TF/PF Optimization

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Basic Premise

- Tokamaks (and large A, N_p stellarators)
  - 1/R toroidal field is aligned with magnetic axis
  - Poloidal fields from circular PF coils have only axisymmetric (n=0) components in plasma

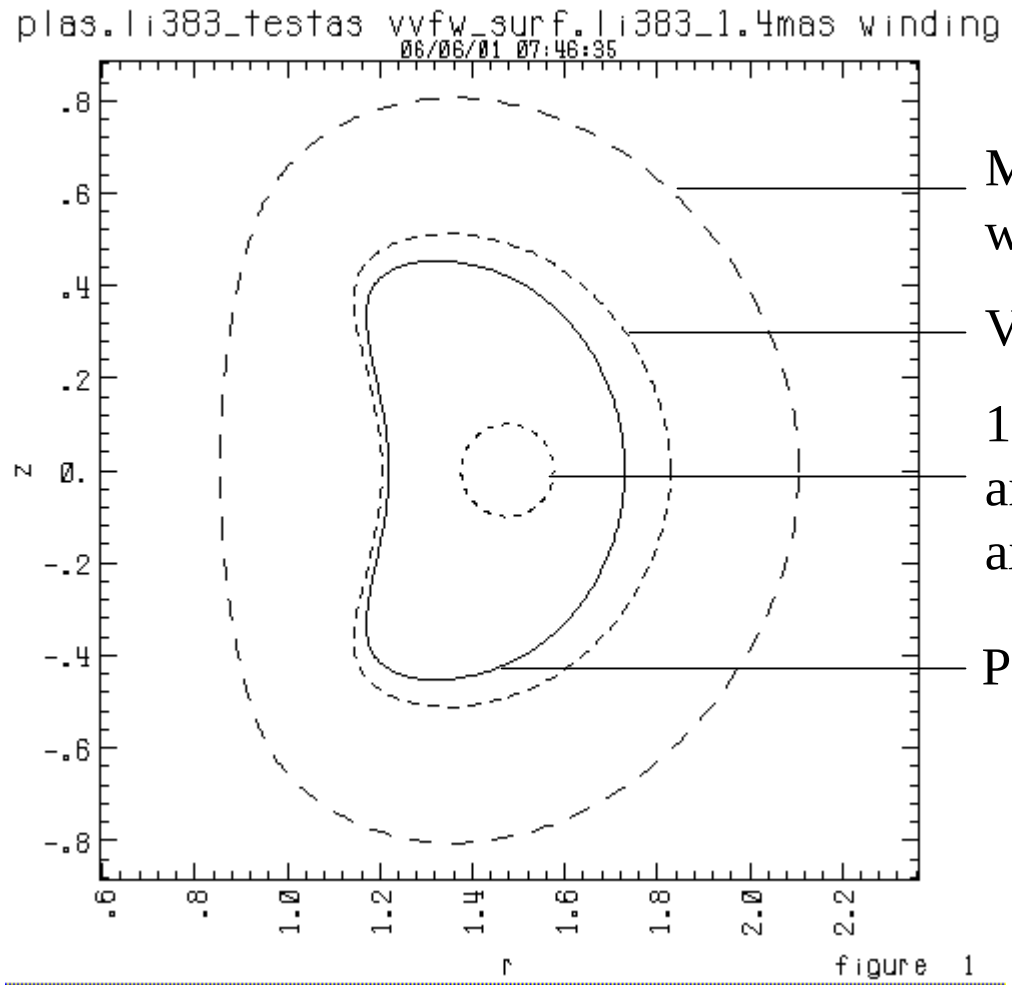
- Low-A stellarators
  - 1/R toroidal field is NOT aligned with magnetic axis
  - Poloidal fields from circular PF coils have $n \neq 0$ components, even in the core (due to non-circular, non-planar magnetic axis)
  - $n \neq 0$ components spoil axisymmetry

- Goal: Design TF and PF coils to have only n=0 (axisymmetric) components near the magnetic axis

