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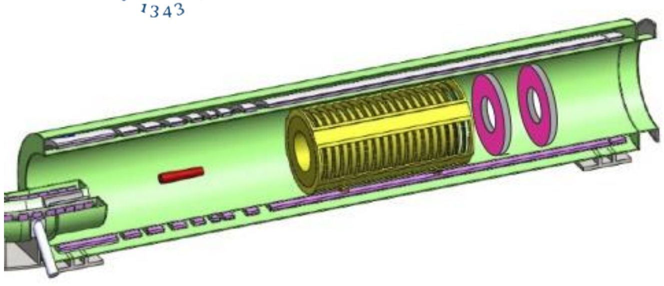
Detector Solenoid Cool Down Analysis for the Mu2e Experiment

Costanza Saletti

University of Pisa

Supervisor: Nandhini Dhanaraj

Co-supervisor: Richard Schmitt

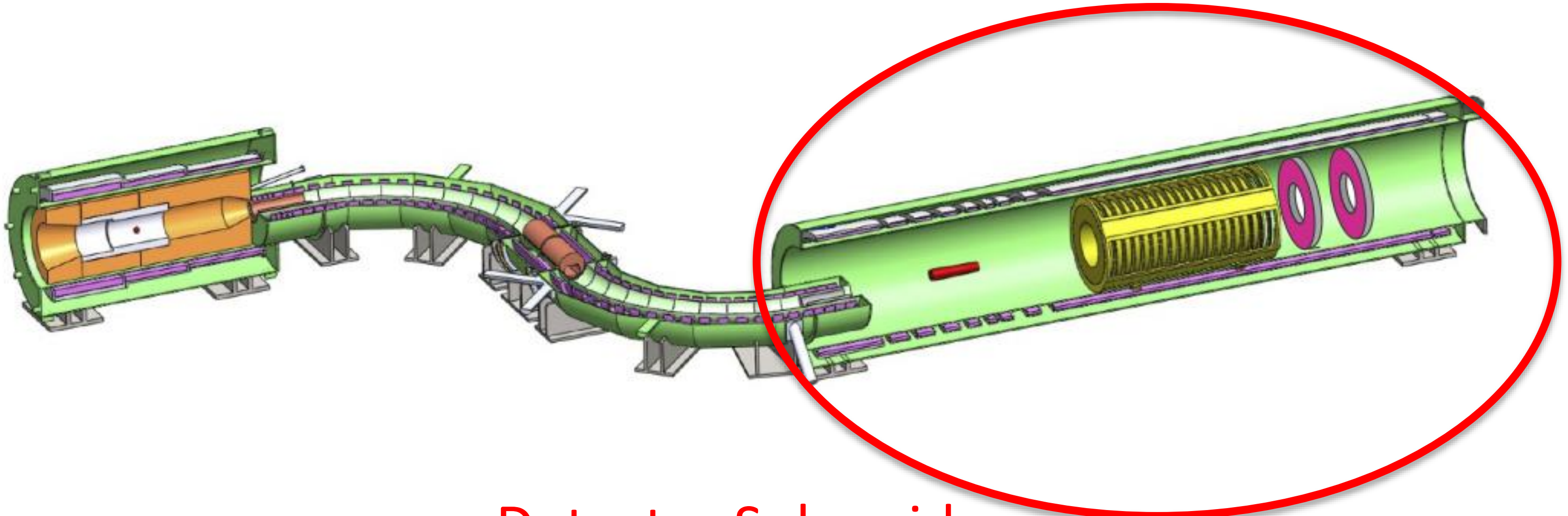


Final Presentation

09/23/2015

Introduction: Mu2e Experiment

- The Mu2e experiment consists of a series of superconducting magnets: Production Solenoid, Transport Solenoid and Detector Solenoid (**DS**).
- These magnets are made of Al-stabilized NbTi conductor and have to be cooled with liquid helium from 300 K to 4.7 K in order to be superconductive.



Detector Solenoid

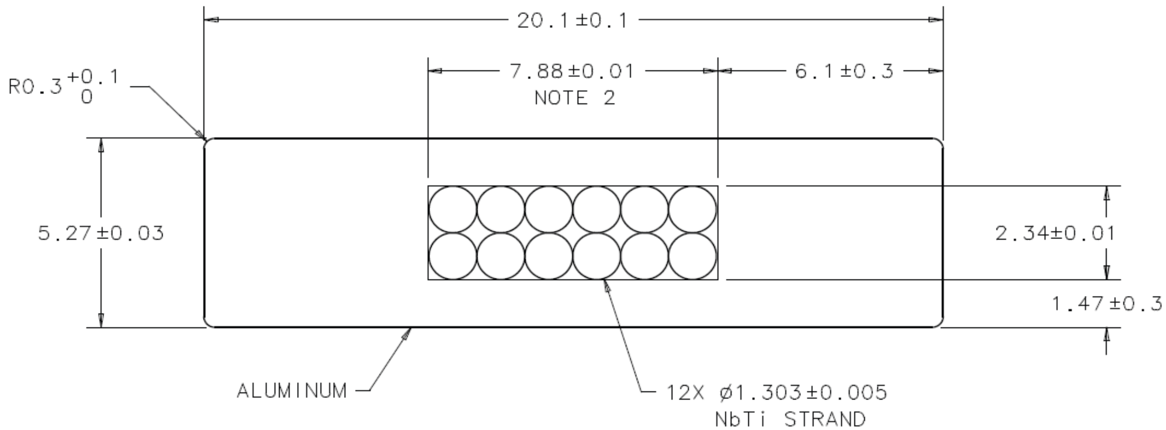
Introduction: Training Program

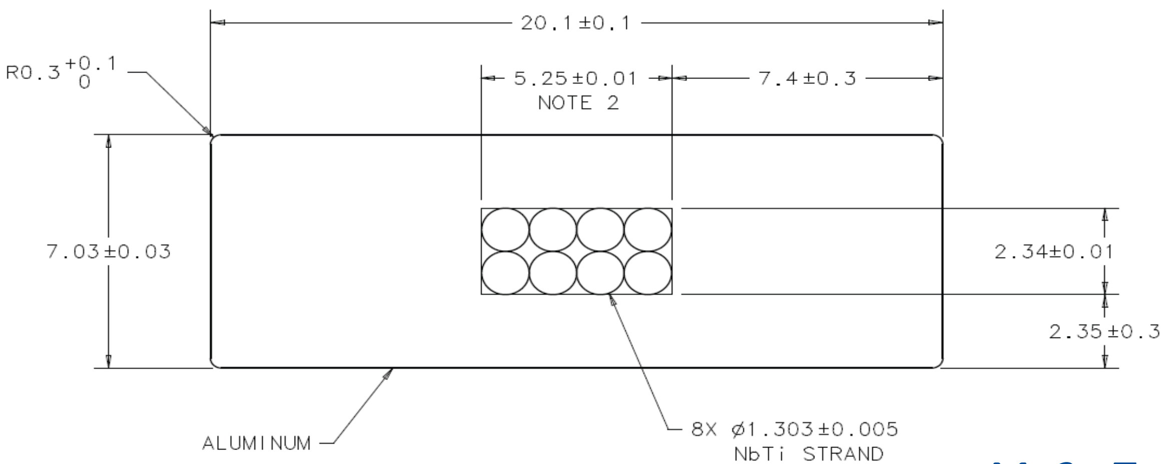
Mu2e cables are composed by various materials that contracts at different rates. The cooling down process has to be controlled to avoid dangerous thermal stresses in the magnets.

Task list:

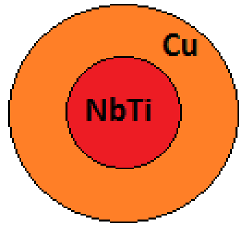
- Focus on the Detector Solenoid
- Model DS1 and DS2 conductors with different materials and insulation.
- Derive average material properties required for a thermal-stress analysis from single conductor model or stack model.
- Perform the 3D FEM thermal-stress analysis for the Detector Solenoid to figure out a safe temperature difference for the cooling down process of the magnet.

Detector Solenoid Cables





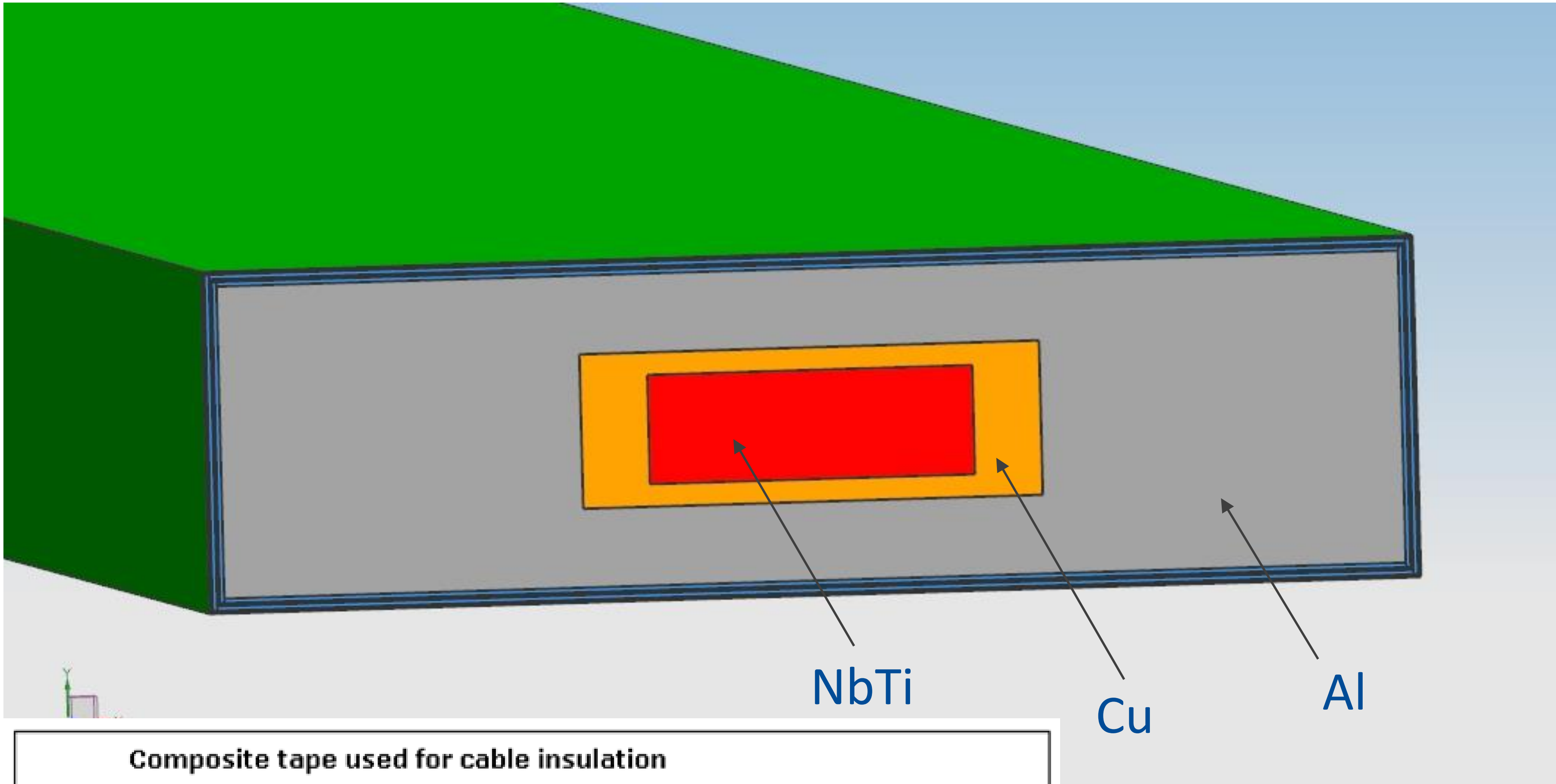
- **Al**-stabilized **NbTi** Rutherford cables

