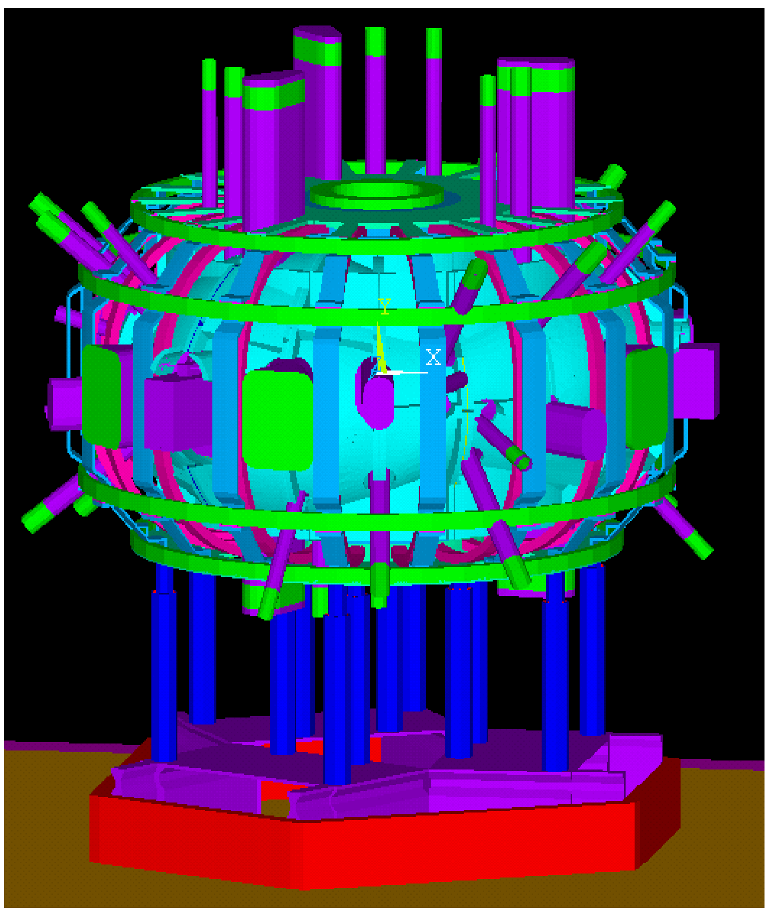
PSFC/JA-03-

DRAFT

SEISMIC ANALYSIS OF THE NATIONAL COMPACT STELLERATOR (NCSX)

Peter H. Titus

May 17 2004 Revision



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1.0 Introduction

Seismic analysis and qualification of NCSX is presented. DOE requirements as outlined in DOE-STD-1020-2002 are followed for determination of the necessity for seismic qualification of the stellarator and its related systems. IBC-2000 is followed for the qualification requirements. The stellarator presents minimal occupational hazards and hazards to the public. The qualification effort is intended to preserve the viability of continuing the experiment after an earthquake, and to explore the sensitivity of the design to dynamic loading from sources other than normal operation. A response spectra modal analysis has been employed. The model is an assemblage of the simpler models of the vessel, and modular coil shells; being employed to qualify these components for normal operational loading. Outer TF and PF coil models and models of the cold mass supports have been generated and added to form a complete model of the stellarator system. The scale of the model is limited by the computational capacity of the windows/Intel system used for the analysis, and the efforts to control runtimes and file sizes are described. Much of the stellarator is robust to resist normal Lorentz forces. Areas sensitive to lateral loads and dynamic application of non-Lorentz loading, include the nested cylinder cold mass support columns, cantilevered vessel ducts, and the radial guides connecting the vessel ducts and modular coil shell. Loads on these structures are quantified, and design adequacy is assessed. .

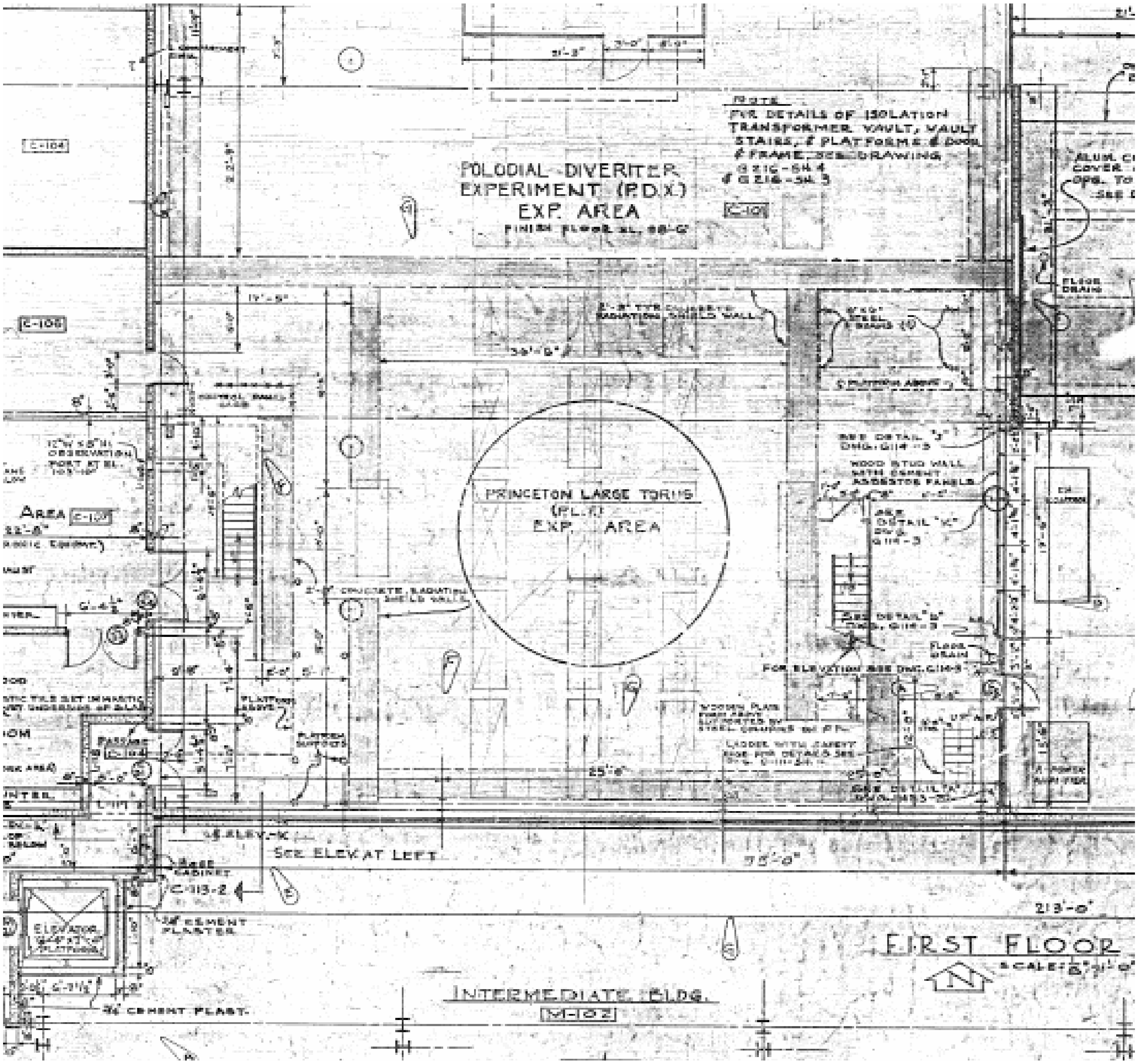

Figure 1.0-1 NCSX will be located in the PLT test cell.

2.0 Summary of Results

The main elements of the Stellarator are robust to take their normal electromagnetic, thermal and "disruption" loads. The gravity support was not analyzed in detail statically prior to this seismic analysis effort, and to form a baseline for stress evaluation, the gravity support was analyzed for cooldown and deadweight. The complex model used for this analysis was probably not necessary. The fundamental mode was a lateral translation with the support columns cantilevered and displacing with clamped –guided end fixity. There was some rocking behavior along with the shear translation, but the first mode behavior could have been obtained with a simple lumped mass-beam model. This lowest frequency mode was 2.1 cps. Entering the ARS this would yield a global acceleration of .72 g in each of the horizontal directions. The next series of mode shapes involved the ports as rigid "sticks" rotating about their connection with the vessel shell with the local shell flexibility providing the rotational spring rate. These make for "wild" looking mode shape animations. Some of these are posted at http://www.psfc.mit.edu/people/titus/ under NCSX memos. Vertical response is ignored in this analysis. At .15 g in the TFTR cell data, combined using SRSS, it would contribute little to the response of the stellarator.Within the stellarator the seismic stresses are modest. Interesting stresses occur at the port/vessel connections and in the support columns. Because of the size of the model, the number of modes extracted must be limited. In run#7 only 10 modes were extracted. Stress results were checked with a second analysis (run#10) with 14 modes extracted and the peak column support stress went from 165 MPa to 167 MPa. Figure 10.2-2 shows the restraint link axial stress of 25.1 Mpa. These are modeled as having a 1 square inch cross section, and as taking tension and compression, but the design appears to allow only compression. The load at each restraint is :25.1e6/6895*2* 1.0in^2= 7251.6 lbs

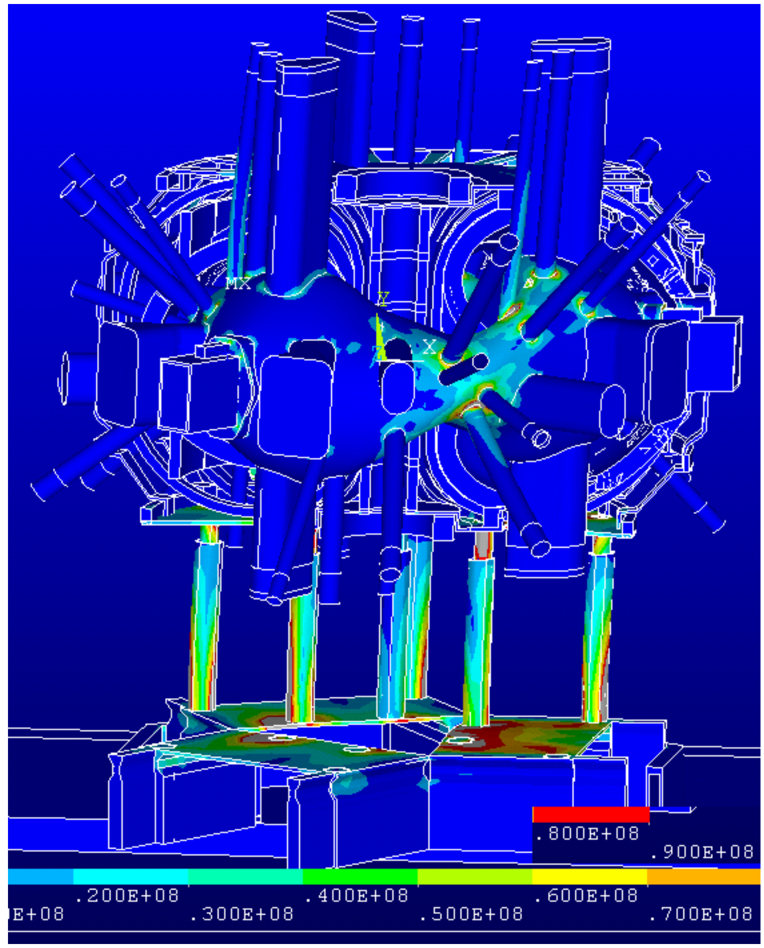

Figure 2.0-1 Seismic Stresses are significant in the support columns, and in the vessel due to port and port extension motions

Table 2.0-1Stress in MPa

Component	D	P	T_O	F_{DBE} (1)	IR	Total Stress	Allow*K	
Outer Support Columns	15		90	233		338	330 (289 weld) (3)	.97
Vessel to Port Intersection	90	30		254		374	370.33(4)	.99

(1) Multiplied be SQRT(2) – This accounts for having only modeled one ARS direction.
(2) K=1.2 for Unlikely Events
(3) 316 SST at RT

(4) Inconel 625 from Table 5, ref [10] multiplied by a K value of 1.2

Interface reaction loads are included in the modeling, in that an attempt is made to model the full stellarator system. Preloads are not included.

Stresses in the modular coil shell are significant in the thermal analysis. This was because the lateral struts or jacks were modeled as tight against the vessel lugs. Some gap should be provided to allow these struts to be warm with respect to the shell, or a single radius rod type restraint should be considered. The only appreciable seismic stress is in the vessel lateral support brackets. This does not appear to be a problem. The major loading of this shell are the modular coil Lorentz forces. The areas of the shell which support these stresses are essentially un effected by the seismic loading.

2.1 Conclusions/Recommendations

The stellarator core and it's proposed gravity/cold mass support system meet conservative seismic requirements. There remains a significant amount of work to assess the effects of peripheral systems on the stellarator.

Differential lengths of the vessel hanger rods appear to stress the vessel shell due to differential temperatures between the modular coil castings, and vessel. This should investigated further.

If lateral restraints are hard up against the port lug prior to cooldown, the bracket stress due to cooldown is large. A one-sided radius rod type restraint might be wiser.

3.0 Criteria

From Ref [2]:

I-1.8 Seismic Loads (F_{DBE})

The NCSX facility will be classified as a Low Hazard (LC)/Hazard Category 3 (HC3) facility. All Structures, Systems, and Components (SSC) of NCSX shall be categorized in accordance with DOE-STD-1021-93 ("Natural Phenomena Hazards Performance Categorization Criteria for Structures, Systems, and Components," 7/93) to determine the appropriate Performance Category. For those SSCs that require seismic design, the applicable Design Basis Earthquake (DBE) acceleration values and evaluation techniques specified in DOE-STD-1020-94 ("Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities," 4/94) and DOE-STD-1024-92 ("Guidelines for Use of Probabilistic Seismic Hazard Curves at Department of Energy Sites," 12/92) shall be used.

I-2.3 Unlikely Events $10^{-2} > P \geq 10^{-4}$

$D + P + T_O + F_{DBE} + IR + L$

$D + P + T_O$ + (EM-F per FMECA)+ IR + L

D=Deadweight, P-Design Pressure, F_{DBE} = Seismic, Design Basis Earthquake, T_O=Normal operation thermal effects, IR= Interaction Loads , L=preloads

Unlikely	In addition to the challenged component, inspection may reveal localized large damage, which may call for repair of the affected components.	Material plasticity, local insulation failure or local melting which may necessitate the removal of the component from service for inspection or repair of damage to the component or support.	The facility may require major replacement of faulty component or repair work.

- Primary membrane plus bending stresses shall not exceed 1.5 KS_m
- For *unlikely* conditions, K = 1.2; evaluation of secondary stress not required

Input ARS

This comes from ref __ via ref. 7. It is the recommended ground motion, exclusive of any amplification of a building. No seismic analysis of the PLT cell is available. To estimate the effects of building amplification, the TFTR cell results will be used. These were used by Scott Perfect in the TPX gravity support qualification The ground motion ARS peaks out at .36g and the TFTR/TPX ARS peak at around twice this. .

