SUMMER STUDENT AT FERMILAB 2015

THE MU2E TRANSPORT SOLENOID ALIGNMENT ISSUES

Veronica Ilardi

Fermilab

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1. Introduction

The following report has the purpose to describe the work that I developed during the two months-program Summer Student at Fermilab, from July 27 to September 25, 2015.

I worked with Mu2e group, Technical Division, with Thomas H. Nicol and Mauricio Lopes as supervisors.
The scope of the work was the Mu2e Transport Solenoid alignment issue.
In the first part of the internship I learned how to realize a mechanical model using a new software, SimMechanics, and I realized a first, simple model of the Mu2e Transport Solenoid.
After that, in the last part of the program, I started to work on simple examples of bodies on which it acts a force, in order to estimate the value of the force in certain points of the body.
The purpose of this work, in fact, is to contribute to solve the Mu2e Transport Solenoid alignment issue, studying how the Transport Solenoid reacts to a force and how this affects the alignment of its rods.
I should realize this part of the work in the next months, during the internship at Fermilab for my Master Degree Thesis.

2. The Mu2e experiment

The Mu2e experiment proposes to measure the ratio of the rate of the neutrino-less, coherent conversion of muons into electrons in the field of a nucleus, relative to the rate of ordinary muon capture on the nucleus. The conversion process is an example of charged lepton flavor violation, a process that has never been observed experimentally.
The conversion of a muon to an electron in the field of a nucleus occurs coherently, resulting in a monoenergetic electron (105 MeV) near the muon rest energy that recoils off of the nucleus in a two-body interaction. At the proposed Mu2e sensitivity there are a number of processes that can mimic a muon-to-electron conversion signal. Controlling these potential backgrounds drives the overall design of Mu2e.
The overview of the Mu2e experiment can be seen in *Figure 2.1*.
It is primarily formed by three large solenoid systems: the Production Solenoid (PS), the Transport Solenoid (TS) and the Detector Solenoid (DS). The muon beam is created by an 8 GeV, pulsed beam of protons striking a production target.

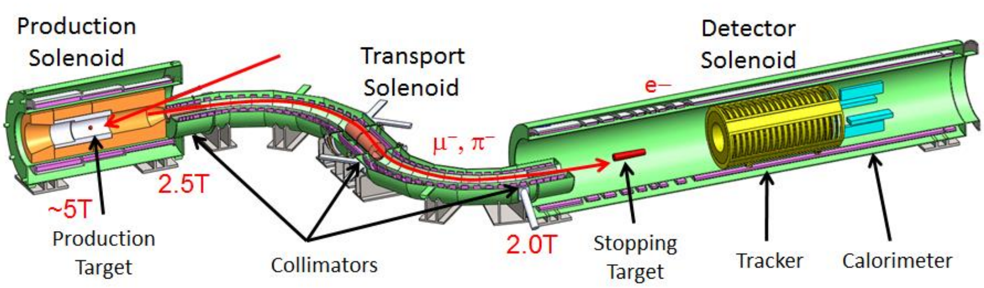

Figure 2.1 – The Mu2e experiment overview

The negative magnetic field gradient in the PS creates a mirror effect on the charged particles produced after the collision, pushing the beam downstream. This beam is then transported by the TS. The three collimators in TS provide charge and momentum selection. In the DS, the muon beam is stopped in the stopping target and the 105 MeV electrons from the conversion are detected in the tracker.

The magnetic system is formed by 3 coils for PS, 52 Coils for TS and 11 coils for DS. Each subsystem is in a separate cryostat module. The TS is divided into two cryostats (named TSu and TSd). [1]

3. Transport Solenoid

3.1 Introduction and General Requirements

The Transport Solenoid consists of a series of wide aperture superconducting solenoid rings contained in two cryostats. Each cryostat has a chimney for superconducting leads, helium supply and return lines and instrument ports.
Internal mechanical supports in each cryostat transmit forces to external mechanical supports that connect to the experiment enclosure structure.
The Transport Solenoid does not have an iron return yoke.

As shown in *Figure 3.1*, the Transport Solenoid is segmented into the following set of components:
• TS1 - Straight section that interfaces with the Production Solenoid;
• TS2 - Toroid section downstream of TS1;
• TS3 - Straight section downstream of TS2: TS3u coils are in the TSu cryostat and TS3d coils are in the TSd cryostat;
• TS4 - Toroid section downstream of TS3;
• TS5 - Straight section downstream of TS4 that interfaces with the Detector Solenoid.

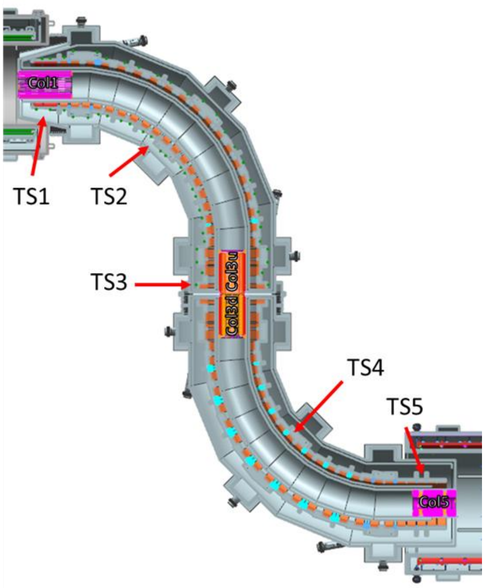

Figure 3.1 - The Transport Solenoid with the significant components identified.

