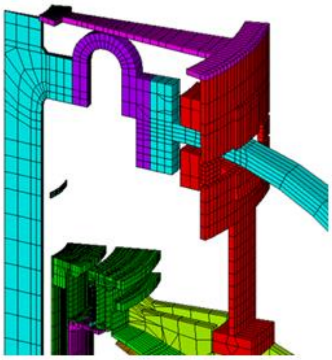
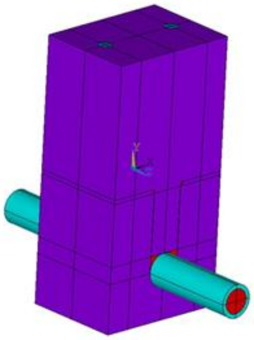
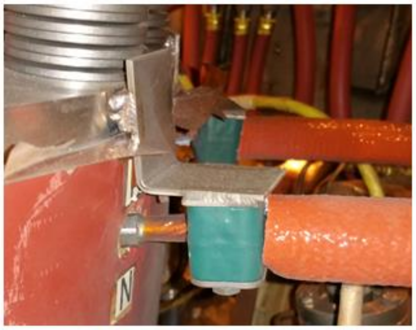
OH Grounding Strap and Centerstack Casing Copper Cooling Tube Evaluations

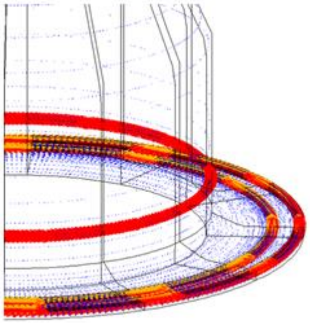
NSTXU-CALC-133-20-0

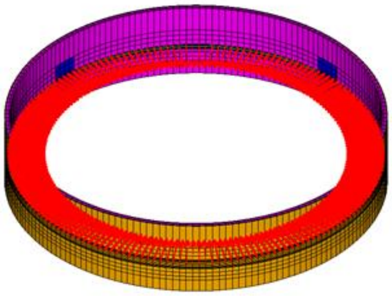
Date October 28 2016

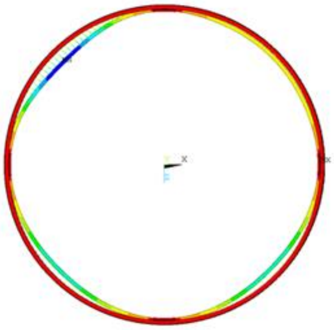












Prepared by P. Titus	Reviewed by
Peter H. Titus Digitally signed by Peter H. Titus DN: cn=Peter H. Titus, o, ou=Princeton Plasma Physics Laboratory, email=ptitus@pppl.gov, c=US Date: 2017.03.21 13:36:15 -04'00'	Han Zhang Digitally signed by Han Zhang DN: cn=Han Zhang, o=PPPL, ou, email=hzhang@pppl.gov, c=US Date: 2017.04.26 12:35:06 -04'00'
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Section 9.0 Prepared by P. Titus Peter H. Titus Digitally signed by Peter H. Titus DN: cn=Peter H. Titus, o, ou=Princeton Plasma Physics Laboratory, email=ptitus@pppl.gov, c=US Date: 2017.03.21 13:36:31 -04'00'	Reviewed by Han Zhang Digitally signed by Han Zhang DN: cn=Han Zhang, o=PPPL, ou, email=hzhang@pppl.gov, c=US Date: 2017.04.26 13:27:15 -04'00'

PPPL Calculation Form

Calculation # **NSTXU-CALC-133-20-00** Revision # **00** ____ WP #, **1672**
(ENG-032)

Purpose of Calculation: (Define why the calculation is being performed.)

The purpose of this calculation is to evaluate currents induced in the OH ground strap as installed and as upgraded. Additionally induced currents in the centerstack casing inner divertor vertical section copper cooling tubes are calculated. These tubes have either failed under load, been crushed, or failed due to corrosion.

References (List any source of design information including computer program titles and revision levels.)

These are included in the body of the calculation, in section 6.3

Assumptions (Identify all assumptions made as part of this calculation.)

Calculation (Calculation is either documented here or attached)

These are included in the body of the following document

Conclusion

The toroidally continuous ground strap originally installed in NSTXU picked up eddy currents from the OH flux swing and disruptions which worked it loose and caused it to arc against the OH water connections. Currents were in the range of 2000 amps and loads in the range of 2000 lbs (vertical). Startup currents have a significant load reversal during the "blip" or plasma initiation. Centerstack Casing Cooling loops also pick up currents caused by flux changes during start-up and disruptions, and also experience the load reversal. Inward buckling calculations indicate the tubes should have survived start-up and even severe disruptions, if the refrigerator tubes avoided annealing during the bake-out. Bake-out temperatures have probably degraded the yield properties of the tubes to the point where Collapse during a disruption is possible but probably not a start-up transient . Additional OH ground plate was analyzed for disruptions and found adequate. The OH water inlet high voltage support was analyzed for the electrostatic field imposed during a normal Hipot. Recommendations were made for geometric refinements that would improve the local electrostatic field. Partial discharges are still possible at the Hipot voltage level of 17.3kV. Filling gaps with dielectric compounds is recommended but should be left to the discretion of the responsible electrical engineer.

Cognizant Engineer's printed name, signature, and date

S. Raftopoulos (Magnet Related) ____________________

M. Sibilia (Vessel or Centerstack Casing Related)____________________

I have reviewed this calculation and, to my professional satisfaction, it is properly performed and correct.

Checker's printed name, signature, and date

Han Zhang, 4/26/2017

2.0 Table of Contents

3.0 Revision Status Table

Rev 0	Initial Issue

4.0 Executive Summary

During the initial startup activities of NSTX-U, a couple of major incidents interrupted operations. The first was an arc fault in April of 2015 that was related to a ground strap that had been installed forming a continuous toroidal loop. The strap carried an induced current which in turn developed Lorentz loads that pushed the strap against a coolant line. . Another incident occurred during the 2016 run period in which PF1au developed a water leak and caused a short. During this second event it was found that the copper cooling tubes . inside the centerstack casing had been mangled and would pose a threat to operations. In this calculation, some of the analyses done to support evaluations of these events, are presented. Analyses of some of the repairs and design improvements are also included

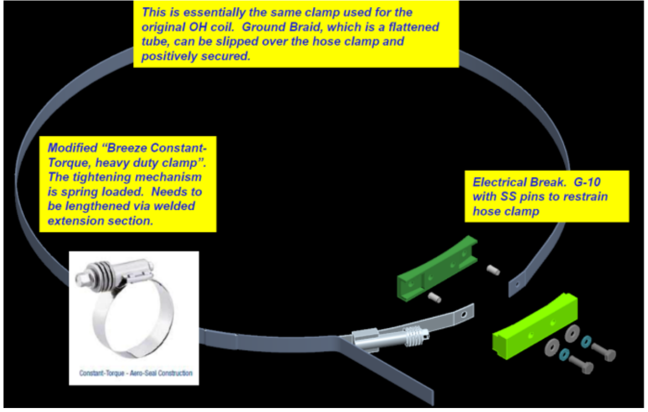
4.1 Induced Currents in the failed ground strap

From the corrective Action plane [2]:

"On April 24, PPPL ESU responded to alarms from the NSTX-U experimental area. An active water leak from NSTX-U was observed. Staff discovered that several of the Ohmic Heating coils external cooling paths were damaged at the top end of the OH coil. Additionally, indications of electrical arcing were observed in the vicinity of the water leaks. Initial inspection showed no damage to the OH or other coil systems. The water was secured and investigation into the cause was initiated."

The cause was found to be a ground strap that was intended to connect the ground plane of the OH coil to the appropriate ground circuit. Unfortunately it was installed without a proper break in the loop formed when wrapping the woven cable around the coil. Addressed in this calculation are calculations of induced currents in the ground strap to aid in the fault assessment. The replacement ground strap does not form a loop.

The EMAG simulation of a start-up produced similar loads to the estimates based on the loop voltage. The small difference is likely the different modeling of the effective conduction cross section of the strap. One interesting thing the simulation shows is there is a sharp load reversal at the OH "blip". The simulation loads went from +512lbs to -714 lbs in .05 seconds. This would have a sizeable dynamic cyclic loading on the strap and would have a tendency to work it loose.


This is essentially the same clamp used for the original OH coil. Ground Braid, which is a flattened tube, can be slipped over the hose clamp and positively secured.

Modified "Breeze Constant-Torque, heavy duty clamp". The tightening mechanism is spring loaded. Needs to be lengthened via welded extension section.

Electrical Break. G-10 with SS pins to restrain hose clamp

Figure 4.0-1 Replacement Ground Loop With Correct Insulator

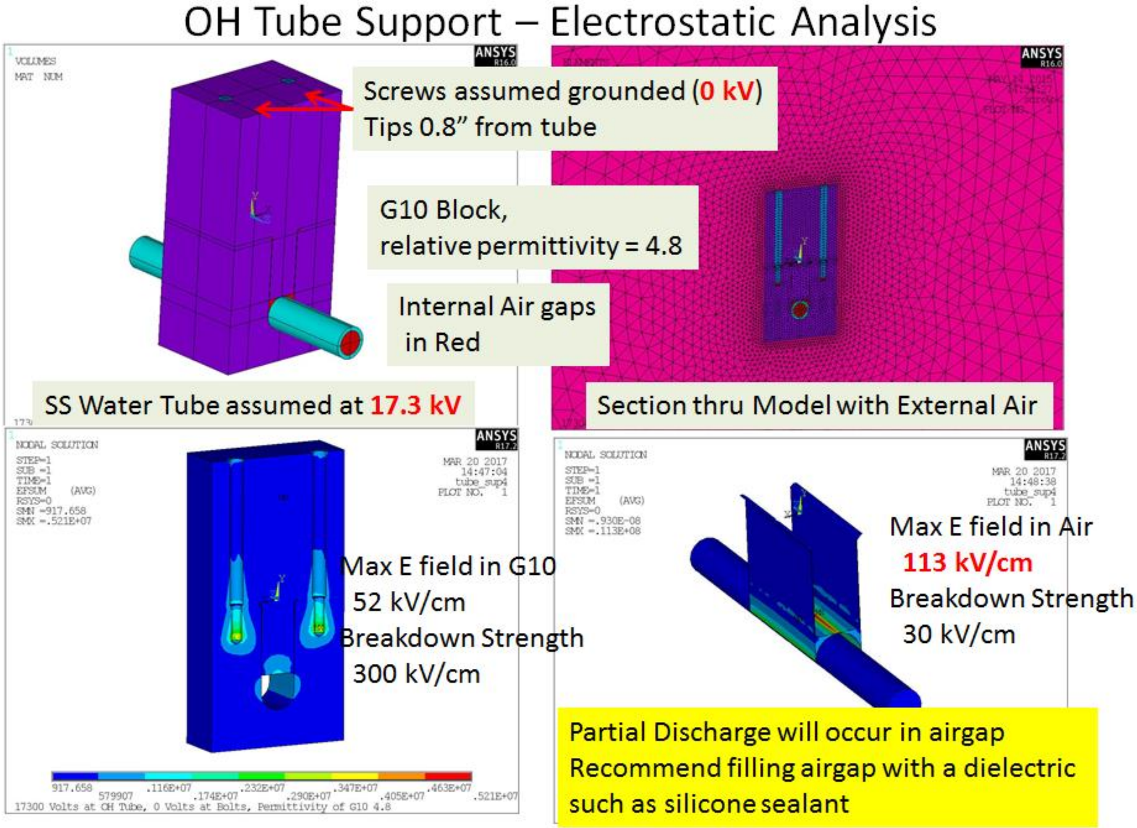
	Strap Current(Amps) Start-up	Strap Load (lbs) Start-up
A. Brooks	2500	2000
S. Gerhart		
Titus Sprreadsheet	4211	2578
Titus EMAG Simulation	1400	512
at "blip"	-2100	-714

The currents and loads vary mainly because the braided strap was approximated differently. A disruption analysis of the strap was not performed. The new strap is toroidally broken and will have negligable currents and thus loads.

4.2 Electrostatic Analysis of the Coolant Tube

The electrostatic analysis of the OH tube support was run to include an air gap under the screw. Figure 4.2-1 shows the results for a 17.3 kV voltage between the tube and ground (ie screws). The peak electric field of 37 kV/cm is in the G10 which has a breakdown strength of 300 kV/cm. The air under the screw is a bit lower - 22 kV/cm vs a breakdown of 30 kV/cm suggesting it should be OK for hipot. During operation at 6 kV the safety margin is much greater (results scale linearly).

The analysis reflects a sharp point on the screw. It is recommended that the screw tip be rounded to further improve the safety margin since it should be an easy thing to do. Further it is recommended that the air gap be filled with a dielectric such as a silicone sealant.



OH Tube Support – Electrostatic Analysis

Screws assumed grounded (0 kV)
Tips 0.8” from tube

G10 Block,
relative permittivity = 4.8

Internal Air gaps
in Red

SS Water Tube assumed at 17.3 kV

Section thru Model with External Air

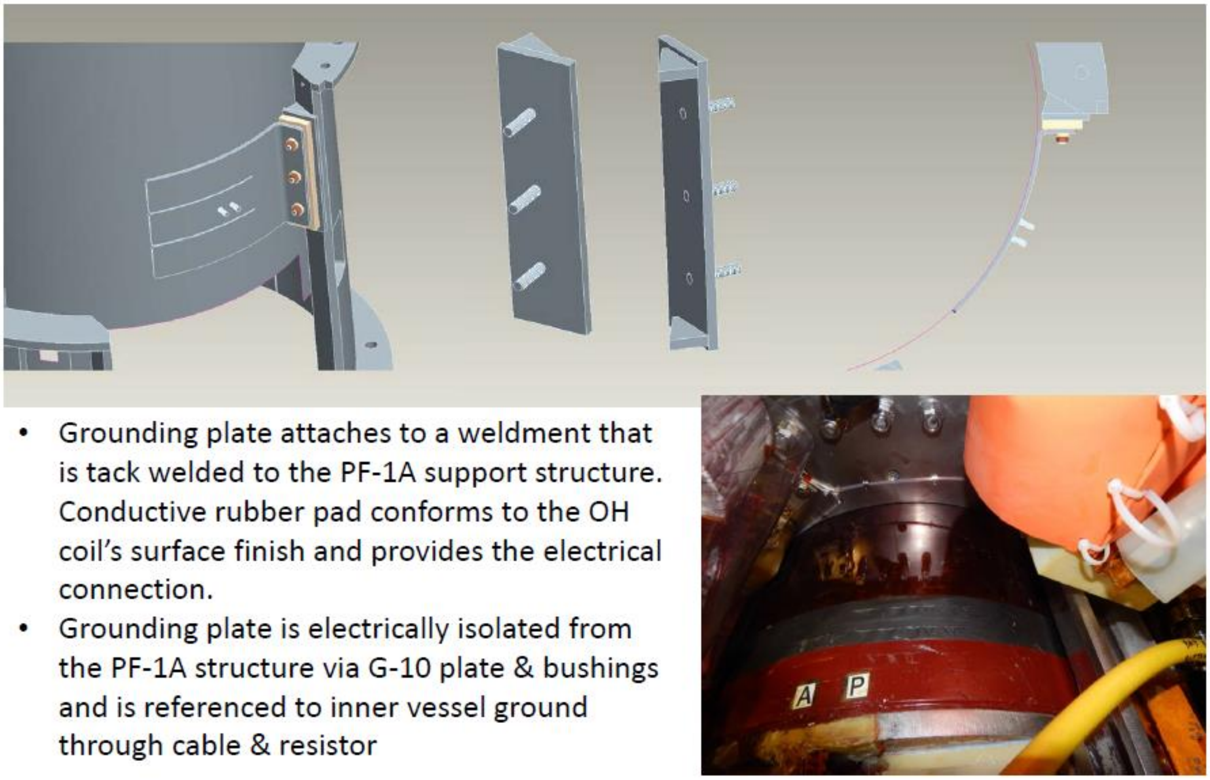
Max E field in G10
52 kV/cm
Breakdown Strength
300 kV/cm

Max E field in Air
113 kV/cm
Breakdown Strength
30 kV/cm

Partial Discharge will occur in airgap
Recommend filling airgap with a dielectric
such as silicone sealant

Figure 4.2-2 Electrostatic Analysis of the Water Cooling Tube Support

4.3 Lower Grounding Plate



- Grounding plate attaches to a weldment that is tack welded to the PF-1A support structure. Conductive rubber pad conforms to the OH coil's surface finish and provides the electrical connection.
- Grounding plate is electrically isolated from the PF-1A structure via G-10 plate & bushings and is referenced to inner vessel ground through cable & resistor

Figure 4.0-3 Lower OH Ground Paint Connection

The bending stress on the plate, supported on its edge, is estimated to be only 150 psi for a dB/dt of 5 Tesla per second resulting from the normal OH charge. A simulation of the VDE disruption yielded a worst case dB/dt of 8 Tesla/sec, so the electromagnetic loads on the plate are small. I have asked Bob Woolley to do a sanity check on this

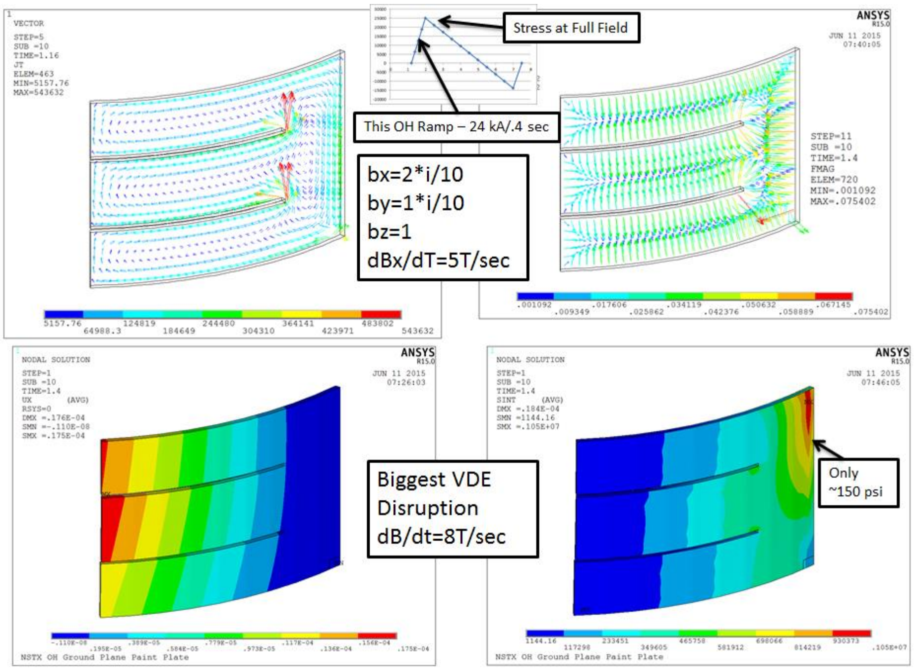


Figure 4.0-4 Start-Up and Disruption Eddy Current Analysis of the Lower Ground Plane Paint Connection Plate

4.4 Centerstack Casing Copper Cooling Tube Induced Currents

During the first run period, it was evident that there were more conducting structures in the inner corners of the vessel than were accounted for by the vessel shells. It was realized the copper cooling tubes were a significant source of toroidal conductivity. This raised the question as to what the response of the tubing was to the Lorentz loads caused by the induced currents. The analyses presented here concludes that, despite significant loads, the tubes were expected to remain in place. This assumes the tubes are annealed during the bake-out, but that corrosion is not significant. This last assumption may not be accurate. At 350C in air, the corrosion rate is probably important in effecting the structural integrity of the thin walled copper refrigerator tubing.

