Flux surface sturdiness

- Requirement: no more than 10% flux loss to islands & stochastic regions
- Extensive analysis
  - As built coil shapes
  - Coil allignment choices
  - Trim coil effectiveness & choices

- Challenges come from high-beta iota profile: shear ⇒ low-n resonant surfaces
  - In vacuum or low-β, can choose (via coil currents) iota to not cross any low-order resonances, always have perfect surfaces.

- As with previous stellarators and tokamaks, plan to use trim coil array to compensate low-n errors
  - LHD, always compensates n=1 construction error using top/bottom trim coils
  - DIII-D, NSTX

- Plan:
  - Build in trim coils for n=1, 2 (n=3 under evaluation, from Lehman)
  - After measuring field errors, add subset of ‘outer’ array if needed.

NCSX design: Plasma will shield some field errors

- Reversed shear: factor ~3 decrease in islands due to neoclassical stabilization at β=4%

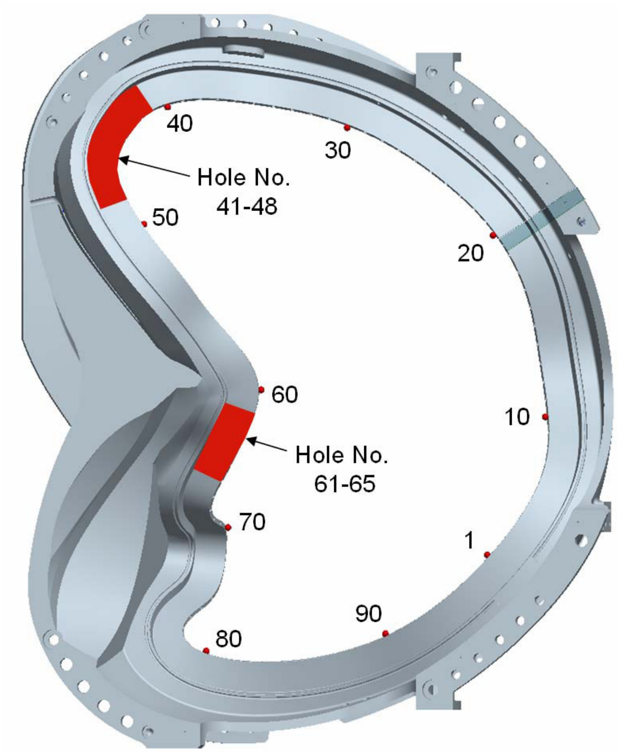
- Iota will change during plasma, as in tokamaks
  - Due to β and bootstrap current
  - Can change coil currents during plasma to force more iota change
  - By starting at an ~irrational iota (far from low-order surfaces), can force good initial surfaces. Then plasma will shield errors as iota changes.

- However, field errors will cause rotation breaking, could cause locking. Want to limit size.

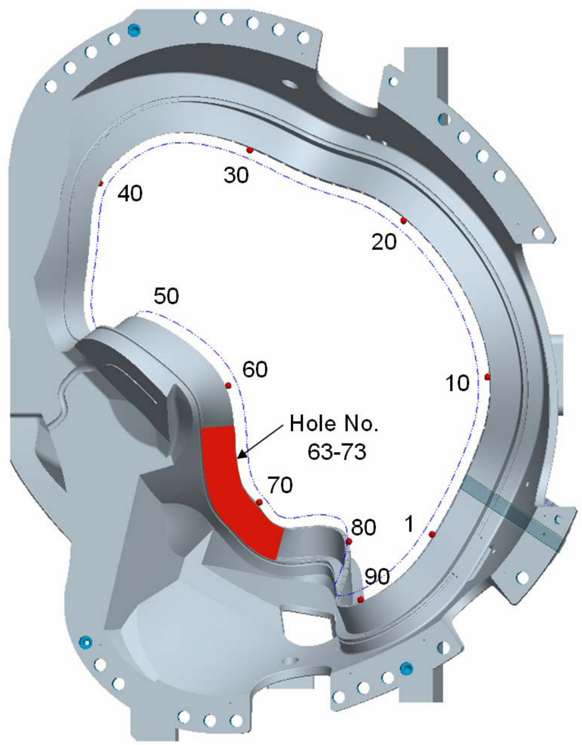
As Built Coil Data

- There are presently 12 of 18 Coils wound and current centers measured (at time of this analysis)
  - A1 thru A4
  - B1 thru B3
  - C1 thru C5
- Design Goal of +/- .020” (0.5 mm) achieved over most of coils but some local deviations.
- Coils wound to match current center achieved on prior wound coils to minimize symmetry breaking field errors. Goal: match shape of each coil-type within +/- .020”