The Transport Solenoid performs the following functions:

• Pions and muons are created in the production target in the Production Solenoid. The Transport Solenoid maximizes the muon yield by efficiently focusing these secondary pions and subsequent secondary muons towards the stopping target located in the Detector Solenoid. High energy negatively charged particles, positively charged particles and line-of-sight neutral particles will be almost completely eliminated by the two 90° bends combined with a series of absorbers and collimators.
• The TS1 field must be merged with the field of the Production Solenoid at the interface for optimum beam transmission.
• There must be a negative axial gradient at all locations in the straight sections (TS1, TS3 and TS5) for radii smaller than 0.15 m to prevent particles from becoming trapped or losing longitudinal momentum.
Through the first toroid section (TS2) the beam will disperse vertically, allowing a collimator in TS3 to filter the particles based on sign and momentum.
• The second toroid section (TS4) will nearly undo the vertical dispersion, placing the muon beam in the center of the TS5 axis.
• The TS5 field must be merged with the field of the Detector Solenoid at the interface for optimum transmission of the muon beam to the stopping target.
• The Transport Solenoid acts as a beamline interface for the antiproton window and various collimators, including the rotating collimator in TS3.

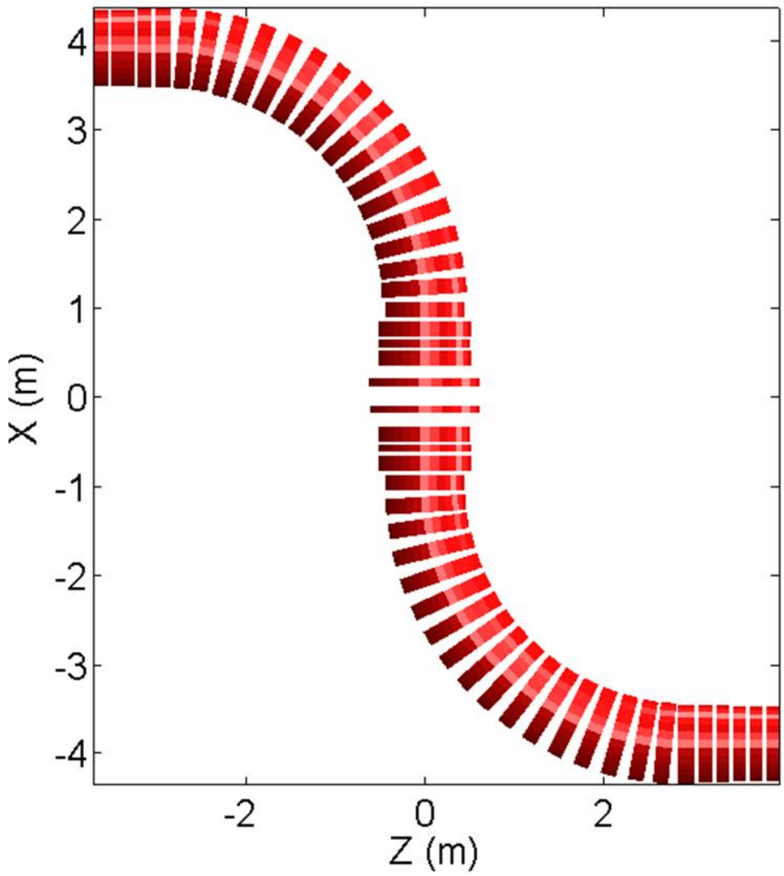

Figure 3.2 - Design of the Transport Solenoid.

The Transport Solenoid consists of two independent cryostats and power units.
The TS1, TS2 and TS3u coils are assigned to the TSu cryostat. The TS3d, TS4 and TS5 coils share the TSd cryostat.
Each cryostat will have its own superconducting link, feed box, power converter and extraction circuit.
All TS coils use the same conductor design and similar cooling schemes.
The TSu unit and the TSd unit are nearly identical, so only the preliminary design of TSu will be presented. [2]

3.2 TSu Design

The TSu is shown in *Figure 3.3* and includes the following design features:

• A single cryostat is employed to avoid gaps between coils and reduce complexity and cost.
• The coils are powered in series to minimize the number of leads and the complexity of the power and quench protection systems.
• The quench protection strategy is based on extracting most of the energy and delivering it to external dump resistors.
• Coils are preassembled and tested inside modules, with two coils per module in most cases, in order to reduce complexity during cold mass assembly.
• The mechanical support system consists of 17 supports including: four supports along the toroid main radius, four axial supports close to each end, and three gravity supports.

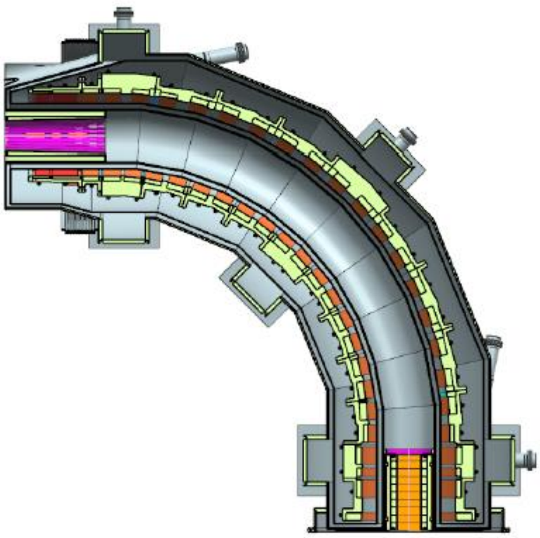

Figure 3.3 - TSu cross section along the horizontal plane.

There is a gap between the TS3u and the TS3d coils as a result of the cryostat interfaces and the mechanical hardware necessary to actuate the rotating collimator and to insert the anti-proton window. To allow for a 220 mm gap, the inner radii of the TS3 coils have been increased to 465 mm, compared to inner radii of 405 mm for the remaining TS coils. [2]

3.3 TSu Coil Design

The TS coils will be wound on collapsible mandrels and then inserted into aluminum shells (modules). The modules are assembled into a single cold mass and power unit. TS1 is a straight solenoid made of 3 coils with different outer diameters and separated by flanges. TS2 is a quarter of a toroid made of 18 coils. TS3u is a straight solenoid made of four coils. *Figure 3.4* shows the distribution of these coils and *Table 3.1* lists the main coil parameters.

