NSTX Upgrade

PF 2/3 Terminal and Flex Bus Analysis

NSTXU-CALC-55-02-01

June 17, 2016

(PF2 Upper)

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PPPL Calculation Form

Calculation # **NSTXU-CALC-12-01-01** Revision # **00** ____ WP #, **1903**
(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 pf 2,3,4,5 bus bars and connections for the upgrade loads and to provide qualification of the final design as reinforced just before initial operation. PF 4 and 5 U&L bus bars are qualified in the PF4 and 5 calculations, but some confirmatory calculations for these connections are included here.

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

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

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

Stiffness and strength of the flex cables are assumed to be minimal. Support in the bus tower is assumed adequate.

Calculation (Calculation is either documented here or attached)

These are included in the body of the following document

Conclusion (Specify whether or not the purpose of the calculation was accomplished.)

Terminal interconnects have been modeled and are adequate to take the local loads at the break-outs if the flex cable supports are within about 23 inches of the coil winding, based on PF2 loading. PF2 cable supports at 29 inches produced stresses that would not satisfy the full life, full load fatigue stress limit of 125 MPa. PF 3 peak loading is 57% of the loading of PF2, and slightly longer spans could be allowed for the PF3 cables. Complexity of the as-built conditions made detailed modeling of flex cabling difficult but a “best effort” at supporting the flex bus connections to PF2 and 3 was done in the field and is documented in Appendix D. Comparisons of the “with added support” and “without added support” showed nearly an order of magnitude improvement in the conductor stress at the terminal. Flex cable supports are either the same or similar to the ones used for NSTX and the service of the original flex cables and supports serves as qualification as to the basic load carrying capacity of the flex cables themselves. Inspections as of June 17 2016 indicate that the reinforcements required by this calculation have been installed. Cable lengths beyond those analyzed here may still have some significant loading and as a consequence they have been strapped together to cancel net loads and TV cameras have been installed to inspect cables and bus connections during operation These lengths have been described in Figure 6.3-10

Cognizant Engineer’s printed name, signature, and date

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

Checker’s printed name, signature, and date

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Appendix A Input file for the NTFTM Biot Savart Calculation
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3.0 Revision Status Table

Rev	Date	Description
0	5-1-2016	Original Issue

4.0 Executive Summary

Connections to the PF coils and bus connections are addressed in a few calculations listed below.

NSTXU Structural Analysis of PF1, TF and OH Bus Bars NSTXU-CALC--55-01-02 [12]
Stress Analysis of the Inner PF Coils (1a,1b &1c), Center Stack Upgrade NSTXU CALC 133-01-2   [9]
NSTXU Analysis of Existing and Upgrade PF4/5 Coils and Supports . NSTXU-CALC-12-05-01 [13]
NSTXU CHI Bus Bar Analysis NSTXU-CALC-54-01-1 Rev 0 [5]
NSTX Upgrade PF 2/3 Terminal and Flex Bus Analysis NSTXU-CALC-55-02-01 (This Calculation)
NSTX Upgrade PF 1 Flex Bus Analysis NSTXU-CALC-55-03-00

Power leads for PF 1 through 5 are routed in the bus bar tower and water cooled flex cables are described in [16]. Solid bus bar is used to connect PF1 a, b, c upper coils to supports mounted on PF3 clamps. These are addressed in other calculations [12]. Flex cable connections from the PF1a, b, c upper solid bar bus to the shelf extension of the bus tower have not been fully installed, but the span between the bars and the bus tower shelf is smaller than the lengths of flex cables that connect PF 2 and 3 to the bus tower. The concern over the loading on the PF 2 and 3 leads arose from an inspection that revealed cracks in the epoxy where the terminal enters the coil build. There was a history of flex cable motion with restraint added with ropes to control the motion. During operation of NSTX, no electrical fault was caused by the cracked epoxy. In NSTX-U, cable and terminal design had been deferred to allow the final routing of the cables to be determined, and these supports were still not detailed until March, 2015. Technicians installing the flex cables to the coil terminal have noted that the terminals themselves move under the deadweight of the cables and the Lorentz forces will be many times the cable deadweight.

Figure 4.0-1

The four terminals for PF2, 3 U&L look similar with a pancake-to-pancake jumper and power lead terminals spread further apart. PF2 Upper is shown in figure 4.0-1, and cracked insulation in the PF2 Lower break-out is also shown in the figure. NSTX Upgrade loads are expected to be approximately four times the loads experienced by NSTX.

The objective of this calculation is to provide guidance on initial design of the PF 2, 3 bus bars and connections for the upgrade loads, and to provide qualification of the final design. The terminals of PF 4 and 5 and the supports have been qualified in the PF 4 and 5 support calculation [13]. Some material covering loads on the PF 4 and 5 terminals are included here because they share the bus tower and may need further qualification depending on their performance.

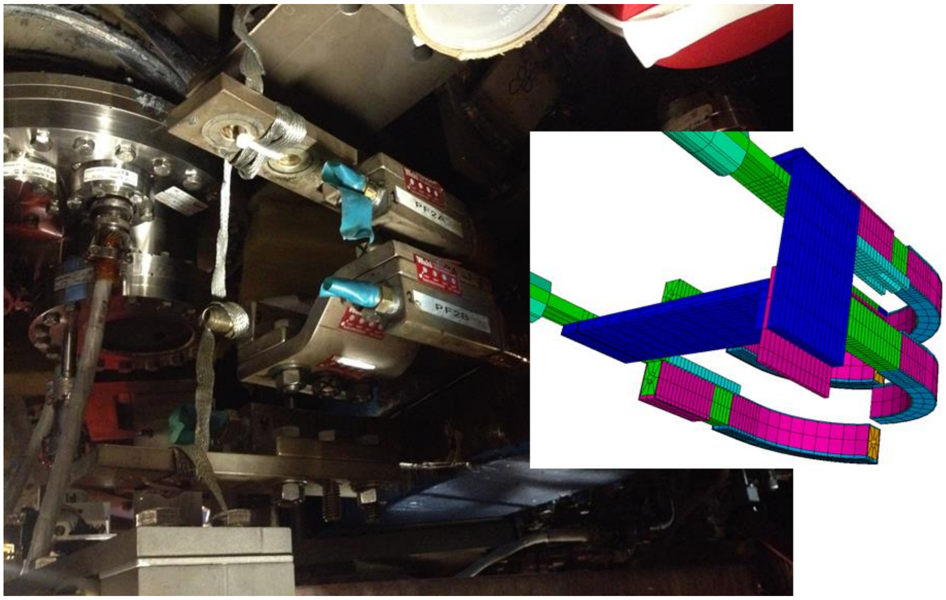


Figure 4.0-2 PF 2 Lower Terminal Reinforcements and Analysis Model Oriented as in the Photo

Two types of supports have been added to the PF 2 and 3 electrical connections. The last support system added is to the flex cables, based on the judgement of the technicians. Photos are included in Appendix D that show these supports and give an indication of the difficulty in specifying or analyzing the supports. The first support to be added is to tie the two terminal conductors together structurally so that most of the loading is canceled. The moments however remain. The added supports taken together provide a substantial improvement over NSTX. Calculations of support and terminal stresses are presented here, but they are really qualitative, showing improvements in stresses when supports are added. This, coupled with the service history of the flex bus during NSTX operation is the basis of the qualification of the upgrade flex supports.

Figure 4.0-3 PF 2 /3 Terminal Reinforcements and Analysis Model Oriented as in the Photo

A couple of approaches have been used to quantify the Lorentz loads on the terminals and flex bus. A "DCPS" algorithm was written that computes the local vertical field at the terminals of PF2 U&L and PF3 U&L, and multiplies that field times the appropriate current for the same EQ for which the field was calculated. The toroidal field is combined using SRSS. For the finite element models, the background fields and peak PF2/3 currents (15 kA) are used to quantify the loads on the coil terminations.

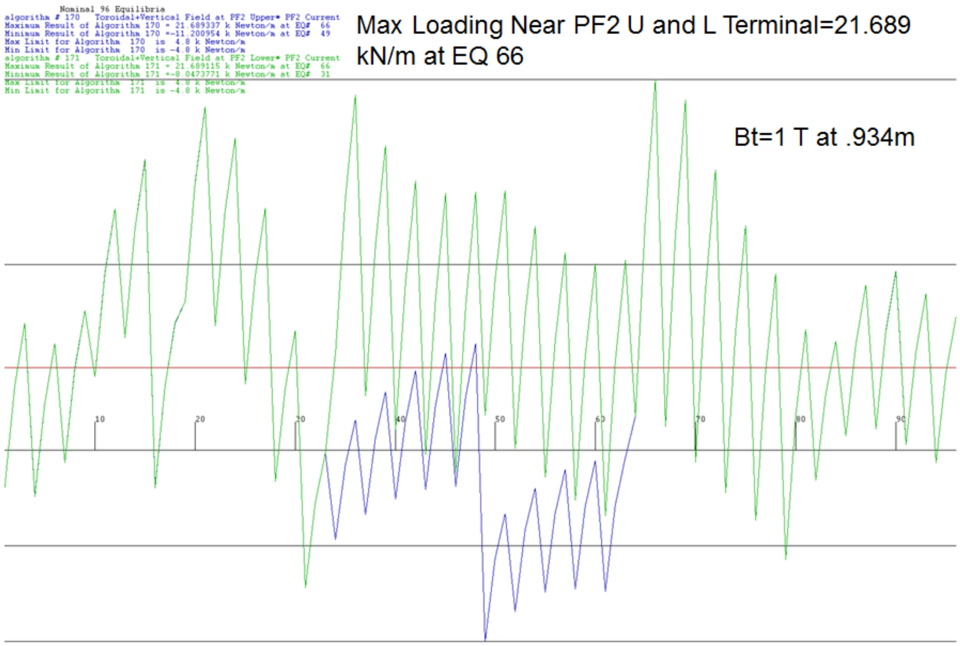


Figure 4.0-4 "DCPS" Algorithm Assessment of the Max Load/m on PF2 Leads

A second approach at calculating the Lorentz forces was also used. This modeled straight runs of cable from the bus tower to the coil terminals inside a full 3D field and force model of the coils and cables. This was the same model used to qualify the CHI bus [5]. This analysis is shown in figure 4.0-5.

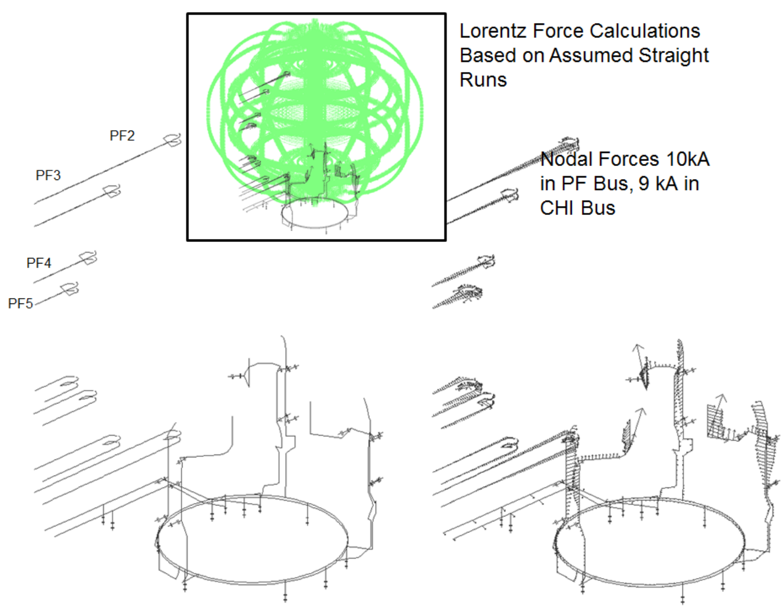


Figure 4.0-5 Biot Savart models of PF 2, 3, 4, 5 bus as straight runs in the CHI model

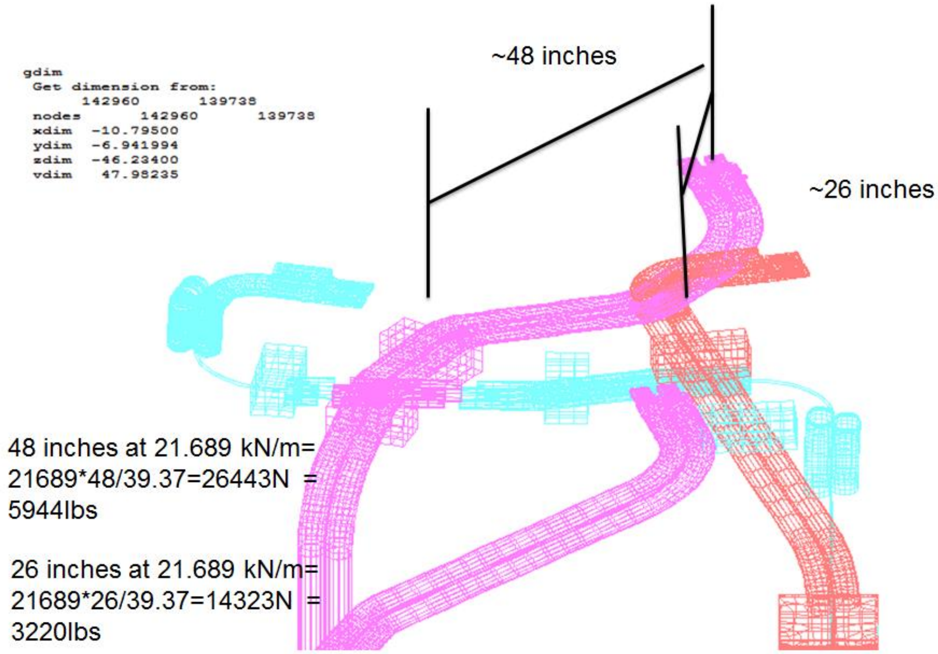


Figure 4.0-6 Unsupported lengths meshed from the IGES file. Note that the Unsupported Lengths are to the end of the flex. There is an additional 12 inches of coil terminals that will require some support.

Geometry of the leads to PF2/3 has been difficult to identify. A CAD model of the leads has been built. An IGES file was supplied by Jean-Pierre Fra. This is shown in figure 4.0-8 and the meshed runs are shown in figure 4.0-6. It wasn't directly converted to magnetic and structural models, but the bus runs close to PF2 and 3 were meshed and dimensions extracted. Given the DCPS algorithm max loading for all 96 equilibria, and estimates of the lengths of the flex cable that would be loaded, approximate load inventories were computed. 3000 to 5000 lbs are representative loads on the PF2 leads. If the bus pair are properly bundled, these would only be loaded by a torque, but the separation of the lead break-outs will make connecting and canceling loads on the leads and bus less effective. The extra 12 inches of coil conductor terminations will also require support. The loads on the lead stubs would still be 1000 to 2000 lbs before they could be joined and loads canceled.

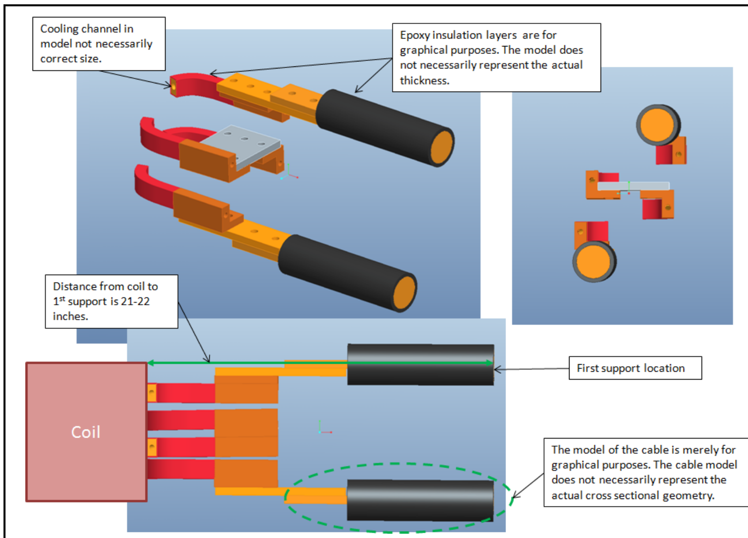
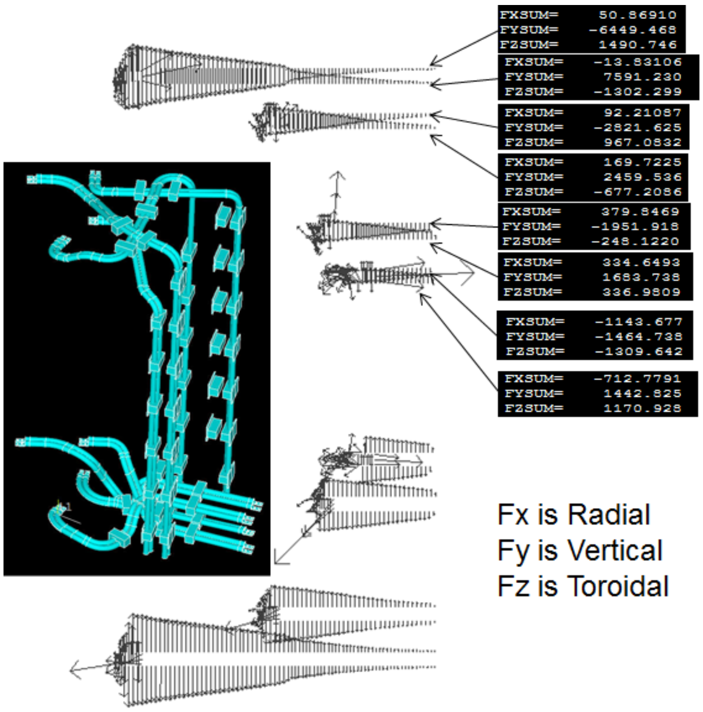


Figure 4.0-7 PF 2, 3, 4, 5 Bus Bar Model Showing Separation of the leads

Earlier in the project, support details for the spans between the bus tower "shelf" and the coils had not been detailed in the CAD model. Consequently, straight runs were analyzed and Lorentz forces computed. These range between 2500 lbs down to 1000 lbs, mostly in the vertical direction. These are tabulated in figure 4.0-8. Loads from TF fields predominate for runs inside the TF "cage".