	Spectral Accelerat ion, g	
Period, Sec	**MCE**	**5% Damped MCE**
0.00	0.144	0.096
0.05	0.360	0.240
0.20	0.360	0.240
0.24	0.360	0.240
0.30	0.284	0.189
0.40	0.213	0.142
0.50	0.170	0.113
0.60	0.142	0.095
0.70	0.122	0.081
0.80	0.106	0.071
0.90	0.095	0.063
1.00	0.085	0.057
1.10	0.077	0.051
1.20	0.071	0.047
1.30	0.065	0.043
1.40	0.061	0.041
1.50	0.057	0.038
1.60	0.053	0.035
1.70	0.050	0.033
1.80	0.047	0.031
1.90	0.045	0.030
2.00	0.043	0.029

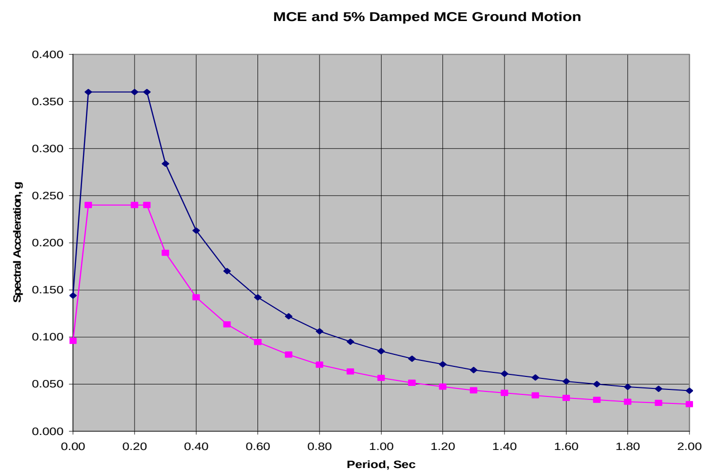

Figure 3.0-1 Required ground motion amplified response spectrum. Dark Blue is MCE and Magenta is 5% Damped MCE

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svtyp,2,2.0*9.8
sed,1,0,0
FREQ,.55555556,.58823529,.625,.66666667,.71428571,.769
23077,.83333333,.90909091,1
FREQ,1.1111111,1.25,1.4285714,1.6666667,2,2.5,3.333333
3,4.1666667,5
FREQ,20,100
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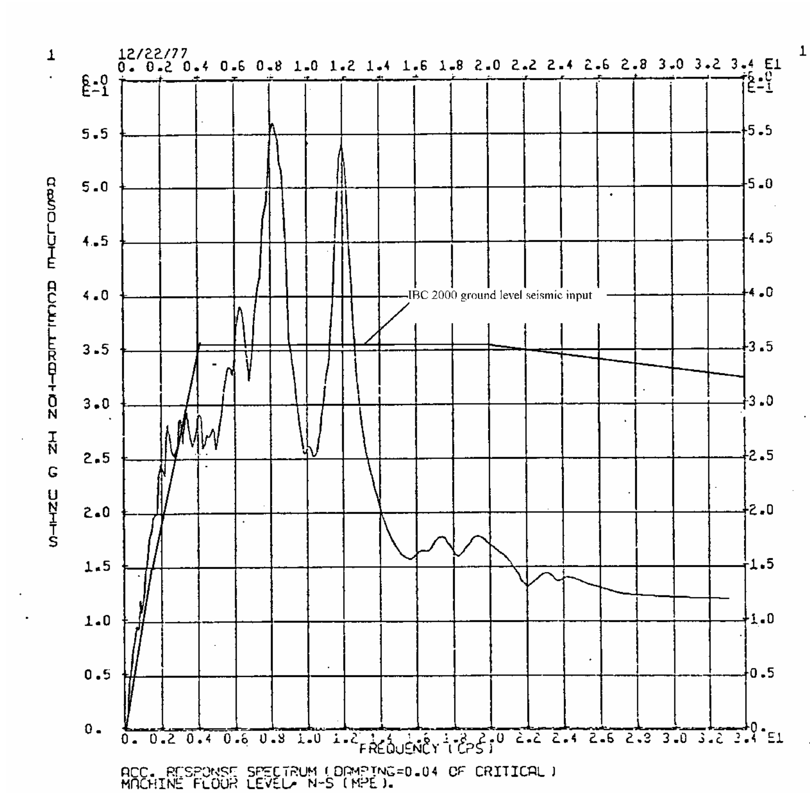


Figire 3.0-2North-South Response Spectrum Curve, TFTR/TPX Test Cell, ref [5]

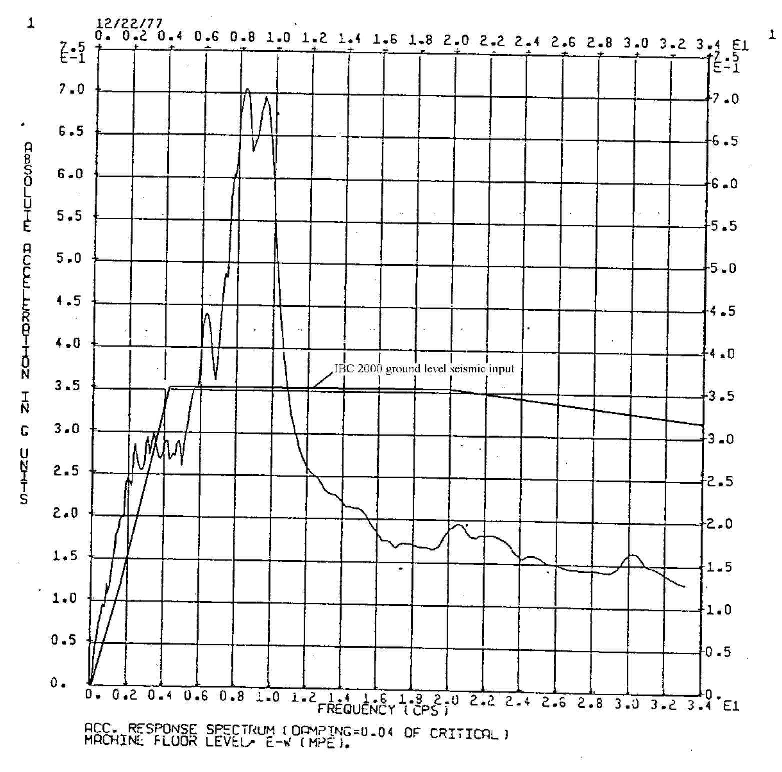


Figure 3.0-3East-West Response Spectrum Curve, TFTR/TPX Test Cell, ref [5]

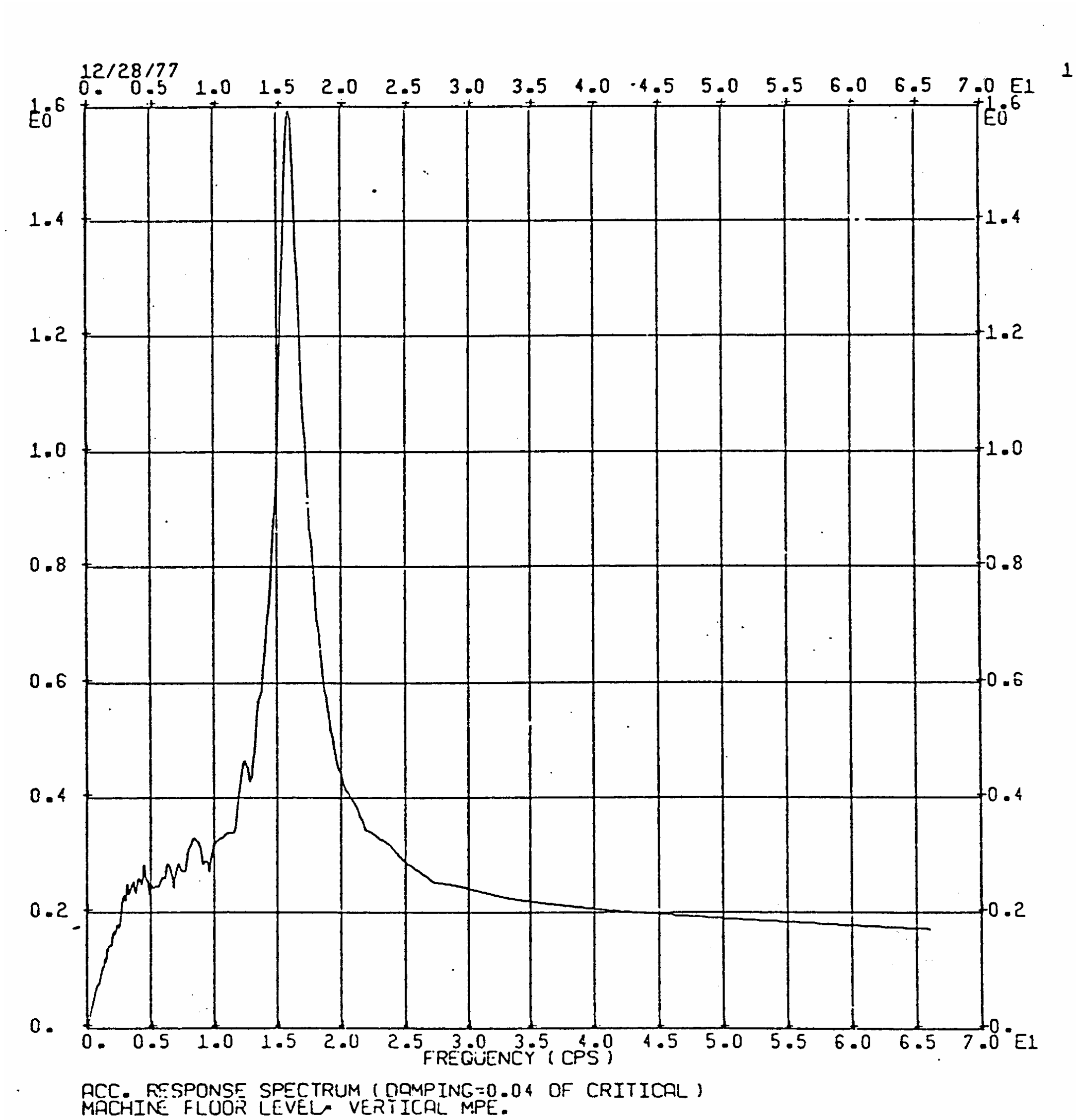


Figure 3.0-4 Vertical Response Spectrum Curve, TFTR/TPX Test Cell, ref [5]

4.0 Materials

Table 4.0-1 Tensile Properties for Magnet Structural Materials

Material	Yield 4 deg K (MPA)	Ultimate 4 deg K, (Mpa)	Yield, 80 deg. K (MPa)	Ultimate, 80 deg. K (MPa)	Yield, 292 deg K (MPa)	Ultimate, 292 deg K (MPa)
316 LN SST	992[8]	1379[8]			275.8[8]	613[8]
316 LN SST Weld	724[8]	1110[8]			324[8]	482[8]
304 SST 50% CW	1613	1896	1344	1669	1089	1241
304 Stainless Steel (Bar,annealed)	404	1721	282	1522	234	640
Aluminum 6061T6	362(20K)	496(20K)	275.8		288	310
Alum 6061 Weld	259(4K)[9]	339(4K)[9]				

Structure Room Temperature (292 K) Maximum Allowable Stresses, Sm = lesser of 1/3 ultimate or 2/3 yield, and bending allowable=1.5*Sm

Material	Sm	1.5Sm	Seismic Allowable (K=1.2)
316 LN SST	183Mpa (26.6 ksi)	275Mpa(40ksi)	330
316 LN SST weld	160MPa(23.2ksi)	241MPa(35ksi)	289

The general equation to compute the elastic modulus for normal concrete from ACI 318 is:
$E_c = 33\ w_c^{1.5}\ (f'_c)^{1/2}$ psi
where:

w_c = the unit weight of concrete
f'_c = the compressive strength of concrete

The general equation to compute the elastic modulus for high performance concrete from ACI 363 is:
$E_c = 40{,}000\ (f'_c)^{1/2} + 1.0 \times 10^6$ psi
For 3,000 psi $< f'_c <$ 12,000 psi

Concrete Density, from: http://www.logicsphere.com/products/firstmix/hlp/html/mixd7zc4.htm
Range: 2100 - 2750 kg/m^3.

Concrete density from: http://hypertextbook.com/facts/1999/KatrinaJones.shtml:
1750-2400 kg/m^3
Volume generally assumed for the density of hardened concrete is 150 lb./ft^3. (2400 kg/m^3)"

5.0 Design Input

A vessel model has been provided by Fred Dalhgren in the form of a Prep7 input listing. The moidular coil shell model was provided by H.M.Fan in the form pf an ANSYS *.db file. Tom brown provided a drawing of the lower support structure which also serves as a sliding assembly fixture. The local bldg details were provided by Fred Dalgren and Tom Brown, including the shield blocks. At present only a slab is included in the model. The edge of the slab is constrained, and is the input point for the ARS

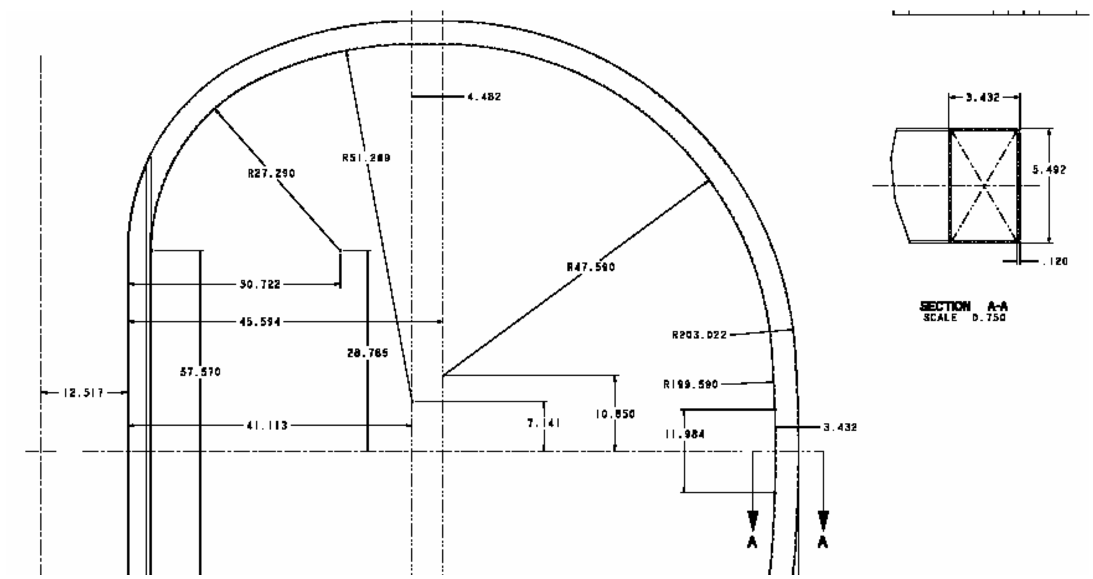


Figure 5.0-1 TF Coil Geometry – Provided by L. Myatt

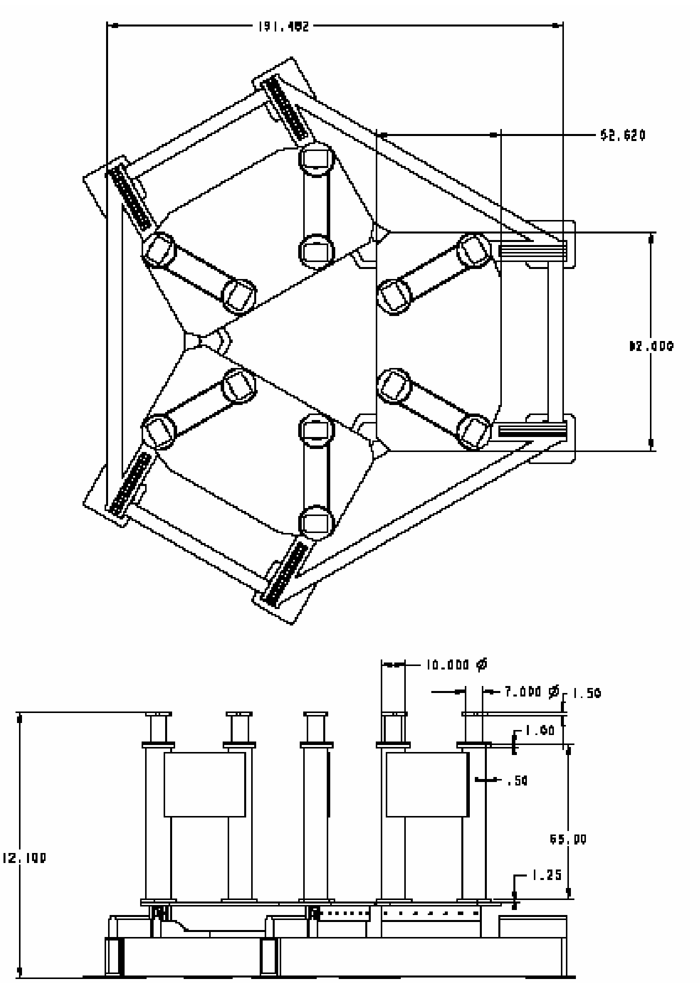


Figure 5.0-2 Lower Gravity Support Geometry, Provided by T. Brown

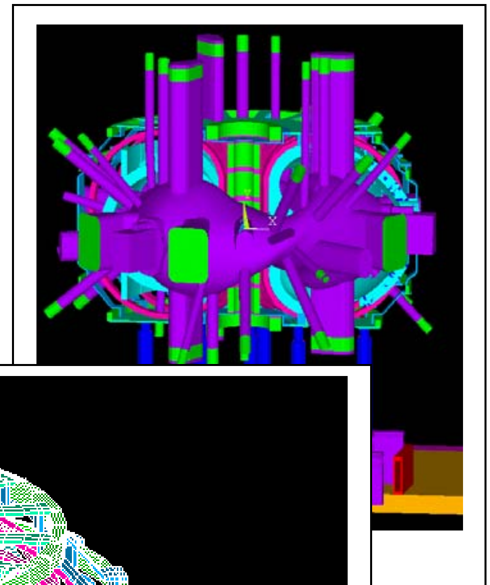
NCSX PF Coil Build (Provided by Len Myatt in ANSYS Parametric Language, for individual conductor modeling, converted to Coil R,Z,DR.DZ data)

R	z	dr	dz
8.625	9.438	3.66	15.93
8.625	28.313	3.66	15.93
8.625	47.188	3.66	15.93
20.549	62.34	7.32	8.85
87.527	60.25	3.66	5.31
107.105	37.562	1.83	6.195
107.105	-37.562	1.83	6.195
87.527	-60.25	3.66	5.31
20.549	-62.34	7.32	8.85
8.625	-47.188	3.66	15.93
8.625	-28.313	3.66	15.93
8.625	-9.438	3.66	15.93