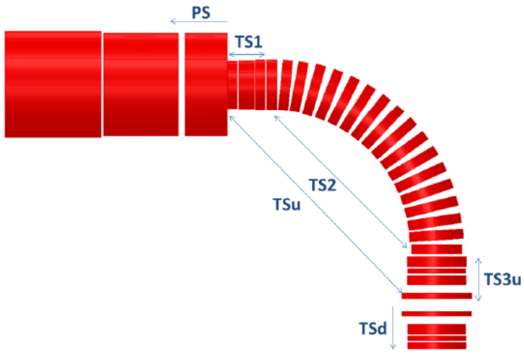

Figure 3.4 - TSu coil locations with respect to the adjacent magnets.

Coil #	Section	Coil Inner Radius [mm]	Coil Outer Radius [mm]	Coil Length [mm]	Yaw [deg]
1	TS1	405	423.13	164.96	0
2		405	434.00	257.75	0
3		405	444.88	154.65	0
4	TS2	405	448.50	175.27	0
5		405	448.50	175.27	-5.7
6		405	448.50	175.27	-10.5
7		405	463.00	175.27	-15.8
8		405	463.00	175.27	-21.3
9		405	463.00	175.27	-26.8
10		405	463.00	175.27	-32.3
11		405	466.63	175.27	-37.8
12		405	466.63	175.27	-43.3
13		405	466.63	175.27	-48.7
14		405	466.63	175.27	-54.2
15		405	470.25	175.27	-59.7
16		405	470.25	175.27	-65.2
17		405	470.25	175.27	-70.7
18		405	470.25	175.27	-76.2
19		405	470.25	175.27	-81.5
20		405	477.50	175.27	-86.3
21		405	448.50	175.27	-90.0
22	TS3u	465	523.00	175.27	-90.0
23		465	512.13	82.48	-90.0
24		465	519.38	175.27	-90.0
25		465	620.88	82.48	-90.0

Table 3.1 – TSu Coil parameters.

The TSu cold mass is comprised of thirteen coil modules.
Each module consists of bobbins made of 5083-0 Al. Most coil modules contain two wound coils inside the inner diameter. There are twenty-five coils total. Modules are bolted together at flanges to create a rigid structural unit. That unit is mounted in the cryostat using seventeen Inconel support rods, each of which have a spherical bearing at each end.
The TS cold mass and cryostat components are shown in *Figure 3.5*.

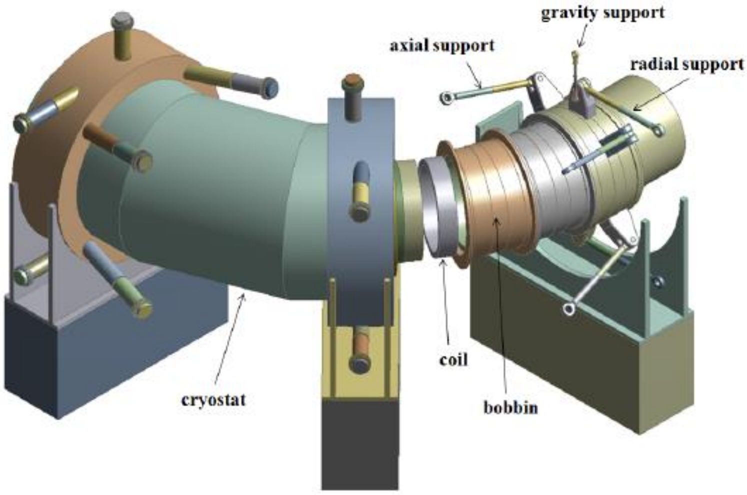

Figure 3.5 - TSu components (partial cutaway).

A typical coil module can be seen in *Figure 3.6*. Each coil is wound in a collapsible mandrel over an aluminum strip, which is used to provide cooling for the coil and ground insulation (around the whole coil). Each module will be warmed up, allowing sufficient clearance (typically 1 mm) for coil insertion followed by a shrink fit. The modules can be fabricated by using a 5-axis industrial milling machine and a CNC lathe.

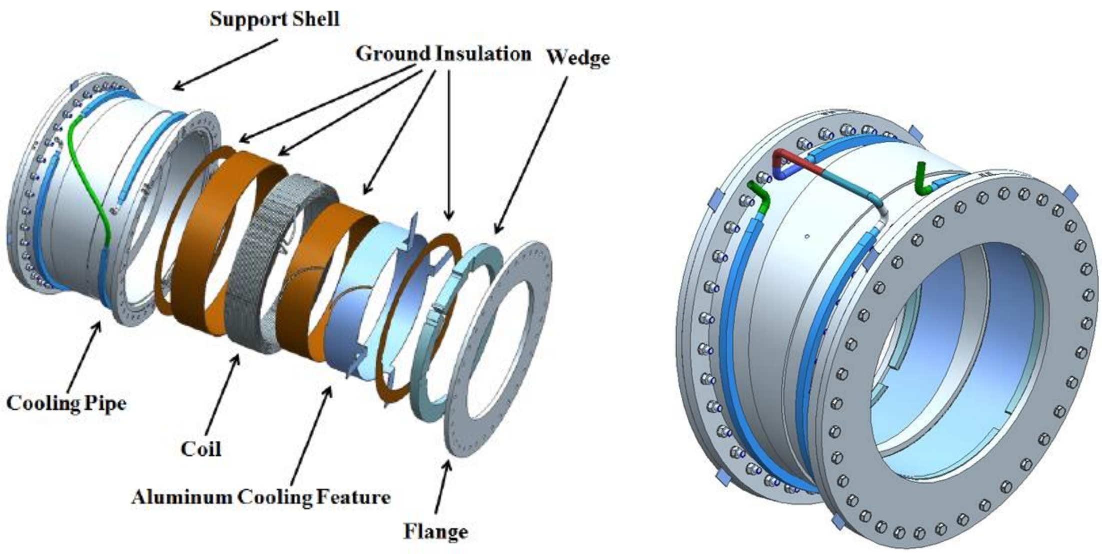

Figure 3.6 - A typical TS coil module.

