Impact of Coil Tolerances on Resonant Field Errors

NCSX Project Meeting

October 16, 2001

Art Brooks

Overview

- Impact of Coil Tolerances are being studied by imposing perturbations to ideal coil geometry and evaluating resonance field induced at plasma to predict impact on island size

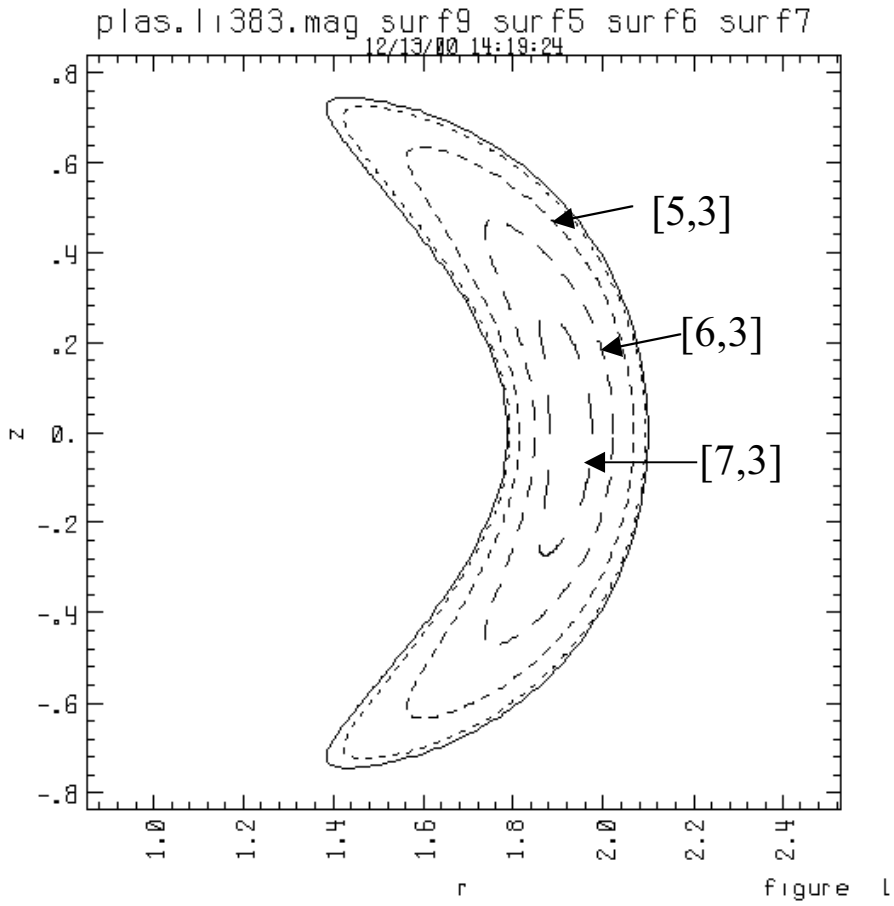
- In parallel, benchmarking of symmetric perturbations with PIES
  - Success would give confidence in prediction of impact of non symmetric perturbations on island size

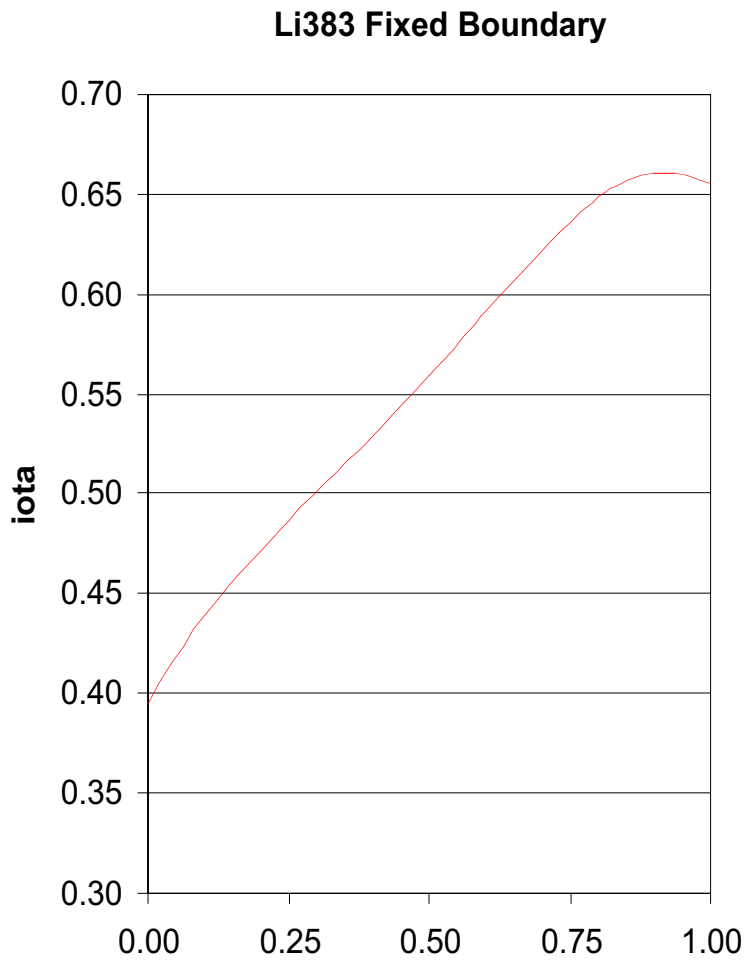
Coil Tolerances Investigated on 0907h Modular Coils

- Coil Distortions Errors (2 mm max, m=0..6)
  - Impose distortions of each modular coil of form:
    - dR = 0.002 * sin(m*th)
    - dZ = 0.002 * sin(m*th)
    - dPHI = 0.002 * sin(m*th)
    - Repeat for cosine distribution