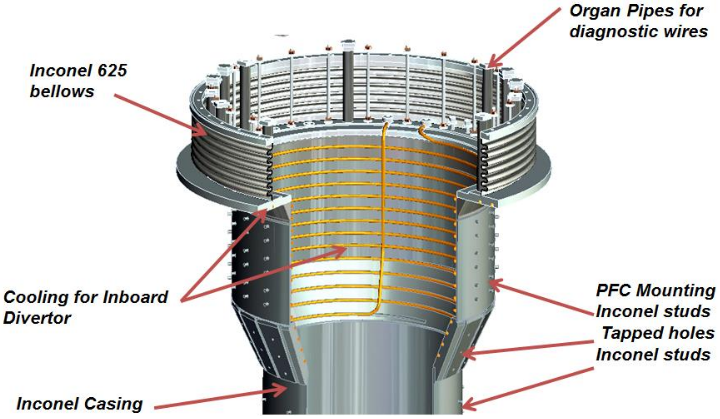
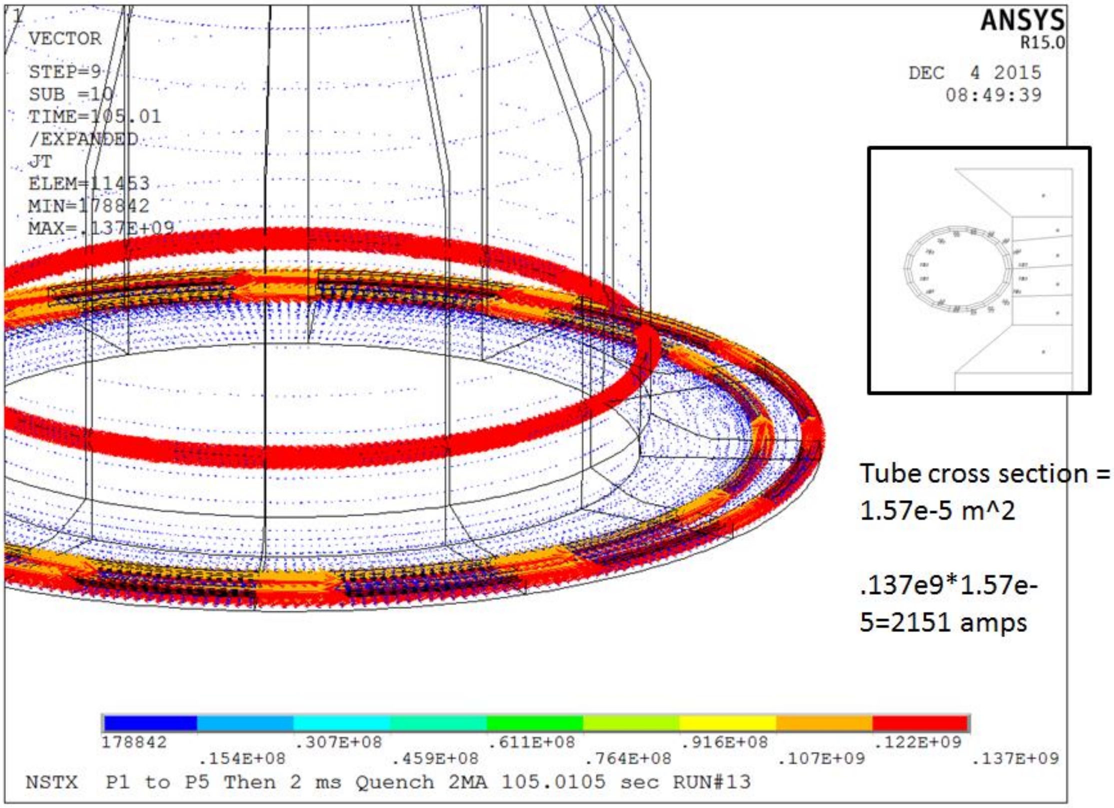


Figure 4.4-1 This is from Jim Chrzanowski's FDR Presention

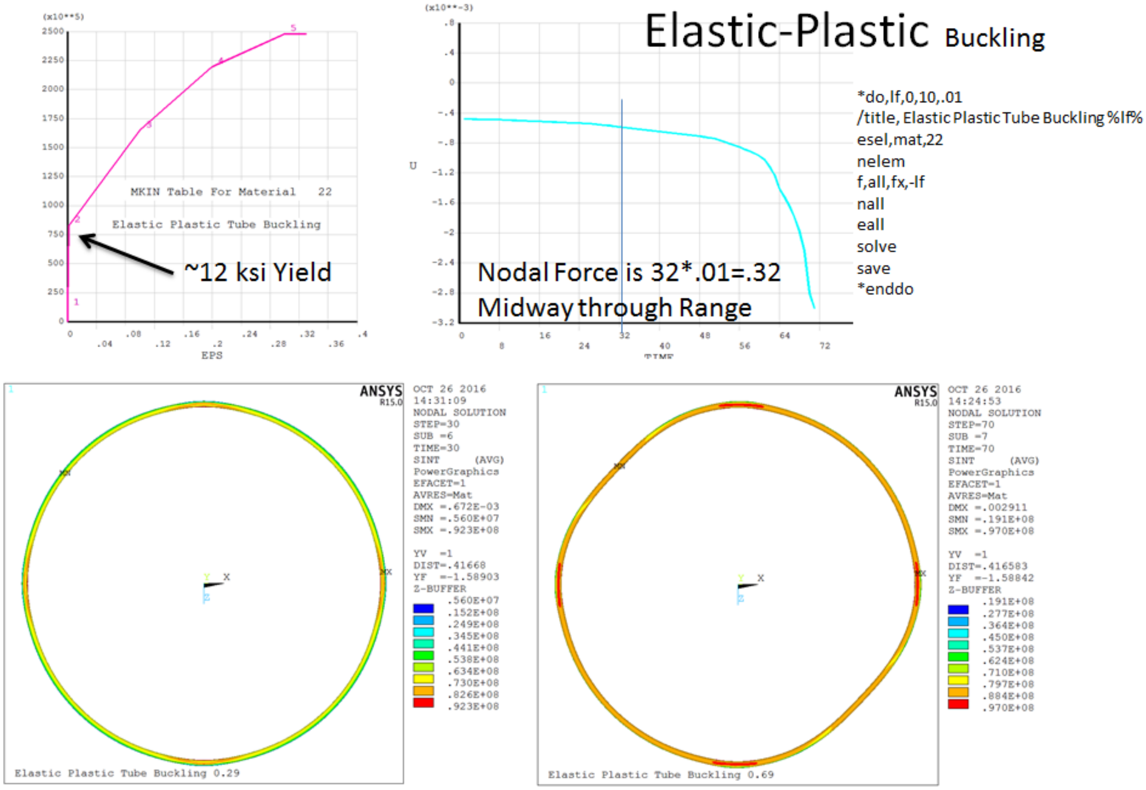
In the spreadsheet analysis, the turns are assumed shorted and the 4 volts is on each of ten tubes or turns in the spiral cooling systems at each end of the centerstack casing. . There is some electrical contact between the tubes and Inconel casing. This gives 2 kA which produces 28 degree heat-up (ignoring the water contained in the tube and conduction to the Inconel 625- The thermal stress will help, producing 50 MPa compression helping hold the tubes in the grooves. The radial load looks significant at 30 lbs/in being restrained by only the four retainer straps but if the tubes take the load in hoop compression the stress is only 19 MPa and the radial motion is tiny. I should worry about buckling, but the tubes are stabilized by the grooves they fit into. Some photos of the tubes were found that made it appear that that there were no grooves. Steve Raftopoulos explained that these photos were taken prior to the final fitting and insertion of the tubes and welding of the restraint straps.



Tube cross section = 1.57e-5 m^2

.137e9*1.57e-5=2151 amps

Figure 4.4-2 Centerstack Casing Cooling Tube Disruption Currents



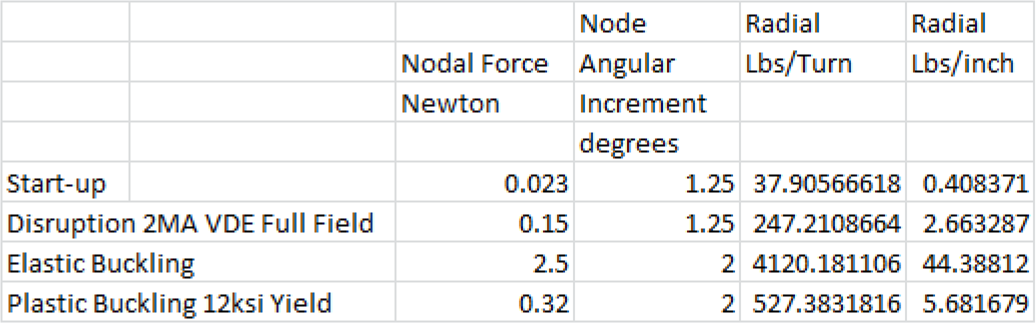
Elastic-Plastic Buckling

~12 ksi Yield

Nodal Force is 32*.01=.32
Midway through Range

```
*do,lf,0,10,.01
/title, Elastic Plastic Tube Buckling %lf%
esel,mat,22
nelem
f,all,fx,-lf
nall
eall
solve
save
*enddo
```

Figure 4.4-3 Centerstack Casing Cooling Tube Elastic-Plastic Buckling Capacity



		Nodal Force Newton	Node Angular Increment degrees	Radial Lbs/Turn	Radial Lbs/inch
Start-up		0.023	1.25	37.90566618	0.408371
Disruption 2MA VDE Full Field		0.15	1.25	247.2108664	2.663287
Elastic Buckling		2.5	2	4120.181106	44.38812
Plastic Buckling 12ksi Yield		0.32	2	527.3831816	5.681679

Figure 4.4-4 Centerstack Casing Cooling Tube Disruption Load Summary –Applied Loads (above) and Capacities (Below

There is a reversal in flux between precharge and initiation that would cause one or the other to pull away from the grooves. I assumed 1/2 sec of induced current duration to calculate the temperature. I used a .5T vertical field to calculate the radial load. Based on the 96 scenarios it might be .9 T. It would be nice to have actuals. .

Mid way through the load cycle, the nodal force is .32 Newtons or 5.68 lbs per inch. The applied load during start up is .408lbs/inch and 2.66 lbs /inch during a (full performance) disruption. So if the yield of the tubes is ~12ksi, then the tubes should have been able to survive a disruption. If the tubes were fully annealed during the bake-out, with a yield of more like 5 ksi, than the tubes could be buckled during a disruption of a full performance plasma, but they should not have been exposed to anywhere near a full 2 MA disruption during the 2016 run.

Figure 4.4-5 Centerstack Casing Cooling Tube Disruption Photos Taken Dec 14 2016

In figure 4.0-8, the cooling tubes are shown in a section where they remained intact and in the casing groove. Elsewhere, the tubing broke apart and separated from the groove posing a potential source of a short. Replacing these tubes (Upper and Lower) is one of the main reasons for the extended outage at the end of 2016/beginning of 2017. The surface of the copper showed extensive corrosion resulting from air exposure during the 350C Bake. Even though the loads on the tubes would indicate that they would stay properly in their grooves, the deteriorated state of the tubes probably caused structural failures during the electromagnetic loading.

5.0 Digital Coil Protection System.

There is no input to the DCPS planned for Induced Currents in Passive Structures other than the normal coil current limits for start-up. Disruption effects are not included in the DCPS.

6.0 Design Input

6.1 Criteria

From the GRD:
"b. All materials utilized within the primary vacuum boundary shall be designed to withstand the anticipated temperatures during plasma operation. Note that the vacuum vessel shall be baked out at a temperature of 150^{o}C, and internal plasma facing components including the CSC, IBD, OBD, and PPs shall be baked out at 350^{o}C. " The cooling tubes covered by this calculation must survive the 350 degree temperature on the air side for the casing cooling tubes and on the vacuum side for the horizontal divertor flange cooling tubes.

The Safety analysis document (SAD) quotes the 350 bake and acknowledges that the input to the helium system must be 420C to get the 350^{o} C tile surfaces. Also the SAD allows temperatures greater than 350C for the centerstack. :

"3.2.3.3.4 Center Stack Casing
The center stack casing is electrically isolated from the outer vacuum vessel and is compatible with operation in high vacuum conditions. Electrical breaks are provided between the vacuum vessel and the center stack casing to support coaxial helicity injection (CHI) during startup. The electrical isolation isvrated for 2kV DC CHI operations (upgradable to 4kV), 5kV DC hipot. The center stack casing includes suitable terminals for electrical connections for CHI, and accommodates the passage of a current in the Z direction for the purpose of resistive heating as a source of heat during the bakeout mode. The center stack casing is bakeable to a temperature > 350°C."

Note the greater than sign. A +/- tolerance on the 350C is implied and the 370C would be acceptable, especially on the centerstack casing.

Stress Criteria are found in the NSTX Structural Criteria Document[3]. Disruption and thermal specifications are outlined in the GRD -Ref [7]

6.2 References

[1] NSTX-U Design Point Spreadsheet, **NSTXU-CALC-10-03-00** C. Neumeyer, http://w3.pppl.gov/~neumeyer/NSTX_CSU/Design_Point.html
[2] NSTX OH Fault Corrective Action Plan Rev. 0 M. Ono, et. al June 8 2015
[3] NSTX Structural Design Criteria Document, NSTX_DesCrit_IZ_080103.doc I. Zatz
[4] ITER material properties handbook, ITER document No. G 74 MA 15, file code: ITER-AK02-22401.
[5] Final Design Review for: OH Coaxial Bus Details & OH Ground Plane Lower Ground Plate Friday, June 19 Steve Raftopoulos/Neway Atnafu
[6] Global Thermal Analysis of Center Stack Heat Balance,NSTXU-CALC-11-01-00 A. Brooks June 1, 2011
[7] NSTX Upgrade General Requirements Document, NSTX_CSU-RQMTS-GRD Revision 6, P. Titus, August 3 2015, Original issue by C. Neumeyer, March 30, 2009
[8] Email from Stefan Gerhart, 12/3/15 from Stefan Gerhardt <sgerhard@pppl.gov> (In Appendix A)
to Charles, Steve, Jonathan, Lawrence, me
"I busted out my EE PhD to do the calculation on the first sheet of the attached."
The attached spreadsheet had the loop voltage and estimate of the tube current.
[9] Inner PF Coils (1a, 1b & 1c), Center Stack Upgrade NSTXU-CALC-133-01-01 March 30, 2012 Rev 0/1 by Len Myatt.
[10] Inner PF Coils (1a, 1b & 1c), Center Stack Upgrade NSTXU-CALC-133-01-02 May, 2014 Rev 2 by Len Myatt. Rev 2 by A Zolfaghari and A Brooks
[11] "OH Coil Cooling Tube Arc Failure New Designs and Re-commissioning" Steve Raftopoulos
M. Sibilia, N. Atnafu, L. Dudek, M. Kalish, S. Ramakrishnan, W. Que, R. Van Kirk, L. Morris, J.