The TS coils will be cooled down to cryogenic temperatures through an indirect cooling method. Each module will have an aluminum tube welded to it where the liquid helium flows providing cooling for the aluminum shell that houses the coil. Pure aluminum strips coming from the inner bore of the coils are attached to this tube providing cooling to the coil. The tube can also provide cooling for the splice boxes.
During the final assembly, modules will be bolted together and cryogenic connections will be made in between the modules, as well as the splices. [2]

3.4 Transport Solenoid alignment

The cold mass is built using the warm dimensions and it is expected that the cold mass will reach the nominal position in the operating condition (cool and energized). Many factors can contribute to the misalignment of the cold and, therefore the magnetic center. Some of these factors were discussed in [3] and they drove some aspects of the mechanical requirements for the supports of the coils.

The alignment of each module relies on mechanical features of each module. The alignment of the fully assembled cold mass is done using 17 support rods in each TS cryostat: 3 vertical, 6 radial, 8 axial (*Figure 3.7*). Each support will be instrumented with load cells that will be monitored during the thermal cycle and powering. Initial alignment of these supports will be done during the assembly based on the simulations results and a survey team using, for example, a laser tracker. Once the cryostat is sealed the cold mass is inaccessible to survey (only the external wall of the cryostat can be surveyed).

Later the alignment can be done using the readings of the load cells during the cool down and powering of the magnet. Hall probes installed in the inner bore of the cryostat's vacuum vessel can give additional information on the alignment of the cold mass. Depending on the position of the magnets, additional readings can be seen that will indicate how the rods have to be readjusted. The support rods can be adjusted with the magnets at cold but not powered.

In addition to the load cells, the cold mass will have displacement sensors that can tell the position of a target (located on a flange of the cold mass) relative to the cryostat wall.

The final alignment may be achieved by a low energy electron source test described in [3].

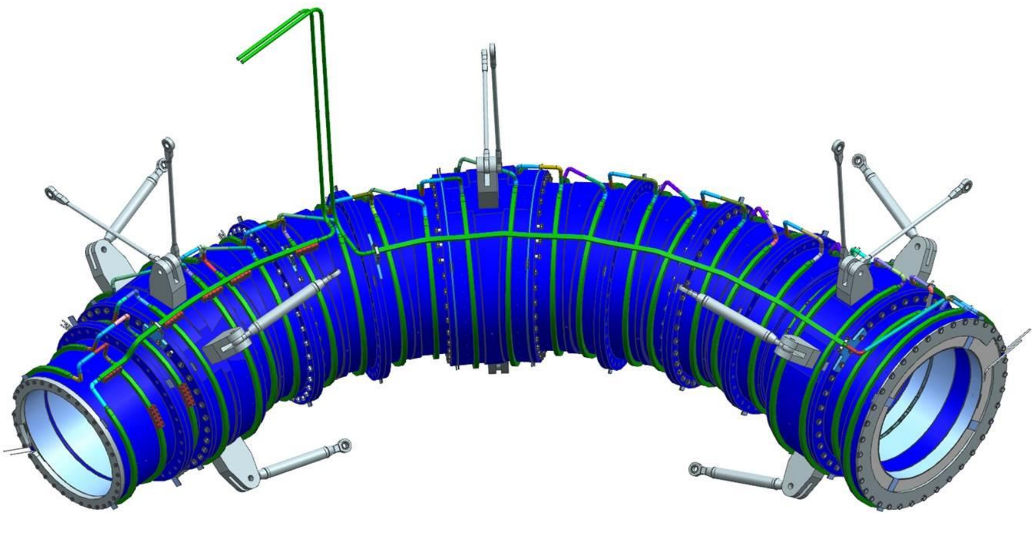

Figure 3.7 – TSu cold mass assembly.

Figure 3.8 and *Figure 3.9*, made by T. Nicol, show the displacement during the cool-down. The shadow represents the warm dimensions, that decrease due to the shrinkage of the TSu.

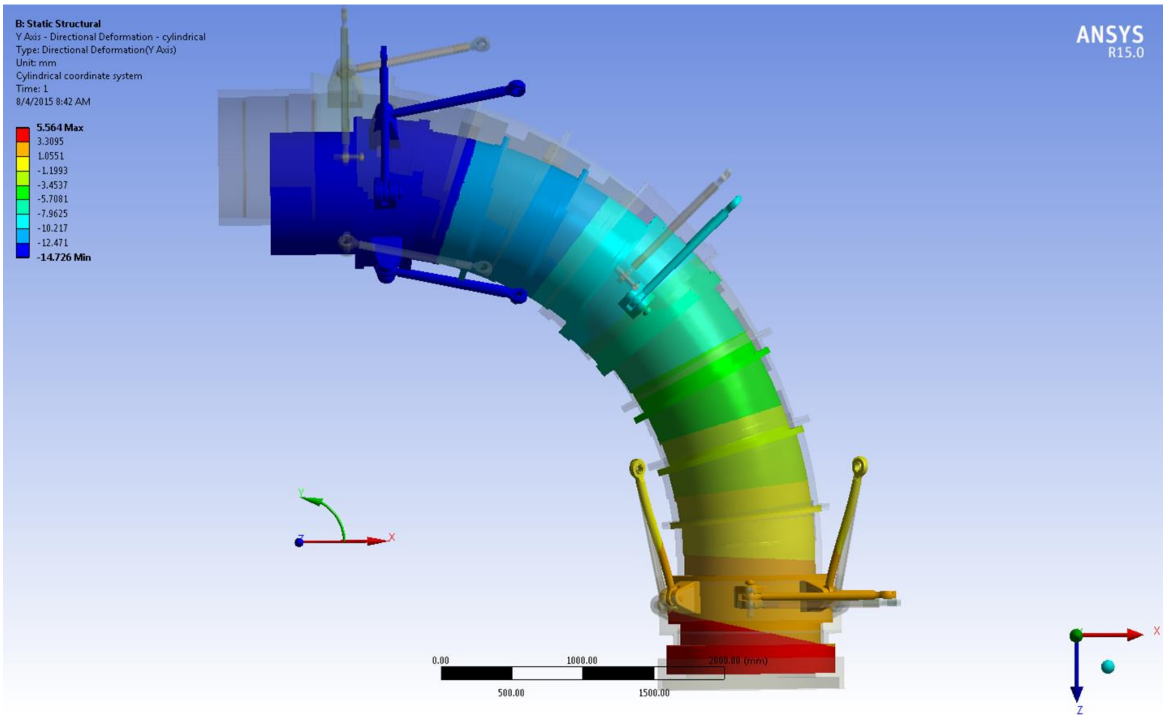

Figure 3.8 –Tsu support lug displacement during cool-down (Y axis).

