NSTX-U OH Coil : Coax and Embedded Leads
M. Mardenfeld
13 July 2011

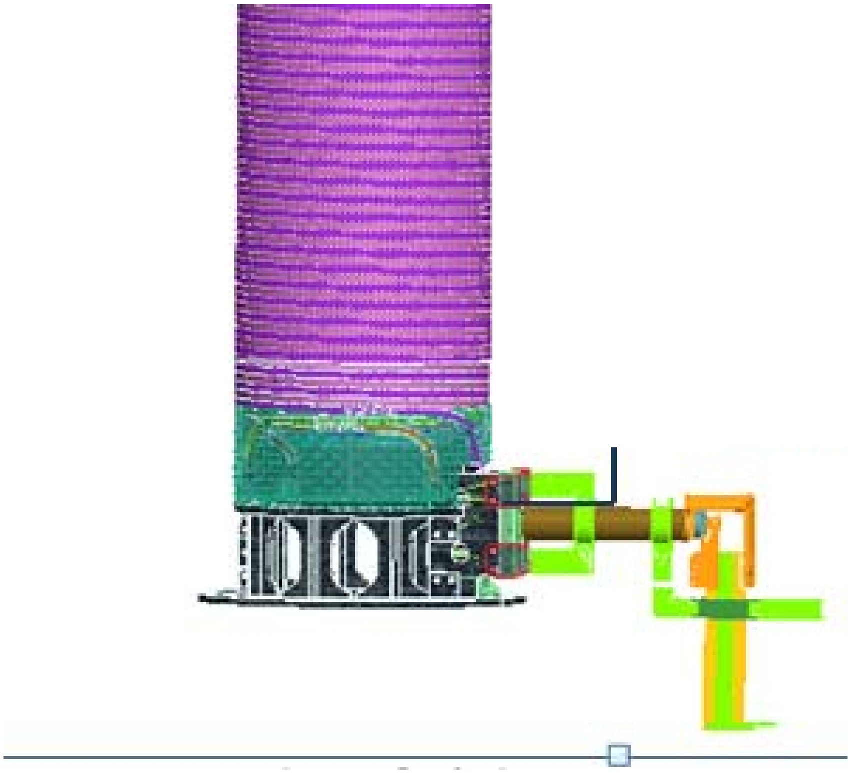
1. **The steel clamp connecting the bus bar to the skirt is not stiff enough and will be redesigned**. This is in agreement with Andrei's calculation of the bus bar. I am assuming in the attached that it is replaced with something very rigid. Andrei will have to qualify that this is acceptable for the bus bars.

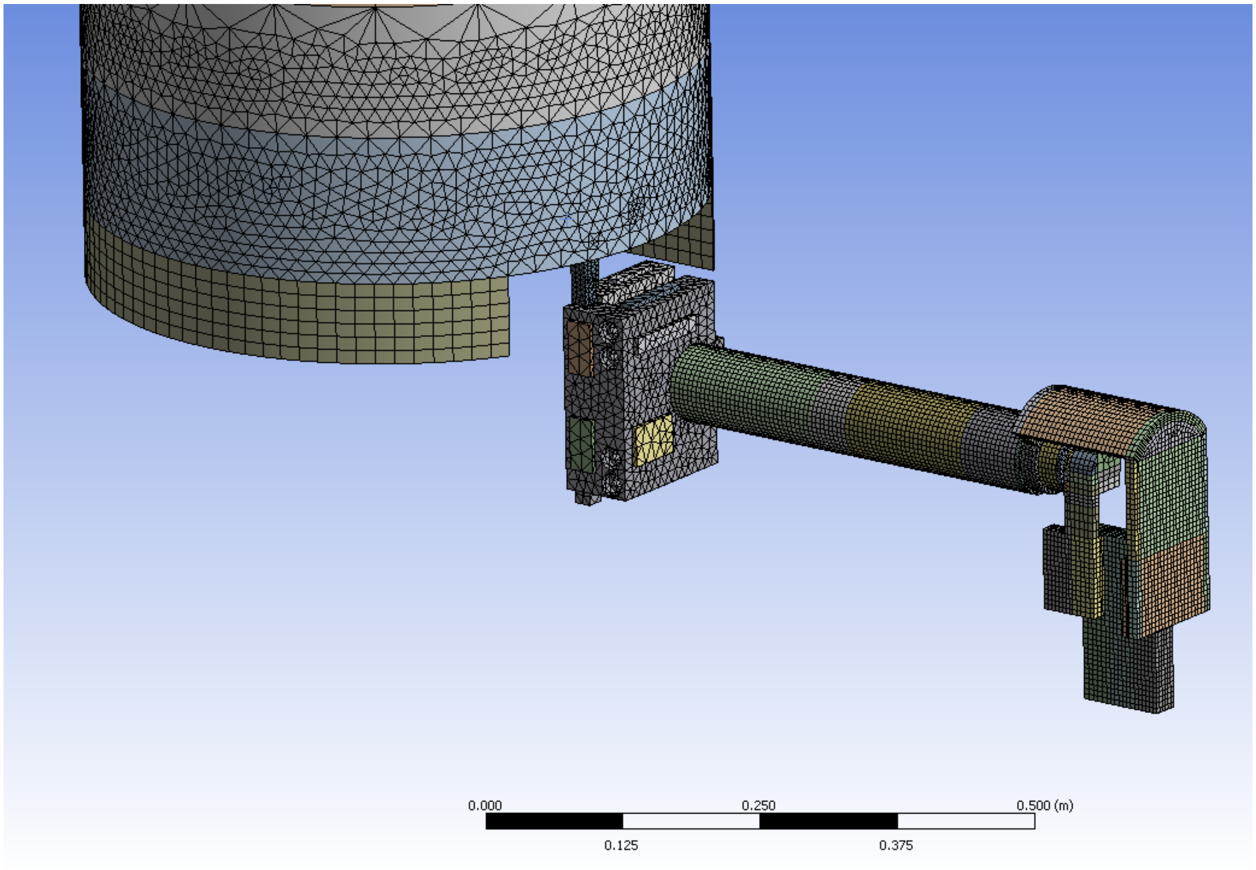
2. **It is my understanding that this redesign of the bus bar will include active cooling (per Mark Smith).** I am assuming that the inlet water temperature is the same as for the OH (12 C) and that it is fed in at the interface between the coax and bus bar, and flows out away from the machine. This reduces thermal differentials across the coax. I've also shown that with the setup, there will be **no ratcheting, and the coax can cool down completely between shots.**

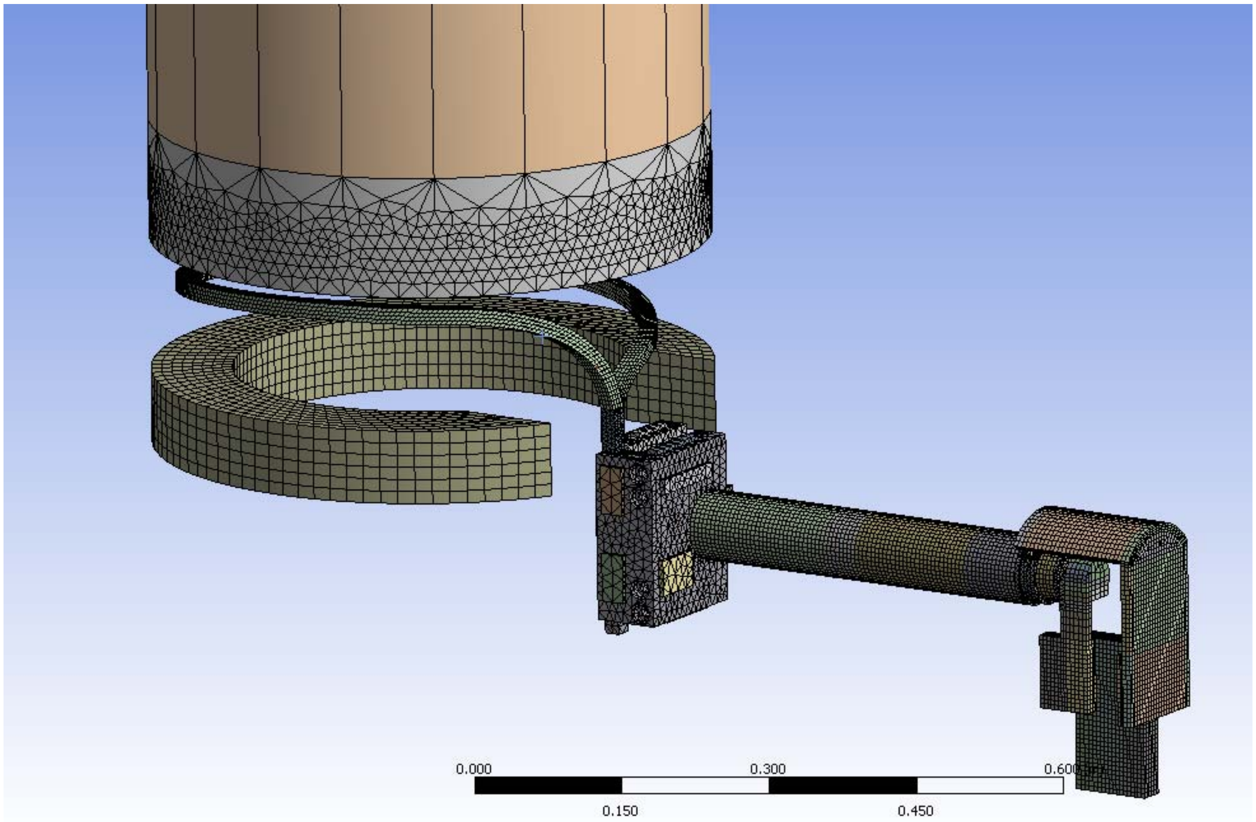
3. **There is a short section of conductor (2 in) between the lead flag and bottom of the G10 annulus that does not meet 2x Stress SN fatigue allowable, but meets 20x Life Sn, and 4x cycle fracture**. **This is the same as the conductor in the body of the OH coil.** This is driven by vertical thermal expansion of the OH coil leads. Small geometry changes in this region have been identified which can alleviate this stress, but not eliminate it. These changes are advisable, but probably not required.

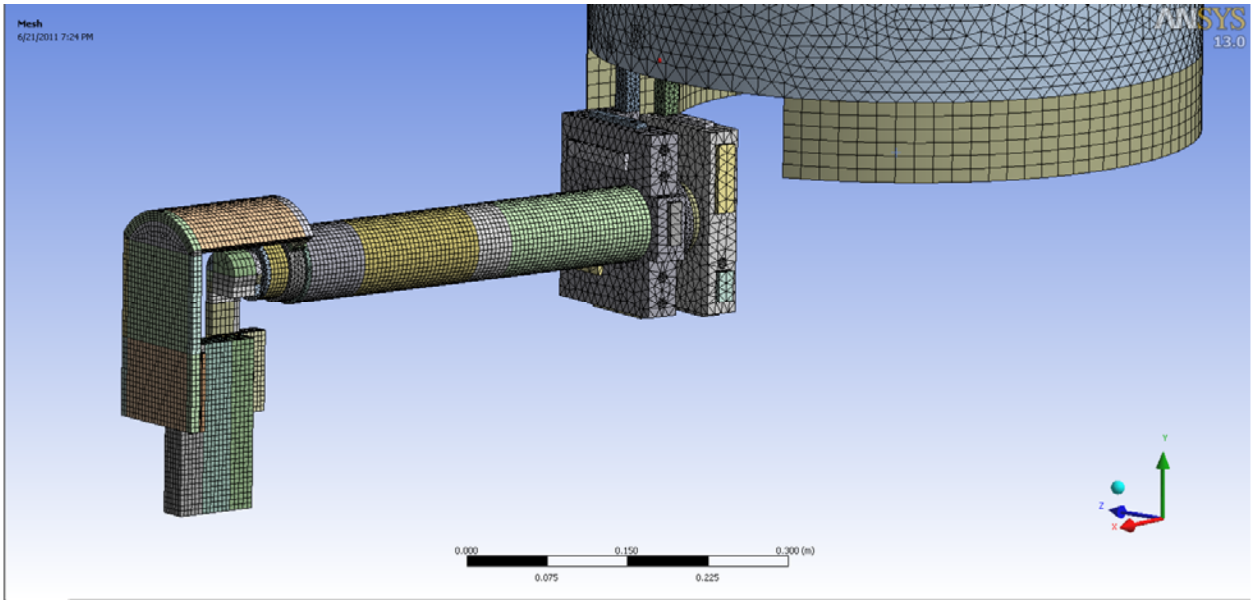
4. **The embedded leads in the G10 have shear stresses of order 40 Mpa and will debond**. I have been advised (per Titus) that this is acceptable because the kapton interwoven with the glass provides a clean parting plane.

5. With the geometric simplification in the model (no "steps in coil", coil modeled of solid copper) ,**the shearing stress between the support annulus of G10 and the bottom turn of the conductor is of order 20 Mpa.** This should be OK with sandblasting and priming performed at the very top and very bottom of the coil.

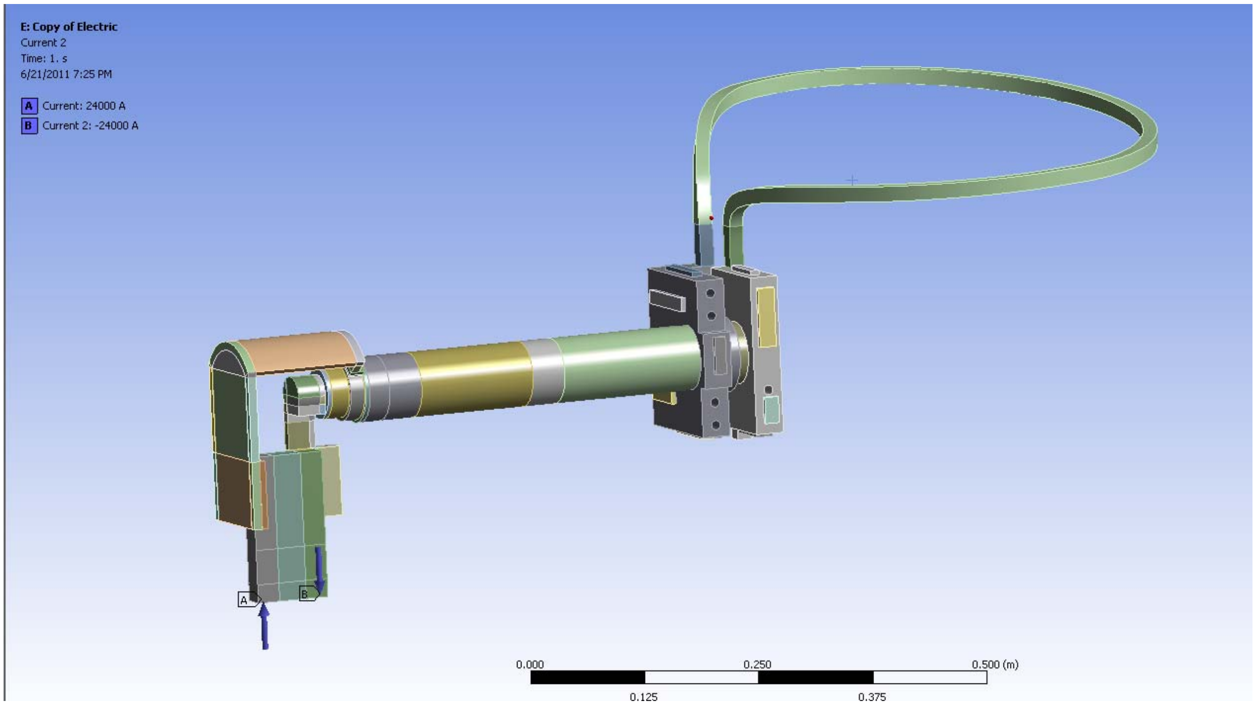



0.000
0.250
0.500 (m)
0.125
0.375

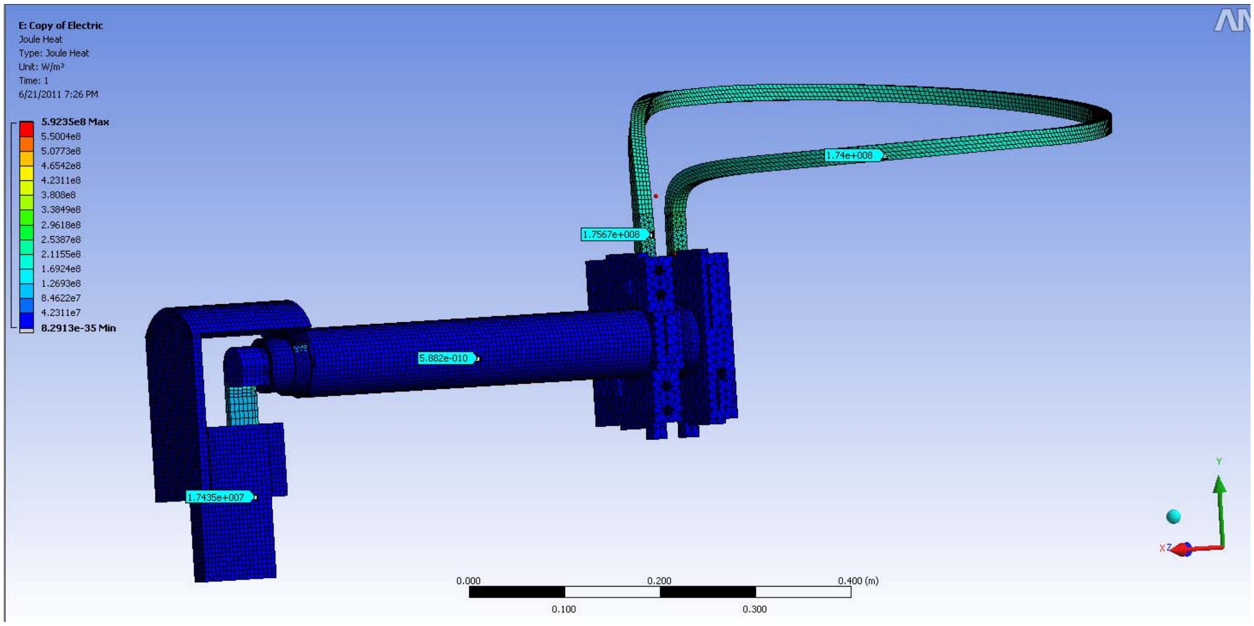

0.000
0.300
0.600
0.150
0.450



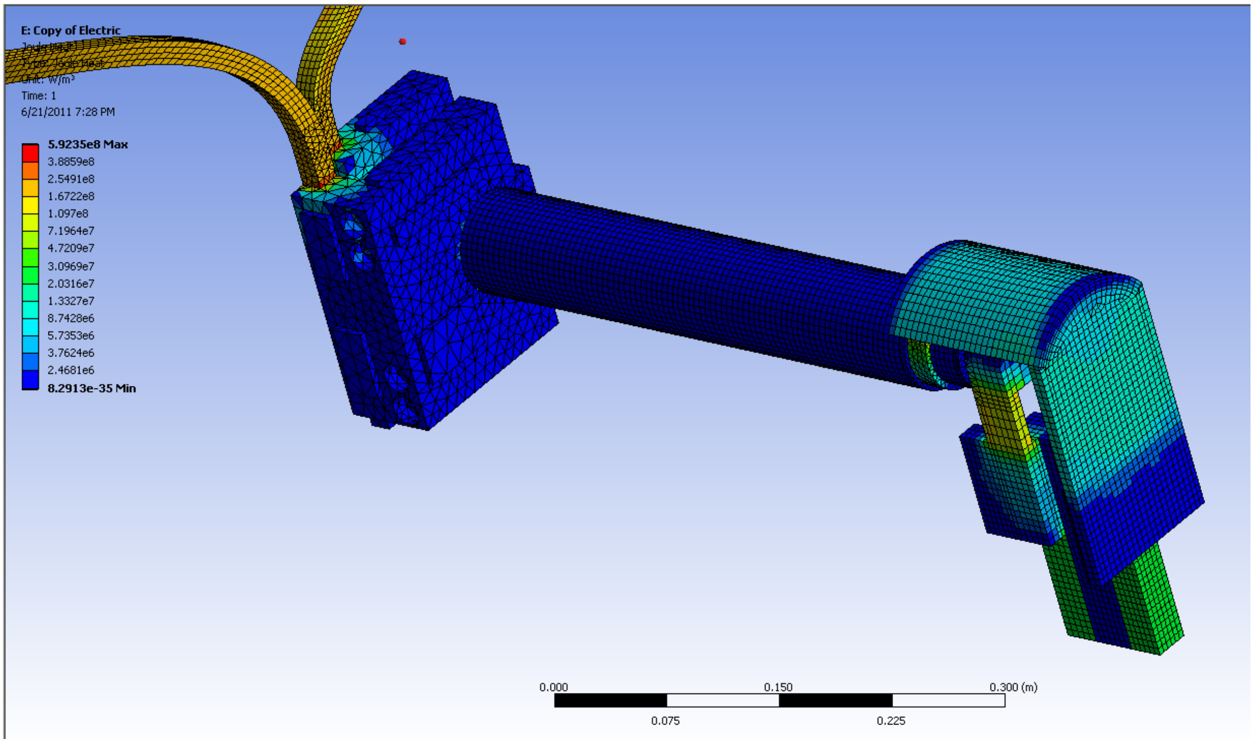
Isotropic G10



Electric Analysis – there is a continuous conduction path

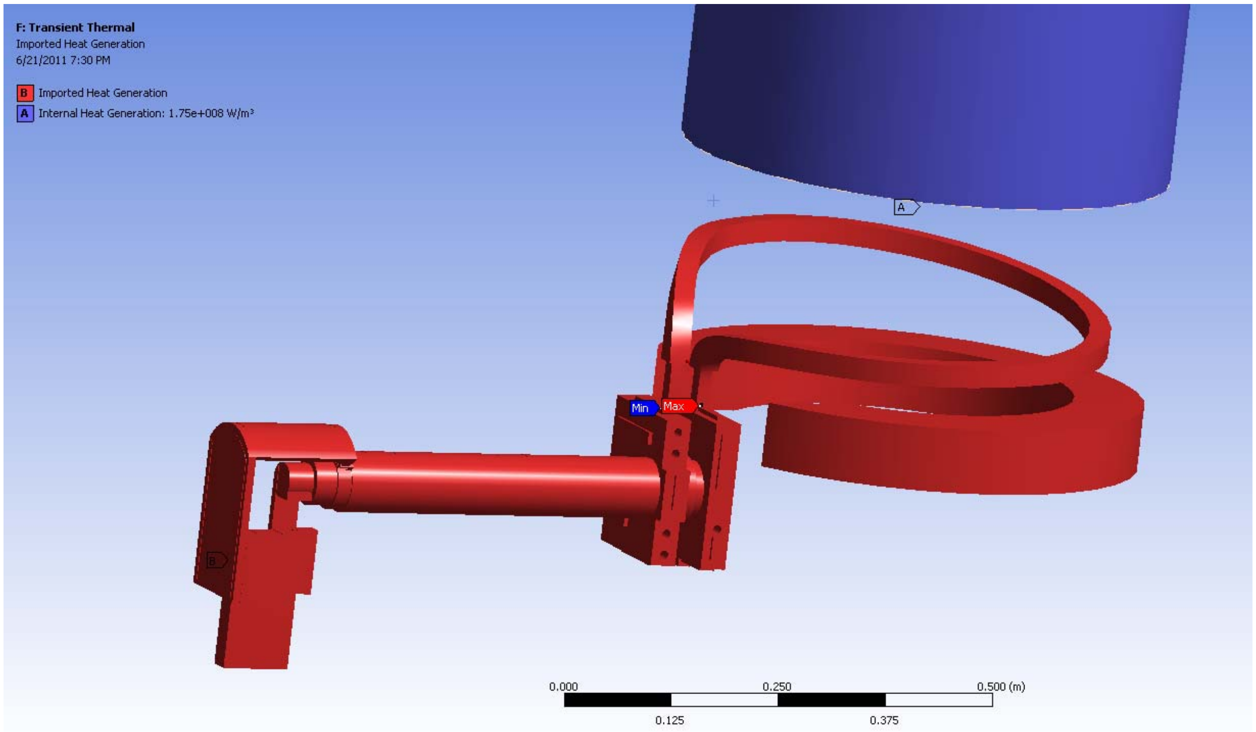


Joule Heat
NOT COUPLED – RESISTIVITY DOES NOT HAVE TEMP DEPENDANCE



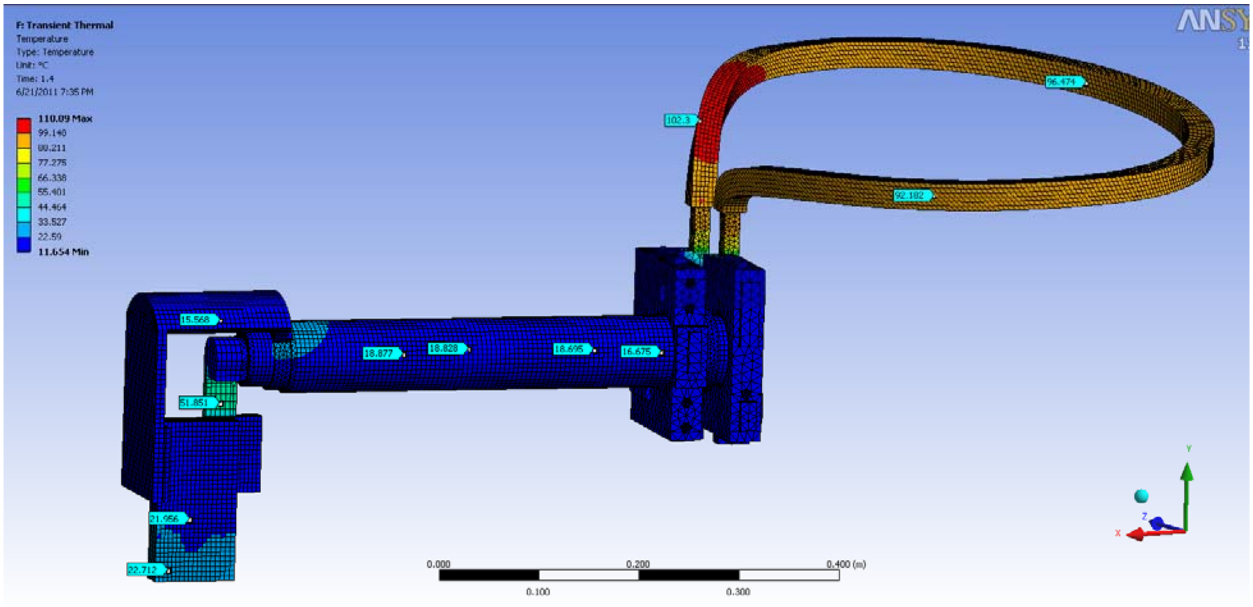
Joule Heat
LOG PLOT

Notice peak joule heat at transitions from large cross section to small cross section