6.3 Photos and Drawing Excerpts

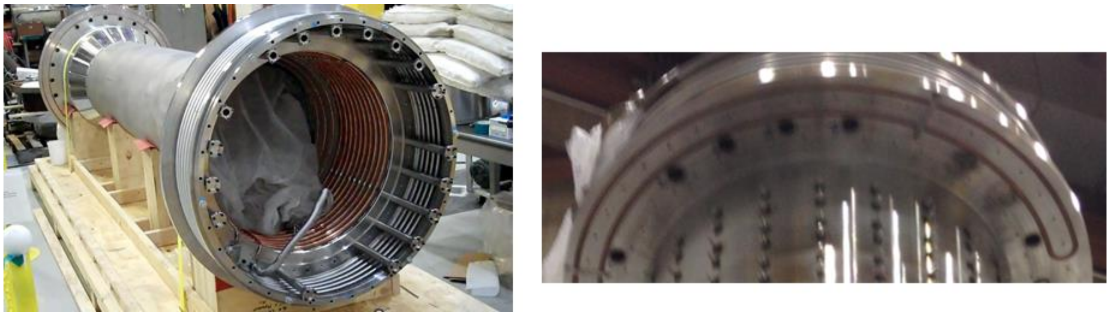


Figure 6.3-1 Centerstack Casing Cooling Tubes and the Divertor Flange Cooling Tube

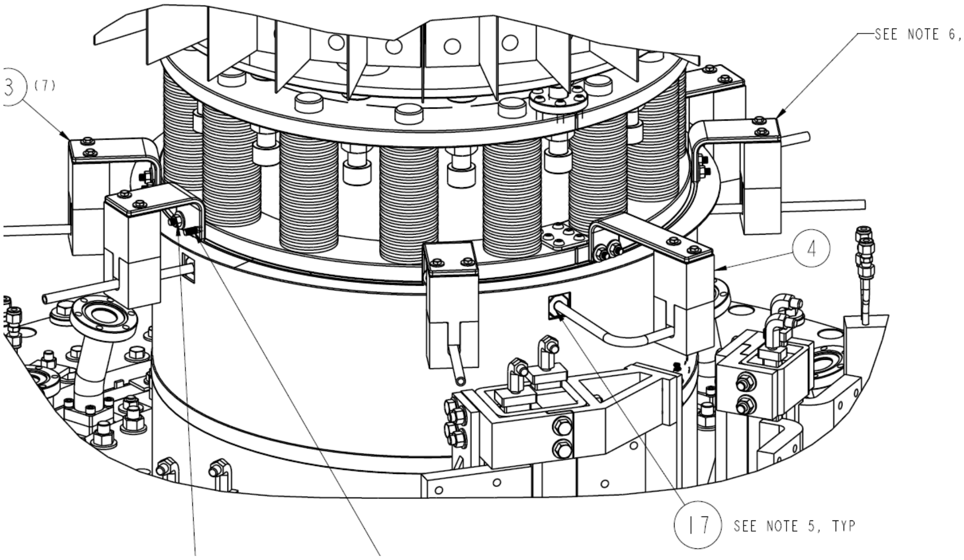


Figure 6.3-2 2EDC1944 Cooling Water Tube Support (Upper Details)

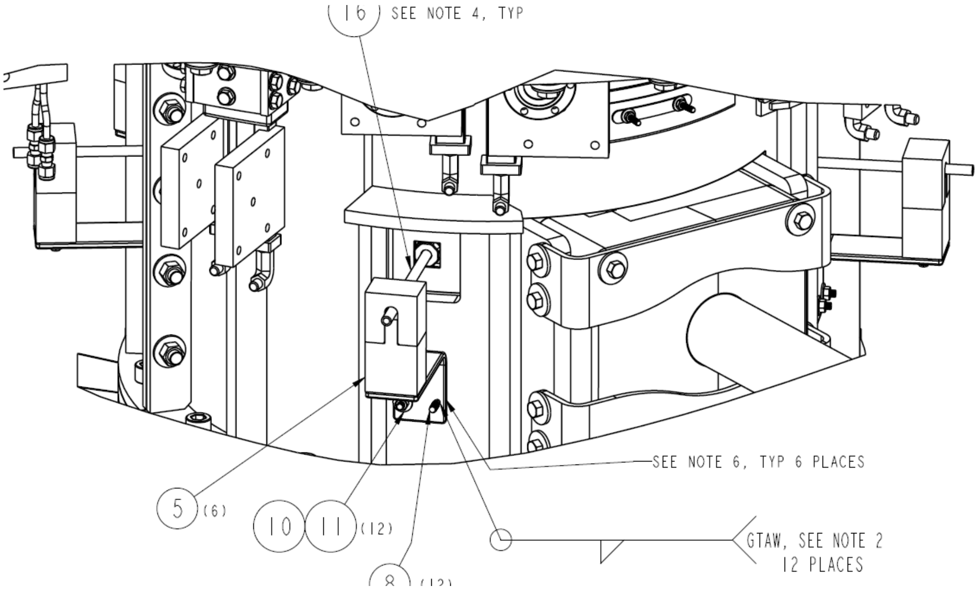


Figure 6.3-3 2EDC1944 Cooling Water Tube Support (Lower Details)

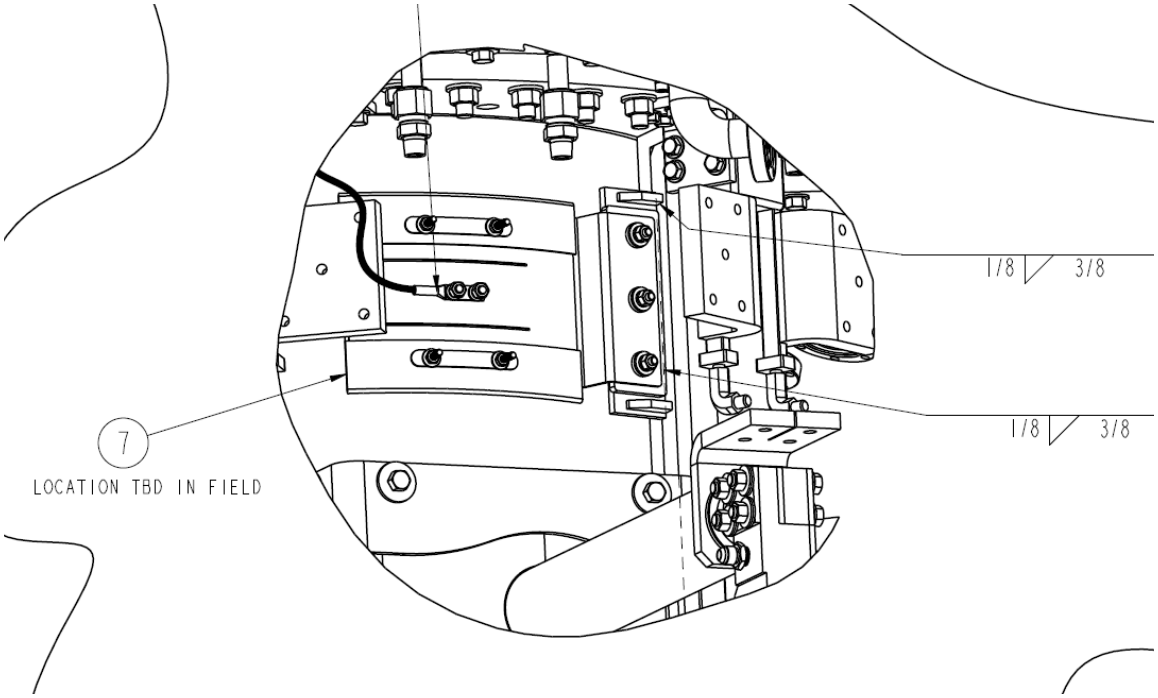


Figure 6.3-3 2EDC1944 Ground Plane Paint Conduction Plate (Lower End of OH)

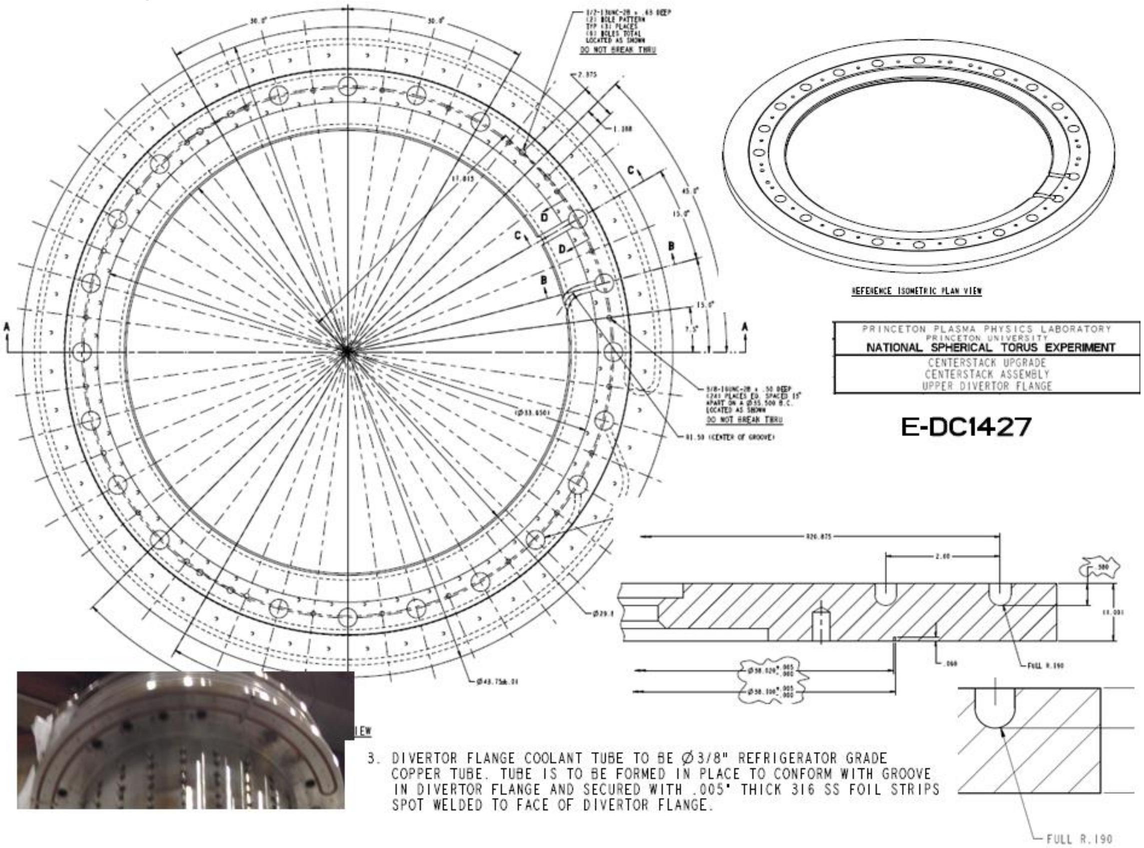


Figure 6.3-4 Centerstack Case Showing upper Inner Horizontal Divertor Cooling Loop (That Leaks)

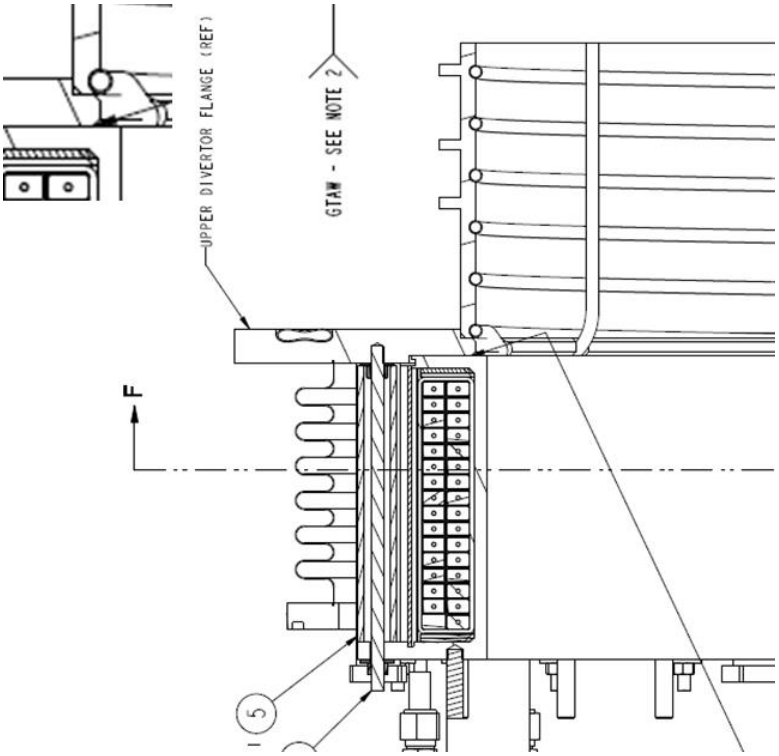


Figure 6.3-5 Centerstack Casing Cooling Tubes – Note Vertical Crossing Return Tube

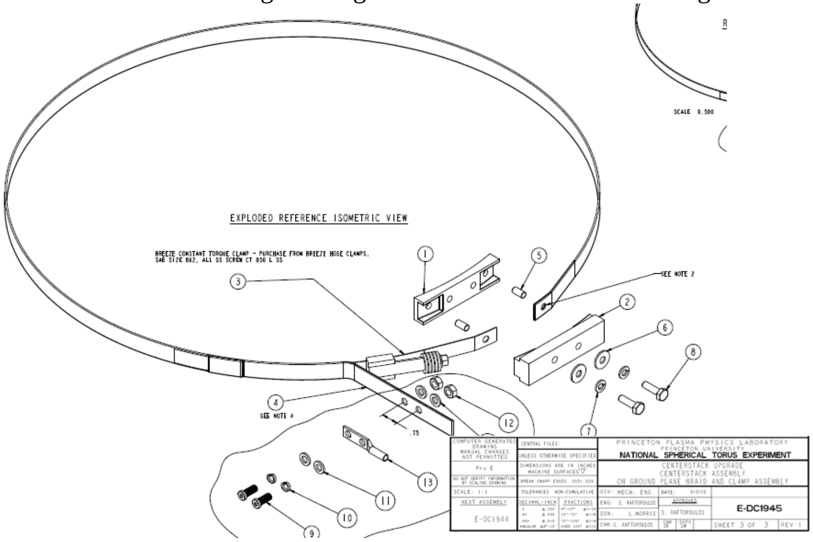


Figure 6.3-6 Replacement OH Grounding Strap

6.4 Materials and Allowables

Table 6.4.1 From the Internet: Recommended Corrosion Allowance for Copper Pipes

CORROSION ALLOWANCE FOR NON-FERROUS METAL PIPES	mm
Copper	0,8
Brass	0,8
Copper-tin alloys	0,8
Copper-nickel alloys with less than 10% of Ni	0,8
Copper-nickel alloys with at least 10% of Ni	0,5
Aluminium and aluminium alloys	0,5

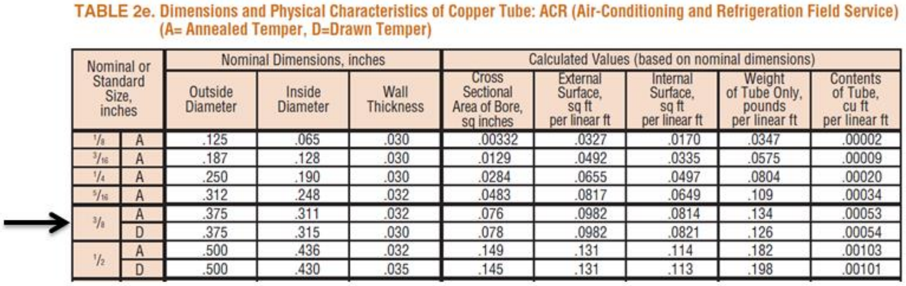


TABLE 2e. Dimensions and Physical Characteristics of Copper Tube: ACR (Air-Conditioning and Refrigeration Field Service)
(A= Annealed Temper, D=Drawn Temper)

Nominal or Standard Size, inches		Nominal Dimensions, inches			Calculated Values (based on nominal dimensions)				
		Outside Diameter	Inside Diameter	Wall Thickness	Cross Sectional Area of Bore, sq inches	External Surface, sq ft per linear ft	Internal Surface, sq ft per linear ft	Weight of Tube Only, pounds per linear ft	Contents of Tube, cu ft per linear ft
1/8	A	.125	.065	.030	.00332	.0327	.0170	.0347	.00002
3/16	A	.187	.128	.030	.0129	.0492	.0335	.0575	.00009
1/4	A	.250	.190	.030	.0284	.0655	.0497	.0804	.00020
5/16	A	.312	.248	.032	.0483	.0817	.0649	.109	.00034
3/8	A	.375	.311	.032	.076	.0982	.0814	.134	.00053
	D	.375	.315	.030	.078	.0982	.0821	.126	.00054
1/2	A	.500	.436	.032	.149	.131	.114	.182	.00103
	D	.500	.430	.035	.145	.131	.113	.198	.00101

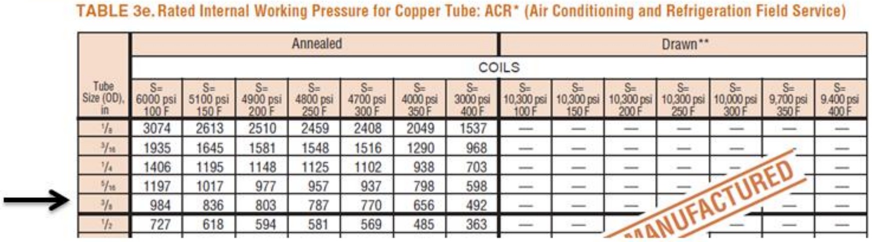
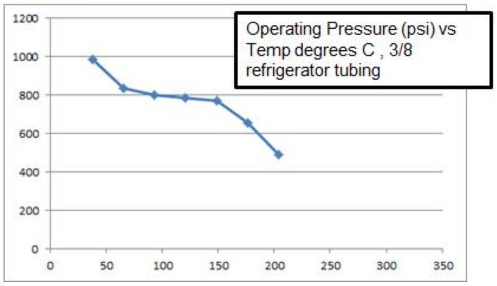


TABLE 3e. Rated Internal Working Pressure for Copper Tube: ACR* (Air Conditioning and Refrigeration Field Service)