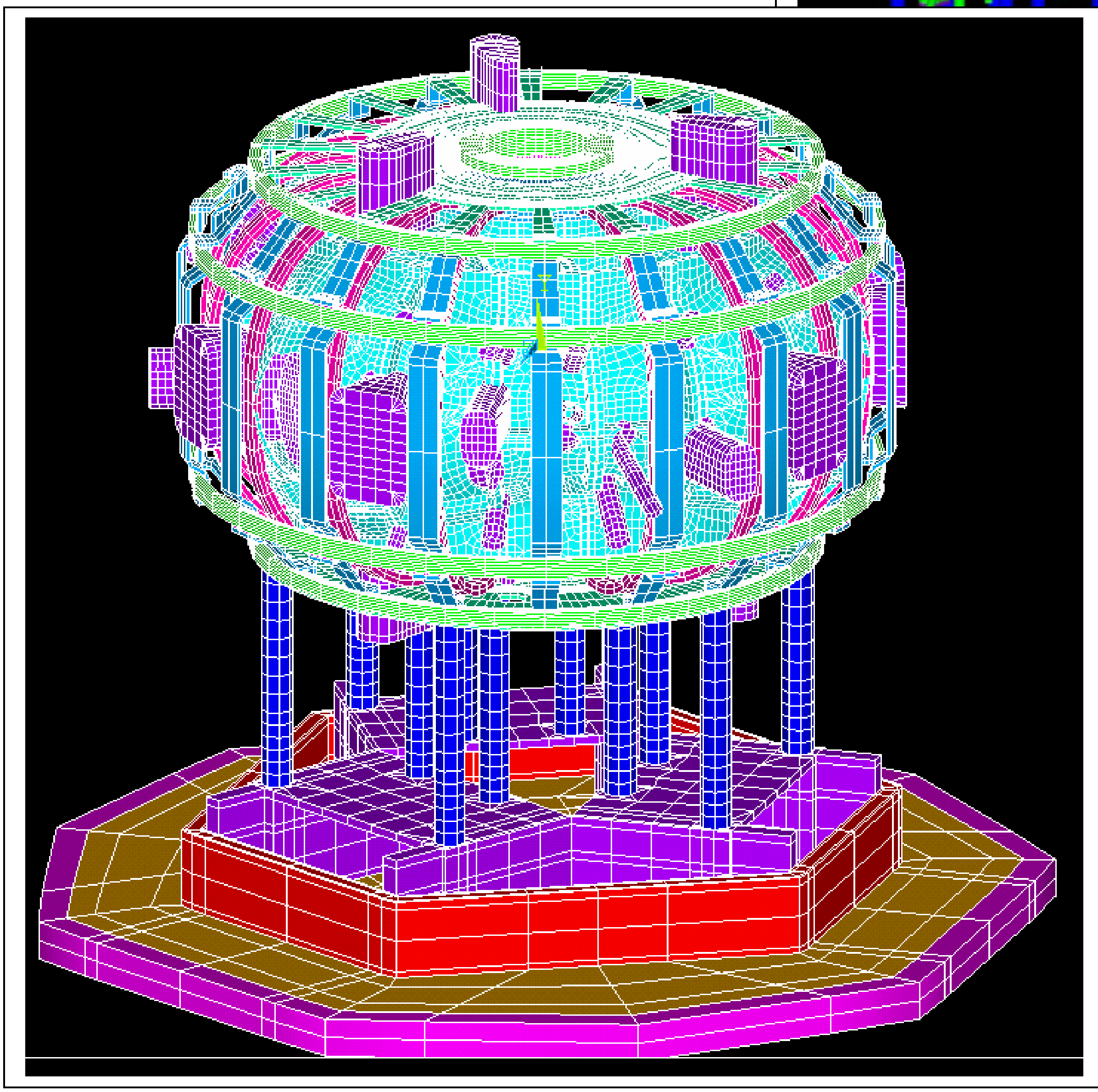
References

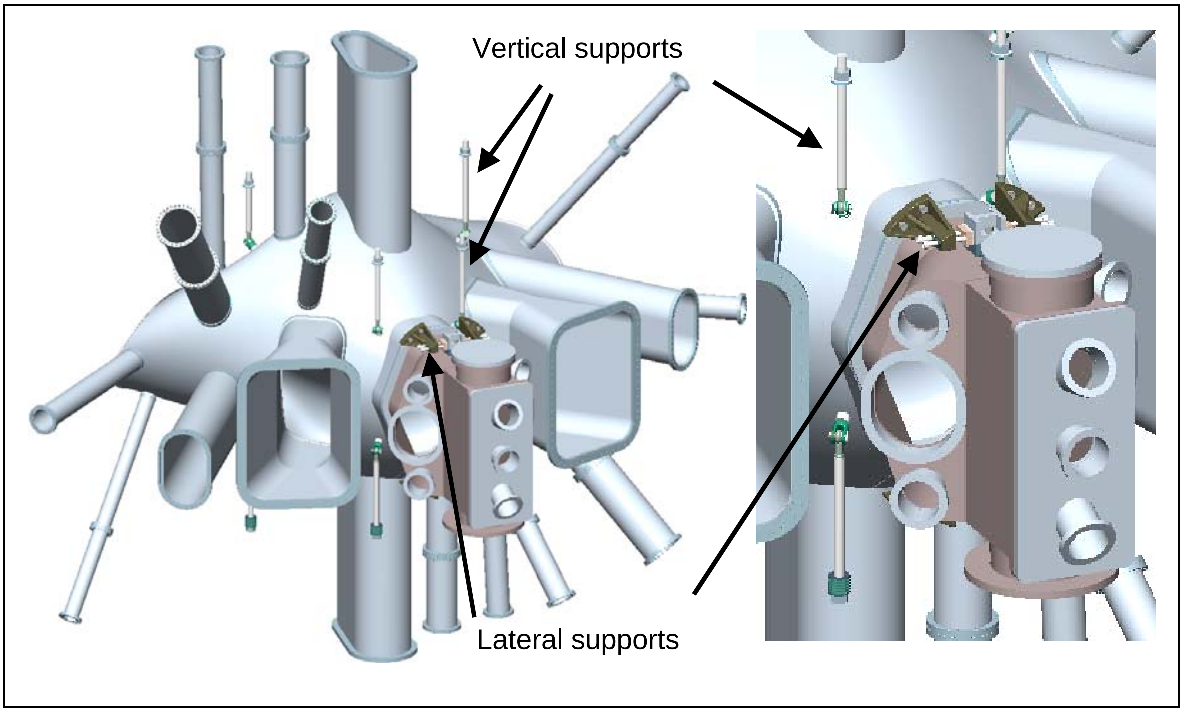
[1] NCSX SPECIFICATION Vacuum Vessel Systems (WBS 12) System Requirements Document (SRD) NCSX-BSPEC-120-00 18 March 2004
[2] NCSX (NATIONAL COMPACT STELLERATOR EXPERIMENT) STRUCTURAL DESIGN CRITERIA - DRAFT B - 4/30/04, I. ZATZ, EDITOR
[3] DOE-STD-1020-2002
[4] Email and attachment from Brad Nelson with the vessel support details, -excerpt from the PDR
[5] Structural Analysis of the TPX Cold-Mass Support System, Scott A. Perfect UCRL-ID-112614, TPX 16-921211-LLNL/S.P.-01, December 11 1992
[6] Seismic Dynamic Analysis of Tokamak Structures, Shaaban, AA. Ebasco Services Inc. Report # EP-D-027, February 7 1978, This is cited in [5] as the source of the ARS curves
[7] PRELIMINARY Summary and derivation of the seismic requirements for NCSX. Preliminary Rev 1 Michael Kalish 3/29/04
[8] "General Electric Design and Manufacture of a Test Coil for the LCP", 8th Symposium on Engineering Problems of Fusion Research, Vol III, Nov 1979
[9] "Handbook on Materials for Superconducting Machinery" MCIC- HB-04 Metals and Ceramics Information Center, Battelle Columbus Laboratories 505 King Avenue Columbus Ohio 43201
[10] NCSX Engineering Design Document, Design Description Vacuum Vesses (WBS12) and In-Vessel Components, NCSX Final Design Review May 19-20 2004

Analysis and Modeling



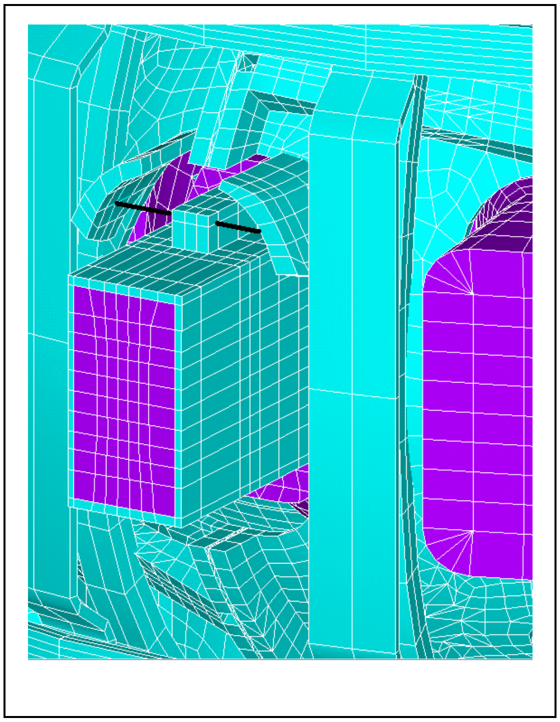
The modular coils are not explicitly modeled in the seismic analysis. Their mass is lumped with the support shell. In this model segments provided by H.M. Fan, the coil volume is 0.8906 m^3 and the support shell volume is 1.50228m^3. The shell density is increased by the factor (1.50228+.8906)/1.50228 to account for the coil mass. The Plasma facing components (PFC's) have not been included in the model. These are to be installed in a later phase of the project, and will be carbon composite. The PFC's are not expected to add significantly to the inertia inventory.

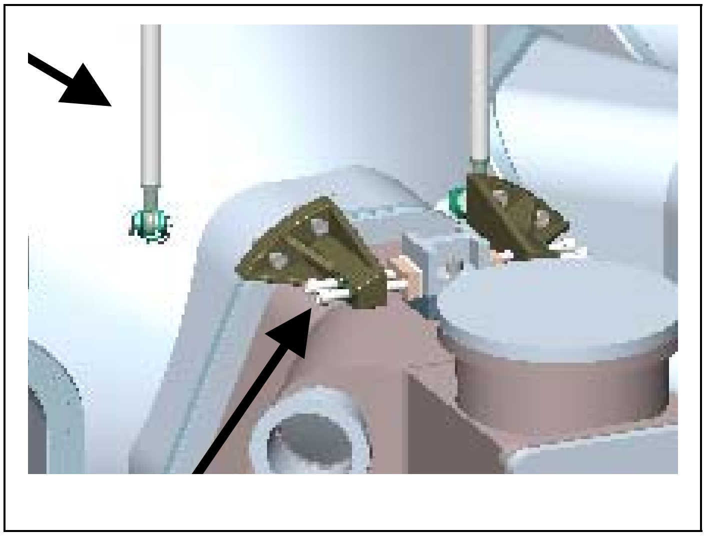


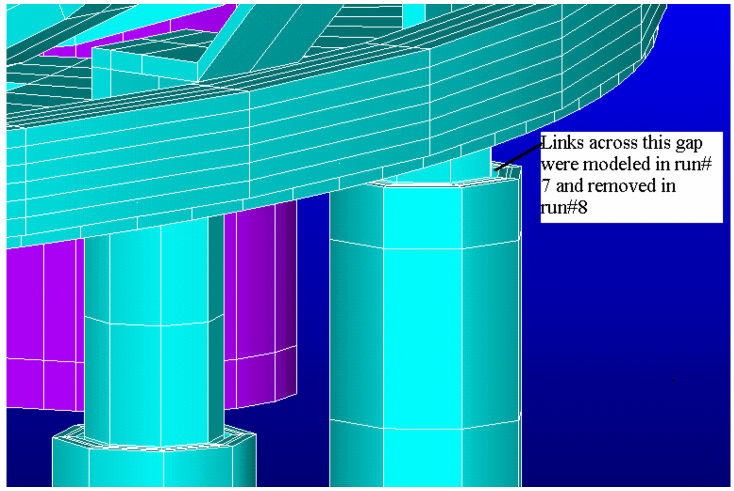


From ref [4]:

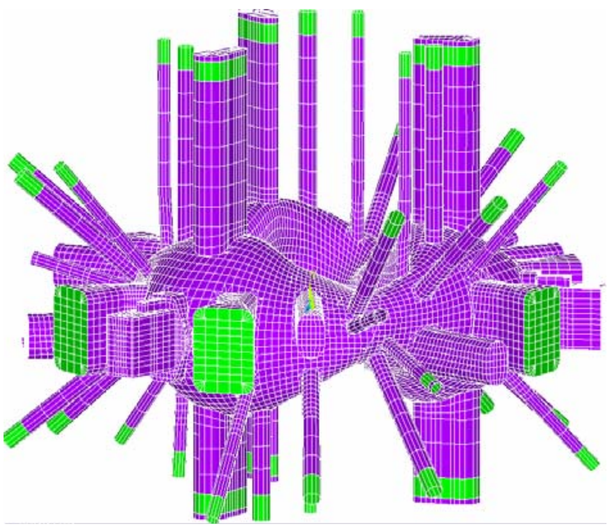
The vessel will be supported from the modular coil structure via vertical support hangers and radial guide lugs, designed for ease of adjustment and minimal heat transfer between the two structures. The vessel gravity load is taken by two hangers located on either side of the NBI ports. Two lower hangers, in each period, are used to react vertical dynamic loads. Radial supports, located at the top and bottom of each neutral beam duct, react lateral loads. The hangar geometry is illustrated in ***Error! Reference source not found.****. Significant relative thermal growth must be accommodated when the modular coils are cooled to cryogenic temperatures or when the vacuum vessel is heated for bakeout.*



