ABSTRACT

THERMAL AND STRUCTURAL ANALYSIS OF BEAMLINE COMPONENTS IN THE
MU2E EXPERIMENT

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Fermi National Accelerator Laboratory will be conducting the high energy particle physics experiment Muons to Electrons (Mu2e). In this experiment, physicists will attempt to witness and understand an ultra-rare process which is the conversion of a muon into the lighter mass electron, without creating additional neutrinos. The experiment is conducted by first generating a proton beam which will be collided into a target within the production solenoid (PS). This creates a high intensity muon beam which passes through a transport solenoid (TS) and into the detector solenoid (DS). In the detector solenoid the muons will be stopped in an aluminum target and a series of detectors will measure the electrons produced. These components have been named the DS train since they are coupled and travel on a rail system when being inserted or extracted from the DS. To facilitate the installation and removal of the DS train, a set of external stands and a support stand for the instrumentation feed-through bulkhead (IFB) have been designed. Full analysis of safety factors and performance of these two designs has been completed. The detector solenoid itself will need to be maintained to a temperature of 22°C ±10°C. This will minimize thermal strain and ensure the accurate position of the components is maintained to the tolerance of ±2 mm. To reduce the thermal gradient, a passive heating system has been developed and reported.

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THERMAL AND STRUCTURAL ANALYSIS OF BEAMLINE COMPONENTS IN THE

MU2E EXPERIMENT

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    Dr. Nicholas Pohlman

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DEDICATION

To my wonderful wife Kayla Joy Martin. Your support, love, and patience
has made completing this thesis possible.

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CHAPTER 1

INTRODUCTION

1.1 Physics Motivation of the Mu2e Experiment

High energy physicists have been actively studying particle interactions for years search-ing for evidence of interactions that lie beyond the standard model. Experimentation and investigation in this field will help scientists discover answers to fundamental questions about matter and the universe. One area of potential discovery during the next few decades will be research at the Intensity Frontier on ultra-rare processes, including the muon to electron conversion. Observing processes such as $\mu + N \rightarrow e + N$ and $\mu \rightarrow e + \gamma$ conversions will remove a hurdle to understanding the relationship among the three generations of leptons (electrons, muons, and taus) and possibly the origin of matter-antimatter asymmetries. Ex-ploration into these unknowns could expand the understanding of phenomena that play an integral role in the universe [1].

1.1.1 Particle Physics Theory

The standard model of particle physics is a theory that classifies all of the known sub-atomic particles and explains particle interactions. The model contains the 24 fundamental fermions, which are 12 particles and their anti-particle counterparts, as well as 6 bosons. The fermions are divided into two groups: quarks and leptons and make up the matter in the universe. The bosons are responsible for electromagnetic, weak, and strong forces, and

through the Higgs boson, the masses of particles. The W and Z bosons are exchange particles of the weak force. The weak force explains things such as the energy production in the sun and is responsible for radioactive beta decay. The strong interaction acts on the quarks. The force carrier is the gluon, which holds together the quarks in the neutrons and protons and even holds the nucleus together. The electromagnetic force includes interactions of charged particles and the force carrier is the photon.
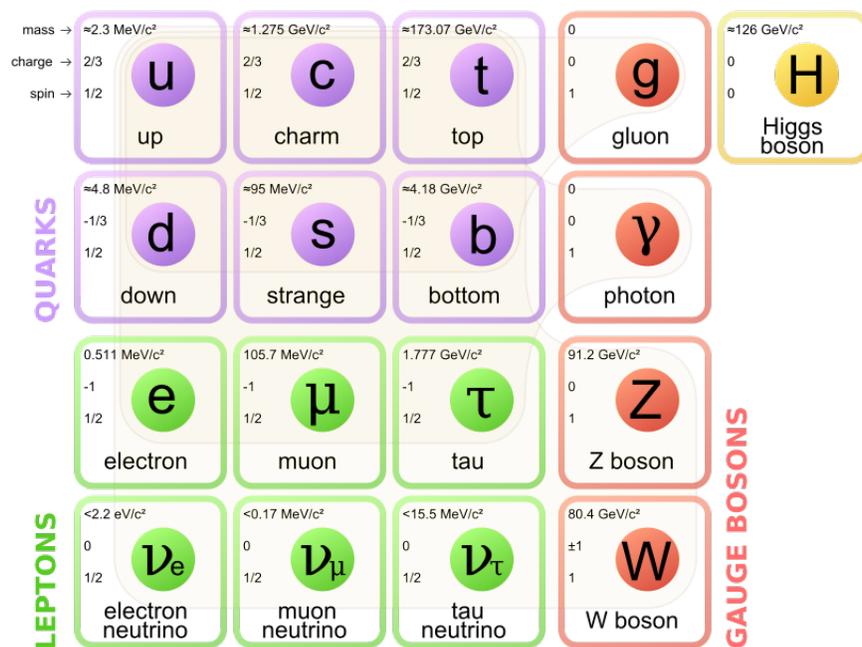
Figure 1.1: The standard model showing spin, electrical charge, and mass properties [2]

With the observation that neutrinos oscillate from one flavor to another, verifying that the neutrinos are not massless, the standard model predicts that muons will convert into electrons. However, due to the very small mass of neutrinos, the predicted standard model rate of neutrinoless conversion of muons to electrons is extremely suppressed and is essentially unobservable. The normal muon decay is $\mu^- \to e^- + \nu_\mu + \bar{\nu}_e$. This transition conserves the muon and electron number. However, the signal for Mu2e is $\mu^- + N \to e^- + N$ which violates the lepton number decay and is a charged lepton flavor violation. The search for evidence

of lepton number violation began soon after the discovery of the muon, and observing it in this channel would provide insight into new areas of physics.

1.2   Experiment Overview

The Mu2e experiment will be conducted at the Fermilab campus in Batavia, IL. The main injector (proton accelerator) for the Mu2e experiment is already built and is commonly used for numerous experiments at Fermilab. A separate beamline and Mu2e building must be built. Currently, the construction is underway and is expected to ongoing until the year 2020. The experimental system is currently being designed and will provide researchers with 10,000 times more data than previous experiments [3].
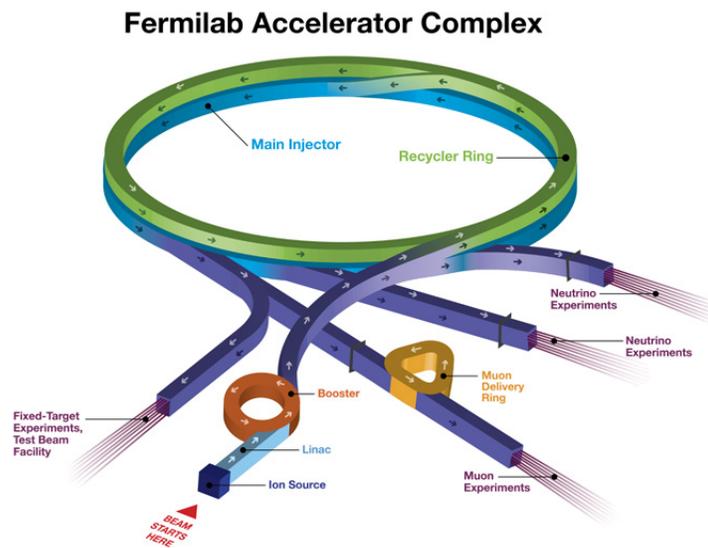
Figure 1.2: Fermilab accelerator complex [4]

1.3   Mu2e Solenoids

The solenoids in the Mu2e experiment are used to produce and transport muons to an aluminum target where a significant fraction of those muons are stopped. This provides an opportunity to observe the muon to electron conversion. Figure 1.3 shows a top view of the three solenoids. The solenoids are connected and each have highly controlled environments that manipulate the beam.
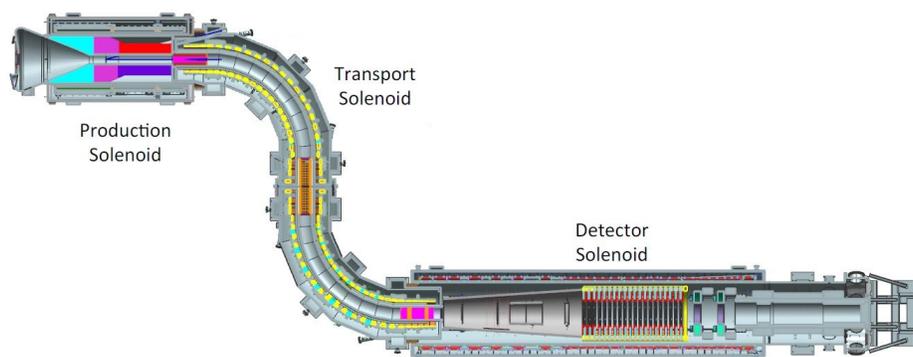
Figure 1.3: The production solenoid (4 m), transport solenoid (13 m), and detector solenoid (11 m) [5]

1.3.1   <u>Production Solenoid (PS)</u>

The production solenoid as the name implies is used to produce muons. Inside the production solenoid is a tungsten target. A proton beam is generated and accelerated by the main injector (see Figure 1.2), manipulated into a tuned bunch structure with a bunch separation of 1695 nanoseconds in the muon delivery ring, and then directed into the target located in the center of the PS. When the beam hits the target there are many particles produced, some of which are charged pions which decay into muons. The protons which do

not interact in the target will leave the PS bore through the end cap and are absorbed by the PS beam dump. The muon beam is directed into the transport solenoid.
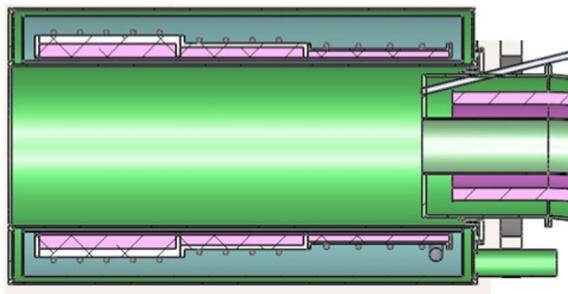
Figure 1.4: The PS, note the beam entering on the right via the pipe [6]

1.3.2   Transport Solenoid (TS)

The primary function of the transport solenoid is to supply the detector solenoid with a low momentum negatively-charged muon beam from the production solenoids. The transport solenoid consists of five sectors label TS1→ TS5, see Figure 1.5. It is separated into an upstream and a downstream section, with TSu (transport solenoid upstream) comprised of TS1, TS2, and half of TS3, while TSd (transport solenoid downstream) includes the second half of TS3, TS4, and TS5.

The PS magnetic field is designed to decrease from the upstream end to the downstream end. The purpose of this design is to minimize risk of trapping charged particles. Once the beam enters the first curved section, TS2, it is dispersed and a collimator selects particles based on their sign and momentum [7]. TS3 maintains the momentum of the particles as they pass through and enter TS4. Once inside TS4 the muon particles converge and become aligned with the center of TS5. TS5 is aligned with the stopping target in the DS and transports the beam out of the TS and into the DS.
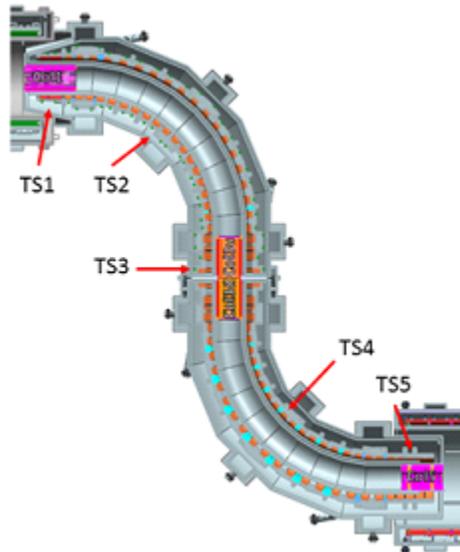
Figure 1.5: The transport solenoid [5]

1.3.3   Detector Solenoid (DS)

The detector solenoid is the last solenoid used in the Mu2e experiment. It is also the location where the direct muon to electron conversion search will occur. The DS is comprised of two concentric tubes. The region between the inner shell and the outer shell contains the superconducting magnet which generates the 1-2 Tesla magnetic field that exists axially along the DS. The inner bore (also known as the warm bore) of the DS is 10900 mm in length and has an inner diameter of 1900 mm. The region between the cylinders contains a liquid nitrogen intercept that will be cooled to 80K. The solenoid coil will only be superconducting when the temperature of the coil is much closer to 5K. The cold mass is cooled to this temperature using liquid helium. To reduce radiative heat loss from the room tempeature inner bore and the 80K intercept, 45 sheets of multilayer insulation (MLI) will be added. Analyses reported in Chapter 4 show the even with the MLI thermal shield, a thermal control system will need to be used in the warm bore.

Calorimeter

Muon Beam Stop

Tracker

Outer Internal
Proton
Absorber

Downstream
External Shielding
(End Cap Shielding)

Detector Solenoid

Downstream External
Shielding (Downstream
Cave)
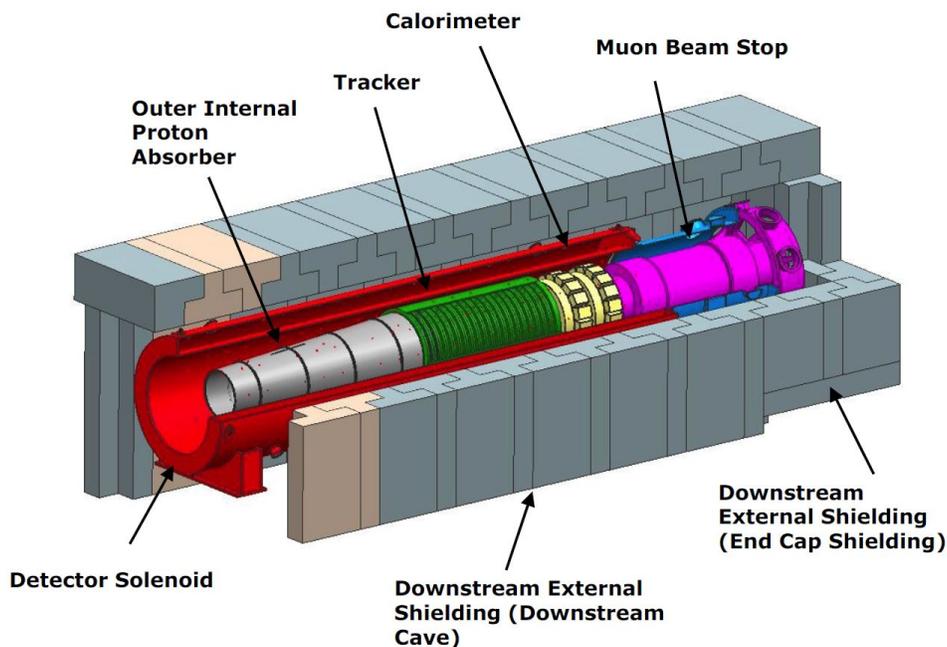
Figure 1.6: The detector solenoid (operational position) [5]

The first component that the muon beam will encounter when entering the DS is the muon stopping target which is located at the center of the proton absorber. After the beam hits the target, approximately 40% [8] of the muons are stopped. These muons are stopped in the target nuclei and then either decay in orbit or are captured by the aluminum nucleus and produce various byproducts such as electrons, neutrons, protons, neutrinos, and gamma rays. However, there is also a conversion where the $\mu^- + Al \rightarrow e^- + Al$ reaction occurs which this is the "signal reaction" whose search is the study of this experiment.

About 15% of the time that a muon is captured a proton is emitted with an energy spectrum center at 7 MeV [9]. These protons generate background in the tracker, and contribute to the aging of the detector. This causes the need for a proton absorber. There are two proton absorbers surrounding the stopping target and they both are used to reduce the momentum of protons which enter the tracker.

The next component the beam passes through is the tracker. The tracker is responsible for measuring the trajectory and momentum of the charged particles. After this is the calorimeter identifies that a particle is an electron and provides a measurement of it's energy. The data from the tracker and calorimeter is used to identify the electrons which originate from interacting with the stopping target.

The final component in the detector solenoid is the muon beam stop (MBS), where the remaining 60% of the muons stop. The purpose of the MBS is to absorb the energy of beam particles and minimize the noise to the detectors that occurs from the muon decays. The detectors are the tracker, calorimeter, and a cosmic ray veto counts which cover the upper 3/4 of the DS cryostat. The muon beamstop consists of a stainless steel tube that has concentric tubes of high density polyethylene throughout the interior as well as over a portion of the outer surface. A series of cut outs have been placed in the bottom to increase gas flow when the DS is being pumped to high vacuum. Additionally, an end plug has been added at the downstream end of the beam to stop muons at small radii.

On the upstream side the muon beam stop is connected to a support called the spherical support which was designed to offer freedom of movement in the back end of the MBS [10]. On the downstream side it is attached to the instrumentation feedthrough bulkhead (IFB) and IFB support, see Figure 1.8. The IFB support structure that will carry approximately 50% of the MBS weight will be discussed in detail in Chapter 2.