Methodology

- Place 10cm radius surface around magnetic axis
  - Design TF to minimize B_n
  - Design PF to provide n=0, m=0,1,2,3 B_n components
    - Corresponds to nullapole, dipole, quadrupole, and hexapole
    - Octupole not required per Pomphrey
- Test procedure for axisymmetric case
- Apply to li383
- Compare flexibility derived from new TF/PF with vintage 1/R TF and circular PF coils (future work)

Axisymmetric equivalent



Modular coil winding surface

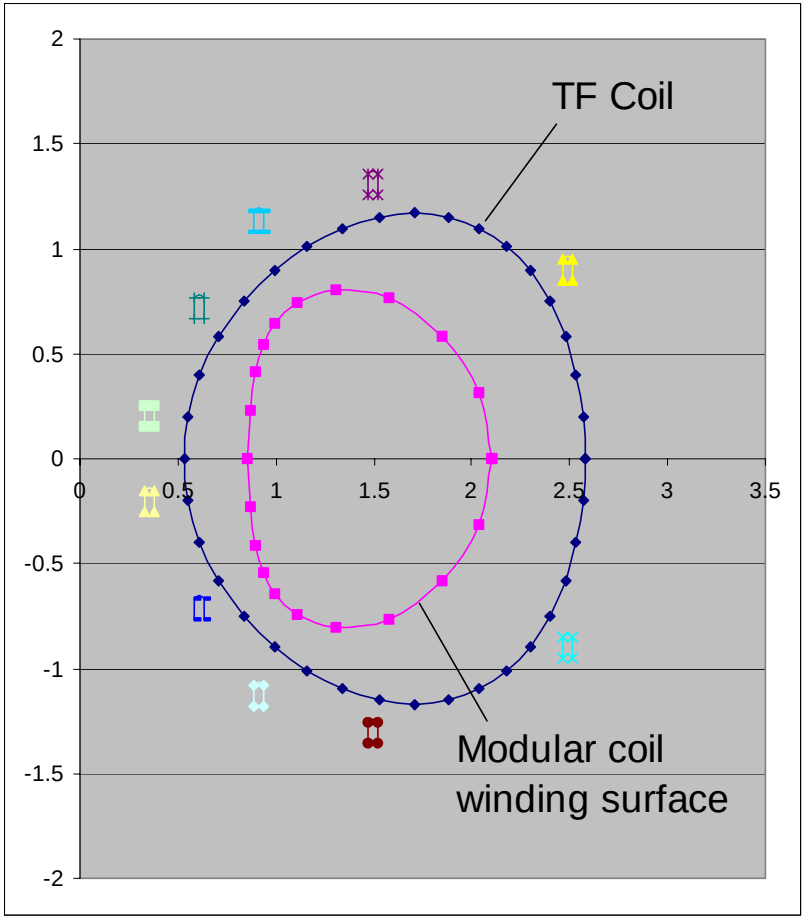
Vacuum vessel

10cm radius around magnetic axis

Plasma

Optimized TF/PF

- Penalty functions
  - B_{avg}, B_{max}
  - Amp-meters
  - Coil-to-coil separation
  - Coil-to-winding surface separation
- TF has reverse D-shape
  - Minimizes ripple
- 5 PF coils

