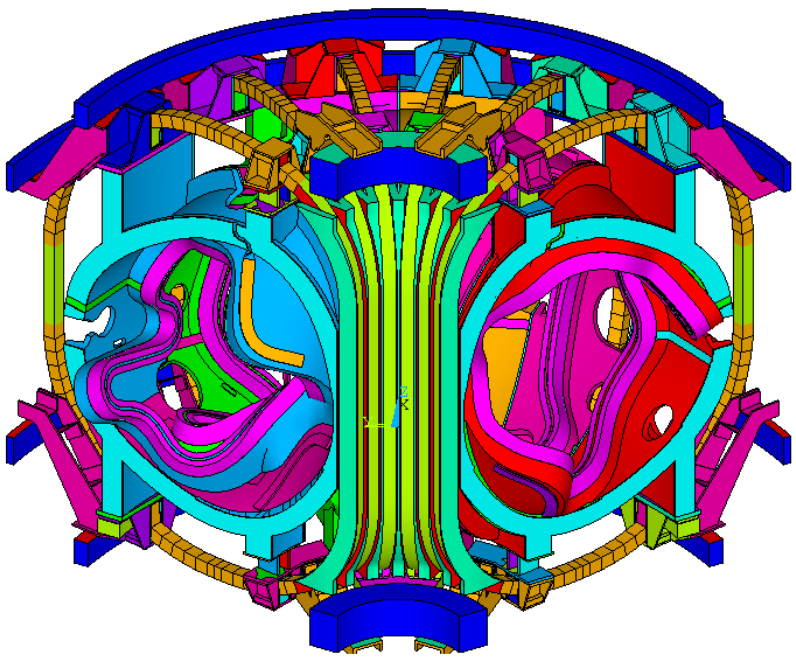
Operating Scenarios for Analyses & Fault Mode Analyses

March 25, 2008

Goals of this meeting

- Pete Titus raised two valid questions in the recent PU review which we must answer:
  - Shouldn't we be analyzing more than the present single 2T high β load case to be sure that future operational flexibility will not be overly restricted?
  - What fault modes should be specified for NCSX?
    - Also, what is required – for some modes, the machine should be able to "passively" withstand the fault; for others active protection circuitry might be an acceptable mitigation.

HM's new FEA model is a good tool for performing additional scans

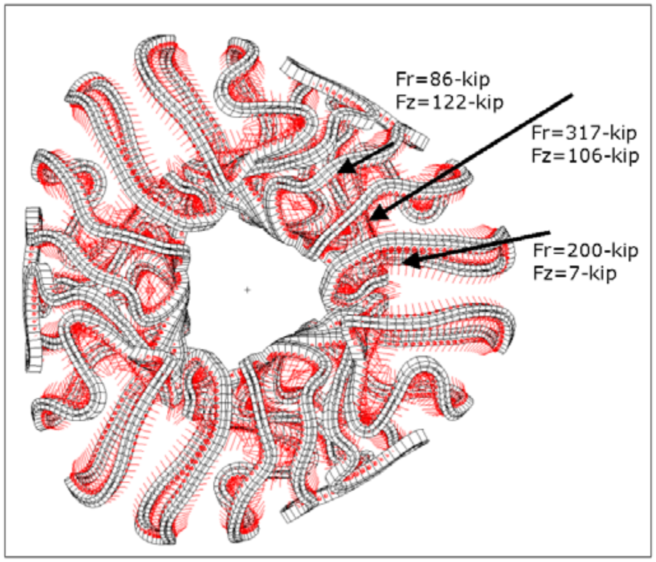


Dead loads:
The weight of model was be generated by acceleration.
One third of the center stack weight was added at the top of TF wedge.
One third of vacuum vessel weight was added at the top of MCWF.

EM loads:
EM forces are calculated on the basis of the total magnetic flux density.
The EM forces in the center stack are neglected due to self-balance.

Displacement Constraints:
Coupled node displacements on two faces at 0 and 120 degrees for MCWF, PF coils, and TF wedge shims.
Displacement restrained by component Uy and Uz at one node in the outboard support block and Uz at one node of the inboard support block.

