Trim Coils for Field Error Compensation

Presented by Art Brooks

for the NCSX Team at
Princeton Plasma Physics Laboratory
Oak Ridge National Laboratory

NCSX Construction Feasibility Review

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Overview

- Requirements
- Concept Design
- Supporting Analysis
- Capabilities for Mitigating Risks due to Construction Inaccuracies

Requirements

General Requirements Document

3.2.1.5.1 Field Error Requirements

a. Field error correction (trim) coils shall be provided to compensate for fabrication errors.

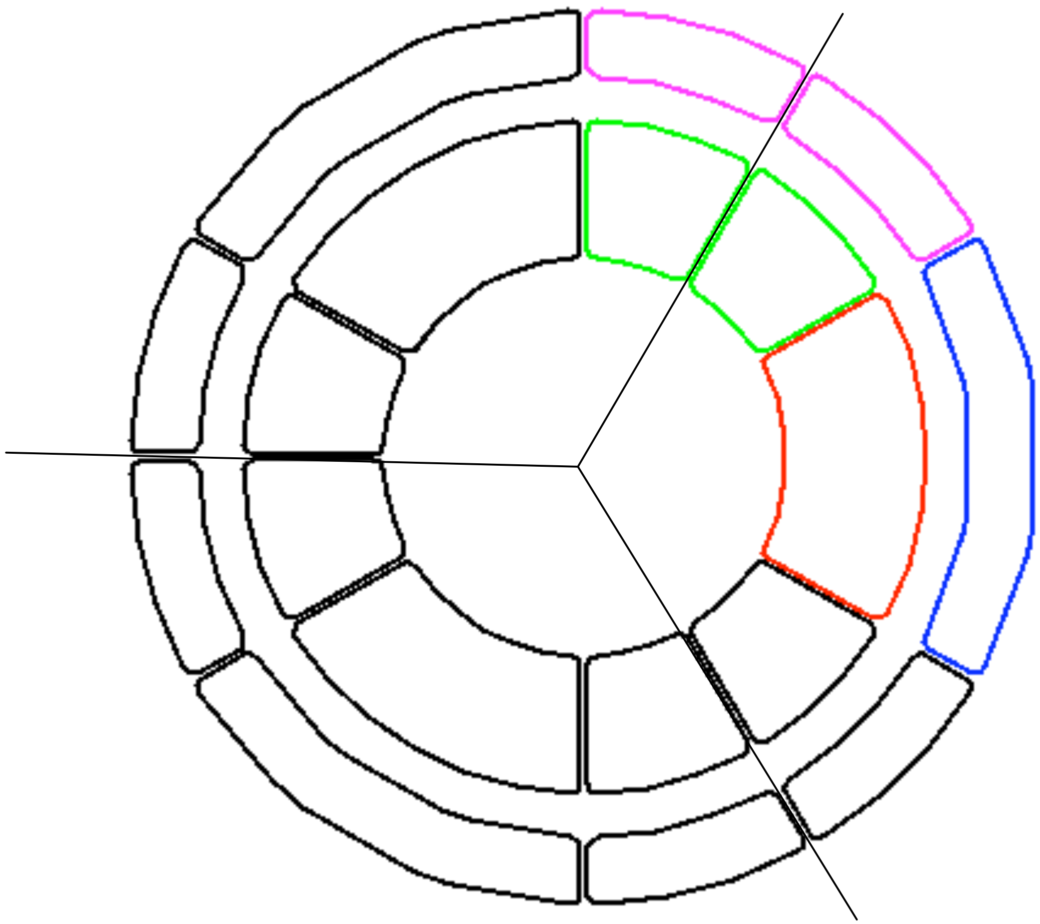
b. The toroidal flux in island regions due to fabrication errors, magnetic materials, and eddy currents shall not exceed 10% of the total toroidal flux in the plasma (including compensation).

To minimize islands, minimize resonant field perturbations.

