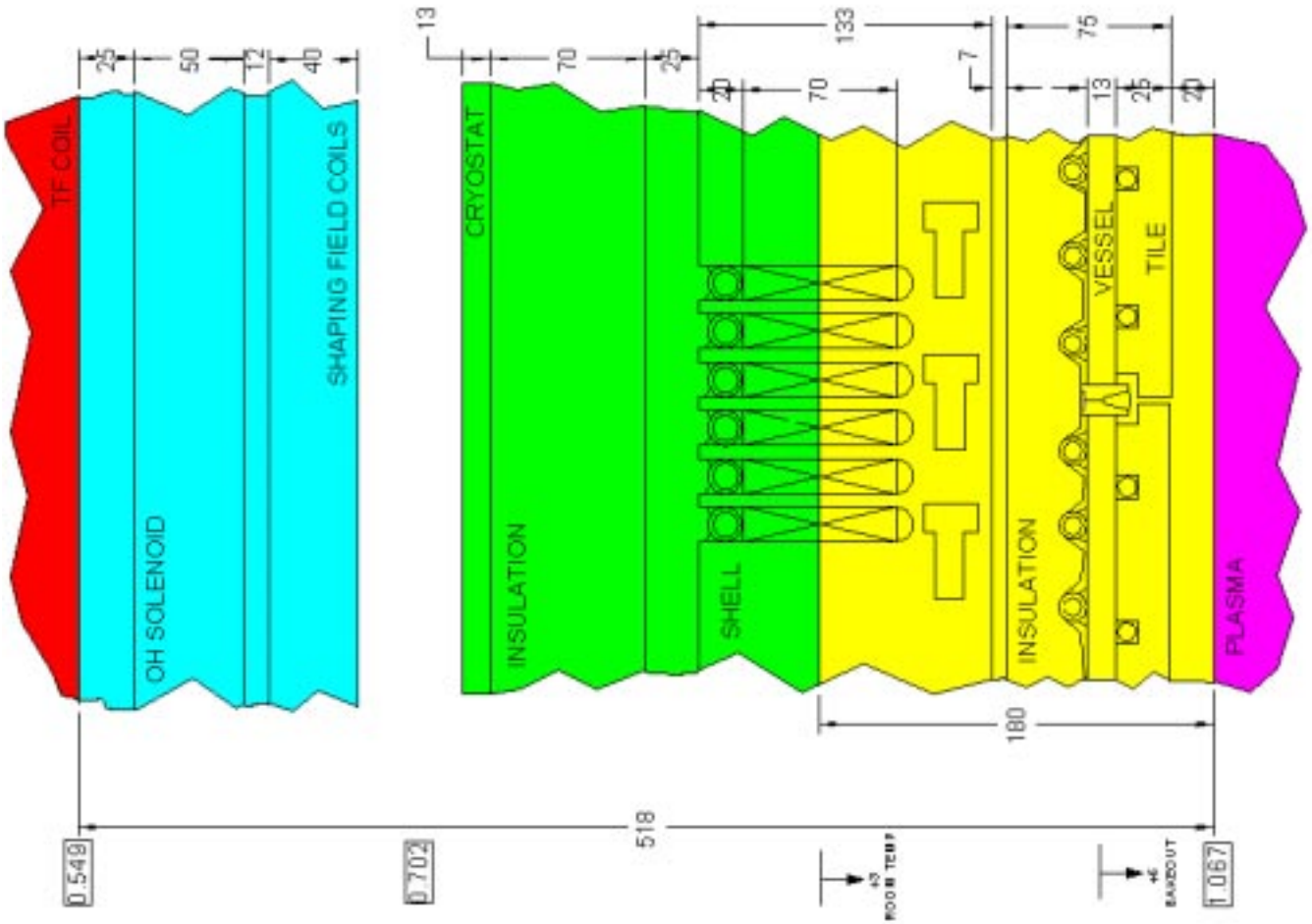
1/1 Helicity

PBX option conformal coil description

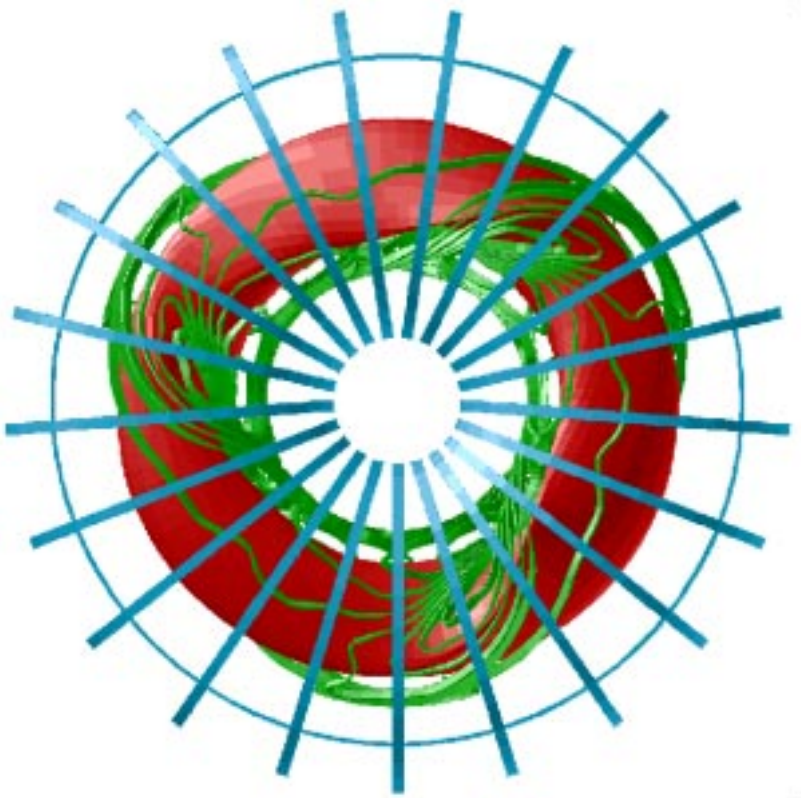


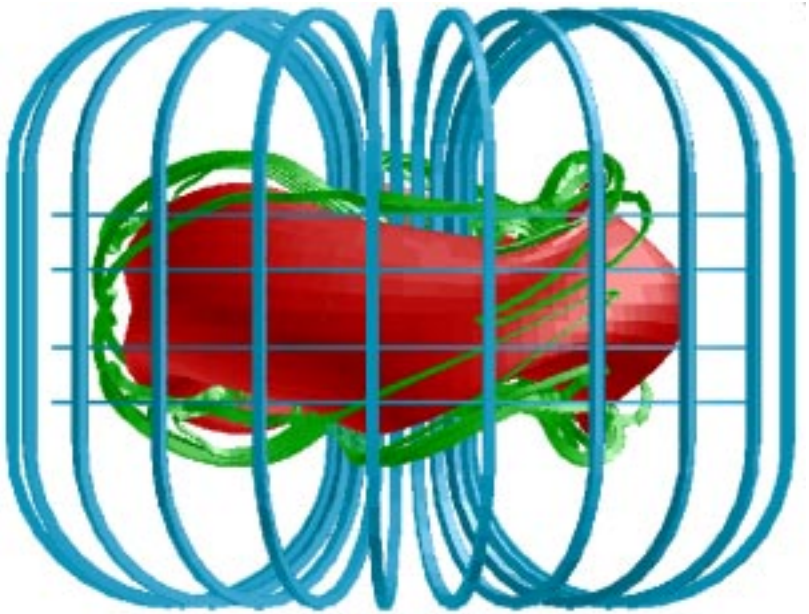
- 4064 design
- 30 coils, all >1m
- 214 m total
- 20 MA-m
- Min separation 3.0 cm
- 5 nested saddle coil circuits (30 coils)
- Saddle coils provide ~2 DOF