Presently all analyses are based on only the 2T, High Beta operating mode which produces the maximum EM forces



Calculations to determine the fields and forces acting on all of the stellarator core magnets have been completed for seven reference operating scenarios. Table 6 summarizes the coil currents for all coils at a time step when the modular coils are at their maximum positive or negative value. *The worst case for determining forces in the modular coils* ***appears*** *to be the 2T high beta scenario at time=0.197-s.*

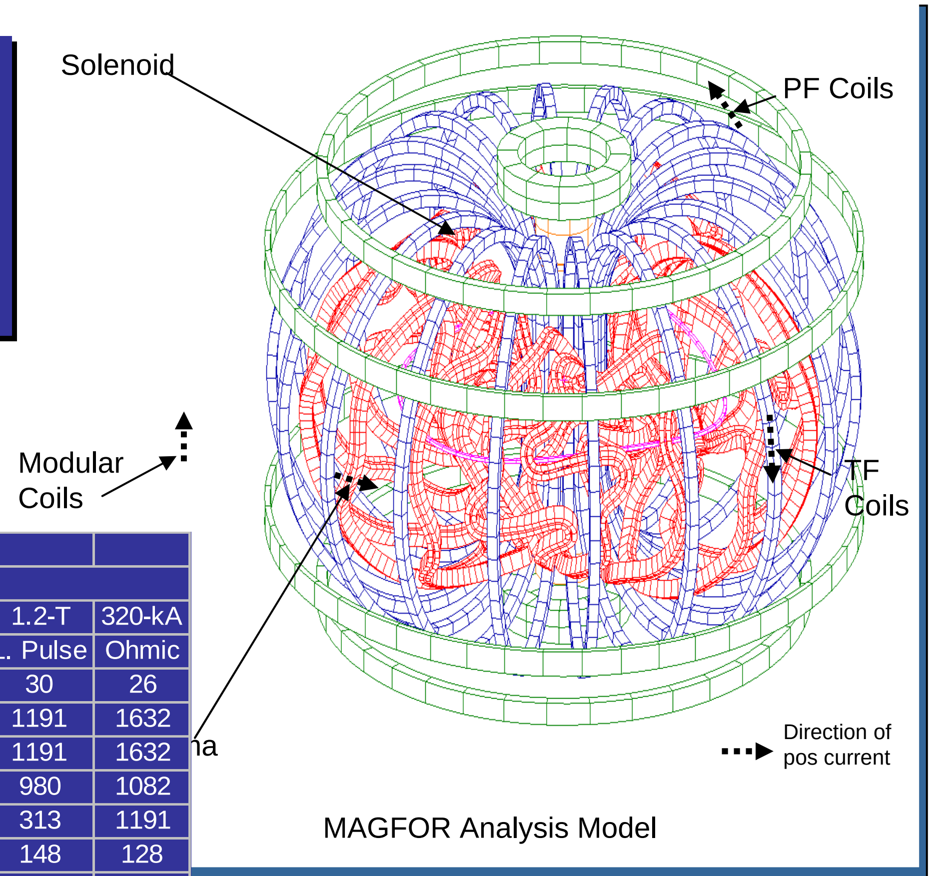
Table 1 Net EM Force on Modular Coils

Coil	Field/Force Component	0.5-T 1st Plasma	Field Mapping	1.7-T Ohmic	1.7-T High Beta	2-T High Beta	1.2-T L. Pulse	320-l Ohm
Type A	Max Field at Coil (T)	1.2	0.2	4.2	4.2	4.9	2.9	4.2
	Net Radial Load (kip)	13	1	152	152	200	76	147
	Net Vert Load (kip)	0.5	0	9	9	7	5	7
Type B	Net Radial Load (kip)	20	1	228	228	317	113	230
	Net Vert Load (kip)	7	0	84	84	106	42	79
Type C	Net Radial Load (kip)	5	0	57	57	86	29	62
	Net Vert Load (kip)	8	0	95	95	122	47	89

Reference: Design Description Modular Coils (WBS 14)
NCSX MCWF Final Design Review
May 19-20, 2004, pg. 22

From the FDR: Electromagnetic Loads Analysis –

- Two independent calculations have been performed using ANSYS, MAGFOR codes
- Seven reference scenarios examined at time step with maximum modular coil current
- Scan of possible coil currents for a more severe fault load condition also conducted



Maximum Current / Coil for Reference Scenarios (kA)								
Circuit	Coil Set	0.5-T 1st Plasma	Field Mapping	1.7-T Ohmic	1.7-T High Beta	2-T High Beta	1.2-T L. Pulse	320-kA Ohmic
1	TF	13	13	43	45	53	30	26
2	PF1	673	0	1479	1120	1340	1191	1632
	PF2	673	0	1479	1120	1340	1191	1632
3	PF3	673	0	1286	998	1208	980	1082
4	PF4	749	734	374	416	287	313	1191
5	PF5	0	0	204	209	82	148	128
6	PF6	32	13	104	101	115	72	73
7	A	224	224	763	763	818	539	695
8	B	209	209	710	710	831	501	707
9	C	188	188	638	638	731	451	621

