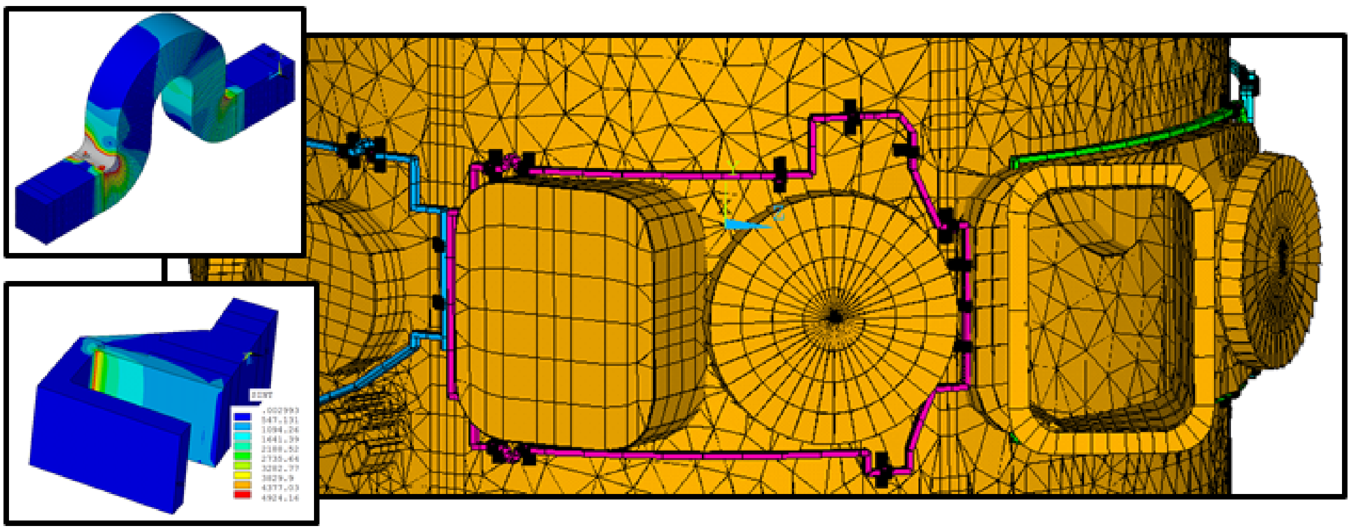
# NSTX Upgrade

# Resistive Wall Mode (RWM) Coils Structural and Thermal Analysis

**NSTXU-CALC-12-12-00**

**Rev 0**

**August 27, 2014**



**Prepared By:**


Peter H. Titus

Digitally signed by Peter H. Titus
DN: cn=Peter H. Titus, o, ou=Princeton Plasma Physics Laboratory, email=ptitus@pppl.gov, c=US
Date: 2014.08.27 11:10:47 -04'00'

Peter Titus,


**Reviewed By:**


Robert D. Woolley

Digitally signed by Robert D. Woolley
DN: cn=Robert D. Woolley, o=Princeton Plasma Physics Laboratory, ou, email=woolley@pppl.gov, c=US
Date: 2014.08.27 12:23:15 -04'00'

Robert Woolley


**Reviewed By:**


Phil Heitzenroeder

Digitally signed by Phil Heitzenroeder
DN: cn=Phil Heitzenroeder, o=MED, ou=PPPL, email=pheitzen@pppl.gov, c=US
Date: 2014.09.15 15:22:32 -04'00'

Phil Heitzenroeder, Head, Mechanical Engineering

# PPPL Calculation Form

Calculation # **NSTXU-CALC-12-12-00** Revision # **00** _____WP #, **1672** (ENG-032)

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

The purpose of this calculation is to qualify the Resistive Wall Mode (RWM) coils for Upgrade Loads and new currents made possible by the addition of new SPA power supplies [10]

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.)

The maximum differential temperature between the RWM coils and the vessel is assumed to be less much less than 100C. Joule heat from operation of the coils is estimated to be small, less than 20 degrees C. Bakeout differential temperature from the inside to the outside of the insulation may allow the vessel to be hotter than the coils. Insulation is applied to allow the RWM coils to be exposed to air, and could be colder than the vessel during bake-out. The vessel is assumed infinitely rigid and at one temperature.

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.)

The RWM coils are acceptable for the upgrade loads resulting from the higher background NSTX-U fields and higher currents in the RWM coils, with the addition of some new clamps.

The power feed connection are currently clamped to PF 5 lower. Since PF5 will be operating at higher temperatures in the upgrade, and will expand radially, the RWM lead clamps must allow radial sliding. New clamps or clamp spacers may be needed.

Thermal expansion behavior of the RWM coils was simulated with 20 degree delta T with respect to the vessel. This can be caused by Joule heating of the coils or by differential heating during bakeout. Expansion is accommodated by "U" flexes in the corners to allow toroidal expansion. Vertical expansion of the vessel is accommodated by leaving a vertical gap in the clamp nearest the corner. A 3mm gap is used in the model and this was found to produce acceptable stresses in the conductors and clamps. To provide vertical constraint of the vertical runs, the gap should only be in the upper clamps. The lower clamps should be tight.

Bay FG requires an additional clamp on the upper dogleg. The only restraint for that upper dogleg is torsional resistance of the conductor and flexes.

Bay LA has a span which is the worst stressed location. It is an upper toroidal run that is approximately 30 inches with flexes at each end. The stress is acceptable but this is a candidate for a mid span clamp. In the lower right hand corner of Bay LA, there is a bending stress that would result from loose and sliding connections at the clamps. These clamps in the lower corner should be tight.

Fundamental frequencies of the RWM coils start at 86 Hz and go up. Time near these frequencies should be limited. Eighty hz operation is near the natural frequencies of the coils. A dynamic amplification factor of 2 was at first estimated and then a transient dynamic solution was performed to better quantify the amplification factor. . Clamp and flex details are within static and fatigue allowables.

Cognizant Engineer's printed name, signature, and date

George Labik

George Labik

Digitally signed by George Labik
DN: cn=George Labik, o, ou, email=glabik@pppl.gov, c=US
Date: 2014.09.26 14:05:48 -04'00'

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

Checker's printed name, signature, and date

Robert D. Woolley

Digitally signed by Robert D. Woolley
DN: cn=Robert D. Woolley, o=Princeton Plasma Physics Laboratory, ou, email=woolley@pppl.gov, c=US
Date: 2014.08.27 12:24:48 -04'00'

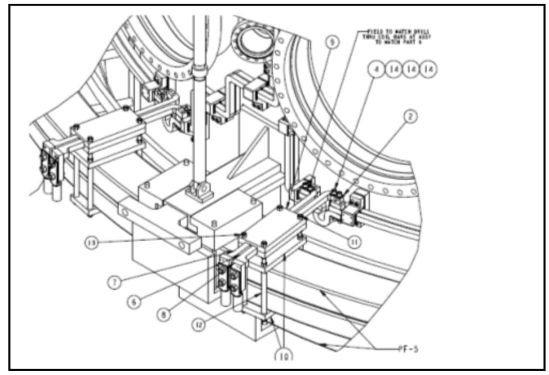
## 2.0 Table of Contents



## 3.0 Revision Status Table

| | |
|---|---|
| Rev 0 | Initial Issue |

## 4.0 Executive Summary



The RWM coils have been found acceptable for the upgrade loads resulting from the higher background NSTX-U fields and expected currents in the RWM coils, with a couple of extra clamps installed and with some improvements in the lead supports.

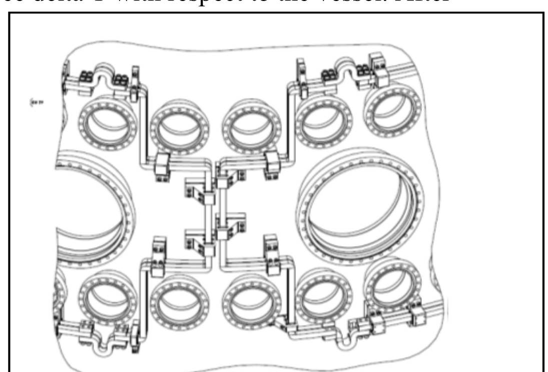
Bay FG requires an additional clamp on the upper dogleg The only restraint for that upper dogleg is torsional resistance of the conductor and flexes.

Bay LA has a span which is the worst stressed location. It is approximately 30 inches with flexes at each end. The stress is acceptable but this is a candidate for a mid span clamp. At the lower right hand corner the clamps should be tight to restrain toroidal motion of the conductor to the right of the flex.

The power feed connection are currently clamped to PF 5 lower. Since PF5 will be operating at higher temperatures in the upgrade, and will expand radially, the RWM lead clamps must allow radial sliding.

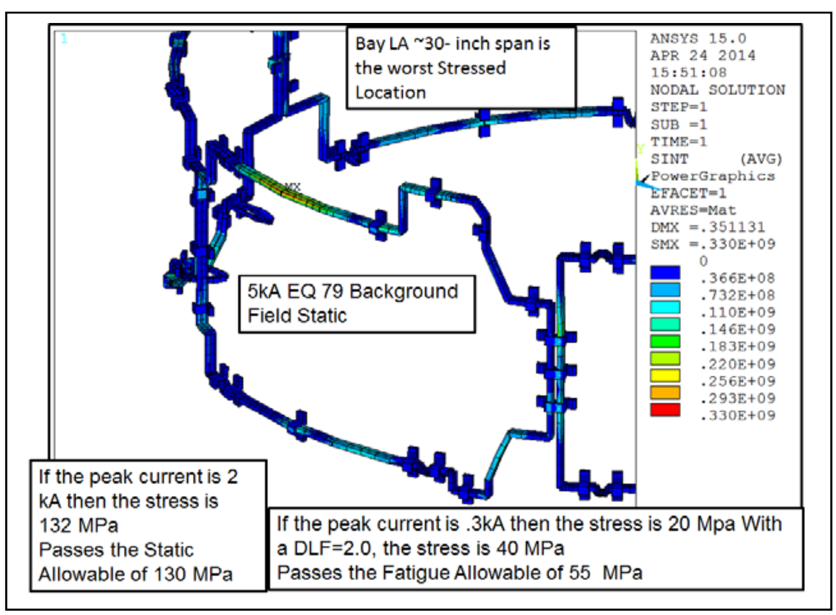
The external resistive wall mode coils were installed in the original NSTX and there is a substantial design analysis and review history prior to NSTX upgrade . One important target conservatism in the original design was to size components for 5 kA operation. The objective of this analysis is to estimate and assess the stresses in the Resistive Wall Mode (RWM) Coils, and their supports for upgrade loads. George Labik originally designed the clamps and coils with hand calculations that had sufficient conservatism to envelope the upgrade Lorentz loads. The coils were intended to be supported every ~20 inches by G-10 lined steel clamps. Details of the support positions and types of supports are shown in drawing E-DC1329, Shell Coils General Arrangement Bays A-L, [1]

Thermal expansion behavior of the RWM coils was simulated with 100 degree delta T with respect to the vessel. After discussions with George and obtaining the actual operating parameters, 20 degrees C is more like the differential temperatures that the coils will see during operation. This can be caused by Joule heating of the coils or by differential heating during bakeout. Expansion is accommodated by "U" flexes in the corners to allow toroidal expansion. Vertical expansion of the vertical legs of the coils is accommodated by leaving a vertical gap in the clamp nearest the corner. A 3mm gap is used in the analysis model and this was found to produce acceptable stresses in the conductors, flexes and clamps. Since the vertical legs require some vertical constraint the gap should occur only on the top clamps.

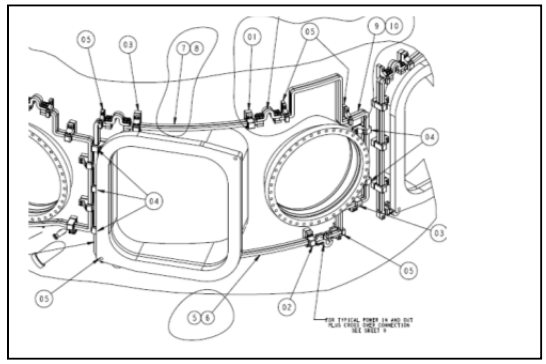

ISOMETRIC OF TYPICAL SUPPORT USE

George Labik provided calculations for the coils and clamps [2] . He has also provided drawings. He calculates 30 lbs per inch. for the original NSTX fields and 5000 amps. I calculate a peak field of 1.36 T which yields 39 lbs/in for the upgrade for 5 kAmp. The peak current for the projected operation of NSTX-U is now 2 kA providing some margin needed at some of the more complex geometries. George's clamp calculations are based on beam equations, and he gets 4 to 8 ksi for a couple of the details that are easy to pick out of his calculation. These would scale to acceptable static stresses for the upgrade.

Web search and communications with S. Gerhardt, Jim Bialek [13] and S Sabaugh yielded Table 6.5-1 of operational currents and frequencies. Eighty hz 300 amp operation forms the bulk of operations with occasional current peaks to 2 kA. After reading many discussions of the current levels, the currents are typically specified as peak-to peak. For calculations of Lorentz forces the peak current is needed. This



was brought up in the April 25 2014 peer review and Stefan Gerhard agreed that the specs were peak to peak and thus 4 kA operation is actually 2 kA peak current. Talking to Jim Bialek [13], he tells me 100 Hz is closer to how the coils operate, but if they are capable of suppressing the instabilities, the duration may be short Fatigue loading required better models than the P/A Mc/I type calculations previously done, although the basic design of the coils is turning out to be good for the upgrade loads,



The natural frequency of the RWM is 86Hz and above. This is close to the normal 80 hz operation. Time near these frequencies should be limited if possible. Dynamic response was estimated in two ways. – Mode frequency analysis and a time transient dynamic analysis. The frequencies of the RWM were calculated for some of the larger span lengths by hand for different end conditions, and a mode-frequency analysis was performed. Many frequencies resulted and many were not of a mode shape that was likely to be driven by the Lorentz forces. The 86 hz minimum is a "consensus" number. The amplification factor with a 80 Hz driving current could be greater than 2.0 for low damping, but a much higher damping is expected with all the potentials for frictional behavior in the clamps and flexes. For evaluation of the components a DLF of 2.0 was assumed first, then transient dynamic analyses were performed to more precisely quantify the dynamic amplification. The 80 Hz operation corresponds to a required life of 5.6e6 cycles See the discussion in section 6.0 after Table 6.5.1. This produced an allowable cyclic stress of 55 MPa with the usual 2 and 20 factors of safety. See Figure 6.4.1.1-2 Stresses from the transient dynamic analysis are a bit above this but damping from clamp friction is expected to bring the stresses down to levels where fatigue faliure will be unlikely. The RWM coils need to be outside the vessel insulation to allow cooling during operation and bake-out and are readily inspectable and with a bit more difficulty, can be repaired.

Flex strap stresses due to a differential temperature between vessel and coil of 20 degree C produces flex stresses Of 20 MPa for the toroidal expansion and 50 MPa for the vertical displacement.

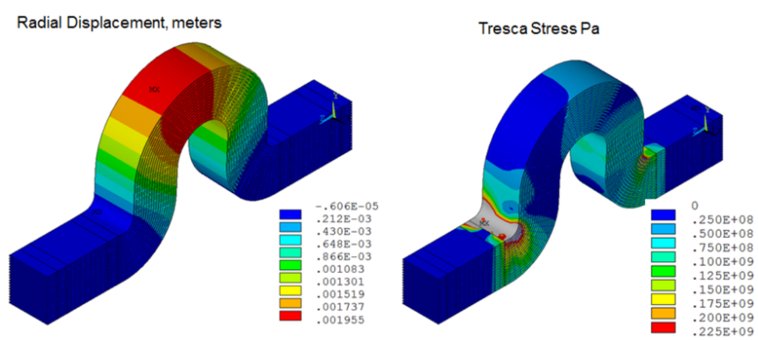



Figure 4.0-3 (15.0-6) Flex Strap Displacements and Stresses With Only 5 kA Lorentz Loads Applied

The strap stresses were computed for 5 kA , From Table 4.0-1, the peak current is 2 kA and the normal operation high cycle operation is 300 amps. For these levels of current the strap stress is 100 MPa and 15 MPa respectively. For the cyclic load a DLF of 2.0 is possible so the cyclic component could be 30 MPa. These are within the static allowable of 240 MPa and fatigue allowable of 55 MPa.

## 5.0 Digital Coil Protection System.

There is no input to the DCPS planned for the RWM coils. The loading calculated for the RWM coils 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. Maximum allowed RWM currents may be found in Table 6.5-1 "NSTX-U Operational Modes"

## 6.0 Design Input

## 6.1 Criteria

Stress Criteria are found in the NSTX Structural Criteria Document[3] Disruption specifications are outlined in the GRD -Ref [5] and are discussed in more detail in section 6.5

## 6.2 References

[1] Drawing E-DC1329, Shell Coils General Arrangement Bays A-L
[2] RWM Coils Job Book, George Labik. This includes design history from the CDR (7/23/2003) to the FDR (12/16/2003) and up to the present.
[3] NSTX Structural Design Criteria Document, NSTX_DesCrit_IZ_080103.doc I. Zatz
[4] NSTX Design Point Spreadsheet
[5] National Spherical Torus Experiment NSTX CENTER STACK UPGRADE GENERAL REQUIREMENTS DOCUMENT NSTX_CSU-RQMTS-GRD, C. Neumeyer Revision 0 March 30, 2009
[6] ITER material properties handbook, ITER document No. G 74 MA 15, file code: ITER-AK02-22401.
[7]
[8] "Mechanical, Electrical and Thermal Characterization of G10CR and G11CR Glass Cloth/Epoxy Laminates Between Room Temperature and 4 deg. K", M.B. Kasen et al , National Bureau of Standards, Boulder Colorado.
[9] Copper Development Association Web Page www.copper.org flat form
[10] 55_040301_CLN_01.doc Memo *FROM: C NEUMEYER SUBJECT: SIMULATION OF RWM/FEC SPA, REVISED* Reference: 55_040206_CLN_01.doc “SIMULATION OF RWM/FEC SPA”
[11] email from George Labik, 8/6/12
It took a while to find the PDF files of the relevant drawings since the drawing title is "Shell Coils" and I had forgotten the name change since in general they are referred to as RWM coils.
The drawing numbers are :
EDC1326 sh 1 to 3
EDC1327 sh 1 to 2
EDC1328 sh 1 to 2
EDC1329 sh 1 to 9
[12] NSTX-CALC-13-001-00 Rev 1 Global Model – Model Description, Mesh Generation, Results, Peter H. Titus March 2011
[13] Email from Jim Bialek Included in Attachment A
[14]Vessel Port Re-work for NB and Thompson Scattering Port, Calculation number NSTXU-CALC-24-01-00
[15] Damping in ANSYS/LS-Dyna Prepared by: Steven Hale, M.S.M.E Senior Engineering Manager CAE Associates (Web Search Results)
[16] “Rotational Stabilization of the Resistive Wall Mode in NSTX” A.C. Sontag, S.A. Sabbagh, J. Bialek, W. Zhu, and the NSTX Research Team, MHD Mode Control Workshop, October 31, 2005 - Madison, WI

## 6.3 Photos and Drawing Excerpts

Excerpts from the drawings[1] are included in the model plots in section 7.1

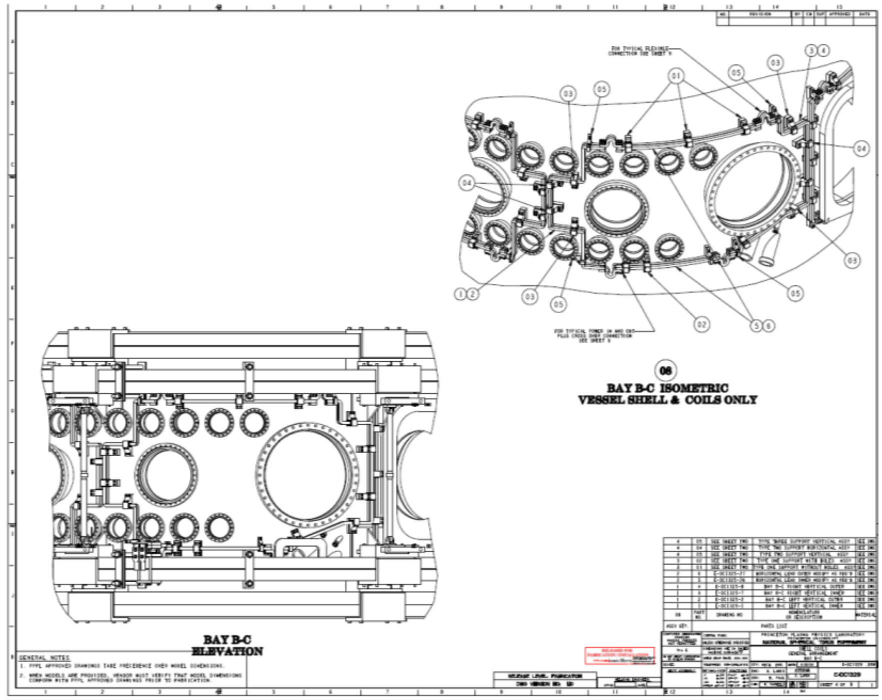
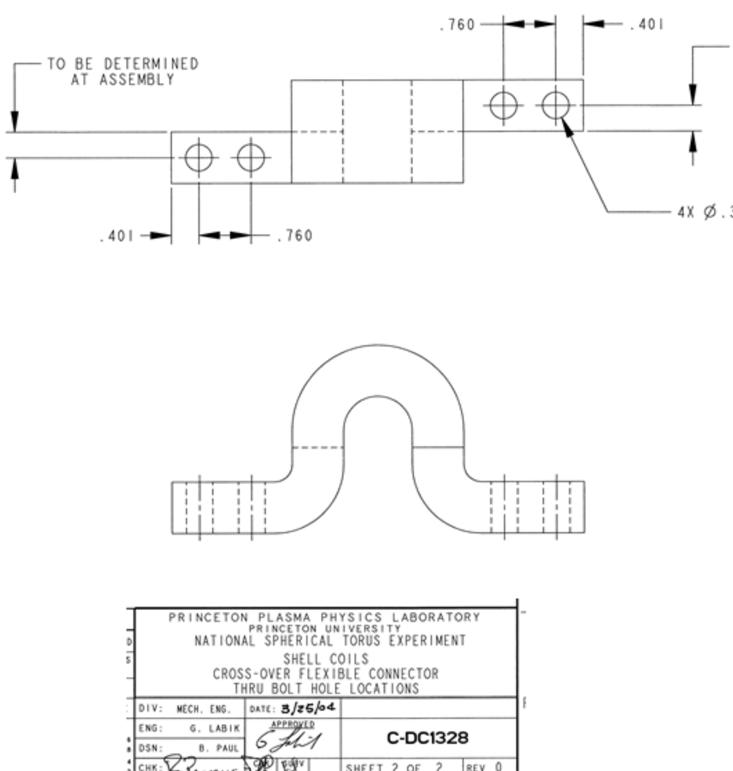


Figure 6.3-1 One Sheet showing Bay BC from the drawing series [1]



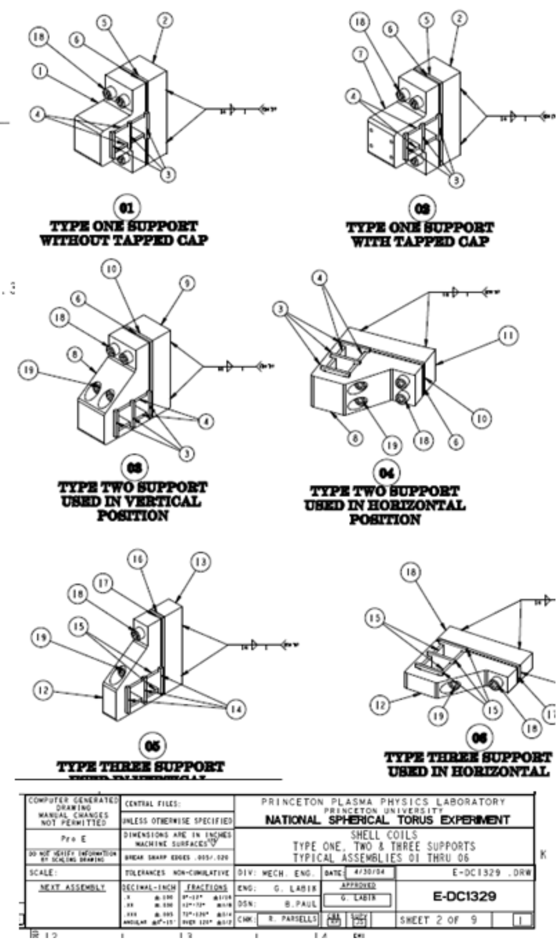
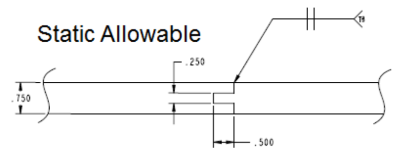
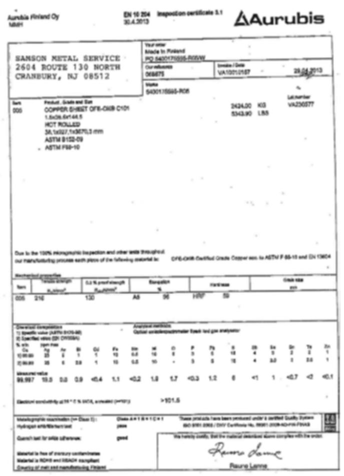



Figure 6.3-2 An Offset Flex on the left and clamp details on the right

## 6.4 Materials and Allowables
## 6.4.1 Copper Allowables
## 6.4.1.1 Copper Static Allowable




Brazed areas will be assumed annealed (8ksi)




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

Assume 130 Mpa yield, Similar to CHI Bus. This is also 1.5 * Sm, The Bending Allowable.

Figure 6.4.1.1-1 Copper Yield

The RWM conductor is assumed to be relatively soft ~ 1/8 hard, possibly softer near the braze. 130 MPa has been selected as a likely yield stress.