		N per 10 kAmp	max Current	Bus Load Newton	Bus Load Lbs
PF2 in	fx	50	15	75	16.86
	fy	-6449	15	-9673.5	-2174.6028
	fz	1490	15	2235	502.428
PF2 Out	fx	-13.8	15	-20.7	-4.65336
	fy	7591	15	11386.5	2559.6852
	fz	1302	15	1953	439.0344
PF3 in	fx	92.21	16	147.536	33.1660928
	fy	-2821	16	-4513.6	-1014.65728
	fz	967	16	1547.2	347.81056
PF3 out	fx	169	16	270.4	60.78592
	fy	2459	16	3934.4	884.45312
	fz	677	16	1083.2	243.50336
PF4 in	fx	379	16	606.4	136.31872
	fy	1951	16	3121.6	701.73568
	fz	248	16	396.8	89.20064
PF4out	fx	334	16	534.4	120.13312
	fy	1683	16	2692.8	605.34144
	fz	337	16	539.2	121.21216
PF5 in	fx	-1143	34	-3886.2	-873.61776
	fy	-1464	34	-4977.6	-1118.96448
	fz	-1309	34	-4450.6	-1000.49488
PF5 out	fx	-712	34	-2420.8	-544.19584
	fy	1442	34	4902.8	1102.14944
	fz	1170	34	3978	894.2544

Figure 4.0-8 IGES Model of PF 2, 3, 4, 5 flex Cable Runs from Jean-Pierre Fra and Loads on Flex Cables If they Were Straight Runs (Used for Preliminary Design.)

Modeling the actual flex cable layout is difficult because of the field fit nature of the runs. A simple model with straight conductors modeling the flex cable was developed. Terminal fixity at coil break-out is uncertain (motion is detected with just loading by hand). The analysis assumes fully fixed at the coil which is conservative for stress prediction at the break-out. The strength and flexibility of the flex cable is uncertain. They are heavy and stiff enough that they load the terminals visibly when installed. The same model was used to address both PF 2 and 3.

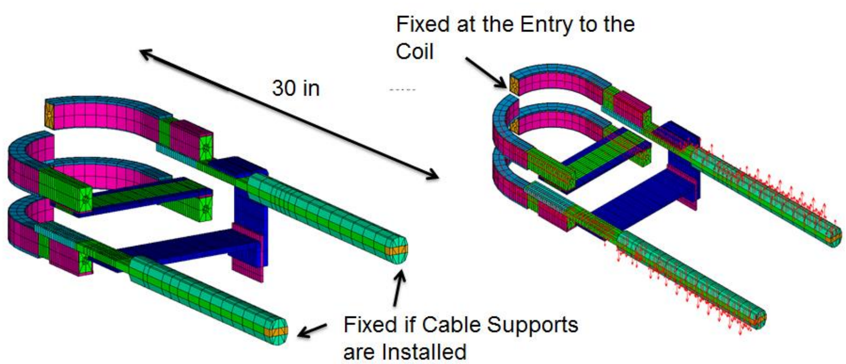


Figure 4.0-9 Model Used to Qualify the Terminal Inter Connections for Both PF2 and 3

A model of the terminals without any supports shows the high stress at the coil entry points and the attachments to the cables.

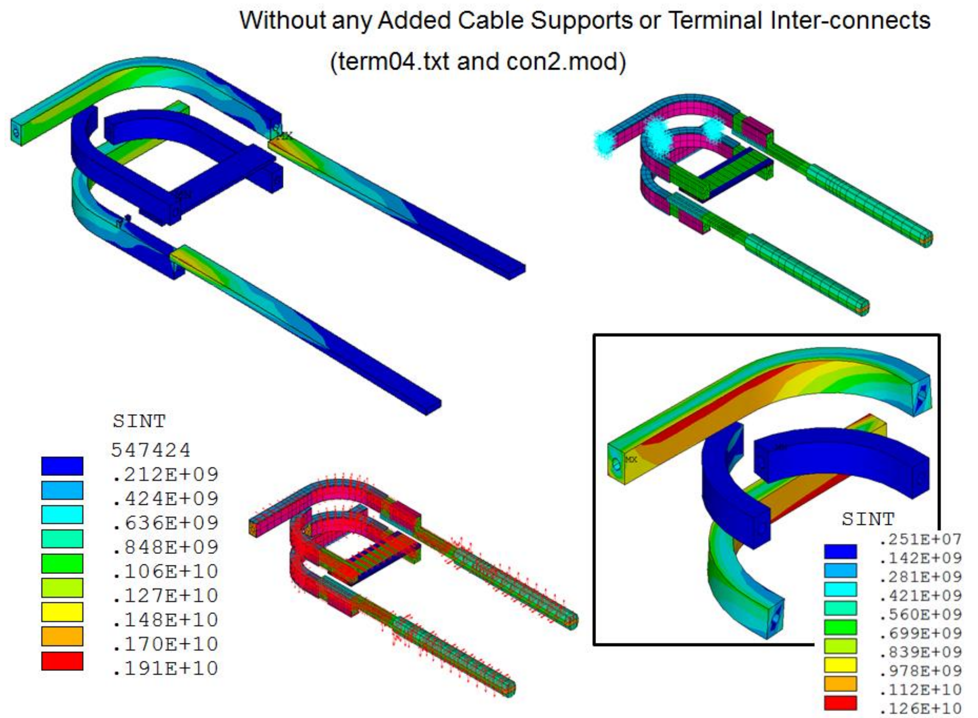


Figure 4.0-10 Stresses in the Terminals With No Added Supports (PF3 Loading)

Stress levels in the conductor of 1260 MPa are an order of magnitude higher than the 125 MPa fatigue allowable chosen for the copper conductor and are an indication of the strains on the coil insulation that would have developed without adding supports.

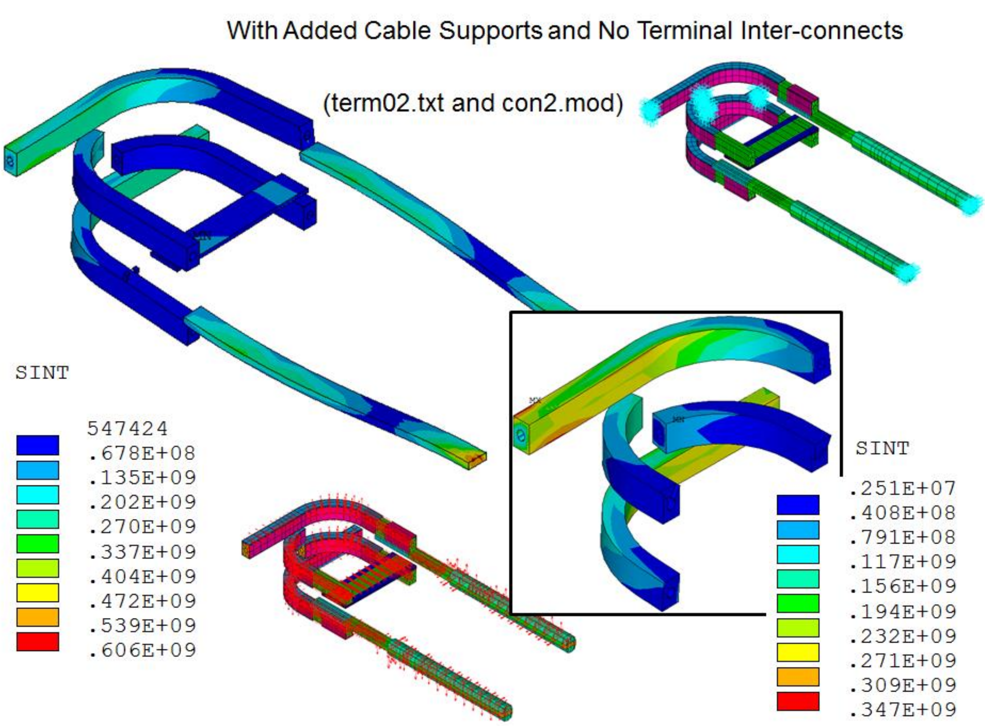


Figure 4.0-9 Break-out Model With Cable Supports and No Added Terminal Interconnect (PF3 Loading)

Adding the cable supports was the most effective solution in improving the stress at the coil break-out. The stress dropped from over a Gigapascal to 347 MPa at the coil. This was the most worthwhile improvement that was made, however, the congested areas into which the supports needed to be installed made design and drafting of the details difficult. The specifics of the cable supports were left up to the technicians. Photos of the resulting supports are included in Appendix D.   They appear robust from the photos.

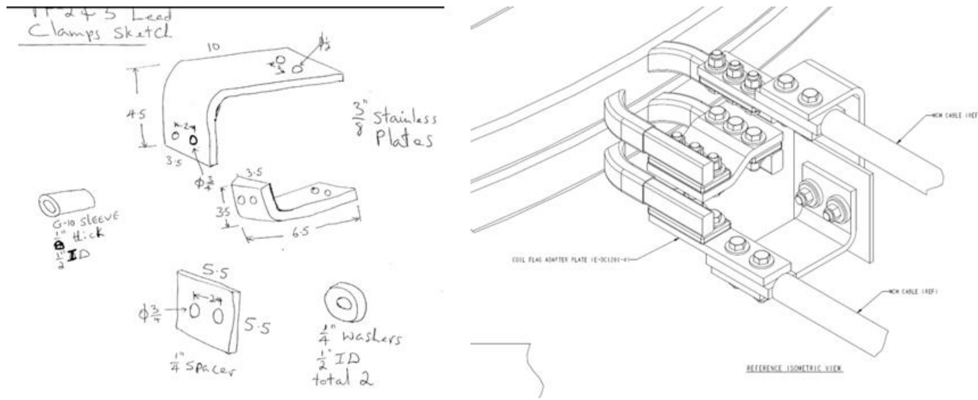


Figure 4.0-10 Original Design Concept for the Terminal Interconnection (Left) and Final Design (Right)

Reacting the opposing forces on the terminals by structurally interconnecting them was also attempted to improve the stress state. The basic design elements used to connect the terminals structurally were developed by Neway Atnafu while interacting with tech’s in the field (Joe Bartzak)

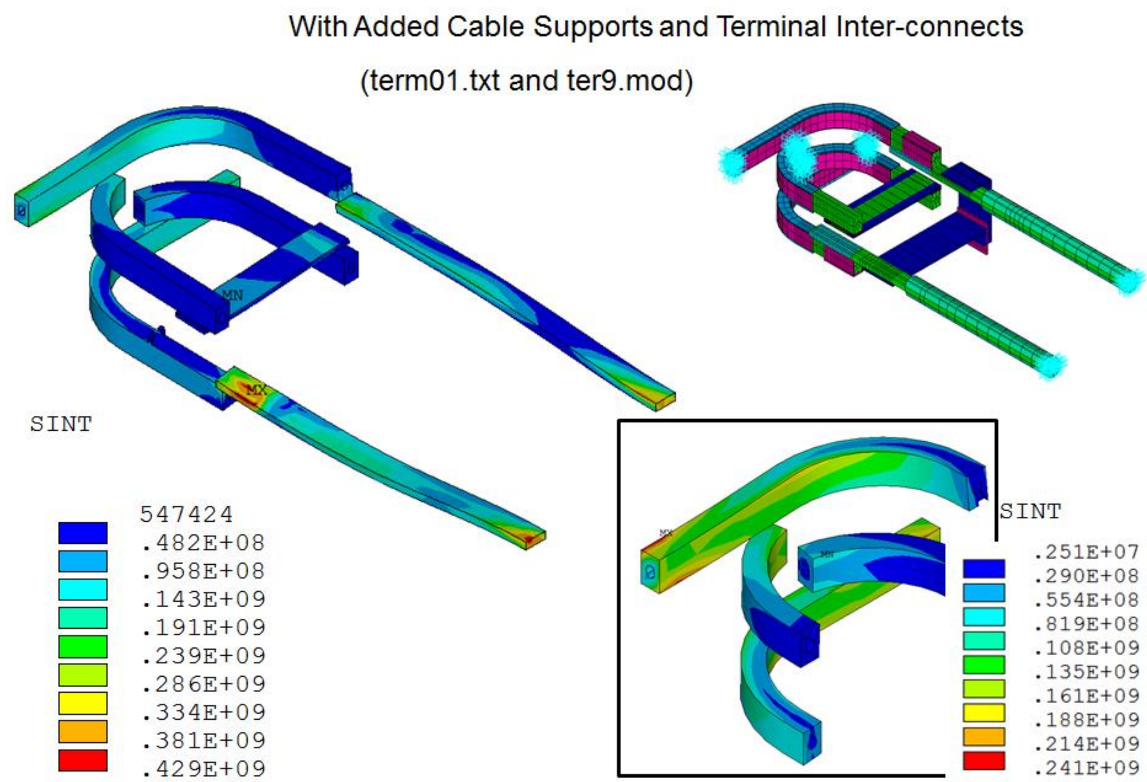


Figure 4.0-11 Stress with the Terminal to Terminal Interconnection and With Cable Support (PF3 Loading)

Addition of the terminal interconnect reduced the stress at the coil another 100 MPa to 241 MPa. While this is still above the fatigue allowable, it is 241/1260 or about 20% the loading that would be experienced by unsupported cables and terminals like the original conditions in NSTX. So the stress levels in NSTX-U should be better than those experienced by NSTX, where NSTX-U loading is four times the NSTX loading, and stresses have been lowered by about a factor of 5 over the poorly supported NSTX connections.

Figure 4.0-11

Because of the difficultly in identifying the precise geometry of the terminals and flex cables, the support details of the flex cables were left to the technicians. Guidance was provided on the magnitude of the expected loads and the expected torques, and the technicians added supports to the cables. Figure 4.0-11 and 12

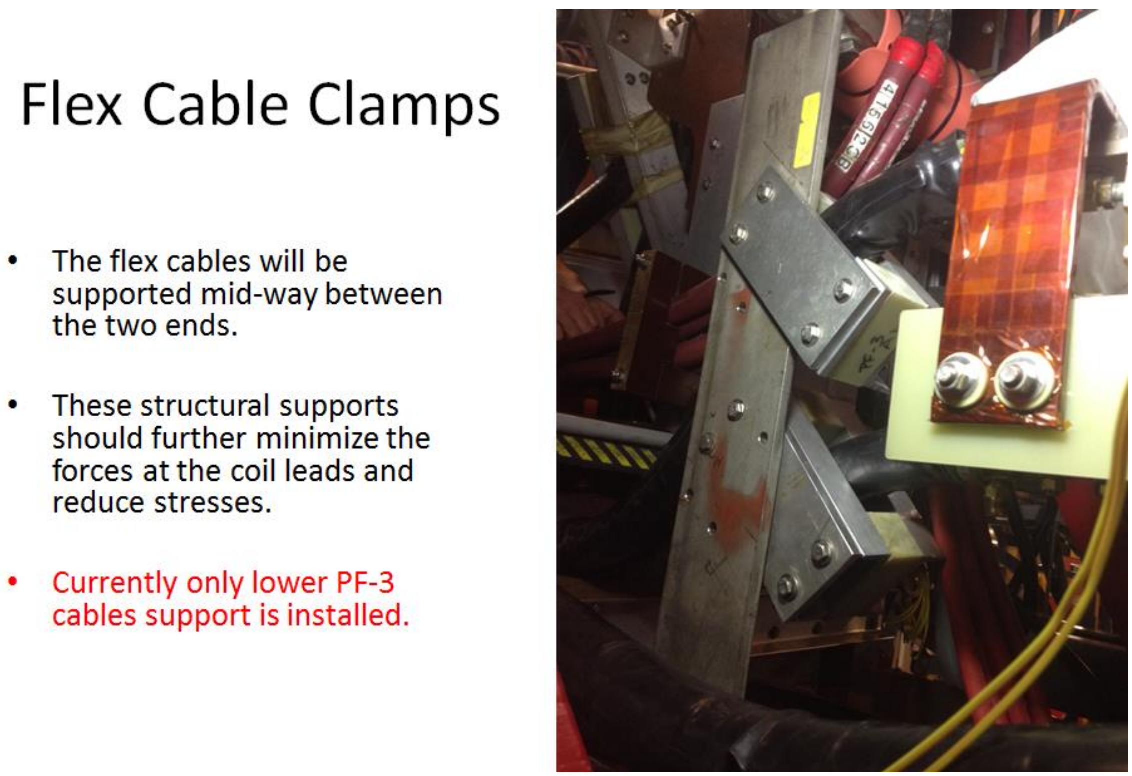


Figure 4.0-12 Representative Flex Cable Restraints [14]

At the peer review in April, 2015 [14] only the PF 3 cable supports had been installed. In April, 2016, Joe Winston showed the author the installed cable clamps for PF2 power leads. These were built off of the PF3 coil brackets. Scott Gifford took a number of pictures of the installed clamps [15]. These are included in Appendix D.

The best we will do for CD-4 is improve the stresses to pre-upgrade values or better, so a comparison between unsupported (NSTX) stresses and reinforced stresses is made. In the comparison shown in figure 4.0-10, the stress improves only modestly. The comparison assumes support of the cables for both the with and without clamp assumptions.

** Bending Allowable from Section 6.4

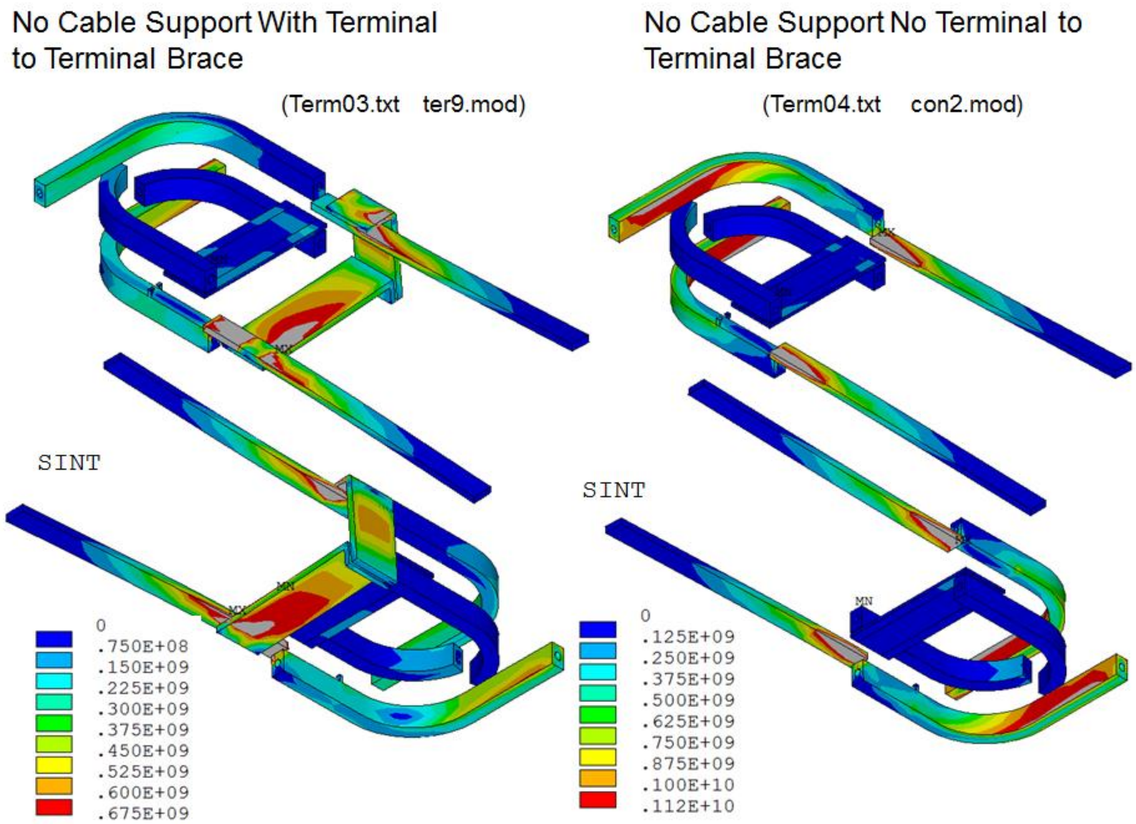


Figure 4.0-13 Without the Cable Clamps and With and Without the Terminal Inter-connect

In Figure 4.0-13, the efficacy of the brace or interconnect between the terminal ends is explored. If there were no cable support clamps, the terminal to terminal brace would halve the stress.