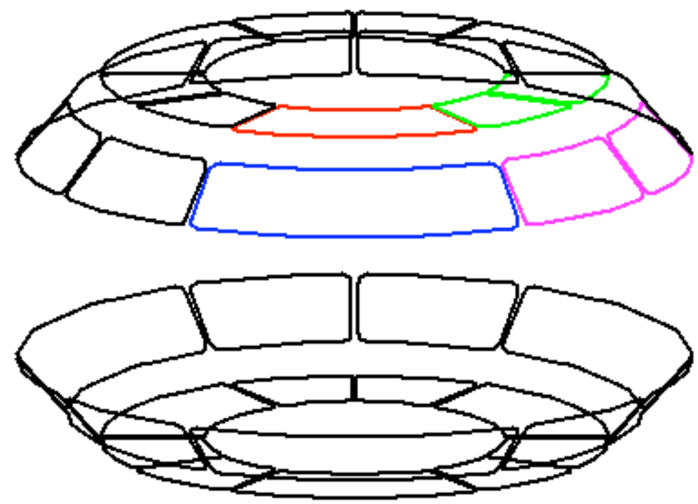
Sources of Field Errors

- Coil Overall Construction Tolerance
  - Modular Coils: +/-1.5 mm on Location of Current Center
  - TF & PF Coils: +/- 3.0 mm
- Coil Deflections
  - Gravity, Thermal and EM loads
- Other Known Sources
  - Coil Leads and Turn Transitions
  - Ferromagnetic Materials
    - Building Steel Largest Component
  - Eddy Currents
    - Initially large but decay with time constant (tau) ~0.027 ms
    - Field Errors evaluated at time 2*tau
- Other Concerns
  - Potential Weld Distortion

Concept Design – Trim Coil Configuration

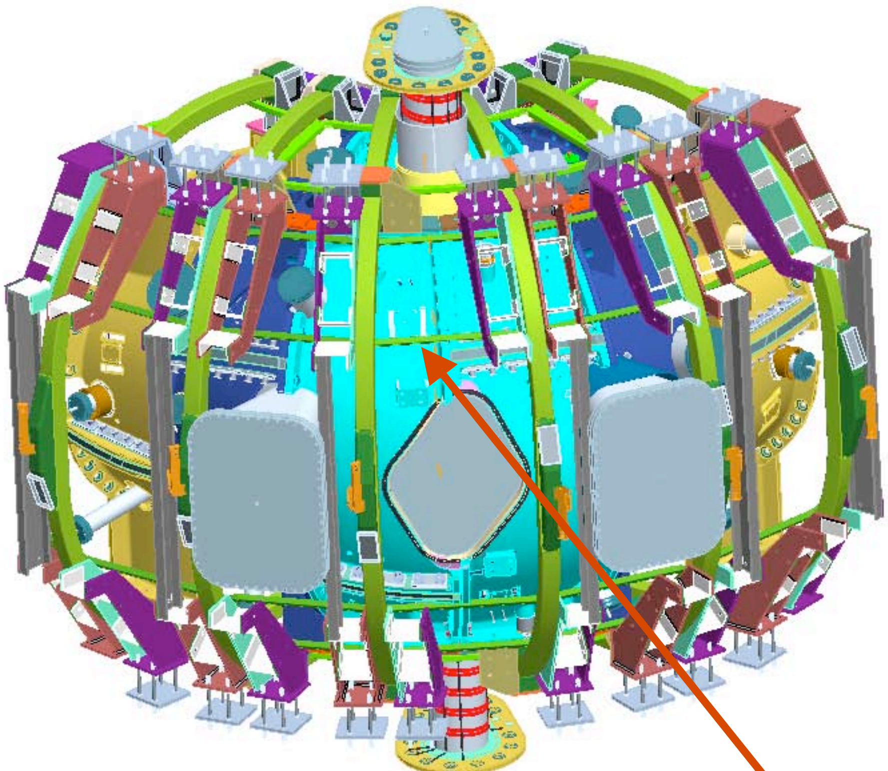


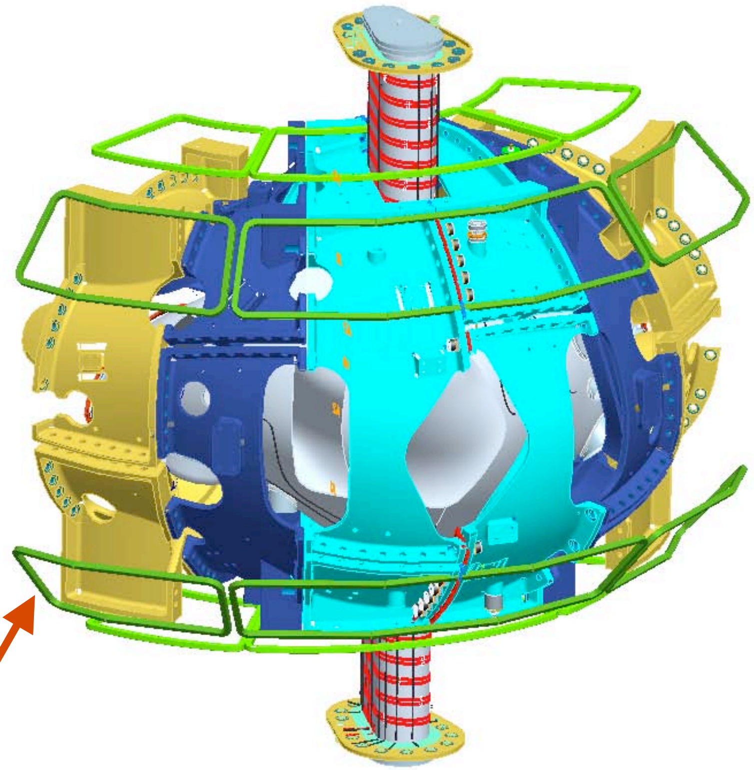
36 Total Coils
Grouped into 24 circuits
Coils Spanning Period Boundary Split for Assembly