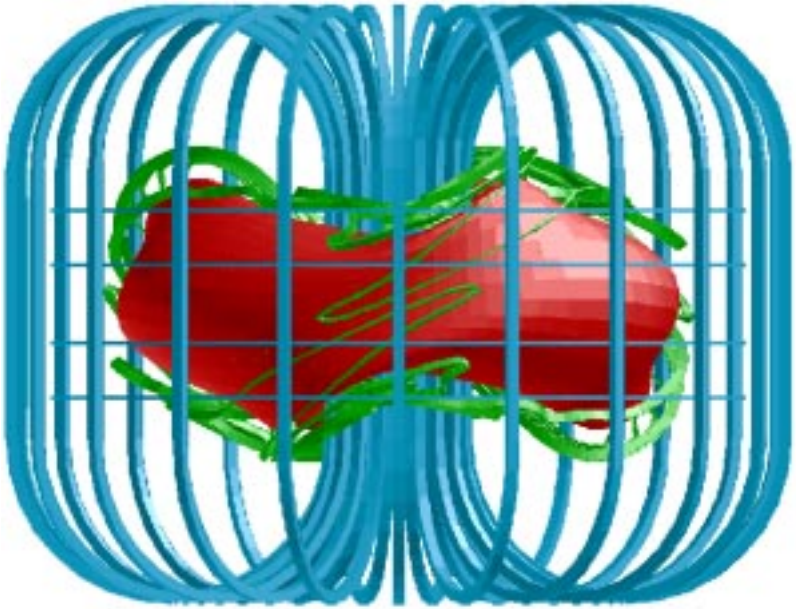
Shape flexibility limited by PBX radial constraints to ~1cm



4064 features good outboard access





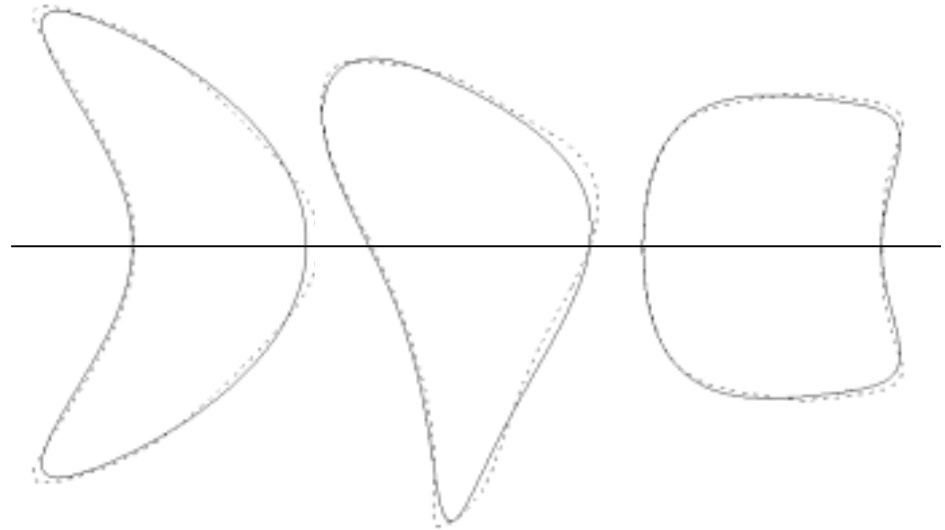


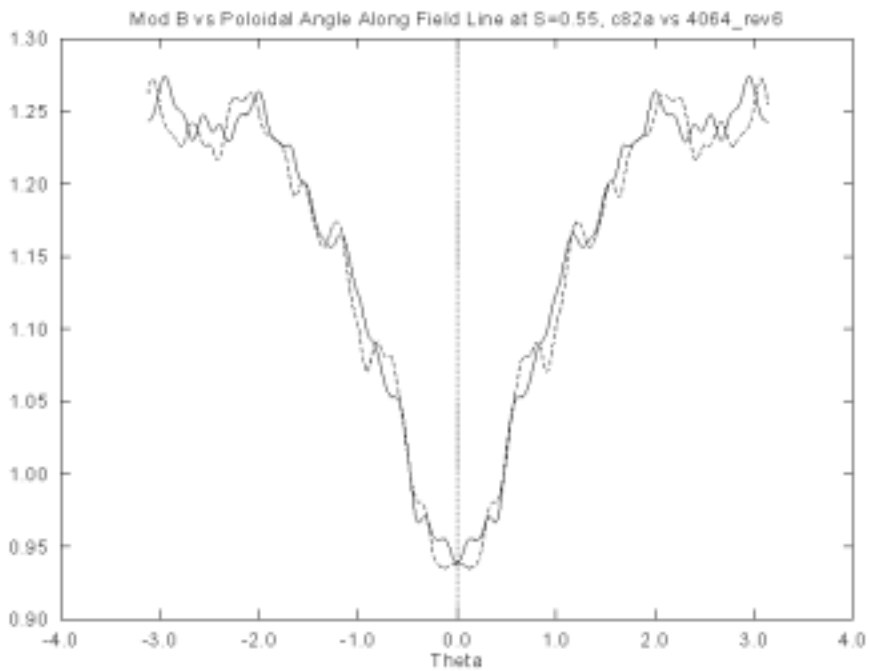
Significant separations from fixed boundary equilibrium at high beta/full current