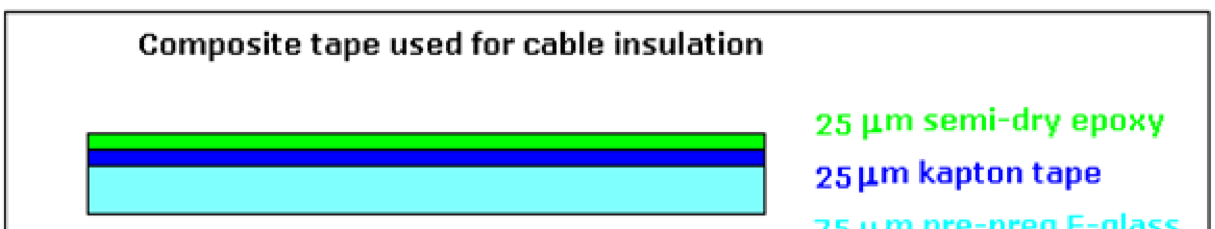


- Two types: DS1 and DS2
- Two layers of insulation each made by **G10**, **kapton**, **epoxy**.

Mu2e Technical Report

DS1 Single Conductor Model

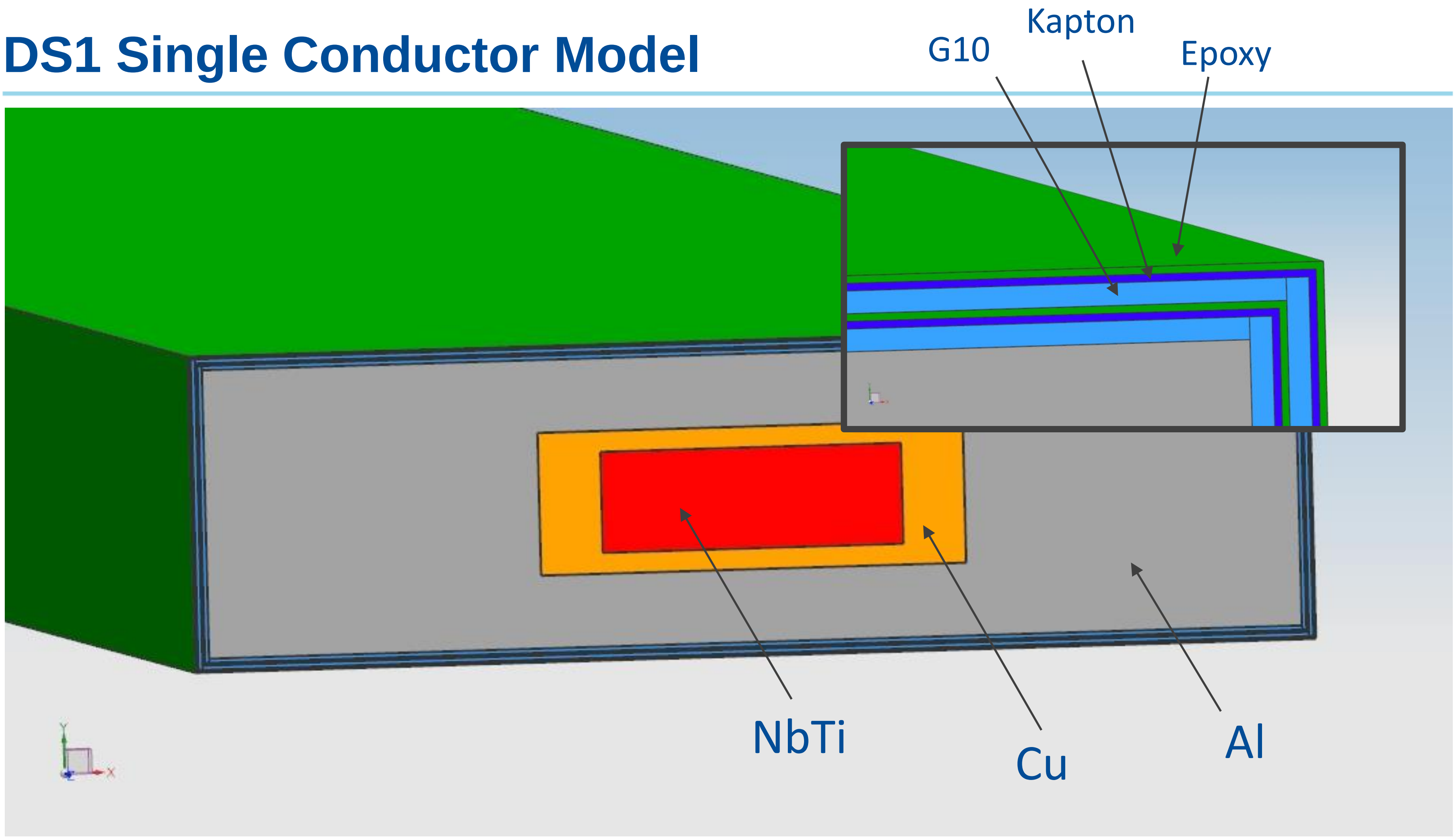




Mu2e Technical Report

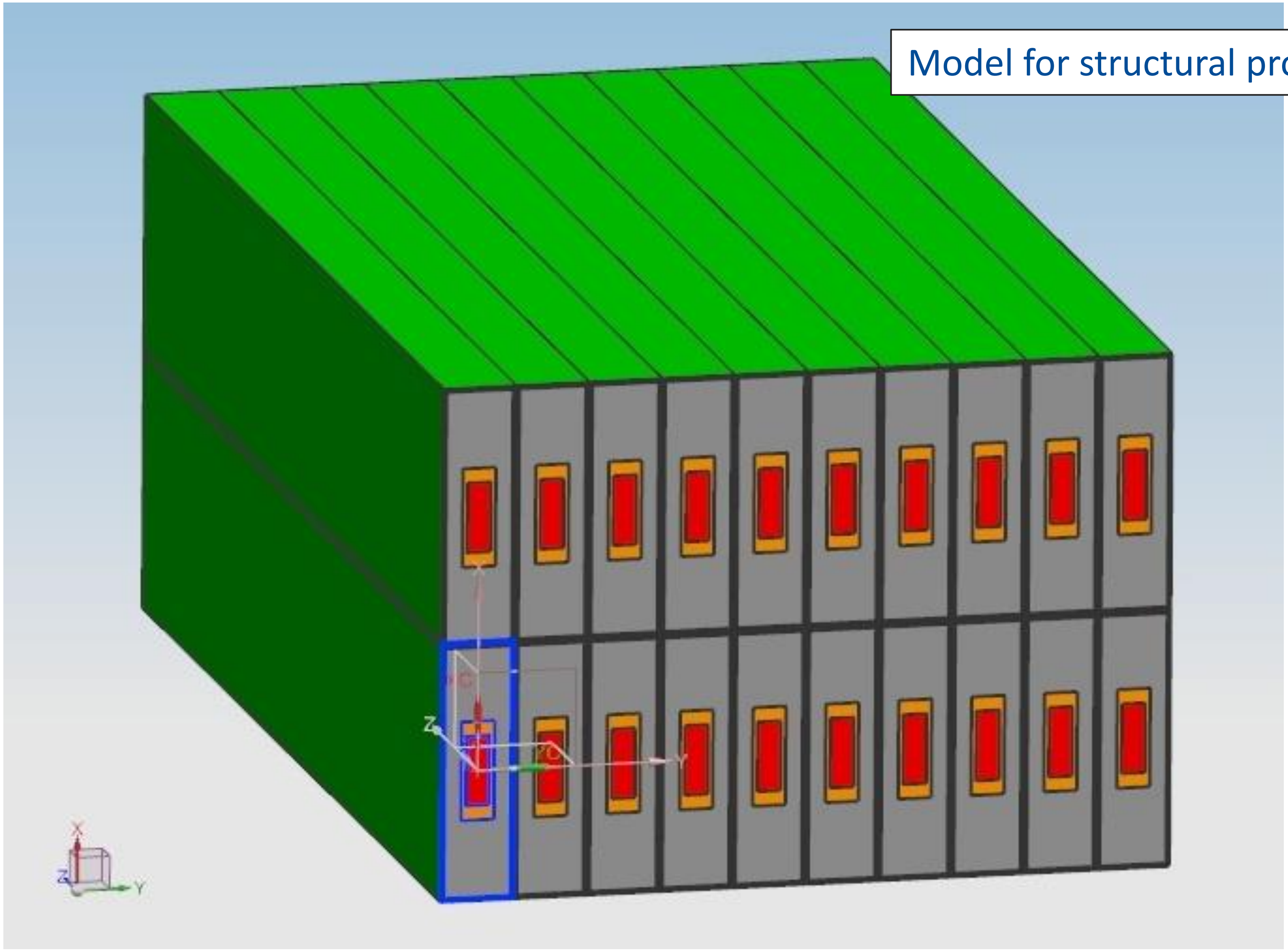
Two layers of insulation

DS1 Single Conductor Model



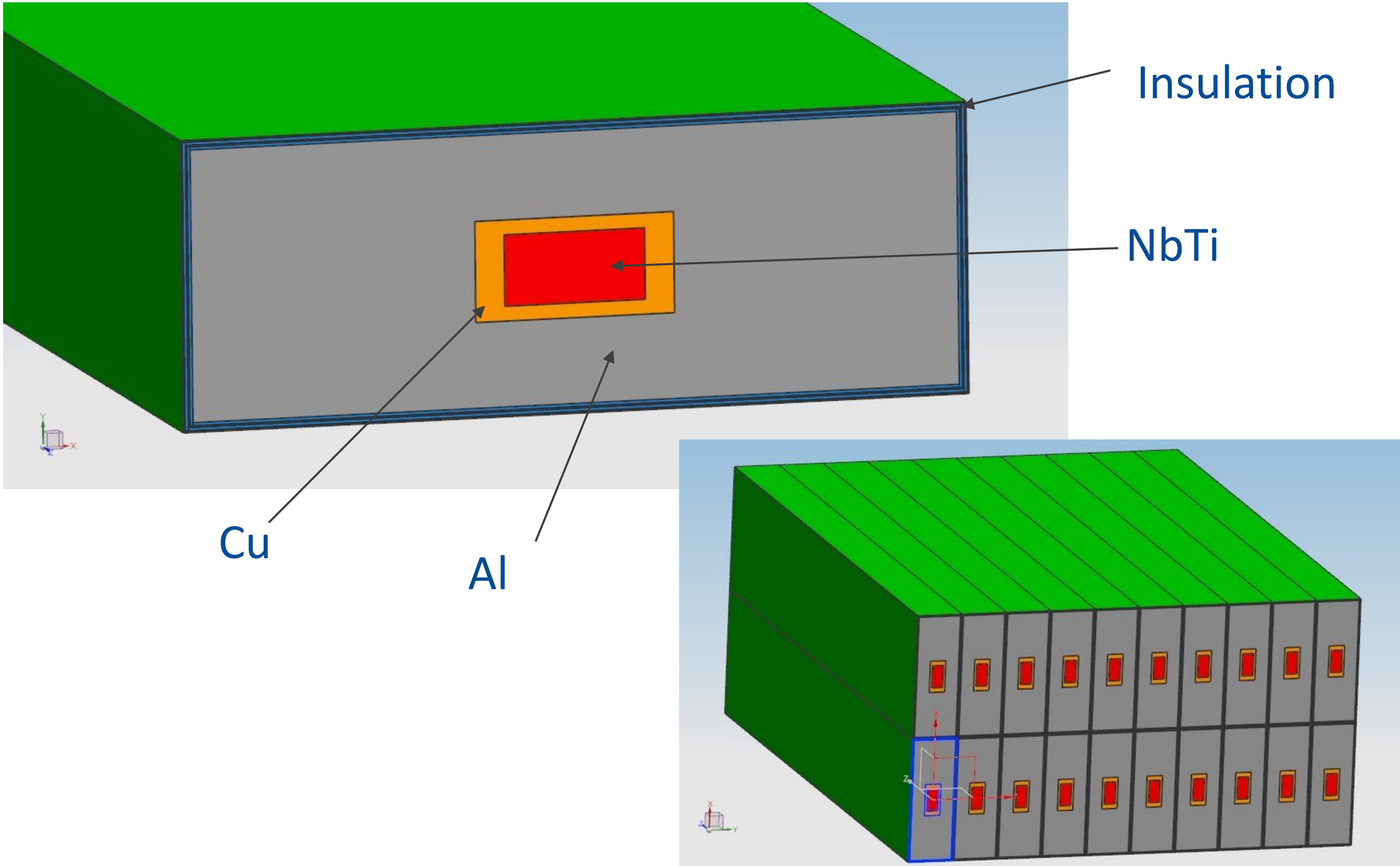
- Copper and NbTi are modelled as rectangles of equivalent areas knowing that the Cu/NbTi area ratio is 1:1.
- G10 is an orthotropic material.

DS1 Stack Model



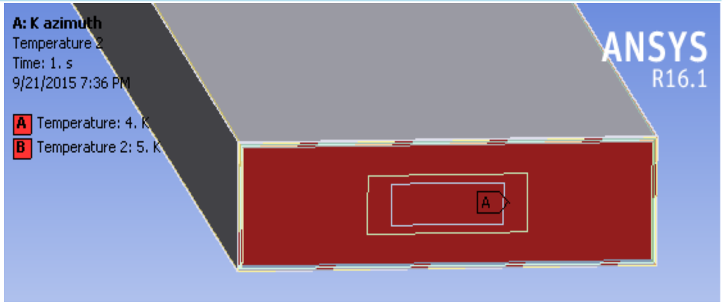