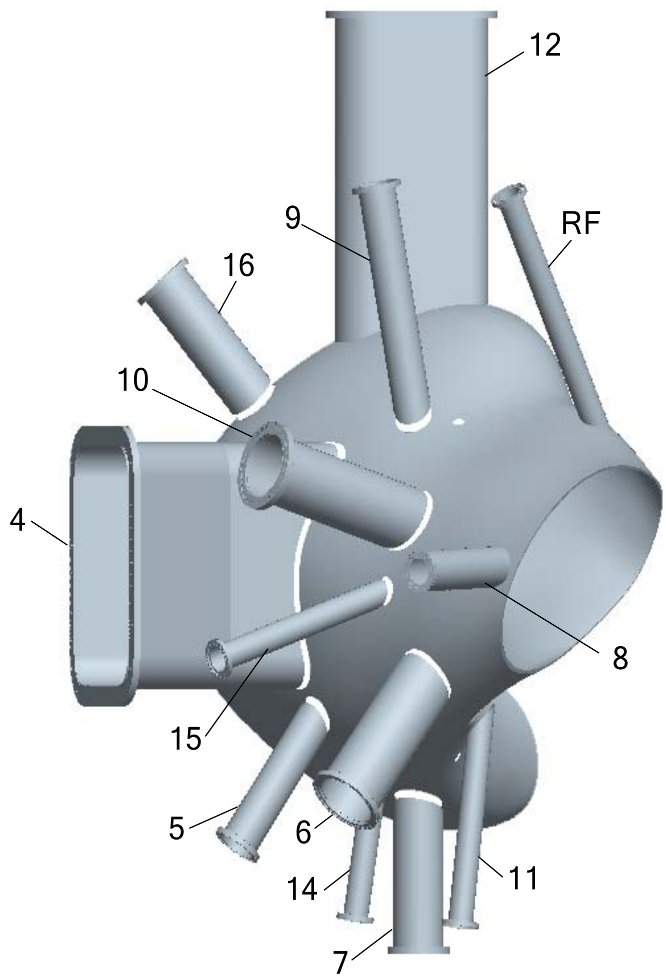


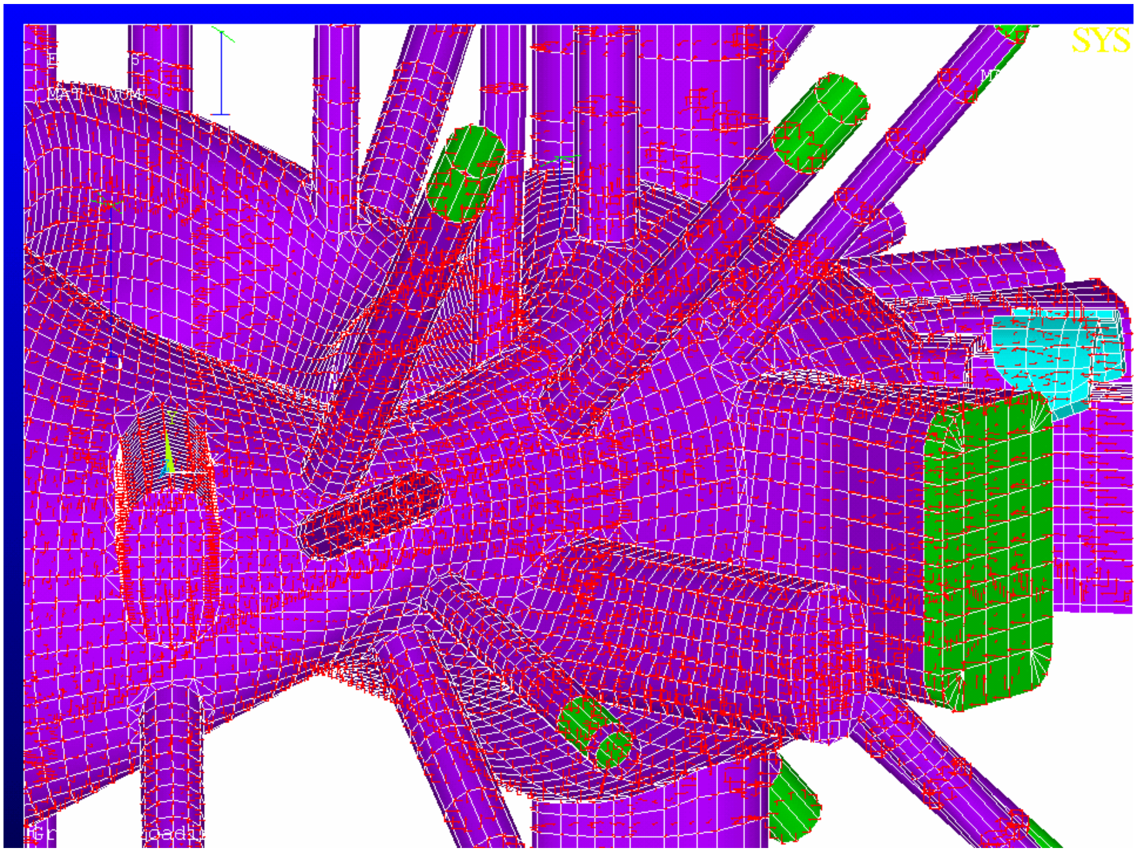


Vessel Port Inertia

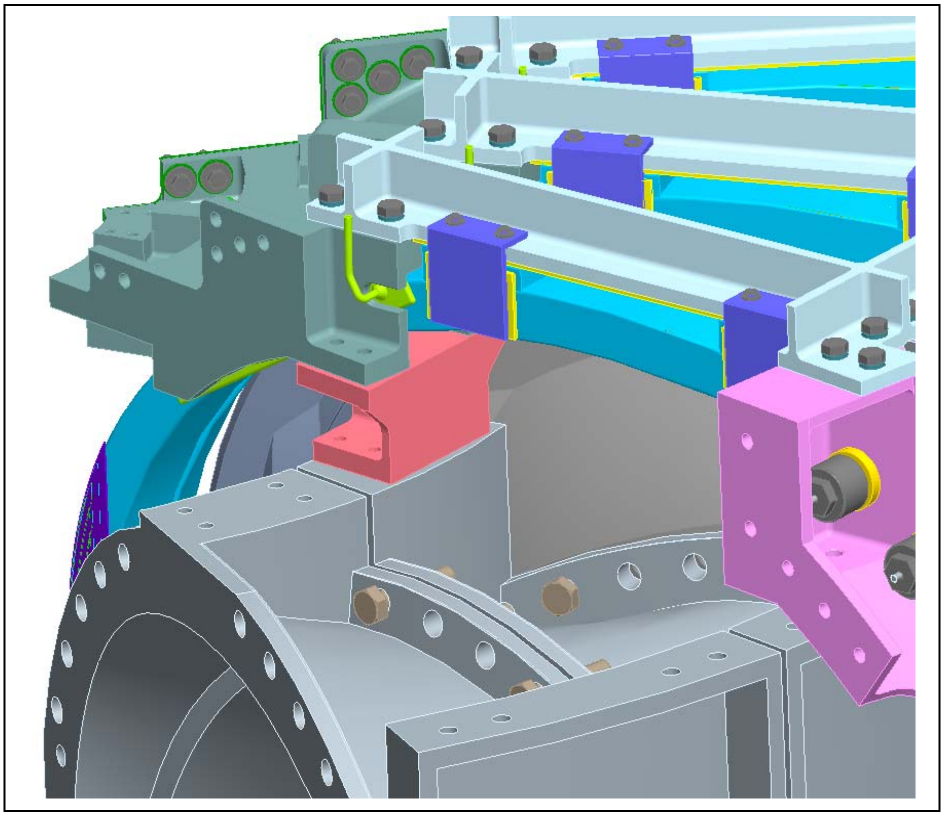


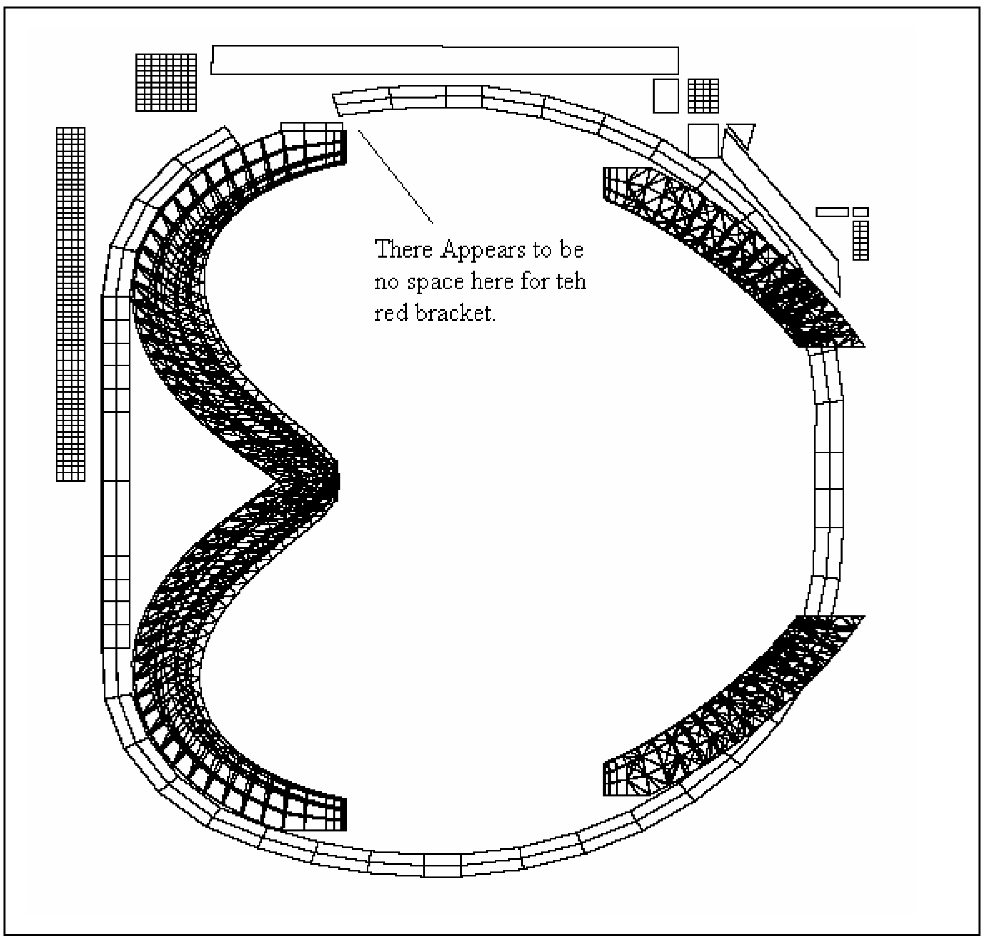
In Runs 7 and later, the ports were extended a meter in length, and a separate material at the end of the port was added to allow a density increase that would model about 200 lbs at the end of the duct. The length of the denser material is .25m and the normal density was multiplied by 10. The shell and port thickness has been taken as 1cm throughout.





Vessel static analysis with vacuum nodal forces shown. This was analyzed in run#6. Cooldown behavior was also studied in this run.

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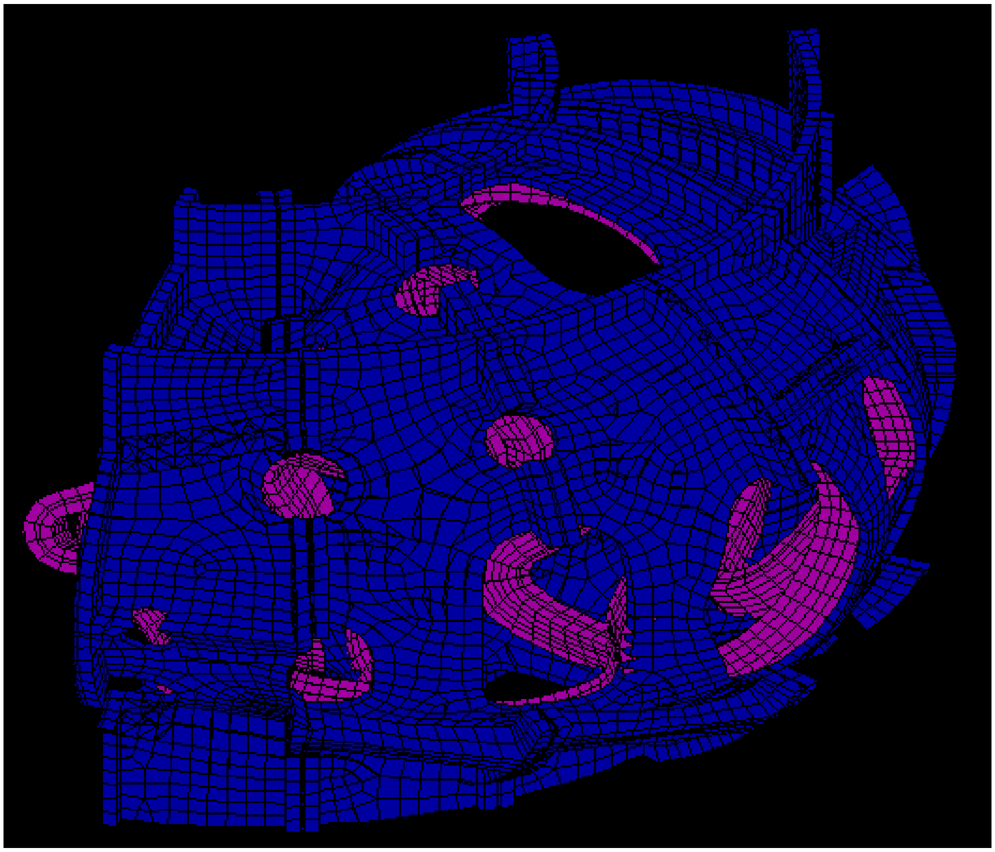


The modular coils are not explicitly modeled in the seismic analysis. Their mass is lumped with the support shell. In this model segments provided by H.M. Fan, the coil volume is 0.8906 m^3 and the support shell volume is 1.50228m^3. The shell density is increased by the factor (1.50228+.8906)/1.50228 to account for the coil mass

Run Log

Run#	Date	Analysis Type	Description
4	5-9-04	Spectrum	8 modes extracted
5	5-12-04	Static	Cooldown, Deadweight
6	5-11-04	Static	Vacuum Vessel Pressure, Deadweight and Cooldown
7	5-12-04	Spectrum	Port Extensions added, 10 Modes
8	5-12-04		12 Modes Extracted, no gaps in nested columns
9	5-14-04	Static	Cooldown, Deadweight
10	5-16-04	Spectrum	14 Modes Extracted

9.0 Displacement Results

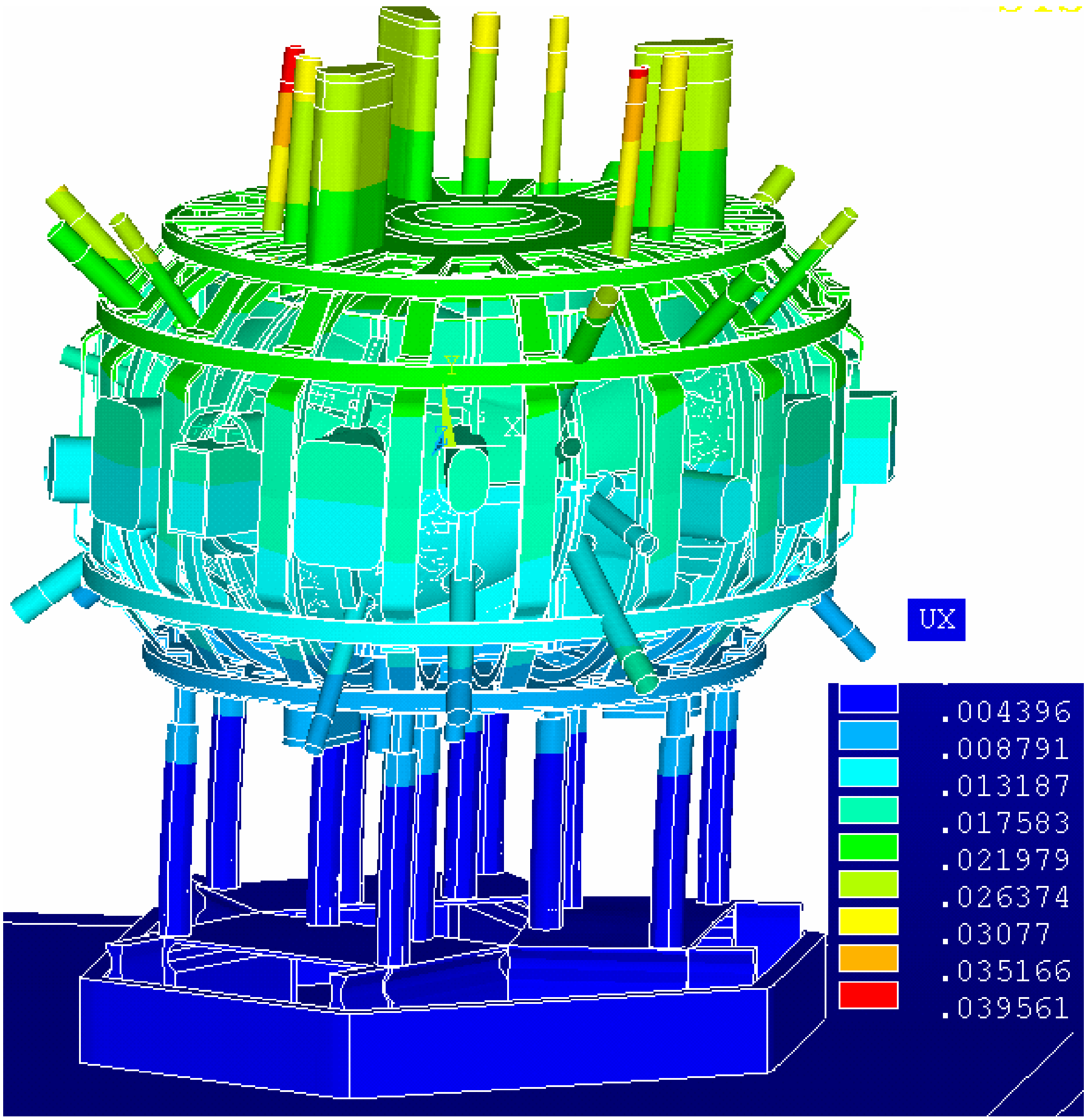


Figure 9.0-1 Spectrum Analysis Lateral Displacement Results, Run#7. This is with a single horizontal response spectrum applied. Results for run#10, in which 4 more modes contributed to the response, the peak displacement went up to 03995m

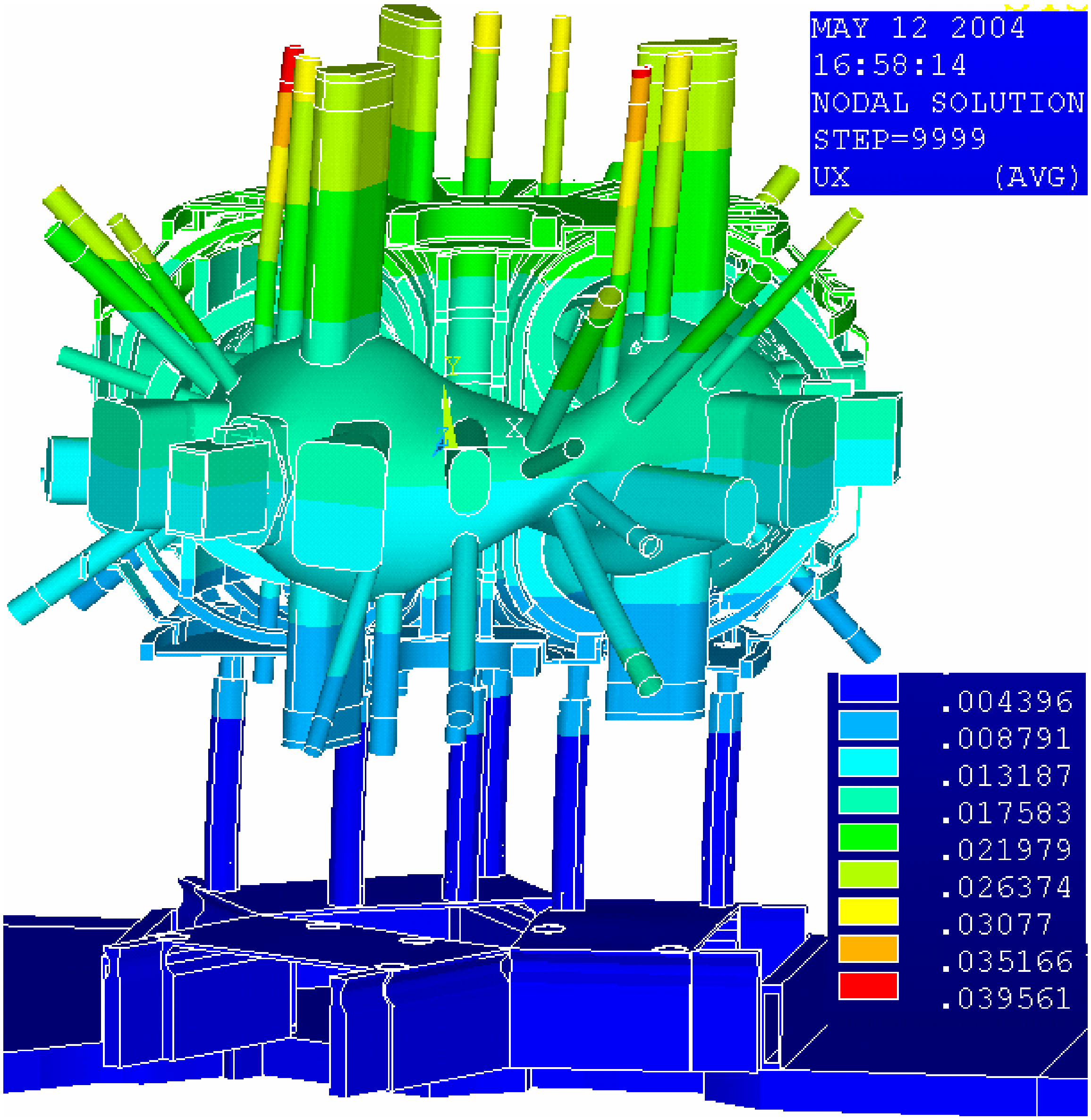


Figure 9.0-2 Spectrum Analysis Lateral Displacement Results, Run#7, With half the coil structure cut away to show vessel relative displacements. This is the SRSS combination of mode shapes. Interesting relative displacements may also be found in the modal deformations section, section 12.0 in which the individual mode displacements are presented.