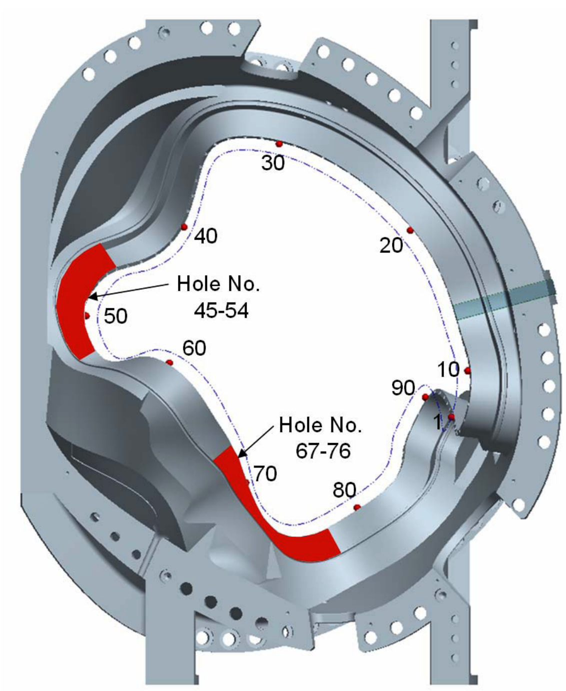
Modular Coil Castings
Clamp Numbering



A

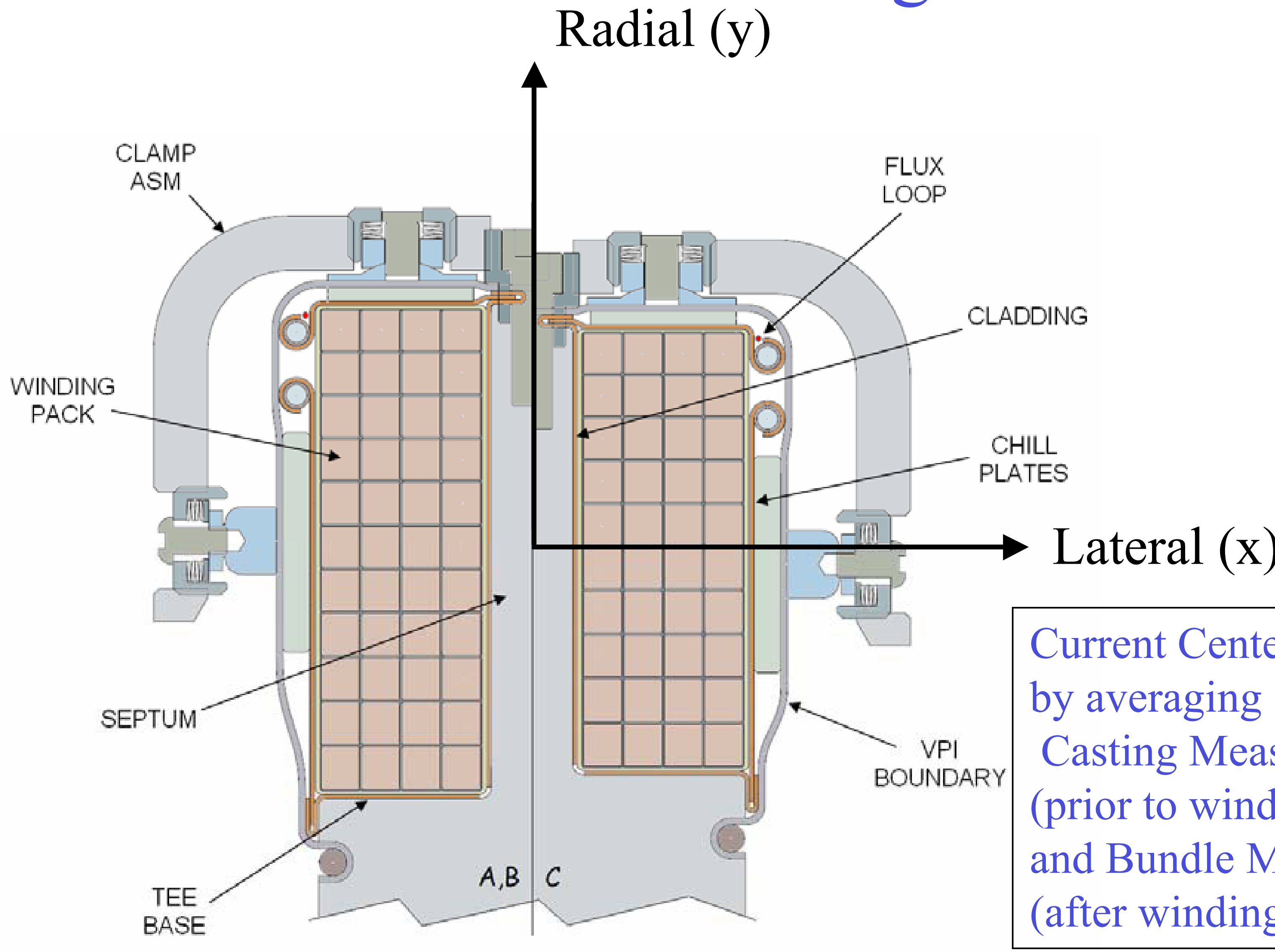


B



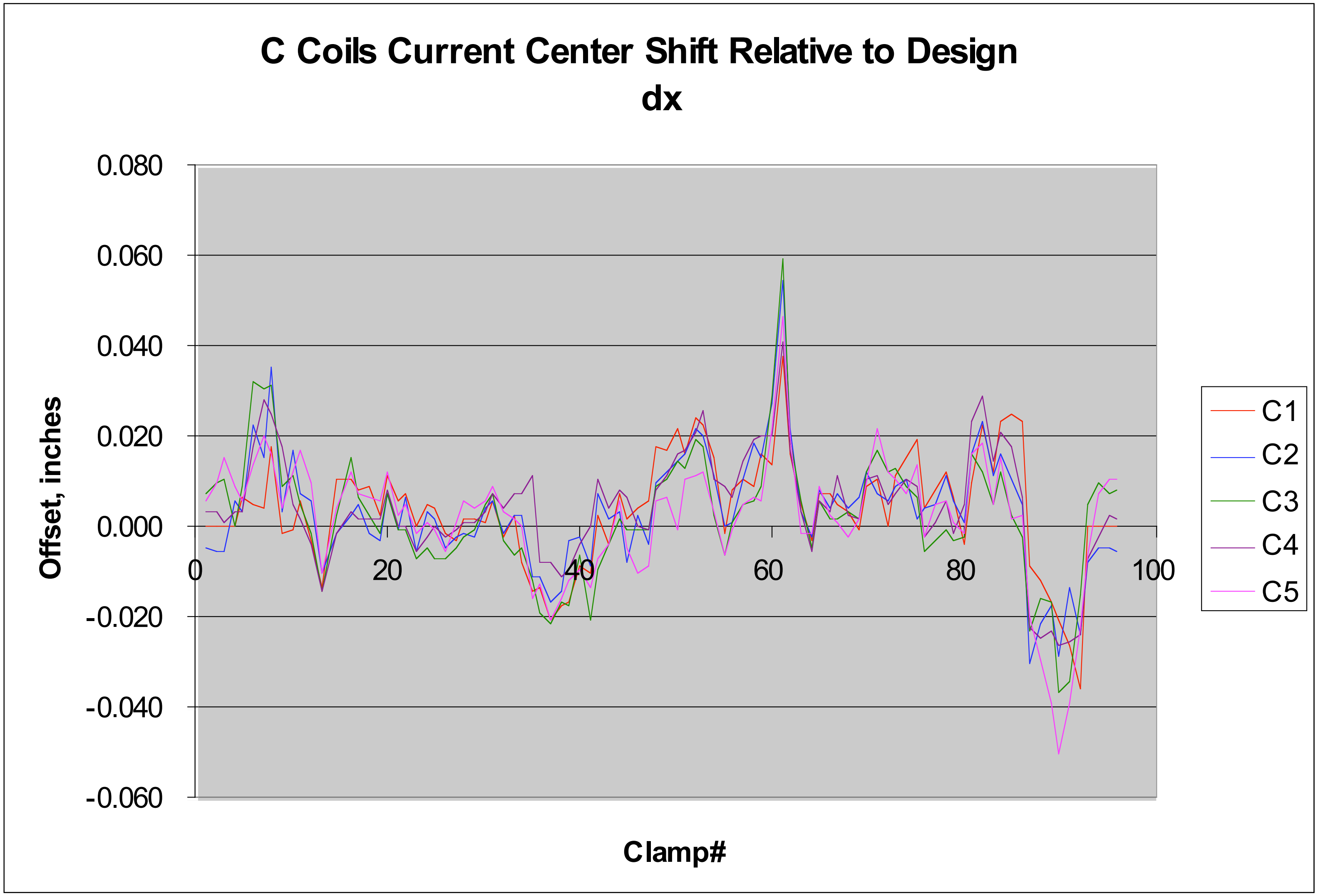
C

Modular Coil Winding Cross Section

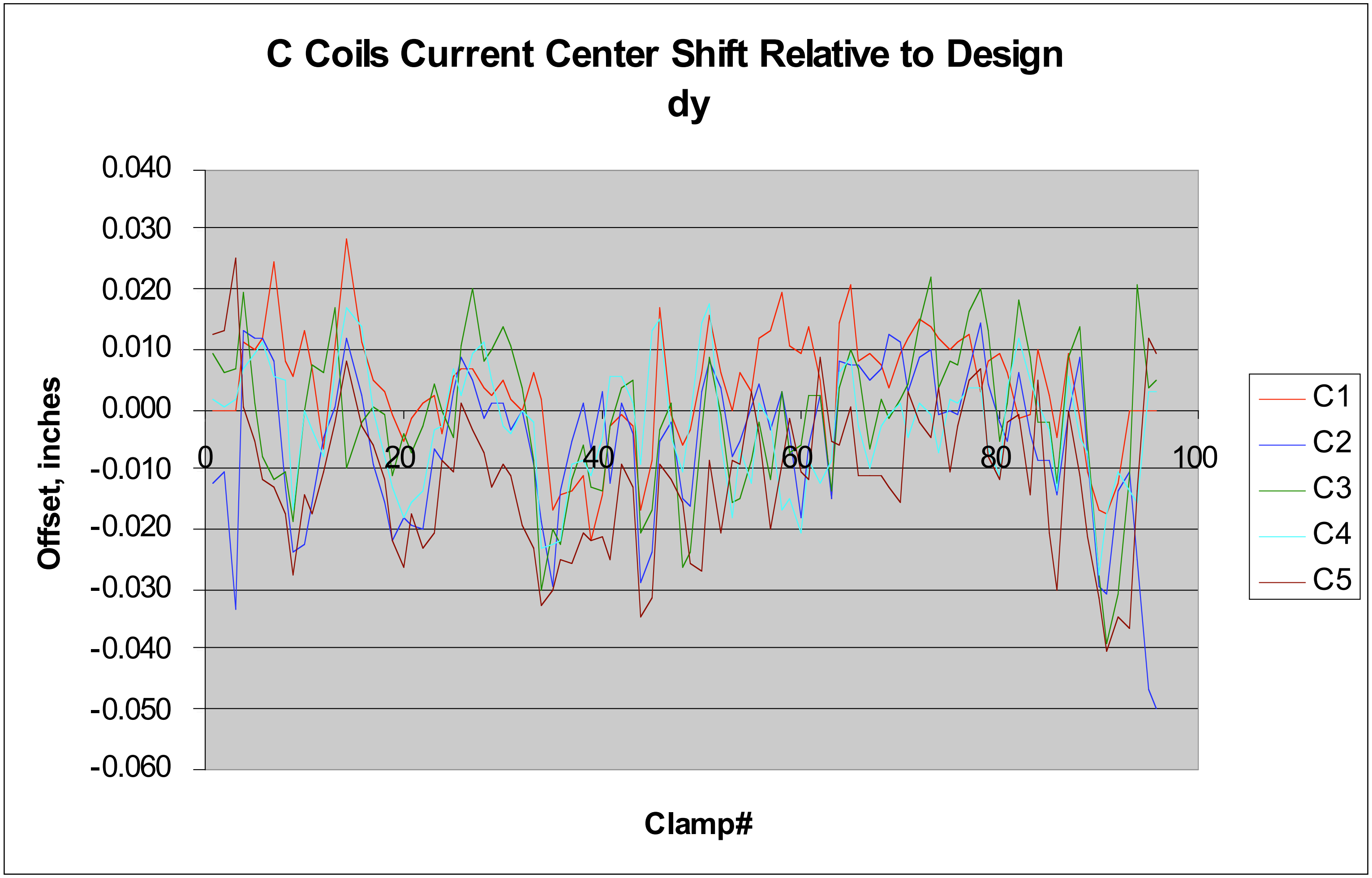


Current Center determined by averaging
Casting Measurements (prior to winding)
and Bundle Measurements (after winding) at each turn.

As-Built Coil Geometry
C1 thru C5 Lateral Current Center Shifts



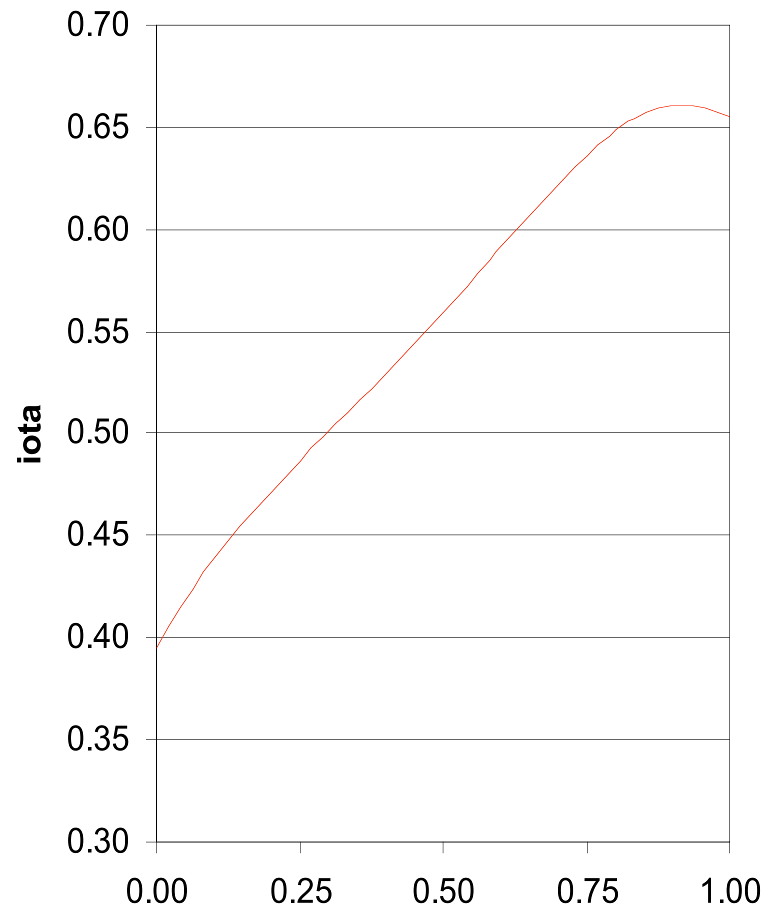
As-Built Coil Geometry
C1 thru C5 Radial Current Center Shifts



Field Errors from As-built Coils

- Differential coil files constructed by adding current center deviations to original coil files and subtracting original coils file (ie reversing current)

- Differential field added to VMEC field for reference plasma configuration (full current, full beta) within VACISLD code and normal (radial) field on resonant surfaces computed. Island size estimated from B_{mn}.