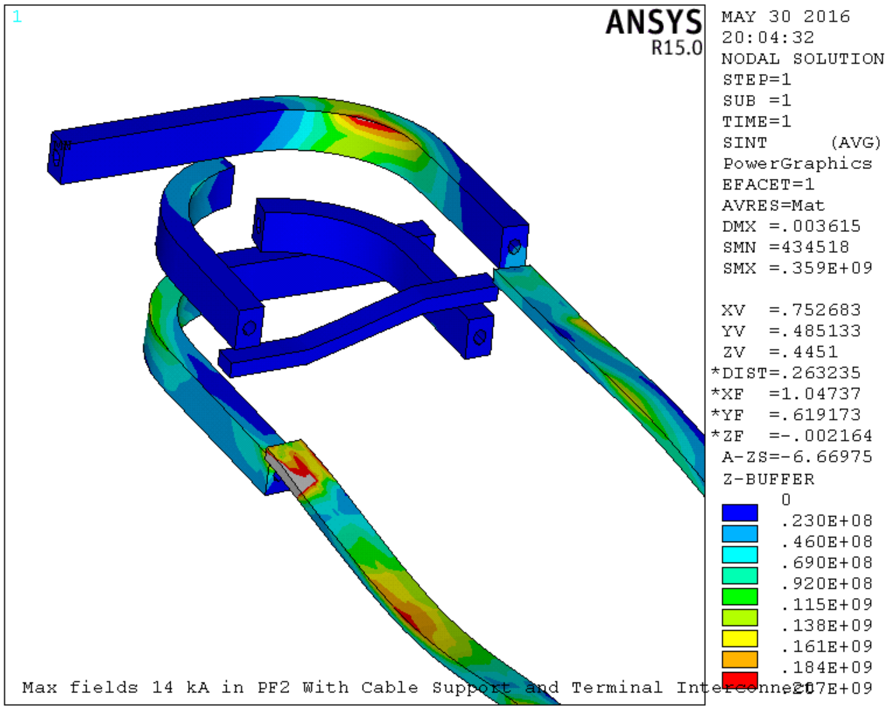


Figure 4.0-15 Stress at Full Load and first support at 29 inches from the coil winding

The stress in Figure 4.0-15 needs to be 125 MPa for full life at full loading.

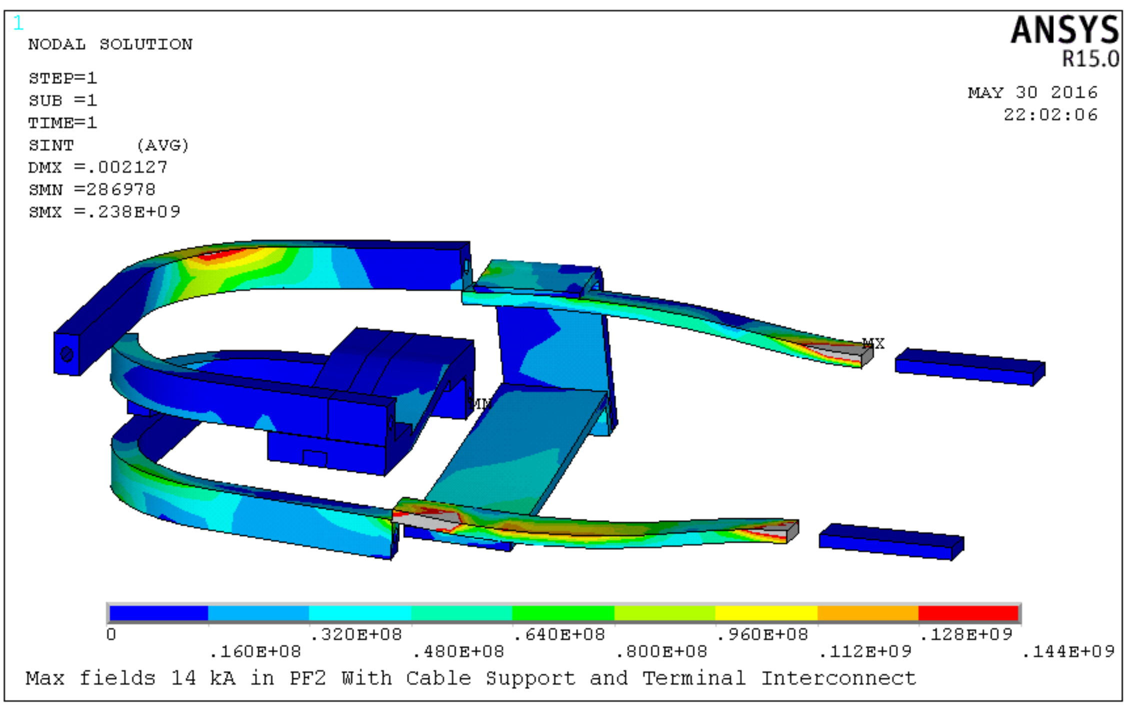


Figure 4.0-16 Stress at Full Load and first support at 23 inches from the coil winding

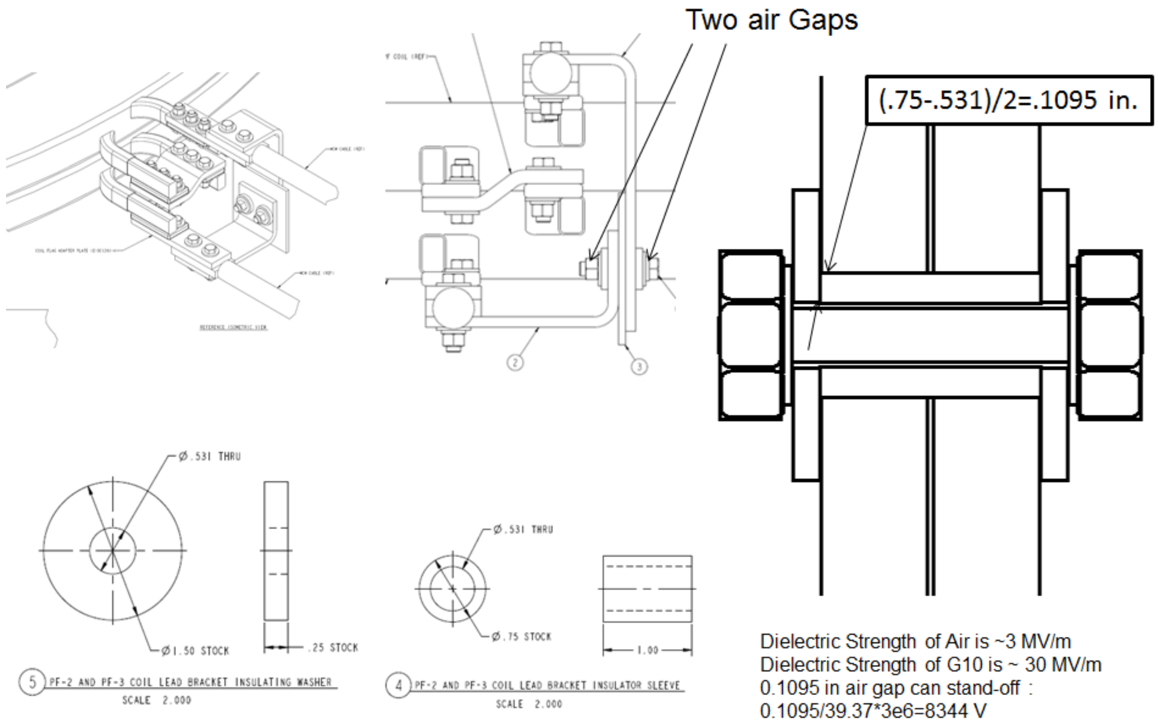


Figure 4.0-17 Evaluation of Voltage Stand-Off at the Bolting Detail

Terminal interconnects have been modeled and are adequate to take the local loads at the break-outs if the flex cable supports are within about 23 inches of the coil winding based on PF2 loading. PF3 supports do not need to be as close. For the PF2 loading, cable supports at 29 inches produced stresses that would not satisfy the full life full load fatigue stress limit of 125 MPa. PF 3 peak loading is 57% of the loading of PF2 (see section 9.3) , and slightly longer spans could be allowed for the PF3 cables. Complexity of the as-built conditions made detailed modeling of flex cabling difficult but a "best effort" at supporting the flex bus connections to PF2,3 was done in the field and is documented in Appendix D. Comparisons of the "with added support" and "without added support" showed nearly an order of magnitude improvement in the conductor stress at the terminal. Flex cable supports are either the same or similar to the ones used for NSTX and the service of the original flex cables and supports serves as qualification as to the basic load carrying capacity of the flex cables themselves. Inspections as of June 17 2016 indicate that the reinforcements required by this calculation have been installed. Cable lengths beyond those analyzed here may still have some significant loading and as a consequence they have been strapped together to cancel net loads and TV cameras have been installed to inspect cables and bus connections during operation These lengths have been described in Figure 6.3-10

5.0 Digital Coil Protection System.

At this point, the protection of PF2 and 3 coils and components is addressed by the radial and vertical force limits and moment/bolt calculations set for the coils and coil supports.

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 limit. Disruption loads should be minimal for these terminal connections. The field and current changes outside the vessel are small compared with the normal operating loads.

6.2 References

[1] NSTX Upgrade General Requirements Document, NSTX_CSU-RQMTS-GRD Revision 5, C. Neumeyer, June 14 2012

[2] NSTX-U Design Point Spreadsheet, **NSTXU-CALC-10-03-00** C. Neumeyer, http://w3.pppl.gov/~neumeyer/NSTX_CSU/Design_Point.html

[3] Drawing E-DC1501 PF-2 and PF-3 Coils Lead Reinforcement Bracket Assembly

[4] Drawing E-DC1500 PF-2 and PF-3 Coils Lead Reinforcement Bracket Details

[5] NSTX Upgrade CHI Bus Bar Analysis NSTXU-CALC-54-01-1 Rev 0 November 21, 2013 by P. Titus, Reviewed by A. Khodak

[6] Power Supply Cables PF and TF flag adapter plate detaila, Drawing E-DC1201

[7]?

[8] PF Coil Feed Changes, Design Basis for Umbrella Bus Loads, S. Ramakrishnan, August 31, 2012

[9]?

[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

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

[13] NSTX Upgrade Analysis of Existing and Upgrade PF4/5 Coils and Supports – With Alternating Columns. NSTXU-CALC-12-05-01 Rev 0 December 2011 Rev 1 April 2016, P. Titus, checked by I. Zatz

[14] PF-2&3 Lead Clamps Design Review 04/02/2015 By Neway Atnafu

[15] Email from Scott Gifford Apr 27 to Neway, and P. Titus: Gentlemen the pictures for the PF 2-3 Supports are in the photo drop.P:\Photo Drop\PF 2-3 Supports

[16] Flex Cable Catalog, Northern Connectivity Systems Inc Commodore Machine Company 1749 Northwood Drive, Troy Michigan

[17] OH & PF1 & 2 Electromagnetic Stability Analyses NSTXU-CALC-133-11-00 Rev 0 March 2 2010 Prepared By: Peter Titus, Reviewed By Ali Zolfaghari, Cognizant Engineer: Jim Chrzanowski WBS 1.1.3

6.3 Photos and Drawing Excerpts

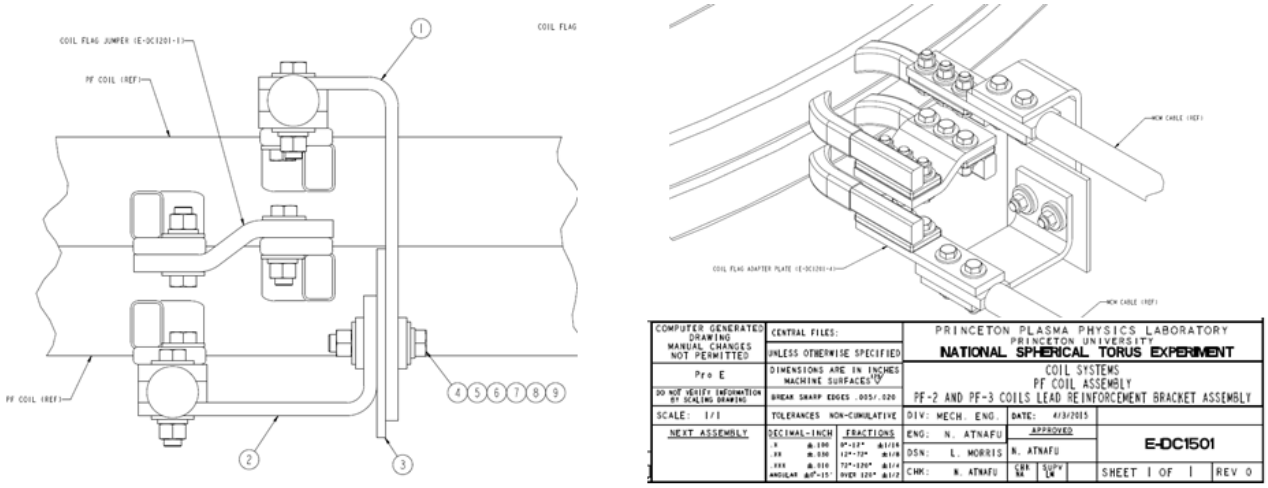


Figure 6.3-1 Reinforcement Configuration Drawing E-DC1501[3]

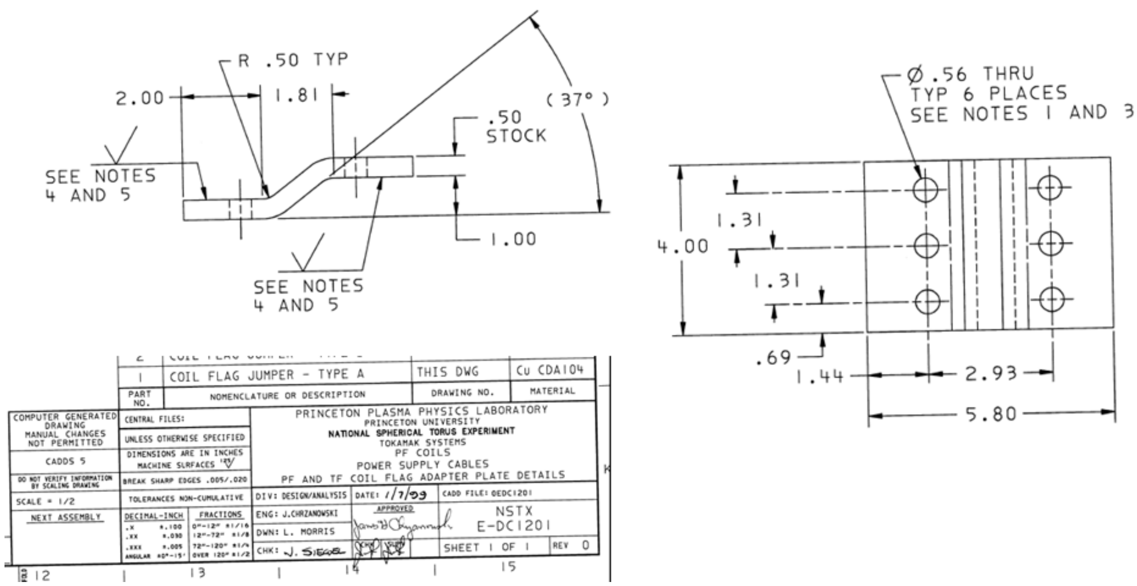


Figure 6.3-2 Copper Pancake to Pancake Jumper E-DC1201[6]

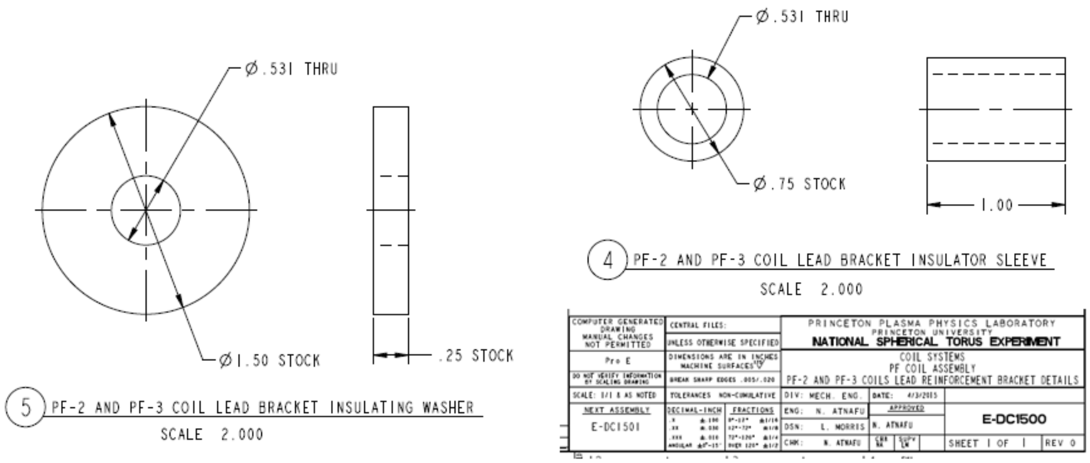


Figure 6.3-3 Insulating Sleeve and Washer Drawing E-DC1500[4]