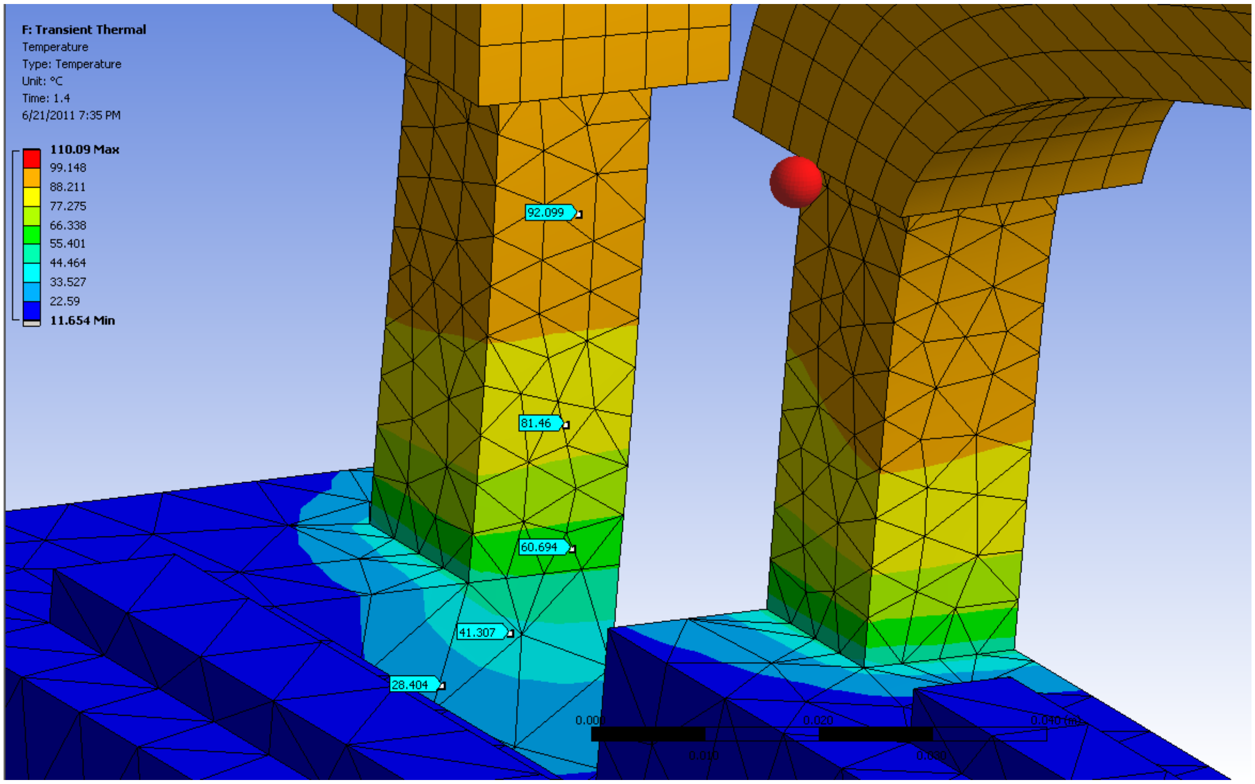
Joule Heat Imported on Coax Components

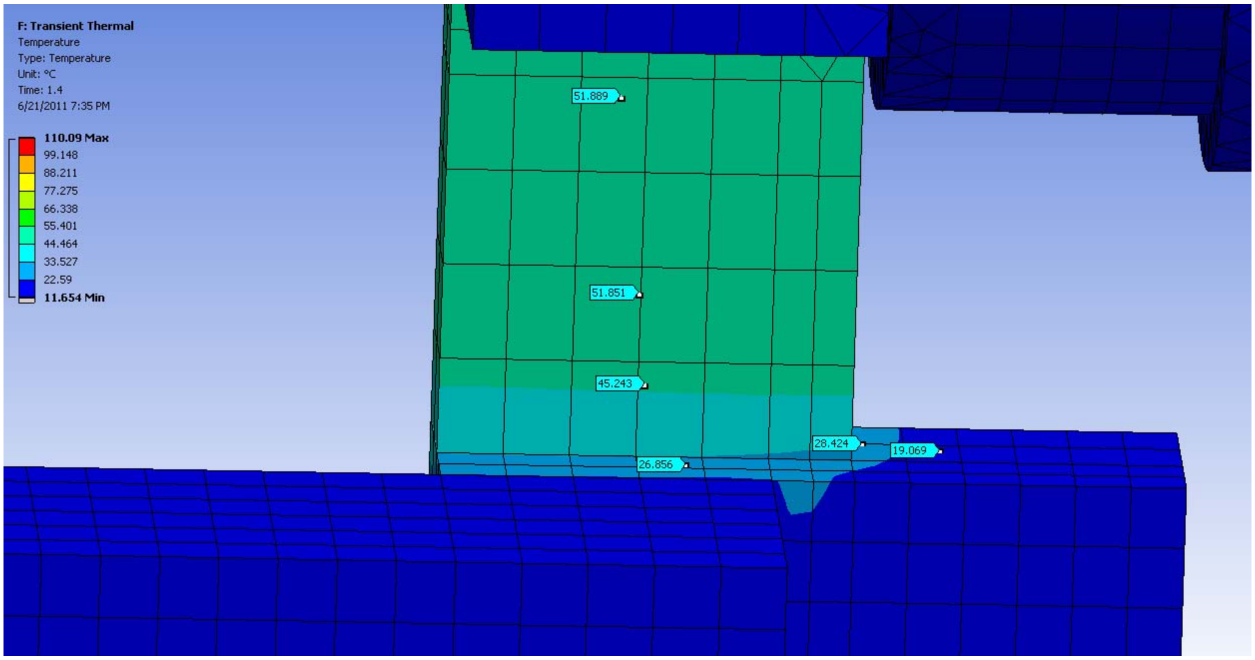
Joule Heat added manually to solid representation of OH Coil to produce effective thermal expansion at interface w/ G10 support annulus



Transient Thermal Analysis – temperature distribution at end of 1.4 second 24 kAmp ESW Pulse

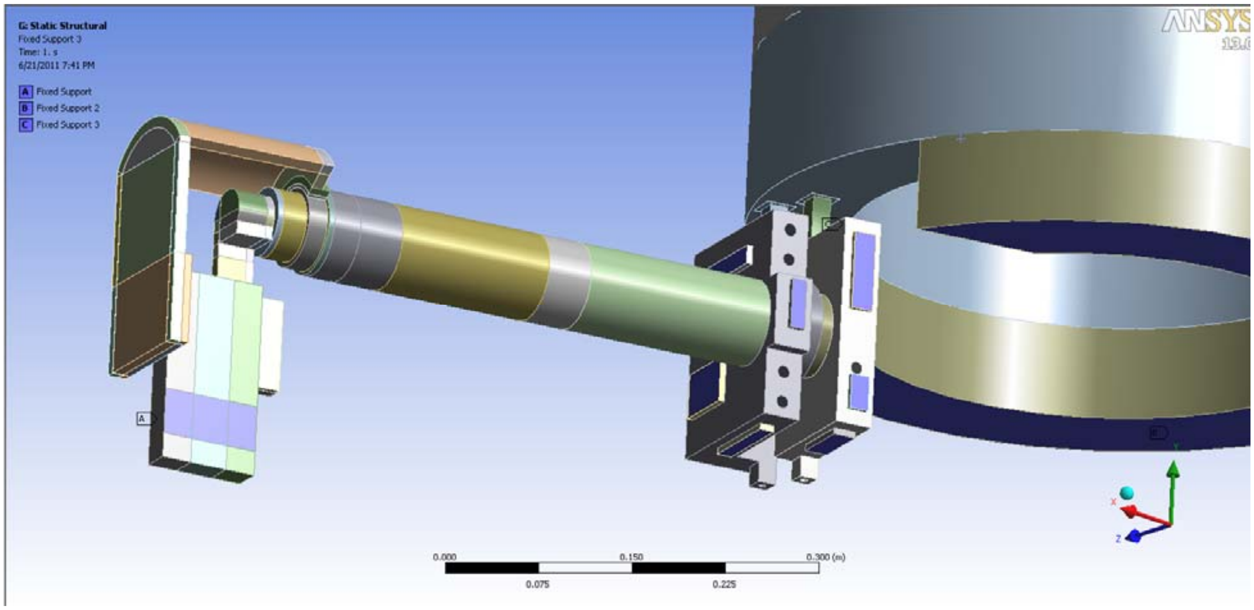
Peaks on conductor loop are probably due to lack of coupling between thermal and electrical analysis – however temperature is still within ~ 8% of hand calc





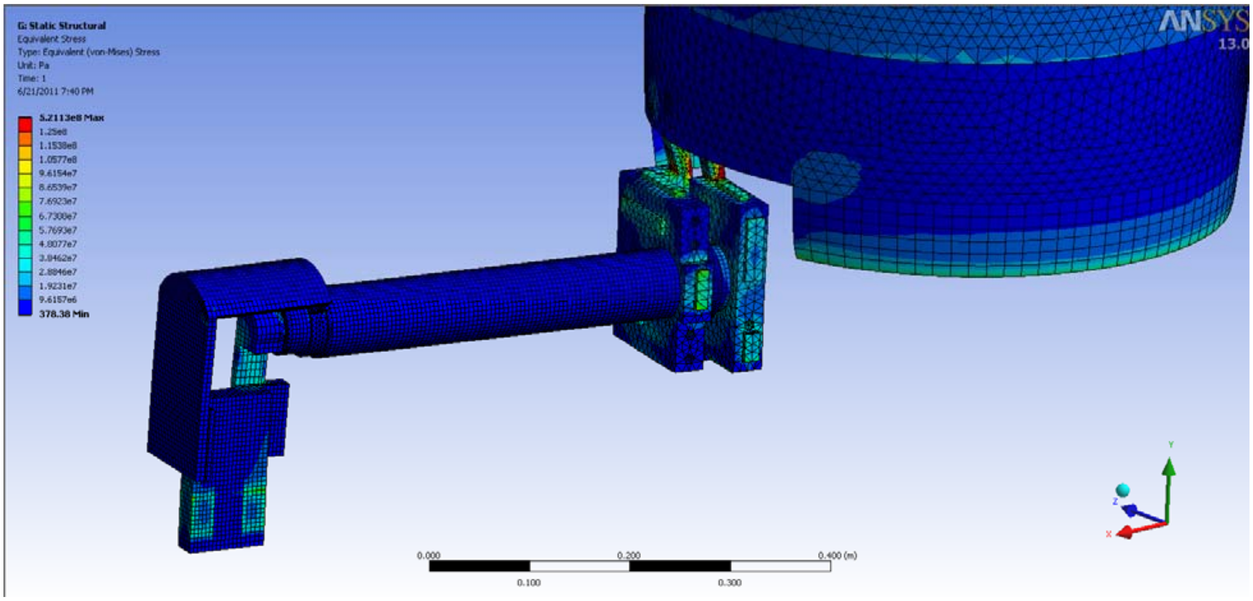
Sharp Thermal Gradients at transition from large to small cross sections

This is from a transient analysis- it considers the thermal diffusive effect of the copper

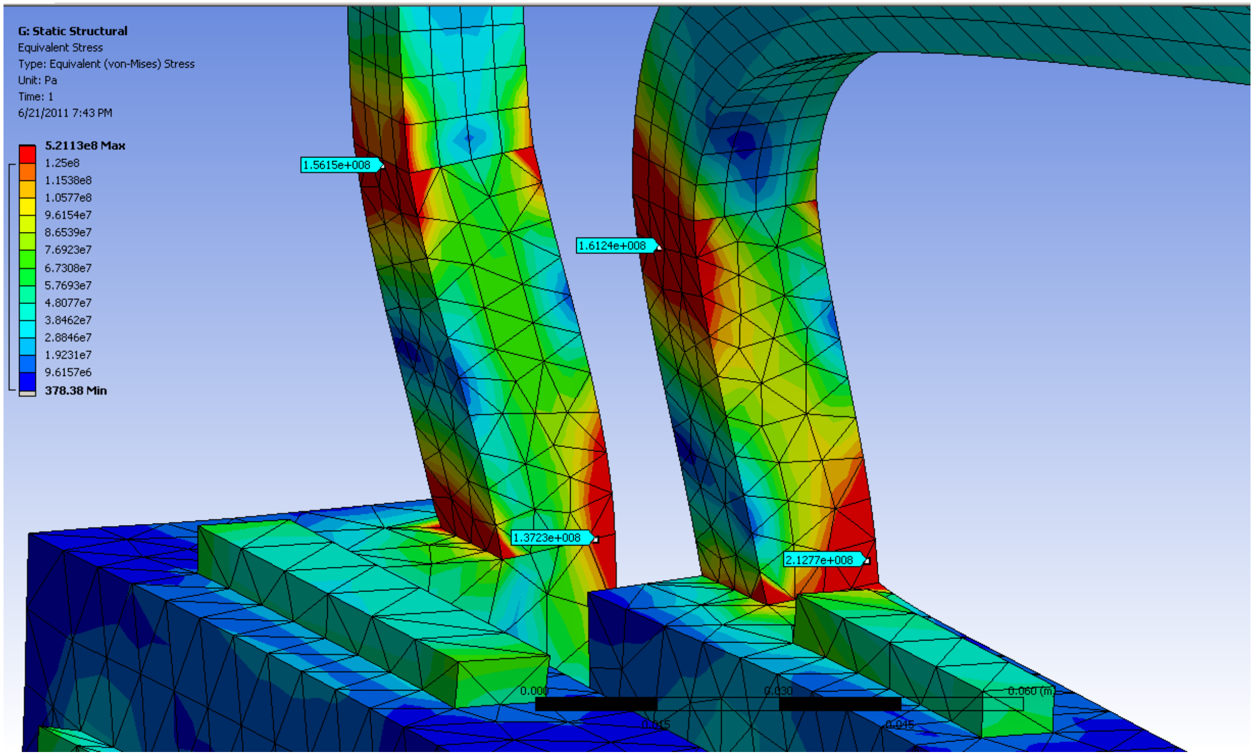


Fixed Boundary at Clamp Location – “rigid clamp” needs to be design
Fixed Boundary at G10 shims inside of coax box
Fixed Boundary at base of G10 support annulus

THERMAL LOADS ONLY

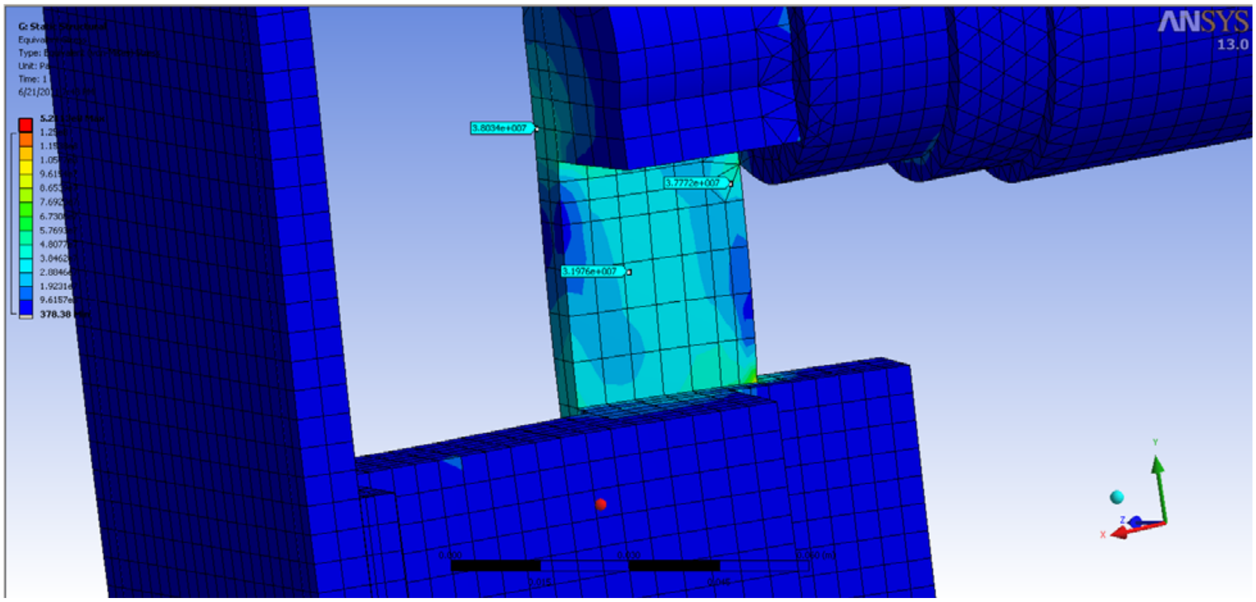


Von Mises Stress

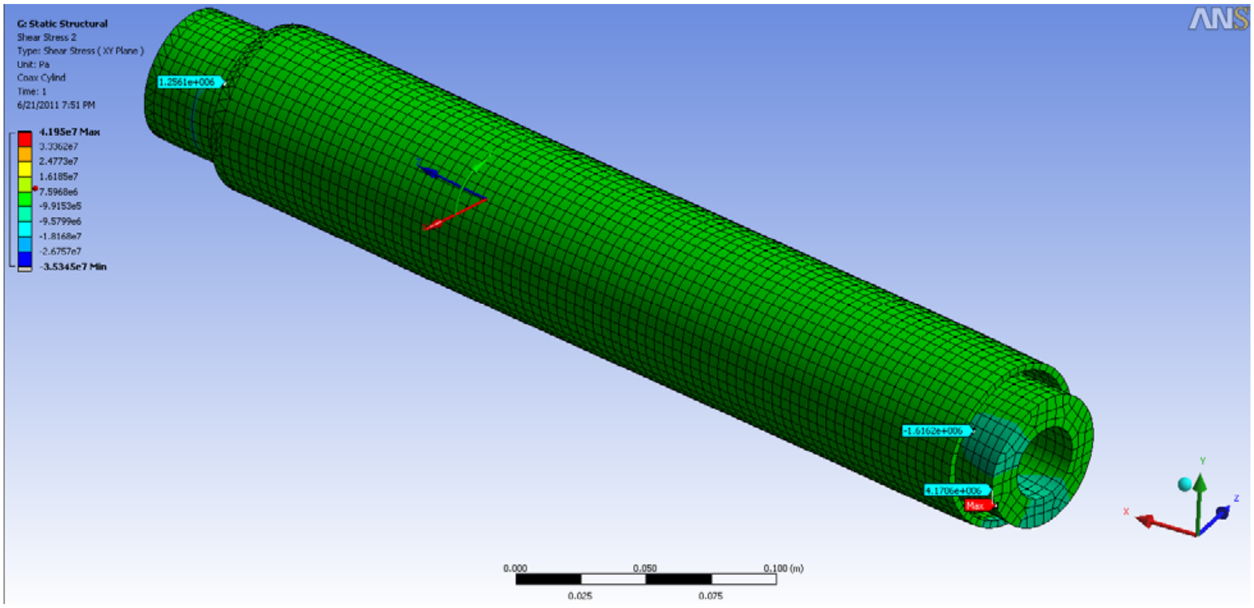


Unembedded Leads which transition from G10 annulus to coax box
THERMAL STRESS ONLY
Von Mises Stress