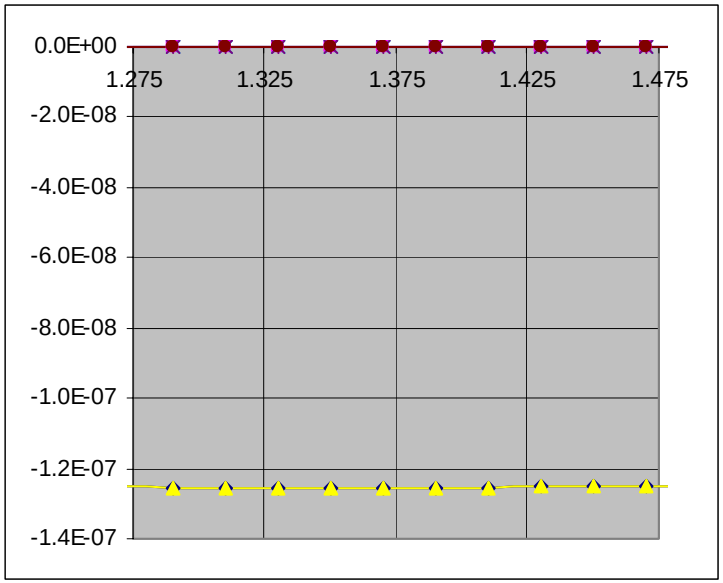


PF generation

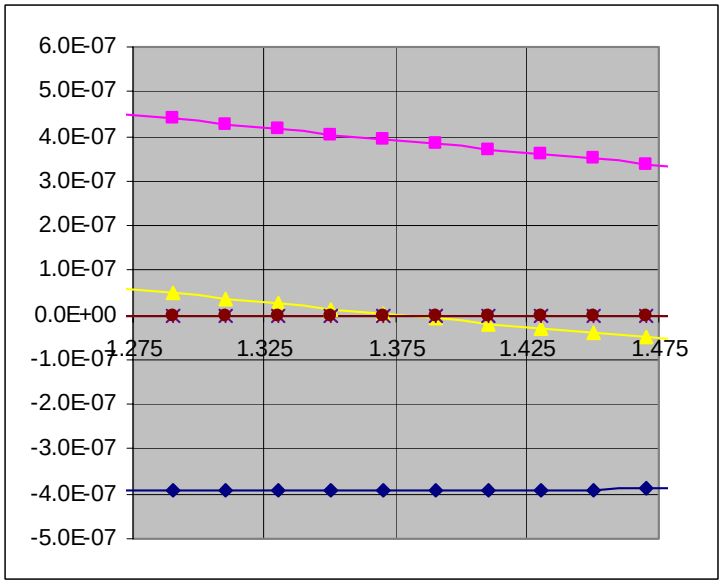
- R, Z, and current were the free parameters
- Five pairs of PF coils generated
  - PF5 located for dipole field
  - PF4 located for quadrupole field (with PF5)
  - PF2 located for hexapole field (with PF4/5)
  - PF1/3 located for ohmic distribution
    - PF1 located near horizontal midplane
    - PF3 located to ‘fill the hole’ between PF2 and PF4

