TF Flex Joint and TF Bundle Stub

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NSTX Upgrade Project
Conceptual Design Review
LSB, B318
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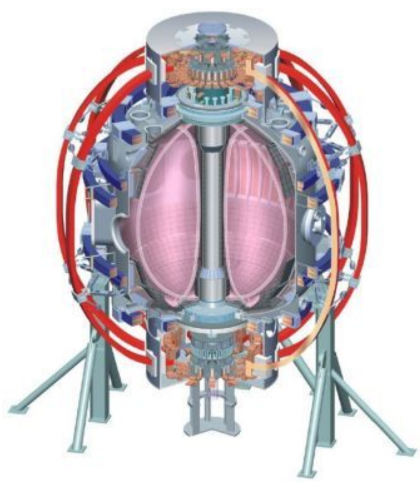

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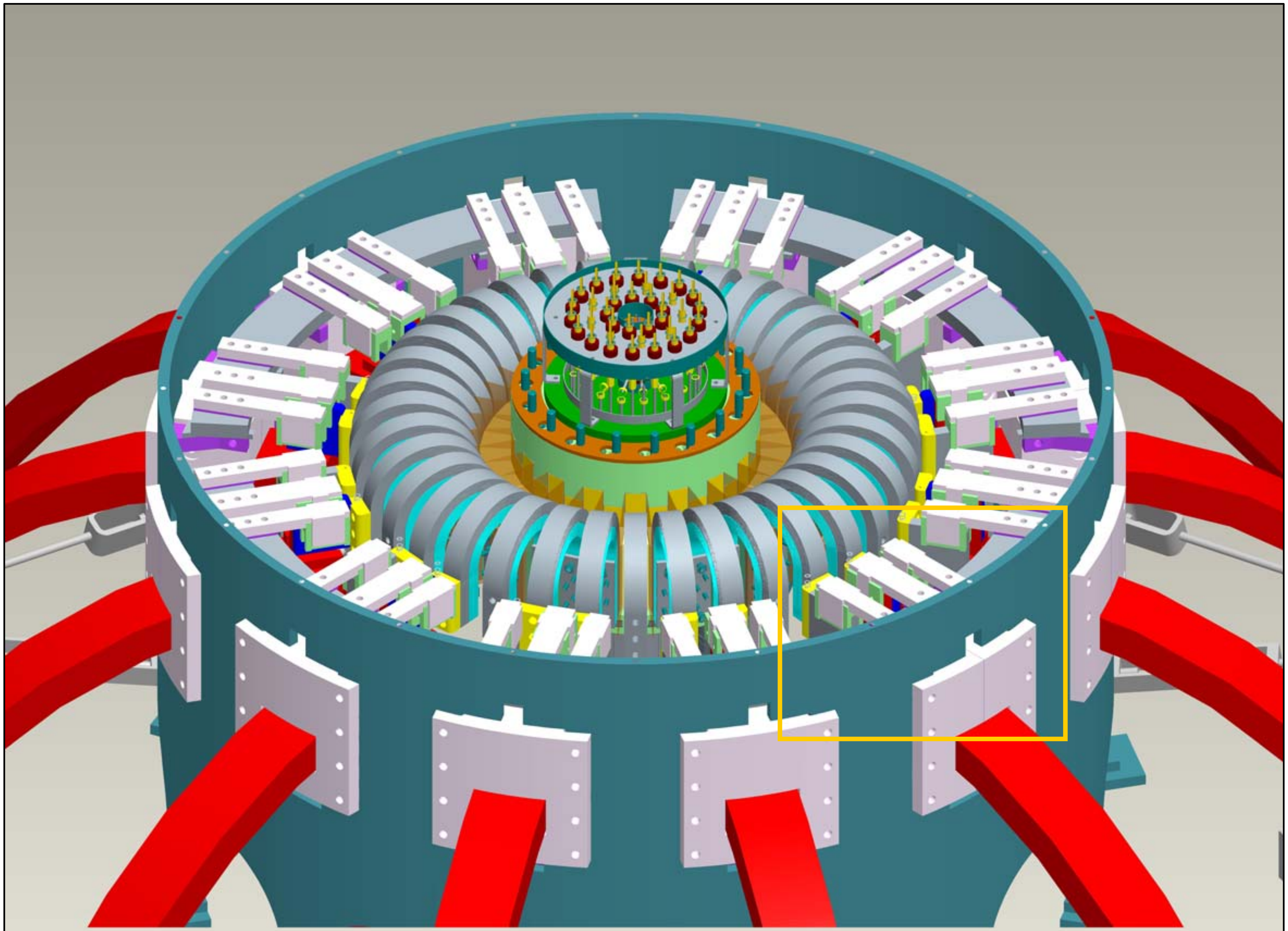
Study Goals

- **Purpose**:

To determine if the upgrade TF flex joint and bundle stub design is adequate to meet the requirements of the NSTX Structural Design Criteria, specifically, the fatigue requirements of Section I-4.2 for 3000 full power and 30,000 two-thirds full power pulses without failure.

  - Strap Laminations
    - Stresses
    - Buckling
  - Bolted Joints
    - Thread shear stress
    - Contact status and pressure