The flexes are specified as "medium hard" copper in the drawings (CDC1327). This is interpreted as half hard with a yield of 248 MPa. The static bending allowable for the flexes would be yield or 248 MPa

The room temperature properties in figure 6.4.1.1 is from the Copper Development Association Web Page www.copper.org flat form [9]

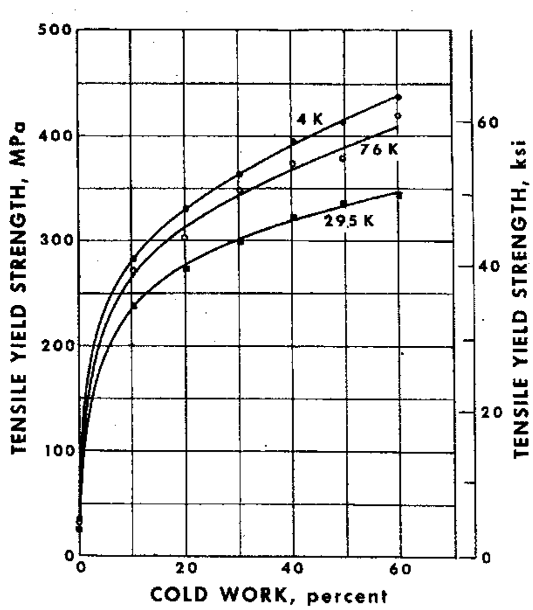



Figure 6.4.1.1-2 NIST Data – Oxygen Free Copper Tensile Properties (4-300K)- C10100 – C10700 Cold Worked

Tensile yield strength for oxygen free copper is given in Fig. 1 at 4 K, 76 K and at 296 K. Yield and Ultimate strength data is given for several variants of copper at RT and 77K in Table 6.4.1.1-1

Table 6.4.1.1-1. Properties of Variants of Copper

| Variant | Yield Mpa at RT | Yield Mpa at 77 K | Ult., Mpa at RT | Ult, Mpa at 77K |
|---|---|---|---|---|
| C10100/C10700 80%CW | 380 | | 420 | 500 |
| C10100 Becker/C-Mod 60%CW | 308 | 373 | 350 | 474 |

### 6.4.1.2 Copper Fatigue Allowable

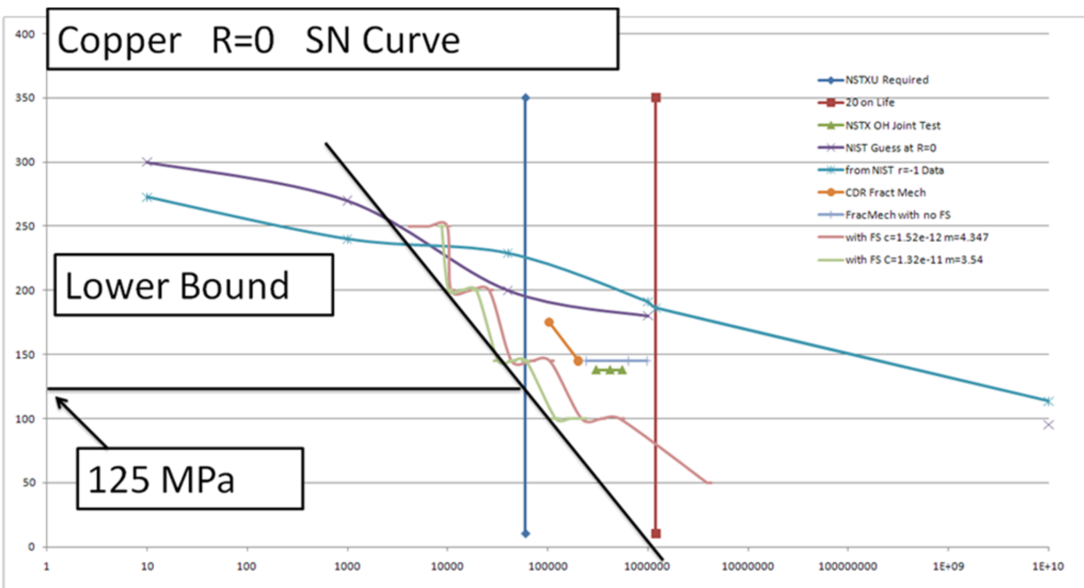


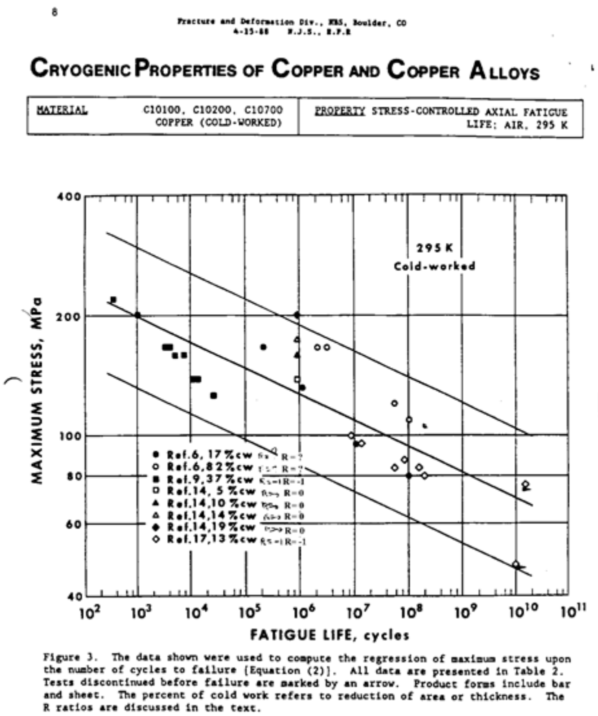

Figure 6.4.1.2-1 Fatigue Curve Used for the OH Copper Conductor

The copper fatigue allowable used throughout much of the NSTX-U assessments is derived from allowables developed for the OH coil which is exposed to 20,000 operational cycles. The OH sees 40,000 cycles with the double swing, but since the second peak is only 13.5 kA rather than 24 ka the fatigue damage of the second peak can be neglected. The RWM coils are driven by alternating currents during the pulse and the number of stress cycles applied to the RWM coils is much higher than the number of shots.

Fatigue Allowable

A reasonable number of cycles for a fatigue analysis would be based on the 80 Hz “Standard RWM” case. Assume an average pulse length, based on Stefan’s guess of .3*5+.5*3+.2*1 = 3.2 second average pulse length. Using 20,000 shots (From the GRD) the cyclic life would have to be: 5.6e6 cycles. The lower bound of the copper SN curve at 1e7 is ~70 MPa peak stress at, R=-1 (140 MPa stress range)

If you base the allowable on ½ the average data, then at 1e7 ~110 Mpa would be the average. Half this would be 55 MPa




**Use 55 MPa at the Fatigue Allowable**

Figure 6.4.1.2-2 Fatigue Curve Used for the RWM Copper Conductor

The support clips are made of steel with a liner of G-10 for insulation. – some may be G-11 to improve their thermal resistance.

## 6.4.2 Stainless Steel Allowables

### 6.4.2.1 Static Stainless Steel Allowables

Table 6.4.2.1-1. Tensile Properties for Stainless Steels and Aluminum

| Material | Yield 4 deg K (MPA) | Ultimate 4 deg K, (Mpa) | Yield, 80 deg. K (Mpa) | Ultimate, 80 deg. K (Mpa) | Yield, 292 deg K (Mpa) | Ultimate, 292 deg K (Mpa) |
|---|---|---|---|---|---|---|
| 316 LN SST | 992 | 1379 | | | 275.8] | 613] |
| 316 LN SST Weld | 724 | 1110 | | | 324 | 482 |
| | | | | | | |
| 304 SST 50% CW | | | 1344 (195 ksi) | 1669 | 1089 | 1241 |
| 304 Stainless Steel (Bar,annealed) | | | 282 (40.9ksi) | 1522 | 234 | 640 |

Table 6.4.2.1-2. Coil Structure Room Temperature (292 K) Maximum Allowable Stresses, Sm = lesser of 1/3 ultimate or 2/3 yield, and bending allowable=1.5*Sm

| Material | Sm | 1.5Sm |
|---|---|---|
| 316 Stainless Steel | 184 | 276 |
| 316 Weld | 161 | 241 |
| 304 Stainless Steel (Bar,annealed) | 156MPa(22.6ksi) | 234 MPa (33.9ksi) |

## 6.4.2.2 Fatigue Stainless Steel Allowables

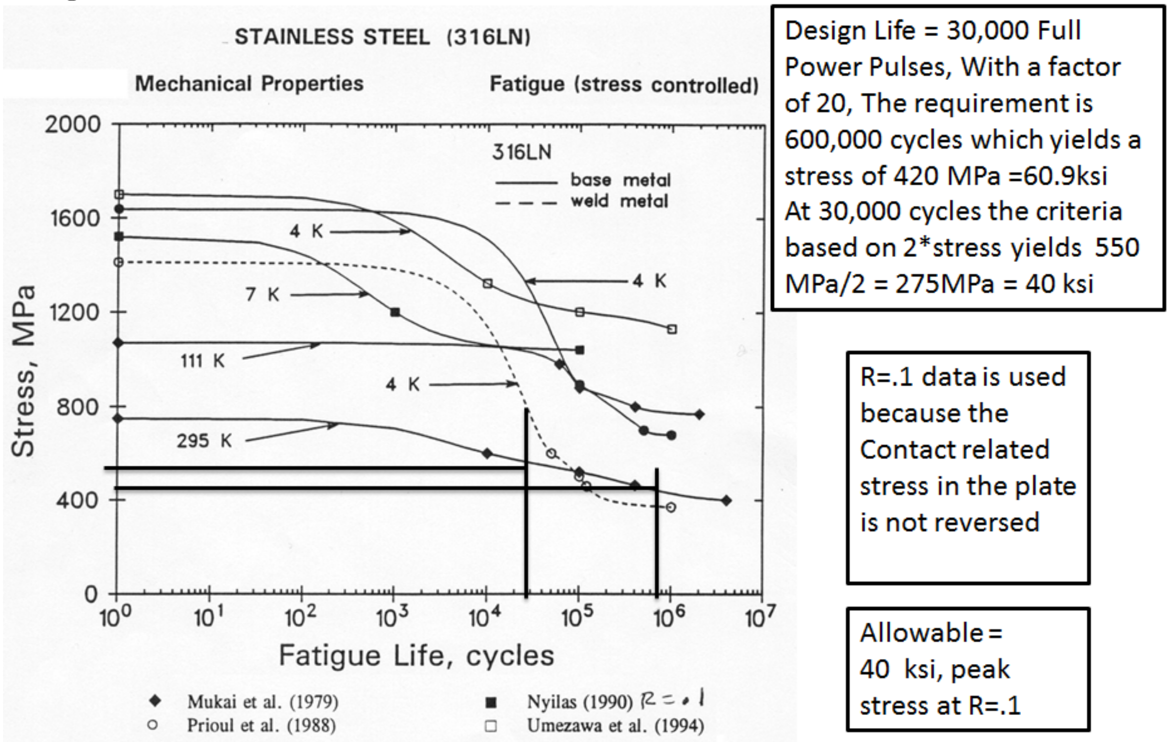



Figure 6.4.2.2-1 Stainless Steel Fatigue Allowable

## 6.4.3 Insulation Allowables

Typical values of mechanical strength for several different types of composite insulating materials is given in Table 6.4.3-1.

Table 6.4.3-1 Insulating Material Strengths

| | @4 | @77 | @292 degK |
|---|---|---|---|
| Comp.Strength Normal to Fiber | | | |
| G-10CR | 749 | 693 | 420 Mpa Ref[8] |
| G-11CR | 776 | 799 | 461 MPa Ref[8] |
| Tensile Strength (Warp) | | | |
| G-10CR | 862 | 825 | 415 MPa Ref[8] |
| G-11CR | 872 | 827 | 469 MPa Ref[8] |
| Tensile Strength (Fill) | | | |
| G-10CR | 496 | 459 | 257 MPa Ref[8] |
| G-11CR | 553 | 580 | 329 MPa Ref[8] |

The RT tensile strength in the reinforced direction is 257 MPa or 37 ksi

## 6.5 Operational Modes of the RWM Coils

. From a web search, I see 3.3 and 3.9 kA operation projected, and 7.5 kHz. Jim Bialek,[13] indicated in an email that 100 Hz is closer to how the coils operate, but if they are capable of suppressing the instabilities, the duration may be short -

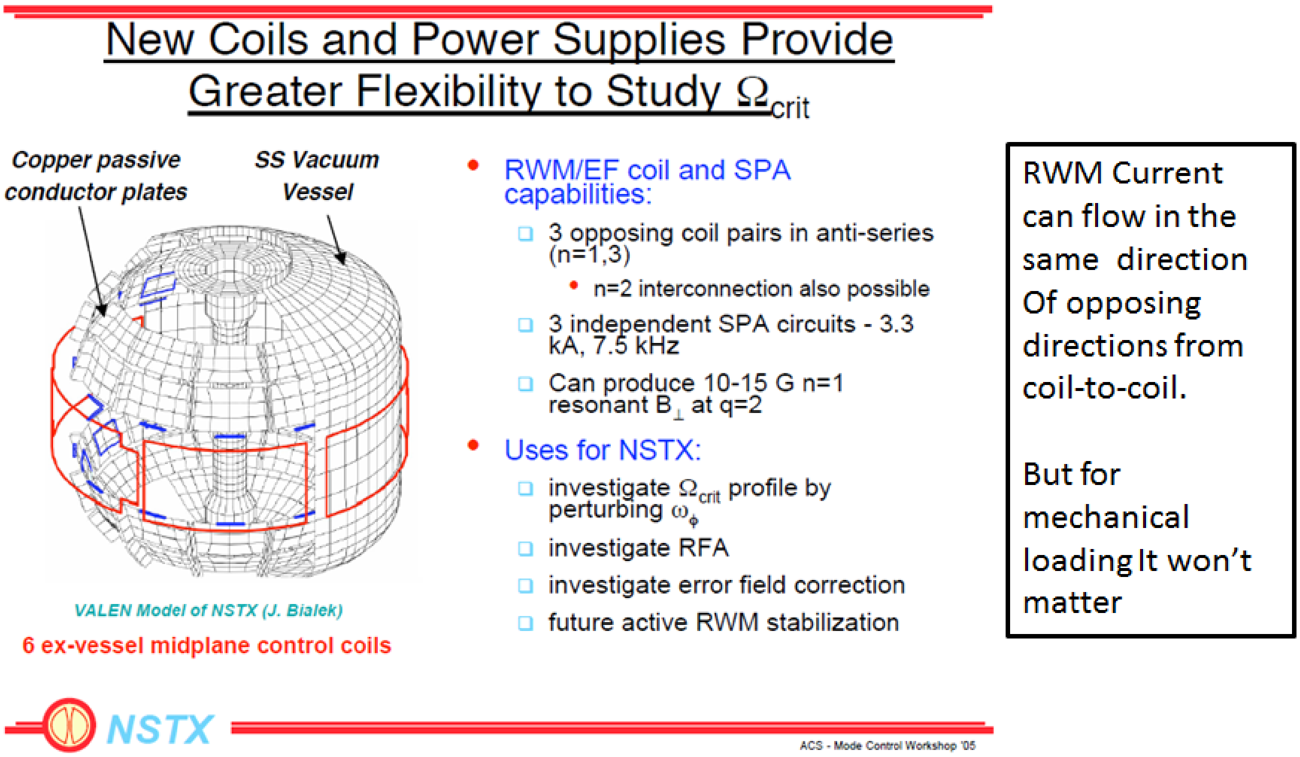



Figure 6.5-1 Slide from "Rotational Stabilization of the Resistive Wall Mode in NSTX" [16]

From an email from Stefan Gerhardt (Appendix A):
For 10 years, 15 run weeks/year, 5 days per week, and 30 shots per day, I see ~22000 shots.
10% of the shots have no EFC on at all. (disruptions and RF shots)
20% of the shots have ~2.0 kA pk-pk at ~35 Hz, and 10% at 4.0 kA 50 Hz. (RFA studies and other ELM pacing things)
60% of the shots have 0.600 kA pk-pk at 80 Hz. (Standard RWM control)
If you want to assume that all shots are 5 seconds long, that is fine. Otherwise, assume that 30% are 5 seconds long, and the 50% are 3 seconds long, and 20% are 1 second long.

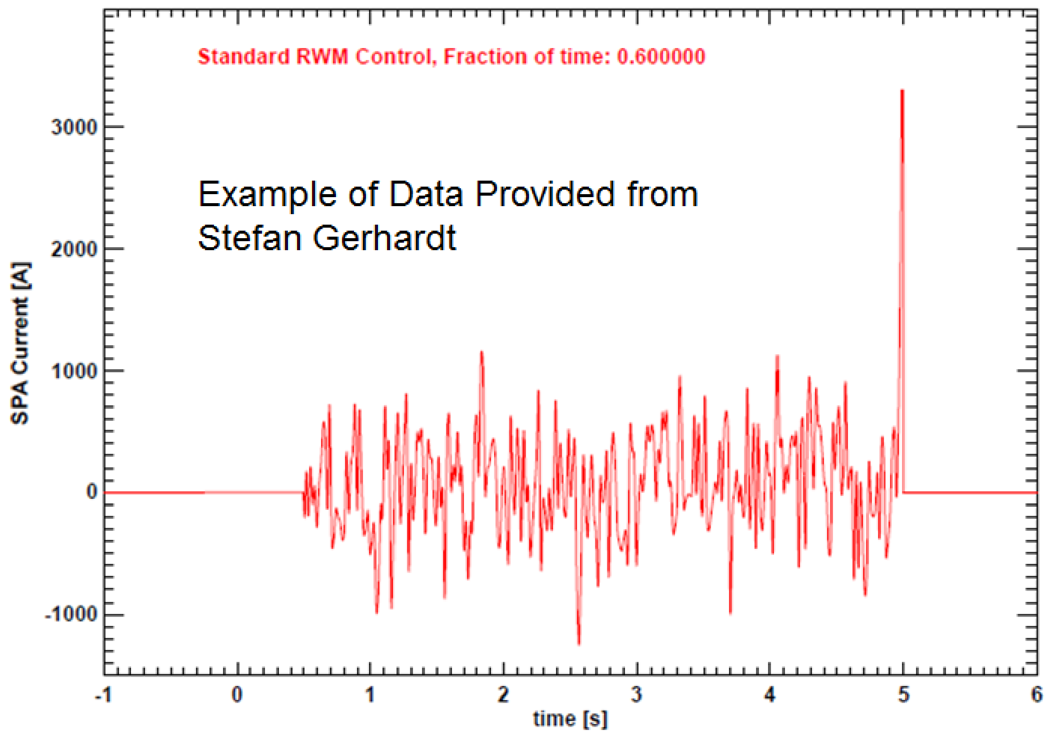



Figure 6.5-2

From Steven A. Sabbagh:
The "1 kHz, 1 kA" case is really a transient, low probability occurrence - meaning that we would not run a continuous AC waveform at 1 kHz for 5 seconds. However, the rise time of the SPAs can allow tracking of modes with growth rates ~ 2 ms. So a transient at 500 Hz might be considered an upper bound (I stated 1 kHz), and 1 kA peak-to-peak is also transient during somewhat strong mode activity. More usual is ~ 600A peak-to-peak for the majority of the time.
Candidly, these numbers are quite aggressive (like they doesn't account for disruptions very well). So, if this looks like it will pose a problem, then please let us know and we can sharpen the pencils a bit more.

Table 6.5-1 NSTX-U Operational Modes

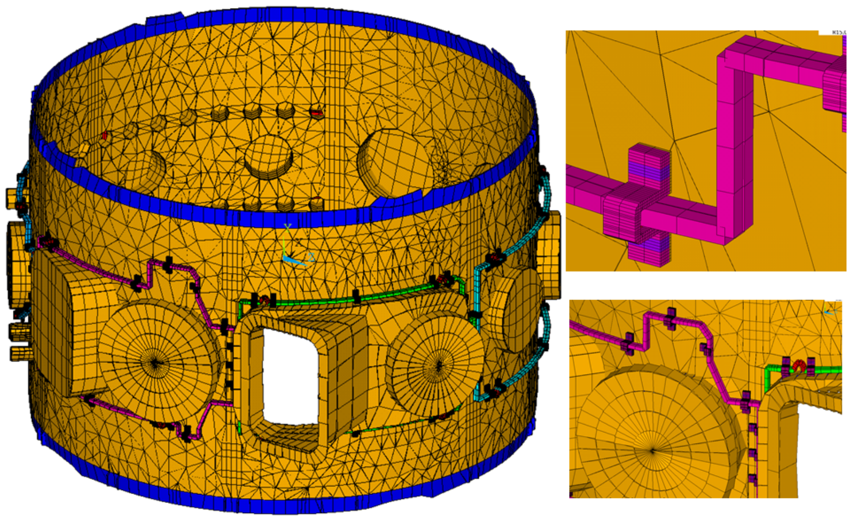
| Name | Current pk to pk | Current Amplitude | Frequency | Shot percentage | Source |
|---|---|---|---|---|---|
| | 3.3 to 3.9kA | ~2kA? | 100Hz | | Web/Bialek[13] |
| No EFC | 0 | 0 | 0 | 10% | S. Gerhardt |
| | 2.0kA | 1.-kA | 35 Hz | 20% | S. Gerhardt |
| RFA+Pacing | 4.0kA | 2.0kA | 50 Hz | 10% | S. Gerhardt |
| Standard RWM | 0.6 kA | 0.3 kA | 80 | 60% | S.Gerhardt |
| | 1.0kA | .5kA? | 1000 Hz | 1% | |
| “usual” | 0.6kA | 0.3 kA | 500 (max) | | S. A. Sabbagh |
| | | | | | |

The peak current amplitude is then 2 kA. Most of analyses are based on a 5kA peak current. Stresses will be scaled from this. For low percentage usage - use static Allowable of 130 Mpa for the conductor and 240 for the half hard flexes
The Standard RWM is .3 kA – Use the Fatigue allowable of 55 MPa

A reasonable number of cycles for a fatigue analysis would be based on the 80 Hz “Standard RWM” case. Assume an average pulse length, based on Stefan’s guess of .3*5+.5*3+.2*1 = 3.2 second average pulse length. Using 20,000 shots (From the GRD[5]) the cyclic life would have to be: 5.6e6 cycles. The lower bound of the copper SN curve at 1e7 is ~70

MPa peak stress at, R=-1 (140 MPa stress range)  If you base the allowable on ½ the average data, then at 1e7  ~110 MPa would be the average. Half this would be 55 MPa

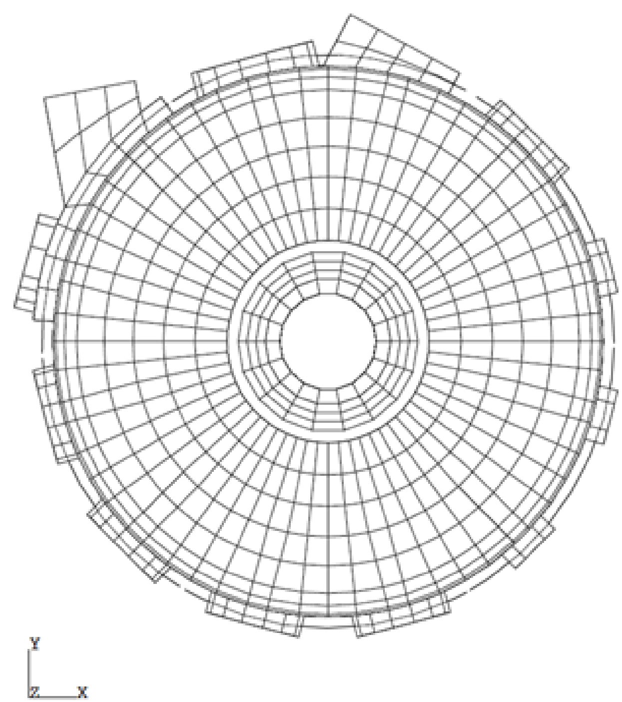
### 7.0 Analysis Models



The "global" model is a stick model using current stick elements for the Biot Savart model which are converted to beam elements in the structural analysis   . Initially the stick model was provided by Jim Bialek and was the model used in the Valen code to assess resistive wall mode operation.

```
01/19/12     10:28:54 EST  VALEN executable: XVPS7
                           checking  i1i1SUM
checking coil geometry
```

Initially the stick model was provided by Jim Bialek and was the model used in the Valen code to assess resistive wall mode operation.



The model evolved as loads were developed and corrections were made to the coil runs. In March of 2013 G. Labik provided details of the new conductor runs around the ports modified for the upgrade.

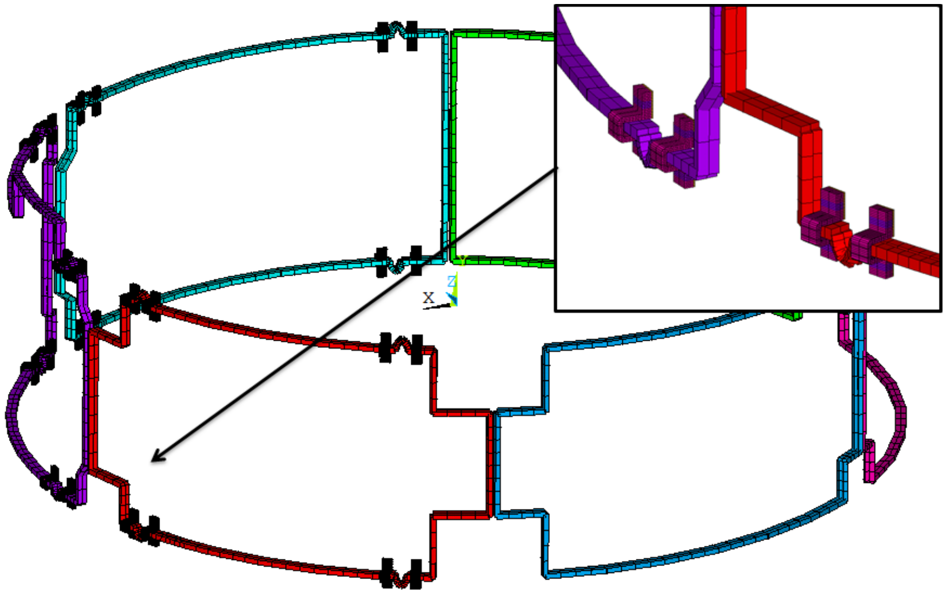


Figure 7.0-1 Early version of the beam element model

The clamps are modeled with solid elements and are connected to the beam elements with spring or gap elements. Each local model of the clamp has a layer of elements at the clamp base that is selected and fully constrained in the analysis run. The deformations of the vessel are not imposed, i.e. the vessel is assumed infinitely rigid and at one temperature.