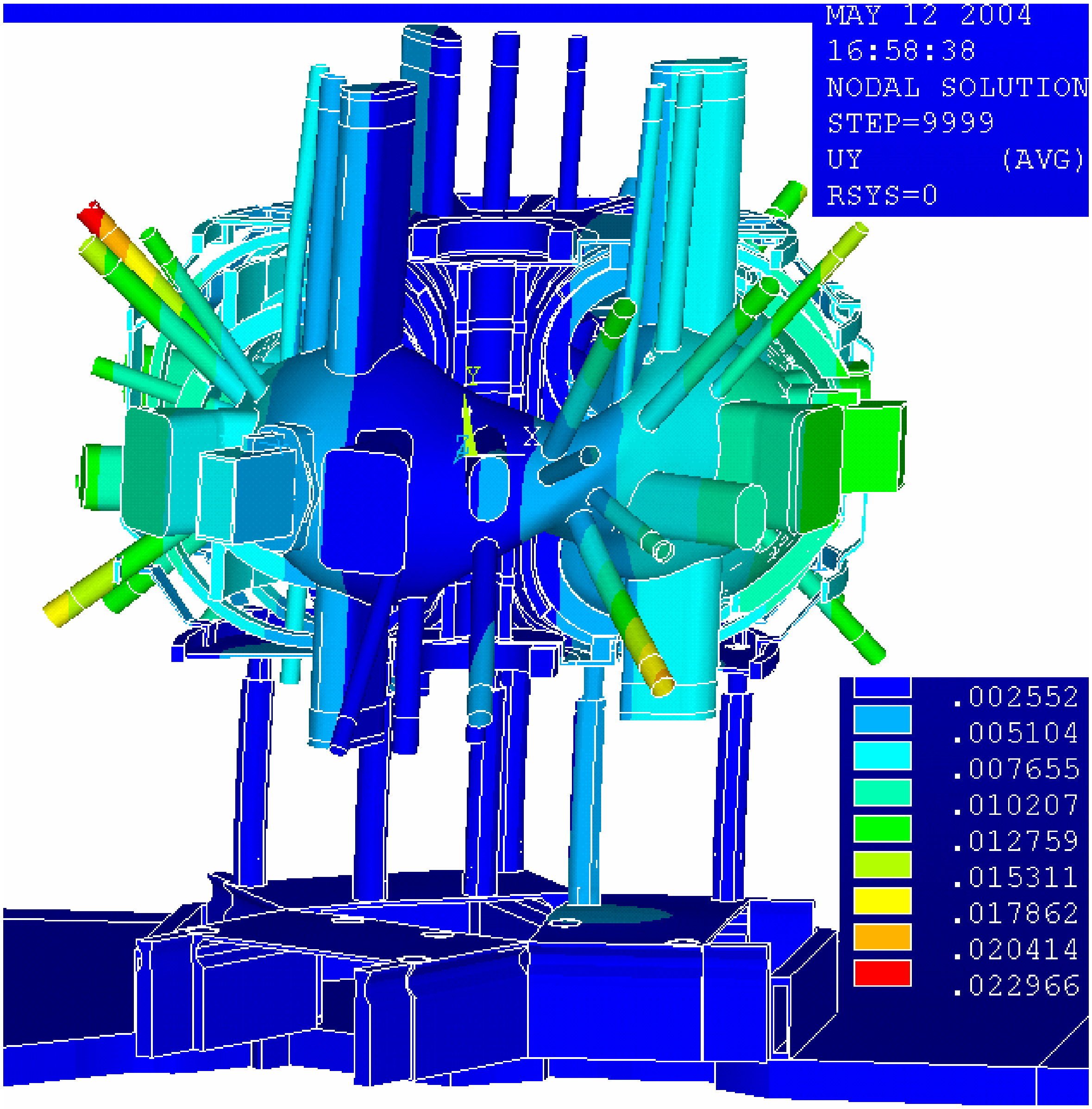
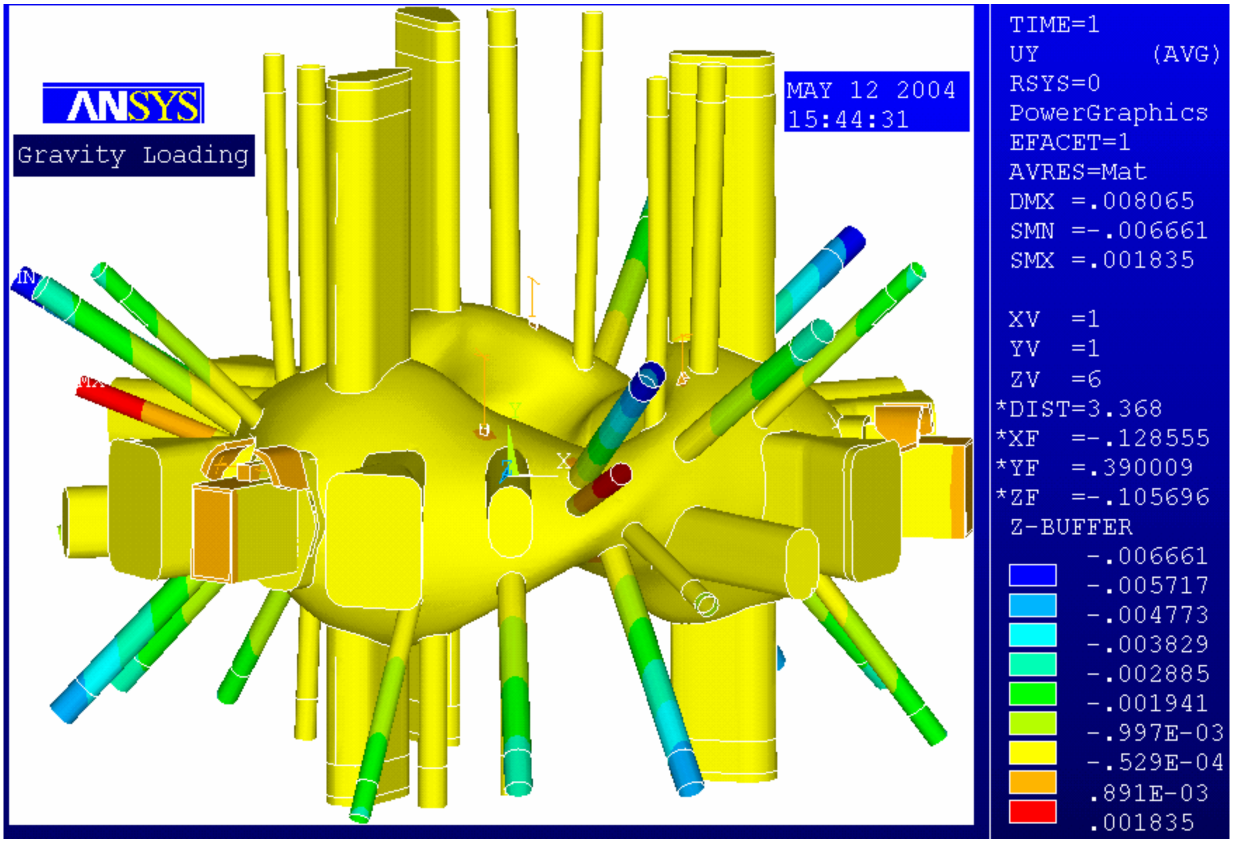


Figure 9.0-3 Spectrum Analysis Vertical Displacement Results, Run#7, With half the coil structure cut away to show vessel relative displacements. This is the SRSS combination of mode shapes. Interesting relative displacements may also be found in the modal deformations section, section 12.0 in which the individual mode displacements are presented.



Vessel and port displacements under deadweight only. Note the interesting behavior of the ports at the reduced region of the vessel where downward displacement of one port causes the upward motion of a neighboring port.

10.0 Stress Results
10.1 Vessel Stresses

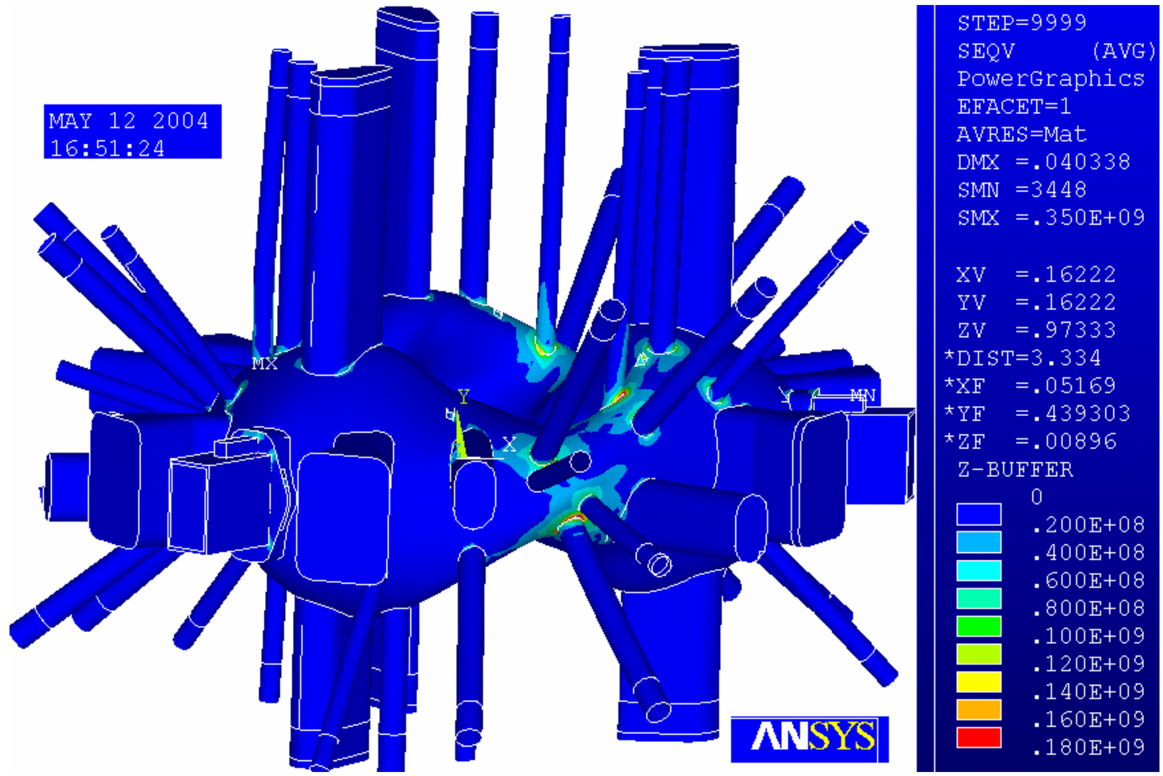


Figure 10.1-1 Spectrum Analysis Results – Single Horizontal Direction

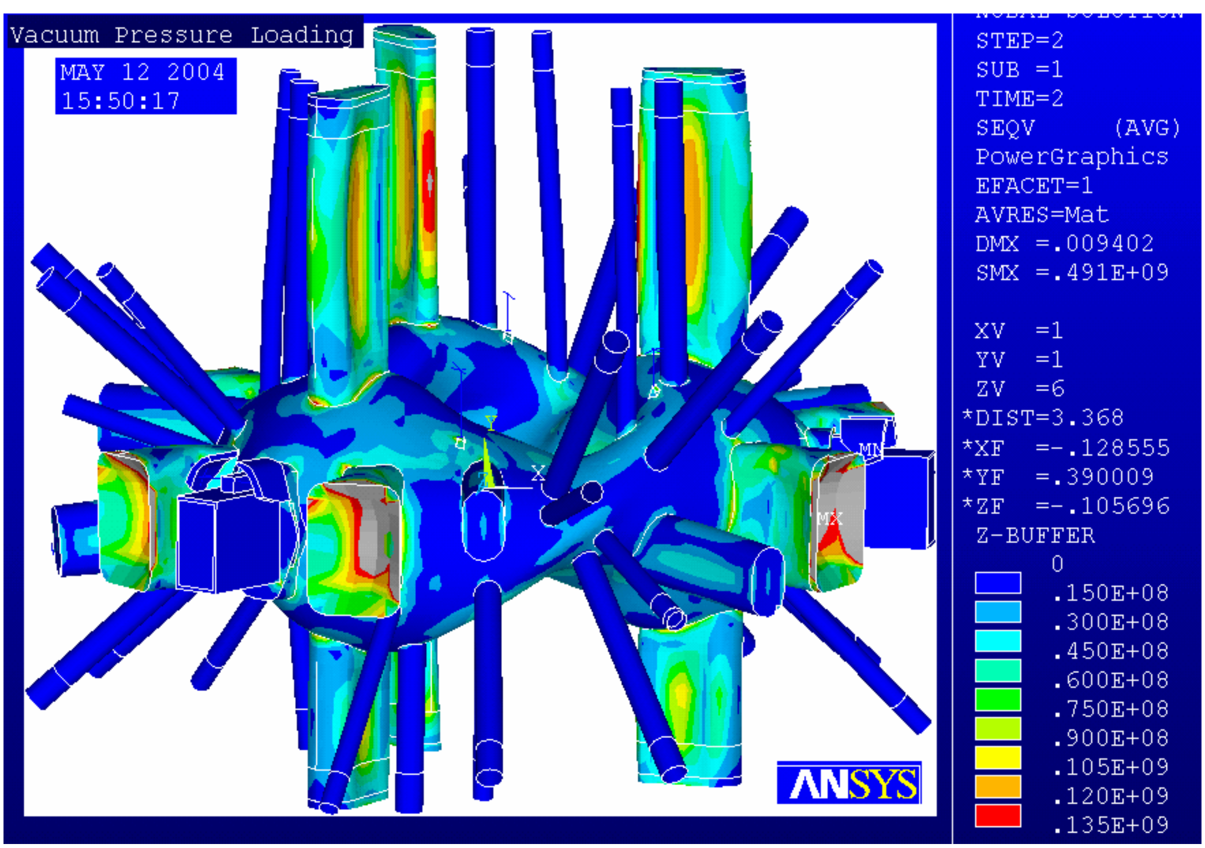


Figure 10.1-2 Vacuum Pressure Loading Stresses

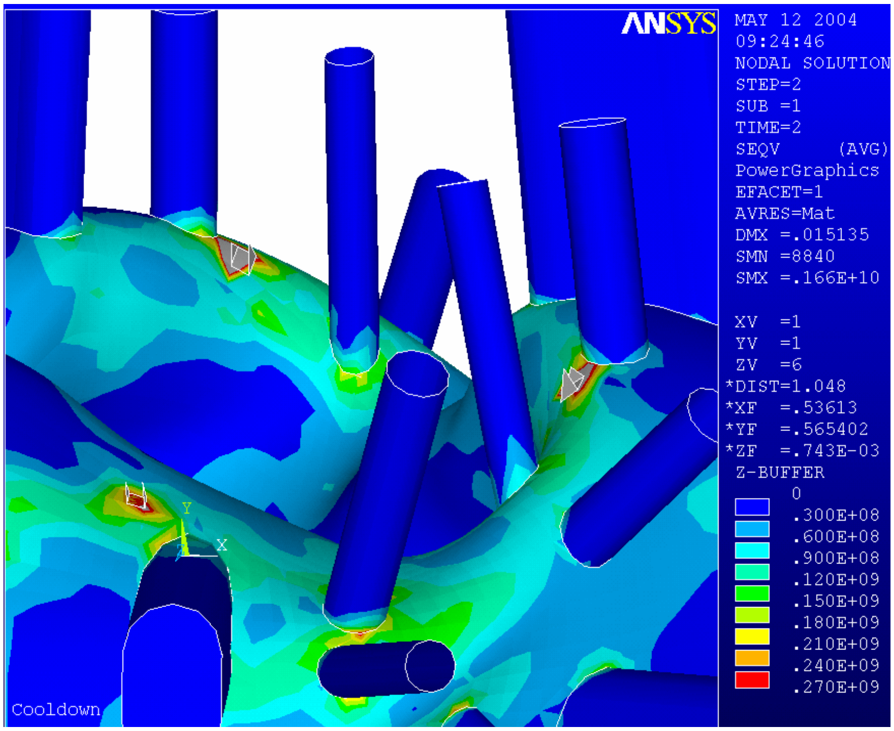


Figure 11.0-3 Stresses in the Vacuum Vessel from only cooldown. These result from different length hangers, and also include shell rotations.