NSTX Upper Umbrella Assembly Upgrade Design



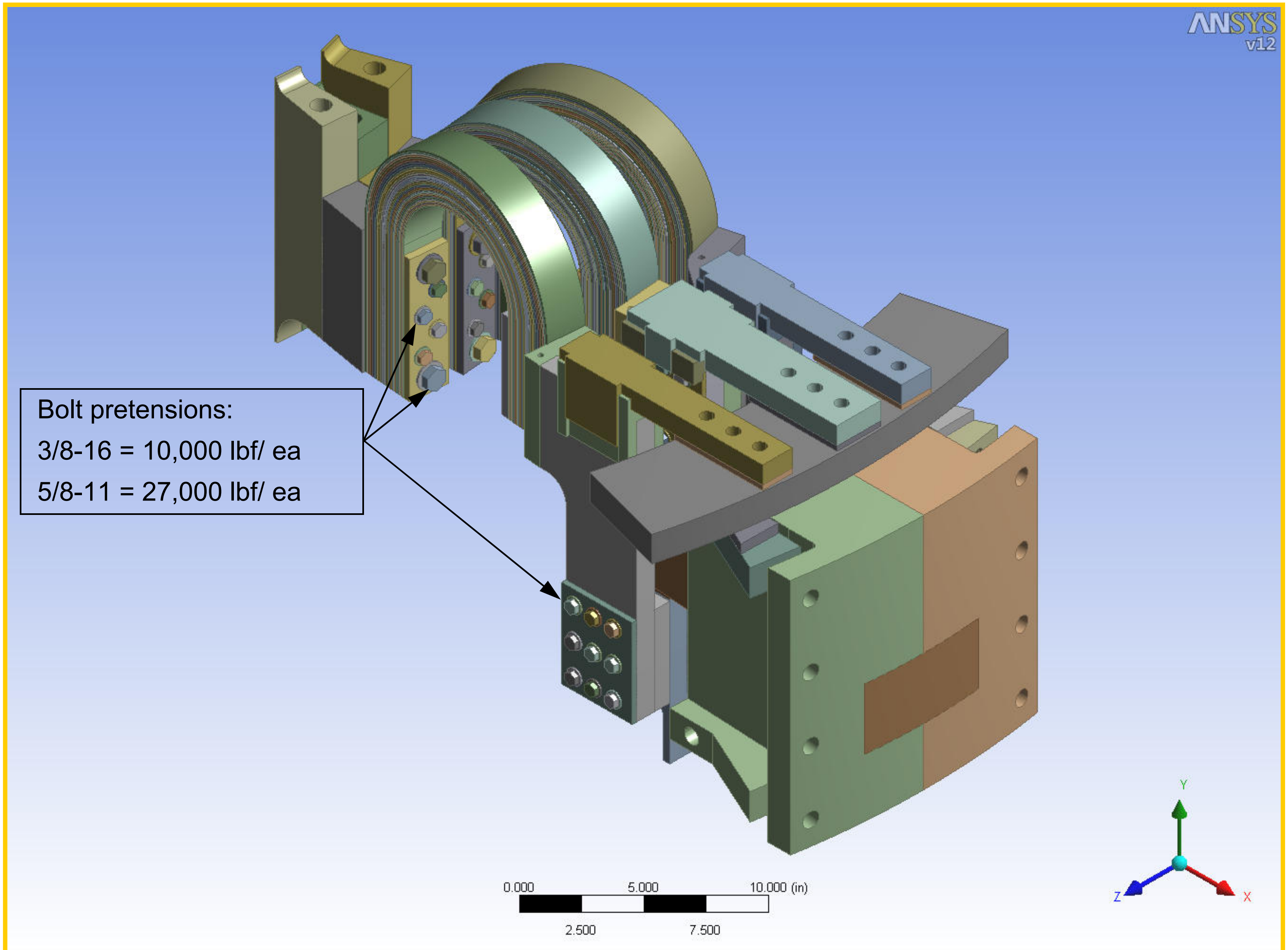
Design: Jim Chrzanowski; Bruce Paul

Single Segment 3-Strap Assembly: Solid Model

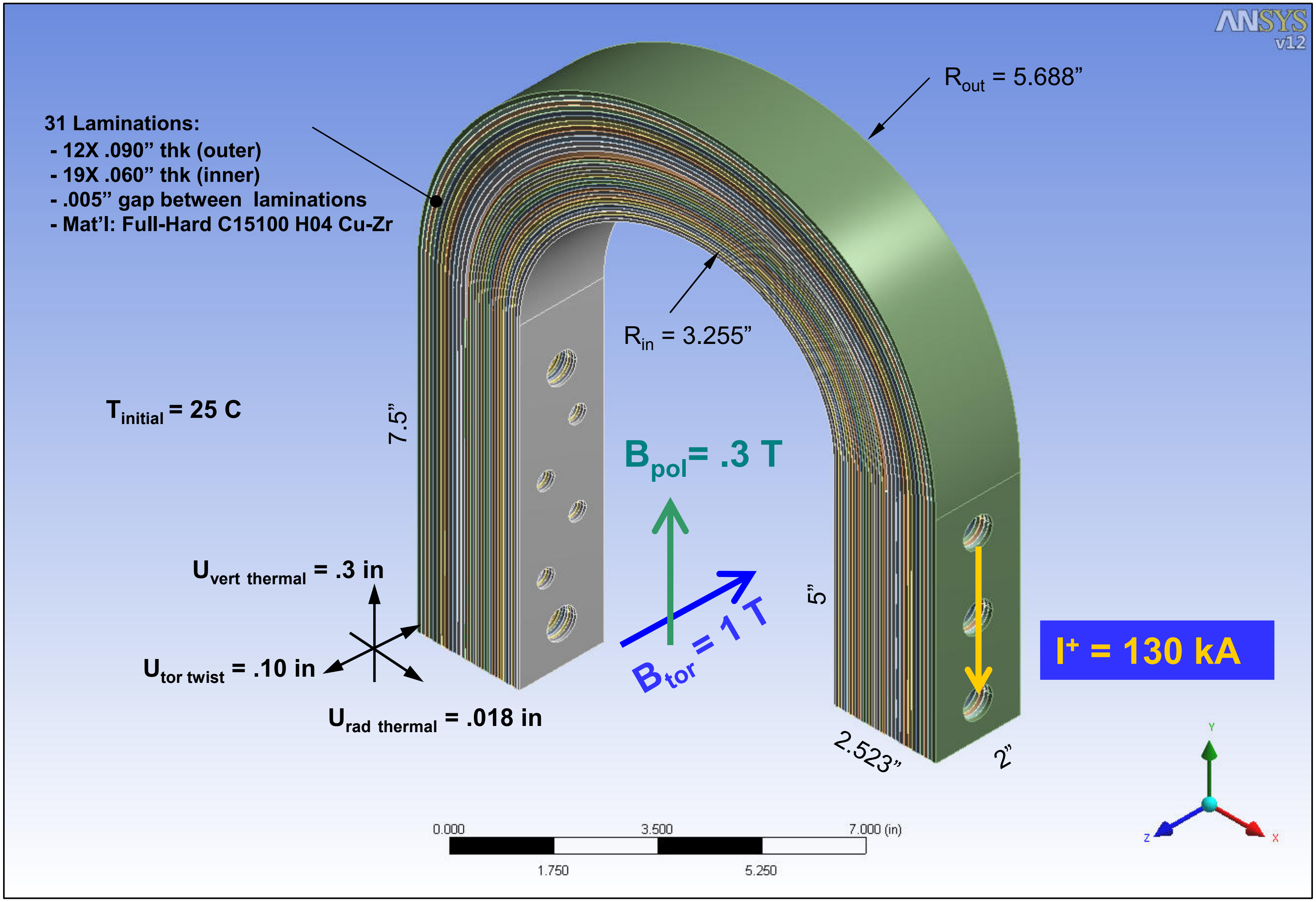
Bolt pretensions:

3/8-16 = 10,000 lbf/ ea

5/8-11 = 27,000 lbf/ ea

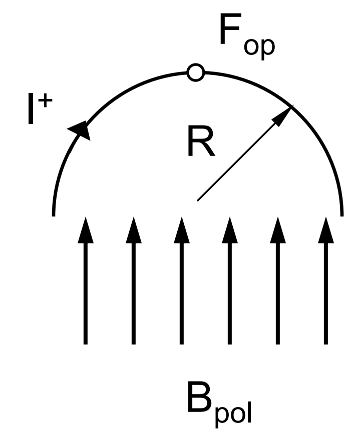


Laminated Strap Assembly with Applied Fields and Current



Calculated Worst-Case EMAG Loads

(Assuming uniform current distribution)



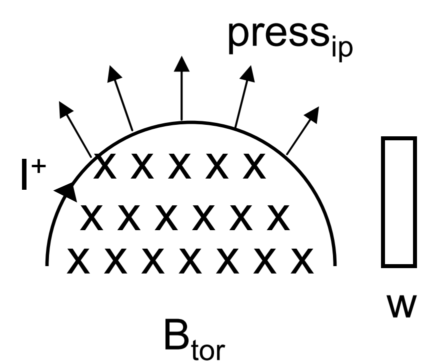
Out-of-Plane Load (z-direction)

$F_{op} = 2*I*B_{pol}*R$

F_{op} = 2 x 130,000 A/ 31 x .3 T x 5.688/39.37 m

F_{op} = 363.5 N = 81.7 lbf [Outer lamination]

In-Plane Load (y-direction)



$F_{ip}/ L = I*B_{tor}$

F_{ip}/ L = 130,000 A/ 31 x 1 T [Outer lamination]

F_{ip}/ L = 4,193.5 N/ m x .2248 lbf/ N x 1 m/ 39.37 in

F_{ip}/ L = 23.95 lbf/ in

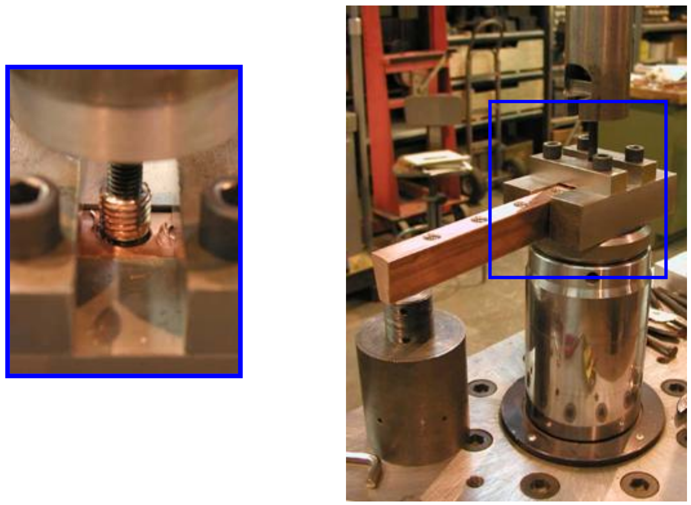
$press_{ip} = (F_{ip}/ L)/ w$

$press_{ip}$ = 23.95 lbf/in / 2 in

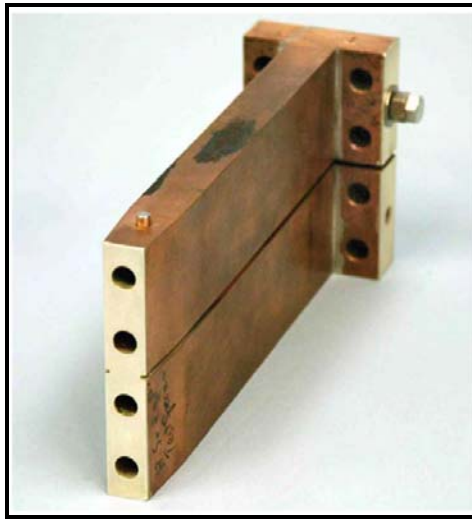
$press_{ip}$ = 11.97 lbf/ in^2 (applied to inside cylindrical face)

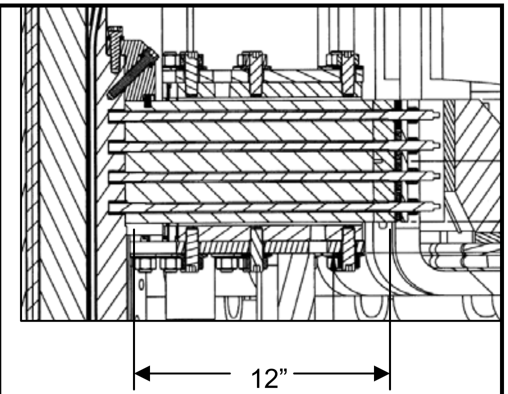
Note: MathCAD analysis performed to determine lamination stresses.

Current Joint Design Development Tests

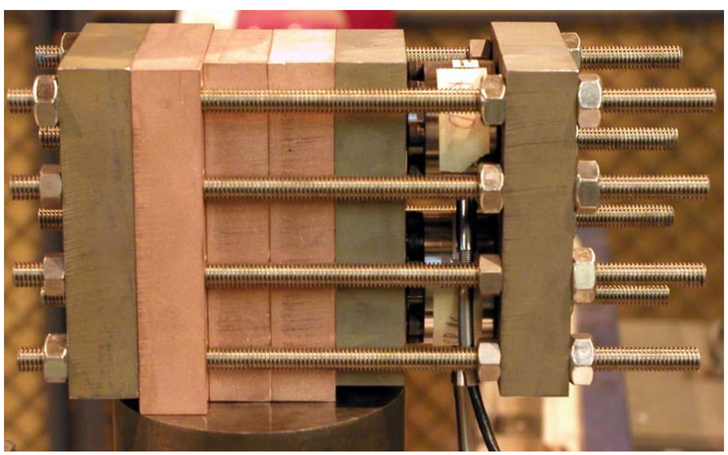


Cyclic Thread Pull-out Test

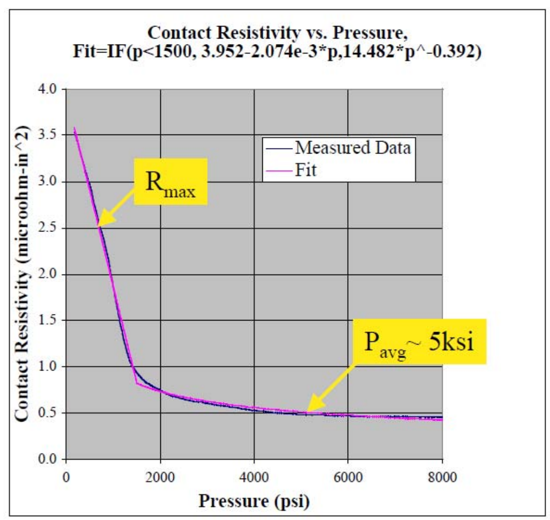




TF Radial Flag

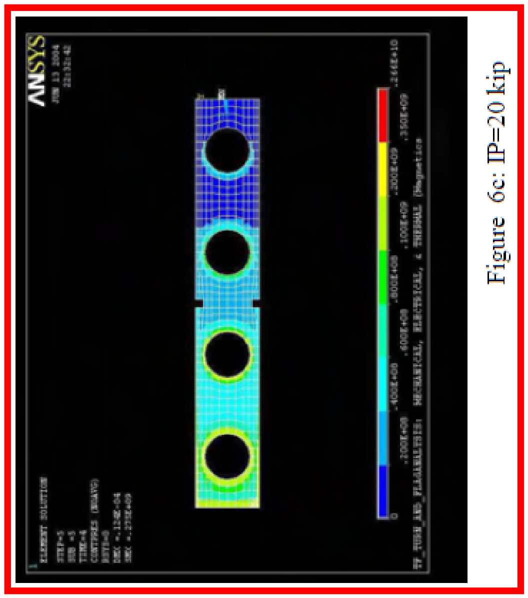


Coefficient of Friction Test



Contact Resistivity vs Pressure Test

Issues with Current Joint Design



ANSYS Model Results:
Contact Pressure

Pitting Damage - 2005

- In-situ voltage/ current measurements indicate separation above .45T
- Pitting damage corresponds with ANSYS coupled field model lift-off areas (R. Woolley, 2005)
- Inconel 718 bolt pretension limited to 5000 lbf/ ea due to low shear strength of C10700 copper threads

Current Joint Design vs Upgrade Comparison

Table I - Design Operating Points				
Design	Total Current (A)	Maximum TF (Tesla)	Maximum PF (Tesla)	On-Time Pulse Duration (sec)
Current	72,000	0.6	0.1	5.0
Upgrade	130,000	1.0	0.3	7.0

Table II - Joint Mechanical Parameters							
Design	Joint Contact Area (in^2)	Total Bolt Force (lbf)	Average Initial Contact Pressure (psi)	Minimum Operating Local Contact Pressure (psi)	Calculated In-Plane Mating Torque (in-lbf)	Max. TF In-Plane Separating Torque (in-lbf)	Lift-off Torque Margin
Current	3.382	20,000	5,914	0	12,500	17,500	-0.29
Upgrade	12.739	94,000	7,379	~2500	90,875	30,143	2.01