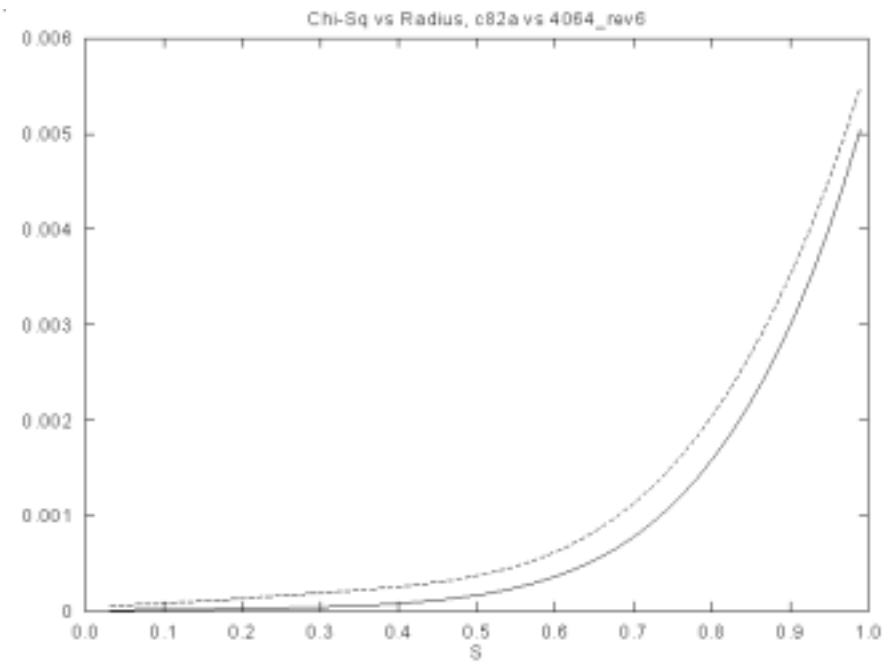
- 4.4cm max, 1.2 cm avg separation

Quasi-symmetry is degraded

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

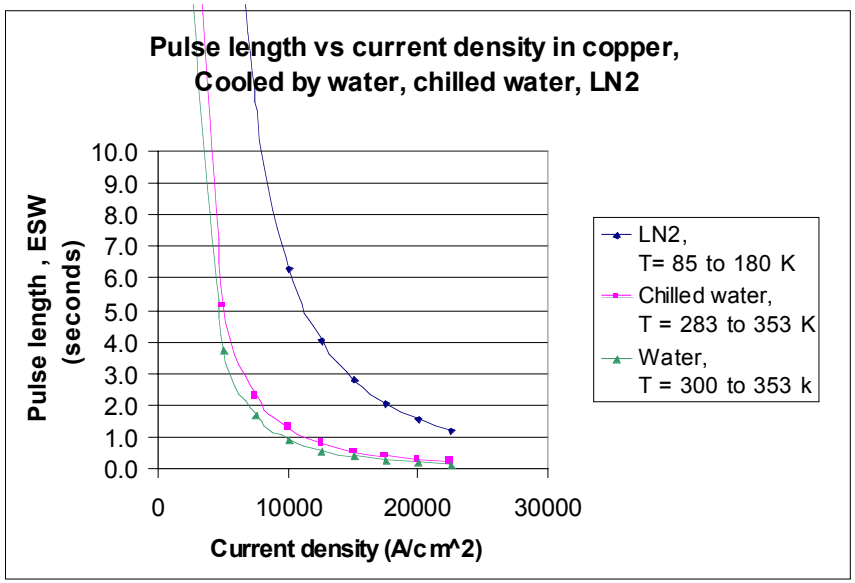






Current density is high (21 kA/cm^2) at high beta/full current

- 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

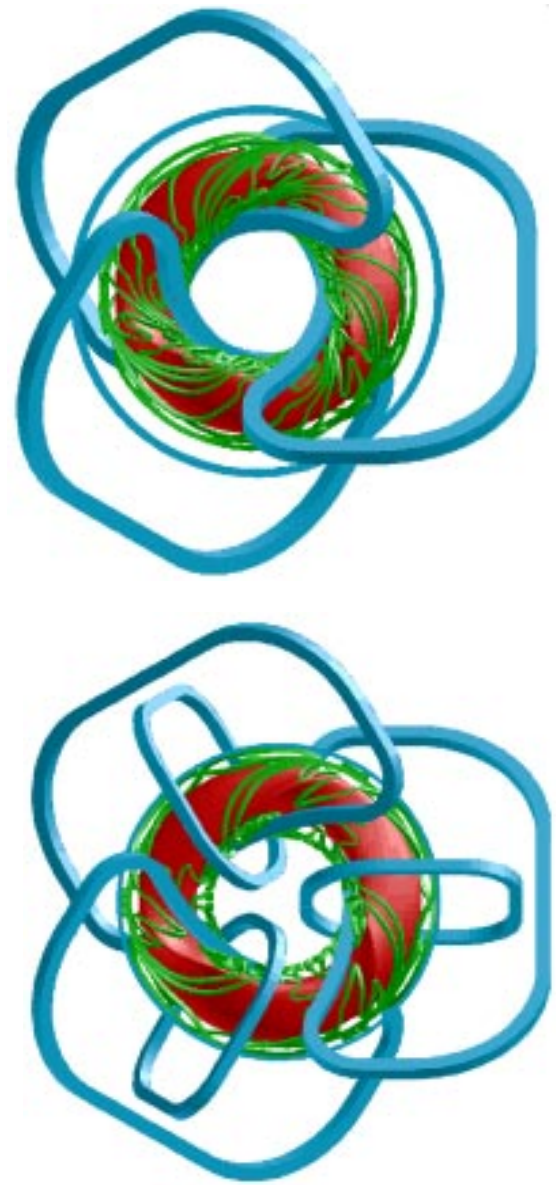
- Current density high but marginally OK for 1s ESW, may limit flexibility
- Access appears adequate for NB and RF, diagnostic access is TBD
- 4064 coil set has a few (~3) extra degrees of freedom (DOF) beyond those required for elementary controls (B_t, I_p, R_p, $iota_{ext}$)
- Shape flexibility limited by PBX radial constraints to ~1cm
- Results of initial investigation of startup flexibility:
  - Kink stable during startup
  - Need to modify FW and winding surface to avoid interferences
  - χ^2 higher than fixed boundary calculation, impact on transport is TBD
  - Surface quality is unknown
- 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%

