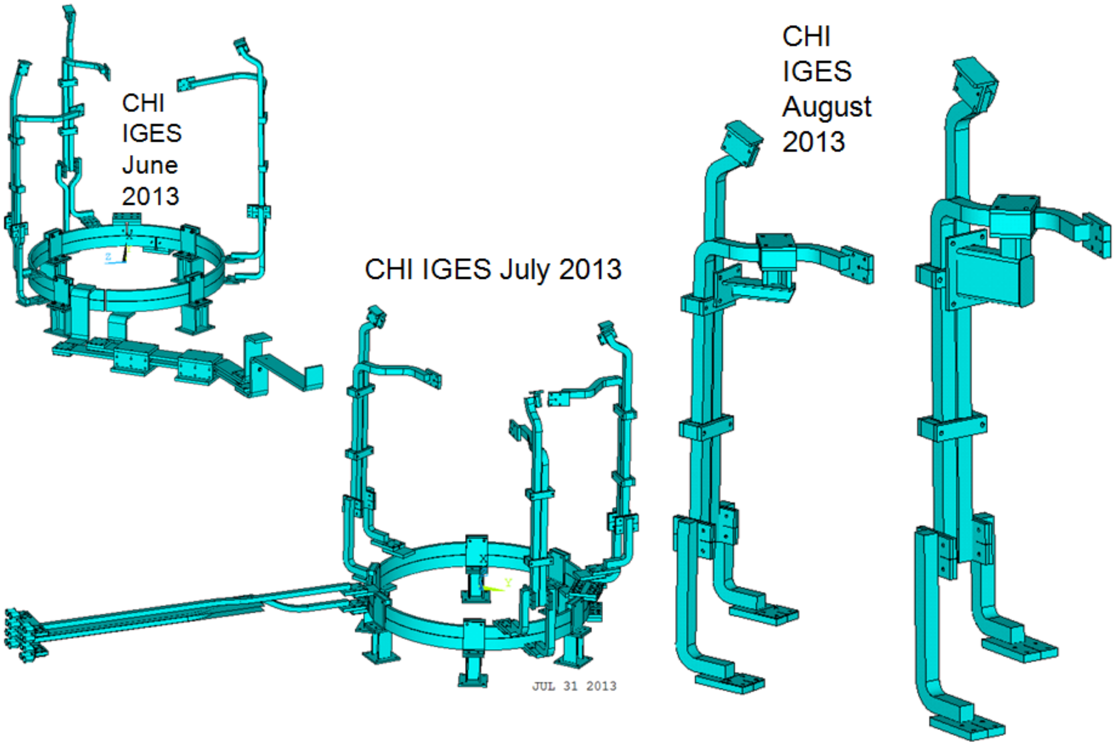
NSTX Upgrade

CHI Bus BarAnalysis

NSTXU-CALC-54-01-0

November 21, 2013



Prepared By:

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Reviewed By:

Andrei Khodak
2013.11.26
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Andrei Khodak

PPPL Calculation Form

Calculation # **NSTXU-CALC-54-01-00** Revision # **00** ____ WP #, **1672**
(ENG-032)

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

The purpose of this calculation is to provide guidance on initial design of the CHI bus bars and connections for the upgrade loads, and to provide qualification of the final design.

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 6.2

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

CHI normal operating currents are assumed to be evenly distributed between the three CHI bars. CHI current drive operation is assumed to be possibly operating during a disruption (see figure 4.0-3) . A peaking factor is applied to the disruption halo currents that raises the peak halo current from 50 kA to 75 kA per leg or 84 kA per vertical CHI bus connection with current drive. Halo currents are assumed not to be uniformly split between the three vertical legs of the Bus. The peaking factor is estimated by Stefan Gerhardt based on NSTX operations. Current drive experiments will be possible when power supplies are upgraded to the Transrex power supplies.

Calculation (Calculation is either documented here or attached)

These are included in the body of the following document

Conclusion

The Upgrade CHI bus bar design is qualified for the increased upgrade loads and currents. The qualified design is based on 2.0 inch square (on a side, 4.0 Sq. inch) air cooled conductor in the vertical runs and a 1 X 3.5 inch cooled ring bus. Mounting plate bolts for the 6 X 3 box beam support should be 5/8 inch ASTM A193 B8M Class 2 bolts. 5/8 inch studs welded to the umbrella structure with a 3/8 weld is also acceptable. High strength bolts should also be used at the connections to the centerstack casing. In order to sustain the separating loads when the paired conductors in the ring bus carry the halo currents, clamps connecting the upper and lower rings should be added at least every 45 degrees. The floor runs carry the full halo current, and there should be four clamps between the bus tower and the ring bus. Most qualifications either considered bake-out thermal stresses or disruption stresses. Normal operating Lorentz stresses will scale down with the normal current/Halo Current or 9kA/84kA. Self load effects scale down with the square of this. The normal Lorentz stresses are small even with respect to the fatigue limit of copper of 125 MPa. CHI rod materials and retainers at the casing flange need to be checked for adequate size and material selection. They should satisfy the same allowable as the bus bar.

Cognizant Engineer's printed name, signature, and date

Neway Atnafu Neway D. Atnafu

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Date: 2013.11.26 08:41:58 -05'00'

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

Checker's printed name, signature, and date

Andrei Khodak
2013.11.26
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4.0 Executive Summary

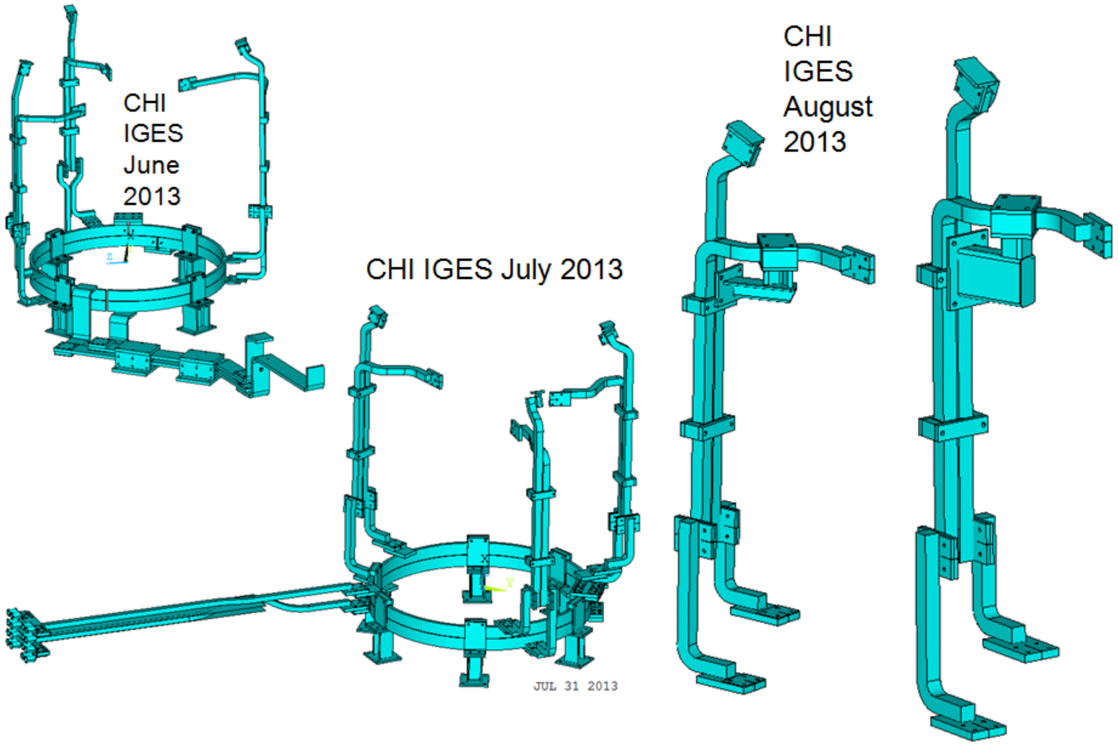


Figure 4.0-1 CHI Bus Design Evolution

The objective of this calculation is to qualify the final design of the CHI bus bars and connections for the upgrade loads. Integrally connected to the bus bars are the CHI rods that run vertically and connect with the centerstack casing flange. The purpose of this calculation is to address the design details of these as well. An earlier version of the bars is addressed in the centerstack casing calculation, NSTXU-CALC-133-03-0 [23]

The Upgrade CHI bus bar design is adequate for the increased upgrade loads and currents. The qualified design is based on 2.0 inch square, ,(4.0 Sq. Inch) air cooled conductor in the vertical runs and a 1 X 3.5 inch water cooled ring bus.

Stick models of the CHI bus bar system were built to support initial sizing. The ring bus, floor runs and lower ends of the vertical legs of the CHI bus were not heavily loaded by electromagnetic loads (see figure 4.0-2). This allows conceptual design to focus on the vertical runs. There are three of these and they are similar enough that only one needs to be modeled in detail, however to get the proper stress at the brazed connection to the ring bus, the ring bus and three identical vertical runs are modeled. Loads from TF fields predominate for conductor runs inside the TF "cage". PF fields were investigated, but in the region where the TF fields are large, the PF field magnitudes are small enough that they can be enveloped by a 1 T upper bound. At the ring bus both the TF and PF fields are lower

There are runs that physically come close to PF2L. The PF2L currents for the 96 Equilibria were plotted. The EQ with the highest PF2L current (15

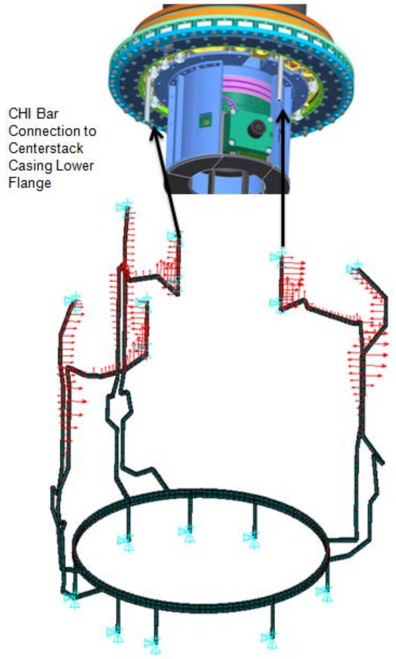


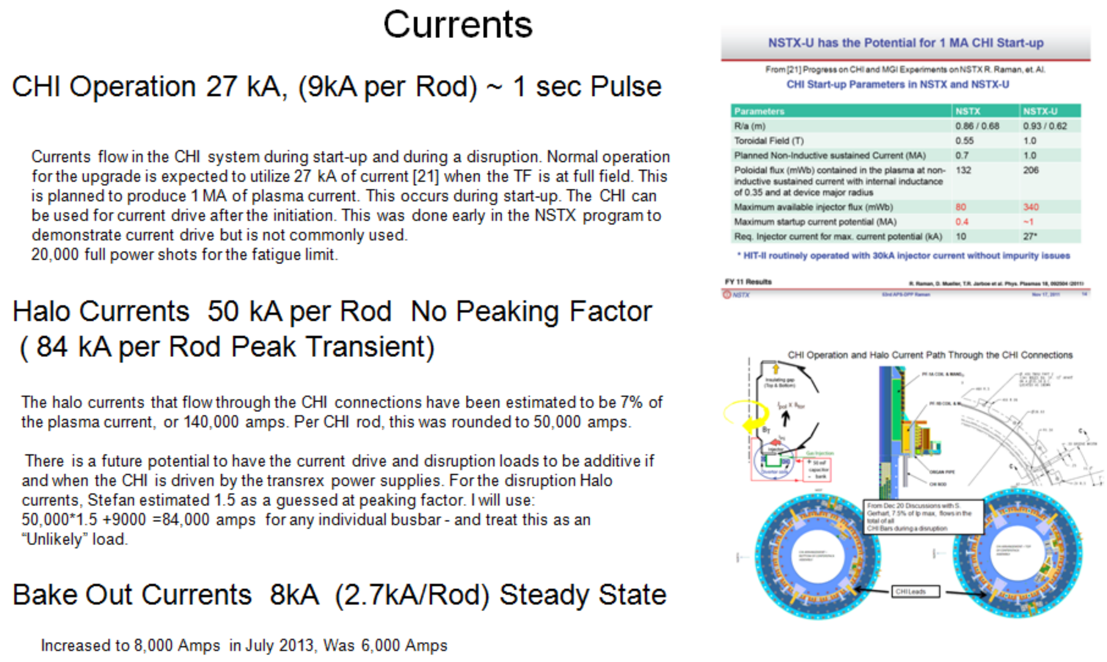
Figure 4.0-2 CHI Bus Bar Beam Element Model and Where the Bar Connects with the CHI Rods

kA in EQ66) was run and the PF loads can still be basically enveloped by the 1 Tesla poloidal field. The fields at the ring bus are estimated to be less than 1.0 T

Initially, self fields were ignored as small compared with the forces due to the background field(See Figure 9.1-2), or because the halo currents were assumed to travel in only one leg of the paired conductors. Based on discussions with Stefan Gerhardt, effects of self fields were added.

Early analyses with a 2 cm (3/4 inch) square conductor with coolant hole was significantly overstressed everywhere that is effected by the TF field. The guidance was to go to a bigger cross section, and adding more supports inside the TF “cage”.

The calculations are based on the halo currents in the CHI bus that have been measured by Stefan Gerhardt. These are 7.5%*Ip with a peaking factor of 1.5. With Concurrent CHI current drive. This turns out to be 84,000 amps per bar. The design currents are summarized in figure 4.0-3.



Currents

CHI Operation 27 kA, (9kA per Rod) ~ 1 sec Pulse

Currents flow in the CHI system during start-up and during a disruption. Normal operation for the upgrade is expected to utilize 27 kA of current [21] when the TF is at full field. This is planned to produce 1 MA of plasma current. This occurs during start-up. The CHI can be used for current drive after the initiation. This was done early in the NSTX program to demonstrate current drive but is not commonly used.
20,000 full power shots for the fatigue limit.

Halo Currents 50 kA per Rod No Peaking Factor
(84 kA per Rod Peak Transient)

The halo currents that flow through the CHI connections have been estimated to be 7% of the plasma current, or 140,000 amps. Per CHI rod, this was rounded to 50,000 amps.

There is a future potential to have the current drive and disruption loads to be additive if and when the CHI is driven by the transrex power supplies. For the disruption Halo currents, Stefan estimated 1.5 as a guessed at peaking factor. I will use:
50,000*1.5 +9000 =84,000 amps for any individual busbar - and treat this as an “Unlikely” load.

Bake Out Currents 8kA (2.7kA/Rod) Steady State

Increased to 8,000 Amps in July 2013, Was 6,000 Amps

NSTX-U has the Potential for 1 MA CHI Start-up

From [21] Progress on CHI and MGI Experiments on NSTX R. Raman, et. Al.

CHI Start-up Parameters in NSTX and NSTX-U

Parameters	NSTX	NSTX-U
R/a (m)	0.86 / 0.68	0.93 / 0.62
Toroidal Field (T)	0.55	1.0
Planned Non-Inductive sustained Current (MA)	0.7	1.0
Poloidal flux (mWb) contained in the plasma at non-inductive sustained current with internal inductance of 0.35 and at device major radius	132	206
Maximum available injector flux (mWb)	80	340
Maximum startup current potential (MA)	0.4	~1
Req. Injector current for max. current potential (kA)	10	27*

* HIT-II routinely operated with 30kA injector current without impurity issues

FY 11 Results

R. Raman, D. Mueller, T.R. Jarboe et al. Phys. Plasmas 18, 092504 (2011)

CHI Operation and Halo Current Path Through the CHI Connections

From Dec 20 Discussions with S. Gerhart, 7.5% of Ip max, flows in the total of all CHI Bars during a disruption

Figure 4.0-3 CHI Bus Bar Currents

Most of the limiting stresses in the bus bars are for the unlikely convergence of a full power shot, use of CHI current drive, and a VDE disruption with a worst case halo peaking factor. This as an “Unlikely” Event as defined by the NSTX Criteria Document [11], Section I 4.1.5 Kfactors . This allows a K factor of 1.2 be applied to the normal allowable.

Table 4.0-1 Stress Summary

Location (Halo Loading Unless Noted)	Peak T (deg C)	Stress	Allowable	Rpt Section
2 X 2 Bus Bar Horizontal Leg Supported By the Box Beam	36	174 MPa (Peak)	156 MPa (Bending)	12.1
2 X 2 Bus Bar Vertical Runs	36	70 MPa (Peak)	156 MPa (Bending)	12.1
Upper 2 X 2 Bus Cantilevered Box Beam Support	36	>270 MPa (Peak)	240 MPa (Bending)	12.2
Upper 2 X 2 Bus Cantilevered Box Beam Support		210 MPa (Bending)	240 MPa (Bending)	12.2
Upper 2 X 2 Bus Cantilevered Box Beam 5/8 Bolting	36	58 ksi	58 ksi	12.2

Upper 2 X 2 Bus Cantilevered Box Beam 3/8 Welded 5/8 Stud	36	21 ksi	21 ksi	12.2
Intermediate Joint ½ Bolting	36	10 ksi	11.3ksi	12.3
Ring Bus to Flag Braze Joints	32			12.4
CHI Bar (connected to Casing) (water cooled)		156	156	12.5.1
½ in Bolts, Connection to the Centerstack Casing Flange (*)	32	33021 psi	66,000psi	12.5.2
Bolted Connection to the Centerstack Casing (with Preload)	32	50,000 psi	66000 psi	12.5.2
Ring Bus 1 X 3.5 Water Cooled Halo Current Self Loads (with supports every 45 degrees around the perimeter)	32	40.75 MPa (peak)	156 MPa (bending)	Figure 9.2.4
Floor Run Water Cooled Self Loads	32	76.5 MPa	156 Mpa	9.3
Bake-Out All CHI Bus Bar	50	<135 (Peak)	130 (Bending)	Fig 8.0-6
Ring Bus Bake-Out (Water Cooled)	25			Fig 8.0-2

(*) ASTM A 193 B8M Class 2 bolts assumed to allow a higher preload

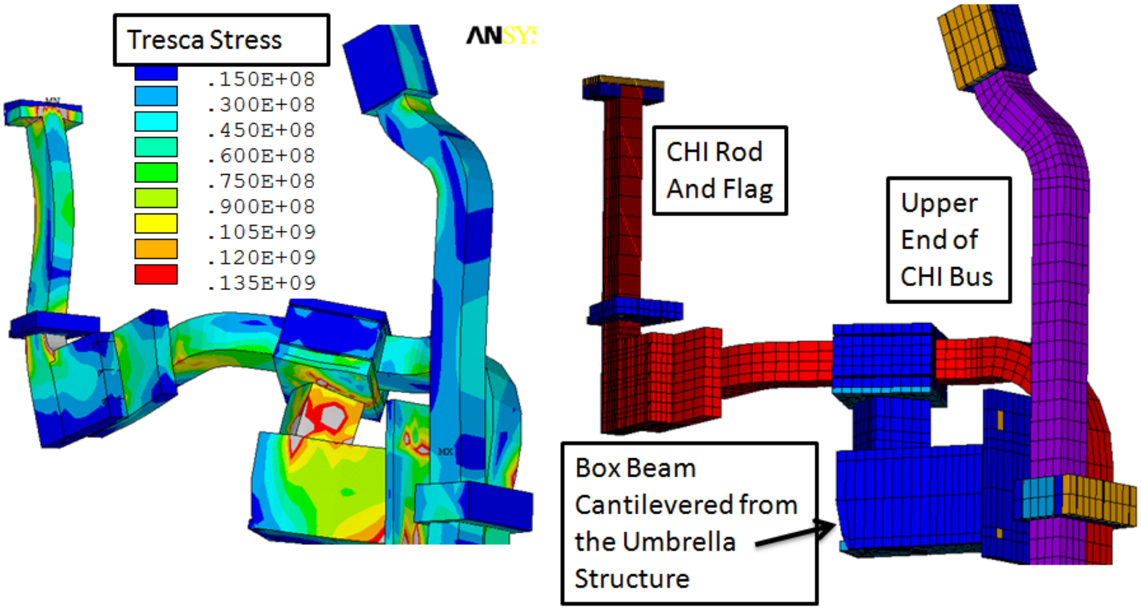
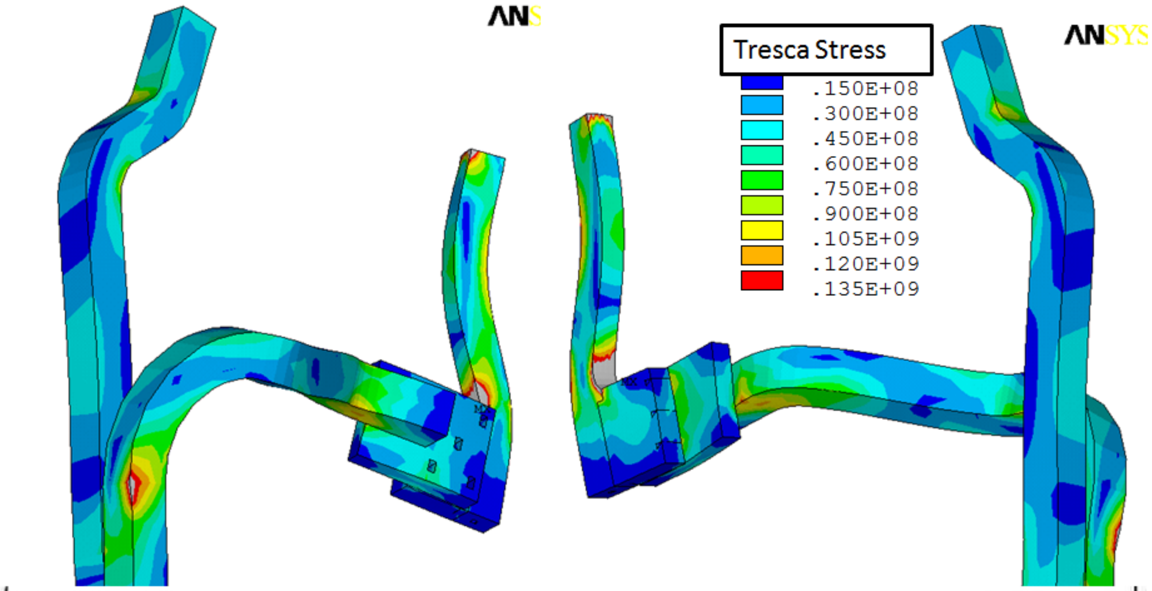
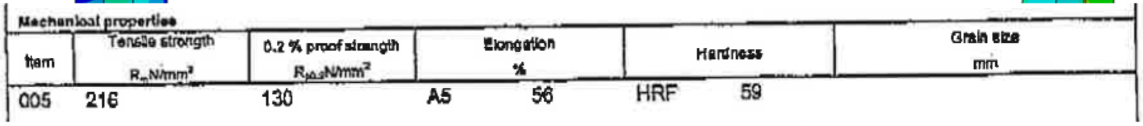


Figure 4.0-4 CHI Rod, Flag and Bus Bar Model and Stresses

The gray area would exceed the contour limit of 135 MPa The allowable for the unlikely event of the peak CHI currents occurring additive to the worst halo currents has a bending allowable of 156 MPa. If the stress in the section were linearized the bending stress would not be much above 135 MPa.





Mechanical properties

Item	Tensile strength R_m N/mm²	0.2 % proof strength $R_{p0.2}$ N/mm²	Elongation %		Hardness		Grain size mm
005	216	130	A5	56	HRF	59	

Figure 4.0-5 CHI Rod, Flag and Bus Bar Model and Stresses (Only Copper). Copper Bus Bar Physicals at Bottom

Figures 4.0-4 and 5 show the results of analyses with the final version of the horizontal leg support. This is a box beam that was chosen to have a torsional rigidity better than the 3 inch angle that was used in a previous iteration. There are still some peak stresses above yield, but this is a worst case loading of a worst case disruption with a worst case halo current along with CHI current drive. These will certainly be infrequent events, not subject to a fatigue evaluation.

For the 3 X 6 box section (or equivalently two 3 X 3 box sections welded together) , mounting plate bolts should be 5/8 inch ASTM A193 B8M Class 2 bolting. Another possibility is to weld 5/8 studs onto the wall of the umbrella structure with 3/8 fillets.

5.0 Digital Coil Protection System (DCPS).

CHI Bus bar stresses have been shown to be dominated by the toroidal field . Restrictions on the PF coil currents for "normal" scenarios is not anticipated. There is no input to the DCPS planned for disruption loading of components. The loading calculated for the CHI Bus and other components in this calculation is based on the maximum toroidal field for the upgrade, and the maximum poloidal fields for the 96 scenarios specified in the design point spreadsheet. No DCPS input is required.

6.0 Design Input

6.1 Criteria

Stress Criteria are found in the NSTX Structural Criteria Document[11]. The stress criteria has been simplified into one tensile stress limit for copper conductors based on an assessment of the fatigue life capabilities of the OH conductor [10]. Maintaining the tensile stress below 125 MPa will satisfy the fatigue limt. Limiting loading on the CHI bus derives from a non-uniform distribution of halo currents during a disruption. Disruption specifications are outlined in the GRD -Ref [7]. Since the most severe disruption currents with the most severe peaking factors are unlikely events, the stress limit will be based on static criteria with a K factor of 1.2.

From ref [11]:

(d) For bolting materials, the design Tresca stress values shall be:

- 2/3 of the ***minimum*** specified yield strength at every point in time

6.2 References

[2] Disruption specification J. Menard spreadsheet: disruption_scenario_currents_v2.xls, July 2010. NSTX Project correspondence, input to Reference [1]

[3] "Characterization of the Plasma Current quench during Disruptions in the National Spherical Torus Experiment" S.P. Gerhardt, J.E. Menard and the NSTX Team Princeton Plasma Physics Laboratory, Plainsboro, NJ, USA Nucl. Fusion 49 (2009) 025005 (12pp) doi:10.1088/0029-5515/49/2/025005

[4] ITER material properties handbook, ITER document No. G 74 MA 15, file code: ITER-AK02-22401.

[7] NSTX Upgrade General Requirements Document, NSTX_CSU-RQMTS-GRD Revision 0, C. Neumeyer, March 30, 2009

[8] Inductive and Resistive Halo Current s in the NSTX Centerstack, A.Brooks, Calc # NSTX-103-05-00

[9] Modeling of the Toroidal Asymmetry of Poloidal Halo Currents in Conducting Structures
N. Pomphrey, J.M. Bialek_, W. Park Princeton Plasma Physics Laboratory,

[10] P. TITUS OH Conductor Fatigue Analysis NSTXU-CALC-133-09-00 Rev 0 Jan 7 2011, PPPL

[11] NSTX Structural Design Criteria Document, NSTX_DesCrit_IZ_080103.doc I. Zatz

[16] Diagnostics Review and Database NSTXU-CALC-40-01-00, Joseph Boales

[17]Vessel Port Re-work for NB and Thompson Scattering Port, Calculation number NSTXU-CALC-24-01-00

[18] Damping in ANSYS/LS-Dyna Prepared by: Steven Hale, M.S.M.E Senior Engineering Manager CAE Associates (Web Search Results)

[19] Disruption Load Calculations Using ANSYS Transient Electromagnetic Simulations for the ALCATOR C-MOD Antennas, P Titus Plasma Sci. & Fusion Center, MIT, Cambridge, MA; Fusion Engineering, 2002. 19th Symposium on Fusion Engineering 02/2002; DOI: 10.1109/FUSION.2002.1027634 ISBN: 0-7803-7073-2

[20] Email from Stefan Gerhart
>> > 2) I suspect that the toroidal symmetry should be fairly good...better than
>> > the symmetry (or lack thereof) for the halo current entrance points. I think
>> > that a peaking factor of 1.5 could be assumed for a first analysis
>> > (max/average = 1.5). If this poses a problem, please let me know and we can revisit. Note that there are no measurements of this peaking, so it will be a guess no matter what.

[21] Progress on CHI and MGI Experiments on NSTX R. Raman, 53rd Meeting of the Division of Plasma Physics, APS 2011 Conference November 14-18 2011 Salt Lake City

[22] NSTX Structural Analysis of PF1, TF and OH Bus Bars NSTX-CALC--55-01-00 February 15, 2011 Andrei Khodak

[23] Centerstack Casing and Lower Skirt Stress Summary, NSTXU-CALC-133-03-00 Feb 10 2012, P. Titus, and Rev 1 – in preparation as of Nov 2013

[24] Umbrella Structure Mill Certs , Email from Larry Dudek October 8 2010
Pete,
Mark found the certs for the umbrellas. Yield stress: 32ksi Larry
(This is ref [11] in NSTXU-CALC-12-07-00

[25] "General Electric Design and Manufacture of a Test Coil for the LCP", 8th Symposium on Engineering Problems of Fusion Research, Vol III, Nov 1979

[26] "Handbook on Materials for Superconducting Machinery" MCIC- HB-04 Metals and Ceramics Information Center, Battelle Columbus Laboratories 505 King Avenue Columbus Ohio 43201

[27] STRUCTURAL DESIGN CRITERIA FOR ITER IN-VESSEL COMPONENTS (SDC-IC) APPENDIX A MATERIALS DESIGN LIMIT DATA July 2004 G 74 MA 8 R0.1

6.3 Photos and Drawing Excerpts

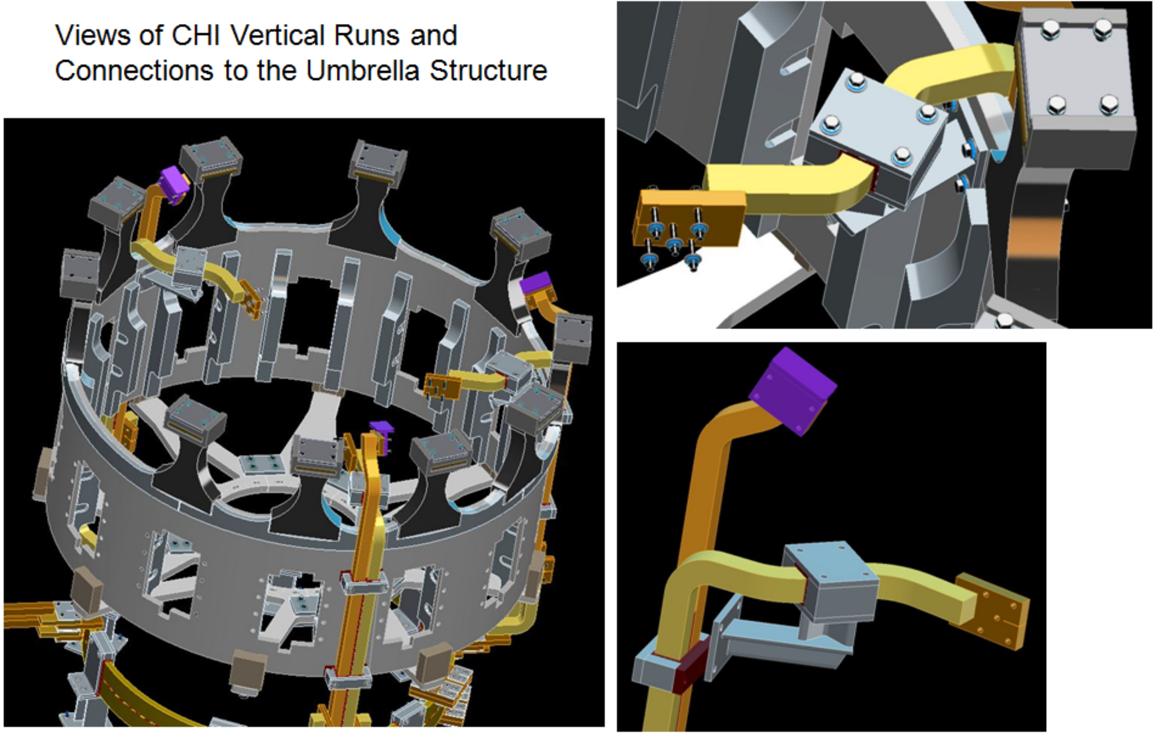

Views of CHI Vertical Runs and Connections to the Umbrella Structure

Figure 6.3-1 CHI Bus Lower Area Arrangement

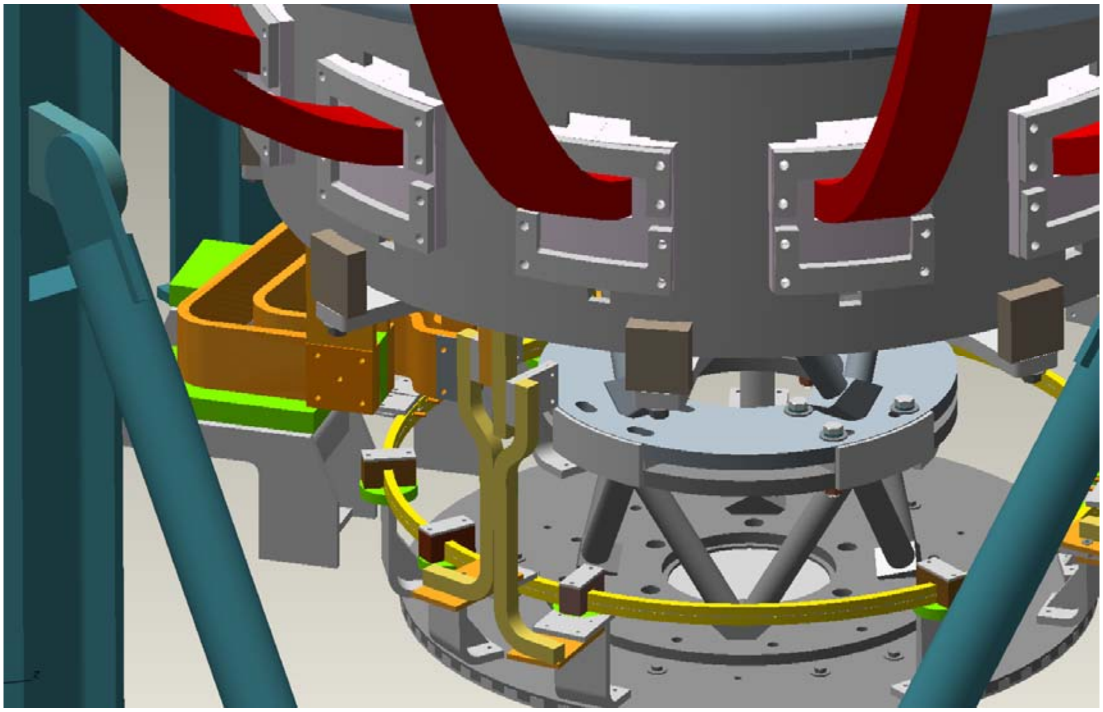
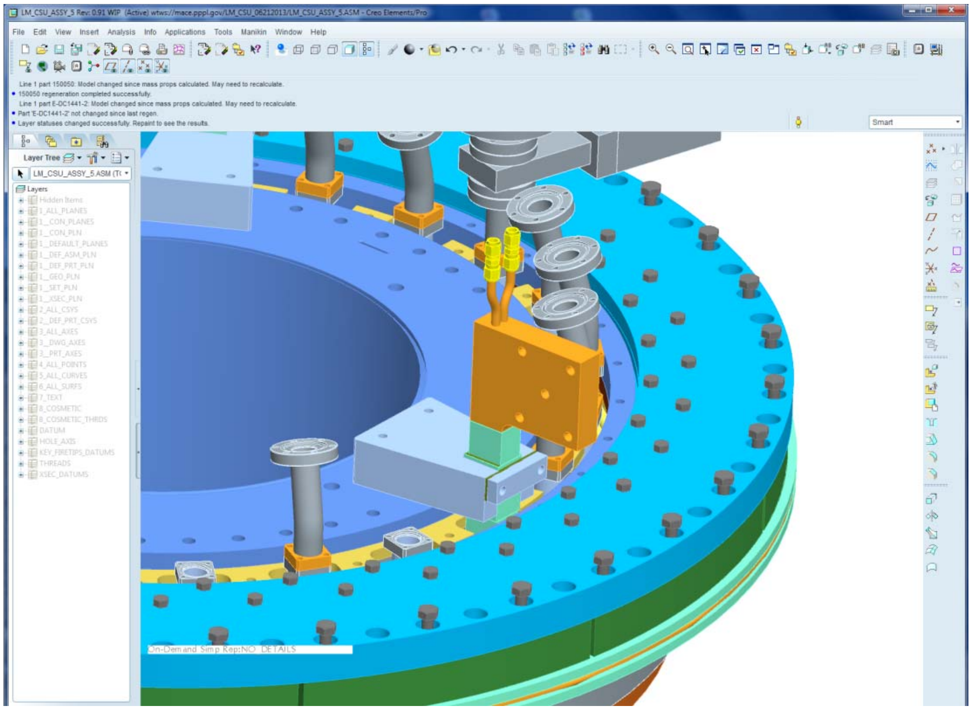


Figure 6.3-2 CHI Bus Lower Area Arrangement


LM_CSU_ASSY_5 Rev: 0.91 WIP (Active) wtws://mace.pppl.gov/LM_CSU_06212013/LM_CSU_ASSY_5.ASM - Creo Elements/Pro

Line 1 part 150050: Model changed since mass props calculated. May need to recalculate.
- 150050 regeneration completed successfully.