Table III - Joint Electrical/ Thermal Parameters						
Design	Current Density (A/in^2)	Initial Electrical Resistance (W)	Heat Generated I^2R (W)	Thermal Power Density (W/in^2)	Initial Thermal Resistance (W/C)	Zero-Heat Capacity Temperature Rise (C)
Current	21,289	1.48E-07	7.66E+02	2.27E+02	1.18E-02	9.1
Upgrade	10,205	3.93E-08	6.63E+02	5.21E+01	3.14E-03	2.1

Current Joint Design vs Upgrade Comparison

Table IV - Static Bolt Strength and Insert Pull-Out Load														
Design	**Bolt Size**	**Qty/ Joint**	**Bolt Mat'l**	**Bolt Yield Strength (psi**	**Bolt NSTX D.C. Allowable (psi)**	**Tensile Stress Area (in^2)**	**Max. Bolt Load**	**Tap-Lok Insert Outer Thread**	**Insert Length (in)**	**Effective Shear Area (in^2)**	**Copper Alloy**	**Yield Strength (psi)**	**Shear Strength (psi)**	**Insert Pull-out Load (lbf)**
Current	**3/8-16**	**4**	**Inconel 718**	**185,000**	**138,750**	**0.0775**	**10,753**	**9/16-16**	**0.562**	**0.4864**	**C10700**	**36,000**	**20,772**	**10,104**
Upgrade	**3/8-16**	**4**	**Inconel 718**	**185,000**	**138,750**	**0.0775**	**10,753**	**9/16-16**	**0.687**	**0.608**	**C18150**	**75,000**	**43,275**	**26,311**
	5/8-11	**2**				**0.226**	**31,358**	**29/32-11**	**1.125**	**1.61**				**120,750**

- Selected Upgrade-Design Bolt Pretensions:

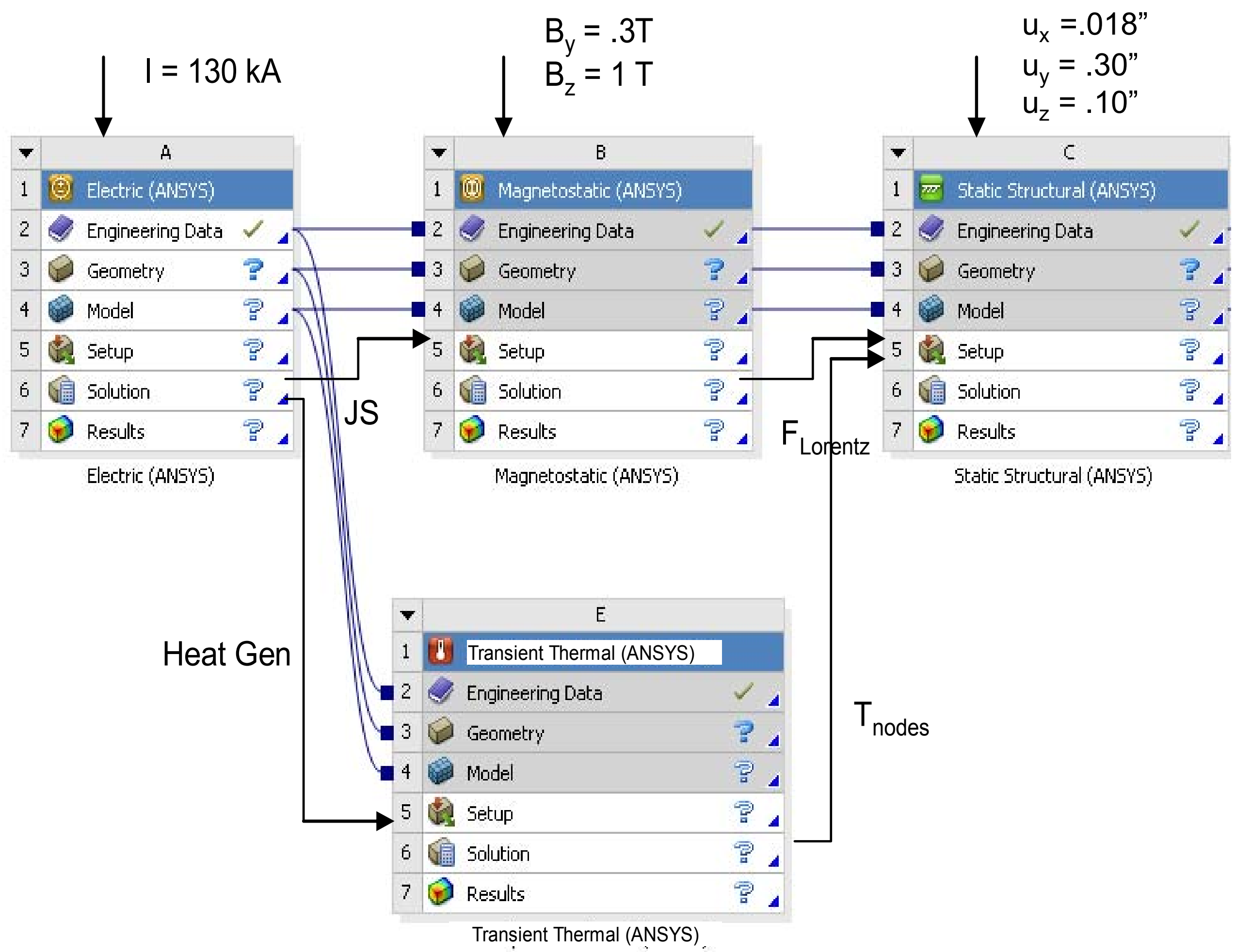
  3/8-16 = 10,000 lbf

  5/8-11 = 27,000 lbf

Current Design Joint vs Upgrade: Summary

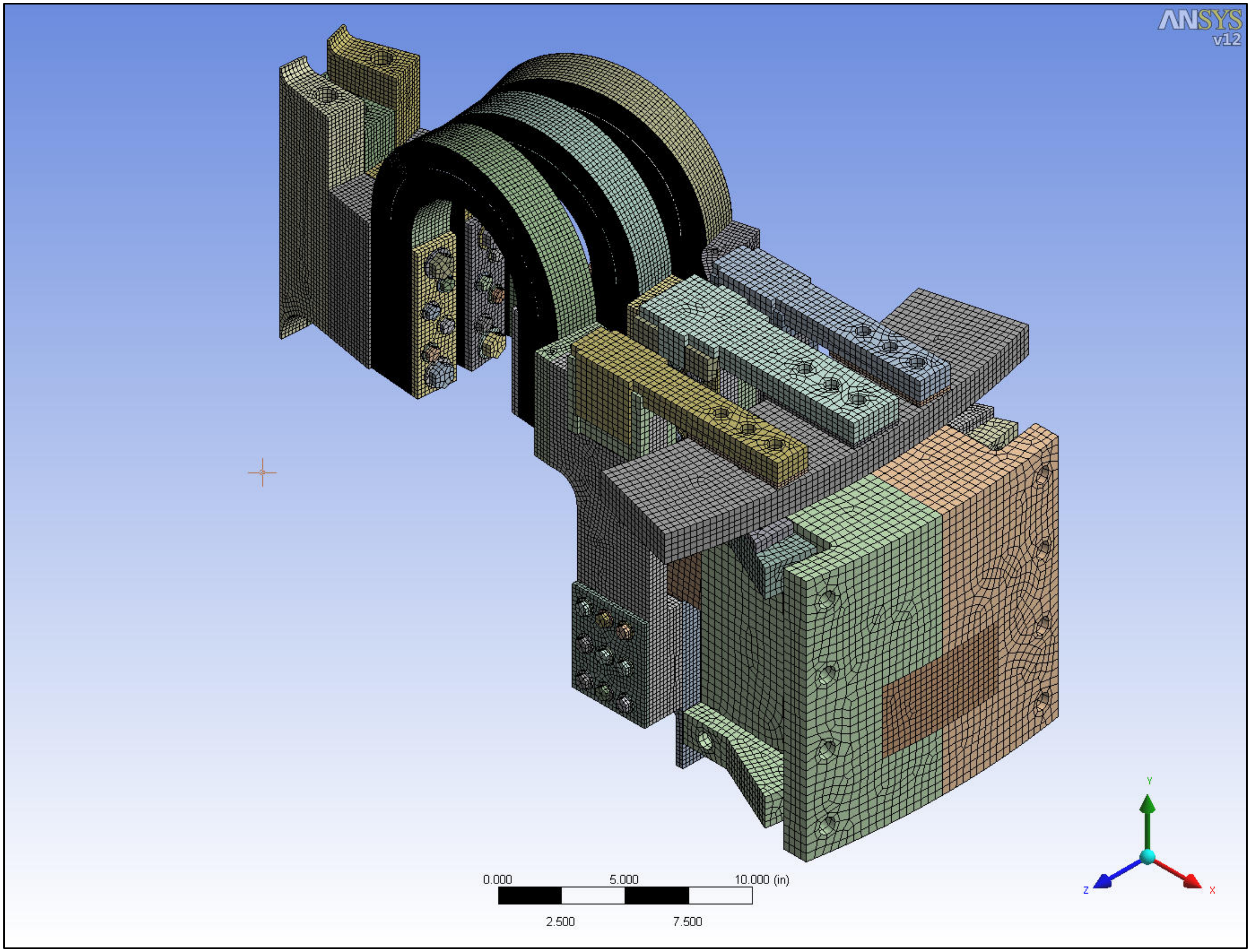
- Joint pitting damage area in current design corresponds to calculated lift-off area in ANSYS coupled-field model for TF > .45 T.
  - No pitting damage on upper-tier joints (further from the plasma) that, according to in-situ resistance measurements, do not separate in operation.
  - Bolt pretension limited by shear fatigue strength of C10700 copper threads (threads fail first).
- No evidence of 'mushrooming'/ partial pull-out of the inserts in current design.
  - May have been an issue in an earlier design, but was eliminated by adhering to Tap-Lok countersunk hole recommendation.
- Upgrade design more robust, should not separate.
  - Flex strap design minimizes prying torque.
  - Preventing lift-off should avoid pitting problem.
  - Adhering to Tap-Lok joint design recommendations should prevent 'mushrooming'/ partial pull-out of insert.
  - Bolt pretension limited by tensile strength of Inconel 718 bolt (bolt fails first).