1.3.3.1 <u>DS Rail System</u>

The detector solenoid is unique among the solenoids due to the fact that the internal components need to be removed periodically for servicing. To accomplish this task a rail system has been developed. The system is broken into two parts: internal and external. The

655 mm from
DS bore
centerline to
center of travel

20mm total
vertical travel

Bearing block

Precision
Rail

2ⁿᵈ Tier Bar

Rail Platform

20mm total horizontal
travel

500 mm from DS bore
centerline to center of
travel
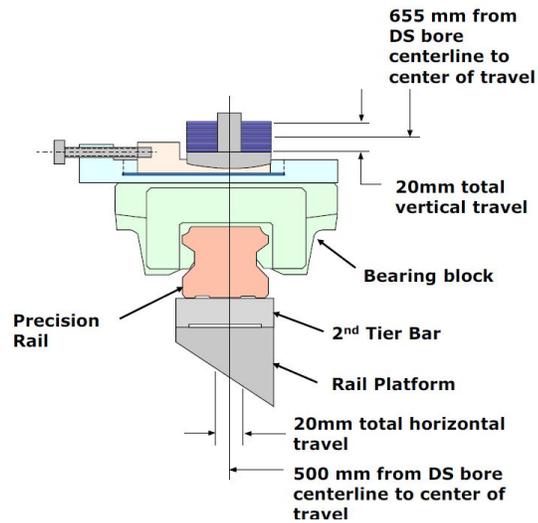
Figure 1.7: Internal rail system design [11]

internal rails are bolted into platforms at the bottom of the DS and separated by 1000 mm center to center. The detector solenoid components are attached to bearing blocks which roll along the rails. The components on the master rail side remain in a fixed position relative to the bearing blocks. Alternatively, the component attachment to the bearing blocks on the slave rail side is "floating" and allows relative movement (between the component and bearing block) in the transverse direction. A view of one side is shown in Figure 1.7, where the rail platform is attached to the DS bore by longitudinal welds. The external rail system consists of 6 aluminum stands and the bearing block rails which bolt to the top of them, see Figure 1.8. The DS bore is a considerable height from the floor, and the external stands bridge the distance from the floor to the rails. The stands provide the support for the detector solenoid train when it is in the maintenance position as shown in Figure 1.8. The stands will be discussed in further detail in Chapter 3.
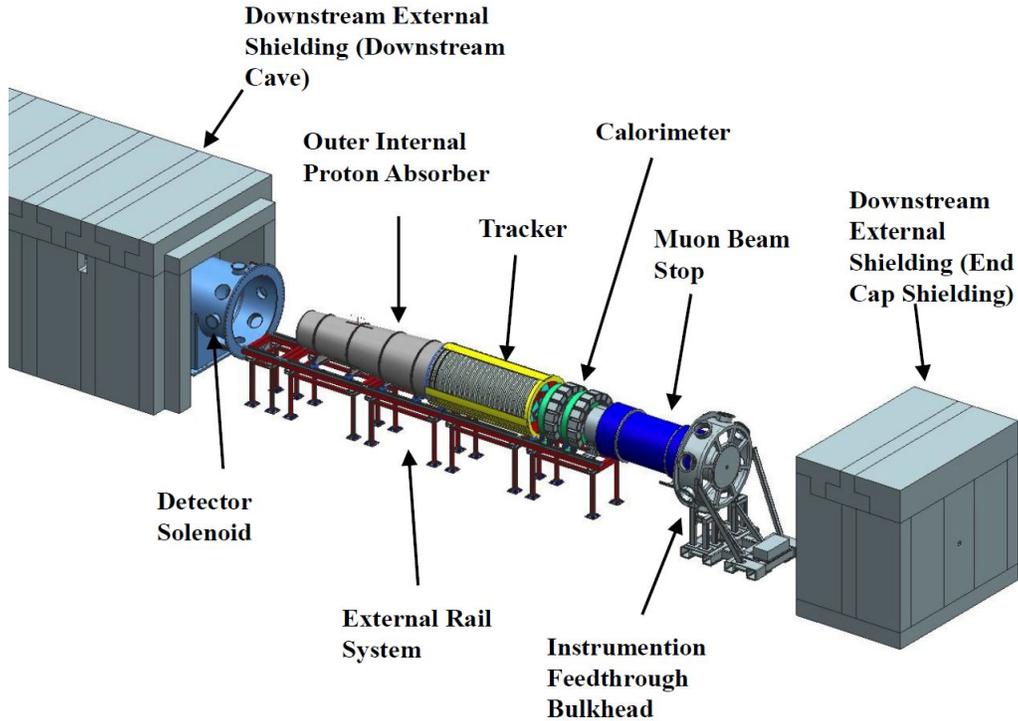
Figure 1.8: Detector solenoid components outside of the bore (maintenance position) [11]

1.4   Thesis Objective

The objective of this thesis is to a) design and analyze the external stands and the instrumentation feedthrough bulkhead, and b) develop a thermal management system to maintain the temperature of the DS warm bore near 22 °C. All of these designs will be used for the lifetime of the Mu2e experiment. Many requirements have been imposed on each of the designs due to environment, geometry, and safety codes. Potential failure methods are considered and addressed. For the external stands and IFB support, prototypes will be ordered and tested.

Chapter 2 is focused on the IFB support design. Constraints and requirements are addressed, and a detailed structural analysis is shown. Chapter 3 describes the external stand design. It also includes both analytical and finite element analyses, as well as alignment

studies that were performed with the prototype. In Chapter 4 the justification of the need for heaters will be addressed, and a design is presented. The analytical and finite element methods to validate and optimize the design are shown.

CHAPTER 2

INSTRUMENTATION FEEDTHROUGH BULKHEAD SUPPORT

2.1   Role of the IFB support
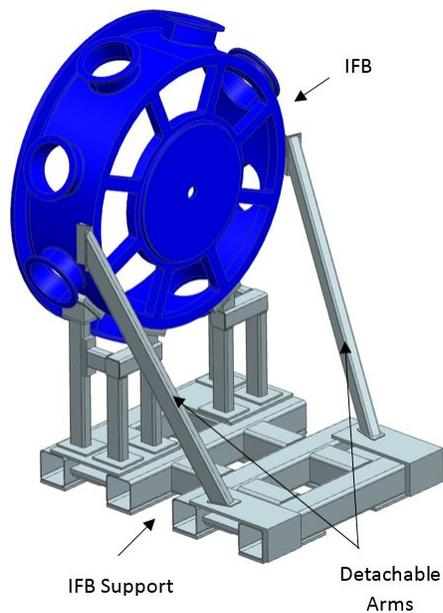
Figure 2.1: IFB (blue) and IFB support (gray)

The instrumentation feedthrough bulkhead (IFB), shown in Figure 2.1, is a welded 316L stainless steel cylindrical shell with a flange welded at one end. The purpose of the IFB is mate with the detector solenoid warm bore to create a vacuum seal. To power the components inside the solenoid cut outs have been made in the steel and replaced with instrumentation panel and port feedthroughs. These instrumentation feedthroughs provide location for power

cables, optical fibers, gas lines, and cooling lines to enter the high vacuum solenoid without creating a leak.
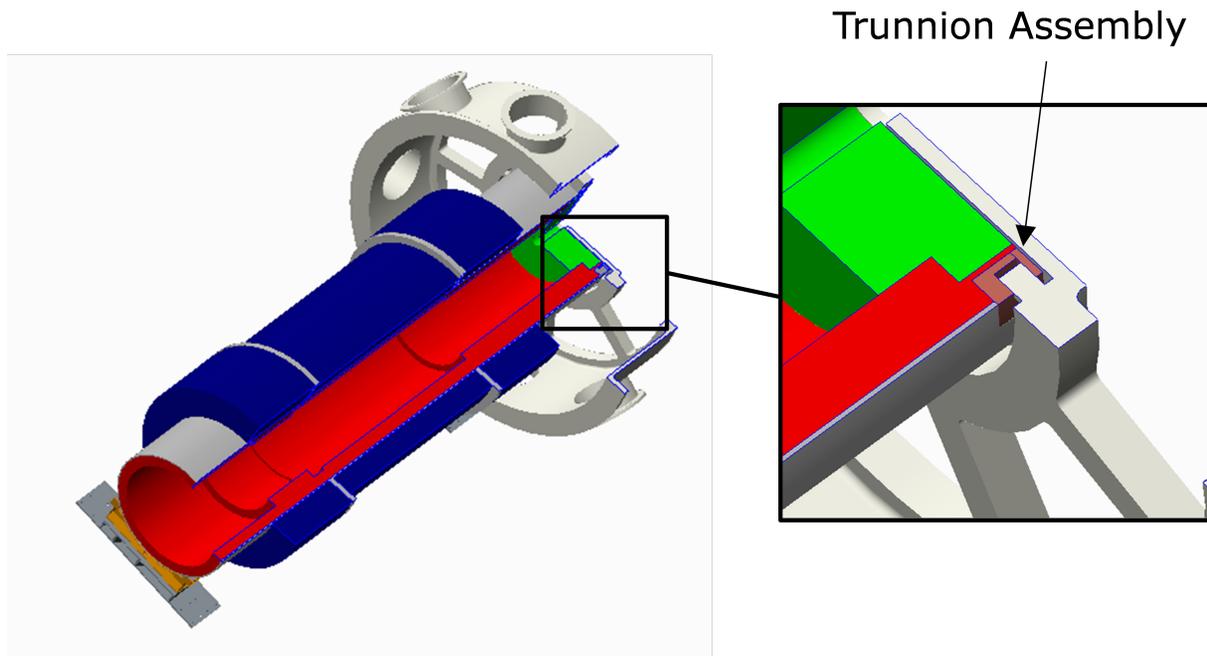
Figure 2.2: IFB-trunnion connection upstream (left) to downstream (right) [10]

The IFB connects to the DS train through a pair of trunnions that interlock with the muon beam stop. The connection between the IFB trunnions and the muon beam stop sockets can be seen in Figure 2.2. The IFB support is the mechanism that translates force as the DS train is installed and removed from the DS, see Figure 1.8.

2.2   Design Specifications

Various requirements have been developed and will continue to evolve for the IFB and IFB support as the Mu2e experiment progresses. Currently, the design is in the preliminary design 2 phase which includes sufficient space for the calorimeter and tracker cables. As the

details of the final designs for active components in the DS (tracker and calorimeter) are completed, the IFB support will undergo another design phase prior to production.

2.2.1   Structural Requirements

The primary function of the IFB support is to carry the gravitational load of the IFB. Since the structural support of the muon beam stop is shared by the rail system and the IFB, the IFB support must be able to withstand this additional load and meet adequate safety factor.

2.2.2   Spatial and Positional Requirements

The IFB support is designed so that it does not interfere with the vacuum pumpout spool piece (VPSP) ports or the VPSP support which is welded to the downstream end of the DS. The design must also fit within the end cap shielding, which encloses the area surround the DS. To achieve this, the bolted diagonal supports, depicted in Figure 2.1, are detachable. Additionally, relief channels have been put into the back of the end cap shielding. This allows the IFB support base to fit underneath the downstream end of the concrete enclose. Another aspect of the design is that the final attached position of the IFB must be extremely precise in order to create a close vacuum seal. This is of critical importance since the detector train components must be aligned to be ± 2 mm from their nominal position. Methodology for for final alignment is still being studied.

2.3   Structural Analysis

The current design for installing the IFB, IFB support, and detector train is to use two hydraulic cylinders to push on the base of the IFB support. Since the length to install the train is approximately 14000 millimeters, and the stroke of the cylinders is much smaller, the following method will be used.

1. The hydraulic cylinders are attached to the base of the IFB support.

2. The hydraulic cylinders are bolted into tapped holes in the steel floor plates.

3. Pressure is applied and the cylinders extended to their full stroke length, driving tehe axially with respect to the DS.

4. Remaining attached to the IFB support, the cylinders are unbolted from the floor plates and compressed.

5. The cylinders are moved to the next upstream (or downstream for extraction) location.

6. Steps 2-5 are repeated until the train is fully installed or removed.

A critical aspect of analyzing the strength of the IFB support was to determine the required force to move the whole system into and out of the DS warm bore. The force that the cylinders must provide is equal to the force overcome the friction between the rails and the detector train as well as the hillman rollers and the steel track on which they roll. Presently, the calculated maximum load that the cylinders can apply is 4.5 kN per side [12].

One critical aspect that the design must satisfy is to not tip or be over stressed if the DS train came to a complete stop during installation. This could occur if the bearing blocks and rails became bound. In this arrangement the DS train (including the IFB) would be

constrained from moving axially to the DS, additional details are provided in the following sections.

2.3.1 Insertion Finite Element Analysis

This analysis is focused on validating the structural integrity of the IFB support using the worst case loading conditions during the insertion procedure. The case analyzed is a simulation of installing the train and assuming that one (or more) of a DS train component bearing blocks binds to the rails, halting the motion of the train and IFB.

2.3.1.1 Analysis Conditions
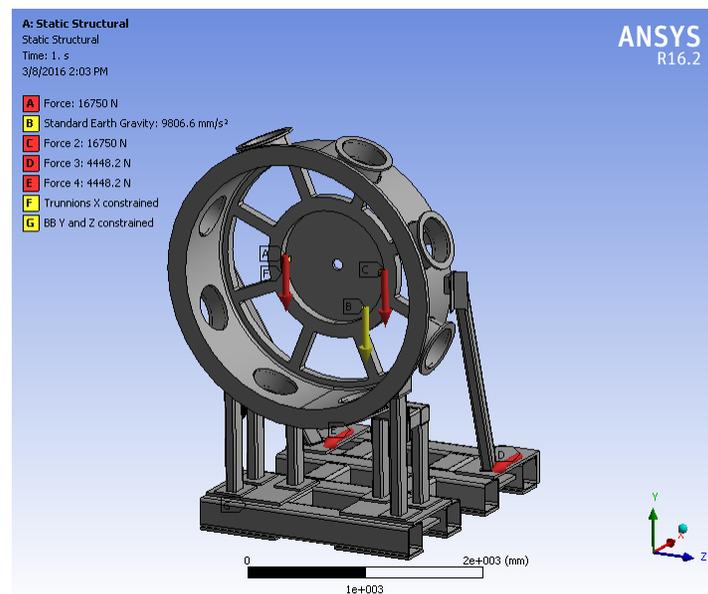
Figure 2.3: IFB analysis loading conditions

In this arrangement the hydraulic cylinders will be applying the maximum load (condition A and C) in the upstream direction to the base of the IFB support. Additionally, the

gravitational load of the IFB (condition B) and muon beam stop (condition D and E) is applied as well. To simulate the degrees of freedom of the rollers and trunnions displacement constraints have been applied. The trunnions are constrained in the axial direction (condition F) due to the nature of the connection between the trunnions and the muon beam stop socket, and free to move in the lateral and vertical direction. Alternatively, the 4 hillman roller locations have been constrained in the vertical and lateral directions (condition G) since they provide vertical support and are unable to roll laterally. They have been set to free in the axial direction, which is the direction they naturally roll.

2.3.1.2 <u>Deformation</u>
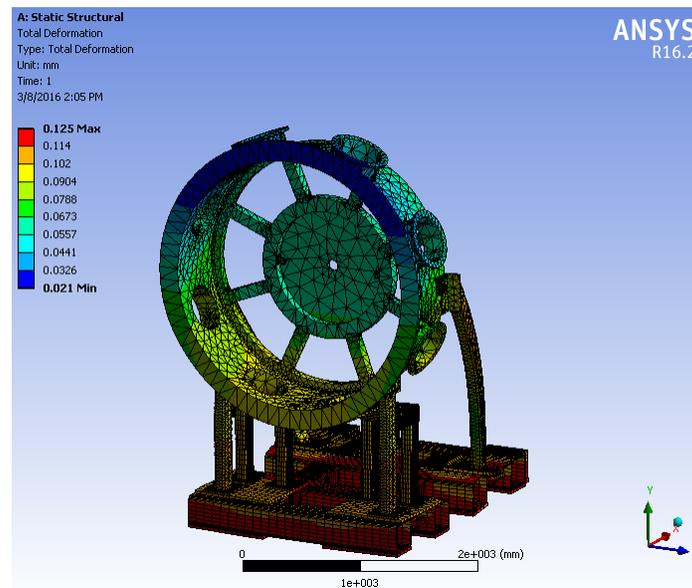
Figure 2.4: IFB insertion deformation

The deformation shown here is the magnitude throughout the support. It is important to note that this deformation is in the elastic range, so once the structure is unloaded it will return to it's original shape. For the purpose of showing high deflection areas, the scale of

deformation is amplified by the software. It can be observed that the diagonal arms bow in response to the loads, thus the need for having them on the support during installation is justified. As can be expected the highest deformation occurs in the base along the line that the force acts in.