Line 1 part E-DC1441-2: Model changed since mass props calculated. May need to recalculate.
- Part 'E-DC1441-2' not changed since last regen.
- Layer statuses changed successfully. Repaint to see the results.

Figure 6.3-3 CHI Upper Flag Connection

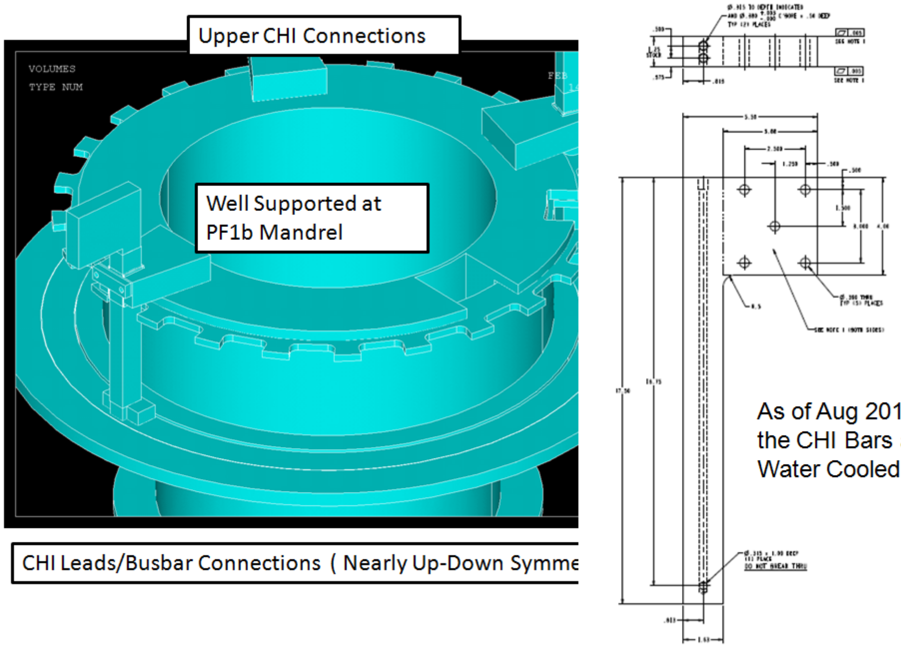


Figure 6.3-4 CHI Upper Flag Connection to the Centerstack Casing

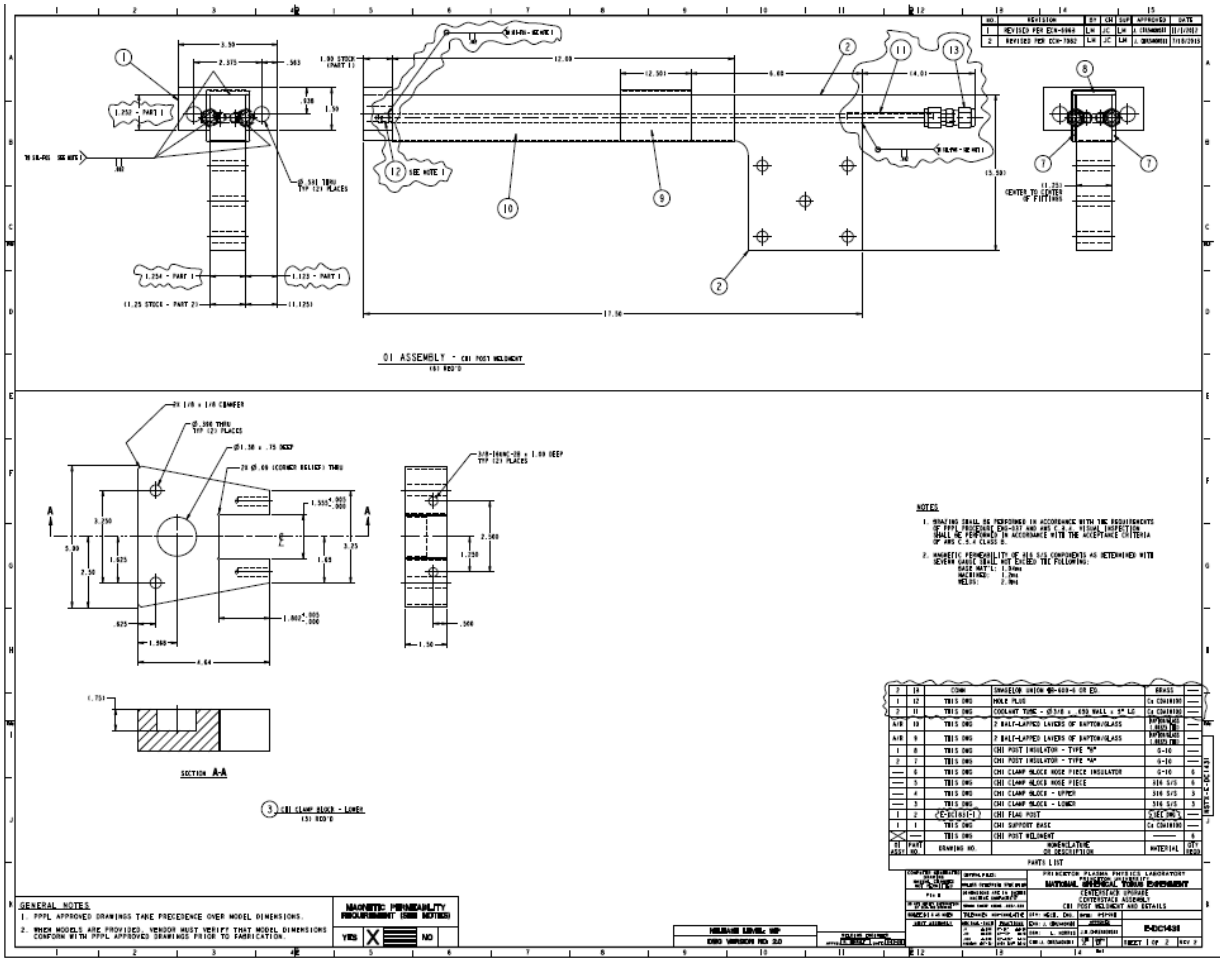


Figure 6.3-5 CHI Upper Flag Connection to the Centerstack Casing

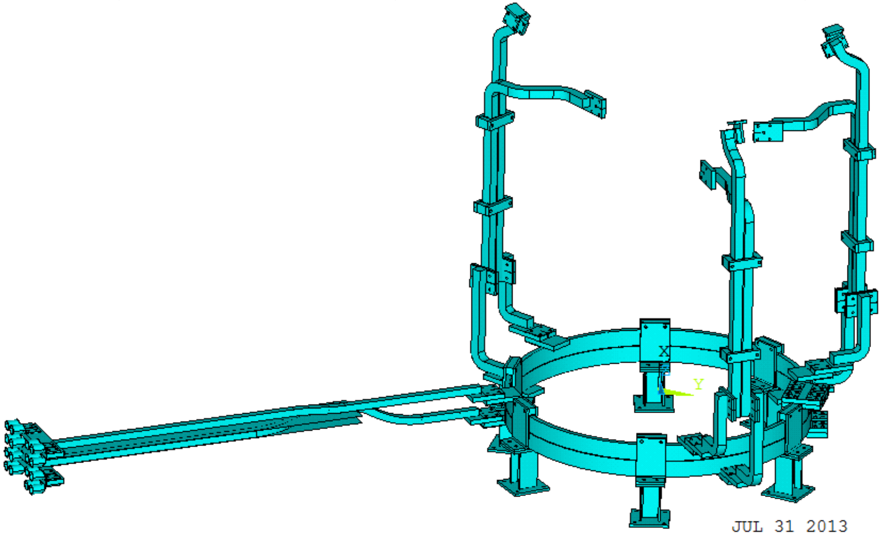


Figure 6.3-6 IGES Model from Jean Pierre Fra, July 2013

6.4 Materials and Allowables

Most of the limiting stresses in the bus bars are for the unlikely convergence of a full power shot, use of CHI current drive, VDE disruption with a worst case halo peaking factor. This as an “Unlikely” Event as defined by the NSTX Criteria Document[11], Section I 4.1.5 K factors . This allows a K factor of 1.2 be applied to the normal allowable discussed below.

6.4.1 Static Allowables for Copper Stresses

Table 6.4.1-1 Room Temperature Properties of Copper, C10200 (OFHC)

Standard	Former	Yield Min	Yield Max	Tensile Min	Tensile Max	Elong %	Rockwell F
O25	Hot Rolled-Annealed	11 ksi (2) 76 MPa		34 ksi (2) 234 MPa(2)		45	
H00	Eighth Hard	28 ksi (2) 193		36 ksi (2) 248 MPa (2)		30	54-82 (1) 60 (2)
H01	Quarter Hard	30 ksi (2) 207		38 ksi (2) 262 MPa (2)	25	25	60-84 (1) 70(2)
H02	Half Hard	36 ksi (2) 248 MPa (2)		42 ksi (2) 290 MPa (2)		14	77-89 (1) 84(2)
H03	¾ Hard						82-91 (1) 85(2)
H04	Hard	40 ksi (2) 276 MPa (2)		45 ksi (2) 310 MPa (2)		6 to 20	86-93 (1) 87 (2)
H06	Extra Hard						88-95 (1)
H08	Spring	50 ksi (2) 345 MPa (2)		55 ksi (2) 379 MPa (2)		4	90-97 (1)

(1) ASTM B152
(2) Copper Development Association Web Page www.copper.org flat form

The copper is either assumed annealed near the brazes or the test reports for the bus bar copper are used. See section 6.4.1.2 and appendix D

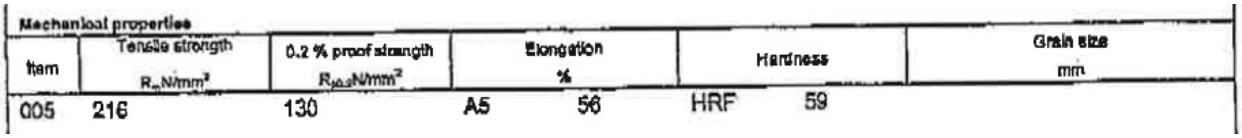
6.4.1.1 For Bus Bars near Flag Brazes

The physicals for annealed copper would apply:

The copper near the brazed flags is expected to be annealed. Use the O25 standard in table 6.4.1-1 for the annealed properties. Sm=2/3*76 MPa = 50.7 MPa, and the bending allowable=76 MPa.

6.4.1.2 For bus bars away from the flag brazes,

The physicals from the copper purchase would apply:



Mechanical properties

Item	Tensile strength R_m N/mm²	0.2 % proof strength $R_{p0.2}$ N/mm²	Elongation %	Hardness	Grain size mm
005	216	130	A5 56	HRF 59	

Figure 6.4.1.2-1 Physicals for Copper Bus Bars – See appendix D

Bus bar yield is 130 MPa (18.8 ksi) and the tensile is 216 MPa , 31.3 ksi. The OH conductor properties are taken as representative of the CHI Bus fatigue.. Sm is 2/3 yield or 87 MPa or 12.6ksi. with adequate ductility, which is the case with this copper which has a minimum of 56% elongation. Note that the ½ ultimate is not invoked for the conductor (it is for other structural materials) . For the “Unlikely Events as defined by the NSTX Criteria document[11], the bending allowable would be 1.2*130 MPa = 156 MPa

For bake-out, these stresses should be further reduced to consider the effects of operation at 100C. This effect is estimated to be 10%, so the Sm value is 78 MPa. and the bending allowable is 117 MPa

- From: 2.4.1.1 Design Tresca Stress Values (Sm), NSTX_DesCrit_IZ_080103.doc [11]
- • (a) For conventional (i.e., non-superconducting) conductor materials, the design Tresca stress values (Sm) shall be 2/3 of the specified minimum yield strength at temperature, for materials where sufficient ductility is demonstrated (see Section 2.4.1.2). [3]

6.4.2 Fatigue Limits for Copper Bus Bar

The normal operating, fatigue based bus bar conductor allowable is taken to be 125 MPa based on the assessment of OH conductor fatigue based allowable in ref [10]. The data used to derive this fatigue allowable included cyclic tests on brazed lap joints done for the original NSTX. The biggest loads on the CHI bus are from very occasional large disruptions that produce significant halo currents that pass from the centerstack casing to ground through the CHI connections. Severe disruption loads and bake-out loads are assumed to occur only a few cycles and do not require a fatigue assessment. Stresses for these cases should meet static allowables.

6.4.3 Fatigue Limits for Braze Joint

Data on the strength of braze joints is scarce and requires a large number of samples to capture the data scatter and include the possibility of voids in the braze. In the figure below, the conductor braze joint planned for the ITER in-vessel coil was tested. For a factor of safety of 20 on life, NSTX would have to qualify 20 * 20000 or 400,000 cycles. That corresponds to a stress around 90 MPa or 13 ksi. This is higher than the static allowable for annealed copper – use the 76 MPa allowable for annealed copper

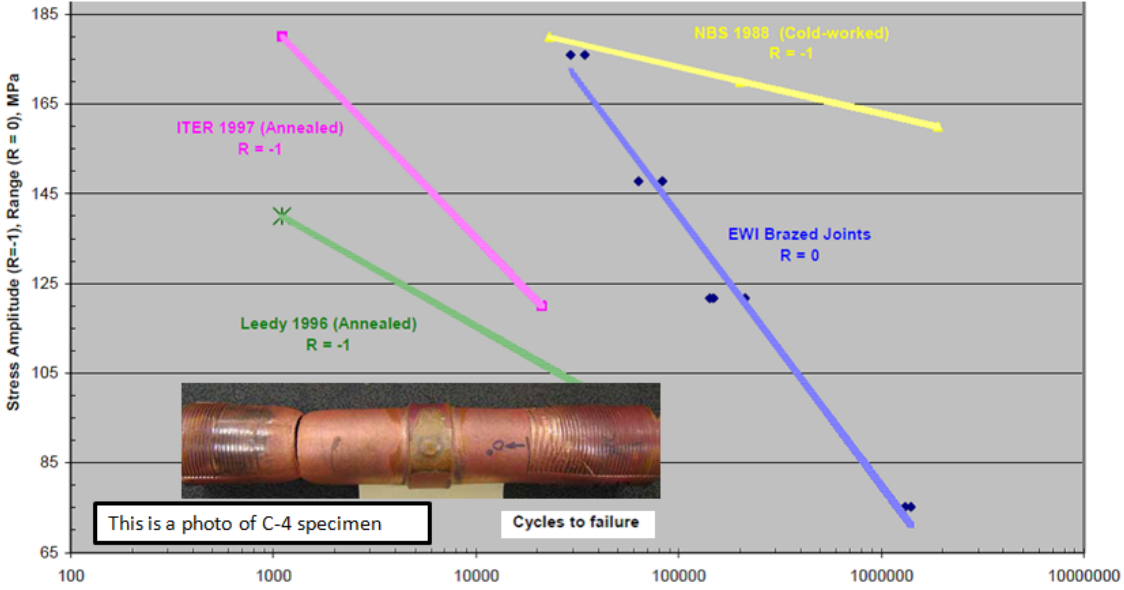


Table 10. Fatigue testing results for in-line conductor assemblies (specimens 5b-1 through 5b-9).

Specimen	Load Ratio	Applied Load Maximum (lb)	Applied Load Minimum (lb)	Applied Load Amplitude (lb)	Applied Load Mean (lb)	Load Range (lb)	Load Range (N)	Date Tested	Cycles	Comments
CF-12	0.0	28,900	0	14,450	14,450	28,900	128,554	1/19/2011	82,946	Base Metal-Sleeve Edge
CF-8	0.0	28,900	0	14,450	14,450	28,900	128,554	1/20/2011	63,284	Grip Failure
CF-5	0.0	14,700	0	7,350	7,350	14,700	65,389	1/3/2011	1,309,459	Base Metal-Sleeve Edge
CF-9	0.0	34,400	0	17,200	17,200	34,400	153,019	1/20/2011	29,245	Base Metal
CF-4	0.0	34,400	0	17,200	17,200	34,400	153,019	1/21/2011	34,343	Base Metal
CF-6	0.0	14,700	0	7,350	7,350	14,700	65,389	1/4/2011	1,397,537	Base Metal-Sleeve Edge
CF-7	0.0	23,800	0	11,900	11,900	23,800	105,868	1/21/2011	148,369	Base Metal-Sleeve Edge
CF-10	0.0	23,800	0	11,900	11,900	23,800	105,868	1/25/2011	142,382	Base Metal-Sleeve Edge
CF-11	0.0	23,800	0	11,900	11,900	23,800	105,868	1/28/2011	212,532	Chamfered-Near butt joint

6.4.4 Bolting Materials

ASTM A193 Bolt Specs from PortlandBolt.com

B8M	Class 1 Stainless steel, AISI 316, carbide solution treated.
B8	Class 2 Stainless steel, AISI 304, carbide solution treated, strain hardened
B8M	Class 2 Stainless steel, AISI 316, carbide solution treated, strain hardened

Mechanical Properties

Grade	Size	Tensile ksi, min	Yield, ksi, min	Elong, %, min	RA % min
B8 Class 1	All	75	30	30	50
B8M Class 1	All	75	30	30	50
B8 Class 2	Up to 3/4	125	100	12	35
	7/8 - 1	115	80	15	35
	1-1/8 - 1-1/4	105	65	20	35
	1-3/8 - 1-1/2	100	50	28	45
B8M Class 2	Up to 3/4	110	95	15	45
	7/8 - 1	100	80	20	45
	1-1/8 - 1-1/4	95	65	25	45
	1-3/8 - 1-1/2	90	50	30	45

For ASTM A-193 B8M Class 5/8 inch bolts, the stress allowable would be 2/3*110 = 73.3 ksi

6.4.5 Weld Allowable

Reference and Weld	Rod or weld wire	Parent Material	Allowable Stress (Exclusive of Weld Efficiency)
AISC Stress on cross section of full penetration Welds		All	Same as Base material
AISC Shear Stress on Effective Throat of fillet weld	AWS A5.1 E60XX	A36 -	21 ksi

6.4.6 Umbrella Structure Base Material Allowable

The yield of the umbrella structure is 32 ksi[24] 2/3 of this is 21 ksi

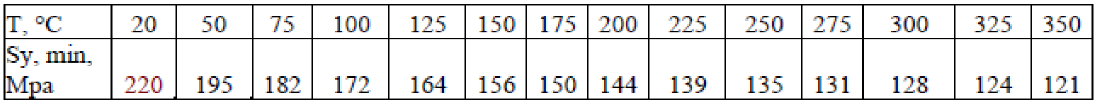
6.4.7 Stainless Steel Structural Shapes

Table 6.4.7 -1Tensile Properties for Stainless Steels

Material	Yield, 292 deg K (MPa)	Ultimate, 292 deg K

		(MPa)
316 LN SST	275.8[25]	613[25]
316 LN SST Weld	324[25]	482[25] 553[25]
316 SST Sheet Annealed	275[26]	596[26]
316 SST Plate Annealed		579
304 Stainless Steel (Bar,annealed)	234 33.6ksi	640 93ksi
304 SST 50% CW	1089	1241 180ksi

Table 6.4.8 316 Stainless Steel Strength and Temperature Dependence
In-Vessel Criteria Appendix A Table A.S1.3.2-1 Ref[27]



T, °C	20	50	75	100	125	150	175	200	225	250	275	300	325	350
Sy, min, Mpa	220	195	182	172	164	156	150	144	139	135	131	128	124	121

There is a discrepancy in the two tables. Take the min yield to be 200 MPa and the bending allowable is 200 MPa. With the K factor for the unlikely halo current events it is 1.2*200 = 240 MPa

6.5 CHI Currents

The most significant Lorentz load on the CHI Bus bar system occurs during a disruption in which the CHI system provides a path to ground for the halo currents in the vessel. Normal operating CHI currents used for break-down and plasma initiation are less demanding. Thermally the bake-out currents are the most challenging because of their steady state nature.

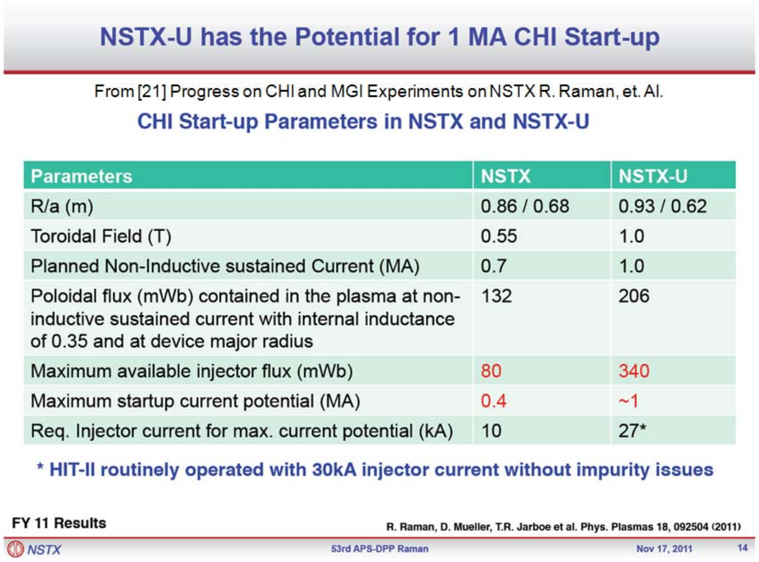
Table 6.5-1 NSTX and NSTX-U Operating Parameters

		NSTX BASE	NSTX CSU
Ro	m	0.854	0.934
A_100		1.3	1.5
Ip	MA	1.0	2.0
Bt@Ro	T	0.6	1.0
I =5e6*radius*Bt at Radius	Amp	2.562e6	4.67e6
I per Turn =	Amp	71166	129722

6.5.1CHI Normal Operation

Currents flow in the CHI system during start-up and during a disruption. Normal operation for the upgrade is expected to utilize 27 kA of current [21] when the TF is at full field. This is planned to produce 1 MA of plasma current. This occurs during start-up. The CHI can be used for current drive after the initiation. This was done early in the NSTX program to demonstrate current drive but is not commonly used.

Use: 9000, amps for 20,000 full power shots for the fatigue limit.



NSTX-U has the Potential for 1 MA CHI Start-up

From [21] Progress on CHI and MGI Experiments on NSTX R. Raman, et. Al.

CHI Start-up Parameters in NSTX and NSTX-U

Parameters	NSTX	NSTX-U
R/a (m)	0.86 / 0.68	0.93 / 0.62
Toroidal Field (T)	0.55	1.0
Planned Non-Inductive sustained Current (MA)	0.7	1.0
Poloidal flux (mWb) contained in the plasma at non-inductive sustained current with internal inductance of 0.35 and at device major radius	132	206
Maximum available injector flux (mWb)	80	340
Maximum startup current potential (MA)	0.4	~1
Req. Injector current for max. current potential (kA)	10	27*

* HIT-II routinely operated with 30kA injector current without impurity issues

FY 11 Results

R. Raman, D. Mueller, T.R. Jarboe et al. Phys. Plasmas 18, 092504 (2011)

NSTX 53rd APS-DPP Raman Nov 17, 2011 14

Figure 6.5-1 Normal Operational CHI Parameters Expected for NSTX Upgrade [21]

The toroidal field at the CHI Rod (connected to the Centerstack casing flange) is .934*1.0/(18.31/39.36) = 2.008T. Normal operating current in the CHI rods is 27 kA/3 = 9kA. The load in the rod over almost a meter of height is 9000*2T = 18000N or 2023 lbs per rod, radially outward. The horizontal run of the bus bar connection sees similar loading in the vertical direction.

6.5.2CHI Bake-Out

During Bake-out, the CHI circuits are used to pass current through the centerstack casing. Early in the project, Larry Dudek calculated the required current for the larger casing used for the upgrade. Raki has updated this to 6 kA total current. In July 2013, Mike Williams was concerned that this was too low and requested that the design current be increased to 8 kA

As the current leaves the CHI ring bus, it is split into three bus bars which connect with the casing CHI rods or leads. Consequently each vertical run is assumed to carry 2.66 kA

6.5.3 Disruption Halo Currents

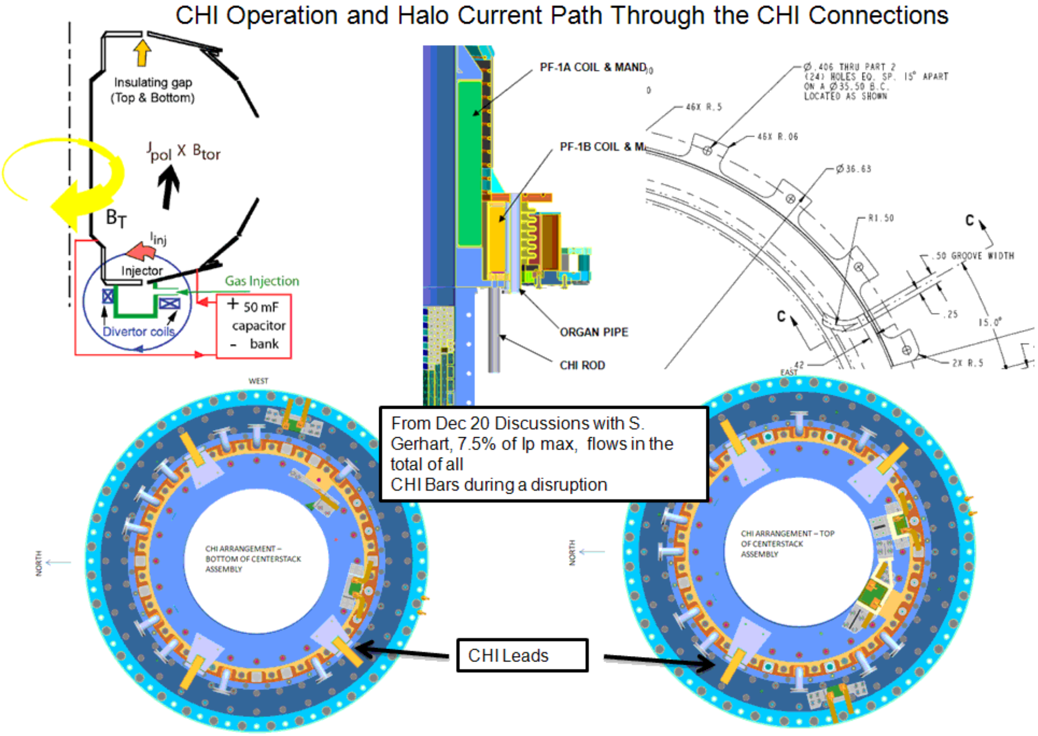
The halo currents that flow through the CHI connections have been estimated by Stefan Gerhardt to be 7.5 % of the plasma current, or 150,000 amps. Or 50,000 amps per CHI rod. There is a future potential to have the current drive and disruption loads to be additive if and when the CHI is driven by the transrex power supplies. For the disruption Halo currents, Stefan estimated 1.5 as a “guessed at” peaking factor. I will use:

50,000*1.5 +9000 =84,000 amps for any individual busbar - and treat this as an “Unlikely” Event as defined by the NSTX Criteria Document[11], Section I 4.1.5 Kfactors . This allows a K factor of 1.2 be applied to the allowable.

The ring bus feeds two vertical runs in one direction and one vertical run in the other. The peaking factor applies to one set of the three vertical runs. High currents in one vertical run would mean the balance of the 7.5 * Ip current would appear in the other two runs. Or (150,000-75000)/2 = 37500 amps So the total in the ring bus in the feed connected to the two of the three vertical runs is 75,000+37500+9000+9000 = 130 kA.

The toroidal field at the CHI Rod (The vertical run from the casing flange) is .934*1.0/(18.31/39.36) = 2.008T. The Halo loading is 7.5% of 2e6 amps*2T*.365m/3 36500N =8205.2 lbs per rod. Where .365m is the length of the rod. This goes up to 12,008 lbs with the peaking factor. The horizontal run of the bus bar connection sees similar loading.

One important observation is that the disruption considered in Art Brooks' simulation is a centered disruption. The disruption that drives currents in the CHI bus is a quench after a VDE. So, the loading in the CHI bus is not additive to those loads calculated by A. Brooks.


CHI Operation and Halo Current Path Through the CHI Connections

From Dec 20 Discussions with S. Gerhart, 7.5% of Ip max, flows in the total of all CHI Bars during a disruption

Figure 6.5.3-1 CHI Halo Current Path

In a Sept 19th 2013 phone call with Stefan Gerhardt, he explained that the halo currents are equal and opposite at the CHI inlet and outlet connections, just as it would be during normal CHI operation. This means that the currents carried in the paired conductors in the vertical runs and the ring bus and the floor feeders, will have large separating self loads. Paired conductors may not experience fully canceled loads because the peaking factors for the centerstack casing and vessel connections may not be the same.

The requirements for disruption analysis are outlined in the NSTX Upgrade General Requirements Document [7]. The latest (August 2010) disruption specification were provided by Jon Menard as a spreadsheet: disruption_scenario_currents_v2.xls.[2] This reference includes a suggested time phasing of the inductively driven currents and the halo currents.