ANSYS Multiphysics Analysis Block Diagram

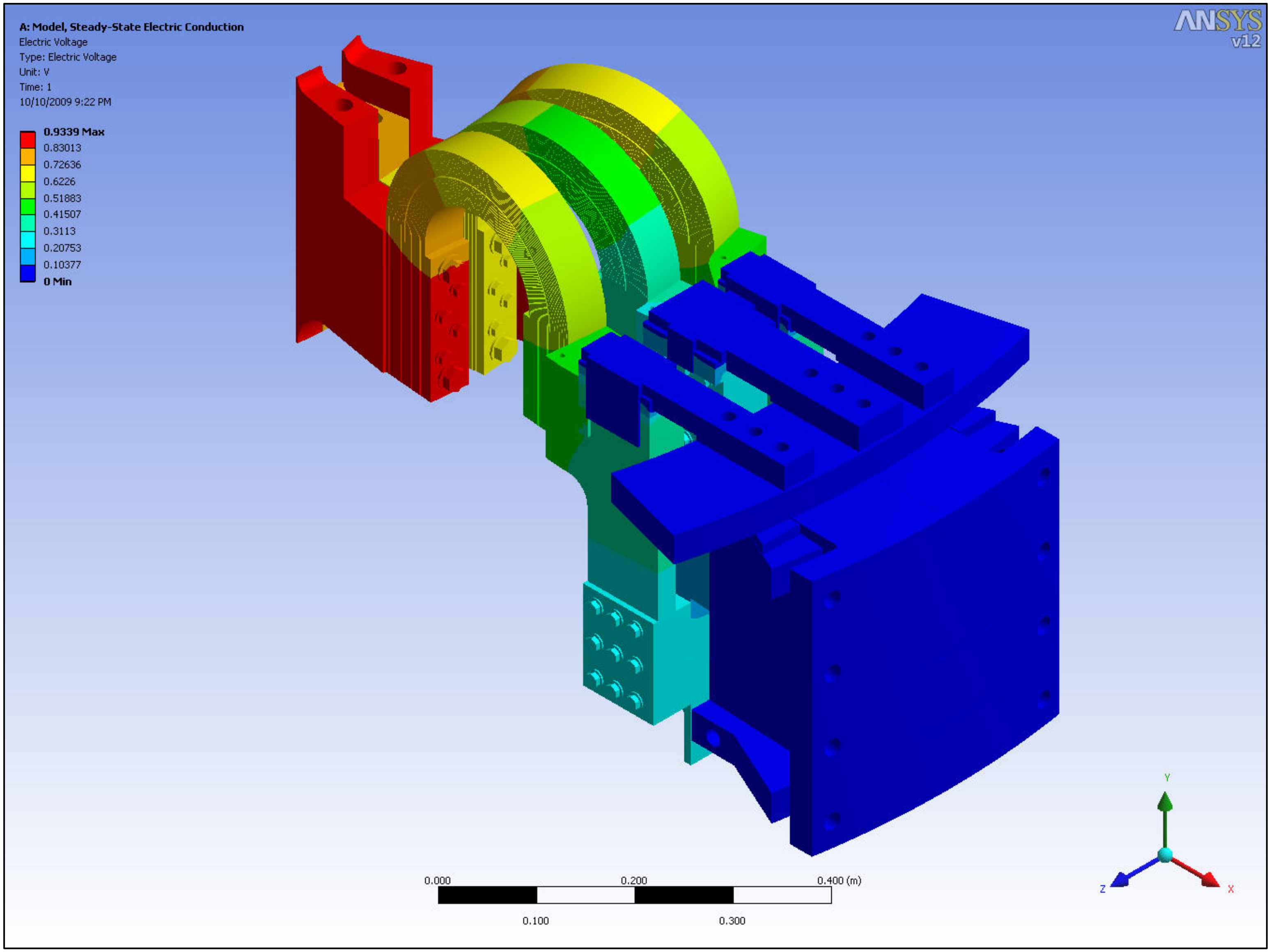


Note: This sequential, one-way coupled analysis is only valid if the bolted joints do not separate, and if the electrical and thermal contact resistances are a weak function of contact pressure, which is true in this case if the minimum local contact pressure is above 1500 psi.

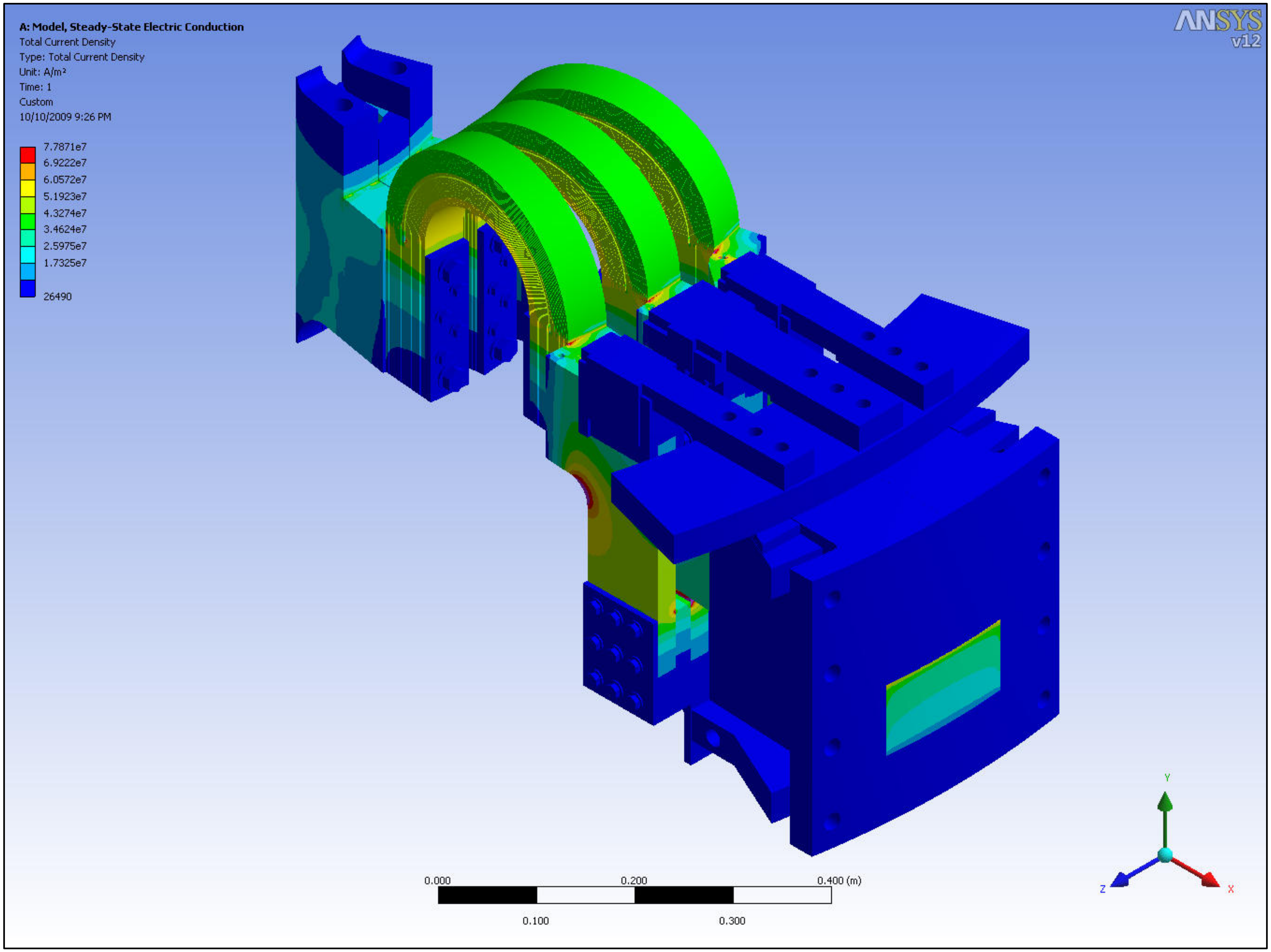
Single Segment 3-Strap Assembly FEA Model: Mesh



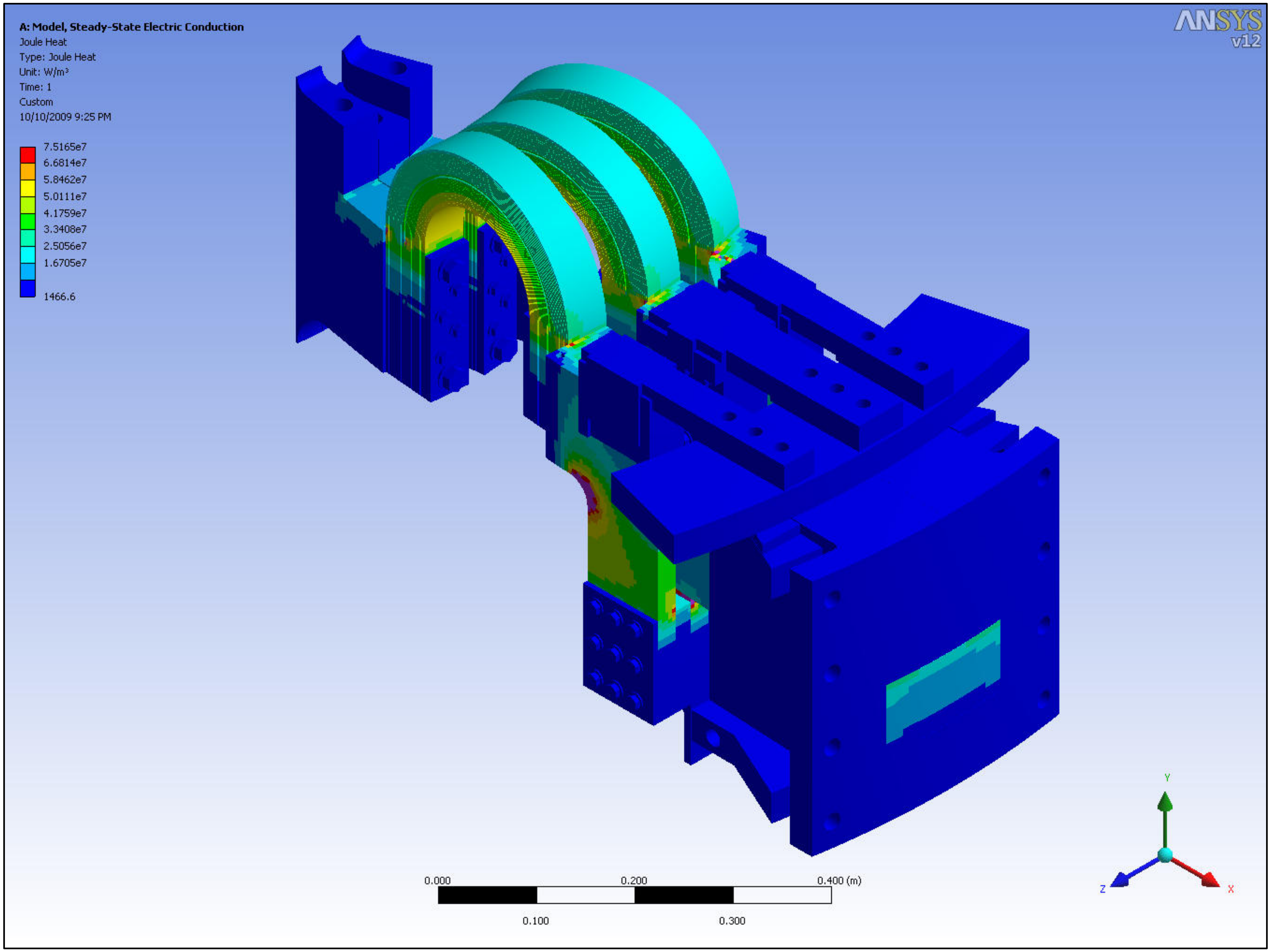
Single Segment 3-Strap Electric Model Results: Voltage



