Fermilab

Detector Solenoid Cool Down Analysis for the Mu2e Experiment

Final Report

Costanza Saletti

University of Pisa

Supervisor: Nandhini Dhanaraj

Co-supervisor: Richard Schmitt

September 25th, 2015

Index

1. Introduction

The work here described has been done during the Summer Student Program at the Technical Division in the Fermi National Accelerator Laboratory, a nuclear physics research center in Illinois, USA.

The program took place under the supervision of the Mu2e Project, whose mission is to design and construct a new facility that will enable scientists to search for and study the conversion of muons into electrons in the field of a nucleus.

The Mu2e experiment is a particle physics detector embedded in a series of superconducting magnets. The magnets are designed to create a low-energy muon beam that can be stopped in a thin aluminum stopping target, where the particles are detected and tracked.

The muon beam is created by making a proton beam strike a small tungsten production target, then the magnetic field created by the superconductive solenoids steer the muons in the correct direction towards the stopping target.
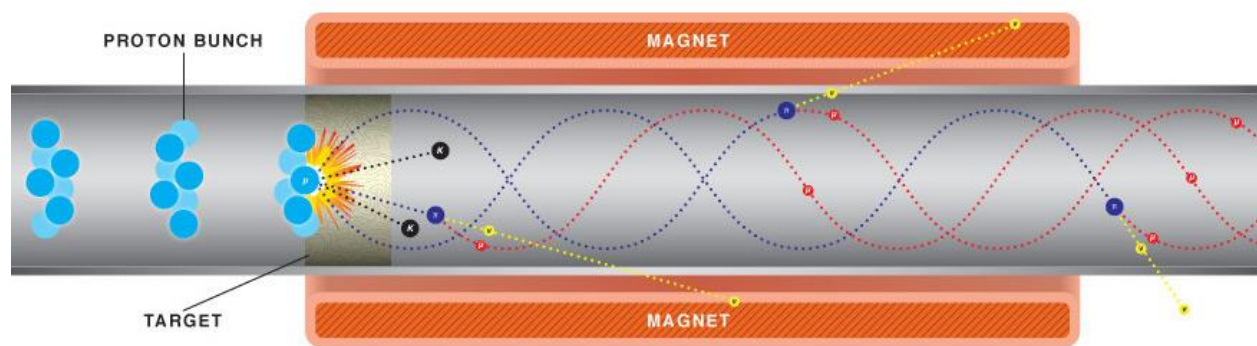

FIGURE 1.1: A proton bunch hits a production target to produce the muon beam.

Therefore, the experiment is composed by:

- The Production Solenoid (PS), 12 feet long and a $4.5\ T$ magnetic field, that contains the target for the primary proton beam;
- The Transport Solenoid (TS), a 40 feet long S-shaped magnet of $2\ T$, that channels the muons with the right charge;
- The Detector Solenoid (DS), 30 feet long and $1\ T$, that houses the muon stopping target and the detector elements. These consist of a tracker that measures the trajectory of the charged particles, a calorimeter that provides measurements of energy, position and time, a magnetic spectrometers and the electronics, trigger and data acquisition required to read out, select and store the data.
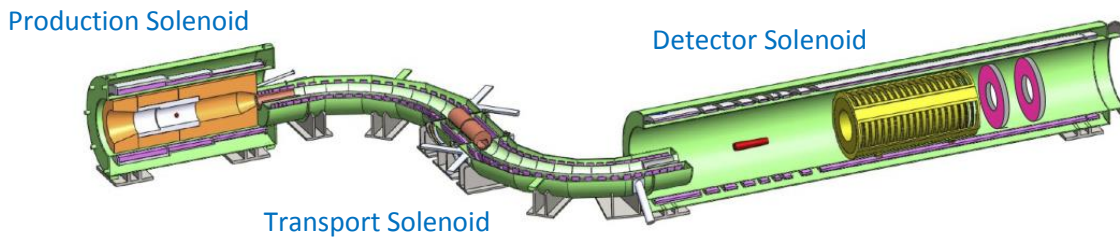
FIGURE 1.2: Mu2e experiment.

In order to reach and maintain the magnetic field specifications, derived from the Mu2e physics requirements, the superconductive solenoids have to be kept at the constant temperature of $4.7\ K$. This is reached with a cooling system based on biphasic liquid helium:

The magnets are located inside four cryostats: one for the PS, two for TS upstream and TS downstream, one for the DS. Liquid helium is provided to the cryostats by a series of feedboxes with four distribution lines. Helium is therefore able to cool the magnets with a series of cooling tubes that envelop the solenoids shells.
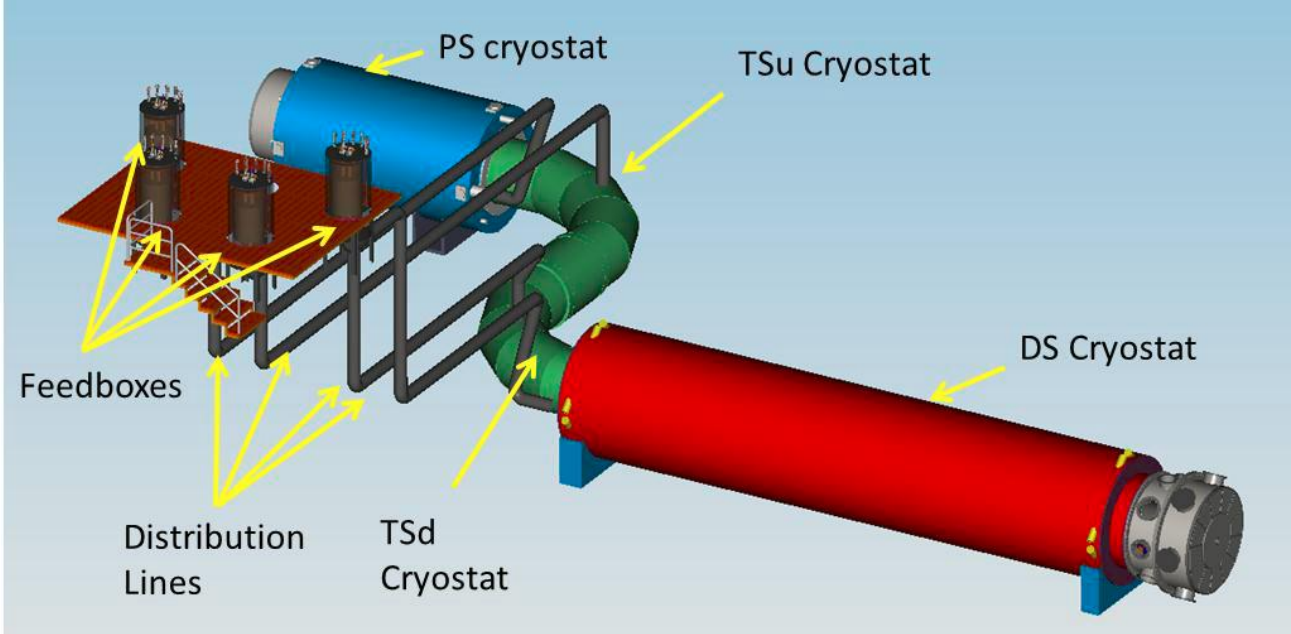

FIGURE 1.3: Mu2e experiment: superconductive solenoid system and cryogenic distribution system.

2. Training program: task description

Mu2e magnets will have to be cooled down from room temperature of $300\,K$ to the helium operating temperature of $4.7\,K$ to enable magnet powering.

The cool down must be controlled as the magnet is made of many different materials which contract at different rates thus inducing thermal stresses within the coil. A thermal-stress analysis will provide information regarding the temperature difference to be maintained during controlled cool down.

The main goal will be finding a safe difference of temperature to be applied not to break the magnets.

The following tasks will be accomplished in order to complete the analysis:

1. Focus the attention on the Detector Solenoid;
2. Model a single conductor with all the different materials and insulation;
3. Understand all the material properties required for a FEM thermal-strass analysis;
4. Derive the average material properties of the stack of coils which can be used in global Detector Solenoid analysis;
5. Obtain the 3D model of the Detector Solenoid and prepare it for the thermal stress analysis;
6. Perform the FEM transient thermal-stress analysis and figure out a safe temperature difference that can be used during cool down of the magnet.

3. Solid Models

a. The conductors

The Detector Solenoid is made of two types of conductors, which differ for the dimensions of the cables. In fact, the solenoid consists of two sections that requires different magnetic field intensities, so a precise disposition of the magnets has to be respected.

The coils are made of high purity Aluminum-stabilized NbTi Rutherford cables.