Stellarator Symmetry Maintained in Coil Geometry
but Coils can be Driven Asymmetrically

Trim Coils are Located Between MCWF and TF

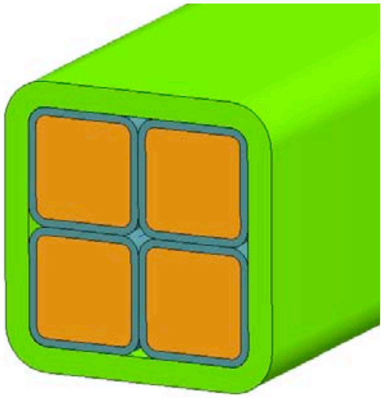




Trim Coils

Key Trim Coil Features

- Located Between MCWF and TF Coils
  - Supported off of MCWF
- 4 Coil Types
- Each Coil has 4 Turns of ½" x ½" Copper Conductor
  - Cooled by natural convection to cryostat 80 K atmosphere
- Design Current of 5 kA per turn (20 kA-T)
  - Limited by C-Site Power Supplies
  - Ample margin in coils for higher currents if desired downstream
    - Heating < 2 K per pulse, Ratcheting to Steady State ~ 6 K at 15 min rep rate
    - Forces ~ 75 lb/in max



Analysis Approach

- Field Errors are from sources that are either
  - known and can be calculated explicitly

  or

  - unknown but bounded as in the case of the coil assembly within specified tolerances

- Coil Assembly field errors analyzed by examining field errors from large set of randomly assembled coils

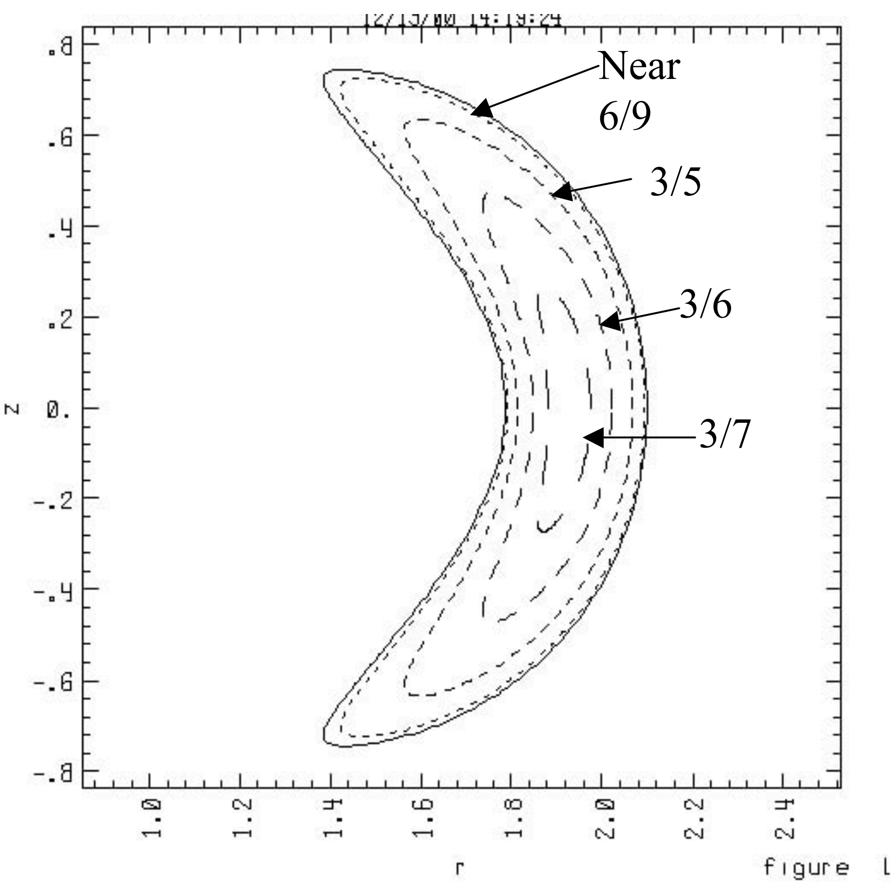
- Resonant Field Error Spectrums from known sources are pre-calculated and included as a background field error in random studies