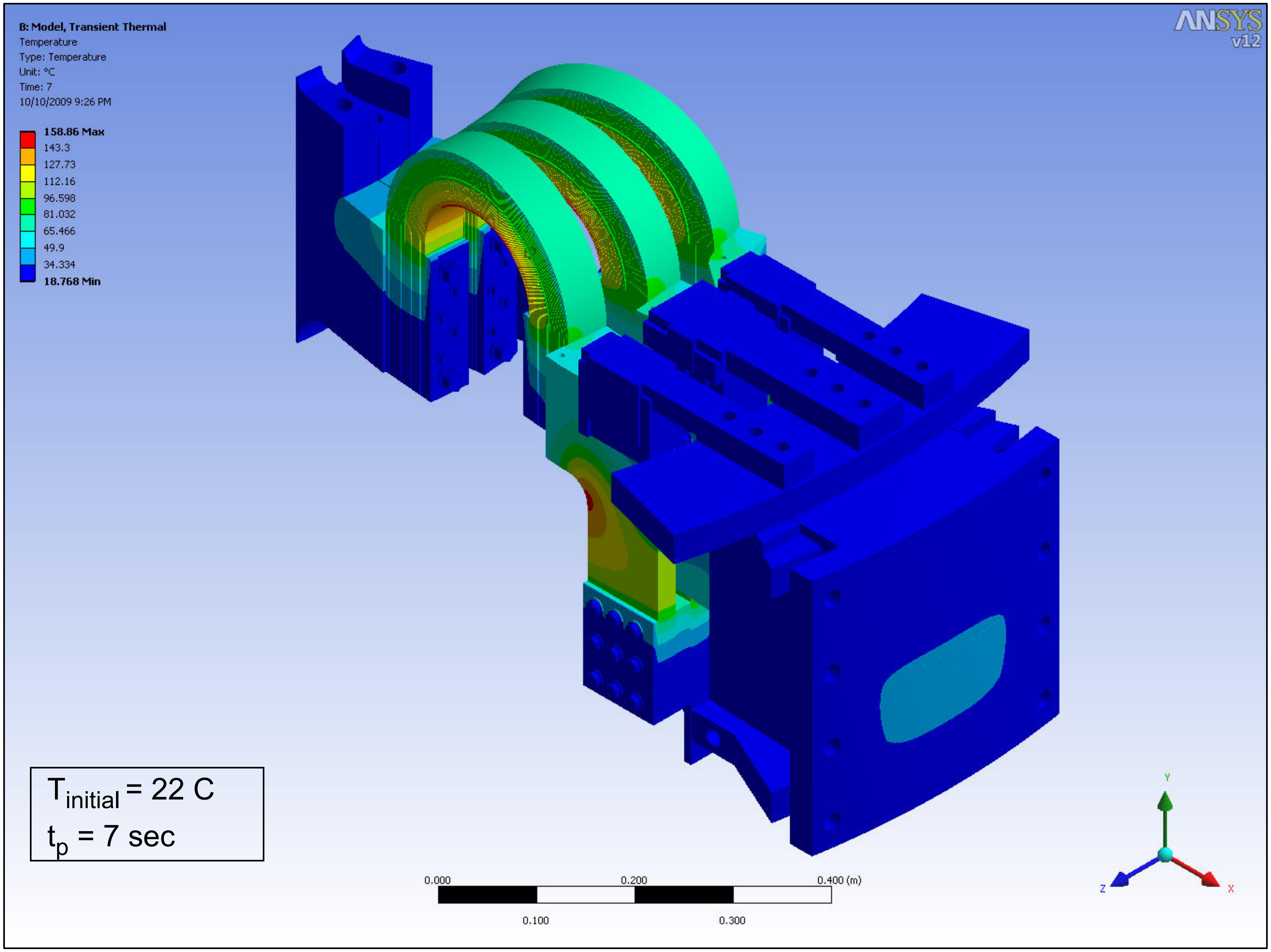
Single Segment 3-Strap Electric Model Results: Current Density