2.3.1.3 Stress
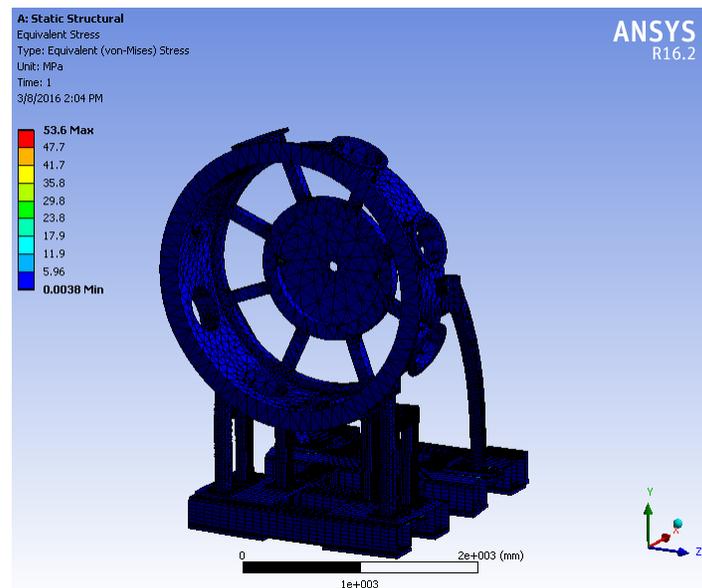
Figure 2.5: IFB insertion stress

The stress analyzed in this case is the von-mises stress, and it is used to calculated the safety factor of the design. The stresses seen in Figure 2.5 are rather minimal and reach approximately 53.6 MPa in joints and near the trunnions. The stress seen in this analysis is far less than the yield stress of 248 MPa for 316L stainless steel [10], providing a safety factor of 4.62.

2.3.2   Extraction Finite Element Analysis

This analysis will determine the strength of the IFB support during an extraction procedure. Worst potential conditions will be simulated as before, but with the load on the base applied in the opposite direction. As in the first analysis, this simulation addresses the possibility of one of the DS train component bearing blocks binding to the rails.

2.3.2.1   Analysis Conditions
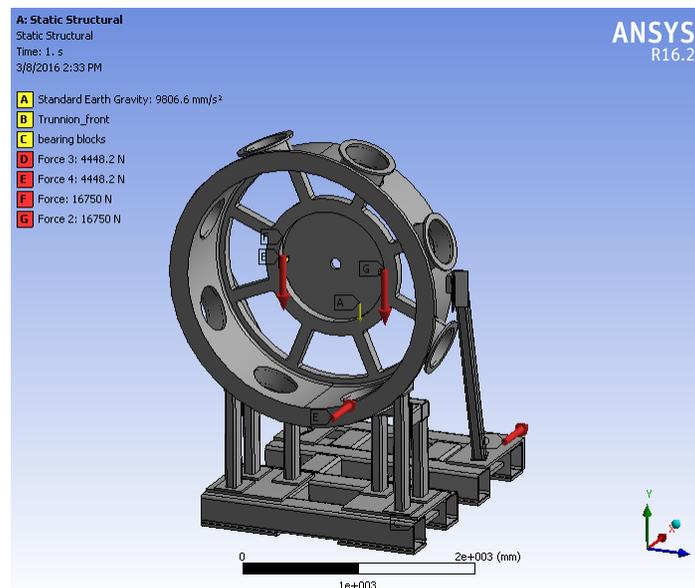
Figure 2.6: IFB analysis conditions

In the new scenario, the hydraulic cylinders will be applying the maximum load (condition D and E) in the downstream direction, notice the vector direction at the base change between Figure 2.3 and Figure 2.6. The IFB support is still responsible for gravitational load (condition A) of the IFB and muon beam stop (condition F and G). The degrees of freedom (condition B and C) shown hear are the same as those simulated before.

2.3.2.2 Deformation
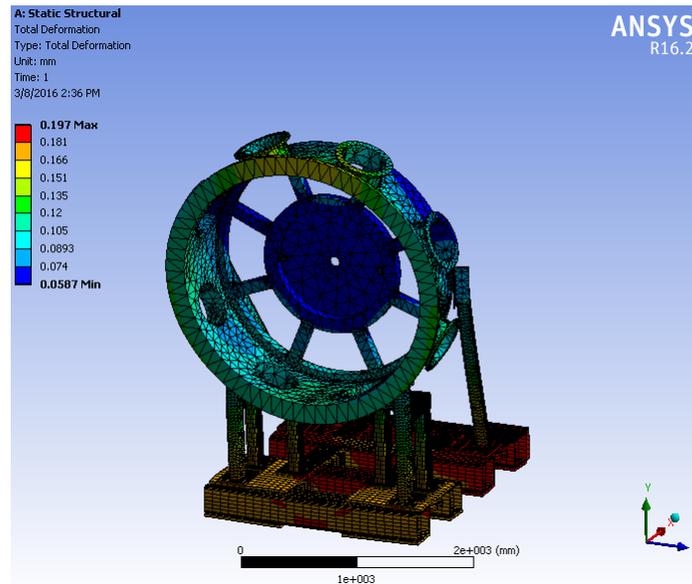
Figure 2.7: IFB extraction deformation

The deformation for the extraction process is greater than that of the insertion process, but is still relatively small and remains in the elastic range. Comparing Figures 2.4 and 2.7 it can be observed that the diagonal tube is flexing in the opposite direction, further validating the importance of the connection.

2.3.2.3 Stress

The stress that develops in this loading case is higher than that of the previous case. However, viewing Figure 2.8 there are a few local high stress regions. During the final design phase, these regions will be optimized and the weld sizes between tubing will be studied in depth. The highest stress found in this analysis is 65.6 MPa and provides a safety factor of 3.68. In this analysis the highest stress regions occur in the base where the welded members
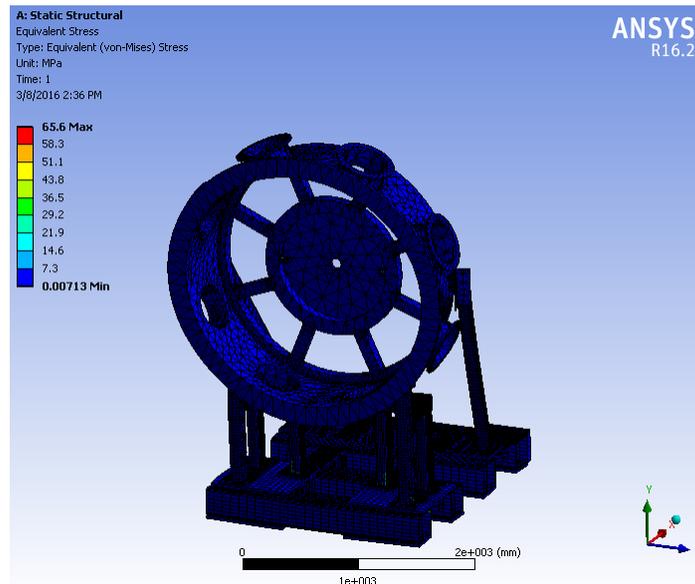
Figure 2.8: IFB extraction stress

are experiencing tension. This analysis examines the worst possible loading that the IFB and IFB support could experience.

2.3.3   Design Status Summary

At the time of this thesis submission, the IFB support is in the preliminary design iteration 2 phase with the engineering drawings currently being generated. Presently, the IFB meets the design specifications and is not expected to change much between now and the time of fabrication. Future attention will need to be given to the routing of cables that exit the DS through the ports on the IFB. Collaboration between the IFB support designer and both the electrical and concrete shielding designers is required.

CHAPTER 3
EXTERNAL STANDS

3.1 Role of the External Stands

The purpose of the 6 external stands, shown in Figure 3.1, is to provide support for the detector solenoid train while it is outside of the DS. The stands will also be used to guide the train into and out of the DS during insertion and extraction procedures. This will occur numerous times over the life of the experiment as necessary when magnetic field mapping of the DS, vacuum test cycles, alignment studies, or component servicing is required. While the train is in the DS and operation is underway, the external stands will be stored in building in the available alcoves.
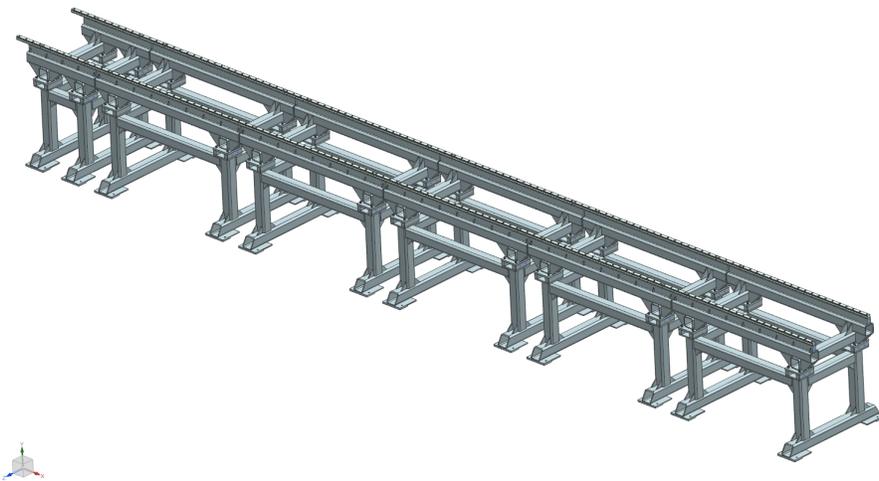
Figure 3.1: Completed iteration 2 design of the external stands

3.2   Design Specifications

The design of the external stands must satisfy several different criteria. To test the alignment procedure of the external stands, a prototype (the current design) of the upper weldment of the shortest stand was ordered, see drawing number F10040614 in the Appendix. Upon arrival at Fermilab, it was installed on one end of A "mock up" rail system and measured, the details will be discussed in a later section.

3.2.1   Geometric and Spacial Requirements

The need for having external stands is to bridge the gap between the floor and the rails inside of the DS. Considerations have been made to ensure that appropriate gaps are left between stands. Additionally, designing the stands in such a way that the legs will rest on steel tracks embedded into the concrete floor was done. Special rail links have been designed that connect the stands together and form a continuous rail. One unique feature that has been included in the design is that they are vertically adjustable. The external stands have been separated into two weldments that bolt together. A slot has been added to the lower portion of the stand that allows room for a jack to be placed. To achieve the proper height, the upper weldment will be jacked up and, shims will be added to the contact interface. After this, the upper weldment will be lowered and securely tightened. This process will be discussed in detail in section 3.5.

3.2.2   Magnetic Requirements

One of the critical studies that will be conducted prior to experiment operation is the magnetic field mapping of the detector solenoid. At the time this is being done, the external stands will be supporting the DS train, and cannot be removed from their nominal position. If the stands were made of a ferromagnetic material such as AISI 1020 steel, the magnetic field lines near the downstream end of the DS would be distorted. This would have a negative impact on the final interpretation of data. For this reason, the stands have been made of 6061-T6 aluminum which is non-magnetic. The temper on the aluminum significantly increases the yield strength to 214 MPa making it a good choice for this structural application [13].

3.2.3   Structural Requirements

An important aspect of the external stand design is the justification of the structural strength. This will be achieved by performing an analytical analysis of the stress, internal moments, and deflections under the maximum loading conditions. These results are also to be confirmed through an ANSYS finite element analysis. The desired project design safety factor to be achieved for the external stands is 2, and is higher than the design safety factor of 1.65 found in the Aluminum Design Manual: 2010.

3.3   Analytical Analysis

To analyze the system the top of the rails will be approximated as a simply supported beam, see Figure 3.2. While the actual system will be a bolted connection, it is common

practice in engineering to make conservative assumptions when doing hand calculations. This assumption will yield a higher deflection and lead to a larger safety factor for the design. An additional assumption that is made for this analysis is that the length of the beam is 1800 mm, while the actual stand will be 2500 mm. The distance between the center of the supports for this beam is 1800 mm and is the reason that is was the length used for this study.
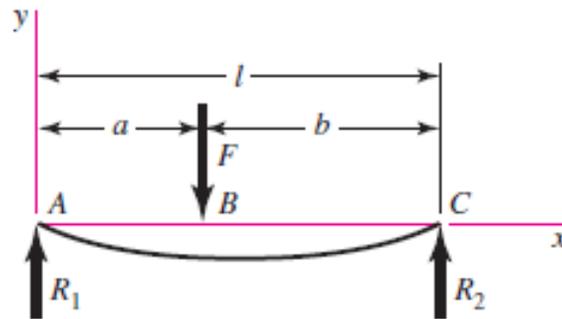
Figure 3.2: Loading schematic [14]

3.3.1   Maximum Deflection Loading Parameters

The maximum loading condition occurs when the sum of the loads can be replaced by a single equivalent load at the center of the support structure. This will produce the maximum possible internal moment causing the largest possible deflection.

The loads that cause the largest loading occur from the calorimeter and MBS (shown as m1 → m4 in Equation 3.2 and 3.3) [11]. The distance between loads is fixed, but at a specific location on the stands they cause the largest possible moment. Setting the moment produced by a centered load with mass (m), gravity (g), and distance (L/2) equal to the mass ($m_1 \to m_4$) of the MBS and calorimeter, gravity (g), and variable position (f(x)) the location can be determined.
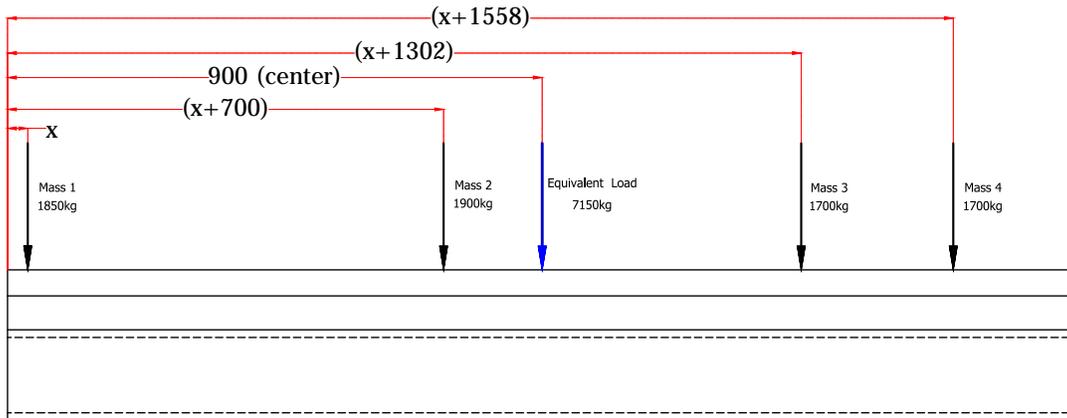
Figure 3.3: Calorimeter load (left two black arrows), MBS load (right two black arrows) centered load (blue)

$$M_{eq} = \Sigma mg\frac{L}{2} = \Sigma mf(x)g \tag{3.1}$$

$$\begin{aligned}
\Sigma mg\frac{L}{2} &= (m_1 + m_2 + m_3 + m_4)g\frac{L}{2} \\
&= (1850\text{kg} + 1900\text{kg} + 1700\text{kg} + 1700\text{kg})(9.81\frac{\text{m}}{\text{s}^2})\frac{1.8\text{m}}{2}
\end{aligned} \tag{3.2}$$

$$\Sigma mgf(x) = [(m_1)(x) + (m_2)(x + 700\text{mm}) + (m_3)(x + 1302\text{mm}) +$$

$$(m_4)(x + 1558\text{mm})]g$$

$$\text{(3.3)}$$

$$= [(1850\text{kg})(x) + (1900\text{kg})(x + 700\text{mm}) + (1700\text{kg})(x + 1302\text{mm}) +$$

$$(1700\text{kg})(x + 1558\text{mm})]g$$

Setting $\Sigma mg\frac{L}{2}$ equal to $\Sigma mf(x)g$ and using a mathematical solver yields the result: $x = 34.0\text{mm}$.

3.3.2   Centroid Calculations

In order to determine the moment of inertia of the system, the centroid must first be found. It's important to note that the centroid in this configuration is not the center of gravity since two different materials are used in the beam. So that symmetry can be utilized, the y-axis (vertical) has been defined to be in the center of the beam. The z-axis (horizontal) has been defined to at the bottom of the beam, parallel with the square tubing bottom surface. The first step in determining the neutral axis of the composite beam is to determine the centroids of each individual material component. Once this is completed the neutral axis of the system can be determined.

