

NCSX Trim Coils for Field Error Correction

Requirements, Methods, Configuration and Performance

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Basic Requirement Comes from GRD



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 (τ) ~ 0.027 ms
 - Field Errors evaluated at time 2τ
- Other Concerns
 - Potential Weld Distortion

Need Design Margin to Account for Possible Failure to Meet Tolerance

Additional Design Constraints Imposed



- Minimize Trim Coil Currents (ampere-turns)
 - Minimizes size (cross-section) and cost of trim coils
 - Minimizes potential impact of non-resonant field errors
 - Minimizes forces on dumped into MCWF and minimizes cost of support structure
- Reduce total number of trim coils and number of types of trim coils
 - Minimizes costs
- Keep Trim Coil Geometry Stellarator Symmetric
 - But provide capability to power each independently
 - Provides flexibility for physics
- Configuration must fit within existing structures
 - Preferred Location between MCWF and TF, close to Plasma

Performance Evaluation Methods



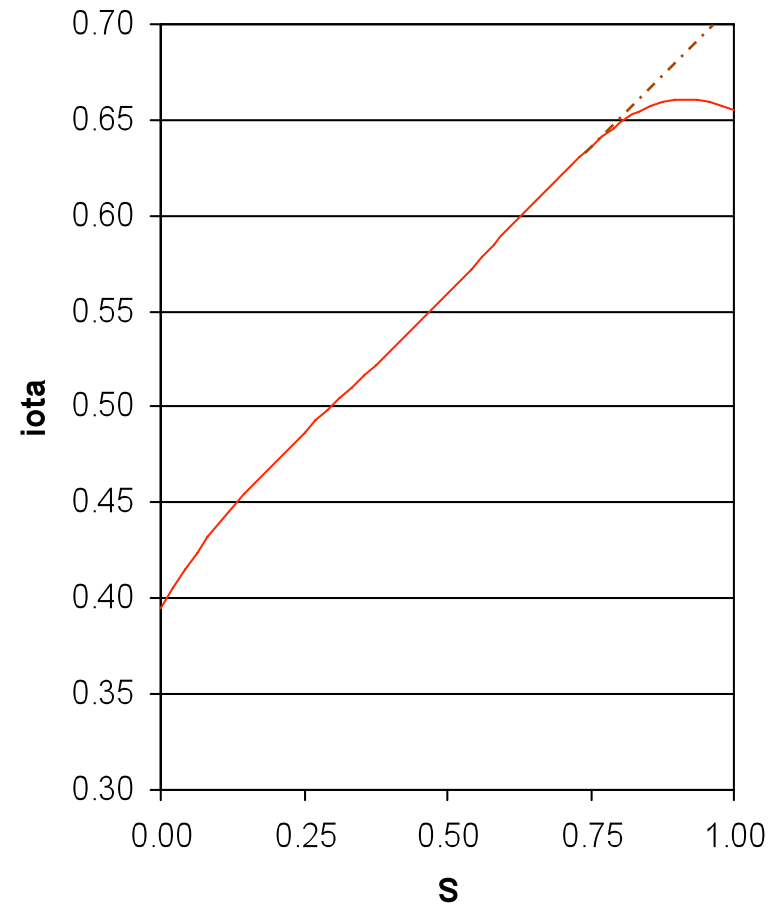
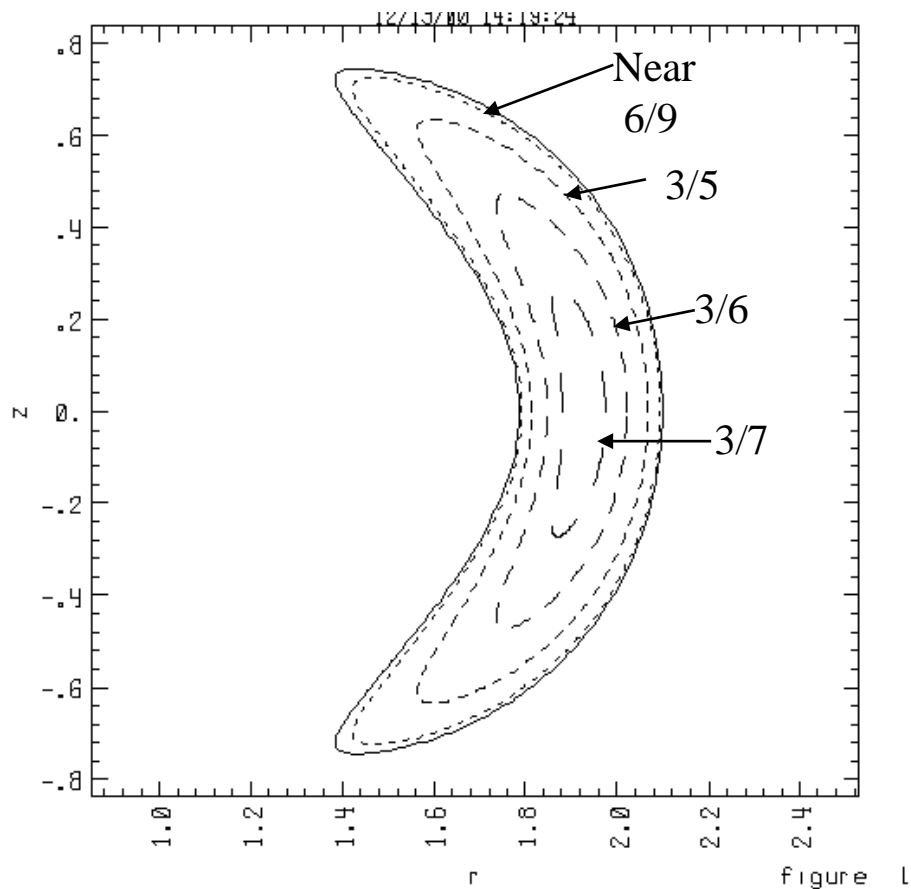
- Field Errors are from sources that are either
 - known and can be calculated explicitlyor
 - unknown but bounded as in the case of the coil assembly within specified tolerances
- Coil Assembly field errors analyzed by examining field errors from large set of randomly assembled coils
- Resonant Field Error Spectrums from known sources are pre-calculated and included as a background field error in random studies