Cannot survive thermal stress

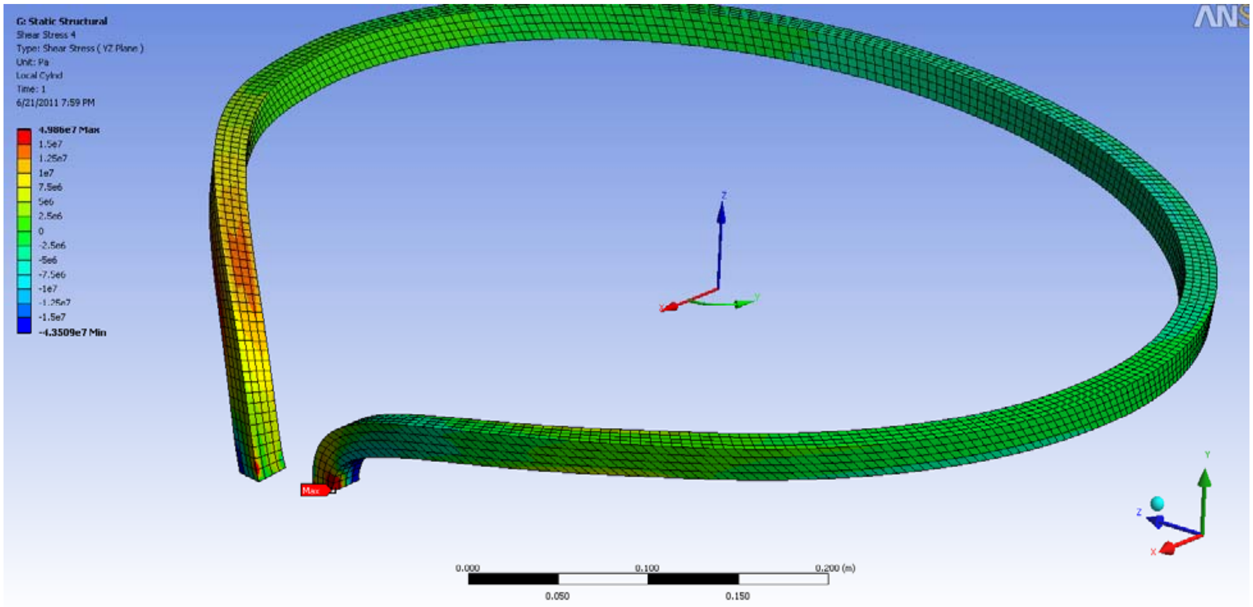


Von Mises Stress – OK here



Shearing Stress on Coax (Tau R-Theta) OK
Coax will not debond during pulse

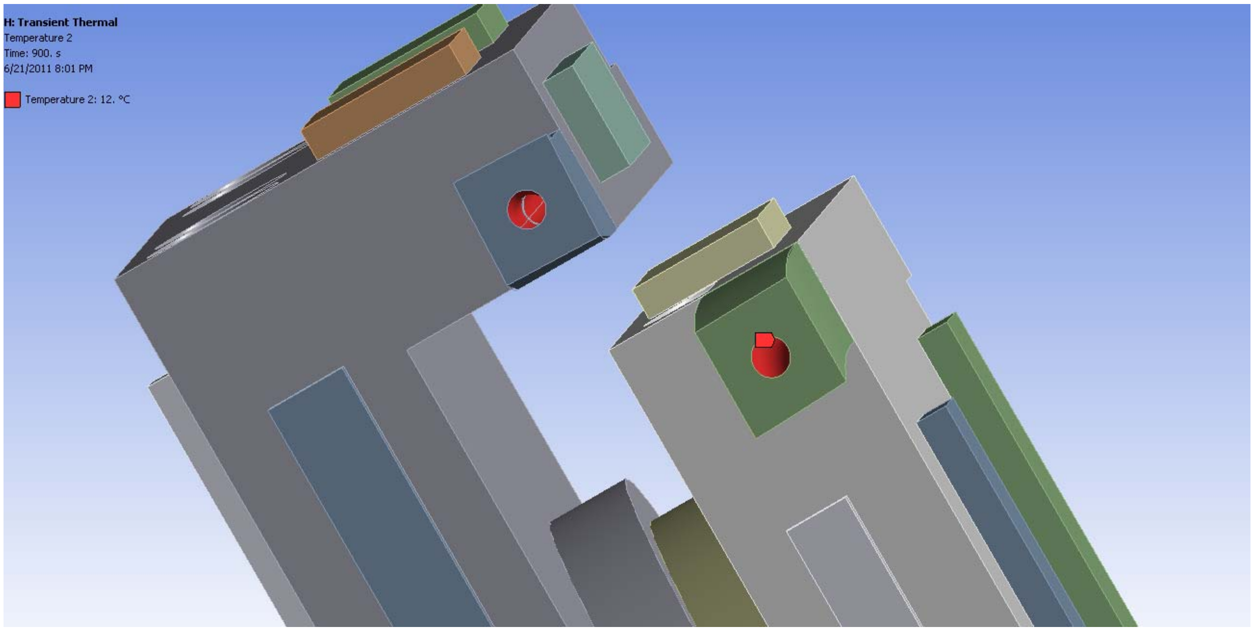
Need to check during transient cool down , but probably OK since temperature excursion is low



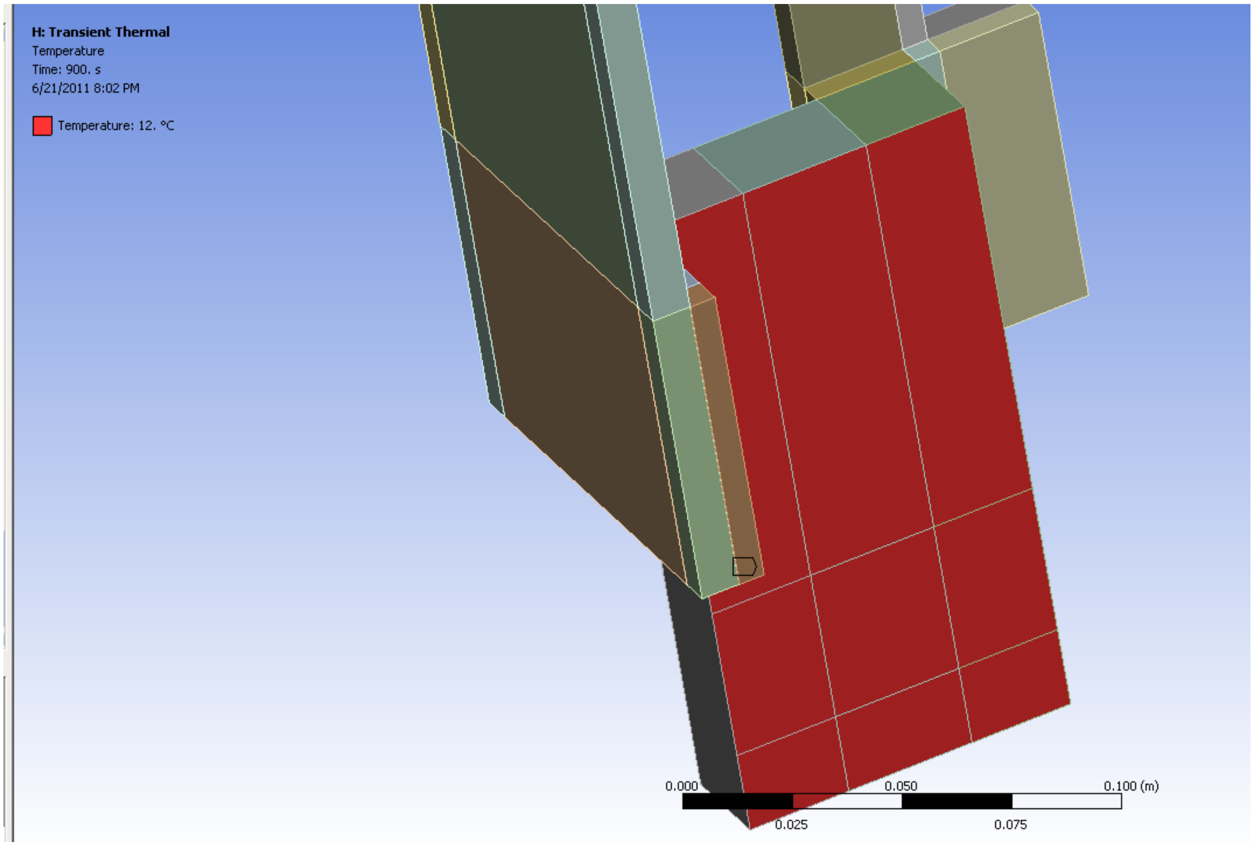
Shearing Stress along Leads – Will Debond

Transient Conduction during cool down

Temperature imported from end of pulse transient thermal BUT

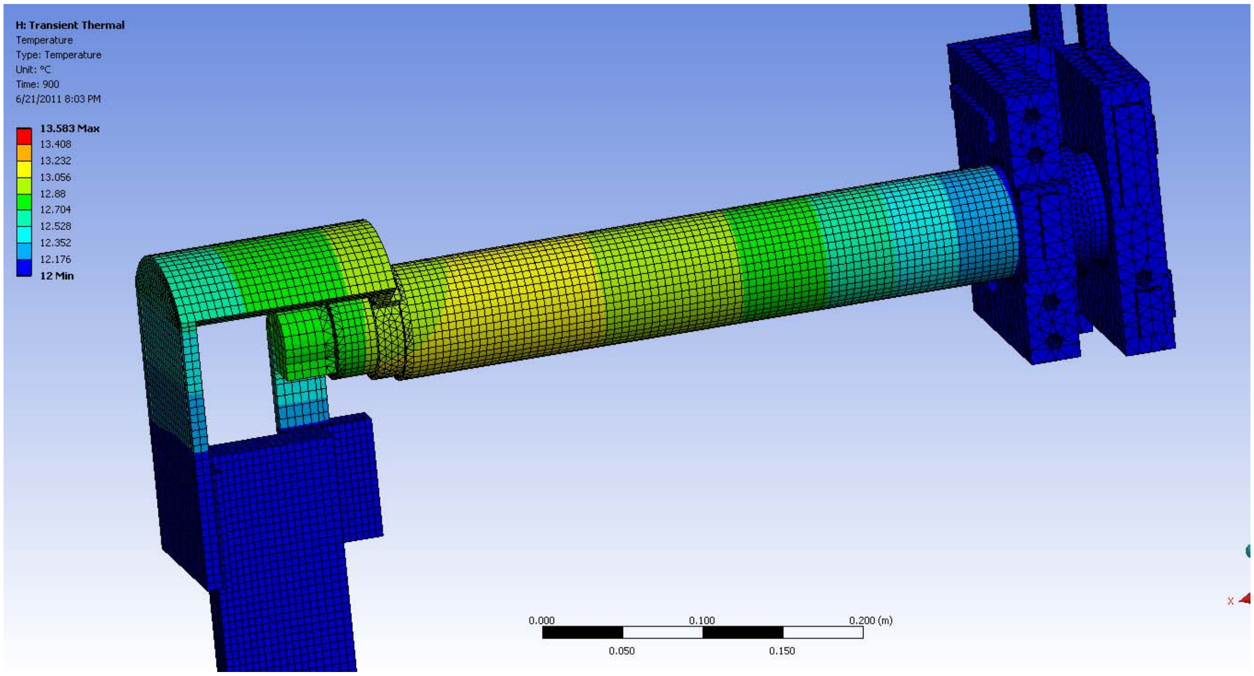


Inner Surface of Conductor Near Inlet only held at 12 C to represent cooling water



Similiarly, bus bar redesign will have cooling

Since holes are not modeled, one face is held at 12 C AS IF COOLANT ENTERS HERE



Transient cooldown after 15 minutes

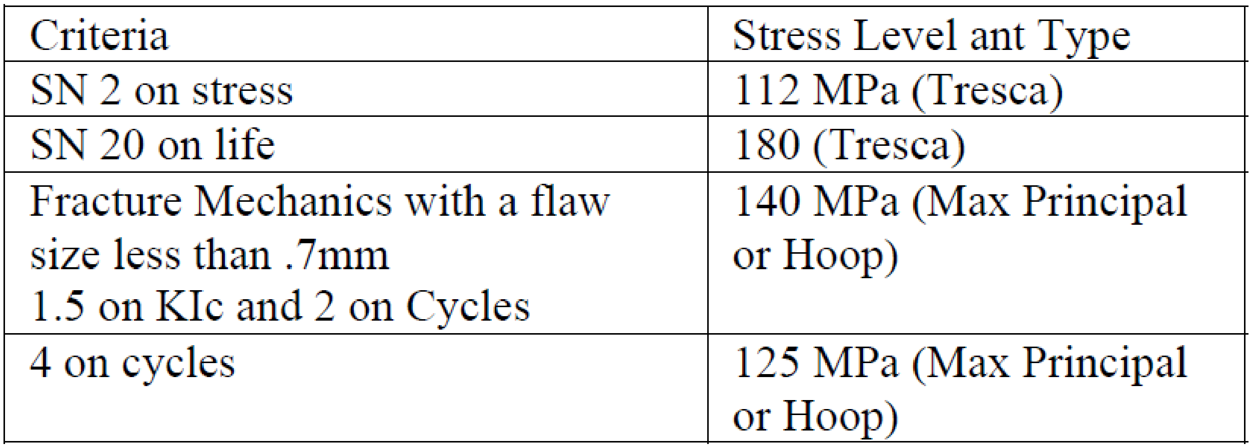
Coax is nearly at 12 C – max temp is 13.5 C, ignoring any beneficial convection on lateral surface area of coax
Coax will not ratchet is inlet coolant water to bus bar is added at coax end

1. Need to check to make sure total energy being dumped to coolant does not impact cooling of main body of OH

2. Transient effect should be investigated to see if thermal gradients are worse during cooldown; however, is not expected

From NSTXU-CALC-133-09-00

OH Conductor Fatigue and Fracture Mechanics Analysis (Rev 0)



Criteria	Stress Level ant Type
SN 2 on stress	112 MPa (Tresca)
SN 20 on life	180 (Tresca)
Fracture Mechanics with a flaw size less than .7mm 1.5 on KIc and 2 on Cycles	140 MPa (Max Principal or Hoop)
4 on cycles	125 MPa (Max Principal or Hoop)

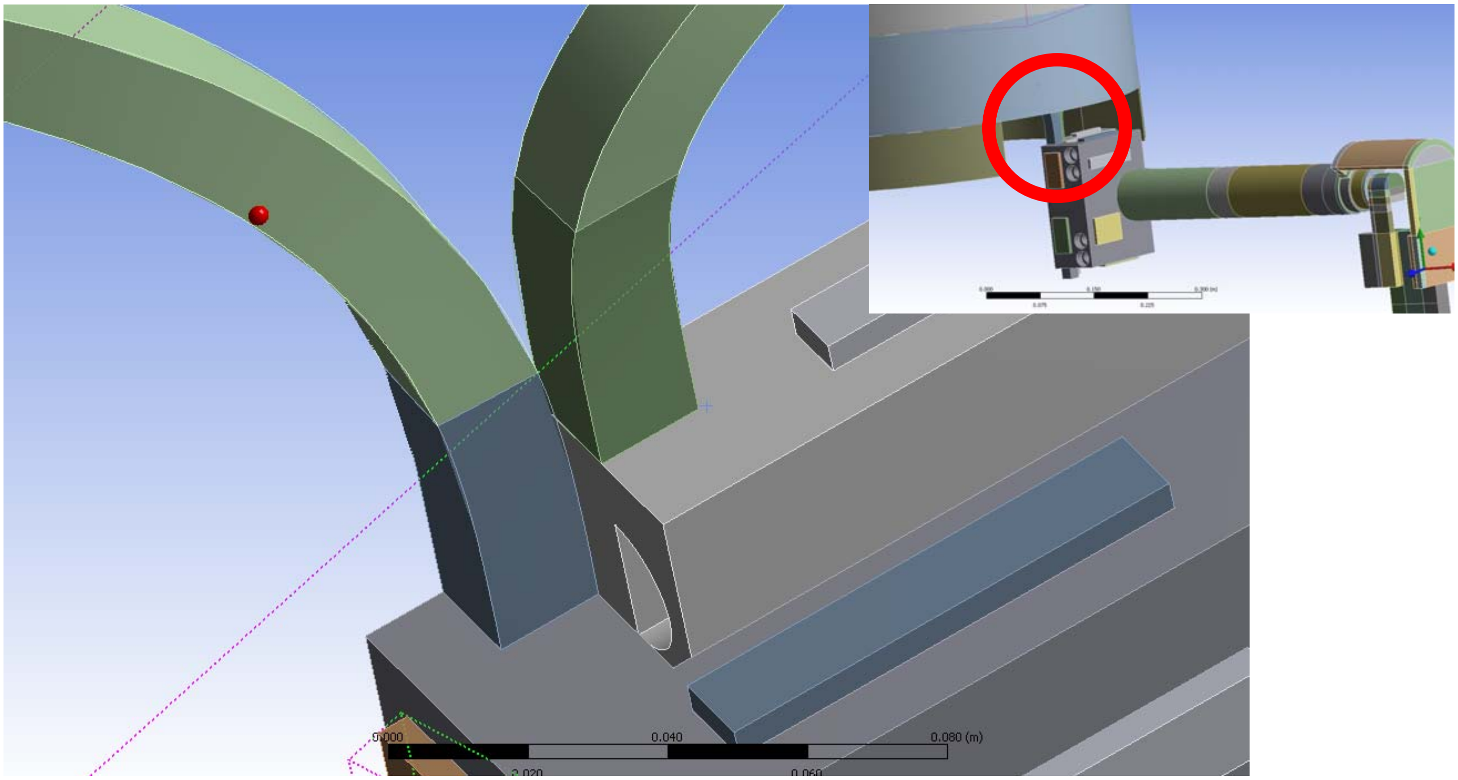
The **BODY of the OH Coil** meets the last three criteria, but not the first criteria (Sn 2x Stress).

The embedded lead area meets the last three criteria, but not the first without changes.

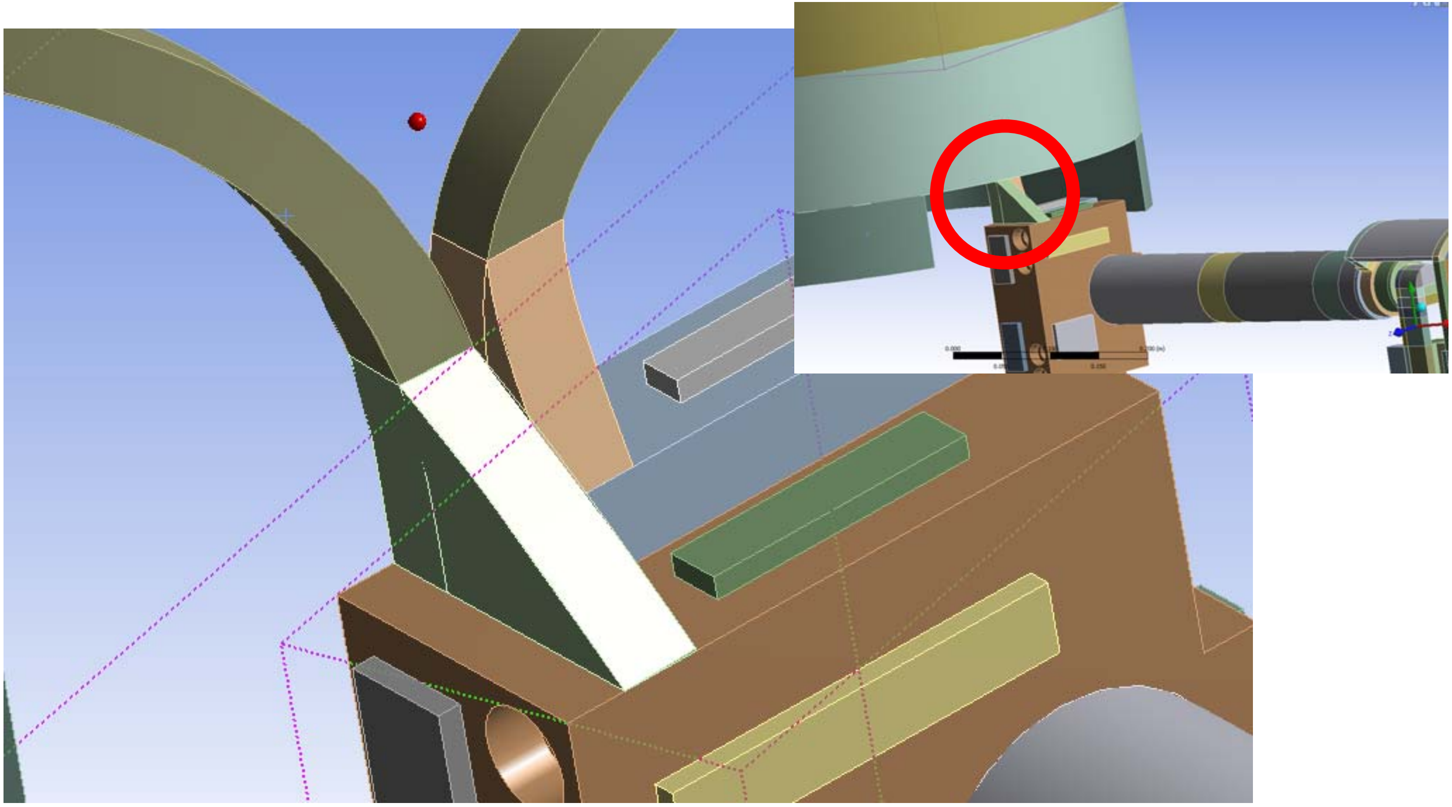
Minor changes to the shaped of the lead flag significantly reduce the volume over which Tresca stresses exceed 112 Mpa, but do not eliminate them.

The proposed changes are therefore beneficial, but may not be absolutely necessary.

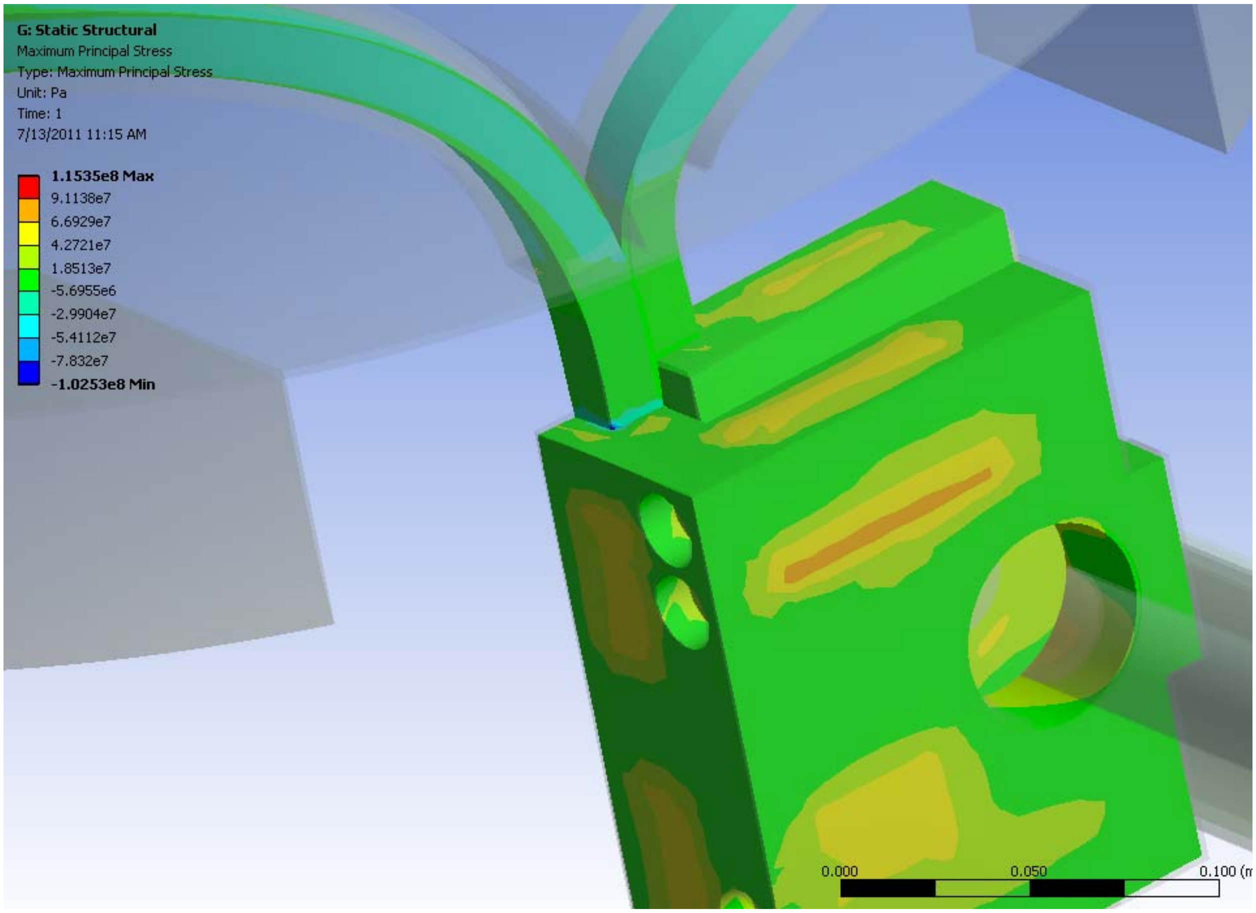
Lorentz forces not included, but hand calculation estimate shows they are of order 20 MPa