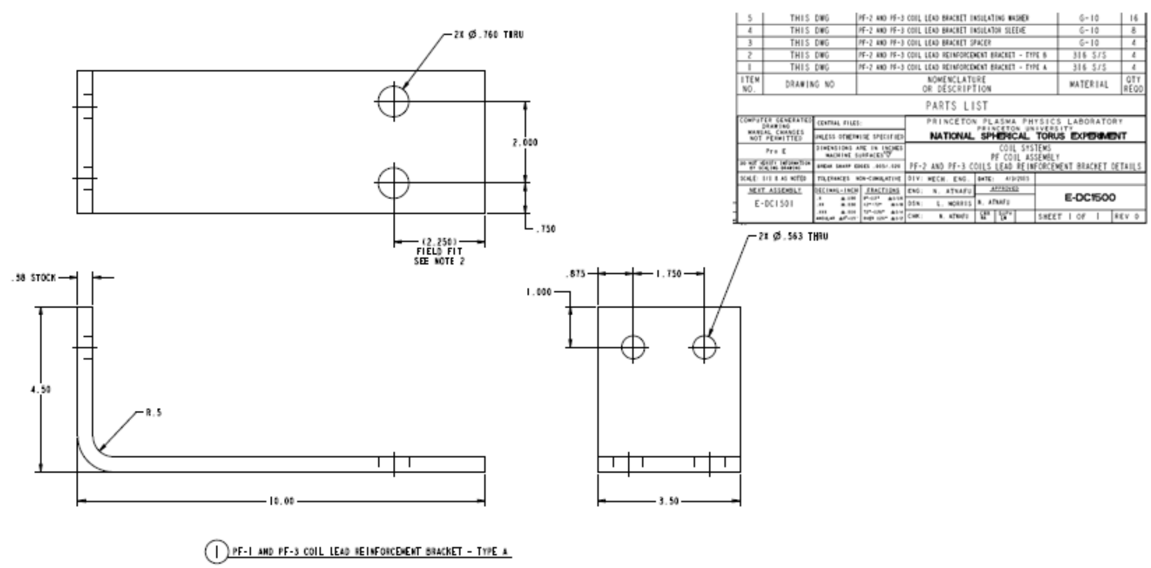


Figure 6.3-4 Bracket E-DC1500[4]

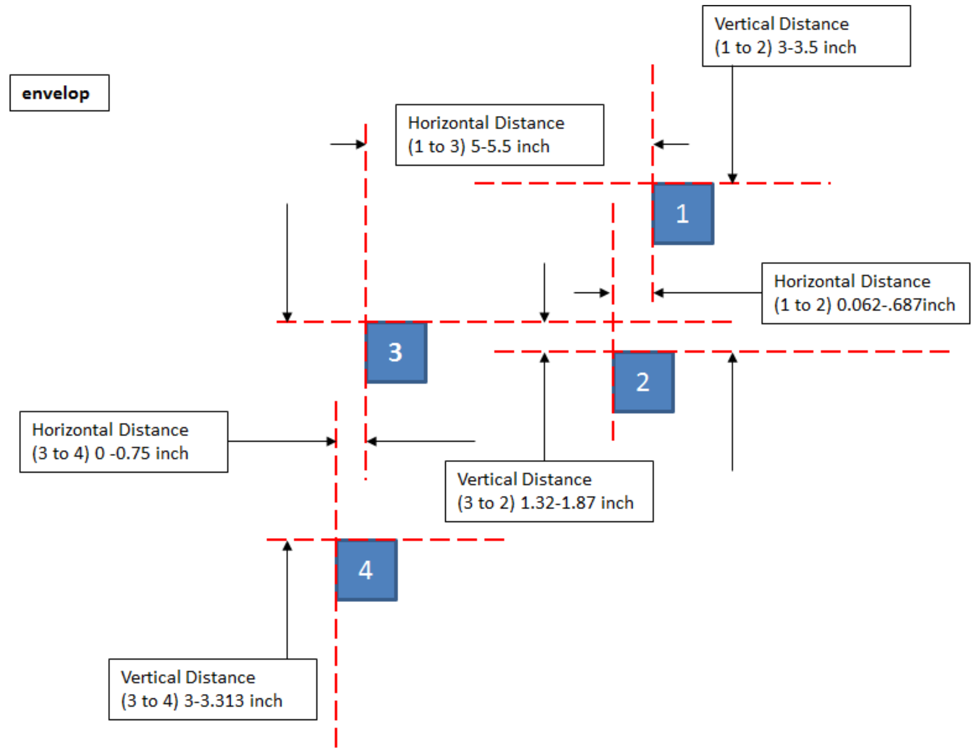


Figure 6.3-5 Terminal Layout Provided by Mark Smith

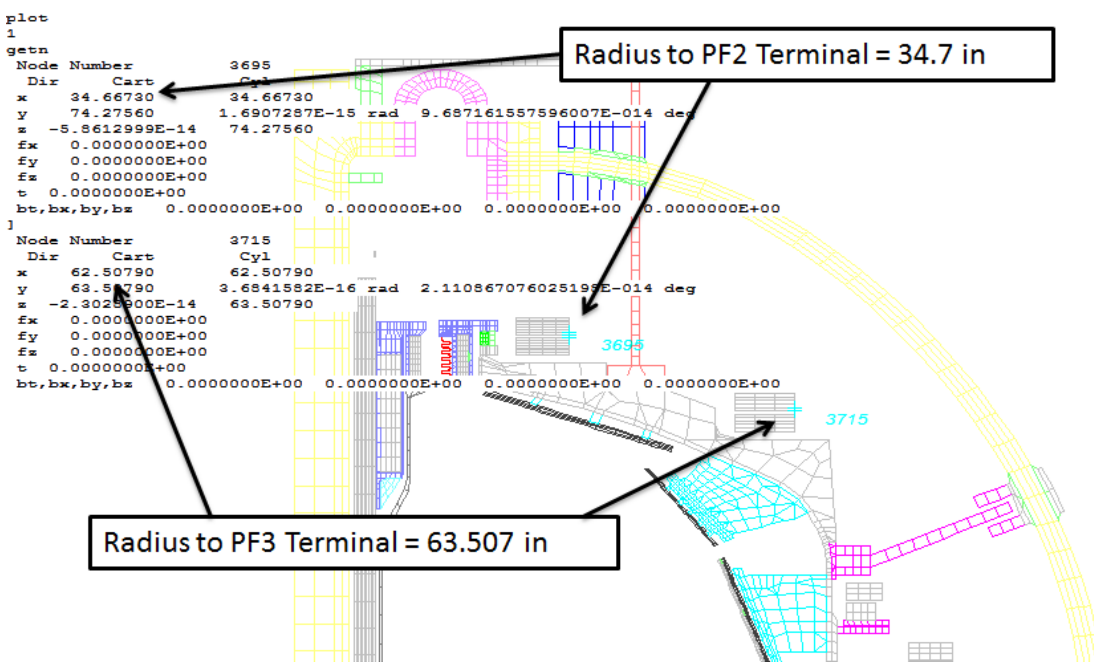


Figure 6.3-6 Radial Positions of the Terminal Break-Outs for PF 2 and 3

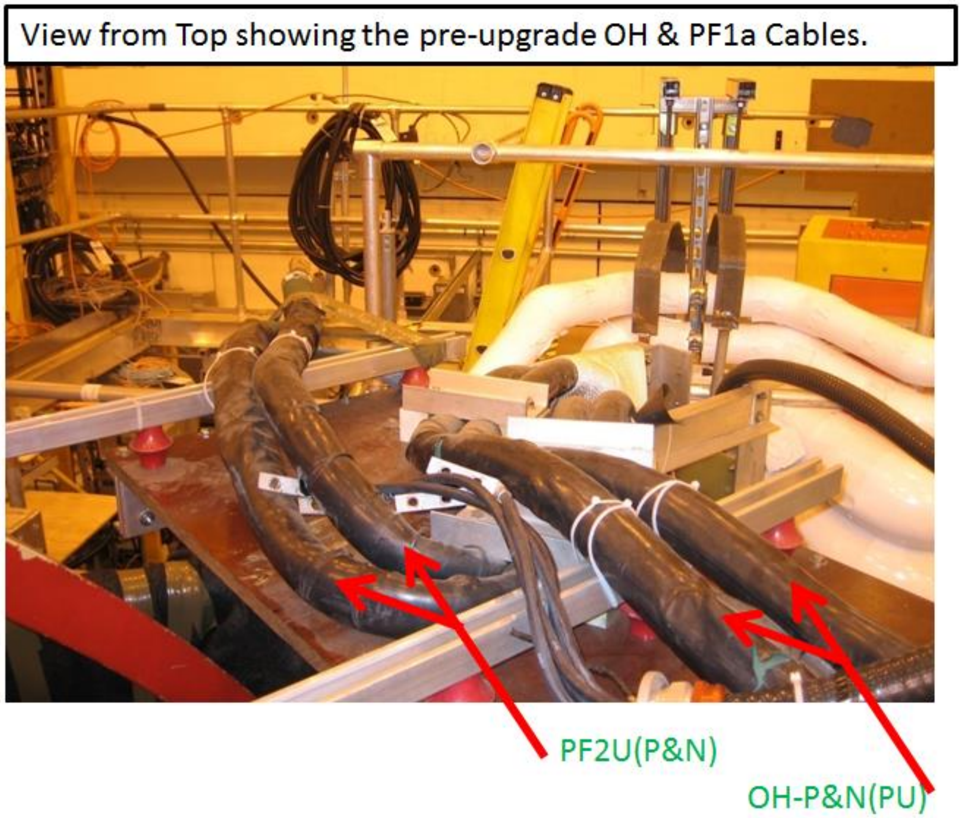


Figure 6.3-7 Cable Supports from Pre- Upgrade Configurations

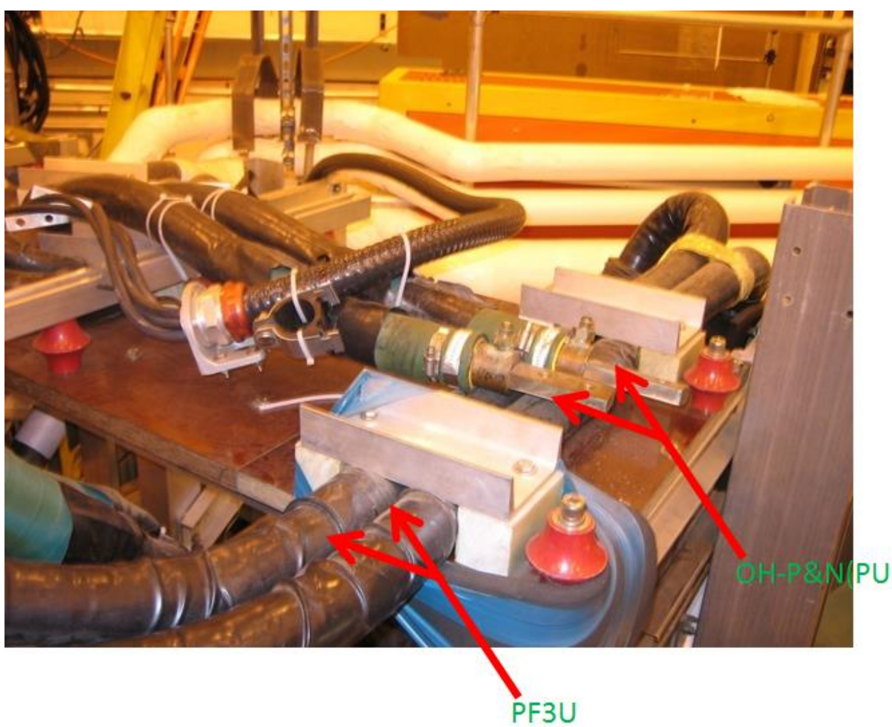


Figure 6.3-8 Cable Supports from Pre- Upgrade Configurations

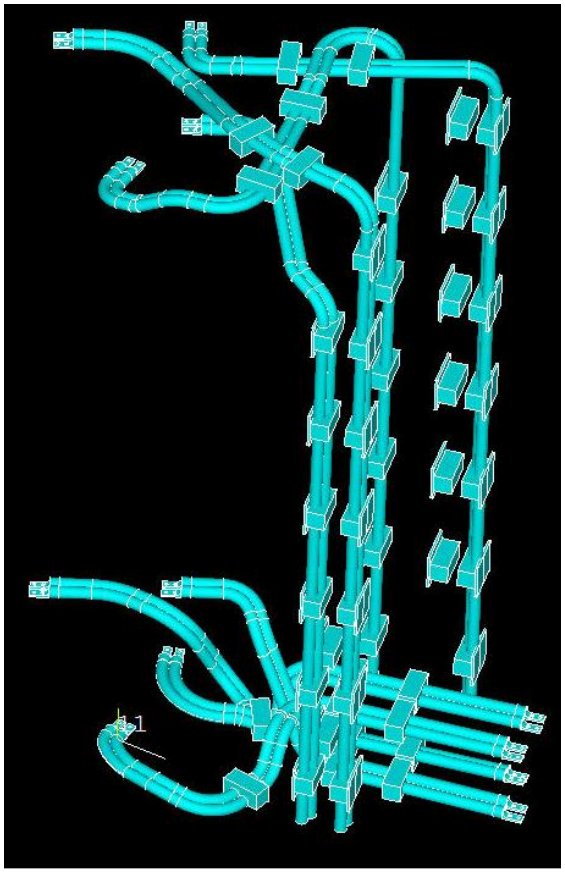


Figure 6.3-9 IGES Model from Jean Pierre Fra

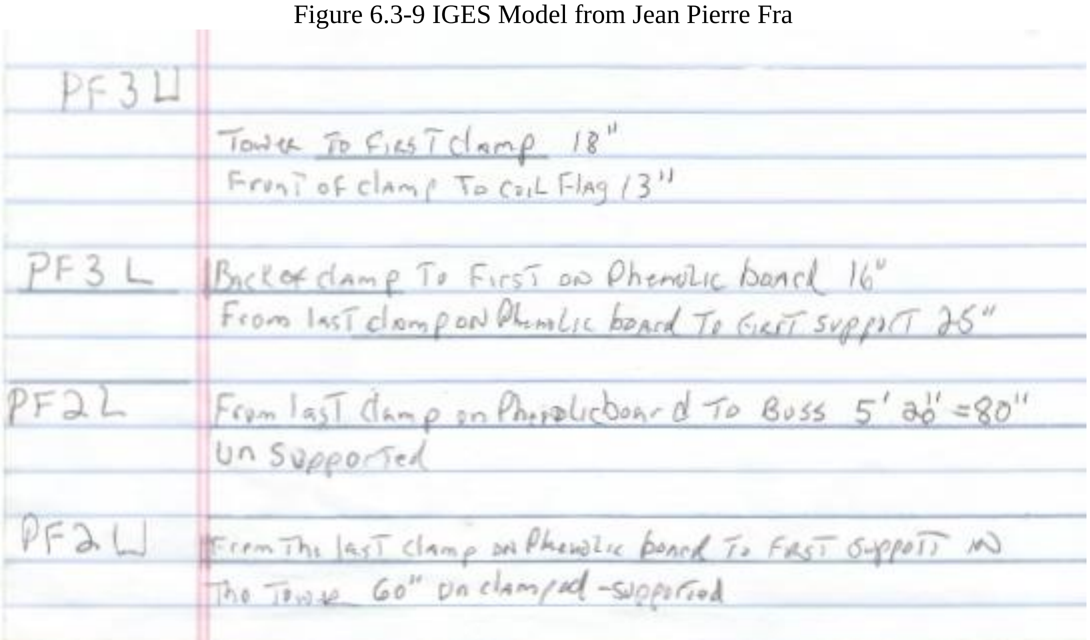


Figure 6.3-10 As Builts of the Flex Cable Runs Beyond the First Flex Cable Support

6.4 Materials and Allowables

6.4.1 Static Allowables for Copper Stresses

The TF conductor properties are taken as representative of the PF 2, 3, 4, 5 bus physicals. The TF copper ultimate is 39,000 psi or 270 MPa. The yield is 38 ksi (262 MPa). Sm is 2/3 yield or 25.3 ksi or 173 MPa – for adequate ductility, which is the case with this copper which has a minimum of 24% elongation. Note that the ½ ultimate is not invoked for the conductor (it is for other structural materials). 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 156 MPa and the bending allowable is 233 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). [11]

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]. Disruption loading has minimal effect on the PF 2, 3, 4, 5 bus bars. 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.

6.5 PF 2, 3, 4, 5 Currents

These are as specified in the design point spreadsheet :

Coil	R (center)	dR	Z (center)	dZ	Min Curr*	Min Curr*	Max Curr*	Max Curr*	Max |I|	Max |I| LPPI
	(in)	(in)	(in)	(in)	(kA)	(kA-Turn)	(kA)	(kA-Turn)	(kA)	(kA)
PF2a	31.496	6.406	76.121	2.676	-11	-154	15	210	15	15
PF2b	31.496	6.406	72.937	2.676	-11	-154	15	210	15	15
PF3a	58.837	7.34	64.31	2.676	-16	-240	12	180	16	16
PF3b	58.837	7.34	61.126	2.676	-16	-240	12	180	16	16
PF4b	70.654	3.604	31.78	2.676	-16	-128	6	48	16	16
PF4c	71.121	4.538	34.964	2.676	-16	-144	6	54	16	16
PF5a	79.244	5.328	25.672	2.7	-34	-408	0	0	34	31.8
PF5b	79.244	5.328	22.756	2.7	-34	-408	0	0	34	31.8

Nominal IP and Toroidal Fields for NSTX and NSTX-U

		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

Toroidal field at PF 2,3,4,5

PF	Radius in Inches	Toroidal Field
PF2	31.496in (.8m)	.934*1.0/(31.496/39.36) = 1.165T
PF3	58.837	.934*1.0/(58.837/39.36) = .624T
PF4	70.654	.934*1.0/(70.654/39.36) = .5204T
PF5	79.244	.934*1.0/(31.496/39.36) = .464T

bgen
1,.168,-.59,0
1,.3,-.5,.43
btor
1,.93,.1,.15,2,3

In a note from Steve Raftopoulos: “The PTP hi-pot is 6kV for pf2 & pf3. The criteria is (2x (operating voltage) + 1) x 2/3. That implies 4kV operating voltage.”