Single Segment 3-Strap Electric Model Results: Joule Heat

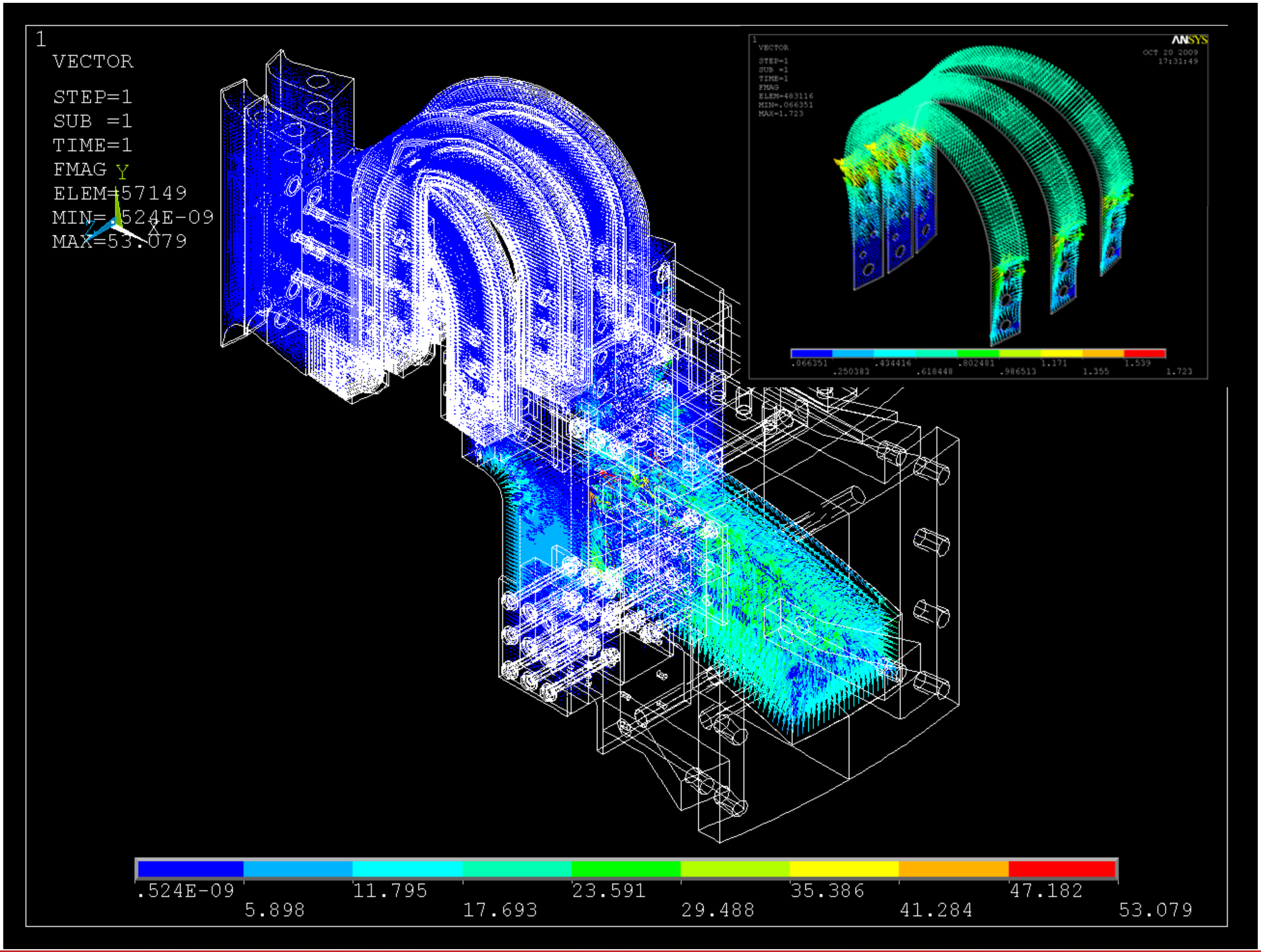


Single Segment 3-Strap Thermal Model Results: Temperature

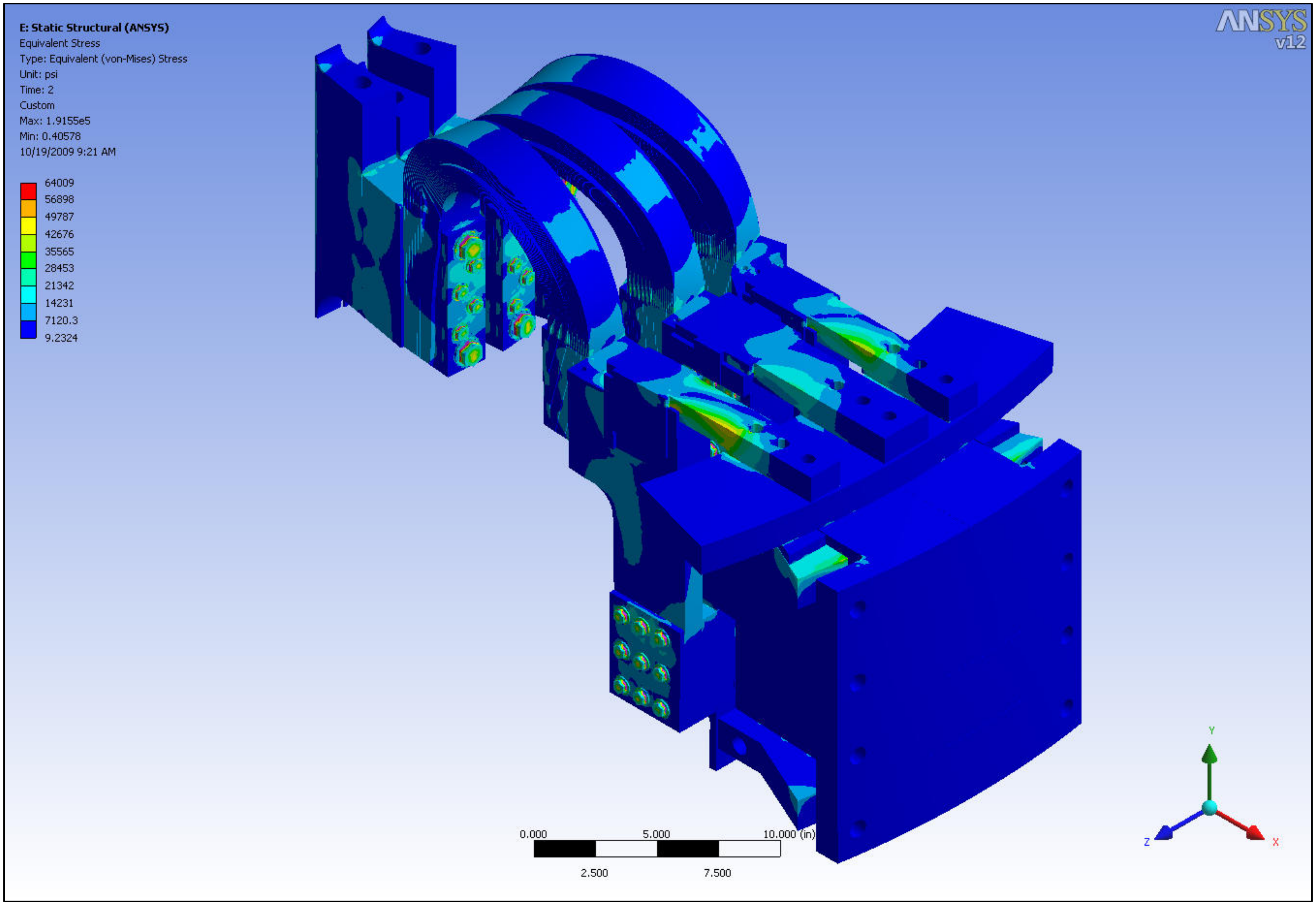


$T_{initial}$ = 22 C
t_p = 7 sec

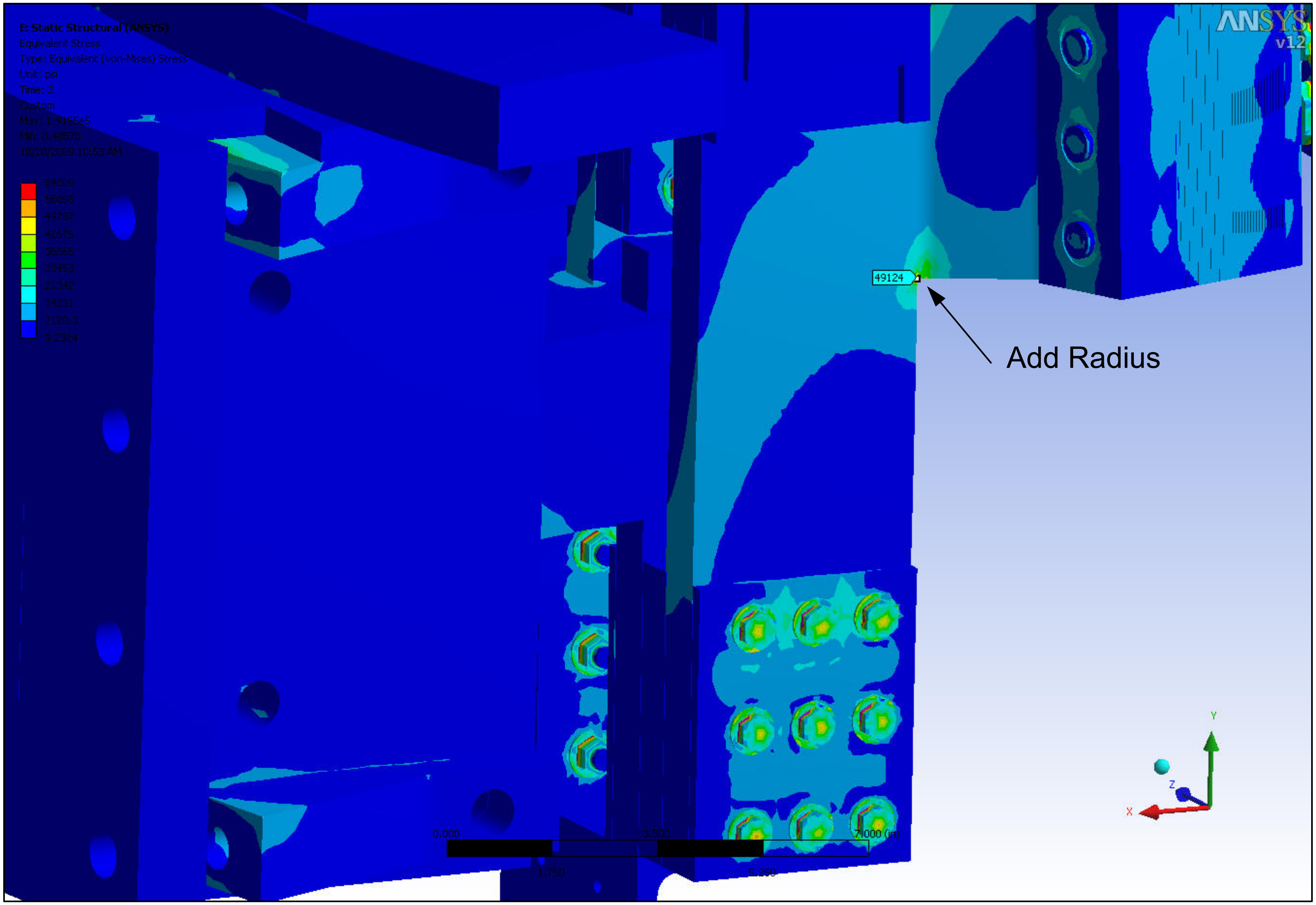
Single Segment 3-Strap EM Model Results: Lorentz Forces



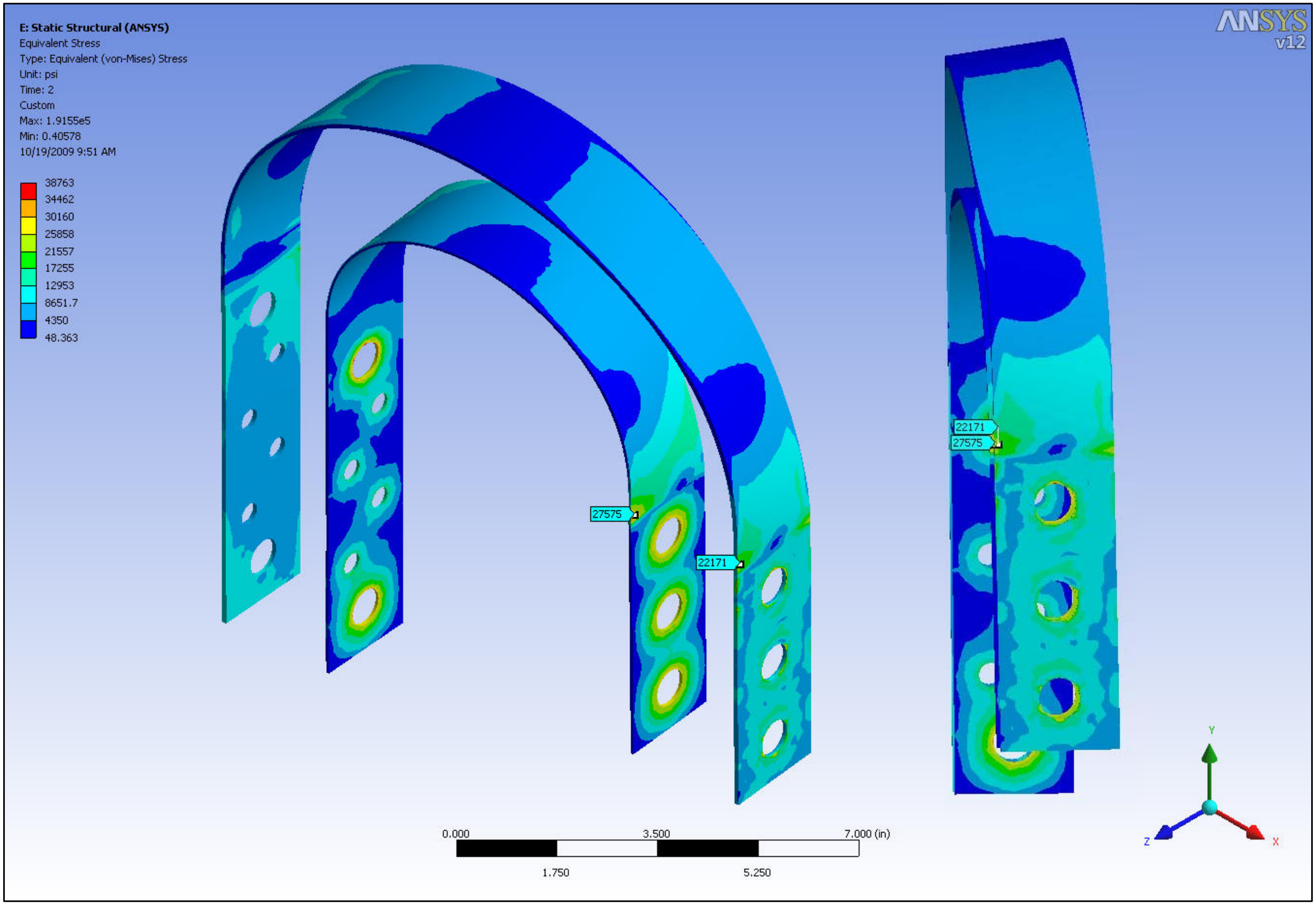
Single Segment 3-Strap Structural Model Results: von Mises Stress