- Coil Assembly Errors (2 mm max, n=0..6)
  - Displace or Rotate each modular coil about it's centroid:
    - dR = 0.002 * sin(n*phi)
    - dZ = 0.002 * sin(n*phi)
    - dPHI = 0.002 * sin(n*phi)
    - Rot_R = 0.002 * sin(n*phi)
    - Rot_Z = 0.002 * sin(n*phi)
    - Rot_PHI = 0.002 * sin(n*phi)
    - Repeat for cosine distribution

Li383 Targeted Resonances





Island Width Evaluation

Using s, θ, ϕ as the magnetic coordinates, island width given by :

$$ds = 4\left|\frac{C_{mn}(s)}{m\iota'(s)}\right|^{1/2}$$

where $C(s) \equiv \frac{B^s}{B^\phi} = \frac{B \bullet \nabla s}{B \bullet \nabla \phi}$

$\frac{B^s}{B^\phi}$ is evaluated by making use of

$$B^\phi = \frac{1}{J_{s,\theta,\phi}} \frac{d\Psi}{ds}$$

and $$\nabla s = \frac{1}{J_{s,\theta,\phi}} \left(\frac{\partial R}{\partial \theta} \times \frac{\partial R}{\partial \phi} \right)$$

leaving an expression which does not require explicit evaluation of the Jacobian and linear in B (and therefore coil currents)

$$\frac{B^s}{B^\phi} = \frac{B \bullet \left(\frac{\partial R}{\partial \theta} \times \frac{\partial R}{\partial \phi} \right)}{\frac{d\Psi}{ds}}$$

Island Size vs Distortion of Modular Coils (sin)

	Plasma Resonant Mode									
	3,5	6,10		3,6	6,12		3,7	6,14		1,2	2,4
Displacement											
Radial											
mod_dr_m0s	0.0%	0.0%		0.0%	0.0%		0.0%	0.0%		0.0%	0.0%
mod_dr_m1s	1.4%	0.4%		0.7%	0.1%		0.1%	0.0%		0.0%	0.0%
mod_dr_m2s	1.7%	0.3%		0.6%	0.0%		0.1%	0.0%		0.0%	0.0%
mod_dr_m3s	0.8%	0.2%		0.4%	0.0%		0.0%	0.0%		0.0%	0.0%
mod_dr_m4s	1.2%	0.3%		0.3%	0.1%		0.1%	0.0%		0.0%	0.0%
mod_dr_m5s	1.2%	0.2%		0.1%	0.0%		0.0%	0.0%		0.0%	0.0%
mod_dr_m6s	2.0%	0.2%		0.6%	0.1%		0.1%	0.0%		0.0%	0.0%
Vertical											
mod_dz_m0s	0.0%	0.0%		0.0%	0.0%		0.0%	0.0%		0.0%	0.0%
mod_dz_m1s	1.1%	0.4%		0.9%	0.1%		0.1%	0.0%		0.0%	0.0%
mod_dz_m2s	1.2%	0.3%		0.8%	0.1%		0.1%	0.0%		0.0%	0.0%
mod_dz_m3s	1.0%	0.2%		0.5%	0.1%		0.1%	0.0%		0.0%	0.0%
mod_dz_m4s	1.7%	0.3%		0.2%	0.1%		0.1%	0.0%		0.0%	0.0%
mod_dz_m5s	0.3%	0.3%		0.3%	0.0%		0.0%	0.0%		0.0%	0.0%
mod_dz_m6s	1.8%	0.2%		0.6%	0.0%		0.1%	0.0%		0.0%	0.0%
Toroidal											
mod_dt_m0s	0.0%	0.0%		0.0%	0.0%		0.0%	0.0%		0.0%	0.0%
mod_dt_m1s	1.7%	0.5%		1.0%	0.1%		0.1%	0.0%		0.0%	0.0%
mod_dt_m2s	0.2%	0.3%		1.0%	0.1%		0.1%	0.0%		0.0%	0.0%
mod_dt_m3s	2.1%	0.3%		0.4%	0.1%		0.1%	0.0%		0.0%	0.0%
mod_dt_m4s	1.4%	0.6%		0.9%	0.1%		0.1%	0.0%		0.0%	0.0%
mod_dt_m5s	0.8%	0.4%		0.4%	0.1%		0.1%	0.0%		0.0%	0.0%

Island Size vs Distortion of Modular Coils (cos)

	Plasma Resonant Mode									
	3,5	6,10	3,6	6,12	3,7	6,14	1,2	2,4
Displacement								
Radial								
mod_dr_m0c	0.4%	0.3%	0.2%	0.1%	0.1%	0.0%	0.0%	0.0%
mod_dr_m1c	1.0%	0.4%	0.6%	0.1%	0.1%	0.0%	0.0%	0.0%
mod_dr_m2c	0.1%	0.3%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%
mod_dr_m3c	0.9%	0.4%	0.5%	0.1%	0.1%	0.0%	0.0%	0.0%
mod_dr_m4c	1.9%	0.3%	0.5%	0.1%	0.1%	0.0%	0.0%	0.0%
mod_dr_m5c	1.1%	0.2%	0.4%	0.0%	0.1%	0.0%	0.0%	0.0%
mod_dr_m6c	2.0%	0.2%	0.6%	0.0%	0.1%	0.0%	0.0%	0.0%
Vertical								
mod_dz_m0c	0.6%	0.2%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%
mod_dz_m1c	0.9%	0.3%	0.6%	0.1%	0.1%	0.0%	0.0%	0.0%
mod_dz_m2c	0.9%	0.2%	0.1%	0.1%	0.1%	0.0%	0.0%	0.0%
mod_dz_m3c	0.6%	0.3%	0.6%	0.1%	0.1%	0.0%	0.0%	0.0%
mod_dz_m4c	1.7%	0.3%	0.7%	0.1%	0.1%	0.0%	0.0%	0.0%
mod_dz_m5c	1.1%	0.2%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%
mod_dz_m6c	1.9%	0.1%	0.5%	0.0%	0.1%	0.0%	0.0%	0.0%
Toroidal								
mod_dt_m0c	1.1%	0.3%	0.3%	0.1%	0.0%	0.0%	0.0%	0.0%
mod_dt_m1c	1.6%	0.3%	0.4%	0.0%	0.1%	0.0%	0.0%	0.0%
mod_dt_m2c	0.4%	0.2%	0.8%	0.1%	0.1%	0.0%	0.0%	0.0%
mod_dt_m3c	3.0%	0.5%	1.0%	0.1%	0.1%	0.0%	0.0%	0.0%
mod_dt_m4c	1.6%	0.5%	0.8%	0.0%	0.1%	0.0%	0.0%	0.0%
mod_dt_m5c	1.5%	0.1%	0.5%	0.1%	0.0%	0.0%	0.0%	0.0%