3.3.2.1   Aluminum Centroid

The 6061-T6 aluminum portion of this beam is comprised of the 6 x 6 (inch) square tube and the 2.5 x 3.0 (inch) platform bar and is modeled as a one part for this analysis. This
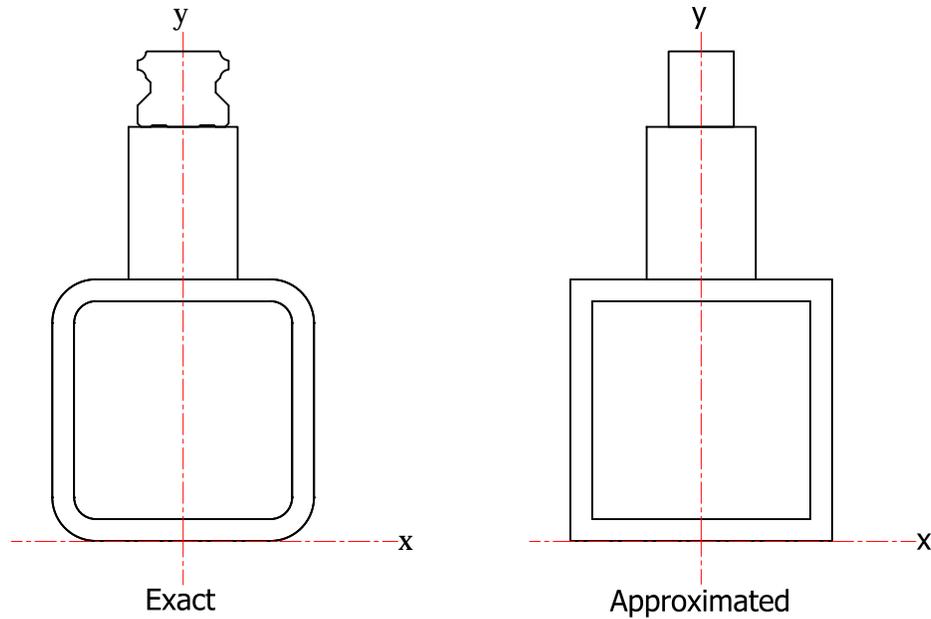
Figure 3.4: Beam cross-sectional view

assumption is made since the platform bar and square tube are welded together. Using the composite method the centroid of the aluminum components is calculated.

Table 3.1: Aluminum centroid calculations

Component	W (mm)	H (mm)	A (mm^2)	$\bar{y}$ (mm)	$\bar{y}A$ (mm^3)
Square Tube	152.4	152.4	23226	76.2	1769800
Sq. Tube Hollow Area	127.0	127.0	-16129	76.2	-1229000
External Stand Bar	60.0	88.9	5334	196.85	1050000
Totals	-	-	12431	-	1590800

$$\bar{y}_{al} = \frac{\Sigma \bar{y} A}{\Sigma A} = \frac{1590798 \text{mm}^3}{12431 \text{mm}^2} = 128.0 \text{mm} \tag{3.4}$$

3.3.2.2   <u>HPM75 and Standard Steel Rail Centroid Calculations</u>

The steel portion of this structure is the THK HSR55 rails. As can be seen in Figure 3.4, the shape of the rails is complex. To simplify the calculations the area is assumed to be rectangular with the dimensions 38 mm (the narrowest width) by 44 mm (the overall height). Thus the centroid located at half of it's height:

$$\bar{y}_{st} = 241.3\text{mm} + \frac{44\text{mm}}{2} = 263.3\text{mm} \tag{3.5}$$

3.3.2.3   <u>Neutral Axis Calculations</u>

In the case of a non-homogeneous beam, the area moments of inertia are calculated about the neutral axis (the location where the stress and strain is zero). The neutral axis has been denoted as x' (horizontal) and y' (vertical) and being centered at the composite centroid, see Figure 3.5. The following equation is used to determined the exact location of this axis, with E representing the modulus of elasticity, $\bar{y}$ the centroid for each material, and A the cross-sectional area.

$$E_{st}\bar{y}'_{st}A_{st} + E_{al}\bar{y}'_{al}A_{al} = 0 \tag{3.6}$$

To determine the location of the neutral axis, the constants c_1 and c_2 have been defined to be the vertical distance from the $y' = 0$ (neutral) axis to the top and bottom of the beam, respectively. Through algebraic manipulation the following equation has been formed and solved.
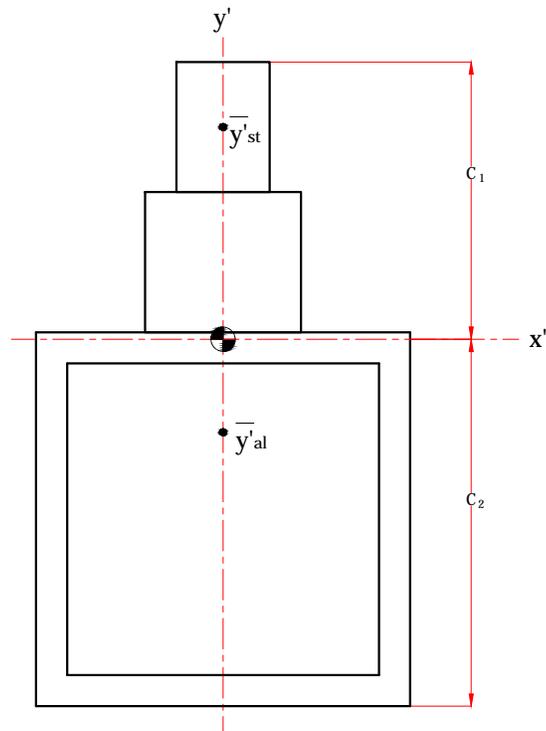
Figure 3.5: Moment of inertia for steel, aluminium, and combined

$$(193\text{GPa})(c_1 - 22.0\text{mm})(1672\text{mm}^2) + (69.6\text{GPa})(c_1 - 157.3\text{mm})(12431\text{mm}^2) = 0 \quad (3.7)$$

$$c_1 = 120.5\text{mm} \ and \ c_2 = 164.8\text{mm} \quad (3.8)$$

3.3.3   Area Moment of Inertia and Weighted Flexural Rigidity Calculations

To determine the deflection about the neutral axis, the area moment of inertia (I) must be calculated. Using the parallel-axis theorem, this value can be found by summing local the area moment of inertia from the materials centroid (I_{xx}) and the total area (A) multiplied by the distance (d) from the local area moment of inertia to the neutral axis.

$$
\begin{aligned}
I_{st} &= I_{xx} + A_{st}d_{st}^2 \\
&= \frac{bh^3}{12} + A_{st}(\bar{y}_{st} - c_2)^2 \\
&= 1.6492\text{E}7 \text{ mm}^4
\end{aligned}
\tag{3.9}
$$

The same method is applied to the aluminum section utilizing the values from Table 3.3.3.

Table 3.2: Area moment of inertia calculations

Component	Base (mm)	Height (mm)	A (mm^2)	$\bar{y}$ (mm)	d (mm)
6" x 6" Sq. Tube	152.4	152.4	23226	76.2	88.6
Tube Hollow Area	127.0	127.0	-16129	76.2	88.6
External Stand Bar	60.0	88.9	5334	196.85	32.05

$$
\begin{aligned}
I_{al} &= \Sigma(I_{xx} + Ad_{al}{}^2) \\
&= \Sigma(\frac{bh^3}{12} + A_{al}d_{al}{}^2) \\
&= 3.9677\text{E}8 \text{ mm}^4
\end{aligned}
\tag{3.10}
$$

Since this beam is bimetalic the weighted flexural rigidity is calculated using the elastic modulus (E) and the area moment of inertia (I) for both materials.

$$\overline{EI} = (E_{st}I_{st} + E_{al}I_{al})$$
$$= 9.306\text{E}12 \text{ N-mm}^2$$

(3.11)

3.3.4   Deflection

One of the critical concerns regarding the installation and extraction of the detector solenoid train is that it be able to roll into and out of the bore as smoothly as possible. To facilitate this, minimal rail deflection is desired. Following the THK guideline for *error allowance in vertical level between rails*, the deflection (δ) should follow the manufacturer guideline: $\delta \leq 600\mu m/m$ length of rail [15]. To determine the deflection throughout the beam the principle of superposition will be applied.

> Superposition resolves that the effect of combined loading on a structure can be determined by finding the effect of each load separately and then adding the results together algebraically. For superposition to be applied the following conditions must be met:
>
> 1. Each effect is linearly related to the load that produces it.
> 2. A load does not create a condition that affects the result of another load.
> 3. The deformations resulting from any specific load are not large enough to appreciably alter the geometric relations of the parts of the structural system. (Budynas, Nisbett, and Shigley, 2011, p. 153)

The equations for the for the deflection at each point are as follows with the variables corresponding to Figure 3.2 [14].

$$\Sigma y_{ab} = \frac{Fbx}{6\overline{EI}l}[x^2 + b^2 - l^2] \tag{3.12}$$

$$\Sigma y_{bc} = \frac{Fa(l-x)}{6\overline{EI}l}[x^2 + a^2 - 2lx] \tag{3.13}$$
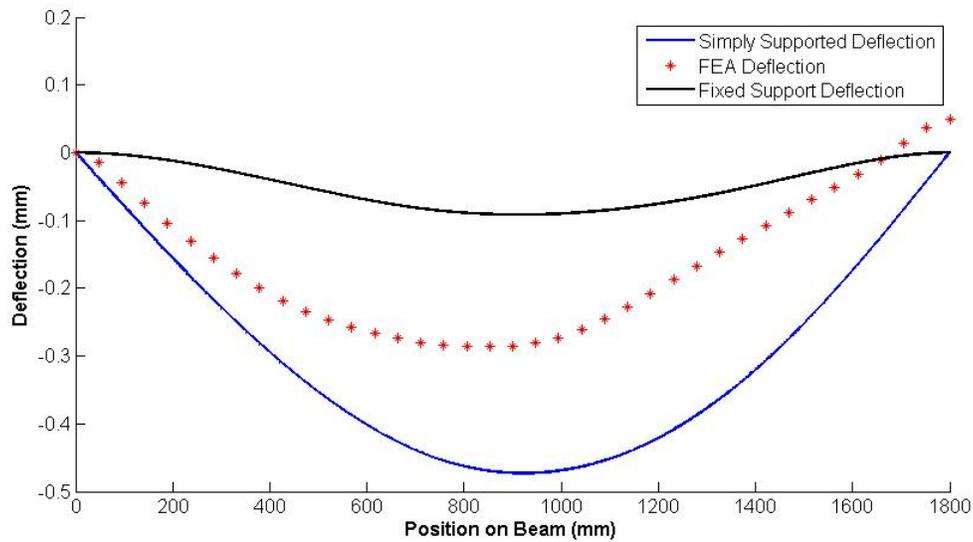
Figure 3.6: Theoretical deflections compared to FEA

Summing the deflections from the individual loads yields a higher deflection when compared to FEA result, which uses the actual geometry. This is due to the fact that the beam is not truly simply supported, and contains gussets which increase the beams stiffness. However, the beam does not exactly follow distribution given by a fixed support plot either. In reality the beam deflection falls in the region between fixed and simply support, which is what one could expect from a real beam. Figure 3.6 does verify that using a simply supported beam is a conservative assumption and will lead to higher stresses than those experienced by the stand. Viewing the deflection from the FEA is can be seen that the deflection is not symmetric like it is for the analytical solutions. This develops since one of the loads falls on

top of the beam where a gusset has been added. This causes the deflection due to that load to be minimized.

3.3.5 <u>Stress</u>

To determine the maximum bending stress in the beam the moment at that point must be calculated. The equation for the internal moment of a beam follows the governing equation:

$$M = EI \frac{dy^2}{dx^2} \tag{3.14}$$

Applying this equation yields the internal moment distribution seen in Figure 3.7. Note that the slope of the moment changes at the points where the loads are applied. The maximum moment is found and will be utilized in determining the stresses in the bimetallic beam.

$$
\begin{aligned}
\sigma_{st} &= \frac{-M E_{st} y}{\overline{EI}} \\
&= \frac{-M E_{st} c_1}{\overline{EI}} \\
&= 32.6 \text{MPa (Compression)}
\end{aligned}
\tag{3.15}
$$

$$
\begin{aligned}
\sigma_{al} &= \frac{-M E_{st} y}{\overline{EI}} \\
&= \frac{-M E_{st} c_2}{\overline{EI}} \\
&= 16.1 \text{MPa (Tension)}
\end{aligned}
\tag{3.16}
$$
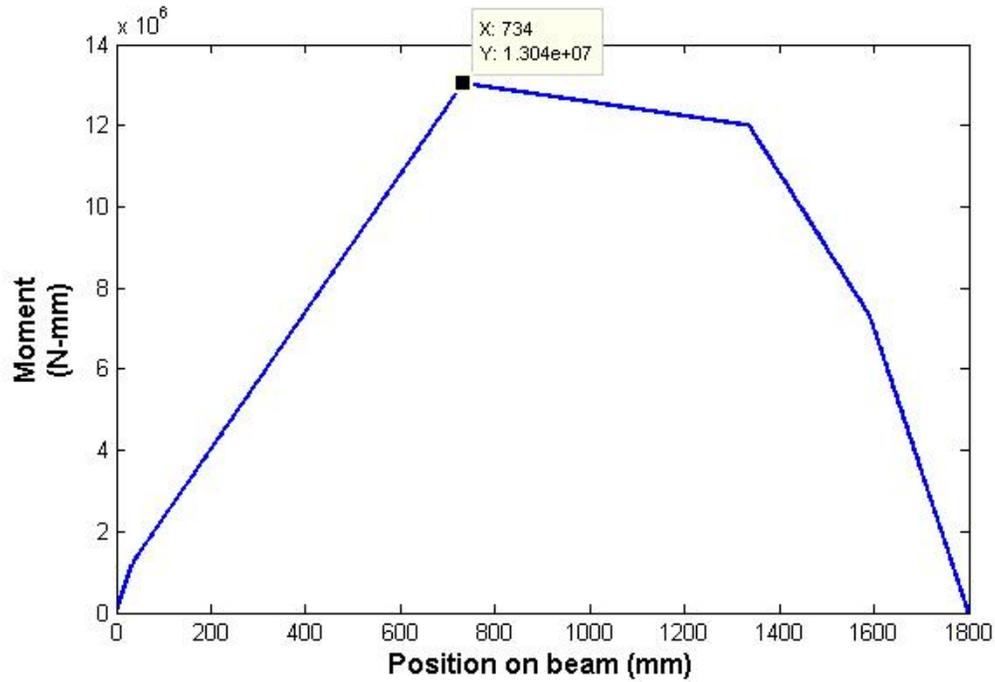
Figure 3.7: Theoretical internal moment for the external stands

Another important aspect to consider in the design of a beam is that the end supports can withstand the necessary reaction forces. To determine reaction forces on each end of the beam, the following equations and variables from Figure 3.2 are used.

$$R_1 = \Sigma \frac{Fb}{l}$$
$$= 35070\text{N}$$

(3.17)

$$R_2 = \Sigma \frac{Fa}{l}$$
$$= 35070\text{N}$$

(3.18)

The smallest cross-sectional area on the vertical support is the square tubing, so it is important to calculation the compressive stress in the member. Using the reactions force (F) and area (A) found in Table 3.3.3 the compressive stress is determined.

$$
\begin{aligned}
\sigma_c &= \frac{F}{A} \\
&= \frac{35070\text{N}}{(23226 - 16129)mm^2} \\
&= 4.94\text{MPa}
\end{aligned}
\tag{3.19}
$$

The stresses found in Equations 3.15, 3.16, and 3.19 result in a minimum safety factor of 7.6 with respect to the yield strength of the materials. Next the stress throughout the entire stand will be considered.

3.4   Finite Element Analysis

To determine the stress, safety factor, and deflection an ANSYS finite element analysis was performed. As shown in the analytical analysis, the maximum loading conditions are used. While adhering to a safety factor of 2 was an important part of the design, the most challenging part of the design optimization was reducing the deflection to the acceptable level.

3.4.1   Loading Conditions

In the analytical analysis point loads were used for simplicity. However, this analysis will use the actual distributed loading areas (condition C-J). Standard earth gravity (condition
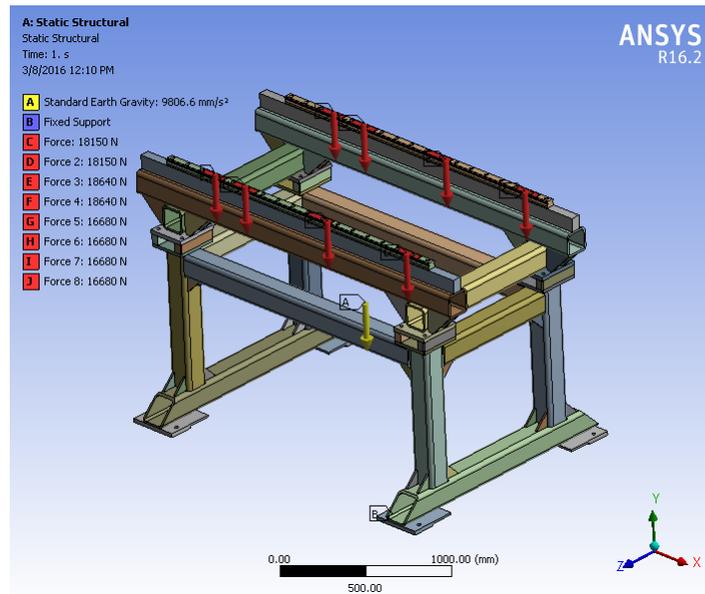
Figure 3.8: External stand loads from tracker, calorimeter, and gravity

A) is also applied in this model, which takes into account the stands weight. Since the stands will be bolted into the floor plates the bottom of each "foot" has been constrained in all directions (condition B).