Resonant Field Error Calculation



- 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



AWB100608

Simulating Coil Assembly Field Errors

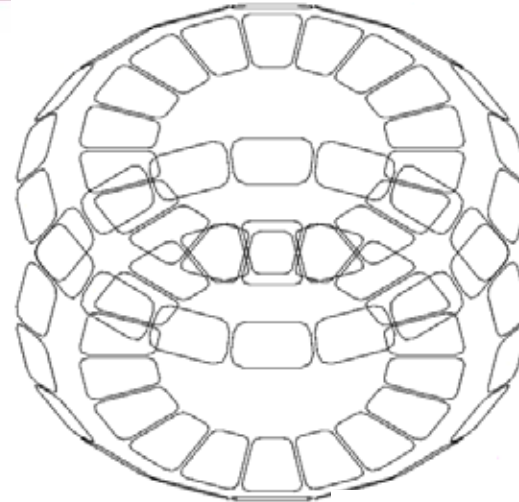
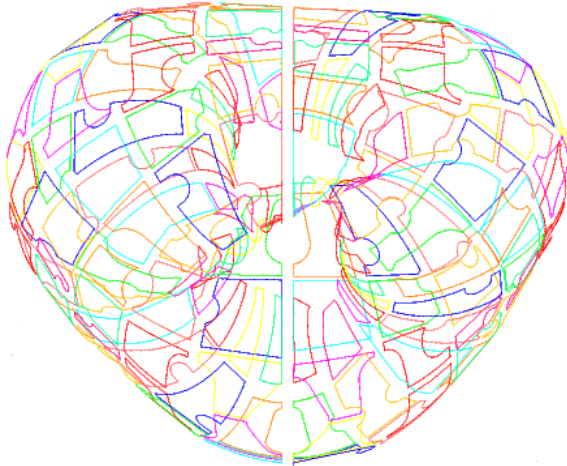


- Before Correction:
 - Resonant Field Errors Calculated with VACISLD Code for Unit Displacements in 6 degrees of freedom (dof) for each Coil
 - Random perturbations of each dof imposed to Coil Location. Net Coil perturbation normalized to keep reference monuments within specified tolerance.
 - > 95% 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
 - Non Linear Programming (NLP) Optimization used to further improve performance
 - Analysis done for all random perturbations of coil assembly
- Other Known Field Errors Sources are added to the Random Assembly Field Errors