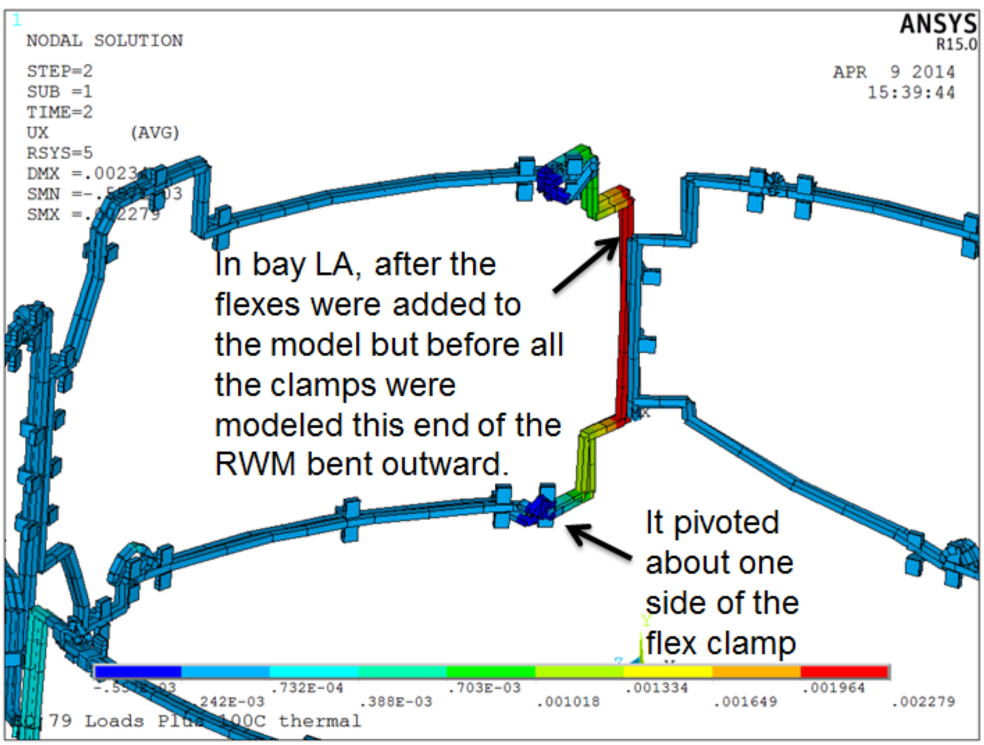
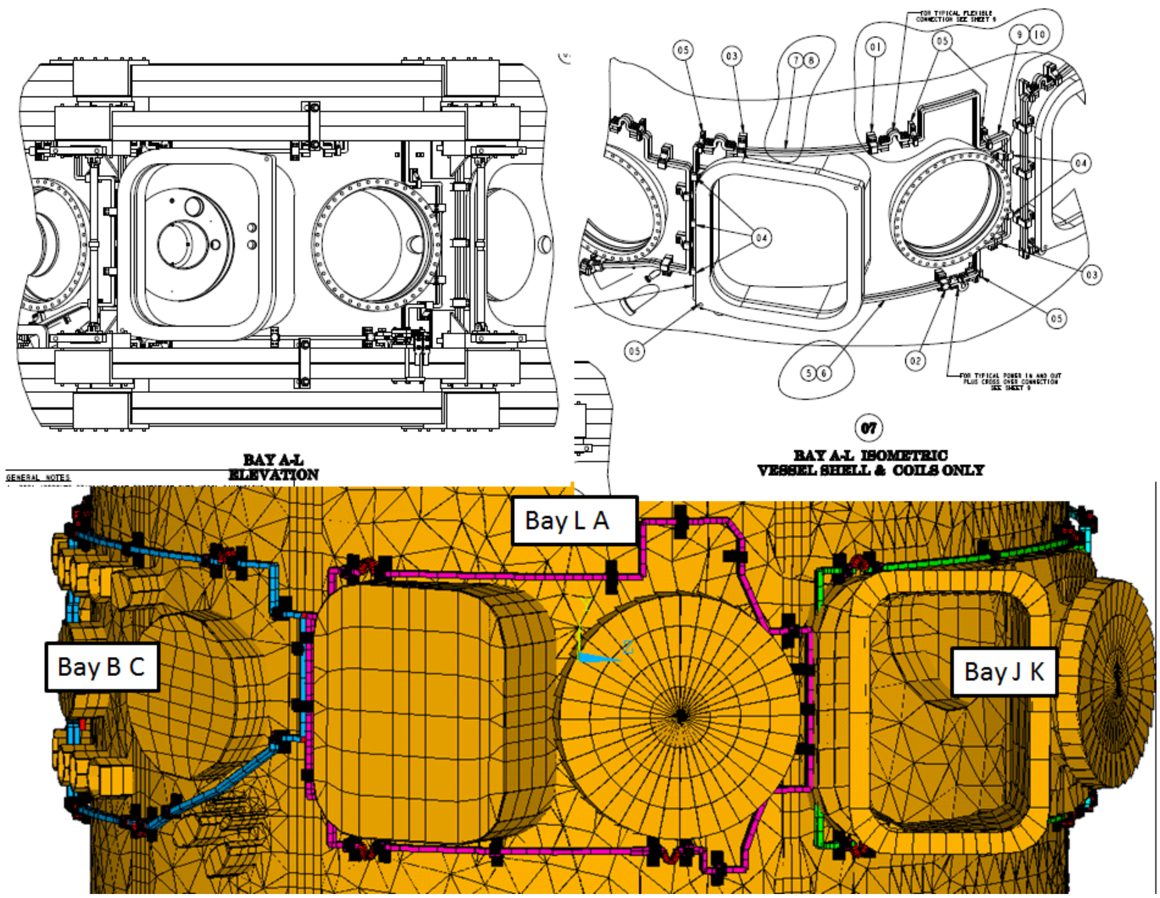



Figure 7.0-2 What happened when the Flexes were added and there were missing clamps

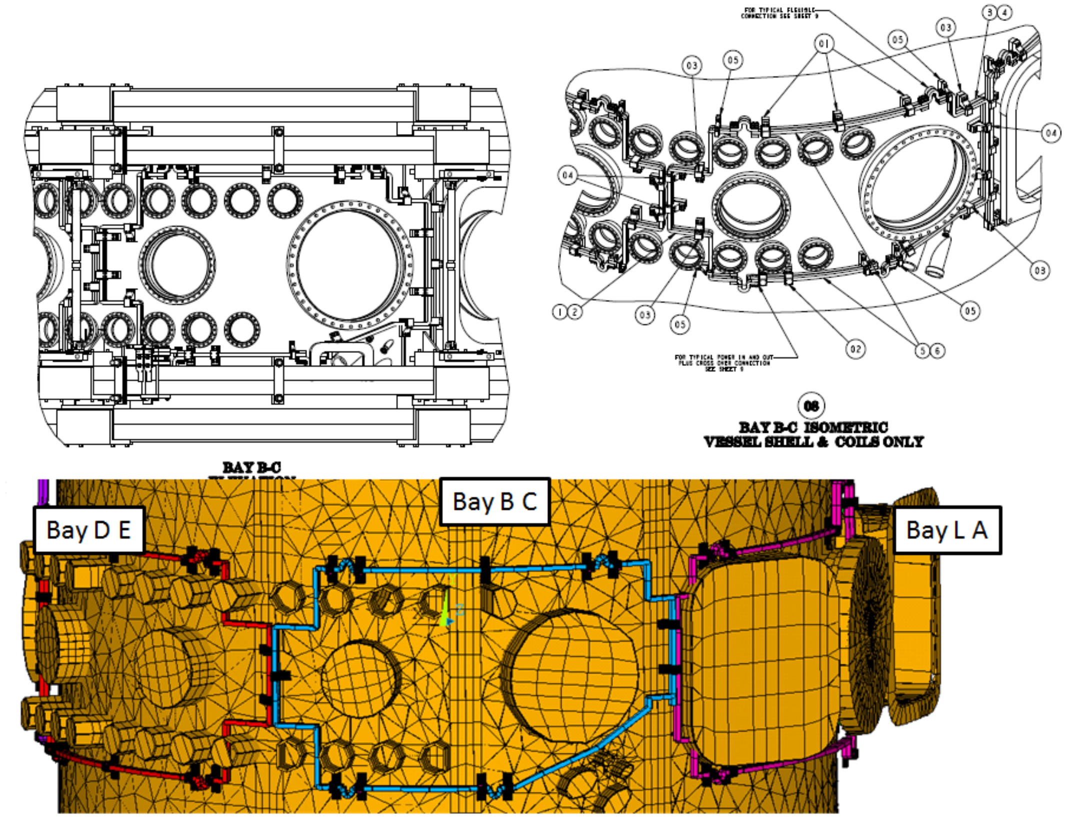
Flexes and clamps were added as the analysis progressed and as support was needed in the analysis model. In figure 7.0-2, corner flexes were added but without radial support of the vertical leg. The “dogleg” region of the vertical run could rotate and translate radially under the Lorentz loads. Addition of the correct support clamps suppressed this.

## 7.1 FEA Model by Port Designation

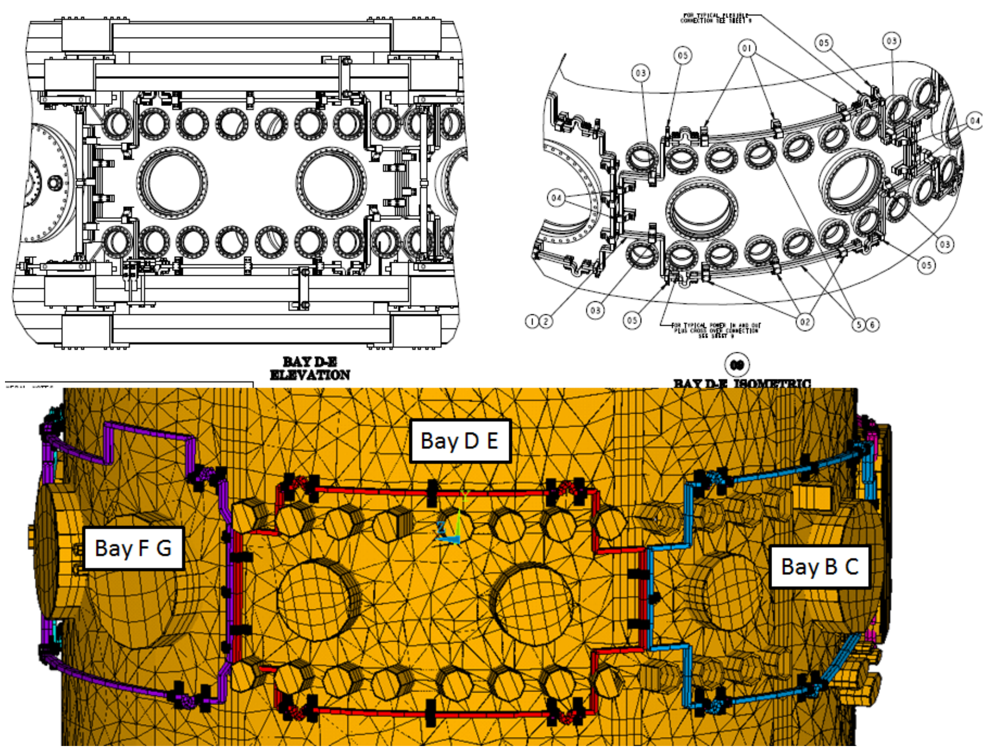
### 7.1.1 Bay LA



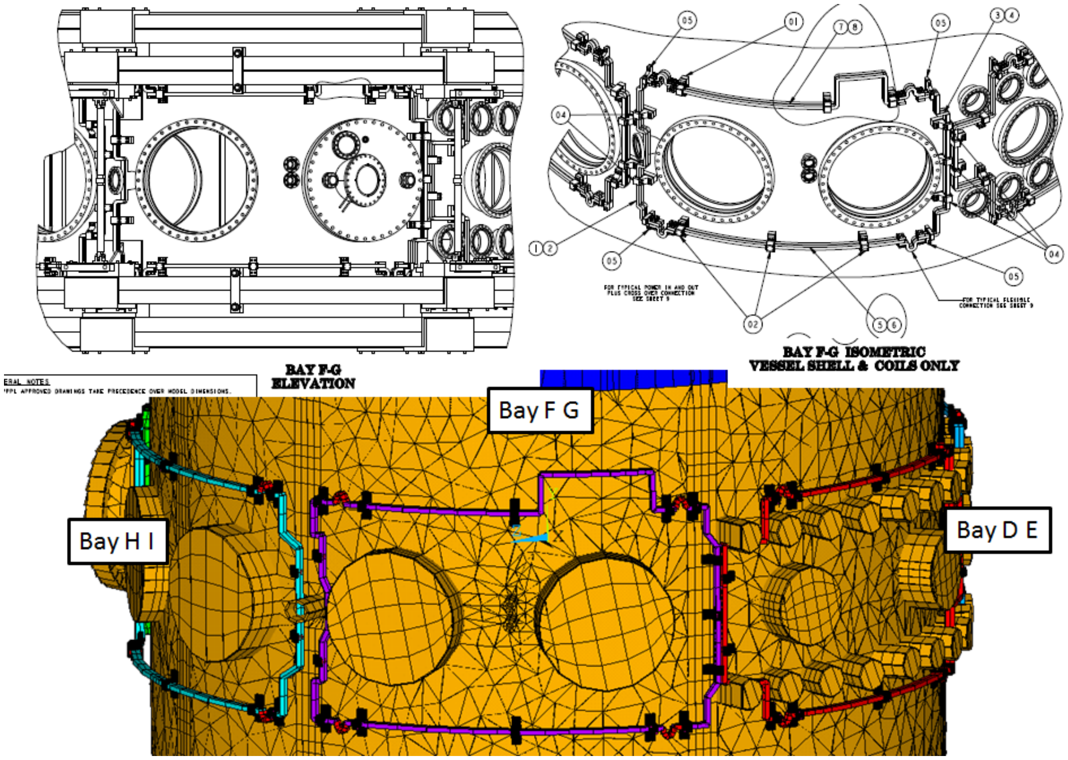

### 7.1.2 Bay BC



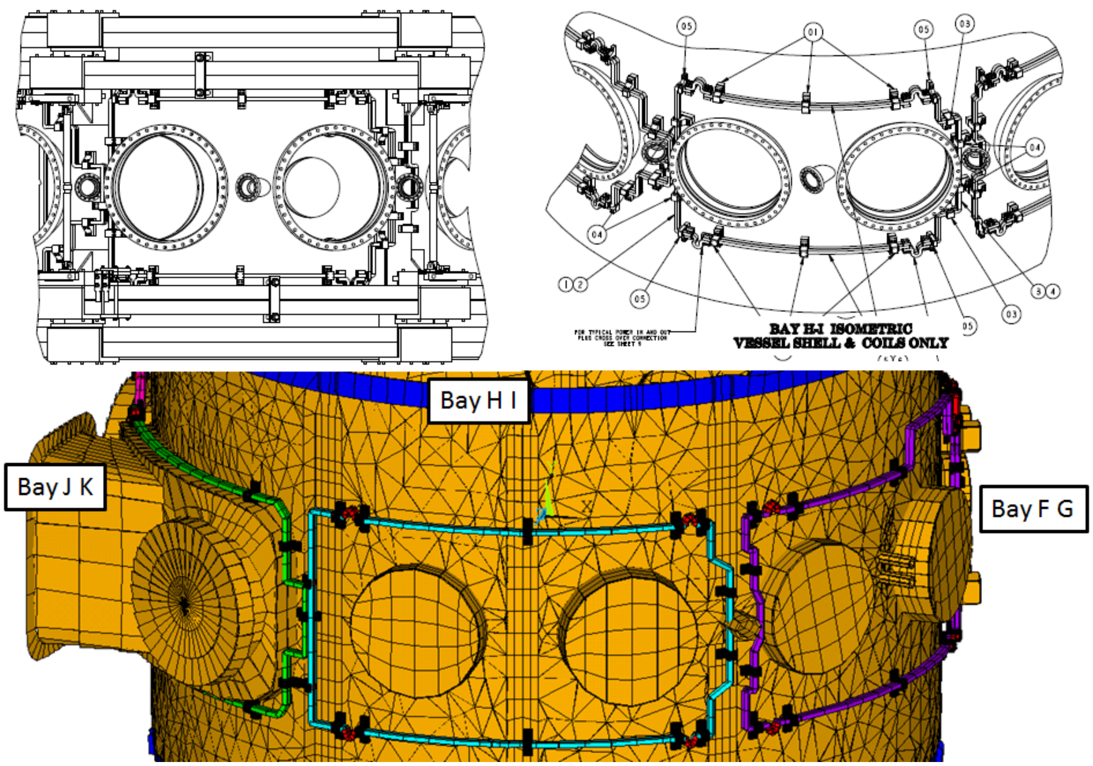

### 7.1.3 Bay DE



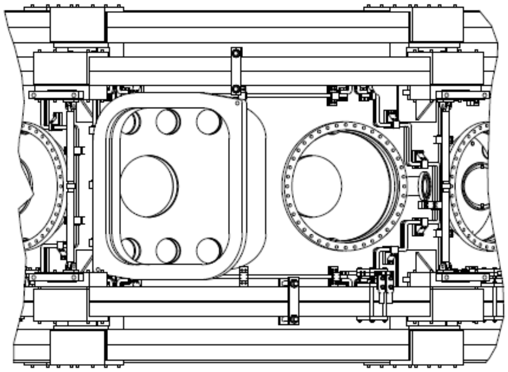

### 7.1.4 Bay FG

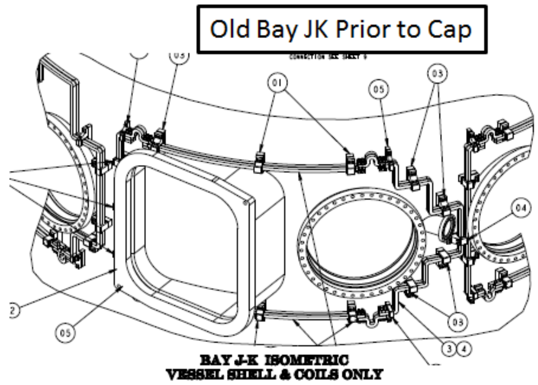


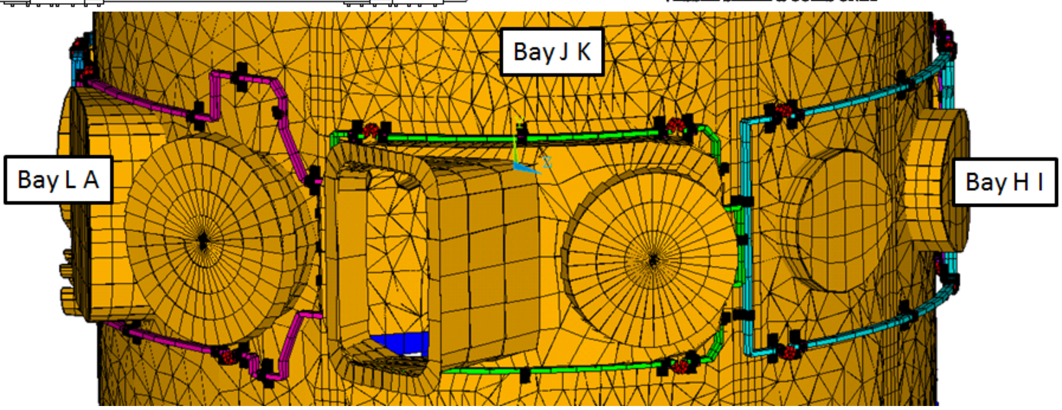

### 7.1.5 Bay HI




### 7.1.6 Bay JK






## 7.2 Damping

The damping value used in the structural dynamic analysis has a significant impact on the results. In these NSTX calculations, a conservative 0.5% damping is used. The figure below is a collection of some other damping value guidance from fission and fusion reactor sources. Larger damping values than 0.5% could be justified for the mechanical behavior of the clamp insulation, clamp gaps, flex joint friction, and proximity to insulation blankets. If the response is fully elastic, , 0.5% is appropriate. Larger values are very likely.

Fission Reactor Experience

**Regulatory Guide 1.61 - Damping Values for Seismic Design of Nuclear Power Plants**

**Table 1 Damping Values[1] (Percent of Critical Damping)**

[1] Table 1 is derived from the recommendations given in Reference 1.

[2] In the dynamic analysis of active components as defined In Regulatory Guide 1.48, these values should also be used for SSE.

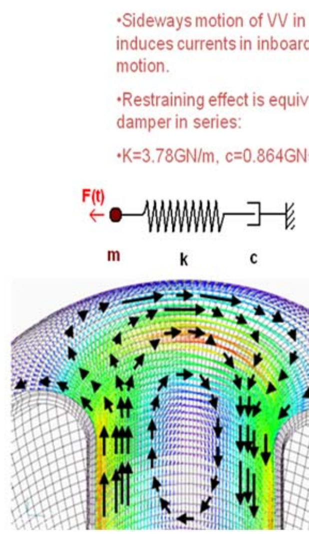
[3] Includes both material and structural damping. If the piping system consists of only one or two spans with little structural damping, use values for small meter piping.

| Structure or Component | Operating Basis Earthquake or $^1/_2$ Safe Shutdown Earthquake[2] | Safe Shutdown Earthquake |
|---|---|---|
| Equipment and large-diameter piping systems[3], pipe diameter greater than 12 in | 2 | 3 |
| Small-diameter piping systems, diameter equal to or less than 12 in. | 1 | 2 |
| Welded steel structures | 2 | 4 |
| Bolted steel structures | 4 | 7 |
| Prestressed concrete structures | 2 | 5 |
| Reinforced concrete structures | 4 | 7 |

Fusion Reactor Experience
(ITER) Vessel Loads Spec

Magnetic Dampi
ITER vessel dyn
Magnetic dampi
neglected in the

Horizontal Support c




**Damping Discussion from Ref [15]:**
**Rayleigh damping constants α and β As Used in ANSYS**
These are applied as multipliers of [M] and [K] to calculate [C]:

$$[C] = \alpha[M] + \beta[K]$$
$$\alpha/2\omega + \beta\omega/2 = \xi$$

Where ω is the frequency, and ξ is the damping ratio. These are input in ANSYS in situations where damping ratio ξ cannot be specified. Alpha is the viscous damping component, and Beta is the hysteresis or solid or *stiffness* damping component.

**Beta Damping As Used in ANSYS**

Good for damping out high-frequency component-level oscillations (typically low amplitude).
From Section 12.0 the predominant modes of oscillation of the RWM coils are around 100 cps. Considering beta damping alone, and ξ = .5%:

$$\beta = 2\,\xi / \omega$$
$$\beta = 2\xi/\omega = 2*.005/(100*2*3.1416) = 3.98E-06$$

**Alpha Damping As Used in ANSYS**

Alpha damping is also known as *mass damping.* It is Good for damping out low-frequency system-level oscillations (typically high amplitude).

 If beta damping is ignored, $\alpha$ can be calculated from a known value of $\xi$ (damping ratio) and a known frequency $\omega$:

$$\alpha = 2\xi\omega$$

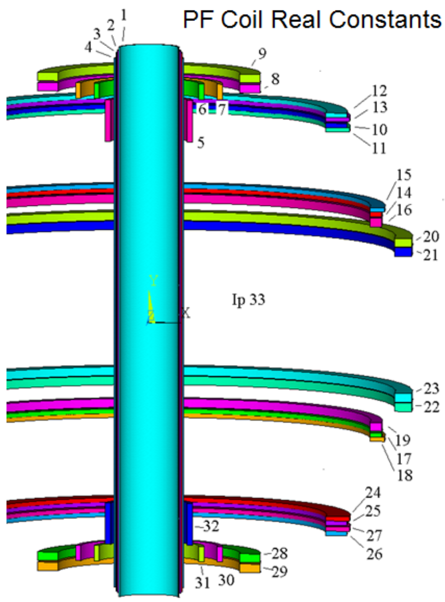
Only one value of alpha is allowed, the most dominant response frequency should be used to calculate $\alpha$.

Considering Alpha damping alone, and $\xi = .5\%$:

$$\alpha = 2\xi\omega = 2*.005*100*2*3.1416 = 6.285$$

## 8.0 Lorentz Force Calculations

Lorentz Forces are computed in a Biot Savart program outside ANSYS and then the loads and model are transferred to ANSYS for structural evaluation.




PF Coil Currents (In bays.txt input script)

```
irdt
2
pfcu
33,4,4,1.1
  1 , -5.3039999   , 0.0000000E+00 ,  2.8782515   , -5.3039999
  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        !PF5U
 21 , -0.3339048   , -0.3279492   , -0.3247161   , -0.3621252        !PF5U
 22 , -0.3339048   , -0.3279492   , -0.3247161   , -0.3621252        !PF5L
 23 , -0.3339048   , -0.3279492   , -0.3247161   , -0.3621252        !PF5L
 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
```

Figure 8.0-1 PF Coil Real Constants and Currents

The Biot Savart program is NTFTM and the input script is bays.txt. The script reads the individual conductor and support files for each RWM coil bay, and then reads in a current stick file for the NSTX-U TF and PF coil set. The program then calculates the fields and forces on the RWM conductor stick elements. During the review of the calculation it was discovered that the OH currents were input too low, nearly zero, in the inner layer of the OH. The fields at the RWM coils are small due to the OH and are mainly the result of the neighboring TF , PF4 and 5 coils. Analyses were re-run with the corrected current and the effect was tiny.

Most of the analyses are based on the EQ 79 loading. To make sure that this is conservative, the SRSS of the radial and vertical fields for all 96 EQ with and without plasma and for the upper half of the RWM's (Algorithm 186) and the lower half of the RWMs (Algorithm 187), were computed. For the upper conductors, EQ 79 is the max. For the lower conductors, EQ 66 is the max, but only slightly higher than EQ 79. EQ 79 is a pretty good representation of the worst loading. Also see the discussion for figure 8.0-6 that compares EQ 17 and 79

```
!                              Algorithm 186 SRSS of Fields at RWM
let algor$(186)="SRSS of Fields at RWM, Upper Conductors, Max limit is EQ 79 no Ip,
Min limit is EQ 79 with Ip"
 let algunits$(186)="Tesla"
let fine=20
let bt=.0001
let x=1.37922
let bt=bt*.6/x
let y=.4826
let numpfs=15
```

```
call
sfield(fine,nmax,numpfs,NomCurrents(,),numturns(),79,pfr(),pfz(),pfdr(),pfdz(),nx(),
ny(),x,y,bxnp,bynp)
 let numpfs=16
call
sfield(fine,nmax,numpfs,NomCurrents(,),numturns(),79,pfr(),pfz(),pfdr(),pfdz(),nx(),
ny(),x,y,bxwp,bywp)
let algaccept(186)=(bxnp^2+bynp^2)^.5
let algnegaccept(186)=(bxwp^2+bywp^2)^.5
for j=1 to 96
 call
sfield(fine,nmax,numpfs,NomCurrents(,),numturns(),j,pfr(),pfz(),pfdr(),pfdz(),nx(),n
y(),x,y,bxwp,bywp)
let numpfs=15
call
sfield(fine,nmax,numpfs,NomCurrents(,),numturns(),j,pfr(),pfz(),pfdr(),pfdz(),nx(),n
y(),x,y,bxnp,bynp)
 let WithPlasmaUp= (bxwp^2+bywp^2+bt^2)^.5
let NoPlasmaUp =(bxnp^2+bynp^2+bt^2)^.5
if withplasmaUp>algresults(186,j) then let algresults(186,j)=withplasmaUp
if NoplasmaUp>algresults(186,j) then let algresults(186,j)=NoplasmaUp
 next j
```

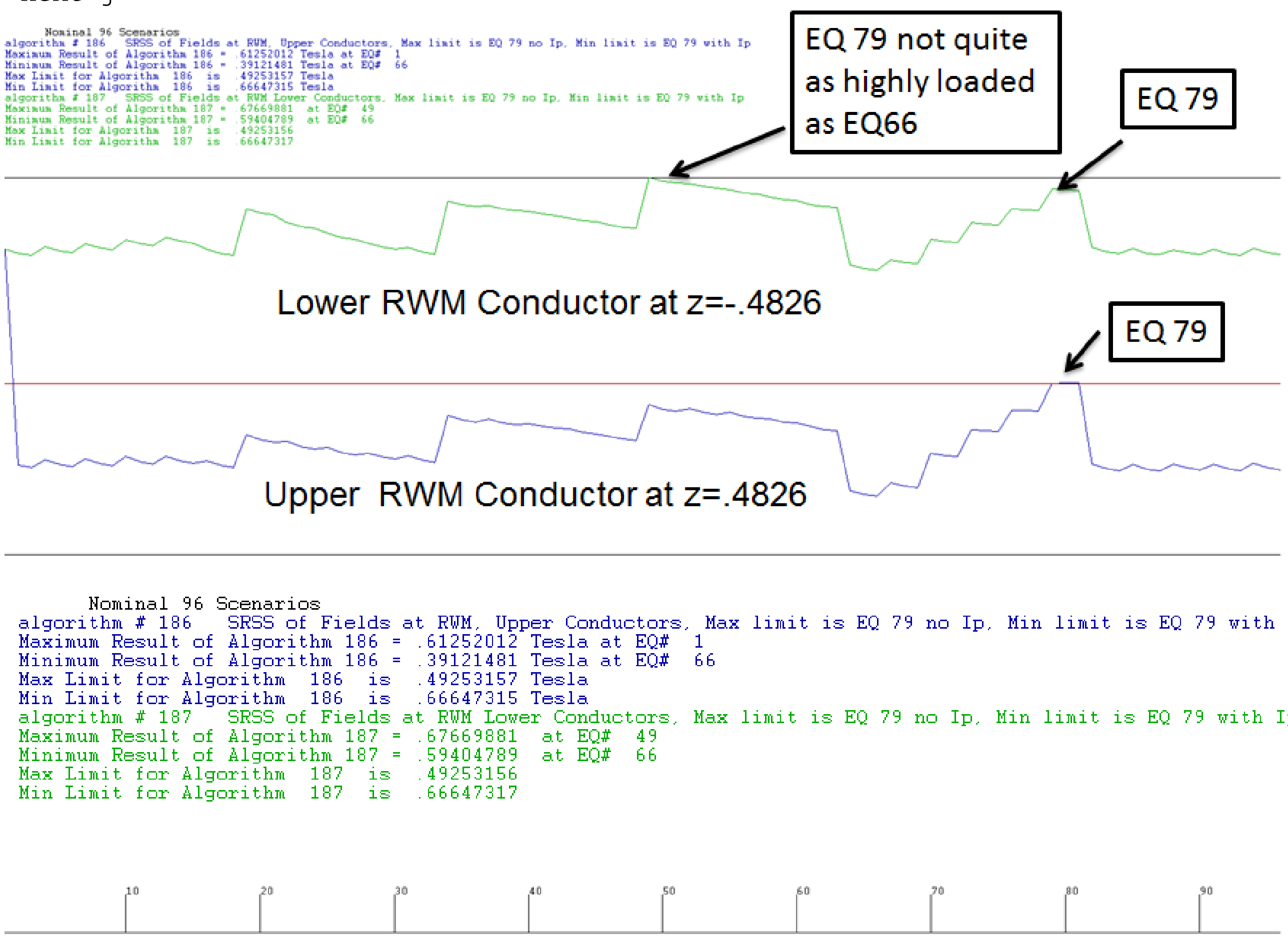



Figure 8.0-2 RWM SRSS of fields for the 96 Equilibria

During the review of the calculation, the source of the real constants of the current sticks used to represent the outer TF conductors was questioned. There appeared to be 8 X 4 current sticks in the outer leg cross section, but 8 of these were created from insulation elements between the conductors and have a zero current. These could be omitted in future analyses.