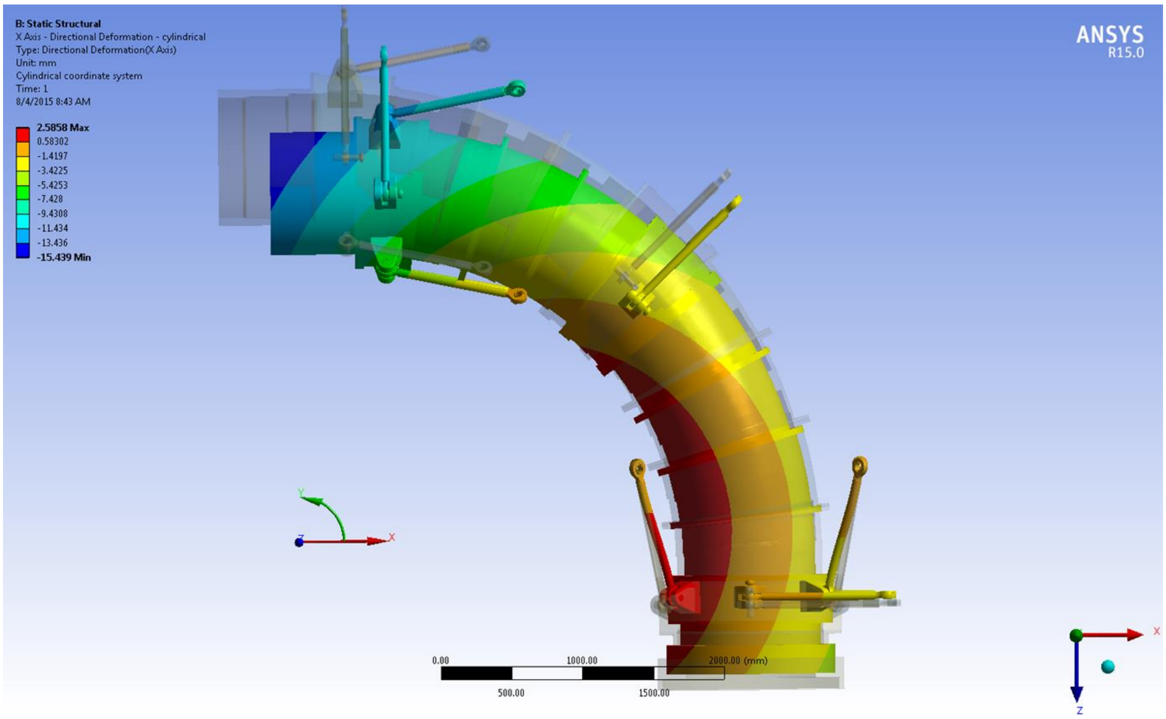

Figure 3.9 –Tsu support lug displacement during cool-down (X axis).

4. Mechanical Modeling: SimMechanics

4.1 Introduction about SimMechanics

During my work I used a software, called SimMechanics, to create a representation of the TSu.
SimMechanics is not a Finite Element Model, but is a physical model that provides a multibody simulation environment for 3D mechanical systems.
You model the multibody system using blocks representing bodies, joints, constraints and force elements, and then SimMechanics formulates and solves the equations of motion for the complete mechanical system. You can also import models from CAD systems, including mass, inertia, joint, constraint, and 3D geometry.
Figure 4.1 and *Figure 4.2* show a very simple example of what this software can do: it is just one of the first exercises that I made to test the software and to learn how to work with it.
In the first one is the principal structure of the mechanical system: it is formed by some blocks that represent bodies, revolute and prismatic joints and rigid transformations like translations and rotations.
Some of these blocks can form a subsystem, as for the crank, the rod and the head, in this case.
The second picture shows the results obtained from this structure.

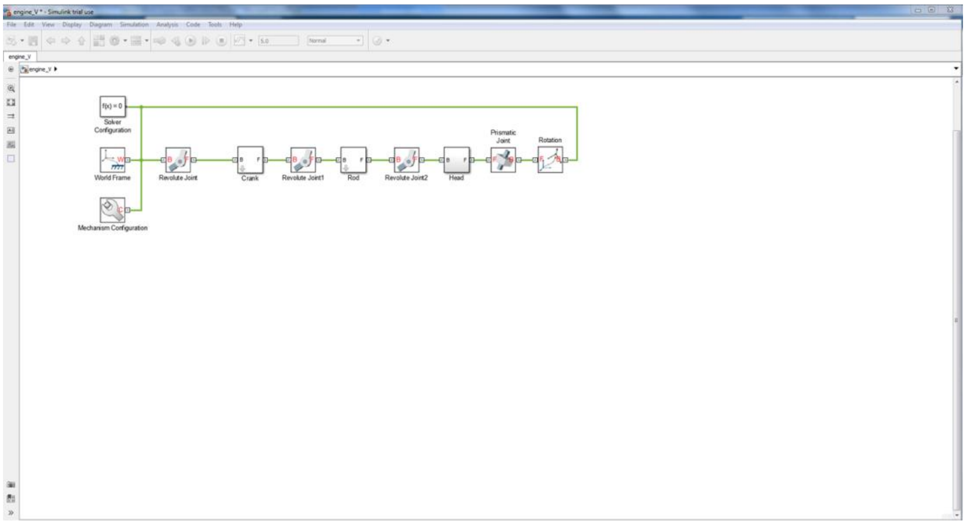

Figure 4.1 – Example of the structure of a mechanical model, made through SimMechanics.