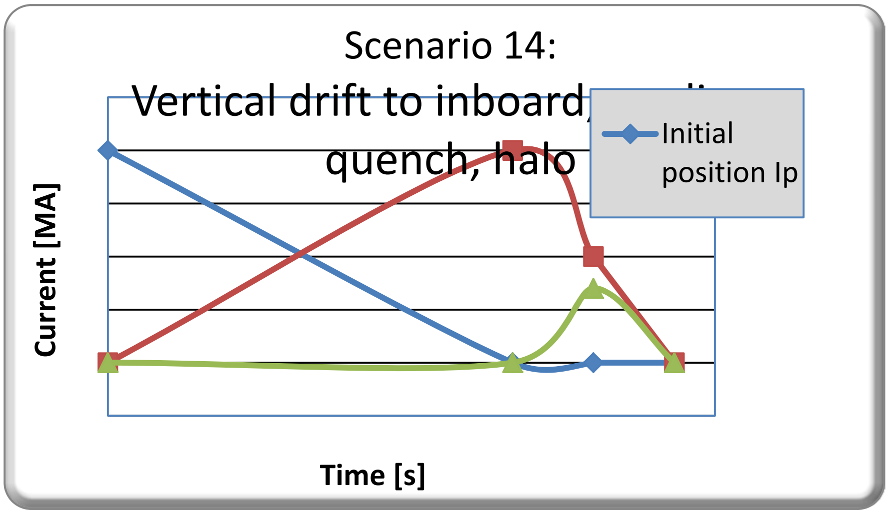


Figure 6.5.3-2Time phasing of the plasma current changes that induce currents in the vessel and vessel components, and the halo currents. From J. Menard

Criteria from the GRD:

Current and field directions (referring to Figure 2.2-2) shall be as follows: Plasma current Ip into the page (counter-clockwise in the toroidal direction, viewed from above) Halo current exits plasma and enters the structure at the entry point, exits the structure and re-enters the plasma at the exit point (counter-clockwise poloidal current, in the view of the figure) Toroidal field into the page (clockwise in the toroidal direction, viewed from above)

7.0 Structural Analysis Models and Boundary Conditions

Magnetic Models are discussed in section 11.0. Structural analysis models evolved along with the design. Initially beam-stick models were used for basic sizing and remain the only analysis of the dynamic load factors for the transient Lorentz forces. These beam stick models and analyses are discussed in more detail in section 13.0. Use of the beam element model made investigations of various bus bar cross sections easier. When the conductor cross section settled down, solid element models were made. First one

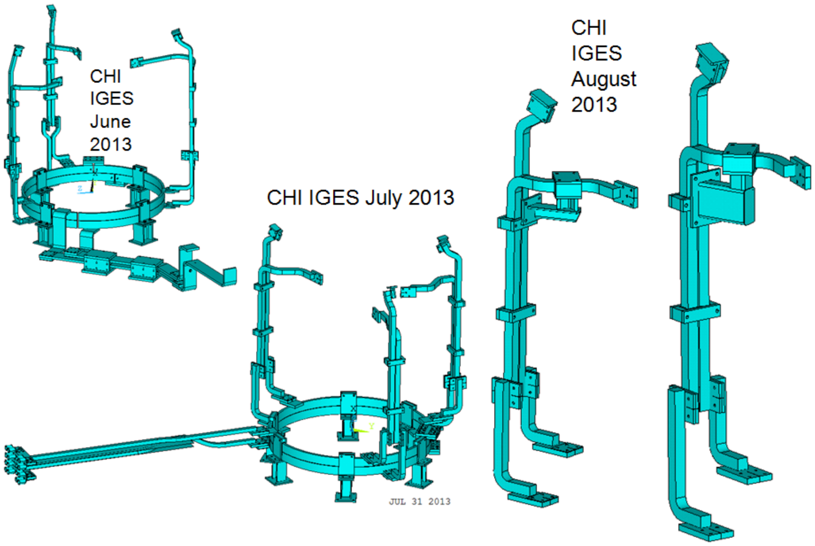


Figure 7.0-1 IGES Geometry of the CHI Bus System and Single Vertical Run Models at Right

geometry of the Pro-E model was passed to ANSYS via IGES files. Parts of the IGES models were meshed. And used for the model mesh and other segments were meshed with ADPL commands, particularly where the solid model had problems with connectivity.

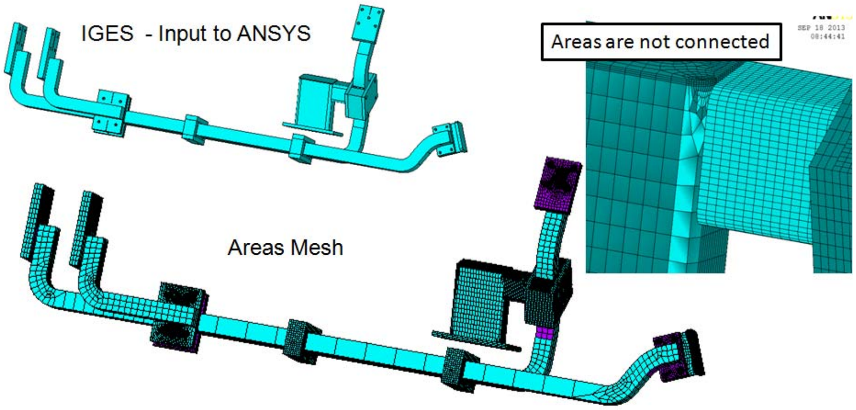
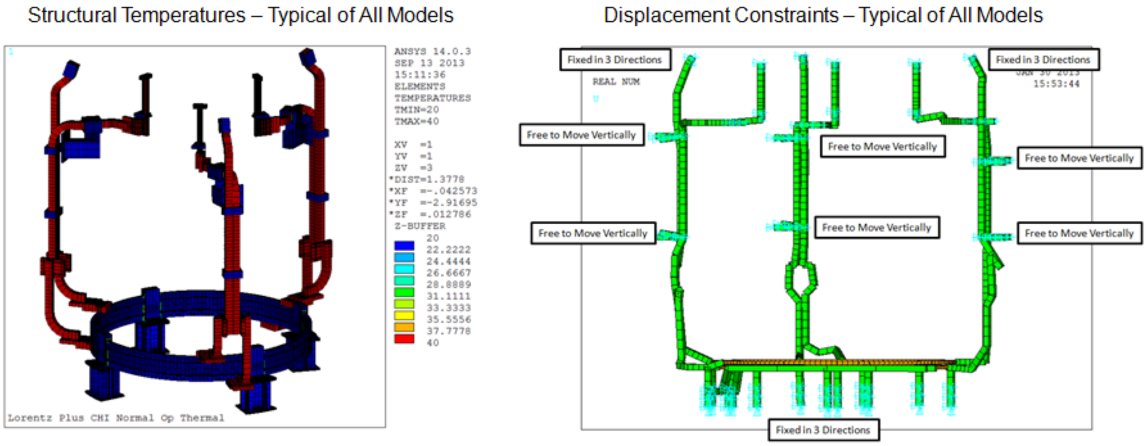


Figure 7.0-2 IGES File Geometry of the Representative Vertical Run

In Figure 7.0-2, the IGES model as read into ANSYS, is shown. The volumes could not be meshed and so the areas were meshed as plates, and then converted to solid elements


Structural Temperatures – Typical of All Models

Displacement Constraints – Typical of All Models

Figure 7.0-3 Boundary Conditions: Temperatures and Displacement Constraints

Figure 7.0-3 shows the boundary conditions applied to the models. At left is the "final" solid element model, and at right is the earlier beam-stick model (plotted to show the size of the beam). Early studies, using the beam-stick model, showed the need to allow the vertical bus bars to grow freely in their clamps. This set the boundary conditions on the vertical run to constrain only lateral motion.

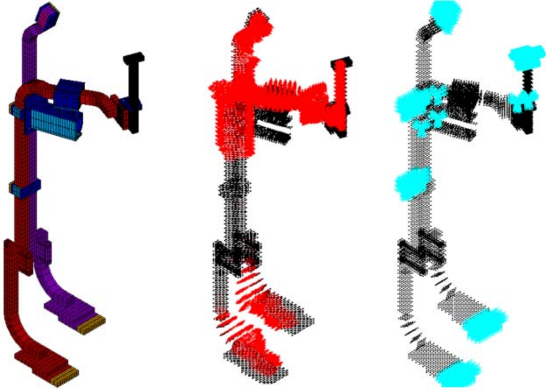


Figure 7.0-4 Single Vertical Model , Nodes and Lorentz Forces (from Background Fields) ; and Nodes and Displacement Constraints

The single vertical run model was used to assess the horizontal leg cantilever support. The radial current crossing the toroidal field produced a large vertical force that bent the horizontal leg. Addition of the support and then upgrade of the support to a box beam section was evaluated in this model.

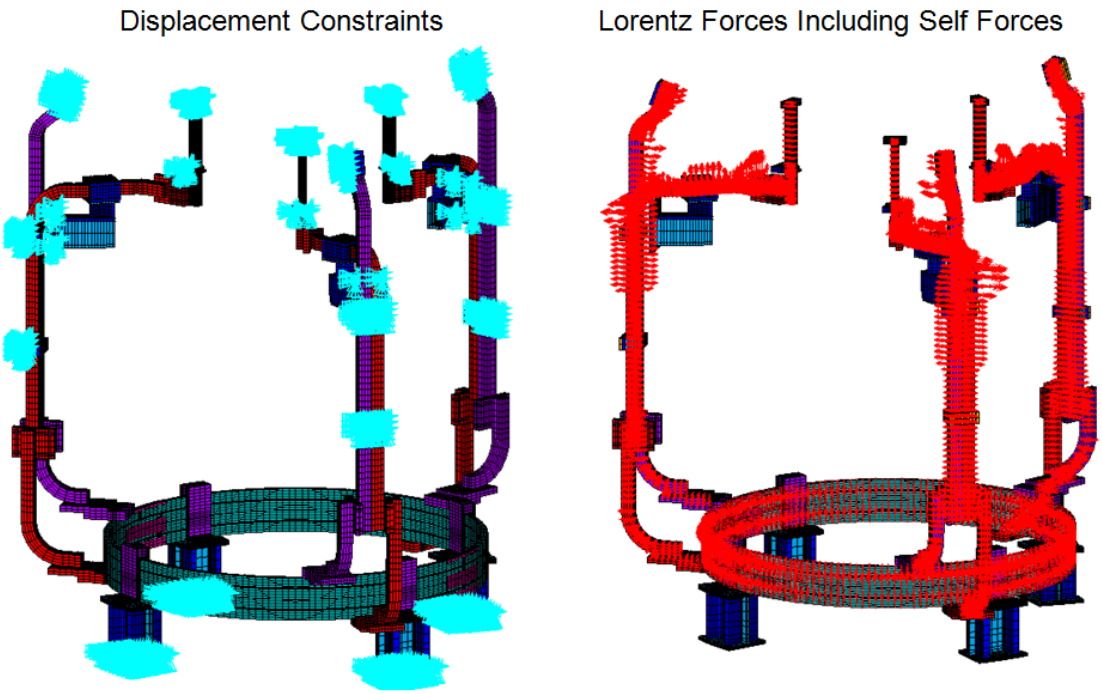


Figure 7.0-5 CHI Bus Model , Model and Constraints (Left) Model and Lorentz Forces (Right)

The vertical run models was repeated and rotated three times and connected to a model of the ring bus in this model. Self loads were added. This model allowed a better representation of the brazed connection to the ring bus.

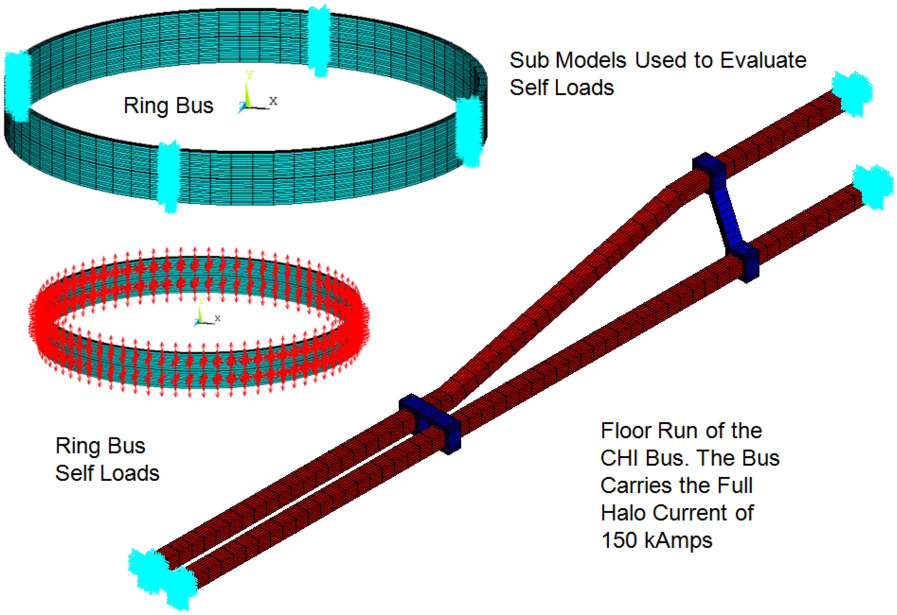


Figure 7.0-6 Models Used to Check Self Loads with the Large Halo Currents flowing Out and Into the Machine

Self loads of the bus that runs along the floor and the ring bus were treated separately. These are well away from any significant background field and the self loads for normal operation are trivial. However large halo currents flow in these bus connections. The realization that the halo current produced large opposing currewnts in the bus pair led to the necessity of adding interconnections to react the large separating forces. This is addressed in section 9.3

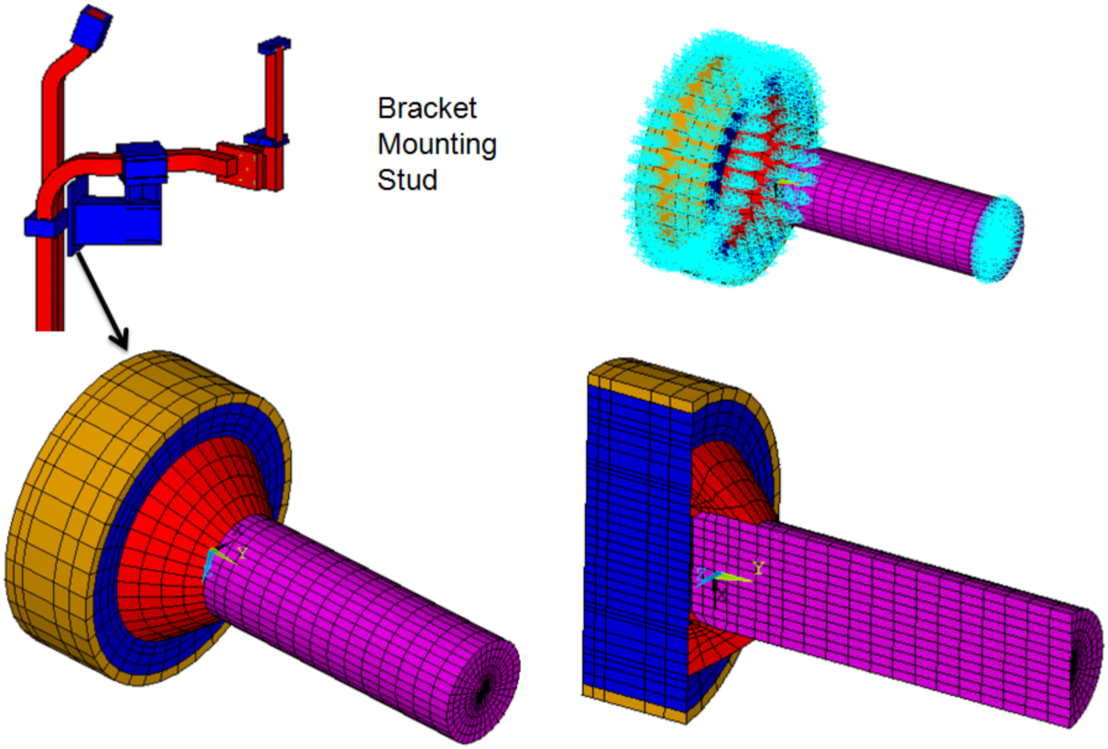


Figure 7.0-7 Welded Stud Model) Used in Section 12.2

The bracket that supports the horizontal run near the centerstack casing is either bolted to the umbrella structure or is connected via welded studs. Use of welded studs avoids the necessity of drilling and taping the umbrella structure. This is addressed in section 12.2

8.0 Conductor Cooling Calculations

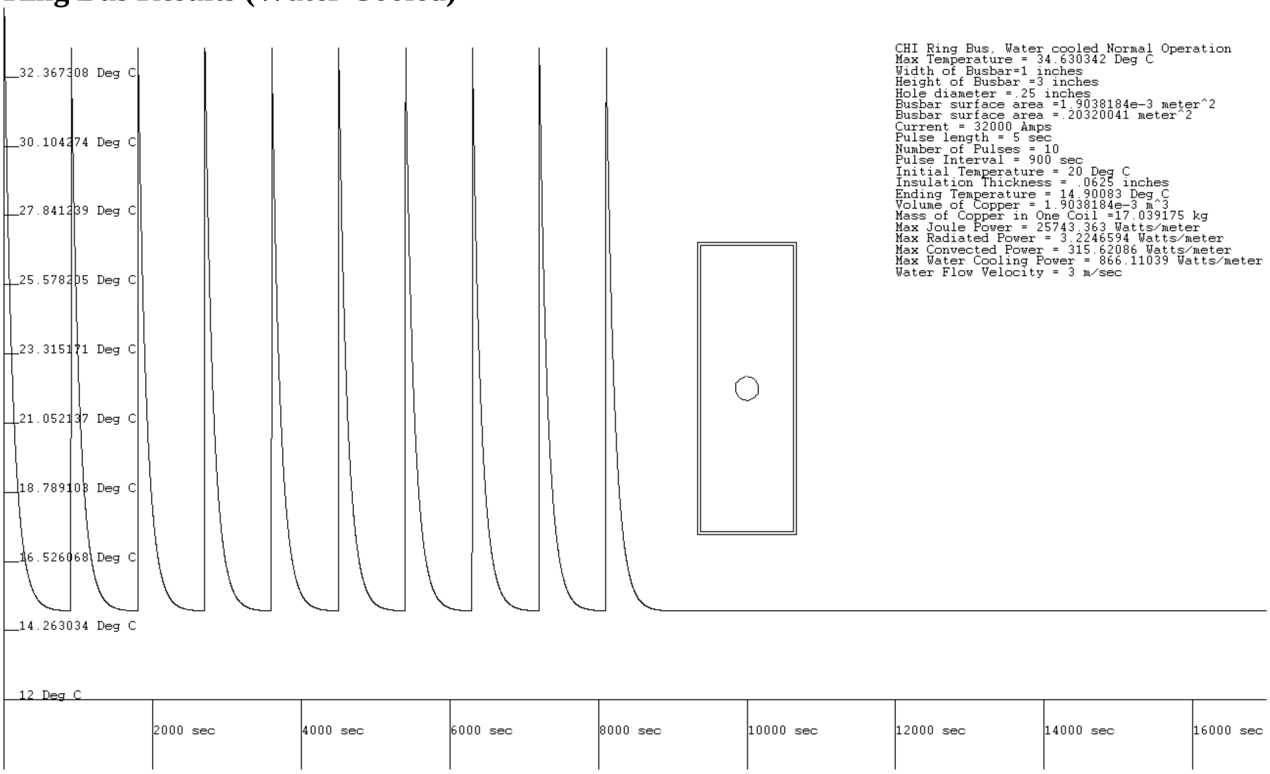
A simple rule of thumb may be used for initial sizing of the bus bar:

Air-cooled Bus Bar :	1 kA/in^2
Water cooled Bus Bar	10 kA/in^2

The vertical runs of the CHI bus are air cooled and are 2 X 2 inches. So they are undersized with respect to the rule of thumb and a more detailed treatment of the thermal behavior of the bus bars is needed.

A True Basic program was developed that computes the transient temperatures of the bus bars given a current profile. The source listing for this code is included in Appendix C

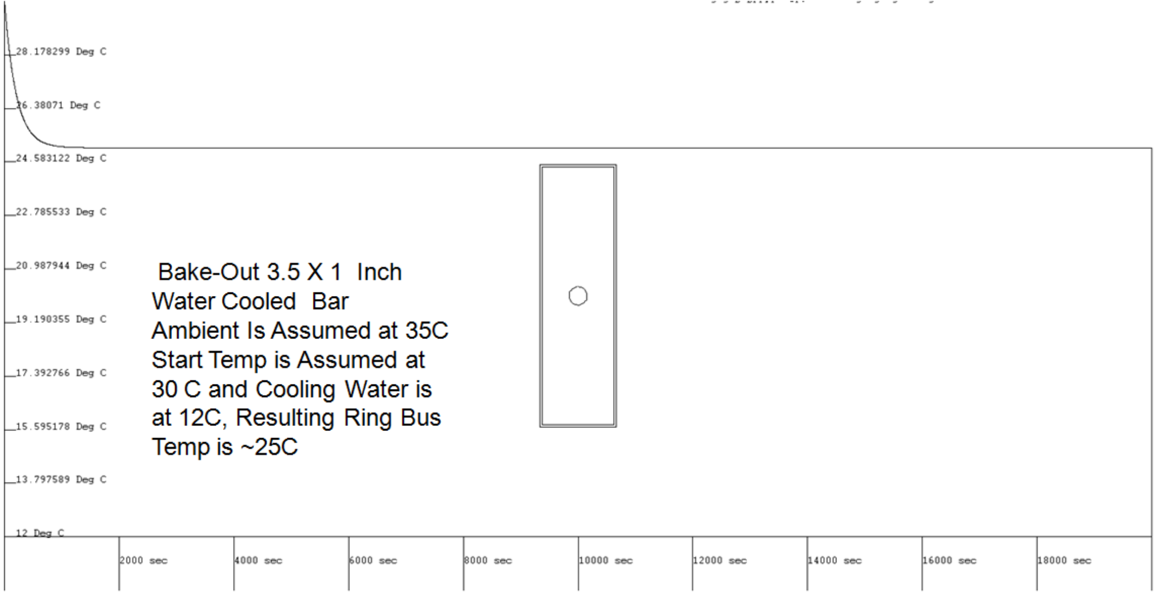
Ring Bus Results (Water Cooled)



```
CHI Ring Bus, Water cooled Normal Operation
Max Temperature = 34.630342 Deg C
Width of Busbar=1 inches
Height of Busbar =3 inches
Hole diameter =.25 inches
Busbar surface area =1.9038184e-3 meter^2
Busbar surface area =.20320041 meter^2
Current = 32000 Amps
Pulse length = 5 sec
Number of Pulses = 10
Pulse Interval = 900 sec
Initial Temperature = 20 Deg C
Insulation Thickness = .0625 inches
Ending Temperature = 14.90083 Deg C
Volume of Copper = 1.9038184e-3 m^3
Mass of Copper in One Coil =17.039175 kg
Max Joule Power = 25743.363 Watts/meter
Max Radiated Power = 3.2246594 Watts/meter
Max Convected Power = 315.62086 Watts/meter
Max Water Cooling Power = 866.11039 Watts/meter
Water Flow Velocity = 3 m/sec
```

Figure 8.0-1 Ring Bus Normal Operations

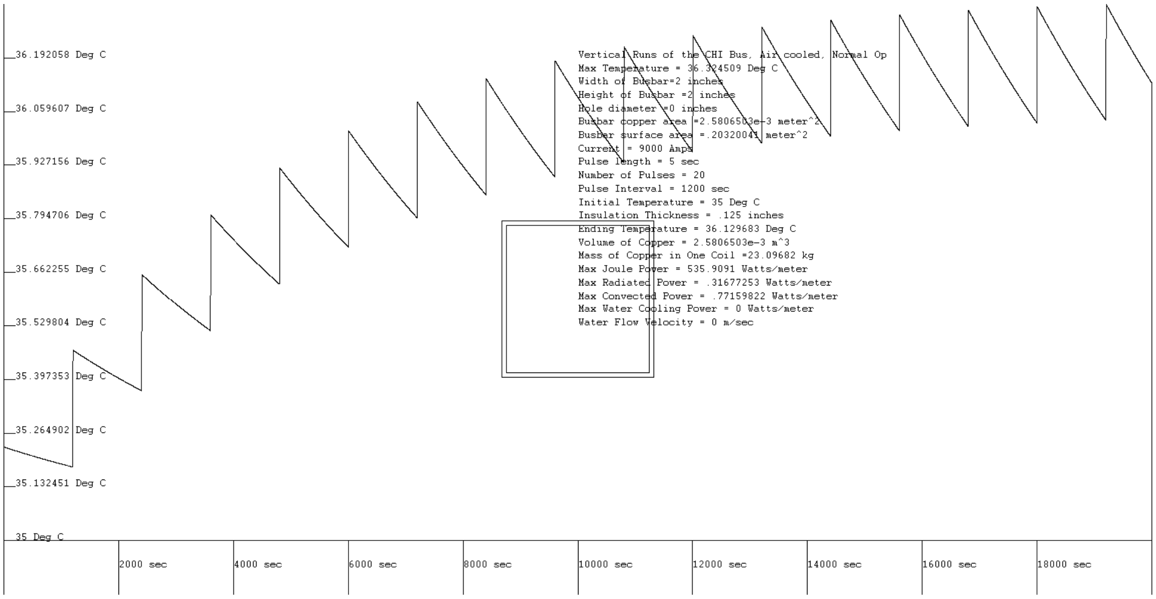
Ring Bus Bake-Out Results (Water Cooled)



Bake-Out 3.5 X 1 Inch
Water Cooled Bar
Ambient Is Assumed at 35C
Start Temp is Assumed at
30 C and Cooling Water is
at 12C, Resulting Ring Bus
Temp is ~25C

Figure 8.0-2 Ring Bus Bake-Out

2 inch X 2 Inch Vertical Bus Results (Air Cooled) Normal Operation

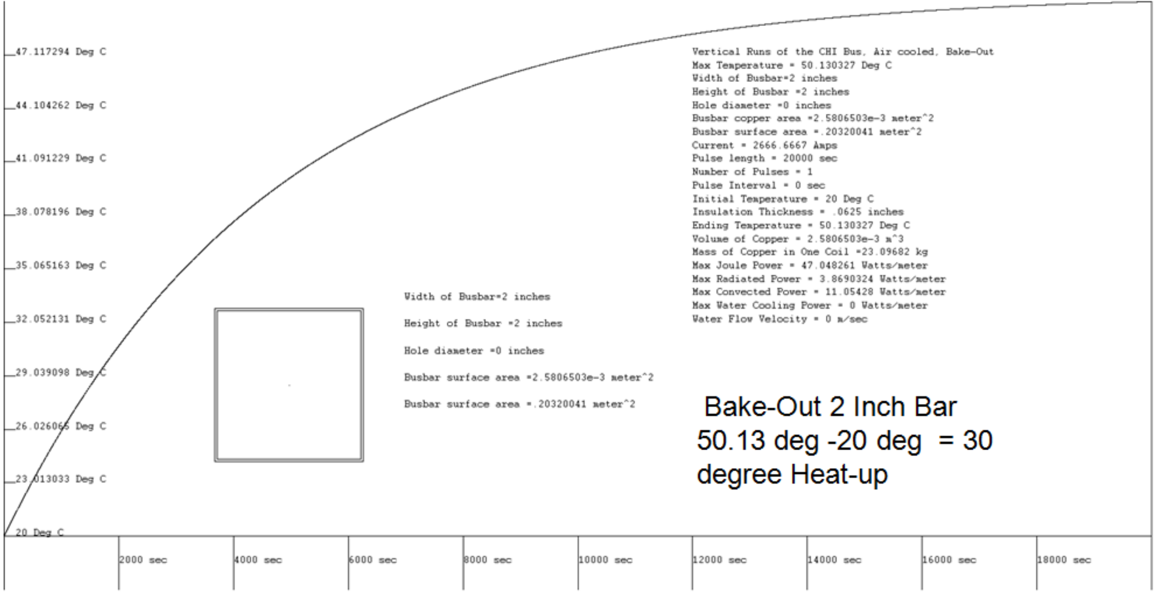


```
Vertical Runs of the CHI Bus, Air cooled, Normal Op
Max Temperature = 36.324509 Deg C
Width of Busbar=2 inches
Height of Busbar =2 inches
Hole diameter =0 inches
Busbar copper area =2.5806503e-3 meter^2
Busbar surface area =.20320041 meter^2
Current = 9000 Amps
Pulse length = 5 sec
Number of Pulses = 20
Pulse Interval = 1200 sec
Initial Temperature = 35 Deg C
Insulation Thickness = .125 inches
Ending Temperature = 36.129683 Deg C
Volume of Copper = 2.5806503e-3 m^3
Mass of Copper in One Coil =23.09682 kg
Max Joule Power = 535.9091 Watts/meter
Max Radiated Power = .31677253 Watts/meter
Max Convected Power = .77159822 Watts/meter
Max Water Cooling Power = 0 Watts/meter
Water Flow Velocity = 0 m/sec
```

Figure 8.0-3 2 X 2 inch Vertical Runs, Air Cooled, Normal Operation

This produces only a 1.5 degree heat-up, so Normal operation is not an issue. The CHI air cooled bus bars are sized for the bake-out operation

2 inch X 2 Inch Vertical Bus Results (Air Cooled) Bake-Out

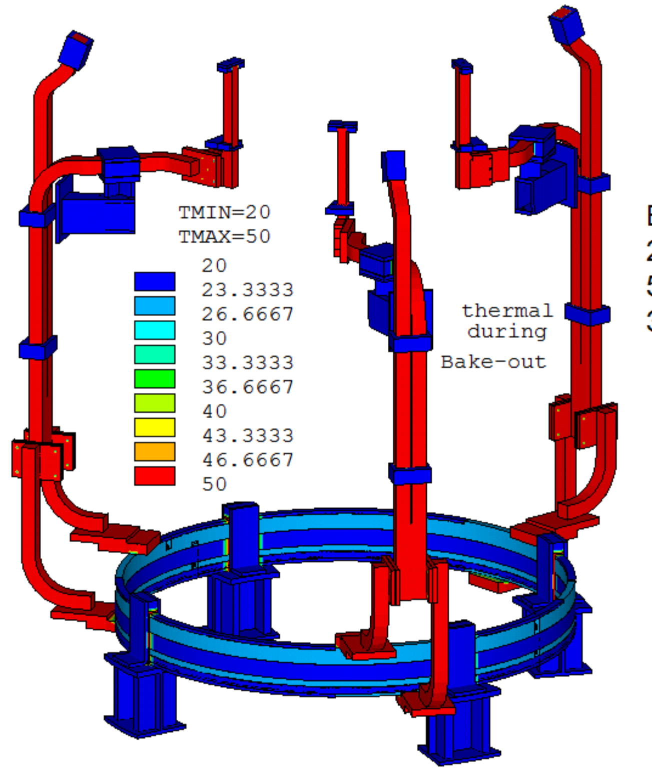


```
Vertical Runs of the CHI Bus, Air cooled, Bake-Out
Max Temperature = 50.130327 Deg C
Width of Busbar=2 inches
Height of Busbar =2 inches
Hole diameter =0 inches
Busbar copper area =2.5806503e-3 meter^2
Busbar surface area =.20320041 meter^2
Current = 2666.6667 Amps
Pulse length = 20000 sec
Number of Pulses = 1
Pulse Interval = 0 sec
Initial Temperature = 20 Deg C
Insulation Thickness = .0625 inches
Ending Temperature = 50.130327 Deg C
Volume of Copper = 2.5806503e-3 m^3
Mass of Copper in One Coil =23.09682 kg
Max Joule Power = 47.048261 Watts/meter
Max Radiated Power = 3.8690324 Watts/meter
Max Convected Power = 11.05428 Watts/meter
Max Water Cooling Power = 0 Watts/meter
Water Flow Velocity = 0 m/sec
```

```
Width of Busbar=2 inches

Height of Busbar =2 inches

Hole diameter =0 inches

Busbar surface area =2.5806503e-3 meter^2

Busbar surface area =.20320041 meter^2
```

Bake-Out 2 Inch Bar
50.13 deg -20 deg = 30
degree Heat-up

Figure 8.0-4 2 X 2 inch Vertical Runs, Air Cooled, Bake-Out



Bake-Out
2 Inch Bar
50.13 deg -20 deg =
30 degree Heat-up

Figure 8.0-5 Bake-Out Temperatures Applied to the Structural Model

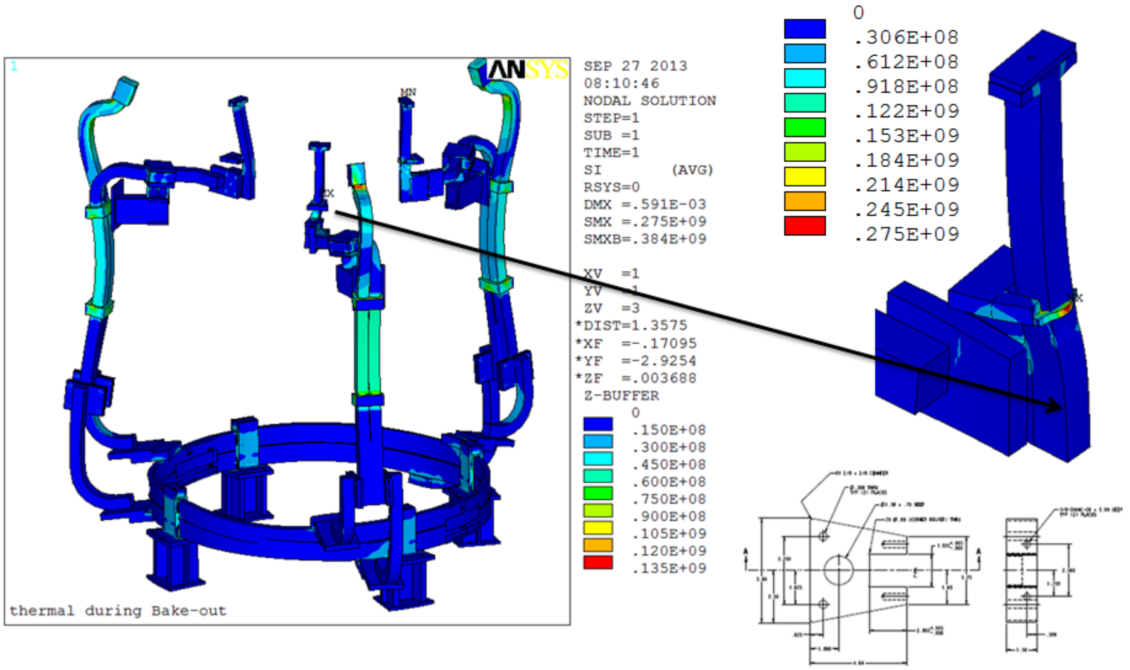
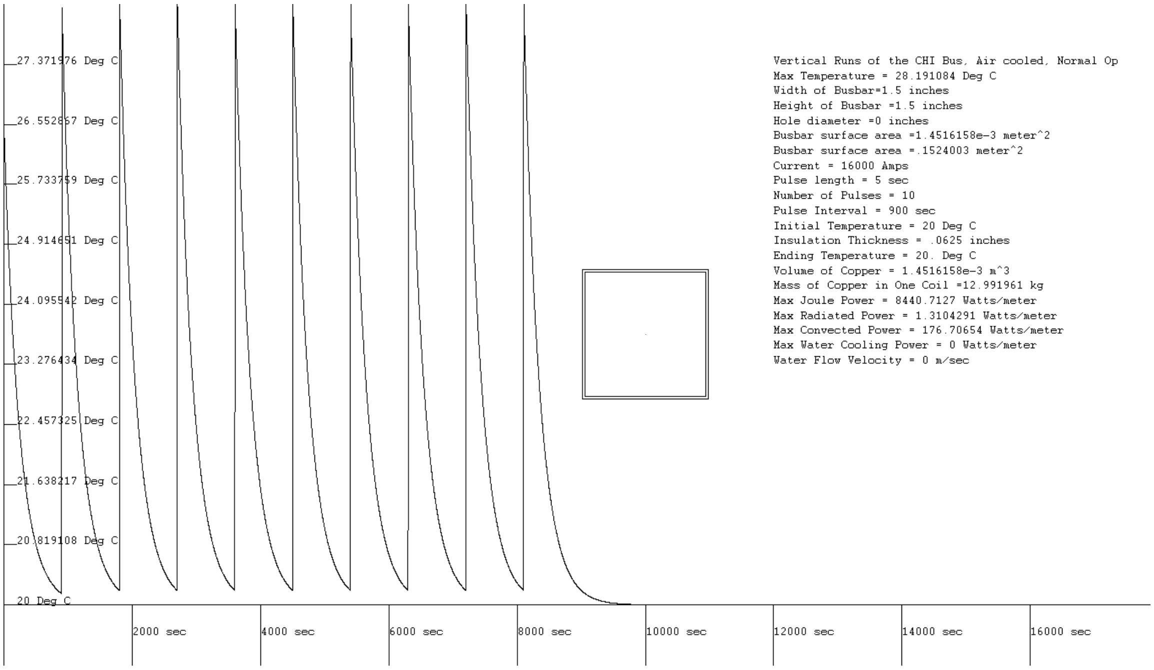


Figure 8.0-6 Bake-Out Stresses

Note that there is a local bending peak stress in the clamp. This will have to be checked – In the finite element model the clamp size was arbitrarily selected as ~ 1 cm square in cross section. It is larger in actuality.