Tube Size (OD), in	Annealed							Drawn**						
	COILS													
	S= 6000 psi 100 F	S= 5100 psi 150 F	S= 4900 psi 200 F	S= 4800 psi 250 F	S= 4700 psi 300 F	S= 4000 psi 350 F	S= 3000 psi 400 F	S= 10,300 psi 100 F	S= 10,300 psi 150 F	S= 10,300 psi 200 F	S= 10,300 psi 250 F	S= 10,000 psi 300 F	S= 9,700 psi 350 F	S= 9.400 psi 400 F
1/8	3074	2613	2510	2459	2408	2049	1537	—	—	—	—	—	—	—
3/16	1935	1645	1581	1548	1516	1290	968	—	—	—	—	—	—	—
1/4	1406	1195	1148	1125	1102	938	703	—	—	—	—	—	[illegible]	—
5/16	1197	1017	977	957	937	798	598	—	—	—	—	[illegible]	[illegible]	—
3/8	984	836	803	787	770	656	492	—	—	—	[illegible]	[illegible]	—	—
1/2	727	618	594	581	569	485	363	—	—	[illegible]	[illegible]	—	—	—

MANUFACTURED



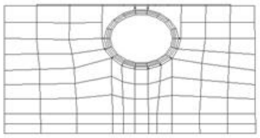


Figure 6.4.2-1 Copper Refrigerator Tubing Pressure Rating vs. Temperature

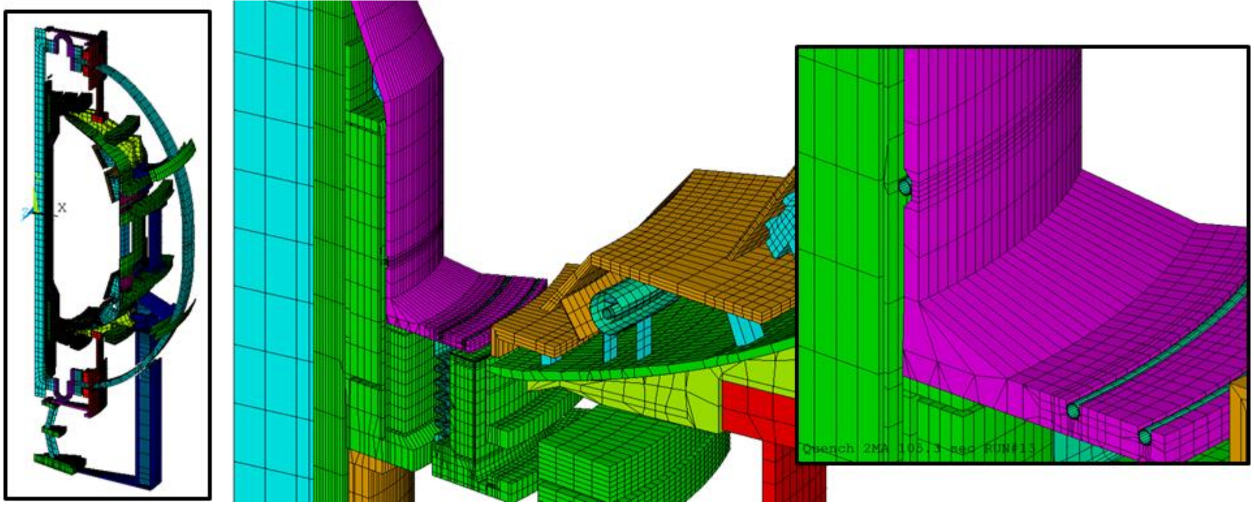
The pressure rating drops off to near zero well before the 350C Bake-out temperature. This is an indication that the copper tubing is at least partially annealed by the bake-out

7.0 Models

7.1 Electromagnetic Model

This modeling is a re-purposing of disruption analyses of the passive plates:
http://nstx-upgrade.pppl.gov/Engineering/Calculations/1_Torus_Systems/1_2_VV/CALC-12-001/NSTXU-CALC-12-01-01%20(Disruption%20Analysis%20on%20NSTX%20Vacuum%20Vessel)-Feb2012_S.pdf

The OH Ground Straps and Centerstack Casing cooling tubes have been added to the model. The input disruption coil and plasma current time histories are the same as in the previous disruption analyses. The input script was modified to consider a normal operation scenario with the start-up OH transients. The input listing of the start-up version of this electromagnetic transient is included in Appendix B. Materials and real constants are used to track the component identities. For example Mat 22 is used for the ground straps and cooling tubes.



.Figure 7.1-1 Lower Section of the EMAG Model Showing the Casing Cooling Tubes

The electromagnetic model is swept from a 2D mesh file. The 3D cyclic symmetry model shown here (derived from the 2D file, ebaj.dat) includes the cryo-divertor enhancement. The horizontal cooling tubes in the divertor flange are modeled, and one of ten tubes cooling the casing shell that supports the inner divertor vertical section tiles is modeled.

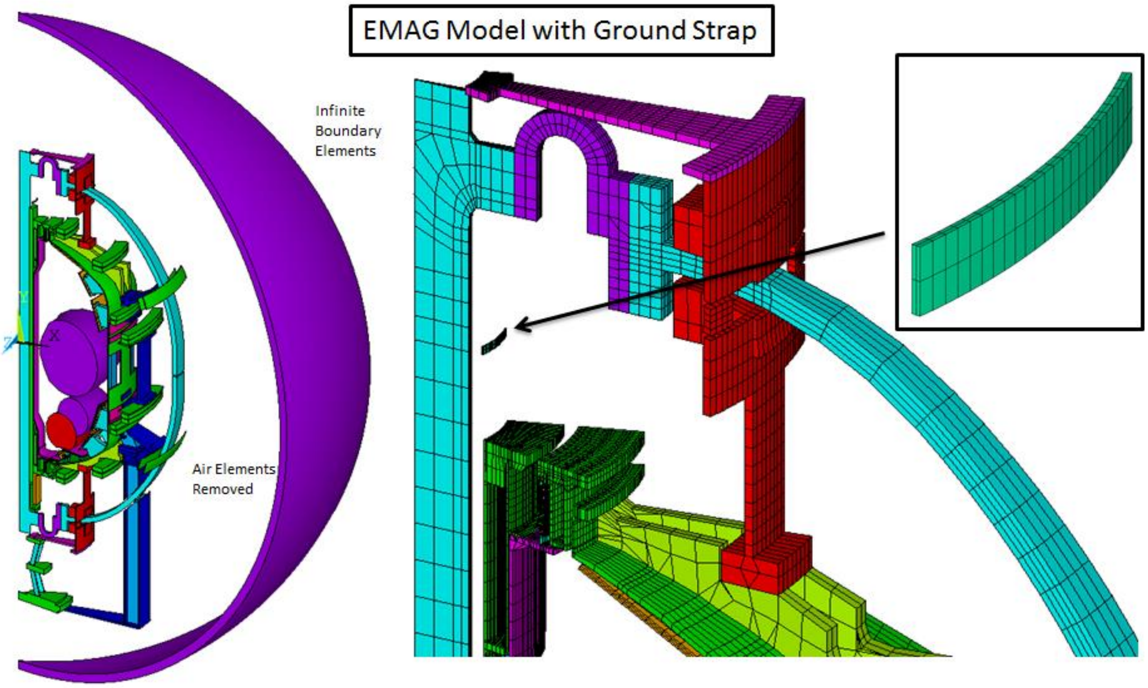


Figure 7.2-2 Upper Section of the EMAG Model Showing the Ground Strap

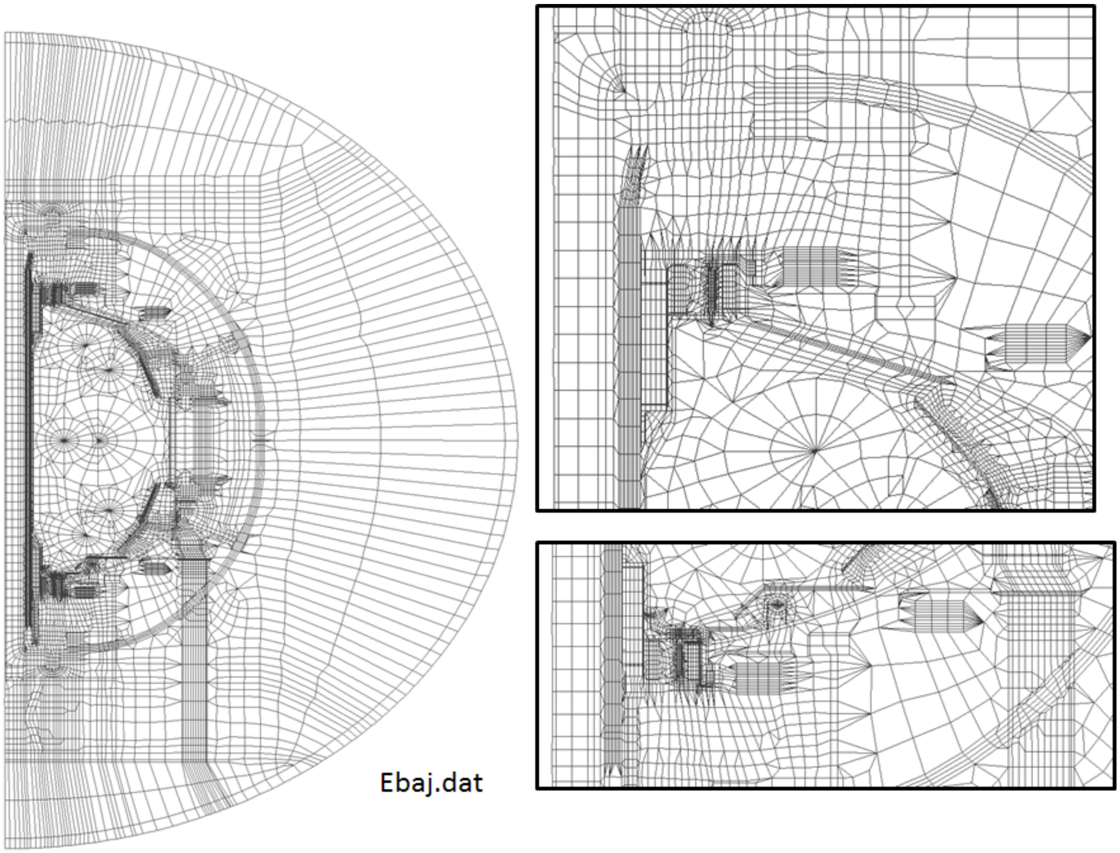


Figure 7.2-3 2D Version of the EMAG Model Showing Upper and Lower Mesh Details With Air

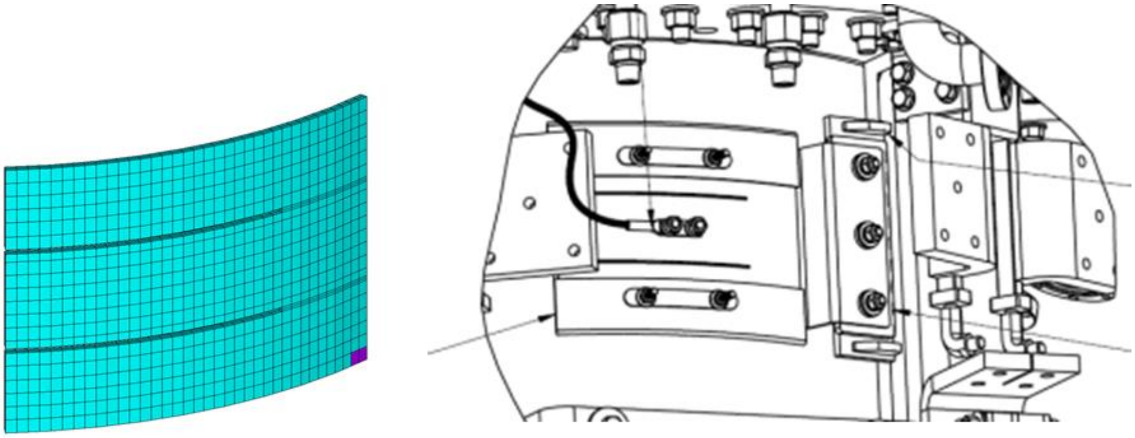


Figure 7.2-4 Lower Grounding Plate ANSYS Model (Left) And Installed Component (Right)

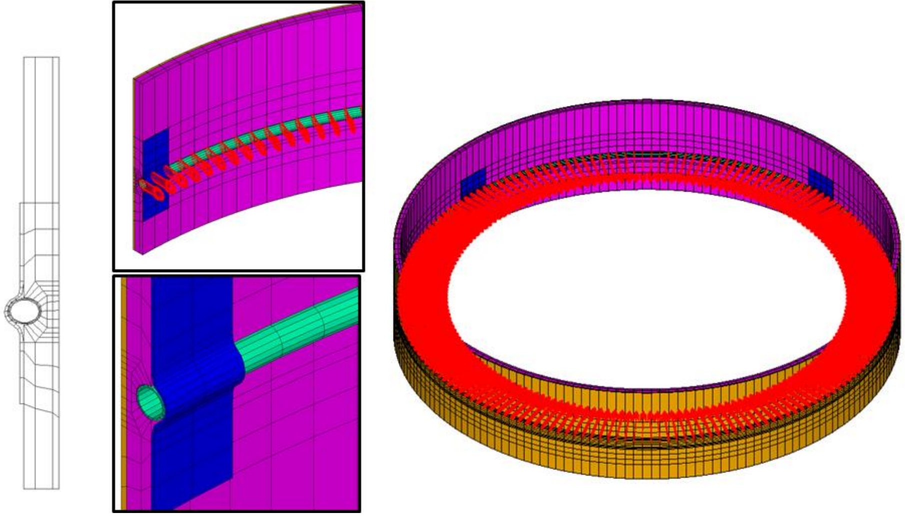
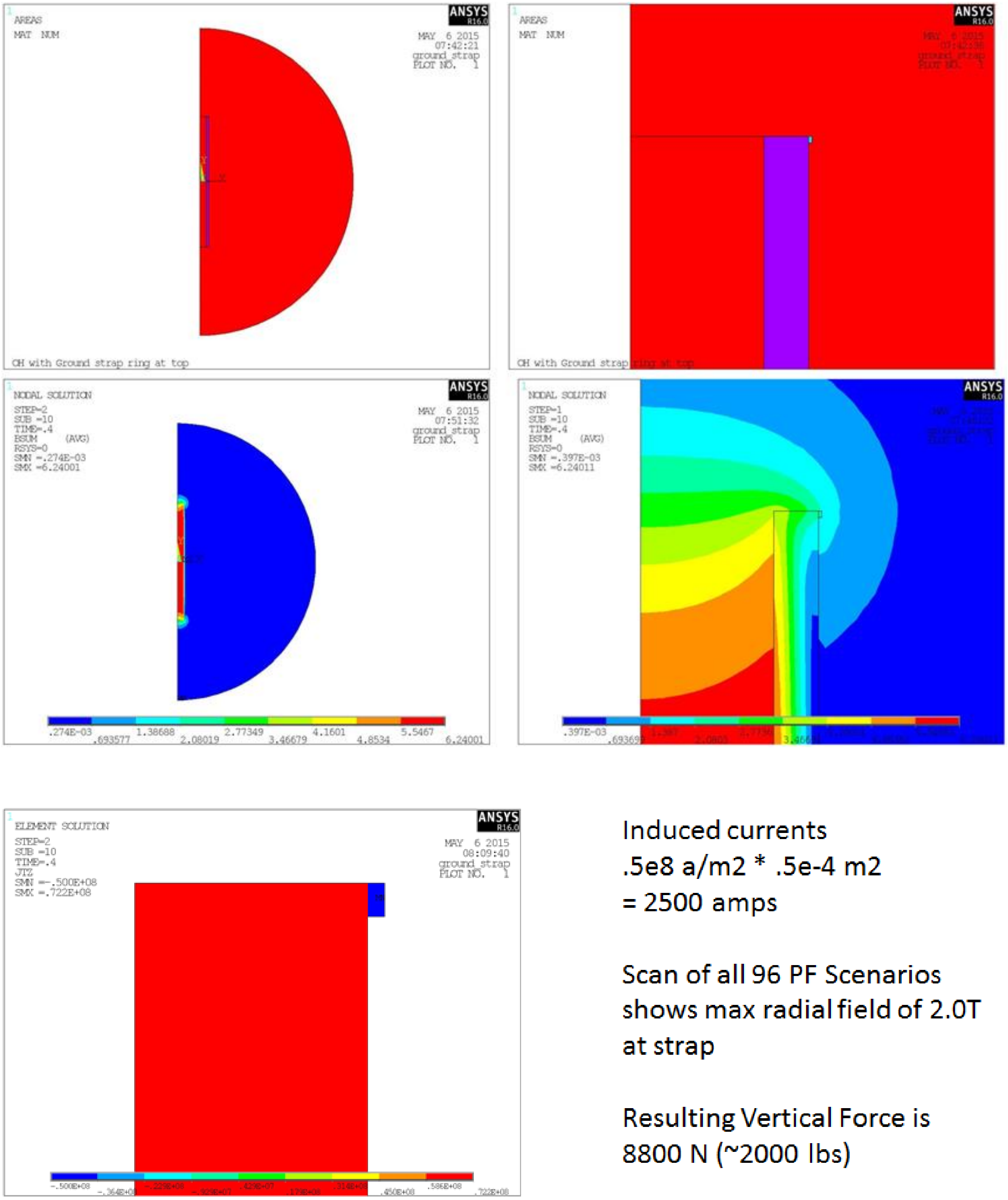


Figure 7.2 -5 Centerstack Casing Cooling Tube Buckling ANSYS Model

8.0 Estimate of Shorted Strap Currents with ANSYS (A. Brooks)



Induced currents
.5e8 a/m2 * .5e-4 m2
= 2500 amps

Scan of all 96 PF Scenarios shows max radial field of 2.0T at strap

Resulting Vertical Force is 8800 N (~2000 lbs)