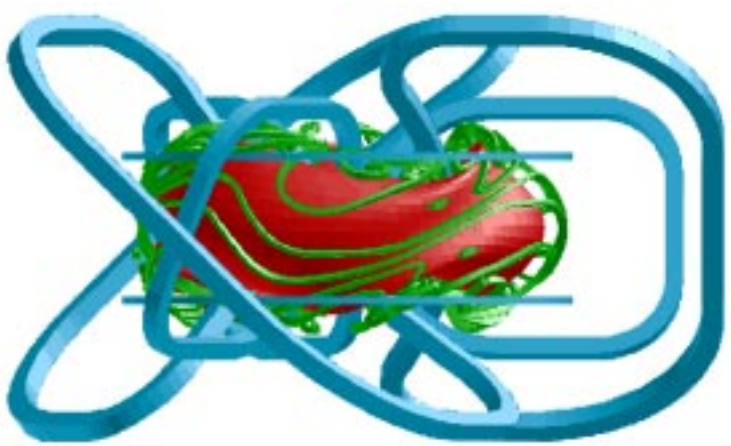


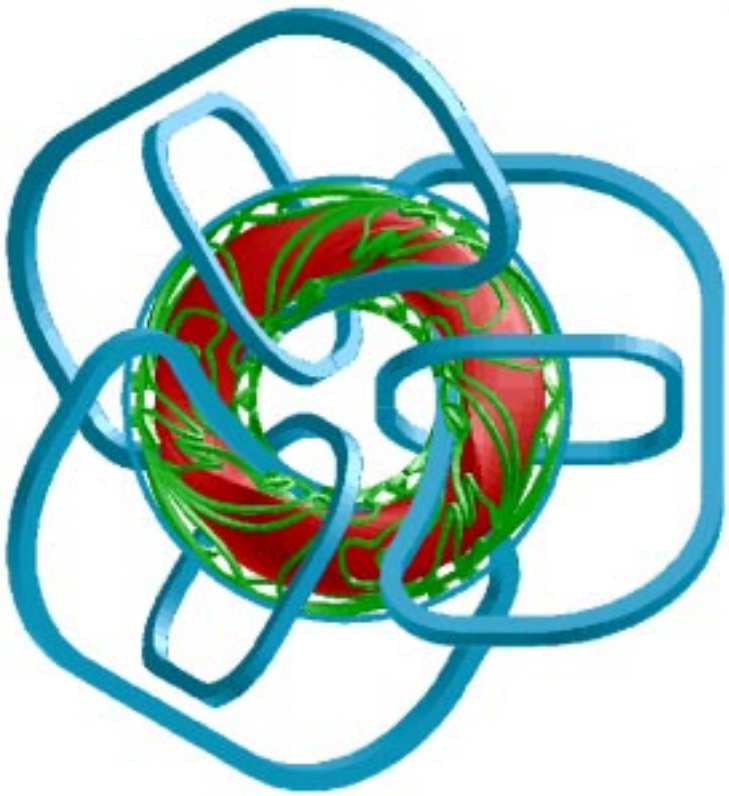
The best CS helicity for the tilted TF option appears to be 0/1 (wavy PF coils)

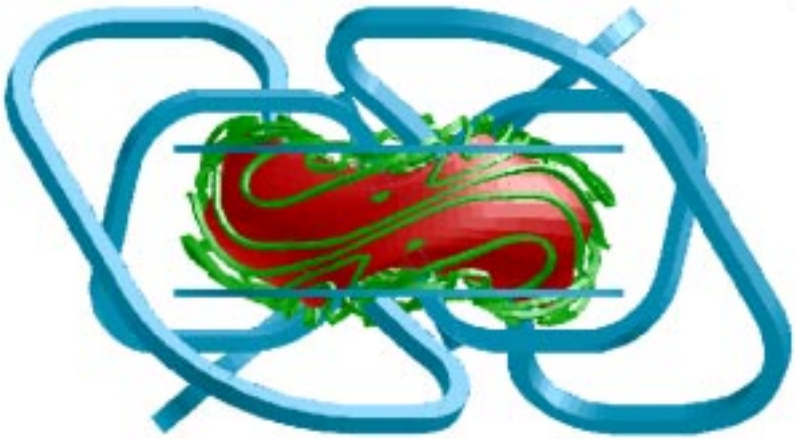
Current sheet helicity		0/0	1/1	1/2	0/1
Case		526a.7	510a.2	528a.3	536.3
Max error	%	6.5	4.3	4.4	4.8
Avg error	%	1.0	1.1	0.5	1.1
Number of coils (>1m)		24	8	21	23
Independent circuits (with coils >1m)		6	2	5	6
Total length	m	196	157	254	169
MA-m	MA-m	18	16	17	18
Min separation	cm	4.2	4.6	3	5.2
J in Cu 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

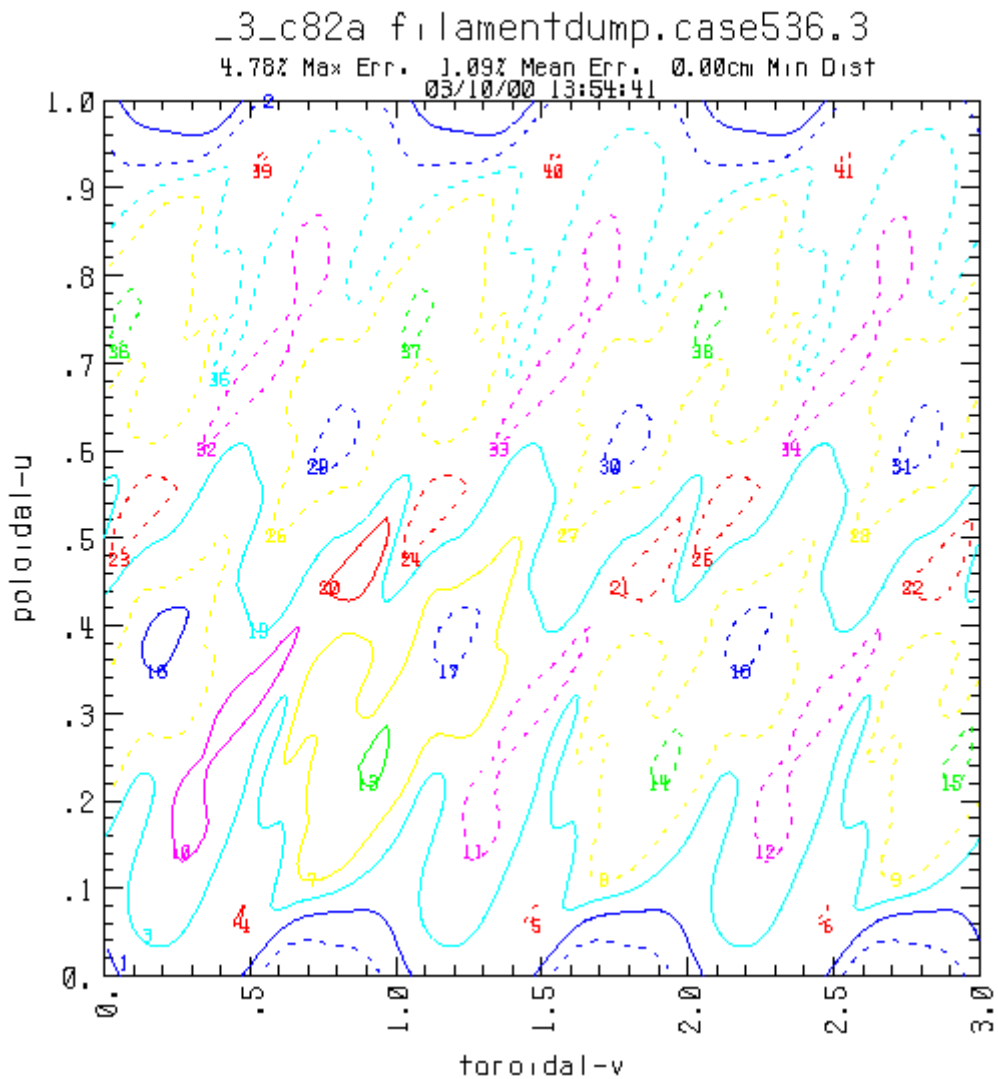
- 6 tilted TF coils with 0/1 helicity
- Current density is 11.0 kA/cm^2, marginally OK for water cooling
- Access appears good if tiny saddles can be eliminated