Aluminum, in fact, has very small resistivity and a large thermal conductivity at low temperatures providing excellent stability. Plus, precise rectangular conductor shapes can be obtained, allowing for high accuracy in the coil winding.
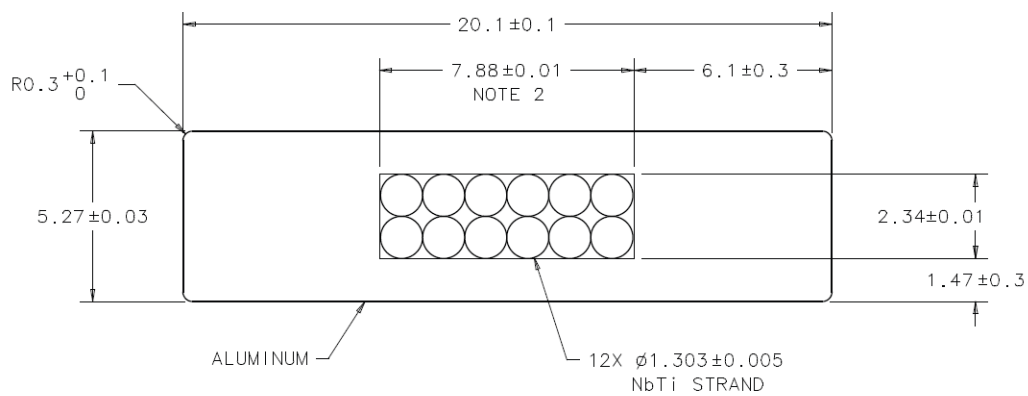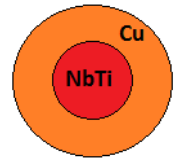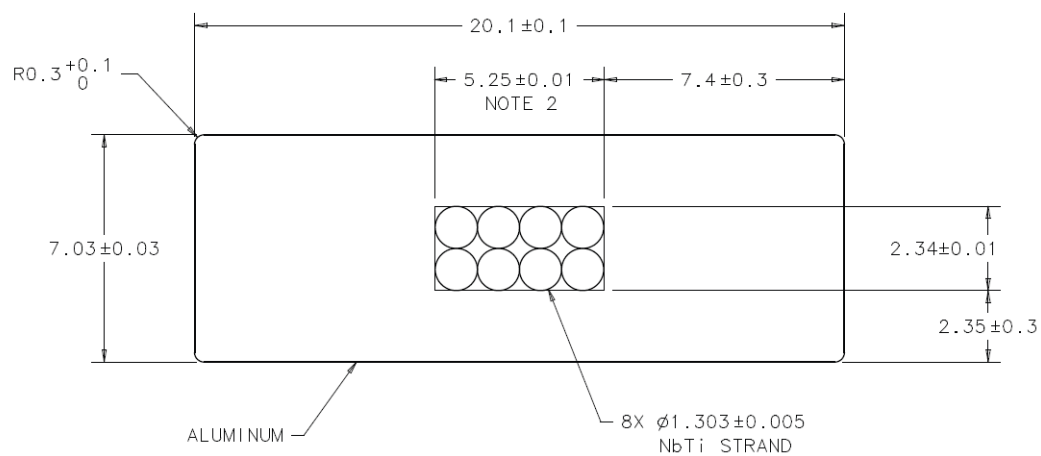

FIGURE 3.1: Cross-section of DS1 conductor.

FIGURE 3.2: Cross-section of DS2 conductor.

The Rutherford cables are then covered with two layers of insulation, each made of three different materials:

- 0.075 mm of G10 (E-glass)
- 0.025 mm of kapton
- 0.025 mm of epoxy.

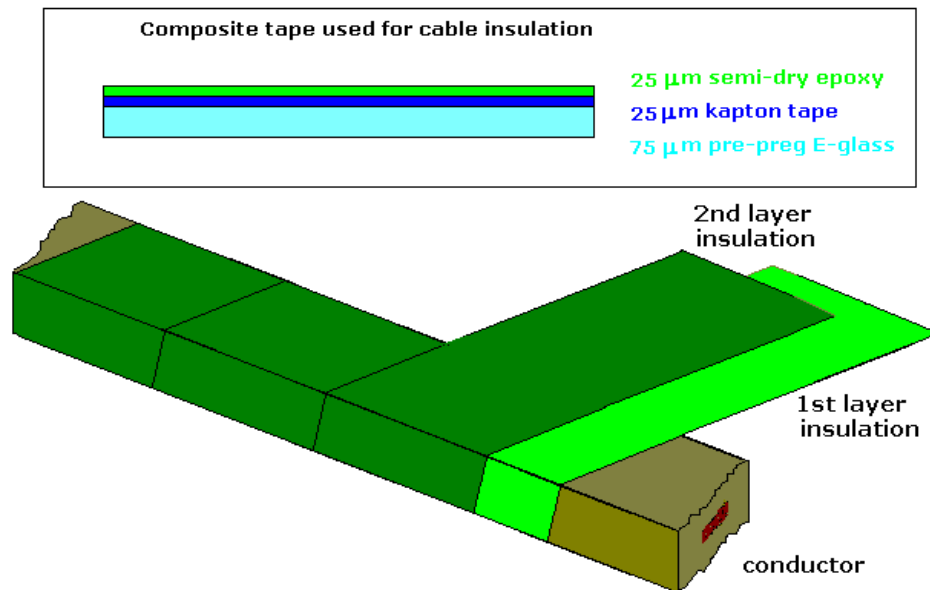Total thickness of insulation is 0.25 mm.

FIGURE 3.3: Representation of a single coil wrapped in two layers of insulation, each made by three thin sublayers of plastic materials.

b. The models

The DS1 and DS2 single conductors, represented below, has been modeled with the software NX CAD.

In order to find the average material properties of the whole conductors with insulation, different FEM analysis will be performed on the single conductor model or on the stack model. The latter will be used to avoid border effects in the structural simulations.
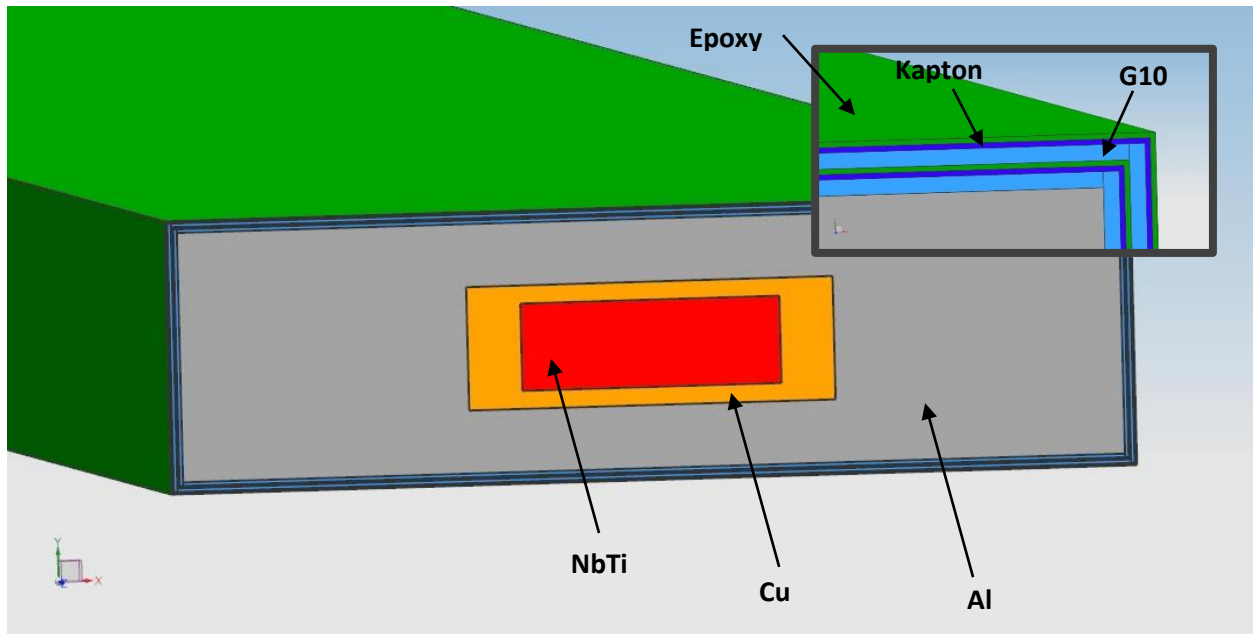
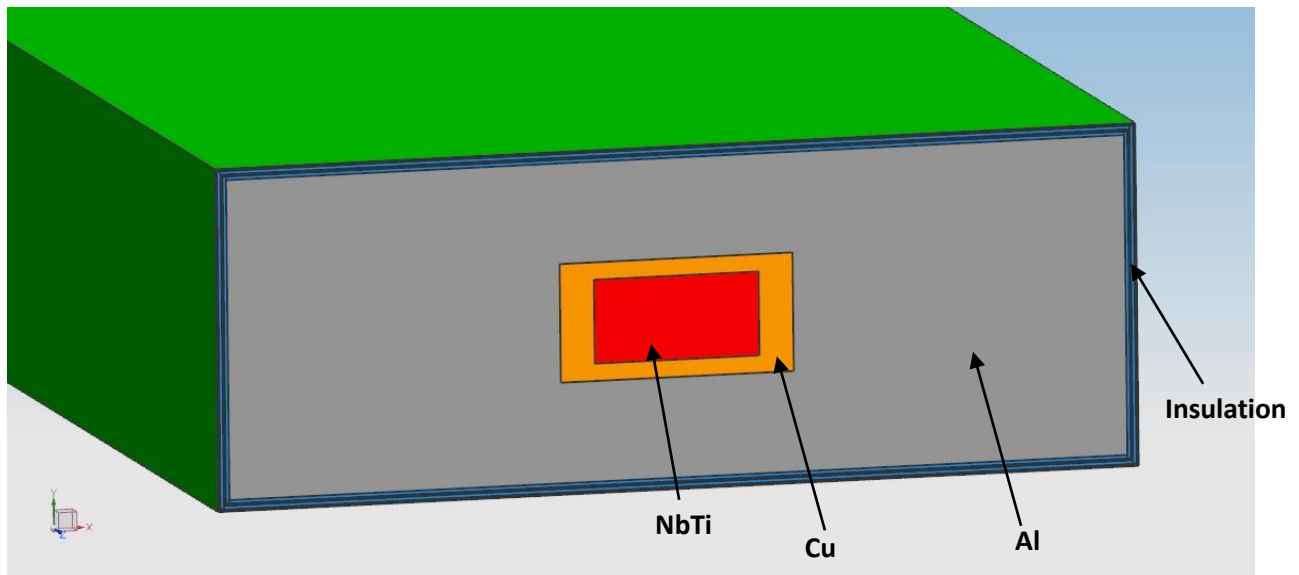*Figure 3.4: DS1 single conductor model.*

Figure 3.5: DS2 single conductor model.