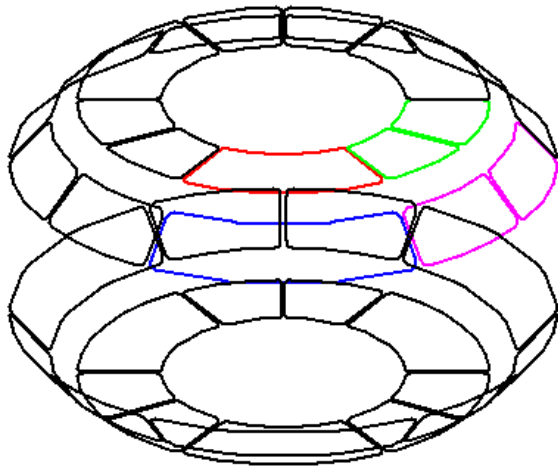
Trim Coil Configuration Evolution



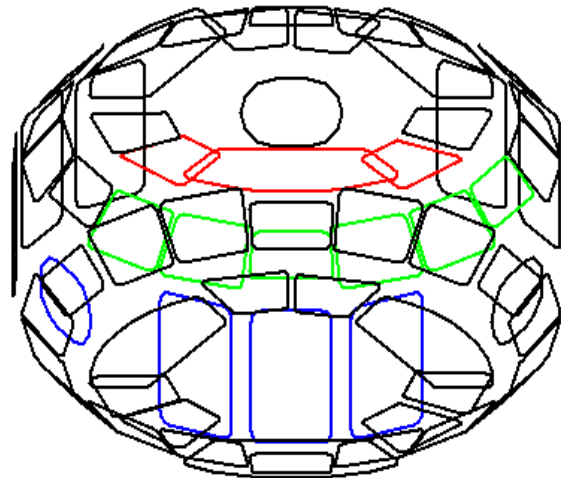
Candidate
MCWF
Array Not
Realizable



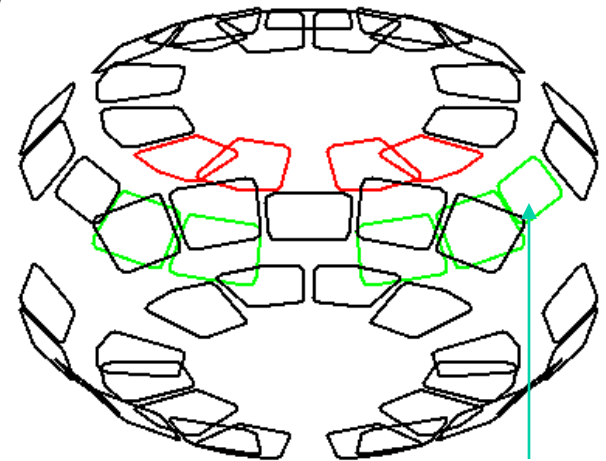
72 Coils Between
MCWF & TF



Original 36 coil, 24 circuit



Modified 54 coil (66
with Midplane)



Final 48 Coil Configuration
Eliminated Coil at CC
Leaving 2 Coil Types

Exploring Subsets of 72 Coils

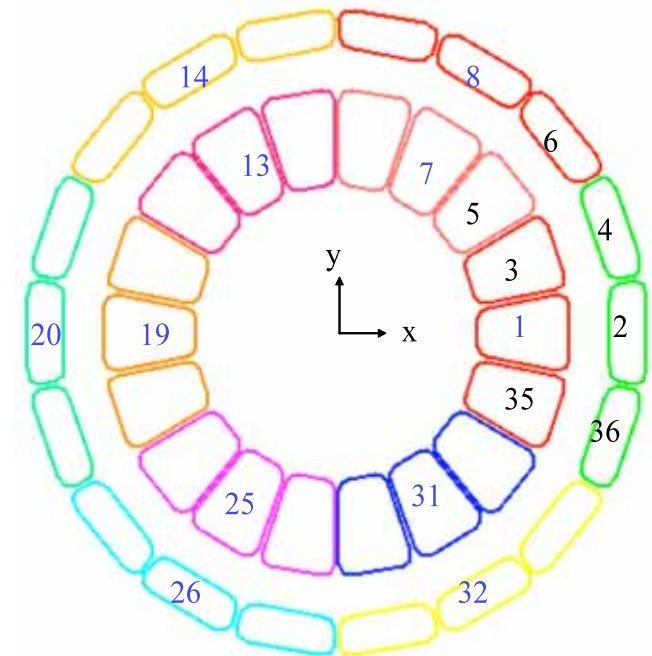


Results of Random Assembly of Modular Coils with Trim Coil Correction
(TF and PF at 3.0 mm assembly tolerance found to have negligible impact on these results)