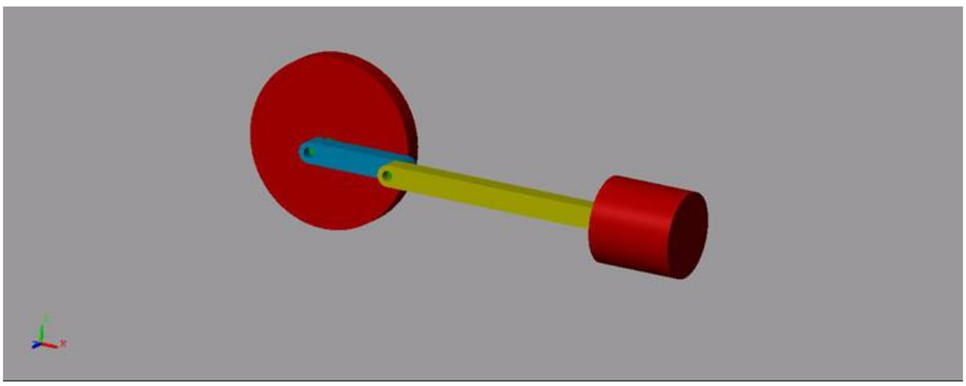

Figure 4.2 – Example of a mechanical model, made through SimMechanics.

4.2 Realization of the TSu mechanical model

In order to realize a mechanical model of the TSu, I made a simple cell (a wedge linked to a cylinder), shown in *Figure 4.3* and *Figure 4.4*, that represents a TSu coil.

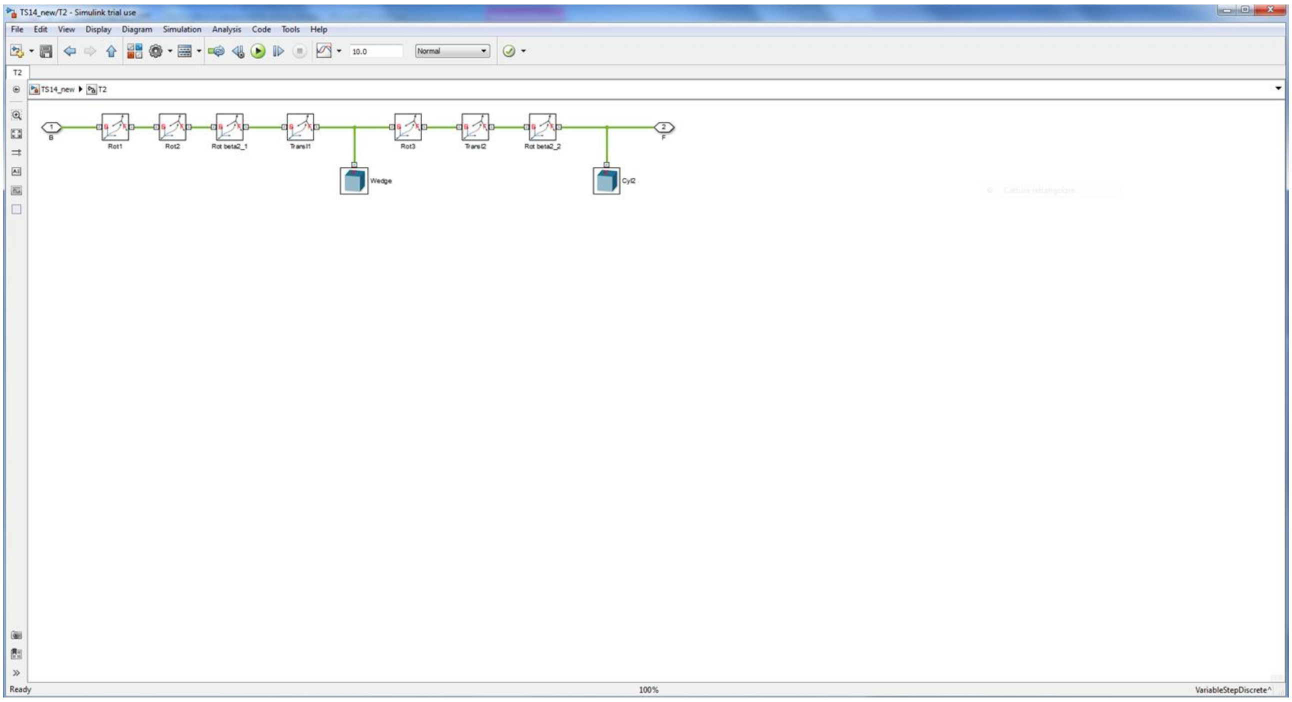

Figure 4.3 – Structure of the TSu coil mechanical model, made through SimMechanics.

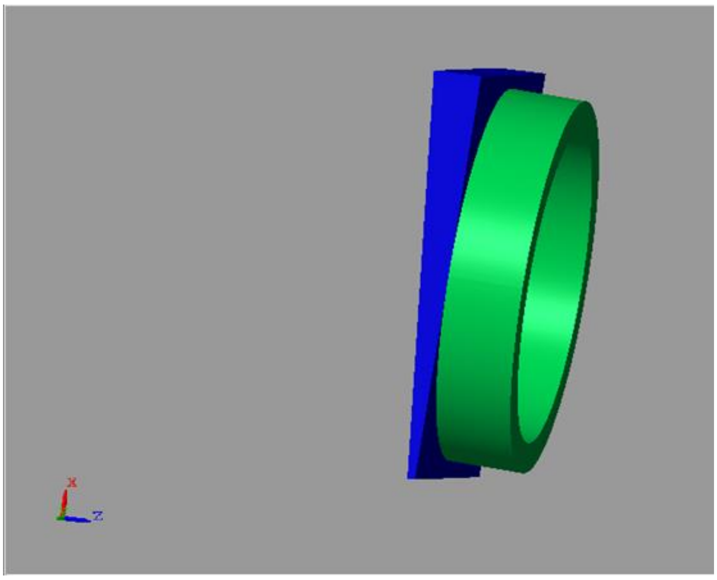

Figure 4.4 – The TSu coil mechanical model, made through SimMechanics.