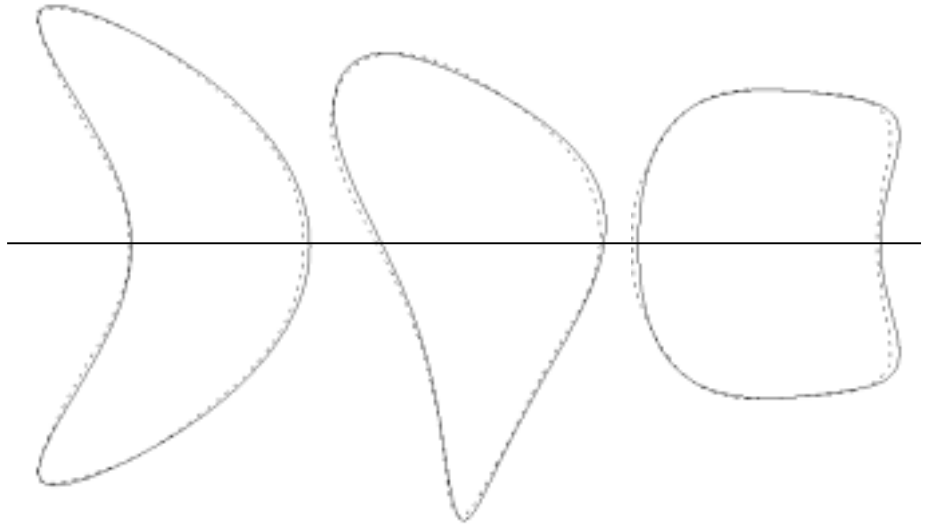
Tilted TF conformal coil description

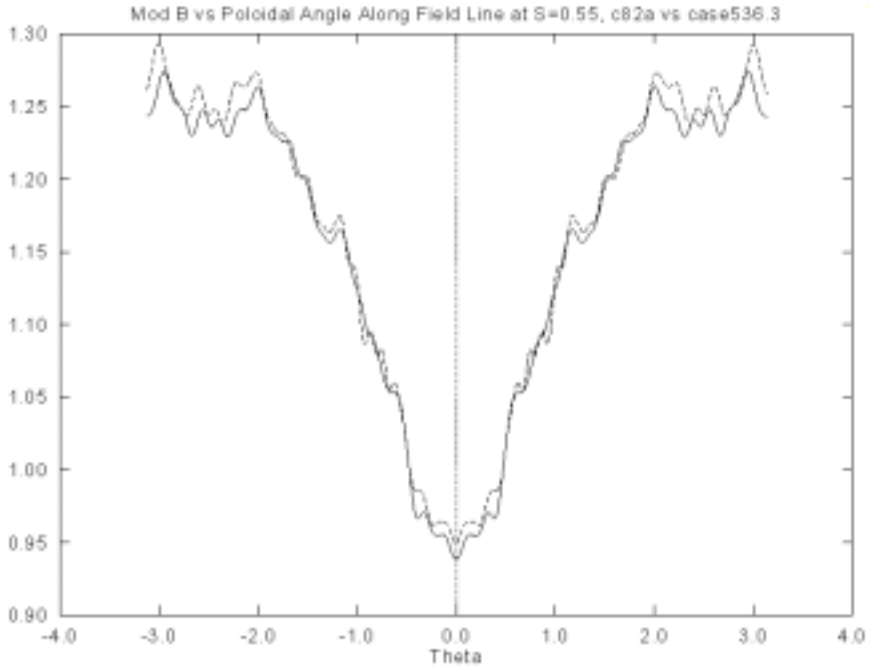


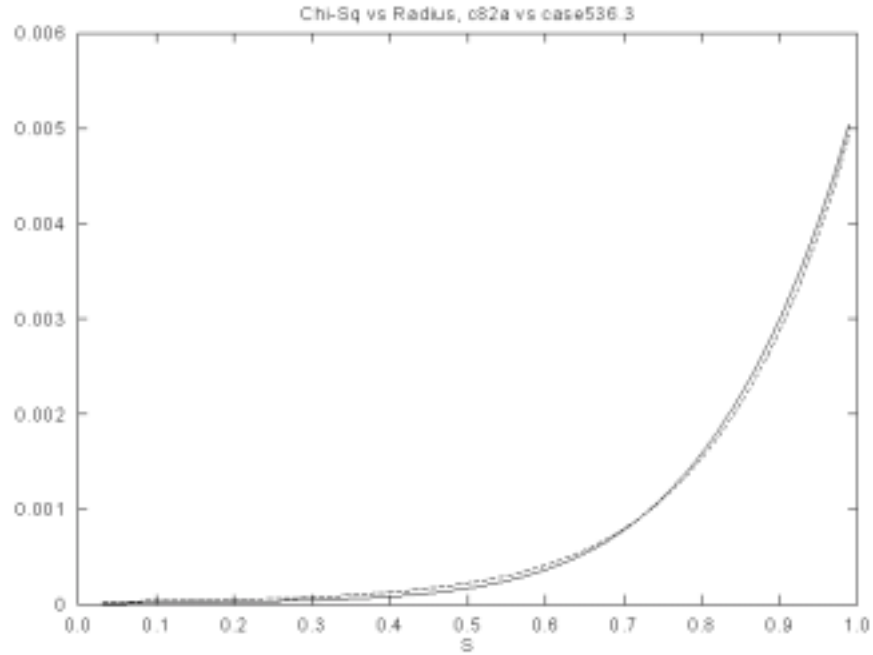
- 41 coils, 23 coils >1m
- 169 m total, 18 MA-m
- Min separation 5.2 cm
- 1 wavy PF coil circuits inboard, 2 wavy PF coil circuits outboard (5 coils)
  - Provide separate in-out control
- 3 large (>1m) saddle coil circuits (18 coils)
- Some of the 3 smaller saddles (<1m) would likely be eliminated or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

Fit is better than for 4064
- 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