B_z distribution

- Dipole (flat)
- PF5 only

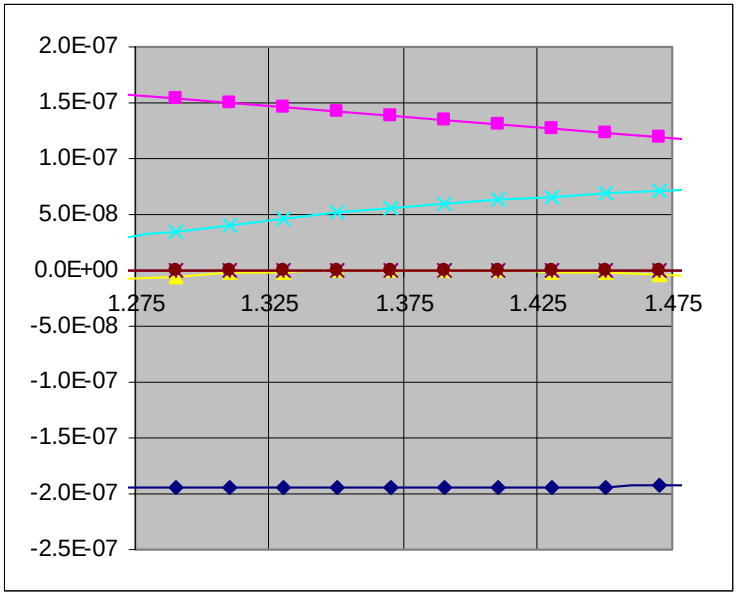


- Quadrupole (linear)
- PF4 and PF5

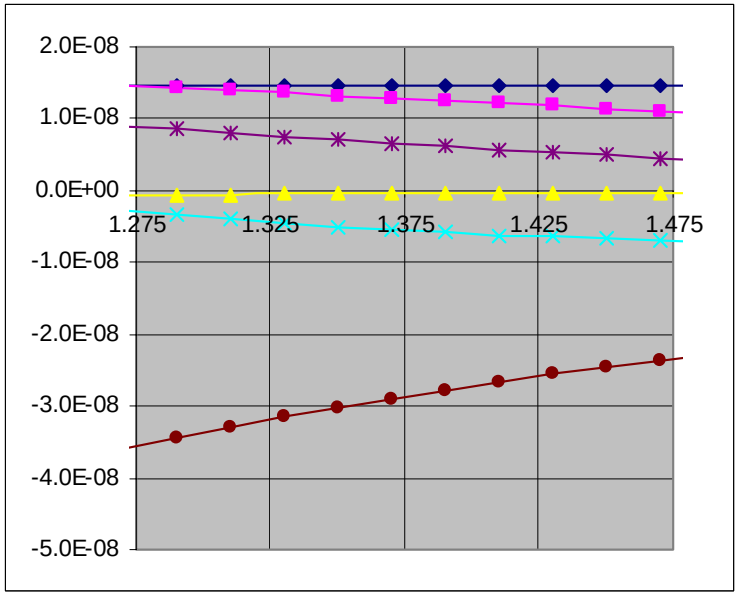


B_z distribution (2)