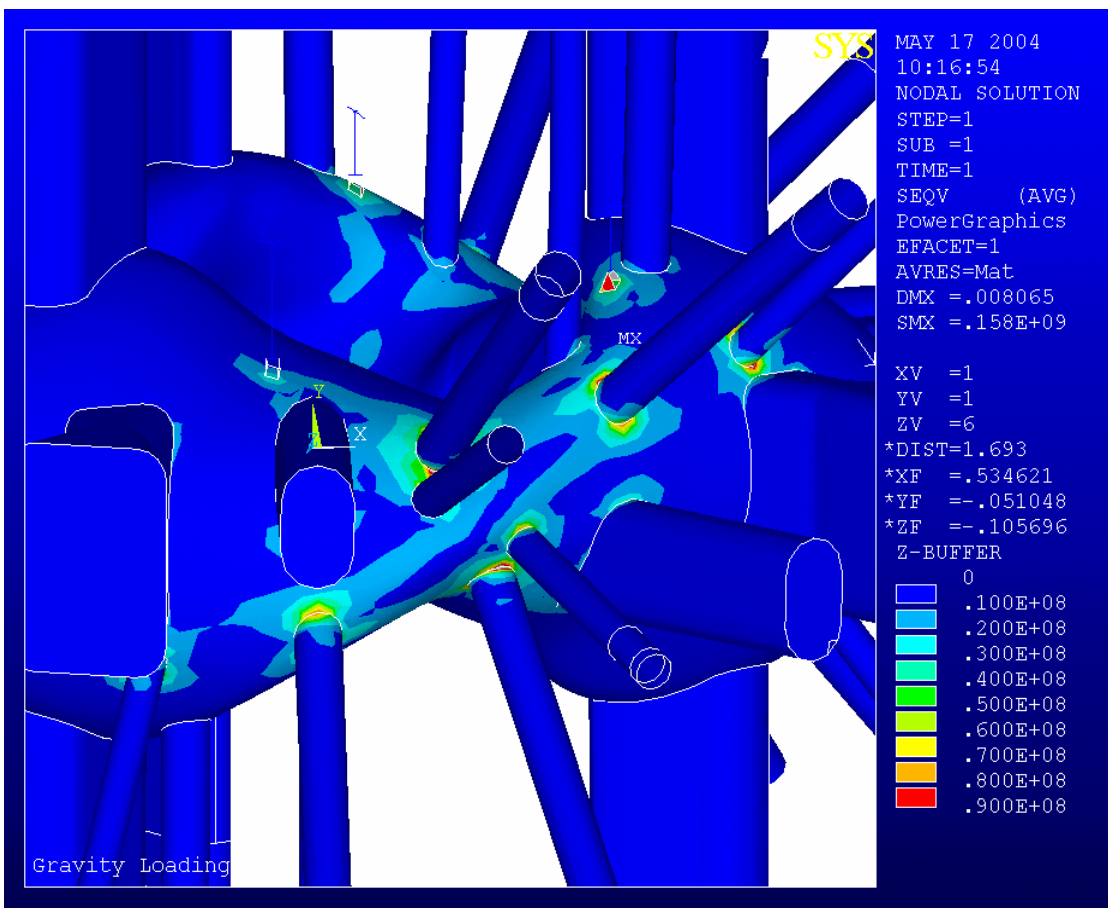


Figure 10.1-4 Deadweight Stress in the vessel

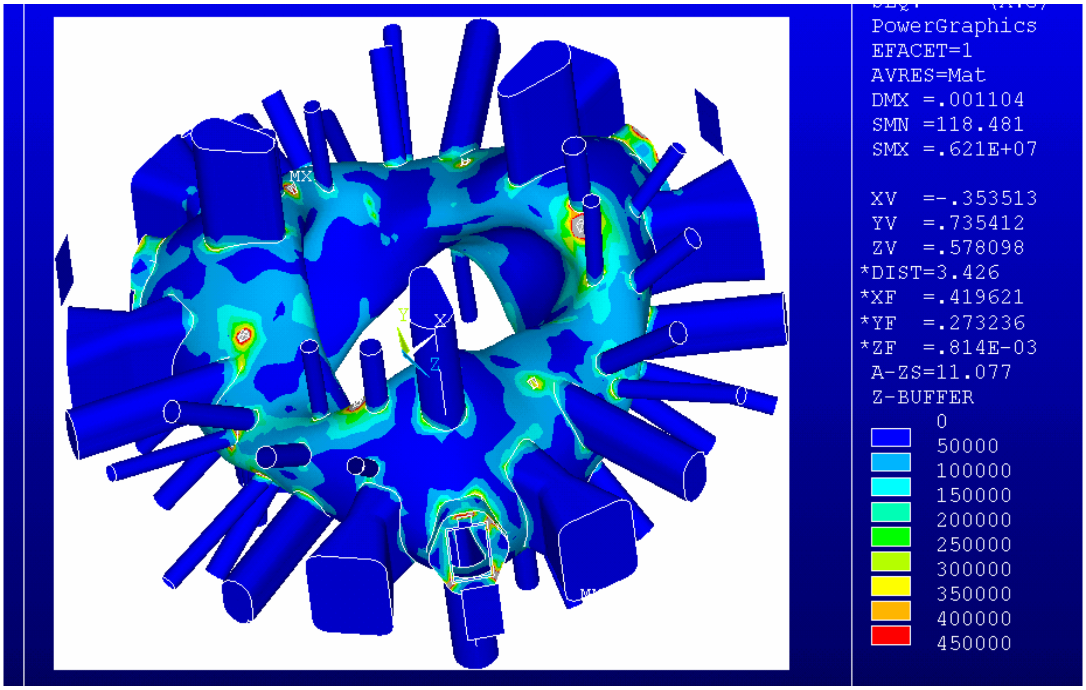


Figure 10.1-5 Spectrum Analysis Results from an earlier analysis in which the port extensions and inertias were not modeled. In this run, the seismic stresses in the vessel due to hanger dynamic loads. This run needed the ARS to be scaled up by 9.8 and 2. The peak stress would then be 8.8 MPa, compared with 18 MPa at the port/vessel interface shown in figure 10,0-1

10.2 Modular Coil Case

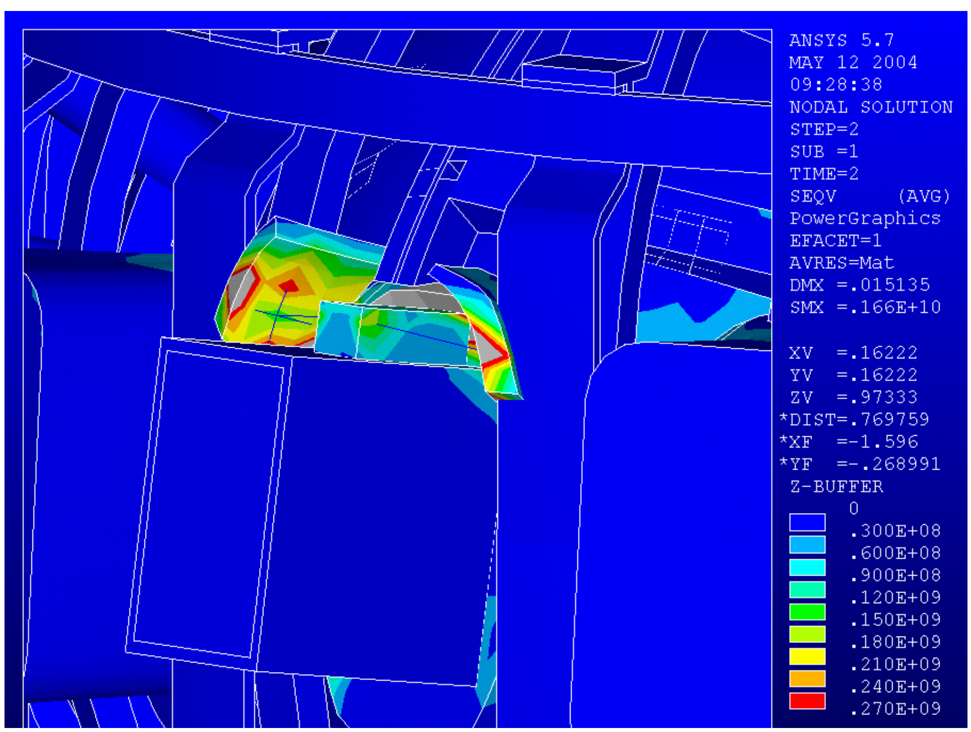


Figure 10.2-1 Stress due to cooldown – If lateral restraints are hard up against the port lug prior to cooldown. A one-sided radius rod type restraint might be wiser.

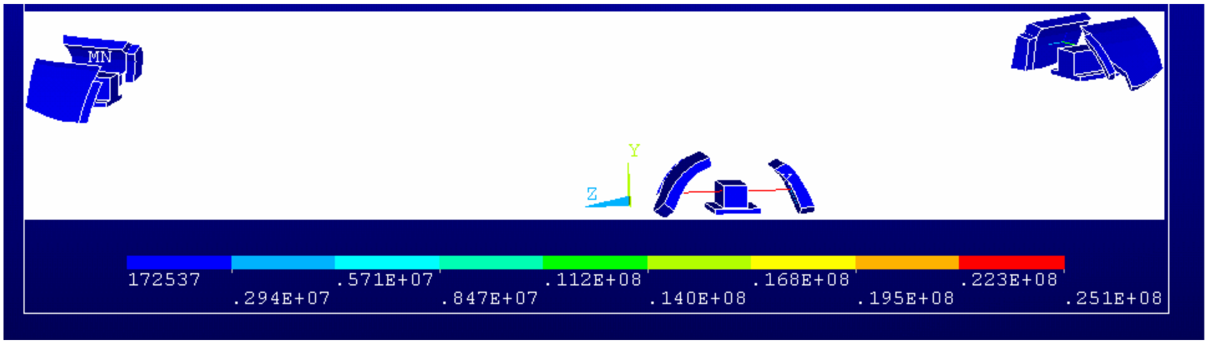


Figure 10.2-2 Restraint Link Stresses. These are modeled as having a 1 square in cross section. These are modeled as taking tension and compression, but the design appears to allow only compression. The load at each restraint is :25.1e6/6895*2* 1.0in^2= 7251.6 lbs

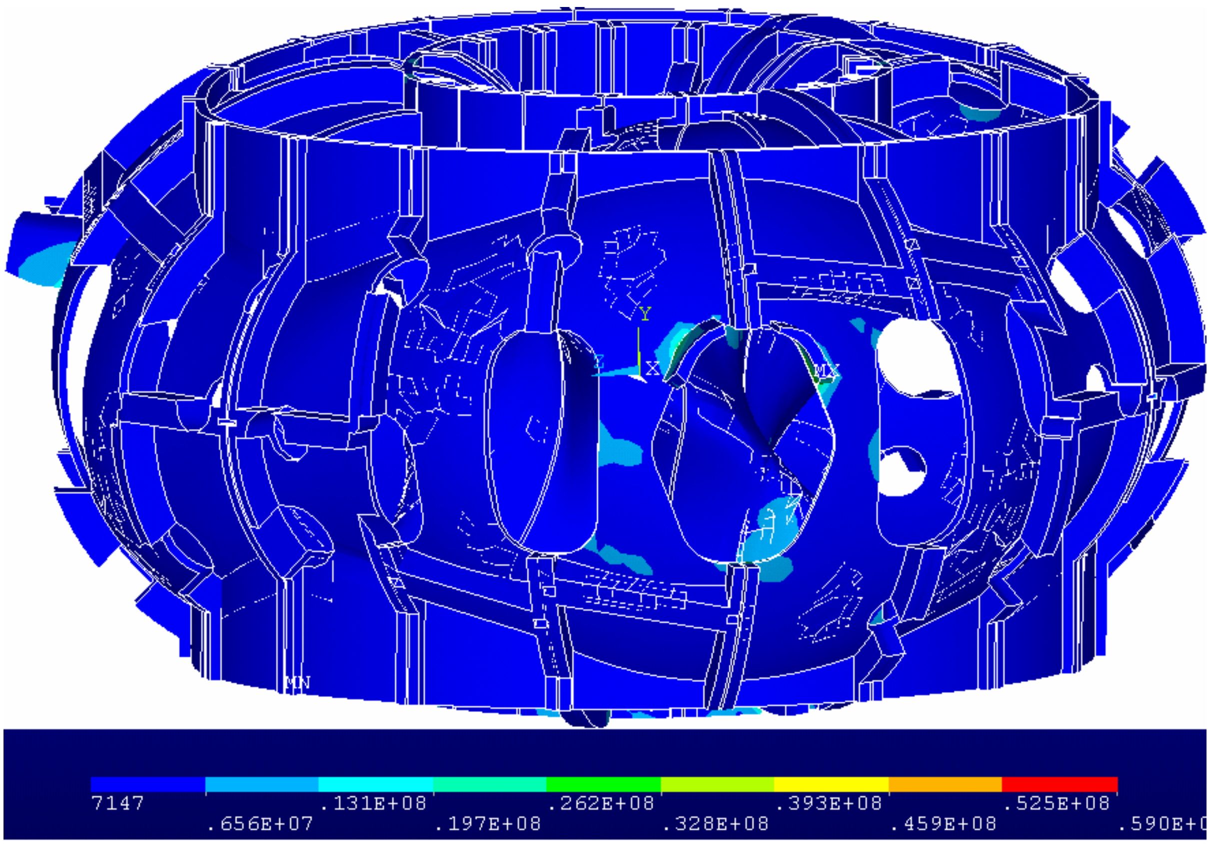


Figure 10.2-3 Modular Coil Shell Stress. The only appreciable stress is in the vessel lateral support brackets. As long as the thermal stress is improved, the bracket stresses do not appear to be a problem. The major loading of this shell are the modular coil Lorentz forces. The areas of the shell which support these stresses are essentially un effected by the seismic loading.

10.3 Support Columns

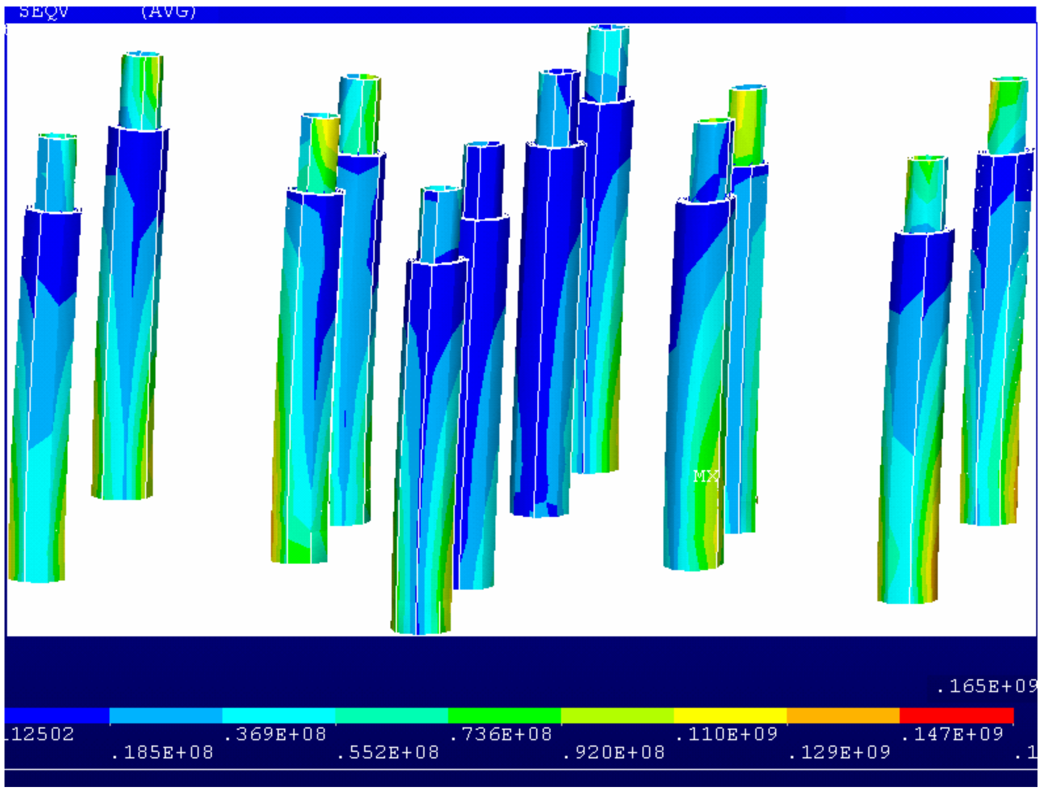


Figure 10.3-1 Spectrum Analysis Results, Single Horizontal Direction ARS, run#7. Run #7 had 10 modes extracted. This analysis was re-run with 14 modes extracted in run#10 and the peak stress went from 165 MPa to 167 MPa.