Island Width Evaluation used in VACISLD on VMEC equilibrium

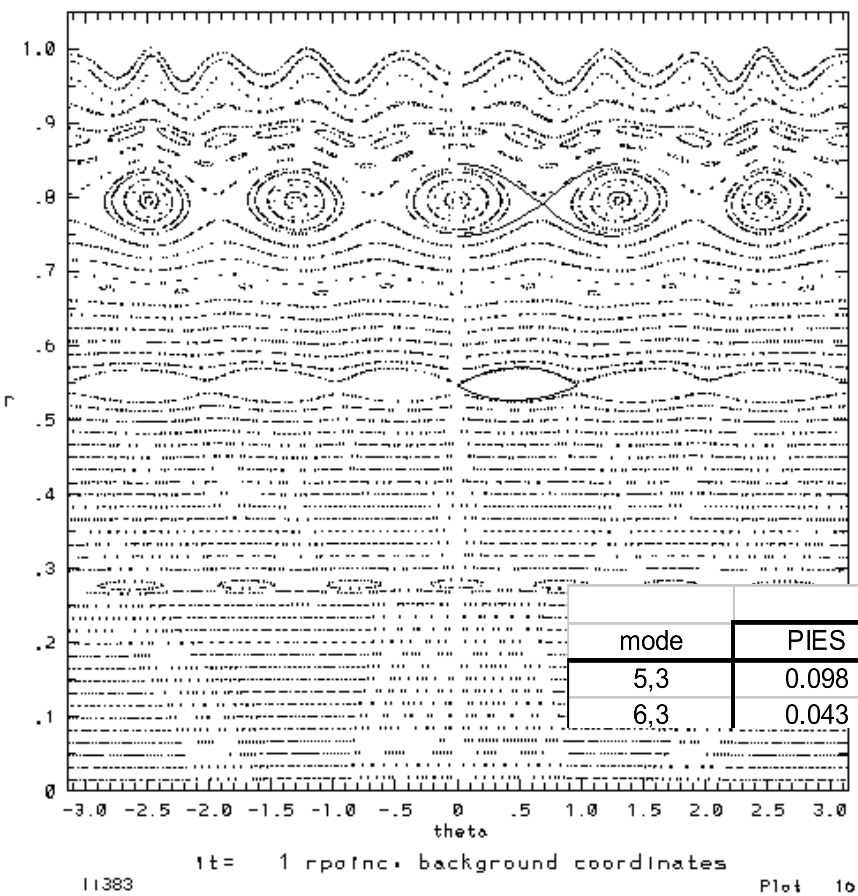
Using s, θ, ϕ as the magnetic coordinates, island width given by:

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

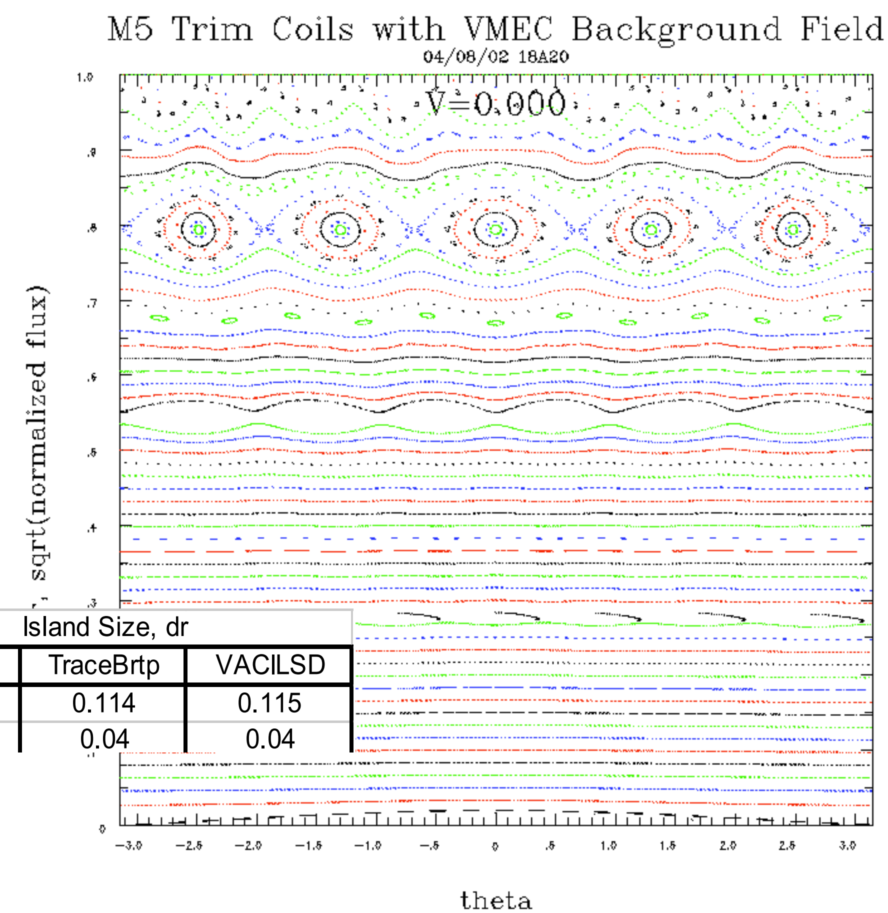
where $$C(s) \equiv \frac{B^s}{B^\phi} = \frac{B \bullet \nabla s}{B \bullet \nabla \phi}$$

- Note, island width only varies as square-root of resonant perturbation
- This analysis does not include self-consistent plasma response currents
- PIES can only calculate for periodic and ‘stellarator symmetric’ cases: not applicable to field error cases
- Improved codes under development using ‘perturbed equilibrium’ approach