It is possible to notice that, according with the cross-sections represented in the technical report, DS2 is higher than DS1 and has a bigger aluminum layer.

In both conductors, NbTi and Copper has been modeled as rectangles of equivalent areas, knowing that the area ratio is $1:1$.
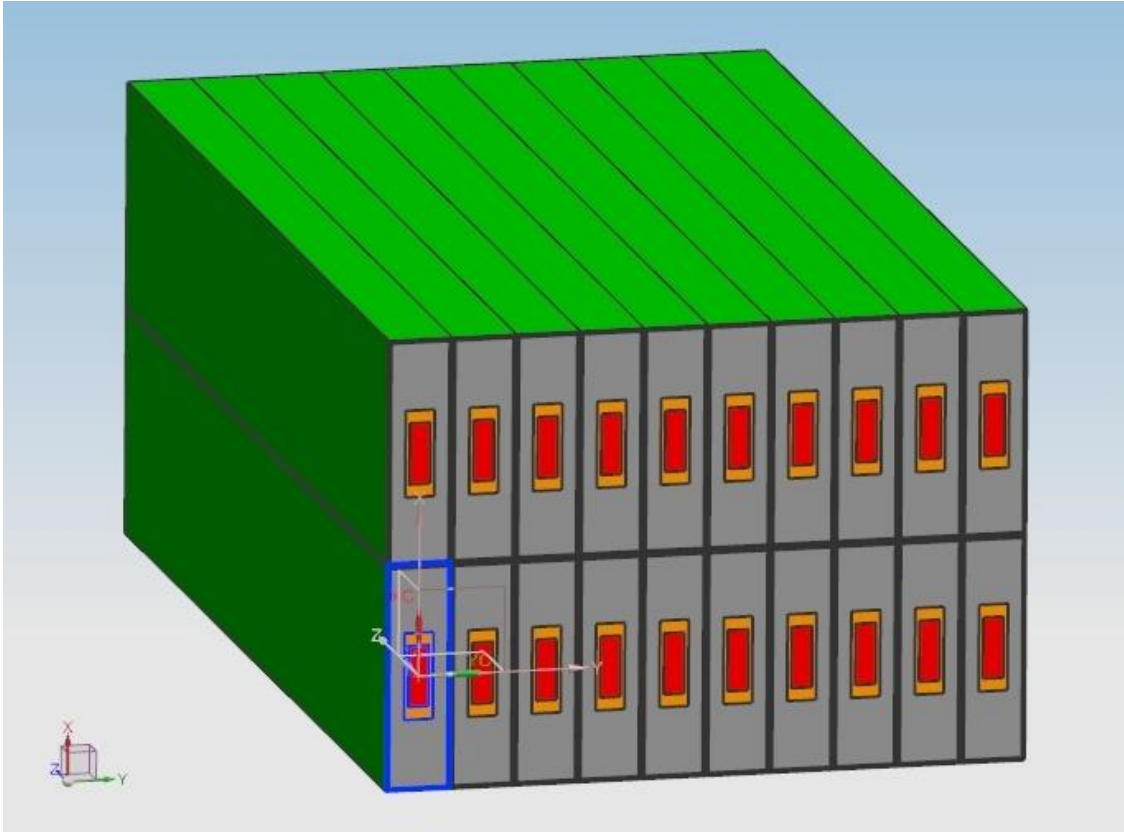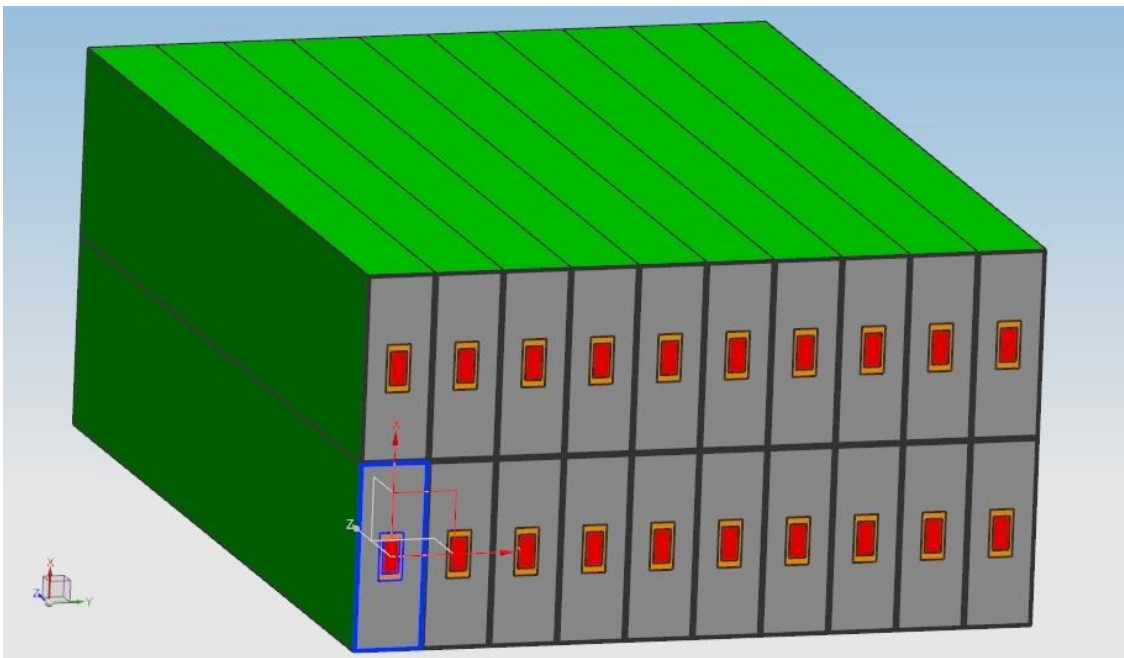
Figure 4.3: DS1 stack model.

Figure 4.4: DS2 stack model.

The stack model for both DS1 and DS2 conductors has been modeled.

4. Material properties

The material properties required for a transient thermal-stress analysis are:

- Thermal conductivity
- Thermal contraction
- Specific heat
- Density
- Elastic properties:
    - Young's modulus
    - Poisson's ratio
    - Shear modulus

Though the DS magnets have to be cooled from environment temperature of $300\,K$ to the helium operating temperature of $4.7\,K$, the range of temperature that interests the analysis is very large. Therefore, the material properties changing during the process is not unimportant.

Each of the required average properties has to be calculated for the stack as an orthotropic material and as functions of temperature from 4 to $300\,K$

To accomplish this task, the following procedure has been followed for both DS1 and DS2 conductors:

1. Collect data regarding the properties for each material composing the magnets for that range of temperatures from the software CryoComp.

Cables	Insulation
• Niobium-Titanium	• G10 (orthotropic)
• Copper RRR 80	• Kapton
• Aluminum RRR 800	• Epoxy

2. Input the values in the Ansys Engineering Data for every simulation.

3. Perform a simulation for each required average property.
4. Use the basic laws of physics to calculate the coefficients at a defined temperature.
5. Repeat the simulation for all the temperatures in the range
6. For orthotropic properties, repeat the simulation in order to obtain values for different directions.

5. Simulations and results

a. Thermal conductivity

- Law: Fourier's law of conduction

$$\dot{Q} = kA\frac{dT}{dx}$$

- Analysis: Steady state thermal
- Model: single conductor. It has been showed that the border effects do not affect the result in this case, so a smaller model permits to reduce computational time.
- Boundary conditions: $1\,K$ temperature difference between two parallel faces in one direction
- Parameters: temperature at which the simulation is performed.
- The simulation calculates the heat reaction probe ($\dot{Q}$) so that it is possible to calculate k.