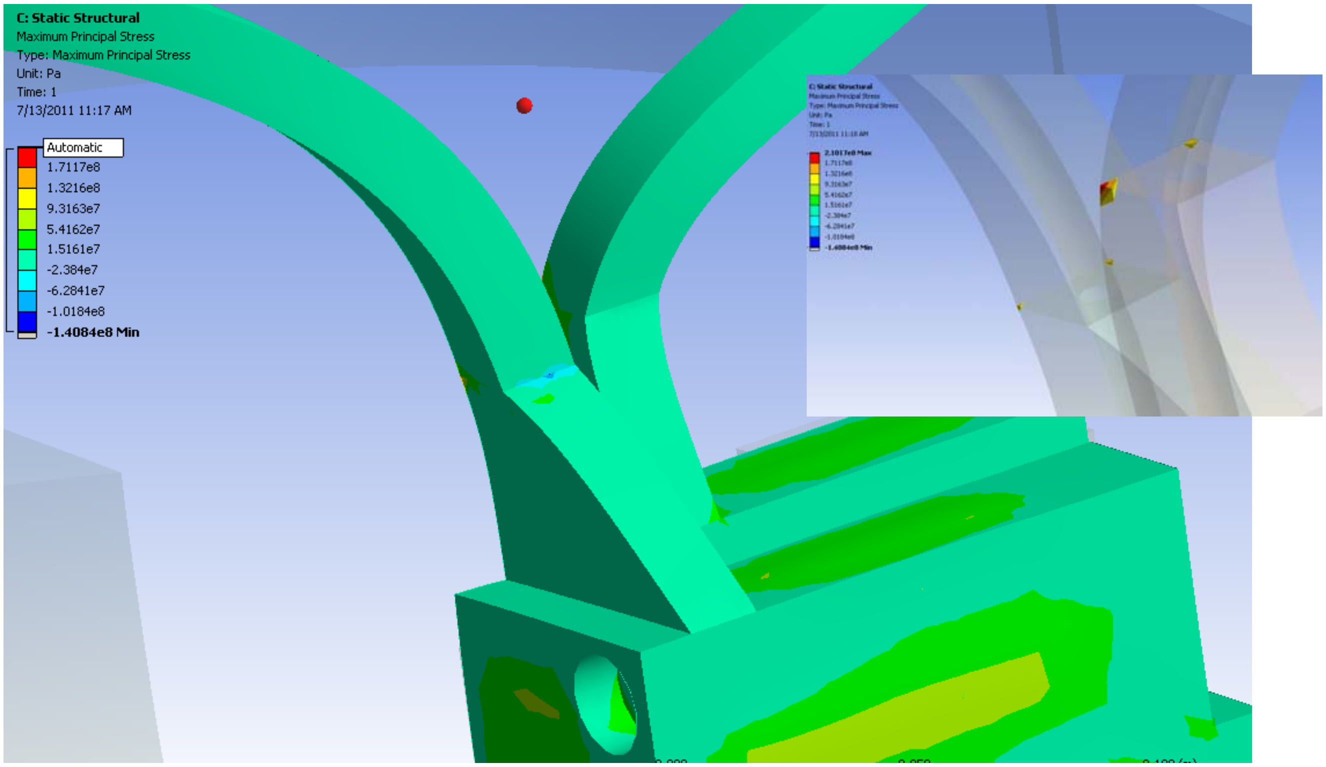
Original Geometry



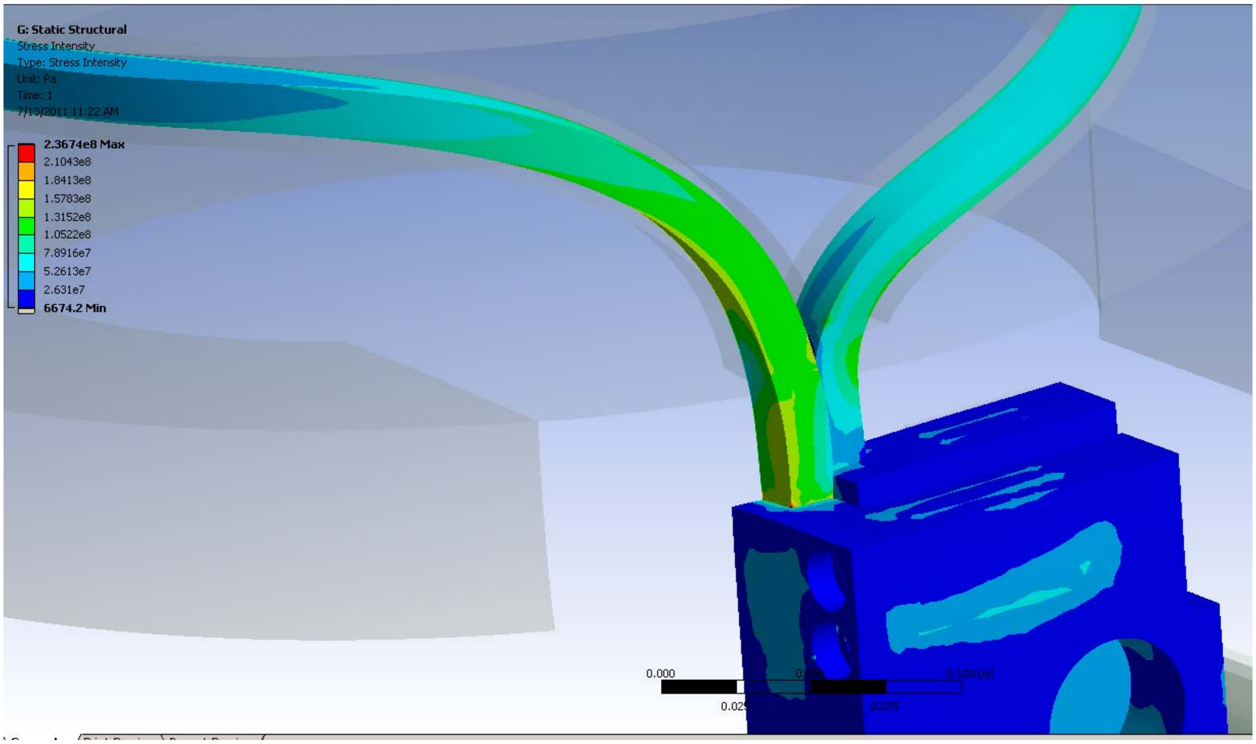
Proposed Change



Original Geometry\
Max Principal

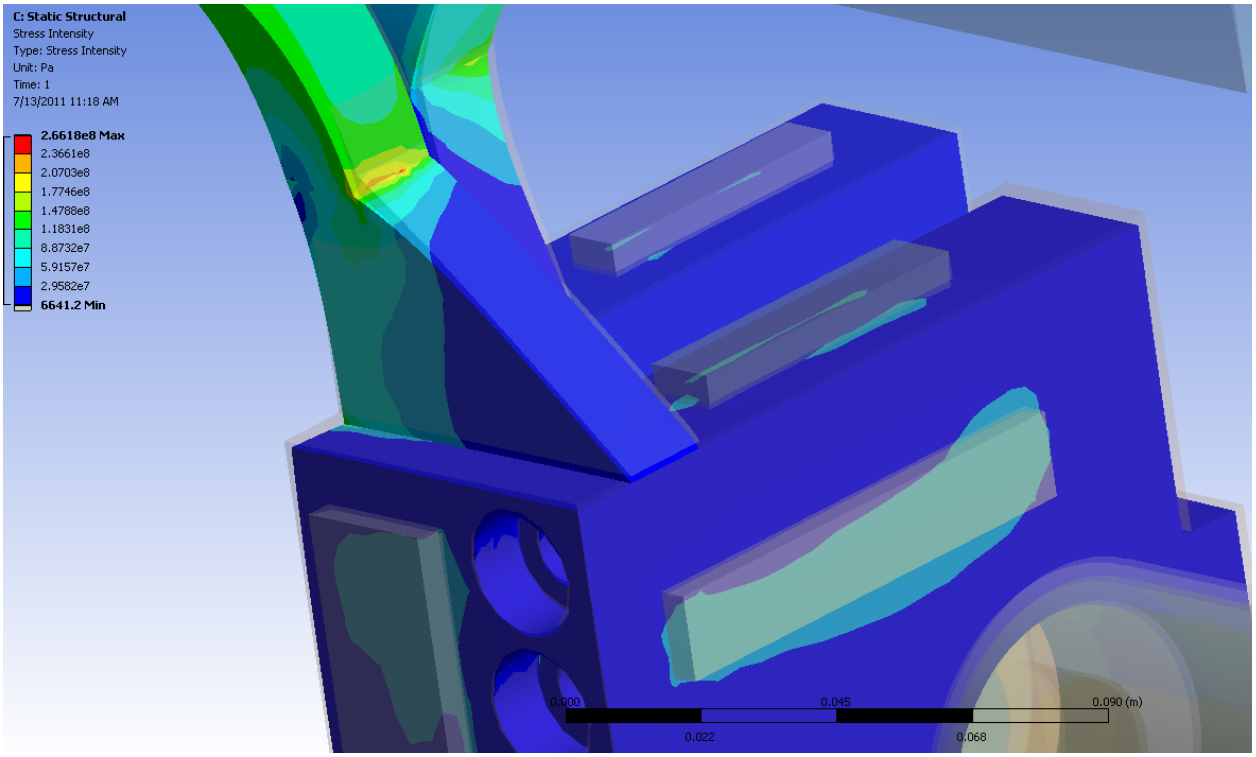


Proposed Change
Change Max Principal
Inset Above 125 Mpa



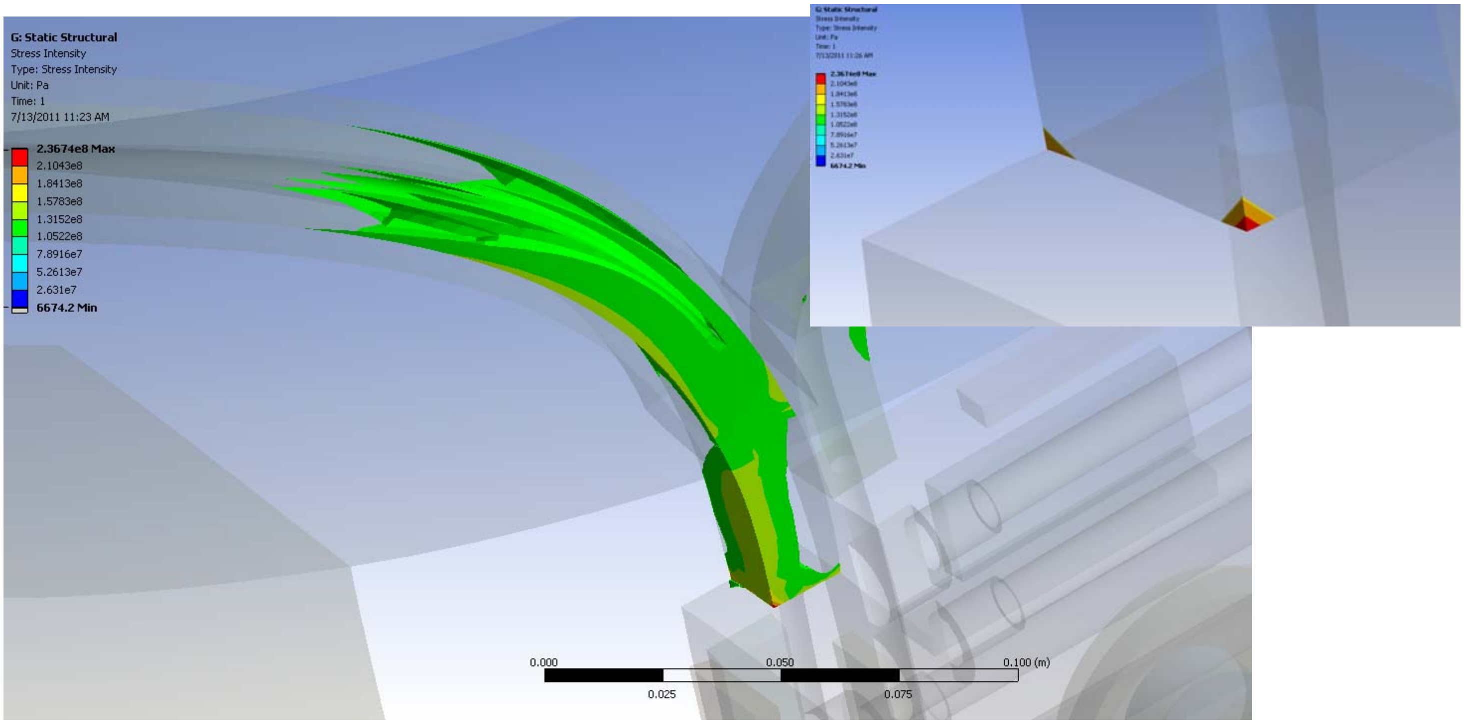
G: Static Structural
Stress Intensity
Type: Stress Intensity
Unit: Pa
Time: 1
7/13/2011 11:22 AM

Original Geometry\
Stress Intensity

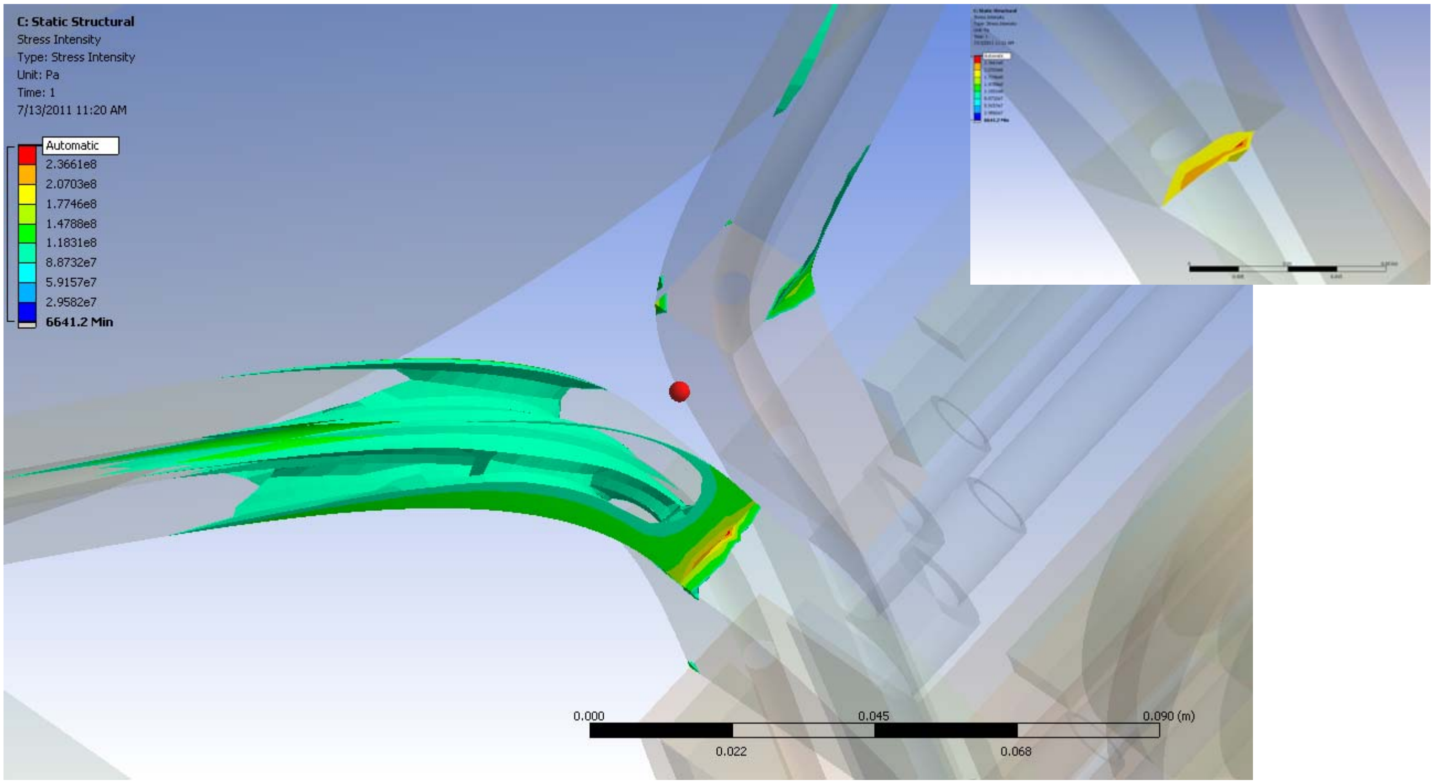


C: Static Structural
Stress Intensity
Type: Stress Intensity
Unit: Pa
Time: 1
7/13/2011 11:18 AM

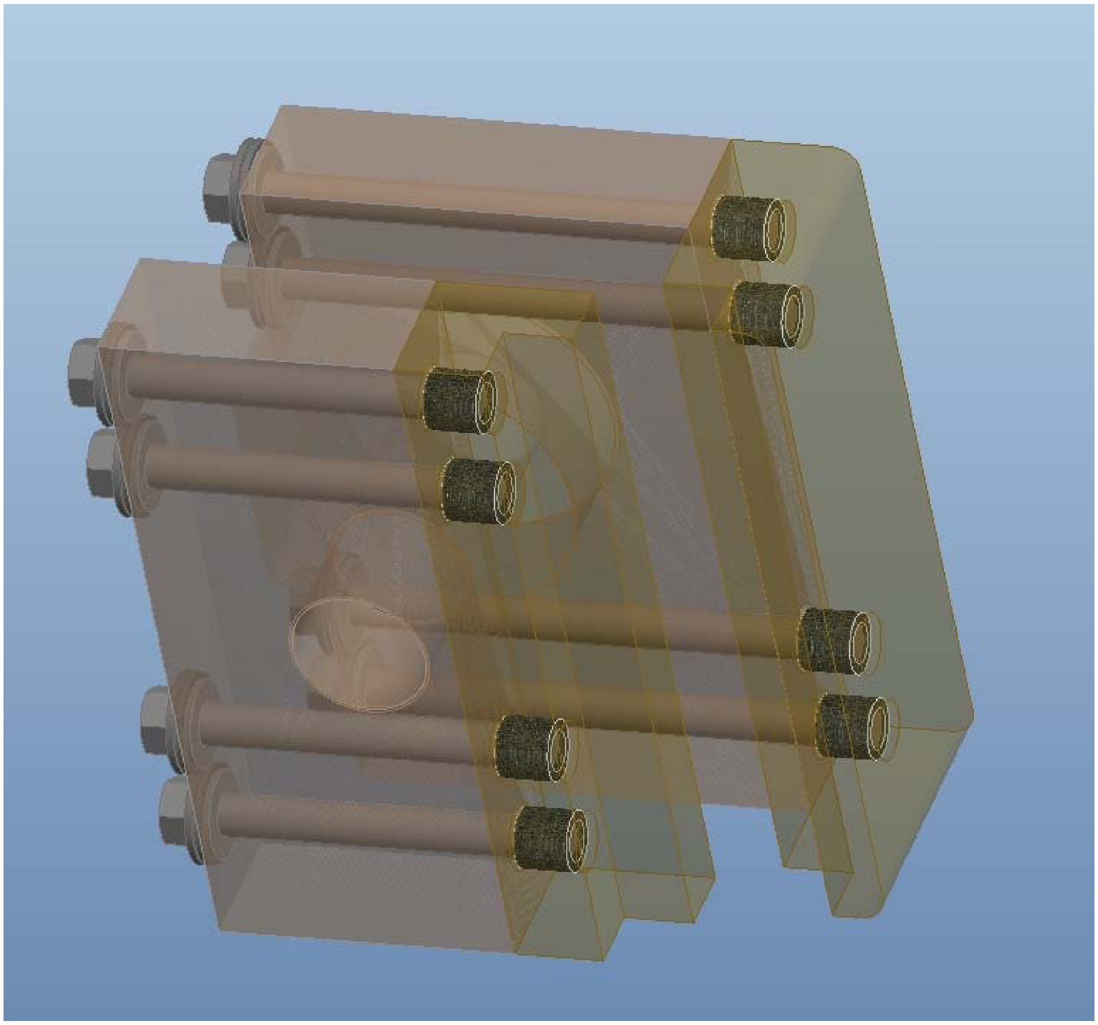
Proposed Change
Stress Intensity

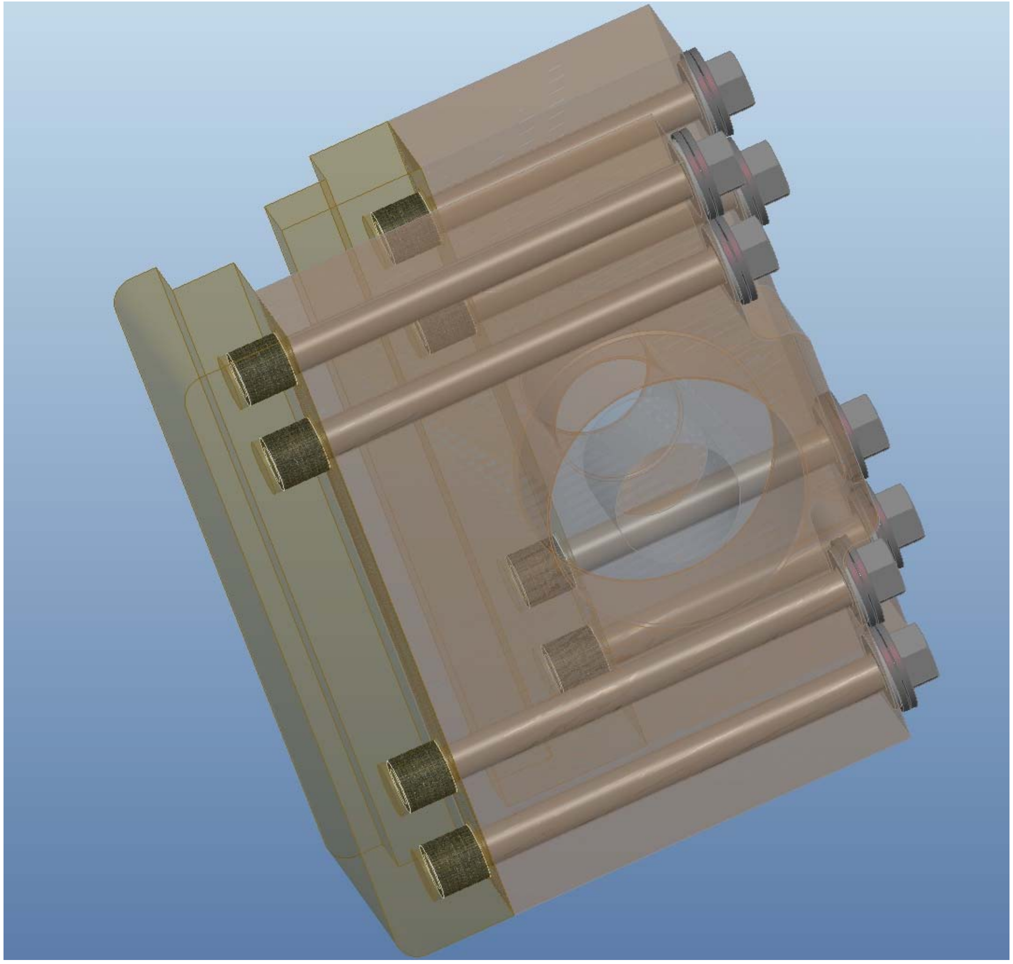


Original Geometry\
Stress Intensity Above 112 Mpa
Inset Above 180 Mpa



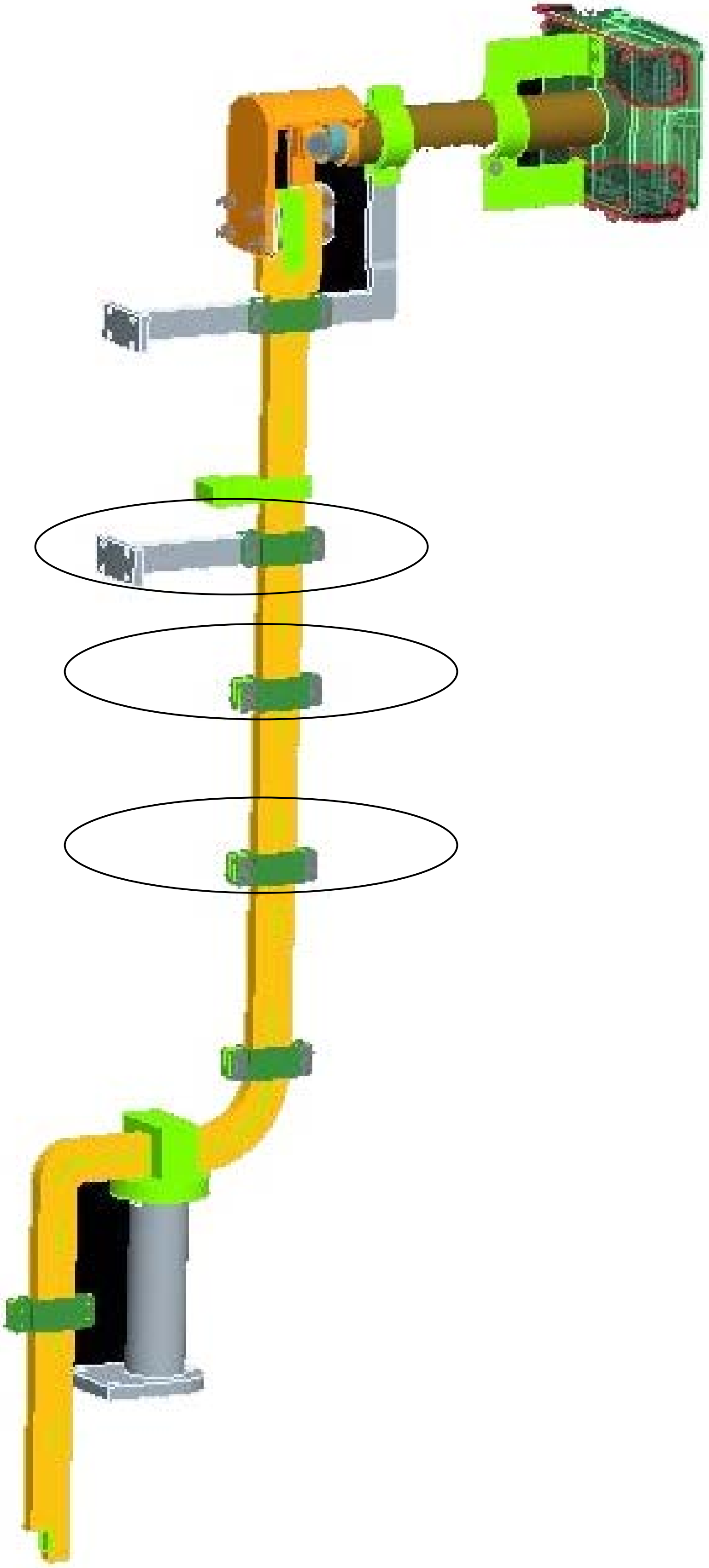
Proposed Change
Stress Intensity Above 112 Mpa
Inset Above 180 Mpa