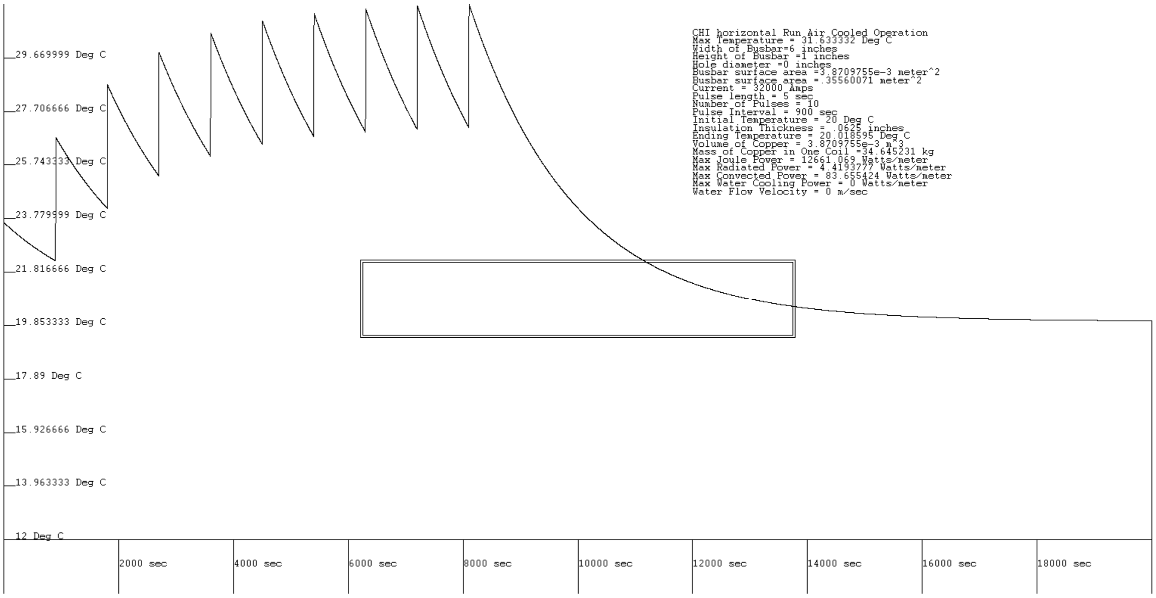
Previous 1.5 inch X 1.5 Inch Vertical Bus Bar Results (Air Cooled)



```
Vertical Runs of the CHI Bus, Air cooled, Normal Op
Max Temperature = 28.191084 Deg C
Width of Busbar=1.5 inches
Height of Busbar =1.5 inches
Hole diameter =0 inches
Busbar surface area =1.4516158e-3 meter^2
Busbar surface area =.1524003 meter^2
Current = 16000 Amps
Pulse length = 5 sec
Number of Pulses = 10
Pulse Interval = 900 sec
Initial Temperature = 20 Deg C
Insulation Thickness = .0625 inches
Ending Temperature = 20. Deg C
Volume of Copper = 1.4516158e-3 m^3
Mass of Copper in One Coil =12.991961 kg
Max Joule Power = 8440.7127 Watts/meter
Max Radiated Power = 1.3104291 Watts/meter
Max Convected Power = 176.70654 Watts/meter
Max Water Cooling Power = 0 Watts/meter
Water Flow Velocity = 0 m/sec
```

Figure 8.0-7

Previous 6.0 inch X 1.0 Inch Horizontal Floor Run Bus Bar Results (Air Cooled)



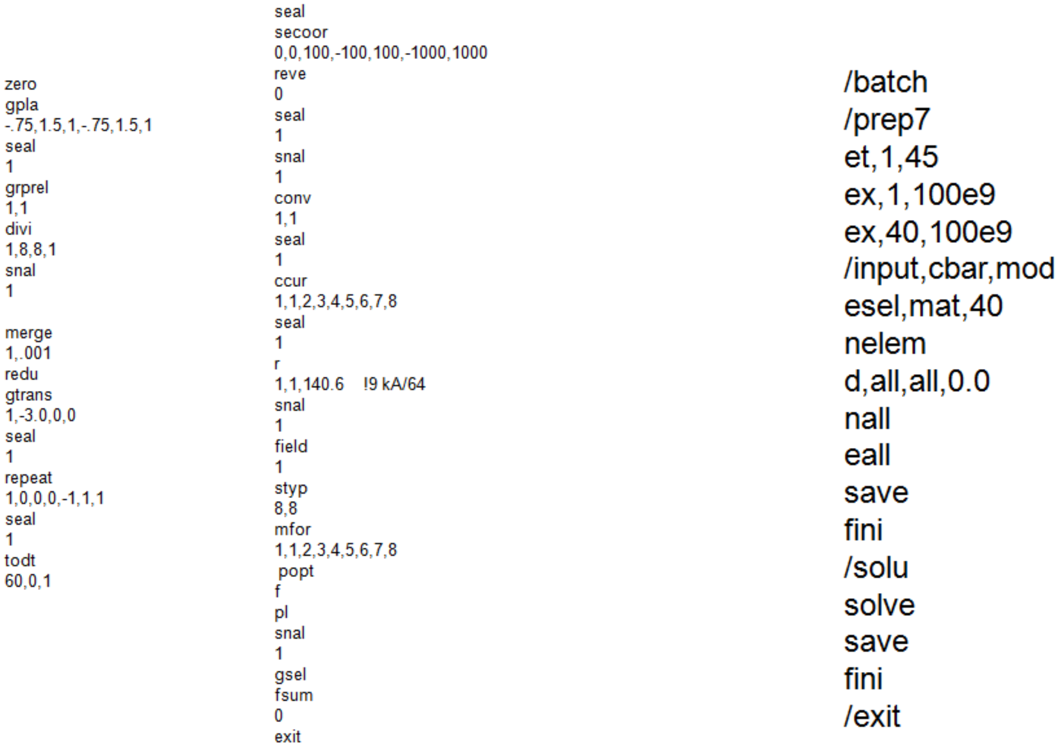
```
CHI horizontal Run Air Cooled Operation
Max Temperature = 31.633332 Deg C
Width of Busbar=6 inches
Height of Busbar =1 inches
Hole diameter =0 inches
Busbar surface area =3.8709755e-3 meter^2
Busbar surface area =.35560071 meter^2
Current = 32000 Amps
Pulse length = 5 sec
Number of Pulses = 10
Pulse Interval = 900 sec
Initial Temperature = 20 Deg C
Insulation Thickness = .0625 inches
Ending Temperature = 20.018595 Deg C
Volume of Copper = 3.8709755e-3 m^3
Mass of Copper in One Coil =34.645231 kg
Max Joule Power = 12661.069 Watts/meter
Max Radiated Power = 4.4193777 Watts/meter
Max Convected Power = 83.655424 Watts/meter
Max Water Cooling Power = 0 Watts/meter
Water Flow Velocity = 0 m/sec
```

Figure 8.0-8

9.0 Self Field Loads

9.1 Self Field Separating Force vs. Separation - Floor Run Bus Bars

Lorentz forces on the bus bar are calculated based on the bar currents crossing the background field from the toroidal and poloidal field coil. The self loads that result when the bars are near each other have been pieced together and added to the Lorentz force calculation for the background fields. To address these loads either the bars are bundled together to internally react the loads or the bars are sufficiently separated to minimize the loads. In this section, Lorentz loads as a function of separation are computed The geometry for the first study is 1.5 inch square bars with variable separation.



```
zero
gpla
-.75,1.5,1,-.75,1.5,1
seal
1
grprel
1,1
divi
1,8,8,1
snal
1

merge
1,.001
redu
gtrans
1,-3.0,0,0
seal
1
repeat
1,0,0,0,-1,1,1
seal
1
todt
60,0,1
```

```
seal
secoor
0,0,100,-100,100,-1000,1000
reve
0
seal
1
snal
1
conv
1,1
seal
1
ccur
1,1,2,3,4,5,6,7,8
seal
1
r
1,1,140.6    !9 kA/64
snal
1
field
1
styp
8,8
mfor
1,1,2,3,4,5,6,7,8
 popt
f
pl
snal
1
gsel
fsum
0
exit
```

```
/batch
/prep7
et,1,45
ex,1,100e9
ex,40,100e9
/input,cbar,mod
esel,mat,40
nelem
d,all,all,0.0
nall
eall
save
fini
/solu
solve
save
fini
/exit
```

Figure 9.1-1 NTFTM Routine to Calculate the Separating Force vs Separation

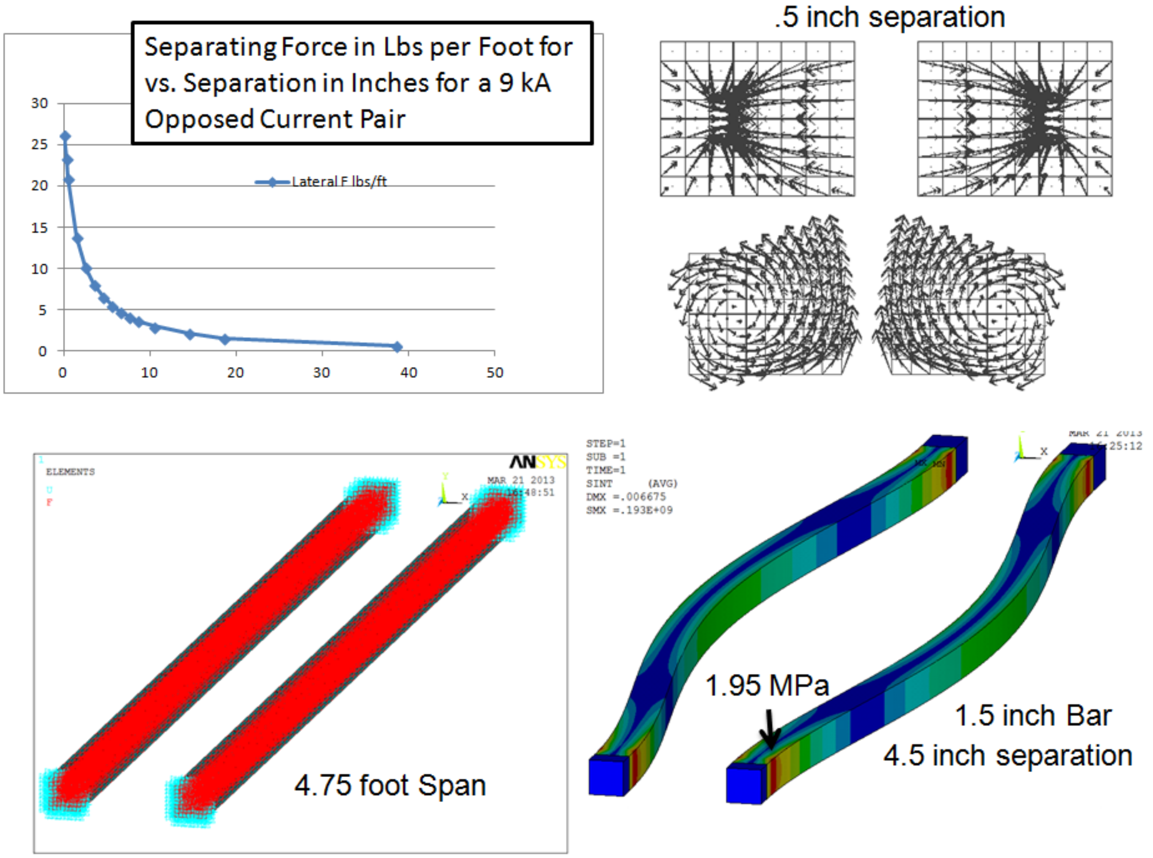
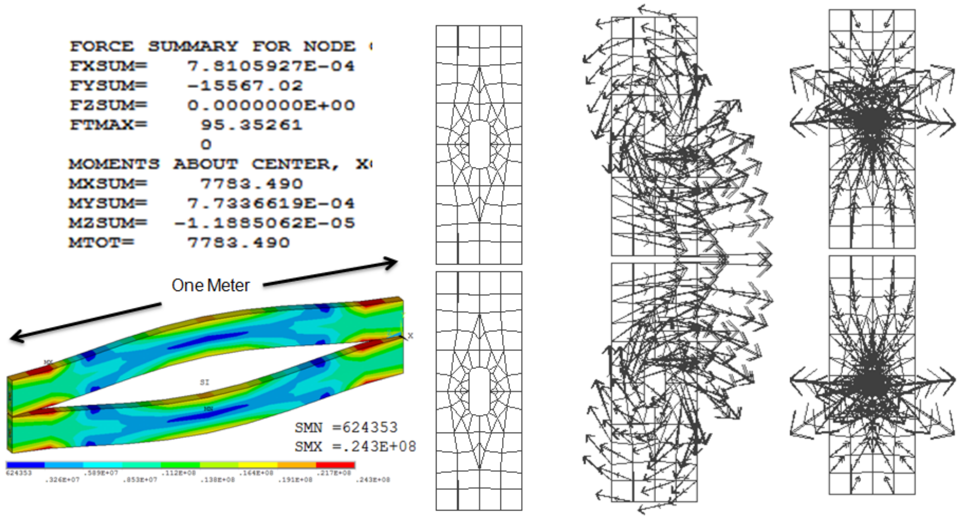


Figure 9.1-2 Forces as a Function of Separation for a Pair of 1.5 X 1.5 inch square inch Bus Bars

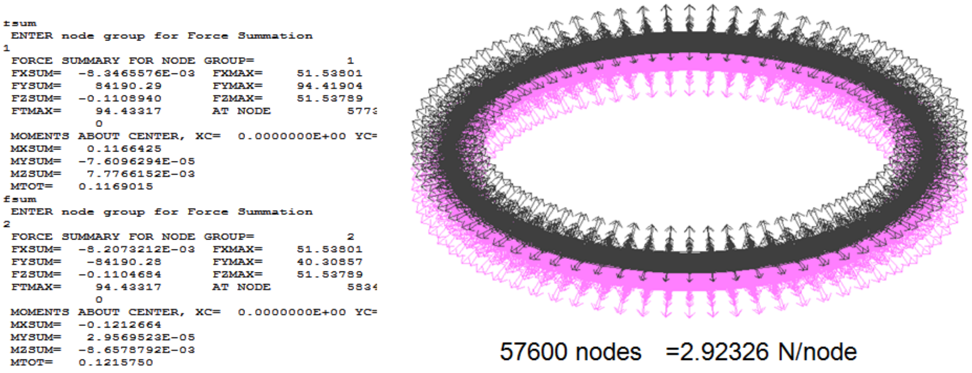
Originally the halo currents were assumed to travel in only one of the paired conductors because it was expected that the vessel was at ground and only the centerstack was connected to ground via the CHI bus. The conductors would only be affected by the background fields. Judging from Figure 6.5.3-1 and after a phone call to Stefan Gerhardt, it was determined that the disruption halo currents also pass through both legs of the CHI bus and thus will have large separating forces. The currents in the vertical paired conductors can't be assumed to fully cancel because the peaking factors for the casing and outer vessel structures are different. The 1.5 inch square water cooled runs along the floor also would carry a reversed set of halo currents. Figure 8.1-2 could be scaled by (150,000/9000)^2

9.2 Ring Coil Self Field Separating Force



```
FORCE SUMMARY FOR NODE
FXSUM=   7.8105927E-04
FYSUM=   -15567.02
FZSUM=   0.0000000E+00
FTMAX=    95.35261
          0
MOMENTS ABOUT CENTER, X
MXSUM=    7783.490
MYSUM=   7.7336619E-04
MZSUM=  -1.1885062E-05
MTOT=    7783.490
```

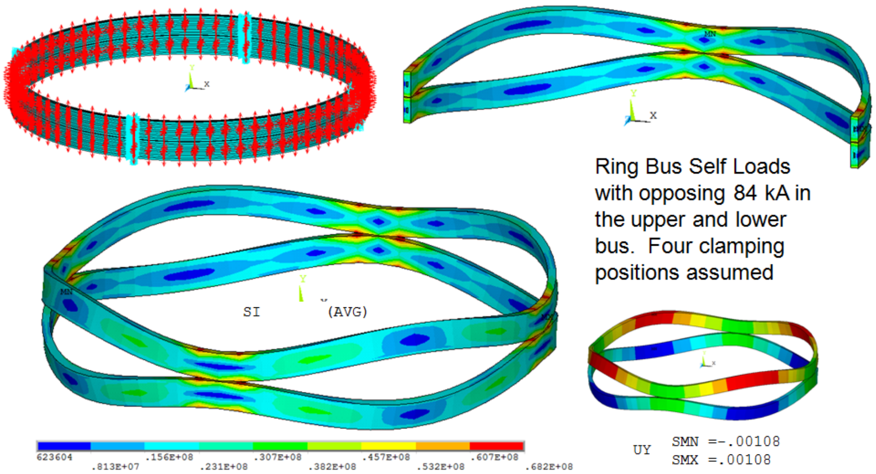
Figure 9.2-1 Self Field Loads and Stresses for a Straight Run of Ring Bus Conductor



```
tsum
 ENTER node group for Force Summation
1
 FORCE SUMMARY FOR NODE GROUP=              1
 FXSUM=  -8.3465576E-03  FXMAX=    51.53801
 FYSUM=    84190.29      FYMAX=    94.41904
 FZSUM=  -0.1108940      FZMAX=    51.53789
 FTMAX=    94.43317      AT NODE         577
           0
 MOMENTS ABOUT CENTER, XC=  0.0000000E+00 YC=
 MXSUM=   0.1166425
 MYSUM=  -7.6096294E-05
 MZSUM=   7.7766152E-03
 MTOT=   0.1169015
fsum
 ENTER node group for Force Summation
2
 FORCE SUMMARY FOR NODE GROUP=              2
 FXSUM=  -8.2073212E-03  FXMAX=    51.53801
 FYSUM=   -84190.28      FYMAX=    40.30857
 FZSUM=  -0.1104684      FZMAX=    51.53789
 FTMAX=    94.43317      AT NODE         583
           0
 MOMENTS ABOUT CENTER, XC=  0.0000000E+00 YC=
 MXSUM=  -0.1212664
 MYSUM=   2.9569523E-05
 MZSUM=  -8.6578792E-03
 MTOT=   0.1215750
```

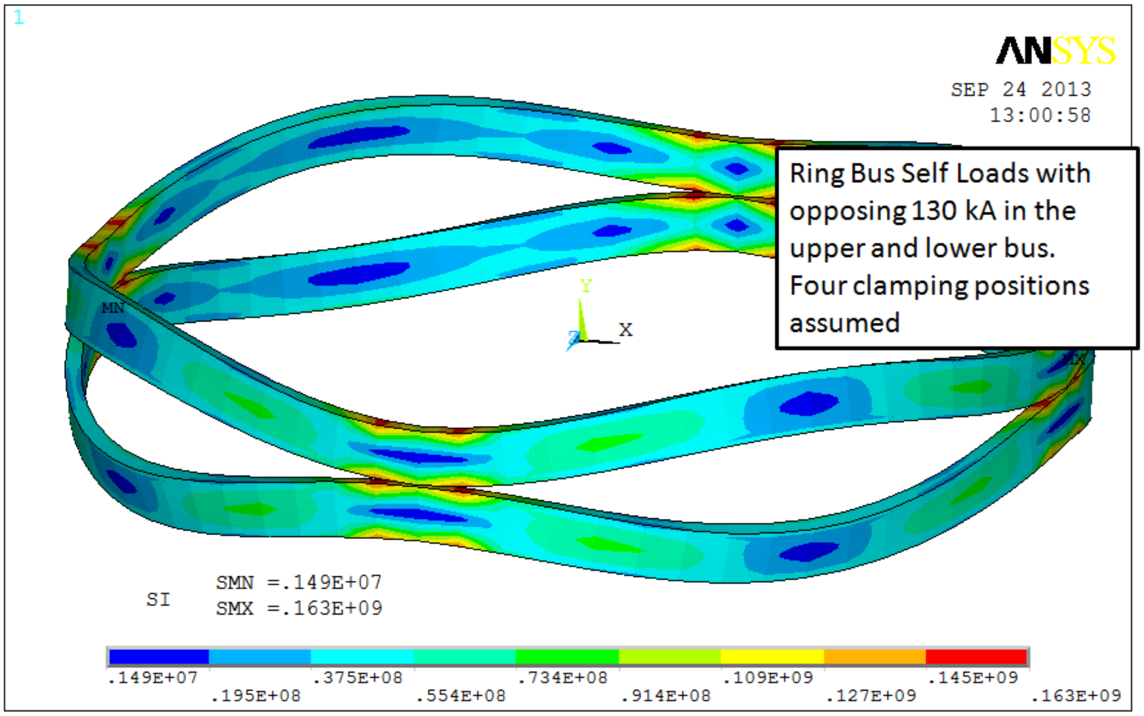
Figure 9.2-2 Self Field Loads and Stresses the Ring Bus Conductor, 84 kA

The currents flowing in the ring bus are discussed in section 6.5.3. the currents are either 84 kA in one direction or 130 kA in the other. This depends on how many of the three vertical runs are connected to a segment of the ring.



Ring Bus Self Loads with opposing 84 kA in the upper and lower bus. Four clamping positions assumed

Figure 9.2-3 Self Field Loads and Stresses for 84 kA



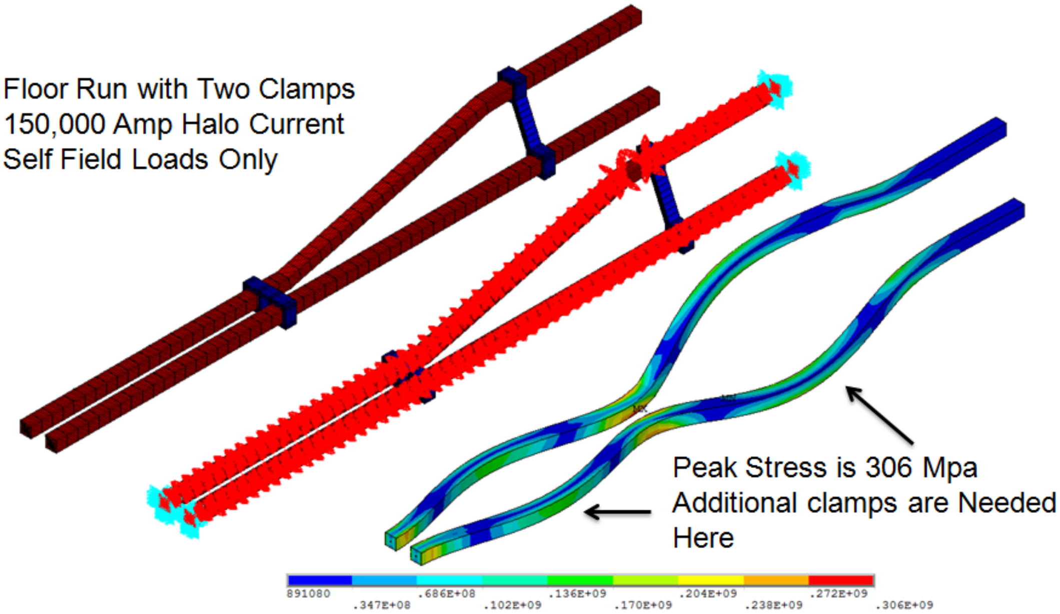
Ring Bus Self Loads with opposing 130 kA in the upper and lower bus. Four clamping positions assumed

Figure 9.2.4 Self Field Loads and Stresses for 130 kA

In order to sustain the separating loads when the paired conductors in the ring bus carry the halo currents, clamps connecting the upper and lower rings should be added at least every 45 degrees. The 163 MPa stress is for supports spaced at 90 degrees. 45 degree support spacing was requested from Jean Pierre Fra. The stress should go down by a factor of 4. To 40.75 MPa

9.3 Floor Run Self Loads with 150 kA Halo Currents

The floor runs were not included in some of the models because the background fields are small. But the self loads on the paired conductors is high if these conductors carry the 150 kA Halo current disruption load.



Floor Run with Two Clamps
150,000 Amp Halo Current
Self Field Loads Only

Peak Stress is 306 Mpa
Additional clamps are Needed
Here

Figure 9.3.1 Model of the Floor Run Connecting the Ring Bus to the Bus Tower

The floor runs carry the full halo current, and there should be four clamps between the bus tower and the ring bus. Figure 9.3.1 shows an analysis with only two clamps and this produces 306 MPa, well above the allowable. Four clamps would halve the spans and should reduce the bending stress by a factor of four. So the estimated stress for the 4 support points is 76.5 with a bending allowable of 130 MPa

9.4 CHI Bus Stresses With Self Loads

In this analysis the self loads are added using a Biot Savart analysis for the PF, TF coils and vertical legs. The net vertical forces from the analysis in section 9.2.2 are added to the lower ring bus.

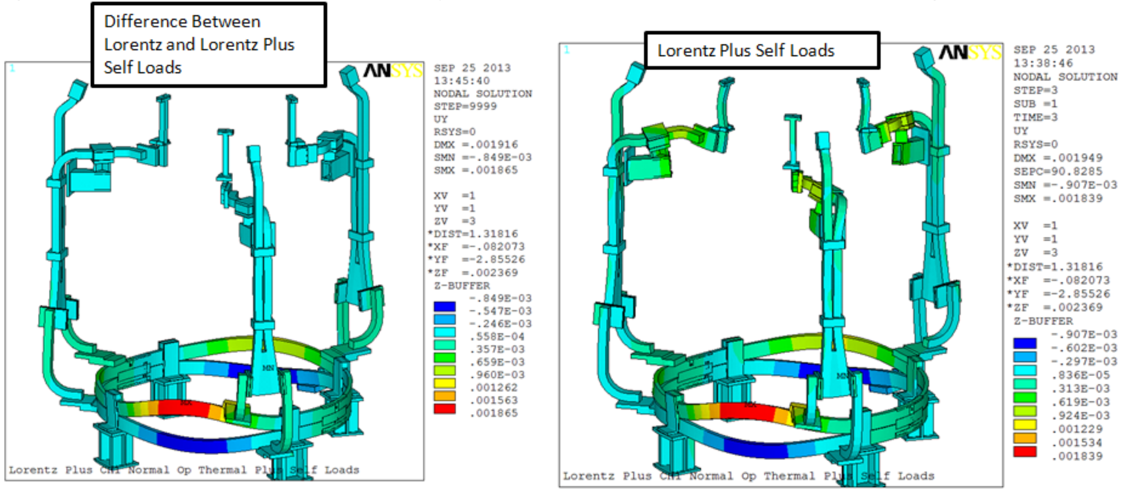


Figure 9.4-1 Vertical Displacements

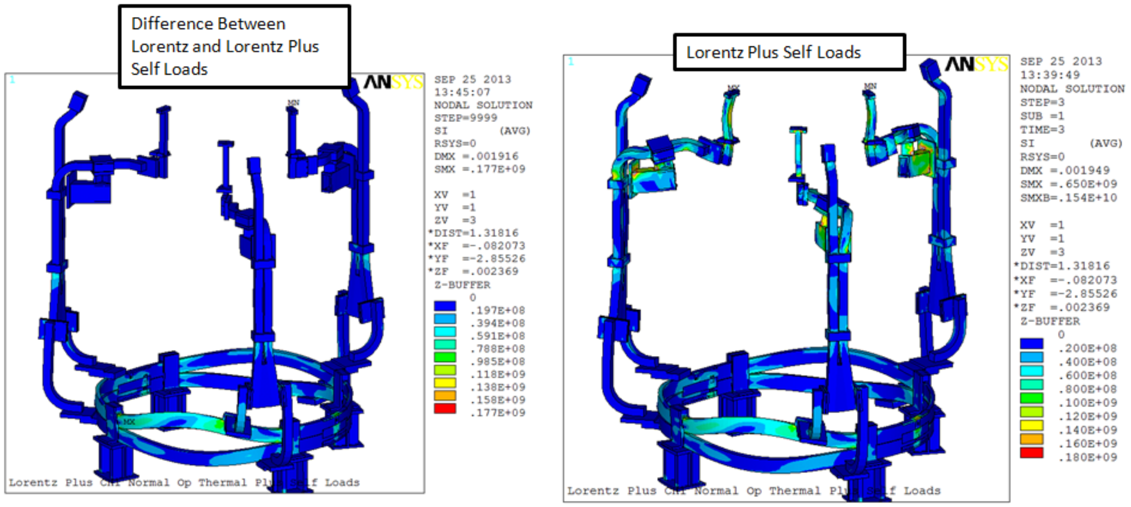


Figure 9.4-2 Tresca Stress Intensity

10.0 Worst Equilibria for CHI Lorentz Force Calculations

For many of the NSTX calculations, EQ 79 is used as the most limiting. This results from global torque assessments for which EQ 79 is the largest. It is not clear if that is the worst for the CHI. The CHI leads inside the TF “cage” are near PF2. The TF field is the largest contributor to the Lorentz forces, but large currents in PF2 could add to the TF effect.

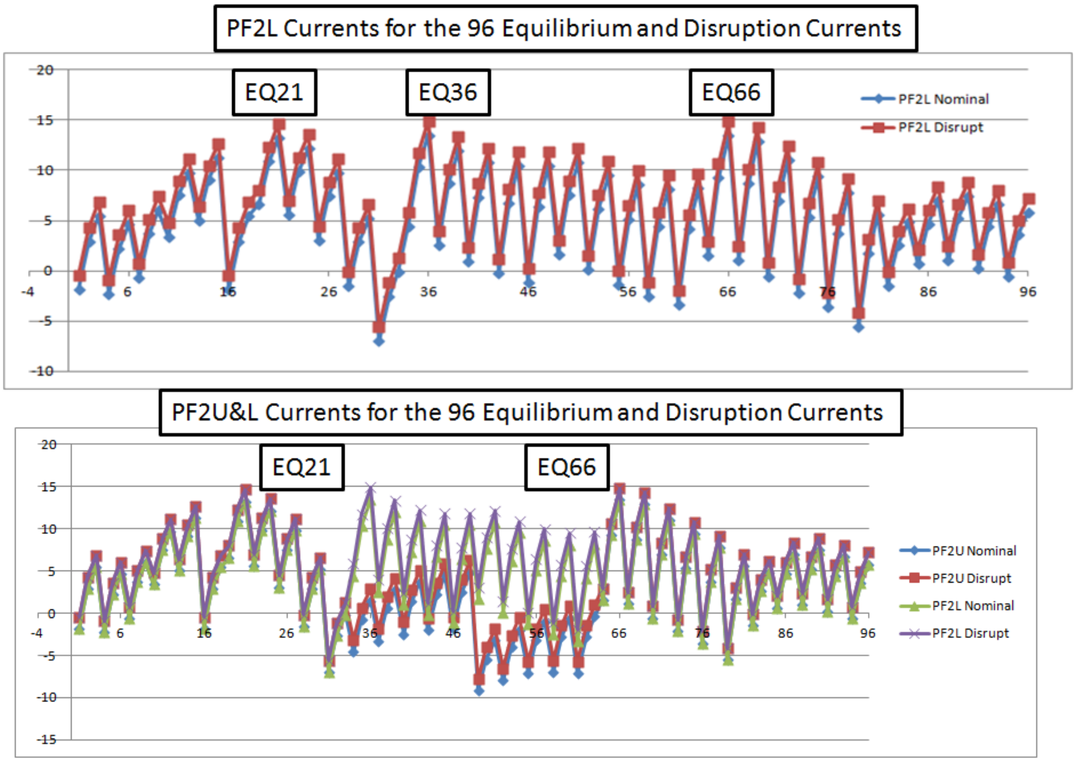


Figure 10.1-1 PF 2 Currents for the 96 Equilibria and Disruption.

Based on the plots in figure 10.1-1, EQ 66 was selected as a likely worst case along with EQ 79.