Model for structural properties

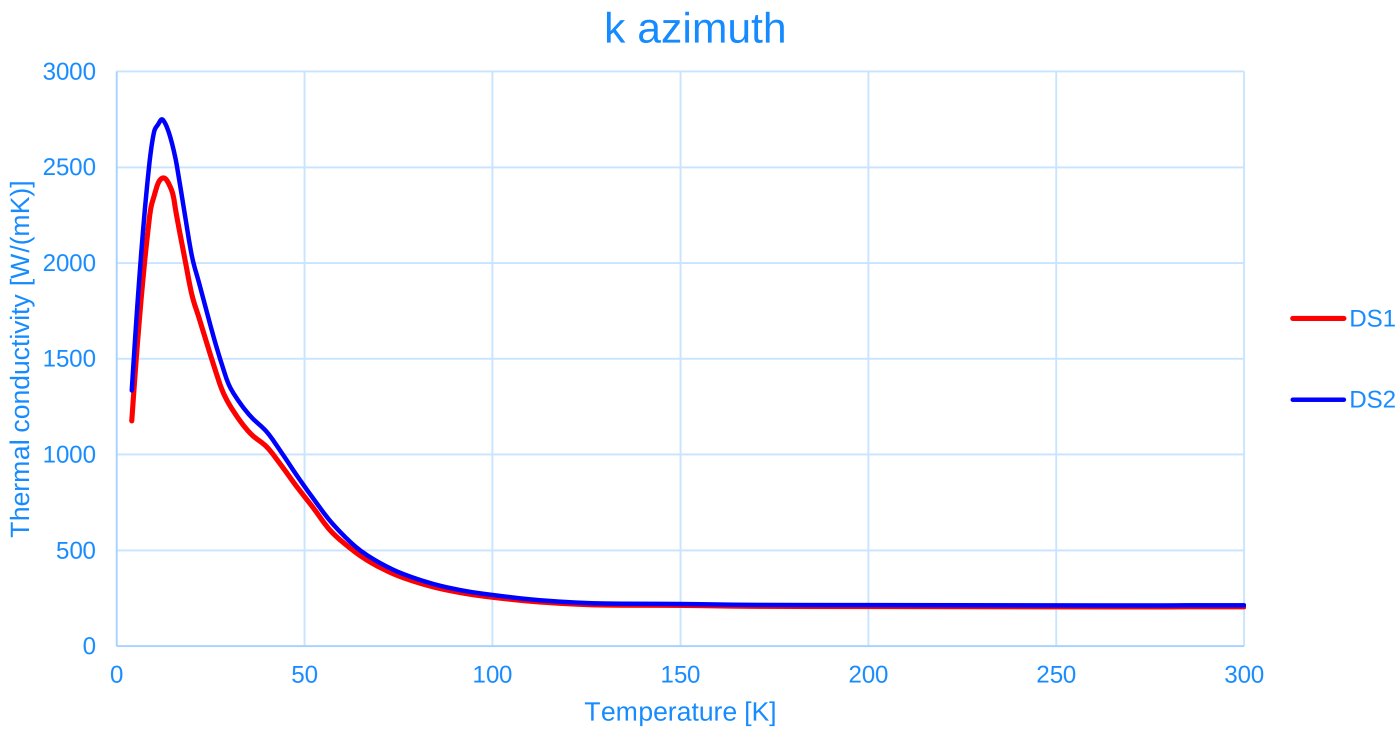
DS2 Single Conductor and Stack Model



Material Properties Required for the DS Analysis

- Orthotropic **thermal conductivity**
  - FEA on single conductor model
  - Steady-state thermal analysis
  - Use of Fourier's law of conduction: $\dot{Q} = kA\frac{dT}{dx}$





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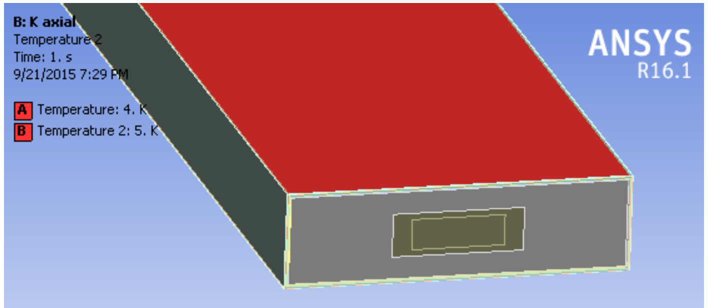

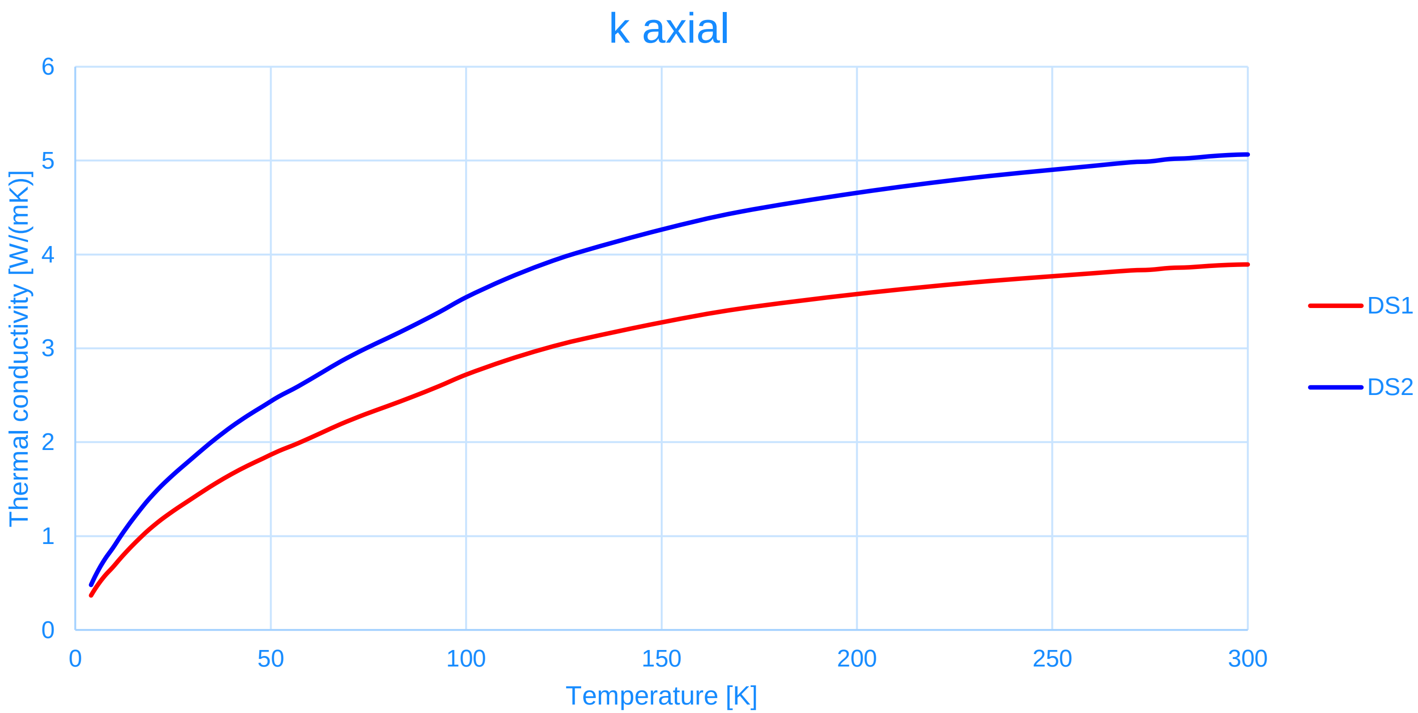

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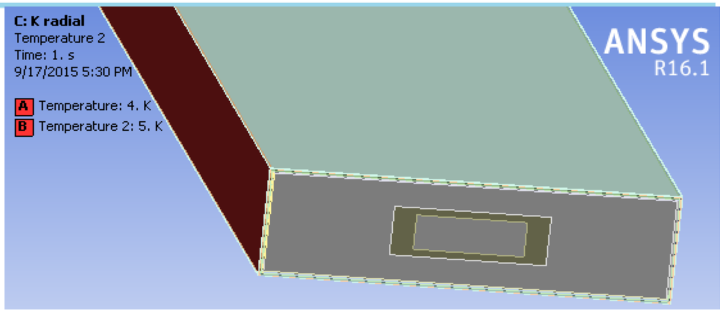
Material Properties Required for the DS Analysis