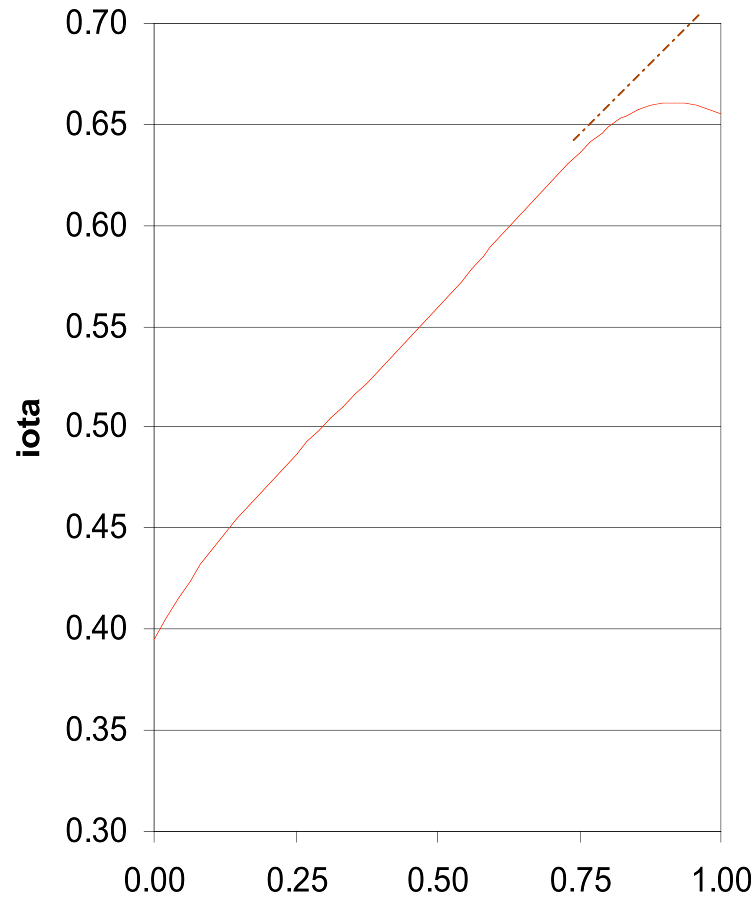
Resonant Field Error Calculation

NCSX National Compact Stellarator Experiment

- Field perturbations are superposed on an island-free (VMEC) plasma equilibrium.
  - Perturbed field = VMEC field + perturbation field.
  - This is an approximation (plasma response neglected).
- An analytic predictor (VACISLD) was developed to evaluate resonant field errors and island width.
- A field line tracing routine (TraceBrtp) was developed to examine visually effects of both symmetric and symmetry-breaking field errors

Targeted Resonances in Reference Plasma





Island Width Evaluation used in VACISLD using VMEC data

NCSX National Compact Stellarator Experiment

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

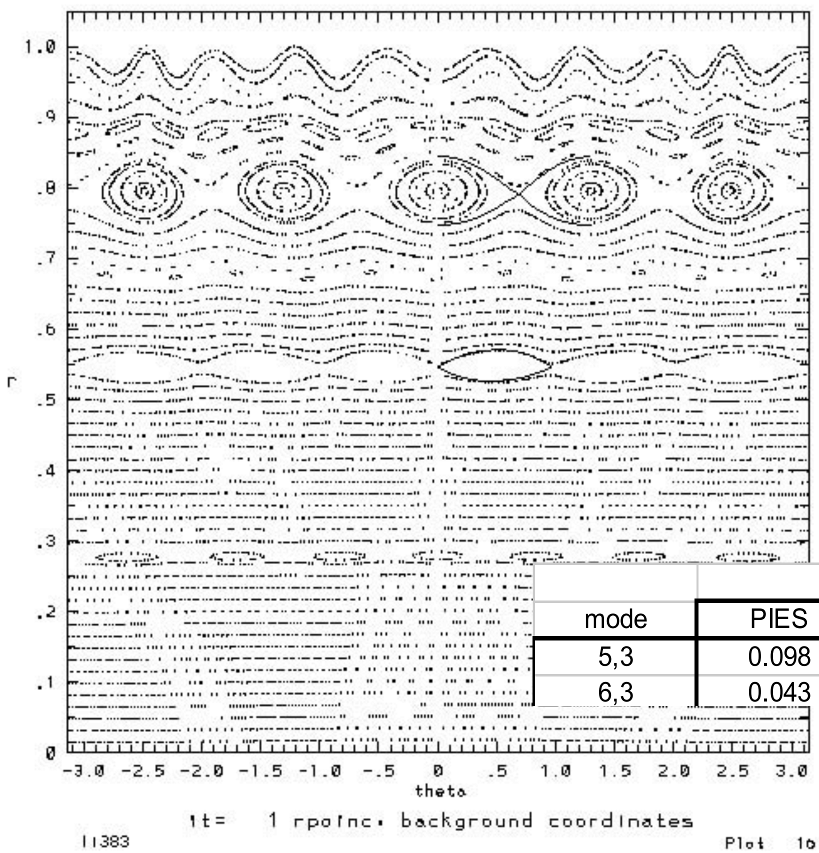
$$B^\phi = \frac{1}{J_{s,\theta,\phi}} \frac{d\Psi}{ds}$$