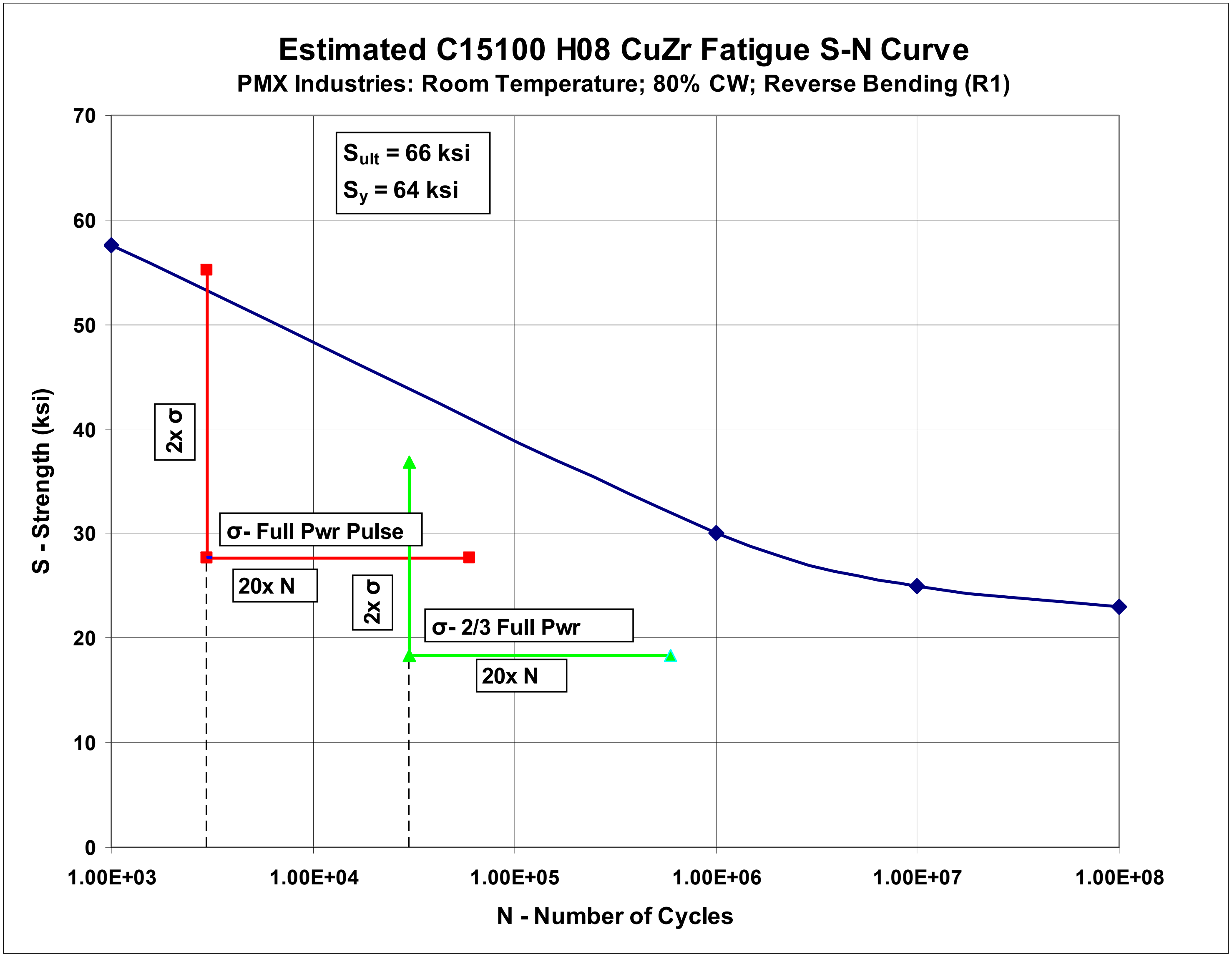
Single Segment 3-Strap Structural Model Results: von Mises Stress



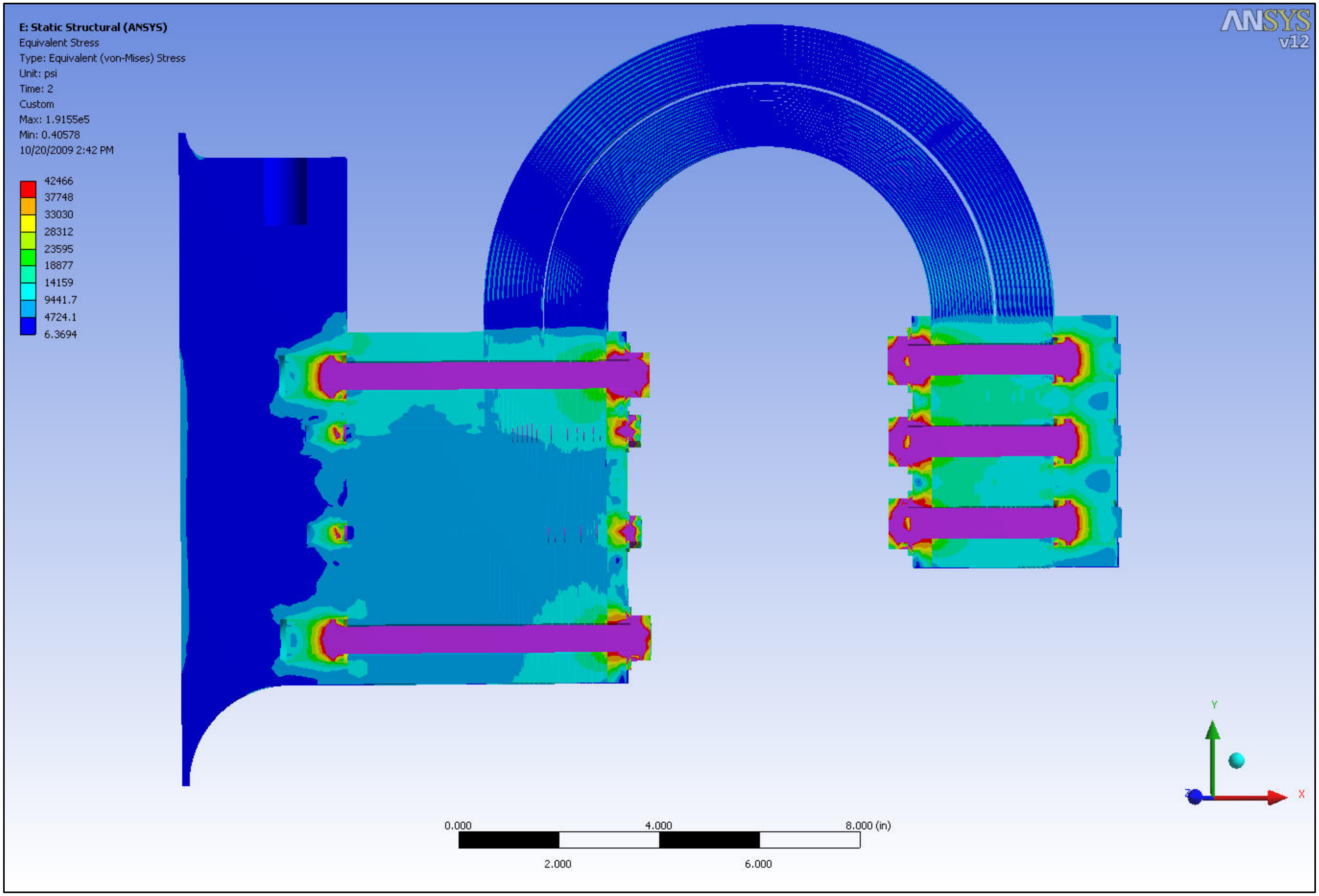
Single Segment 3-Strap Structural Model Results: Lamination Stress