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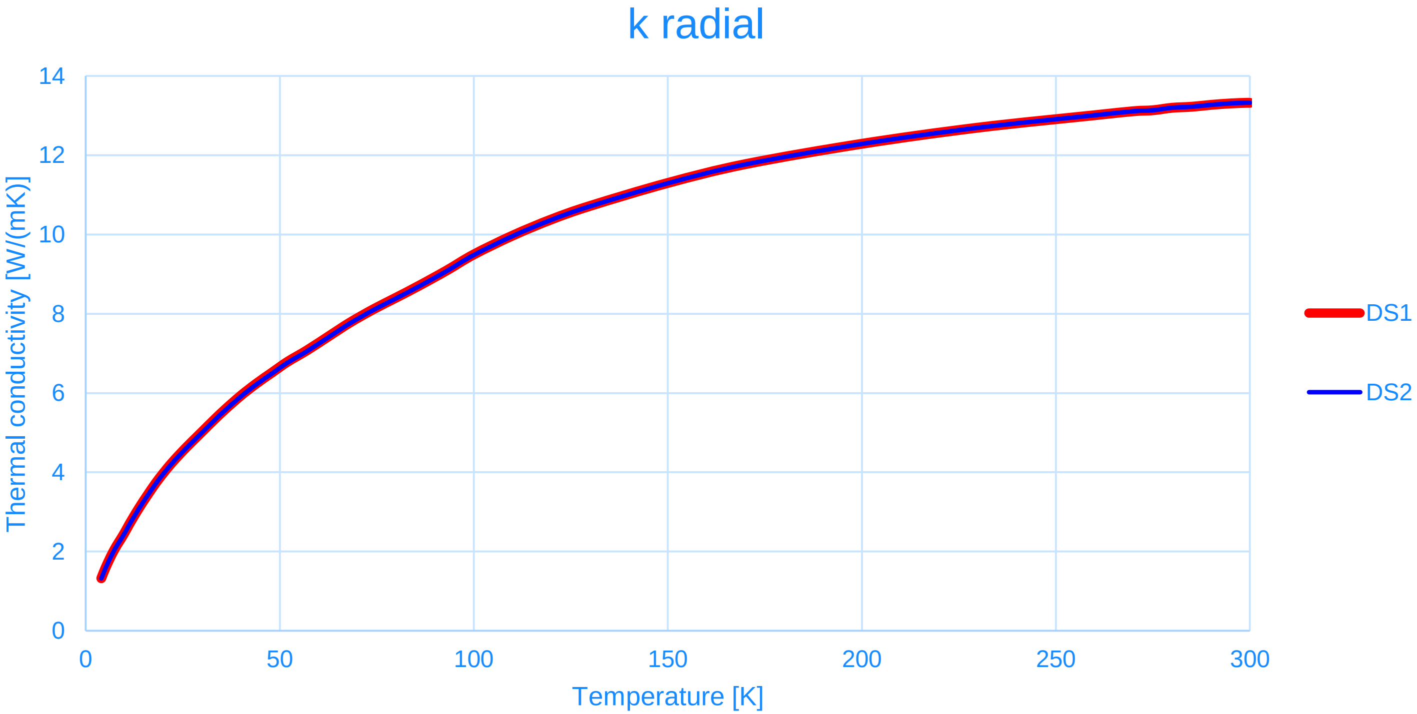
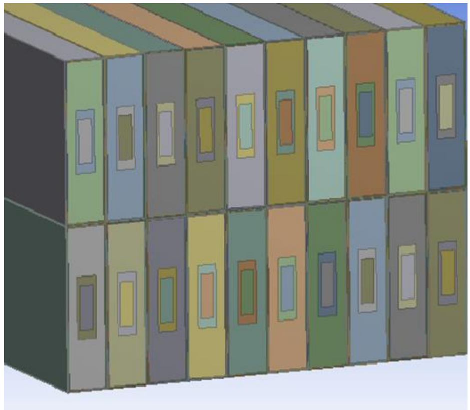
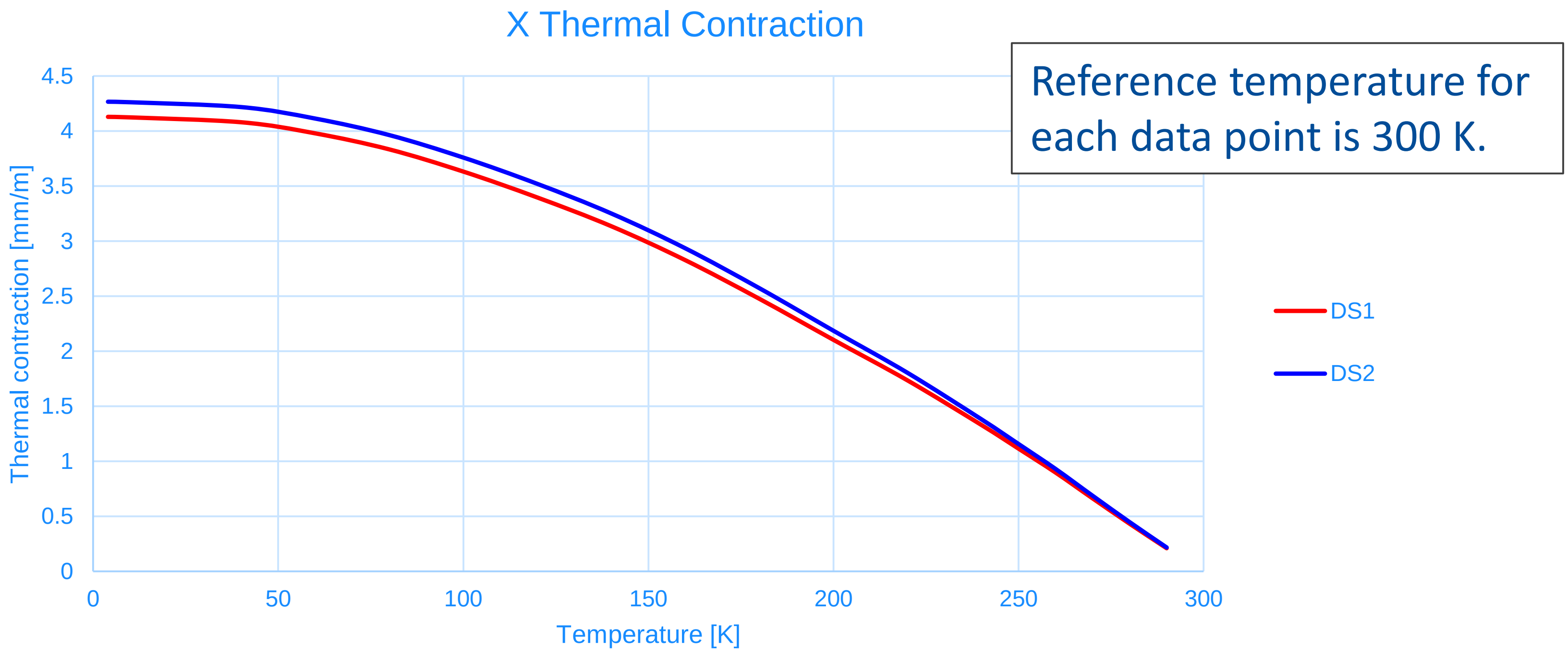


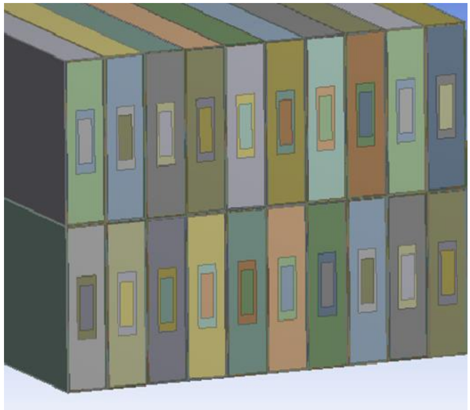
Material Properties Required for the DS Analysis

- Orthotropic **thermal contraction**
  - FEA on stack model
  - Static structural analysis with thermal condition
  - Use of law of thermal expansion: $\Delta L = \beta L \Delta T$