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

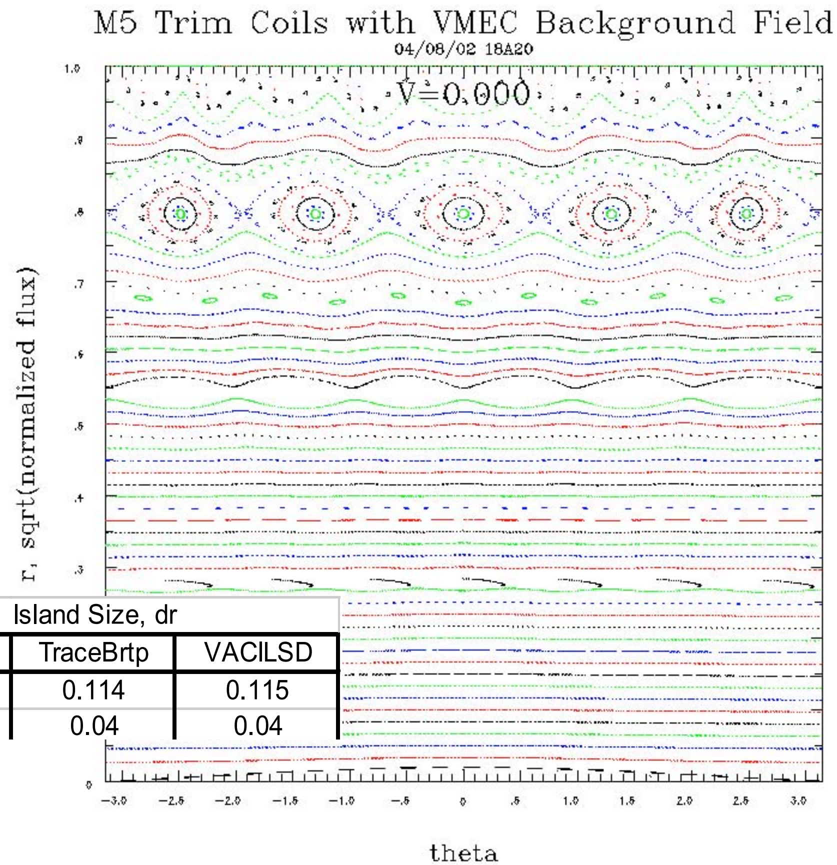
leaving an expression which does not require explicit evaluation of the Jacobian and linear in B (and therefore coil currents)