3.4.2 Total Deformation

The total deformation of the stand are given as magnitude. The red shading is the highest deflection and occurs at the midpoint of the beam. The blue is the least deflection which occurs on the feet near the ends. Comparing the maximum total deflection to the maximum vertical deflection yields almost the same amount. However certain regions will have some component of x and z deformation.
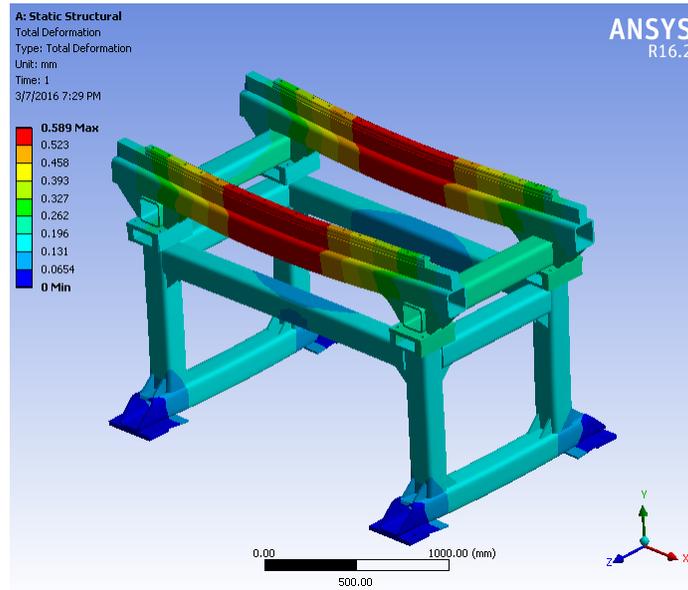
Figure 3.9: External stands total deformation

3.4.3 <u>Vertical Deformation</u>
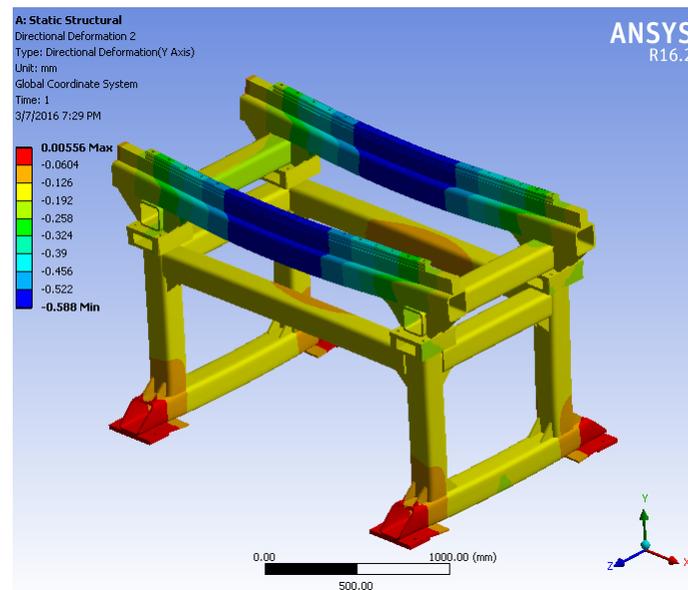
Figure 3.10: External stand vertical deformation

The maximum vertical displacement of the rails is 588 μm in the downward direction. The criteria for the design is that it should not exceed 600 μm per 1 meter of travel. Half the length of this stand is 1.25 meters, thus the stand is within the allowable deflection range.

3.4.4   Stress
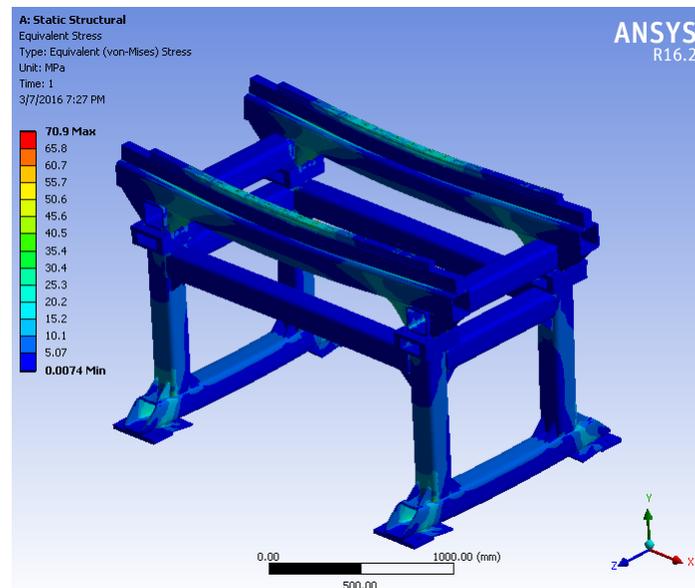
Figure 3.11: External stand von-mises stress

Analyzing the stress of the external stand was a challenging endeavor. As it appears from Figure 3.11 the visible stresses do not exceed 52.5 MPa. However taking a very close look at some of the connections, stresses near 71 MPa are reached. The areas that these high stress points occur are places where sharp corners meet flat, bending surfaces. In finite element terms this is called a considered singularity. In reality all physical surfaces will have some radius and the stress in such areas will not be so high. Furthermore, the extra material that will be added to these areas by welding has not been included in this model.

An additional stress concern in this design is that weld affected areas have a lower yield strength than the nominal strength of the tempered aluminum. When welding occurs in an area the region within 25.4 mm (1 inch) of the weld center-line is considered to be "weld-affected". The strength of the material in these zones depends on the base metal, temper, and the alloy filler used for the weld. For 6061-T6 aluminum that has been welded with 5183, 5356 or 5556 alloy filler the yield strength is 105 MPa. [13]

3.4.5 Safety Factor
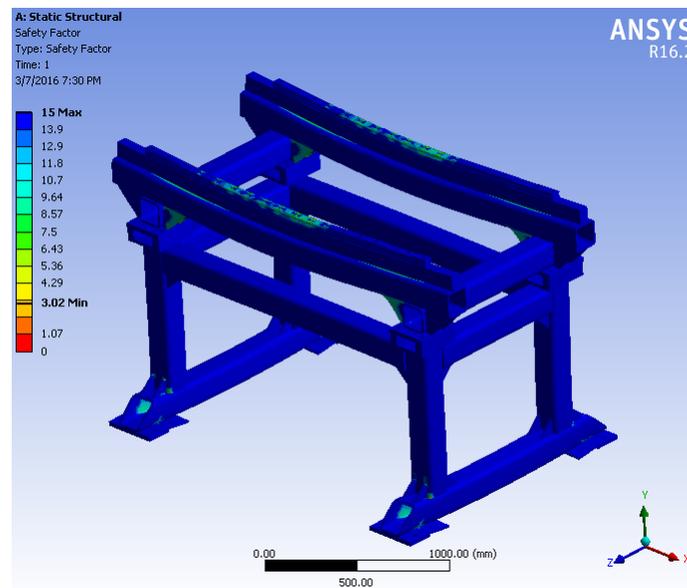
Figure 3.12: External stand safety factor

Even with several small stress singularities, the safety factor of this design is above 3 relative to the strength of the tempered aluminum. As discussed in the stress section, the regions that are weld-affected will have a lower yield strength and must be reviewed during the final phase of the design.

3.5 Mock Up Testing

As shown in Figure 1.8, a system of external stands will be used to support the interior DS components and transport them into the DS bore. In order to be sure that the desired alignment between stands could be achieved the top weldment of the small stand was fabricated. This system was tested on a rail mock up at Fermilab in the Industrial Center Building between February 15th and 24th, 2016 and shown in Figure 3.13. Four small weldments were used to imitate the bottom portion of the external stands.
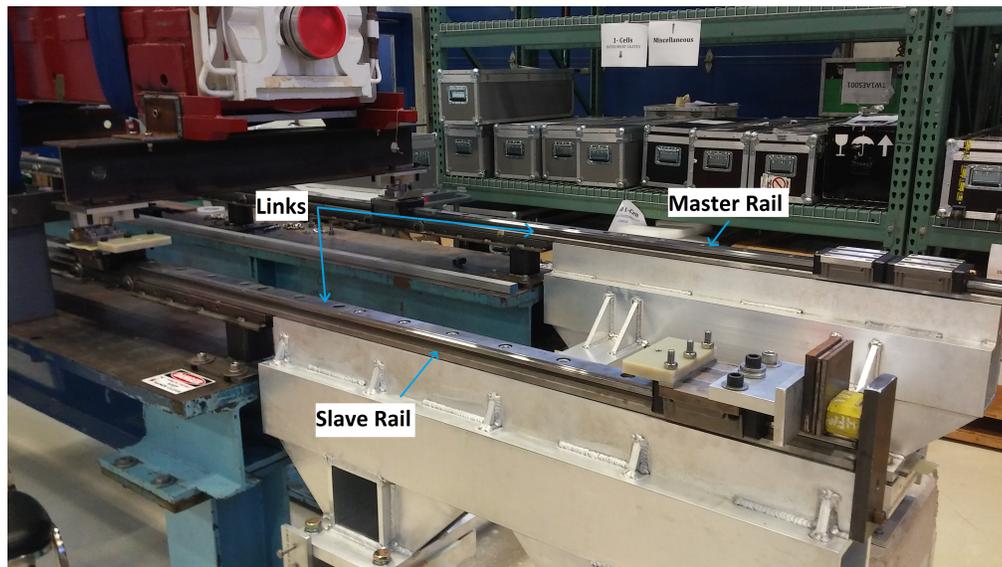
Figure 3.13: External stand mock up

By design, the two surfaces of the top segment to which the rails are bolted is machined as a plane which has a maximum out-of-flatness tolerance of 75 μm. The top segment can then be leveled as a whole by four inclined-plane jacks that fit in a slot between the upper and lower weldment, see Figure 3.14. The procedure developed for this test will be replicated in the actual Mu2e experiment.

Figure 3.14: External stand adjustment region

3.5.0.1 Adjustment Methodology

1. Inspect the upper stand weldment to ensure that the platforms to which the rails will be attached are flat within 75 μm.

2. Bolt the four lower supports into the upper segment.

3. Bolt the main (center) rail segments onto the upper stands.

4. Align the assembly into its approximate desired position, both vertically and laterally, using a straightedge.

5. Bolt the links into place, aligning them laterally with the original rail with a straight edge.

6. The alignment crew takes measurements of the original rails which comprise the already-constructed mockup. Vertical measurements are taken of both rails and lateral measurements are taken of the master rail only. An ideal plane is created from the measurements, which represents a best-fit extension of the original rails.

7. Adjust the upper external stand to the ideal frame.

   (a) Place the inclined plane jacks into the four appropriate openings between the bottom stands and the top segment.

   (b) Loosen the bolts which attach the upper segment to the lower stands.

   (c) Raise or lower the upper stand to the vertical positions defined by the ideal frame, from instructions given by the alignment crew.

   (d) Place shims between upper and lower stands to fill in the spaces between them.

   (e) Adjust the stand laterally in both x and z using adjustment angles.

   (f) Tighten the bolts to firmly attach the upper and lower stands.

   (g) Measure the vertical and lateral positions of the rails.

   (h) Add or subtract shims or adjust laterally to correct any positional errors.

   (i) Repeat steps e-h until stand is within 125 μm of the ideal frame.

   (j) Slightly loosen the bolts which attach the slave rail to the upper external stand segment.

   (k) Using the alignment cart adjust the lateral position of the slave rail, including the link.

   (l) Loosen the bolts slightly on the master-side link.

   (m) Using the alignment cart, adjust the lateral position of the master link.

8. Take a final measurement of both the master and slave rails, laterally and vertically.

9. Roll the heavy weight (4200 kg) conventional Main Injector quadrupole over the external stand to test the ease of travel.

10. Roll the heavy weight off the external stand.

11. Measure the external rails after the magnet has been removed.

12. Review the results to ensure desired tolerances were achieved.

3.5.0.2   Adjustment Results

The measurements from before and after loading can be seen in Figure 3.15, where the deflection relative to the initial alignment is observed. During loading both sides temporarily deflected by 75 μm near the center of the support. When comparing the results, from before and after loading, small variations were expected since layers of shims can be slightly compressed or flattened. However, the objective of this experiment was to ensure rails stay stay within 125 μm of the original plane. Based upon the measurements, shown in Figure 3.15, the alignment stayed within tolerance. From this experiment, it was concluded that the desired alignment can be achieved when the stands are fabricated and aligned in the detector hall.
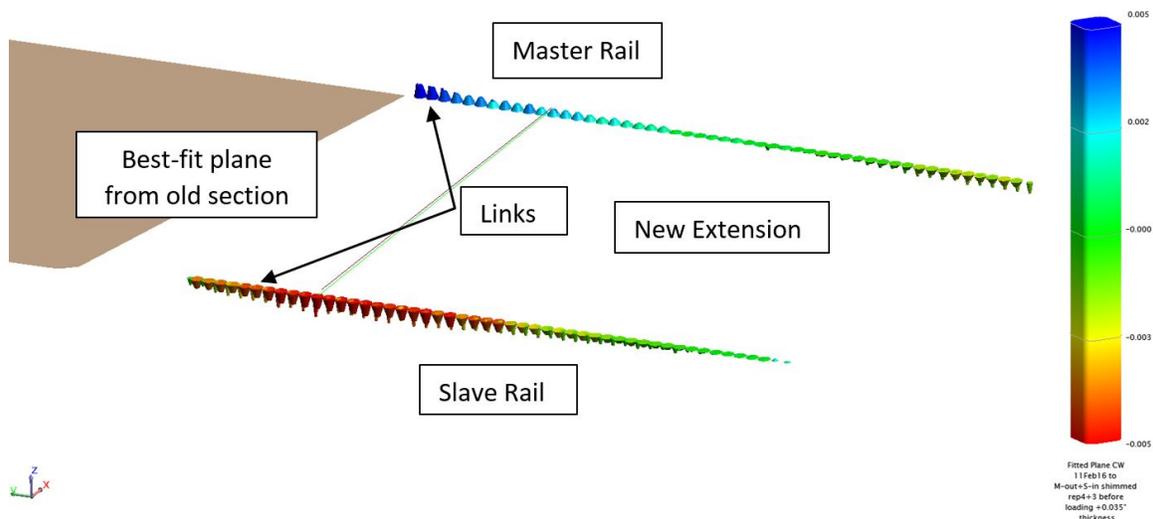
Figure 3.15: External stand measurements large cones (before loading), small cones (after loading)

3.6   Design Status Summary

At the time of this thesis submission, the external stands are in the preliminary design iteration two phase. It is expected that only small changes will be made (if any) during the final design phase. Detailed drawings of the external stands can be found in the Appendix. One of the primary aspects to consider during the next phase is the final height difference between the floor and the center of the DS. Until the concrete floor has been poured and measured, the final dimensions cannot be determined. Fortunately, all of the custom adjustments can be made in the overall leg height and then smaller shimming can be performed at the stand mount.

CHAPTER 4

DETECTOR SOLENOID THERMAL CONTROL

4.1   Purpose of a Thermal Management System

As discussed in section 1.3.3, the DS contains a cold mass (cooled to 5K) between two concentric cylinders. The inner cylinder is a warm bore and provides a location and environment to acquire data. There are two motivating factors in controlling the temperature of the DS warm bore. The first is that if the temperature is allowed to drop below 0 the bore, and when the DS is brought back to atmospheric pressure (from high vacuum) the water vapor in the air will condense on the cold surfaces. This is problematic since numerous electronic circuit boards, sensors, and wires exist inside the DS. The effects of condensed water on these components would cause failure. The second area of concern is the thermal contraction that would be experienced by the rails system and consequently the DS train. Thermal contraction could cause two potential problems: binding of the rails and misalignment of components. To achieve optimum performance, the parallelism between rails should be within 70 μm [15]. In addition, the desired positional accuracy of the DS train components is $\pm$ 2 mm and in some cases $\pm$ 1 mm. This accuracy allows a specific spectrum focus for the physics measurements. If a large temperature gradient developed, then it would be difficult to achieve this tolerance. To determine if there was a need for temperature control, a detailed deflection and stress analysis of the detector solenoid under vacuum was completed.

4.2   Heat Transfer

Since the tube boundary conditions and geometry are symmetric both axially and tangentially, the problem can be analyzed in 2D. The 2D model is a quarter cross-sectional cut. The simplified model of the DS is represented in Figure 4.1. The two ends of the solenoids and the outside are at 20°C and the radiation heat transfer from the 293.15K (20°C) vessel to the 80K MLI is represented by a heat flux $q'' = 1.5\frac{W}{m^2}$. This value was determined by measurements from Fermilab engineers in prior experiments and is the value assumed for design purposes [16].

Conduction heat transfer occurs inside the material and is expressed by the Fourier law, Equation 4.1.

$$\dot{Q}_{cond} = -kA\frac{\partial T}{\partial z} \tag{4.1}$$

With $\dot{Q}_{cond}$ representing the heat transfer rate, A the cross-sectional area, and $\frac{\partial T}{\partial z}$ the change in temperature with respect to the Z direction. The coefficient of thermal conductivity for 316L stainless steel ranges between 14 $\frac{W}{mK}$ and 15.9 $\frac{W}{mK}$, and is assumed to be $k = 14.6 \frac{W}{mK}$ in this analysis.