Material Properties Required for the DS Analysis



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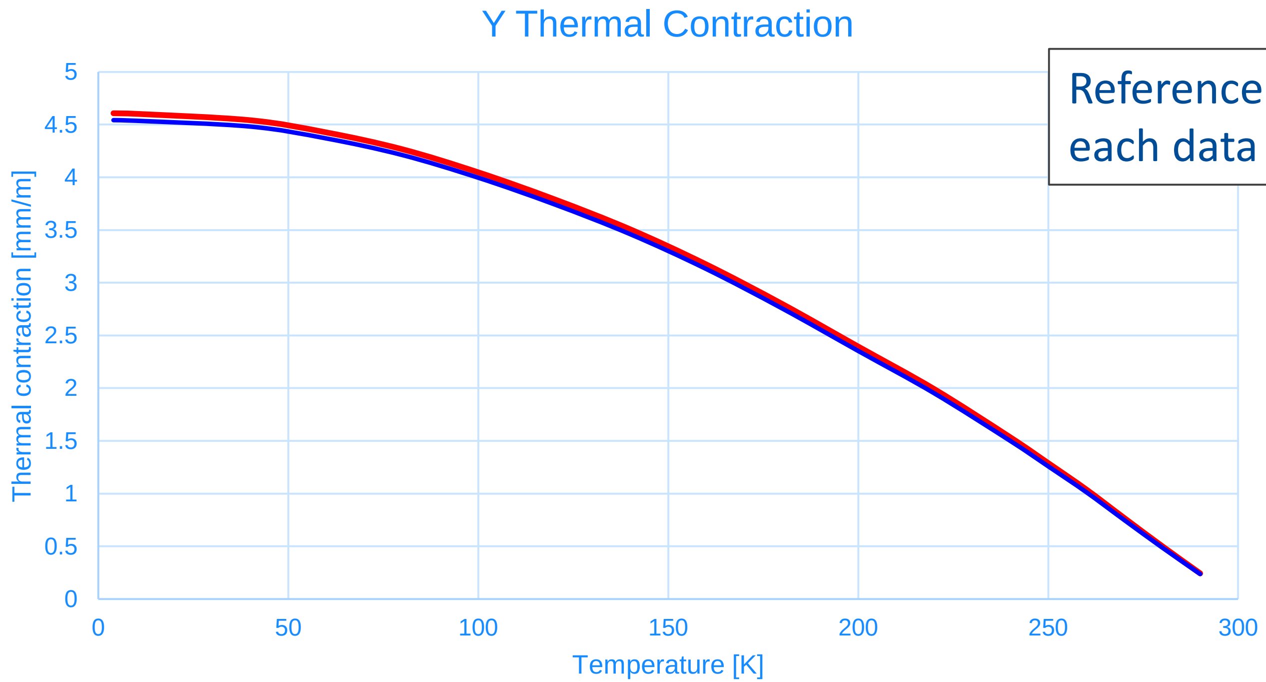
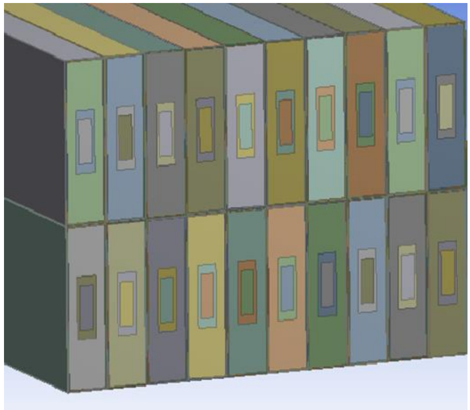
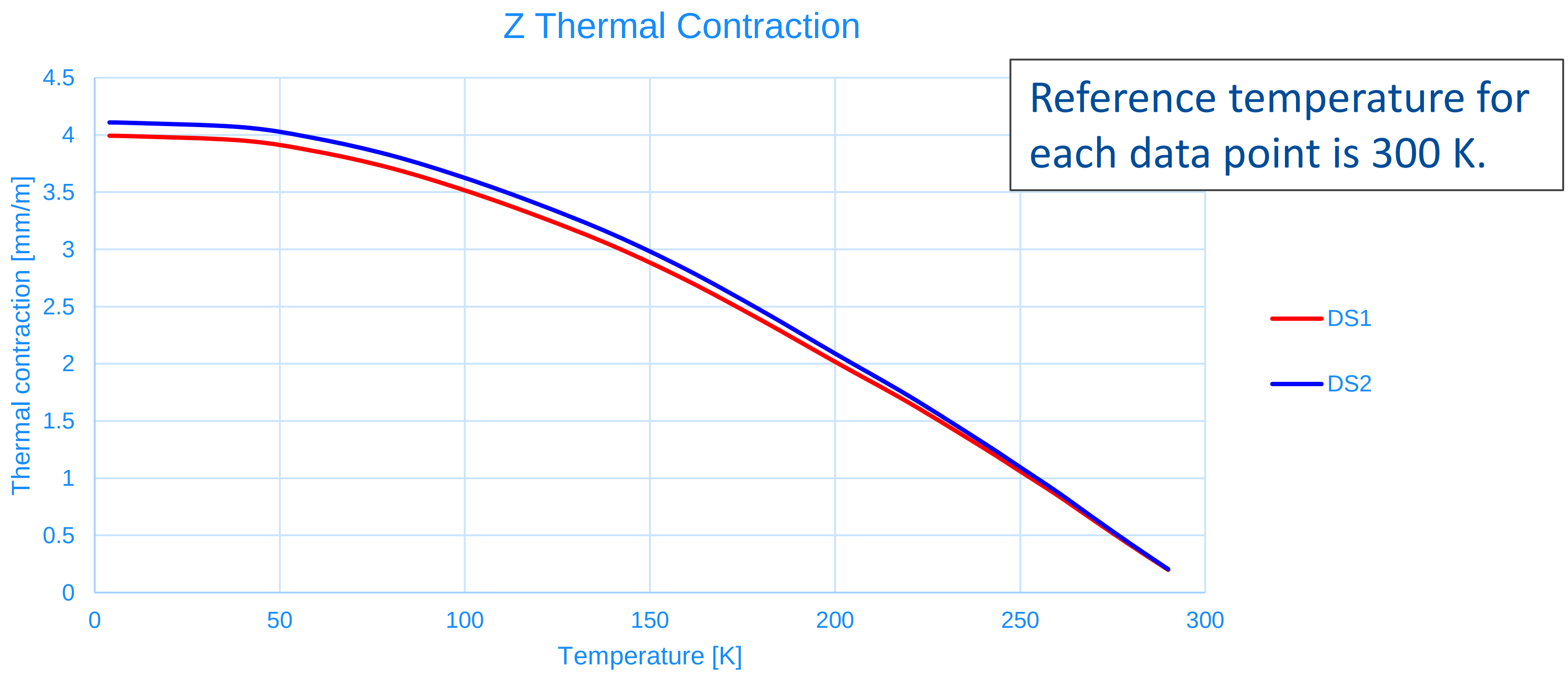


Reference temperature for each data point is 300 K.

Material Properties Required for the DS Analysis

- Orthotropic **thermal contraction**
  - FEA on stack model
  - Static structural analysis with thermal condition
  - Use of law of thermal expansion: $\Delta L = \beta L \Delta T$



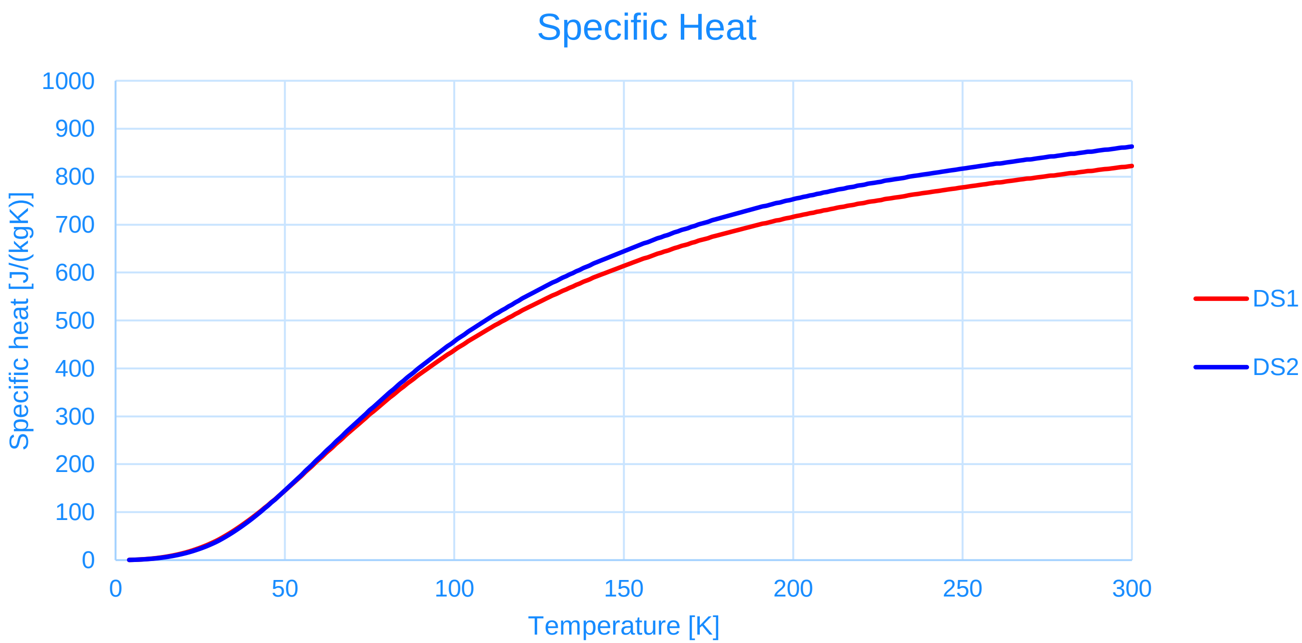


Material Properties Required for the DS Analysis

- **Density**
  - Weighted average method: $\rho = \sum_i \rho_i f_i$ where f_i is the volume fraction of each material.

DS1: $3454\ {}^{kg}/_{m^3}$ DS2: $3050\ {}^{kg}/_{m^3}$

- **Specific heat**
  - $c = \sum_i c_i f_i$



Material Properties Required for the DS Analysis

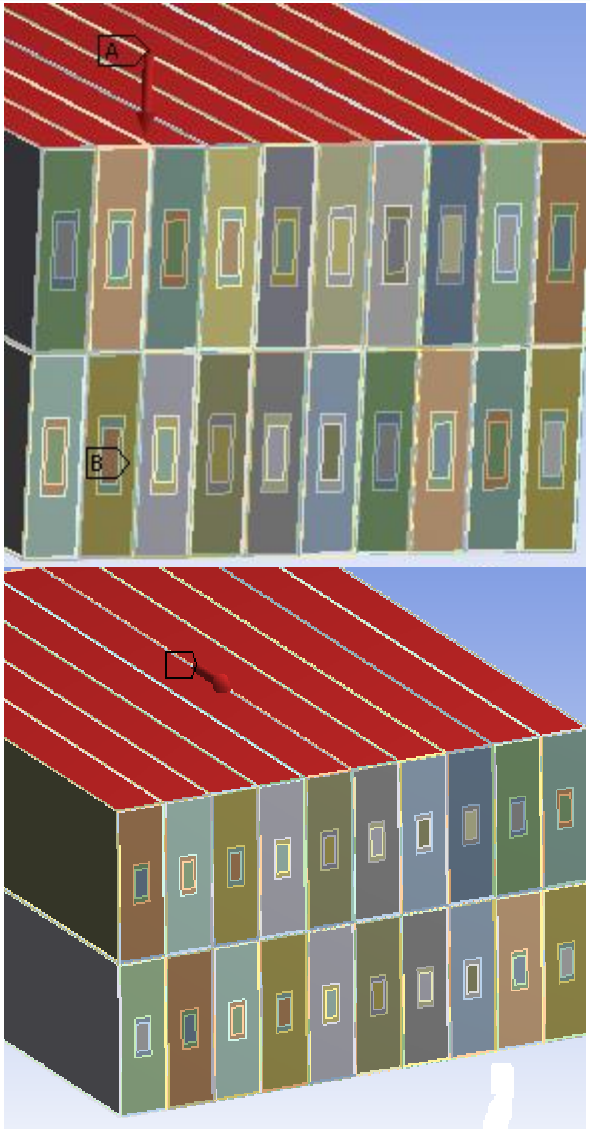
- Orthotropic **elasticity**

Young's modulus: $E_{ii} = \frac{\sigma_{ii}}{\varepsilon_i}$

Poisson's ratio: $\nu_{ij} = -\frac{\varepsilon_j}{\varepsilon_i}$

Shear modulus: $G_{ij} = \frac{\tau_{ij}}{\Delta x_i / L}$

  – FEA on stack model
  – Static structural analysis with known force on known area



Material Properties Required for the DS Analysis

- Orthotropic **elasticity: r**esults for **DS1**

Young's modulus	Poisson's ratio	Shear modulus
• $E_x = 43.890\ GPa$	• $\nu_{xy} = 0.284$	• $G_{xy} = 2.590\ GPa$
• $E_y = 31.762\ GPa$	• $\nu_{yz} = 0.308$	• $G_{yz} = 2.906\ GPa$
• $E_z = 57.571\ GPa$	• $\nu_{zx} = 0.376$	• $G_{zx} = 11.93\ GPa$

Material Properties Required for the DS Analysis

- Orthotropic **elasticity:** results for **DS2**

Young's modulus	Poisson's ratio	Shear modulus
• $E_x = 43.737\ GPa$	• $\nu_{xy} = 0.316$	• $G_{xy} = 2.071\ GPa$
• $E_y = 36.046\ GPa$	• $\nu_{yz} = 0.305$	• $G_{yz} = 4.239\ GPa$
• $E_z = 57.237\ GPa$	• $\nu_{zx} = 0.412$	• $G_{zx} = 9.439\ GPa$