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

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

Verification of Addition of Perturbation Field On VMEC Field. Not Full Pies Run

Results from Earlier Studies With Trim Coils Outside TF

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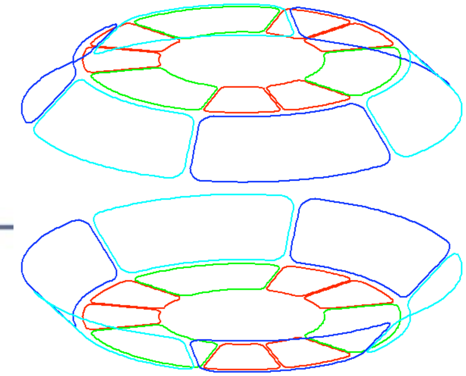
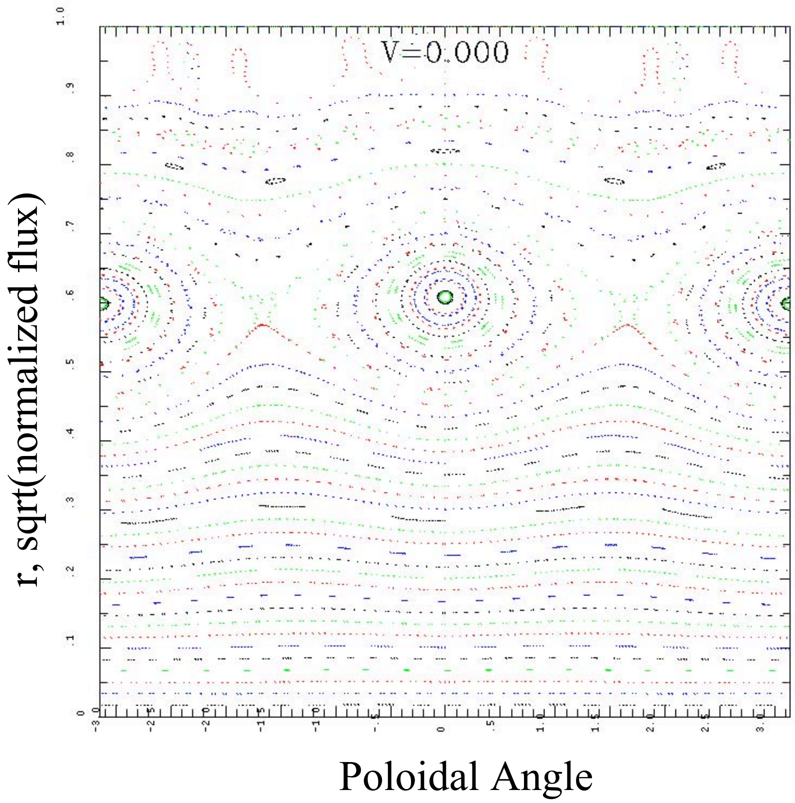
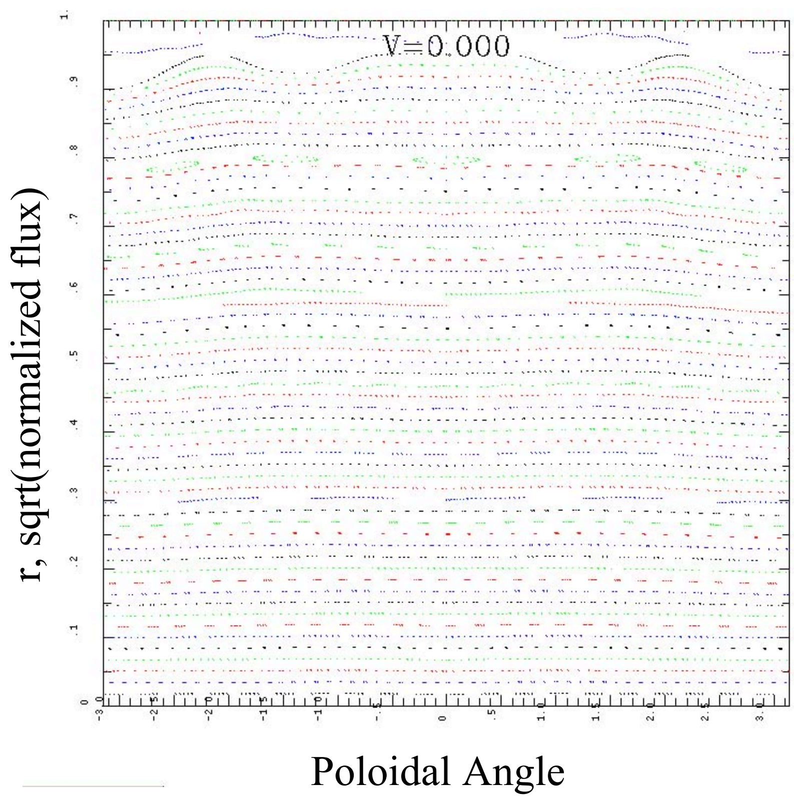
National Compact Stellarator Experiment







Very Large iota=½ Island Induced by coil tolerance

Iota=½ Island Suppressed, Max trim coil current = 30.5 kA-T

Simulating Coil Assembly Field Errors

- Before Correction:
  - Resonant Field Errors Calculated with VACISLD Code for Unit Displacements in 6 degrees of freedom (dof) for each Coil
  - Random perturbations of each dof imposed to Coil Location. Net Coil perturbation normalized to keep reference monuments within specified tolerance.
    - > 95% of cases have one point in coil at tolerance limit
  - Field Errors shown to vary linearly over range of tolerances considered allowing for quick evaluation of Total Resonant Field Errors for many cases (100,000) with simple matrix multiplication

- With Trim Coil Correction
  - Resonant Field Errors Calculated with VACISLD Code for Unit Currents in each Coil or Coil Group
  - Singular Value Decomposition (SVD) analysis done to solve for required currents to suppress all or a subset of the resonant field errors from coil displacements
    - Targeted resonances in general fully suppressed
    - Resonances Not Targeted generally weakly excited
  - Analysis done for all random perturbations of coil assembly