- Hexapole (parabolic)
- PF2, PF4, and PF5



- Nullapole (zero)
- All PF coils

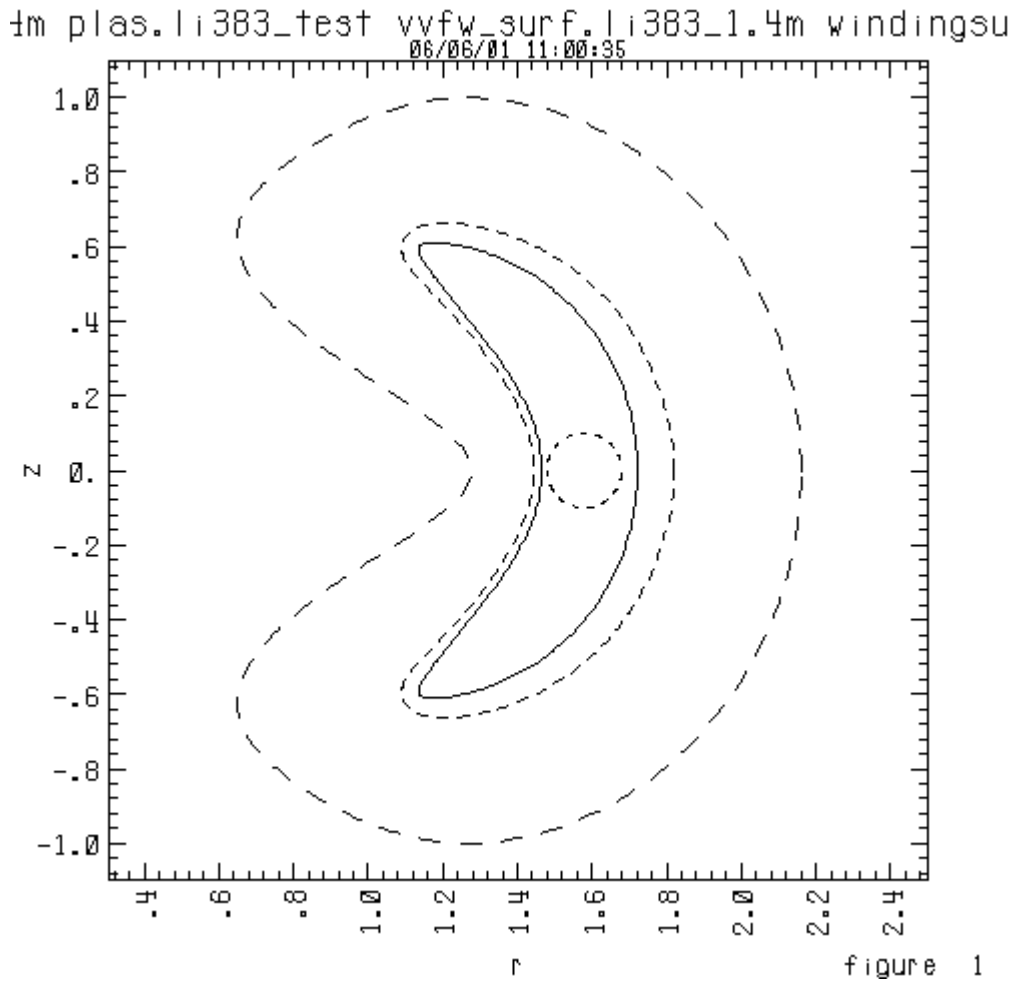


Axisymmetric results look plausible

- Reverse D-shape TF coils minimizes ripple
- 5 PF coil pairs spaced like we would expect
- Conclusion: Methodology provided good and reasonable results in axisymmetric case

- **On to LI383!**

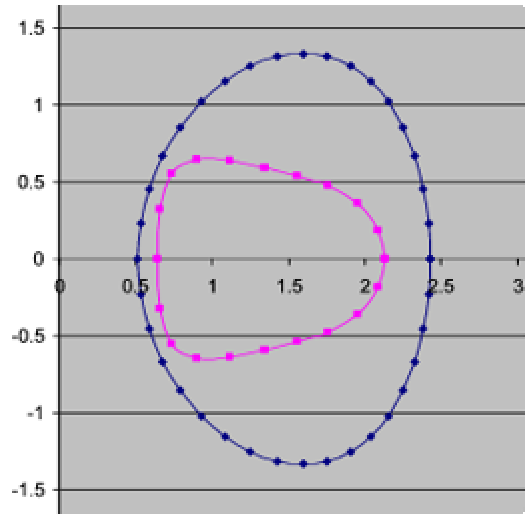
Process now applied to non-axisymmetric surfaces



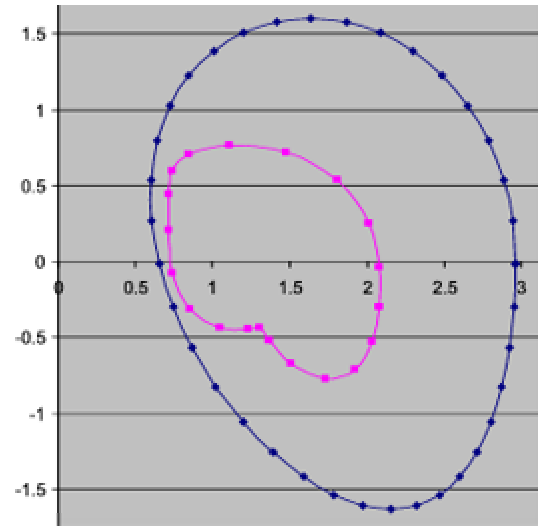
Modest improvements in optimized TF

Configuration	Bavg	Bmax	Amp-m	Min coil-to-coil (cm)	Min coil-to-surf (cm)	Comments
Reference TF coil set						
Nominal currents	2.3%	4.9%	27	15	21	0.143 A/coil
Optimized currents	2.1%	4.8%	27	15	22	0.426, **0, 0,** 0.287 A/coil at v=0.5, 0.36, 0.21, 0.07
Vertical coils						
Elliptical coils (0 modes)	1.9%	5.1%	34	17	25	0.5, **-0.06, 0**, 0.31
Elliptical coils (0 modes)	1.7%	**5.8%**	23	**24**	**35**	**0.44, 0.28 (only 2 coil types)**
Shaped coils (2 modes)	**1.8%**	**4.7%**	**23**	**15**	**30**	**All improvements over reference TF**
	0.77	*0.95*	*0.87*	*0.99*	*1.38*	*Relative to reference TF*
Tilted coils						
Shaped coils (2 modes)	**1.5%**	**4.0%**	**23**	**18**	**30**	**Best results but requires tilting TF coils - a significant configuration change**