Then, I repeated the cell twenty-five times, in order to obtain the complete TSu with the twenty-five coils, as shown in *Figure 4.5* and *Figure 4.6*, and I parameterized the structure so as we could change independently the dimensions of each coil.

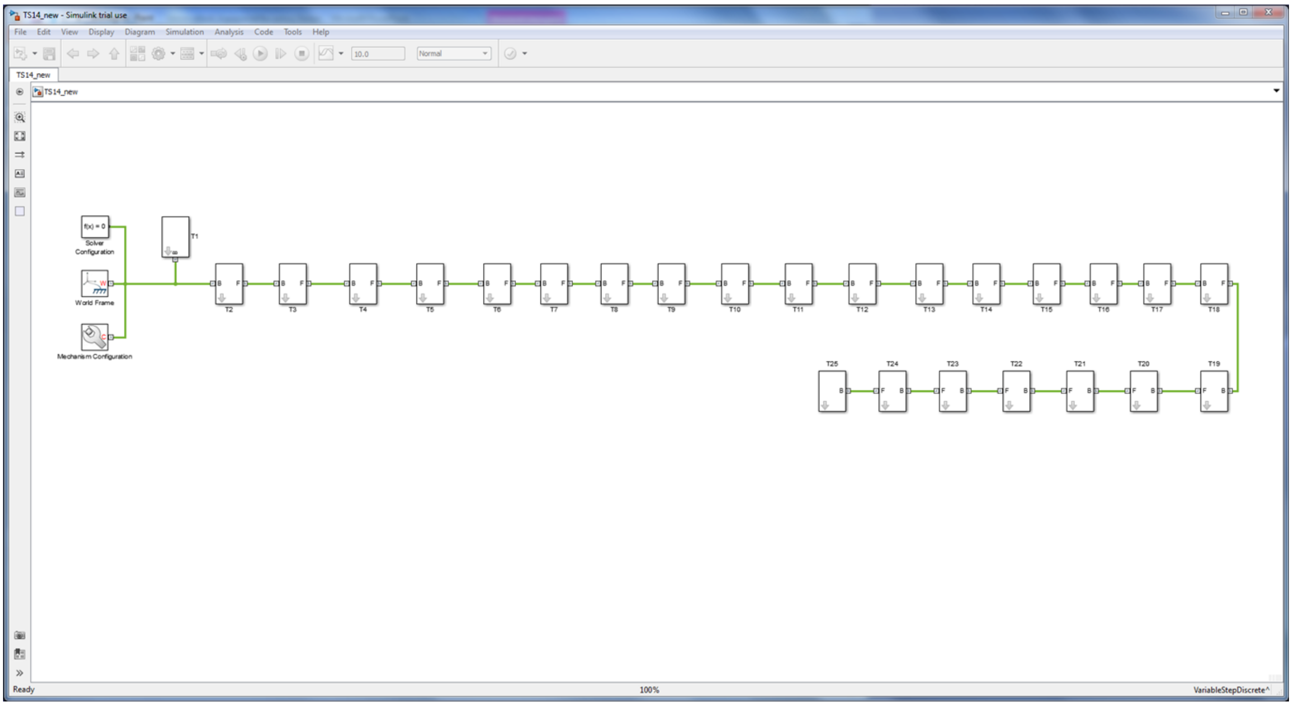

Figure 4.5 – Structure of the TSu mechanical model, made through SimMechanics.

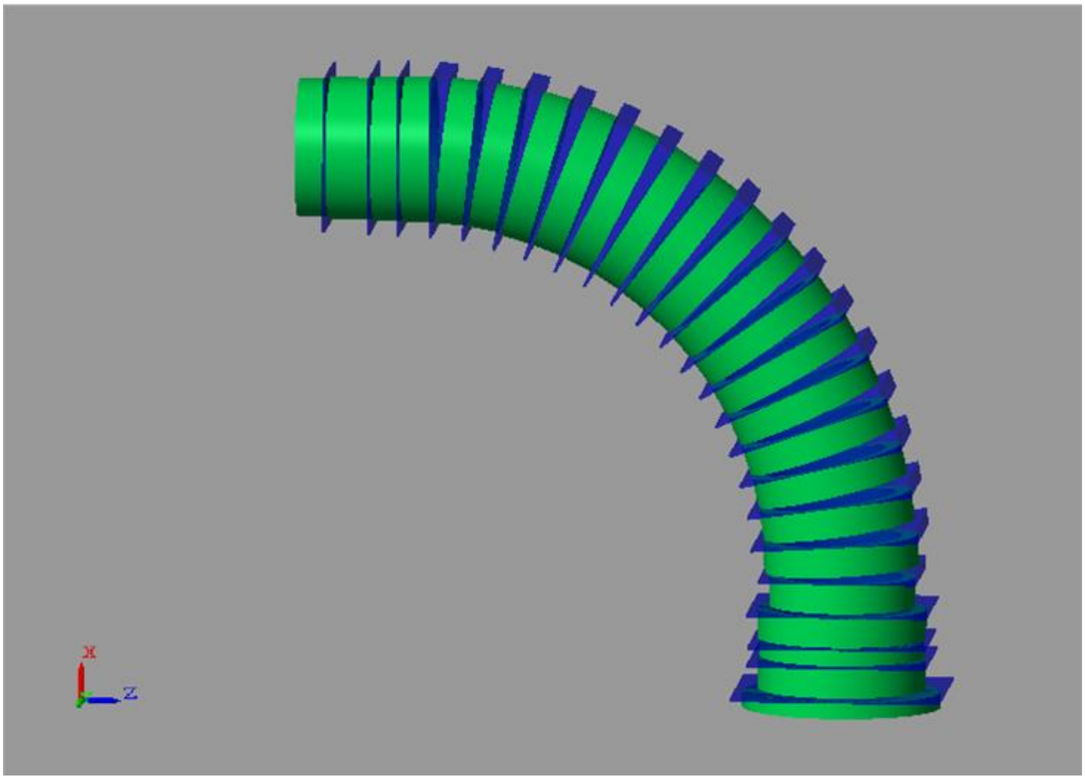

Figure 4.6 – The TSu mechanical model, made through SimMechanics.