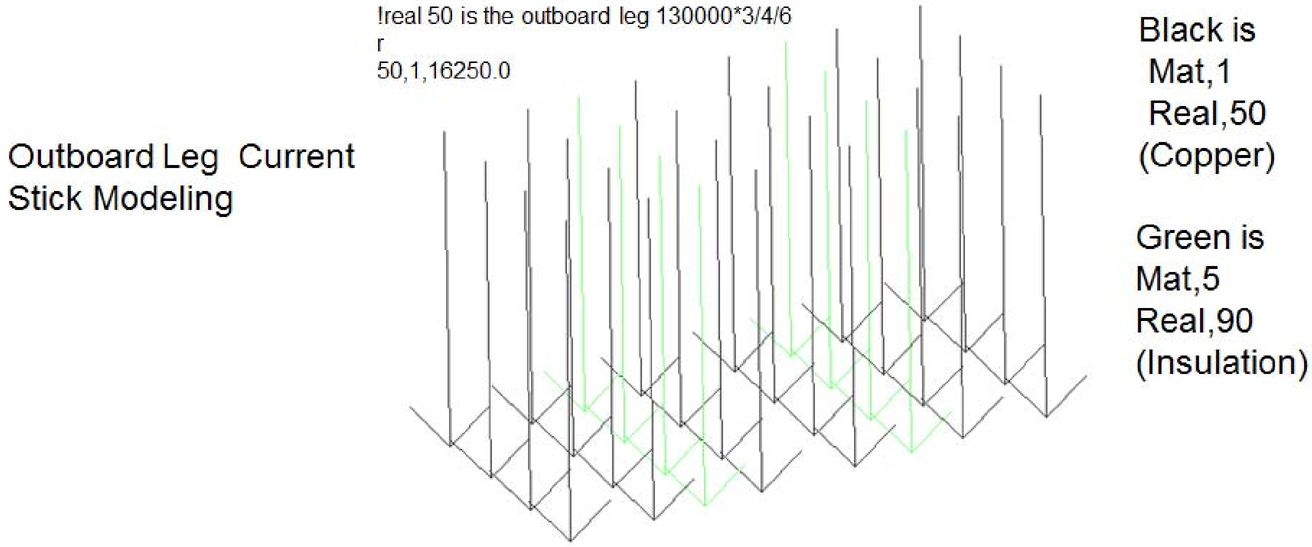



Figure 8.0-3 Outer TF Real Constant in the NTFTM script bays.txt and vect.dat

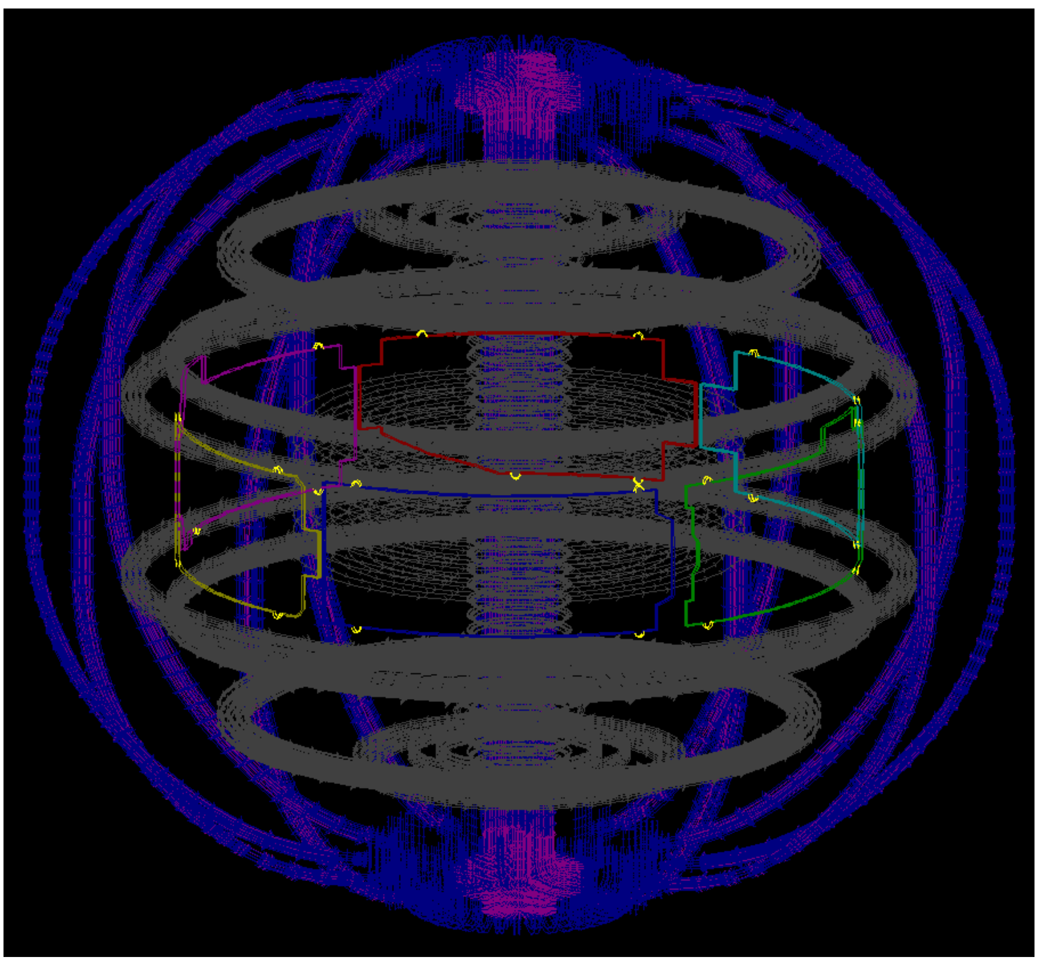


Figure 8.0-4 Biot Savart Model of NSTX U and the RWM coils

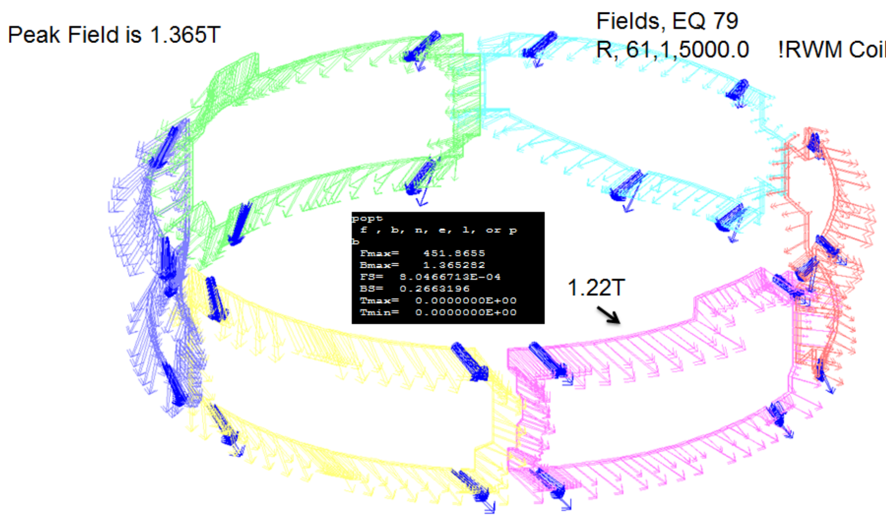



Figure 8.0-5Vector plot of the fields for EQ 79

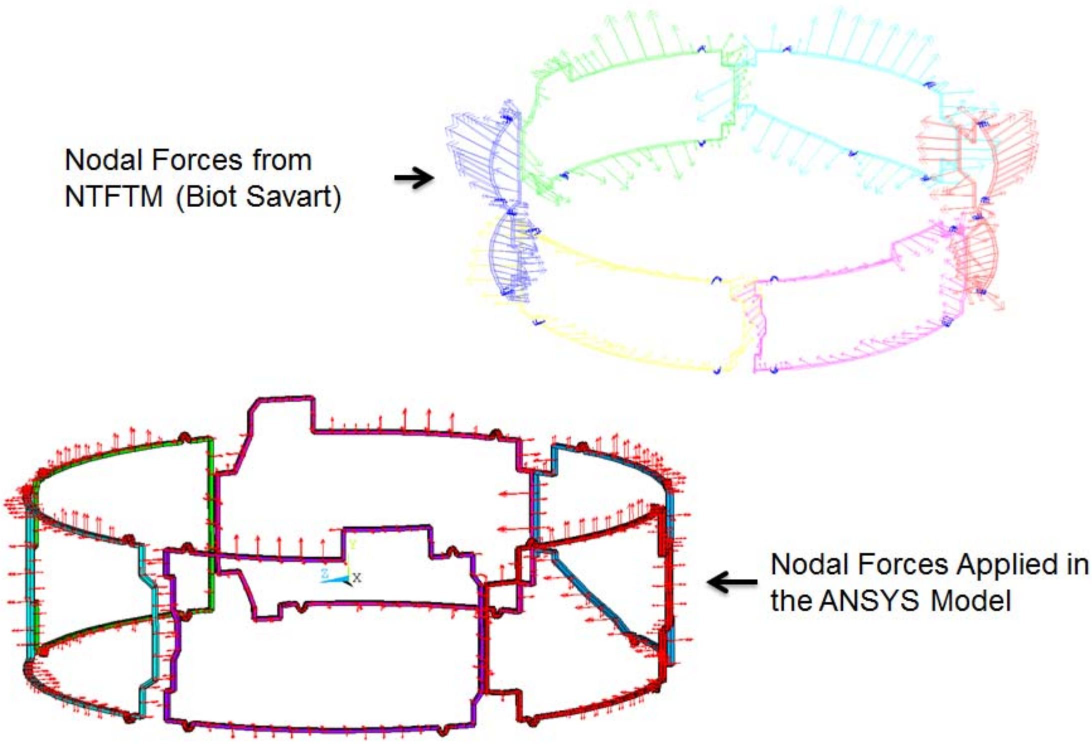



Figure 8.0-6

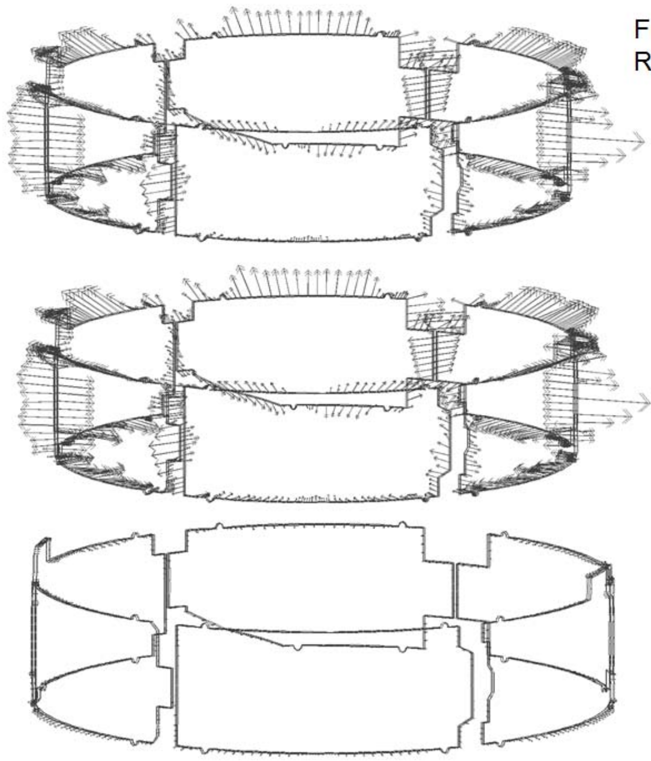



Figure 8.0-7 Comparison of the Loads on the RWM Coils for EQ 17 and 79

Figure 8.0-7 shows the force distributions for two equilibria. EQ 17 was chosen because it was one of the limiting ones for PF4 and 5 and currents in these coils were expected to produce local Lorentz Loads in the RWM coils. The difference between the two equilibria is small. EQ 79 is used in subsequent loading of the RWM coils.

## 9.0 Thermal Calculations

A special purpose code was written to read data provided by Stefan Gerhardt. First the Joule heating is computed and then an attempt was made to calculate a response spectra for subsequent dynamic modal analysis.

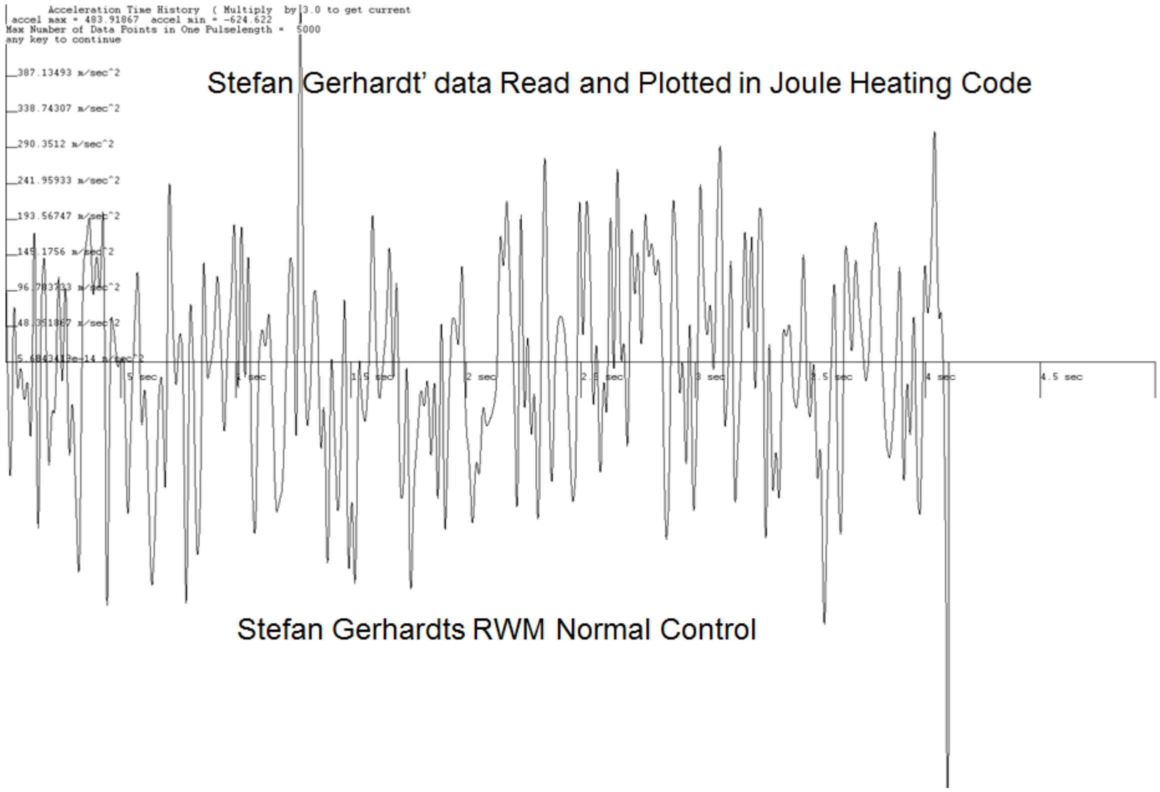
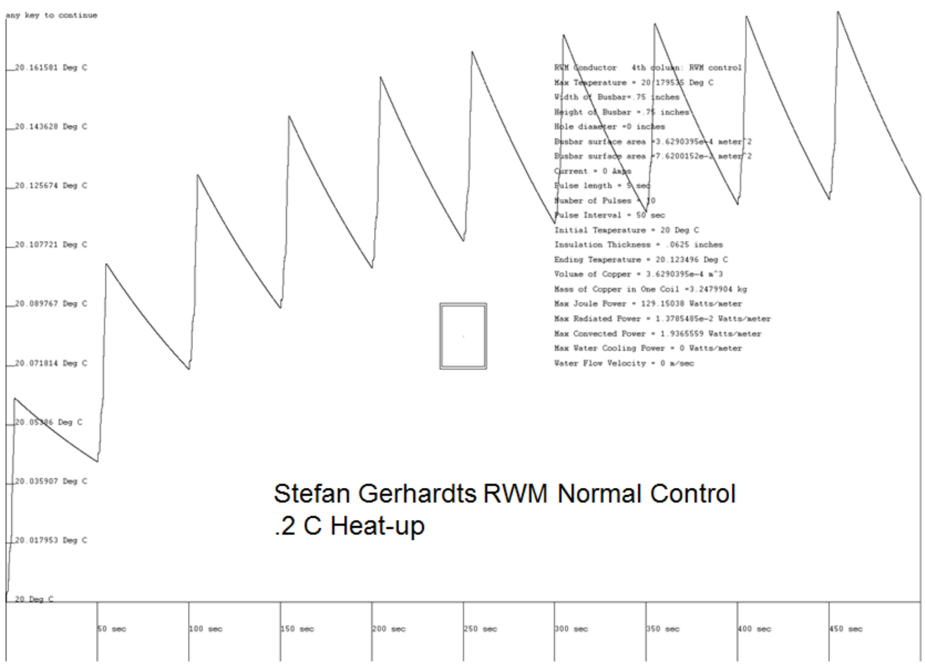

Acceleration Time History ( Multiply by 3.0 to get current
accel max = 483.91867 accel min = -624.622
Max Number of Data Points in One Pulselength = 5000
any key to continue
387.13493 m/sec^2
338.74307 m/sec^2
290.3512 m/sec^2
241.95933 m/sec^2
193.56747 m/sec^2
Stefan Gerhardt' data Read and Plotted in Joule Heating Code
.5 sec
1 sec
1.5 sec
2 sec
2.5 sec
3 sec
3.5 sec
4 sec
4.5 sec
Stefan Gerhardts RWM Normal Control

Figure 9.0-1


any key to continue
20.161581 Deg C
20.143628 Deg C
20.125674 Deg C
20.107721 Deg C
20.089767 Deg C
20.071814 Deg C
20.035907 Deg C
20.017953 Deg C
20 Deg C
RWM Conductor 4th column: RWM control
Max Temperature = 20.179535 Deg C
Width of Busbar=.75 inches
Height of Busbar =.75 inches
Hole diameter =0 inches
Busbar surface area =3.6290395e-4 meter^2
Busbar surface area =7.6200152e-2 meter^2
Current = 0 Amps
Pulse length = 5 sec
Number of Pulses = 10
Pulse Interval = 50 sec
Initial Temperature = 20 Deg C
Insulation Thickness = .0625 inches
Ending Temperature = 20.123496 Deg C
Volume of Copper = 3.6290395e-4 m^3
Mass of Copper in One Coil =3.2479904 kg
Max Joule Power = 129.15038 Watts/meter
Max Radiated Power = 1.3785485e-2 Watts/meter
Max Convected Power = 1.9365559 Watts/meter
Max Water Cooling Power = 0 Watts/meter
Water Flow Velocity = 0 m/sec
Stefan Gerhardts RWM Normal Control
.2 C Heat-up
50 sec
100 sec
150 sec
200 sec
250 sec
300 sec
350 sec
400 sec
450 sec

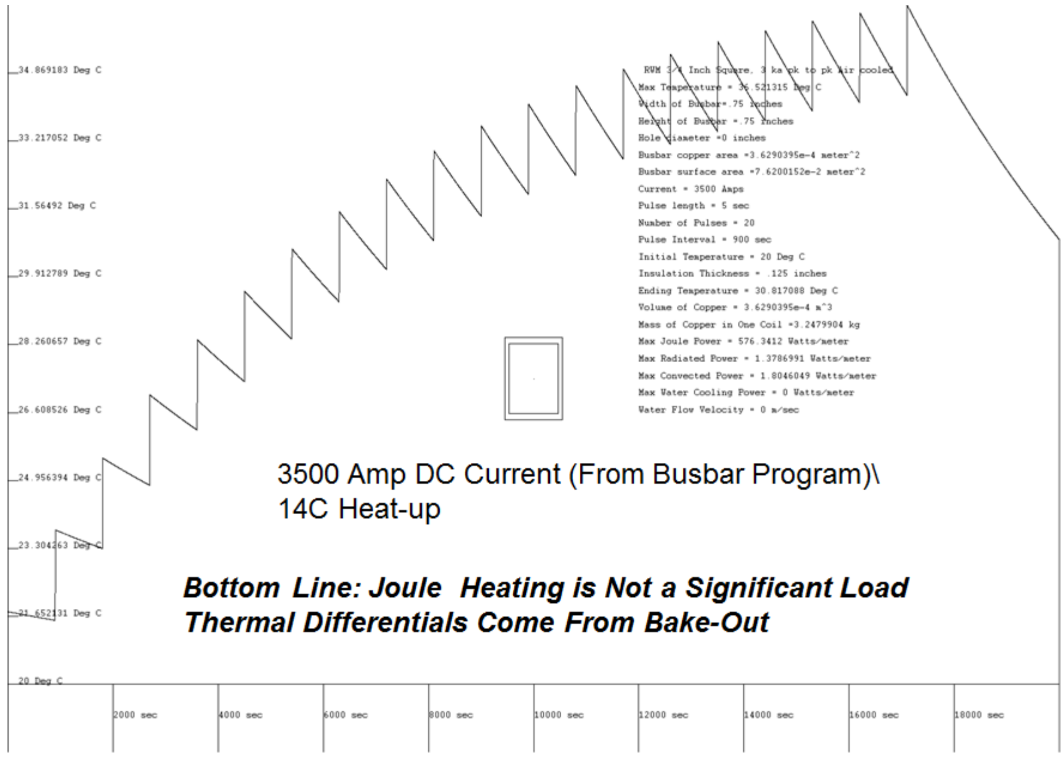

34.869183 Deg C
33.217052 Deg C
31.56492 Deg C
29.912789 Deg C
28.260657 Deg C
26.608526 Deg C
24.956394 Deg C
23.304263 Deg C
21.652131 Deg C
20 Deg C
2000 sec
4000 sec
6000 sec
8000 sec
10000 sec
12000 sec
14000 sec
16000 sec
18000 sec
RWM 3/4 Inch Square, 3 ka pk to pk Air cooled
Max Temperature = 36.521315 Deg C
Width of Busbar=.75 inches
Height of Busbar =.75 inches
Hole diameter =0 inches
Busbar copper area =3.6290395e-4 meter^2
Busbar surface area =7.6200152e-2 meter^2
Current = 3500 Amps
Pulse length = 5 sec
Number of Pulses = 20
Pulse Interval = 900 sec
Initial Temperature = 20 Deg C
Insulation Thickness = .125 inches
Ending Temperature = 30.817088 Deg C
Volume of Copper = 3.6290395e-4 m^3
Mass of Copper in One Coil =3.2479904 kg
Max Joule Power = 576.3412 Watts/meter
Max Radiated Power = 1.3786991 Watts/meter
Max Convected Power = 1.8046049 Watts/meter
Max Water Cooling Power = 0 Watts/meter
Water Flow Velocity = 0 m/sec
3500 Amp DC Current (From Busbar Program)\
14C Heat-up
Bottom Line: Joule Heating is Not a Significant Load
Thermal Differentials Come From Bake-Out

Figure 9.0-2

## 10.0 Global Model Analysis

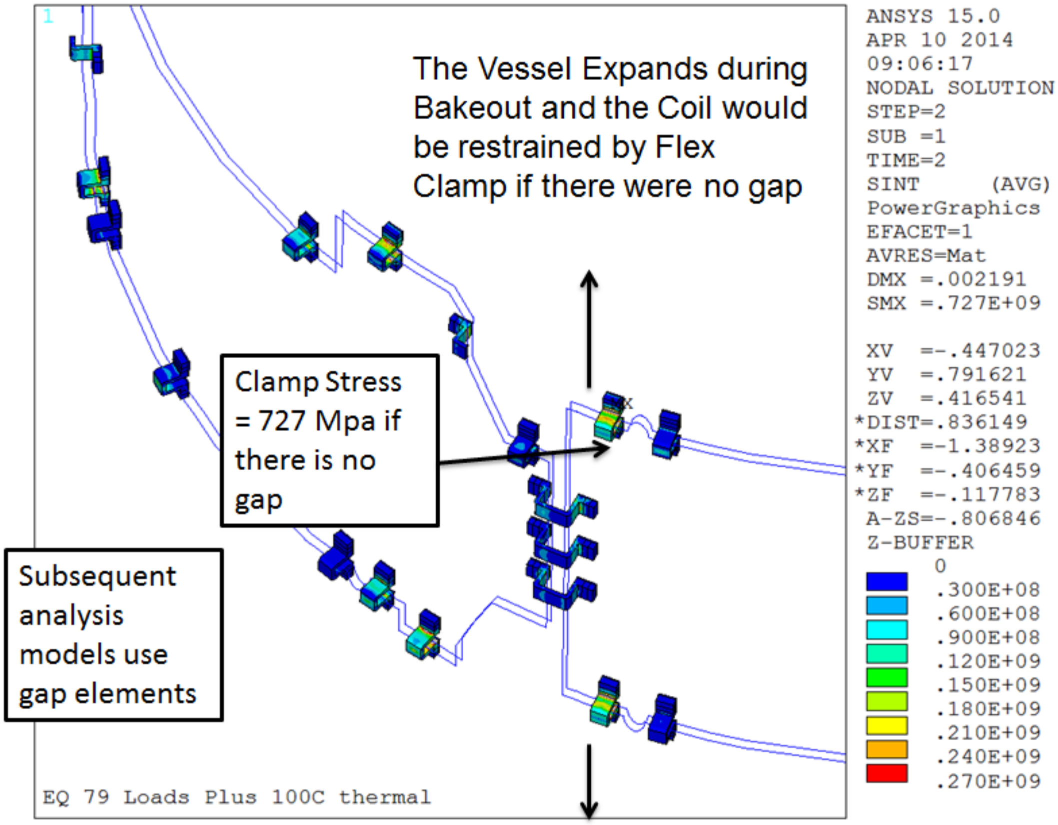



Figure 10.0-1 Stresses due to constraint of the vertical leg

The clamps hold the conductors to the vessel and allow axial motion along the axis of the conductor. In figure 9.1.1, the vertical run of the left hand side of the Bay JK coil was restrained by tight fitting clamps at the left of the flex. This produced unacceptable stresses in the clamp and conductor . G. Labik has provided gaps in the clamps to allow the vertical expansion of the vessel with respect to the vertical legs. The flexes accommodate toroidal growth of the toroidal legs of the coils.