Preparing the Final Simulation

- Results have been obtained for:
  - ✓ Thermal conductivity
  - ✓ Thermal contraction
  - ✓ Density
  - ✓ Specific heat
  - ✓ Elasticity

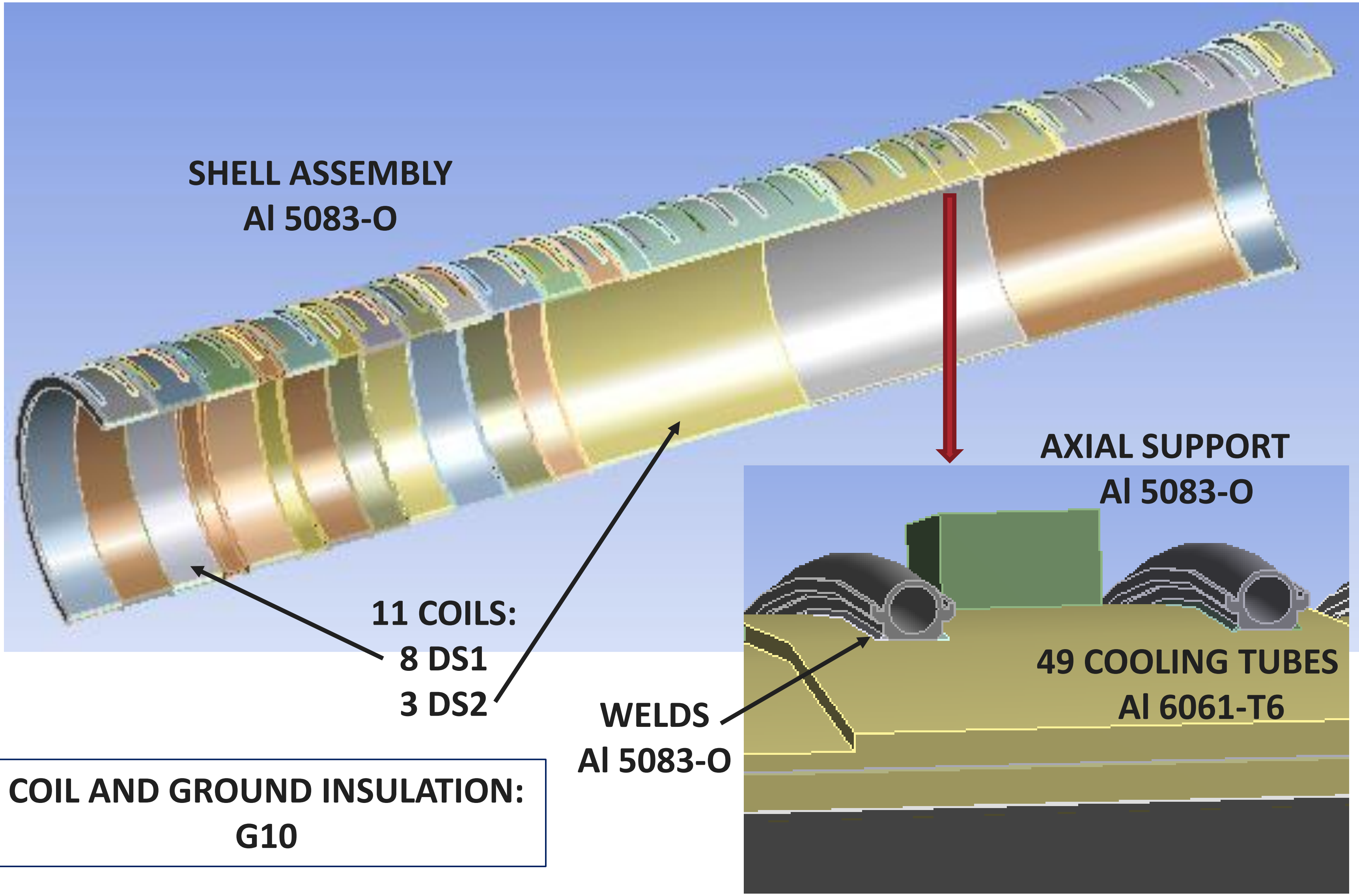
Properties of Outline Row 5: DS1 Conductor

	A	B	C
1	Property	Value	Unit
2	Density	3454.3	kg m^-3
3	Orthotropic Secant Coefficient of Thermal Expansion		
4	Coefficient of Thermal Expansion	Tabular	
11	Reference Temperature	300	K
12	Orthotropic Elasticity		
13	Young's Modulus X direction	4.389E+10	Pa
14	Young's Modulus Y direction	5.7571E+10	Pa
15	Young's Modulus Z direction	3.1762E+10	Pa
16	Poisson's Ratio XY	0.37639	
17	Poisson's Ratio YZ	0.30796	
18	Poisson's Ratio XZ	0.28446	
19	Shear Modulus XY	1.193E+10	Pa
20	Shear Modulus YZ	2.9059E+09	Pa
21	Shear Modulus XZ	2.5895E+09	Pa
22	Field Variables		
26	Orthotropic Thermal Conductivity	Tabular	
33	Specific Heat	Tabular	

- Results can be considered reasonable:
  - – DS1 and DS2 are similar,
  - – in DS2 aluminum properties are more relevant
- Average properties are imported in Ansys Engineering Data. Computational time will be reduced.

1	Contents of Engineering Data
2	Material
3	Al5083-O
4	Al6061-T6
5	DS1 Conductor
6	DS2 Conductor
7	G10-CR_parallel_to_coil
8	G10 -CR_perpendicular_to_coil

Detector Solenoid 3D Model



COIL AND GROUND INSULATION:
G10

DS Transient Thermal-Stress Analysis

Geometry

- Contact between cooling tubes and shell: **welds**
- Cylindrical coordinate system for coils
- Simmetry

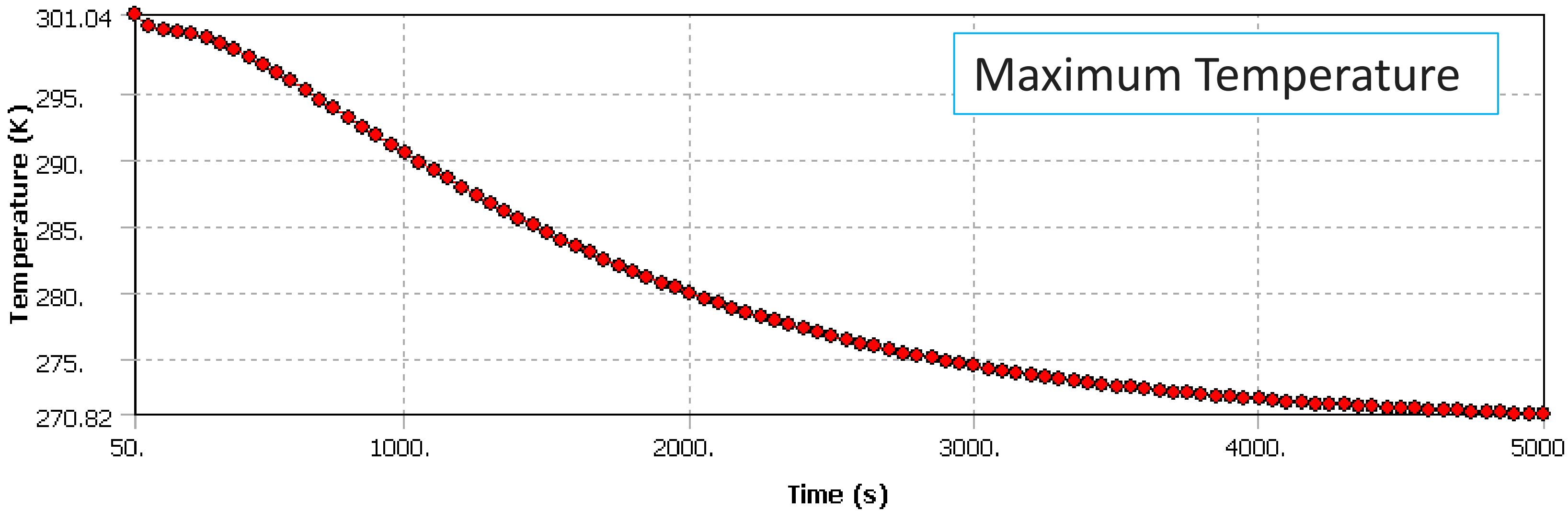
Transient Thermal Analysis

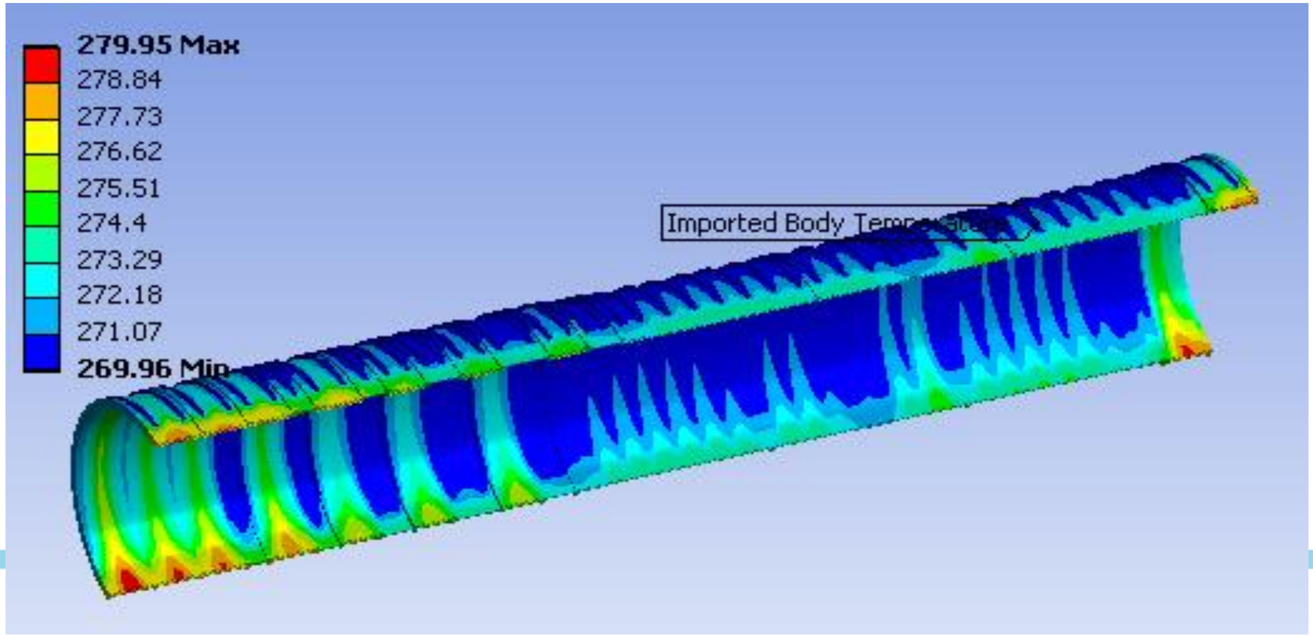
- Initial Temperature: 300 K
- Cooling tubes temperature: 270 K
- End time: 5000 s

Static Structural Analysis

- Boundary condition: axial displacement
- Thermal condition: imported from transient thermal analysis
- 100 or 200 seconds increments for the analysis