11.0 Biot Savart Model, Lorentz Force Calculations

Lorentz forces were computed outside ANSYS with a macro/program that uses the element connectivity to define current directions. The background fields and forces are computed from a Biot Savart analysis . Lorentz forces are computed from I X B

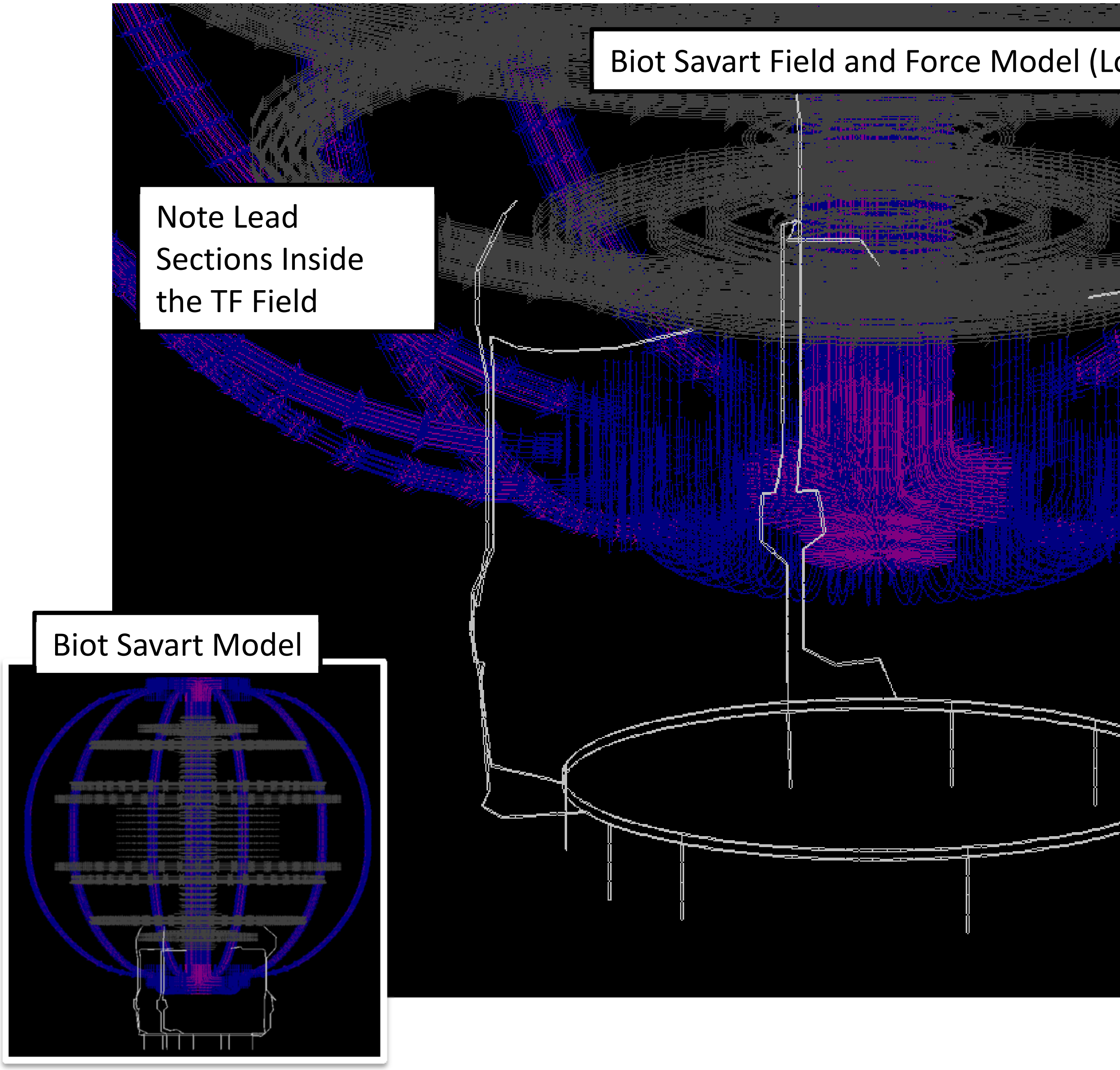


Figure 11.2-1 Biot Savart Model of NSTX and the CHI Bus Bar Stick Model

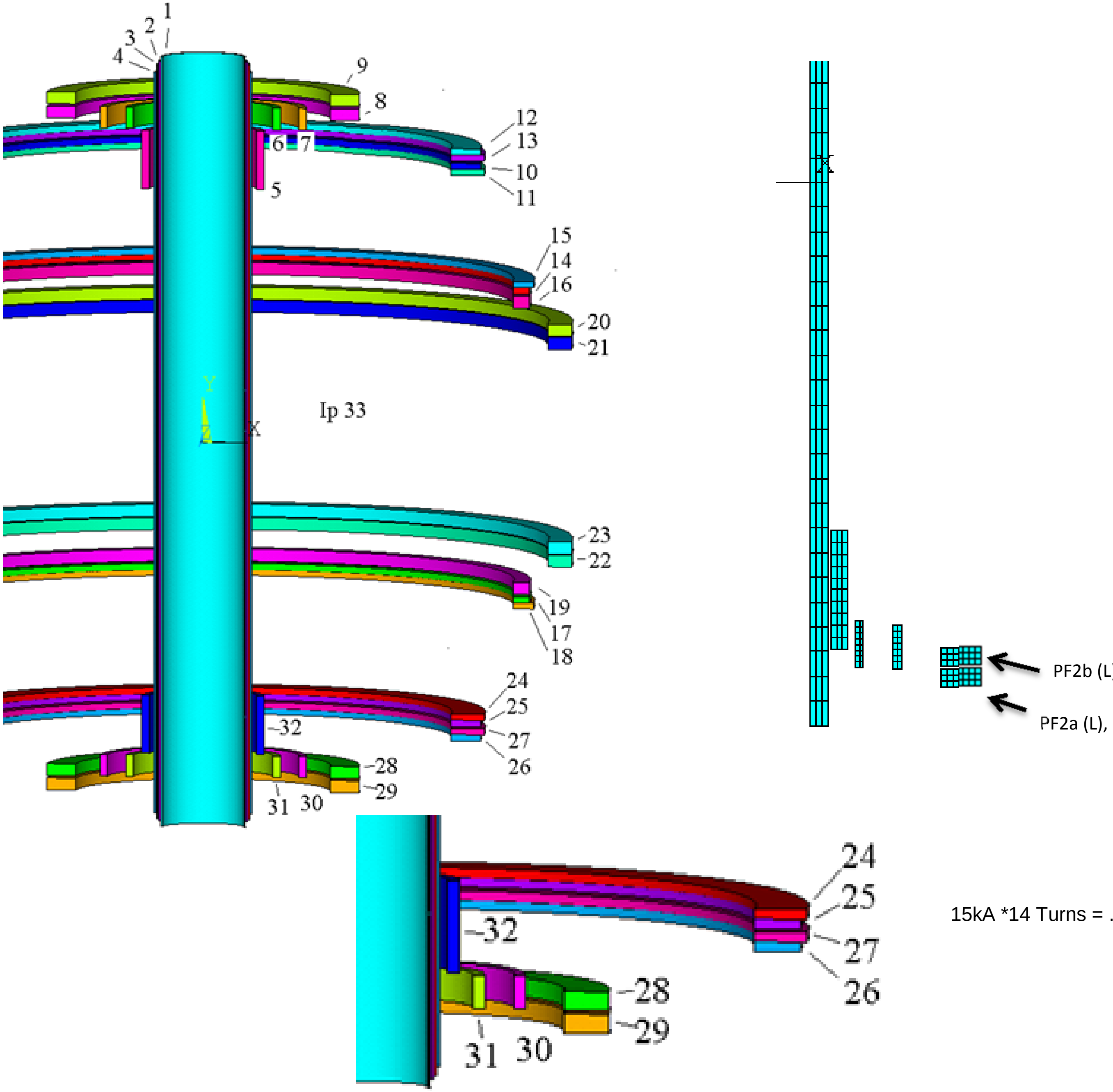


Figure 11.2-2 NSTX PF Coil Model and Real Constants used in the CHI Bus Bar Analysis

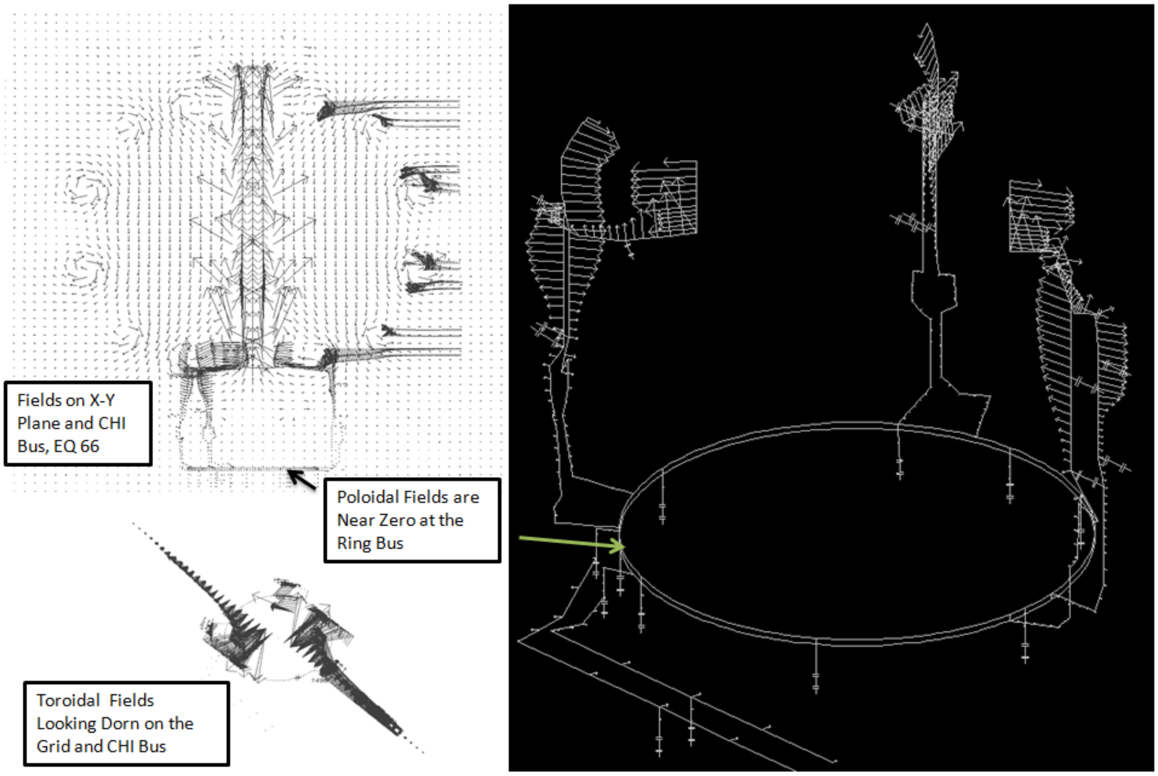


Figure 11.2-3 Fields(left) and Lorentz Forces (Right) from the Biot Savart Analysis

12.0 Solid Models Including flags

IGES Files were provided by J.P. Fra. These formed the basis for meshing the vertical runs. Modeland the mesh are described in section 7.0

12.1 July – September 2013 Analyses

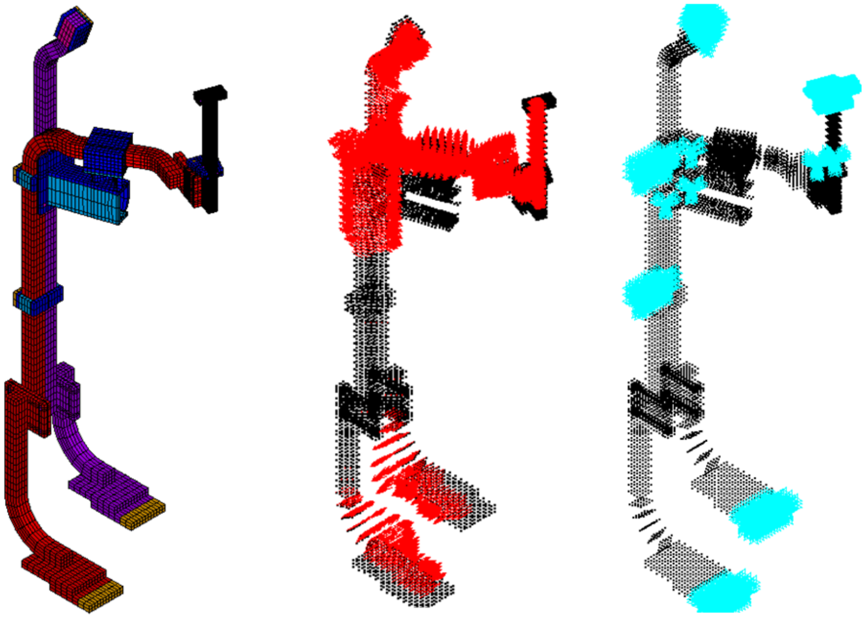
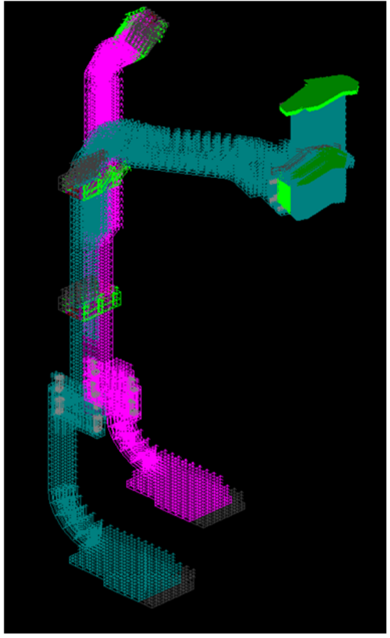


Figure 12.1-1 Model of Single “Worst” Vertical Leg

Figure 12.1-1 shows the model of one of the three vertical runs. It includes a box beam support that is cantilevered off the lower umbrella structure. The model has a 3 X 5 box section without the end cap. In the actual design, two 3 X 3 box beam are welded together to form the equivalent of a 3 X 6 beam. A cap is welded to the end of the beam to stabilize the box section against “racking”. In subsequent models the single vertical run model was repeated , and the ring bus added to represent the three vertical runs and their brazed connection to the ring bus.



Application of Fields for Lorentz Force Calculation

```
snal
0
btor
1.0,.934,.03,.3,3.0,3.2
scoor
1,-100,100,-100,-2.64,-100,100

bscale
1,.001,.001,.001
snal
1
bgen
1,0,1,0
```

This eliminates TF field outside the TF “Cage”

This adds 1 Tesla vertical field everwhere

Figure 12.1-2 Calculation of the Lorentz Forces on the Vertical Leg

The Lorenz forces are calculated outside ANSYS by simply imposing a 1/r toroidal field on the conductors inside the TF “cage” and adding a 1 T vertical field everywhere. Conductor elements are meshed with known and consistent connectivity so that the length and direction of the current vectors can be derived from the connectivity The forces are computed by crossing the currents and fields. This is done in the simple fortran code, NTFTM. The resulting meshed model with Lorentz forces is imported into ANSYS with a /input command. The full listing of the NTFTM commands is included in Appendix A.

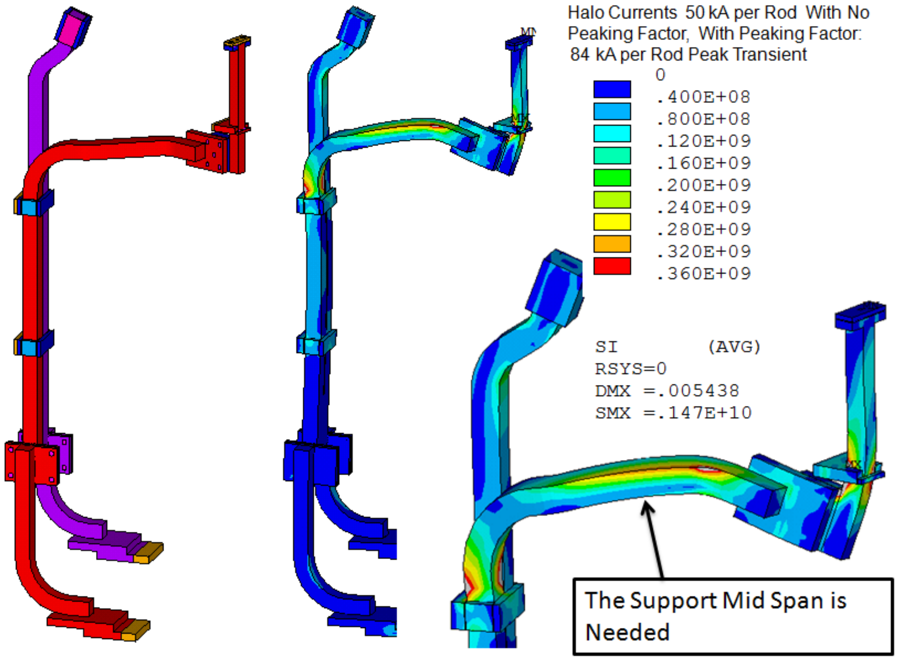


Figure 12.1-3 Model of Single Vertical Leg before a Mid Span Support was Added.

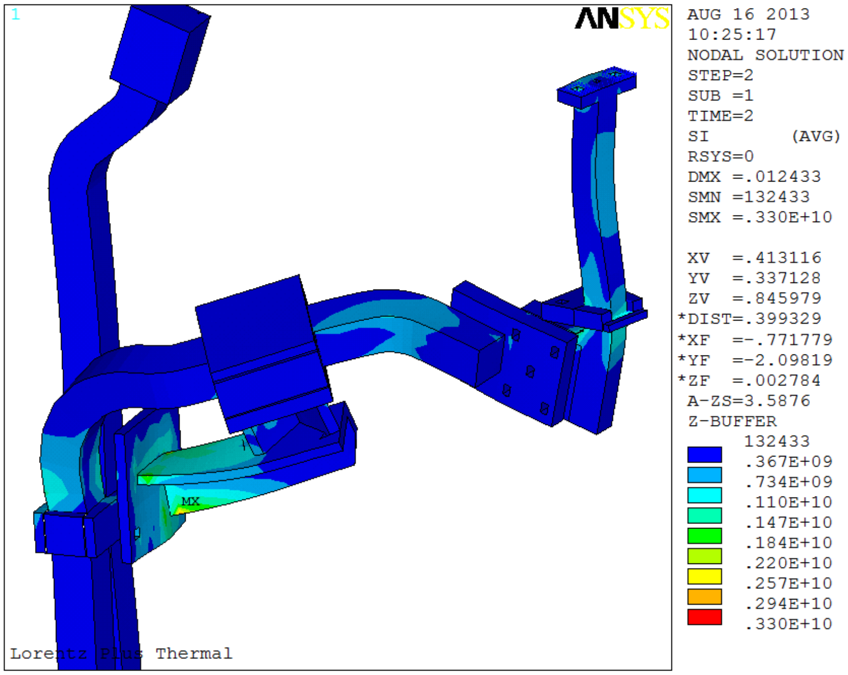


Figure 12.1-4 Model of Single Vertical Leg with a 3 X 3 X 3/8 Angle Mid Span Support.

Note the rotational flexibility of the angle and the peak stress at the lower end of the angle leg. The rotational flexibility of the angle led to the selection of a closed section box beam. All stresses were unacceptable.

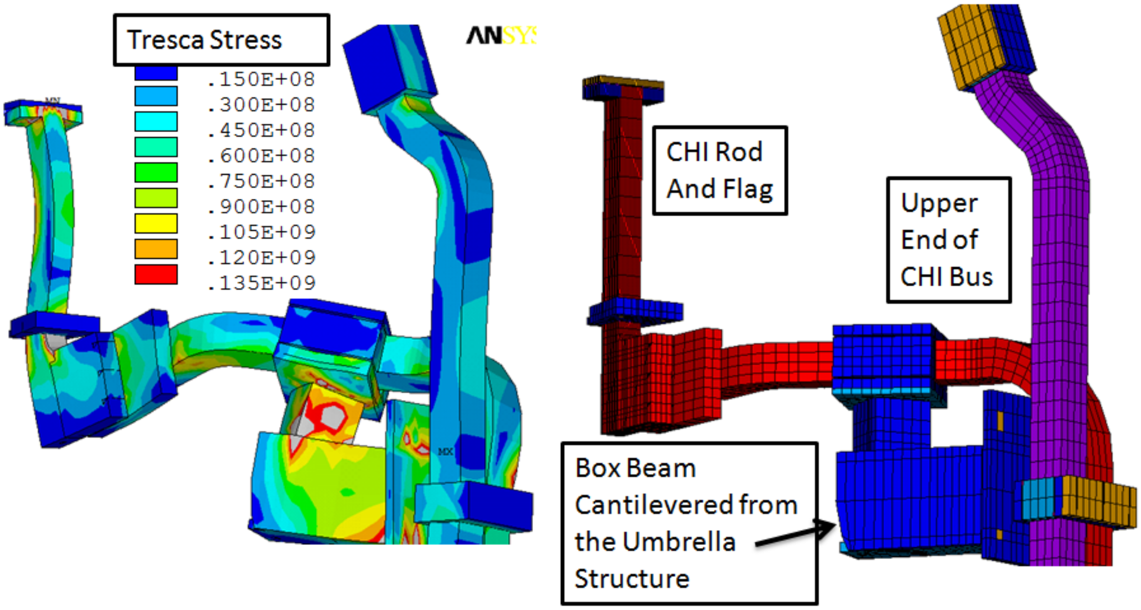


Figure 12.1-5 Model of Single Vertical Leg With the Box Beam Support

The stress in the horizontal leg of the bus bar went from 360 MPa to less than 135 MPa with the addition of the box beam support. The bulk of the bar is lower than 135 MPa. The small areas with a peak stress above 135 MPa are only at local corners, and this is acceptable for the very few numbers of events that will produce a concurrent worst case halo current and CHI current drive currents. The short vertical element connecting the box beam and the bus bar clamp is modeled as a 3 X 3 angle. This has been changes to a 3 X 3 box section. So the stresses in this piece will be much reduced.

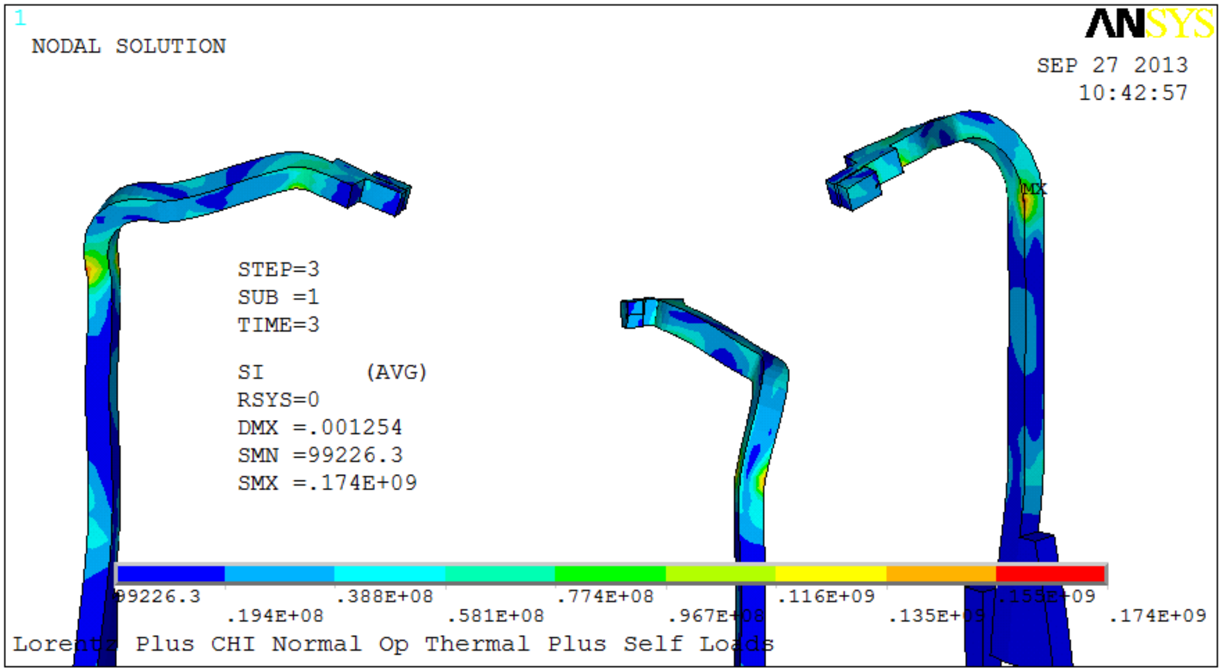


Figure 12.1-6 Stress at Vertical to Horizontal Bend

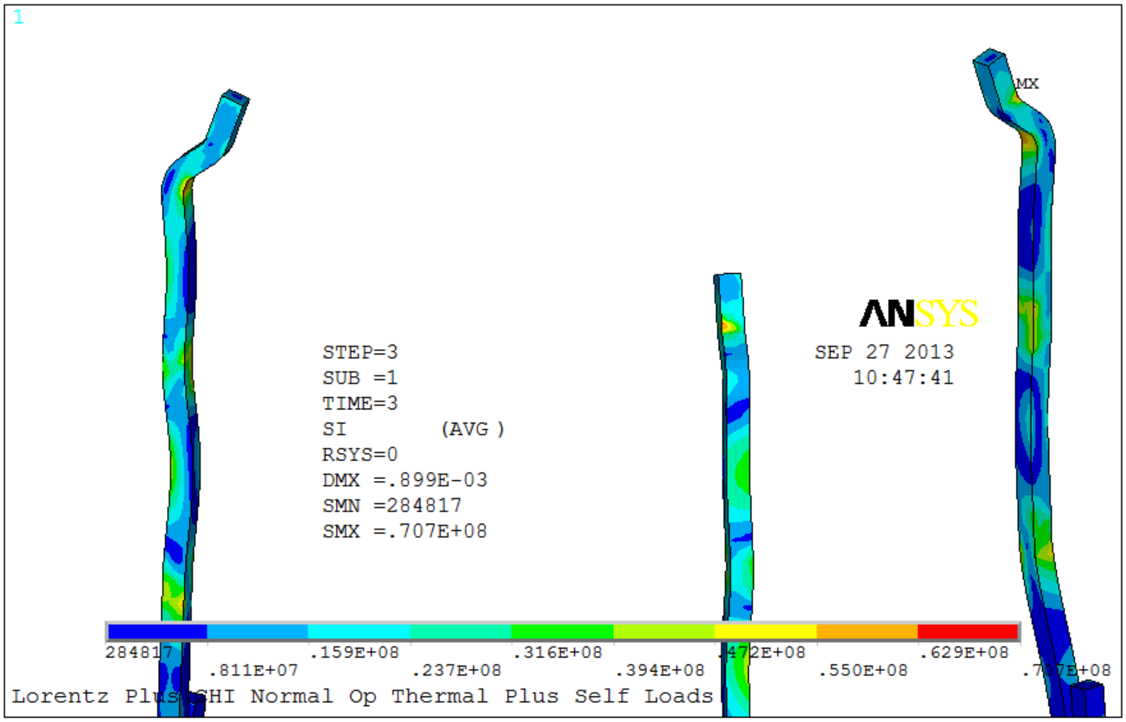


Figure 12.1-7 Stress at Vertical Runs of the 2 X 2 Bar

12.2 Vertical to Horizontal Support and Bolting/Studs

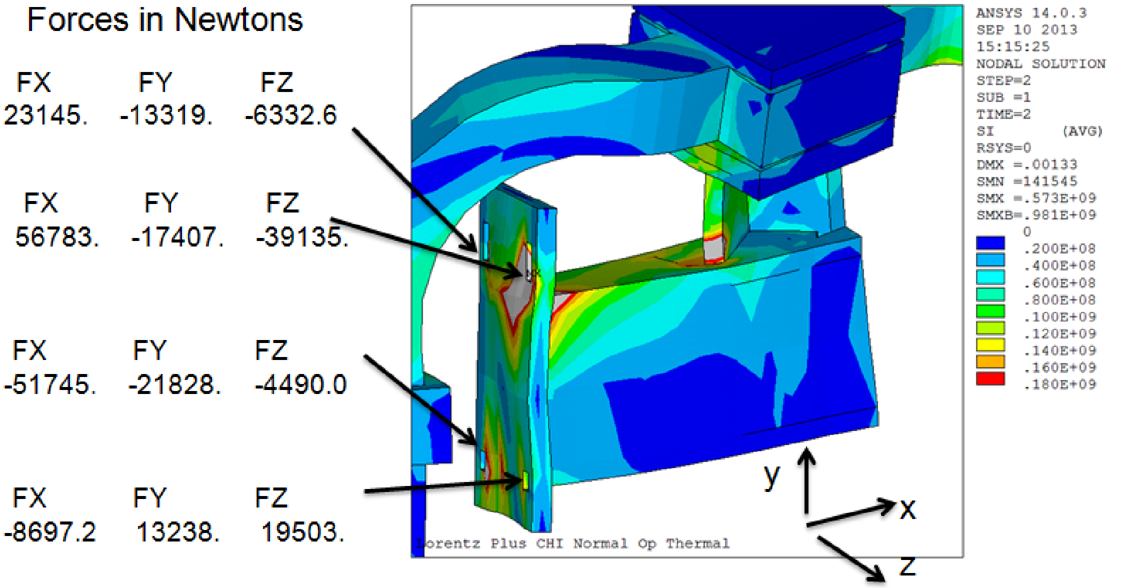


Figure 12.2-1 Umbrella Structure Bolting Reactions

The biggest tensile load is 56783 N or 12,765 lbs. ½ inch bolts have a stress area of .14 sq in. This would stress the bolt to 91 ksi. 5/8 bolts have a stress area of .2246 in^2 and the tensile stress would be 57 ksi. For ASTM A-193 B8M Class 1 bolts, the stress allowable would be 2/3*110 = 73.3 ksi, (see section 6.4.3) So 5/8inch bolts are required for the attachment. There may be a preference for a welded stud to replace the threaded bolt hole in the umbrella structure.

The stress on a 5/8 stud would be 12765/(.625^2*pi/4)= 41607 psi

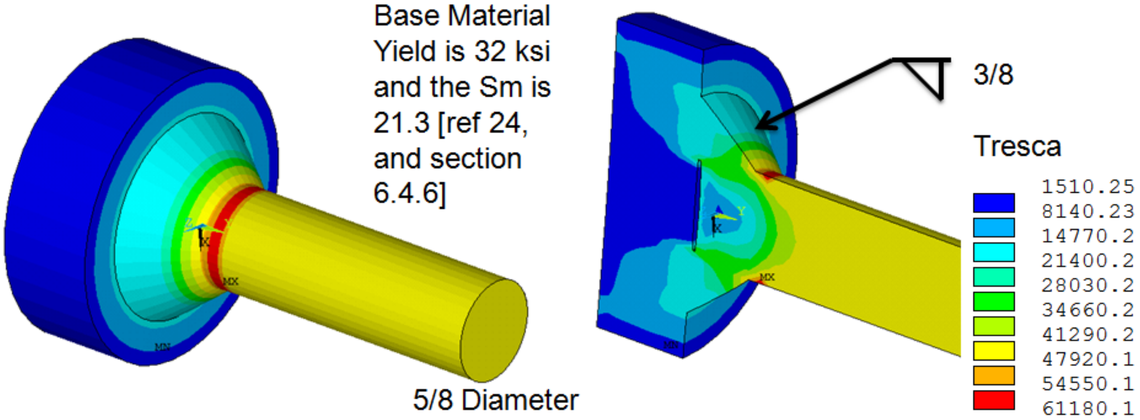


Figure 12.2-2 Umbrella Structure Welded Stud Stresses

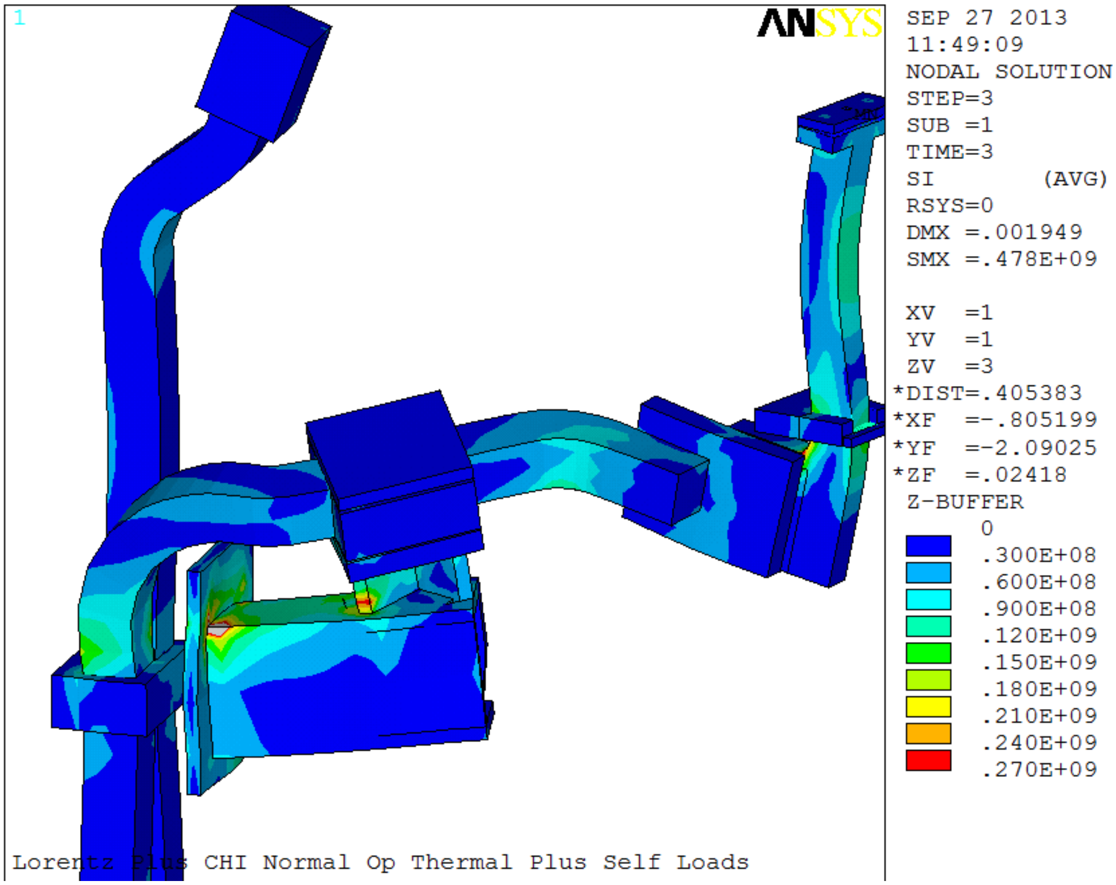


Figure 12.2-3 Cantilever Support Box Beam Stresses

The bending allowable for the 316 cantilever box beam is 240 MPa with the 1.2 K factor. There is a peak above 270 MPa but the linearized bending stress should be ~210 MPa contour.