C: K radial
Temperature 2
Time: 1. s
9/17/2015 5:30 PM

A Temperature: 4. K
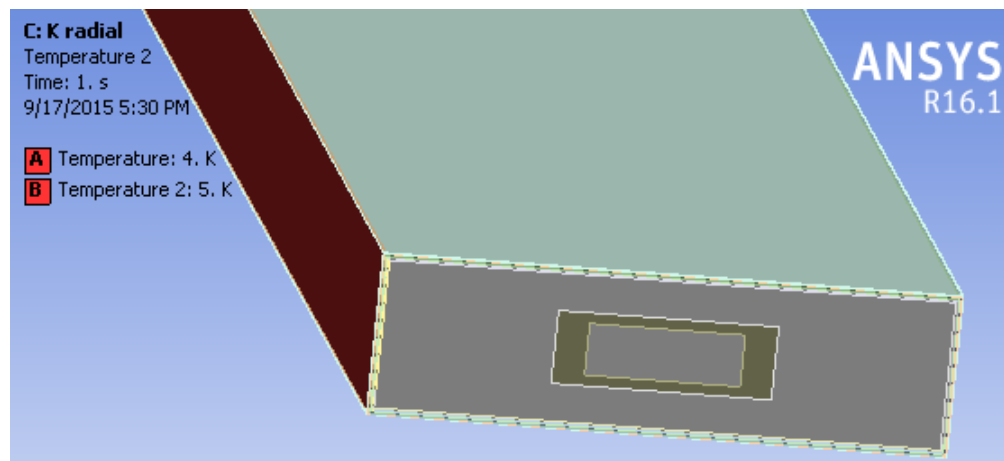B Temperature 2: 5. K

ANSYS
R16.1

Figure 5.1: Radial analysis for thermal conductivity.

Thermal conductivity for the two types of cable in the three directions (azimuth, axial, radial) can therefore be calculated as a function of temperature.
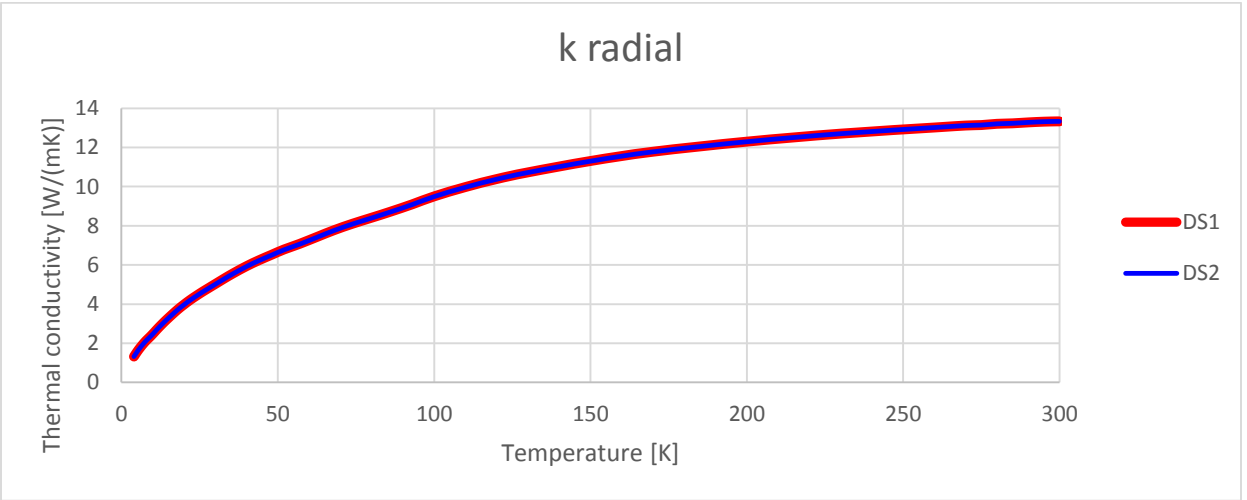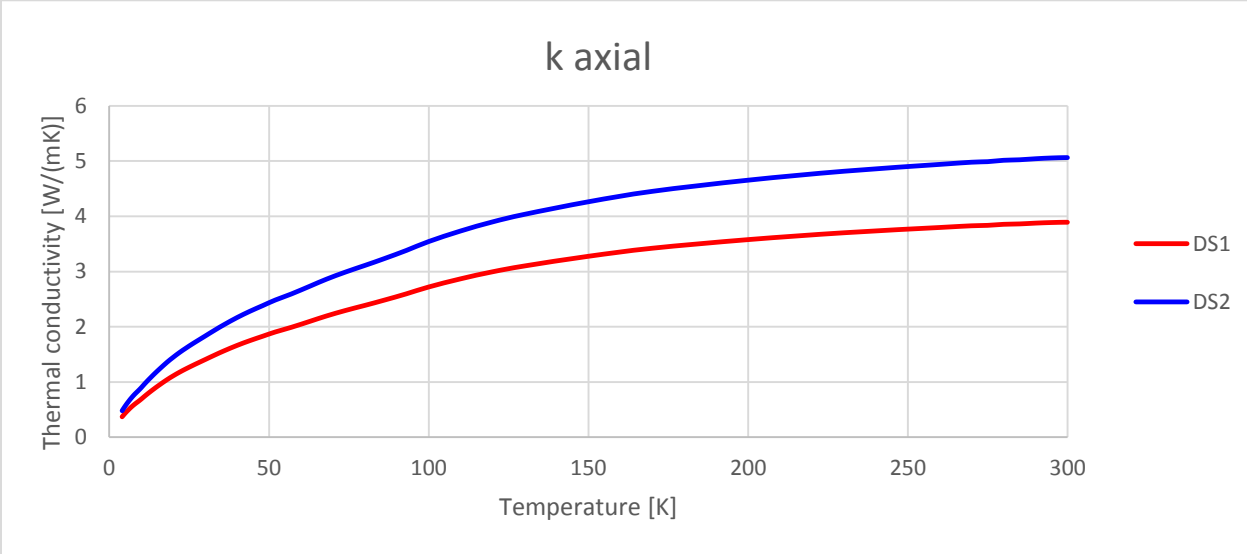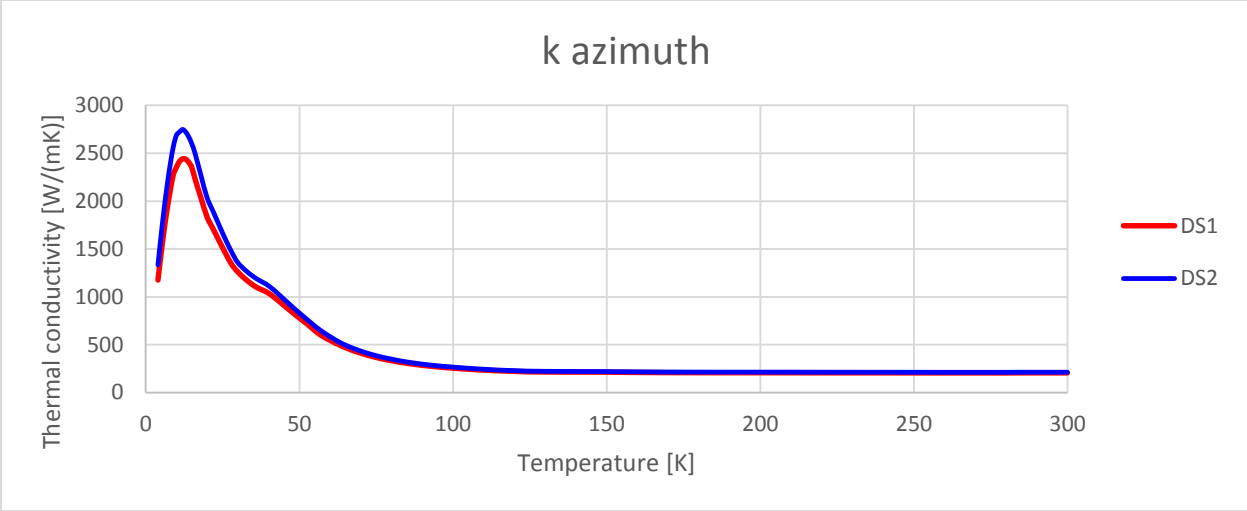
Figure 5.2: Results of thermal conductivity for DS1 and DS2 in the three directions.
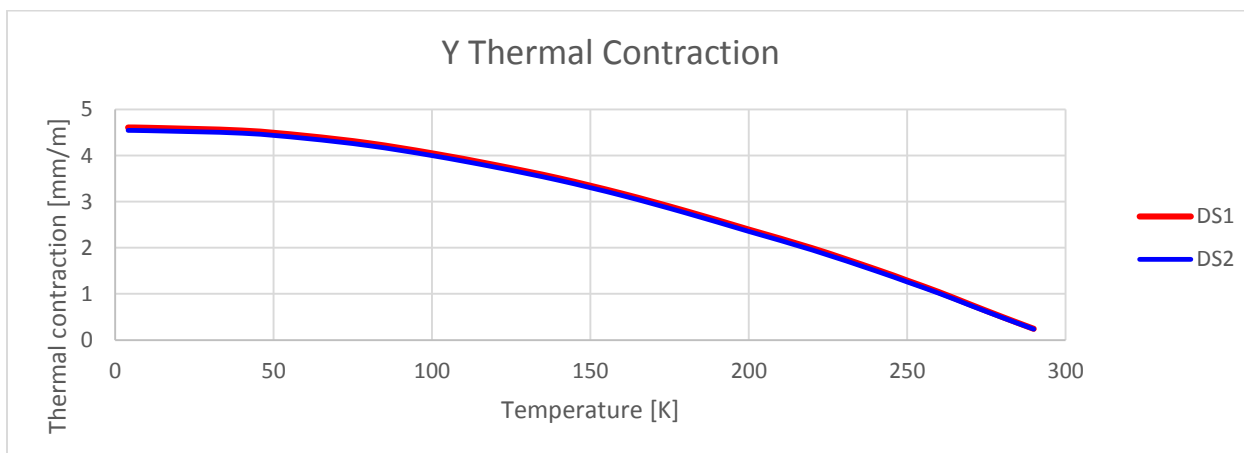
b. Thermal contraction