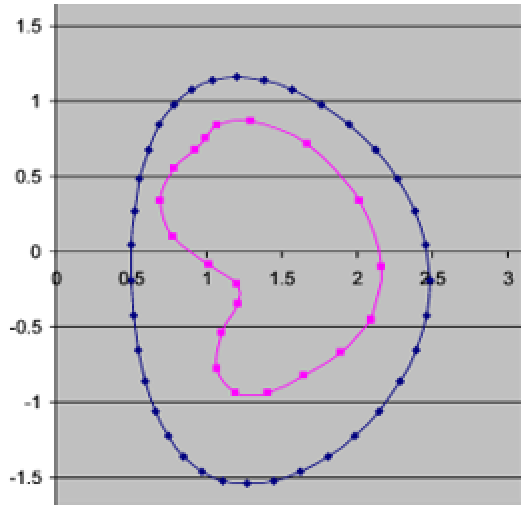
- **May be hard to track magnetic axis with planar, vertical coils outside modular coil winding surface**
- **TF coils ‘conform’ to winding surface, inside reference TF**
- **More latitude for non-circular, non-planar PF coils?**
- **Better diagnostic access? Conformal cryostat?**



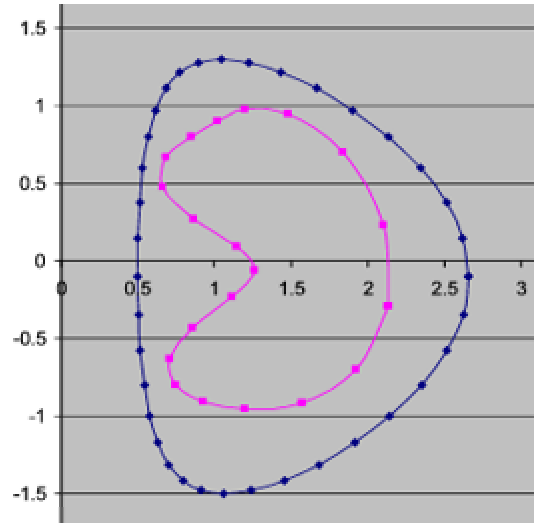
v=0.5



v=0.35



v=0.21



v=0.07

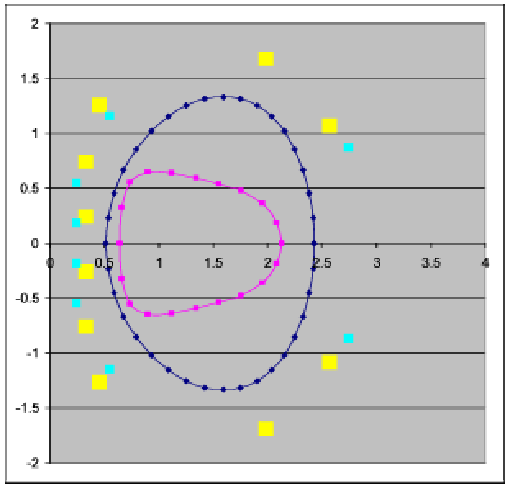
PF shaping options

- Reference is flat and circular
- Flat and non-circular provides added flexibility, still easy to wind
- Non-flat and non-circular is a 3D winding, akin to a modular coil

Dipole coil configuration	Rel. Bavg	Rel. Bmax	Rel. Amp-m
Flat and circular	1.00	1.00	1.00
Flat and non-circular (2 modes)	0.84	0.86	0.95
Non-flat and non-circular (2 modes)	0.82	0.80	0.91