Flexibility Coil Current Ranges

- The GRD calls for specific flexibility in various parameters.
- Neil Pomphrey evaluated the implied coil-current variations for the Project CDR using the old M45 coil design, and his coil currents are tabulated in Chapter 8 of the CDR Physics Basis document.
- We have evaluated similar vacuum scans using the final design (M50) coils, and they are tabulated at http://twikisrv.pppl.gov/twiki/bin/view/Research/PlasmaConfigs

The flexibility that causes the most variation in TF currents is due to changes in iota

- Taking coil current configurations from http://twikisrv.pppl.gov/twiki/bin/view/Research/PlasmaConfigsVac#Iota_scan_low_ripple_all_coil_cu
  gives the following cases at the approximate iota extremes of the GRD
- For a nominal Bt=1.7T. Origional calculations included PF3, but ignored because it has a small effect on plasma shape.
- This range of MC and TF currents is similar to Neil's calculations for M45 in his Table 8-10.

Iota	M1 kAt	M2 kAt	M3 kAt	PF4 kAt	PF5 kAt	PF6 kAt	TF kAt
0.19	517.9	523.8	448.4	80.7	3.3	-5.779	164.1
0.65	814.2	812.2	676.7	419.8	62.2	9.772	-106.8

The shear scan causes large variations in the ratio of the MC currents

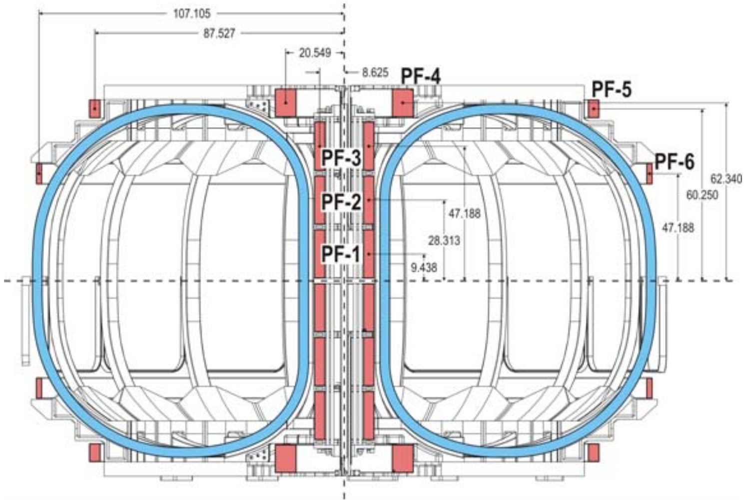
- The most extreme cases at http://twikisrv.pppl.gov/twiki/bin/view/Research/PlasmaConfigsVac#Shear_scan_all_coil_currents_var are

- Note that the GRD calls for achieving a delta shear of -0.2, but we have not yet found a set of coil currents to obtain this:

Delta shear	M1 kAt	M2 kAt	M3 kAt	PF4 kAt	PF5 kAt	PF6 kAt	TF kAt
+0.2	619.9	902.9	566.3	-723.8	-18.9	41.13	-35.51
-0.1	601.8	871.5	552.3	944.4	150.26	-157.9	-14.39

Which cases should be analyzed?

The PF System



Parameter	Units	PF-1	PF-2	PF-3	PF-4	PF-5	PF-6
Max total current	MA-turns	1.809	1.809	0.927	1.115	0.201	0.126
Radius	m	0.22	0.22	0.27	0.52	2.22	2.72
Installed height, Z	m	0.24	0.72	1.2	1.58	1.53	0.95
bundle dr	mm	96.9	96.9	96.9	188.5	96.9	51.1
bundle dz	mm	426.6	426.6	426.6	249.6	161.0	183.2
gross current density	A/mm^2	43.7	43.7	22.4	23.7	12.9	13.5
total turns	#	72	72	72	80	24	14
turns high	#	18	18	18	10	6	7
turns wide	#	4	4	4	8	4	2
current per turn	A	-25123	-25123	-12877	-13936	8356	-8997
packing fraction		0.75	0.75	0.75	0.75	0.75	0.75
length per turn	m	1.38	1.38	1.38	3.28	13.97	17.09
total length of copper, per coil	m	99.11	99.11	99.11	262.36	335.25	239.3
turn height	mm	20	20	20	20	20	20
turn width	mm	20	20	20	20	20	20
coolant hole width	mm	9	9	9	9	9	9
conductor area	mm^2	335.2	335.2	335.2	335.2	335.2	335.2