Tom's 72 Coil Set Between Located MCWF & TF			1.5 mm Tolerance	
#Coil Sets	#Coils	Coil Subset	Total Islands, %Flux	Max Current, KAT
2	12	7_11	2.02	79.62
3	18	1_2_8	2.34	42.71
4	24	1_2_7_8	1.90	29.48
5	30	1_2_7_9_12	1.82	25.83
12	72	All	1.80	14.15

Configurations Expanded Toroidally 3x (ie includes adjacent coils at same current)			1.5 mm Tolerance	
#Coil Sets	#Coils	Coil Subset	Total Islands, %Flux	Max Current, KAT
2	12	7_11	1.93	38.27
3	18	1_2_8	2.40	20.49
4	24	1_2_7_8	1.89	12.86
5				

*Note: The 1_2_7_8 is the set of all coils that straddle symmetry planes (ie A-A & C-C)
 The expanded set provides complete coverage toroidally (3x24=72)
 In graphic at right, like colors are joined into a single coil
 For all cases only 12 modes targeted to allow comparison*



**Expanding Best 24 Coil Subset
 3x Toroidally Results in Full Coverage
 with Fewer Coils**

Trim Coils Meet Design Objective with Margin to Spare



Field Error Source	Uncorrected		Corrected			
	Island Size	%Total Flux	95% All Cases		100% All Cases	
	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 (Mod +/- 1.5mm, TF&PF +/- 3 mm)	21.56	28.65	1.98	9.77	2.01	16.08
Coil Assemble + Other Known Sources	22.76	28.96	2.95 4.42	19.49 8.34	2.95 4.49	27.47 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 + Same as above but with additional 1 mm Wing Distortion (example of extra distortion)	23.39	29.76	2.90 9.67	25.02 8.89		

Design Point
< 10% Islands
< 20 kA-T

100% Margin on
Trim Coil Current
and Field Errors

Trim Coil Performance Improvements with NLP Methods



Trim Coil Configuration	Total Number Coils	Using SVD Solution		Using NLP Solution	
		Total Island Size	Max Current	Total Island Size	Max Current
		%Total Flux	kA-T	%Total Flux	kA-T
Original 36 coils, 24 circuits	36	4.42	8.34	3.35	10.00
Original with 12 Midplane Coils	48	4.41	7.85	2.55	10.00
All Inner/Outer Coils Only (as Modified)	54	4.30	9.96	2.87	10.00
All Inner/Outer Coils Only (as Modified) (but without Outer AA)	48	4.29	11.36		
		6.95	10.00		
All Inner/Outer & Midplane Coils	66	4.26	9.21	2.17	10.00
All Inner/Outer & Midplane Coils (but without Outer AA)	60	4.25	9.56		
All Inner/Outer Coils (port12 split) (with Outer AA Coils)	60	4.47	10.00	2.89	10.00
		4.21	10.30		
All Inner/Outer Coils (port12 split) (without Outer AA Coils)	54	7.98	10.00	3.00	10.00
		4.18	11.88		
All Inner/Outer Coils (port12 split) (without Outer AA and CC Coils)	48	8.49	10.00	3.12	10.00
		4.06	12.25		
Above Plus Wings Distorted +40 mils (Stellarator Symmetric)		-	-	3.88	10.00
		-	-	3.88	10.00
Above Plus Wings Distorted +40 mils (1 HP Only, Non Stellarator Sym)		-	-	3.25	10.00
All Inner/Outer Coils (port12 split) (with Smaller Outer AA Coils)	60	6.91	10.00	2.68	10.00
		4.15	11.33		

Final

AWB10

12

Summary



- A Set of Trim Coils Have Been Designed for NCSX that meet our Design Goals with 100% Margin on Coil Currents and Field Errors
 - Shown to Correct Known and Anticipated Field Errors From Field Coil Fabrication and Assembly plus Other Sources
 - Used Techniques Developed for Rapid Assessment of Configurations
 - Provides Ample Margin for the Unexpected