- <u>Law</u>: law of thermal expansion

$$\Delta L = \beta L \Delta T$$

- <u>Analysis</u>: static structural
- <u>Model</u>: stack, to avoid border effects
- <u>Boundary conditions</u>: thermal condition, set as parameter. Environment temperature is set at $300\ K$.
- The simulation calculates the deformation in X, Y and Z direction

Thermal contraction for the two types of cable can be calculated as a function of temperature. For each data point, the reference temperature is $300\ K$. Thus, thermal contraction at $300\ K$ is obviously zero.
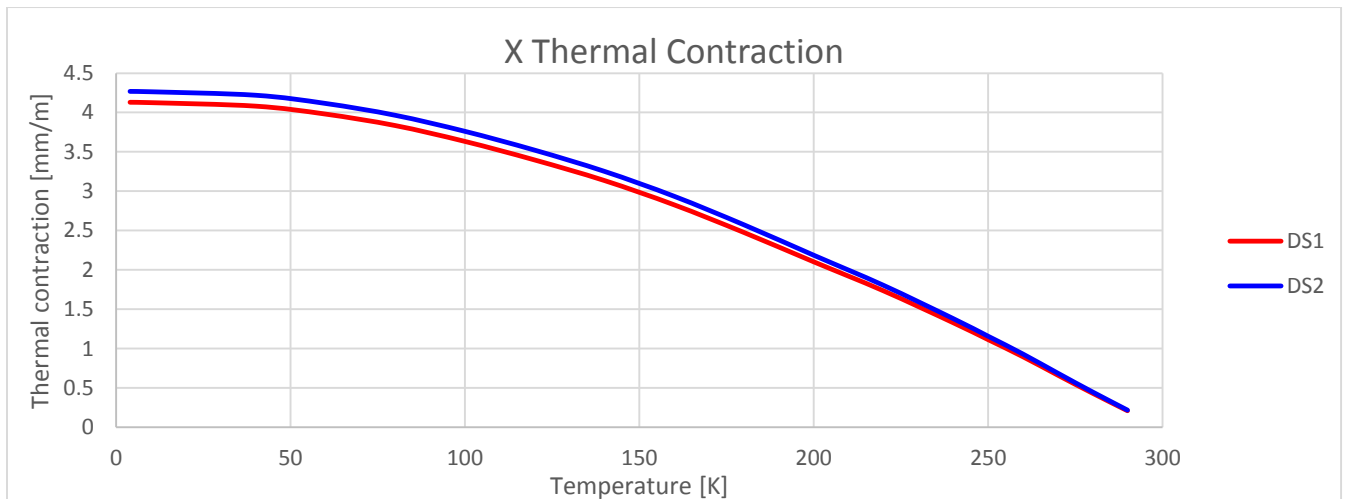
Figure 5.3: Results of thermal contraction for DS1 and DS2 in the three directions.
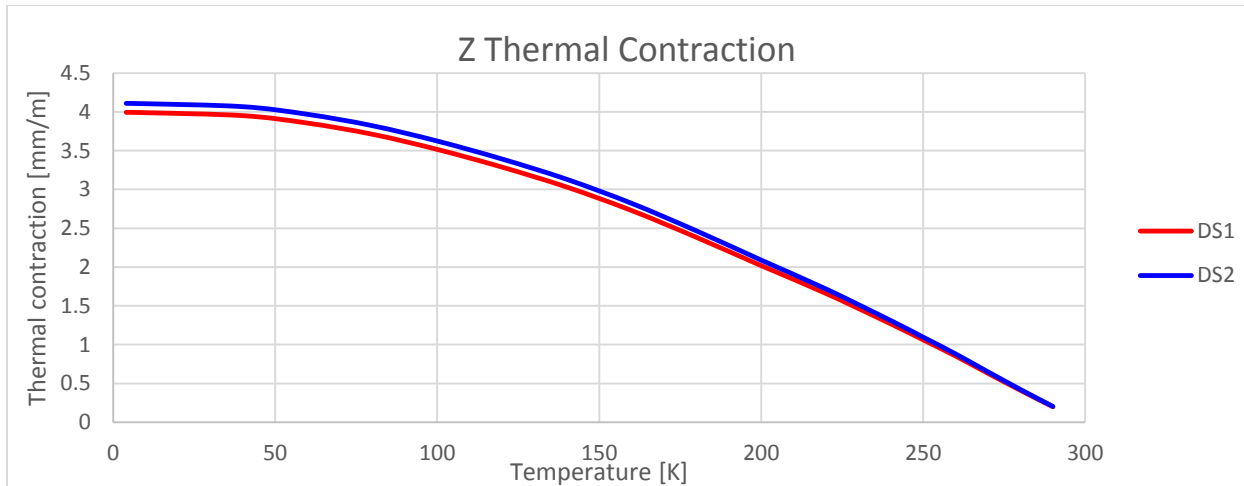
c. Density

- <u>Weighted average method</u>:

$$\rho = \sum_i \rho_i f_i$$

where $f_i = \frac{V_i}{V} = \frac{A_i}{A}$ is the volume fraction of each material, obtained dividing the area of the material by the total area of the cross-section.

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

d. Specific heat

- <u>Weighted average method</u>:

$$c = \sum_i c_i f_i$$

where $f_i = \frac{V_i}{V} = \frac{A_i}{A}$ is the volume fraction of each material, obtained dividing the area of the material by the total area of the cross-section
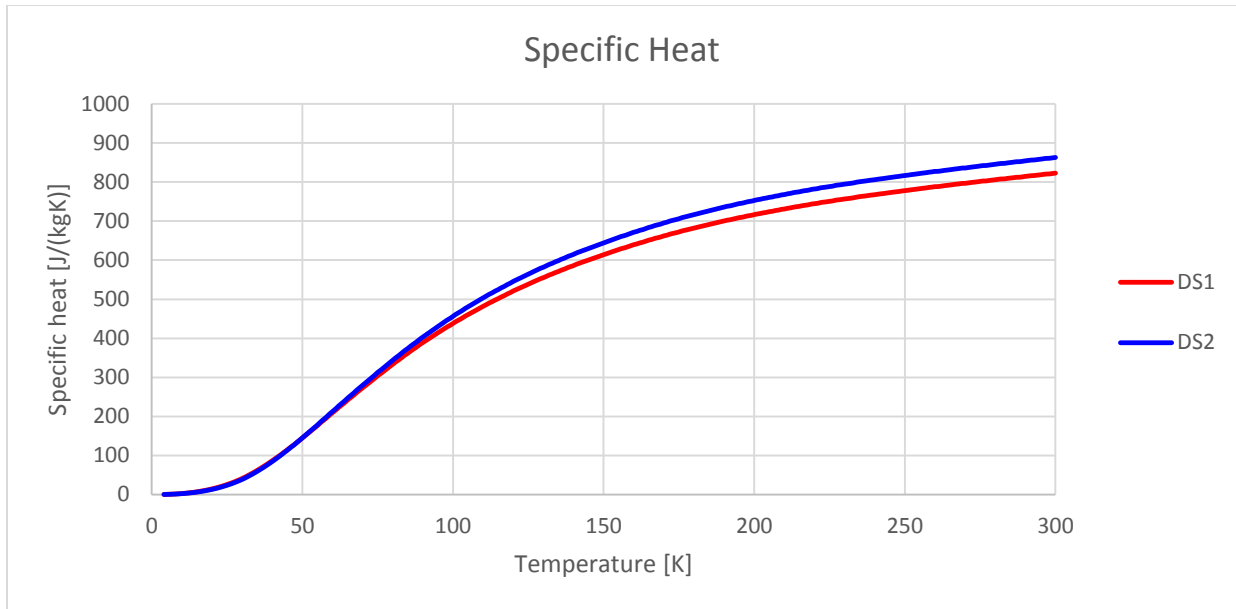
14

Figure 5.4: Specific heat for DS1 and DS2 as function of temperature.

e. Elastic properties

- Laws of elasticity:

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

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

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

- Analysis: Static structural
- Model: stack
- Boundary conditions: a known force on a known surface, so that the stress, either normal or shear, is known. A displacement on the opposite surface also has to be set to constrain the assembly.
- The simulation calculates the deformation in the three directions X, Y and Z, so that it is possible to calculate the strain.