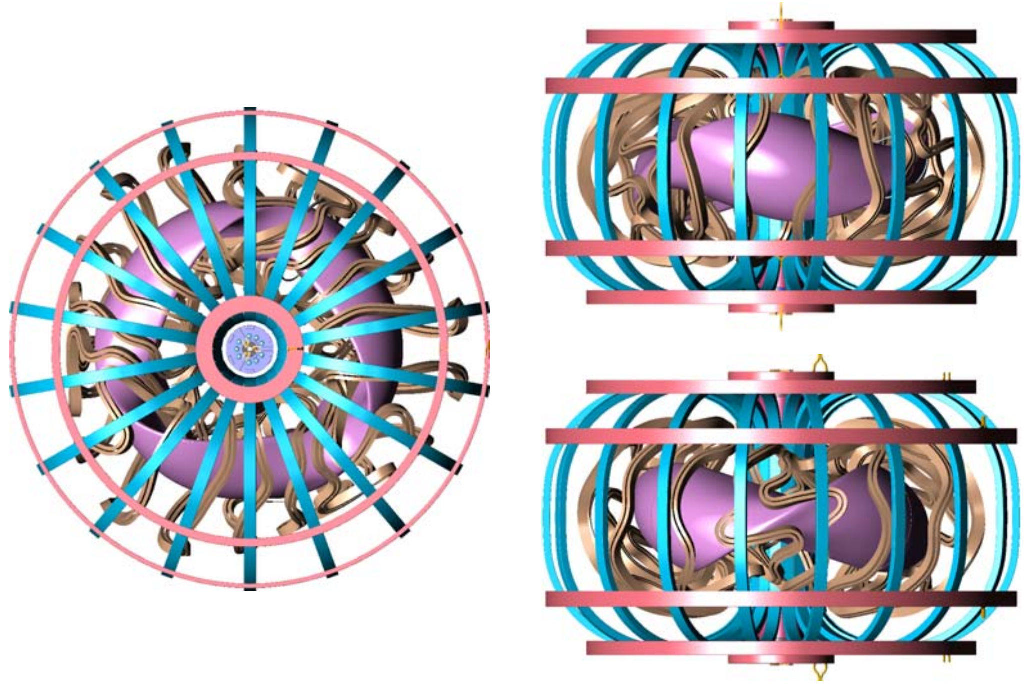
Fault mode "strawman":

- NCSX must be able to survive any single PF coil being effectively shorted across its terminals at any time during any of the required operating scenarios without damage.

The TF System

Table 1 TF coil parameters

Parameter	Unit	Value
Number of TF coils		18
Number of turns per coil		12
Maximum toroidal field at 1.4 m (TF coils only)	T	±0.5
Maximum current per turn	kA	16
Winding length along winding center	m	8.66
Conductor Length	m	107.7
Bundle height	mm	100.8
Bundle width	mm	99.8
Bundle area	mm2	10,066
Conductor height	mm	18.0
Conductor width	mm	24.5
Corner radius	mm	2.5
Cooling hole diameter	mm	8.0
Conductor area	mm2	392
Weight/coil,	kg	414
Max current in reference scenario	kA	16
Maximum copper current density	kA/cm^2	3.8



Fault mode “strawman”:

NCSX must be able to survive any single TF coil being effectively shorted across its terminals at any time during any of the required operating scenarios without damage.

The Modular Coil System

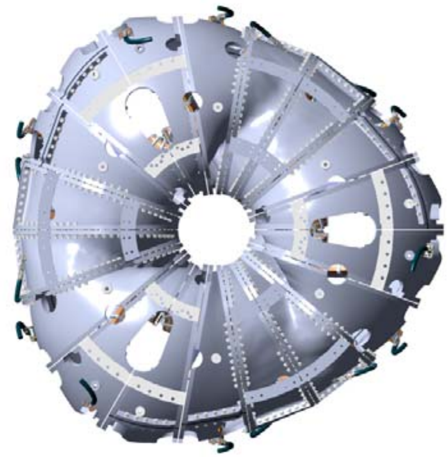
Fault mode “strawman”:

a. NCSX must be able to survive any single modular coil being effectively shorted across its terminals at any time during any of the required operating scenarios without damage.

b. ..must be able to survive any series connected string of modular coils having zero current throughout any of the operating scenarios without damage.