G-10 Property Typical Values:
Electric Strength (Flat Rapid) MV/m 24
Electric Strength (Flat Step by Step) MV/m 15
Breakdown Voltage (Edge Step by Step) kV 80
Thickness Needed: 6kV/15MV/m= .0004 m =.4 mm
Another Source:
    Dielectric strength= 800 v/mil
    Thickness needed= 6000/800=7.5 mil = .2 mm
Another Source:
    Dielectric strength= 960 to 1000 v/mil

7.0 Models
7.1 Global Biot Savart model

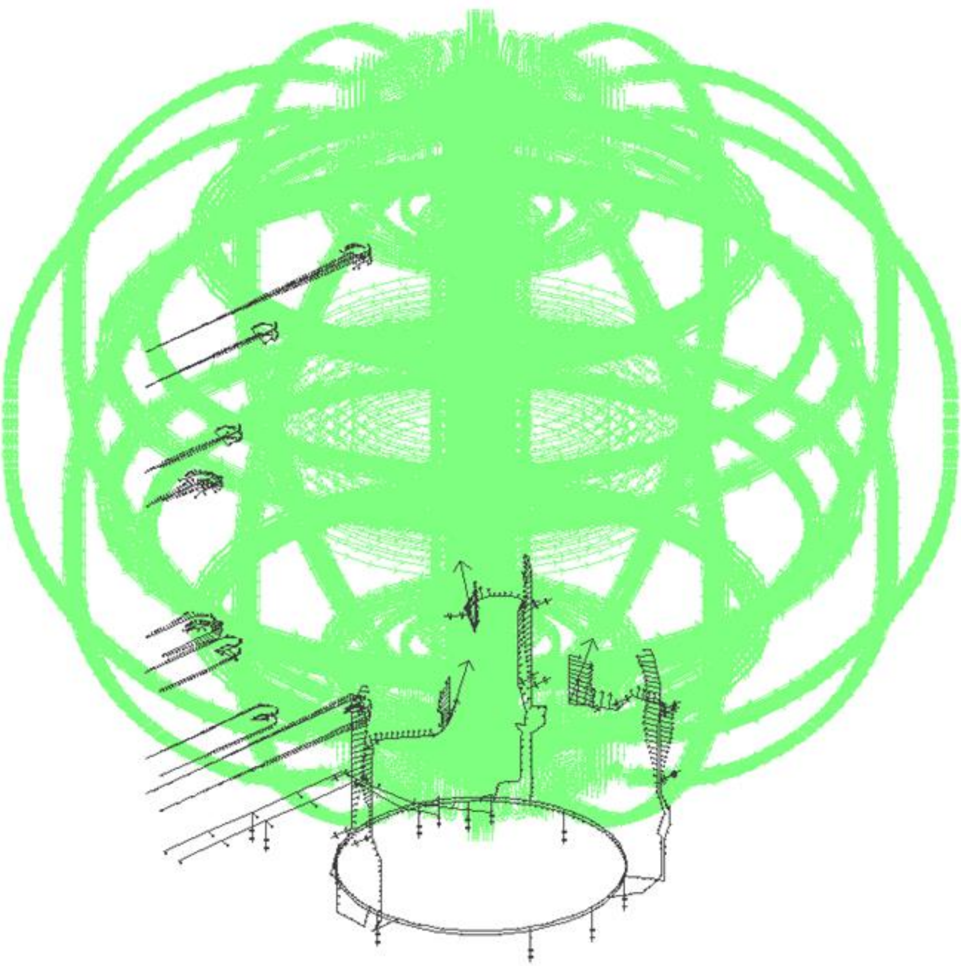


Figure 7.1-1 Biot Savart Model of NSTX and the PF 2,3,4,5 Bus Bar Including the CHI Lower Bus

7.2 Local Model of Break-Out and Reinforcement

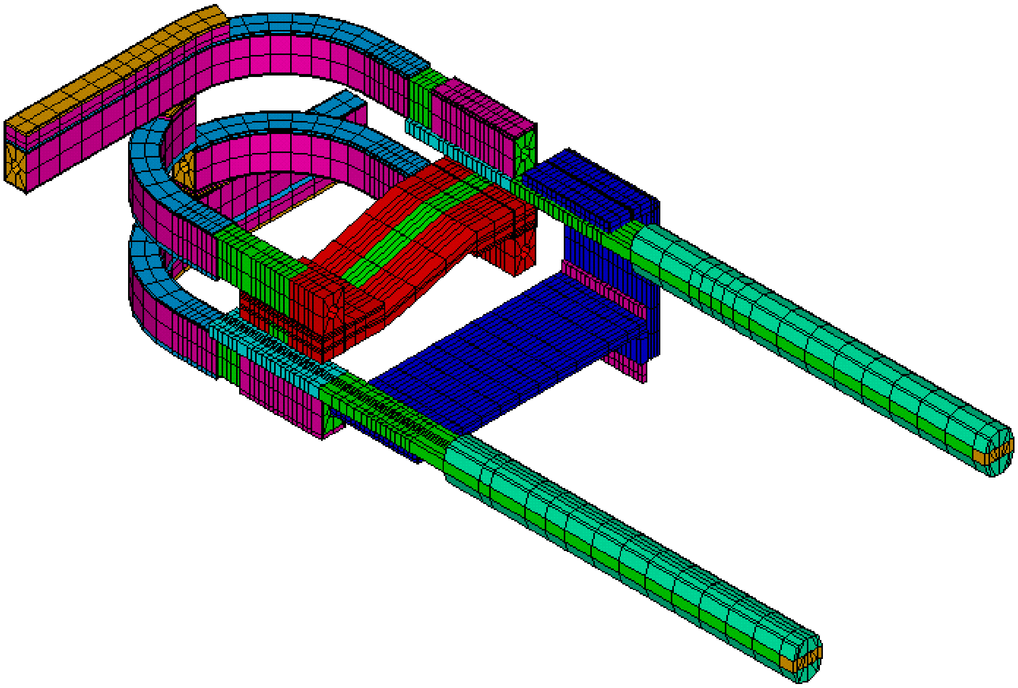


Figure 7.2-1 Model of NSTX PF 2,3,4,5 Break-Out and Cables Up to the First Support

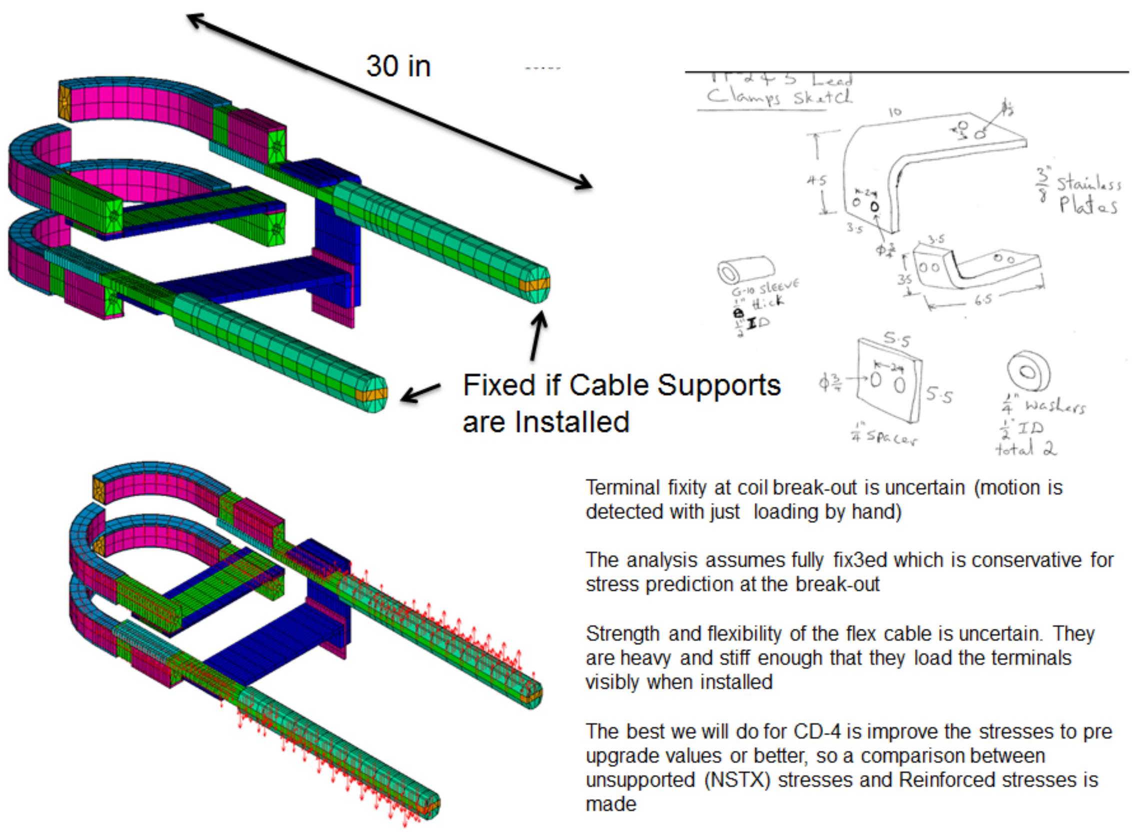


Figure 7.2-2 Model of NSTX PF 2,3,4,5 Break-Out and Cables Up to the First Support

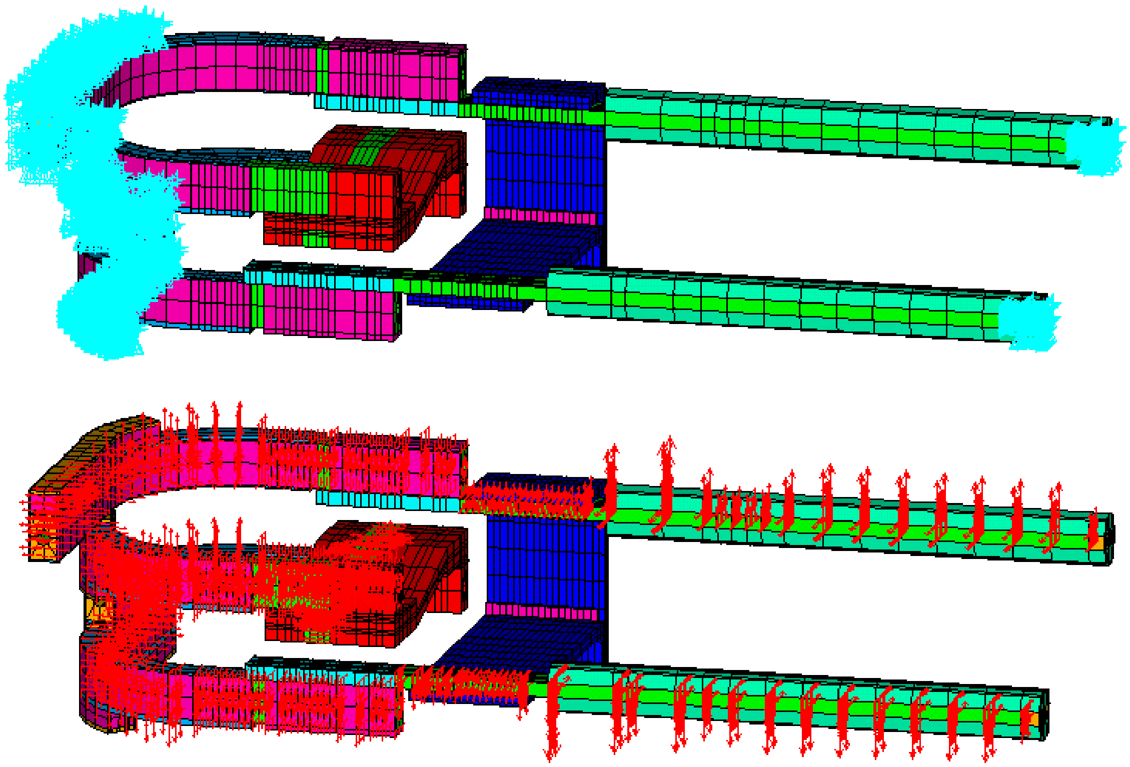


Figure 7.2-3 Model of NSTX PF 2,3,4,5 Break-Out and Cables Up to the First Support Constraints and Forces

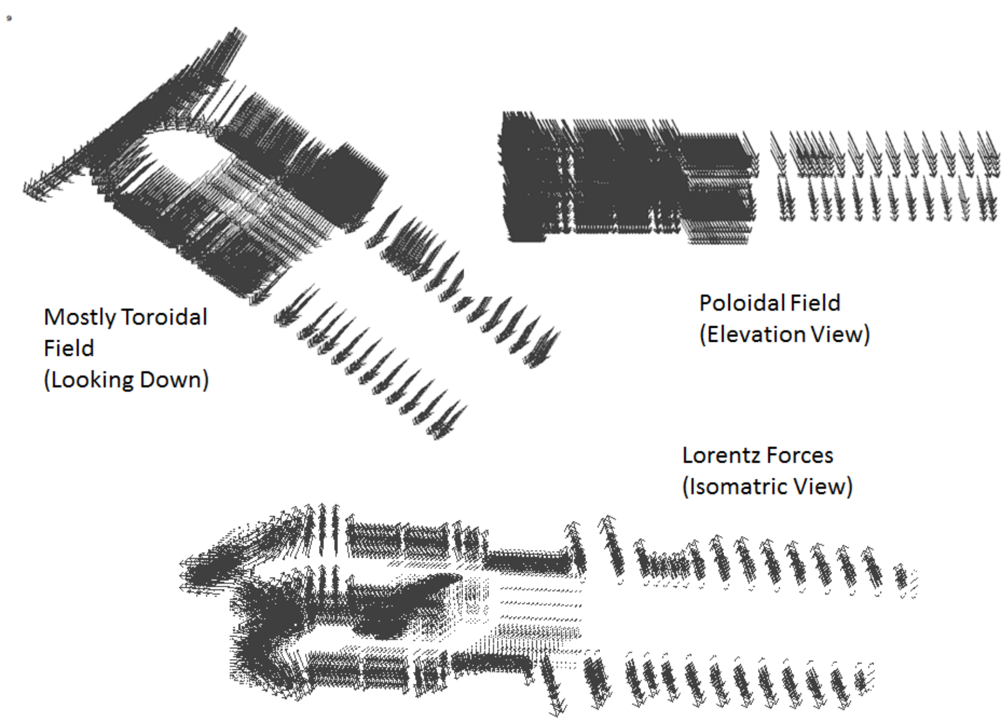


Figure 7.2-4 Model of NSTX PF 2,3,4,5 Break-Out and Cables Fields and Forces

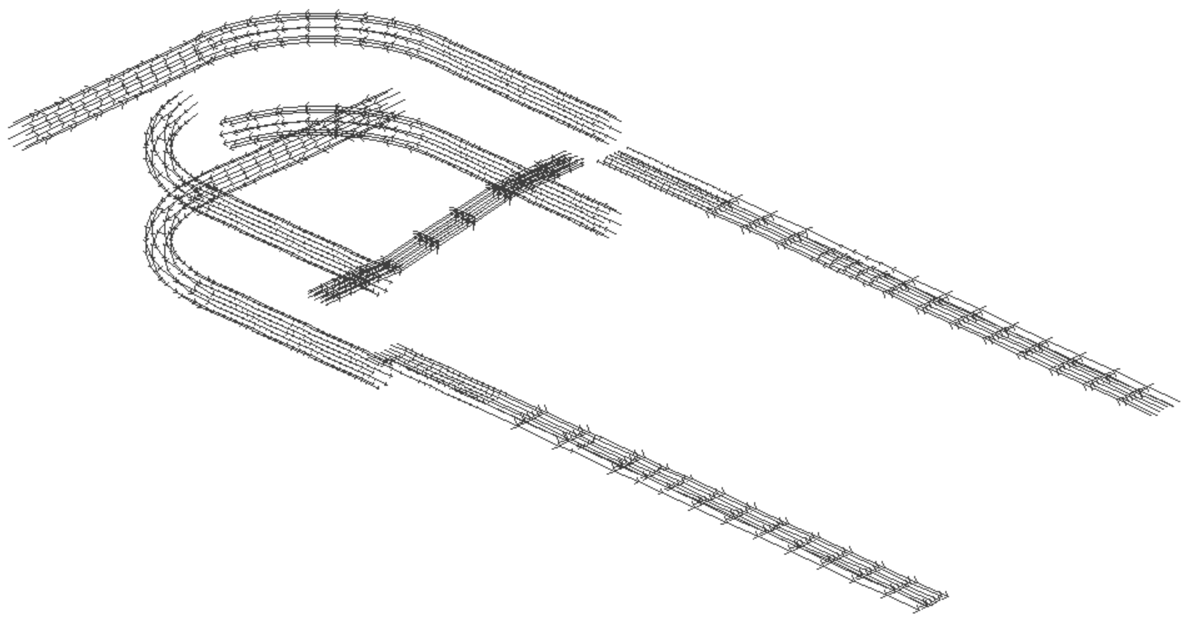


Figure 7.5 Current Vectors Associated with the Solid Conducting Elements

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 flex cables used for PF 2, 3, 4 and 5 are water cooled and are selected (by others) to meet the joule heating requirements of their currents.

9.0 Fields and Forces
9.1 Max Currents for pf 2,3,4,5 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 PF 2 and 3 leads. The PF 2 ,3 ,4 ,5 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.

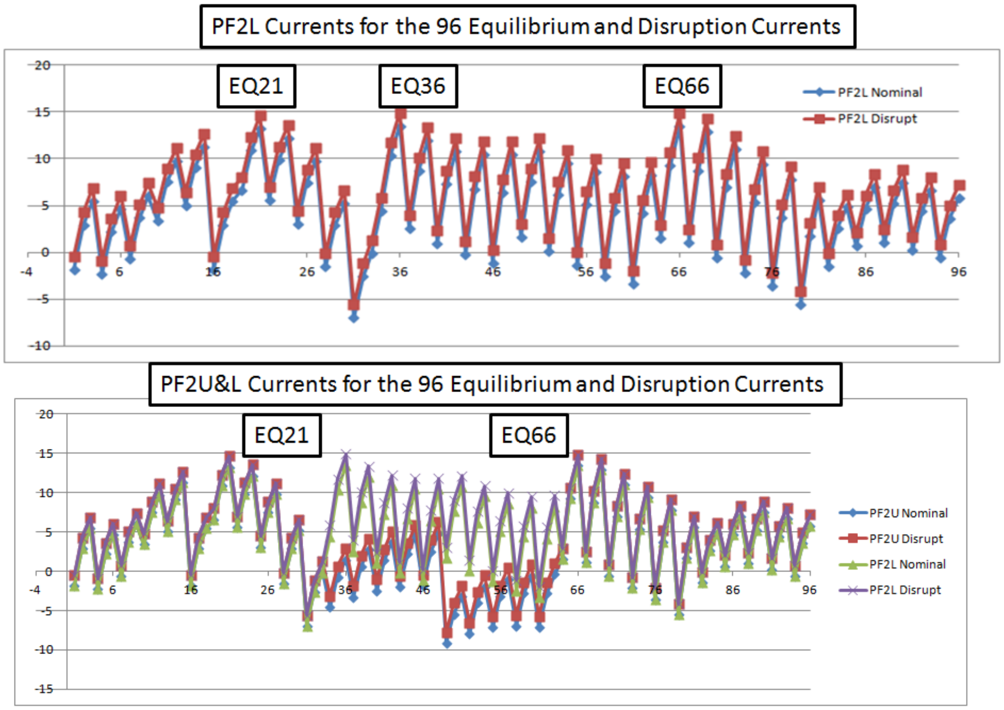


Figure 9.1-1 PF 2 Currents for the 96 Equilibria and Disruption.