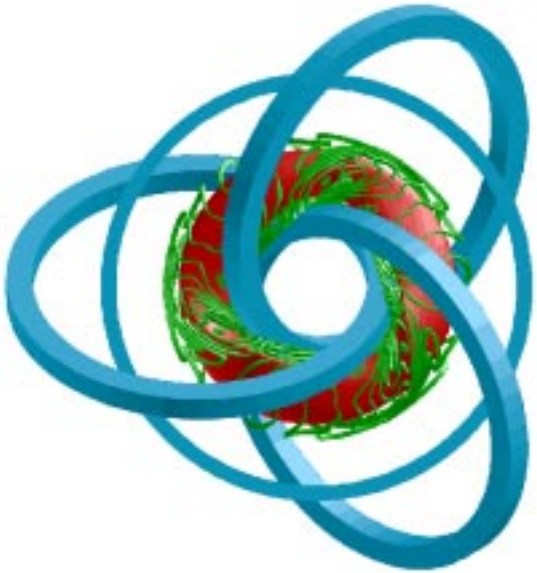


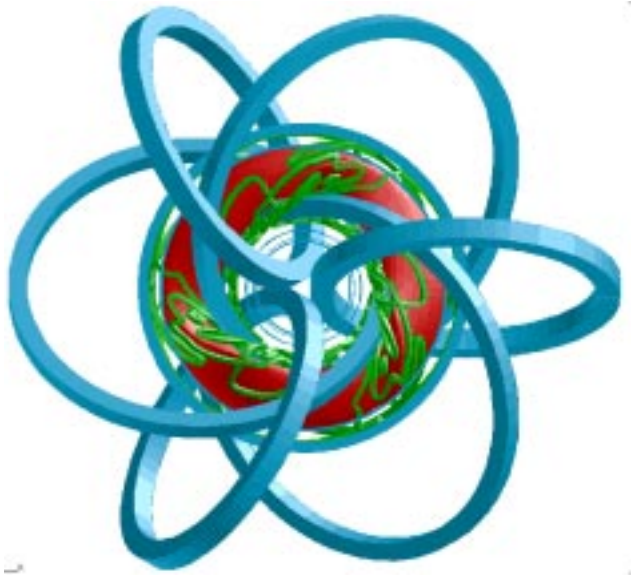




L=3 Coil Options

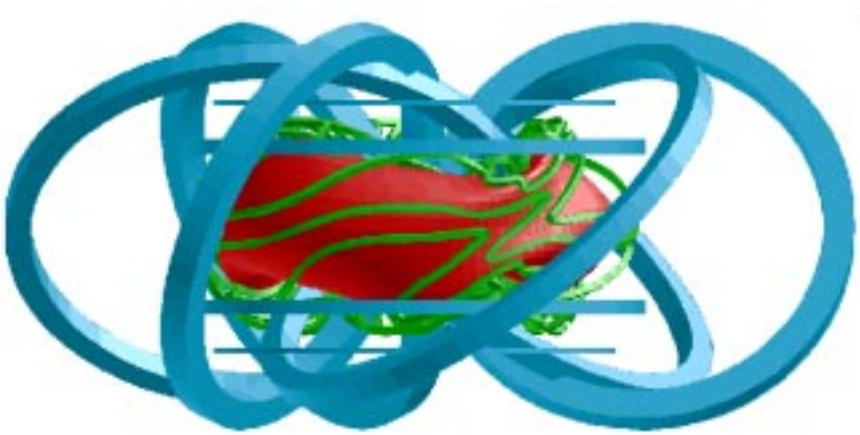
- L=3 coils close on themselves after one poloidal and one toroidal revolution
- Circular planar coils were studied for use with conformal coils – simple, can be wound
- Replacing the TF set with 3 circular L=3 coils reduces the current density (J) in the conformal coils by 30%
- Adding 3 circular TF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

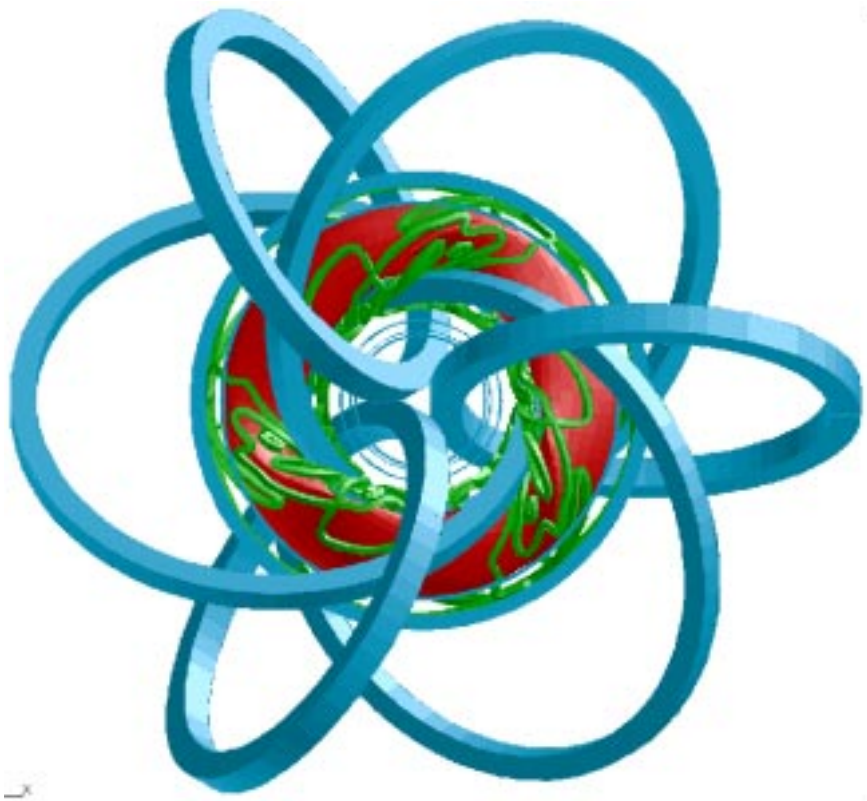


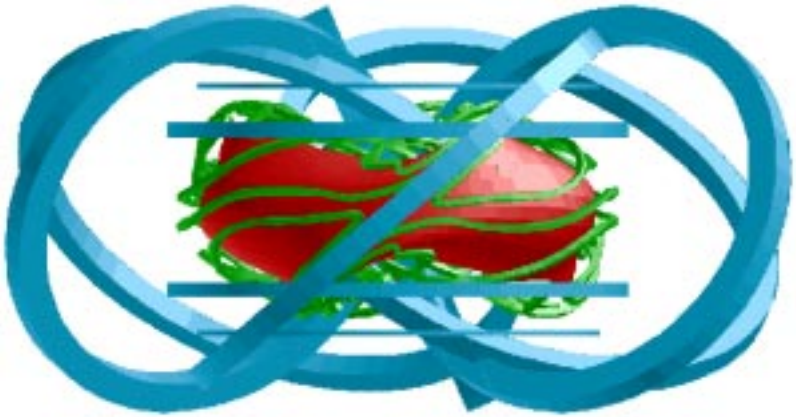


Case 393j.7

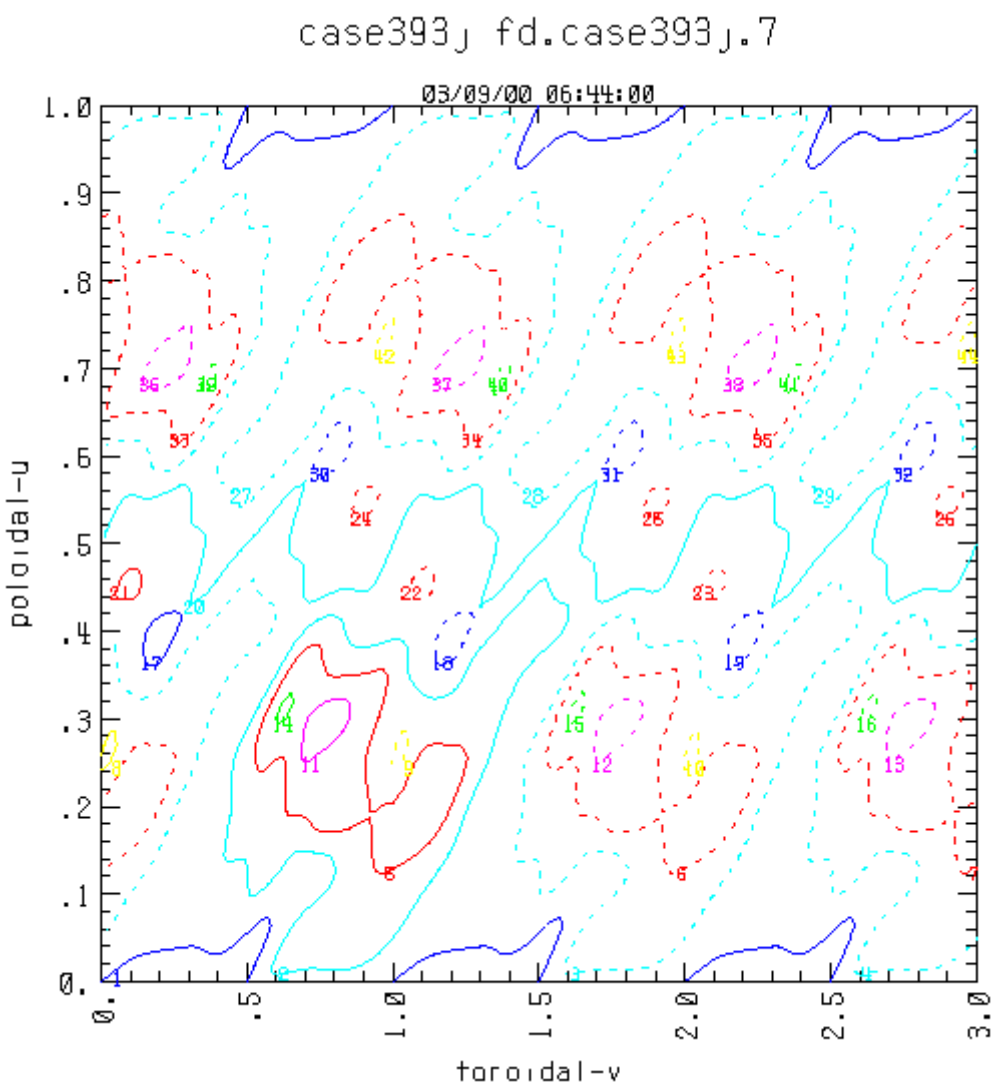
- 3 L=3 coils with 3 tilted TF coils (all circular)
- 0/0 helicity (unoptimized)
- 8.7 kA/cm^2
- Access needs improvement
- Transport and kink stability are TBD