With reference to Figure 4.1, the geometry of the detector solenoid is defined in Table 4.1

Table 4.1: DS geometry

Inner Shell ID [mm]	Inner Shell tk [mm]	Outer Shell OD [mm]	Outer Shell tk [mm]	End Wall tk [mm]	Length [mm]
1900	20	2656	20	40	10900
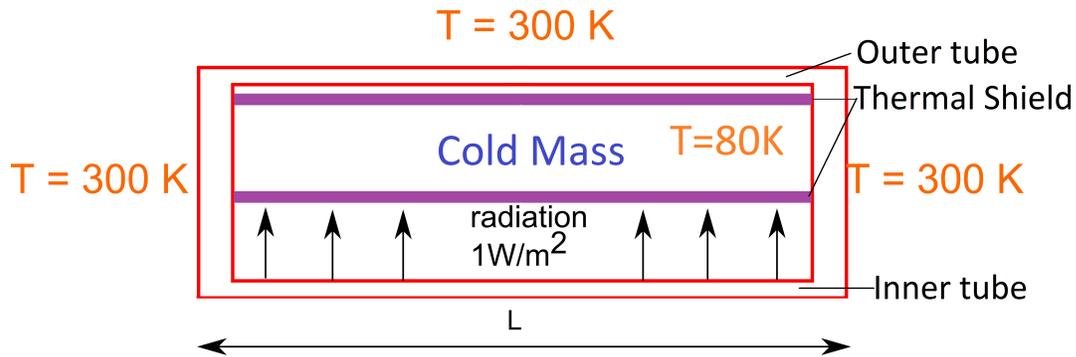
Figure 4.1: Simplified scheme of the solenoid and vessel.

4.2.1 Preliminary DS Finite Element Analysis

Once of the first steps in many engineering analyses is to perform a simplified analysis to develop an understanding of the physics of the system. This was done by for the DS by assuming a 2D model and applying boundary conditions.

4.2.1.1 Boundary Conditions

The temperature of the air surround the DS will be controlled to be between 20-27 °C. To be conservative the end of the DS is assumed to be equal to the lowest possible air temperature. To justify this is a valid assumption, hand calculations were performed by Fermilab engineers that showed the convection environment caused air and ends of the DS to remain the same temperature within one degree [16]. The expected radiative heat flux of 1.5 $\frac{W}{m^2}$ is applied to the outer diameter of the inner (warm) bore. Within the 3000 element

model a symmetry plane has been imposed on the right side, where the center of the DS would be located.
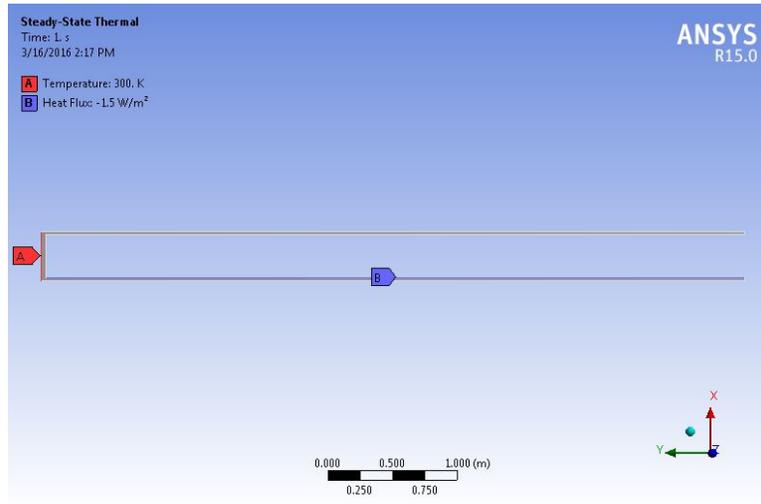
Figure 4.2: Boundary conditions and load in vacuum with symmetry imposed

4.2.1.2 Temperature Distribution

The temperature different between end and center of the DS in analysis was found to be 75°C. This shows a very significant temperature change that required a more in depth study.
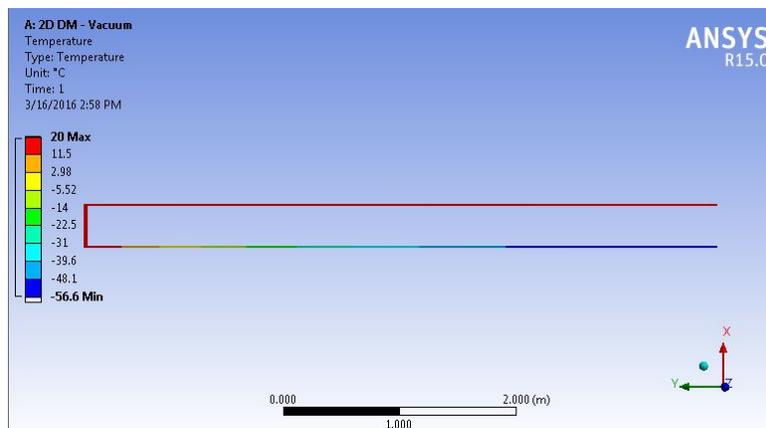
Figure 4.3: Temperature distribution in half of the model of the DS

4.2.2   Secondary DS Finite Element Analysis

After completing the simplified 2D case and reviewing the results, it became clear that the full model should be constructed. The ultimate concern with a large thermal gradient is that high deflection and stresses will develop in the system. To analyze these properties a coupled steady-state thermal and static structural analysis has been performed.

4.2.2.1   Thermal Boundary Conditions

The applied boundary conditions in the steady-state thermal analysis are the same as those imposed in the 2D case. A key difference that has been added to this model is the addition of the "box dimensions" of the internal rail geometry.
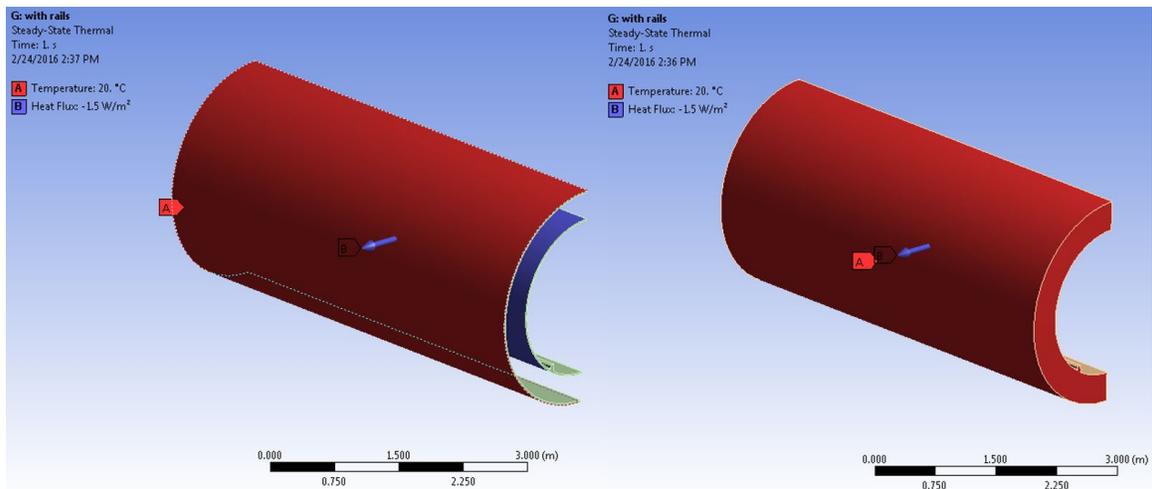
Figure 4.4: Boundary conditions and load in vacuum

4.2.2.2   Temperature Distribution

Completing the analysis results in a temperature that ranges from 20°C on the ends and reaches -50°C at the center, see Figure 4.5. This change is similar to that observed in the 2D analysis. To determine the impact this has on the structural integrity of the DS, the temperature data was imported in an ANSYS static structural environment.
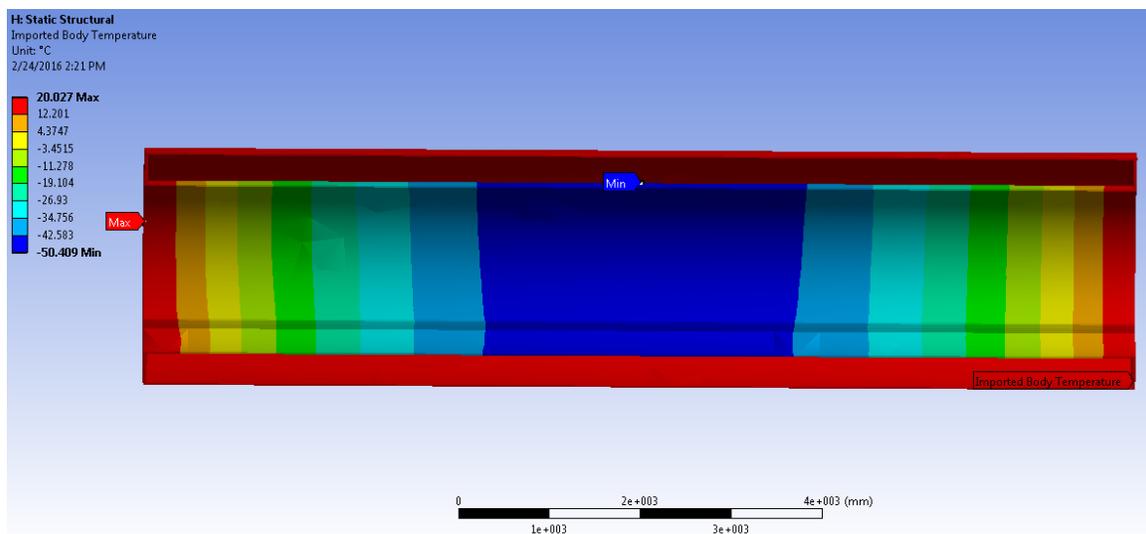
Figure 4.5: Steady state temperature distribution

4.2.2.3   Structural Boundary Conditions

Once the temperature profile was added to the model, the outside diameter of the outer shell was set constrained to have zero displacement (fixed). In reality the DS will have two stiffening rings that surround it as well as saddle supports that extend to the floor. While this assumption may lead to higher stress near the constraint, the overall deflections will be smaller (more conservative) than those that will actually develop.
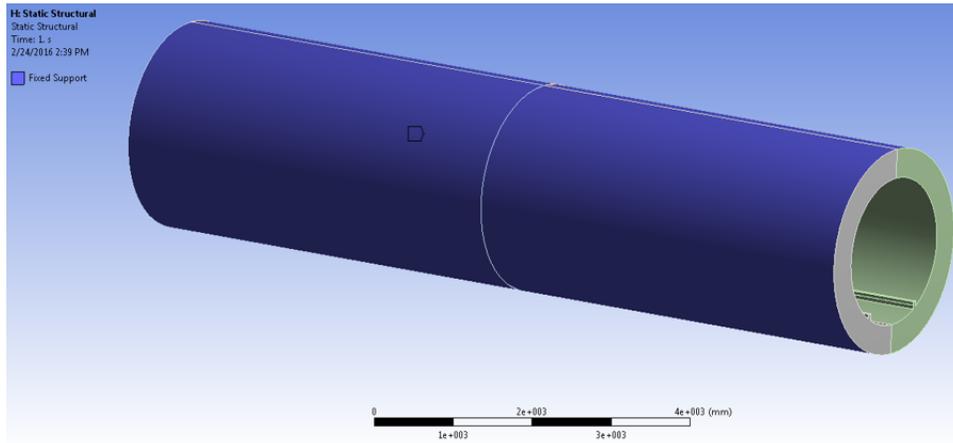
Figure 4.6: Boundary condition: displacement constraints

4.2.2.4   Deformation
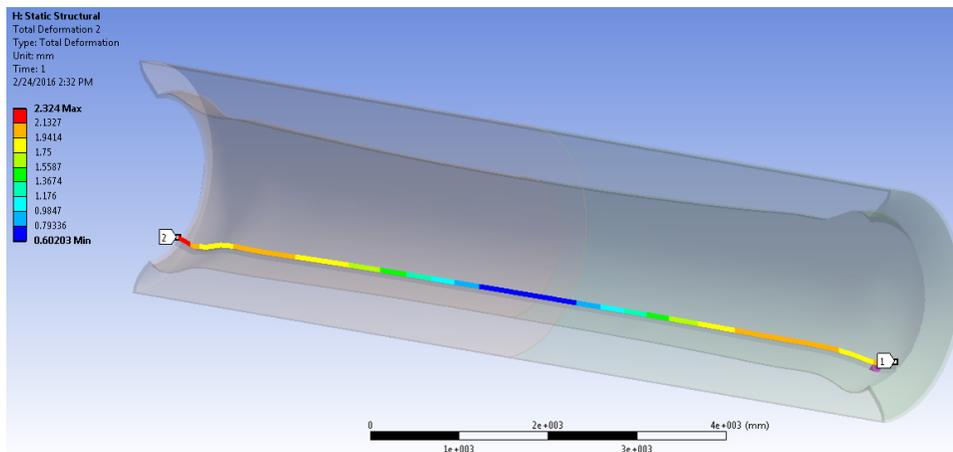
Figure 4.7: Total deformation from thermal contraction

Since the region of interest in this study is the rail deflection, the nodes along the rail were mapped to a path so that the the deformations could be examined. Reviewing the magnitude of the total deformation is can be seen that the deformation exceeds what is allowed for the system. To obtain a better understand of the deformation components the deflection in each direction will be reviewed.
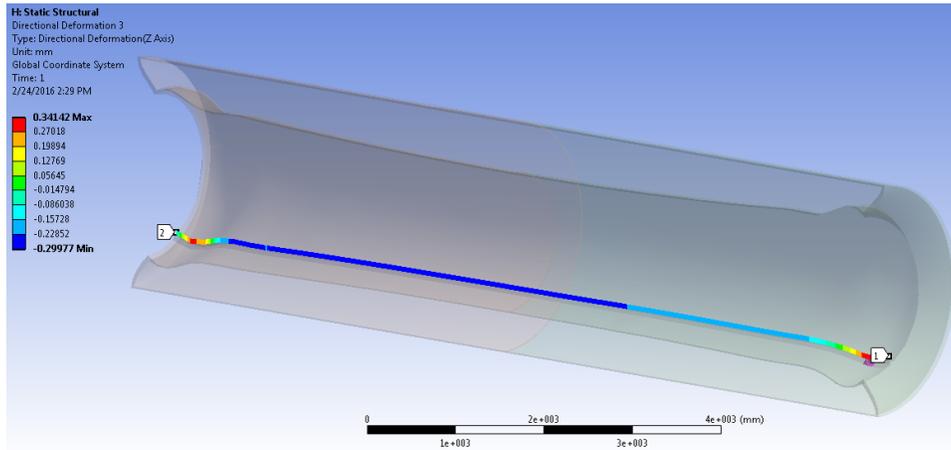
Figure 4.8: Transverse deformation from thermal contraction

Figure 4.8 shows that the maximum transverse displacement is 0.34 mm. The rails in the DS will be installed to have a nominal separation of 1000 mm between the center of the rails. The components on the master rail side will remain in a fixed position while the slave side can float (discussed in section 1.3.3.1). Considering this the center of the detector component would shift away from or towards the slave side at twice the magnitude shown in Figure 4.8.
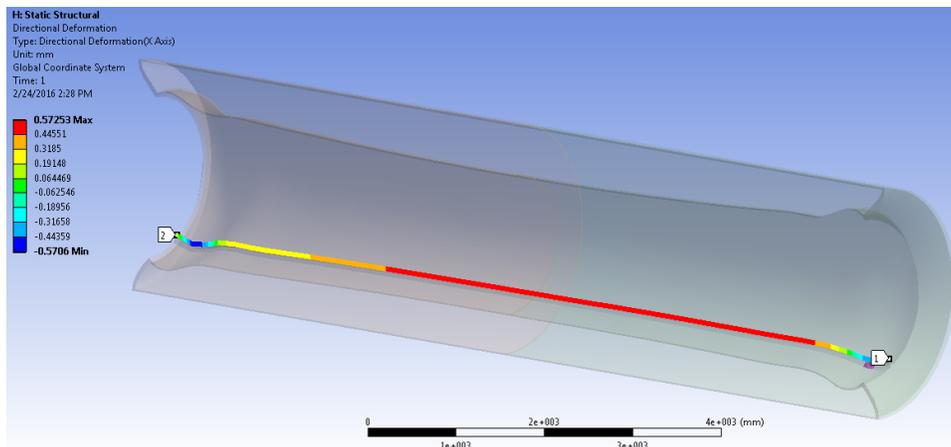
Figure 4.9: Vertical deformation from thermal contraction

The vertical displacement in the DS is symmetric between the master and slave side. As can be expected, this magnitude is greatest at the center of the DS where the temperature change is greatest shown in Figure 4.9.
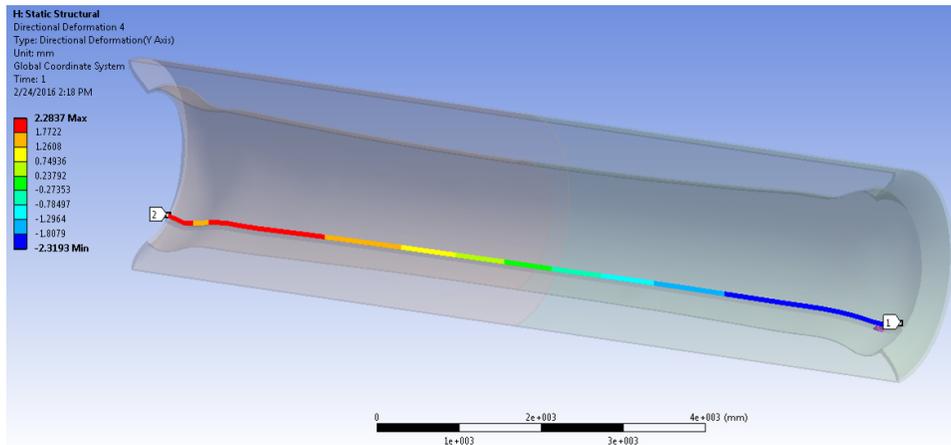
Figure 4.10: Axial deformation from thermal contraction

The axial displacement is the most significant contributor to the overall deflection. This can be explained through Equation 4.2, where L is the length, alpha is the coefficient of thermal expansion, and T is the temperature.

$$\Delta L = \alpha L \Delta T \tag{4.2}$$

From this governing equation it can be seen that by increasing the length, the change in length (ΔL) linearly increases. Since the tube is longest in the axial direction, this is the direction of maximum displacement. It is important to note that while the rails and DS will shrink, the position of the DS train will be fixed relative to the downstream end IFB to VPSP connection.