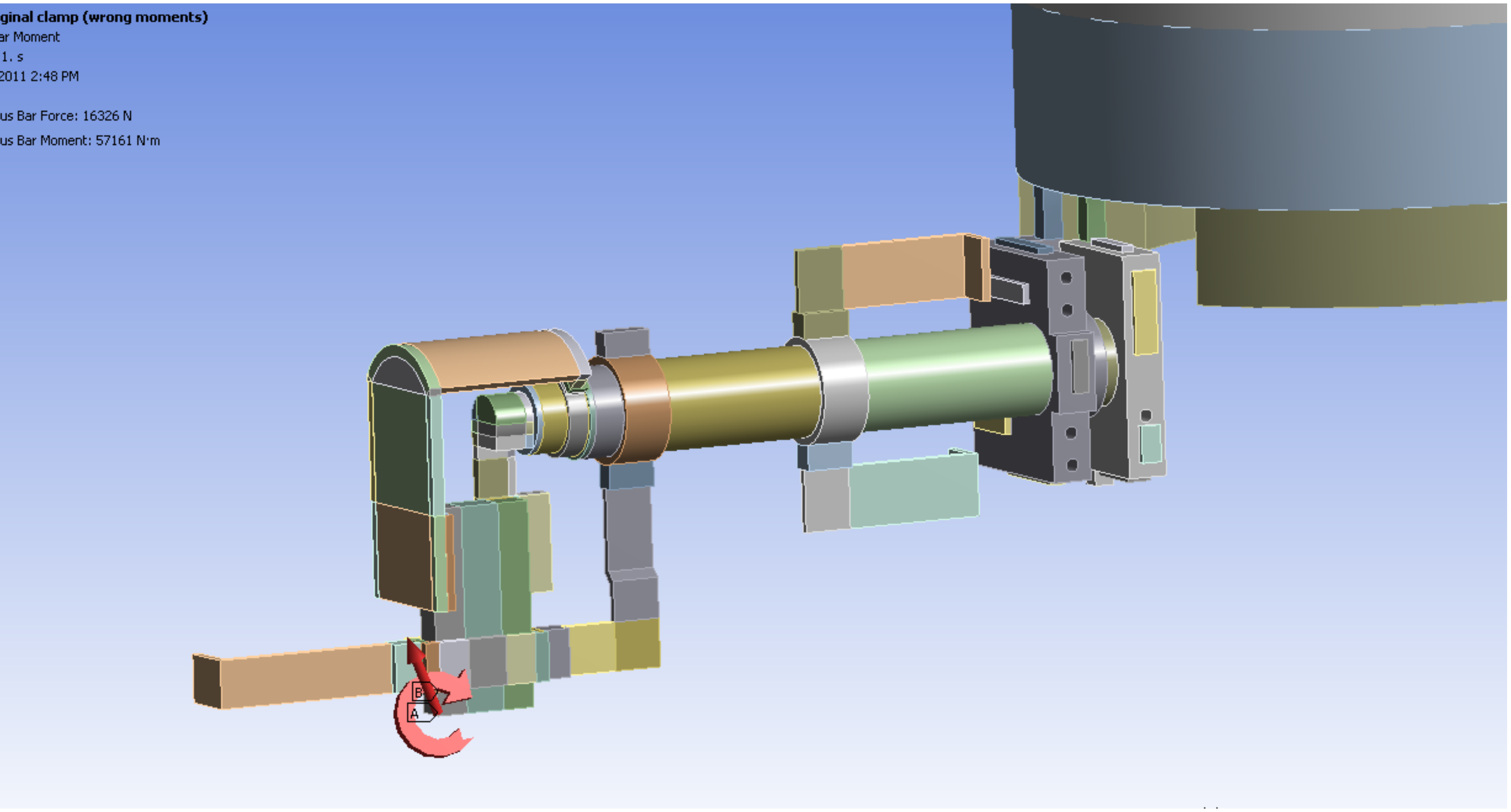




Circled Clamps are New additions since analysis

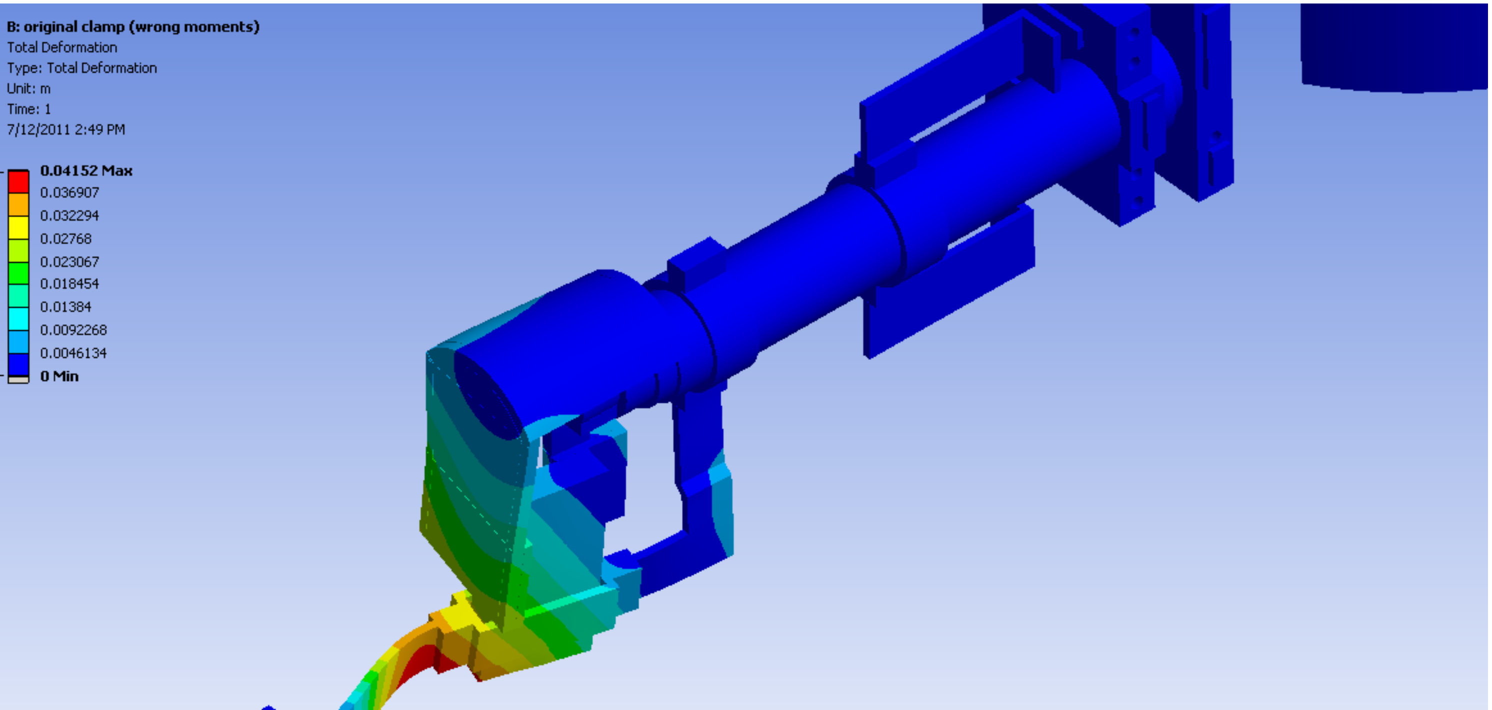
Also, spacing between turns has been reduced → reduces torqueing moment



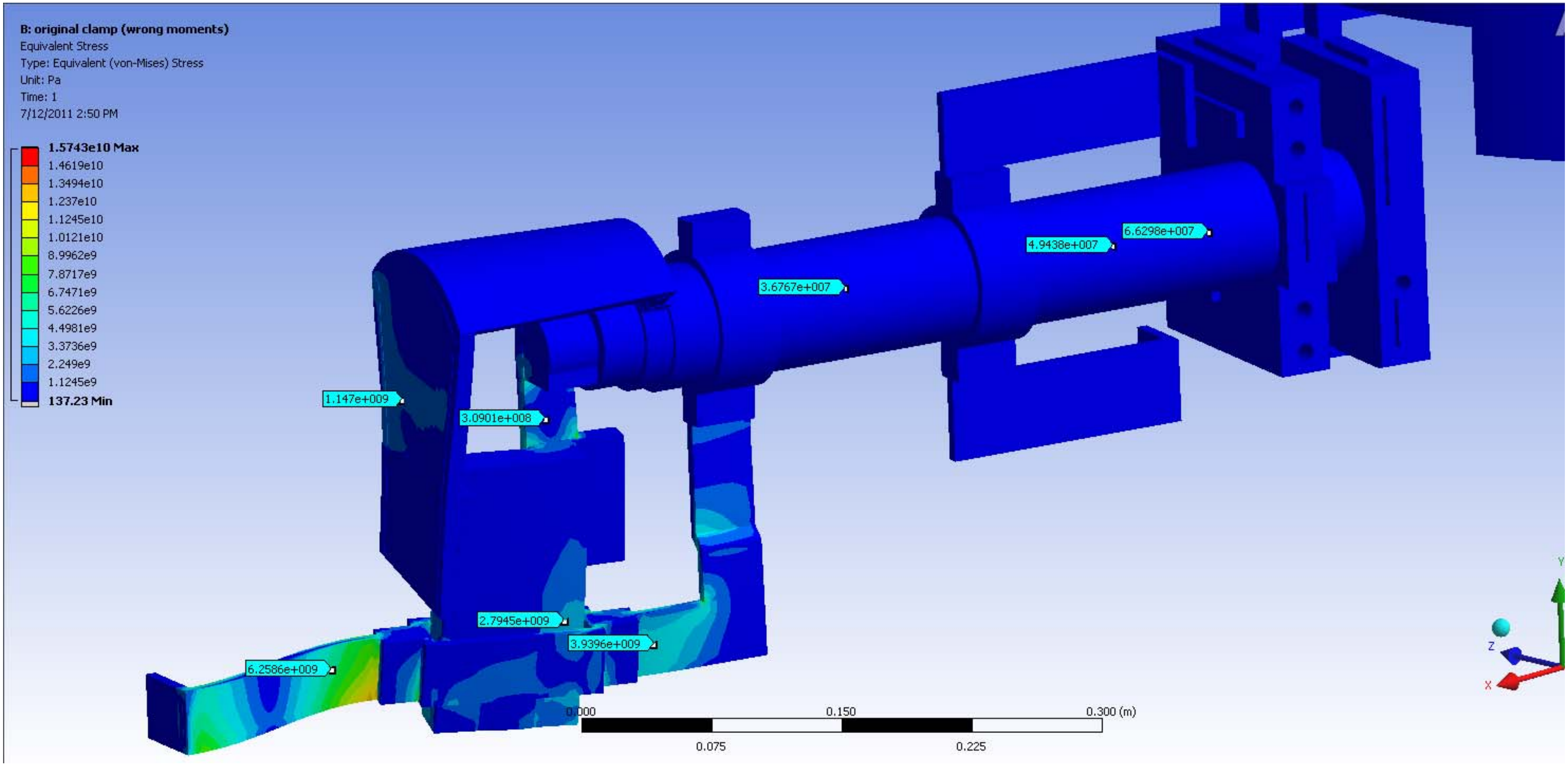


ginal clamp (wrong moments)
ar Moment
1. s
2011 2:48 PM

us Bar Force: 16326 N
us Bar Moment: 57161 N·m

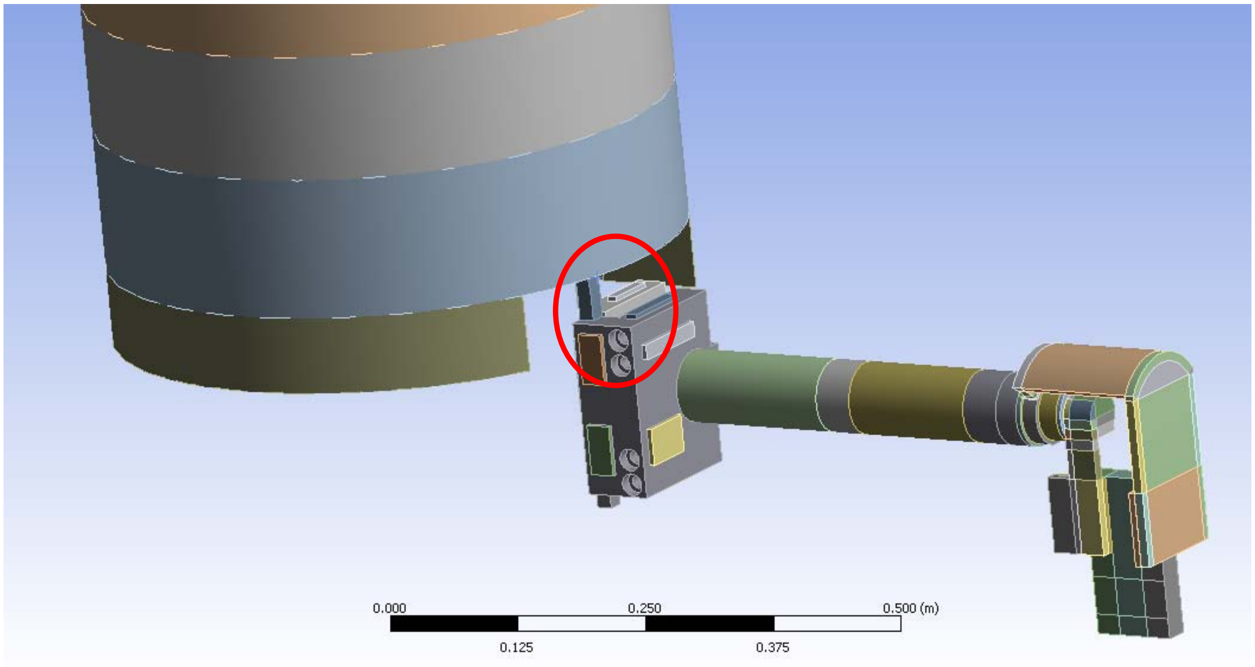


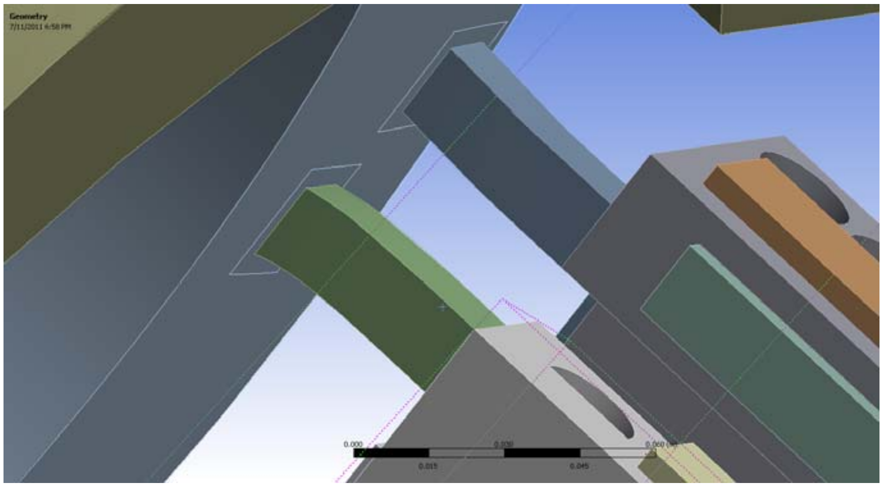
B: original clamp (wrong moments)
Total Deformation
Type: Total Deformation
Unit: m
Time: 1
7/12/2011 2:49 PM



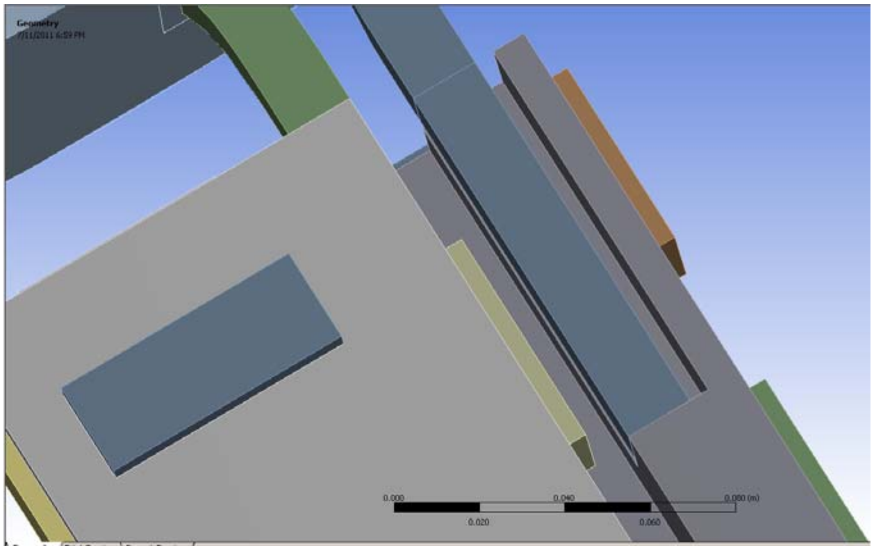
B: original clamp (wrong moments)
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: Pa
Time: 1
7/12/2011 2:50 PM

Older Analysis / Unsuccessful Alternative

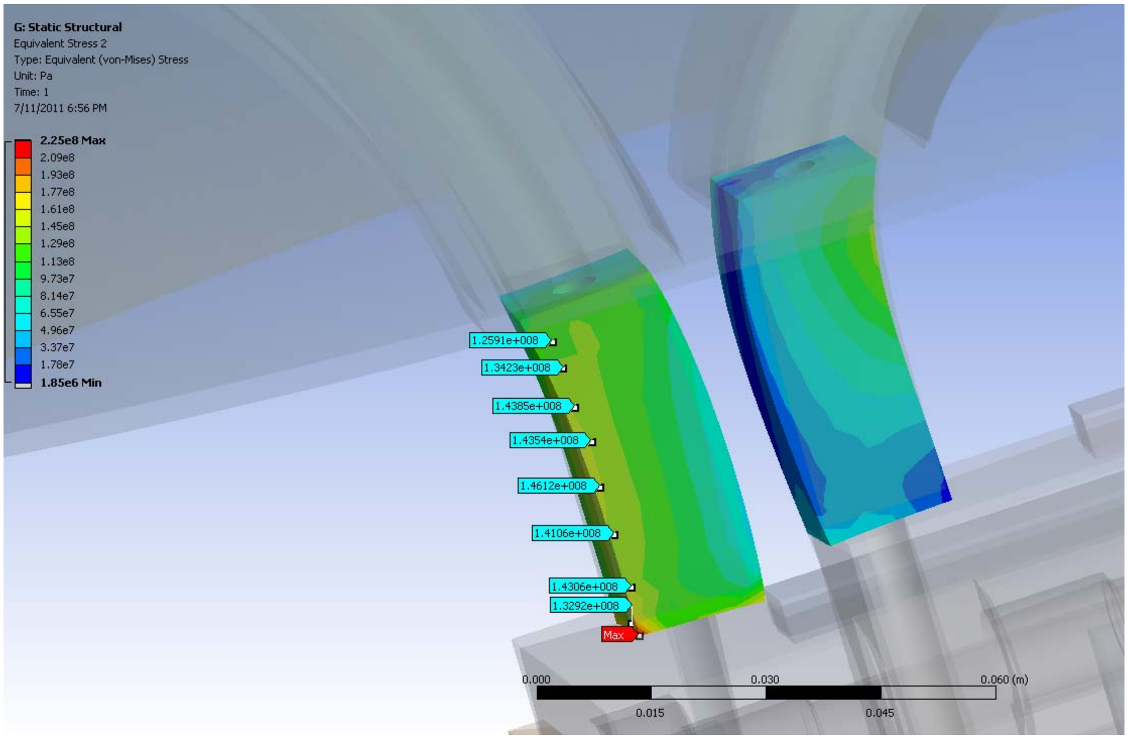




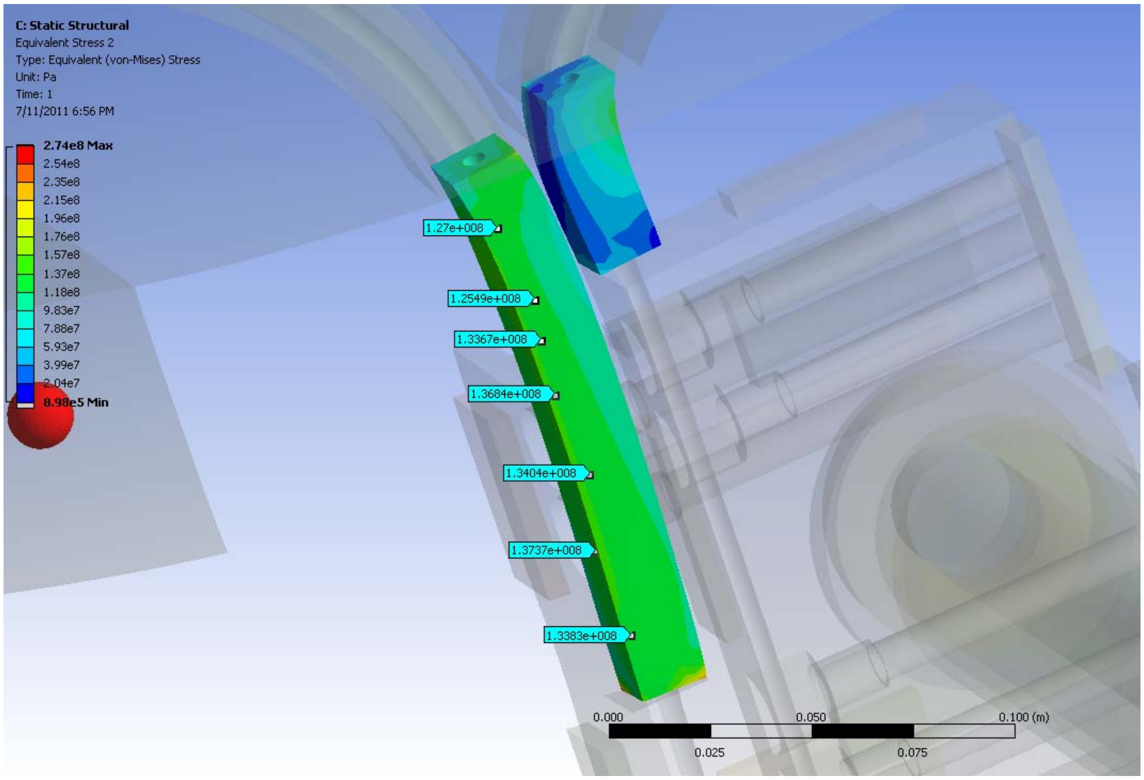
Original Geometry



Changed Geometry – Length of Braze b/w Flag and Lead significantly shortened to increase flexibility (One Lead Only)