12.3 Intermediate Joint Bolting

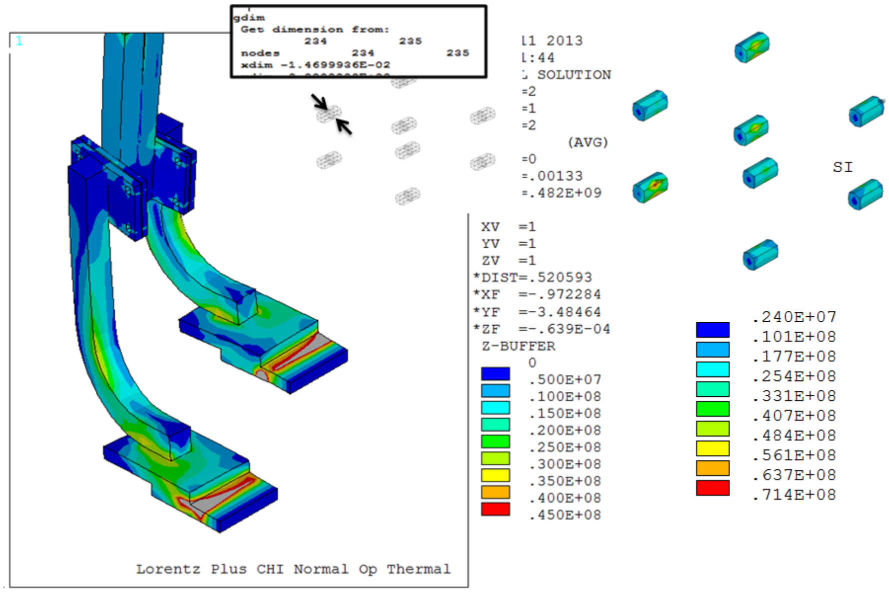
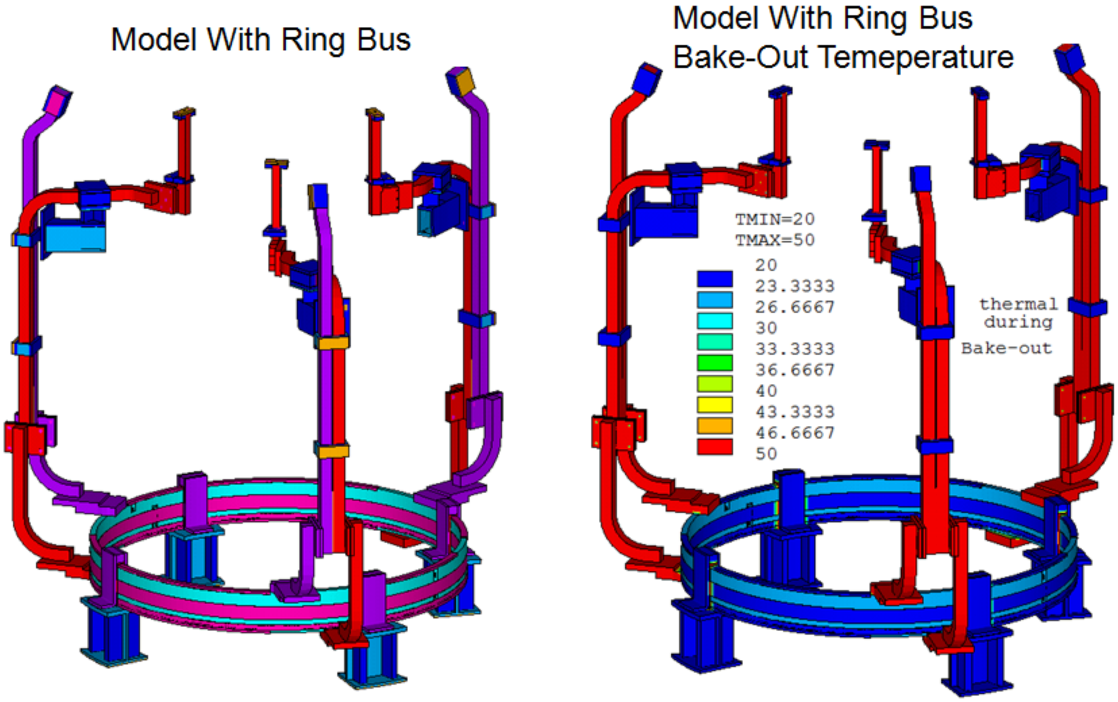


Figure 13.3-1 Lower “Paddle” Bolting Stresses

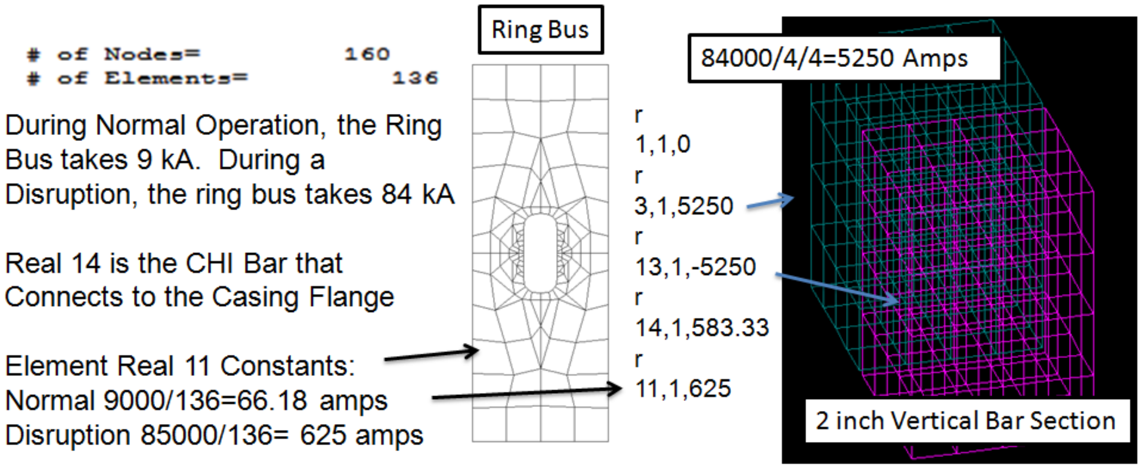
The finite elements that model the bolts model a diameter of .0147 m or .59 inches. These are stressed to a maximum of 71 MPa and an average around 35 MPa or 5.1 ksi. For ½ inch bolts, which have a stress area of .14 inches^2, the stress would be pi*.59^2/4/.14*5.1ksi = 10 ksi. ½ inch standard bolts should be OK.

12.4 Ring Bus and Ring Bus to Flag Braze


Model With Ring Bus

Model With Ring Bus
Bake-Out Temeperature

Figure 12.4-1 Model With Ring Bus



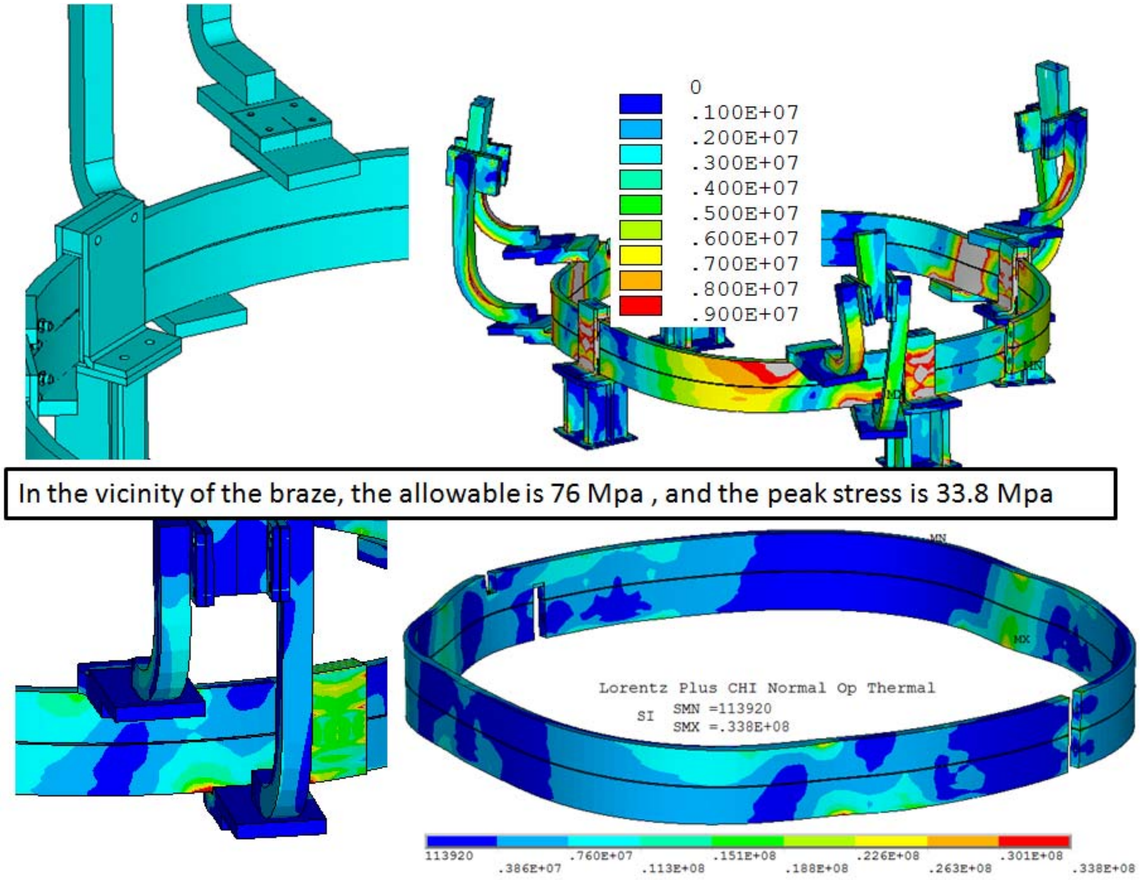
```
 # of Nodes=           160
 # of Elements=            136
```

During Normal Operation, the Ring Bus takes 9 kA. During a Disruption, the ring bus takes 84 kA

Real 14 is the CHI Bar that Connects to the Casing Flange

Element Real 11 Constants:
Normal 9000/136=66.18 amps
Disruption 85000/136= 625 amps

Figure 12.4-2 Real Constants Used to Assign Constants in the Field Calculation



In the vicinity of the braze, the allowable is 76 Mpa , and the peak stress is 33.8 Mpa

Figure 12.4-3 Ring Bus Stresses Including the Flag Braze

12.5 CHI Bar Bolted to Centerstack casing Flange

12.5.1 CHI Stress

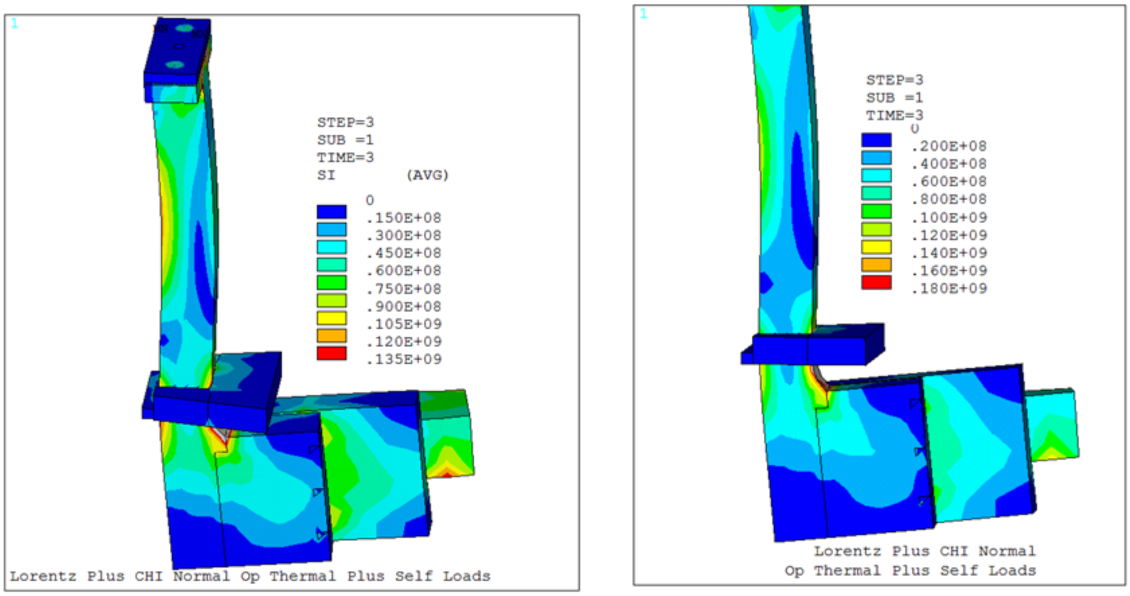


Figure 12.5.1-1 Chi Bar Flag Corner Stress

These stresses are for the “unlikely” Halo current scenario which has an allowable of 156 MPa. The linearized stresses would satisfy this allowable. There is a peak at the radius of 180 MPa. Note that the CHI bar and flag are fabricated as one piece and there is no braze at the flag to conductor joint to degrade the bar physicals(see Figure 6.3-5)

12.5.2 CHI Bar Bolted Connection to Centerstack casing Flange

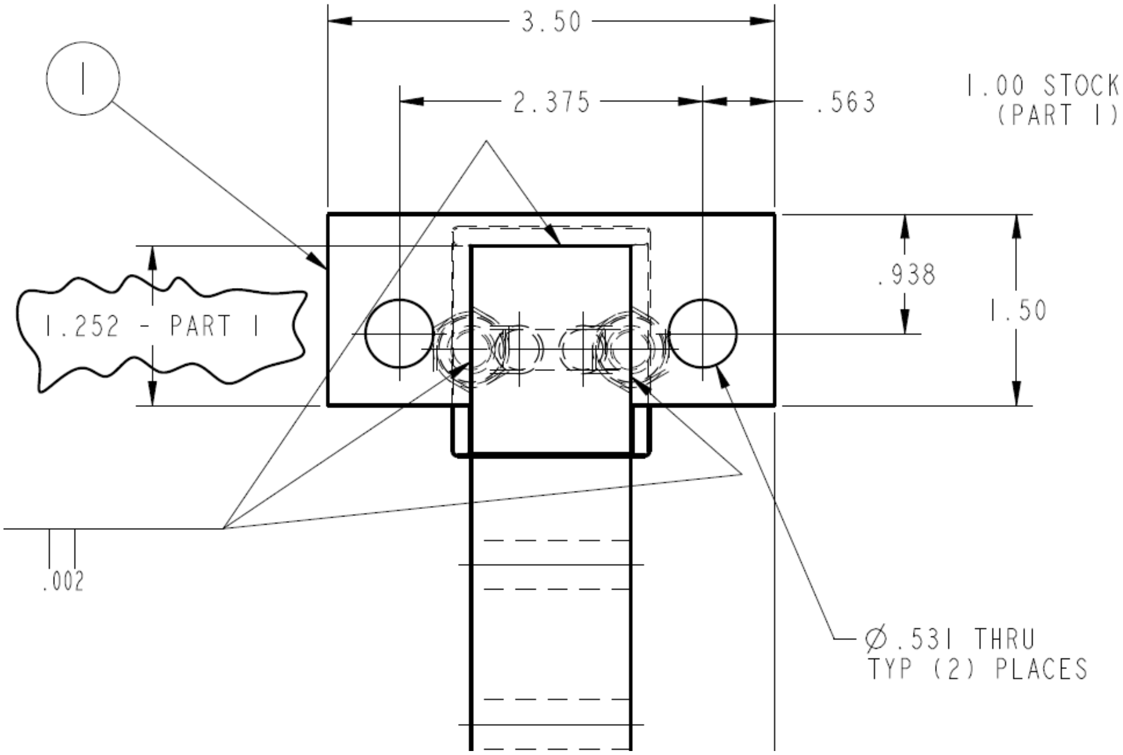


Figure 12.5.2-1 Flange Connection to Centerstack casing

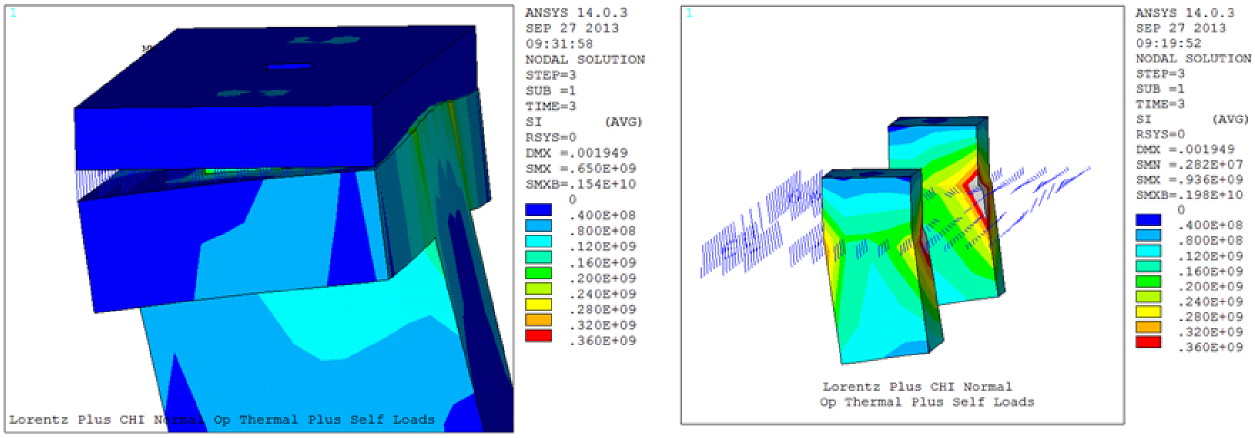


Figure 12.5.2-2 Stress in Flange Connection to Centerstack Casing Bolts

Each “block” that models the bolts is 1 X 1.3 cm in cross section. Ignoring the bolt bending, the bolt tensile load is ~160 MPa *.01*.013 = 20,800 N or 4700 lbs. ½ inch bolts are used in this flange. The stress in the bolt is then 4700/.1416 = 33021 psi. This should be preloaded beyond this to overcome the prying lift-off and resulting bolt bending stress. A high strength bolt is recommended for this reason.

13.0 Beam Element Structural Calculations

Initial sizing and recommendations for support of the horizontal run that connects to the CHI bar were based on beam stick modeling of the ring bus and vertical runs. These had only the background field applied. The background field was computed using a Biot Savart current stick modeling shown in section 11.0 Later the self field calculations were added, and the Halo peaking fraction was added.

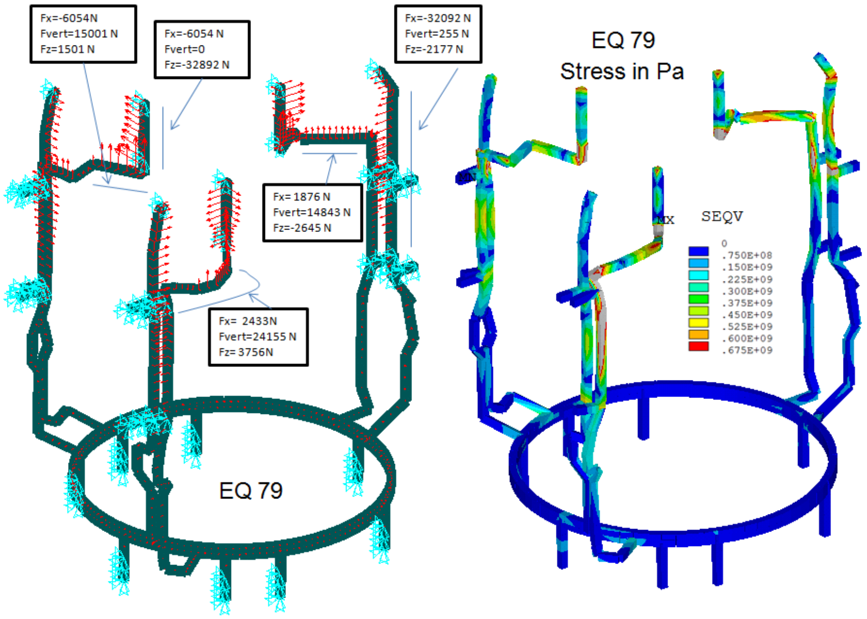


Figure 13.0-1 EQ 79 Loads on the CHI Bus for Preliminary Design. And stresses for the ¾ inch water cooled conductor.

This generation of analysis model used a water cooled conductor that was only ¾ inch by ¾ inch square. The section properties for this beam element are shown in figure 14.3. These beam models did not include the halo current peaking factor of 1.5 and the self field effects that were added in the later solid models.

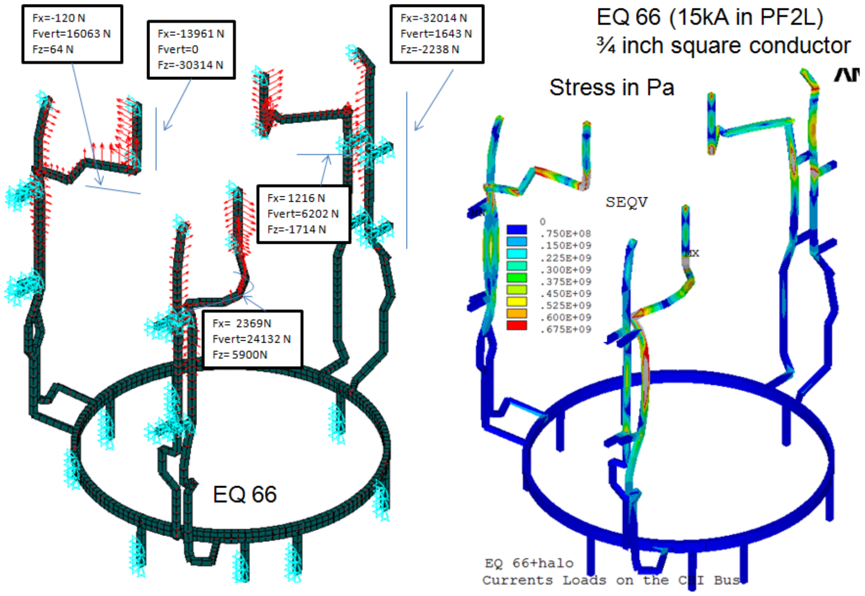


Figure 13.0-2 EQ-66 Stress Summary (Dynamic Unless Otherwise Noted)

Figure 13.0-2 shows the over-stress conditions for the original ¾ inch conductor. This was partly the motivation for increasing the size to 1.5 X 1.5 inch square and then to 2 X 2 inches. The ring bus and the connections to the ring bus that run along the floor have small Lorentz forces resulting from interactions with the background field. Self fields from the disruption halo currents are, however large. The Lorentz forces on these conductors don't effect the conductor selection so much as the requirements to clamp the paired conductors together. The normal current for CHI start-up is 27 kA for ~ 1 sec. If you used the steady state allowable of 1 kA per sq in. then the ¾ inch square bar would be undersized. If it was used for 8 kA bakeout it would be undersized. Even the currently chosen 2 X 2 inch bar would be undersized. See section 8.0 for a more detailed calculation of the temperatures of the bus bars. Actual temperatures from that section are included in Table 4.0-1.

Portions of the ring bus and floor connections between the ring bus and bus tower see the halo current of 7.5% of the plasma current. - or 2 MA* .075 = 150 kA but this is only for ~milli second and won't integrate to a significant temperature.

The 1.5 X 1.5 inch water cooled floor run is acceptable for the connections to the CHI ring so long as it interconnected to react the bursting loads which develop when the leads carry the Halo currents. At least 4 clamps are recommended between the bus tower and ring bus connection.

13.1 Air Cooled 1.5 X 1.5 Square Vertical Bus Beam Element Model

13.1.1 All Clamps Fixed in All 3 Directions

In this model, the vertical bars are 1.5 inch square and the ring bus is ¾ inch water cooled square cross section. The air cooled vertical run heats up during operation, and thermal strains must be considered.

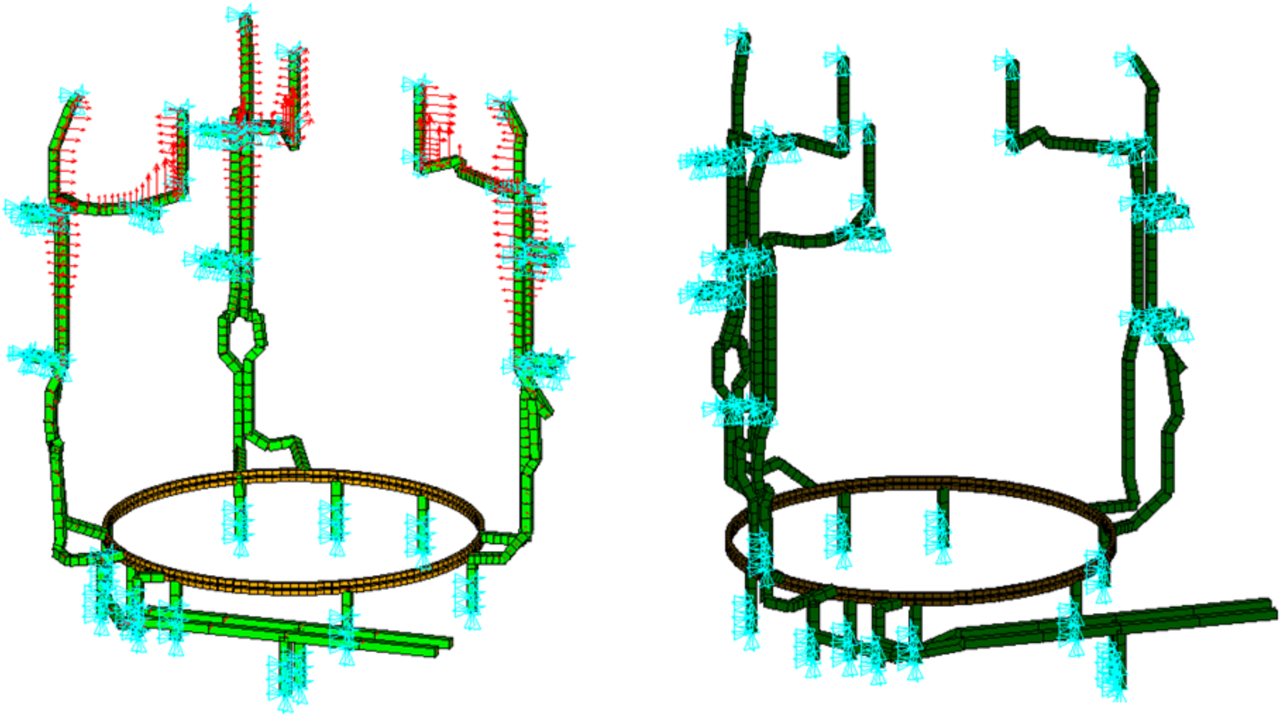


Figure 13.1.1-1 Model with all Clamps Fixed in Three Directions

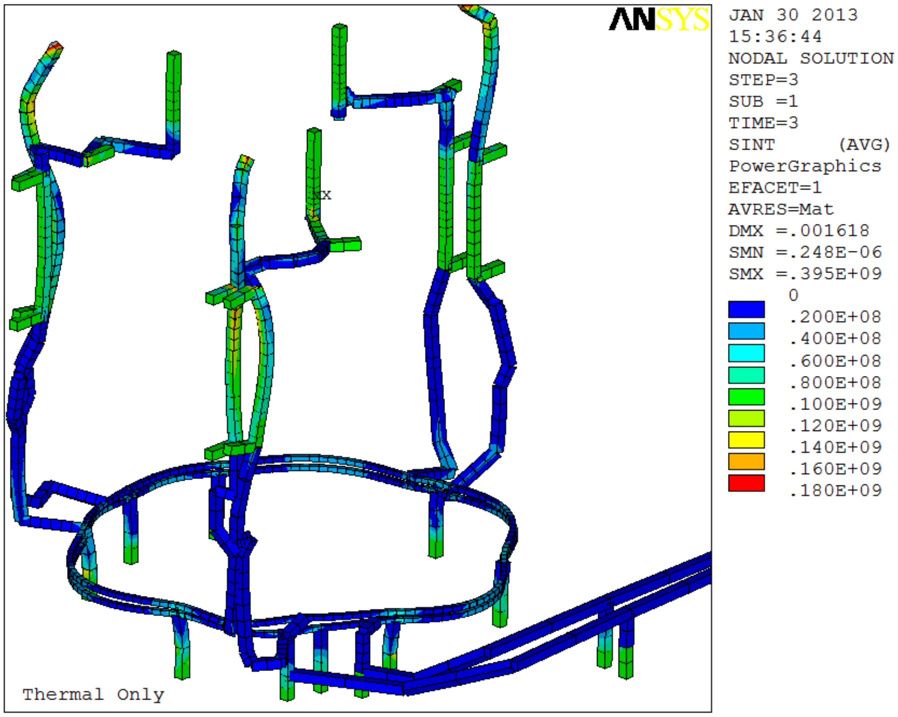


Figure 13.1.1-2 Thermal Stress Only, 50 C heat-up

For the thermal-only load case, the peak stress is 180 MPa. This compares with the static bending allowable of 233 MPa (Section 6.4.1). There are higher localized stresses but the beam modeling doesn't accurately capture these. In figure 13.1.1-3, the normal operating Lorentz force for equilibrium 66 is added. The peak stress remains at 180

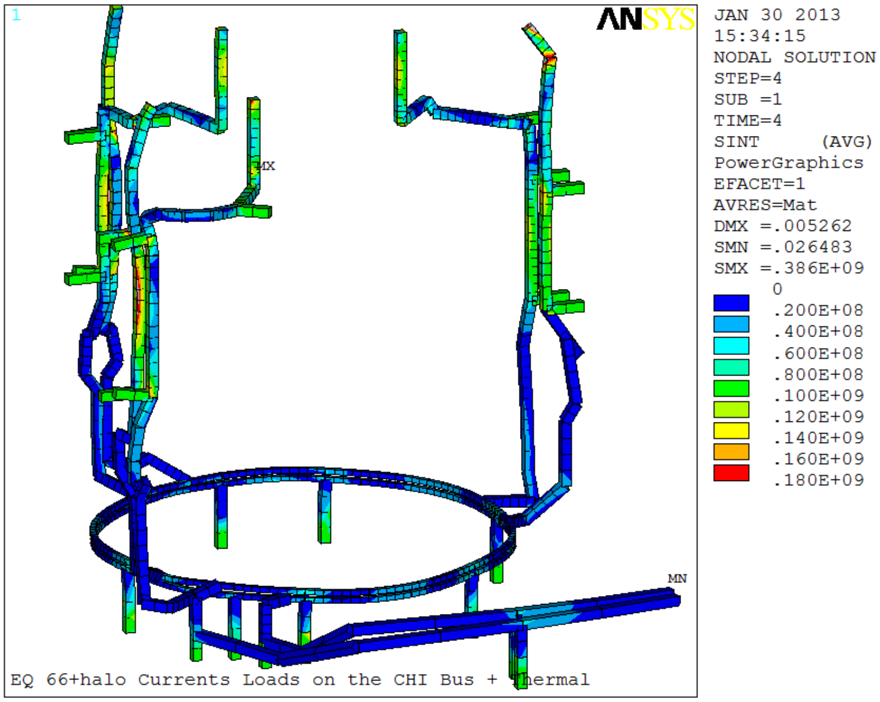


Figure 13.1.1-3 EQ 66 Plus Thermal Stress, 50 C heat-up Peak Stress is 180 MPa

The peak stress for these analyses of Lorentz and thermal is 180 MPa with the provision that the very localized stress of 386 MPa is an anomaly of the beam modeling. The static bending allowable is 233 MPa (Section 6.4.1).

13.1.2 All Mid Height Clamps Fixed only in Horizontal Plane

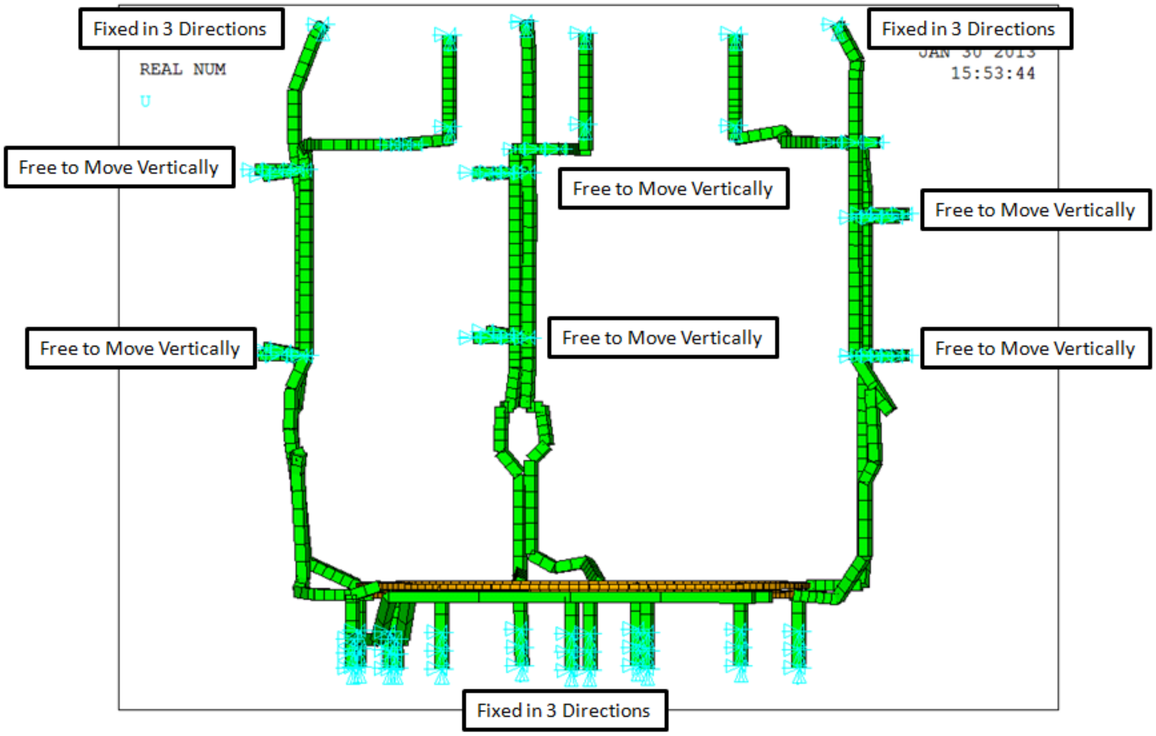


Figure 13.1. 2-1 Model with all Clamps Free in Vertical Directions

In this analysis the vertical legs are allowed to slide in their clamps and the stress is reduced to 90 MPa from the 180 MPa

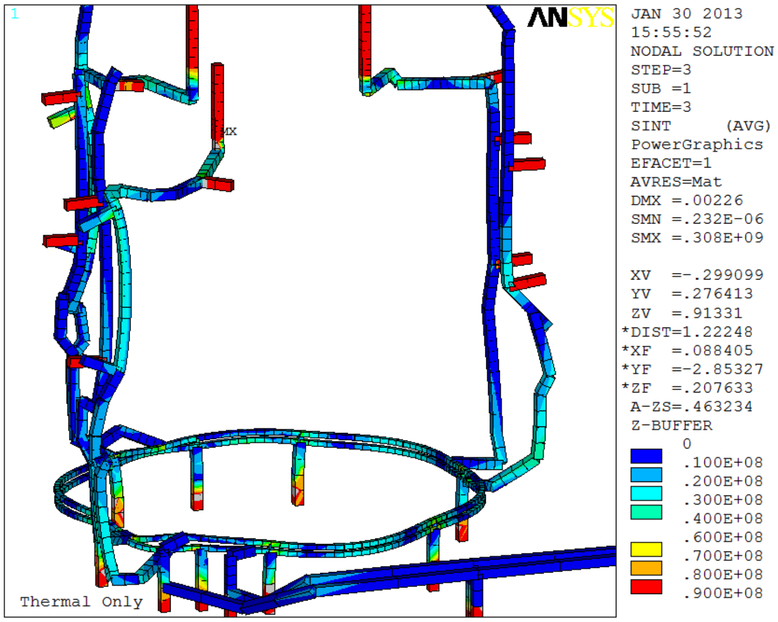


Figure 13.1.2-2 Thermal Stress Only, 50 C Heat-up Mid Height Clamps Allow Vertical Growth

Where the peak Stress was 180 MPa for the fully constrained supports, the stress is now around 10 or 20 MPa.