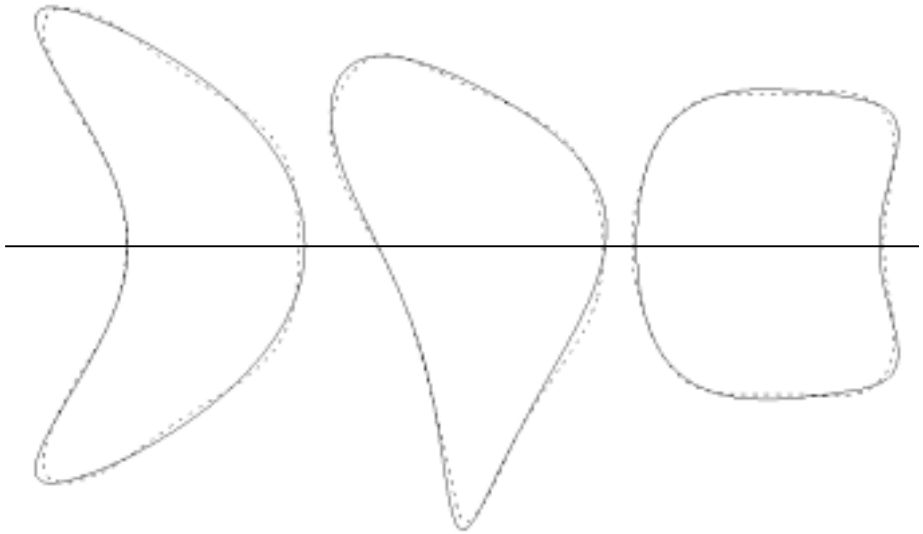


L=3 coil option conformal coil description

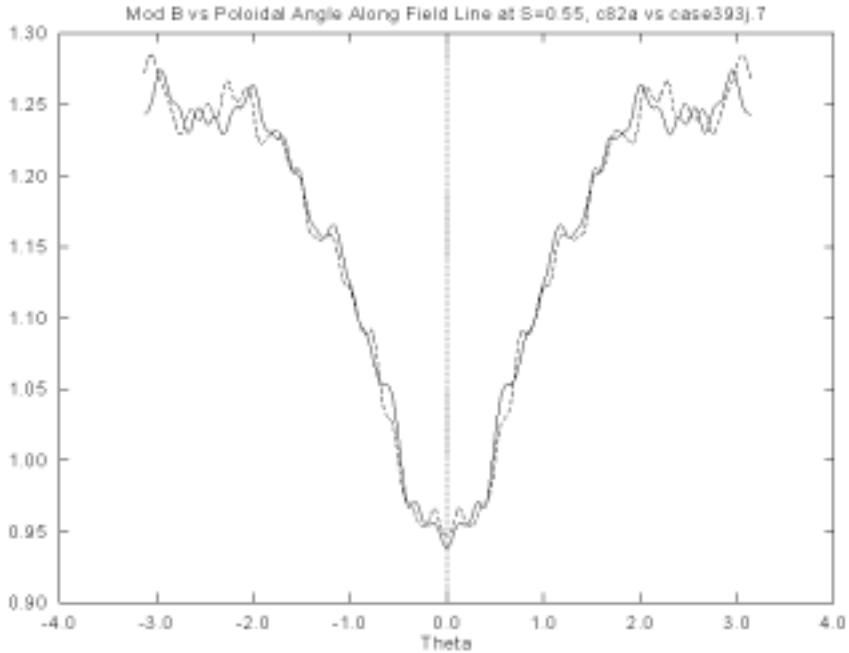


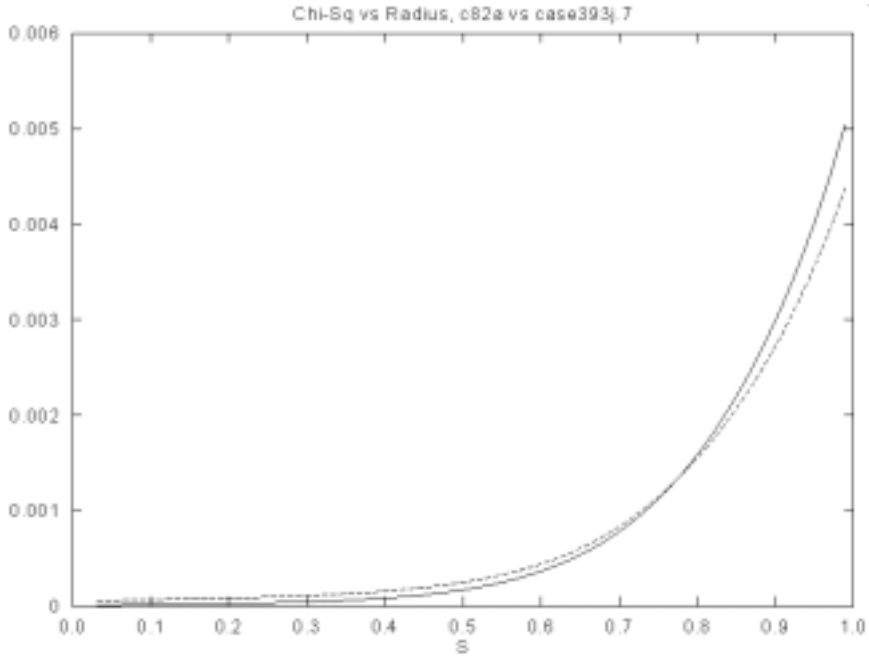
- 44 coils, 20 coils >1m
- 154 m total
- 17 MA-m
- Min separation 6.8 cm
- 1 wavy PF coil circuits inboard, 1 wavy PF coil circuits outboard (2 coils)
  - Provide separate in-out control
- 1 large saddle coil circuit with 2 nested saddles inside, 1 outside (18 coils)
- 4 smaller saddles (<1m) would likely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