4.3 Sensing forces

In the last part of my work I studied how to put a force on a certain point of a mechanical model and to read its value on another point of it.
Figure 4.7 and *Figure 4.8* show a simple example of a solid linked to two rods: I put a force on the first rod and I would like to read its value on the second rod.
The value of the force is shown in the blocks called "Display".

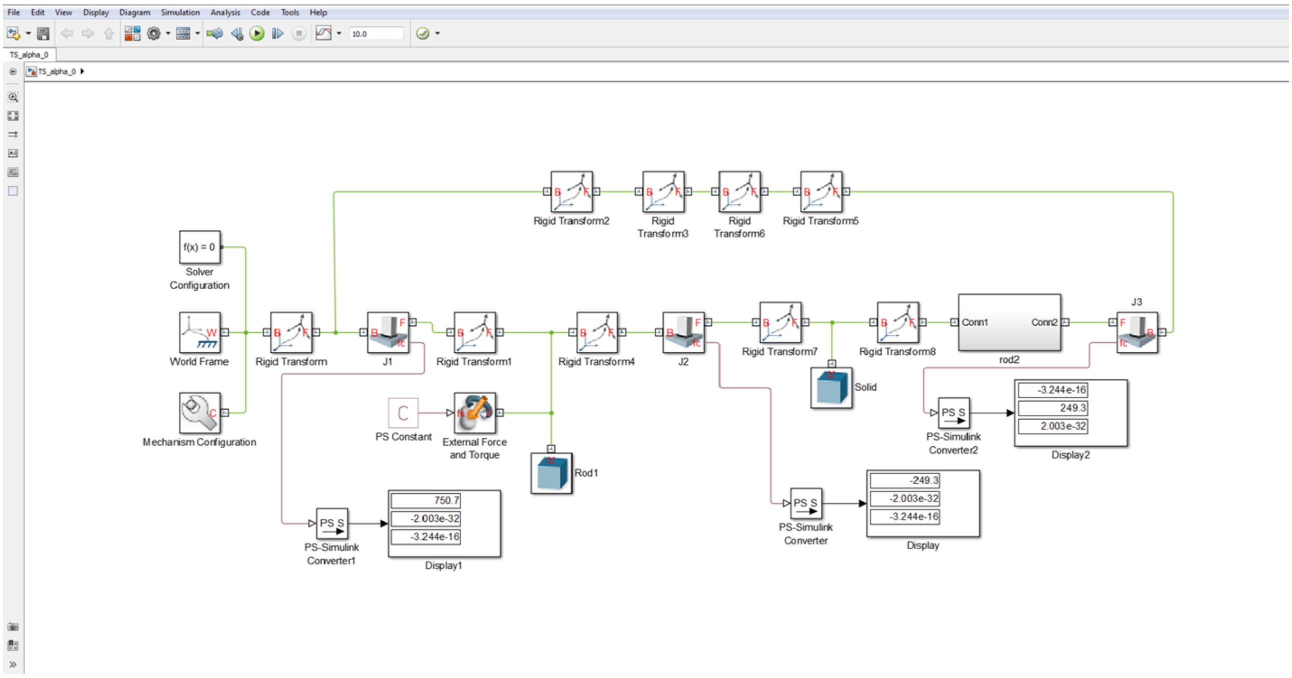

Figure 4.7 – Structure of a mechanical model subjected to a force, made through SimMechanics.

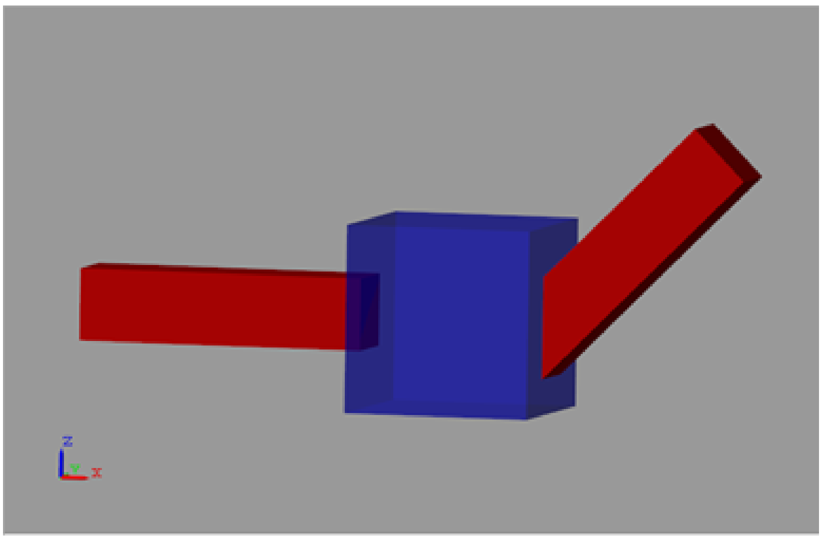

Figure 4.8 – Mechanical model subjected to a force, made through SimMechanics.

We want to do the same thing on the TSu: the goal is to evaluate the ranges of expected variations of the forces applied on the rods, in order to contribute to understand the alignment of each support rod.
At last we would like to compare the results obtained from the Mechanical Modeling and those from the Finite Element Method analysis.

5. Bibliography

[1] M. Lopes, Development of an alignment procedure for the Mu2e Transport Solenoid

[2] Mu2e Collaboration, Mu2e Technical Design Report, arXiv:1501.05241

[3] M. Lopes et al., Studies on the Magnetic Center of the Mu2e Solenoid System, IEEE Transactions on applied superconductivity, vol. 24, n. 3