Island Size vs Displacement of Modular Coils (sin)

	Plasma Resonant Mode									
	3,5	6,10		3,6	6,12		3,7	6,14		1,2	2,4
Displacement											
Radial											
mod_dr_m0s	0.0%	0.0%		0.0%	0.0%		0.0%	0.0%		0.0%	0.0%
mod_dr_m1s	0.1%	0.0%		0.0%	0.0%		0.0%	0.0%		1.5%	0.4%
mod_dr_m2s	0.1%	0.0%		0.0%	0.0%		0.0%	0.0%		2.5%	0.5%
mod_dr_m3s	1.1%	0.2%		0.6%	0.0%		0.0%	0.0%		0.0%	0.0%
mod_dr_m4s	0.1%	0.0%		0.0%	0.0%		0.0%	0.0%		2.2%	1.5%
mod_dr_m5s	0.1%	0.0%		0.0%	0.0%		0.0%	0.0%		3.1%	0.6%
mod_dr_m6s	1.5%	0.3%		0.6%	0.1%		0.1%	0.0%		0.0%	0.0%
Vertical											
mod_dz_m0s	0.0%	0.0%		0.0%	0.0%		0.0%	0.0%		0.0%	0.0%
mod_dz_m1s	0.1%	0.0%		0.0%	0.0%		0.0%	0.0%		2.6%	0.8%
mod_dz_m2s	0.1%	0.0%		0.0%	0.0%		0.0%	0.0%		4.0%	0.7%
mod_dz_m3s	1.1%	0.3%		0.8%	0.1%		0.1%	0.0%		0.0%	0.0%
mod_dz_m4s	0.1%	0.0%		0.0%	0.0%		0.0%	0.0%		1.1%	1.5%
mod_dz_m5s	0.1%	0.0%		0.0%	0.0%		0.0%	0.0%		2.9%	0.5%
mod_dz_m6s	1.3%	0.4%		0.6%	0.1%		0.1%	0.0%		0.0%	0.0%
Toroidal											
mod_dt_m0s	0.0%	0.0%		0.0%	0.0%		0.0%	0.0%		0.0%	0.0%
mod_dt_m1s	0.0%	0.0%		0.0%	0.0%		0.0%	0.0%		1.5%	0.1%
mod_dt_m2s	0.0%	0.0%		0.0%	0.0%		0.0%	0.0%		2.7%	0.3%
mod_dt_m3s	0.6%	0.2%		0.3%	0.0%		0.0%	0.0%		0.0%	0.0%
mod_dt_m4s	0.0%	0.0%		0.0%	0.0%		0.0%	0.0%		1.3%	0.2%
mod_dt_m5s	0.0%	0.0%		0.0%	0.0%		0.0%	0.0%		1.8%	0.5%

Island Size vs Rotation of Modular Coils (sin)

	Plasma Resonant Mode								
	3,5	6,10	3,6	6,12	3,7	6,14	1,2	2,4
Rotations								
Radial								
mod_rr_m0s	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
mod_rr_m1s	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	3.1%	0.4%
mod_rr_m2s	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.0%	0.1%
mod_rr_m3s	0.7%	0.1%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%
mod_rr_m4s	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.5%	0.5%
mod_rr_m5s	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.2%	0.5%
mod_rr_m6s	0.8%	0.1%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%
Vertical								
mod_rz_m0s	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
mod_rz_m1s	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.4%	0.4%
mod_rz_m2s	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.4%	0.0%
mod_rz_m3s	0.8%	0.2%	0.3%	0.1%	0.0%	0.0%	0.0%	0.0%
mod_rz_m4s	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.6%	0.4%
mod_rz_m5s	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.0%	0.6%
mod_rz_m6s	0.6%	0.0%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%
Toroidal								
mod_rt_m0s	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
mod_rt_m1s	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.7%	0.3%
mod_rt_m2s	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	3.9%	0.8%
mod_rt_m3s	0.3%	0.1%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%
mod_rt_m4s	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.0%	0.8%
mod_rt_m5s	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.9%	0.5%

Island Size vs Displacement of Modular Coils (cos)