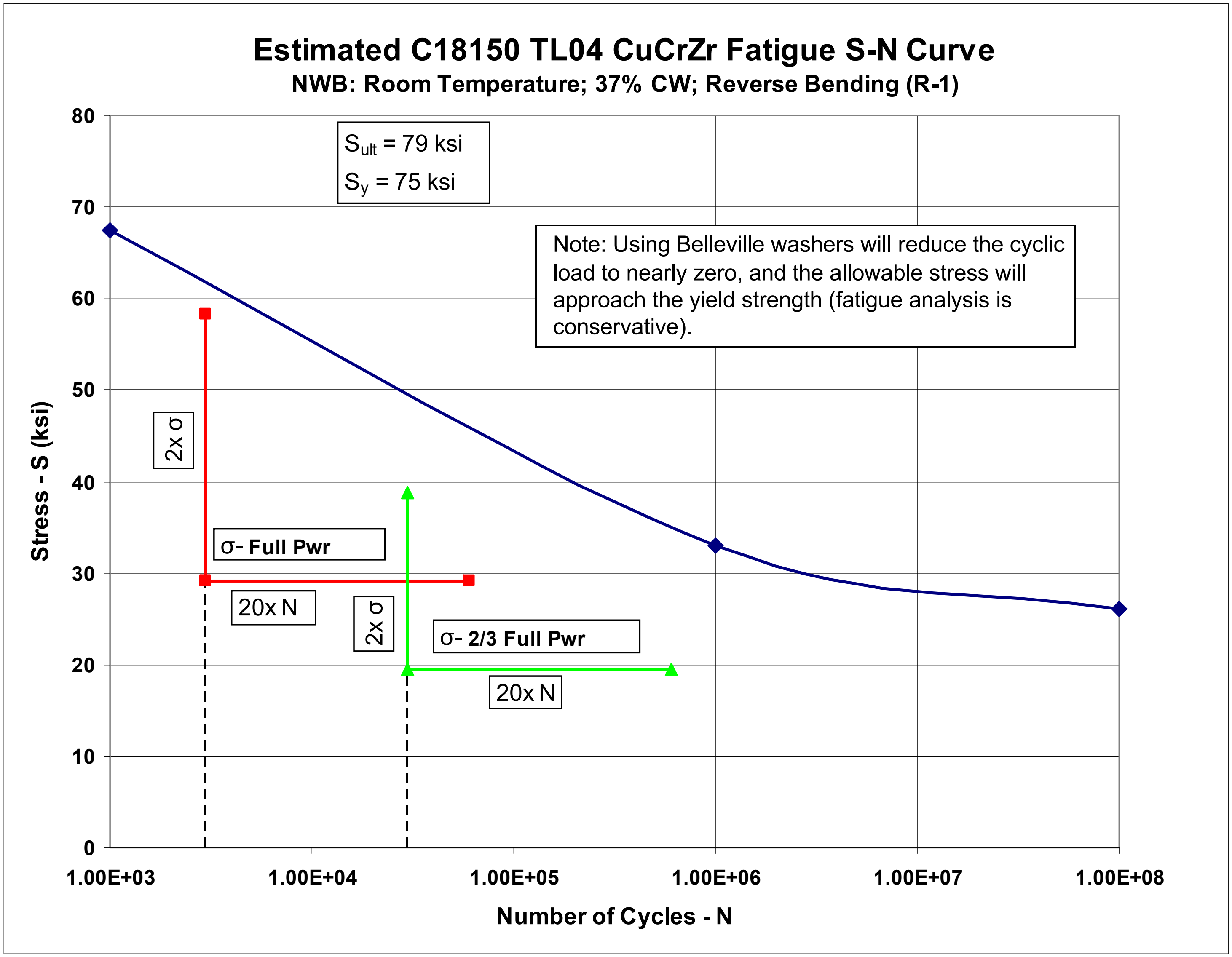
Flex Strap Lamination Fatigue Life



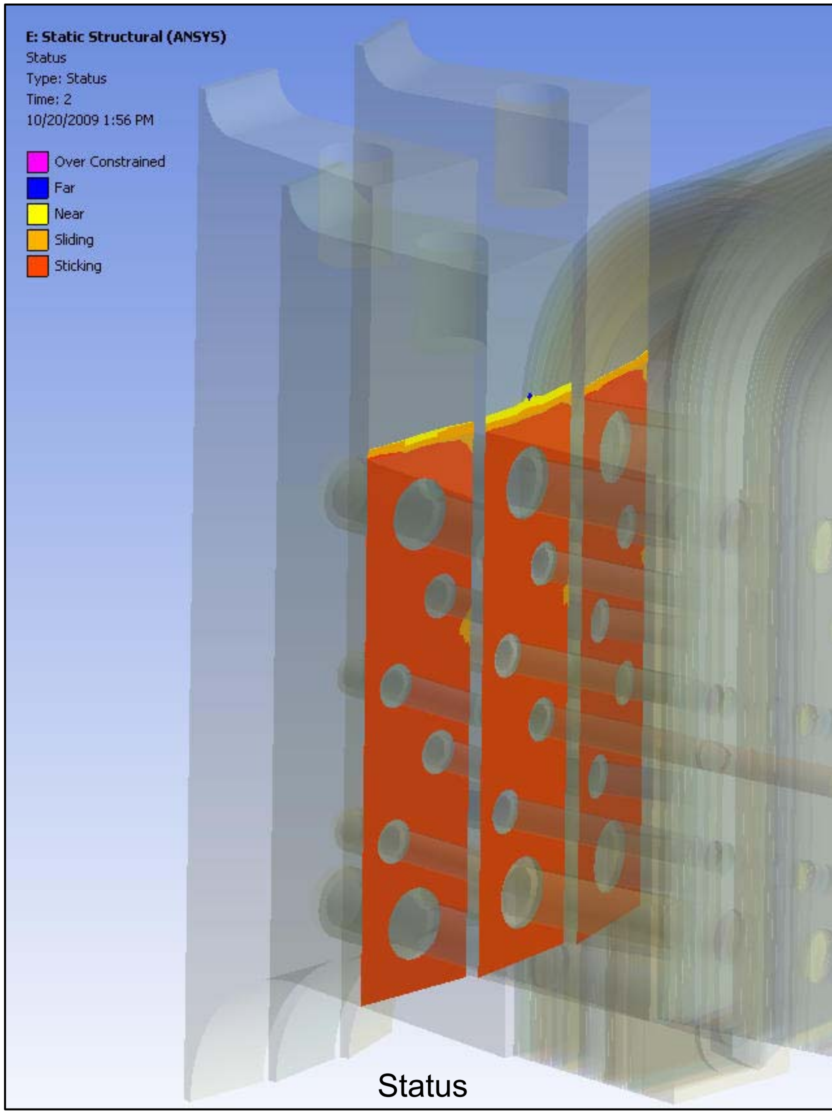
Single Segment 3-Strap Structural Model Results: Copper Flag Thread Stress

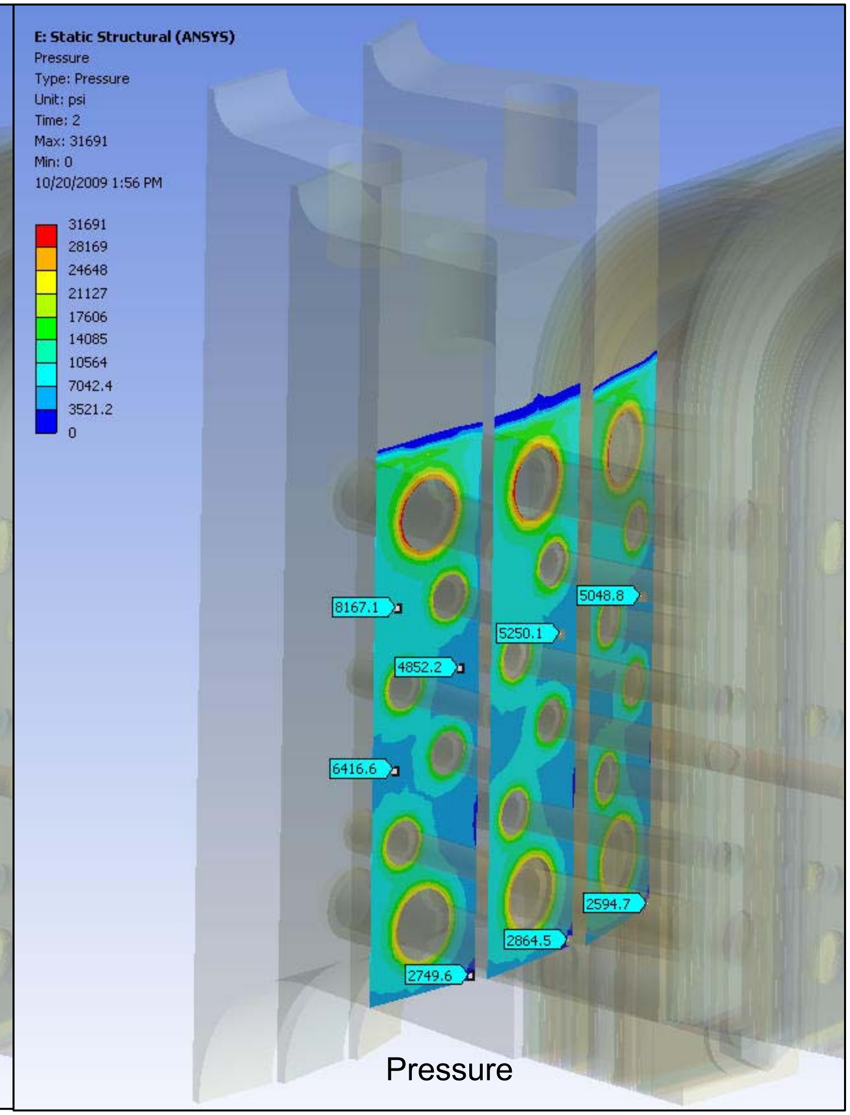


Bolted Joint Copper Thread Fatigue Life

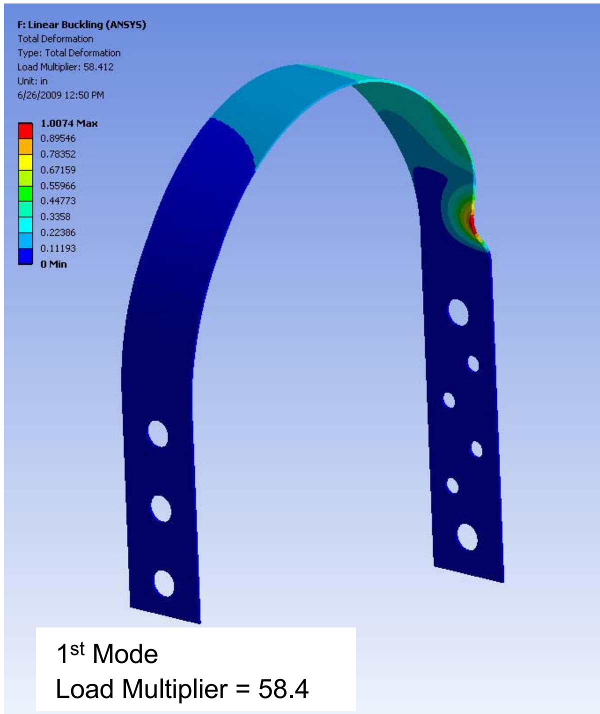


Single Segment 3-Strap Structural Model Results: Joint Contact Status and Pressure



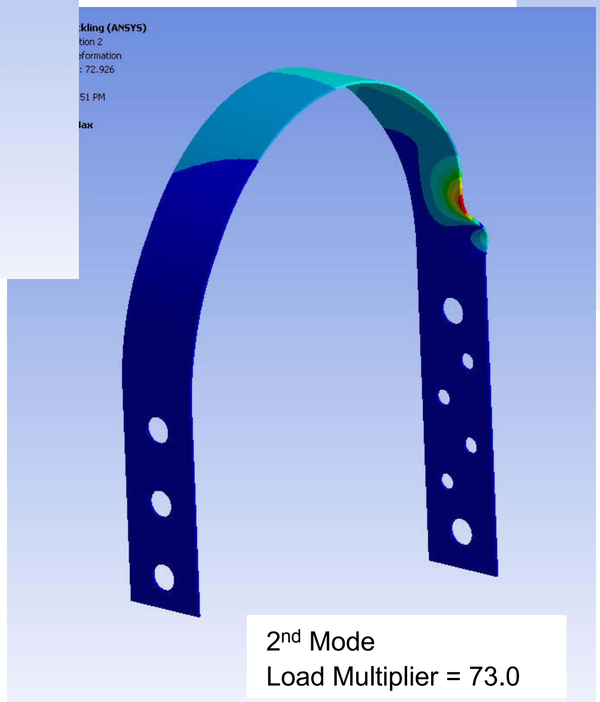


Single Lamination Linear Buckling Model Results

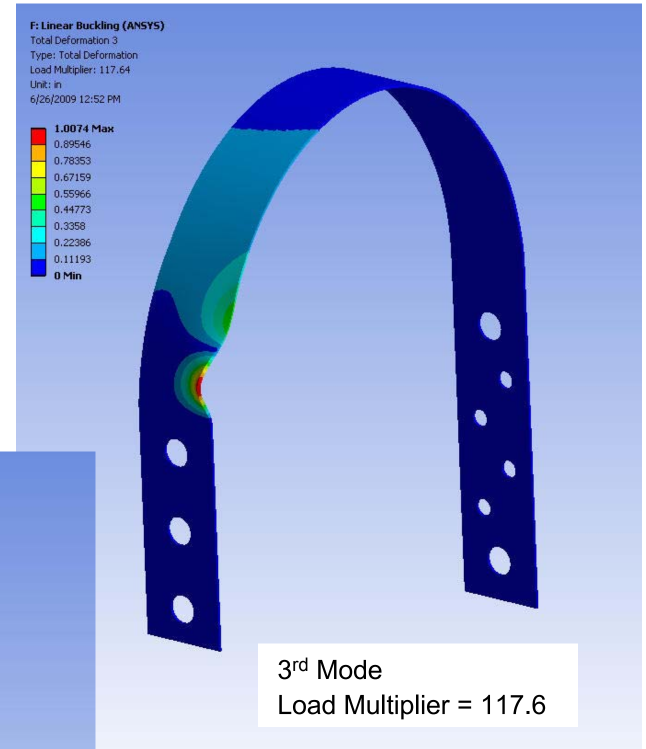


1st Mode
Load Multiplier = 58.4

(Nonlinear 1st Mode
Load Multiplier = 50)



2nd Mode
Load Multiplier = 73.0



3rd Mode
Load Multiplier = 117.6

Large deflection = Off

Conclusions

1. **Lamination Stress**:

   The maximum combined stress in the laminations is 27.5 ksi. To satisfy the requires of the NSTX Structural Design Criteria, the fatigue strength at 3000 cycles must be greater than twice this stress, or the fatigue strength at 60000 cycles (20x N) must be equal to or greater than this stress, whichever is the more severe requirement.

   – The fatigue S-N curve for C15100 copper-zirconium, including plots of full power and 2/3 full power stresses at N = 3000 cycles and N = 60000 cycles, is shown above. The design stress slightly exceeds the Factor of Safety = 2 requirement of the Design Criteria. Need a more accurate S-N curve and/or in-house fatigue tests to verify that stress level is not excessive.

2. **Copper Flag Thread Stress**:

   The maximum equivalent stress in the copper threads is 29.1 ksi.

   – The fatigue S-N curve for C15000 copper-zirconium, including plots of full power and 2/3 full power stresses at N = 3000 cycles and N = 60000 cycles, is shown above. The design stresses meet the requirements of the Design Criteria.

3. **Contact Status/ Pressure**:

   Results show that none of the joints separate, and that the minimum local contact pressure is approximately 2600 psi.

   – Initial assumptions are correct, sequential model is valid.

4. **Lamination Buckling Load Multiplier Factor (LMF)**:

   The 1st mode LMF is 58, well above the Design Criteria linear buckling requirement of 5.