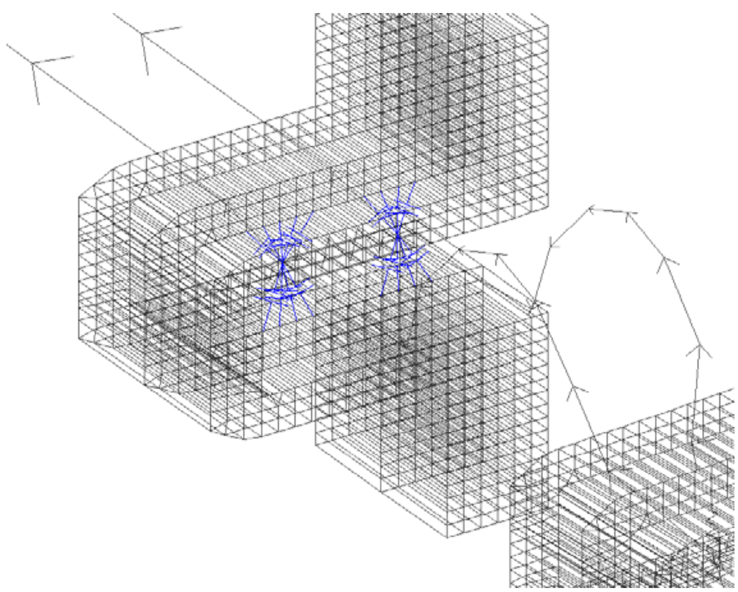


Figure 10.0-2 Gap Elements Added to Allow Vertical Growth of the Vessel during Bake-out

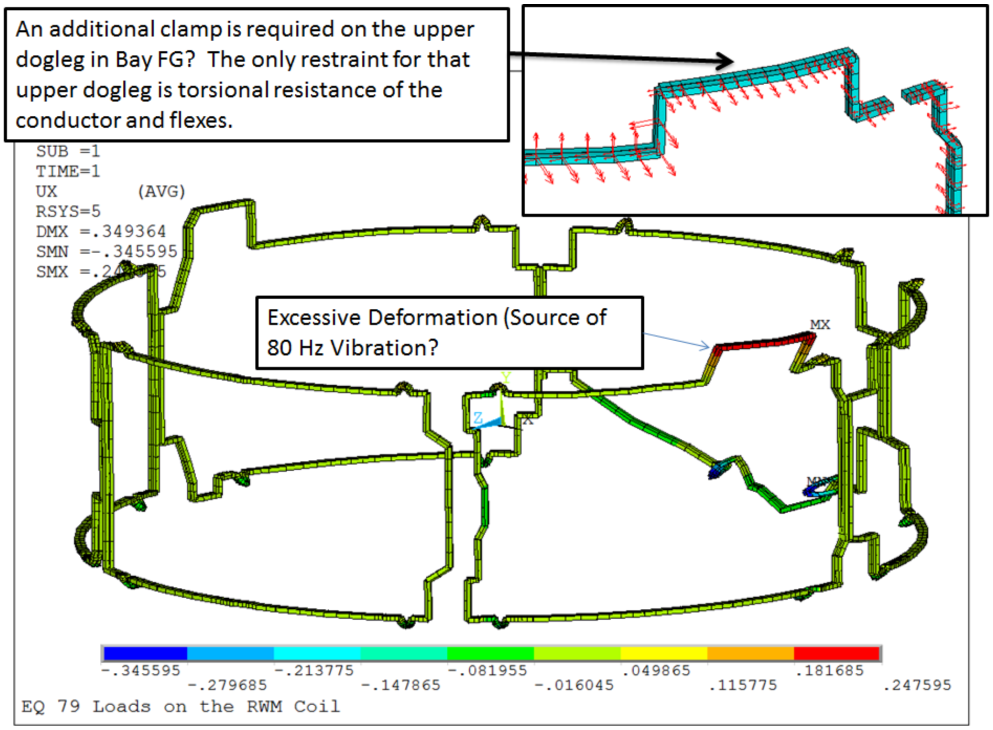



Figure 10.0-3 Displacement of Upper Dogleg in Bay FG

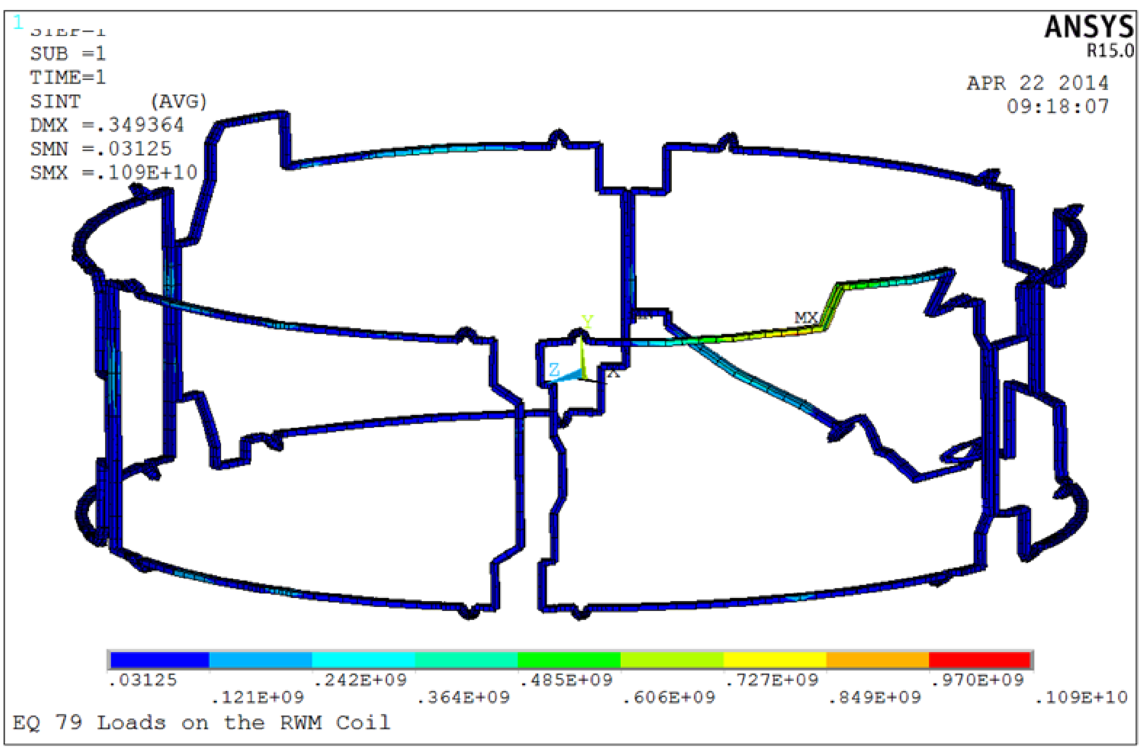



Figure 10.0-4 Stress in Upper Dogleg in Bay FG
At the Peer Review, April 25 2014, it was agreed to add the clamp in Bay FG

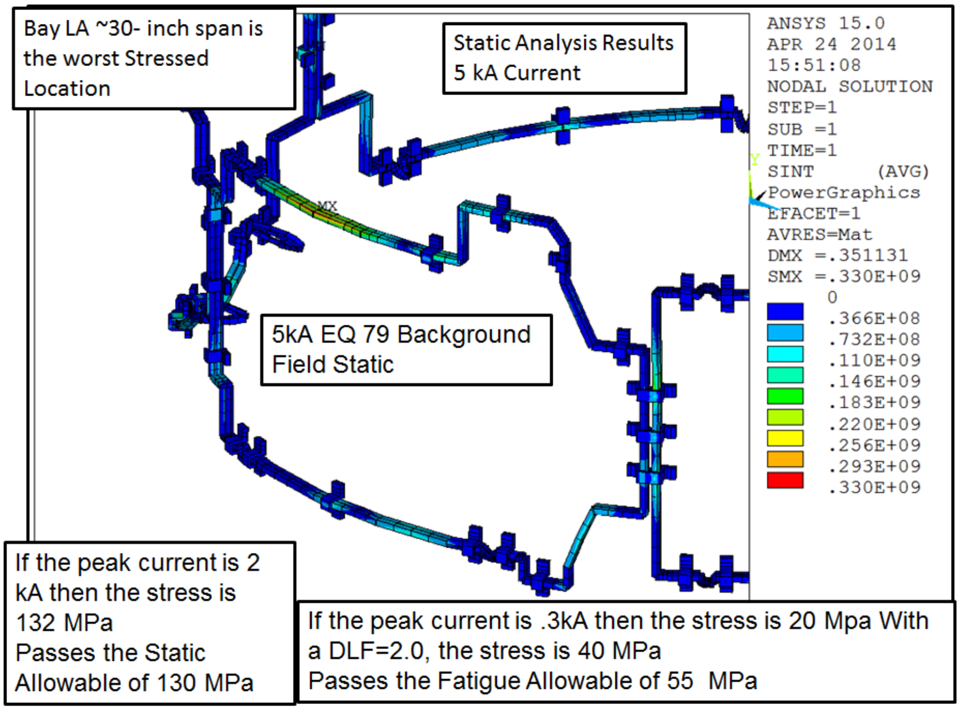



Figure 10.0-5 Worst Stress in the RWM Coil System – Static Analysis

This span in bay LA, is longer than the target length of 20 inches. The bending stress and frequency response make this one of the limiting sections of the RWM coils. The transient dynamic analysis described in section in section 12.3 produced lower stresses in this span and higher stresses in the lower right hand corner of Bay LA

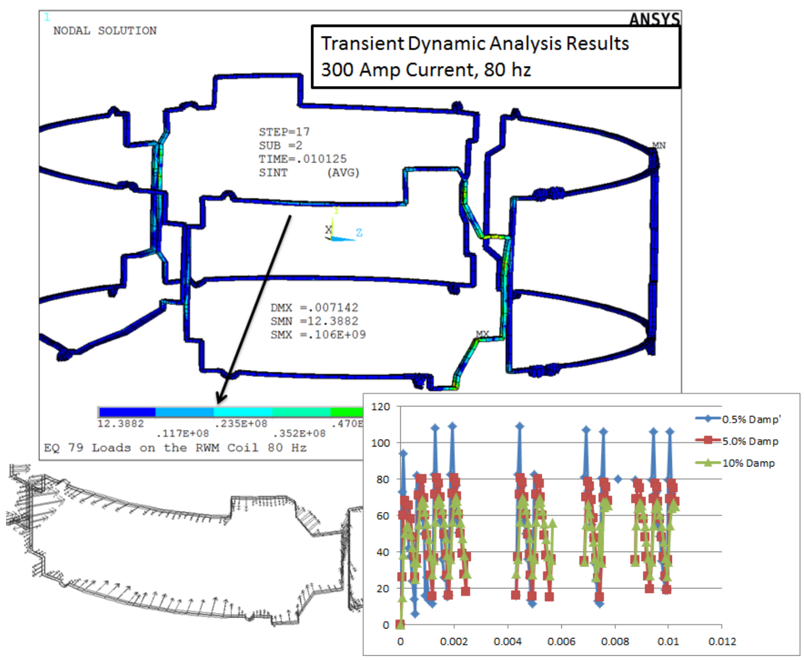



Figure 10.0-6 Worst Stress in the RWM Coil System – Dynamic Analysis

Figure 10.0-6 shows a partial plot of the max stress for all the coils by time. This was constructed by looking at each load step and tabulating the max stress reported for all the coils, and all the coil locations. The effect of damping is fairly strong - .5% damping produced 110 MPa maxima, 5% damping produced 80 MPa and 10 % produced 70 MPa. The allowable was conservatively derived at 55 MPa but the SN curve would predict nearly infinite life without the usual factors of safety. If the two clamps are tight fitting and do not allow sliding then the stress would go away .

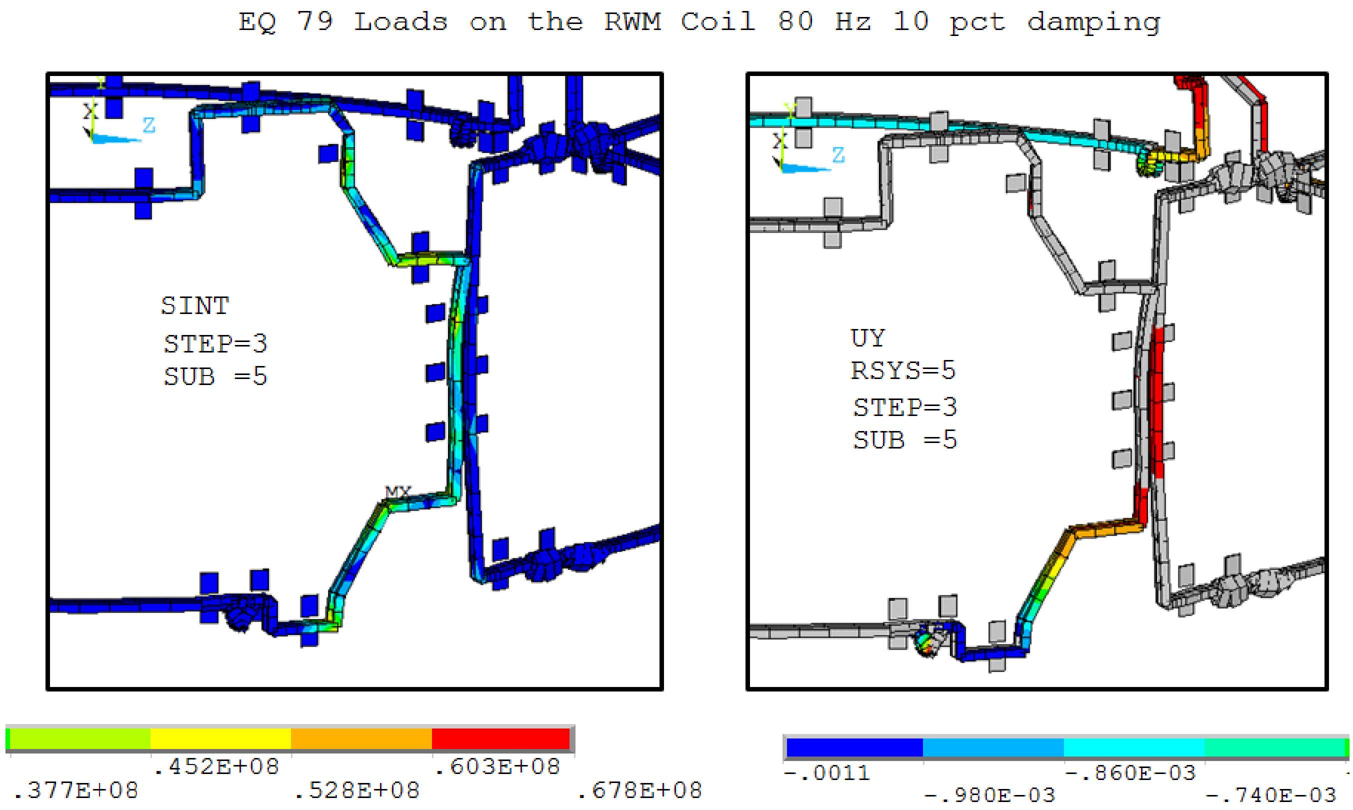



Figure 10.0-7 Worst Stress location in the RWM Coil System – From the Dynamic Analysis

Figure 10.0-7 shows the location where the peak stresses are occurring in the dynamic analysis, The cause of the stress is a toroidal displacement of the bent corner in Bay LA which requires sliding in two sets of clamps. Tight clamps would eliminate this stress. This is a 10% damping result which would be high for a normal structure but because of the sliding it is probably reasonable. The model uses link elements in the clamps which do not model the frictional restraint provided by the clamps.

**11.0 Sub Model Calculations**

**11 Single Span Models**

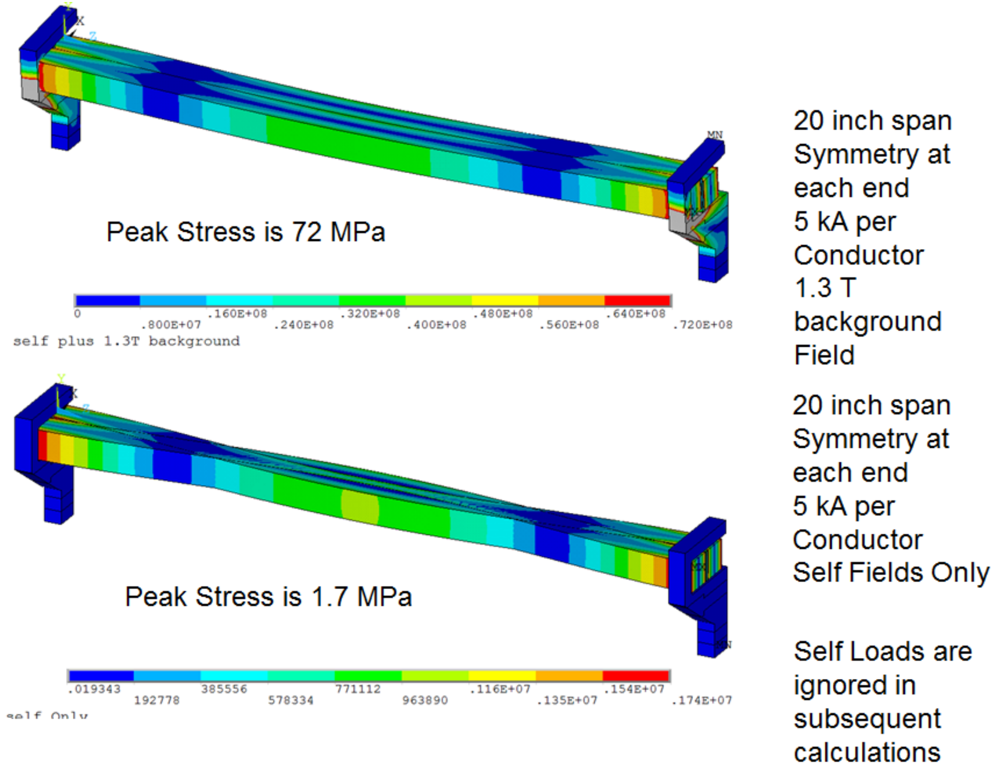



Figure 11.1-1 Comparison of Loads due to Background Field and Self Fields

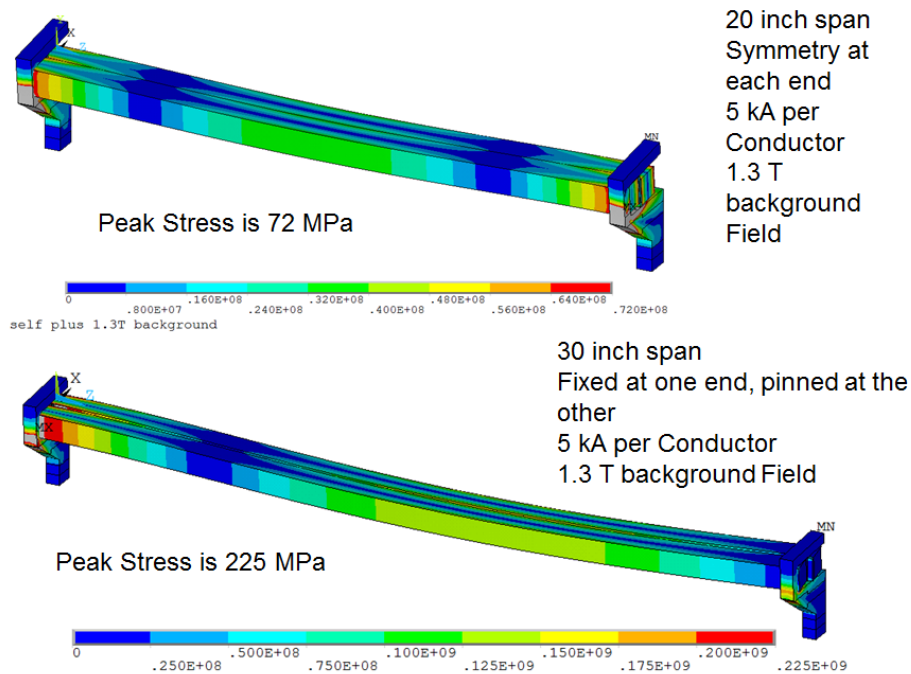
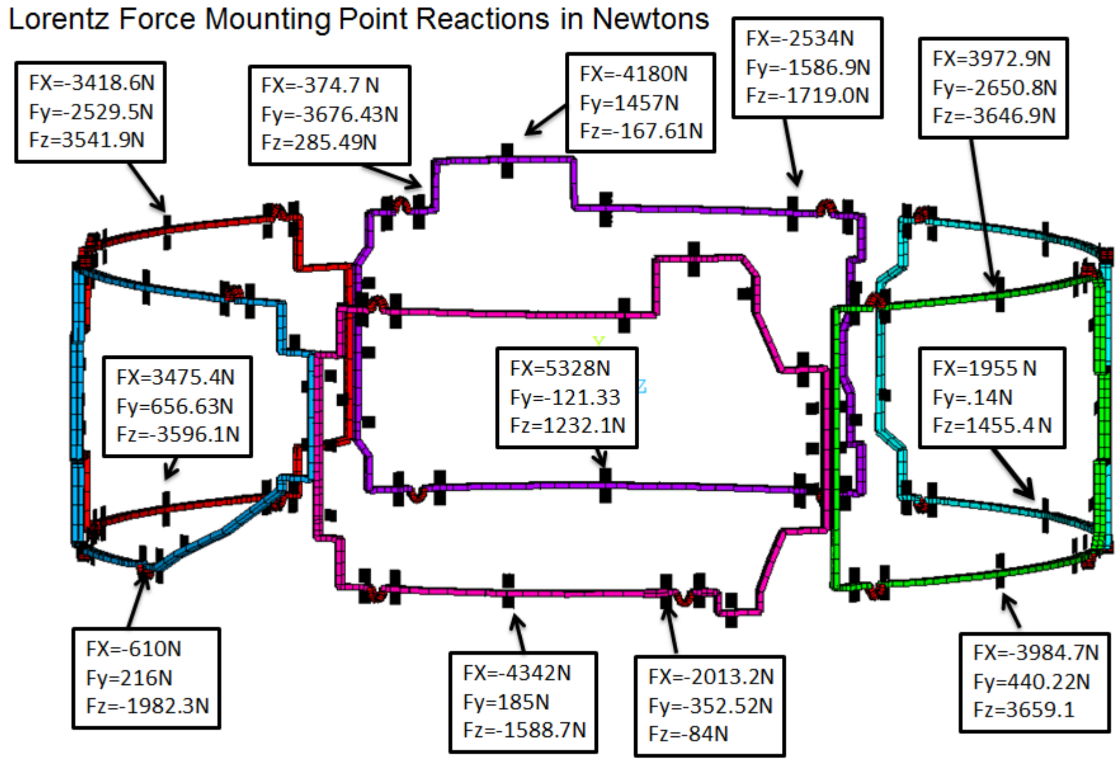
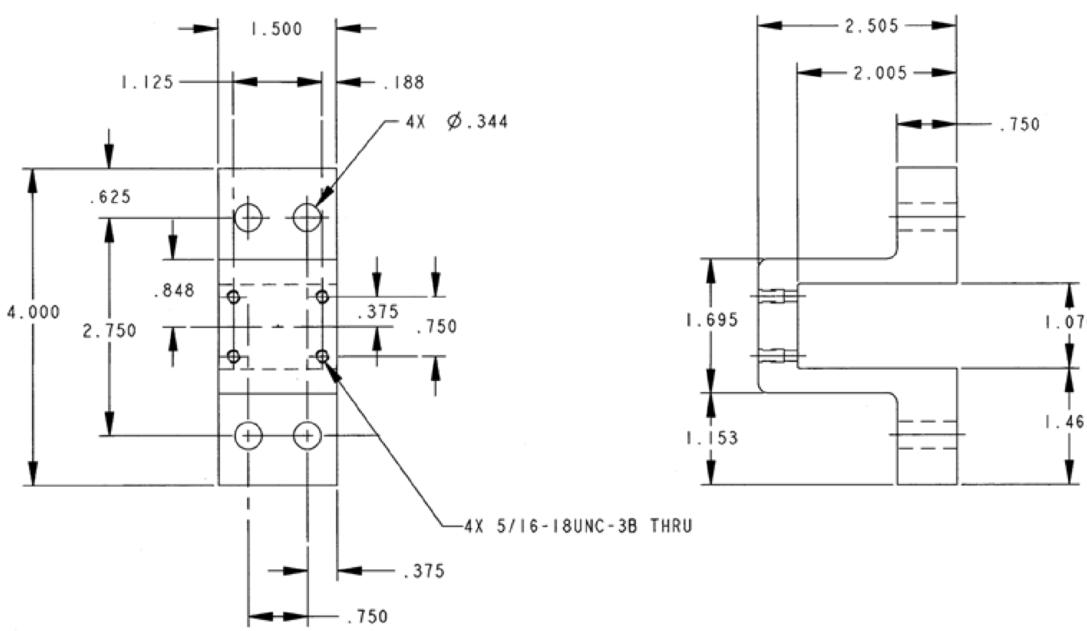