- PF coils far from the plasma (outside winding surface and TF coils) may also have trouble following magnetic axis

5 coil PF design generated



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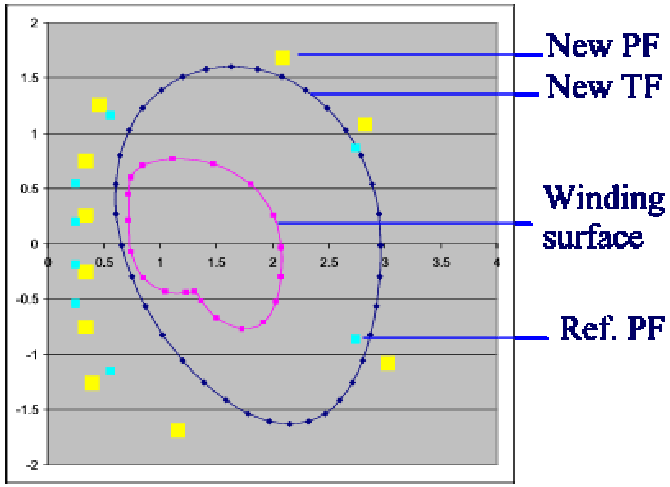

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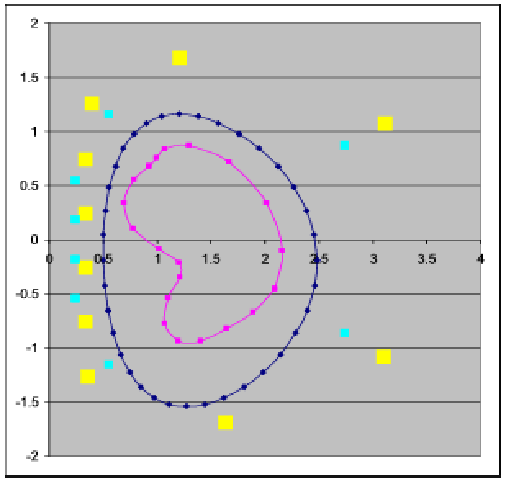

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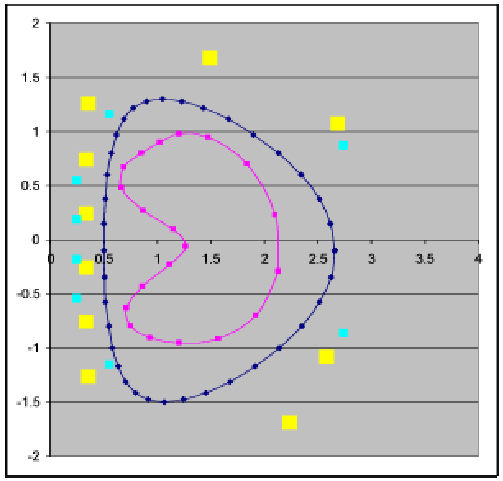