Benchmark of Field Line Tracing of Perturbation Field* from Coils on VMEC Field



PIES

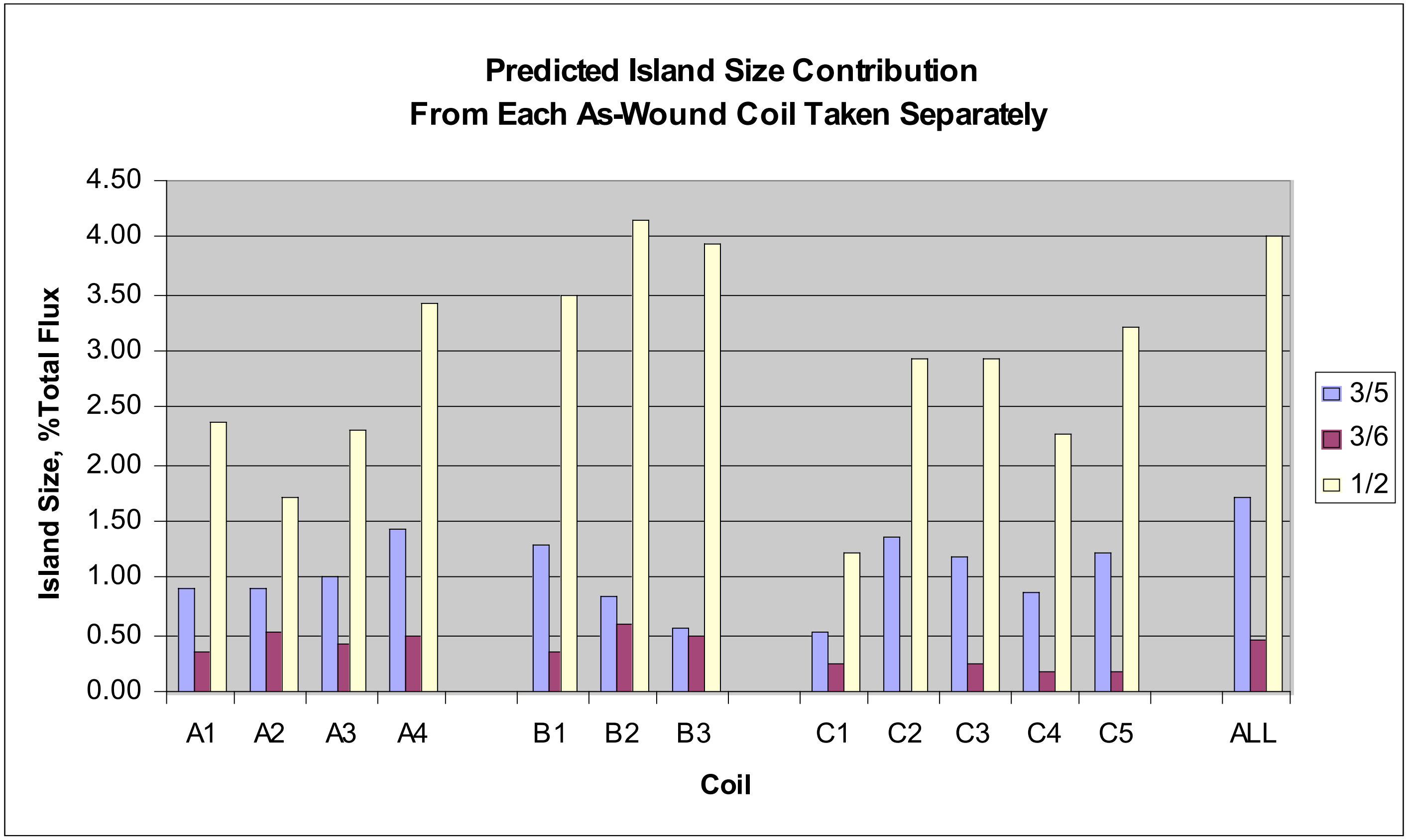


TraceBrtp

	Island Size, dr		
mode	PIES	TraceBrtp	VACILSD
5,3	0.098	0.114	0.115
6,3	0.043	0.04	0.04

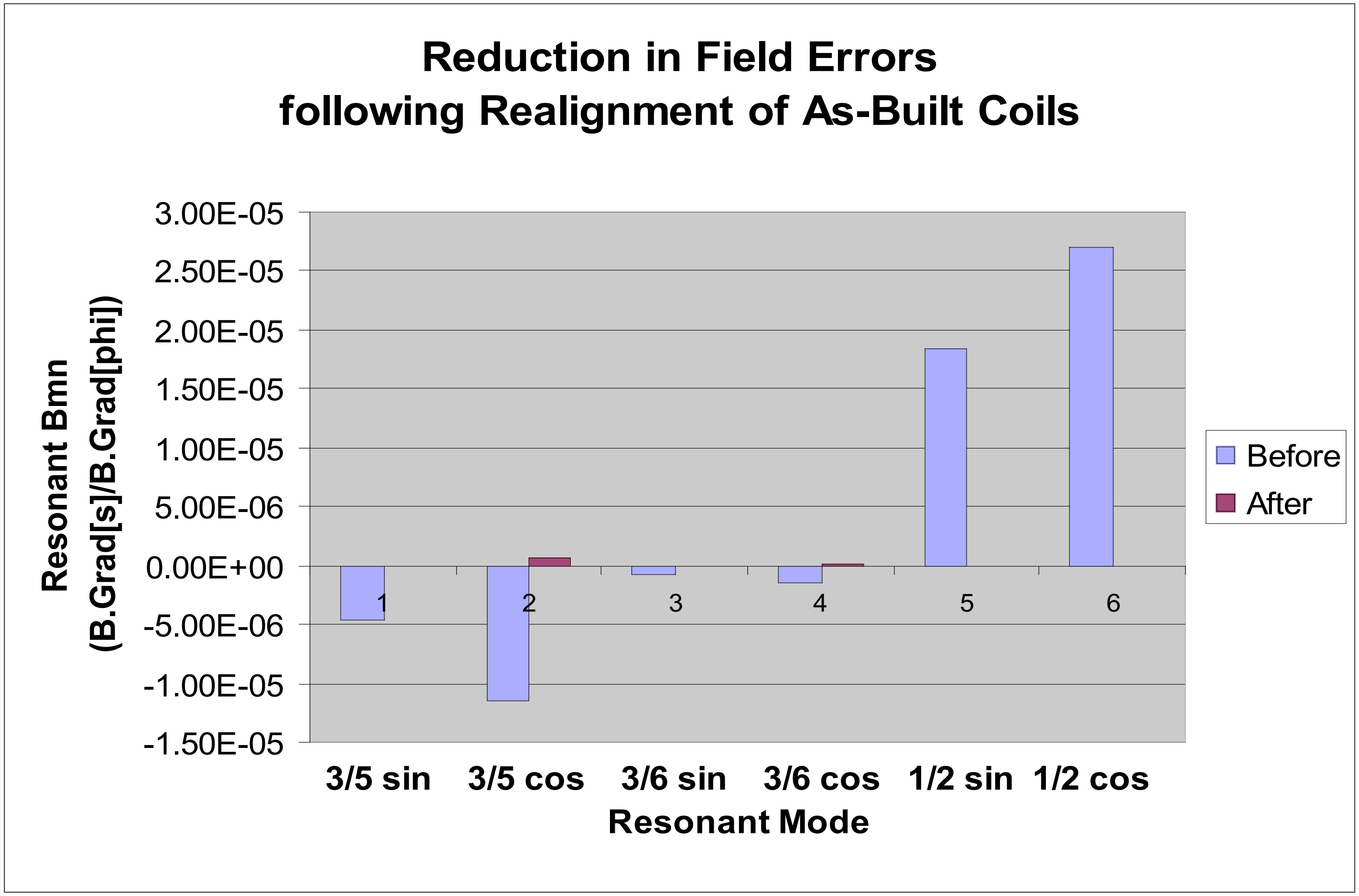
*From 1 KA M5 Trim Coils

Field Error from All Coils not much different than worst individual coil



- Winding Error Only – Assumes Coil Perfectly Positioned
- Incoherent field errors: lots of cancellation