Based on the plots in figure 9.1-1, EQ 66 was selected as a likely worst case along with EQ 79.

9.2 Max Fields for PF 2, 3, 4, 5 Lorentz Force Calculations

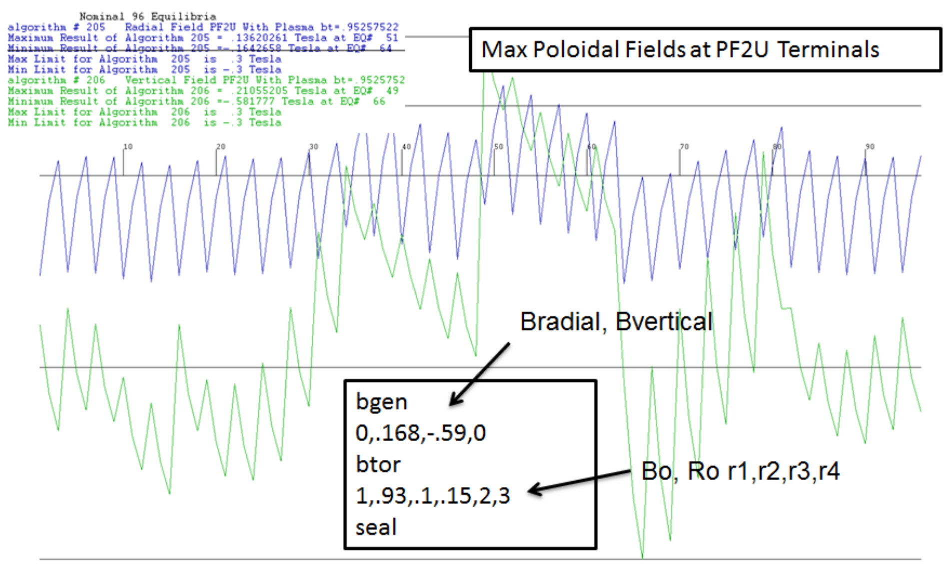


Figure 9.2-1 PF 2 Currents for the 96 Equilibria and Disruption.

! Algorithm 170 Toroidal+Vertical Field at PF2 Upper* PF2 Current
let algor$(170)="Toroidal+Vertical Field at PF2 Upper* PF2 Current"

```
let algunits$(170)="k Newton/m"
let algaccept(170)=.3*16
let algNegAccept(170)=-.3*16
let fine=20
let numpfs=15
let x=.89
let y=1.8696
let bt=.934/x
for j=1 to 96
call sfield(fine,nmax,numpfs,NomCurrents(,),numturns(),j,pfr(),pfz(),pfdr(),pfdz(),nx(),ny(),x,y,bx,by)
let algresults(170,j)= ((bt^2+by^2)^.5)*NomCurrents(j,5)
next j

! Algorithm 171 Vertical Field PF2 Lower
let algor$(171)="Toroidal+Vertical Field at PF2 Lower* PF2 Current"
let algunits$(171)="k Newton/m"
let algaccept(171)=.3*16
let algNegAccept(171)=-.3*16
let fine=20
let numpfs=15
let x=.89
let y=-1.8696
let bt=.934/x
for j=1 to 96
call sfield(fine,nmax,numpfs,NomCurrents(,),numturns(),j,pfr(),pfz(),pfdr(),pfdz(),nx(),ny(),x,y,bx,by)
let algresults(171,j)= ((bt^2+by^2)^.5)*NomCurrents(j,12)
next j
```

9.3 Max Loading for the 96 Equilibrium

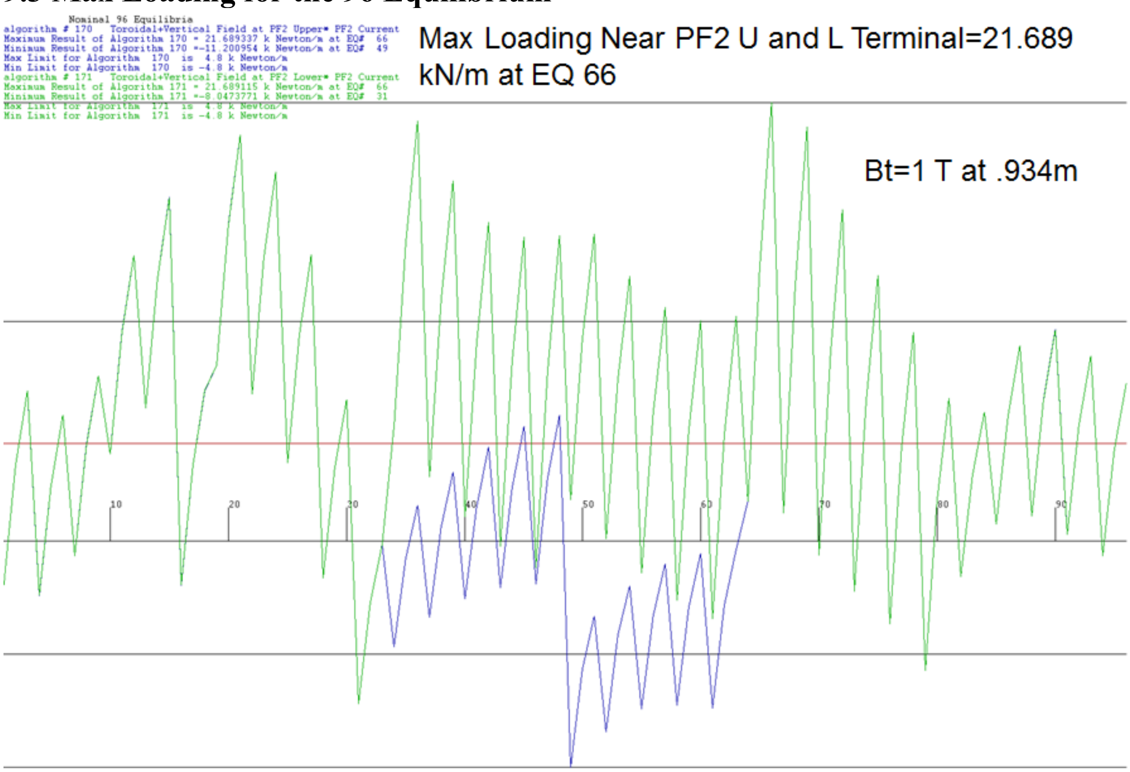


Figure 9.3-1

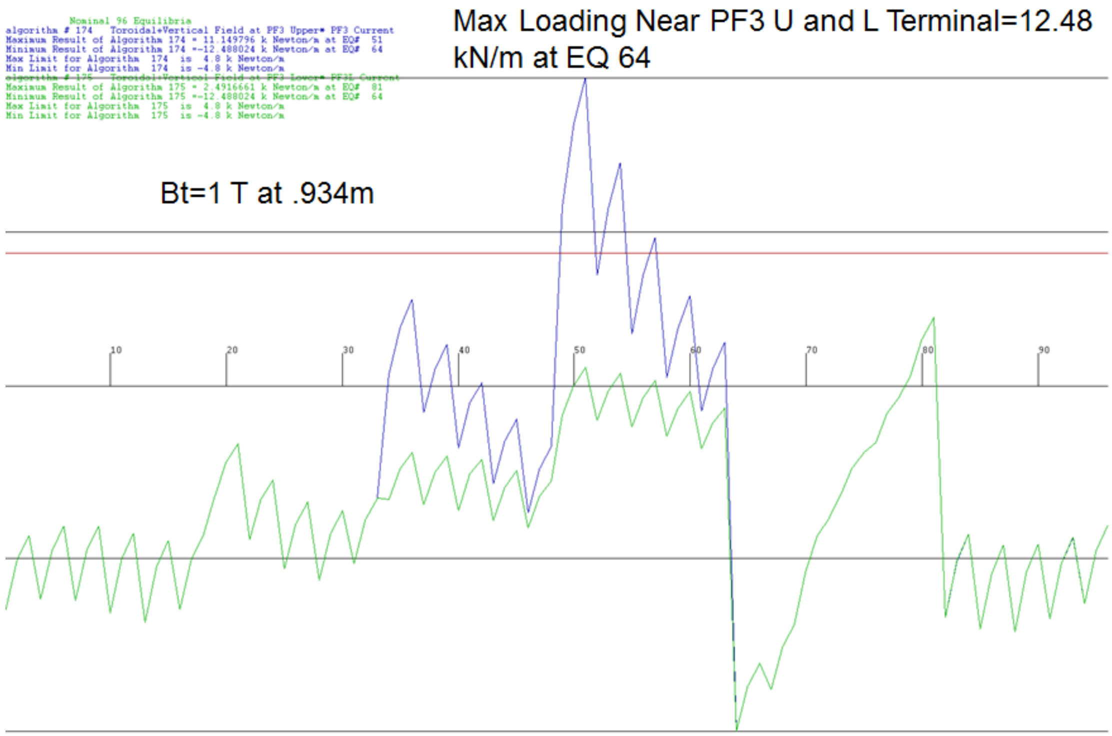


Figure 9.3-2 Max loading at PF3U and L

Note that the PF 3 loading is 12.48/21.689 = 57 % of the PF2 loading

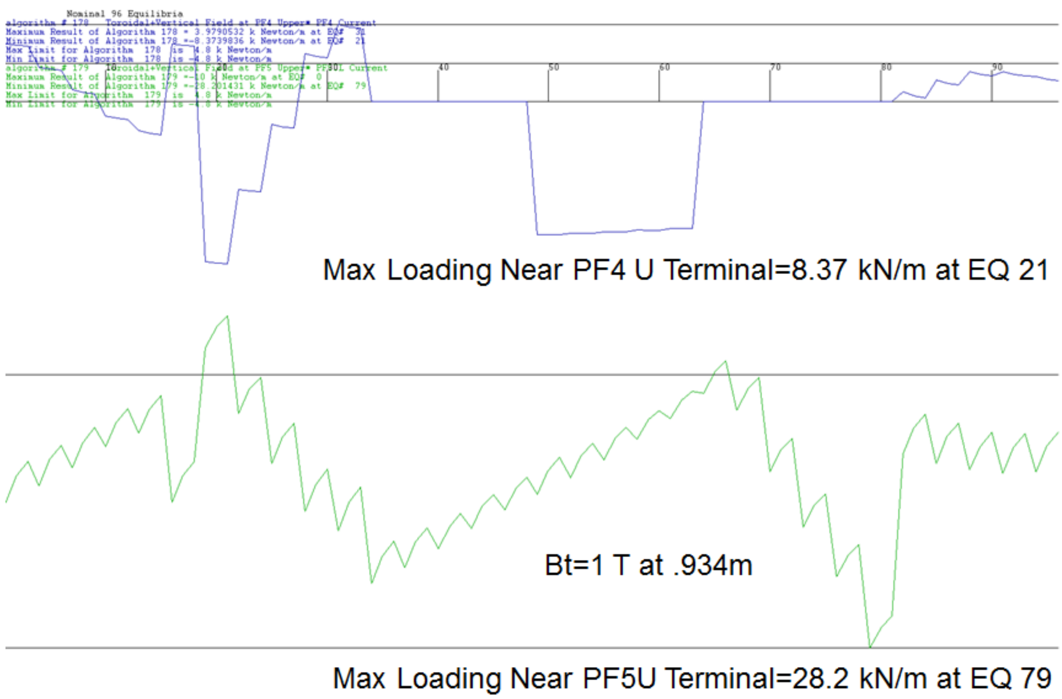


Figure 9.3-3

10.0 Lorentz Forces and Biot Savart Model

The mesh generation and calculation of the Lorentz forces is done outside of ANSYS using a code written by the author of this report. The mesh generation feature of the code is checked visually and within ANSYS during the PREP7 geometry check. The author's code can use a Biot Savart solution for field calculations as used in section 10 with the model shown in Figure 7.1-1. But for the calculation of loads on the terminals and stress analysis of the terminals, a simpler model is used. This is shown in figure 7.2-1. The input listing for load generation for this model is included in **Appendix A "Input file for the NTFTM Biot Savart Calculation"**

Information on the code, named FTM (Win98) and NTFTM2 (NT,XP), is available at: on the p: drive under \public\snap-srv\titus\ftm

The loads can be calculated within ANSYS, but the constraints on magnetic modeling vs. structural modeling make it tough to vary the structure. Coil mesh files and load files are separate in the structural model, and the support structure can be changed without changing the magnetics. The model segments and load files are input with the /INPUT command within the ANSYS batch file and look like ANSYS text commands. All the solid elements are SOLID 45's. Higher order under Public/snap-srvelements are not used because the force calculations, if done outside of ANSYS, need some correction at the mid side nodes. Recent checks of the accuracy of NTFTM are included in the magnet stiffness calculation [17]] in which the non-concentric loading between a misaligned OH and PF1a and b is quantified by both MAXWELL and NTFTM. Gap elements are the point-to-point type – Type 52. The use of the author's meshing tools is largely a result of wanting to control the mesh alignment at the interfaces, required by the point to point elements. Target surface elements take up too much solution time.

The program, NTFTM was used to generate the input currents to the Biot Savart Analysis. The Subroutine that converts terminal currents to 33 coil segment real constants is included in Appendix B. Below is the input that takes the currents from the spreadsheet and produces 8 sets of currents in the appropriate format in Meg-Amp-Turn MAt for the 33 coil regions used in this calculation:

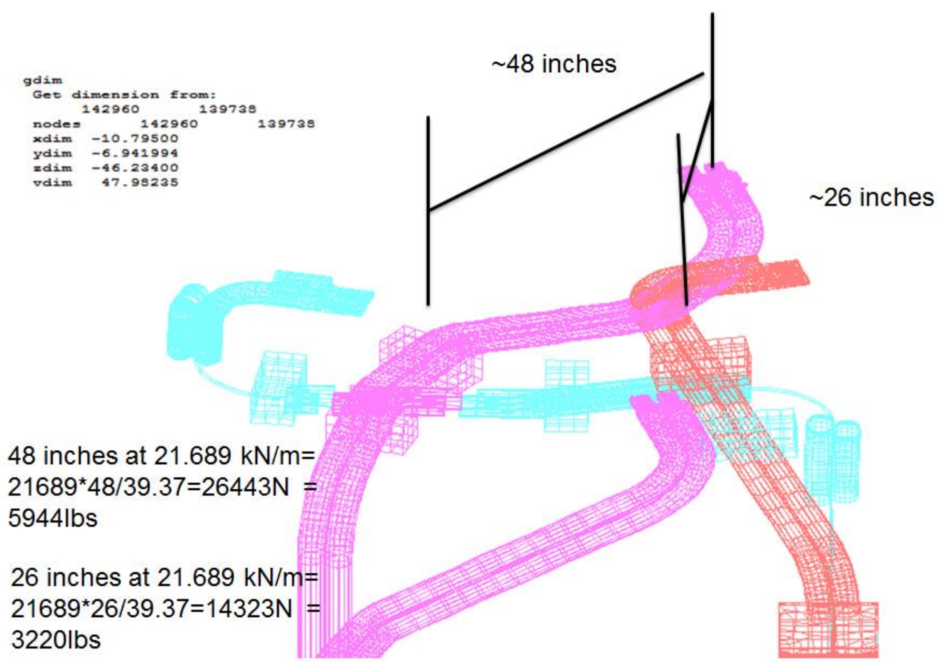


Figure 10.0-1

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].