Figure 8.0-1 Estimate of Strap Current Using ANSYS

9.0 Shorted Strap Currents and Loads (Titus)

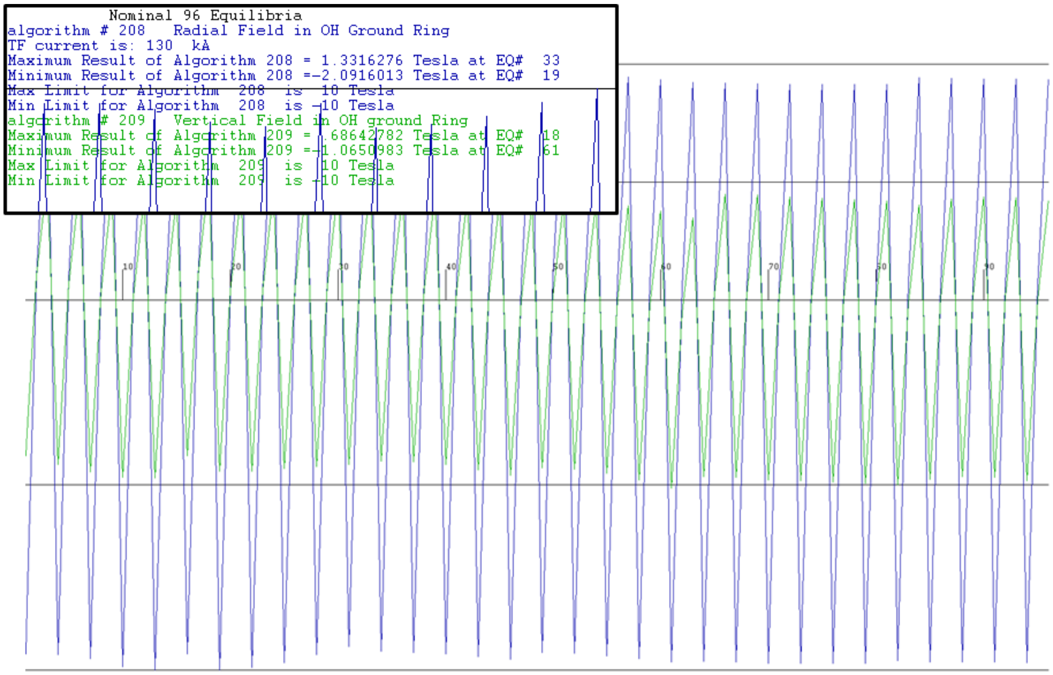
9.1 Spreadsheet Calculation

```
getn

getn
 Node Number           184
  Dir      Cart        Cyl
 x   0.2757500       0.2757500
 y    2.120800       0.0000000E+00 rad  0.000000000000000E+000 deg
 z   0.0000000E+00    2.120800
 fx   0.0000000E+00
 fy   0.0000000E+00
 fz   0.0000000E+00
 t  0.0000000E+00
 bt,bx,by,bz   0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
```

Figure 9.1-1 Coordinates of Upper Outer Location on the OH

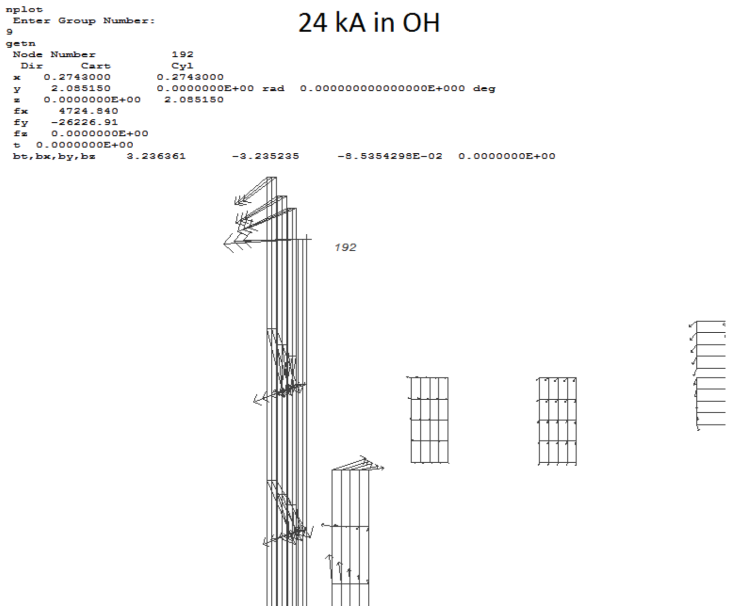
The coordinates of the upper outer corner of the OH are x=.2757m and y=2.1208m. This is below the ground strao but will provide a conservative background field.



```
              Nominal 96 Equilibria
algorithm # 208   Radial Field in OH Ground Ring
TF current is: 130  kA
Maximum Result of Algorithm 208 = 1.3316276 Tesla at EQ#  33
Minimum Result of Algorithm 208 =-2.0916013 Tesla at EQ#  19
Max Limit for Algorithm  208  is  10 Tesla
Min Limit for Algorithm  208  is -10 Tesla
algorithm # 209   Vertical Field in OH ground Ring
Maximum Result of Algorithm 209 = .68642782 Tesla at EQ#  18
Minimum Result of Algorithm 209 =-1.0650983 Tesla at EQ#  61
Max Limit for Algorithm  209  is  10 Tesla
Min Limit for Algorithm  209  is -10 Tesla
```

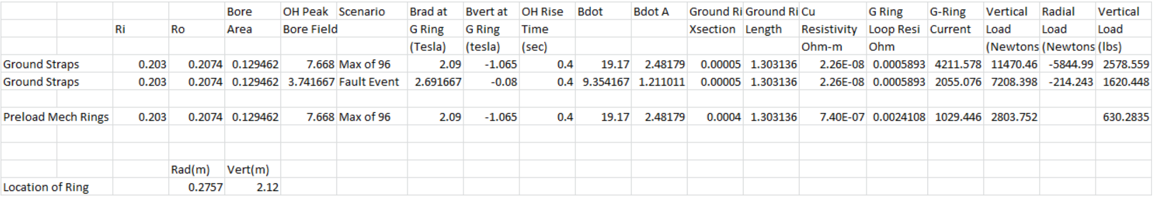
Figure 9.1-2 Peak Local Fields at the Coordinates of the OH Ground Strap Strap and Ring, 96 EQ

The max maginitude of the Raidal field is 2.09 T and the vertical field magnitude is -1.0651T.



```
nplot
 Enter Group Number:
9
getn
 Node Number            192
  Dir      Cart         Cyl
 x    0.2743000       0.2743000
 y     2.085150       0.0000000E+00 rad  0.000000000000000E+000 deg
 z    0.0000000E+00    2.085150
 fx     4724.840
 fy    -26226.91
 fz    0.0000000E+00
 t  0.0000000E+00
 bt,bx,by,bz     3.236361      -3.235235     -8.5354298E-02  0.0000000E+00
```

Figure 9.1-3 Peak Local Fields at the Coordinates of the OH Corner – Only the OH Current



				Bore	OH Peak	Scenario	Brad at	Bvert at	OH Rise	Bdot	Bdot A	Ground Ri	Ground Ri	Cu	G Ring	G-Ring	Vertical	Radial	Vertical
		Ri	Ro	Area	Bore Field		G Ring	G Ring	Time			Xsection	Length	Resistivity	Loop Resi	Current	Load	Load	Load
							(Tesla)	(tesla)	(sec)					Ohm-m	Ohm		(Newtons	(Newtons	(lbs)
Ground Straps		0.203	0.2074	0.129462	7.668	Max of 96	2.09	-1.065	0.4	19.17	2.48179	0.00005	1.303136	2.26E-08	0.0005893	4211.578	11470.46	-5844.99	2578.559
Ground Straps		0.203	0.2074	0.129462	3.741667	Fault Event	2.691667	-0.08	0.4	9.354167	1.211011	0.00005	1.303136	2.26E-08	0.0005893	2055.076	7208.398	-214.243	1620.448
Preload Mech Rings		0.203	0.2074	0.129462	7.668	Max of 96	2.09	-1.065	0.4	19.17	2.48179	0.0004	1.303136	7.40E-07	0.0024108	1029.446	2803.752		630.2835
			Rad(m)	Vert(m)															
Location of Ring			0.2757	2.12															

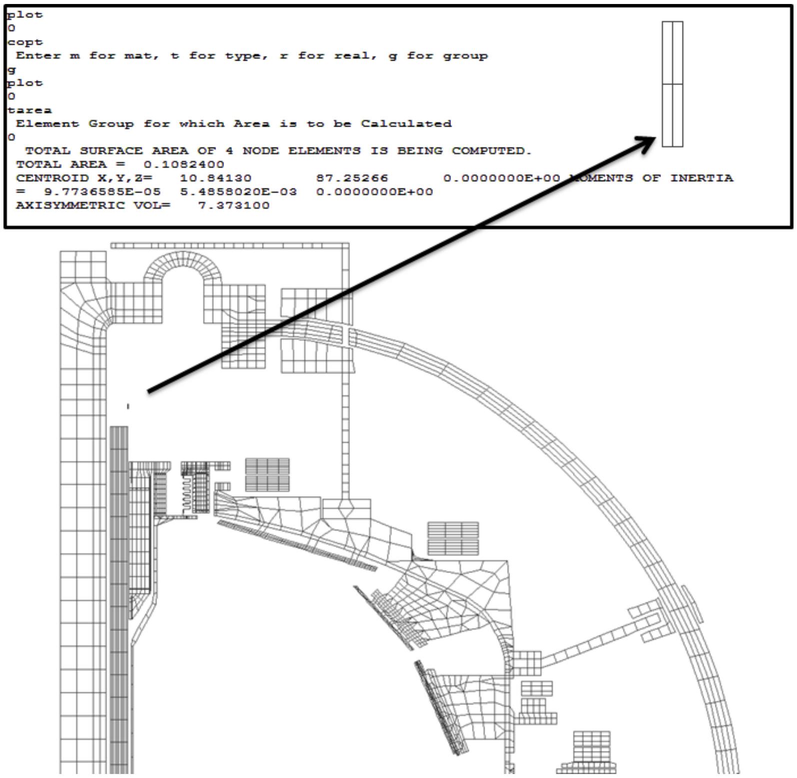
Figure 9.1-4 Spreadsheet Calculation of the Strap Currents and Loads

In the table/figure above, the net vertical load is then 1620 Lbs for the operating level at the fault event, and 2578 lbs for the max loading from the 96 equilibria. The fields came from figure 9.1.2 which is from the DCPS algorithms as checked in a True Basic Program.

9.1 EMAG Calculation

This modeling is a re-purposing of disruption analyses of the passive plates: http://nstx-upgrade.pppl.gov/Engineering/Calculations/1_Torus_Systems/1_2_VV/CALC-12-001/NSTXU-CALC-12-01-01%20(Disruption%20Analysis%20on%20NSTX%20Vacuum%20Vessel)-Feb2012_S.pdf

The OH Ground Straps and Centerstack Casing cooling tubes have been added to the model. The input disruption coil and plasma current time histories are the same as in the previous disruption analyses. The input script was modified to consider a normal operation scenario with the start-up OH transients. The input listing of the start-up version of this electromagnetic transient is included in Appendix B.



```
plot
0
copt
 Enter m for mat, t for type, r for real, g for group
g
plot
0
tarea
 Element Group for which Area is to be Calculated
0
  TOTAL SURFACE AREA OF 4 NODE ELEMENTS IS BEING COMPUTED.
 TOTAL AREA =  0.1082400
 CENTROID X,Y,Z=   10.84130       87.25266      0.0000000E+00 MOMENTS OF INERTIA
 =  9.7736585E-05  5.4858020E-03  0.0000000E+00
 AXISYMMETRIC VOL=   7.373100
```

Figure 9.1 EMAG Model, Upper Half Showing Strap Elements

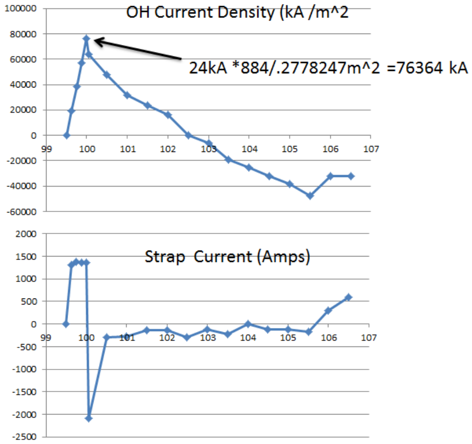


Figure 9.2 OH Scenario Current (Top) and Resulting Strap Current (Bottom)

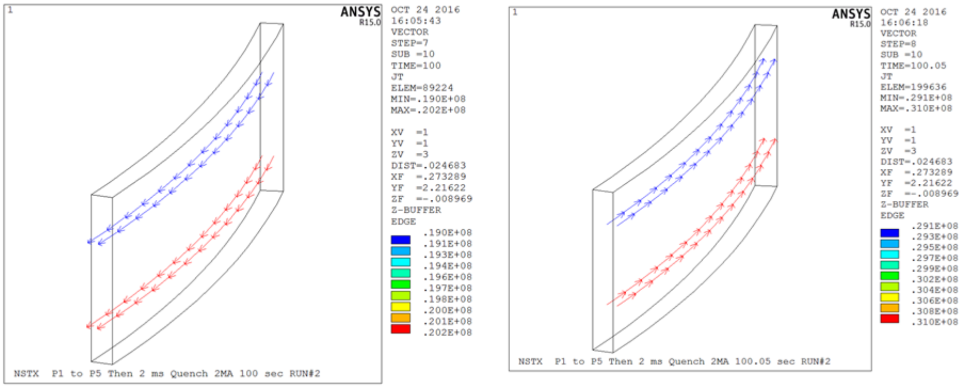
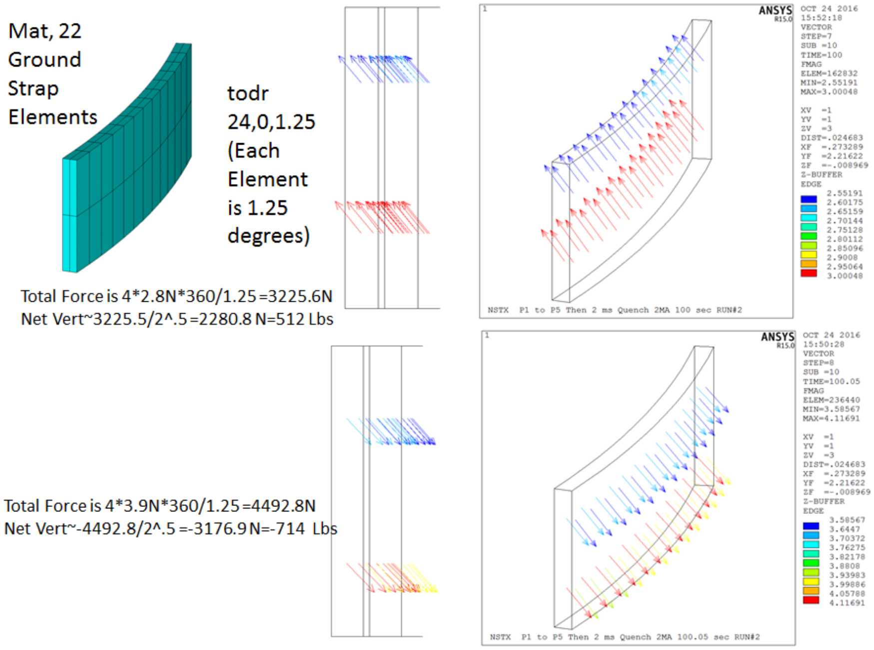


Figure 9.3 Strap Element Start-Up Currents



Total Force is 4*2.8N*360/1.25=3225.6N
Net Vert~3225.5/2^.5=2280.8 N=512 Lbs

Total Force is 4*3.9N*360/1.25=4492.8N
Net Vert~-4492.8/2^.5=-3176.9N=-714 Lbs

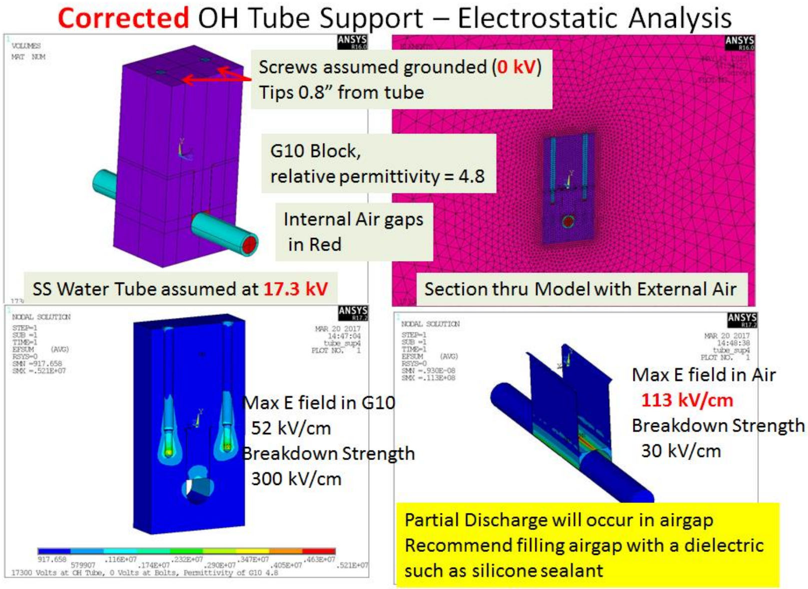
Figure 9.3 Strap Element Start-Up Forces

10.0 Electrostatic analysis of the OH tube support

Figure 10.0-1 Coolant Tube Support As- Installed After the Arc Fault

The electrostatic analysis of the OH tube support was re-run to include an air gap under the screw. Figure 10.0-1 shows the results for a 17.3 kV voltage between the tube and ground (ie screws). The peak electric field of 37 kV/cm is in the G10 which has a breakdown strength of 300 kV/cm. The air under the screw is a bit lower - 22 kV/cm vs a breakdown of 30 kV/cm suggesting it should be OK for hipot. During operation at 6 kV the safety margin is much greater (results scale linearly).