Von Mises
Original Geometry

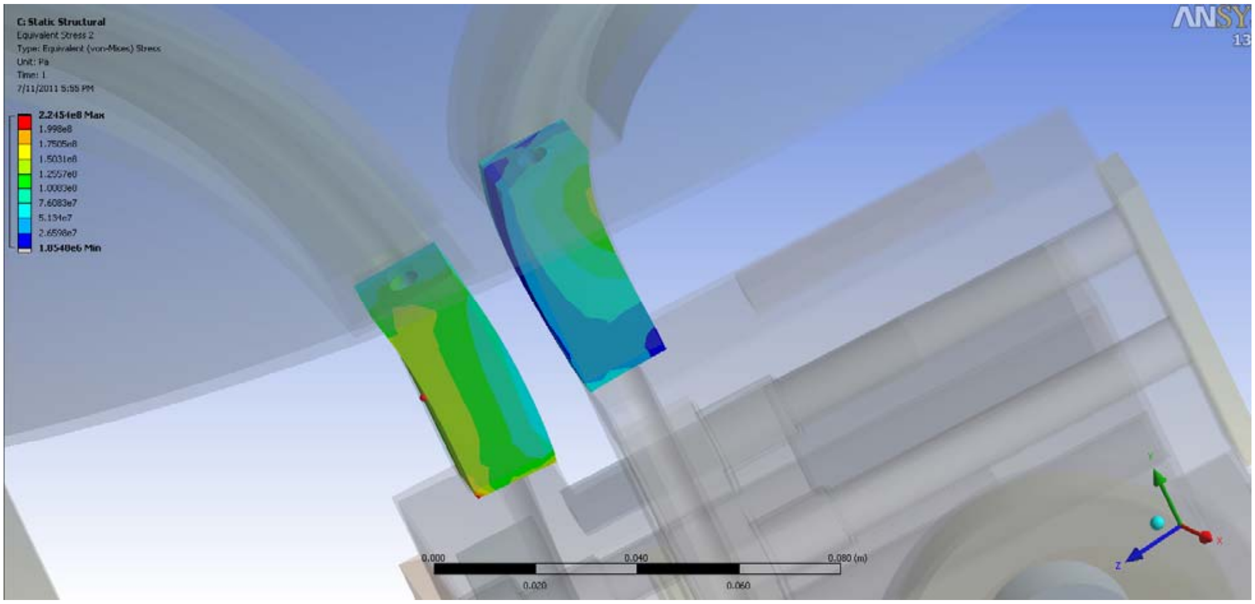


Von Mises
After Geometry Modification (Left Lead Only)

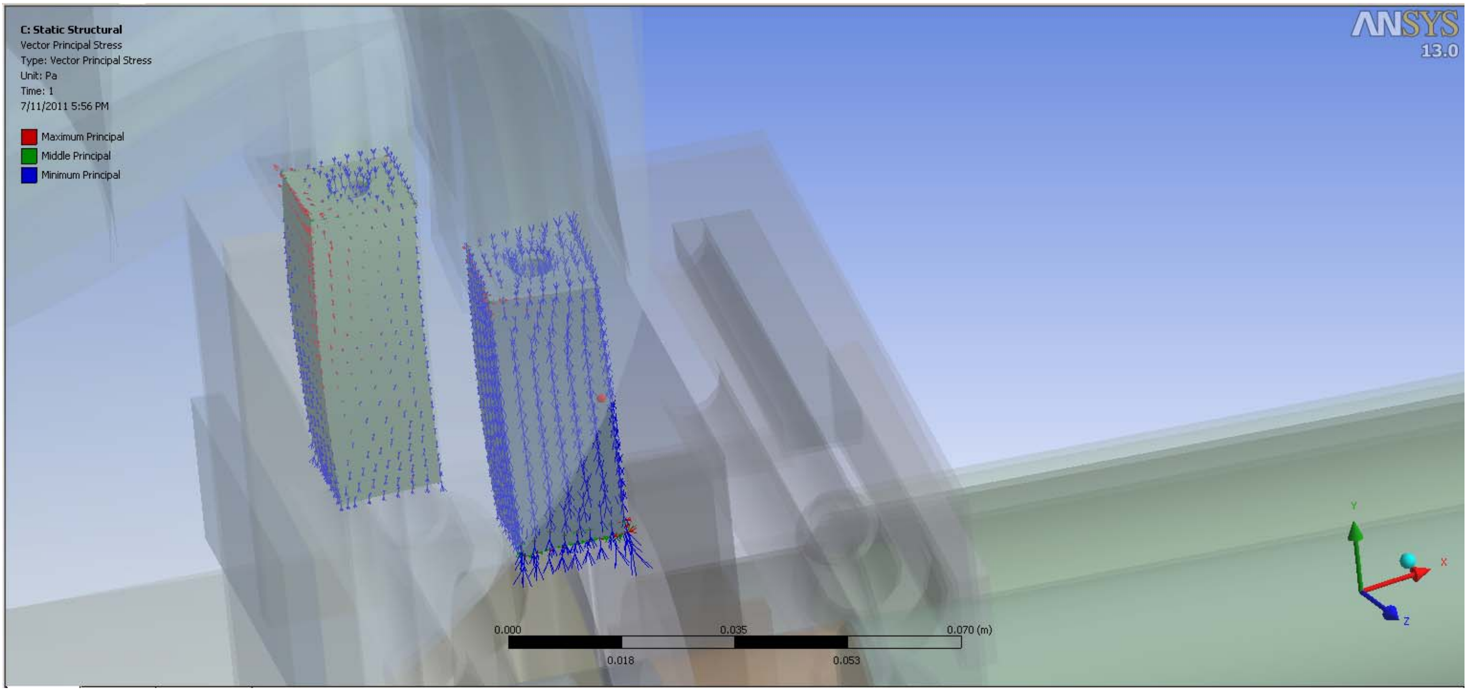
NO SIGNIFICANT CHANGE

Why Not?

Primary stress state is COMPRESSION from thermal expansion NOT BENDING as previously thought

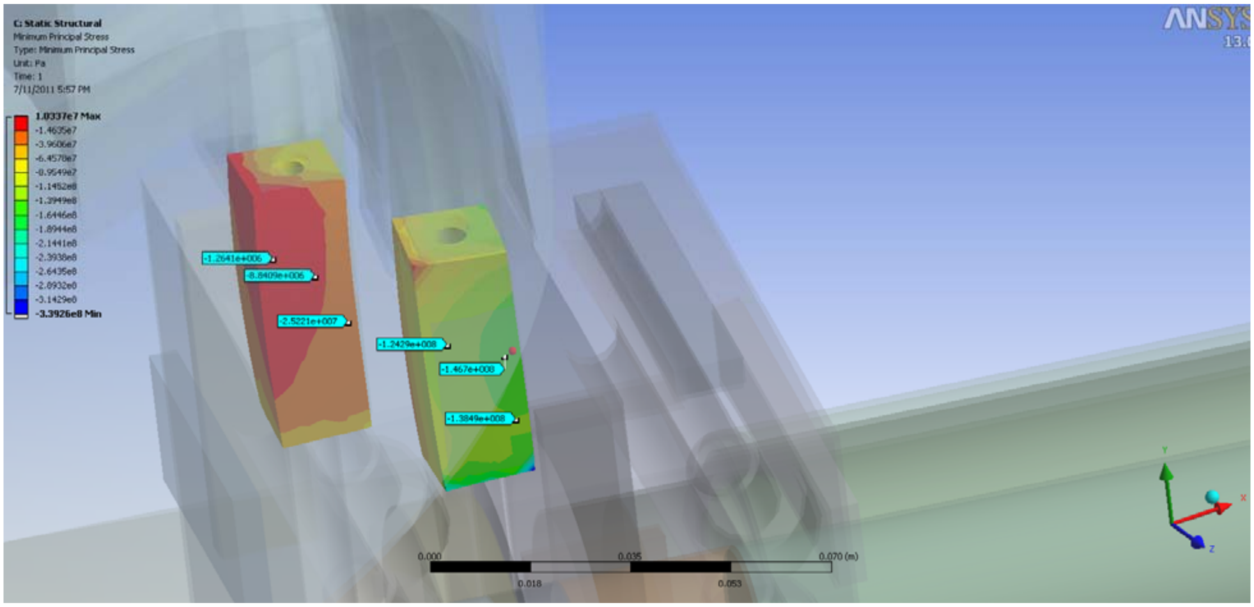


Von Mises, Original

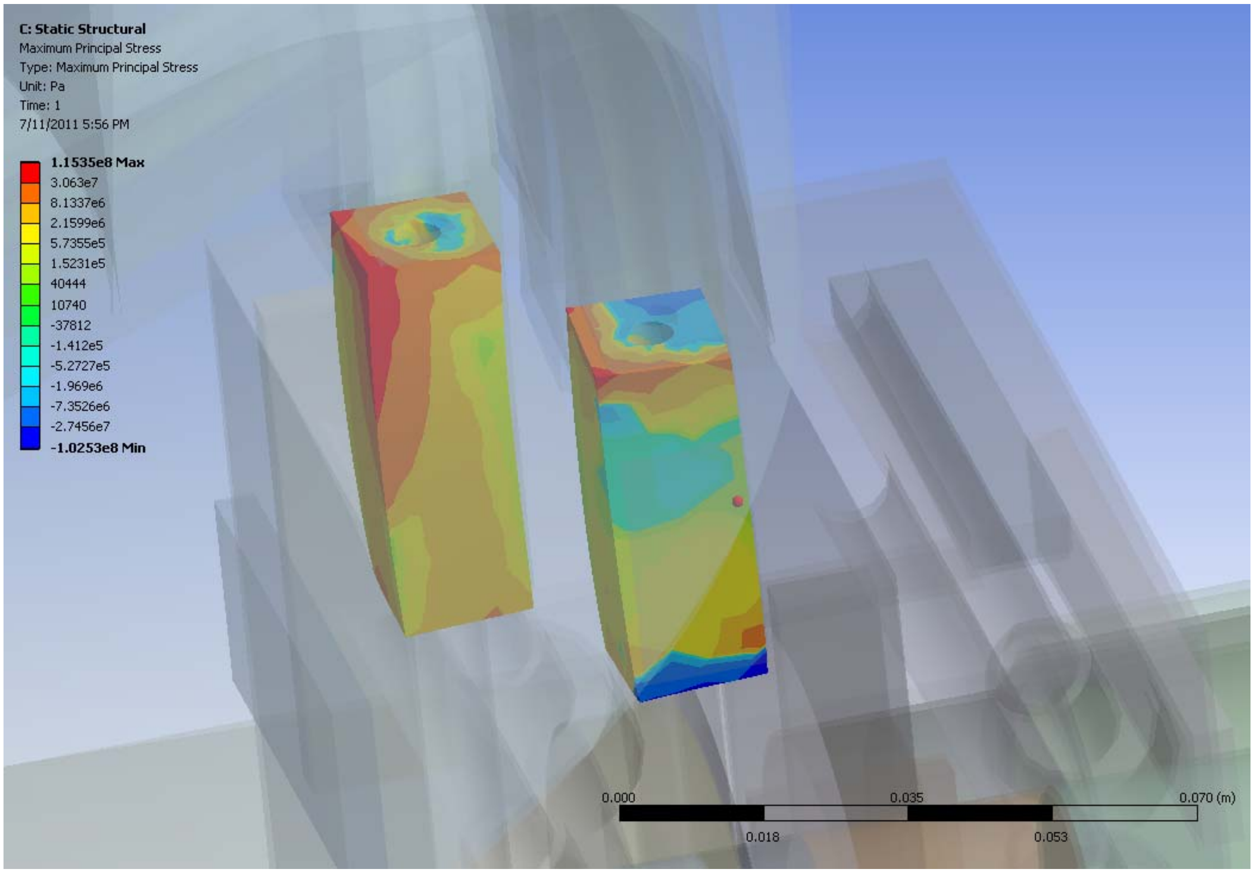


Vector Principal, Original
Arrows to Scale

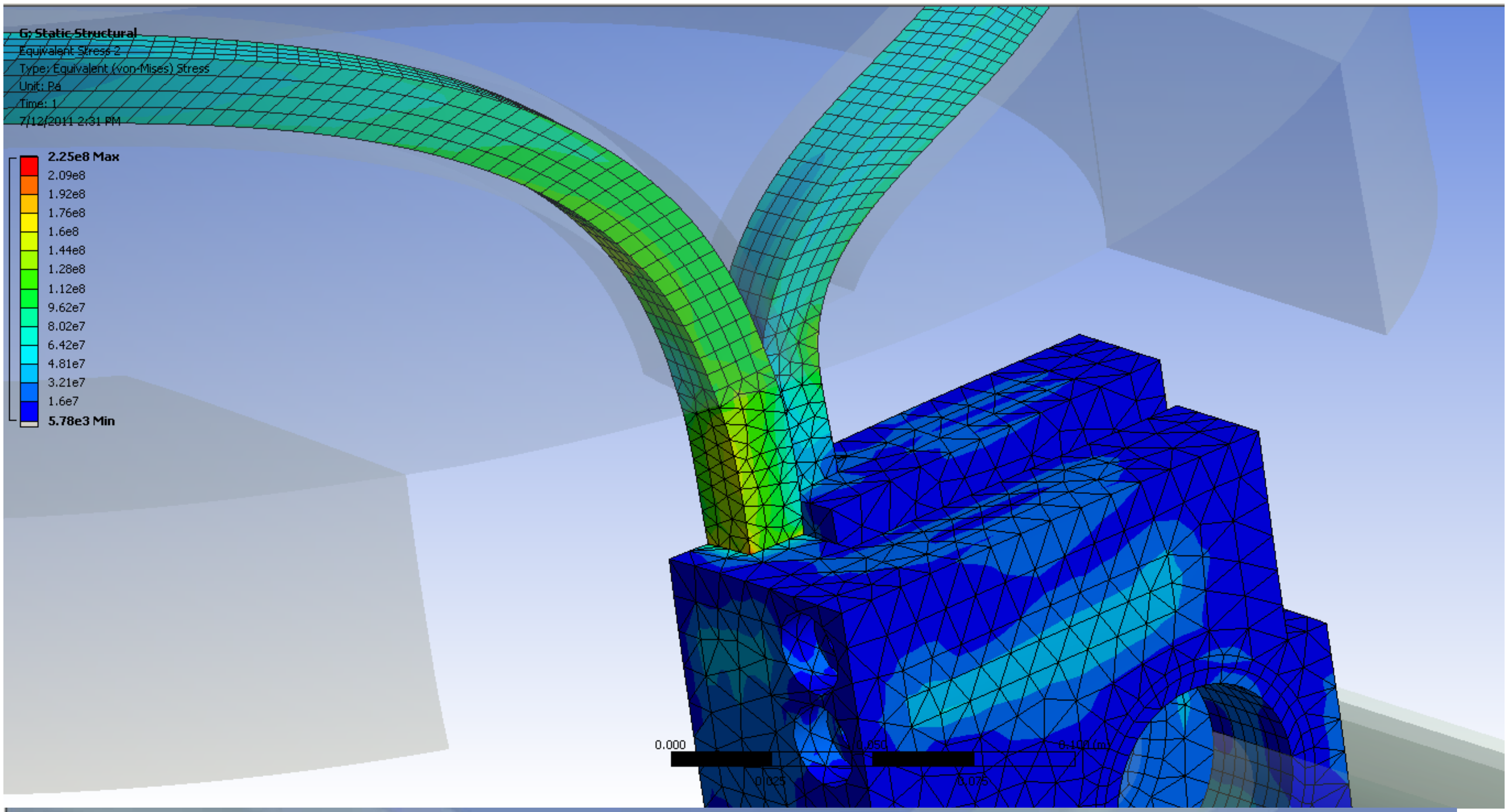
Notice Overwhelming Vertical Compression