- Other Known Field Errors Sources are added to the Random Assembly Field Errors

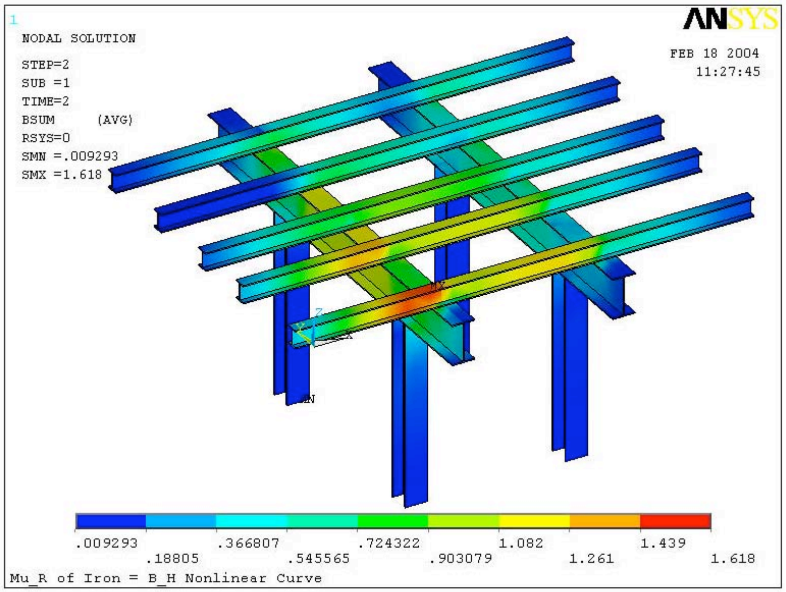
Trim Coils Meet Design Objective with Margin to Spare

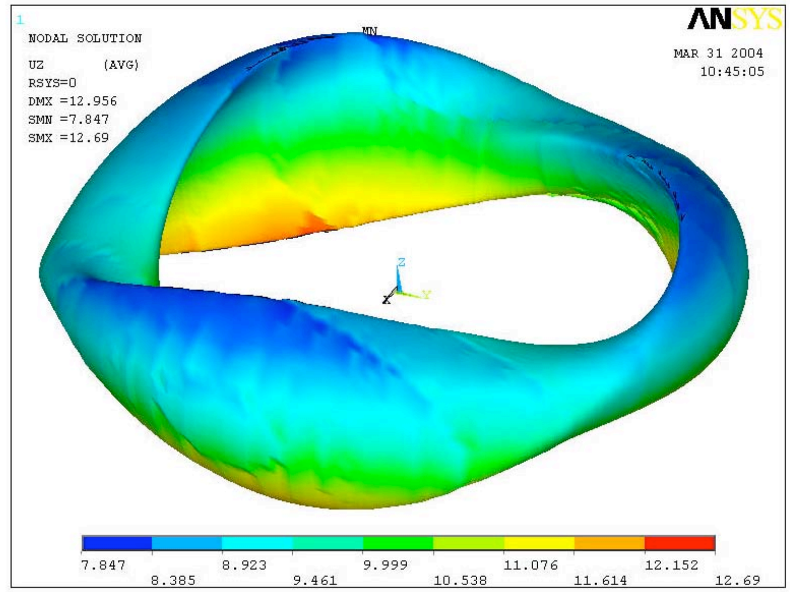
	Uncorrected		Corrected			
	Island Size	%Total Flux	95% All Cases		100% All Cases	
Field Error Source	95% All Cases	100% All Cases	Island Size %Total Flux	Trim Coil Current Max, KAT	Island Size %Total Flux	Trim Coil Current Max*, KAT
Coil Assembly Tolerance Only	21.56	28.65	1.98	9.77	2.01	16.08
(Mod+/- 1.5mm, TF&PF +/-3 mm)						
Coil Assemble + Other Known Sources	22.76	28.96	2.95	19.49	2.95	27.47
			4.42	8.34	4.49	13.81
Module Coil Leads						
Residual Field Errors from As-Built Modular Coils (ie after realignment)						
EM Deflections						
Building Steel (with PF6 Correction)						
MCWF Eddy Currents						
Coil Assemble + Other Known Sources +	23.39	29.76	2.90	25.02		
Same as above but			9.67	8.89		
with additional 1 mm Wing Distortion						
(example of extra distortion)						

Design Point
< 10% Islands
< 20 kA-T

100% Margin on
Trim Coil Current
and Field Errors

Remote Field Magnetizes Building Steel which in turn produces Error Field at Plasma