Coil-construction low-order errors can be eliminated by Re-allignment



Required Realignment Movements
are Small

	Displacement, mm			Rotation, mrad		
	dx	dy	dz	rx	ry	rz
A1	0.34	0.09	-0.57	0.15	-0.08	0.07
A2	0.55	-0.27	0.20	0.30	0.10	0.23
A3	0.60	0.14	-0.55	-0.01	-0.04	0.18
A4	0.63	-0.18	0.60	0.05	0.38	0.42
B1	0.18	0.02	-0.22	-0.07	-0.03	0.05
B2	0.51	-0.11	-0.12	-0.08	-0.50	-0.15
B3	0.38	0.07	-0.07	0.15	0.16	0.11
C1	0.02	-0.01	-0.06	-0.08	-0.12	-0.04
C2	-0.05	-0.05	0.09	-0.02	-0.08	-0.03
C3	0.06	0.06	-0.01	-0.02	0.00	-0.06
C4	0.00	-0.13	0.03	0.04	-0.22	-0.01
C5	0.02	0.00	-0.09	-0.04	-0.11	-0.05

Comparable to coil winding tolerance of +/- 0.5 mm

Assembly errors: Expected internal islands within tolerance. However, Maximum size could be too big.

	Island Size, % Total Flux											
Mode	3/5	6/10	3/6	6/12	3/7	6/14	1/2	2/4	2/3	4/6	Phase Corrected	w/o 2/3&4/6
Average	2.24	0.34	0.8	0.1	0.27	0.02	6.26	1.84	5.44	2.66	15.04	8.86
StDev	0.63	0.1	0.22	0.03	0.08	0.01	1.74	0.51	1.51	0.74	2.44	1.77
Max	4.71	0.72	1.71	0.23	0.57	0.04	12.89	3.78	11.18	5.56	26.08	16.35
Min	0.04	0.01	0.03	0	0.01	0	0.28	0.04	0.21	0.05	6.79	3.46

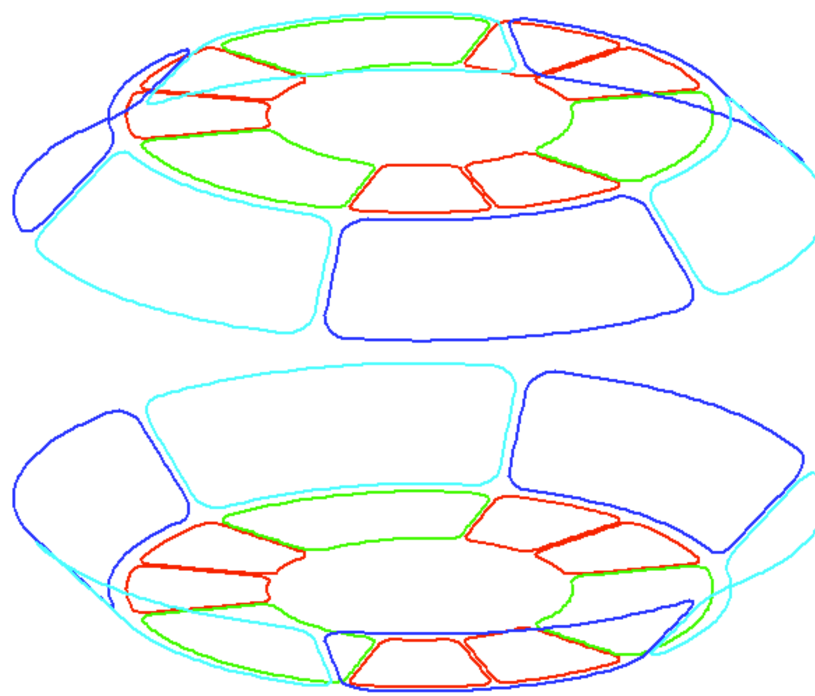
*2/3 and 4/6 are only near resonances. Resonant surface outside plasma.
Island Size based on assuming ι' = 0.34 as on 1/2 surface

- Assume nominal coil positions adjusted to compensate winding effects
- Based on +/- 1 mm Displacement and +/- 1 mrad Rotation Tolerance with Random Uniform Distribution
  - Statistics based on 1,000,000 random cases
- Coil Displacements from above Normalized to limit Tooling Ball Net Motion to +/- 1 mm
  - 98% of Random Uniform Distributions required normalization
- Only A1-A5, B1-B3, and C1-C5 wound to date. Surrogates (A5, B3 & C5) used for unwound coils.

- Island Size scales as square root of Tolerance
  - Doubling of Island Size occurs at 4 times the tolerance

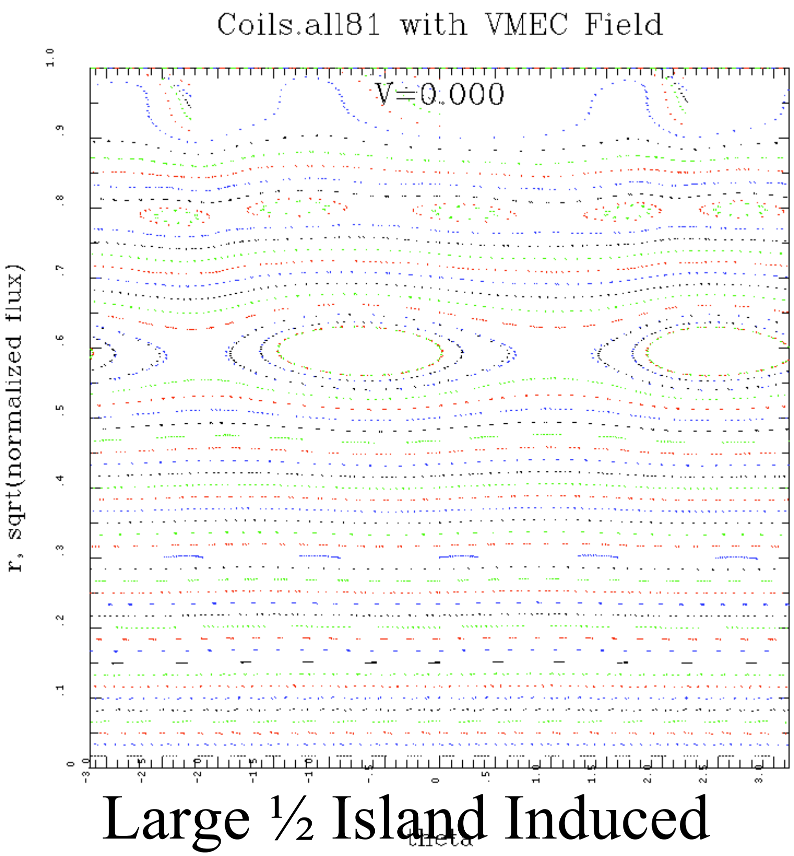
Trim Coil Current Array

- 30 External Trim Coils, mounted outside PF coils, at surface of cryostat
- designed for 80 KAT max current
  - 8 turns at 10 KA