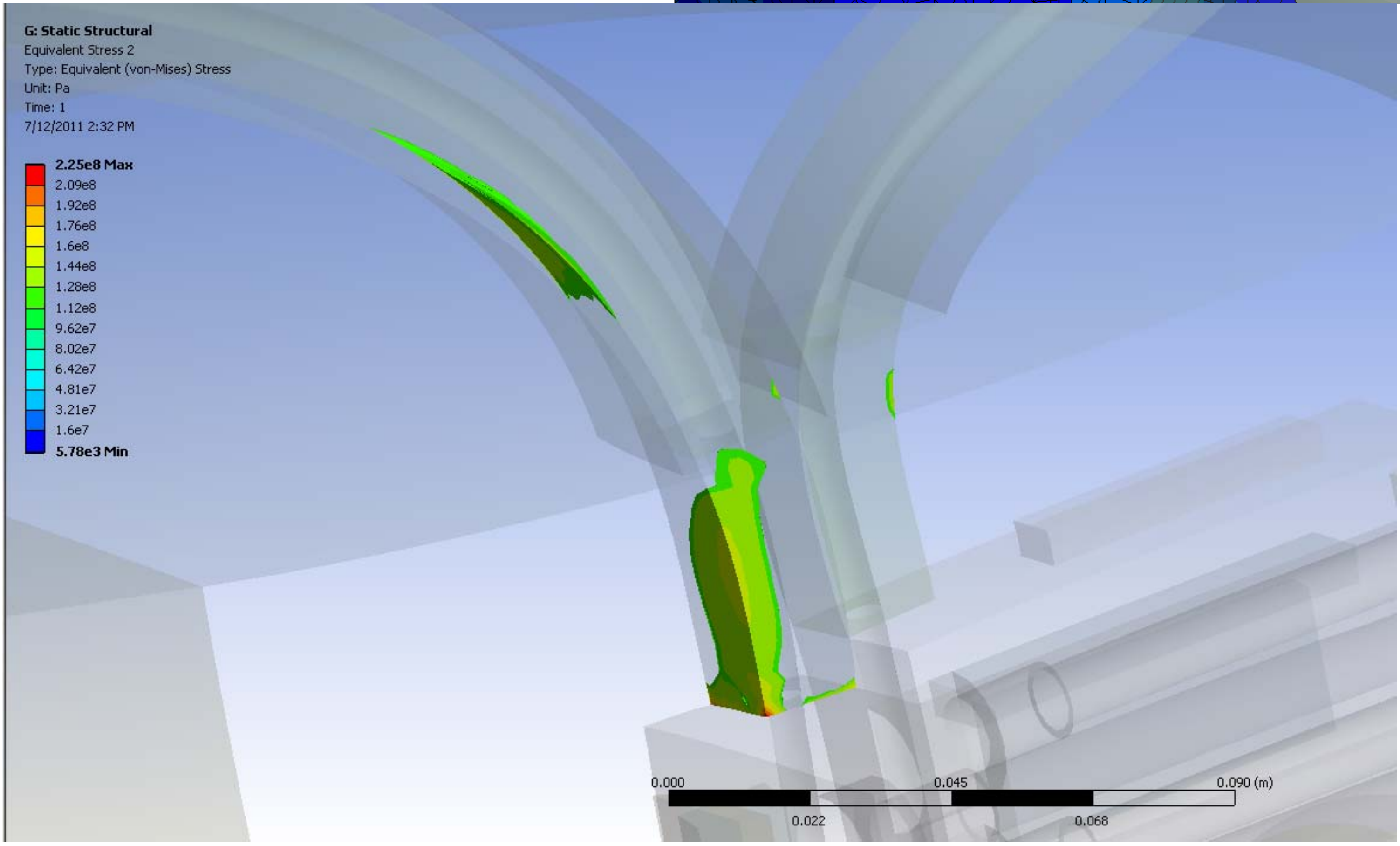


Original
Contour Plot, Minimum Principal

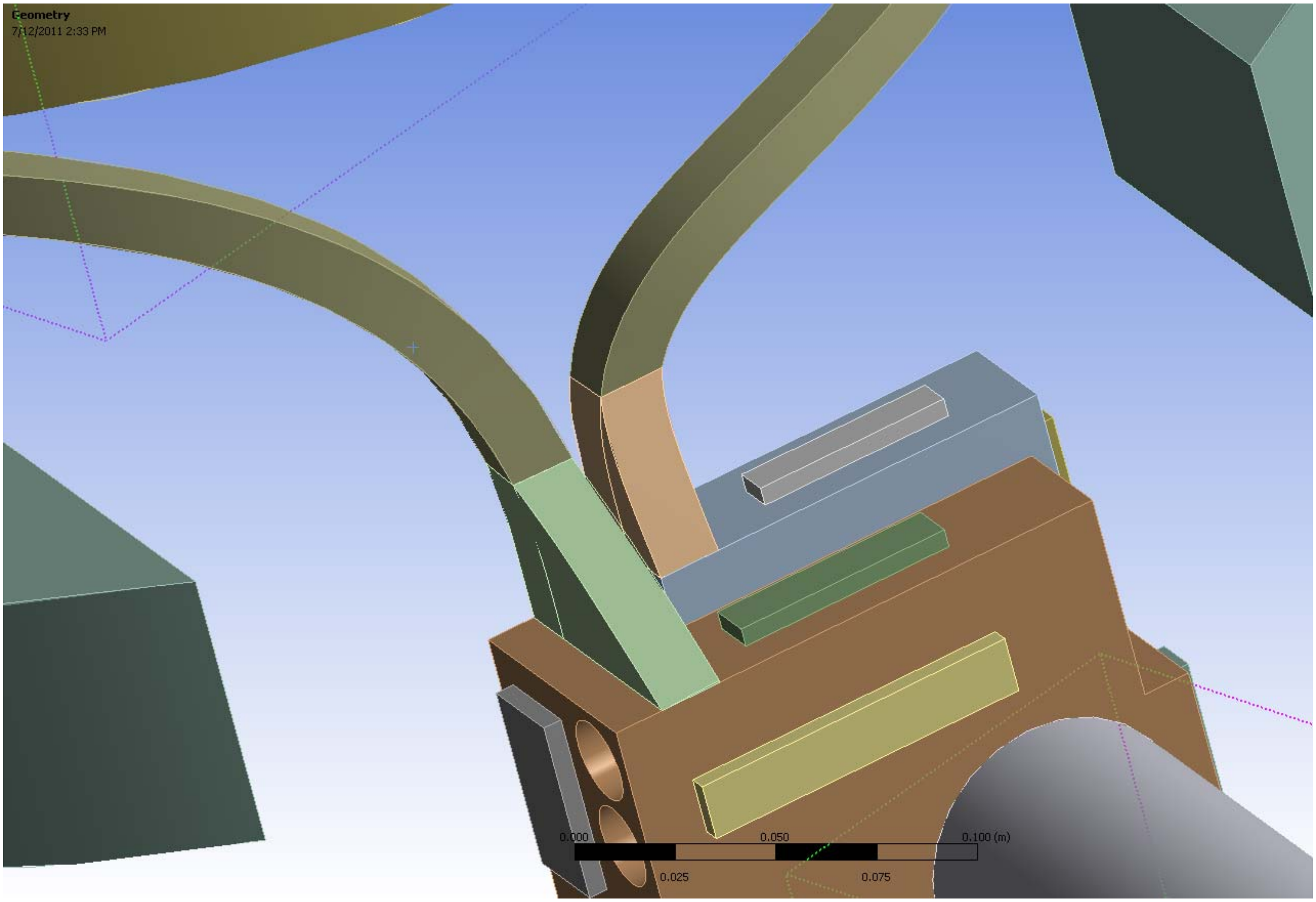


Original
Contour Plot, Max Principal





Colored Regions Above 125 MPa

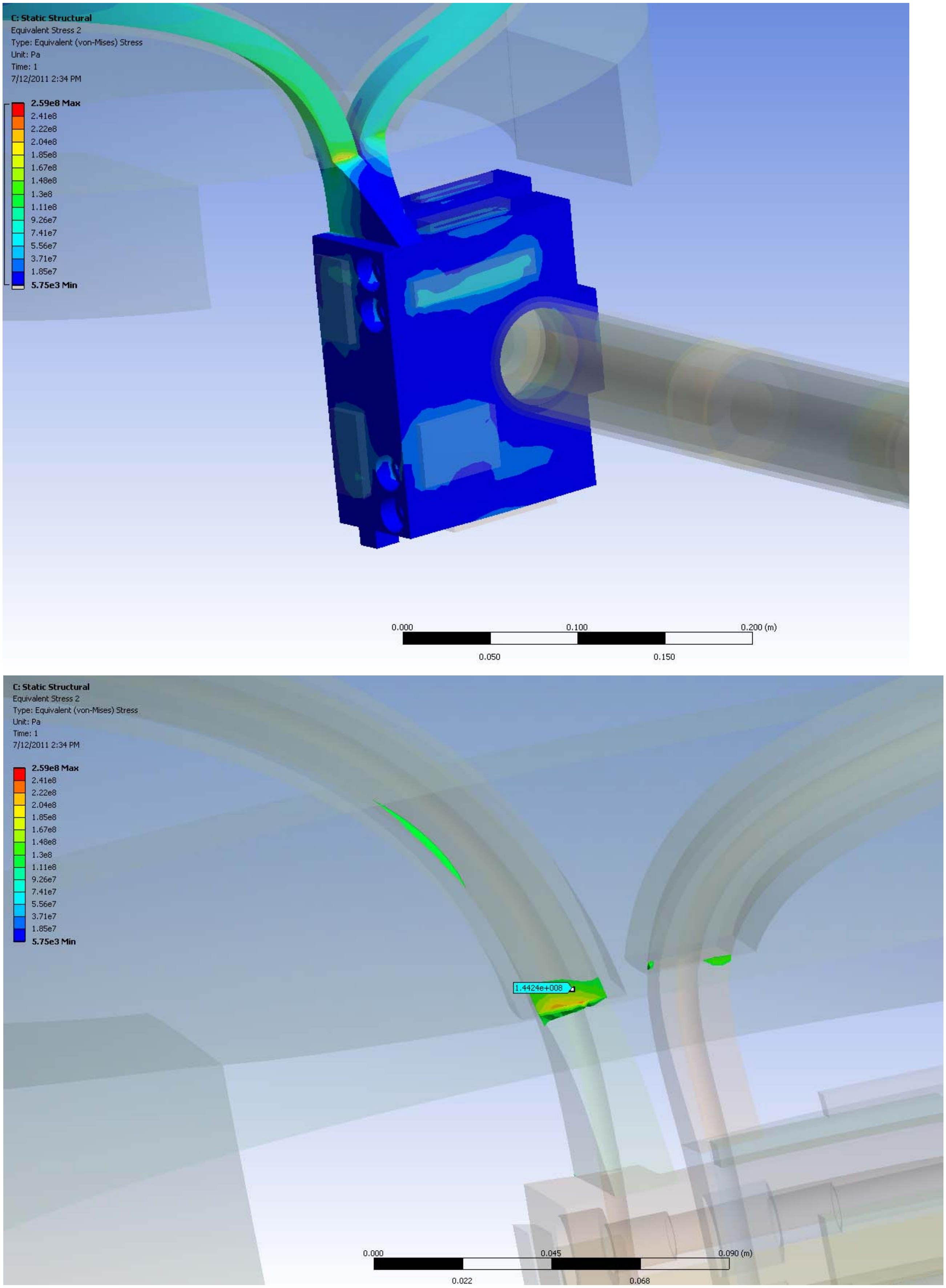


Lead Flag and Bottom of Coil are well supported and relatively immobile

The vertical leg of the conductor heats up, tries to expand, and is compressed

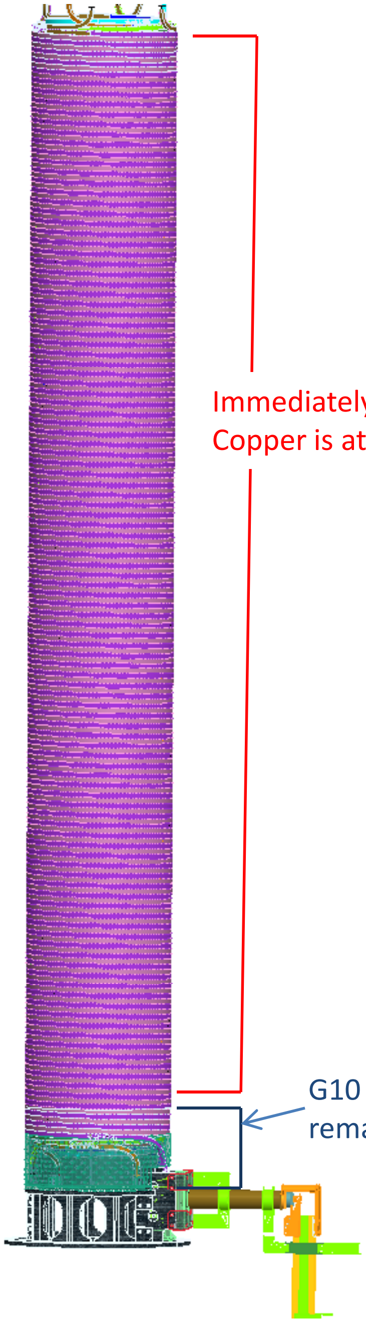
By adding “Triangle Pieces” to increase cross section, the current density is sufficiently reduced to lower the thermal expansion stress

(This compression effect is no longer prevalent once the conductor bends from a vertical orientation to horizontal one, become of the gross radial expansion of the entire OH coil. This explains why the stresses are higher on one lead, and not the other – because one lead has a longer vertically oriented leg.)



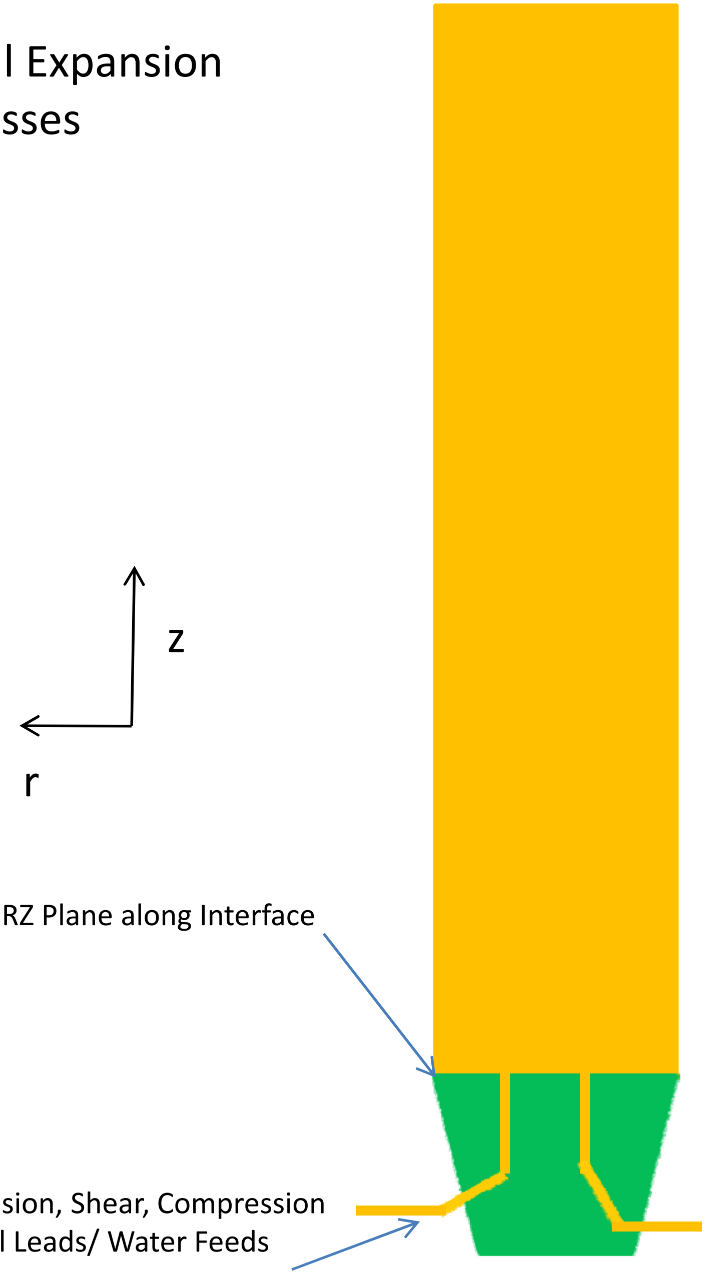
Colored Regions Above 125 Mpa – Significant Improvement

Differential Thermal Expansion Causes Stresses



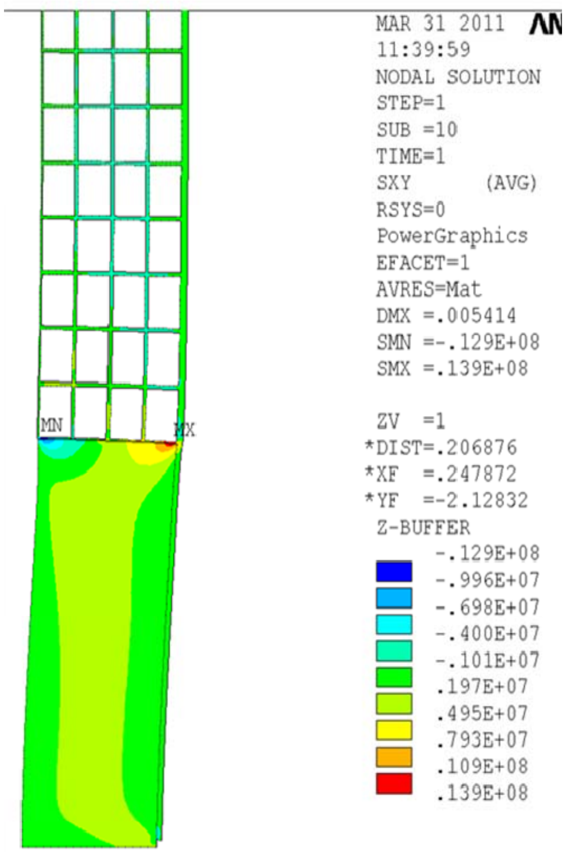
Immediately After Pulse
Copper is at ~ 100 C

G10 Support Annulus
remains “cold”

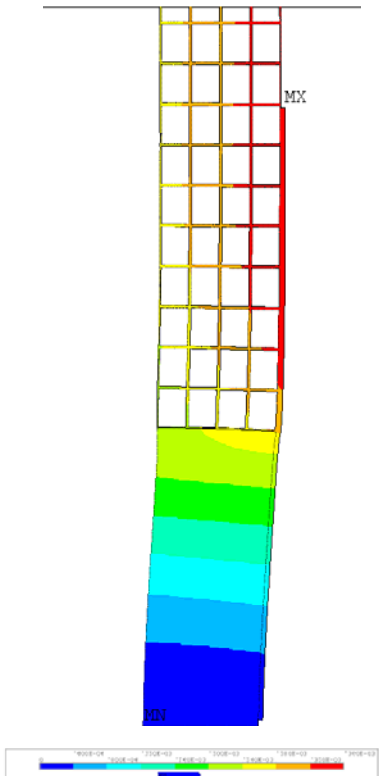


Shear along RZ Plane along Interface

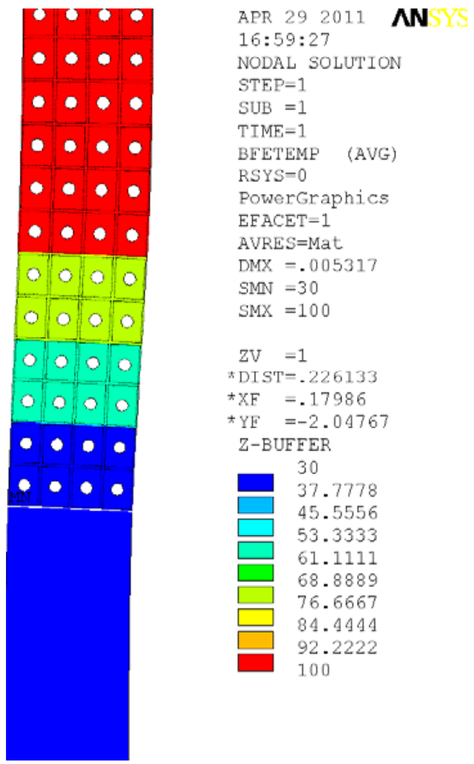
Bending , Hoop Tension, Shear, Compression
Along Electrical Leads/ Water Feeds



Shear (In Plane of Viewing), Pa



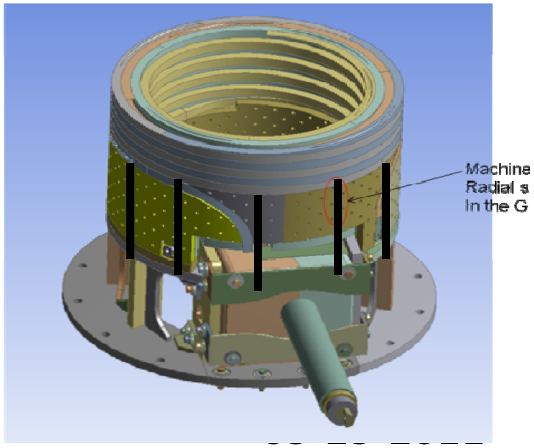
Deflection ~ 0.3 mm



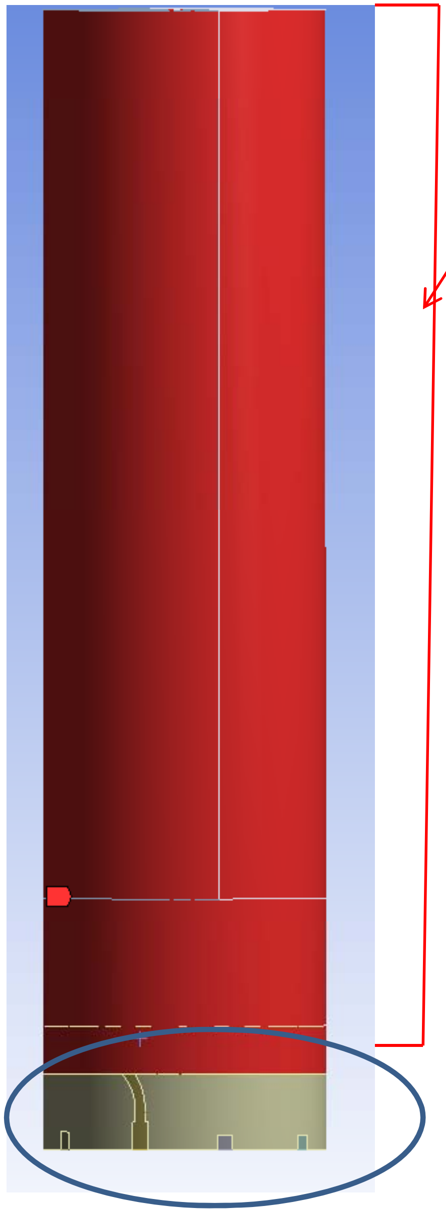
Temp Distribution, C
(Wave has travel several turns)

A. Zolfaghari, in his axisymmetric coil model, calculates this effect,

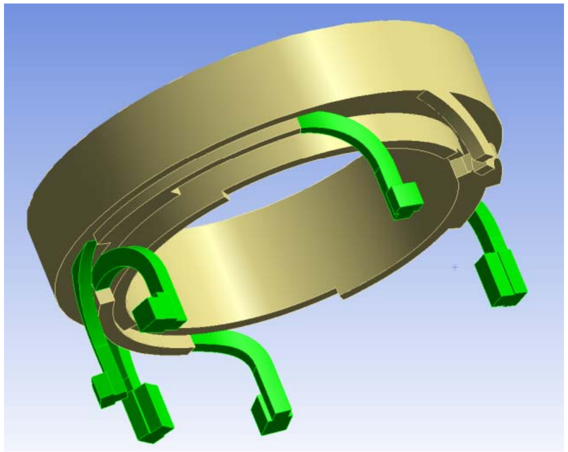
assuming slots have been cut into the G10 to induce flexibility
(slots parallel to tangential plane)



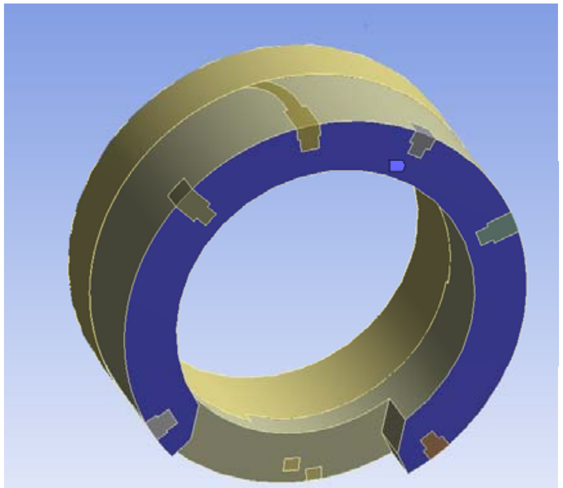
3D Model Developed to Check this Effect



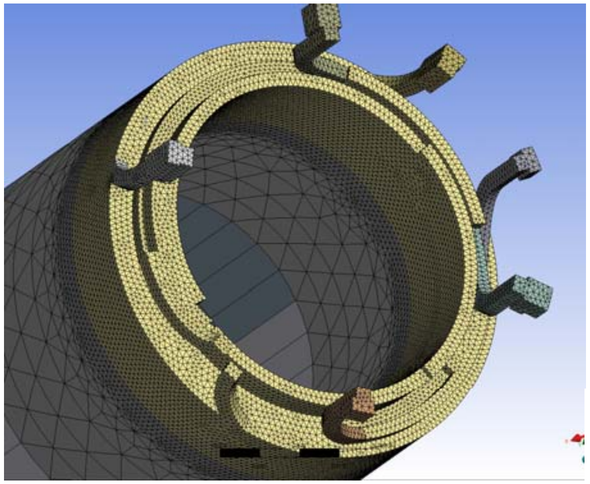
Solid Copper Modeled @ 100 C to provide Thermal Expansion



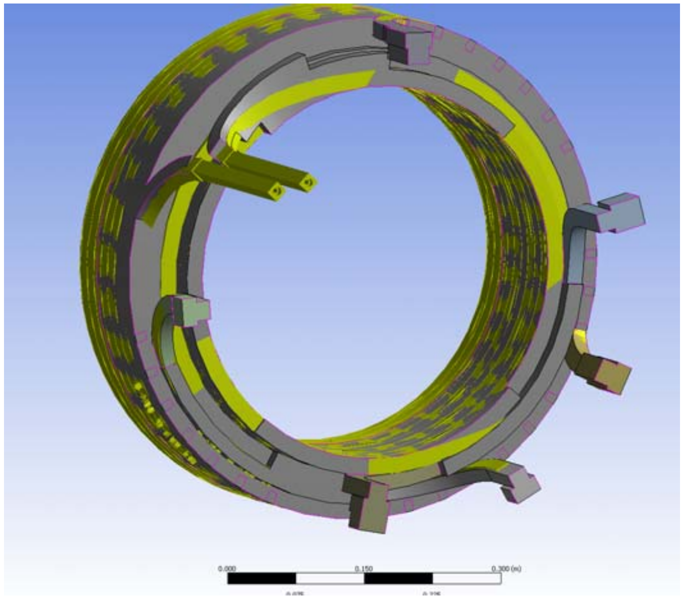
Water Feeds and G10 remain Cold



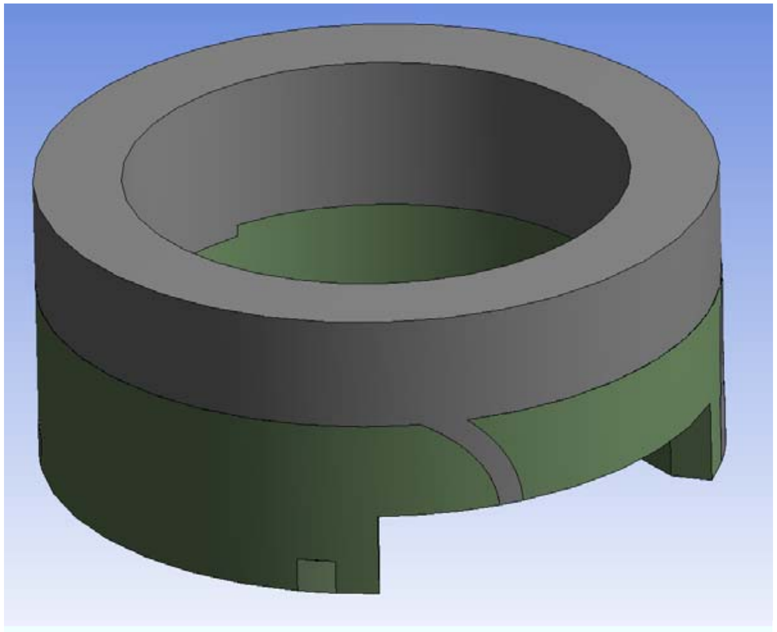
Bottom of G10 Fixed
(representing bolts to Support Pedestal)