	Plasma Resonant Mode									
	3,5	6,10		3,6	6,12		3,7	6,14		1,2	2,4
Displacement											
Radial											
mod_dr_m0c	0.5%	0.3%		0.0%	0.1%		0.1%	0.0%		0.0%	0.0%
mod_dr_m1c	0.1%	0.0%		0.0%	0.0%		0.0%	0.0%		1.1%	0.6%
mod_dr_m2c	0.1%	0.0%		0.0%	0.0%		0.0%	0.0%		3.6%	0.6%
mod_dr_m3c	1.2%	0.2%		0.2%	0.1%		0.0%	0.0%		0.0%	0.0%
mod_dr_m4c	0.1%	0.0%		0.0%	0.0%		0.0%	0.0%		2.4%	1.6%
mod_dr_m5c	0.1%	0.0%		0.0%	0.0%		0.0%	0.0%		5.0%	0.8%
mod_dr_m6c	1.7%	0.3%		0.7%	0.0%		0.1%	0.0%		0.0%	0.0%
Vertical											
mod_dz_m0c	0.6%	0.2%		0.2%	0.0%		0.0%	0.0%		0.0%	0.0%
mod_dz_m1c	0.1%	0.0%		0.0%	0.0%		0.0%	0.0%		2.3%	0.4%
mod_dz_m2c	0.1%	0.0%		0.0%	0.0%		0.0%	0.0%		3.8%	0.7%
mod_dz_m3c	0.2%	0.1%		0.2%	0.0%		0.1%	0.0%		0.0%	0.0%
mod_dz_m4c	0.1%	0.0%		0.0%	0.0%		0.0%	0.0%		2.6%	1.6%
mod_dz_m5c	0.1%	0.0%		0.0%	0.0%		0.0%	0.0%		4.8%	0.8%
mod_dz_m6c	1.7%	0.2%		0.6%	0.0%		0.1%	0.0%		0.0%	0.0%
Toroidal											
mod_dt_m0c	0.8%	0.3%		0.1%	0.0%		0.0%	0.0%		0.0%	0.0%
mod_dt_m1c	0.0%	0.0%		0.0%	0.0%		0.0%	0.0%		1.8%	0.7%
mod_dt_m2c	0.0%	0.0%		0.0%	0.0%		0.0%	0.0%		4.5%	0.4%
mod_dt_m3c	0.5%	0.1%		0.1%	0.1%		0.1%	0.0%		0.0%	0.0%
mod_dt_m4c	0.0%	0.0%		0.0%	0.0%		0.0%	0.0%		0.7%	1.2%
mod_dt_m5c	0.0%	0.0%		0.0%	0.0%		0.0%	0.0%		2.4%	0.3%

Island Size vs Rotation of Modular Coils (cos)

	Plasma Resonant Mode								
	3,5	6,10	3,6	6,12	3,7	6,14	1,2	2,4
Rotations								
Radial								
mod_rr_m0c	1.0%	0.1%	0.3%	0.0%	0.1%	0.0%	0.0%	0.0%
mod_rr_m1c	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	3.1%	0.4%
mod_rr_m2c	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.0%	0.1%
mod_rr_m3c	0.5%	0.1%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%
mod_rr_m4c	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.5%	0.5%
mod_rr_m5c	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.2%	0.5%
mod_rr_m6c	0.7%	0.1%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%
Vertical								
mod_rz_m0c	1.5%	0.3%	0.5%	0.0%	0.1%	0.0%	0.0%	0.0%
mod_rz_m1c	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.4%	0.4%
mod_rz_m2c	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.4%	0.0%
mod_rz_m3c	0.3%	0.2%	0.2%	0.1%	0.0%	0.0%	0.0%	0.0%
mod_rz_m4c	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.6%	0.4%
mod_rz_m5c	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.0%	0.6%
mod_rz_m6c	0.7%	0.1%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%
Toroidal								
mod_rt_m0c	0.5%	0.1%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%
mod_rt_m1c	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.7%	0.3%
mod_rt_m2c	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	3.9%	0.8%
mod_rt_m3c	0.9%	0.1%	0.2%	0.0%	0.1%	0.0%	0.0%	0.0%
mod_rt_m4c	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.0%	0.8%
mod_rt_m5c	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.9%	0.5%

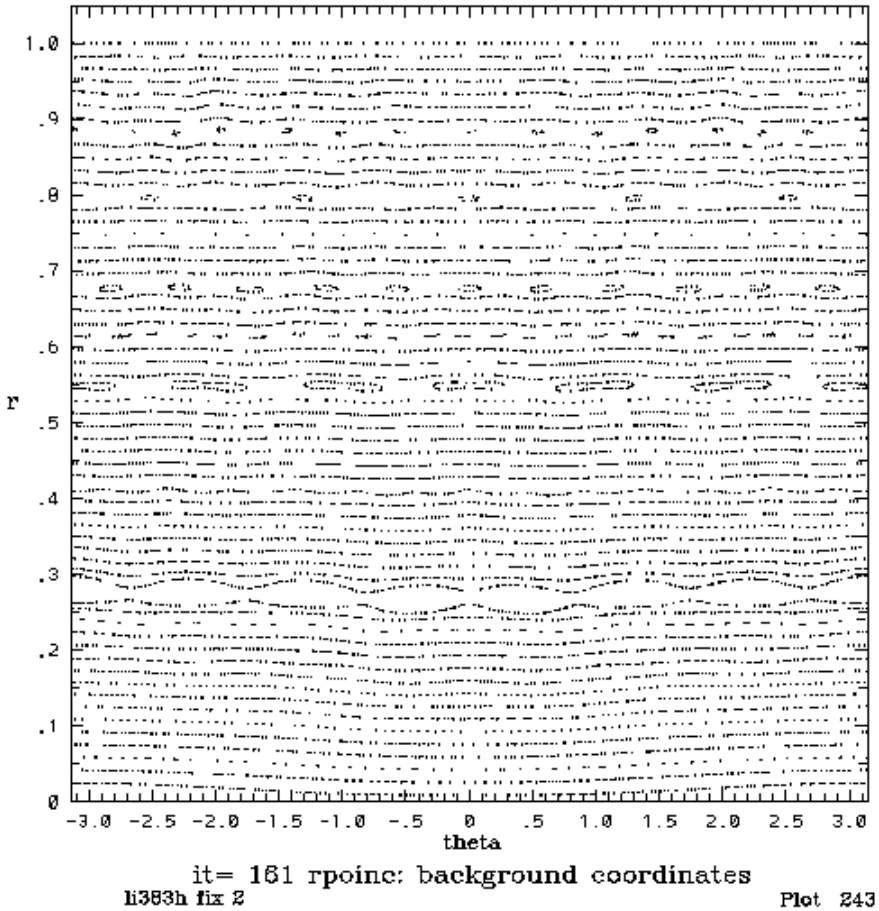
Maximum Predicted Island Size

- Modular Coil Distortion:
  - 3.0% Islands based on total flux
- Modular Coil Assembly
  - 5.0%
- Larger Islands may develop due to combinations of assumed coil perturbations