To summarize the total displacements Figure 4.11 has been generated. The total displacement is shown plotted as an absolute magnitude. Comparing the axial to the total shows little difference.
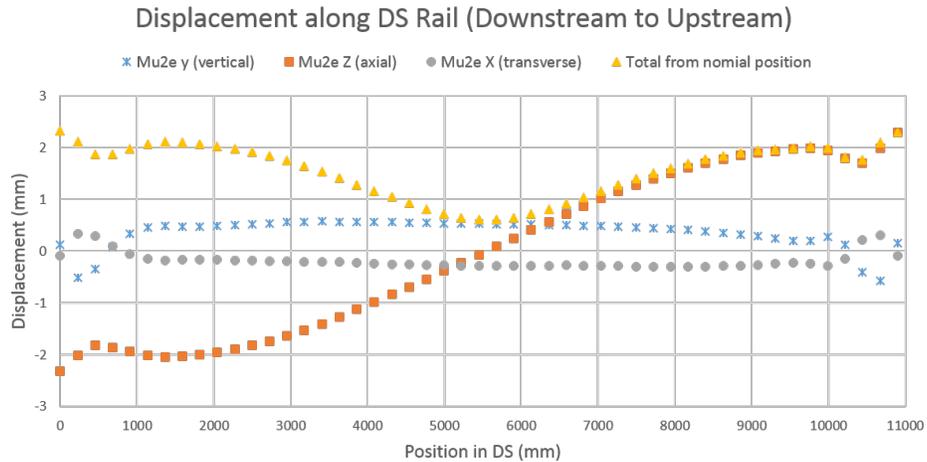
Figure 4.11: DS displacement of individual components

4.2.2.5 Stress along Rail
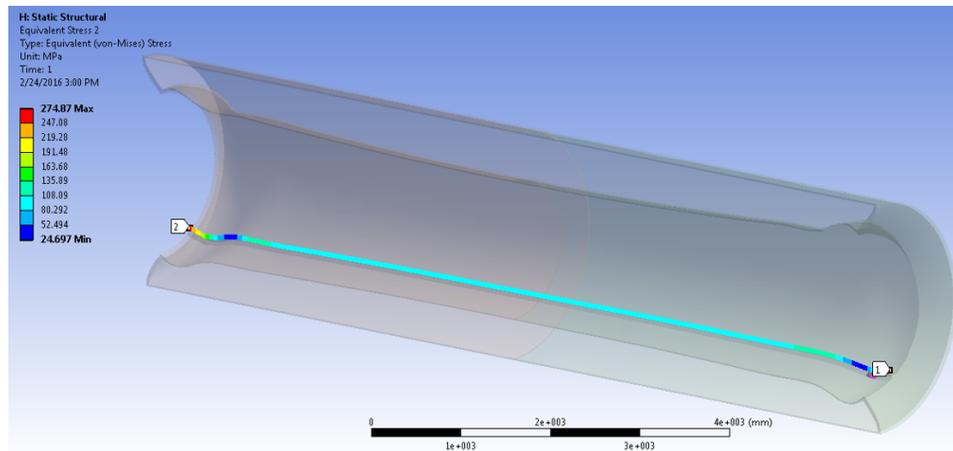
Figure 4.12: Stress along the rail from thermal contraction

As can be seen in both Figure 4.12 and 4.13, the stress that develops in the rail is significant. The peaks on both ends lie around 275 MPa which is greater than the yield stress of 248 MPa for 316L stainless steel [10]. Along the most of the rail the stress remains around 100 MPa. Even though these stresses are lower than yield, the stress due to loading

and gravitational forces have been neglected, and if included could exceed that allowed by the design. While not explicitly reported in this thesis a separate analysis was conducted that found the DS support welds yielding [16].

Figure 4.13: Stress from thermal contraction

4.3 Model Validation

To ensure the accuracy of the results, the theoretical temperature distribution will be calculated. If one considers only a quarter model (as previously done in the finite element analysis), and a simplified one dimensional case using the differential equation and the BC are as follows:

$$k\frac{\partial^2 T}{\partial x^2} + \dot{q}_{rad} = 0 \tag{4.3}$$

$$T\left(x = 0m\right) = 20°\text{C} \tag{4.4}$$

$$T'(x = 5.45m) = 0\frac{°C}{m} \tag{4.5}$$

Solving the 2nd order, linear, non-homogeneous, constant coefficient differential equation yields the following solution:

$$T(x) = 2.568x^2 - 28.0x + 20 \tag{4.6}$$

4.3.1 Comparison
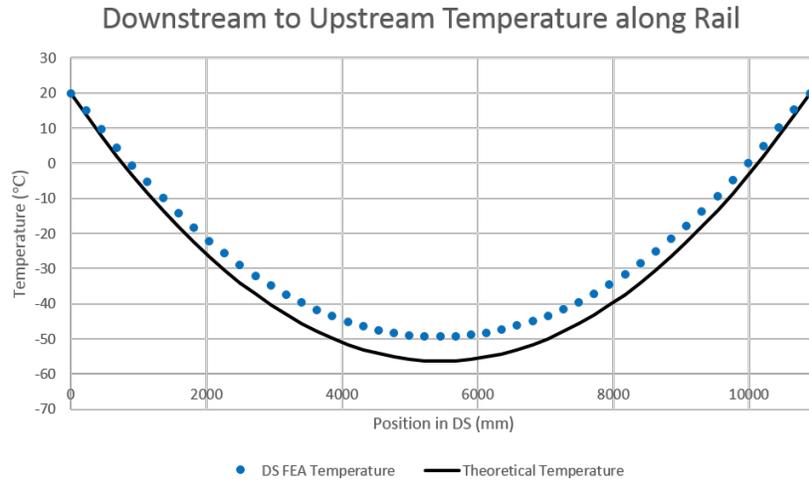
Figure 4.14: Comparison between theoretical and finite element solution

Reviewing the plot from Figure 4.14 and Equation 4.5, it can be see that both methods have very similar results. The finite element method achieved a smaller temperature difference than the analytical solution. This was expected since the FEA model contained the rails and increased the cross-sectional area and conductive capacity of tube, whereas the simplified theoretical formulation did not. The important aspect that this plot shows is that the FEA and analytical solution curves behave in the same manner. The maximum

difference between the results over the total temperature gradient is less than 10% at the center of the tube.

4.3.2   Necessity of Temperature Control

After studying the results from the ANSYS static structural analysis, it became apparent that a need for temperature control is necessary. Introducing a new design into the pre-existing system and budget will have several implications. To meet project goals the following constraints and requirements must be considered.

4.3.2.1   Geometric Constraints

The heating equipment for the DS bore must be able to fit into a small space. The DS consists of two concentric tubes and the inner diameter of the inside tube will be the area available for a heating system. Other components also exist inside the warm bore and any additional components must not interfere with the previously allocated space.

In Figure 4.15, the outer diameters of each component is shown. Note that the outer diameters do not explicitly establish the radial constraints since several of the components have cooling and electrical lines that will exist outside of their maximum radius. Since all of the depicted components are not final designs, the cabling and consequently the routing has not been determined yet. However, current estimates state that the area to be avoided could reach but not exceed 1820 mm in diameter. Since the inner diameter of the bore is toleranced to be 1900 mm at minimum, the available area for heating equipment is between 1820 and 1900 mm.
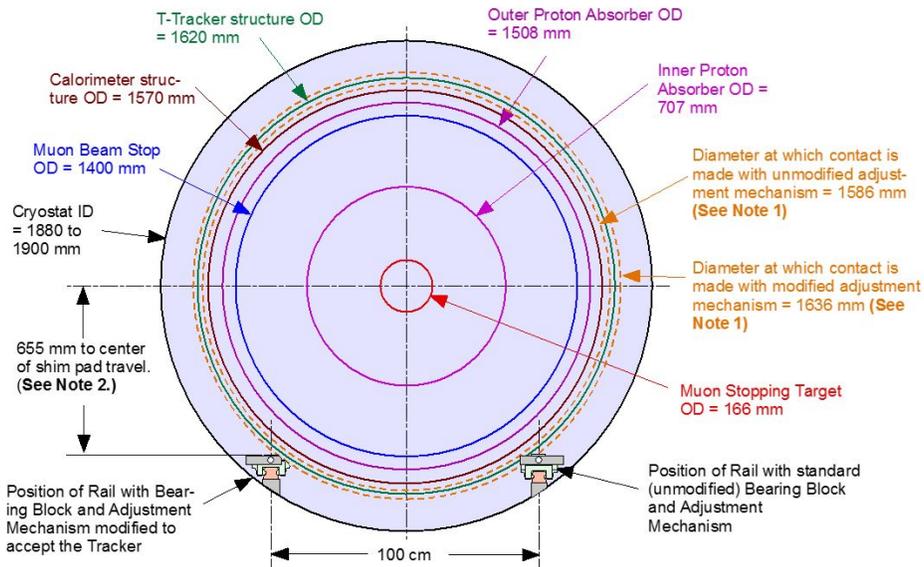
Figure 4.15: Cross-sectional view of the DS [11]

4.3.2.2 <u>Magnetic Constraints</u>

The heating system will exist within a magnetic field that ranges between 1T and 2T. An inherent trait of superconducting magnets is the phenomena of a quench. A quench occurs when a local area on the magnet ceases to be superconducting. This causes a rapid change in the magnetic field. To avoid the development of eddy currents, complete loops of electrically conductive materials cannot be made around the warm bore.

4.3.2.3 <u>Temperature Requirements</u>

Prior to completing a thermal analysis the baseline requirement for the allowable temperature range inside the DS bore was 22°C ±10°C. This range was chosen because it stays above freezing and reduces the deflection from thermal contraction.

4.3.3   Preliminary Passive Heating System Finite Element Analysis

Two methods of controlling the temperature in the DS are currently being pursued. A Fermilab engineer is currently exploring the possibility of using polymide thermofoil heaters that requires feedback and temperature sensors. Alternatively, the system studied in this thesis is passive and does not require additional attention once installed. The best method to increase that temperature at the center of the DS is to increase the thermal conductivity in the axial direction. The approach used in this analysis is mounting copper bars to the warm bore. Since copper has a thermal conductivity k=400 $\frac{W}{mK}$, much greater than stainless steel, the effective thermal conductivity in the axial direction will be increased.

4.3.3.1   Copper Geometry

In this analysis 8 copper bars with a 6 inch length and 0.75 inch thickness have been added axially and spaced 45 degrees apart. To fabricate such bars, a bending method would be applied to achieve a contour that matched that of the DS. To physically connect the bars to the bore it is likely that brazing would be the chosen method.

4.3.3.2   Thermal Boundary Conditions

The boundary conditions applied to this system are identical to those of the 2D case. As can be seen in Figure 4.17, the only difference between this and the previous analysis is the presence of copper bars.
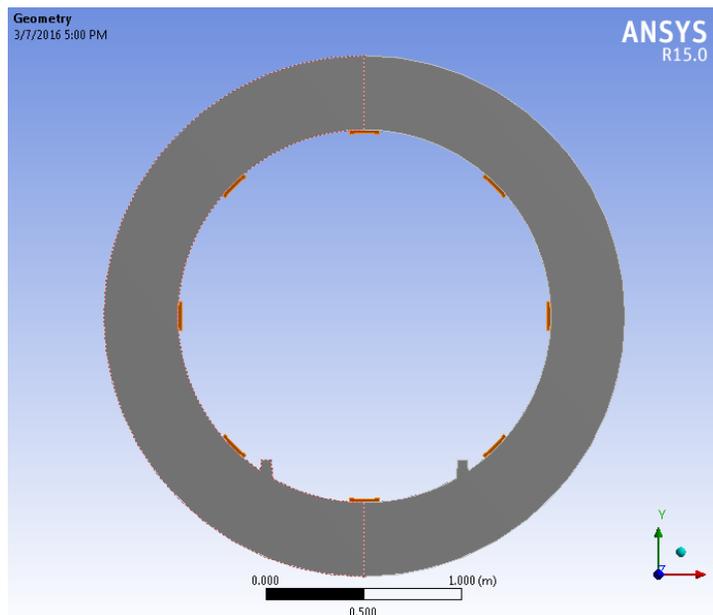
Figure 4.16: Geometry of with copper bars
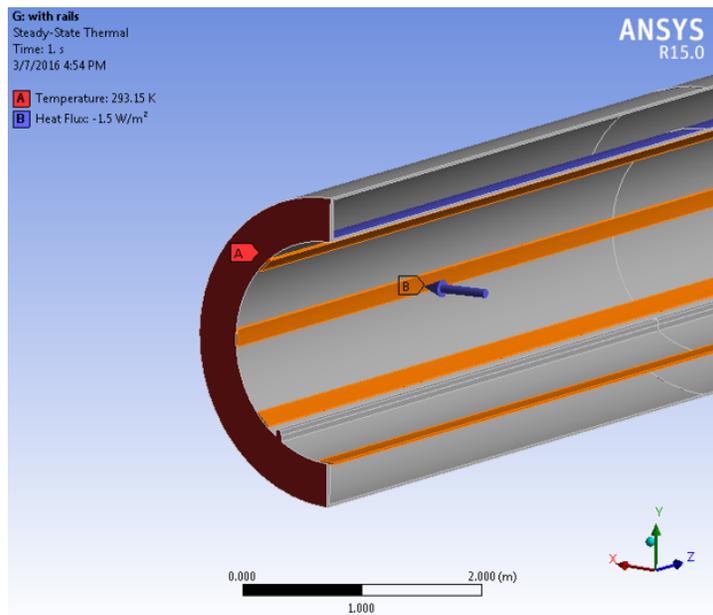
Figure 4.17: Thermal boundary conditions

4.3.3.3   Temperature Distribution

The resulting temperature difference by adding the copper bars has gone from 70°C to 12°C. Assuming that the temperature difference between end and center remained to be 12°C regardless of the temperature at the end of the DS. The outside of the DS could be held to a temperature of 25°C or greater, and the copper bar method would meet the original constraints of the design.
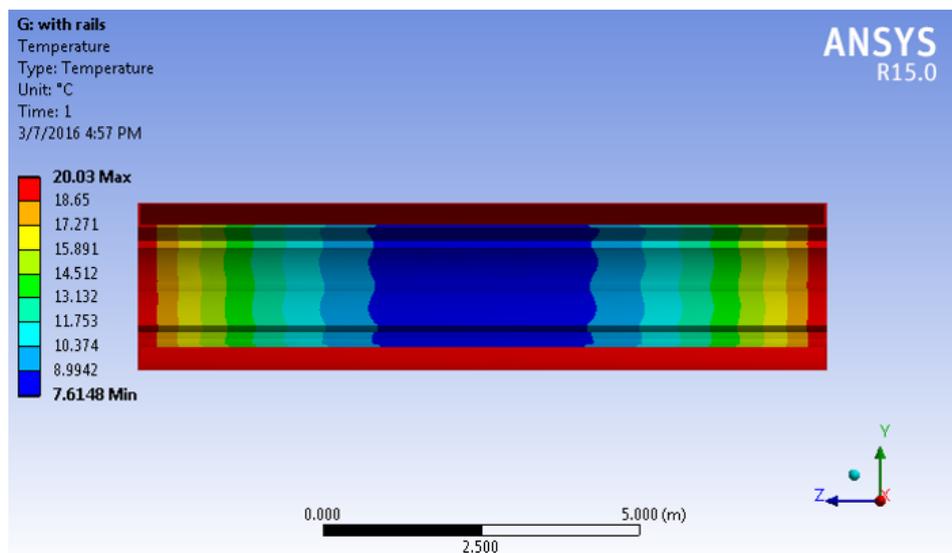
Figure 4.18: Temperature distribution with copper bars

4.4   Design Status Summary

The design of a passive heating system has been conceptualized and analysed. Future pursuits will require a more in depth study of potential heat leaks in the system. At this point in time, design alternatives and modifications are under consideration. However, it is apparent that some method of temperature control either active or passive will be required.