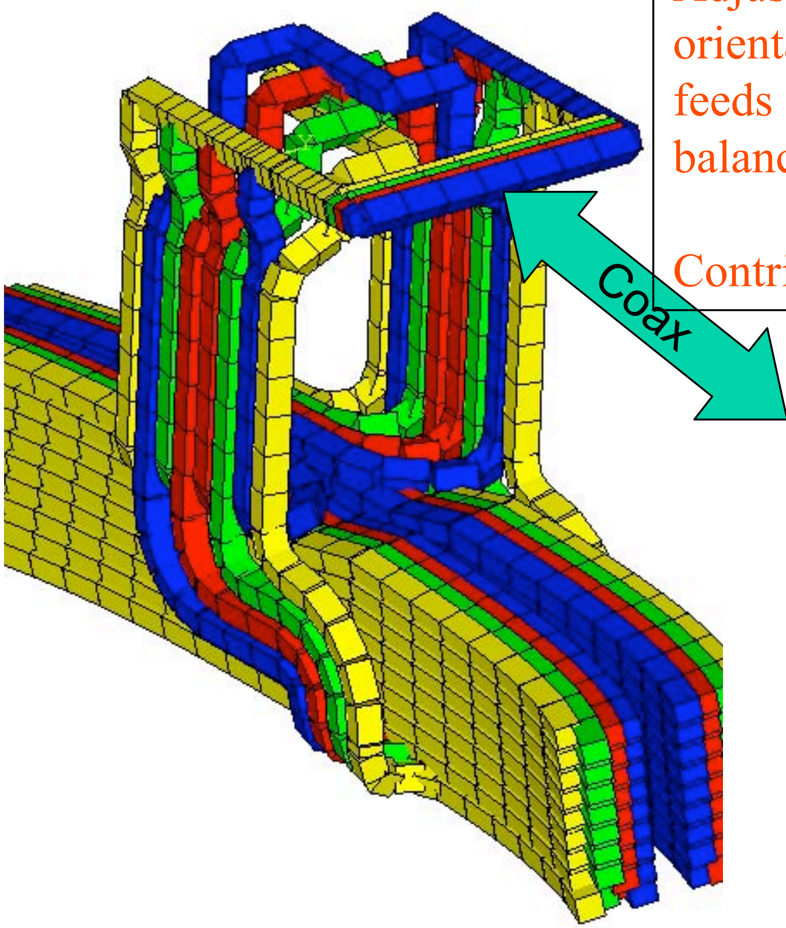


Field at Plasma ~ 10 Gauss, primarily vertical. If uncorrected, produces islands totaling ~5% of plasma flux. 2.5 kA-T in PF6 used to compensate. Balance handled by trim coils.

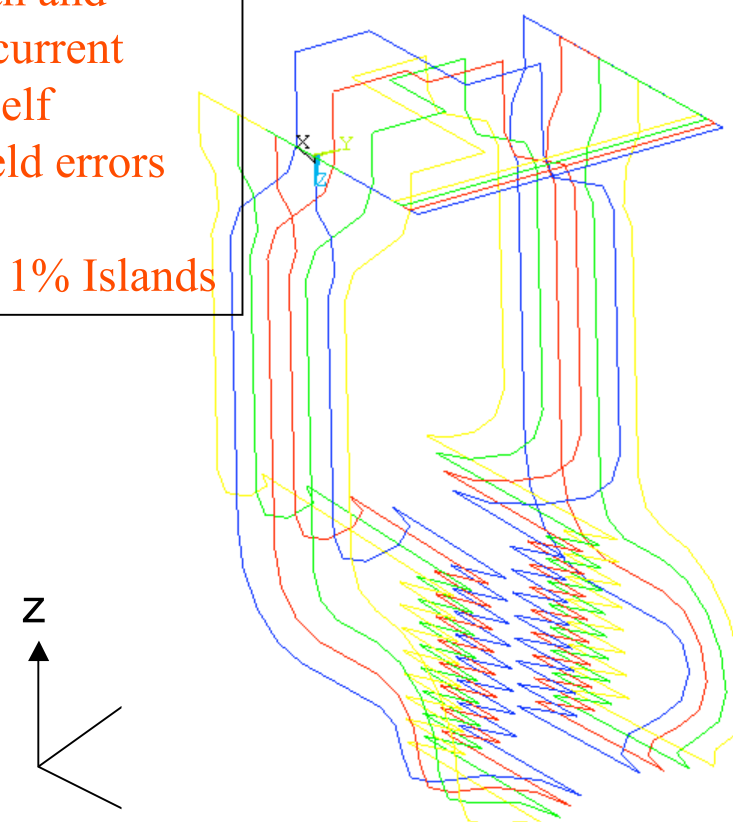
Modular Coil Leads and Feeds Arranged to Minimized Field Errors

Adjusting length and orientation of current feeds allowed self balancing of field errors

Contributes << 1% Islands



Detailed Model



Equivalent Current Loops For Field Error Calculations

Summary

- Field error requirements, including tight tolerances, are driven by the sensitivity of magnetic surfaces to resonant magnetic perturbations. Islands result.

- Larger errors can be accepted under many conditions as long as fundamental requirement (island width <10%) is satisfied.

- Efficient tools have been developed to evaluate resonant field errors and island widths due to field errors.

- Trim coils can compensate for construction errors, with **100% Margin** to mitigate field-error risks.