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





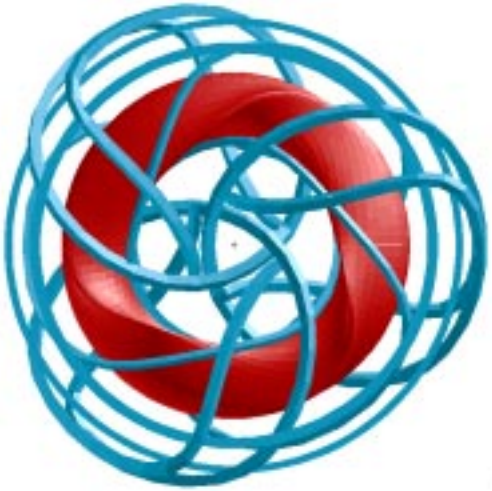
New background coil options show promise relieving PBX option deficiencies

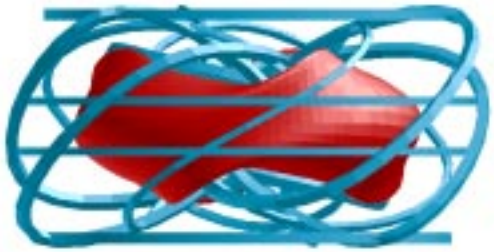
Background Field Coils		20 PBX TFCs	6 Tilted TFCs	3 L=3 plus 3 Tilted TFCs
Case		4064	536.3	393j.7
Current sheet helicity		0/0	0/1	0/0
Max error	%	7.1	4.8	5.2
Avg error	%	1.5	1.1	1.2
Number of coils (>1m)		30	23	20
Total length	m	214	169	154
MA-m	MA-m	20	18	17
Min separation	cm	3.0	5.2	6.8
J in Cu at 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

- Improved access with conformal coils eliminated
- Longer pulse length with no conformal coils
- Improved shape flexibility with expanded vessel
- Reactor relevant development path





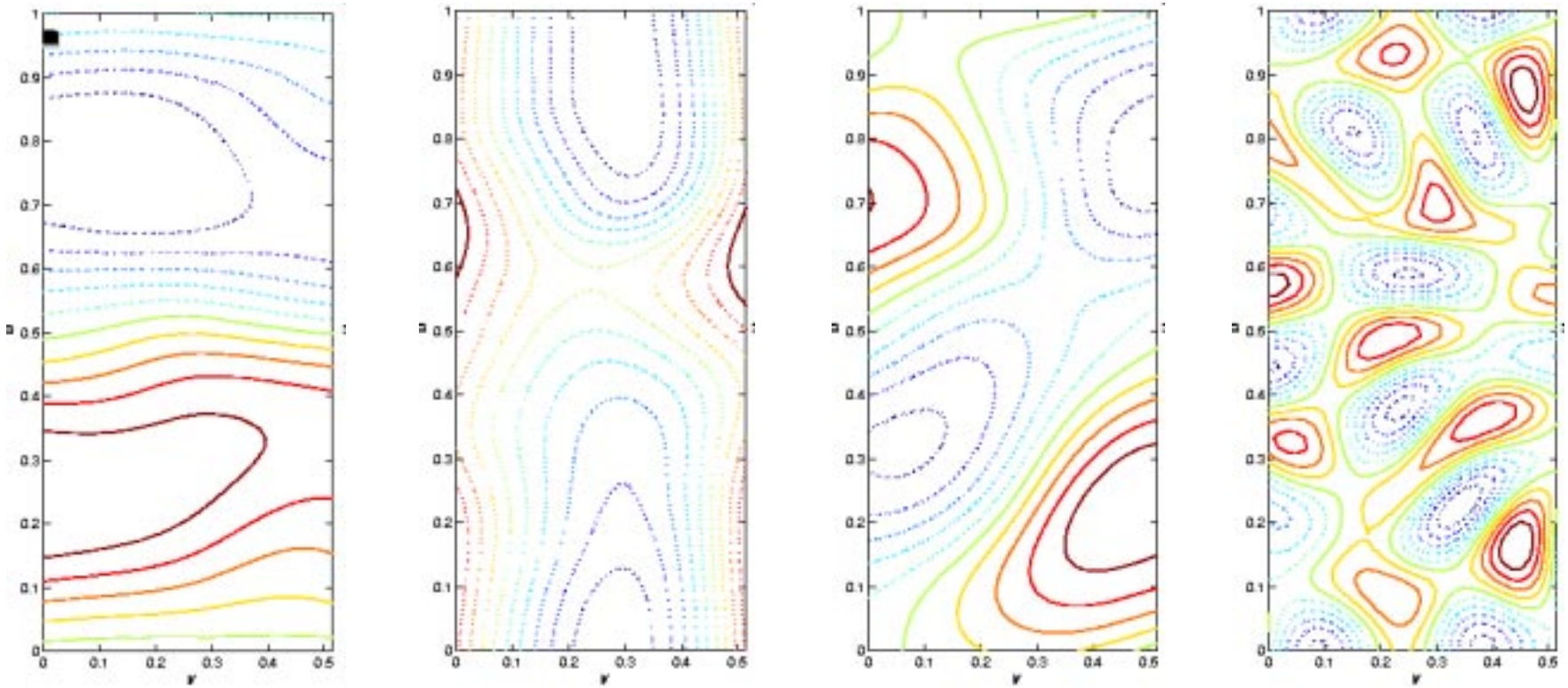
The future paradigm for plasma optimization and coil design?

- Define a control surface outside the plasma
- Calculate the lowest-order natural functions
  - Each function labelled by an eigenvalue that tells how rapidly the magnetic field dies away from the control surface
  - Lowest-order functions have the smallest eigenvalues
- Calculate the external magnetic field from a linear combination of lowest-order natural functions
- Optimize the plasma performance by varying the coefficients of the natural functions (rather than plasma shape parameters)
- Proposed by A. Boozer, being developed in collaboration with N. Pomphrey

The motivation

- The fundamental ill-conditioning inherent in using NESCOIL to reverse engineer the coils is avoided
- Provides a convenient mechanism to specify coil flexibility requirements (with a plasma shape that is changing)
- Should result in better coils
- May have smoother landscape than present method – improved optimization

Lowest-order natural functions



#1 #2 #3 #30

Summary

- An attractive compact, QAS plasma configuration for NCSX has been generated (c82)
- Coil design options are being studied based on c82
  - Attractive modular coil solutions not found
  - PBX option results in high J (LN2 cooling) in conformal coils
  - New background coils result in lower J (water cooling) in conformal coils, better access, improved flexibility
  - Study of options w/o conformal coils is underway
- Plasma optimization studies are continuing
  - Current model involves varying plasma shape parameters
  - A promising alternative in which natural function coefficents are varied, is being implemented and may revolutionize the way we do plasma optimization