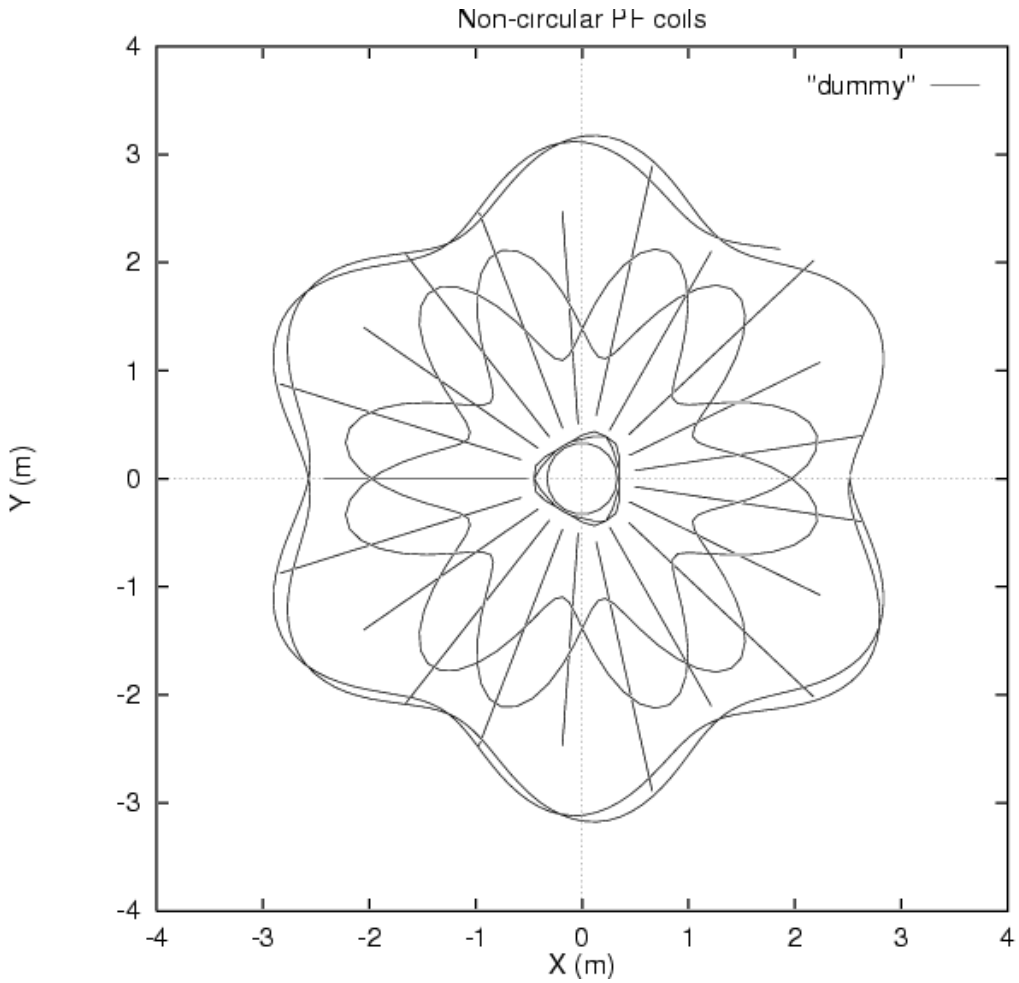
v=0.07

New PF design is more effective

Field	Relative B_{avg}	Relative B_{max}	Comments
Dipole (1,0)	**0.64**	**0.87**	**1 coil**
Quadrupole (2,0)	**0.56**	**0.57**	**2 coils**
Hexapole (3,0)	**0.62**	**0.71**	**3 coils**

PF4 (and PF5) has strong n=2 character

- n=0,1,2 modes allowed
- Reason for n=2 dominance TBD
  - Performance?
  - TF geometry?
  - Quirk of optimizer?
- Need systematic study of coil behavior versus number of modes allowed



Conclusions

- A useful methodology for designing flexible TF and PF coils developed
- TF coils with non-uniform current and geometry can provide modestly reduced ripple on axis
- Improved control of axisymmetry in the core might be realized by allowing independent control of the TF coils
  - Time honored method
- A 5 coil PF set can effectively and efficiently provide n=0, m=0,1,2,3 modes
  - Correlation between coils and modes (e.g., PF5 for dipole field) might simplify plasma control and optimization

Conclusions (2)

- New TF/PF set not ready for prime time
  - TF geometry needs to checked v. 1017 coils set and refined
  - Strong n=2 character apparent in non-circular PF coils not understood
  - Systematic study required of performance versus TF/PF modes planned (complete by end of next week, 6/22)

Next steps

- Generate improved axisymmetric PF for reference TF
  - Does it provide improved flexibility?
  - Does it facilitate improved configurations?
  - Does independent control of TF coils improve axisymmetry in core?

- Refine new TF/PF design
  - Assess configuration impacts of new TF coils
  - Perform systematic study of PF coil design v. mode numbers
  - Check if it provides improved flexibility or facilitates improved configurations