The analysis reflects a sharp point on the screw. It is recommended that the screw tip be rounded to further improve the safety margin since it should be an easy thing to do.



Corrected OH Tube Support – Electrostatic Analysis

Screws assumed grounded (**0 kV**)
Tips 0.8” from tube

G10 Block,
relative permittivity = 4.8

Internal Air gaps
in Red

SS Water Tube assumed at **17.3 kV**

Section thru Model with External Air

Max E field in G10
52 kV/cm
Breakdown Strength
300 kV/cm

Max E field in Air
113 kV/cm
Breakdown Strength
30 kV/cm

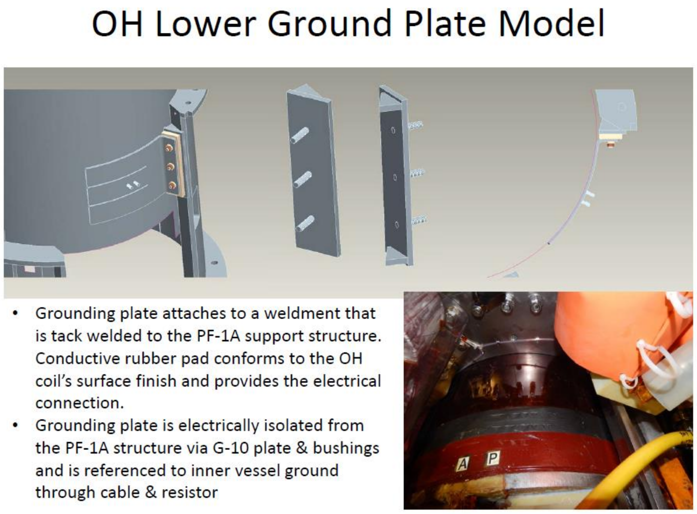
Partial Discharge will occur in airgap
Recommend filling airgap with a dielectric
such as silicone sealant

Figure 10.0-2 Electrostatic Analysis of the OH Coolant Tube (Corrected refers to a correction that Han picked up in the review)

11.0 Estimate of Lower Ground Plate Eddy Currents and Stresses

For the lower ground plane a conductive rubber patch on the ground plane paint with a cover plate is used. The cover plate bolted edge will use a mounting angle to cause the plate bend to act as a spring holding the outward plate against the conductive rubber. The ground will go through a 25 ohm resistor package. Analysis for eddy currents and disruption loads show very minimal forces.

The lower ground plate that you show as substituting for the copper braid will also have some loads on it. the radial field transient as the OH is charged will induce an eddy current. I estimate the load to be ~50 lbs for a 6 inch square plate, 3/16 thick. Do you have it attached well enough that it won't lift off when the OH is energized? -Peter

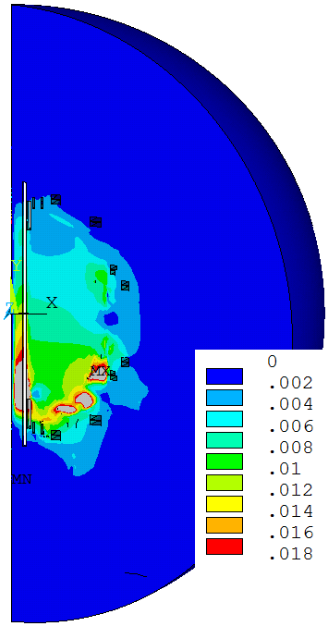


OH Lower Ground Plate Model

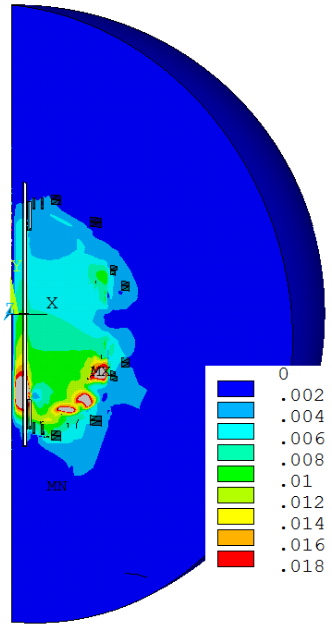
- Grounding plate attaches to a weldment that is tack welded to the PF-1A support structure. Conductive rubber pad conforms to the OH coil's surface finish and provides the electrical connection.
- Grounding plate is electrically isolated from the PF-1A structure via G-10 plate & bushings and is referenced to inner vessel ground through cable & resistor

Figure 11.0-1 From [5] Lower Ground Plate

The eddy currents induced in the plate were developed using a disruption simulation of a downward VDE with a quench.



Difference Between Steps 15 and 16
Step 15 Time=105.015
Step 16 Time=105.016
dBdT=.004/.001 = 4T/sec



Difference Between Steps 16 and 17
Step 16 Time=105.016
Step 17 Time=105.017
dBdT=.004/.001 = 4T/sec

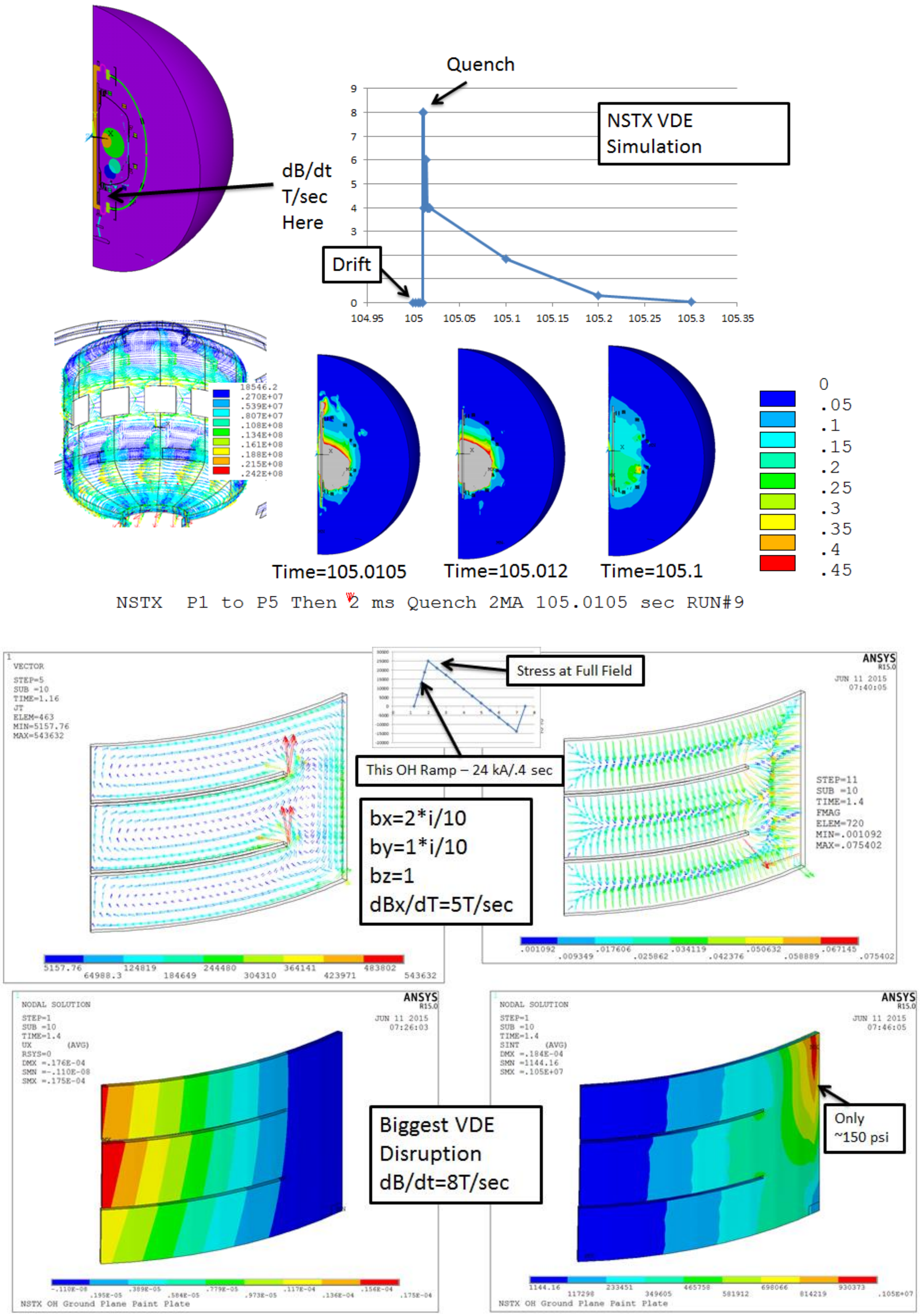


Figure 11.1.2-2 Load deflection of the 225 degree C sample

12.0 Centerstack Casing and Divertor Flange Copper Cooling Tube Induced Currents – EMAG Solution

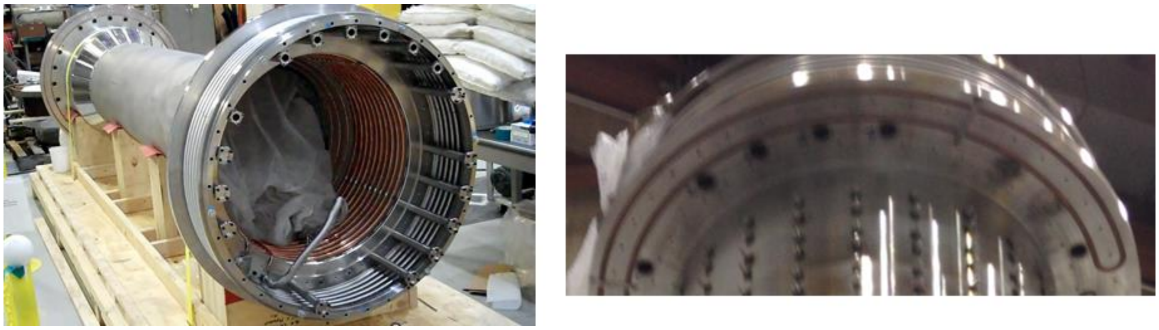
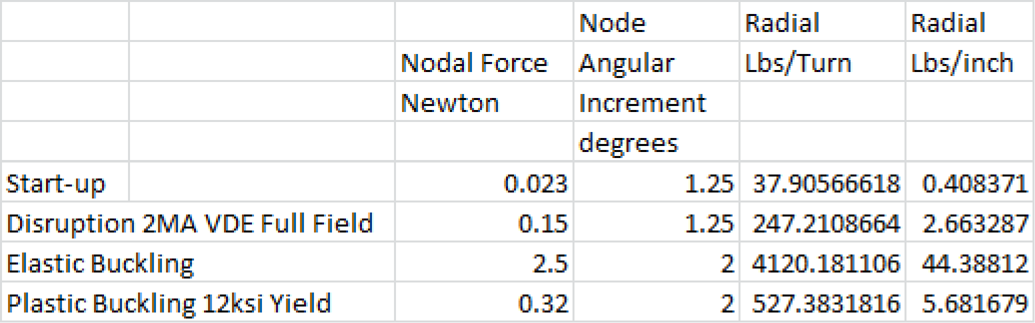
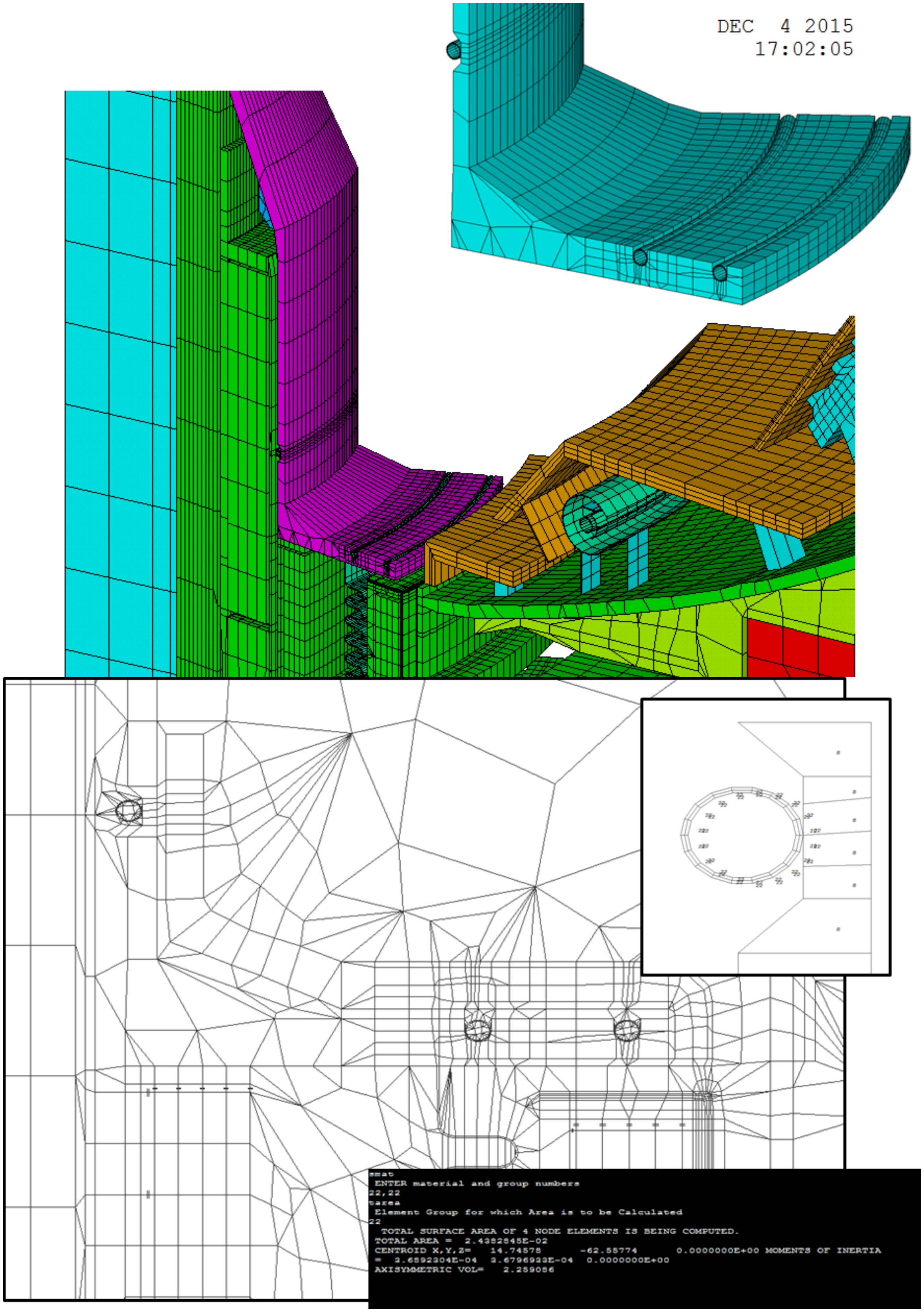


Figure 12.0-1 Centerstack casing before the tubes were well seated in the casing Grooves(Left) and the Horizontal Divertor Flange Cooling Tubes (Right)



		Nodal Force Newton	Node Angular Increment degrees	Radial Lbs/Turn	Radial Lbs/inch
Start-up		0.023	1.25	37.90566618	0.408371
Disruption 2MA VDE Full Field		0.15	1.25	247.2108664	2.663287
Elastic Buckling		2.5	2	4120.181106	44.38812
Plastic Buckling 12ksi Yield		0.32	2	527.3831816	5.681679

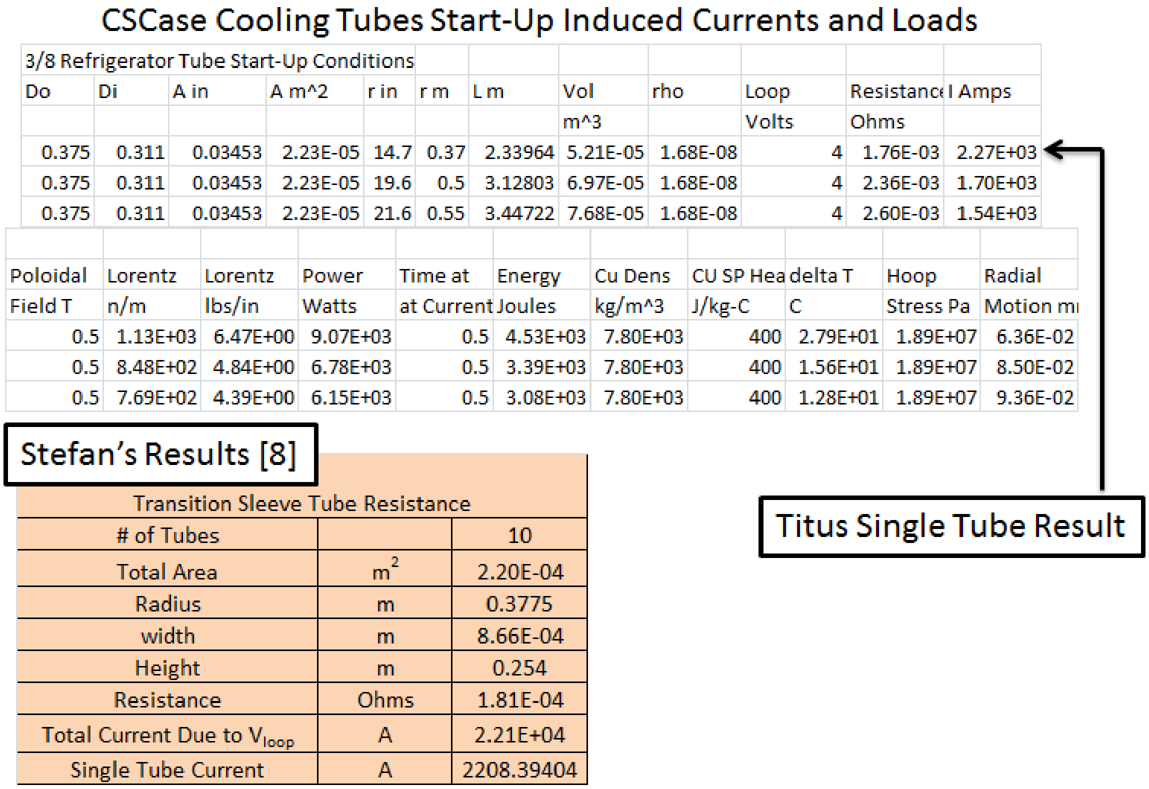


```
smat
 ENTER material and group numbers
22,22
tarea
 Element Group for which Area is to be Calculated
22
  TOTAL SURFACE AREA OF 4 NODE ELEMENTS IS BEING COMPUTED.
 TOTAL AREA =  2.4382845E-02
 CENTROID X,Y,Z=   14.74578      -62.55774      0.0000000E+00 MOMENTS OF INERTIA
 =  3.6892304E-04  3.6796933E-04  0.0000000E+00
 AXISYMMETRIC VOL=   2.259086
```

12.1 Start Up Induced Currents In The Centerstack Casing Copper Cooling Tube

Teh

Resistivity of copper at 400 K is 2.443e-8 Ohm-m
Resistivity of Stainless Steel= 74e-8 Ohm m
Resistivity of Inconel is 123e-8 Ohm m
Loads for a stainless tube go down by 74/2.44 = 30 times.