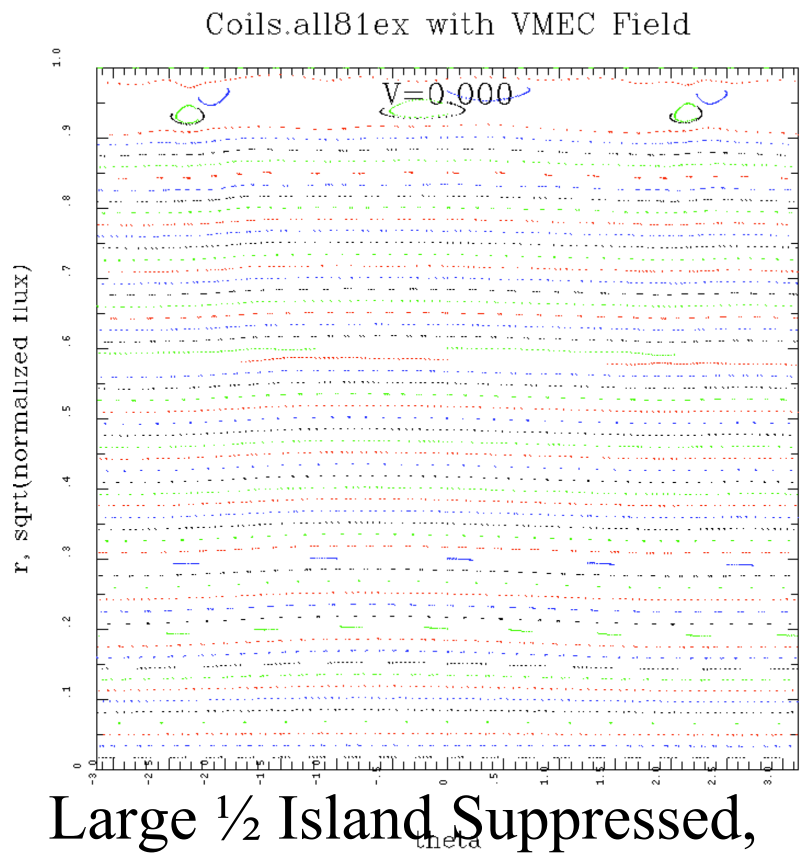


- Have also evaluated trim coils mounted on modular-coil shell
  - More effective, due to plasma proximity

Suppressing Worse Case Islands from Random distribution of Coil Tolerances



Large ½ Island Induced by coil tolerance



Large ½ Island Suppressed, Max trim coil current = 20 KA*

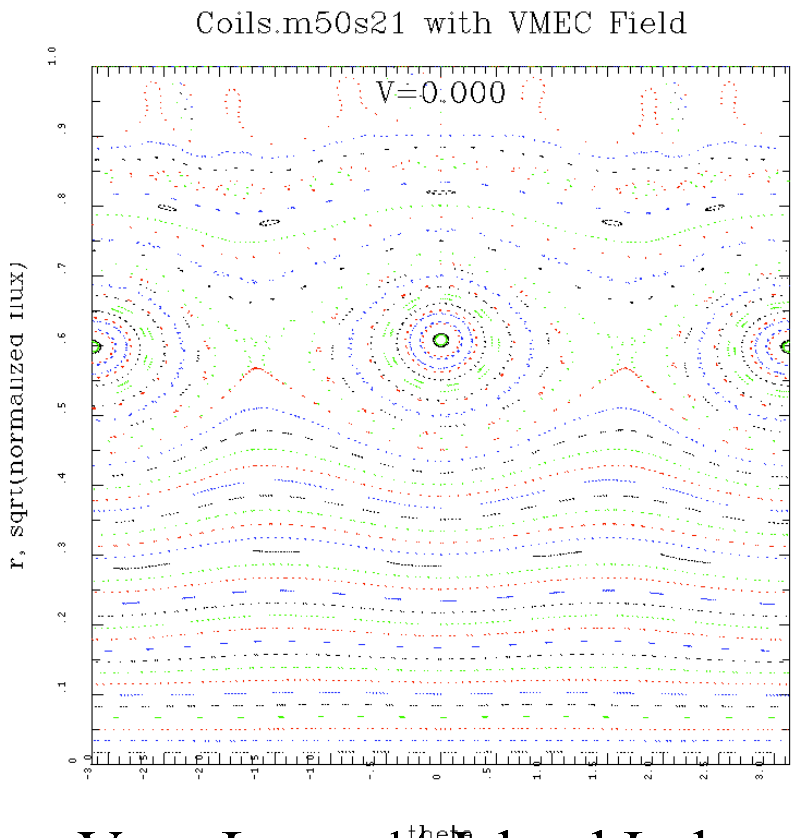
*Less Current Required if not targeting higher order modes

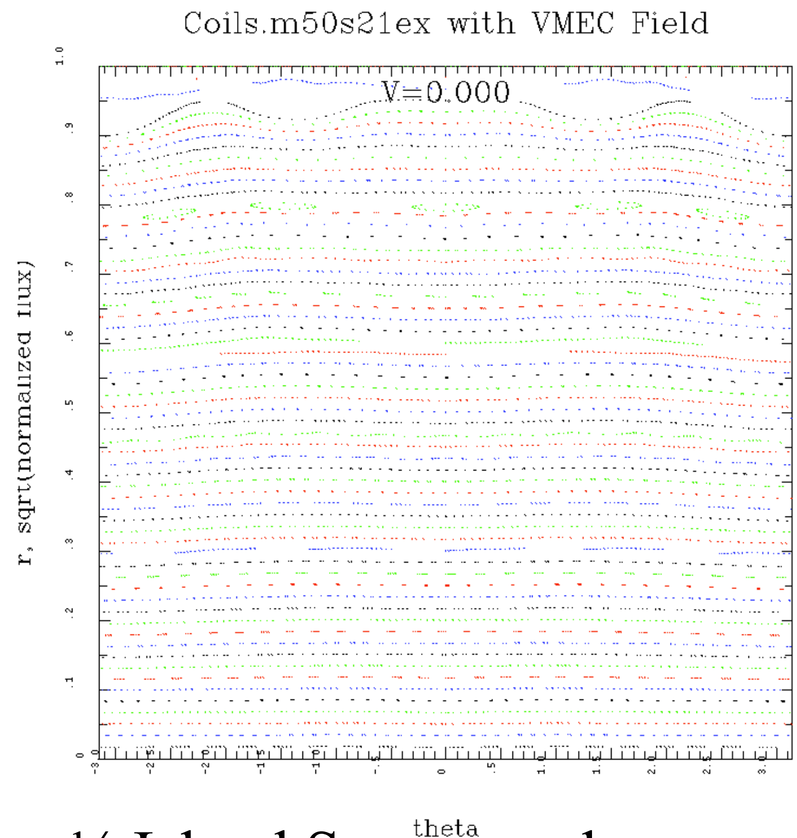
Looking for a Worse Case Systematic Coil Distortion

- If we wanted to deliberately produce a coil distortion with the worse possible impact, it would most probably be and a resonant helical perturbation similar to the perturbations used in coil healing. Excluding the $\iota=2/3$ zero shear surface, the $\iota=½$ surface should be the worse.