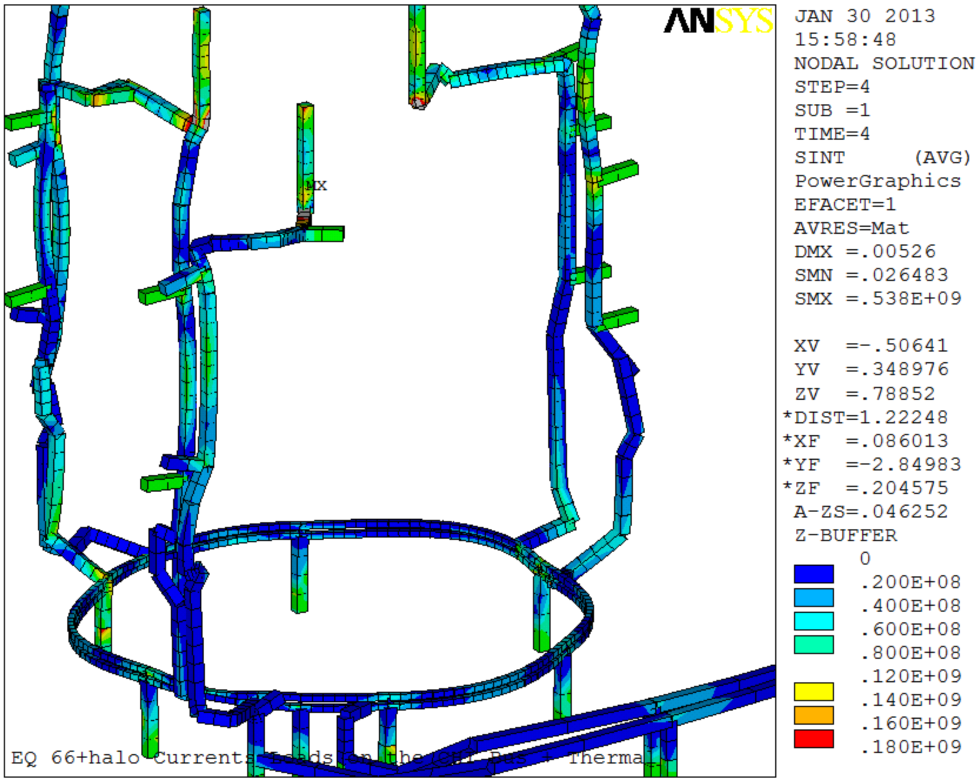
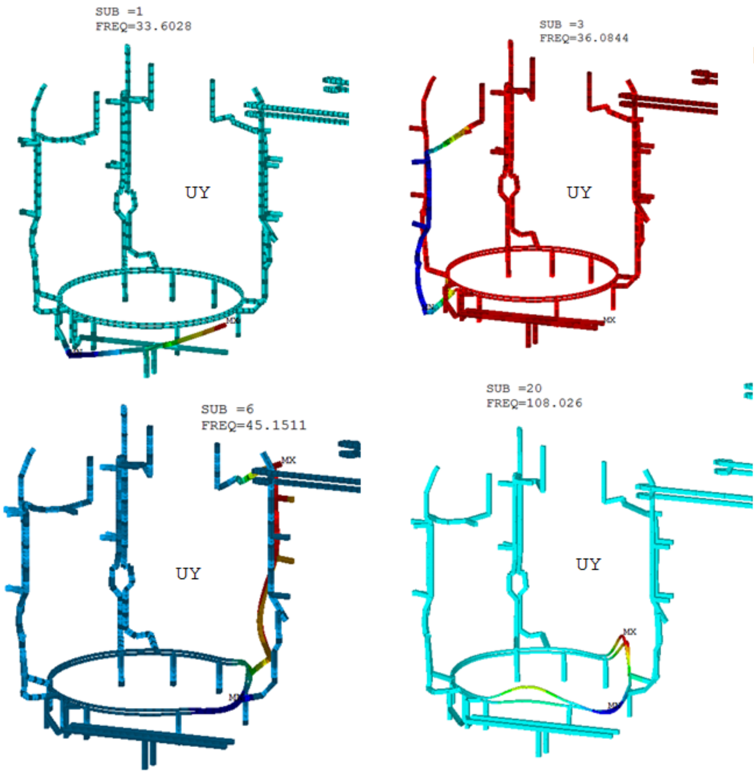


Figure 13.1.2-3 EQ 66 Plus Thermal Stress, 50 C Heat-up Mid Height Clamps Allow Vertical Growth

MPa. In the plot in figure 13.1.2-2, the contour range is set zero to 90 MPa. In figure 13.1.1-2, the contour range is zero to 180 MPa. The static bending allowable is 233 MPa (Section 6.4.1)

13.2 Frequency Analysis of the Bus Bars

Some estimate of the dynamic loading effects is needed. A modal analysis has been performed to quantify the frequency content of the CHI bus to aid in the evaluation of the dynamic load factors that would result from a full dynamic analysis



MODE	FREQUENCY
1	33.60
2	36.00
3	36.08
4	36.99
5	39.47
6	45.15
7	48.17
8	52.25
9	55.84
10	59.18
11	72.56
12	73.70
13	77.95
14	80.89
15	86.91
16	88.22
17	92.77
18	97.52
19	107.1
20	108.0
21	114.2
22	116.8
23	121.5
24	123.4

Figure 13.2.1 Mode Frequency Analysis

Amplification factor or, Dynamic Load Factor (DLF) for a single degree of freedom oscillator with a “truncated” harmonic forcing function. Half a wavelength or a load pulse of half a period would give a DLF ~1.5 for a ratio of forcing function to natural frequency of .5. When the forcing function frequency is high with respect to the structure frequency, the DLF can be less than 1.0

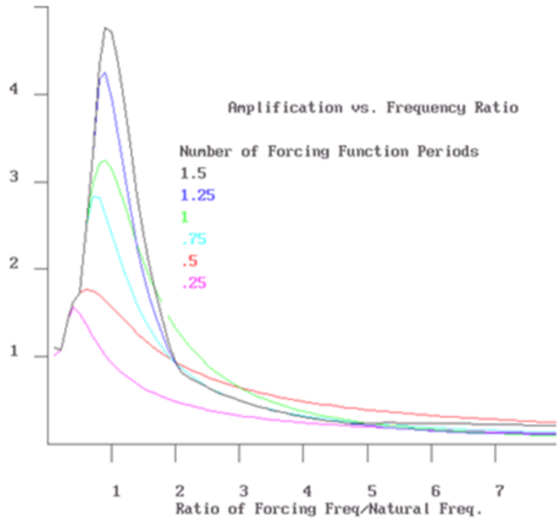


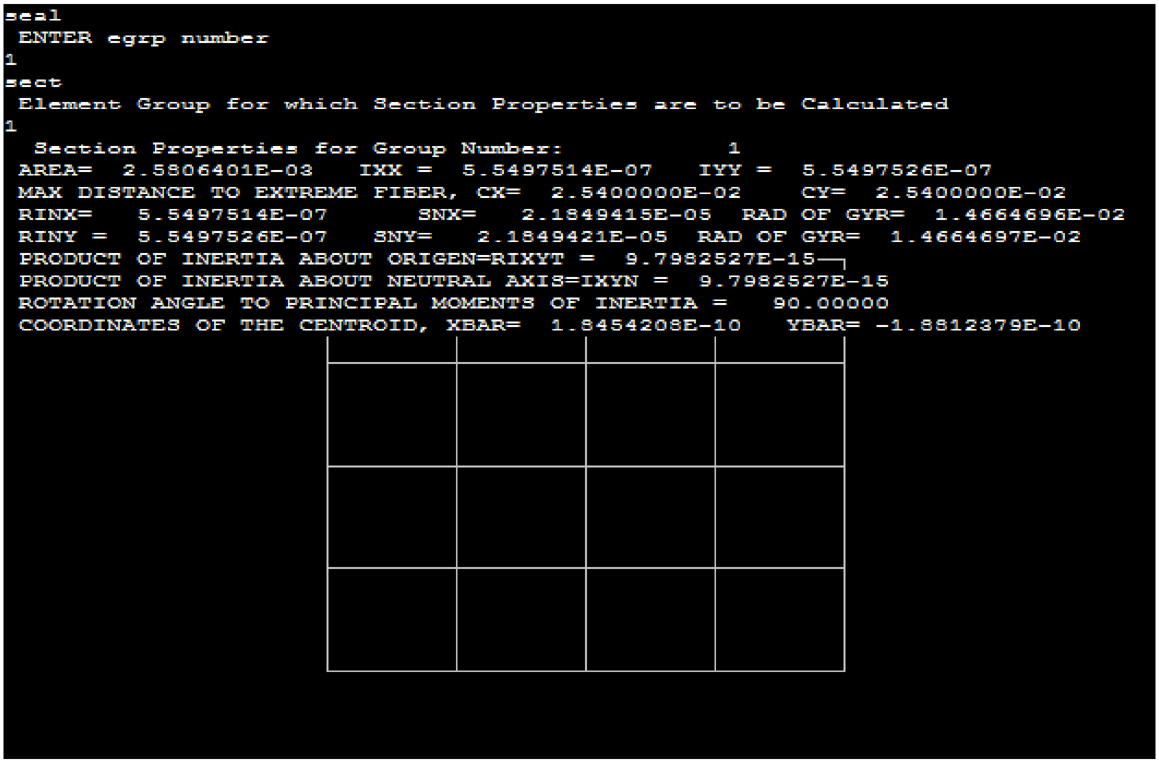
Figure 13.2.2 Response of a single Degree of Freedom oscillator to Partial Periods of Excitation

Normal loading on the CHI Bus will be driven by Lorentz Forces that have frequencies related to the PF and TF ramp times. These are fractions of a second which yields partial period forcing function frequencies of less than 10 hz This makes the DLF ~1.2 to 1.5.But the normal operating currents are small compared with disruption loads.

During the disruption, the CHI bus is exposed to halo currents which are millisec events. The CHI bus bars are low frequency oscillators with respect to disruption forces and the DLF would be less than 1.0.

14.0 Conductor Cross Section Calculations

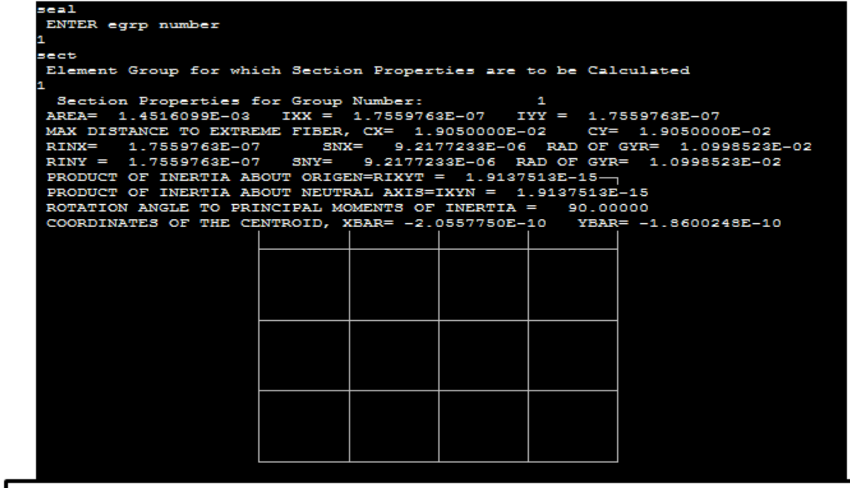
14.1 2.0 inch Square Bus Bar



```
seal
 ENTER egrp number
1
sect
 Element Group for which Section Properties are to be Calculated
1
  Section Properties for Group Number:           1
 AREA=  2.5806401E-03   IXX =  5.5497514E-07   IYY =  5.5497526E-07
 MAX DISTANCE TO EXTREME FIBER, CX=  2.5400000E-02    CY=  2.5400000E-02
 RINX=   5.5497514E-07      SNX=   2.1849415E-05  RAD OF GYR=  1.4664696E-02
 RINY =  5.5497526E-07   SNY=   2.1849421E-05  RAD OF GYR=  1.4664697E-02
 PRODUCT OF INERTIA ABOUT ORIGEN=RIXYT =  9.7982527E-15─┐
 PRODUCT OF INERTIA ABOUT NEUTRAL AXIS=IXYN =  9.7982527E-15
 ROTATION ANGLE TO PRINCIPAL MOMENTS OF INERTIA =   90.00000
 COORDINATES OF THE CENTROID, XBAR=  1.8454208E-10   YBAR= -1.8812379E-10
```

```
!      area     Iyy       Izz      Thy   Thz   ang  IXX
r,imat,2. 58064e-3, 5.549e-7 , 5.549e-7,  .0254*2 ,. .0254*2  ,0 , 2*5.549e-7
```

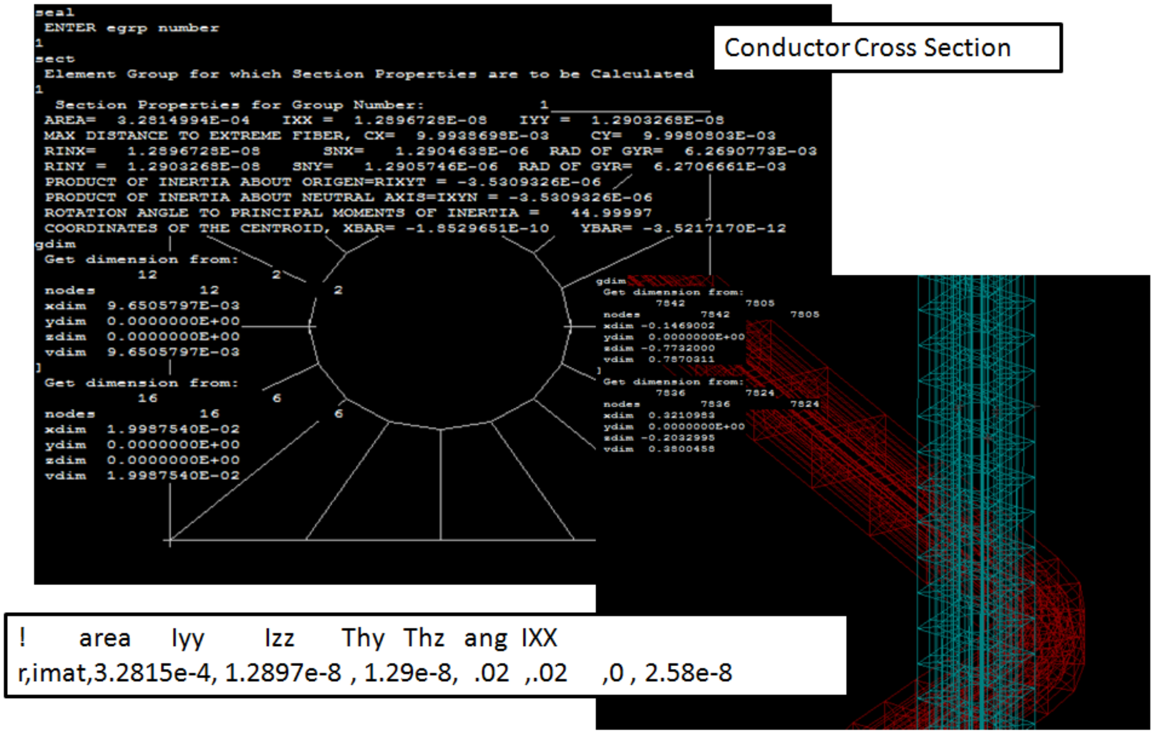
14.2 1.5 inch Square Bus Bar



```
seal
 ENTER egrp number
1
sect
 Element Group for which Section Properties are to be Calculated
1
  Section Properties for Group Number:           1
 AREA=  1.4516099E-03   IXX =  1.7559763E-07   IYY =  1.7559763E-07
 MAX DISTANCE TO EXTREME FIBER, CX=  1.9050000E-02    CY=  1.9050000E-02
 RINX=   1.7559763E-07      SNX=   9.2177233E-06  RAD OF GYR=  1.0998523E-02
 RINY =  1.7559763E-07   SNY=   9.2177233E-06  RAD OF GYR=  1.0998523E-02
 PRODUCT OF INERTIA ABOUT ORIGEN=RIXYT =  1.9137513E-15─┐
 PRODUCT OF INERTIA ABOUT NEUTRAL AXIS=IXYN =  1.9137513E-15
 ROTATION ANGLE TO PRINCIPAL MOMENTS OF INERTIA =   90.00000
 COORDINATES OF THE CENTROID, XBAR= -2.0557750E-10   YBAR= -1.8600248E-10
```

```
!     area     Iyy      Izz     Thy  Thz  ang  IXX
r,imat,1.4516e-3, 1.75597e-7 , 1.75597e-7,  .0381  ,.0381    ,0 ,
3.51e-7
```

14.3 ¾ inch Square Water Cooled Bus Bar



Conductor Cross Section

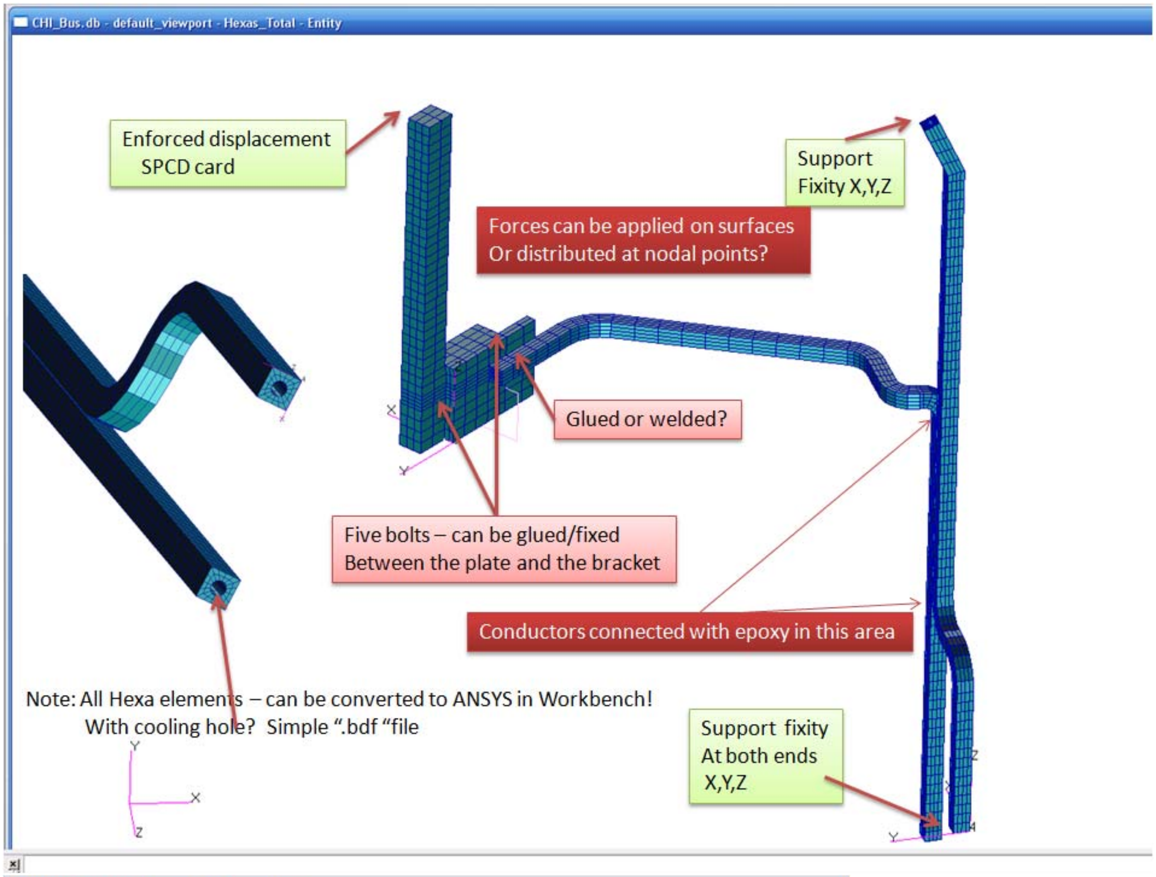
```
seal
 ENTER egrp number
1
sect
 Element Group for which Section Properties are to be Calculated
1
  Section Properties for Group Number:           1
 AREA=  3.2814994E-04   IXX =  1.2896728E-08   IYY =  1.2903268E-08
 MAX DISTANCE TO EXTREME FIBER, CX=  9.9938698E-03    CY=  9.9980803E-03
 RINX=   1.2896728E-08      SNX=   1.2904638E-06  RAD OF GYR=  6.2690773E-03
 RINY =  1.2903268E-08   SNY=   1.2905746E-06  RAD OF GYR=  6.2706661E-03
 PRODUCT OF INERTIA ABOUT ORIGEN=RIXYT = -3.5309326E-06
 PRODUCT OF INERTIA ABOUT NEUTRAL AXIS=IXYN = -3.5309326E-06
 ROTATION ANGLE TO PRINCIPAL MOMENTS OF INERTIA =   44.99997
 COORDINATES OF THE CENTROID, XBAR= -1.8529651E-10   YBAR= -3.5217170E-12
gdim
 Get dimension from:
          12           2
 nodes           12           2
 xdim  9.6505797E-03
 ydim  0.0000000E+00
 zdim  0.0000000E+00
 vdim  9.6505797E-03
]
 Get dimension from:
          16           6
 nodes           16           6
 xdim  1.9987540E-02
 ydim  0.0000000E+00
 zdim  0.0000000E+00
 vdim  1.9987540E-02
```

```
gdim
 Get dimension from:
        7842         7805
 nodes        7842         7805
 xdim -0.1469002
 ydim  0.0000000E+00
 zdim -0.7732000
 vdim  0.7870311
]
 Get dimension from:
        7836         7824
 nodes        7836         7824
 xdim  0.3210983
 ydim  0.0000000E+00
 zdim -0.2032995
 vdim  0.3800458
```

```
!      area      Iyy        Izz       Thy  Thz   ang  IXX
r,imat,3.2815e-4, 1.2897e-8 , 1.29e-8,  .02  ,.02     ,0 , 2.58e-8
```

15.0 P. Rogoff Nastran Model

This is section included for historical reasons. Pete Rogoff did some modeling of the CHI Bar that runs across the TF field, and concluded that a mid span support or some other reinforcement was needed.



Enforced displacement
SPCD card

Support
Fixity X,Y,Z

Forces can be applied on surfaces
Or distributed at nodal points?

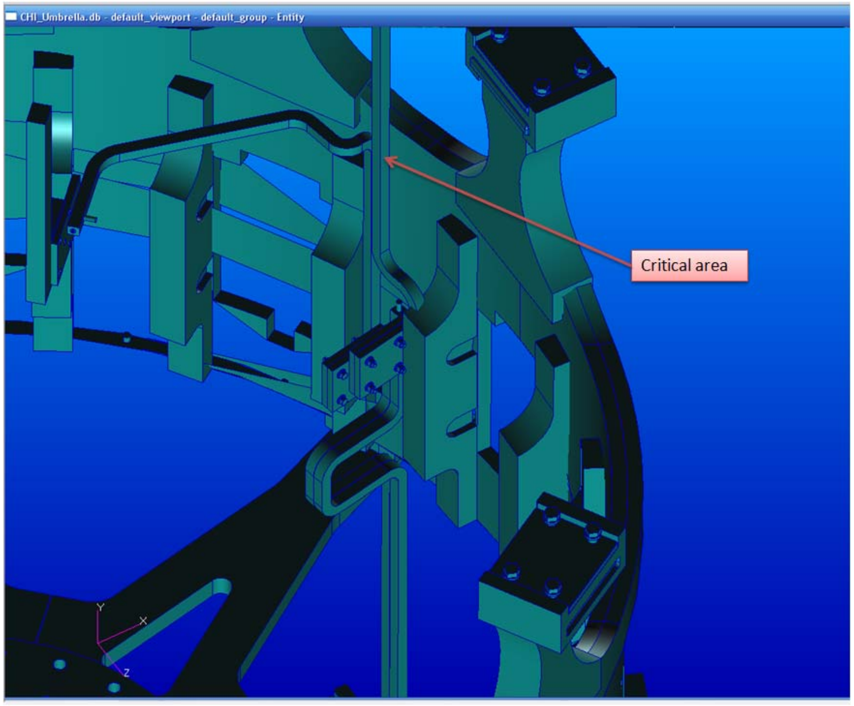
Glued or welded?

Five bolts – can be glued/fixed
Between the plate and the bracket

Conductors connected with epoxy in this area

Note: All Hexa elements – can be converted to ANSYS in Workbench!
With cooling hole? Simple ".bdf "file

Support fixity
At both ends
X,Y,Z



Critical area

Appendix A
Input file for the NTFTM Biot Savart Calculation

```
zero
ngrp
0
egrp
0
read
chi2
conv
0,1
divi
0,2,1,1,1
merge
0,.001
redu
snal
1
seal
1
stype
2,2
grpt
1,4
repla
rwmb
zero

mat
17
pfcb
33
 1 , .2344 , .0021 , .01 , 4.3419 ,2,20
 2 , .2461 , .0067 , .01 , 4.2803 ,2,20
 3 , .2577 , .0022 , .01 , 4.2538 ,2,20
 4 , .2693 ,-.0021 , .01 , 4.1745 ,2,20
 5 , .3239 , 1.5906 , .0413 , .3265 ,4,4
 6 , .4142 , 1.8252 , .042 , .1206 ,4,4
 7 , .56 , 1.8252 , .042 , .1206 ,4,4
 8 , .7992 , 1.8526 , .1627 , .068 ,4,4
 9 , .7992 , 1.9335 , .1627 , .068 ,4,4
 10 , 1.4829 , 1.5696 , .1631 , .034 ,4,4
 11 , 1.4945 , 1.5356 , .1864 , .034 ,4,4
 12 , 1.4829 , 1.6505 , .1631 , .034 ,4,4
 13 , 1.4945 , 1.6165 , .1864 , .034 ,4,4
 14 , 1.795 , .8711 , .0922 , .034 ,4,4
 15 , 1.8065 , .9051 , .1153 , .034 ,4,4
 16 , 1.7946 , .8072 , .0915 , .068 ,4,4
 17 , 1.795 ,-.8711 , .0922 , .034 ,4,4
 18 , 1.8065 ,-.9051 , .1153 , .034 ,4,4
 19 , 1.7946 ,-.8072 , .0915 , .068 ,4,4
 20 , 2.0118 , .6489 , .1359 , .0685 ,4,4
 21 , 2.0118 , .5751 , .1359 , .0685 ,4,4
 22 , 2.0118 ,-.6489 , .1359 , .0685 ,4,4
```

```
 23 , 2.0118 ,-.5751 , .1359 , .0685 ,4,4
 24 , 1.4829 ,-1.5696 , .1631 , .034 ,4,4
 25 , 1.4945 ,-1.5356 , .1864 , .034 ,4,4
 26 , 1.4829 ,-1.6505 , .1631 , .034 ,4,4
 27 , 1.4945 ,-1.6165 , .1864 , .034 ,4,4
 28 , .7992 ,-1.8526 , .1627 , .068 ,4,4
 29 , .7992 ,-1.9335 , .1627 , .068 ,4,4
 30 , .56 ,-1.8252 , .042 , .1206 ,4,4
 31 , .4142 ,-1.8252 , .042 , .1206 ,4,4
 32 , .3239 ,-1.5906 , .0413 , .3265 ,4,4
 33 , .9344 , 0 , .5696 , 1 ,6,8
seal
0
srel
1,1
srel
2,1
srel
3,1
srel
4,1
divi
1,1,2,1
snal
1
merge
1,.0001
redu


irdt
2
pfcu
33,4,4,1.1
          1 , -5.3039999E-03 ,  0.0000000E+00 ,  2.8782515E-03 , -5.3039999E-03
          2 ,  -5.304000     ,  0.0000000E+00 ,   2.878252     ,  -5.304000
          3 ,  -5.304000     ,  0.0000000E+00 ,   2.878252     ,  -5.304000
          4 ,  -5.304000     ,  0.0000000E+00 ,   2.878252     ,  -5.304000
          5 ,  0.3600512     ,  0.4526656     ,  0.5014717     ,  0.3967936
          6 ,  0.0000000E+00 ,  0.0000000E+00 ,  0.0000000E+00 ,  0.0000000E+00
          7 ,  0.0000000E+00 ,  0.0000000E+00 ,  0.0000000E+00 ,  0.0000000E+00
          8 , -4.9789600E-02 ,  5.2687600E-02 ,  0.1084556     , -7.7762999E-02
          9 , -4.9789600E-02 ,  5.2687600E-02 ,  0.1084556     , -7.7762999E-02
         10 , -2.2112999E-02 , -1.0420200E-02 , -4.1494756E-03 ,  3.8717000E-03
         11 , -2.5271999E-02 , -1.1908800E-02 , -4.7422578E-03 ,  4.4247997E-03
         12 , -2.2112999E-02 , -1.0420200E-02 , -4.1494756E-03 ,  3.8717000E-03
         13 , -2.5271999E-02 , -1.1908800E-02 , -4.7422578E-03 ,  4.4247997E-03
         14 ,  0.0000000E+00 ,  0.0000000E+00 ,  0.0000000E+00 ,  0.0000000E+00
         15 ,  0.0000000E+00 ,  0.0000000E+00 ,  0.0000000E+00 ,  0.0000000E+00
         16 ,  0.0000000E+00 ,  0.0000000E+00 ,  0.0000000E+00 ,  0.0000000E+00
         17 ,  0.0000000E+00 ,  0.0000000E+00 ,  0.0000000E+00 ,  0.0000000E+00
         18 ,  0.0000000E+00 ,  0.0000000E+00 ,  0.0000000E+00 ,  0.0000000E+00
         19 ,  0.0000000E+00 ,  0.0000000E+00 ,  0.0000000E+00 ,  0.0000000E+00
         20 , -0.3339048     , -0.3279492     , -0.3247161     , -0.3621252
         21 , -0.3339048     , -0.3279492     , -0.3247161     , -0.3621252
         22 , -0.3339048     , -0.3279492     , -0.3247161     , -0.3621252
```

```
        23 , -0.3339048     , -0.3279492     , -0.3247161     , -0.3621252
        24 , -2.5271999E-02 , -1.1908800E-02 , -4.7422578E-03 ,  4.4247997E-03
        25 , -2.2112999E-02 , -1.0420200E-02 , -4.1494756E-03 ,  3.8717000E-03
        26 , -2.2112999E-02 , -1.0420200E-02 , -4.1494756E-03 ,  3.8717000E-03
        27 , -2.5271999E-02 , -1.1908800E-02 , -4.7422578E-03 ,  4.4247997E-03
        28 , -4.9789600E-02 ,  5.2689001E-02 ,  0.1084562     , -7.7762999E-02
        29 , -4.9789600E-02 ,  5.2689001E-02 ,  0.1084562     , -7.7762999E-02

  30 ,  0.0000000E+00 ,  0.0000000E+00 ,  0.0000000E+00 ,  0.0000000E+00
        31 ,  0.0000000E+00 ,  0.0000000E+00 ,  0.0000000E+00 ,  0.0000000E+00
        32 ,  0.3600512     ,  0.4526656     ,  0.5014717     ,  0.3967936
        33 ,  0.0000000E+00 ,  0.0000000E+00 ,  0.0000000E+00 ,  0.0000000E+00



rscale
1,1,1,.5
rscale
2,1,2,.5
rscale
3,1,3,.5
rscale
4,1,4,.5

zero
read
vec2

snal
1
seal
1
ngrp
5
egrp
5
read
rwmb



!real 50 is the outboard leg 130000*3/4
r
50,1,16250.0
r
51,1,16250.0
! real 52 is the arch/flex 130000/4
r
52,1,32500.0
r
61,1,50000.0    !CHI Coil Halo Currents = .075*2e6/3
62,1,50000.0    !CHI Coil Halo Currents = .075*2e6/3
61,1,9000.0    !CHI Coil Normal Operating Load
stype
8,8
snel
```

```
8,8
repla
cvec
!exit
field
5
stype
8,8
gerase
8
stype
2,2
grpt
5,1
redu
mfor
5,1,1,1,1,2,2,2,2
repla
chif
tmsa
chi2,2

exit
```