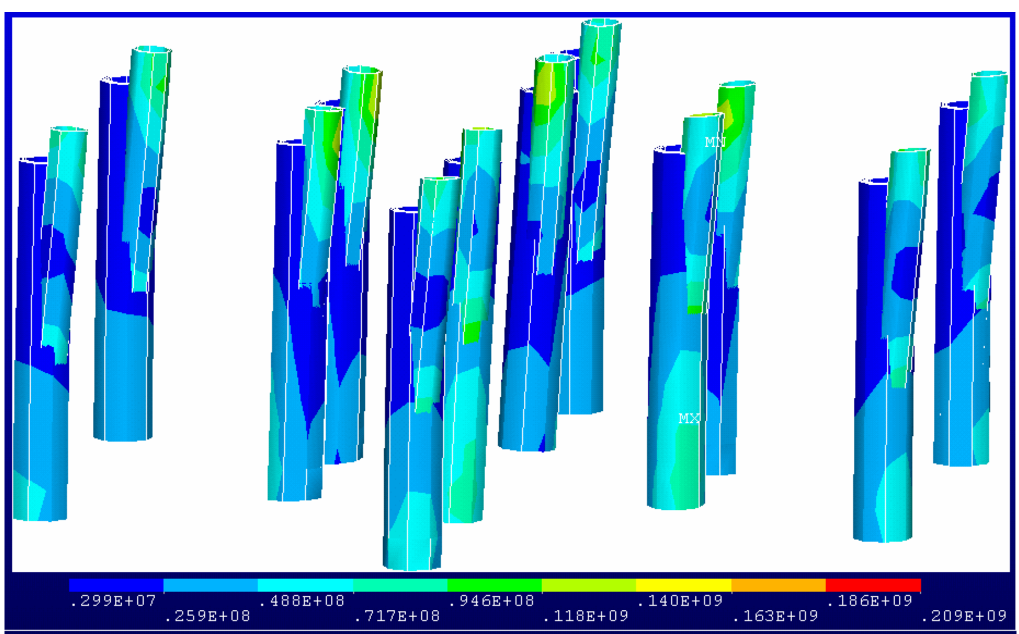


Figure 10.3-2 Spectrum Analysis Results, Single Horizontal Direction ARS, run#8. This is for the case where the gap at the top pf the column, between nested cylinders is not filled.

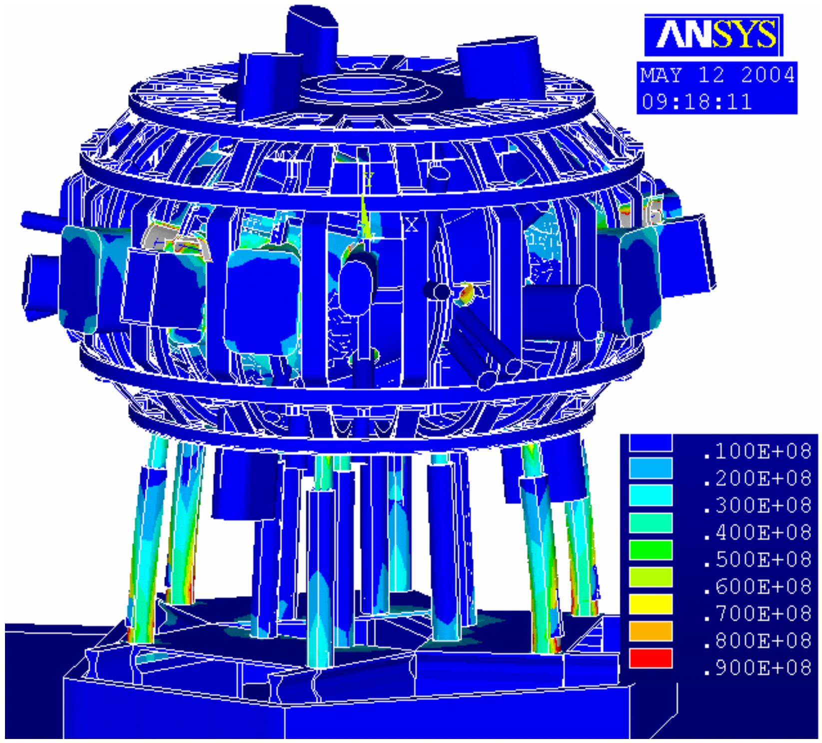


Figure 10.3-3 Run #5 Cooldown to LN2 Temperature

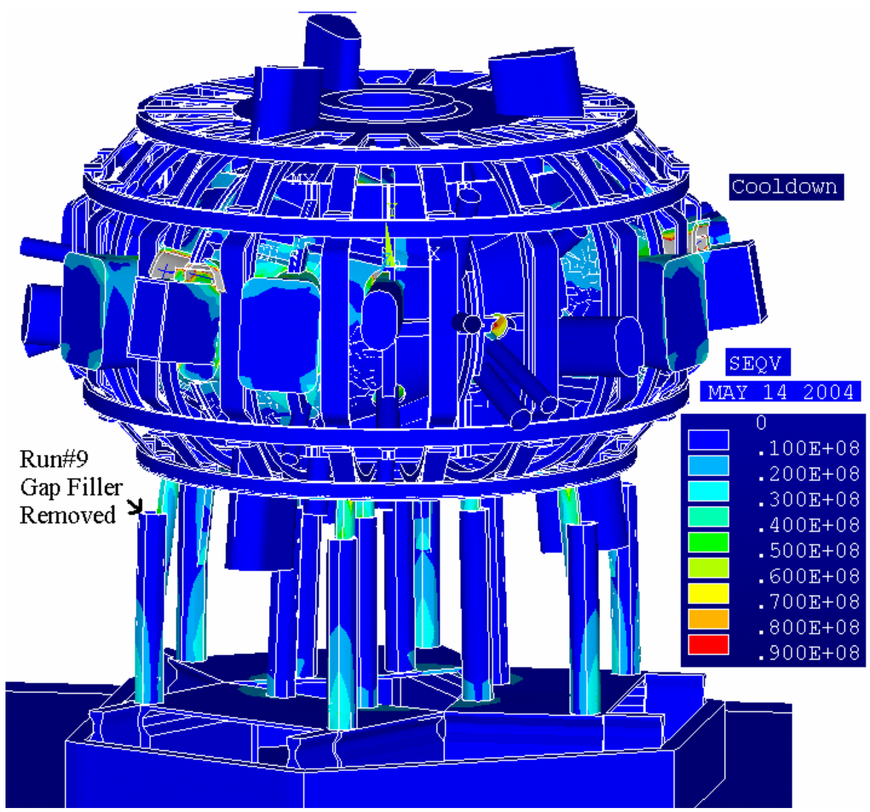
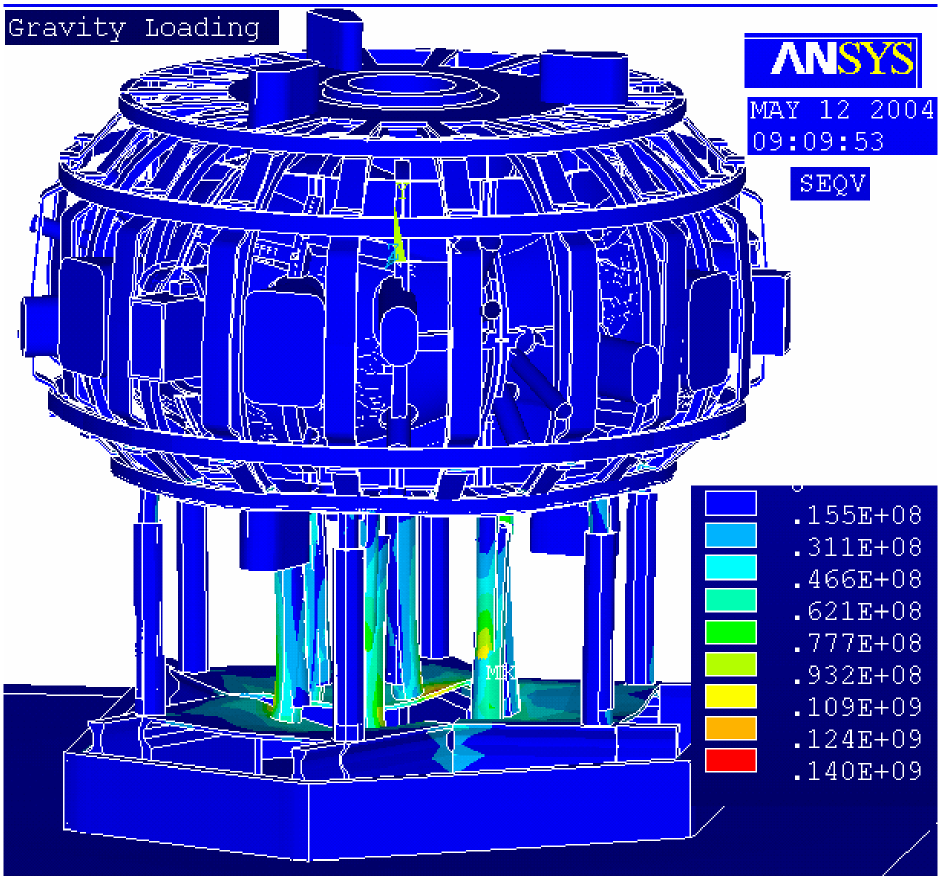
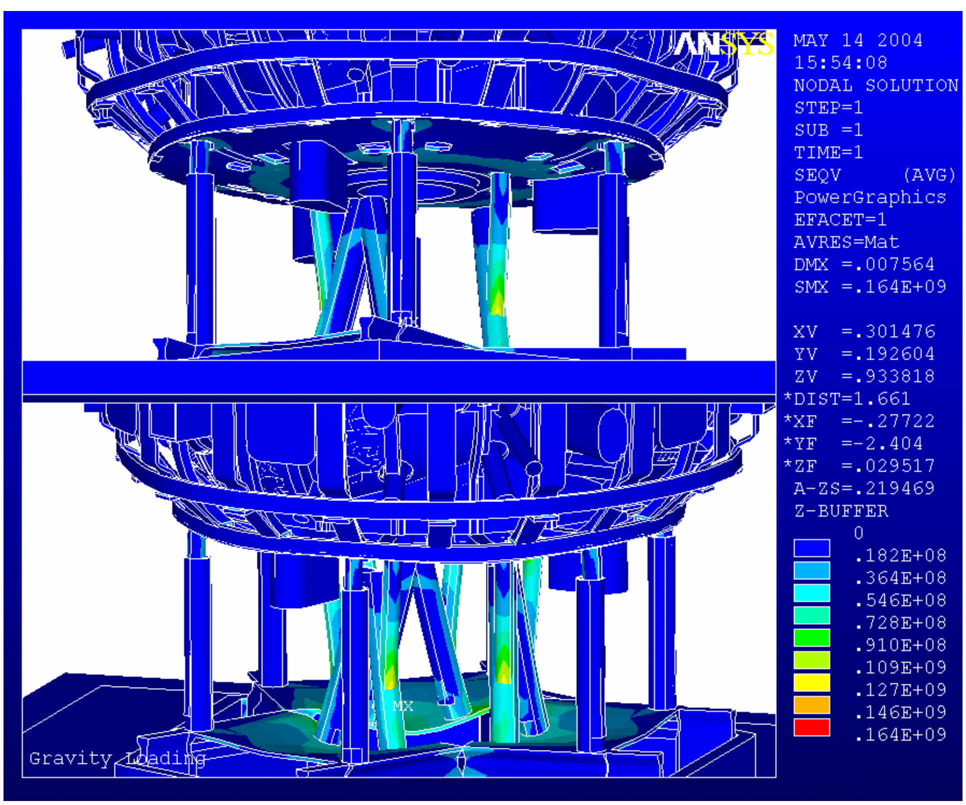


Figure 10.3-4 Run #5 Cooldown to LN2 Temperature



Run #5 Deadweight from the Static Analysis



Run #9 Deadweight from the Static Analysis – Column Gap Filler Removed

11.0 Modes and Mode Shapes

With the addition of the port extensions and the added mass at the end of the ports, mode shapes involving port motion predominated. Earlier runs show more of the mode shapes involving global motion. Figure 11.0-1 shows the vertical mode which was around 10 hz.

	Run#	Frequency cps	Description
1	7	2.105	Rocking Mode
2	7	2.618	Rocking
3	7	3.11	Global Twist about a Vertical Axis
4	7	4.692	Vessel Port Rotation
5	7	4.743	Vessel Port Rotation
6	7	4.84	Vessel Port Rotation
7	7	4.8625	Vessel Port Rotation
8	7	4.886	Vessel Port Rotation
9	7	5.021	Vessel Port Rotation
10	7	5.29	Vessel Port Rotation

***** PARTICIPATION FACTOR CALCULATION *****
RUN#7 X (HORIZONTAL) DIRECTION CUMULATIVE

MODE	FREQUENCY	PERIOD	PARTIC.FA CTOR	RATIO	EFFECTIVE MASS	MASS FRACTION
1	2.10470	0.47513	-0.30572	0.000954	0.0934649	0.866092E-06
2	2.61764	0.38202	320.45	1.000000	102690.	0.951575
3	3.11108	0.32143	-0.086956	0.000271	0.756134E-02	0.951575
4	4.69222	0.21312	1.9722	0.006155	3.88971	0.951611
5	4.74312	0.21083	-0.82273	0.002567	0.676892	0.951617
6	4.84035	0.20660	-45.370	0.141581	2058.42	0.970692
7	4.86256	0.20565	3.3938	0.010591	11.5181	0.970798
8	4.88580	0.20467	-56.133	0.175168	3150.91	0.999996
9	5.02102	0.19916	0.24012	0.000749	0.576581E-01	0.999997
10	5.29082	0.18901	0.57879	0.001806	0.334998	1.00000
		SUM OF	EFFECTIVE	MASSES=	107916.	

***** PARTICIPATION FACTOR CALCULATION *****
Y DIRECTION (VERTICAL) CUMULATIVE RUN#7

MODE	FREQUENCY	PERIOD	PARTIC.FACTOR	RATIO	EFFECTIVE MASS	MASS FRACTION
1	2.10470	0.47513	-0.29200	0.009149	0.0852669	0.740569E-04
2	2.61764	0.38202	-6.6399	0.208029	44.0881	0.0383660
3	3.11108	0.32143	-0.55075	0.017255	0.303324	0.0386294
4	4.69222	0.21312	31.918	1.000000	1018.77	0.923460
5	4.74312	0.21083	-0.32076	0.010049	0.102885	0.923549
6	4.84035	0.20660	-1.6432	0.051480	2.69995	0.925894
7	4.86256	0.20565	1.2547	0.039310	1.57428	0.927261
8	4.88580	0.20467	-3.1297	0.098053	9.79475	0.935768
9	5.02102	0.19916	8.5937	0.269241	73.8511	0.999910
10	5.29082	0.18901	0.32139	0.010069	0.103291	1.00000
		SUM OF	EFFECTIVE	MASSES=	1151.37	

***** PARTICIPATION FACTOR CALCULATION *****
RUN#7 Z (HORIZONTAL) DIRECTION CUMULATIVE

MODE	FREQUENCY	PERIOD	PARTIC.FACTOR	RATIO	EFFECTIVE MASS	MASS FRACTION
1	2.10470	0.47513	342.15	1.000000	117068.	0.965828
2	2.61764	0.38202	0.26121	0.000763	0.0682315	0.965828
3	3.11108	0.32143	-4.5350	0.013254	20.5662	0.965998
4	4.69222	0.21312	0.10075	0.000294	0.0101496	0.965998
5	4.74312	0.21083	-59.436	0.173713	3532.65	0.995143
6	4.84035	0.20660	1.2189	0.003562	1.48565	0.995155
7	4.86256	0.20565	-12.510	0.036564	156.508	0.996446
8	4.88580	0.20467	-1.1359	0.003320	1.29018	0.996457
9	5.02102	0.19916	-0.052562	0.000154	0.00276280	0.996457
10	5.29082	0.18901	20.723	0.060566	429.438	1.00000
		SUM OF	EFFECTIVE	MASSES=	121210.	