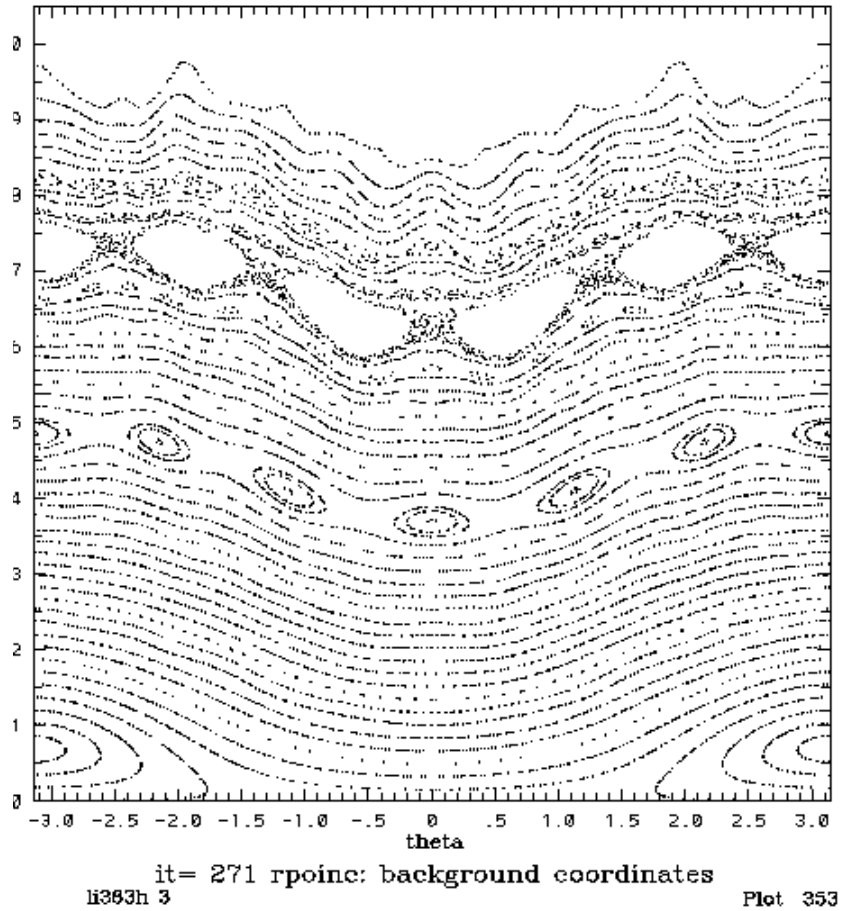
Benchmarking Effort

- Initially tried to measure impact of coil perturbations against a clean free boundary PIES run for the reference li383 plasma at full current, full beta
  - Use healed 0907 coils
  - However, reconstructed PIES run not sufficiently Island free
- Presently trying to generate a high accuracy current sheet solution to the healed fixed boundary
  - Use 180 modular coils (dBavg=0.1%, dBmax=0.8%)
  - Still not producing adequate PIES run

PIES Fixed Boundary vs Free Boundary



Healed li383 Fixed Boundary



Current Sheet Solution For li383 healed fixed boundary

More on Benchmarking

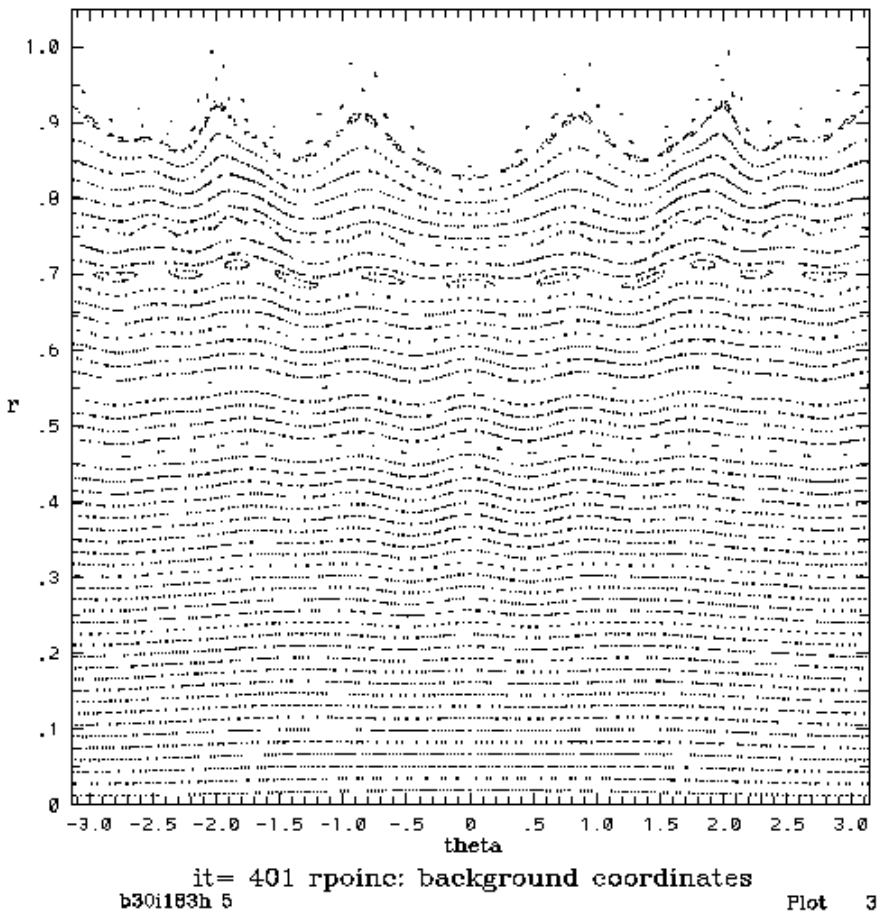
- Fallback - Use existing clean PIES runs from PVR
  - Beta = 3%, Ip = 183 KA which crosses iota = 0.5
  - Vacuum (z64x) which crosses iota = 0.6

- Results
  - Analytic estimates (vacisld code) tend to under estimate Island Size
  - Analytic estimates show perturbation size fairly linear with estimated island size squared. PIES results are not linear.