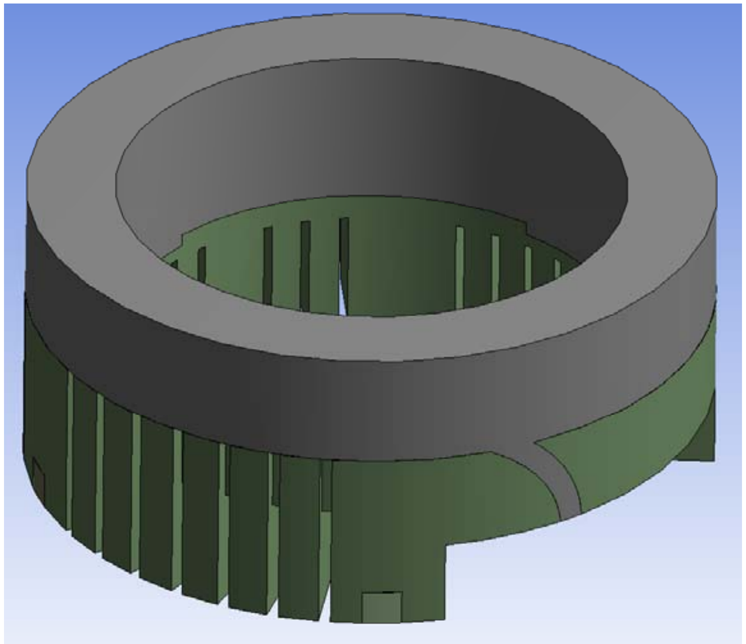


Detail of Conductors in Lead Area



True Conductor Geometry, Yellow
overlaid on
FEA approximation

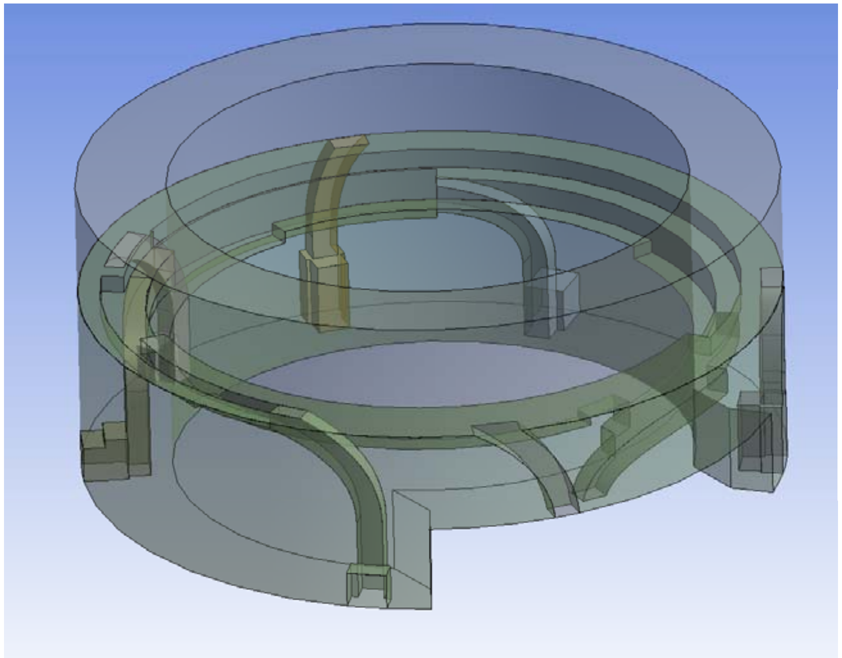


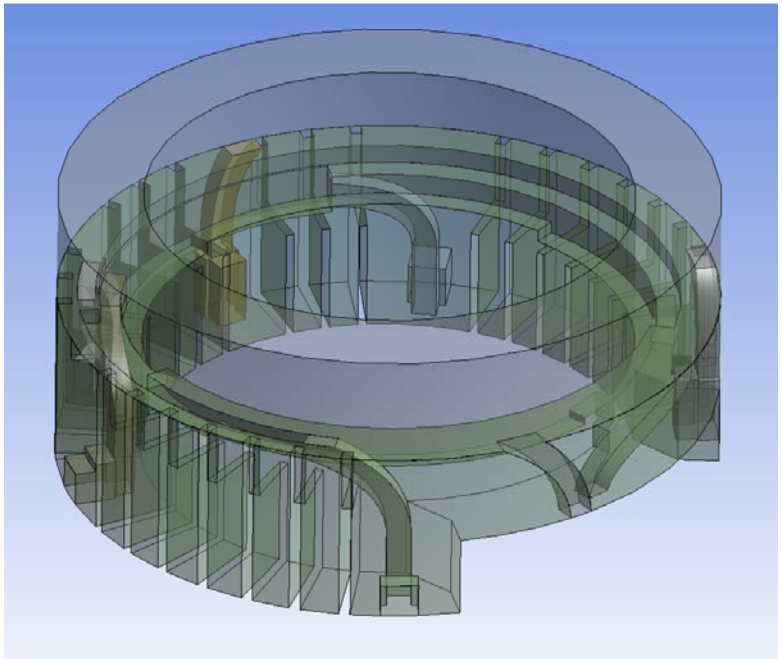


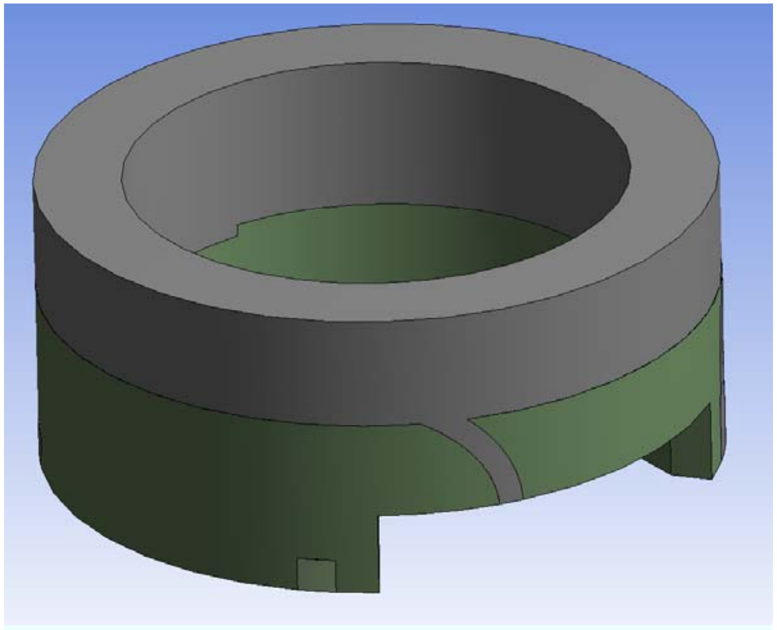
No Slots

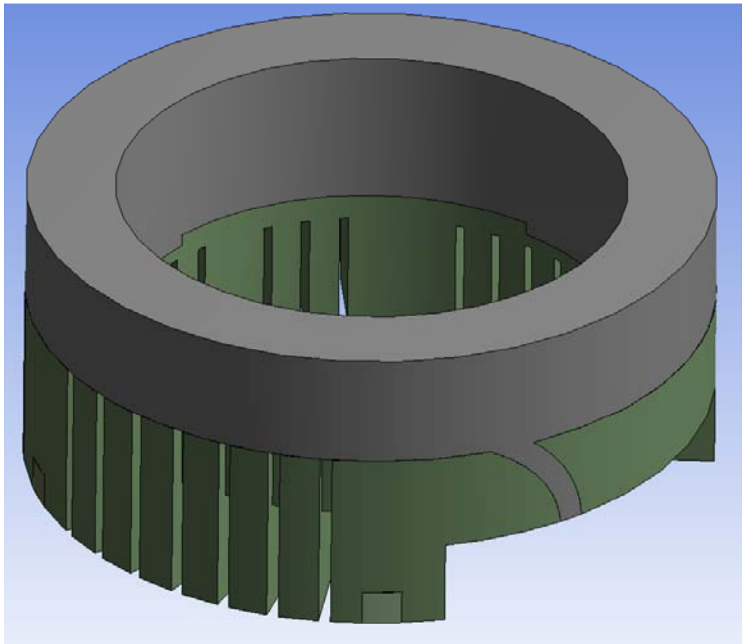
Vs

With Slots

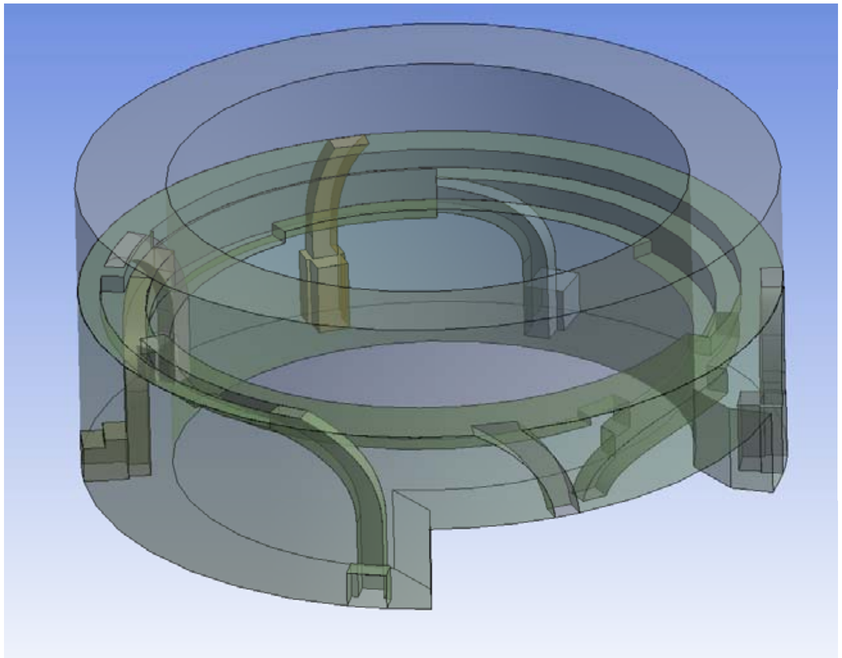


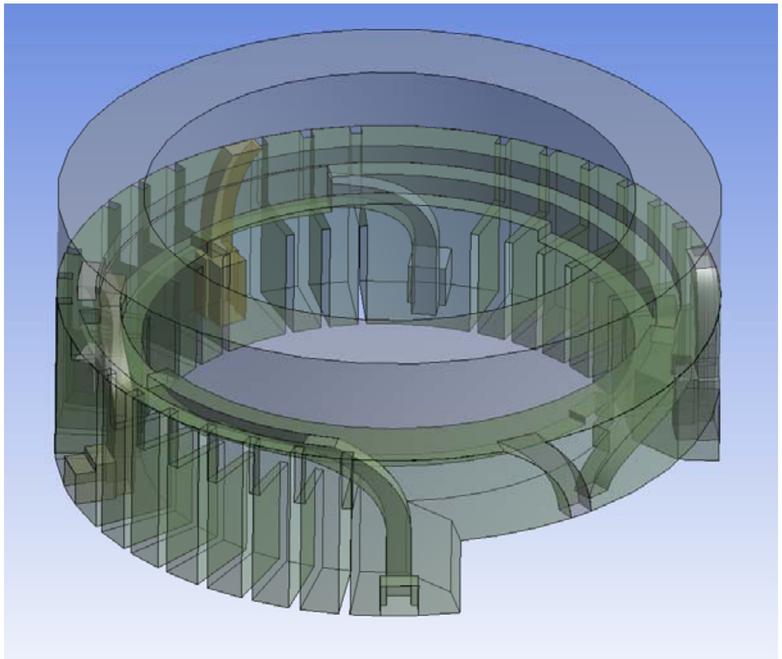




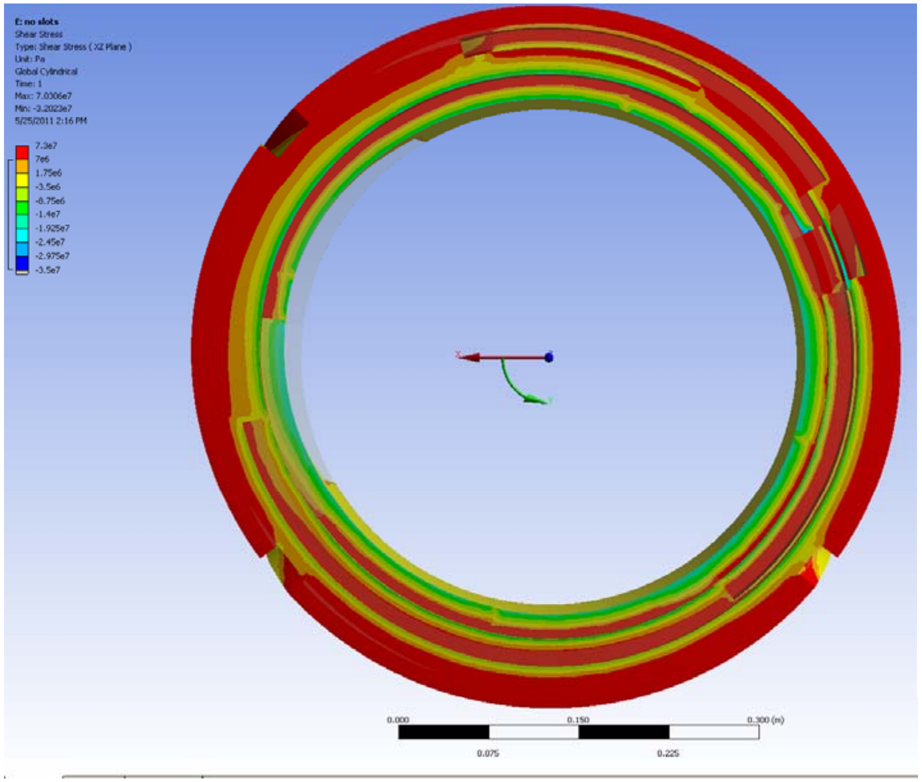


No Slots Vs With Slots

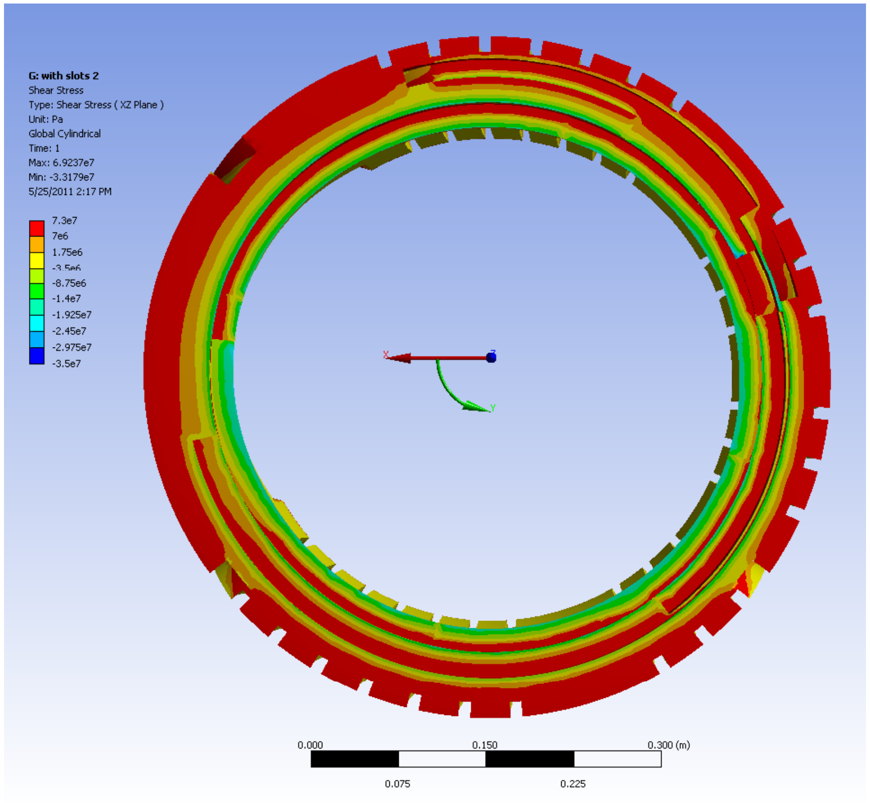




XZ Shear (Pa)



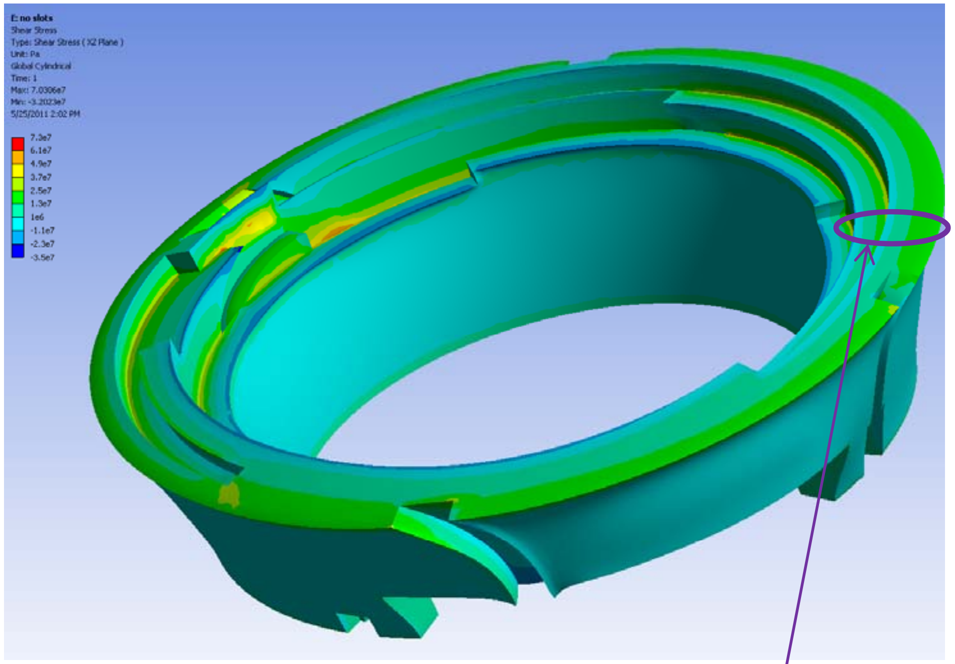
No Slots



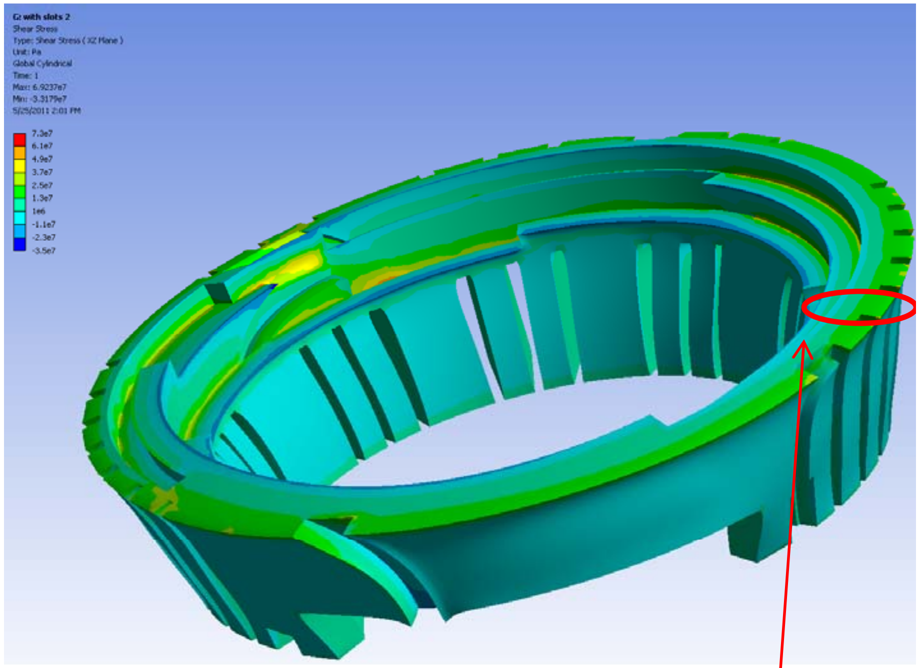
With Slots

Red Contour are stresses above 7 Mpa
(Shear Strength between CTD101K and Cu)

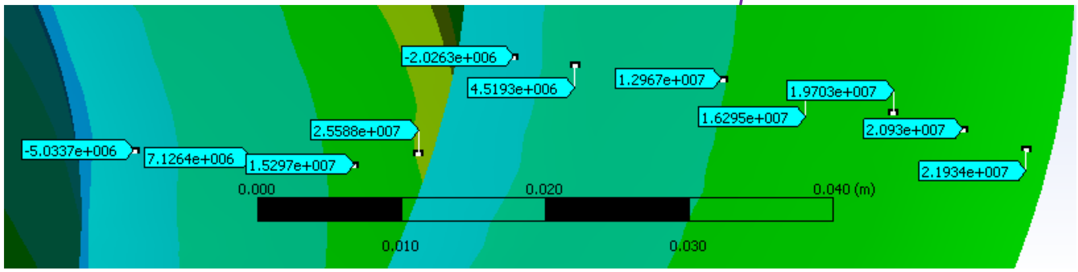
XZ Shear (Pa)



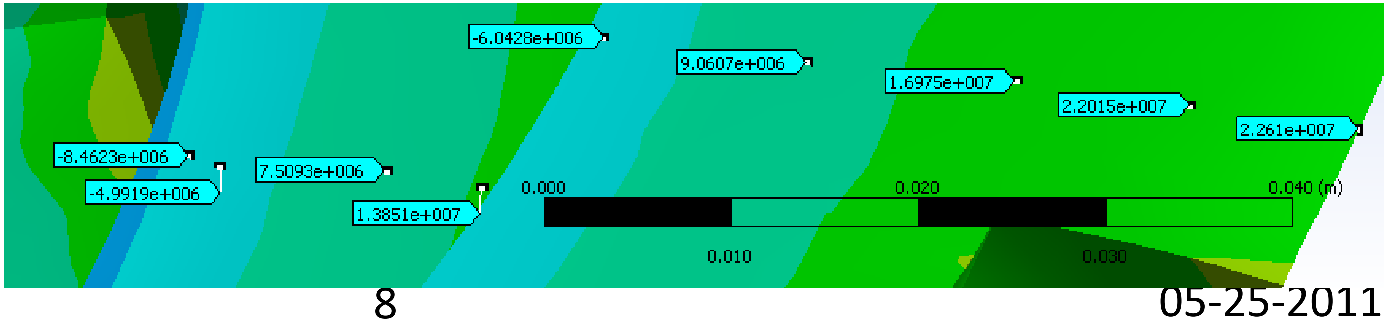
E: no slots
Shear Stress
Type: Shear Stress (XZ Plane)
Unit: Pa
Global Cylindrical
Time: 1
Max: 7.0306e7
Min: -3.2023e7
5/25/2011 2:02 PM
7.3e7
6.1e7
4.9e7
3.7e7
2.5e7
1.3e7
1e6
-1.1e7
-2.3e7
-3.5e7



G: with slots 2
Shear Stress
Type: Shear Stress (XZ Plane)
Unit: Pa
Global Cylindrical
Time: 1
Max: 6.9237e7
Min: -3.3179e7
5/25/2011 2:01 PM
7.3e7
6.1e7
4.9e7
3.7e7
2.5e7
1.3e7
1e6
-1.1e7
-2.3e7
-3.5e7



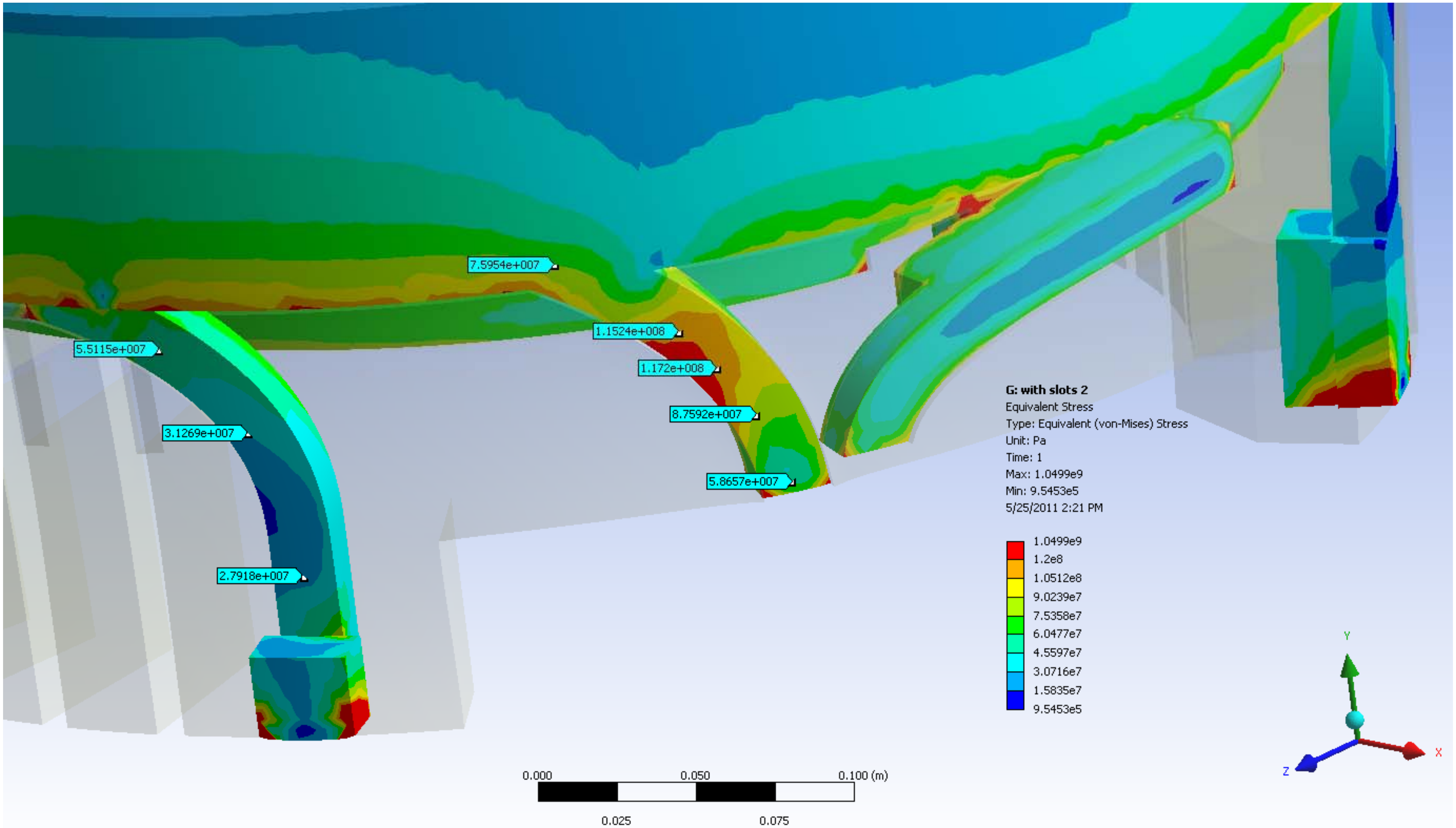
-2.0263e+006
4.5193e+006
1.2967e+007
1.9703e+007
1.6295e+007
2.5588e+007
2.093e+007
-5.0337e+006
7.1264e+006
1.5297e+007
2.1934e+007
0.000
0.020
0.040 (m)
0.010
0.030



-6.0428e+006
9.0607e+006
1.6975e+007
2.2015e+007
2.261e+007
-8.4623e+006
7.5093e+006
-4.9919e+006
1.3851e+007
0.000
0.020
0.040 (m)
0.010
0.030

Von Mises Stress in Copper (Pa) (With Slots, slightly higher than w/o slots)

Red Contour is 120 Mpa ~ Fatigue Allowable)



(Copper Cross Section in model is too big: needs to be refined)

1. Demonstrative of Distribution
2. Slots slightly increase stresses in leads