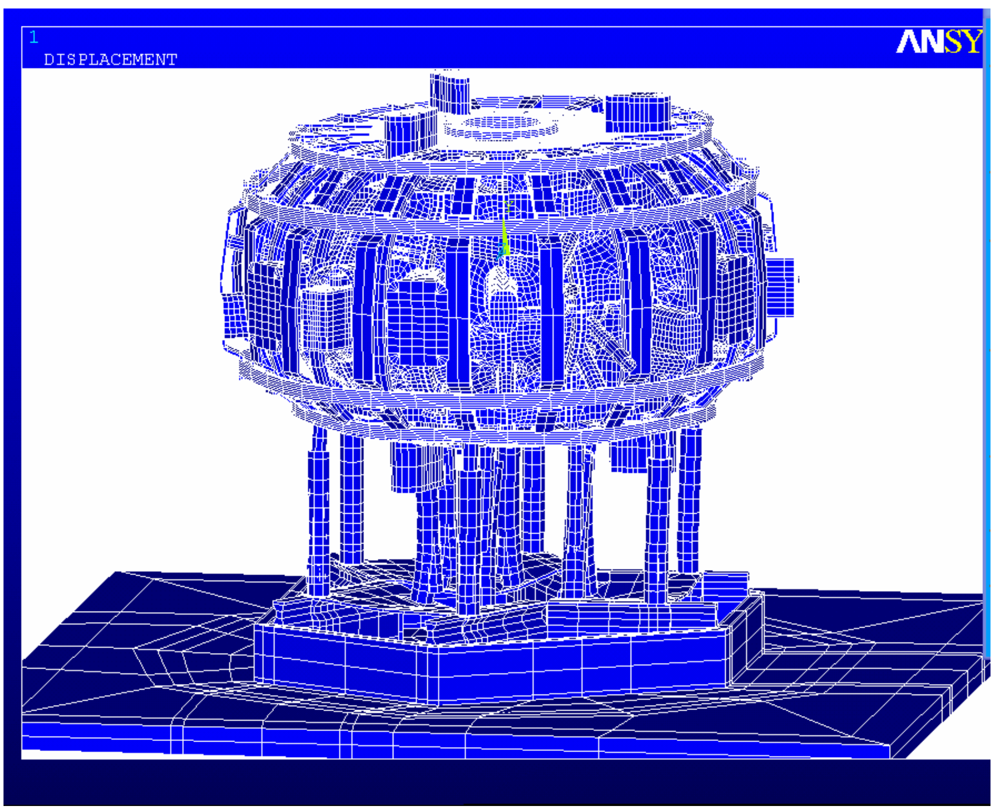
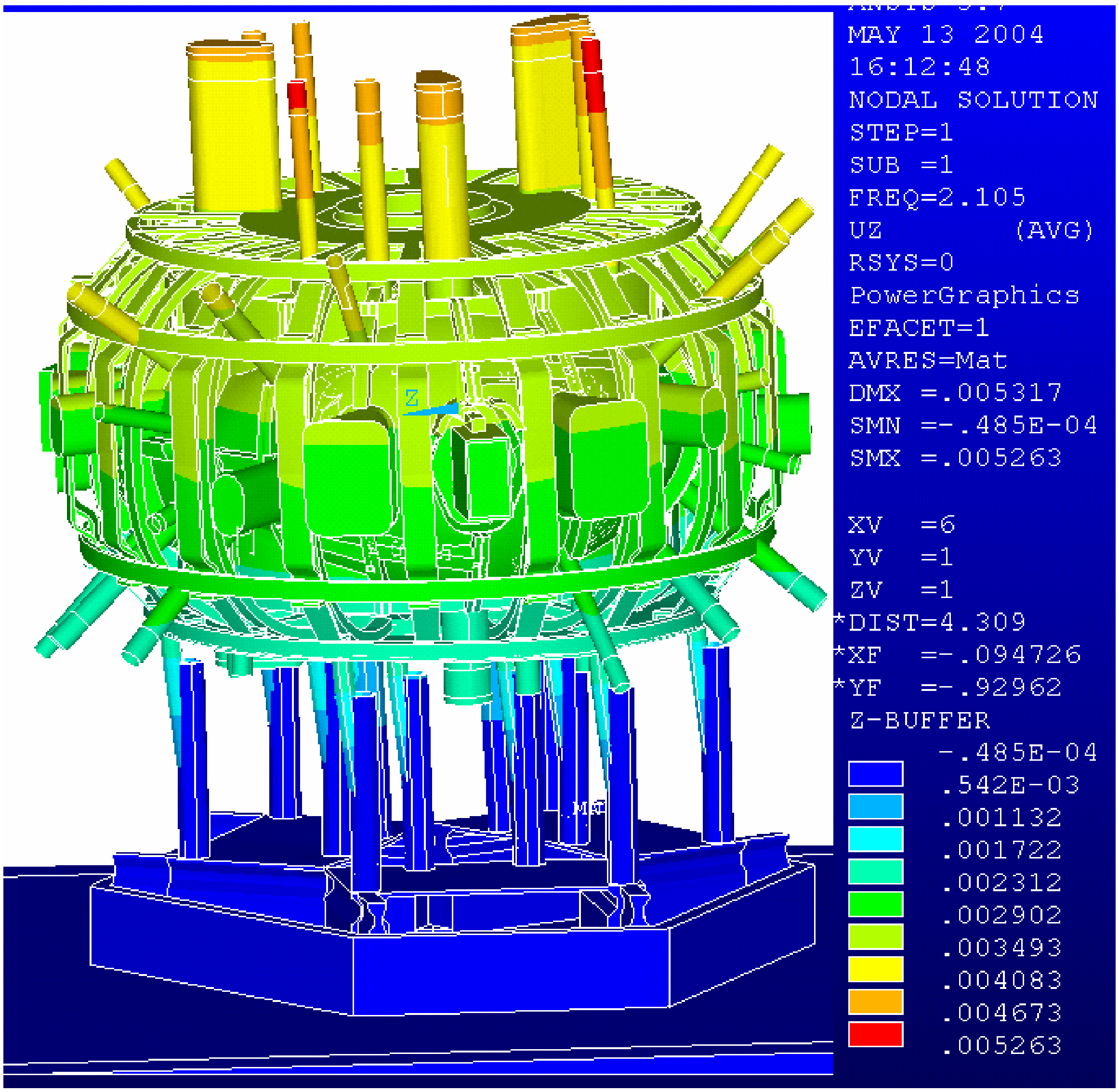
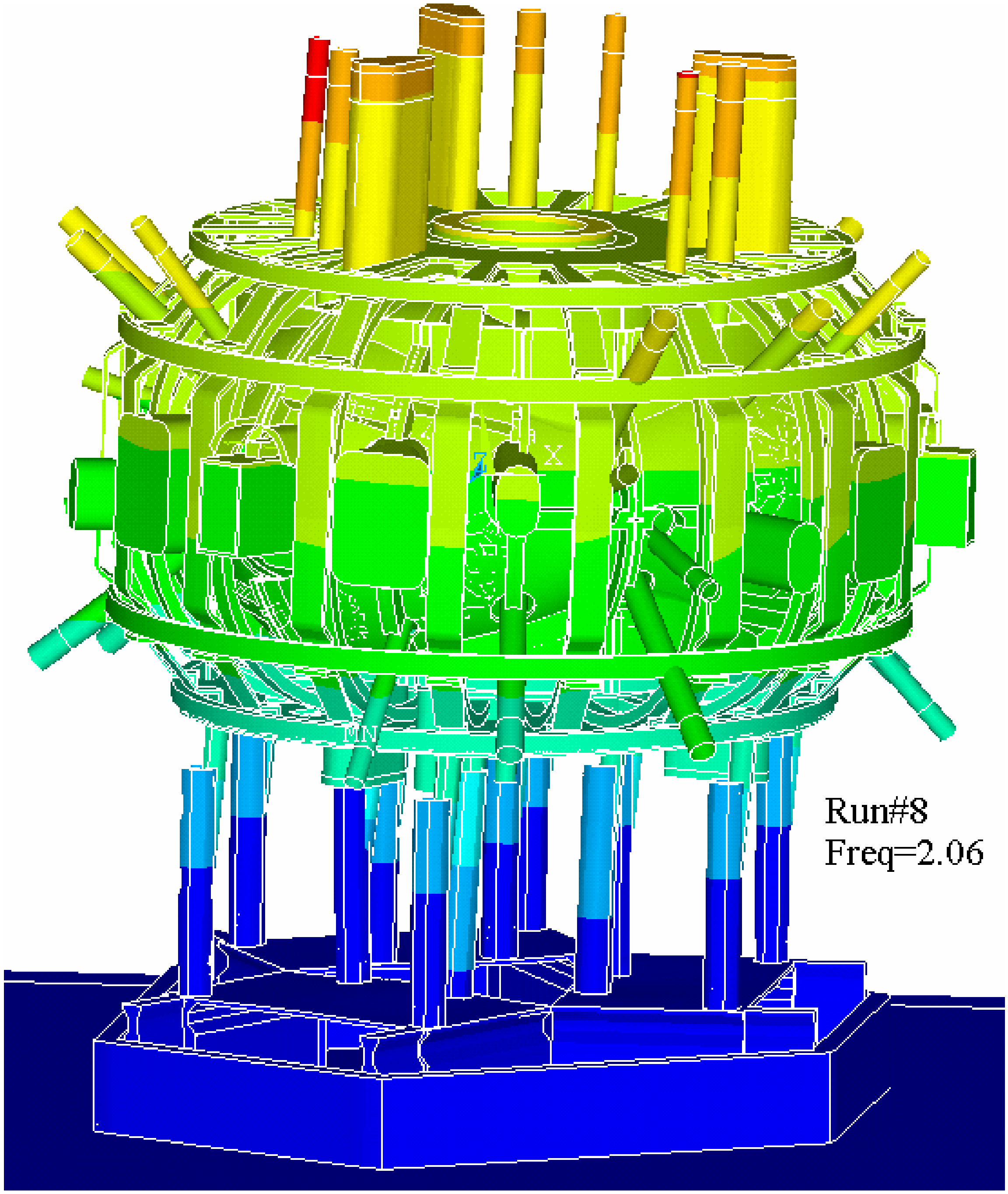


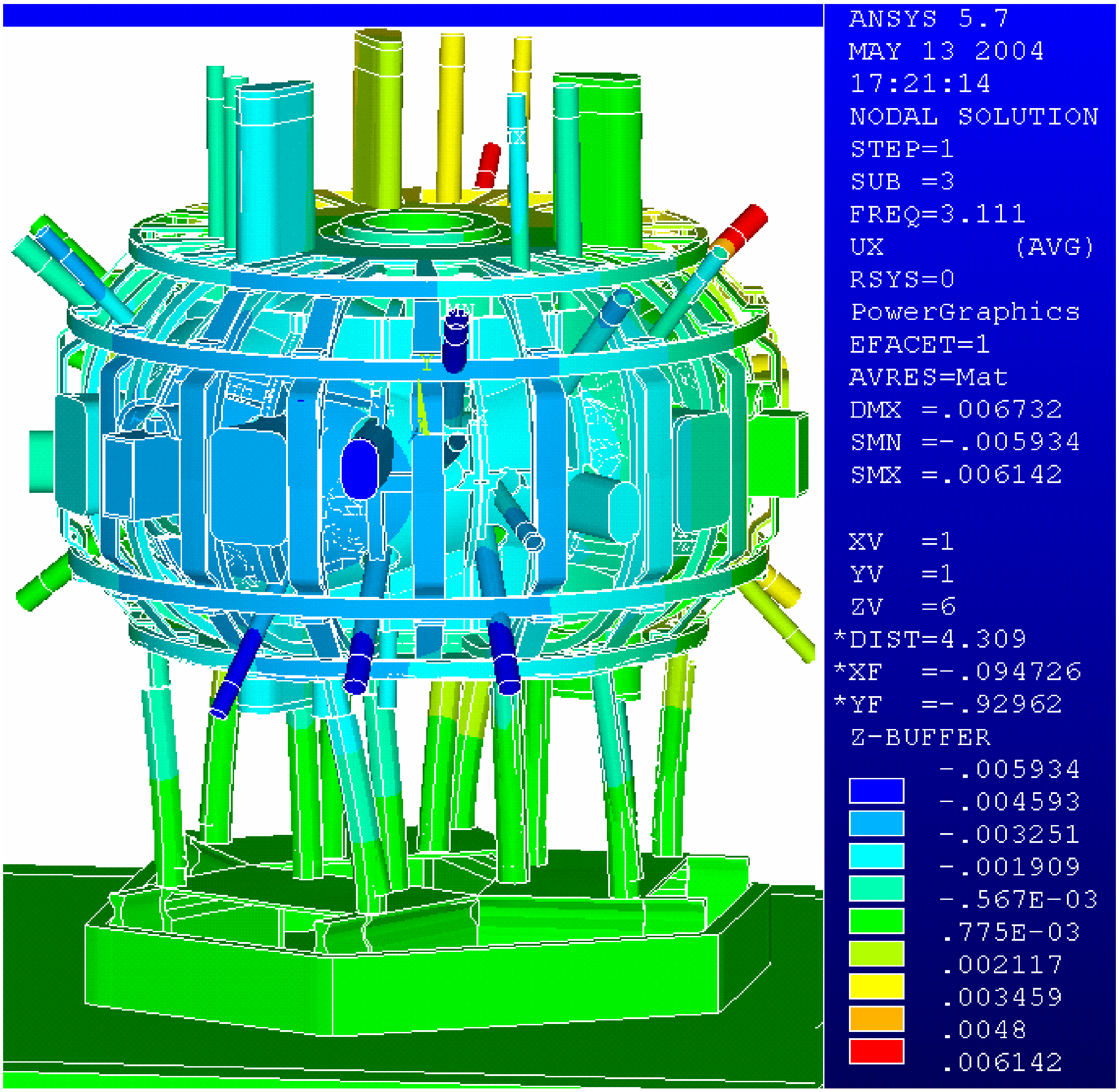
Figure 11.0-1 Mode 6 Vertical This was around 10 hz.



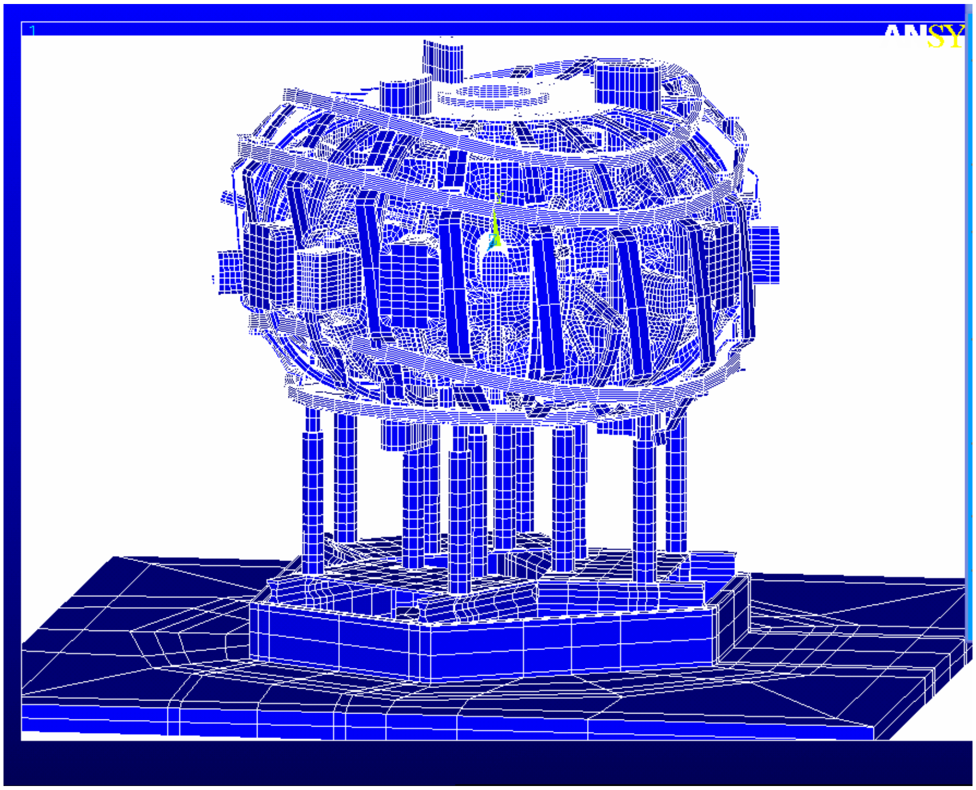
Run #7 First Mode, Global translation in Z. Displacements are not multiplied by the modal participation factor



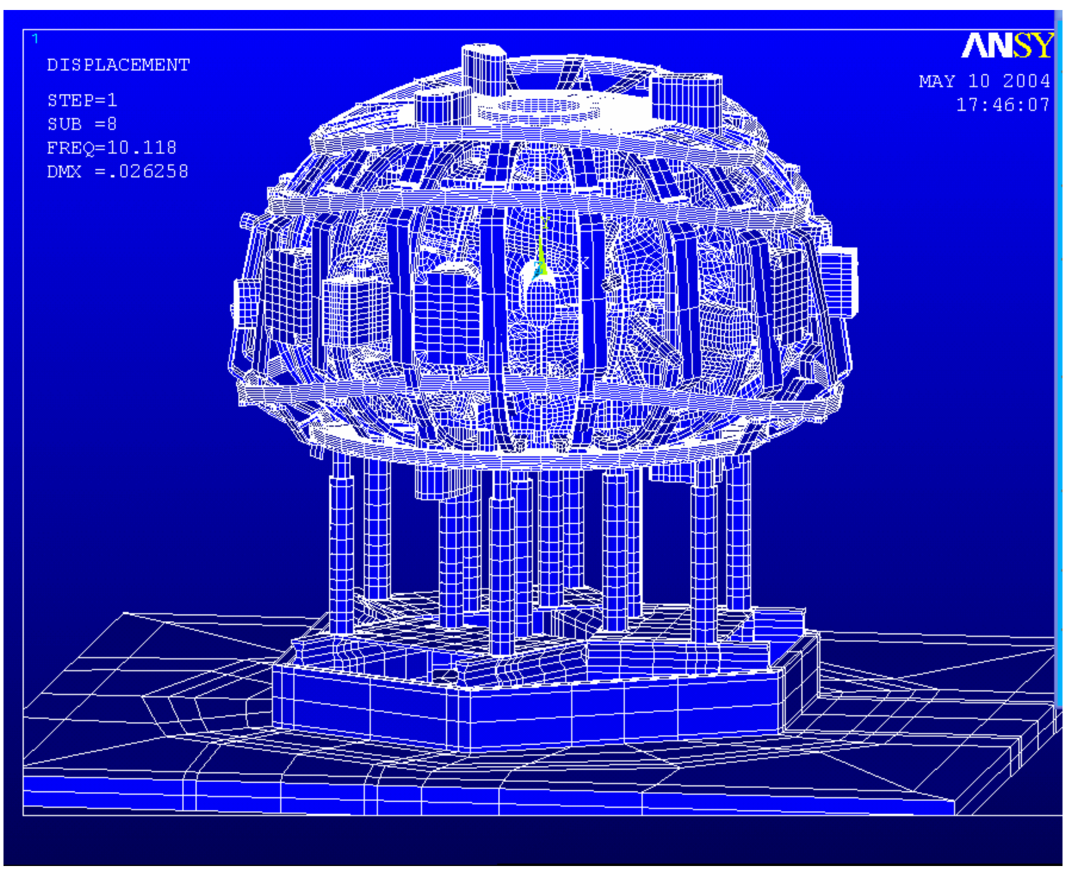
Run #8 First Mode, Global translation in X



Mode Three – Global Twist about a Vertical Axis



Mode 7 Run #4



Mode 8, Run #4 Before Port Extensions

12.0 Modal Deformations

(Later)