Knowing the stress and the strain, calculation of the elastic coefficient is immediate.

All the simulation are run at the environment temperature of $300\ K$. The materials become stronger as the temperature decreases, but the analysis has to be conservative, and the worst case has to be considered. So the elastic properties are calculated at one temperature only.
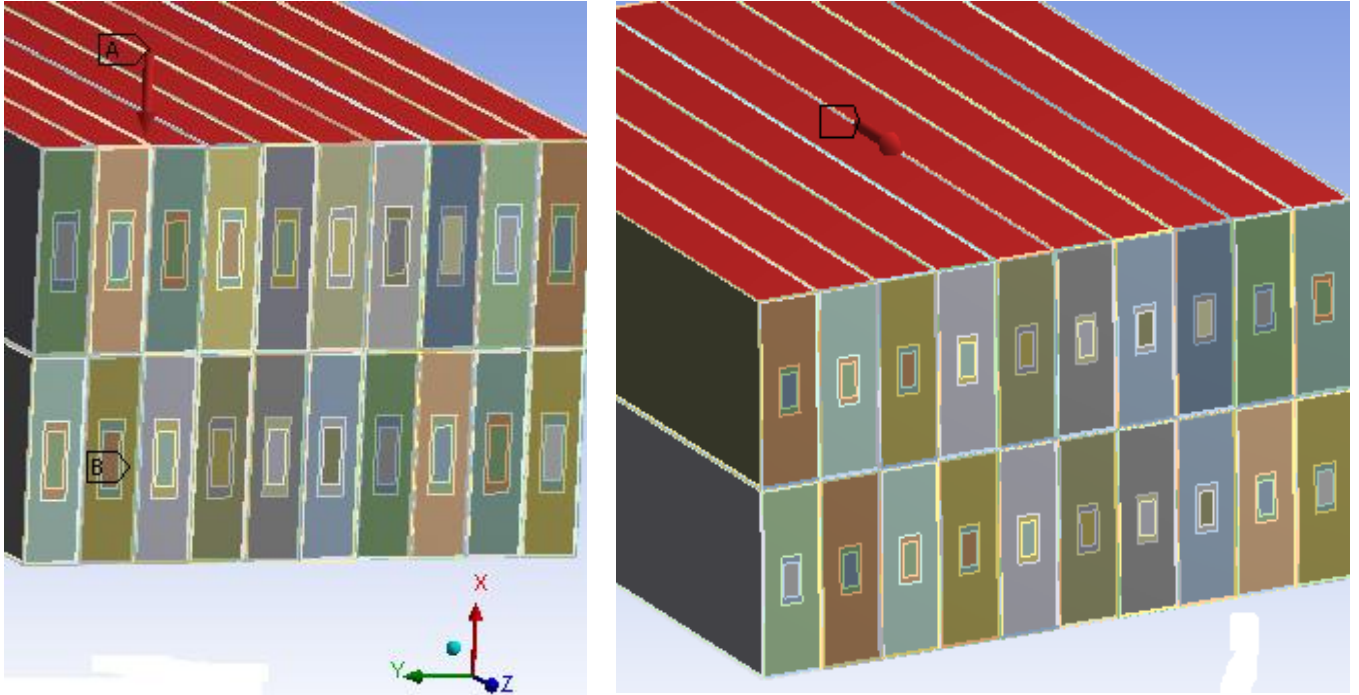
15

Figure 5.5: Two examples of analysis for calculation of elastic properties: on the left Poisson's ratio and Young's modulus for DS1 (force applied is perpendicular to the surface), on the right, shear modulus for DS2 (force applied is parallel to the surface).

The values obtained for DS1 are:

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

The values obtained for DS2 are:

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

All the properties required for a transient thermal-stress analysis have been obtained and considered reasonable.

In fact, making a comparison between the two types of conductors of the Detector Solenoid, it is possible to notice that the properties are quite similar. In DS2, though, aluminum properties are more relevant, according to the geometry of the model.

6. Detector Solenoid transient thermal-stress analysis

In order to find out a temperature difference that can be applied safely without breaking the model, the cooling down process of the entire Detector Solenoid must be simulated: a transient thermal FEA is performed to find out the temperature trend; a static structural analysis with a thermal condition imported from the transient thermal at some data point is necessary to calculate the equivalent stress in the assembly.
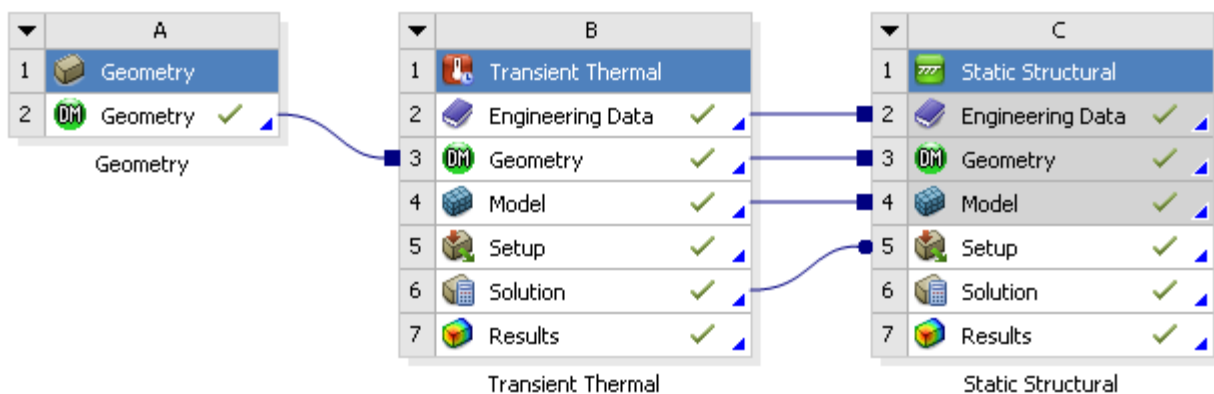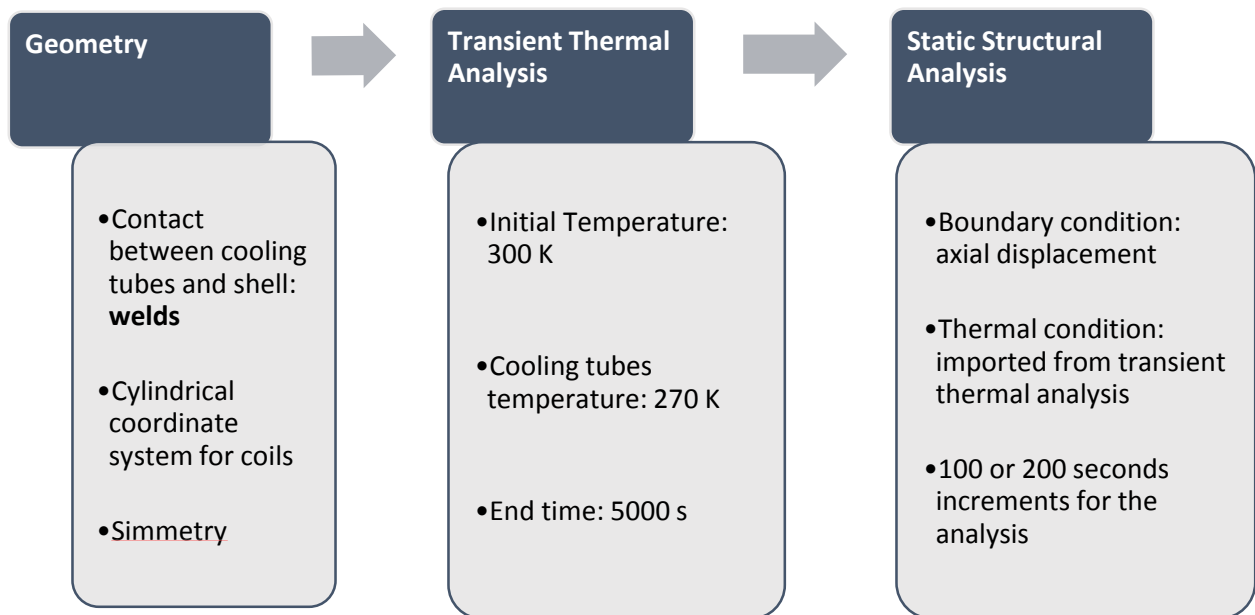
Geometry → **Transient Thermal Analysis** → **Static Structural Analysis**

Geometry	Transient Thermal Analysis	Static Structural Analysis
• Contact between cooling tubes and shell: **welds** • Cylindrical coordinate system for coils • Simmetry	• Initial Temperature: 300 K • Cooling tubes temperature: 270 K • End time: 5000 s	• Boundary condition: axial displacement • Thermal condition: imported from transient thermal analysis • 100 or 200 seconds increments for the analysis

	A			B			C
1	Geometry		1	Transient Thermal		1	Static Structural
2	Geometry ✓		2	Engineering Data ✓		2	Engineering Data ✓
			3	Geometry ✓		3	Geometry ✓
	Geometry		4	Model ✓		4	Model ✓
			5	Setup ✓		5	Setup ✓
			6	Solution ✓		6	Solution ✓
			7	Results ✓		7	Results ✓
				Transient Thermal			Static Structural