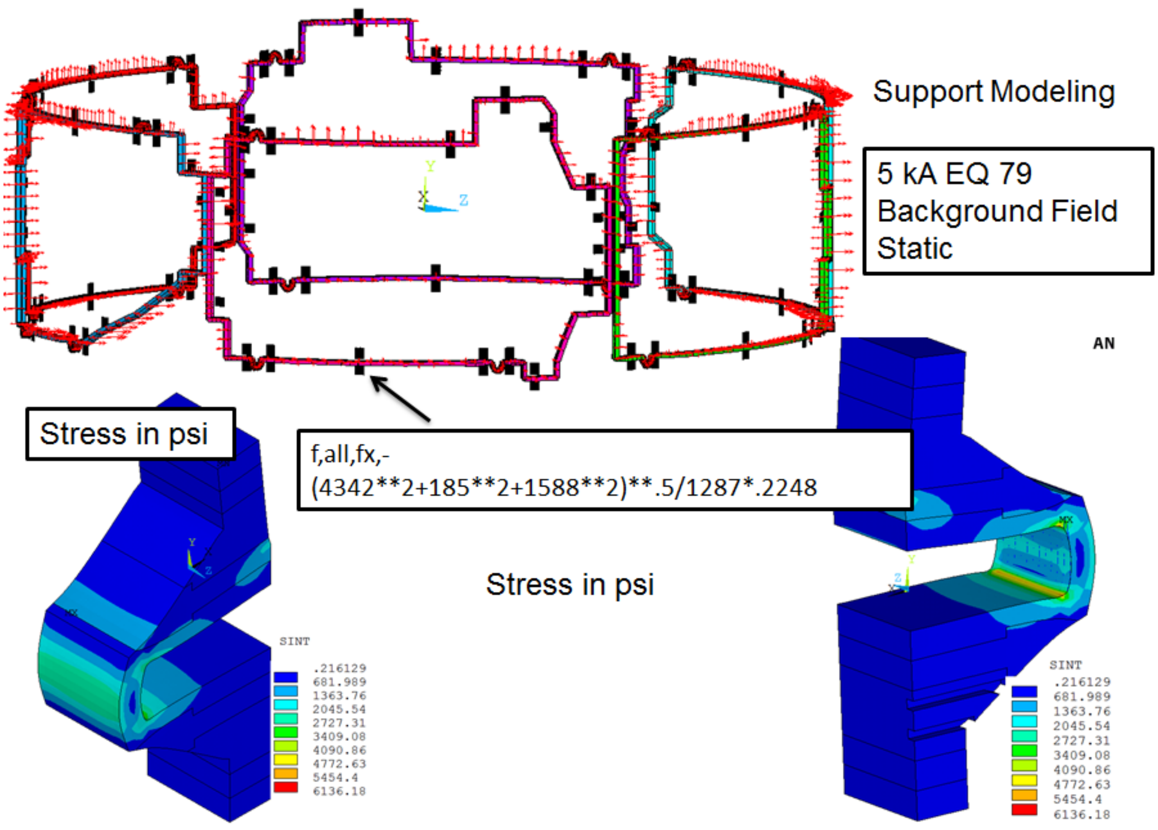

Figure 13.1-2 Comparison of short span and long span with one end un-constrained in rotation

## 11.2 Local Clamp Analysis

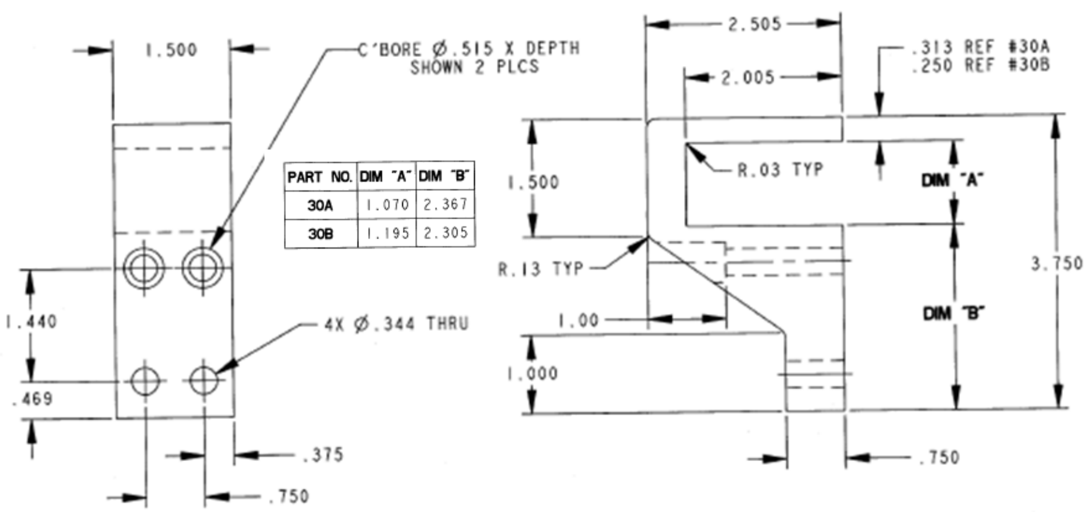
### 11.2.1 Two Sided Clamp






### 11.2.1 One Sided Clamp



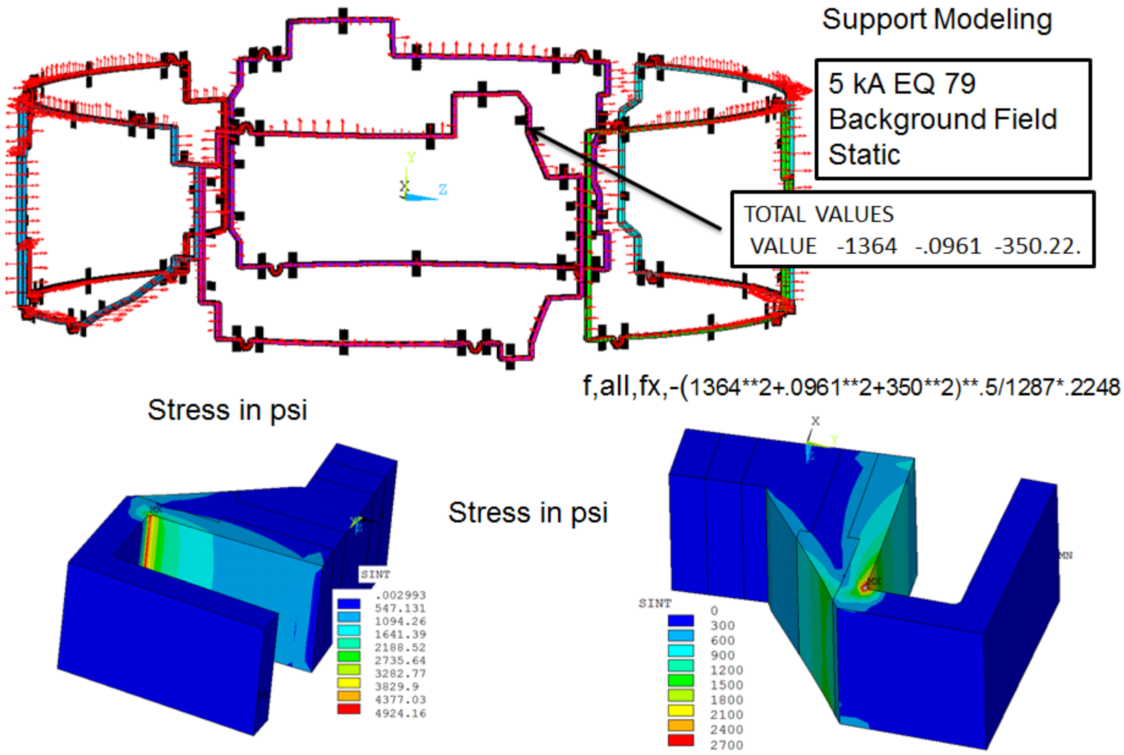



Figure 11.2- One-Sided Clamp Stress in a Typical Location

In these 5 kA analyses of the clamps, the peak stress is 6.1 ksi for the two sided clamp and 4.9 ksi for the one sided clamp. Scaling this down to 300 amps and up for a DLF of 2, the stresses are .732 ksi or 5.05 MPa for the two sided clamp and less for the one sided clamp. These stresses are well within the fatigue limit of stainless steel for infinite life. For the 2 kA peak operation, the streses are well within the static limits of stainless steel.

## 11.3 Flex Connector Analysis

The corner flexes have to absorb the thermal expansion displacements and survive the Lorentz loads – both self field and due to the background field. The peak background field is ~ 1.36 T (See Figure 8.0-2). Due to modeling practicalities, only 16 sheets of copper are modeled. Approximately the loads applied FEA analysis should be halved to account for the missing sheets. .

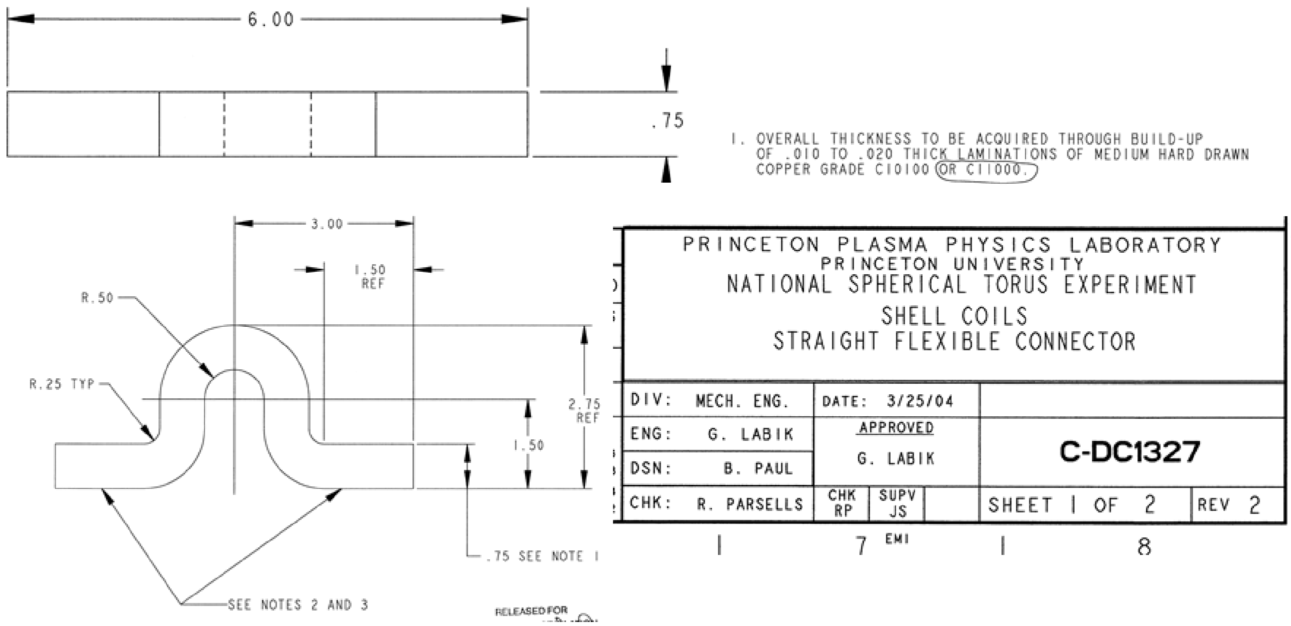


Figure 13.3-1 Straight Flex Details

```
! NTFTM Script
read
fba3
gtrans
0,0,.09375,0
read
fba3
gtrans
0,0,.09375,0
read
fba3
gtrans
0,0,.09375,0
read
fba3
gtrans
0,0,.09375,0
read
fba3
gtrans
0,0,.09375,0
read
fba3
gtrans
0,0,.09375,0
read
fba3
gtrans
0,0,.09375,0
read
fba3
gtrans
0,0,.09375,0
read
fba3
gtrans
0,0,.09375,0
snal
1
merge
1,.001
redu

gtrans
1,0,-.46875,0

spat
0,0,0,1,0,0
tpat
15,0,0,.1
rpat
12,0,.625,1.5, 1,0,0,-90,0,0
tpat
5,0,.1,0
rpat
24,0,1.125,3,1,0,0,180,0,0
tpat
5,0,-.1,0
rpat
12,0,.625,4.5, 1,0,0,-90,0,0
tpat
15,0,0,.1
epat
todf
88,path

chkg
gerase
99
gerase
98
gerase
97
gerase
96
```

```
! NTFTM Script (Continued)
redu
sbri
1
stype
2,2
grpmat
1,1
grpmat
2,2
secoor
40,-1,1,-1,100,.2,.4
secoor
40,-1,1,-1,100,1.2,1.4
secoor
40,-1,1,-100,100,4.6,4.8
secoor
40,-1,1,-100,100,5.6,5.8
secoor
1,.2,1,-100,100,-100,100
secor
1,-1,-.2,-100,100,-100,100
grpmat
40,40
snal
1
conv
1,1
seal
1
stype
2,2

ccur
1,1,2,3,4,5,6,7,8
seal
1
grprel
1,1
r
1,1,62.5
seal
0
snal
0
sbri
1
snel
1,1


field
1
bgen
1,.511,-.7595,-.47159
stype
8,8
gerase
8
redu
seal
0
sbri
1
mfor
1,1,2,3,4,5,6,7,8
seal
2
sbri
1
grpt
2,2
repla
flex
tmsa
flex,2
exit
```

```
/batch    ! ANSYS Batch File
/prep7
et,1,45
et,2,52
*do,imat,1,100
ex,imat,117e9
alpx,imat,16e-6
r,imat,1e8
*enddo
/input,flex,mod
esel,mat,40
nelem
nrsel,x,-.005,.005
d,all,all,0.0
nall
eall

save
fini
/solu
nlgeo,on
tref,292
tunif,292
/title,EQ 79 Loads on the RWM Coil Flex
fscale,.5
solve
save

/title, Bakeout 20 C thermal Toroidal expansion
differential
fscale,.000001
esel,mat,40
nelem
nrsel,x,-.005,.005
nrsel,z,0,.038
d,all,uz,1.43*17e-6*20/2   ! /2 because there at flexes at
each end
nall
eall
solve
save

/title, Bakeout 20 C thermal Toroidal expansion
differential
fscale,.000001
esel,mat,40
nelem
nrsel,x,-.005,.005
nrsel,z,0,.038
d,all,uy,.97*17e-6*20   ! Only Top Flex takes expansion
end
nall
eall
solve
save

/title,EQ 79 Loads Plus 10C Vertical thermal Differential
bf,all,temp,372
esel,mat,40
nelem
nrsel,x,-.005,.005
d,all,all,0.0 !
nall
eall
solve
save
fini
/exit
```

Largest Fields at RWM Conductor (T)

| | NSTX Labik/Neumeyer[2] | NSTX U Titus |
|---|---|---|
| Br | .008 T | .846 |
| Bv | .024 | -.772 |
| Bt | .29 | -.505 |

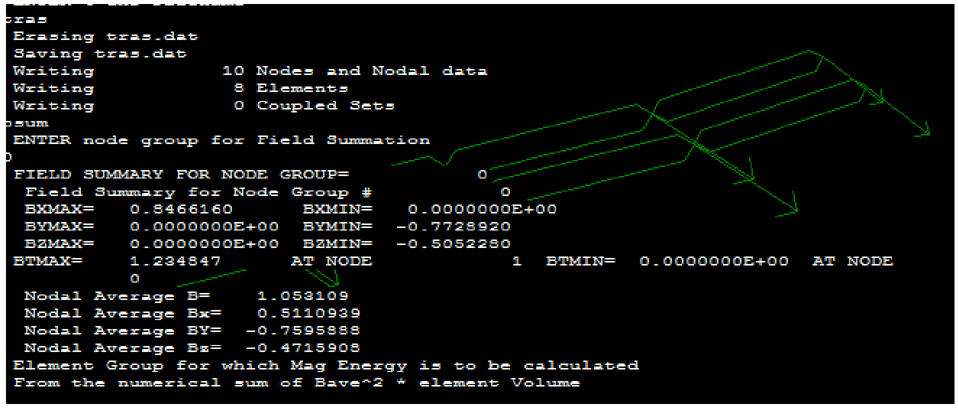



Figure 11.3-2 Background Fields Applied to the flex model

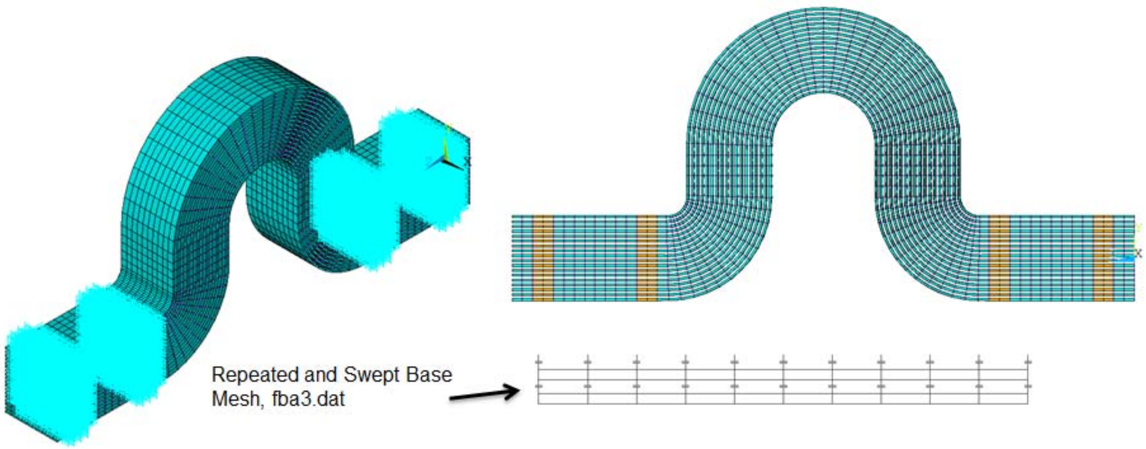



Figure 11.3-3 Strap Model

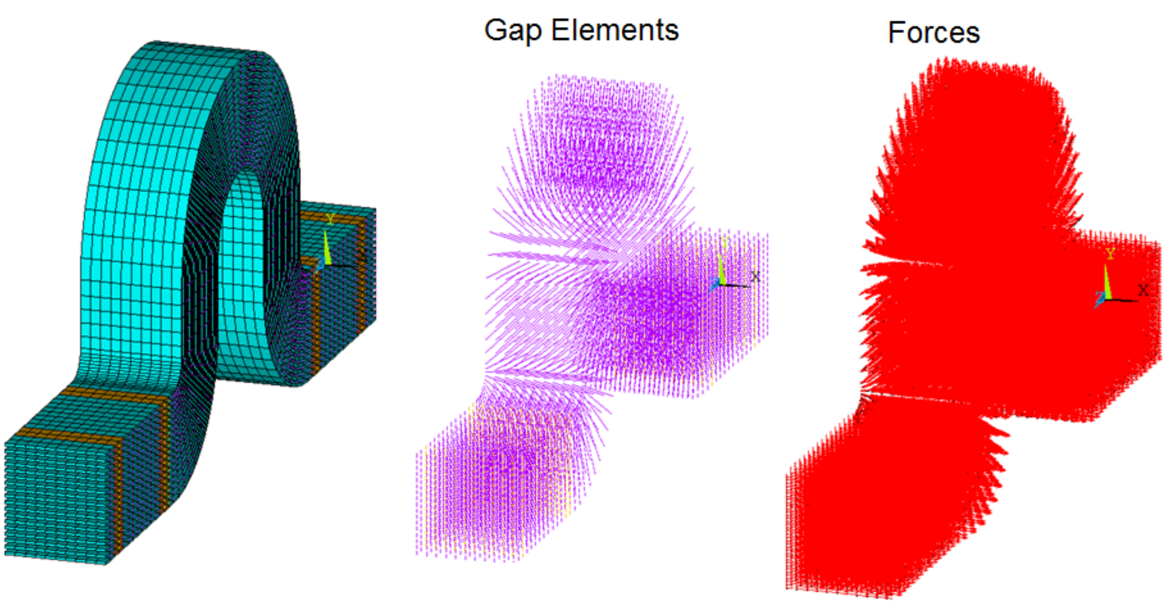



Figure 11.3-4 Strap Model

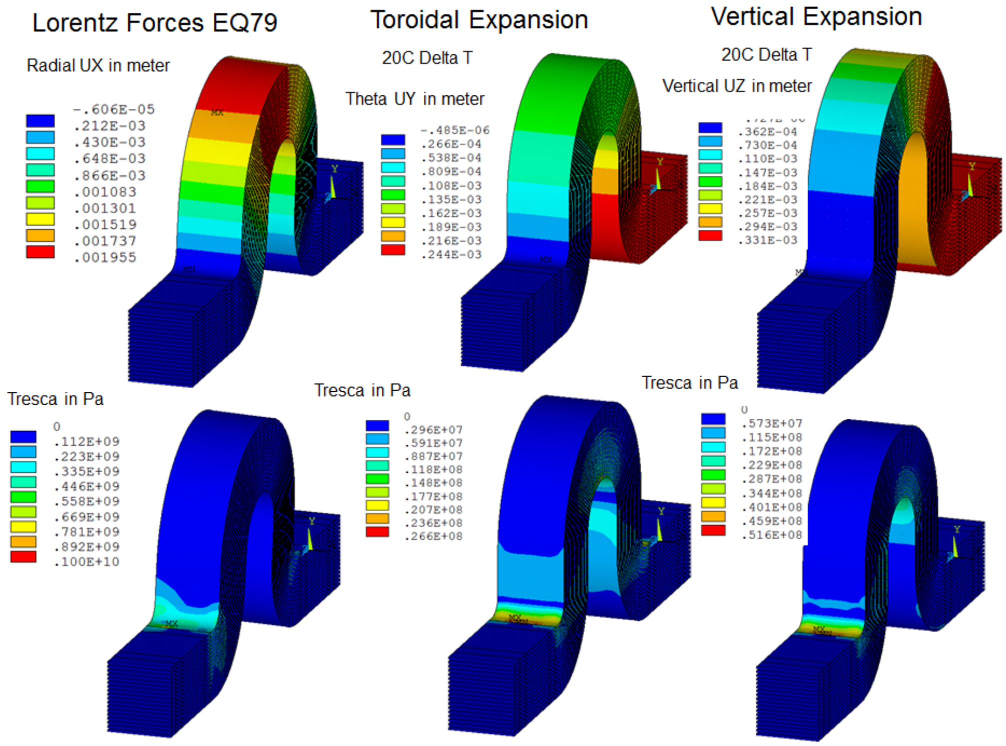



Figure 11.3-5 Flex Strap Displacements and Stresses

Strap stresses due to a differential temperature between vessel and coil of 20 degree C produces peak flex stresses of 20 MPa for the toroidal expansion and 50 MPa for the vertical displacement. These are below the fatigue allowables and well below the static allowables

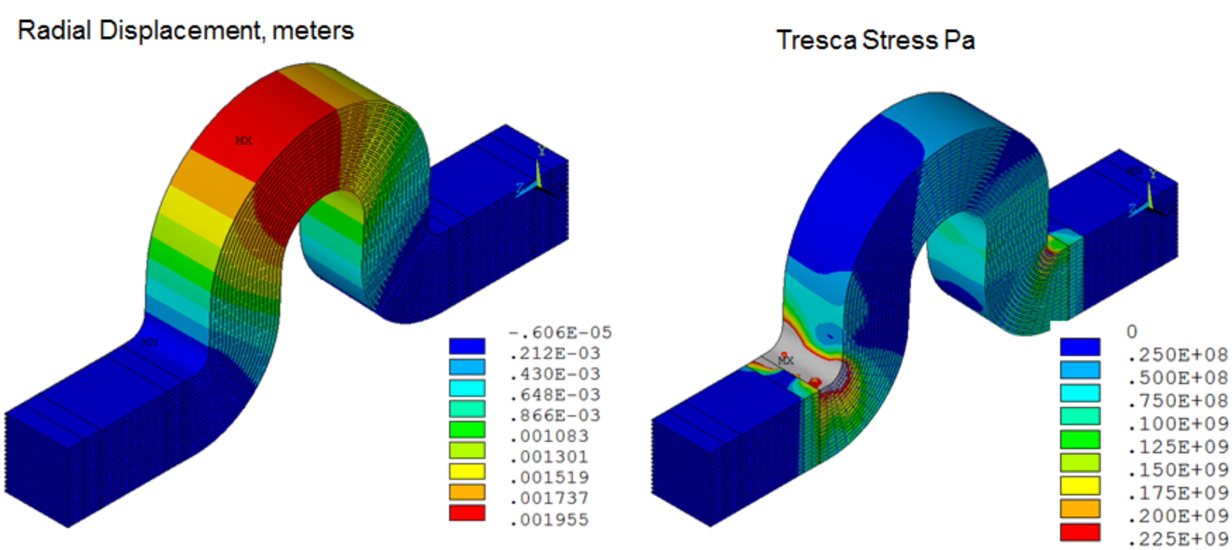



Figure 11.3-6 Flex Strap Displacements and Stresses With Only Lorentz Loads Applied

Figure 15.0-6 shows the Lorentz force displacements and stresses for 5 kA operation. The contours were chosen to max out at 225 MPa. Otherwise the peak at the constraint would dominate, and because the bolt/screw and washer details are expected to be less severe in terms of developing the local stress, the peak at the constraints is ignored.

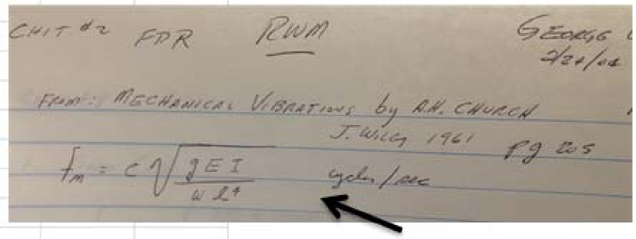
Most RWM cycles are at a 300 amp level. The fatigue allowable for this level of current is 55 MPa , (See Figure 6.4.1.1-2) If the significant flex stress in the figure is ~250 MPa this would scale down to 15 MPa for the 300 amp current that represents the bulk of the RWM operation. If a DLF of 2 is applied, this is still only 30 MPa. In table 4.0-1, the peak occasional current is 2 kA and the 250 MPa stress would scale down to 2/5*250 = 100 MPa which is less than the static bending allowable of 240 MPa for the half hard copper strip material that is used for the flexes.