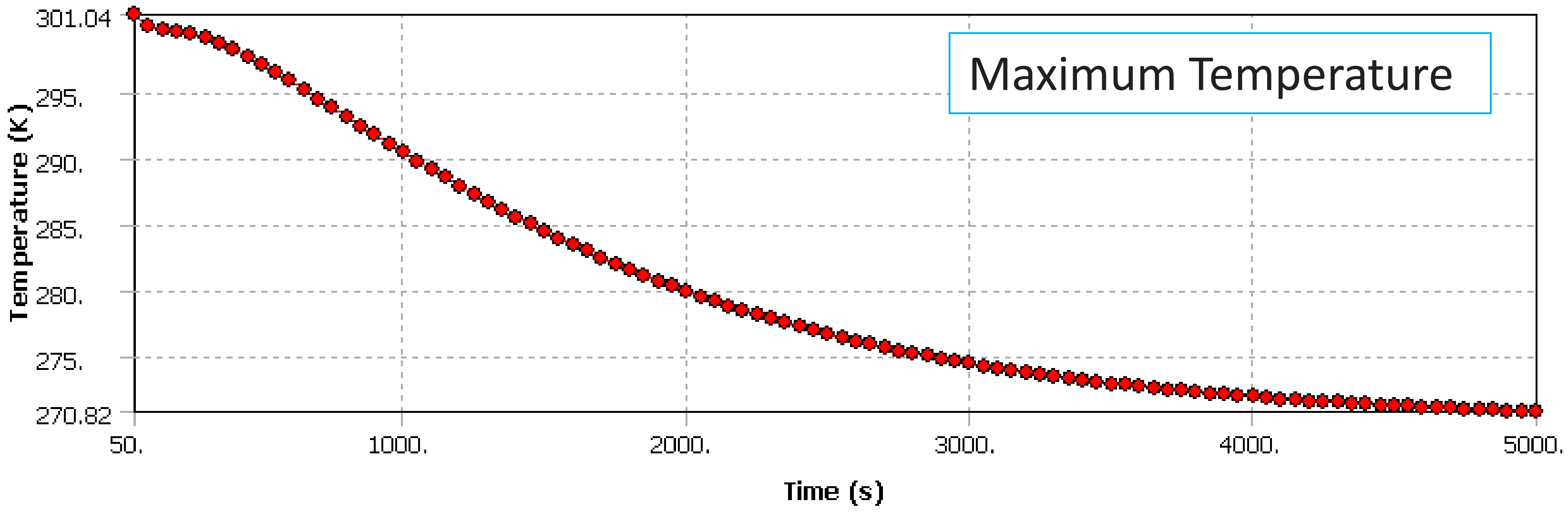
Transient Thermal Results

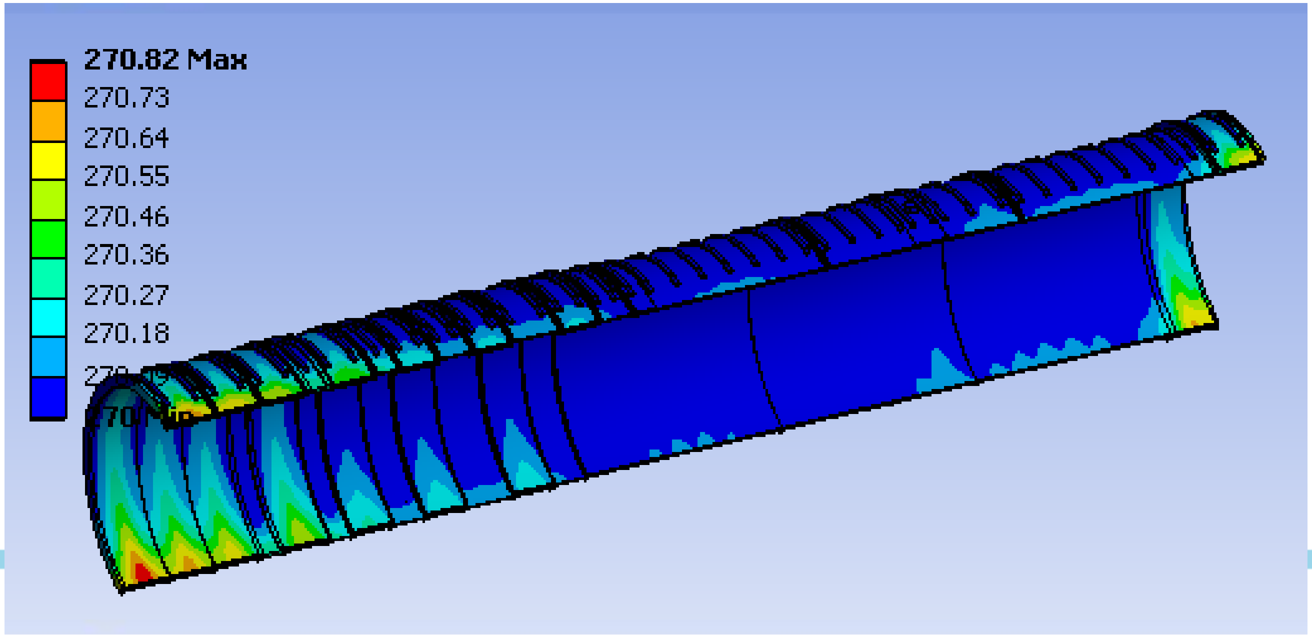




Temperature at **2000 s**: maximum stress should occur here

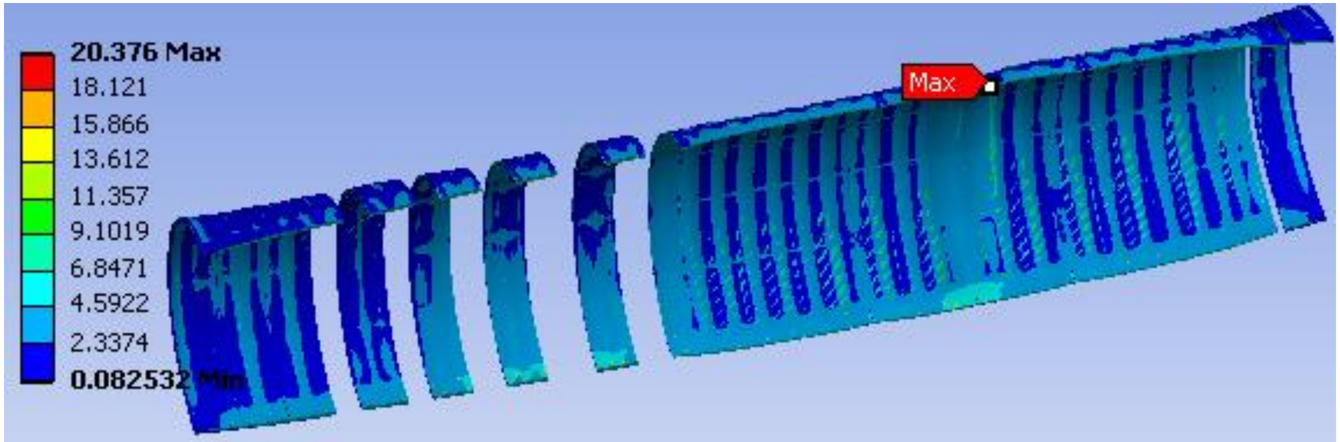
Transient Thermal Results

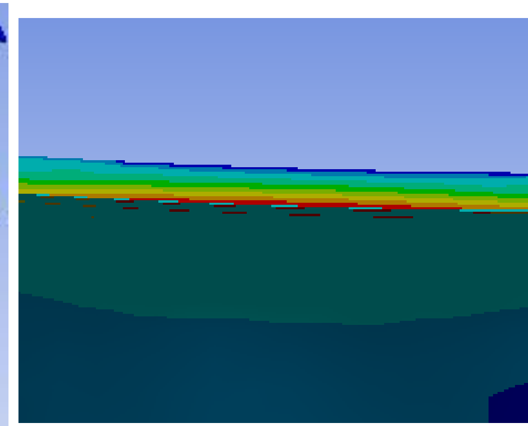


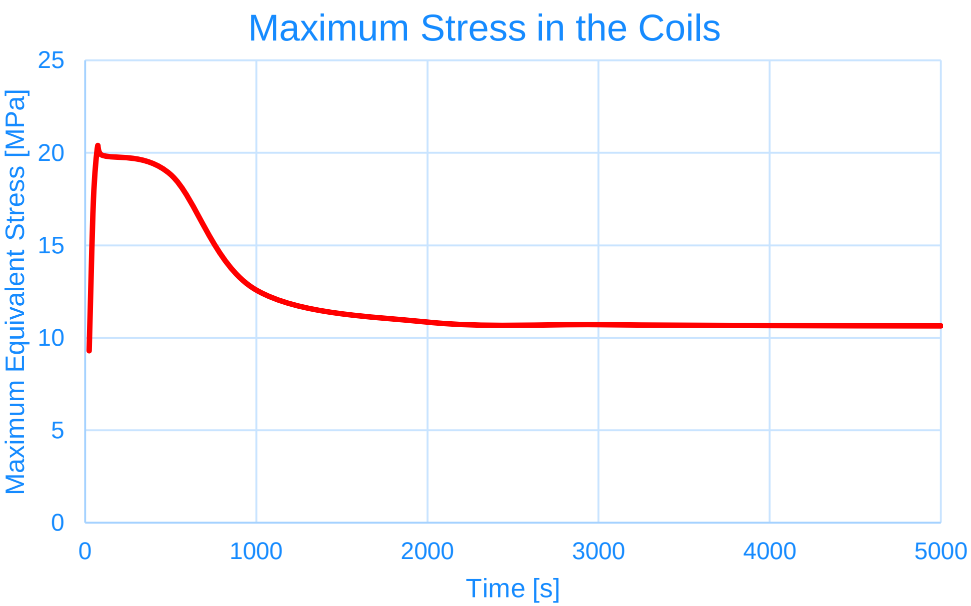


Temperature at **5000 s**: the Detector Solenoid cools down completely

Stress Results: coils

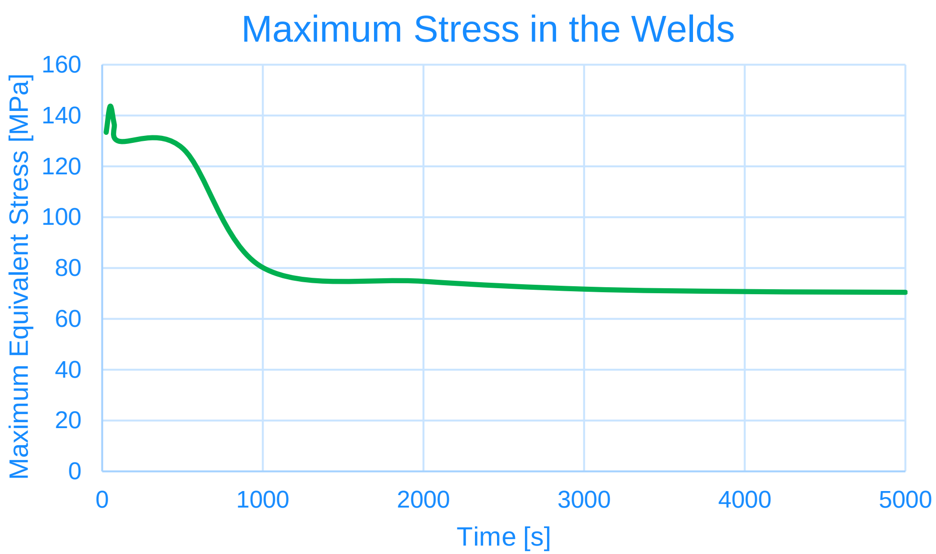


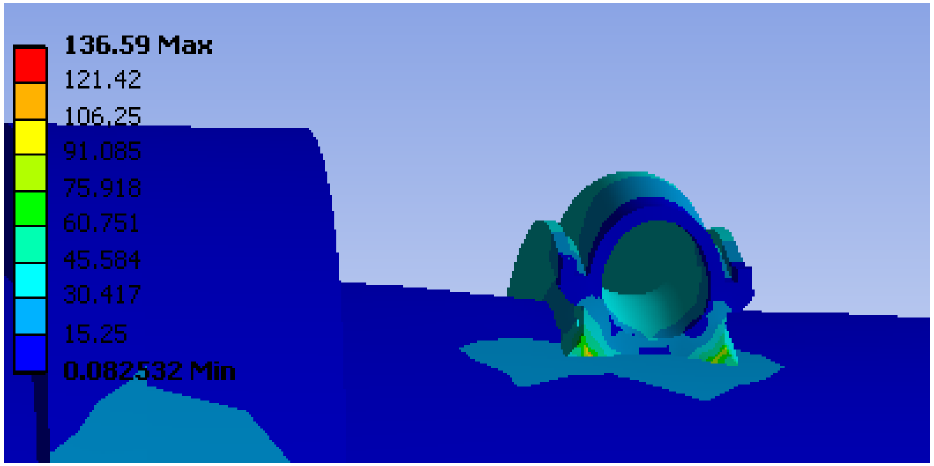


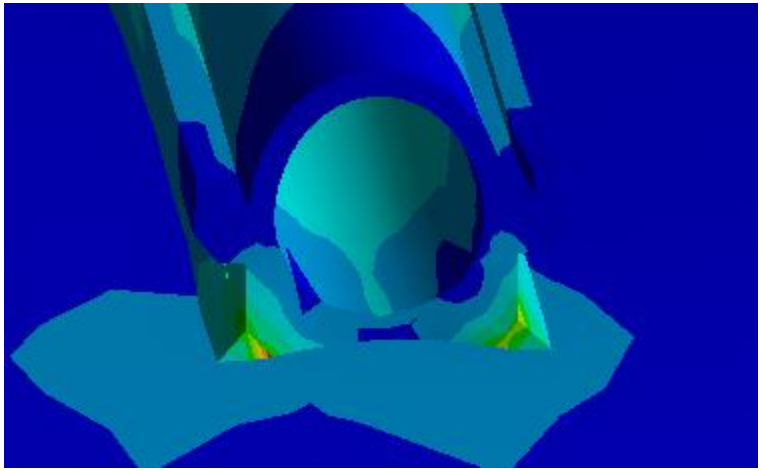


- Maximum stress in the coils occurs at 75 s and is 20.34 MPa (2950 psi)
- Allowable stress for Al-stabilizer is 30 MPa (4351 psi).
- Temperature difference is **SAFE!**

Stress Results: welds

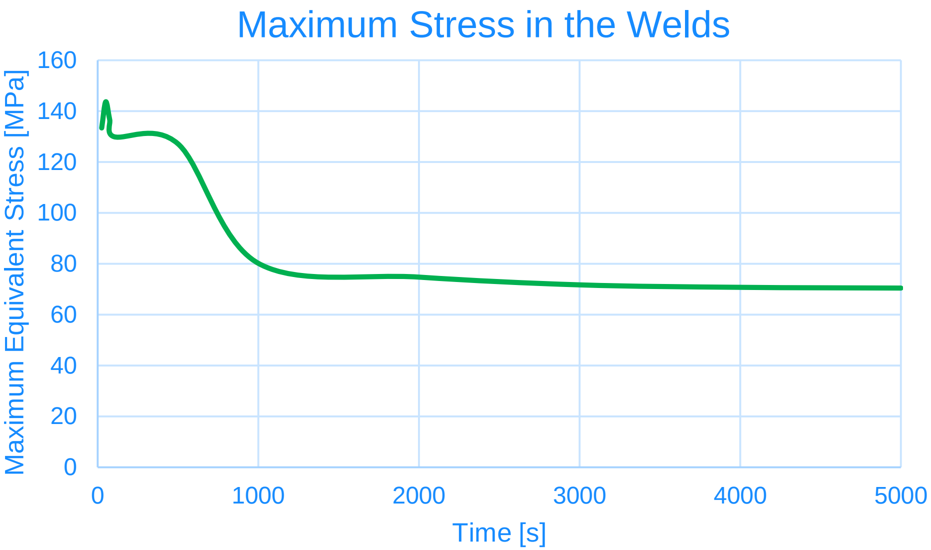


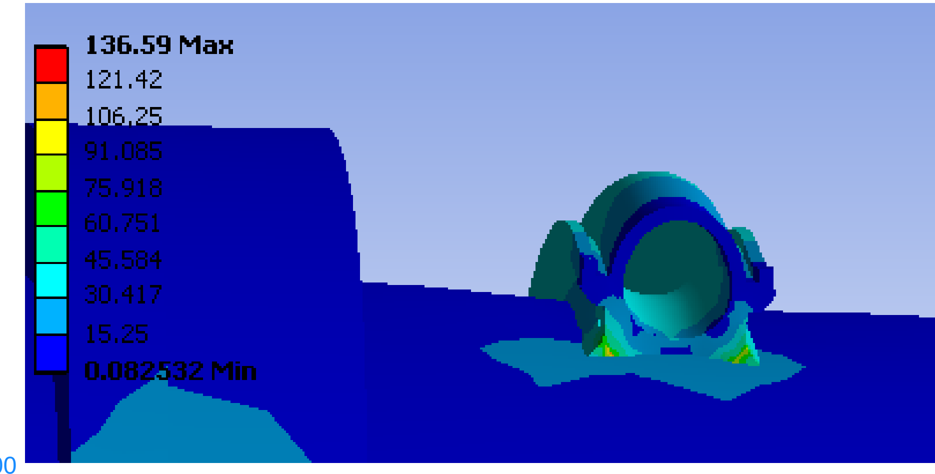




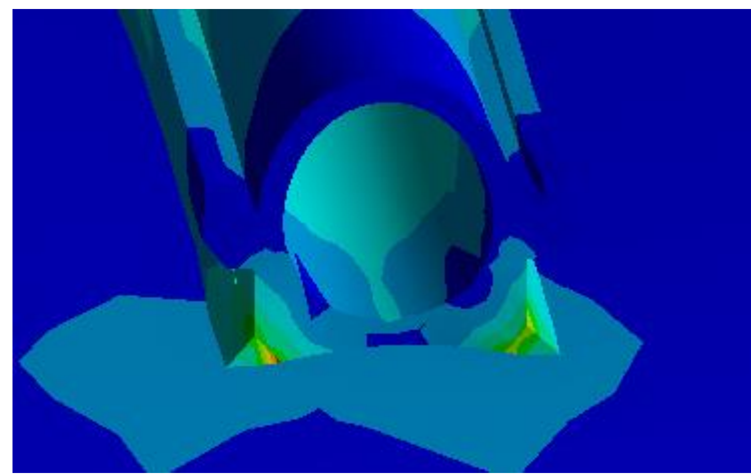
- Maximum stress in the welds is 136.6 MPa (19800 psi).
- According to *Aluminum Association Specifications*, allowable stress for aluminum welds is 75 MPa (10900 psi).

Stress Results: welds



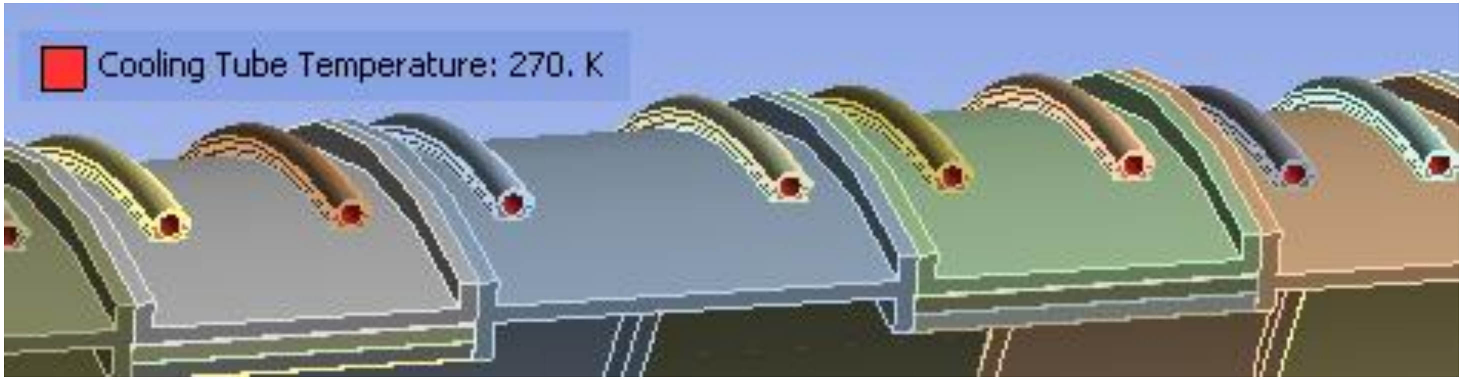


- Reason for high stress is because conservative analysis has been performed.