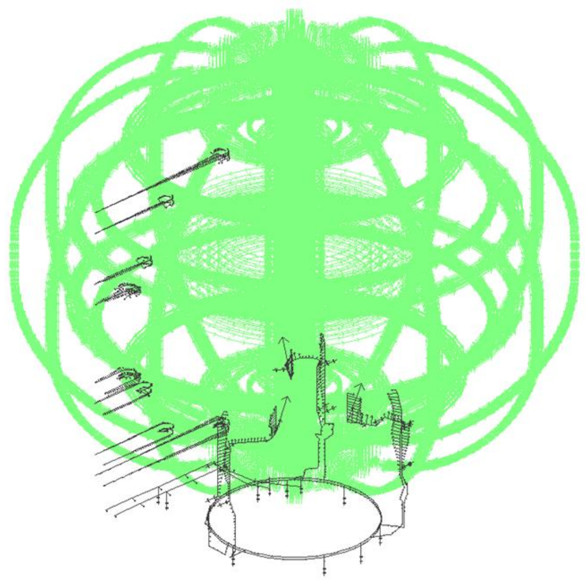


Figure 10.0-2 Biot Savart Model of NSTX and the PF 2,3,4,5 Bus Bar

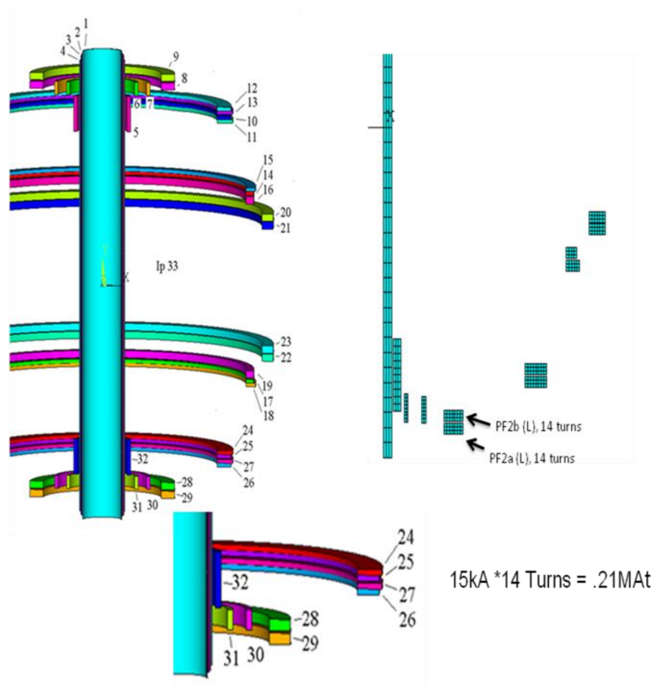
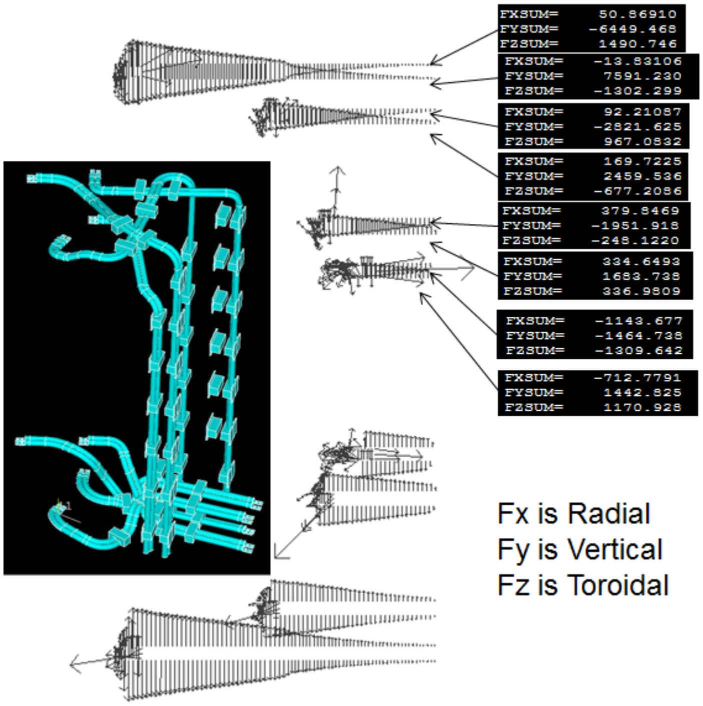


Figure 10.0-3 NSTX PF Coil Model and Real Constants used in the PF 2,3,4,5 Bus Bar Analysis



		N per 10 kAmp	max Current	Bus Load Newton	Bus Load Lbs
PF2 in	fx	50	15	75	16.86
	fy	-6449	15	-9673.5	-2174.6028
	fz	1490	15	2235	502.428
PF2 Out	fx	-13.8	15	-20.7	-4.65336
	fy	7591	15	11386.5	2559.6852
	fz	1302	15	1953	439.0344
PF3 in	fx	92.21	16	147.536	33.1660928
	fy	-2821	16	-4513.6	-1014.65728
	fz	967	16	1547.2	347.81056
PF3 out	fx	169	16	270.4	60.78592
	fy	2459	16	3934.4	884.45312
	fz	677	16	1083.2	243.50336
PF4 in	fx	379	16	606.4	136.31872
	fy	1951	16	3121.6	701.73568
	fz	248	16	396.8	89.20064
PF4out	fx	334	16	534.4	120.13312
	fy	1683	16	2692.8	605.34144
	fz	337	16	539.2	121.21216
PF5 in	fx	-1143	34	-3886.2	-873.61776
	fy	-1464	34	-4977.6	-1118.96448
	fz	-1309	34	-4450.6	-1000.49488
PF5 out	fx	-712	34	-2420.8	-544.19584
	fy	1442	34	4902.8	1102.14944
	fz	1170	34	3978	894.2544

Figure 10.0-4 Loading Provided for Initial Design

11.0 Sub Model Structural Calculations

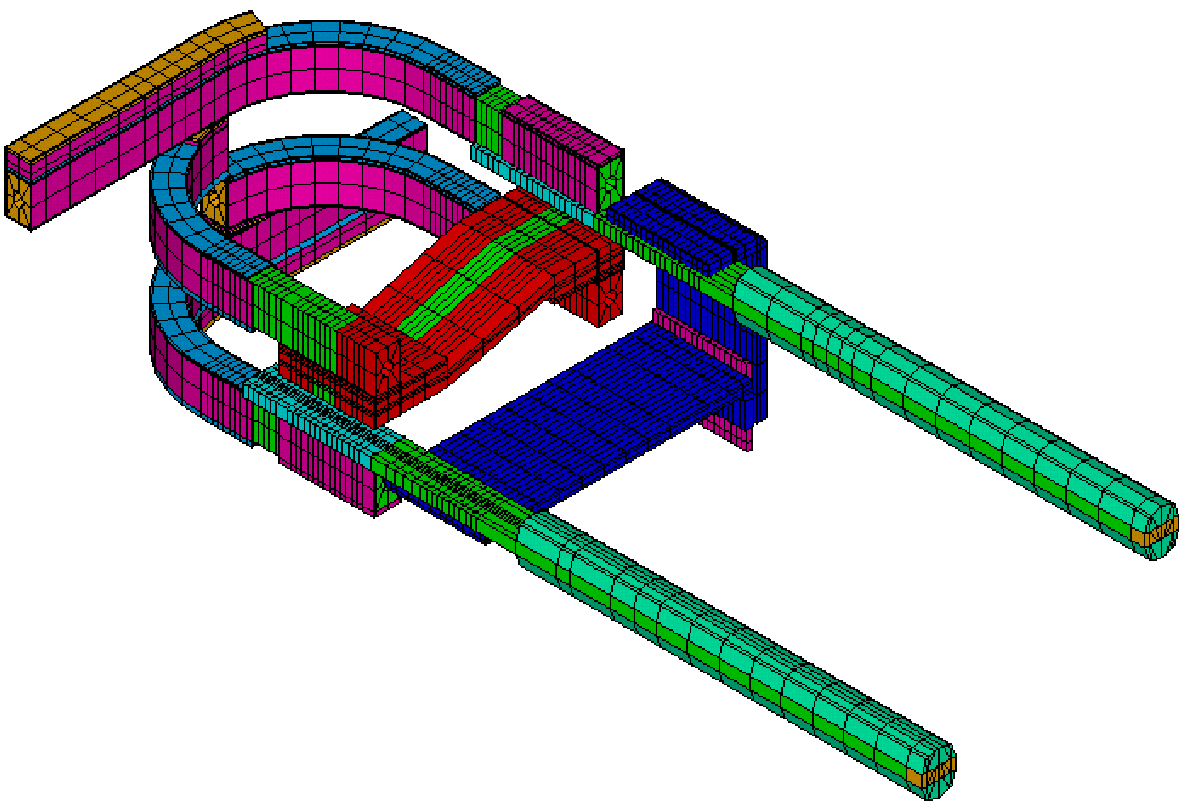


Figure 11.0-1 Sub Model of the Break-out and Flex Cable Clamps

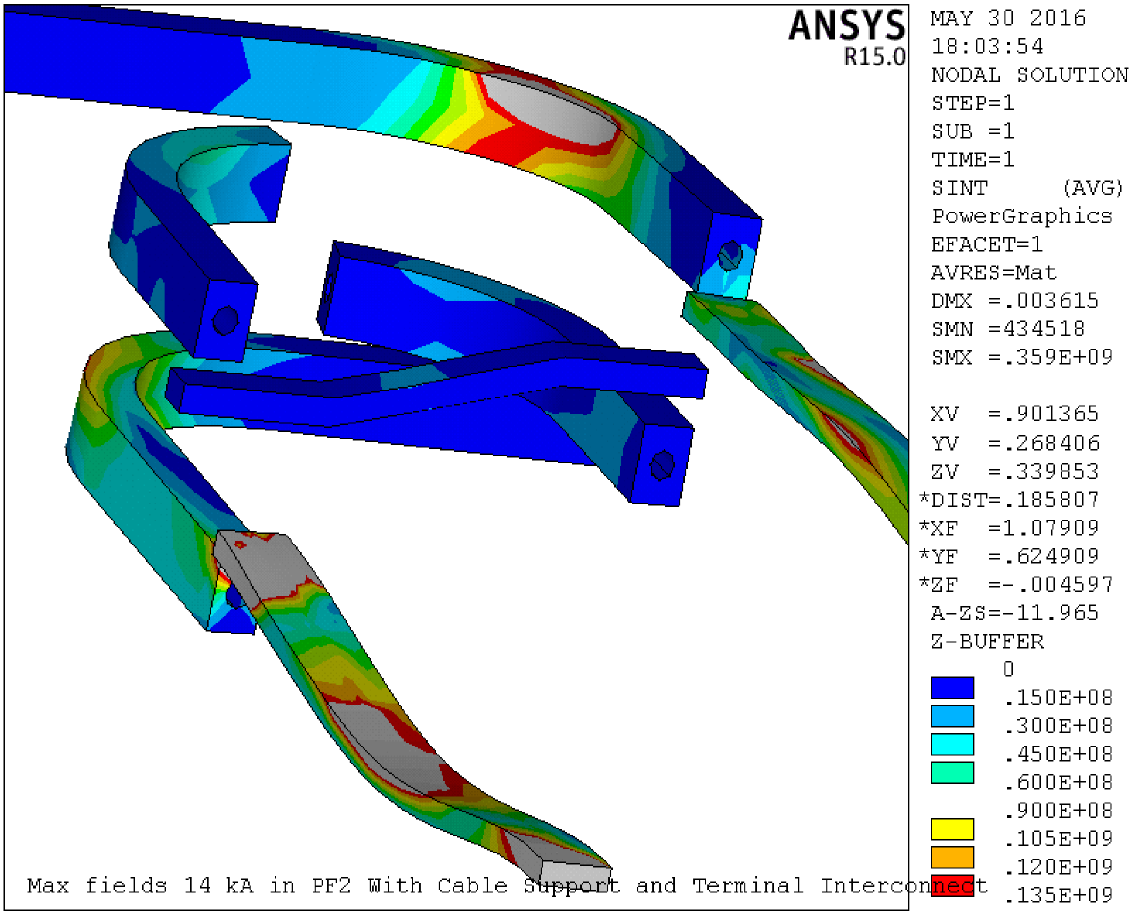


Figure 11.0-2 Stress with PF2 Loading and the Cable Support at 29 inches

Stresses for the PF2 loads and with a cable support at 29 inches are too high. The distance to the first cable support was shortened and as of June 17, Inspections indicate this is consistent with installed conditions – See Appendix D

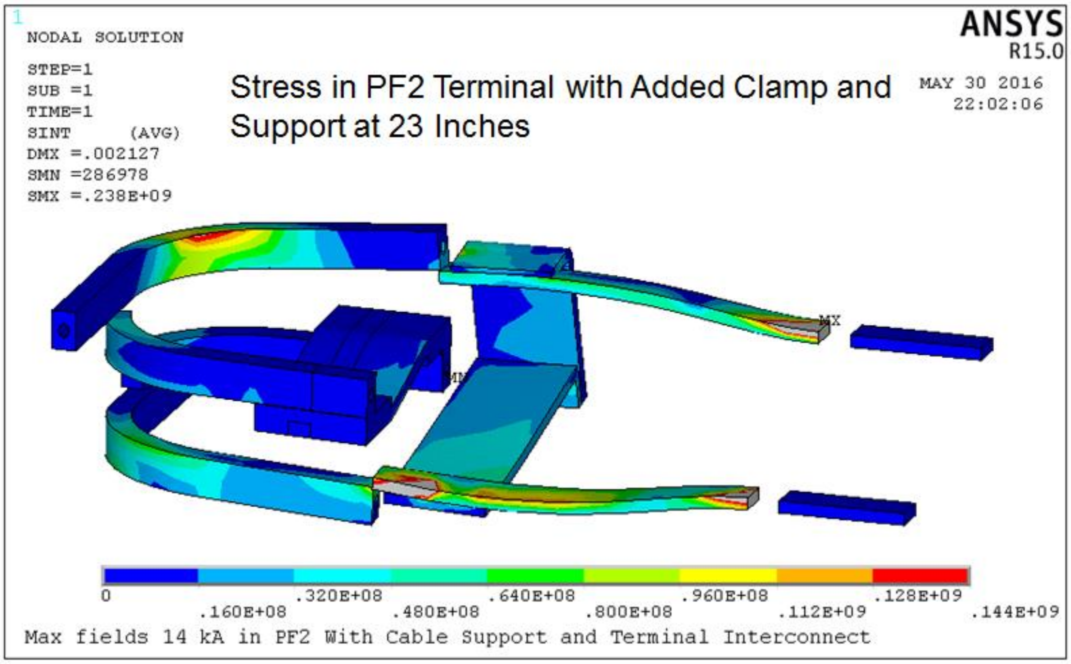


Figure 11.0-3 Stress with a Shortened Length Between the terminal and Flex Cable Support

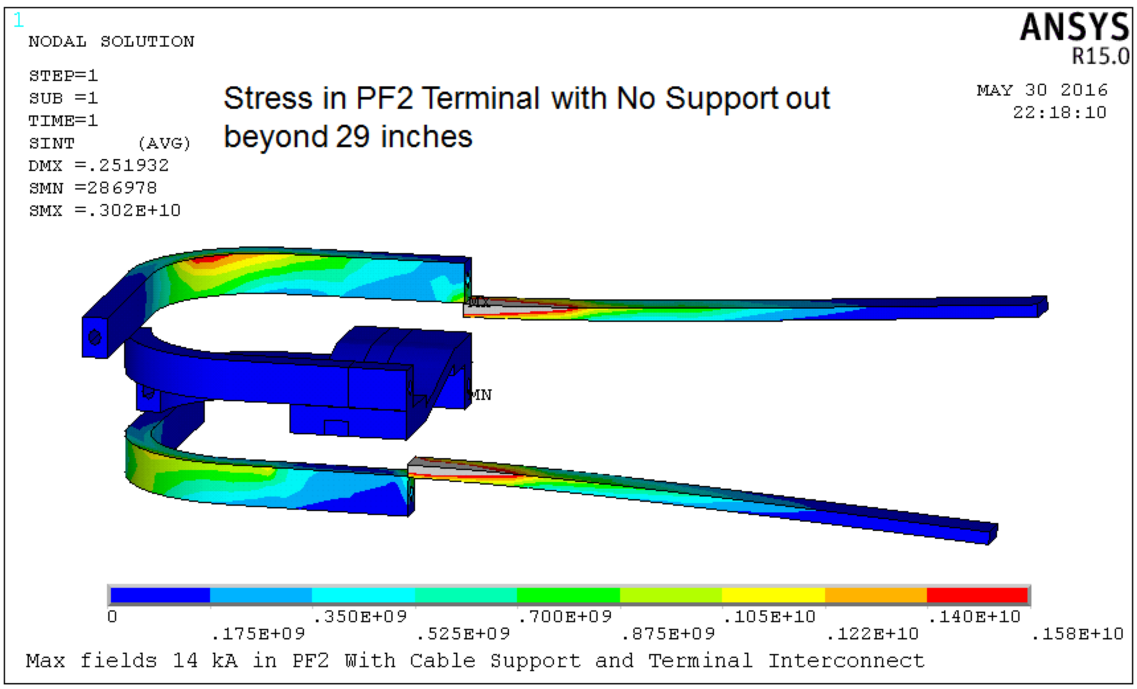
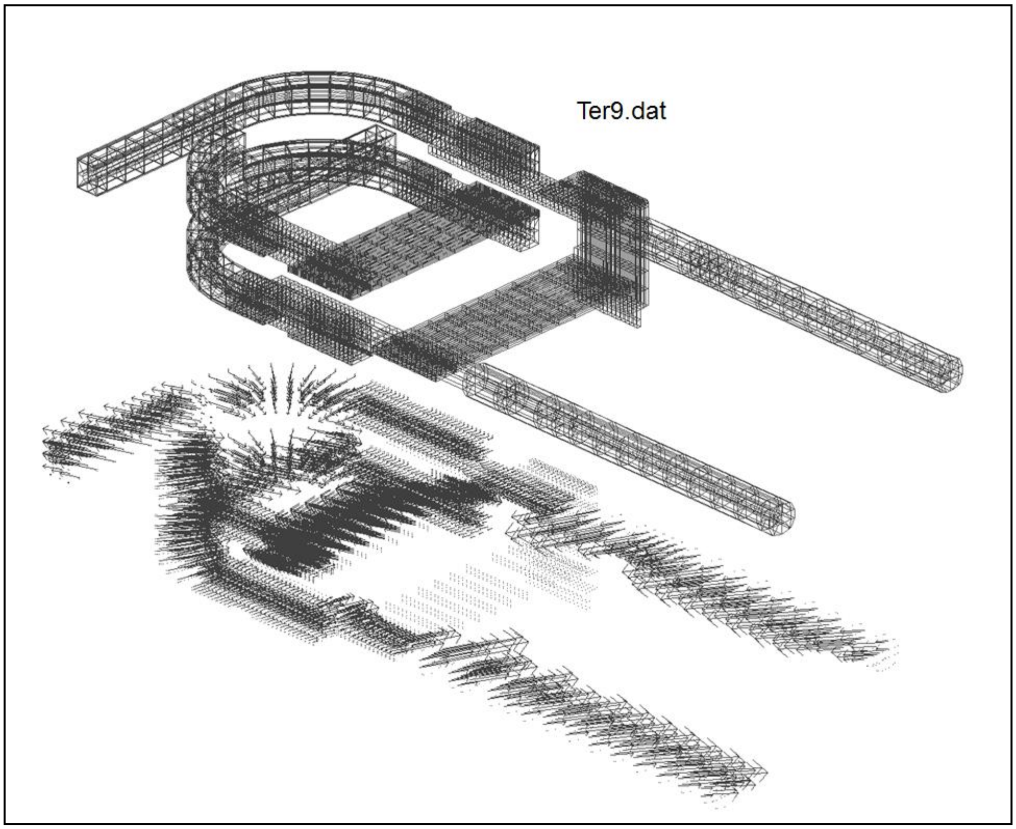


Figure 11.0-4 Stress in the PF2 Terminal With No Support of the Flex Cable

Appendix A
Input file for the NTFTM Terminal Load Calculation, ter9.txt

```
zero
read
ter9
gtrans
0,-47.748,0,0   !shift from PF5 radius to PF2
0,-20,0,0,      !shift from PF5 radius to PF3
0,0,0,0,0       !Remain at PF5 Radius

tera
smat
10,10
snal
1
merge
1,.000001
chke
gerase
99
redu
conv
1,1
redu

bgen
1,.168,-.59,0
1,.3,-.5,.43
btor
1,.93,.1,.15,2,3
seal
1
smat
17,17
grprel
17,17
r
17,1,1846     !14770/8

mfor
17,1,2,3,4,5,6,7,8
tmsa
ter9,2
exit
```