A.1.1.2 Turns per Coil

	M1	M2	M3	PF1A	PF4	PF6	Plasma
Turns	22	22	20	48	80	14	1



Performance and Operational Requirements

When assembled into a structural shell, the main performance requirement for the winding forms is to support the coil electromagnetic loads with a minimum of deflection. Table 1lists the range of loads that are expected:

Table 1 Maximum Operational Loads on Structural Shell

	Max Radial Load (kip)	Max Vertical Load (kip)	Avg Inboard Pressure (psi)	Avg Outboard Pressure (psi)	Max Coil Radial Load (kip/in)	Max Coil Lateral Load (kip/in)
Segment / Coil 1	200	10	220	70	3	6
Segment / Coil 2	320	110	280	75	6	7
Segment / Coil 3	90	120	170	80	4	6.5

Modular coil background material

The modular coil windings must be capable of meeting the reference operating scenarios defined in GRD Section 3.2.1.5.3.3 and summarized in Table 2.

Table 2 Reference Scenarios and Modular Coil Current

Scenario	Max Current (kA)	Max I^2t (A^2-s)	Max ESW (s)
First Plasma (0.5-T)	225	93 E6	0.76
Field Mapping	225	450 E6	3.6
1.7-T Ohmic	763	1400 E6	1.0
1.7-T High Beta	763	1350 E6	0.97
2.0-T High Beta	818	1530 E6	0.90
1.2-T Long Pulse	538	1300 E6	2.0
320-kA Ohmic	707	1270 E6	1.0

From Raki's SDD

Table 1 NCSX power supply requirements

			Circuit 1	Circuit 2	Circuit 3	Circuit 4	Circuit 5	Circuit 6	Circuit 7	Circuit 8	Circuit 9	Circuit 10	Total
Initial configuration		NSTX	TF Branch 1	TF Branch 3	PF3U	PF3L	PF1a	OH (part)					
37 MW 88 MVA 25 MJ	First Plasma FL Mapping	NCSX	M1	M2,M3	PF1/2/3	PF4	PF6	TF					
	Max I2t (10^6 A2-s)		94	84	100	5	1	4					
	Max I (A)		11218	10435	12877	2774	1401	1043					
	tESW (s)		0.75	0.77	0.60	0.69	0.50	4.01					
	Idc (A)		323	306	333	77	33	70					
	Cables per pole		1	1	1	1	1	1					12 Cables
	Series PSS per branch		2	2	2	2	2	2					14 PSS
	Branches		1	1	1	1	2	1					
	Branch configuration						Anti-parallel						
Ultimate configuration		NSTX	TF Branch 1/2	TF Branch 3/4	CHI	PF3L	PF1aL	OH (part)	OH (part)	PF3U	PF2U	PF2L	
154 MW 408 MVA 124 MJ	1.7T Ohmic 1.7T Hi Beta 2T Hi Beta 1.2T Long Pulse 320kA	NCSX	M1	M2	M3	PF4	PF6	TF	PF1/2	PF3	PF5U	PF5L	
	Max I2t (10^6 A2-s)		1512	1539	1433	137	64	225	430	91	47	47	
	Max I (A)		40961	41597	40542	13891	8973	4423	25147	11832	8340	8340	
	tESW (s)		0.90	0.89	0.87	0.71	0.79	11.50	0.68	0.65	0.68	0.68	
	Idc (A)		1296	1308	1262	391	266	500	691	318	229	229	
	Cables per pole		2	2	2	1	1	1	1	1	1	1	26 Cables
	Series PSS per branch		2	2	2	2	2	4	4	2	2	2	40 PSS
	Branches		2	2	2	1	2	2	2	1	1	1	
	Branch configuration		Parallel	Parallel	Parallel		Anti-parallel	Anti-parallel	Anti-parallel				
Circuit ratings (ultimate configuration)	Max I (A)		50000	50000	50000	24000	24000	24000	24000	24000	24000	24000	
	Idc (A) forward		1800	1800	1800	900	900	900	900	900	900	900	
	Idc (A) reverse		-	-	-	900	900	750	750	750	750	750	