## 12.0 Dynamic Response

### 12.1 Frequency Analysis

Simple beam calculations should be adequate to predict the frequency response of the RWM conductors. George Labik calculated 278 hz for the fixed-fixed 20 inch span. In figure 12.1-1 Othger spans and end conditions are tabulated. All are above the 80 hz nominal operational frequency, but the longer span with pinned ends, at 97 hz is close. A modal analysis was performed and it shows more complexity.

| | Meters kg | Meters kg | Meters kg | Meters kg | | In Lbs | |
|---|---|---|---|---|---|---|---|
| | Fixed | Pinned | Fixed | Pinned | | (G. Labik, [2]) | |
| G= | 9.8 | 9.8 | 9.8 | 9.8 | | 386.4 | |
| e | 1.17E+11 | 1.17E+11 | 1.17E+11 | 1.17E+11 | | 1.70E+07 | |
| a= | 0.01905 | 0.01905 | 0.01905 | 0.01905 | | 0.75 | |
| B= | 0.01905 | 0.01905 | 0.01905 | 0.01905 | | 0.75 | |
| i | 1.1E-08 | 1.1E-08 | 1.1E-08 | 1.1E-08 | | 0.026367 | |
| rho | 8000 | 8000 | 8000 | 8000 | | 0.314634 | |
| L | 0.508001 | 0.508001 | 0.58 | 0.58 | | 20 | |
| w | 28.45167 | 28.45167 | 28.45167 | 28.45167 | | 0.176981 | Weight per length |
| | | | | | | | |
| C | 3.56 | 1.56 | 3.56 | 1.56 | | 3.56 | |
| | | | | | | | |
| fn= | 2.90E+02 | 1.27E+02 | 2.23E+02 | 9.75E+01 | | 2.78E+02 | |



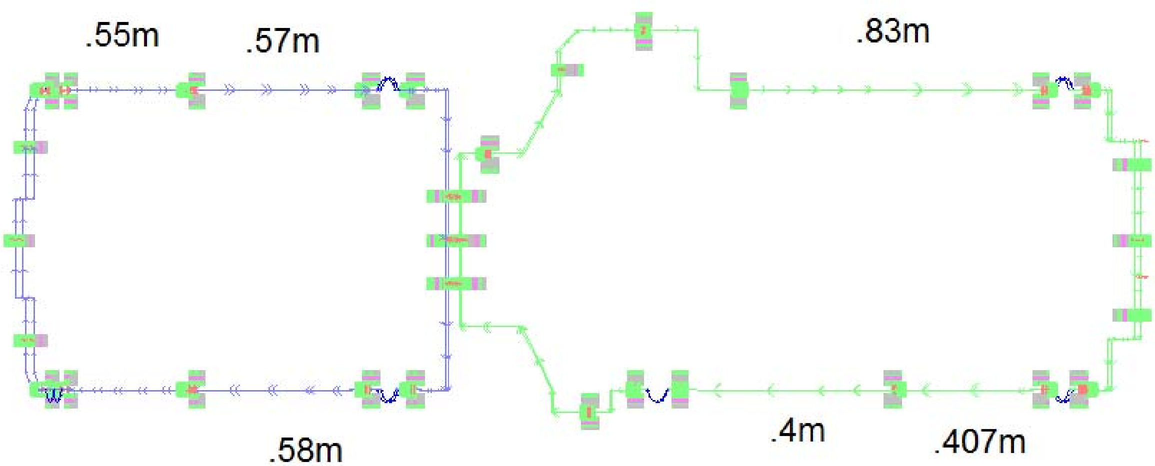
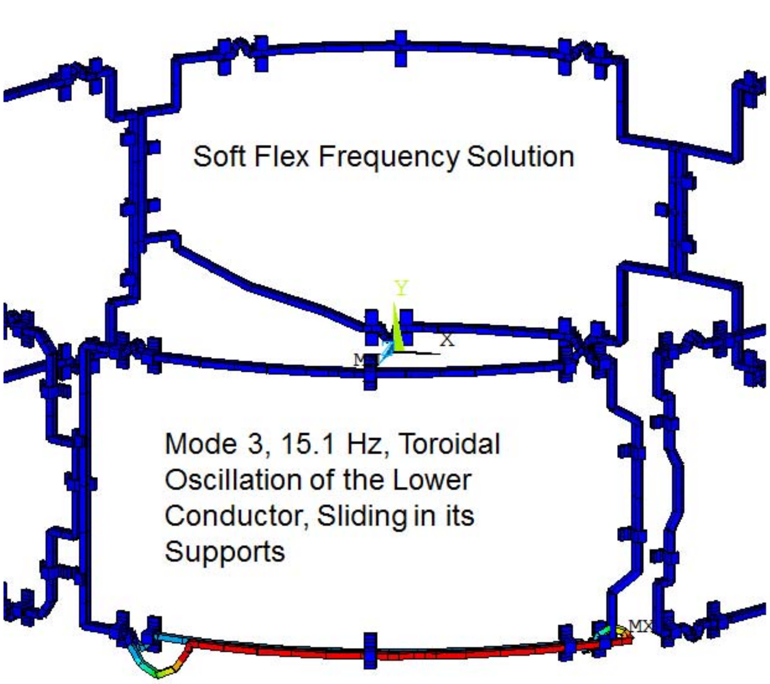




Figure 12.1-1 "Hand" Calculations

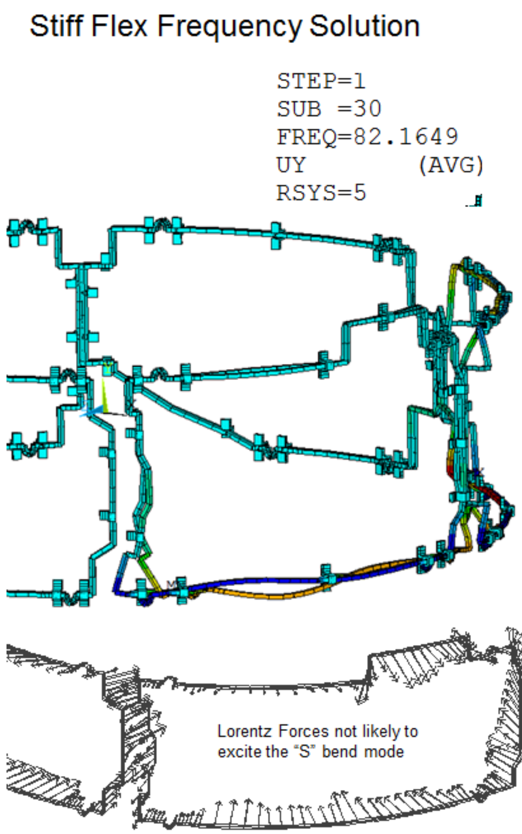
With the flexures modeled as soft – which is what they actually are, there are some conductor legs that are restrained at each end only by flexes. These lengths of conductor rely on the stiffness of the flexes to resist axial motion of the conductor if it was allowed to slide in the clamps. The clamps are not really clamped onto the conductor, there are some gaps in most of the clamps. The frequency analysis with soft clamps will produce these toroidal conductor sliding modes. In reality there is frictional restraint, and more importantly, there is minimal participation of these modes with respect to the Lorents loads, which by nature must be perpendicular to the axial current direction and conductor axial direction.




*** FREQUENCIES FROM BLOCK LANCZOS ITERATION ***

| MODE | FREQUENCY (HERTZ) |
|---|---|
| 1 | 13.74001176330 |
| 2 | 13.96286676917 |
| 3 | 15.18093926500 |
| 4 | 15.24122629070 |
| 5 | 15.57019841579 |
| 6 | 15.58856788273 |
| 7 | 16.84530886926 |
| 8 | 17.30653942320 |
| 9 | 22.17967199040 |
| 10 | 22.69467606848 |
| 11 | 24.20727473859 |
| 12 | 24.94683875394 |
| 13 | 27.06818979008 |
| 14 | 28.66399736354 |
| 15 | 31.08887890277 |
| 16 | 31.87821050792 |
| 17 | 32.94876097169 |
| 18 | 33.50215004834 |
| 19 | 34.26245218538 |
| 20 | 40.01843396253 |
| 21 | 42.86368955523 |
| 22 | 44.52099864676 |
| 23 | 48.57929590624 |
| 24 | 52.20723042303 |

Figure 14.1-1 Soft Flex Frequencies




MODE FREQUENCY (HERTZ)
*** FREQUENCIES FROM BLOCK LANCZOS ITERATION

| MODE | FREQUENCY (HERTZ) |
|---|---|
| 1 | 41.71849573659 |
| 2 | 42.70897458098 |
| 3 | 49.12700915285 |
| 4 | 53.27349335276 |
| 5 | 53.79271859560 |
| 6 | 58.17755283258 |
| 7 | 69.09432563504 |
| 8 | 71.15556369912 |
| 9 | 72.00807643494 |
| 10 | 72.07525851360 |
| 11 | 72.31620578046 |
| 12 | 72.47250721850 |
| 13 | 73.47557070728 |
| 14 | 74.10448595680 |
| 15 | 74.77411417339 |
| 16 | 75.42720842735 |
| 17 | 75.51292030985 |
| 18 | 76.43662681125 |
| 19 | 77.95296483825 |
| 20 | 79.95413436647 |
| 21 | 82.43411815237 |
| 22 | 83.19877425257 |
| 23 | 83.68611045346 |
| 24 | 84.29008641485 |
| 25 | 85.84161808885 |

MODE FREQUENCY (HERTZ)
*** FREQUENCIES FROM BLOCK LANCZOS ITERATION

| MODE | FREQUENCY (HERTZ) |
|---|---|
| 26 | 86.69704234225 |
| 27 | 87.51853182740 |
| 28 | 88.04085490362 |
| 29 | 88.65863073308 |
| 30 | 88.87497877060 |
| 31 | 89.49250428266 |
| 32 | 89.99469767957 |
| 33 | 90.06321679335 |
| 34 | 92.32362904418 |
| 35 | 92.39015619052 |
| 36 | 94.56701240817 |
| 37 | 95.46163131705 |
| 38 | 95.65203685610 |
| 39 | 97.63567961281 |
| 40 | 98.40888079266 |
| 41 | 99.48066276196 |
| 42 | 101.4749602619 |
| 43 | 101.5747147678 |
| 44 | 102.5697798222 |
| 45 | 102.9969165453 |
| 46 | 104.1782195848 |
| 47 | 109.0909611809 |
| 48 | 110.6665468645 |
| 49 | 113.1711871575 |
| 50 | 113.8481862843 |

Figure 12.1-2 Stiff Flex Frequencies

The mode shown in figure 12.1-3 is close to the operating frequency. It is a combination of toroidal motion and a vertical "S" bend. In both cases, the participation of this mode shape will be small with respect to the Lorentz Loads.

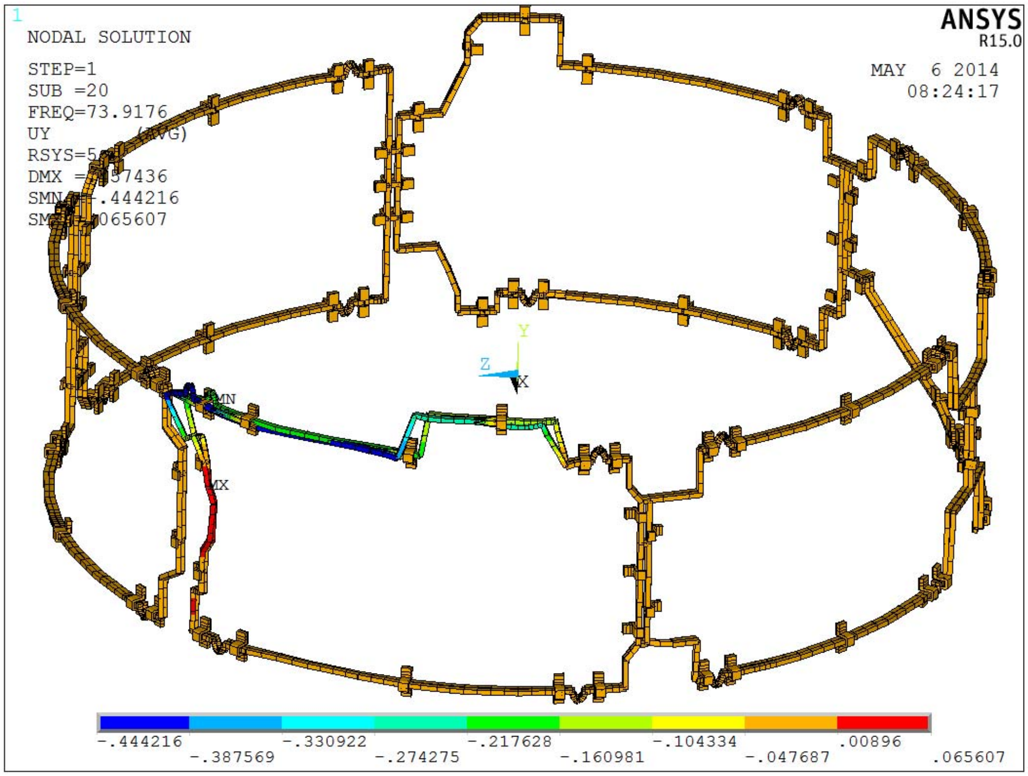



Figure 12.1-3 Another mode with predominantly toroidal motion

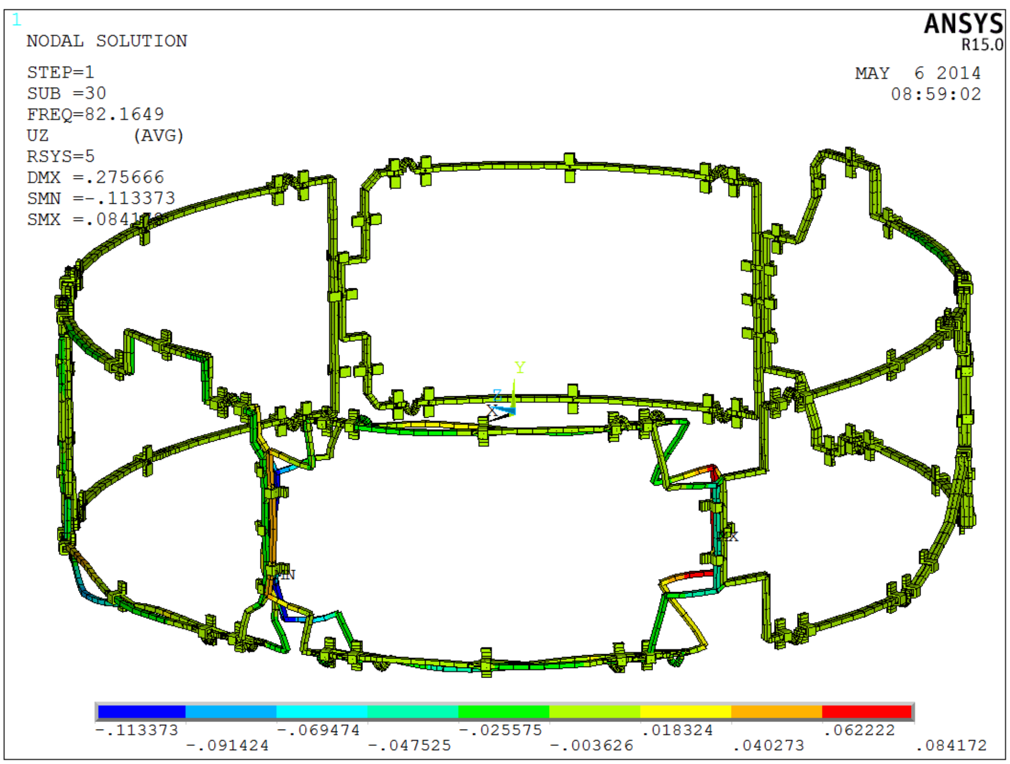



Figure 12.1-4 A more complicated 82 Hz mode with predominantly toroidal motion

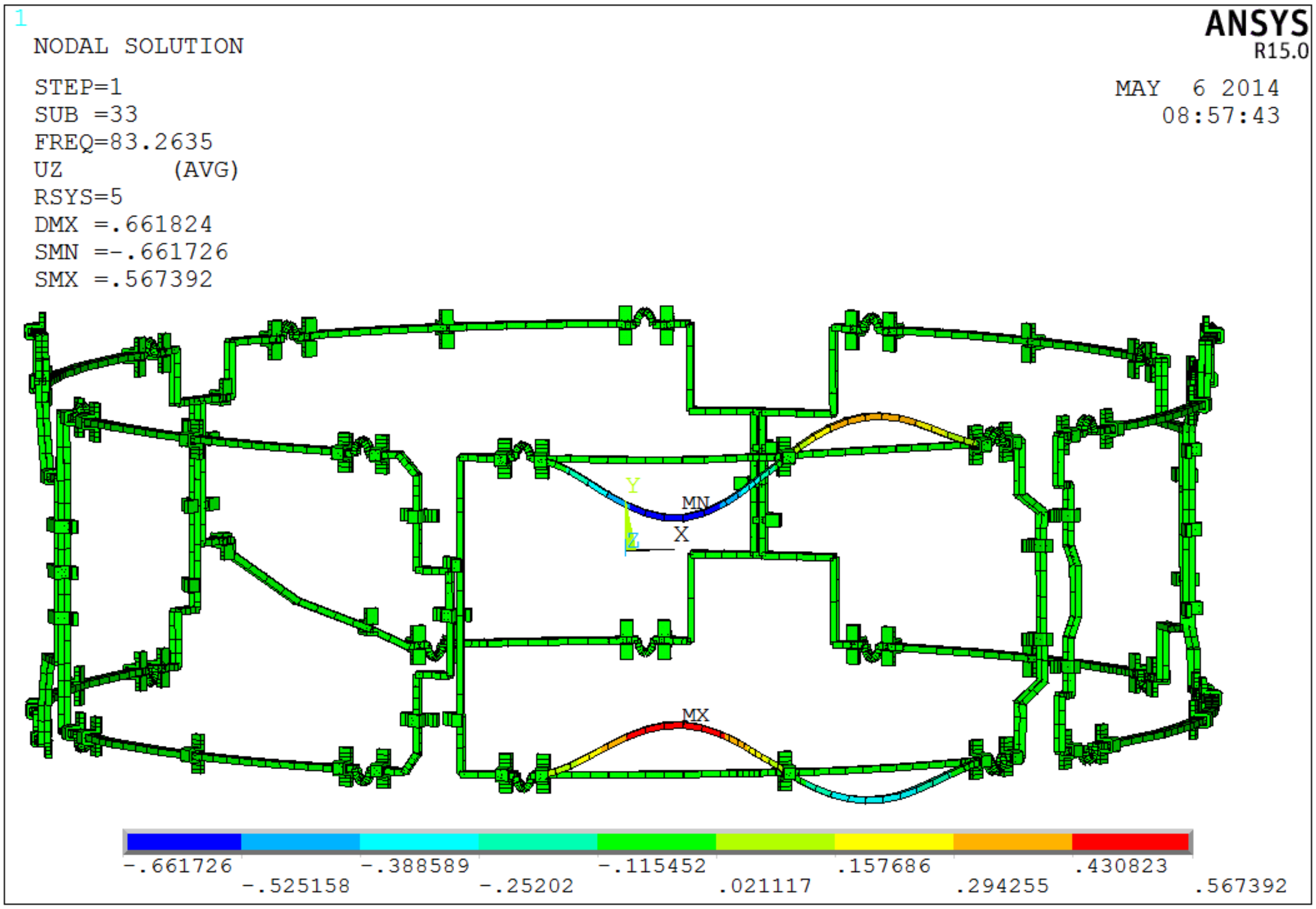



Figure 12.1-5 An “S” bend 82 Hz mode with predominantly vertical motion

In the case of the mode in figure 12.1-5, the “S” bend is not likely to resonate with the Lorentz loads that are unidirectional along the span.

## 12.2 Modal Analysis

The RWM coils operate in complex alternating current modes. The frequency content of the RWM excitation is predominantly 80 hz or lower. There is some potential for forcing function frequencies to go to 500 hz which is the maximum possible for the SPA power supplies. Natural frequencies of the RWM coils occur throughout the forcing function frequency range. Simple hand calculations of fixed-fixed and pinned pinned models yield 97 to 200 hz. . Many of the lower frequencies are for modes that would not be excited by the directions of the Lorentz loading. For example the lowest frequencies are for toroidal motion of the toroidal runs of conductor which have flexes at each end. There is no toroidal Lorentz load . Other lower frequencies are for “S’ bend mode shapes that would require local reversals of Lorentz loads – which do not occur.

RWM Natural Frequencies 100 to 300. RWM Driving Frequencies are mostly below the Natural frequencies – some at or above.

Amplification factor or, Dynamic Load Factor (DLF) for a single degree of freedom oscillator with a harmonic forcing function. Driving Freq=80 80/100 = .8 DLF=~2 depending on damping

Forcing Function Frequency

| Frequency |
| --- |
| 100Hz |
| 0 |
| 35 Hz |
| 50 Hz |
| 80 |
| 1000 Hz |
| 500 (max) |
| |

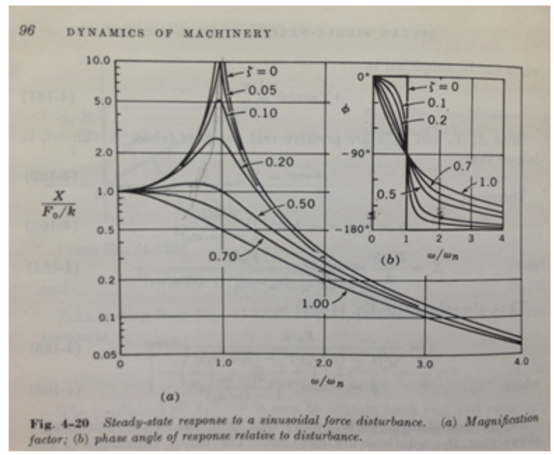



Figure 14.7.2 Response of a single Degree of Freedom oscillator to a Harmonic Excitation

For natural frequencies in the range of 100 Hz To address the possibility of resonance with the primary forcing function, a transient dynamic analysis was performed and is described in the next section

## 12.3 Transient Dynamic Analysis, 80 Hz Sine Wave

The beam element model is small enough that it can be run with a transient sine wave excitation. The solution portion of the batch script is shown below. Damping is important in this analysis, because if there are resonances, damping will limit the response. Calculation of the damping coefficients is discussed in section 7.2

```
/solu
antype,transient
outres,all,1     ! writes results every sub step.  Use smaller # for more resolution
nsubst,10        ! For more finer results use larger #.
betad,7.97e-6        !Damping
alphd,12.57/2        !Damping
kbc,0
fdele,all,all

tref,292
tunif,292
pi=3.1416
frequency=80
Period=1/frequency
dt=period/20
tottime=0
```

```
*do,ld,1 ,1000
tottime=tottime+dt
/title,EQ 79 Loads on the RWM Coil 80 Hz
time,tottime
/input,forc,mod
fscale,300/5000*sin(2*pi*tottime/period)
solve
save
*enddo
fini
/exit
```

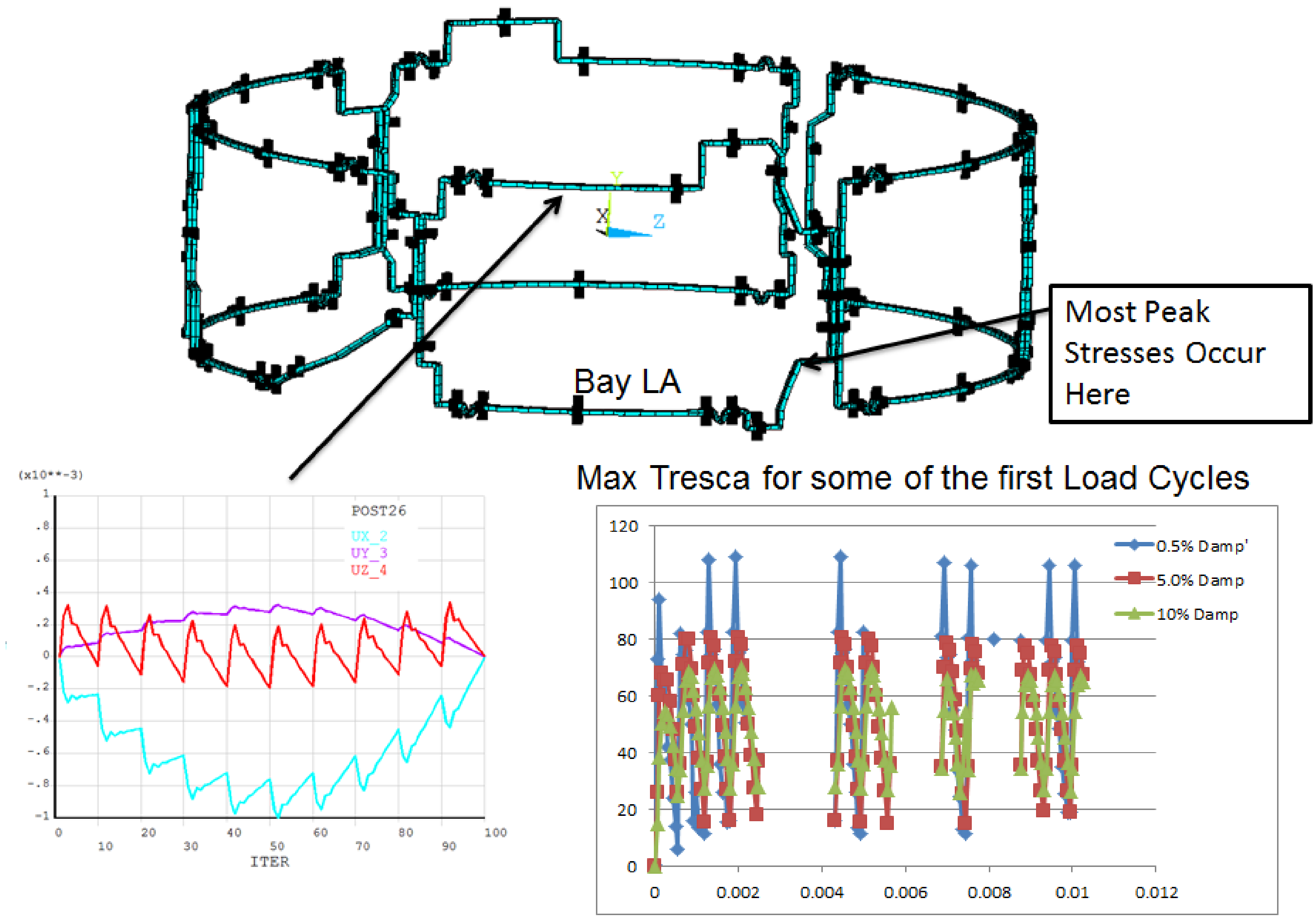



Figure 12.3-1 Displacements mid span at one of the more highly loaded legs of Conductor (left) and Partial Max Tresca Data

The analysis is for a 80 Hz 300 amp driving current. Transient results are plotted in figure 12.3.1. and figure 10.0-6. The Tresca plot has to be constructed from plotting individual load steps and tabulating the data. Post 26 doesn't work for beam elements. So data was plotted until a pattern was evident. The peak stress is 108 MPa in the lower right hand corner of Bay LA. and is above what would be expected for a DLF of 2 applied to the static analysis results. This is 40 MPa at the long span for which the displacement results are plotted. The stress results for the long span actually aren't too different from the static results with a smaller DLF applied. This is shown in Figure 10.0-6. A transient run with higher than 0.5% damping produced lower results. With 5% damping the peak stresses were 80 MPa and 70 MPa for 10% damping.

**Appendix A August 8 2012 email from Stefan Gerhardt**

**From:** Stefan Gerhardt [mailto:sgerhard@pppl.gov]
**Sent:** Wednesday, August 08, 2012 9:02 AM
**To:** Steven A. Sabbagh
**Cc:** Peter Titus; Larry Dudek; Ronald Strykowsky; George Labik; Philip Heitzenroeder; Jonathan E. Menard
**Subject:** Re: RWM coil qualification for upgrade loads

A few comments:

Pre-programmed PCS waveforms can only change on a 1 kHz time-base. So the fastest possible pre-programmed waveform is 500 kHz. And I have never heard of anybody doing this, because the fields would not get into the vessel.

- There was apparently some resonance in the ~80 Hz range; this was observed before I joined NSTX. I am curious if Pete will find that in analysis, and what it implies. That subject may or may not be related to the upgrade qualification, which is at least for now more related to pulse length, higher load levels, and fatigue. Pete should comment on that as well.
- RWM control is in feedback, so of course anything is possible. That said, there are typically two things that happen in RWM control:
    - Low(er)-level, 20-200 Hz control oscillations during the shot. This is item 3 below, collapsed to a single frequency.
    - One or two large amplitude oscillations during a disruption, as the system tries to recover control and fails. This is folded into item 2.
- We did cause some damage to those clamps during the 2008 run, by applying waveforms like in the attached. I am collapsing them into item 2 in the list below. Pete can comment if this style of waveform should get an additional specification.

Now, I think we need to keep this from getting too complicated. So, I stand by the recommendation below, which are only slightly modified from that of a few days ago.

For 10 years, 15 run weeks/year, 5 days per week, and 30 shots perday, I see ~22000 shots.
I would assume the following:

1. 10% of the shots have no EFC/RWM currents on at all. (disruptions and RF shots)
2. 20% of the shots have ~2.0 kA pk-pk @ ~35 Hz, and 10% at 4.0 kA pk-pk @ 60 Hz.(RFA studies and other ELM pacing things)
3. 60% of the shots have 600A pk-pk at 80 Hz. (Surrogate for standard RWM control)

If you want to assume that all shots are 5 seconds long, that is fine.