Figure 6.1: Summary of the final DS analysis.
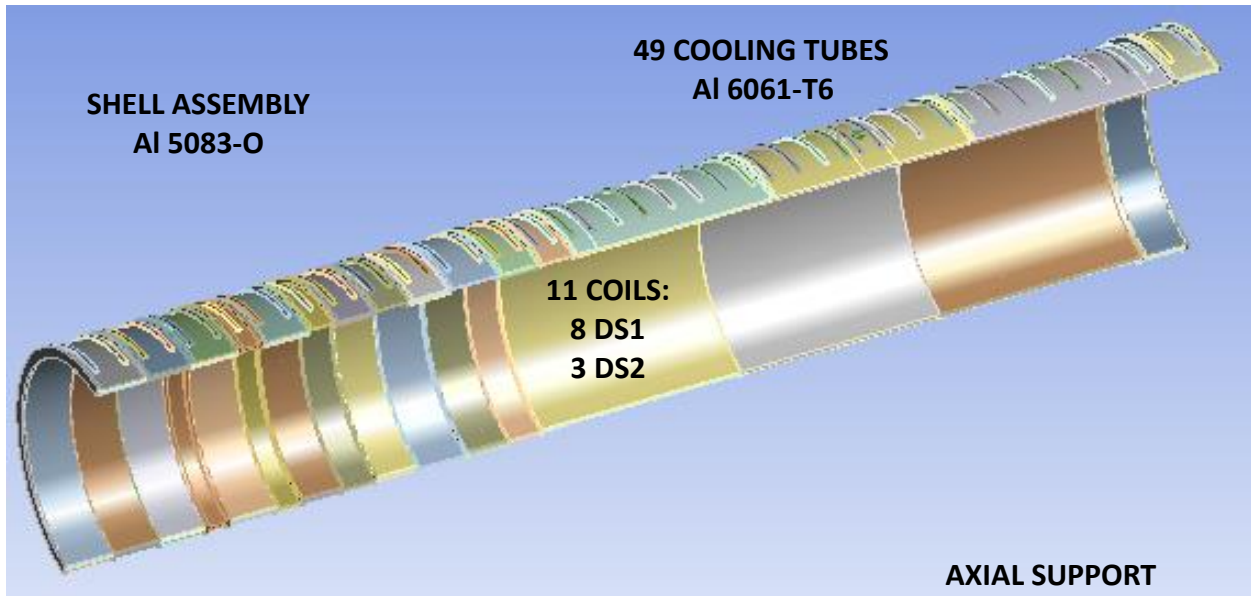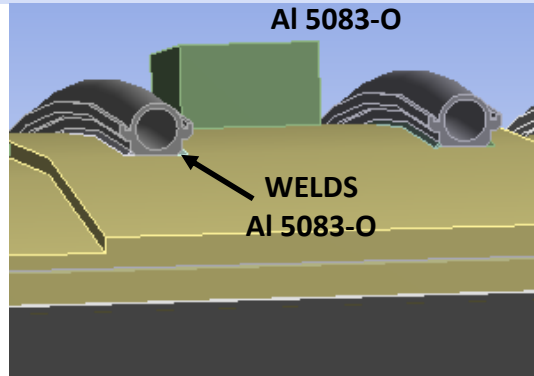
18

a. The model

Figure 6.2: Detector Solenoid 3D half model.

The Detector Solenoid is made by a cylindrical aluminum shell with forty-nine welded cooling tubes where gaseous or liquid helium flows to cool down the entire structure. In the internal surface of the shell, eleven coils are bonded to the shell with a layer of G10 insulation in the middle.

The disposition of the two types of conductors is correlated with the magnetic field required by the physics of the experiment.
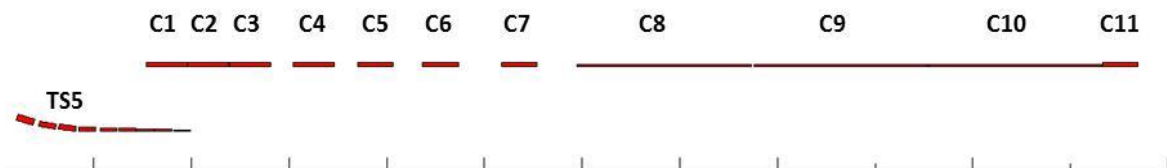
Here is an outline of that.

Figure 6.3: Layout of the DS coils.

Coil Number	Center Z (mm)	Length (mm)	Length Tolerance (mm)	Inner Radius (mm)	Radius Tolerance (mm)	Turns
1	241	422.5	2	1053.5	1	2x73 DS1
2	668	422.5	2	1053.5	1	2x73 DS1
3	1095	422.5	2	1053.5	1	2x73 DS1
4	1751	422.5	2	1053.5	1	2x73 DS1
5	2382	364.5	2	1053.5	1	2x63 DS1
6	3075	364.5	2	1053.5	1	2x63 DS1
7	3905	364.5	2	1053.5	1	2x63 DS1
8	5332	1838.5	7	1053.5	1	1x244 DS2
9	7175	1838.5	7	1053.5	1	1x244 DS2
10	9018	1838.5	7	1053.5	1	1x244 DS2
11	10177	364.5	2	1053.5	1	2x63 DS1

Table: Parameters of the Detector Solenoid coil segments. Both DS1 and DS2 cables included the 0.25 mm composite cable and 0.5 mm ground insulation.

b. Engineering Data

The materials that compose the Detector Solenoid are:

- Al 5083-O for the shell assembly, the axial support fixed to the shell and the cooling tubes welds;
- Al 6061-T6 for the cooling tubes;
- DS1 Conductor for eight out of eleven coils;
- DS2 Conductor for three out of eleven coils;
- G10: due to the fact that it is an orthotropic material, it is differentiated in parallel and perpendicular to the coil in order to assign the material properties in the correct direction.

The properties previously obtained are the average of the stacks of conductors. They are imported in Ansys Engineering Data in the sections DS1 Conductor and DS2 Conductor.

For the other materials, properties required are directly imported from the software CryoComp.

c. Geometry

In this section, some features have to be applied:

- o It is important to be sure that the contacts between the shell assembly and the cooling tubes is realized with the welds. This makes the model as realistic as possible.
- o A cylindrical coordinate system have to be applied as reference for the coils to assign the properties.
- o A symmetry region has to be applied to simulate the entire DS.

d. Transient thermal analysis

The transient thermal analysis simulates the cooling down process of the Detector Solenoid:

- Initial temperature of $300\ K$ is set, since the structure is at the environment temperature at the beginning of the analysis;
- The boundary condition chosen is a gaseous helium temperature of $270\ K$ on the inner surfaces of the cooling tubes. This is a conservative situation, since a sudden temperature shock instead of a convective condition is applied.
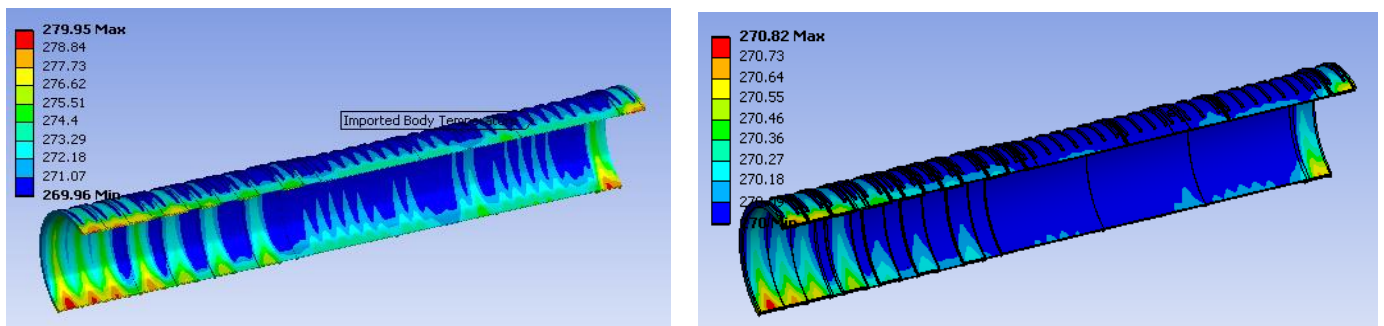- The simulation is set to run for $5000\ s$.

Figure: 6.4: Temperature distribution in the DS at 2000 s (left) and 5000 s (right).