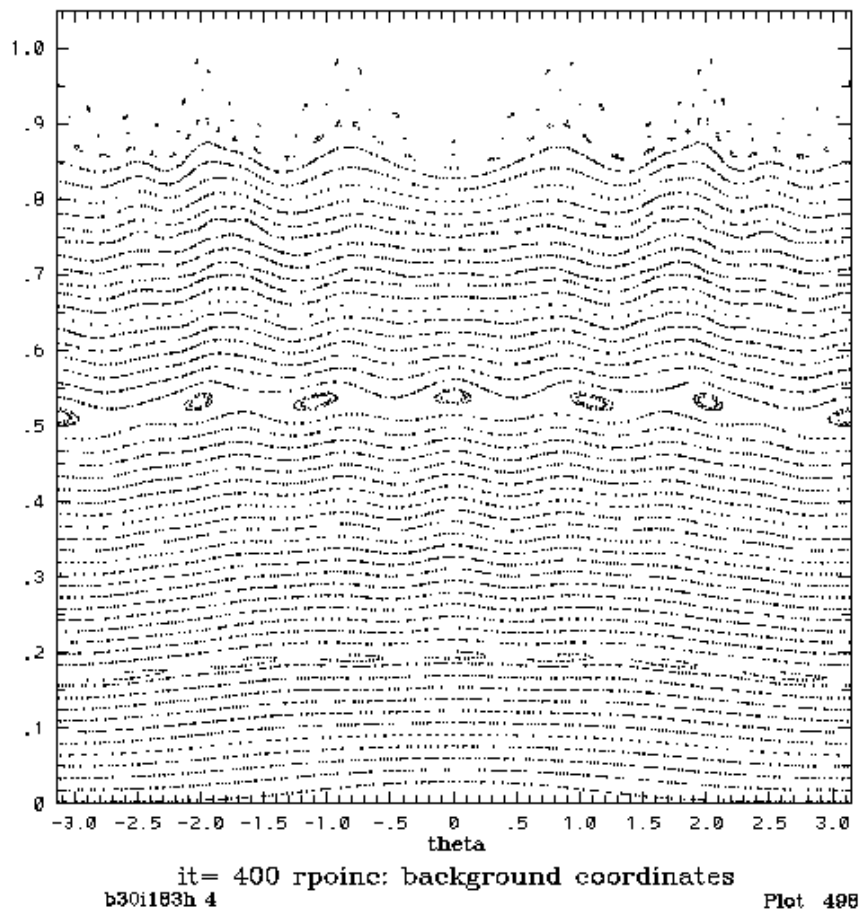
Benchmarks somewhat less than perfect

Benchmarking of Island Size Estimates from Field Perturbations										
ID	**Comment**	**Resonace**		**PIES Islands**						**VACISLD***
		n,m		**iota**	**dr**	**r**	**s**	**ds**		ds
b30i183h	Mike Z's beta=3%, Ip=183 KA	3,6		0.500	0.008	0.558	0.311	0.009		NA
		6,13		0.462	0.002	0.391	0.153	0.002		NA
b30i183h.dx1	Modular Coils at v=0 displaced 1 cm	3,6		0.500	0.032	0.540	0.291	**0.036**		**0.014**
		6,13		0.462	0.002	0.373	0.139	0.001		0.001
b30i183h.dx2	Modular Coils at v=0 displaced 2 mm	3,6		*0.500*	*0.021*	*0.580*	*0.336*	***0.025***		**0.006**
	(Note: Values after 200 iterations)	6,13		*0.462*	*0.003*	*0.401*	*0.161*	*0.002*		
z64x	Mike Z's Vacuum, iota = .57 -> .63	3,5		0.600	0.024	0.894	0.799	**0.043**		**0.013**