CSCase Cooling Tubes Start-Up Induced Currents and Loads

3/8 Refrigerator Tube Start-Up Conditions

Do	Di	A in	A m^2	r in	r m	L m	Vol m^3	rho	Loop Volts	Resistanc Ohms	I Amps
0.375	0.311	0.03453	2.23E-05	14.7	0.37	2.33964	5.21E-05	1.68E-08	4	1.76E-03	2.27E+03
0.375	0.311	0.03453	2.23E-05	19.6	0.5	3.12803	6.97E-05	1.68E-08	4	2.36E-03	1.70E+03
0.375	0.311	0.03453	2.23E-05	21.6	0.55	3.44722	7.68E-05	1.68E-08	4	2.60E-03	1.54E+03

Poloidal Field T	Lorentz n/m	Lorentz lbs/in	Power Watts	Time at at Current	Energy Joules	Cu Dens kg/m^3	CU SP Hea J/kg-C	delta T C	Hoop Stress Pa	Radial Motion m
0.5	1.13E+03	6.47E+00	9.07E+03	0.5	4.53E+03	7.80E+03	400	2.79E+01	1.89E+07	6.36E-02
0.5	8.48E+02	4.84E+00	6.78E+03	0.5	3.39E+03	7.80E+03	400	1.56E+01	1.89E+07	8.50E-02
0.5	7.69E+02	4.39E+00	6.15E+03	0.5	3.08E+03	7.80E+03	400	1.28E+01	1.89E+07	9.36E-02

Stefan's Results [8]

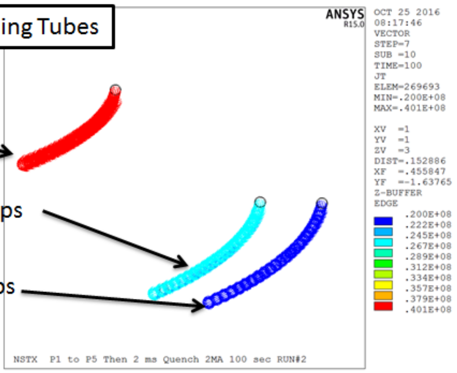
Transition Sleeve Tube Resistance		
# of Tubes		10
Total Area	m^2	2.20E-04
Radius	m	0.3775
width	m	8.66E-04
Height	m	0.254
Resistance	Ohms	1.81E-04
Total Current Due to V_{loop}	A	2.21E+04
Single Tube Current	A	2208.39404

Titus Single Tube Result

The current calculated for the 4 volt loop voltage [8] is 2270 Amps, which is essentially the same as Stefan got at 2208.4 Amps per tube. This produces 28 degree heat-up (ignoring the water contained in the tube and conduction to the Inconel 625- The thermal stress will help, producing 50 MPa hoop compression helping hold the tubes in the grooves. The radial load looks modest at 6.47 lbs/in being restrained by only the four retainer straps but if the tubes take the load in hoop compression the stress is only 19 MPa and the radial motion is tiny. The tubes could buckle, but the tubes are stabilized by the grooves they fit into. There is a reversal in flux between precharge and initiation that would cause one or the other to pull away from the grooves. I assumed 1/2 sec of induced current duration to calculate the temperature. A 0.5T vertical field was used to calculate the radial load. Based on the 96 scenarios it might be .9 T. but for start-up the 96 equilibria are inappropriate for a field source.

Resistivity of copper at 400 K is 2.443e-8 Ohm-m
Resistivity of Stainless Steel= 74e-8 Ohm m
Resistivity of Inconel is 123e-8 Ohm m
Loads for a stainless tube go down by 74/2.44 = 30 times.

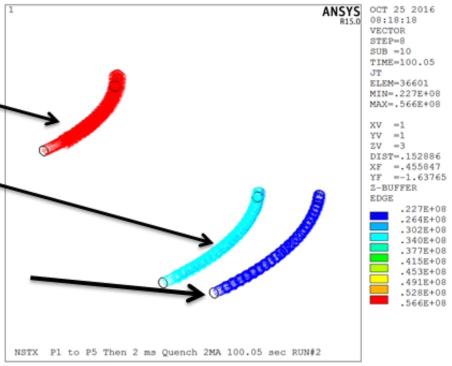
Start Up Currents in the Copper Cooling Tubes



7.315e-2/3/39.37/39.37*.4e8=629 Amps

7.315e-2/3/39.37/39.37*.27e8=629 434 Amps

7.315e-2/3/39.37/39.37*.2e8=629 324 Amps

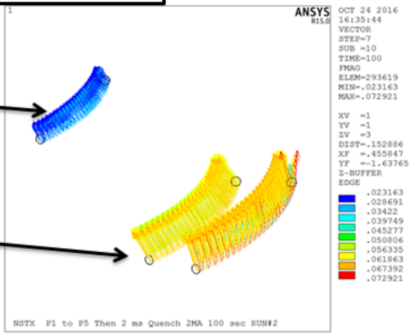


7.315e-2/3/39.37/39.37*.4e8=890.3 Amps

7.315e-2/3/39.37/39.37*.34e8=544 Amps

7.315e-2/3/39.37/39.37*.227e8=357 Amps

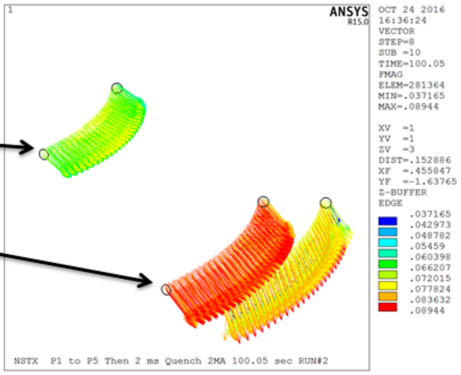
Start Up Forces in the Copper Cooling Tubes



Total Force is 36*.023N*360/1.25=207.36N
Net Vert~207.36/2^.5=146.6 N=33Lbs Total per turn

Total Force is 36*.067N*360/1.25=694.7N
Net Vert~694.7/2^.5=491.2 N=110.427Lbs Total per tube

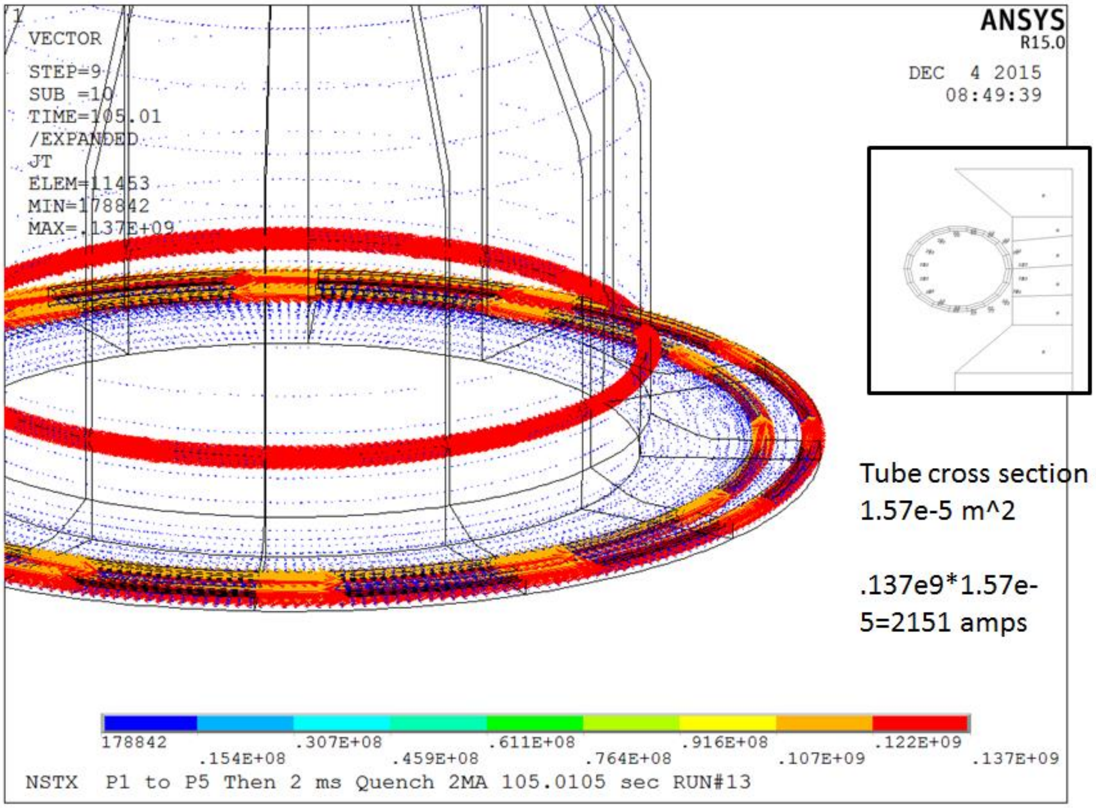
Assumes a 45 degree angle



Total Force is 36*.07N*360/1.25=725.7N
Net Vert~725.7/2^.5=513.2 N=115 Lbs

Total Force is 36*.089N*360/1.25=922.7N
Net Vert~922.7/2^.5=652.5N=146.7 Lbs

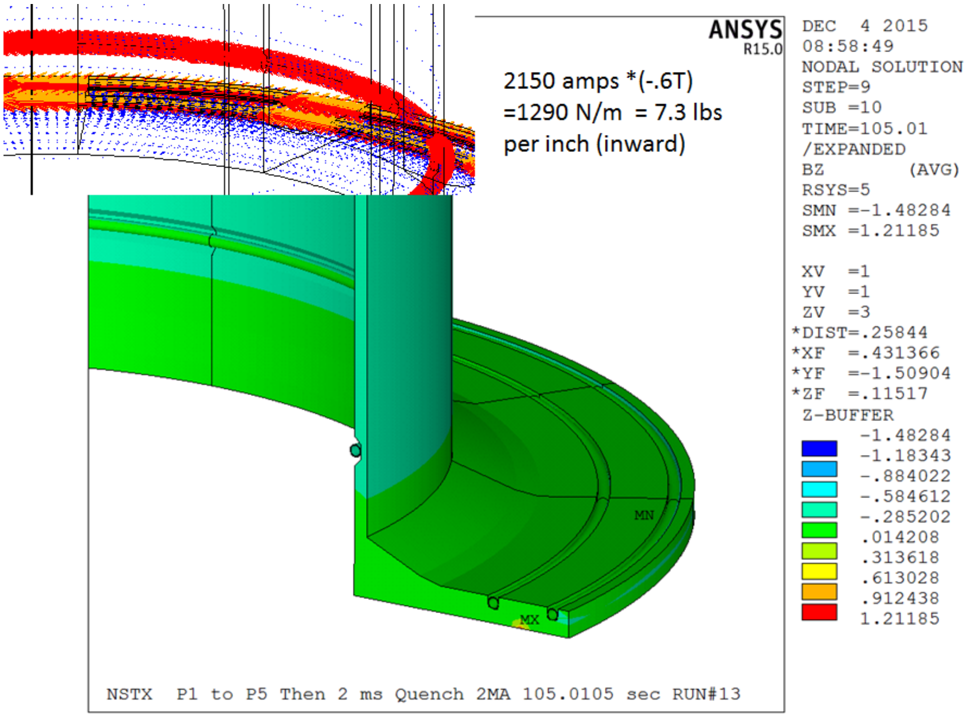
12.1 Disruption Induced Currents In The Centerstack Casing Copper Cooling Tube



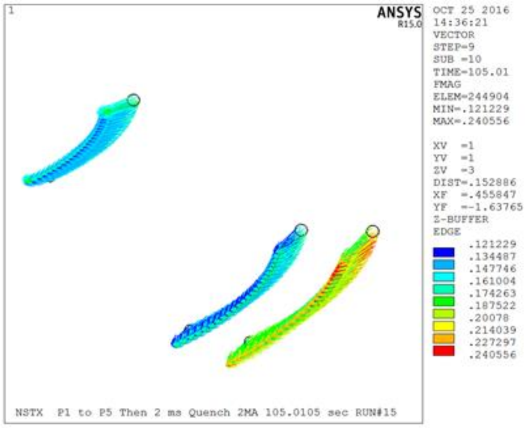
Tube cross section = 1.57e-5 m^2

.137e9*1.57e-5=2151 amps

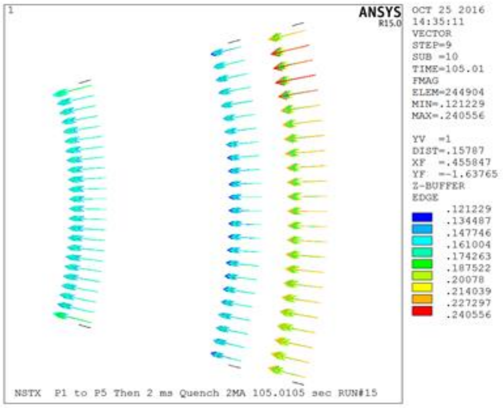
The disruption current is comparable with the start-up current

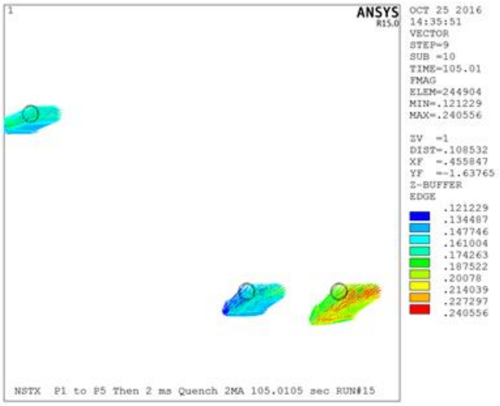


2150 amps *(-.6T)
=1290 N/m = 7.3 lbs
per inch (inward)



Total Force is 36*.15N*360/1.25 =1555.2N
Net Radial or Vert~1555.2/2^.5 =1099.7 N=247.2
Lbs Total per tube

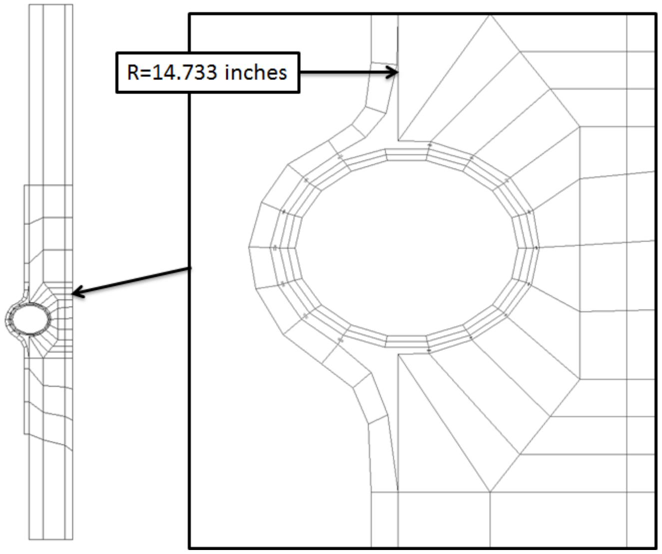




The disruption load is 247.2 lbs total per tube

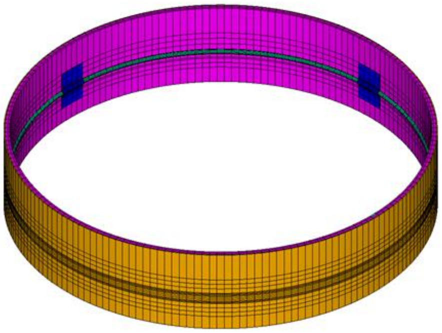
13.0 Centerstack Casing Copper Cooling Tube Buckling Stability

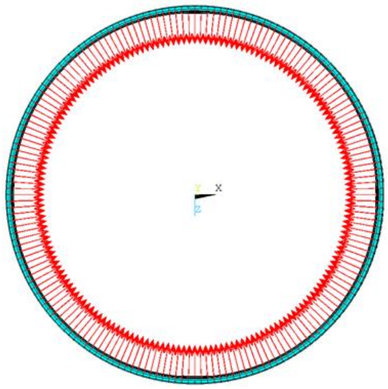
During start-up and disruptions the tubes can be loaded radially inward with tube hoop compression and thin straps providing restraint. In order to assess the stability of this system, a large displacement solution was performed with the tubes supported in the grooves at the ID of the casing. Nodal loads were ramped up in steps and the point at which convergence was lost, was considered the buckling limit. The dynamic aspects of the loading were not simulated.