It is clear from the images and the maximum temperature chart that the Detector Solenoid completely cools down at $270\ K$ in $5000\ s$.
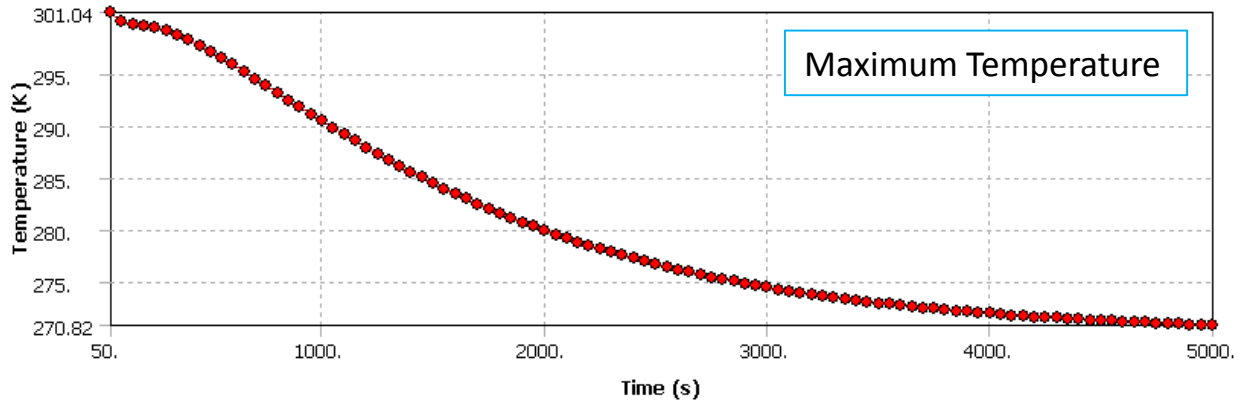
*Figure: 6.5 .Maximum temperature distribution in time.*

e. Stress analysis

A static structural analysis is performed at 100 or $200 \ s$ intervals to calculate the stress in the structure, in particular in the crucial bodies: the coils and the welds. The material with the lowest allowable stress is the Aluminum-stabilizer, so it is preferable to keep all the stack under this stress.

- An axial displacement is applied on the axial support to impede the deformation in the axial direction;
- The thermal condition is imported from the previous transient thermal analysis step by step.

The distributions in time of the Von Mises equivalent stress in coils and welds are shown in the following charts:
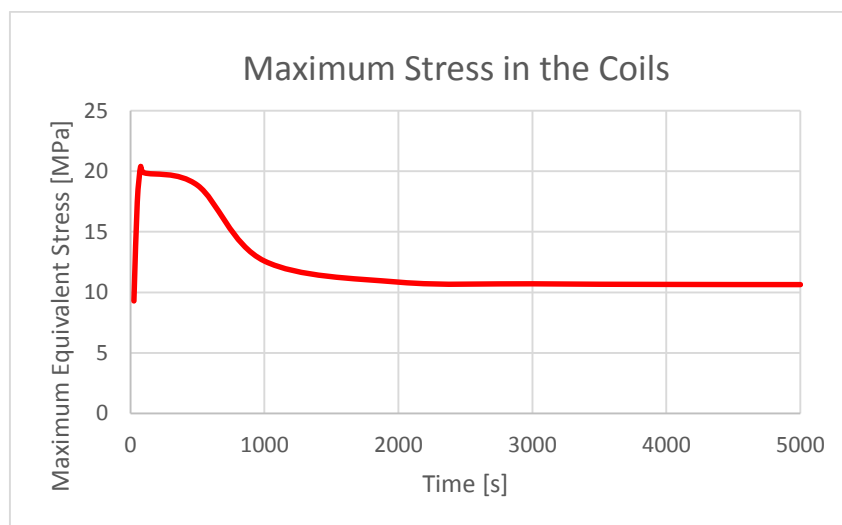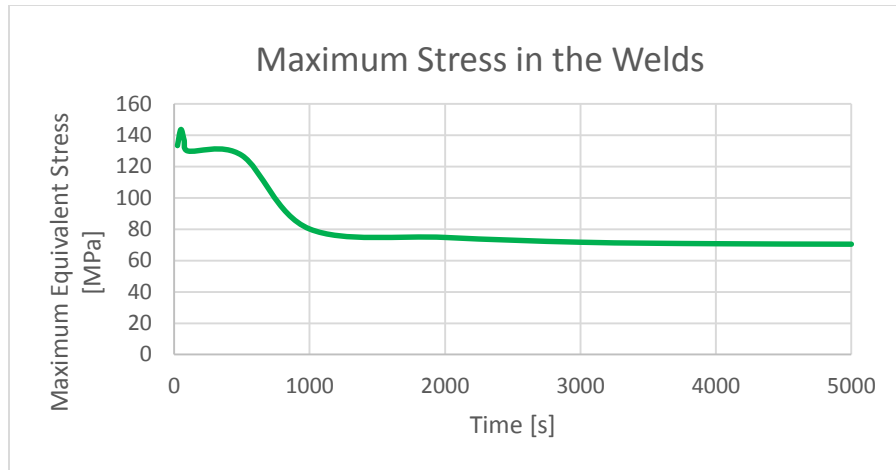
It's possible to notice from these results that the maximum stress occurs at about 75 s.
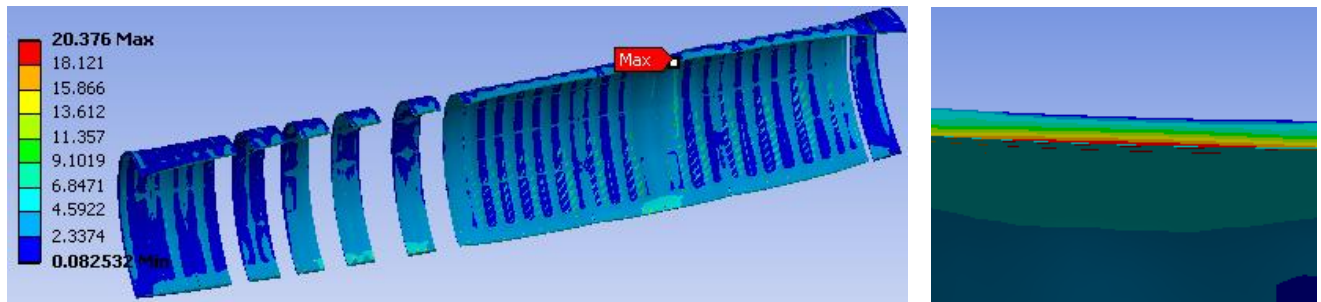

Figure 6.6:.Stress distribution in the DS coils at 75 s. On the right, zoom on the coils where the maximum stress is located.

In the following table, the results are resumed:

	Maximum Equivalent Stress (MPa)	Allowable Stress (MPa)
Coils	20.34	30
Welds	136.6	75

For the coils, the 30 K temperature difference can be considered safe since the maximum stress is lower than the acceptable one.

Instead, in the welds maximum stress exceeds the allowable one. This is not a dangerous situation though, since the area interested by the higher stress is very small.

Other analysis on similar bodies has given comparable results and experimental tests havent't shown any break.

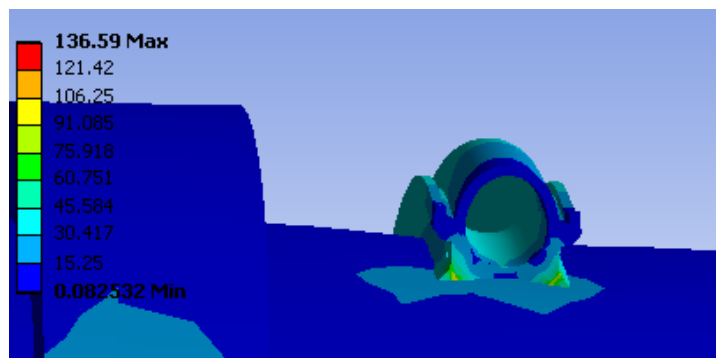Plus, reason for high stress is that a very

Figure 6.7:.Stress distribution in the most stressed weld.

23

conservative analysis has been performed.

In fact, a more realistic and less conservative analysis would see a convective condition with a proper convection coefficient instead of a sudden step of $270\,K$. This would lead to lower stresses and a more realistic distribution, pushing maximum stress farther up in time.

It is possible to say, though, that the difference of temperature applied in the analysis is safe for the entire Detector Solenoid, since it has been verified for the worst case scenario.

7. Conclusions

The analysis can therefore be considered successful.

The Detector Solenoid has been studied by building solid models of single cables and stacks, for both DS1 and DS2 conductors.

Different simulations on this models has permitted to calculate the average orthotropic thermal and structural properties of the conductors as functions of temperature for the range 4 to $300\,K$.

Then the values obtained in this first part of the work have been imported as input data in the Detector Solenoid transient thermal-stress analysis. In fact, the conductors has been modeled as single bodies made by a single material with known properties, in order to reduce computational time.

The 3D DS model has been prepared for the FEM analysis by setting the correct contacts and time steps and choosing the boundary condition of a $270\,K$ step temperature.

Considered the fact that the analysis was performed in the most conservative case possible, this $30\,K$ difference of temperature has been found safe for the structure.

Since the Detector Solenoid completely cools down in $5000\,s$, it has also been possible to calculate the cool down rate: $21.6\ ^{K}/_{hour}$.

Due to the fact that the analysis was conservative and the stress was still low enough, it will be possible to perform new simulations on the same model in different conditions. For example, a more realistic convection coefficient and a more aggressive cool down rate (i.e. $40\,K$) might be applied to see how the cooling down process and the stress distribution evolves. The analysis will continue and the best result will be used.

In any case, as far as the Detector Solenoid is concerned, the Mu2e experiment will be able to start safely.

Acknowledgments

Reference for the figures: Mu2e Technical Report.