B30i183h with 0907h modular coils on symmetry plane displaced 1 cm radially

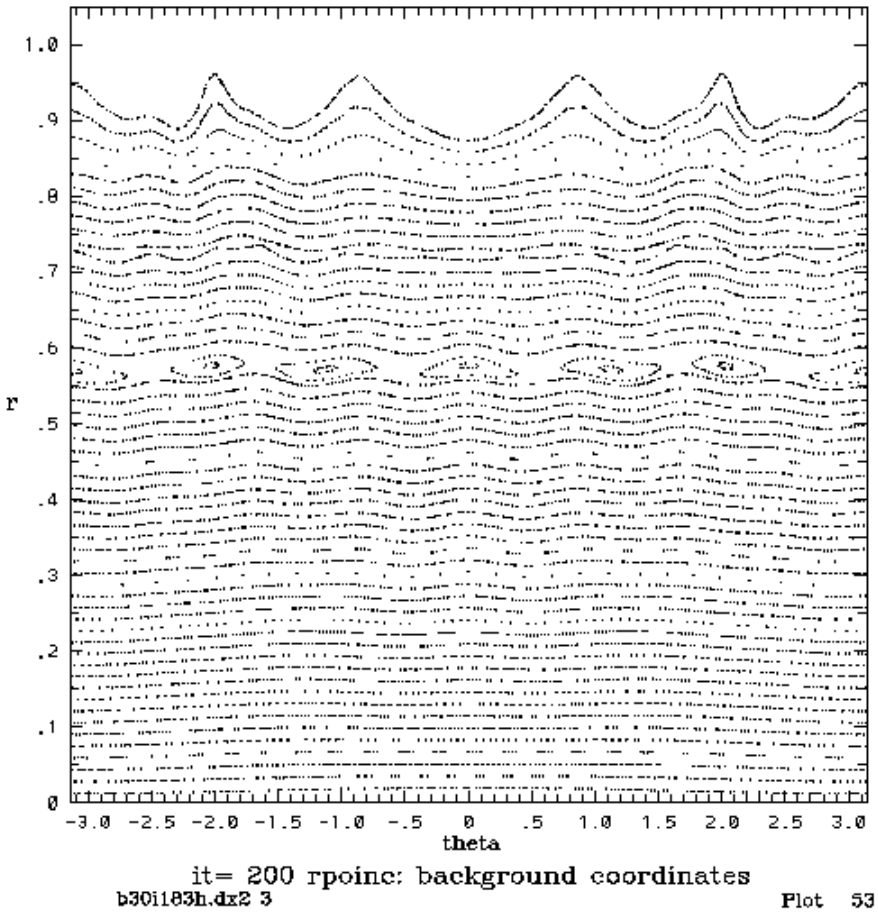


Unperturbed coil set

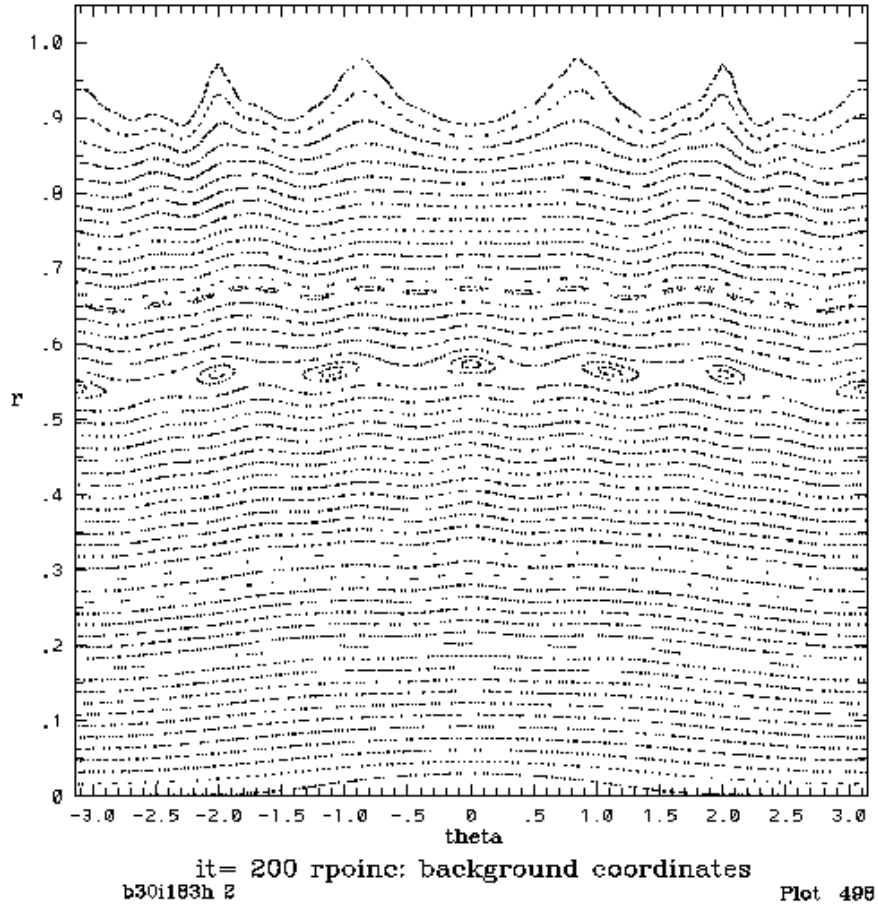


dr = 1 cm

B30i183h with 0907h modular coils on symmetry plane displaced 2 mm radially

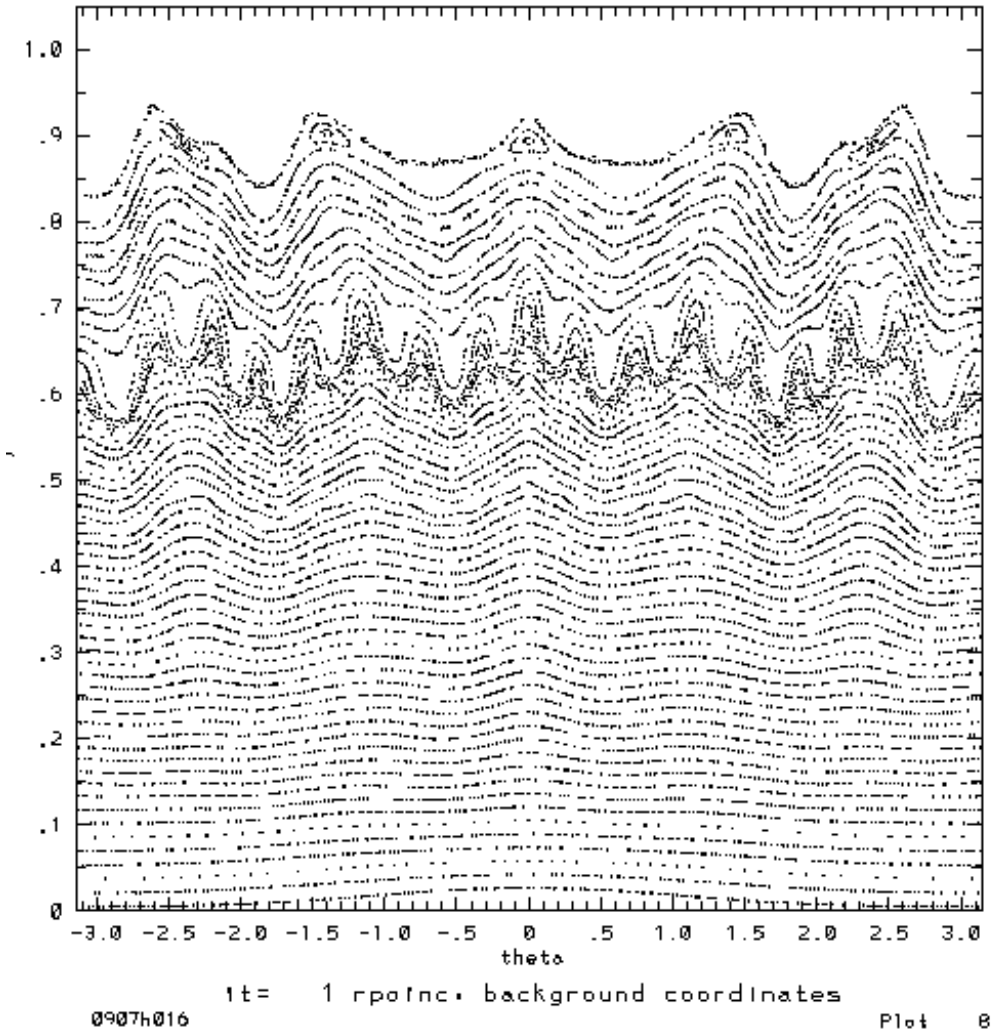


dr = 2 mm



dr = 1 cm

Z64x Vacuum



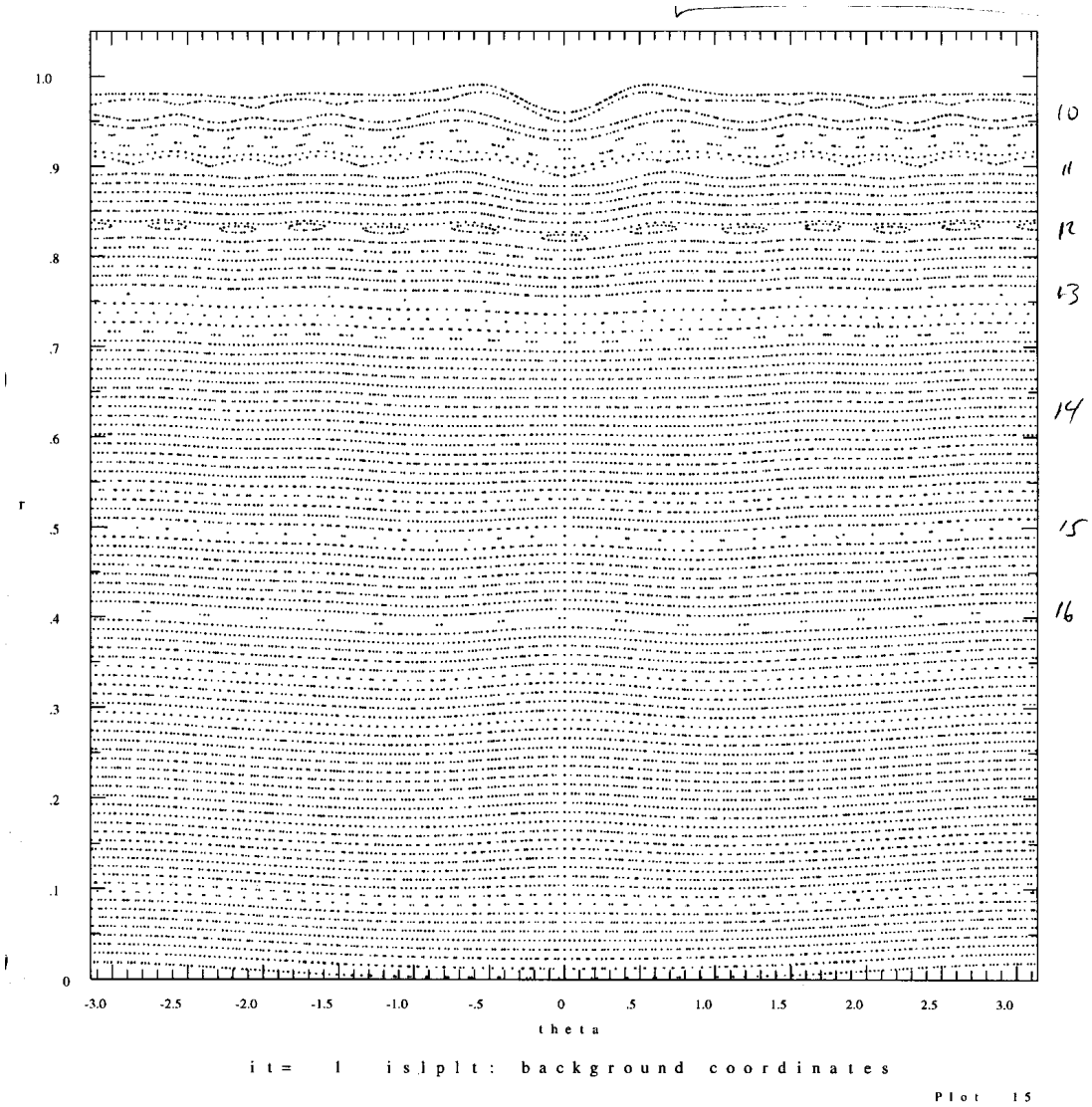
M=5 at edge

Note:
Stuart Hudson's surface through m=5 Islands output from PIES used in vacisld

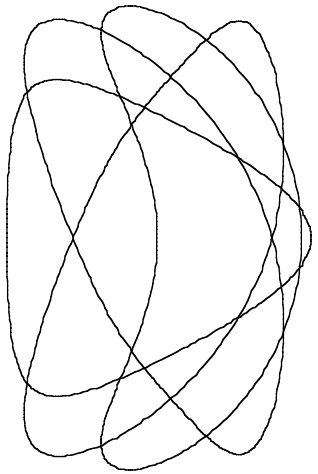
Summary

- Study so far suggests ~2 mm tolerance on Modular Coils may be adequate based on analytic model
  - Need to evaluate similar impact on TF and PF
  - Need to look at single coil tolerances
  - Should combinations of perturbations be considered?
- Benchmarking so far suggests results may need a factor of 2 or more safety margin
  - Open to suggestions for improving benchmarking

Earlier Benchmark using PG1



Small Islands visible on [10,3], [11,3], and [12,3] surfaces

Island Width

resonance, m	dρ, curropt calculated	dρ, pies observed
10	0.02	~0.02
11	0.019	~0.02
12	0.014	0.01 - 0.015
13	0.0048	~0.0
14	0.0028	~0.0
15	0.0019	~0.0
16	0.0001	~0.0