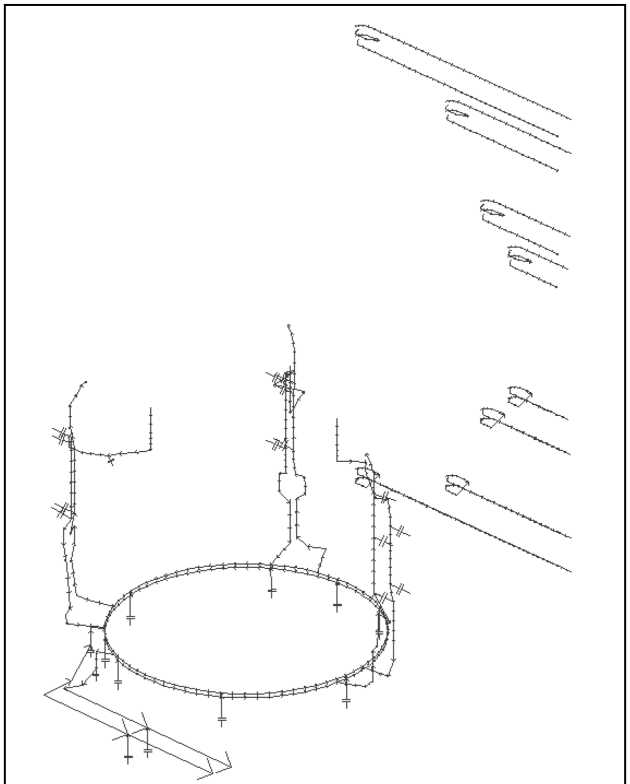


Appendix B
Input file for the ANSYS Stress Analysis of the Small Terminal and Cable Model

```
/batch
/prep7
et,1,45
*do,imat,1,100
ex,imat,117e9
r,imat,.1
```

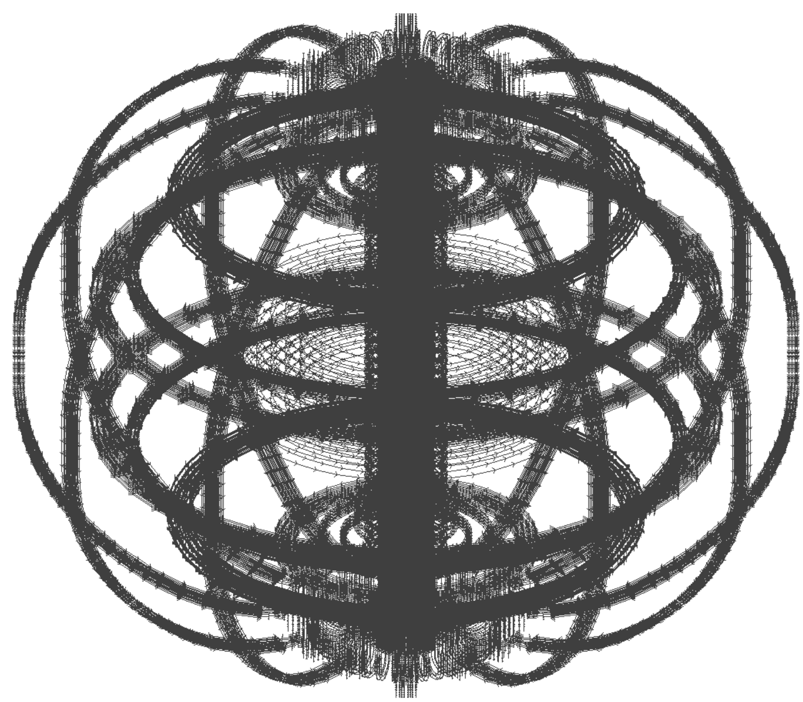
```
ex,5,20e9
ex,10,185e9
ex,11,1e6
*enddo
/input,conn,mod
nummer,node,.0001
esel,mat,40
nelem
d,all,all,0,0
nall
eall
save
fini
/solu
/title, Max fields 14 kA in PF2
solve
save
fini
/exit
```

Appendix C
Biot Savart Beam=-Stick Model (ch66.txt)


Chi2.dat

```
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



Vec2.dat

irdt
2
pfcu
33,8,8,1.1
1 , 0.0000000E+00 , 2.8782515E-03 , -5.3039999E-03 , 0.0000000E+00 , 2.8782515E-03 , -5.3039999E-03 , 0.0000000E+00 , 2.8782515E-03
2 , 0.0000000E+00 , 2.878252 , -5.304000 , 0.0000000E+00 , 2.878252 , -5.304000 , 0.0000000E+00 , 2.878252
3 , 0.0000000E+00 , 2.878252 , -5.304000 , 0.0000000E+00 , 2.878252 , -5.304000 , 0.0000000E+00 , 2.878252
4 , 0.0000000E+00 , 2.878252 , -5.304000 , 0.0000000E+00 , 2.878252 , -5.304000 , 0.0000000E+00 , 2.878252
5 , 0.6669568 , 0.7544626 , 0.3486400 , 0.4294720 , 0.4729505 , 0.3366080 , 0.4194112 , 0.4624799
6 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00 , 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 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00
8 , -3.8801003E-02 , -5.6559579E-03 , 2.1805000E-02 , 0.1295574 , 0.1880718 , 1.5450400E-02 , 0.1227352 , 0.1809008
9 , -3.8801003E-02 , -5.6559579E-03 , 2.1805000E-02 , 0.1295574 , 0.1880718 , 1.5450400E-02 , 0.1227352 , 0.1809008
10 , 6.5442999E-03 , 1.5126851E-02 , -9.8340198E-02 , -9.0846702E-02 , -8.6778782E-02 , -9.0611503E-02 , -8.2838699E-02 , -7.8333564E-02
11 , 7.4791997E-03 , 1.7287830E-02 , -0.1123888 , -0.1038248 , -9.9175751E-02 , -0.1035560 , -9.4672799E-02 , -8.9524068E-02

12 , 6.5442999E-03 , 1.5126851E-02 , -9.8340198E-02 , -9.0846702E-02 , -8.6778782E-02 , -9.0611503E-02 , -8.2838699E-02 , -7.8333564E-02
13 , 7.4791997E-03 , 1.7287830E-02 , -0.1123888 , -0.1038248 , -9.9175751E-02 , -0.1035560 , -9.4672799E-02 , -8.9524068E-02
14 , -3.9999999E-02 , -3.9999999E-02 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00
15 , -3.9999999E-02 , -3.9999999E-02 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00
16 , -9.0000004E-02 , -9.0000004E-02 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00
17 , -3.9999999E-02 , -3.9999999E-02 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00
18 , -5.0000001E-02 , -5.0000001E-02 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00
19 , -7.9999998E-02 , -7.9999998E-02 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00
20 , -0.2478456 , -0.2443637 , -0.2489736 , -0.2394372 , -0.2343124 , -0.2578608 , -0.2485920 , -0.2437394
21 , -0.2478456 , -0.2443637 , -0.2489736 , -0.2394372 , -0.2343124 , -0.2578608 , -0.2485920 , -0.2437394
22 , -0.2478456 , -0.2443637 , -0.2489736 , -0.2394372 , -0.2343124 , -0.2578608 , -0.2485920 , -0.2437394
23 , -0.2478456 , -0.2443637 , -0.2489736 , -0.2394372 , -0.2343124 , -0.2578608 , -0.2485920 , -0.2437394
24 , -1.6039200E-02 , -9.5841894E-03 , -0.1123888 , -0.1038248 , -9.9175751E-02 , -0.1035560 , -9.4672799E-02 , -8.9524068E-02
25 , -1.4034300E-02 , -8.3861658E-03 , -9.8340198E-02 , -9.0846702E-02 , -8.6778782E-02 , -9.0611503E-02 , -8.2838699E-02 , -7.8333564E-02
26 , -1.4034300E-02 , -8.3861658E-03 , -9.8340198E-02 , -9.0846702E-02 , -8.6778782E-02 , -9.0611503E-02 , -8.2838699E-02 , -7.8333564E-02
27 , -1.6039200E-02 , -9.5841894E-03 , -0.1123888 , -0.1038248 , -9.9175751E-02 , -0.1035560 , -9.4672799E-02 , -8.9524068E-02
28 , 5.8469601E-02 , 0.1153399 , 2.1805000E-02 , 0.1295574 , 0.1880718 , 1.5450400E-02 , 0.1227352 , 0.1809008
29 , 5.8469601E-02 , 0.1153399 , 2.1805000E-02 , 0.1295574 , 0.1880718 , 1.5450400E-02 , 0.1227352 , 0.1809008
30 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00 , 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 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00
32 , 0.4439488 , 0.4851560 , 0.3486400 , 0.4294720 , 0.4729505 , 0.3366080 , 0.4194112 , 0.4624799
33 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00 , 0.0000000E+00

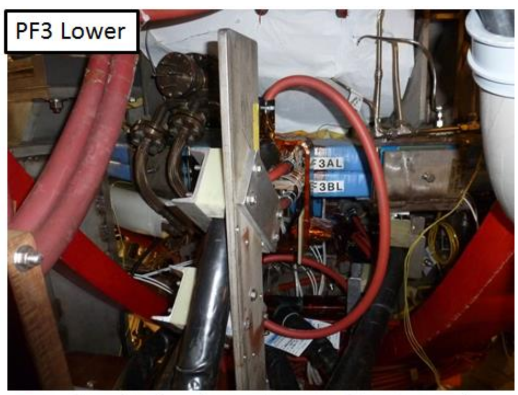
rscale
1,1,1,.5
rscale
2,1,2,.5
rscale
3,1,3,.5
rscale
4,1,4,.5

```
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
61,1,9000.0    !CHI Coil Normal Operating Load
61,1,50000.0    !CHI Coil Halo Currents = .075*2e6/3

r
62,1,9000.0    !CHI Coil Normal Operating Load
62,1,50000.0    !CHI Coil Halo Currents = .075*2e6/3
r
63,1,10000
r
64,1,150000.0   ! Main Feeds take the full halo curren
stype
8,8
snel
8,8
repla
cvec
!exit
field
5
stype
8,8
gerase
8
stype
2,2
grpt
5,1
redu
mfor
```

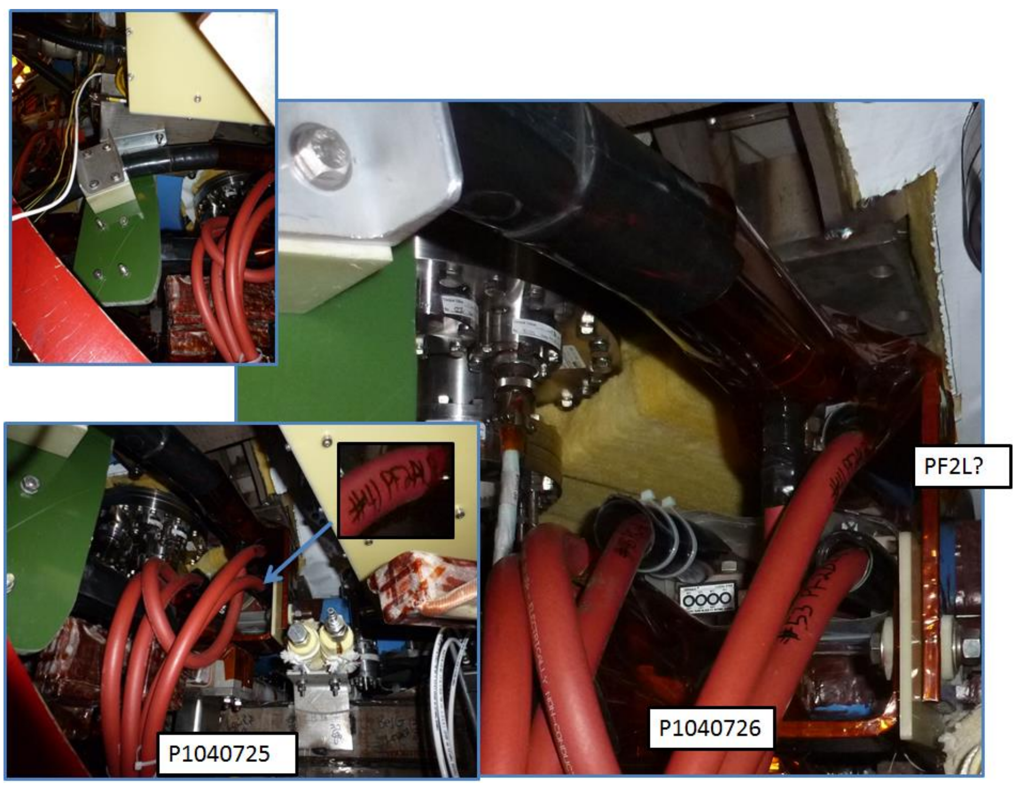
```
5,1,1,1,1,2,2,2,2
repla
chif
tmsa
chi2,2

exit

srel
33,33
gera
33
redu


tmsa
ch79,3


exit
```

Appendix D

Photos of Installed Cable Supports [15]




Mount

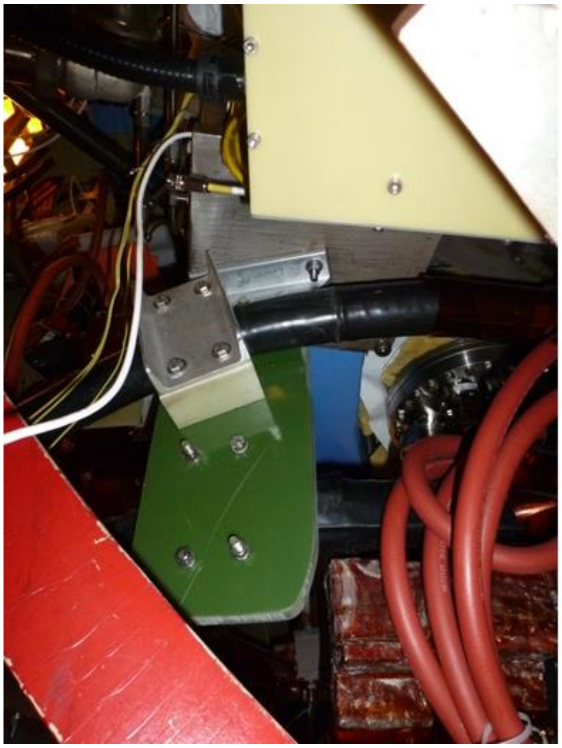

PF2L?
P1040725
P1040726


Mount

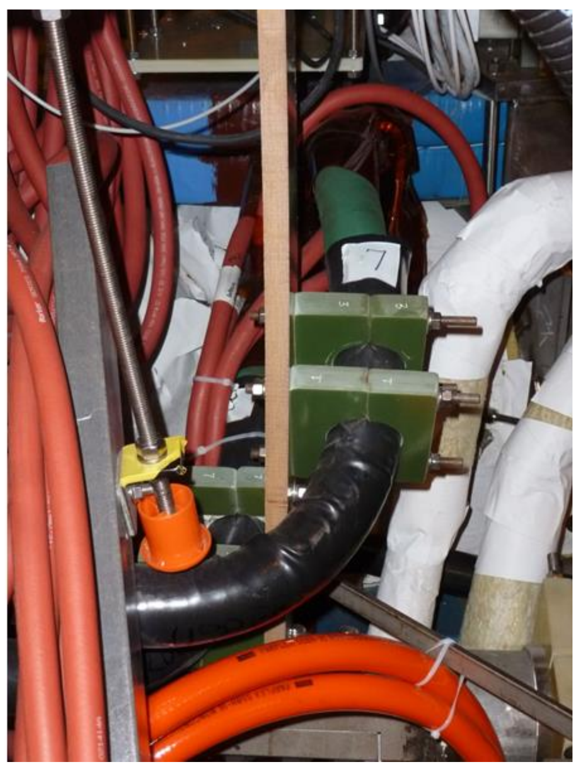


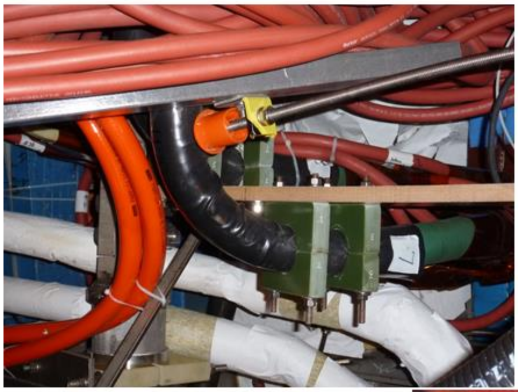

PF3 Upper?

PF3 Upper?




PF3 Lower





Appendix E
Flex Cable Catalog

FLEX - CABLE

NCS Northern Connectivity Systems Inc.

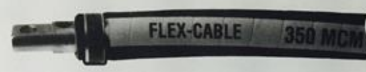
CMC COMMODORE MACHINE COMPANY

Presented to:

D i v i s i o n s o f B a l a g u e r C o r p o r a t i o n

1749 Northwood Drive
Troy, Michigan 48084
www.flexcable.com

248-269-1900
fax: 248-269-6016
1-800-CHK-FLEX



Applications **Our standard cable. Suitable for both manual and robotic applications.**

Technical Data

MCM Ratings	350	400	500	600	700	10[illegible]
Min. Bend Radius	2"	2"	3"	3"	4"	4"
Hose OD	1.45	1.56	1.69	1.81	1.93	2.2[illegible]
Color Code	Black with White Identifying Stripe					
Jacket Material	SBR					
Reinforcement	Polyester Tire Cord					
Working Pressure	150psi					
Voltage Rating	100V					
Temperature Rating	180°F					
Torsional Flexibility Factor	4.2					
Bend Flexibility Factor	7.4					
Abrasion Resistance Factor	3.0					

Very-Flex™

Applications **Very-Flex has an extra reinforcing spiral which provides abrasion and impact resistance along the entire length of the cable. Recommended for tough robotics applications.**

Technical Data

MCM Ratings	350	400	500	600	700	[illegible]
Min. Bend Radius	2"	2"	3"	3"	4"	4"
Hose O.D.	1.59	1.65	1.78	2.00	2.19	[illegible]
Color Code	Yellow with Black Stripe					
Jacket Material	SBR with Rope Impression					
Reinforcement	Polyester Tire Cord					
Working Pressure	150psi					
Voltage Rating	100V					
Temperature Rating	180°F					
Torsional Flexibility Factor	3.6					
Bend Flexibility Factor	6.8					
Abrasion Resistance Factor	5.1					