Appendix B
Input file for the ANSYS beam element analysis

Appendix C
True Basic Cooling Program

```
dim cur(1000000),
power(1000000),CuTemp(1000000),Qrad(1000000),QCond(1000000),QConvect(1000000)
dim QWater(1000000), Qcon(1000000)
clear
Print "Enter BUS Bar Option"
print " 1    Vertical Runs of the CHI Bus, Air cooled, Normal Op"
print " 2    Vertical Runs of the CHI Bus, Air cooled, Bake-Out"
print " 3    Vertical Runs of the CHI Bus, Air cooled, Disruption"
print " 4    CHI Ring Bus, Water cooled Normal Op"
print " 5    CHI Ring Bus, Water cooled Bake-Out"
print " 6    CHI Ring Bus, Water cooled Disruption"
print " 7    Horizontal Runs of the TF Bus, Air cooled"
print " 8    OH"
print " 9    One Inch Square 1 kA Steady State Benchmark"
print " 10   One Inch Square 10 kA Water Cooled Benchmark"
print " 11   One Inch Square 10 kA Water Cooled Benchmark"
print " 12   Nominal TF"
input boption
        !Times
let MaxN=20000
let dt=1.0
let PulseLength=5    !Sec
let PulseInterval = 20*60            ! 15 minute intervals
let numpulses=10

let BusBarLength = 1.0     ! Unit Meter Long
let Tinlet = 12     ! Degrees C
let tinit=30
let tfloor=20
let tambient=35
let insthick=1/16
let ConLength =1.0   ! Conduction length to heat sink or to water cooled portion
let ConArea = 0    ! Conduction Link Cross Section
let ConTemp = 12     ! Conduction Heat Sink Temp or Ave temp of water cooled part

if boption =1 then
let BusBarName$="Vertical Runs of the CHI Bus, Air cooled, Normal Op"
let bwidth=2.0      ! Dimensions in inches
let bheight=2.0      ! Dimensions in inches
let insthick=.125
let HoleDiameter = .0
let PulseLength=5.0   !Sec
let PulseInterval = 20*60            ! 20 minute intervals
let numpulses=20
let MaxN=20000
let dt=1
Let Current = 9000
let FlowVelocity=0.0
let tinit=35
let tinlet=tinit
```

```
let BusVerticalarea=(2*(bheight)+2*bwidth)*BusBarLength/39.37
let ConLength =1.0   ! Conduction length to heat sink or to water cooled portion
let ConArea = bwidth*bheight/39.37/39.37   ! Conduction Link Cross Section
let ConTemp = 35     ! Conduction Heat Sink Temp or Ave temp of water cooled part
end if


if boption =2 then
let BusBarName$="Vertical Runs of the CHI Bus, Air cooled, Bake-Out"
let bwidth=2.0
let bheight=2.0
let HoleDiameter = .0
let BusVerticalarea=2*(bheight+bwidth)*BusBarLength/39.37
Let current = 8000/3
let MaxN=20000
let dt=1.0
let PulseLength=20000    !Sec
let PulseInterval = 0            ! Steady State
let numpulses=1
let tinit=20
let tinlet=tinit
let ConLength =1.0   ! Conduction length to heat sink or to water cooled portion
let ConArea = bwidth*bheight/39.37/39.37   ! Conduction Link Cross Section
let ConTemp = 20     ! Conduction Heat Sink Temp or Ave temp of water cooled part
end if

if boption =3 then
let BusBarName$="Vertical Runs of the CHI Bus, Air cooled, Disruption"
let bwidth=2.0
let bheight=2.0
let dt=1
let HoleDiameter = .0
let BusVerticalarea=2*(bheight+bwidth)*BusBarLength/39.37/39.37
Let current = 85000
let pulselength=1
let FlowVelocity=0.0
let tinit=20
let tinlet=tinit
end if

if boption =4 then
let BusBarName$="CHI Ring Bus, Water cooled Normal Operation"
let bwidth=1.0
let bheight=3.5
let HoleDiameter = .25
let BusVerticalarea=2*(bheight)*BusBarLength/39.37
Let current = 27000/3
let insthick=.0625
let pulselength=5
let tinit=35
let tinlet=tinit
let FlowVelocity=3.0
end if

if boption =14 then
let BusBarName$="CHI horizontal Run Air Cooled Operation"
```

```
let bwidth=6.0
let bheight=1.0
let HoleDiameter = 0
let BusVerticalarea=2*(bheight)*BusBarLength/39.37
Let current = 32000
let FlowVelocity=0.0
end if

if boption =5 then
let BusBarName$="CHI Ring Bus, Water cooled Bake Out"
let bwidth=1.0
let bheight=3.5
let HoleDiameter = .25
let BusVerticalarea=2*(bheight)*BusBarLength/39.37
Let current = 8000
let FlowVelocity=3.0
let MaxN=20000
let dt=1.0
let PulseLength=200000    !Sec
let PulseInterval = 0          ! Steady State
let numpulses=1
let Tinlet = 12     ! Degrees C
let tinit=30
let tfloor=20
let tambient=35
end if

if boption =6 then
let BusBarName$="CHI Ring Bus, Water cooled Disruption"
let bwidth=1.0
let bheight=3.0
let HoleDiameter = .25
let BusVerticalarea=2*(bheight)*BusBarLength/39.37
Let current = 150000
let FlowVelocity=0.0
end if

if boption =7 then
let BusBarName$="Horizontal Runs of the TF Bus, Air cooled"
let bwidth=1
let bheight=6
let insthick=.125
let HoleDiameter = 0.0
let BusVerticalarea=2*(bheight)*BusBarLength/39.37
Let current = 129000/2
let FlowVelocity=0.0
let PulseLength=7.04    !Sec
let PulseInterval = 20*60          ! 10 minute intervals
let numpulses=20
let ConLength =3.0   ! Conduction length to heat sink or to water cooled portion
let ConArea = bwidth*bheight/39.37/39.37   ! Conduction Link Cross Section
let ConTemp = 12     ! Conduction Heat Sink Temp or Ave temp of water cooled part

end if

if boption =8 then
```

```
let BusBarName$="OH Water Cooled Needs Updating"
let bwidth=.75
let bheight=1.0
let insthick=.125
let HoleDiameter = .125
let BusVerticalarea=2*(bheight)*BusBarLength/39.37
Let current = 24000
let FlowVelocity=3.0
let tinit = 20
let tinlet= 40
let PulseLength=1.472    !Sec
end if

   if boption =9 then
let BusBarName$=" One Inch Square, 1 ka Air cooled"
let bwidth=1.0
let bheight=1.0
let insthick=.125
let HoleDiameter = 0
let BusVerticalarea=2*(bheight)*BusBarLength/39.37
Let current = 1000
let FlowVelocity=3.0
let PulseLength=20000    !Sec
let PulseInterval = 0           ! Steady State
let numpulses=1
end if
    if boption =10 then
let BusBarName$=" One Inch Square, 10 ka Water cooled"
let bwidth=1.0
let bheight=1.0
let insthick=.125
let HoleDiameter = .125
let BusVerticalarea=2*(bheight)*BusBarLength/39.37
Let current = 1000
let FlowVelocity=3.0
let PulseLength=20000    !Sec
let PulseInterval = 0           ! Steady State
let numpulses=1
end if

      if boption =11 then
let BusBarName$="OH Air Cooled Horizontal Run"
let bwidth=1.5
let bheight=1.5
let insthick=.125
let HoleDiameter = 0.0
let BusVerticalarea=2*(bheight)*BusBarLength/39.37
Let current = 24000
let FlowVelocity=0.0
let tinit = 20
let tinlet= 40
let PulseLength=1.472    !Sec
end if
     if boption =12 then
let tinit=12
let tfloor=12
```

```
let tambient=12
let BusBarName$="Nominal TF Cross Section Watercooled"
let bwidth=1*.85
let bheight=4.739
let insthick=.125
let HoleDiameter = .25
let BusVerticalarea=2*(bheight)*BusBarLength/39.37
Let current = 129000
let FlowVelocity=3.0
let PulseLength=7.04    !Sec  ESW from Charlie's spreadsheet
let PulseInterval = 15*60            ! 10 minute intervals
let numpulses=1
let MaxN=2000
end if
call plotbar
        !Temperature and Cooling
        !  Plot Controls
let plotmint = 199
let plotmaxt = 209
let plotmint = 0
let plotmaxt = MaxN

let rhoSST=72e-8
let spheCopper=402.83        ! Joule/m^3/K   120C
let spheSST=500      !J/kg/K
let spheWater=4.1813*1000            ! at 20-100C Joule/g/degreeK*1000g/kg
let DensCopper=8950
let DensSST=7999
let DensWater=1000.             !kg/cu meter
let ThermCondSST=16.2
let ThermCondCopper=393
let thermCond=ThermCondCopper


!            Areas and Volumes  are Per Bar
let areacopper=bwidth*bheight/39.37^2 -pi*holediameter^2/4/39.37/39.37
let volcopper=areacopper*BusBarLength
let Busperimeter=2*(bwidth+bheight)/39.37   ! meters
let Bussurfacearea=Busperimeter*BusBarLength

            !Conduction Constants
call KEpoxy(tinit+273,kepoxy)
print "Kepoxy,temp ";kepoxy;tinit+273

!get key kinp
            ! Radiation Constants
let emisSO=.3              !emissivity of the Busbar outside
let emisV=.3               !Ambient emissivity
let stefBoltz=5.67e-8
            ! Convection Constants
let ConvectCoeff = 5      !W /(m^2K)  Air Free Convection
let ConductConvect=(1/convectcoeff+1/(kepoxy/insthick))^(-1)
!           Computed Values
let heatcap=spheCopper*densCopper*volCopper
let flowarea=pi*holediameter^2/4/39.37/39.37
!print areacopper,volcopper,denscopper,sphecopper
```

```
          ! Create Current Profile

for i=1 to maxn
let ptime=dt*i
let cur(i)=0
next i

for i=1 to numpulses
for j=(i-1)*pulseinterval+1 to (i-1)*pulseinterval+pulselength step 1
let cur(j)=current
next j
next i

                  !Compute Power,Temperature Arrays
let maxpower=0
let maxtemp=0
let CuTemp(1)=Tinit

for i=2 to MaxN
let pTime=dt*i
!let resist=rhoCopper*2*busbarlength/areacopper
call rhocop(CuTemp(i),rhocopper)
let resist=rhoCopper*busbarlength/areacopper

let Qrad(i)=1*Bussurfacearea*emisSO*emisv*StefBoltz*((Cutemp(i-1)+273)^4-
(tambient+273)^4)/(emisSO+emisv-emisSO*emisV)
let Qconvect(i)=ConductConvect*(BusVerticalArea)*(CuTemp(i-1)-Tambient)
let Qwater(i)=sphecopper*denswater*flowvelocity*flowarea*(CuTemp(i-1)-tinlet)
call Kcop(CuTemp(i),Kcopper)
let Qcon(i)=Kcopper*ConArea/ConLength*(CuTemp(i-1)-ConTemp)


let power(i) = cur(i)^2*resist
let CuTemp(i)=CuTemp(i-1)+(power(i)-Qrad(i)-Qconvect(i)-Qwater(i)-Qcon(i))*dt/HeatCap
if CuTemp(i)>maxTemp then Let MaxTemp=CuTemp(i)
if power(i)>maxpower then let maxpower=power(i)
if Qrad(i)>maxRadpower then let maxRadpower=Qrad(i)
if Qcond(i)>maxCondpower then let maxCondpower=QCond(i)
if QConvect(i)>maxConvectpower then let maxConvectpower=QConvect(i)
if Qwater(i)>maxwaterpower then let maxwaterpower=Qwater(i)
next i

!set window -100,MaxN,-10000,VSCurrent*1.1
set window plotmint/dt,plotmaxt/dt,-1,Current*1.1
call YScale2(Current,0,plotmint/dt,plotmaxt/dt," Amp Turns")
call Timescale2(0,current,plotmint/dt,plotmaxt/dt)
for i=1 to MaxN
plot i,cur(i);
next i
let px=plotmint+(plotmaxt-plotmint)*.6
let py=current
plot text, at px,py*.875:busbarname$
plot text, at px,tinit+py*.70:"Width of Busbar="&Str$(bwidth)&" inches"
plot text, at px,tinit+py*.65:"Height of Busbar ="&Str$(bheight)&" inches"
```

```
plot text, at px,tinit+py*.60:"Hole diameter ="&Str$(Holediameter)&" inches"
plot text, at px,tinit+py*.55:"Busbar surface area ="&Str$(AreaCopper)&" meter^2"
plot text, at px,tinit+py*.50:"Busbar surface area ="&Str$(Bussurfacearea)&" meter^2"
print "enter any key"
get key kinp

clear
call plotbar
set window -100,MaxN,-.1*maxpower,maxpower*1.1
!set window -100, Maxn, 0,100
call YScale(maxpower,0,maxn," Watts")
call Timescale(0,maxpower,maxn)

let px=plotmint+(plotmaxt-plotmint)*.6
let py=maxpower
plot text, at px,py*.875:busbarname$
plot text, at px,tinit+py*.60:"Max Joule Power = "&Str$(maxpower)&" Watts/meter"
plot text, at px,tinit+py*.575:"Max Radiated Power = "&str$(maxRadpower)&" Watts/meter"
plot text, at px,tinit+py*.55:"Max Convected Power = "&str$(maxconvectpower)&" Watts"
plot text, at px,tinit+py*.525:"Max Power Conducted Through Supports = "&str$(maxcondpower)&" /meter"
plot text, at px,tinit+py*.50:"Max Water Cooling Power = "&str$(maxwaterpower)&" /meter"
for i=1 to MaxN
plot i,power(i);
next i
plot i-1,0
for i=1 to MaxN
plot i,Qrad(i);
next i
plot i-1,0
for i=1 to MaxN
plot i,Qcond(i);
next i
plot i-1,0
for i=1 to MaxN
plot i,Qconvect(i);
next i
plot i-1,0
print "enter any key"
get key kinp

let tlow=maxtemp
if tinlet<tlow then let tlow=tinlet
if tinit<tlow then let tlow=tinut

clear
call plotbar
set window plotmint/dt,plotmaxt/dt,Tlow-(maxtemp-tlow)/10,MaxTemp
   !Plot Text Coordinates

let px=plotmint/dt+(plotmaxt/dt-plotmint/dt)*.5
let py=(MaxTemp-tinit)
plot text, at px,tinit+py*.9:busbarname$
plot text, at px,tinit+py*.875:"Max Temperature = "&Str$(maxtemp)&" Deg C"
plot text, at px,tinit+py*.850:"Width of Busbar="&Str$(bwidth)&" inches"
plot text, at px,tinit+py*.825:"Height of Busbar ="&Str$(bheight)&" inches"
```

```
plot text, at px,tinit+py*.8:"Hole diameter ="&Str$(Holediameter)&" inches"
plot text, at px,tinit+py*.775:"Busbar copper area ="&Str$(AreaCopper)&" meter^2"
plot text, at px,tinit+py*.750:"Busbar surface area ="&Str$(Bussurfacearea)&" meter^2"
plot text, at px,tinit+py*.725:"Current = "&Str$(current)&" Amps"
plot text, at px,tinit+py*.7:"Pulse length = "&Str$(pulselength)&" sec"
plot text, at px,tinit+py*.675:"Number of Pulses = "&Str$(numpulses)&" "
plot text, at px,tinit+py*.65:"Pulse Interval = "&Str$(pulseinterval)&" sec"
plot text, at px,tinit+py*.625:"Initial Temperature = "&Str$(tinit)&" Deg C"
plot text, at px,tinit+py*.6:"Insulation Thickness = "&Str$(insthick)&" inches"
plot text, at px,tinit+py*.575:"Ending Temperature = "&str$(CuTemp(maxn))&" Deg C"
plot text, at px,tinit+py*.55:"Volume of Copper = "&str$(Volcopper)&" m^3"
plot text, at px,tinit+py*.525:"Mass of Copper in One Coil ="&str$(volcopper*denscopper)&" kg"
plot text, at px,tinit+py*.50:"Max Joule Power = "&Str$(maxpower)&" Watts/meter"
plot text, at px,tinit+py*.475:"Max Radiated Power = "&str$(maxRadpower)&" Watts/meter"
plot text, at px,tinit+py*.45:"Max Convected Power = "&str$(maxconvectpower)&" Watts/meter"
plot text, at px,tinit+py*.425:"Max Water Cooling Power = "&str$(maxwaterpower)&" Watts/meter"
plot text, at px,tinit+py*.40:"Water Flow Velocity = "&str$(Flowvelocity)&" m/sec"
!set window -100,MaxN,Tinit*.9,MaxTemp*1.1
call YScale2(maxtemp,tlow,plotmint/dt,plotmaxt/dt," Deg C")
!call Timescale(tlow,maxtemp,maxn)
call Timescale2(tlow,maxtemp,plotmint/dt,plotmaxt/dt)
for i=1 to MaxN
plot i,CuTemp(i);
next i
plot i-1,0

Sub YScale(min,max,maxn,unit$)
for i=1 to 10
plot 0,min+i*(max-min)/10   ;  .01*(maxn),min+i*(max-min)/10
plot text, at .01*(maxn),min+i*(max-min)/10: str$(min+i*(max-min)/10)&unit$
next i
end sub

Sub YScale2(min,max,minn,maxn,unit$)
for i=1 to 10
plot minn,min+i*(max-min)/10   ;  minn+.01*(maxn-minn),min+i*(max-min)/10
plot text, at minn+.01*(maxn-minn),min+i*(max-min)/10: str$(min+i*(max-min)/10)&unit$
next i
end sub

Sub Timescale(min,max,maxn)
plot 1,0 ;1,max
plot 0,min;maxn/dt,min

for i=1 to 10
plot i*maxn/10,min;i*maxn/10,min-.1*(max-min)
next i
for i=1 to 10
plot text, at i*maxn/10,min-.05*(max-min): str$(i*maxn/10*dt)&" sec"
next i
end sub

Sub Timescale2(min,max,minn,maxn)
plot 1,0 ;1,max
plot 0,min;maxn/dt,min
```

```
for i=1 to 10
plot minn+i*(maxn-minn)/10,min;minn+i*(maxn-minn)/10,min-.1*(max-min)
next i
for i=1 to 10
plot text, at minn+i*(maxn-minn)/10,min-.05*(max-min): str$(minn*dt+i*(maxn-minn)/10*dt)&" sec"
next i
end sub

sub plotbar
clear
let diag=(bwidth^2+bheight^2)^.5
let diag=4
set window -4*diag,4*diag,-2*diag,2*diag
plot -bwidth,-bheight;bwidth,-bheight;bwidth,bheight;-bwidth,bheight;-bwidth,-bheight
let iwidth=bwidth+insthick
let iheight=bheight+insthick
plot -iwidth,-iheight;iwidth,-iheight;iwidth,iheight;-iwidth,iheight;-iwidth,-iheight
for i=1 to 360 step 10
let th=pi*i/180
plot holediameter*sin(th),holediameter*cos(th);
next i
end sub

sub KEpoxy(etemp,kepoxy)
DATA 0,-0.706,-0.241,2.30E-03,7.50E-04,7.57E-04   ! Guess
DATA 4.2,-0.706,-0.241,2.30E-03,7.50E-04,7.57E-04
DATA 10,-0.706,-0.241,2.00E-02,1.20E-03,1.40E-03
DATA 20,-0.706,-0.241,4.72E-02,1.56E-03,1.98E-03
DATA 40,-0.690,-0.234,1.20E-01,2.10E-03,2.70E-03
DATA 60,-0.667,-0.223,1.80E-01,2.50E-03,3.40E-03
DATA 80,-0.638,-0.211,2.50E-01,2.85E-03,4.10E-03
DATA 100,-0.603,-0.197,3.17E-01,3.10E-03,4.48E-03
DATA 120,-0.563,-0.182,3.90E-01,3.40E-03,5.00E-03
DATA 140,-0.517,-0.165,4.60E-01,3.70E-03,5.40E-03
DATA 160,-0.465,-0.148,5.20E-01,3.95E-03,5.90E-03
DATA 180,-0.408,-0.129,5.90E-01,4.20E-03,6.40E-03
DATA 200,-0.346,-0.108,6.64E-01,4.45E-03,6.74E-03
DATA 220,-0.279,-0.086,7.30E-01,4.70E-03,7.10E-03
DATA 240,-0.208,-0.064,8.00E-01,5.00E-03,7.40E-03
DATA 260,-0.133,-0.040,8.60E-01,5.30E-03,7.80E-03
DATA 273,-0.082,-0.025,9.10E-01,5.55E-03,8.00E-03
DATA 293,0.000,0.000,9.70E-01,5.95E-03,8.40E-03
DATA 1000,0.000,0.000,9.70E-01,5.95E-03,8.40E-03
!set window 0,100,0,17
dim t(100),temp(50),Kth(50)
for i=1 to 19
read temp(i),thexpN,thexpW,speche,KthN,Kth(i)
let kth(i)=kth(i)*100   ! data was Watts/cm-K
next i
for j=1 to 19
if etemp>=temp(j) and etemp<=temp(j+1) then let kepoxy=kth(j)
next j
end sub

sub rhocop(temp,rhocopper)
let rhocopper=1.7074e-8+(2.3931e-8 -1.7074-8)/(120-20)*temp
```

```
!let rhocopper =1.7074e-8     !RT zero field
!let rhocopper =2.2494e-8     !100C zero field
!let rhocopper =2.2576e-8     !100C 4T
!let rhocopper =2.3931e-8     !120C 4T
end sub

sub Kcop(temp,Kcopper)
let Kcopper=401+(386-401)/(200)*(temp-28)
!Kcopper=401 at 300K
!Kcopper=386 at 500K
end sub
end
```

Appendix B
Input file for the ANSYS beam element analysis

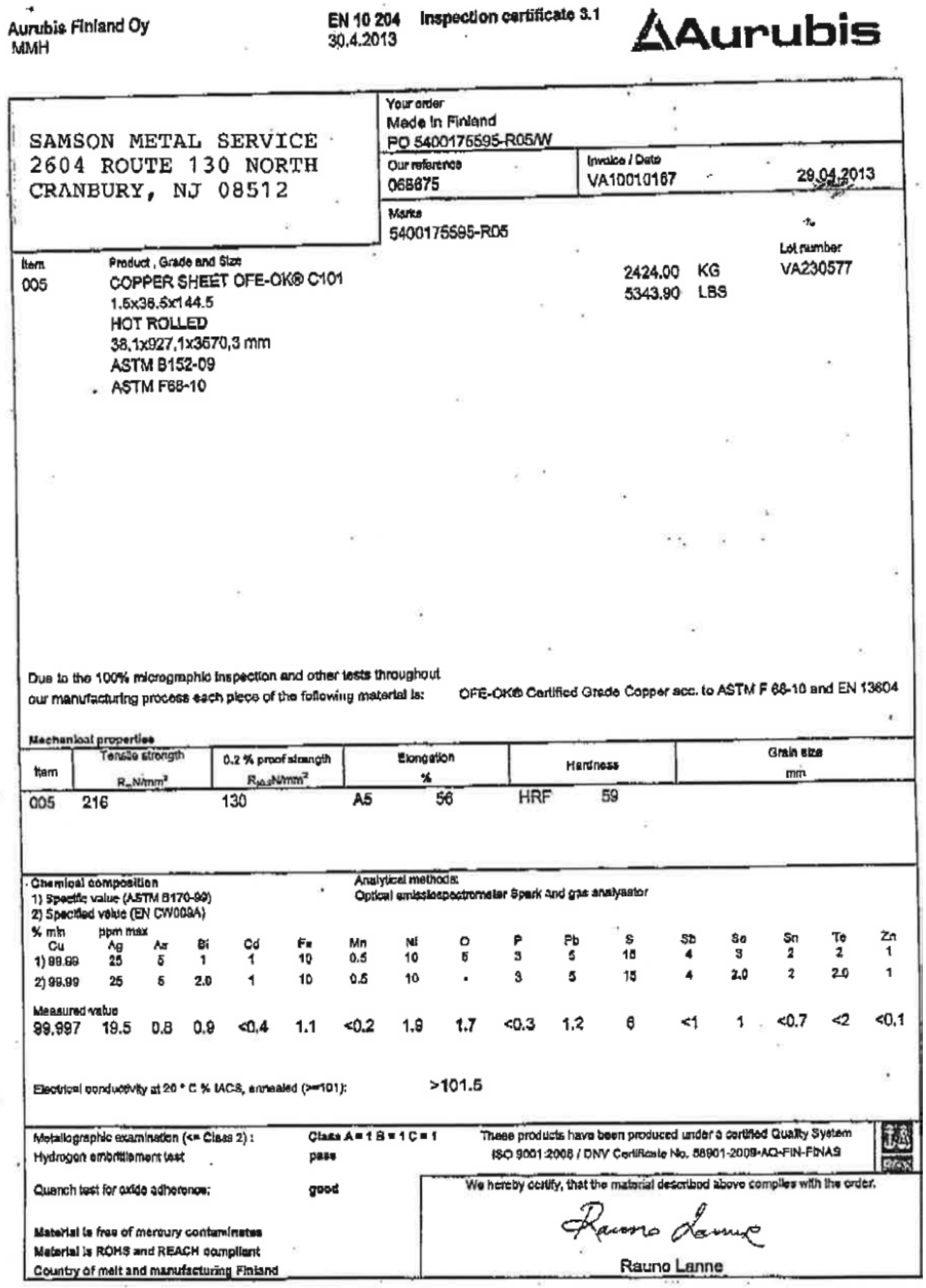
```
/batch
/prep7
runn=3
et,8,4
et,1,4
et,2,4
*do,imat,1,100
ex,imat,100e9
alpx,imat,17e-6
!       area      Iyy         Izz       Thy   Thz   ang  IXX
r,imat,1.4516e-3, 1.75597e-7 , 1.75597e-7,  .0381 ,.0381 ,0 , 3.51e-7
!r,imat,3.2815e-4, 1.2897e-8 , 1.29e-8,  .02  ,.02     ,0 , 2.58e-8
*enddo
r,61,1.4516e-3, 1.75597e-7 , 1.75597e-7,  .0381 ,.0381 ,0 , 3.51e-7
r,62,3.2815e-4, 1.2897e-8 , 1.29e-8,  .02  ,.02     ,0 , 2.58e-8
/input,chi2,mod


nummer,node,.0001
nsel,y,-4,-3.92
nasel,y,-1.698,-1
d,all,all,0.0
csys,5
nsel,x,.5,.535
nrsel,z,-2.06,-2.03
d,all,all,0.0
nsel,x,.5,.535
nrsel,z,-1.74,-1.73
d,all,all,0.0
esel,type,2
nelem
d,all,ux,0.0
d,all,uy,0.0
d,all,uz,0.0


csys,0
nall
eall
save
fini
/solu
tref,20
tunif,70
/title,EQ 79+halo Currents Loads on the CHI Bus
solve
save

/title,EQ 66+halo Currents Loads on the CHI Bus
fscale,.00001
/input,ch66,mod
bf,all,temp,70
solve
```

```
save

/title, Thermal Only
fscale,.00001
solve
save

/title,EQ 66+halo Currents Loads on the CHI Bus + Thermal
fscale,.00001
/input,ch66,mod
solve
save




fini
/exit
/exit
```

Appendix D Bus Bar Physicals

Gentlemen, Please see the attached test report from one of our vendor. I need your response ASAP. The Copper materials are made using hot rolled technique; tensile strength 216 N/mm2 (31.3 Ksi) and 0.2% Proof strength 130 N/mm2 (18.9 Ksi). Is this strength OK for use on our bus bars and flags. If not, please give me the required material properties for the bus bars and flags.

Thank you.Neway



Aurubis Finland Oy
MMH

EN 10 204 **Inspection certificate 3.1**
30.4.2013

Aurubis

SAMSON METAL SERVICE
2604 ROUTE 130 NORTH
CRANBURY, NJ 08512

Your order
Made in Finland
PO 5400175595-R05/W

Our reference
068675

Invoice / Date
VA10010167 29.04.2013

Marks
5400175595-R05

Item	Product , Grade and Size			Lot number
005	COPPER SHEET OFE-OK® C101 1.5x36.5x144.5 HOT ROLLED 38,1x927,1x3670,3 mm ASTM B152-09 ASTM F68-10	2424.00 5343.90	KG LBS	VA230577

Due to the 100% micrographic inspection and other tests throughout our manufacturing process each piece of the following material is: OFE-OK® Certified Grade Copper acc. to ASTM F 68-10 and EN 13604

Mechanical properties

Item	Tensile strength R_m N/mm²	0.2 % proof strength $R_{p0.2}$ N/mm²	Elongation %		Hardness		Grain size mm
005	216	130	A5	56	HRF	59	

Chemical composition
1) Specific value (ASTM B170-99)
2) Specified value (EN CW009A)

Analytical methods:
Optical emissiospectrometer Spark and gas analyastor

% min	ppm max															
Cu	Ag	As	Bi	Cd	Fe	Mn	Ni	O	P	Pb	S	Sb	Se	Sn	Te	Zn
1) 99.99	25	5	1	1	10	0.5	10	5	3	5	15	4	3	2	2	1
2) 99.99	25	5	2.0	1	10	0.5	10	-	3	5	15	4	2.0	2	2.0	1
Measured value																
99.997	19.5	0.8	0.9	<0.4	1.1	<0.2	1.9	1.7	<0.3	1.2	6	<1	1	<0.7	<2	<0,1

Electrical conductivity at 20 ° C % IACS, annealed (>=101): >101.5

Metallographic examination (<= Class 2) : Class A = 1 B = 1 C = 1
Hydrogen embrittlement test pass
Quench test for oxide adherence: good

These products have been produced under a certified Quality System
ISO 9001:2008 / DNV Certificate No. 58901-2009-AQ-FIN-FINAS

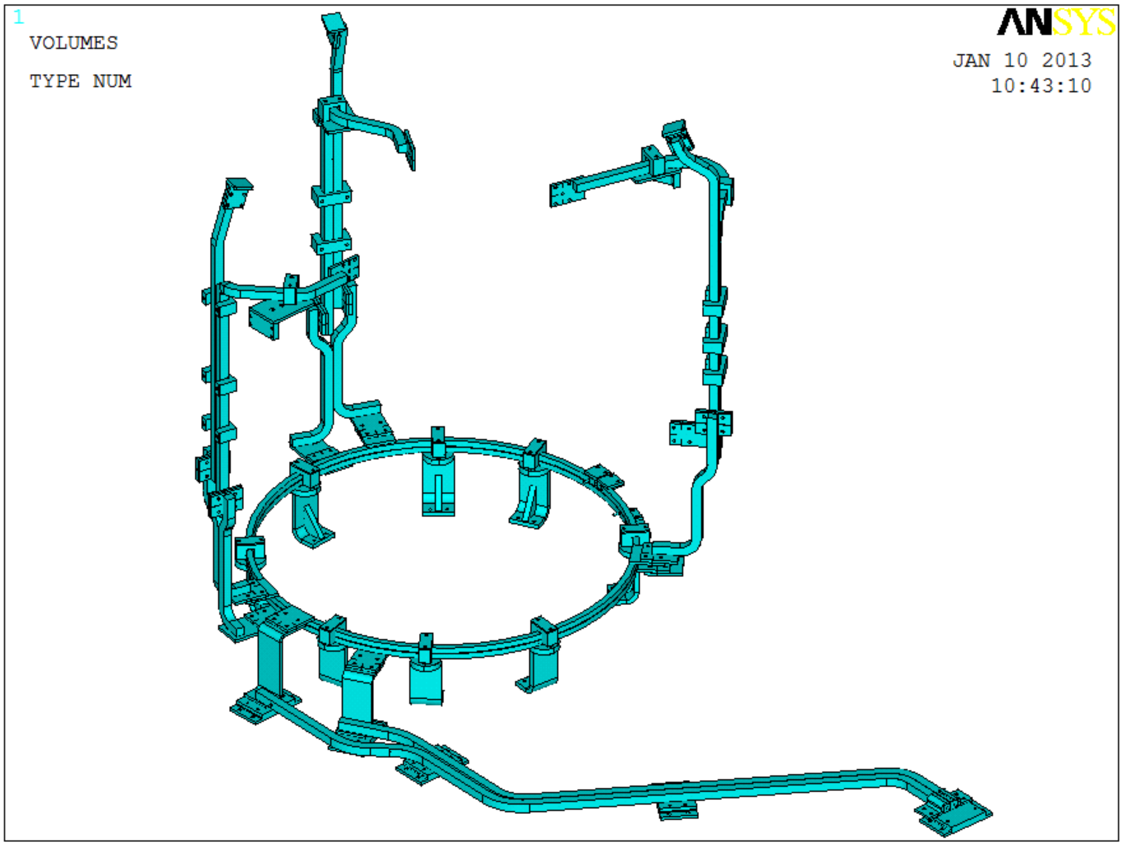
Material is free of mercury contaminates
Material is ROHS and REACH compliant
Country of melt and manufacturing Finland

We hereby certify, that the material described above complies with the order.

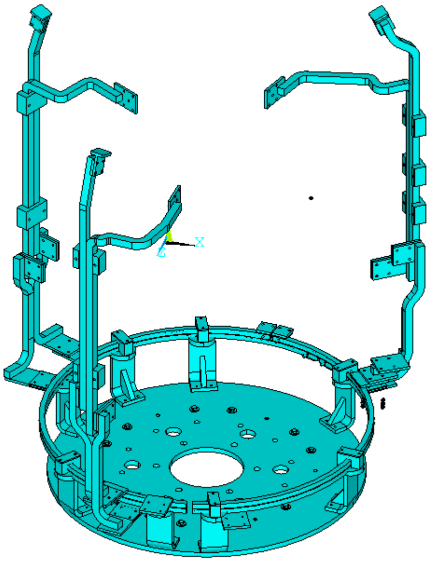
Rauno Lanne

Rauno Lanne

Appendix E Superseded IGES models of earlier designs



IGES Model from Neway Atnafu, January 2013



IGES Model from Gerry Peluzzi, June 2013