Otherwise, assume that 30% are 5 seconds long, and the 50% are 3 seconds long, and 20% are 1 second long.

Again, if these pose a problem, then we can revisit the assumption.

**Email from George Labik :**

From the FDR the max load is 30 lb per inch on the pair of horizontal members and 60 lb per inch per pair of vertical members. The FDR did not stipulate the load vector which can be inferred from the field strengths or obtained from the calculations. I will continue to look for the calculations.

The requirements from the FDR was 5000 amps and since they are two turn coils, 10 000 ampere turns. The potential was estimated at a few hundred volts.

Email from Jim Bialek 1/19/2012 [13]

Attached please find 3 files, hopefully they will adequately describe the RWM coils on NSTX-u. This is the best information i have. Please get back to me with any questions or comments. This data dates from the last day of work at pppl in December 2011.

Two of the files show coils geometry (pdf style files). the first attached file shows only coils, the second attached file shows the coils together with my model of NSTX-u

The 3rd file is a text file (built on a unix platform) that is a 'cleaned up' description of the coils, this is where you can find numerical data describing the coils. I have a code that strips out all un-used nodes and renumbers the entire model. I think this stripped down description is preferred to one with several thousand extra and un-used nodes. This text file is also available on the pppl cluster in my directory

```
pwd
 /p/spitfire/s1/jbialek/CU/mesh

 ls -l cleani1NSTXtitus
-rw-r--r--+ 1 jbialek users 8309 Jan 19 10:33 cleani1NSTXtitus
```

My coordinate system is cartesian using MKS units ( lengths in meters ). The origin of coordinates is at the very center of the model with the 'z-axis' upward. The x axis points east and the y axis points north (between bay A & L ). Every figure has a coordinate triad drawn in the lower left corner to assist you in understanding the selected view of the model.

The format of the file is as follows

title info ( lines #1 & 2)
line 3 = number of nodes to follow
then node #, X, Y, Z for each node

The coils are described as if connected pairwise in antiseries and the coil description starts right after the line containing the text string 'numhole'.  therefore there are 3 coils described ( not 6 individual coils).

each coil is described as follows:

one line contain coil#, #line_segments,#turns,cross-sectional_area_perturn, material resistivity

then there are '#line-segments' lines of information , each line contains the start-node & end-node for a line segment within the coil

if you have any questions please contact me,  it is probably easier to answer your questions than to write out lots & lots of description

best wishes
jim b

cc sabbagh,labik

## Appendix B

### PPPL Calculation Form

Calculation # RWM-3 Revision # 0 WP #, if any (ENG-032) 1076

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

DETERMINE FORCES ON COIL MEMBERS & CURRENT FEED TO SIZE SUPPORTS.

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

PRINCIPLES of COLLEGE PHYSICS by SHORTLEY & WILLIAMS

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

1. SMALL DEFLECTIONS IN CONDUCTORS
2. CURRENT FLOWS THROUGH GEOMETRIC CENTER of CONDUCTOR

Calculation (Calculation is either documented here or attached)

attached

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

THE FORCES WERE CALCULATED PER INCH LENGTH of CONDUCTOR AND WILL BE USED TO DETERMINE GEOMETRY of SUPPORTS and REQUIRED WELDS.

Cognizant Engineer's printed name, signature, and date

GEORGE LABIK [signature] 3/10/04

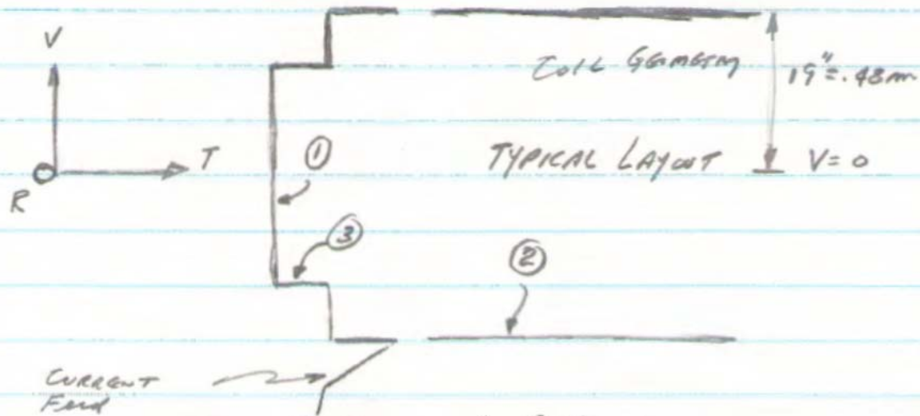
**I have reviewed this calculation and, to my professional satisfaction, it is properly performed and correct.**

Checker's printed name, signature, and date

James Bialek, [signature] 17 March 2004

RWM COILS 3/10/04

$I \times \beta$ FORCE CALCULATION




T = TANGENTIAL

V = VERTICAL

R = RADIAL

I = 5000 AMPS PER TURN

No. of TURNS = 2

FROM J. BIALEK & C. NEUMEYER

@ R = 69.3 INCHES = 1.76 m = RADIAL ℄ of RWM COILS

let R = 1.8 m FOR $\beta$ VALUES

$\beta_T$ = .29 TESLA use $\beta_T$ = .3

$\beta_V$ = .024 TESLA @ V = .48 DECREASES TO .011 TESLA @ V = 0 use $\beta_V$ = .024

$\beta_R$ = .0069 TESLA @ V = .48 m max = .0078 @ V = .42 m

use $\beta_R$ = .008 TESLA

① VERTICAL MEMBER

$I \times \beta_T = F_R$
$I \times \beta_V = 0$
$I \times \beta_R = F_T$

$\frac{F}{\ell} = \beta I$

$\frac{F}{\ell} = \frac{N}{m} =$

$\beta = Wb/m^2$
$I = $ AMPS

$I = 10,000$ Amp (2 turns)

$\ell = 1$ inch

$F = \frac{N}{m} \times \frac{.225 \text{ lb/N}}{39.37 \text{ inch/m}}$

$= .00572\, \beta I$

$\frac{F_R}{\ell} = 10,000 A * .3T (.00572)$

$= 17.16$ lb/inch

1 GAUSS = $1 \times 10^{-4}\, wb/m^2$
1 TESLA = $1 \times 10^{4}$ GAUSS
1 TESLA = $1\, wb/m^2$

$\frac{F_T}{\ell} = 10,000 A * .008T (.00572)$

$= 0.46$ lb/inch

## Horizontal Member

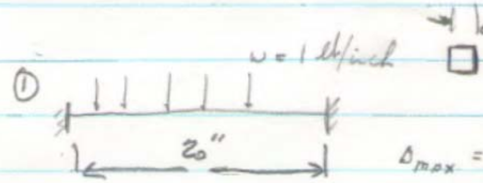
②③ use max values for $\beta_V$ & $\beta_R$

$$I \times \beta_T = 0$$
$$I \times \beta_V = F_R$$
$$I \times \beta_R = F_V$$

$$\frac{F_R}{l} = 10{,}000\,A \times .024\,T\,(.00572) = 1.37\ \text{lb/inch}$$

$$\frac{F_V}{l} = 10{,}000\,A \times .008\,T\,(.00572) = 0.46\ \text{lb/inch}$$

Deflection ①




$$\Delta_{max} = \frac{wl^4}{384EI}$$

$$= \frac{16\times10^4}{(384)(18.7\times10^6)(.026)}$$

$$= .00086''$$

$$\approx .001 \text{ for } 1.37\ \text{lb/inch}$$

$E_{copper} = 18.7\times10^6$ psi

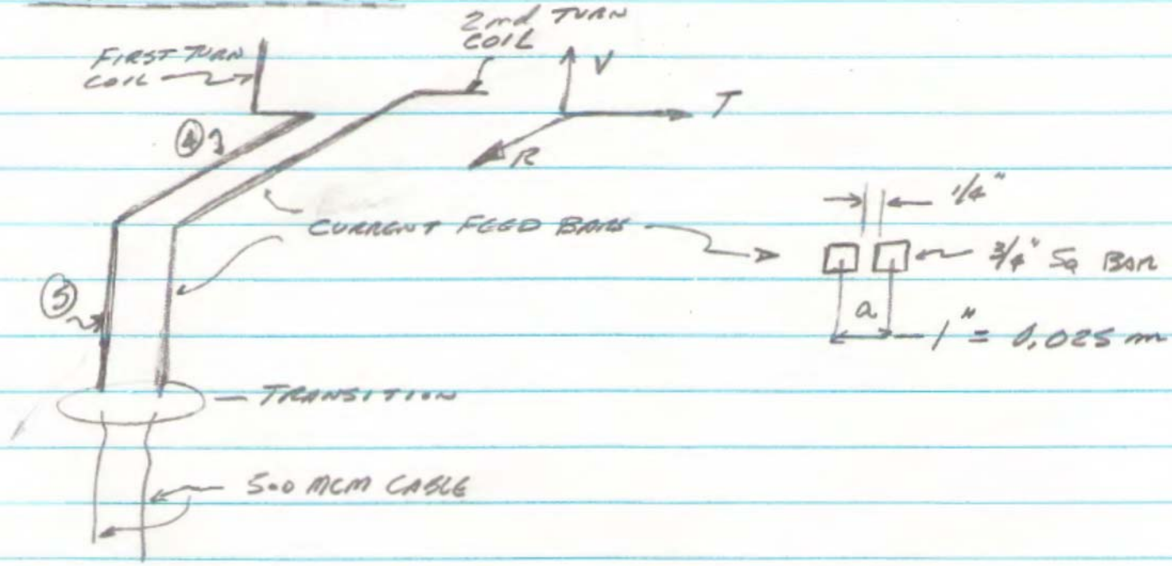
$I = \frac{s^4}{12} = .026$

$l^4 = 16\times10^4$

② Simple support

$$\Delta_{max} = 5wl^4/384EI$$
$$= (5)(.001) \approx .005$$

## CURRENT FEED BARS




## SELF INDUCED FORCES

A.

$$\beta = \frac{2I}{a} \times 10^{-7} \ Wb/m^2 \qquad I = \text{Amps}, \quad a = \text{meter}$$

$$\beta = \frac{2 \times 5000A}{.025} \times 10^{-7} = .04 \ Wb/m^2 = .04 \ \text{Tesla}$$

→ $\beta_V$ on ④ Bar

→ $\beta_R$ on ⑤ Bar

Bar ④

$I \times \beta_T = 0$ — $\beta_T$ small

$I \times \beta_V = F_T$

$I \times \beta_R = 0$ — $\beta_R = 0$

$$F_T = 5000A \times .04T \,(.00572) = 1.14 \ lb/inch.$$

## Current Feed Bars

### Self Induced Forces

Bar (5) $I \times B_T = 0$ — $B_T$ is small

$I \times B_V = 0$

$I \times B_R = F_T$

$F_T = 1.14$ lb/inch — I & a same as pg 4

### Interaction with Field Coils

Bar (4) $I \times B_T = F_V$

$I \times B_V = F_T$

$I \times B_R = 0$

use same values from Pg 1 for $B_T$, $B_V$, $B_R$

$F_V = 5000\,A * .3T(.00572) = 8.58$ lb/inch

$F_T = 5000\,A * .024T(.00572) = 0.69$ lb/inch

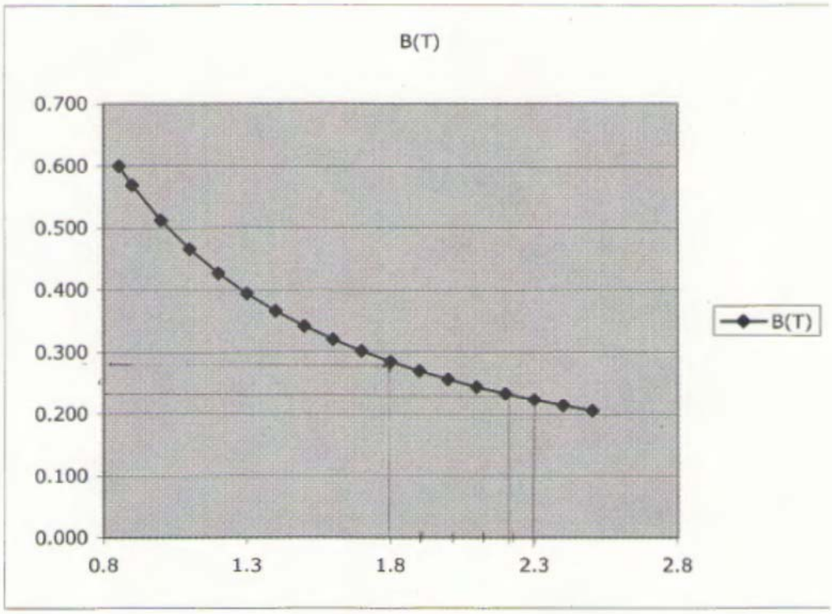
Bar (5) $I \times B_T = F_R$

$I \times B_V = 0$

$I \times B_R = F_T$

| | | |
|---|---|---|
| R0 | 0.854 | m |
| Bt@R0 | 0.6 | T |
| Rx | 0.854 | m |
| Bt@Rx | 0.6 | T |

| R (m) | B(T) |
|---|---|
| 0.854 | 0.600 |
| 0.9 | 0.569 |
| 1 | 0.512 |
| 1.1 | 0.466 |
| 1.2 | 0.427 |
| 1.3 | 0.394 |
| 1.4 | 0.366 |
| 1.5 | 0.342 |
| 1.6 | 0.320 |
| 1.7 | 0.301 |
| 1.8 | 0.285 |
| 1.9 | 0.270 |
| 2 | 0.256 |
| 2.1 | 0.244 |
| 2.2 | 0.233 |
| 2.3 | 0.223 |
| 2.4 | 0.214 |
| 2.5 | 0.205 |




RWM COIL ℄ R = 69.323" = 1.76 m

$\beta_T \approx .28$ TESLA

Feeder Cable TANGENTIAL RUN ~ R = 2.2 m

$\beta_T = .23$ TESLA.

```
!This is an attempt to write a program that  reads an acel time
!history and calculate an ARS from that time history


dim x(0:400000),accel(400000),th(10000),dum(20),d$(20),dd(30),pdam(10),col$(10),cur(10000)
!print "Enter Time History Filename"
!input file$
let file$="SPAWaveforms.csv"
!let file$="SPAWaveforms.txt"
let Col$(1)= "   1st column: Time,   Do not use"
let Col$(2)= "   2nd column: 35 Hz Sine Wave"
let Col$(3)= "   3rd column: 60 Hz Sine Wave"
let Col$(4)= "   4th column: RWM control"
let Col$(5)= "   5th column: ELM pacing at 30 Hz"
let Col$(6)= "   6th column: Chirping waveform"
let Col$(7)= "   DC 3500 Amps"
let Col$(8)= "   Enter zero for zero additional current"
print "Thermal Part Only - y or n"
input thermopt$
let baseline$="n"

for i=1 to 8
print col$(i)
next i
print "Select a Column to be analyzed: "
input column
print "Select a second Column to be superimposed: "
input column2
print "Select a Third Column to be superimposed: "
input column3
print ""

 let pulselength=5 !sec
 let peakFreq=150
 let DT=.001
 let NITTER=20

 let qmax=6      !Max number of damping values to be computed
 let pdam(1)=.01          ! Damping Coefficient/Critical
 let pdam(2)=.02
 let pdam(3)=.03
 let pdam(4)=.04
 let pdam(5)=.05
 let pdam(6)=.06


print " Column Number ";column; "is being analyzed"
print " Pulse Length ";pulselength; " seconds"
print " Data Timestep =  ";dt; " seconds"
print " Number of iterations ";nitter; "is being analyzed"
print " Peak Frequency ";peakfreq; " Hertz"
print "          Reading "&file$

OPEN #1: name file$, create old
set #1: pointer begin
for k=1 to 1000
line input #1: title$
```

```
next k
print title$
!print "any key to continue"
!get key kinp
let i=0
let valmax=0
let valmin=0
do while more #1
line input #1 :a$
!print d$(2)
call comint(",",a$,d$(),dd())
let i=i+1

let th(i)=0

if column>0 and column <> 7 then let th(i)=val(d$(column))
if column2>0 then let th(i)=th(i)+val(d$(column2))
if column3>0 then let th(i)=th(i)+val(d$(column3))
if column=7 then let th(i)=3500
let cur(i)=th(i)

    ! Convert RWM Current to an Acceleration
    ! Base it on a unit length and Field, accel = current*field*length/mass
    ! mass of the conductor per unit length is 8000*.01905*.01905 = 3.0 kg/meter
    let th(i) = th(i)/3.0

if th(i)>valmax then let valmax=th(i)
if th(i)<valmin then let valmin=th(i)
!print th(i)
if i>pulselength/dt then exit do
loop

print "any key to continue"
get key kinp

!set mode "egahires"
clear
                !!!! Acceleration Time History
print "       Acceleration Time History  ( Multiply  by 3.0 to get current"
print " accel max =";valmax; " accel min = ";valmin
set window 0,pulselength/dt,valmin,valmax
call YScale2(valmax,0,0,pulselength/dt," m/sec^2")
call Timescale2(0,valmax,0,pulselength/dt)
for i=1 to pulselength/dt
plot i,th(i);
next i
let MaxN=i-1
print "Max Number of Data Points in One Pulselength = ";MaxN

print "any key to continue"
get key kinp


PRINT"             Amplified Response Spectrum (ARS)"
print"             From Acceleration Time History"
PRINT" "
 DIM IM(10,200),JM(10,200),KM(10,200),KK(10,200),DU(10,200)
```

```
 DIM FF(10,200),AA(10,200),MX(10,200)
 rem

 !let G=386.4
 let G = 9.8


 let dtt=dt/nitter
 let DS=DT^2/(NITTER^2)
let x(1)=0
let x(2)=0      !.5*th(1)*g*ds

 REM     Calculate Displacement Time History from the Acceleration"
 let iter=2
 let t=0
for i=1 to MaxN
FOR K=1 TO NITTER
 let iter=iter+1
 let accel(iter)=(th(i)+(th(i+1)-th(i))/nitter*(k-1) )*g
 let x(iter)=2*x(iter-1)-x(iter-2)+accel(iter)*DS
 IF ABS(accel(i))>MA THEN LET MA=ABS(accel(i))
 IF ABS(x(iter))>Mxx THEN LET Mxx=ABS(x(iter))
next k
next i
let iterlast=iter
let avevel=0
let valmin=0
let valmax=0

if baseline$="y" then
        ! Baseline correct
for i=1 to iterlast
let aveVel=avevel+x(i)/(i*dt/nitter)
next i
let avevel=avevel/iterlast
let ti=0
for i=1 to iterlast
let ti=ti+dt/nitter
let x(i)=x(i)-avevel*ti
next i
end if
for i=1 to iterlast
if x(i)>valmax then let valmax=x(i)
if x(i)<valmin then let valmin=x(i)
next i

                          !!!! Plot Displacement Time History
clear
print "       Displacement Time History"
print " xmax =";valmax; " x min = ";valmin
set window 0,pulselength/dt*nitter,valmin,valmax
call YScale2(valmax,0,0,pulselength/dt," meters")
call Timescale2(valmin,valmax,0,pulselength/dt)
for i=1 to pulselength/dt*nitter
plot i,x(i);
next i
```

```
print "any key to continue"
get key kinp

!stop
                    !!!!   integrate motion of oscillators"
if thermopt$="n" then
FOR F=1 TO peakfreq
 for q=1 to qmax
 let KK(q,F)=(F*2*PI)^2
 next q
NEXT F

let iter=0
 FOR TI=0 TO pulselength STEP DT
 FOR K=1 TO NITTER
let iter=iter+1
 let T=TI+(K-1)*DT/NITTER

FOR I=1 TO peakfreq
for q=1 to qmax
 let im(q,1)=0
 let jm(q,1)=0
 let aa(q,I)=-KK(q,I)*(IM(q,I)-x(iter))
! let aa(q,i)=accel(iter)
 let DU(q,I)=IM(q,I)
 let cd=2*pdam(q)*i*2*pi      ! Calc Damp Coef from % Critical
 rem let IM(I)=2*IM(I)-JM(I)+aa(I)*DS
 let IM(q,i)=((2+cd*dtt/2)*im(q,i)-jm(q,i)+aa(q,i)*ds)/(1+cd*dtt/2)
 let JM(q,I)=DU(q,I)
 IF ABS(AA(q,I))>MX(q,I) THEN LET MX(q,I)=ABS(AA(q,I))
 next q
 NEXT I
 NEXT K

 for i=1 to peakfreq
 for q=1 to qmax
 if abs(mx(q,i))>mxac then let mxac=mx(q,i)
 next q
 next i
call plotter
 NEXT TI
end if


dim  runcur(1000000), power(1000000),CuTemp(1000000),Qrad(1000000),QCond(1000000),QConvect(1000000)
dim QWater(1000000)
clear
Print "Enter BUS Bar Option"
print " 1    RWM, Normal Op"

!input boption
let boption=1
          !Times
let MaxN=10000
let dt=1.0
let PulseLength=5    !Sec
let PulseInterval = 5*60           ! 5 minute intervals
```

```
let numpulses=10

let BusBarLength = 1.0     ! Unit Meter Long
let tinit=20
let tfloor=20
let tambient=20
let insthick=1/16

if boption =1 then
let BusBarName$="RWM Conductor"&col$(column)
let bwidth=.75
let bheight=.75
let HoleDiameter = .0
let BusVerticalarea=2*(bheight+bwidth)*BusBarLength
Let Current = 0.0
let FlowVelocity=0.0
let tinit=20
let tinlet=tinit
let dt=.01
let PulseLength=5   !Sec
let PulseInterval = 50          !
let numpulses=10
let tinit=20
let tinlet=tinit
end if

 let maxn = pulseinterval*numpulses/dt

         !Temperature and Cooling
         !  Plot Controls
call plotbar
let plotmint = 99
let plotmaxt = 109
let plotmint = 0
let plotmaxt = MaxN

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
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
let StrapArea = .001*.01
let StrapLength = .1
call KEpoxy(tinit+273,kepoxy)
print "Kepoxy ";kepoxy

!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

let resist=rhoCopper*2*busbarlength/areacopper

               ! Create Current Profile

for k=1 to numpulses
for i=1 to (pulseinterval)/dt
let j=j+1
if i<pulselength/dt then let runcur(j)=cur(i)
next i
next k

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

for i=2 to MaxN
let pTime=dt*i
let Qrad(i)=1*Bussurfacearea*emisSO*emisv*StefBoltz*((Cutemp(i-1)+273)^4-(tambient+273)^4)/(emisSO+emisv-emisSO*emisV)
let Qcond(i)=ThermCond*(StrapArea/StrapLength)*(CuTemp(i-1)-Tfloor)
let Qconvect(i)=ConductConvect*(BusVerticalArea)*(CuTemp(i-1)-Tambient)
let Qwater(i)=sphecopper*denswater*flowvelocity*flowarea*(CuTemp(i-1)-tinlet)
let power(i) = runcur(i)^2*resist
let CuTemp(i)=CuTemp(i-1)+(power(i)-Qrad(i)-Qconvect(i)-Qwater(i))*dt/HeatCap
if runcur(i)>Maxcurrent then let maxcurrent=runcur(i)
If runcur(i)<mincurrent then let mincurrent=runcur(i)
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 plotmint,plotmaxt,mincurrent,maxcurrent
call YScale2(maxurrent,0,plotmint,plotmaxt," Amp Turns")
```

```
call Timescale2(0,current,plotmint,plotmaxt)
for i=1 to MaxN
plot i,runcur(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,plotmaxt,Tlow-(maxtemp-tlow)/10,MaxTemp
  !Plot Text Coordinates
```

```
let px=plotmint+(plotmaxt-plotmint)*.6
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 surface 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,plotmaxt," Deg C")
!call Timescale(tlow,maxtemp,maxn)
call Timescale2(tlow,maxtemp,plotmint,plotmaxt)
for i=1 to MaxN
plot i,CuTemp(i);
next i
plot i-1,0



print "any key to continue"
get key kinp



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 theta=pi*i/180
plot holediameter*sin(theta),holediameter*cos(theta);
next i
end sub



sub plotter
 clear
if mxac>0 then
 set window -10,peakfreq+10,0,mxac
else
 set window -10,peakfreq+10,0,1
end if
 plot 0,0;0,mxac
 plot 0,0;60,0
 for i=5 to peakfreq+10 step 5
 plot i,0;i,mxac/peakfreq
 plot text,at i,mxac/peakfreq:str$(i)
 next i
 for i=1 to 10
 plot 0,mxac/10*i;1,mxac/10*i
 plot text, at -10,mxac/10*i:str$(mxac/10*i)
 next i
 plot text, at 5,mxac*.95: title$
plot text, at 30,mxac*.65:"Amplified Response Spectrum (ARS)"
```

```
plot text, at 30,mxac*.6:"Acceleration (m/sec^2 vs Frequency"
plot text, at 30,mxac*.55:"From Acceleration Time History"
plot text, at 30,mxac/2:"time="&str$(ti)
plot text, at 30,mxac*.45:"ma="&str$(mA)
plot text, at 30,mxac*.4:"mxac="&str$(mxac)
plot text, at 30,mxac*.35:"damp="&str$(pdam(1))&" "&str$(pdam(2))&" "&str$(pdam(3))
if column>0 then PLOT TEXT, AT 30,mxac*.30:col$(column)
if column2>0 then PLOT TEXT, AT 30,mxac*.25:col$(column2)
if column3>0 then PLOT TEXT, AT 30,mxac*.20:col$(column3)
PLOT TEXT, AT 30,mxac*.15:time$&" "&date$


FOR q=1 TO qmax
set color q+3
plot 0,0;1,mx(q,1)
for i=1 to peakfreq
rem PRINT I;MX(I);I+1;MX(I+1);I+2;MX(I+2);I+3;MX(I+3);I+4;MX(I+4)
rem NEXT I
plot i,mx(q,i);
next i
plot peakfreq,mx(q,peakfreq)
next q
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)
dim temp(50),Kth(50)
for i=1 to 18
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 18
if etemp>=temp(j) and etemp<=temp(j+1) then let kepoxy=kth(j)
next j
end sub
end
```

```
 SUB comint(del$,a$,d$(),dd())
  FOR q=1 TO 12
   LET D$(Q)=""
   LET dd(q)=0
  NEXT Q
  LET a$=ucase$(a$)
  IF del$=" " then
     DO
     LET lbs=len(a$)
     LET pob=pos(a$,"  ")
     IF pob>0 then LET a$=a$[1:pob]&a$[pob+2:lbs]
     LOOP while pob>0
     LET lbs=len(a$)
     IF a$[1:1]=" " then LET a$=a$[2:lbs]
  END IF
  LET i=0
  DO
     LET i=i+1
     IF pos(a$,del$)=0 then EXIT DO
     LET pc=pos(a$,del$)
     LET d$(i)=a$[1:pc-1]
     LET a$=a$[pc+1:100)
  LOOP
  LET d$(i)=a$
  for i=1 to 12
  let d$(i)=trim$(d$(i))
when error in
  let dd(i)=val(d$(i))
use
  let dd(i)=0
end when
  next i
  ! End of data parsing
 END SUB
```