- Very little area is interested so this is not dangerous.



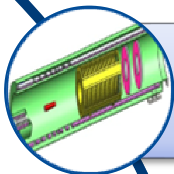
Stress Result

- Analysis is conservative since a sudden shock of 270 K has been applied as boundary condition.

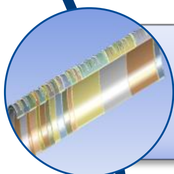


- To obtain a more realistic result, a convection coefficient should be applied in the cooling tubes.
- This would give a more realistic distribution reducing and pushing farther up in time high stresses.
- Anyway, 30 K deltaT has been verified in the worst case.

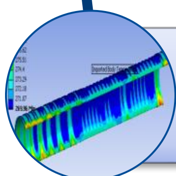
Conclusions



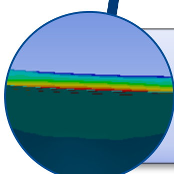
The analysis can be considered **successful**.



A **safe** difference of temperature of $30\ K$ has been verified.



The Detector Solenoid completely cools down to $270\ K$ in 5000 seconds. The cool down rate is $\mathbf{21.6}\ {}^{\boldsymbol{K}}/_{\boldsymbol{hour}}$



It is possible to simulate a more aggressive cool down rate (i.e. $\Delta T = 40\ K$) and verify the stress.

In any case, the experiment can start safely.

Acknowledgments

- TD-Design & Drafting
- Mu2e Project
- Computing Division
- Organizers of the Summer Student Program

Thank you for your attention!