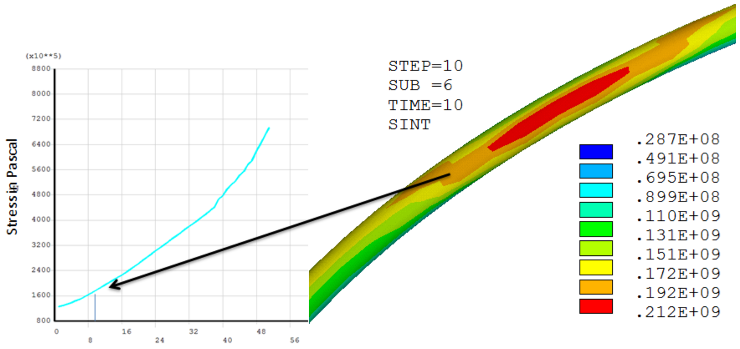


```
zero
read
tube
todr
180,0,2
snal
1
merge
1,.00001
redu
smat
10,10
secoor
0,-100,100,-100,100,-1,1
secoor
0,-1,1,-100,100,-100,100
gerase
10
redu
plce
pl
exit
```

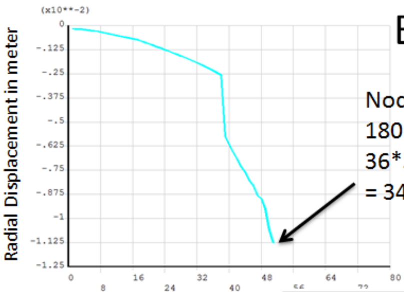
Figure 13.0-1 2D Mesh Used as the Swept Basis for the Tube Model



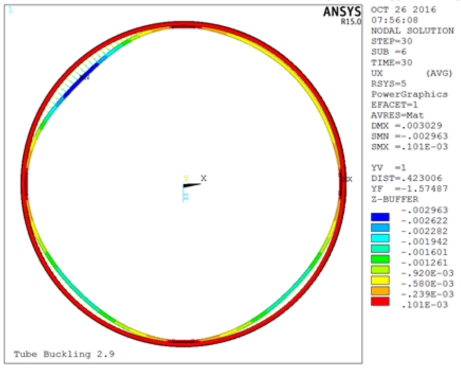


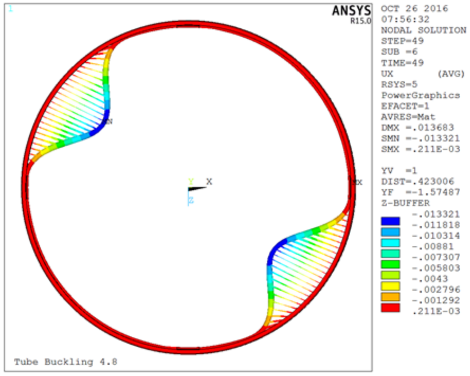


Elastic Buckling

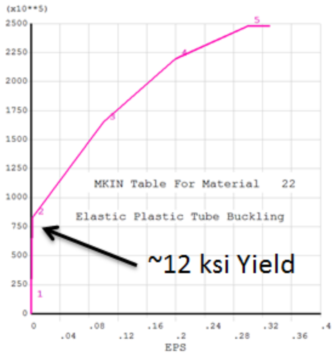


Nodal force 5N/node,
180 N per 2 degrees or
36*5/(14.773*2*pi/180)
= 349 lbs/inch

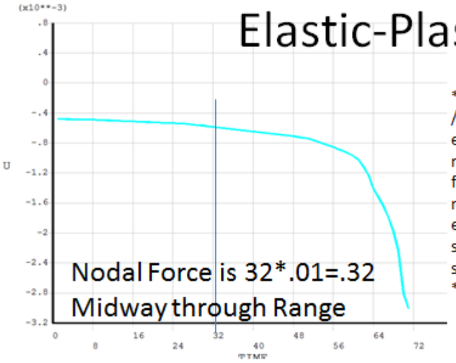




Elastic-Plastic Buckling

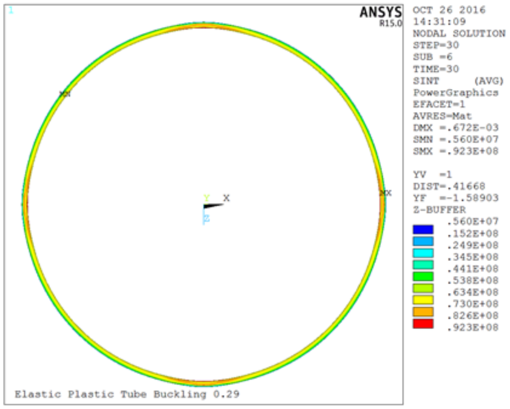


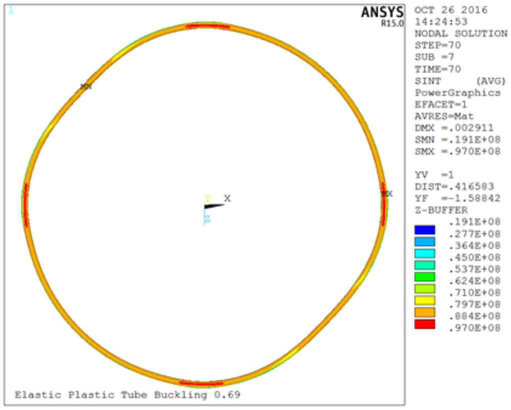
~12 ksi Yield



Nodal Force is 32*.01=.32
Midway through Range

```
*do,lf,0,10,.01
/title, Elastic Plastic Tube Buckling %lf%
esel,mat,22
nelem
f,all,fx,-lf
nall
eall
solve
save
*enddo
```





Mid way through the load cycle, the nodal force is .32 Newtons or 5.68 lbs per inch. The applied load during start up is .408lbs/inch and 2.66 lbs /inch during a (full performance) disruption. So if the yield of the tubes is ~12ksi, then the tubes should have been able to survive a disruption. If the tubes were fully annealed during the bake-out, with a yield of more like 5 ksi, than the tubes could be buckled during a disruption of a full performance plasma.

Appendix A
EMAILS

On May 12, 2015, at 8:52 AM, Charles L. Neumeyer <neumeyer@pppl.gov> wrote:
A few comments:
- The design should pass at least 1.5 x 17kV. The margin of 1.5 should be considered a minimum; more would be better.
- If the mock-up passes and it fits the available space, then I suppose that would be good enough if time is too short to allow for E-field analysis and design iteration.

My issue is that PPPL has been designing these coil appendages in an entirely empirical way without any clear set of rules or any analysis to base it upon and this has caused weaknesses over and over again.
Ch

Email from Stefan Gerhart, 12/3/15 :
Stefan Gerhardt <sgerhard@pppl.gov>
Attachments 12/3/15
to Charles, Steve, Jonathan, Lawrence, me
I busted out my EE PhD to do the calculation on the first sheet of the attached.
Get ready to be amazed.
Stefan
On Thu, Dec 3, 2015 at 12:26 PM, Charles L. Neumeyer <neumeyer@pppl.gov> wrote:
This looks worrisome. Pete, do you have the actual drawing so you can determine the number of turns on this accidental coil? Ch

Appendix B
EMAG Start-Up Listing

```
/batch
runn=2
estep=0
tstep=0
ipmax=2.0
/com
/com
! Run with mat 24 in the NCC loop to measure voltage
! CREATE BASE ELECTROMAGNETIC SOLUTION
/filnam,elect
/PREP7
antype,trans
/COM   11-25-98   Electrical/Thermal analysis
ET,1,97,1    ! (Ax, Ay, Az, VOLT) EM for current regions
!ET,1,97,4    ! (Ax, Ay, Az, VOLT,curr) EM for current regions
!ET,1,97,0    ! (Ax, Ay, Az) EM for non current regions
et,2,97,0    ! (Ax, Ay, Az) EM for prescribed current regions
et,3,97,0    ! (Ax, Ay, Az) EM for air
et,4,111
TREF,292.0

*create,matt
packf=.9
/COM   MAT,1  TF COIL COPPER, Inner Leg
/COM   MAT,90  Air
/com   MAT,50  Vessel
/com   MAT,19  Cover and Torque Shell
/com   MAT,52  Plasma
```

```
/com   MAT,54  Lower Hybrid Antenna Mounting Hardware
/com   MAT,55  Inner divertors

/com   MAT,54  Lower Hybrid Antenna Mounting Hardware
/com   MAT,55  Cryo pump
/com   MAT,57  Baffle
/com   MAT,58  Gusset
/com   MAT,41  TF Coil
/com   MAT,42  TF Coil
/com   MAT,43  TF Coil

/com   Real,61 and 62  Plasma 1
/com   Real 62,63 Plasma 2

*do,imat,1,100
mp,dens,imat,8950
mp,murx,imat,1.0
mp,rsvx,imat,74e-8      !Generic Stainless Steel
mp,c,imat,100
*enddo


mp,rsvx,54,74e-8 !Antenna support


!TF Coil
mp,rsvx,1,2e-8
!   TF Joint Strap
mp,rsvx,2,2e-8
!         Passive Plates
mp,rsvx,7,.85*2.443e-8 ! @400K
mp,rsvx,27,.85*2.443e-8 ! @400K     ! NCC CoilsPoloidal Run
mp,rsvx,28,.85*2.443e-8 ! @400K     ! NCC Coils Toroidal Run
mp,rsvx,24,.85*2.443e-8 ! @400K     ! Voltage Link
!      Centerstack Casing
mp,rsvx,8,123e-8 ! Inconel 625 at 4K
mp,rsvx,22,2e-8  ! Ground Strap and cooling tubes
!      Air
mp,kxx,90,.000001
mp,rsvx,90,2e-8
mp,rsvx,91,2e-8
!    Cryo Pump
mp,rsvx,55,60e-8 !Cryo Pump   !SST at 80K
mp,rsvx,57,123e-8 !Cryo Pump Helium Tube Inconel 625 at 4K
!    BES Aluminum Cylinder
mp,rsvx,21,2.65e-8     ! Aluminum
!    Graphite Tiles
mp,rsvx,30,100e-6      ! Set arbitrarily high
*end

*use,matt
/com
/input,ebaj,mod
!/input,ebah,mod
!/input,ebar,mod
/com
```

```
nummer,node,.000001
eall   $nall
LOCAL,12,1,0,0,0,0,-90.0,0.0
CSYS,12  $NROTAT,all
esys,12

cpdele,all,all
cpcyc,ax,.00001,12,0,30,0
cpcyc,ay,.00001,12,0,30,0
cpcyc,az,.00001,12,0,30,0
nall
eall
csys,12


esel,type,1
nelem
nrsel,y,-16,-14.9
d,all,volt,0.0
esel,type,1
nelem
nrsel,y,14.9,16
d,all,volt,0.0

nall
eall

tunif,80

csys,5
curd= .01
esel,mat, 61,62
bfe,all,js,1,0,0,curd
eall
nall

!  TF Currents
esel,real,40
nelem
f,all,amps,130000/25   ! TF is 4 X 4 elements, 5 X 5 nodes
d,all,volt,0.0
nelem
esel,real,41
nelem
f,all,amps,-130000/25
nall
eall

!PF Coil Data

!Terminal Current   Number of turns      Area m^2     Coil   Real Constant
TerCur2=  -24   $numturns2=  884  $Area2=  .2778247       !OH     ,    2
TerCur3=   6.2  $numturns3=    64 $Area3=  .0333619      !PF1aU  ,    3
TerCur4=  0.0   $numturns4=    32 $Area4=  .00608698      !PF1bU  ,    4
TerCur5=  0.0   $numturns5=    20 $Area5=  .00818269      !Pf1cU  ,    5
TerCur6=-5.555  $numturns6=    28 $Area6=  .022127185     !PF2U   ,    6
```

```
TerCur7=  .553  $numturns7=    30 $Area7=  .02535049      !PF3U   ,    7
TerCur8=  0.0   $numturns8=    17 $Area8=  .014062411     !PF4    '    8
TerCur9=-30.177 $numturns9=    24 $Area9=  .01861829      !PF5    ,    9
TerCur10=  .553 $numturns10=   30 $Area10=  .02535049     !PF3L   ,   10
TerCur11=-5.555 $numturns11=   28 $Area11=  .022127185    !PF2L   ,   11    Max Current in PF1cL
TerCur12= -16.0 $numturns12=   20 $Area12=  .00818269     !PF1cL  ,   12
TerCur13=  0.0  $numturns13=   32 $Area13=  .00608698     !PF1bL  ,   13
TerCur14=  6.2  $numturns14=   64 $Area14=  .0333619      !PF1aL  ,   14

! This sets the currents initially at a given equilibrium.
csys,5
*do,ipf,2,14
esel,mat,17
ersel,real,ipf
!bfe,all,js,1,0,0, 32740820.
bfe,all,js,1,0,0, tercur%ipf%*1000*numturns%ipf%/area%ipf%
*enddo



eall
nall
/show,vtr%runn%,pic
/view,1,1,1,2
/num,1
mnum,1
eplot
/pbc,a,1
eplot
nplot
/view,1,0,1,0
nplot
/pbc,a,0
/view,1,1,1,2
/pbc,cp,1
nplot
/pbc,cp,0
/pbc,volt,1
nplot
/pbc,volt,0
esel,mat,50
easel,mat,51
easel,mat,52
nelem

allsel,all
csys,2
nsel,s,loc,x,5.05,5.1
nmodif,all,5.08001016,
sf,all,inf
nall
eall
csys,12
save
fini
!/exit
```

```
/solu
esel,mat,50
cm,vess,elem
esel,mat,51
cm,covt,elem
esel,mat,52
easel,mat,61
cm,plas,elem
esel,mat,54
cm,asup,elem
eall
nall

p1area= .962278    !Plasma 1    Real 61, 62
p2area= .25051     !Plasma 2    Real 62, 63
p3area=  1         !Plasma 3    Real 64
p4area= .2494      !Plasma 4    Real 65, 67
p5area= .2498      !plasma 5    Real 66


!In this table, the i variable will be the starting plasma volume
!              the p variable will be the end plasma volume before quench
! The OH current swing is set up here -Note that the rest of the PF currents are not reassigned
t1= 0.100000  $TerCur21=-.001 $i1= .001   $p1= .001
t2= 99.5000   $TerCur22=-.001 $i2= .001   $p2= .001
t3= 99.625000 $TerCur23=-6    $i3= .001   $p3= .001
t4= 99.75     $TerCur24=-12   $i4= .001   $p4= .001
t5= 99.875    $TerCur25=-18   $i5= .001   $p5= .001
t6= 100.00    $TerCur26=-24   $i6= .001   $p6= .001
t7= 100.05    $TerCur27=-20   $i7= .001   $p7= .001
t8= 100.5     $TerCur28=-15   $i8= 1.0e6  $p8= .001
t9= 101.0     $TerCur29=-10   $i9= 2.0e6  $p9= .001
t10=101.5     $TerCur210=-7.5 $i10=2.0e6  $p10= .001
t11=102.0     $TerCur211=-5   $i11=2.0e6  $p11= 0.001
t12=102.5     $TerCur212=.001 $i12=2.0e6  $p12= 0.001
t13=103.0     $TerCur213=2    $i13=2.0e6  $p13= 0.001
t14=103.5     $TerCur214=6    $i14=2.0e6  $p14= 0.001
t15=104.0     $TerCur215=8    $i15=2.0e6  $p15= 0.001
t16=104.5     $TerCur216=10   $i16=2.0e6  $p16= 0.001
t17=105.0     $TerCur217=12   $i17=2.0e6  $p17= 0.001
t18=105.5     $TerCur218=15   $i18=2.0e6  $p18= 0.001
t19=106.0     $TerCur219=10   $i19=.001   $p19= 0.001
t20=106.5     $TerCur220=5    $i20=.001   $p20= 0.001
t21=107.0     $TerCur221=0    $i21=.001   $p21= 0.001
nsubst,10,10,3
time,.01
/com Elecromagnetic Solution
esel,mat,17
ersel,real,2
bfe,all,js,1,0,0, .0001
nall
eall
estep=estep+1
solve
save
```

```
!    SETUP TRANSIENT MACRO
*create,load
/com solve electromagnetic problem
time,timpt


csys,0

curd= Ipmax*i%ls%/p1area
esel,real, 61,62
!bfe,all,js,1,0,0,curd

curd= Ipmax*p%ls%/p5area
esel,real, 66,67
!bfe,all,js,1,0,0,curd

! The OH current swing is set up here -Note that only the OH is being swung  tercur2%ls%
*if,ls,gt,0,then     !I changeed 1 to 0 because the initiAL OH currents were not set to zero
csys,5   $esel,mat,17  $ersel,real,2
bfe,all,js,1,0,0, tercur2%ls%*1000*numturns2/area2
nall   $eall
csys,0
*endif

!estep=estep+1
nall $eall
solve
save
!parsav,,file,parm

*end

!   START TRANSIENT

*do,ls,1,21,1
!*do,ls,1,8,1
timpt=t%ls%
curamp=i%ls%
/TITLE, NSTX  P1 to P5 Then 2 ms Quench %Ipmax%MA %timpt% sec RUN#%runn%

*use,load


*enddo

save
fini


/exit

/filnam,stru
/prep7
```

```
antype,static
/TITLE, NSTX  P1 to P5 Then 2 ms Quench %Ipmax%MA %timpt% sec RUN#%runn%
et,1,45
!et,2,45          ! Prescribed current regions will not be stress analyzed in this run
esel,type,1
nelem

*do,imat,1,100
ex,imat,200.0e9
alpx,imat,17.0e-6
*enddo
ex,8,100e9

   ! Add Support Boundary Constraints
esel,mat,50
nelem
d,all,all,0.0
esel,mat,7
easel,mat,12
nelem    !
fscale,.00001
tref,292
tunif,292
save
fini
/solu

*do,iload,1,21,1
ldread,forc,iload,,,,elect,rst
solve
save
*enddo

fini

/exit
```