- Imposing a m=2, n=1 toroidal perturbation of maximum magnitude 1.5 mm, leads to induced islands of 33%

Suppressing Worse Case Islands from Systematic distribution of Coil Tolerances

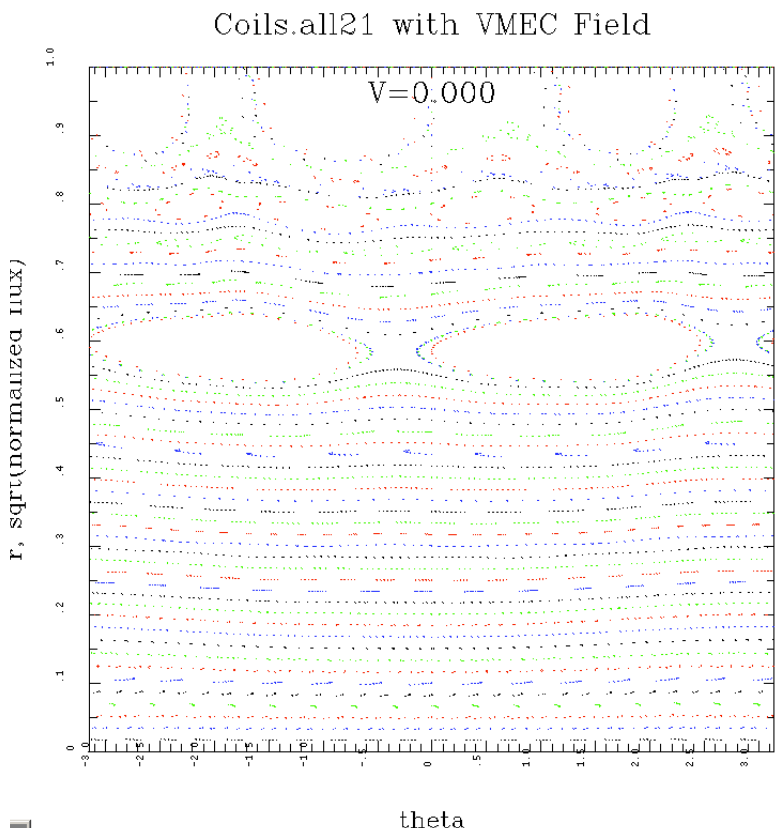


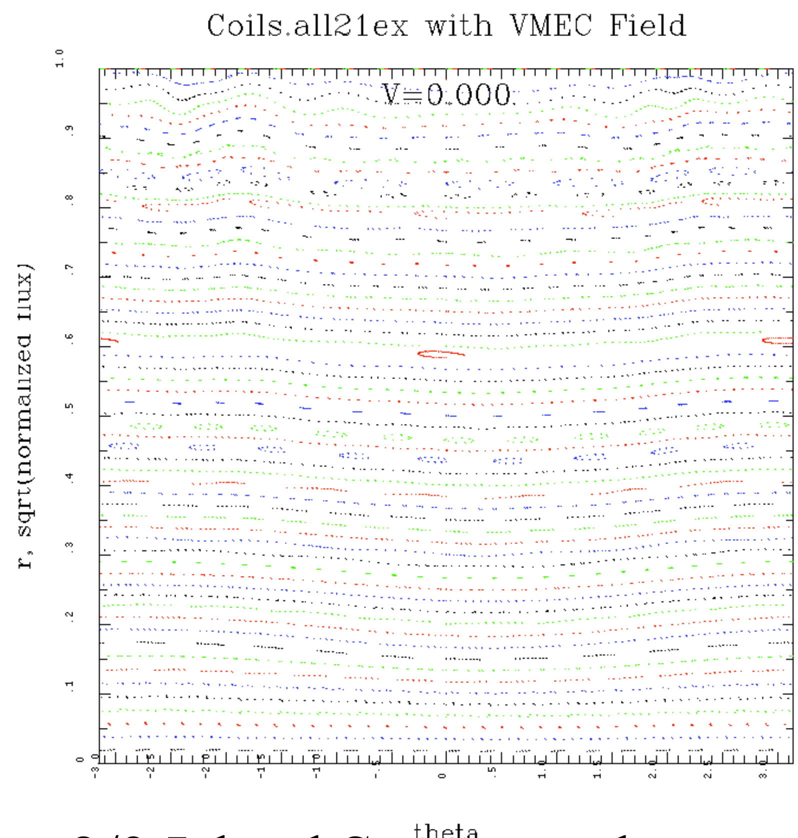


Very Large ½ Island Induced by coil tolerance

½ Island Suppressed, Max trim coil current = 30.5 KA

Suppressing Worse Case 2/3 with ½ Islands from Random distribution of Coil Tolerances





- Largest 2/3 Island Induced by coil tolerance

2/3 Island Suppressed, Max trim coil current = 63.2 KA

Low-n Islands of of most concern: start with trim coil subset to target them

	Island Size, % Total Flux											Phase	w/o
Mode	3/5	6/10	3/6	6/12	3/7	6/14	1/2	2/4	2/3	4/6		Corrected	2/3&4/6
Average	2.24	0.34	0.8	0.1	0.27	0.02	6.26	1.84	5.44	2.66		15.04	8.86
StDev	0.63	0.1	0.22	0.03	0.08	0.01	1.74	0.51	1.51	0.74		2.44	1.77
Max	4.71	0.72	1.71	0.23	0.57	0.04	12.89	3.78	11.18	5.56		26.08	16.35
Min	0.04	0.01	0.03	0	0.01	0	0.28	0.04	0.21	0.05		6.79	3.46

*2/3 and 4/6 are only near resonances. Resonant surface outside plasma.
Island Size based on assuming ι' = 0.34 as on 1/2 surface

Plan:

- Build in trim coils for n=1, 2 (and maybe n=3) compensation, mounted on modular coil shell, to control possible maximum errors.

- Measure errors, using e-beam mapping and mutual-inductance (coils and sensors) mapping methods
- Add all or subset of outer time coil set, if needed

Expect flux surface quality to be within requirements. Simple trim coils will guarantee. More sophisticated trim coils can be added.