The proposed copper bar solution is viable under current constraints and will play a role in the development of the final system.

REFERENCES

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APPENDIX

EXTERNAL STAND DRAWINGS

PARTS LIST

ITEM	PART NUMBER	DESCRIPTION	QTY
6	FC0053056	BAR, 60mm X 88.9mm X 1180mmLG, 6061-T6 ALUMINUM	2
5	FC0052606	WEDGE GUSSET, TOP WELDMENT, EXT RAIL STAND, 6061-T6 ALUMINUM 1/2" THICK STK	10
4	FC0052599	SUPPORT RIB, TOP WELDMENT, EXT RAIL STAND, 6061-T6 ALUMINUM 1/2" THICK STK	16
3	FC0041412	PLATE, BASE 200x272x25.4THK, 6061-T6 ALUMINUM	4
2	FC0051380	TUBE SQ, 6"X6"X1/2"WALL, 1180LG, SHORT 6061-T6 ALUMINUM	2
1	FC0051379	TUBE SQ, 6"X6"X1/2"WALL, 1152.4LG, CROSS 6061-T6 ALUMINUM	2

VIEW A-A
SCALE 1:4

FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY

NAME: EXTERNAL STAND, UNIT A, TOP WELDMENT

SIZE A1   DRAWING NUMBER F10040614   REV -

SCALE 1:6   SHEET 1 of 1

DRAWN J.KURNAT   DATE 24-Apr-2015

SEE PARTS LIST

REVISION CONTROL DOCUMENT
F10040614--RCD

NOTES (UNLESS OTHERWISE SPECIFIED):
1. WELDMENT MUST BE FREE OF DIRT, GREASE, OIL, AND CHIPS.
2. WELDMENT TO BE FREE OF SHARP EDGES, CORNERS, AND BURRS.
3. TRAILING ZEROS DENOTE TOLERANCE.

PARTS LIST

ITEM	PART NUMBER	DESCRIPTION	QTY
9	FC0051696	BOTTOM SUPPORT, 6" X 6" X 1/2"WALL X 64.0"LG TUBE, 6061-T6 ALUMINUM	2
8	FC0051578	SUPPORT RIB, 95.25mm X 95.25mm X 1/2" 6061-T6 ALUMINUM	32
7	FC0051574	PLATE, STAND BASE TO TRACK, 12" X 6" X 1", 6061-T6 ALUMINUM	4
6	FC0051573	STAND LEG, 6" X 6" X 1/2"WALL X 36.11"LG TUBE, 6061-T6 ALUMINUM	4
5	FC0051566	LONG SUPPORT, 6" X 6" X 1/2"WALL X 19.58"LG TUBE, 6061-T6 ALUMINUM	2
4	FC0051565	CROSS SUPPORT, 6" X 6" X 1/2"WALL X 33.37"LG TUBE, 6061-T6 ALUMINUM	2
3	FC0044950	PLATE, JACK GUIDE, 272mm X 2.4" X 2" 6061-T6 ALUMINUM	8
2	F10044102	COVER PLATE, BOTTOM WELDMENT, EXT STAND	4
1	F10043004	PLATE, FRAME INTERFACE	4

DRAWN J.KURNAT DATE 11-May-2015

FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY

NAME: EXTERNAL STAND, UNIT A, BOTTOM WELDMENT

SEE PARTS LIST

SIZE A1 DRAWING NUMBER F10041524 REV -

SCALE 1:10 SHEET 1 of 1

GROUP: Technical Division, Design and Drafting

NOTES (UNLESS OTHERWISE SPECIFIED):
1. WELDMENT MUST BE FREE OF DIRT, GREASE, OIL, AND CHIPS.
2. WELDMENT MUST BE FREE OF SHARP EDGES, CORNERS, AND BURRS.
3. APPROXIMATE WEIGHT OF WELDMENT: 487 kg

REV REVISION CONTROL DOCUMENT
- F10041524--RCD

DESCRIPTION: STAND, EXTERNAL, UNIT A, BOTTOM WELDMENT
PROJECT CATEGORY: WELDMENT

FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY

EXTERNAL STAND, UNIT A, TOP ASSEMBLY

	DRAWING NUMBER	SIZE	REV
	F10042653	A1	-

SCALE 1:5   SHEET 1 of 1

PARTS LIST

ITEM	PART NUMBER	DESCRIPTION	QTY
3	FC0006009	SHCS, M14x2x60LGx40T, SS1B-B	14
2	F10040614	EXTERNAL STAND, UNIT A, TOP WELDMENT	1
1	F10040566	LINEAR RAIL, DS EXT RAIL SHORT	2

J.KURNAT   05-Jun-2015

REV REVISION CONTROL DOCUMENT DATES SIGNATURES
- F10042653--RCD

UNLESS OTHERWISE SPECIFIED
BREAK ALL SHARP EDGES 0.5 MAX.
DO NOT SCALE DRAWING
DIMENSIONING BASED ON ASME Y14.5-2009
MAX. ALL INCH SURFACES 3.2
DRAWING UNITS: MM

USED ON F10042655

SEE PARTS LIST

NOTES (UNLESS OTHERWISE SPECIFIED):
1. ASSEMBLY MUST BE FREE OF DIRT, GREASE, OIL, AND CHIPS.
2. ASSEMBLY MUST BE FREE OF SHARP EDGES, CORNERS, AND BURRS.

(1272)
(1180)
(463.1)
2X 200

FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY

EXTERNAL STAND, UNIT A, FULL ASSEMBLY

SIZE A0   DWG NO. F10042655   REV -

DATE 05-Jun-2015

SCALE 1:8

PARTS LIST

ITEM	PART NUMBER	DESCRIPTION	QTY
5	F00052617	SHCS, M20x2.5x100.0x52.4, SS18-8	8
4	F00006009	SHCS, M14x2x2x80.0x40T	4
3	F10040603	EXTERNAL STAND, UNIT A, TOP ASSEMBLY	1
2	F10041524	EXTERNAL STAND, UNIT A, BOTTOM WELDMENT	2
1	F10037913	LINEAR RAIL LINK, DS INTERNAL RAIL SYSTEM	2

NOTES (UNLESS OTHERWISE SPECIFIED):
1. ASSEMBLY MUST BE FREE OF DIRT, GREASE, OIL, AND CHIPS.
2. ASSEMBLY MUST BE FREE OF SHARP EDGES, CORNERS, AND BURRS.

(1825.6)
(866.5)
(1400)
(1180)

VIEW A-A
SCALE 1:4

18X 6.35
18X 50.8
18X 25.4
8X 25.4
8X 114.3

PARTS LIST

ITEM	PART NUMBER	DESCRIPTION	QTY
6	FC0053057	BAR, 60.0mm X 88.9MM X 2500.0mmLG, 6061-T6 ALUMINUM	2
5	FC0052606	WEDGE GUSSET, TOP WELDMENT, 12.7mm THICK ALUMINUM	18
4	FC0052599	SUPPORT RIB, TOP WELDMENT, EXT RAIL STAND, 6061-T6 ALUMINUM 12mm THICK STK	16
3	FC0051381	TUBE SQ, 6x6 1/2" WALL, 2500LG, 6061-T6 ALUMINUM	2
2	FC0051379	TUBE SQ, 6x6 1/2" WALL, 1152.4LG, 6061-T6 ALUMINUM	2
1	FC0041412	PLATE, BASE 200x272x25.4THK, 6061-T6 ALUMINUM	4

DRAWN J.KURNAT DATE 24-Apr-2015

FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY

NAME EXTERNAL STAND, UNIT B, TOP WELDMENT

SCALE 1:8   SIZE A1   DRAWING NUMBER F10040615   SHEET 1 of 1   REV -

SEE PARTS LIST

USED ON F1004-2658

NOTES (UNLESS OTHERWISE SPECIFIED):
1. WELDMENT MUST BE FREE OF DIRT, GREASE, OIL, AND CHIPS.
2. WELDMENT TO BE FREE OF SHARP EDGES, CORNERS, AND BURRS.
3. TRAILING ZEROS DENOTE TOLERANCE.

UNLESS OTHERWISE SPECIFIED
BREAK ALL SHARP EDGES 0.5 MAX.
DO NOT SCALE DRAWING
DIMENSIONING AND TOLERANCING BASED ON ASME Y14.5-2009
DIMENSION UNITS: MM

REV REVISION CONTROL DOCUMENT DATES SIGNATURES
- F1004-0615-RCD

16X Ø21.0
Ø 0.5 A B C

2X 152.4
4X
6
150-300
150-300
2X (60)
940.0
1152.4
2X 728 ±1
354.0
2X 2195.2
2129.2
1759.6
1792.0
(1272)
1196
804
50
170
230
350
470
590
710
830
950
1070
1190
1310
1430
1550
1670
1790
1910
2030
2150
2270
2330
2450

2X 25.4
2X 330
2X 634.5
2X 939.1
2X 1243.6
2X 1548.2
2X 1852.8
2X 2157.3
2X 2461.9
8X 49.2
8X 201.6
16X
6
6
4X
12
12
4X
12
12
2X (2500)
2X (419.1)
8X 152.4
(177.8)

REV REVISION CONTROL DOCUMENT
F10041526--RCD

		SIGNATURES
	DRAWN	
DATES	APPROVED	

NOTES (UNLESS OTHERWISE SPECIFIED):
1. WELDMENT MUST BE FREE OF DIRT, GREASE, OIL, AND CHIPS.
2. WELDMENT MUST BE FREE OF SHARP EDGES, CORNERS, AND BURRS.
3. APPROXIMATE WEIGHT OF WELDMENT: 465 kg

1473.2
1196
804

2173
2129.2
1759.6
1715.8

2X (1693.6)
2X (1792)
2X (2249.2)

5

32X C 6.4
16X Ø21
⌖ Ø 0.5 A B C
THRU ITEM 2

8X Ø20
16X Ø21
⌖ Ø 0.5 A B C

4X 74.6
4X 76.2
4X 25.4
16X 114.3
4X 885.6
8X (1143.4)

6∠
6∠
4X
6∠
4X
6∠ 6∠
32X
12∠ 12∠
4X (152.4)
B

A

2X (847.6)
2X (1625.6)
4X 45°
4X 25.4

12∠ 12∠
8X
12∠ 12∠
4X 12∠ 12∠
8X
6∠ 6∠
32X
C

3
1
6
8
9
7

4X
6∠ 6∠

PARTS LIST

ITEM	PART NUMBER	DESCRIPTION	QTY
9	FC0051696	BOTTOM SUPPORT, 6" X 6" X 1/2"WALL X 64"LG TUBE 6061-T6 ALUMINUM	2
8	FC0051578	SUPPORT RIB, 95.25mm X 95.25mm X 1/2", 6061-T6 ALUMINUM	16
7	FC0051574	PLATE, STAND BASE TO TRACK, 12" X 6" X 1", 6061-T6 ALUMINUM	4
6	FC0051573	STAND LEG, 6" X 6" X 1/2"WALL X 36.11"LG TUBE, 6061-T6 ALUMINUM	4
5	FC0051567	LONG SUPPORT B, 6" X 6" X 1/2"WALL X 70.55"LG TUBE, 6061-T6 ALUMINUM	2
4	FC0051565	CROSS SUPPORT, 6" X 6" X 1/2"WALL X 33.37"LG TUBE, 6061-T6 ALUMINUM	2
3	FC0044950	PLATE, JACK GUIDE, 272mm X 2.4" X 2" 6061-T6 ALUMINUM	8
2	F10044102	COVER PLATE, BOTTOM WELDMENT, EXT STAND	4
1	F10043004	PLATE, FRAME INTERFACE	4

FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY

NAME: EXTERNAL STAND, UNIT B, BOTTOM WELDMENT

UNLESS OTHERWISE SPECIFIED:					DRAWN	J.KURMAT	DATE	11-May-2015
.X	.X.X	.X.XX	.X°		CHECKED		DATE	
±.2	±.1	±.05			APPROVED		DATE	
.X	.X.X	.X.XX	.X°					
±.5	±.3	±.12	N/A	1°				

BREAK ALL SHARP EDGES 0.5 MAX.
DO NOT SCALE DRAWING
DIMENSIONING BASED ON ASME Y14.5-2009
MAX. ALL MACH SURFACES 3.2
DRAWING UNITS: MM

USED ON: F10042658

MATERIAL: SEE PARTS LIST

SCALE	SIZE	DRAWING NUMBER	REV
1:10	A1	F10041526	-

SHEET 1 of 1

DESCRIPTION: EXTERNAL UNIT B, BOTTOM WELDMENT
PROJECT: BUILDING
CATEGORY: WELDMENT

PARTS LIST

ITEM	PART NUMBER	DESCRIPTION	QTY
3	FC0006009	SHCS, M14x2x60Lg×40T, SS1B-B	36
2	F10040615	EXTERNAL STAND, UNIT B, TOP WELDMENT	1
1	F10040567	LINEAR RAIL, DS EXT RAIL MID LENGTH	2

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UNITED STATES DEPARTMENT OF ENERGY

EXTERNAL STAND, UNIT B, TOP ASSEMBLY

DRAWING NUMBER F10042656

SIZE A1 SCALE 1:5 SHEET 1 of 1 REV -

SEE PARTS LIST

USED ON F10042658

NOTES (UNLESS OTHERWISE SPECIFIED):
1. ASSEMBLY MUST BE FREE OF DIRT, GREASE, OIL, AND CHIPS.
2. ASSEMBLY MUST BE FREE OF SHARP EDGES, CORNERS, AND BURRS.

REV REVISION CONTROL DOCUMENT DATES SIGNATURES
- F10042656--RCD

200
2X 200
(1272)
(2500)
(463.1)

UNLESS OTHERWISE SPECIFIED:
X ±1 .X ±.3 .XX ±.12 X° ±1°
BREAK ALL SHARP EDGES 0.5 MAX.
DO NOT SCALE DRAWING
DIMENSIONS BASED ON ASME Y14.5-2009
MAX. ALL MACH SURFACES 3.2
DRAWING UNITS: MM

PARTS LIST

ITEM	PART NUMBER	DESCRIPTION	QTY
5	FC0052617	SHCS, M20x2.5x100.0x52.4 , SS19-B	8
4	FC0006009	SHCS, M14-2x2-60.0x40T , SS19-B	4
3	F10043658	EXTERNAL STAND, UNIT B, TOP ASSEMBLY	1
2	F10041526	EXTERNAL STAND, UNIT B, BOTTOM WELDMENT	2
1	F10042560	LINEAR RAIL LINK, DS EXT RAIL SYSTEM	1

FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY

EXTERNAL STAND, UNIT B, FULL ASSEMBLY

F10042658

SEE PARTS LIST

NOTES (UNLESS OTHERWISE SPECIFIED):
1. ASSEMBLY MUST BE FREE OF DIRT, GREASE, OIL, AND CHIPS.
2. ASSEMBLY MUST BE FREE OF SHARP EDGES, CORNERS, AND BURRS.

(3200)
(2720)
(200)
(1825.6)
(1606.5)

VIEW A-A
SCALE 1:4

NOTES (UNLESS OTHERWISE SPECIFIED):
1. WELDMENT MUST BE FREE OF DIRT, GREASE, OIL, AND CHIPS.
2. WELDMENT TO BE FREE OF SHARP EDGES, CORNERS, AND BURRS.
3. TRAILING ZEROS DENOTE TOLERANCE.

PARTS LIST

ITEM	PART NUMBER	DESCRIPTION	QTY
6	FC0053058	BAR, 60.0mm X 88.9mm X 2420.0mmLG, 6061-T6 ALUMINUM	2
5	FC0052606	WEDGE GUSSET, TOP WELDMENT, EXT RAIL STAND, 6061-T6 ALUMINUM, 12.7mm THICK STOCK	18
4	FC0052599	SUPPORT RIB, TOP WELDMENT, EXT RAIL STAND, 6061-T6 ALUMINUM, 12.7mm THICK STOCK	16
3	FC0051382	TUBE SQ, 6x6 1/2" WALL, 2420LG, 6061-T6 ALUMINUM	2
2	FC0051379	TUBE SQ, 6x6 1/2" WALL, 1152.4LG, 6061-T6 ALUMINUM	2
1	FC0041412	PLATE, BASE 200x272x25.4THK, 6061-T6 ALUMINUM	4

FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY

NAME: EXTERNAL STAND, UNIT C, TOP WELDMENT

SIZE A1   DRAWING NUMBER F10040616   REV -

SCALE 1:8   SHEET 1 of 1

SEE PARTS LIST

DRAWN J.KURNAT   DATE 24-Apr-2015

USED ON F10042660

76

PARTS LIST

ITEM	PART NUMBER	DESCRIPTION	QTY
9	FCC051696	BOTTOM SUPPORT, 6" X 6" X 1/2"WALL X 64"LG TUBE 6061-T6 ALUMINUM	2
8	FCC051578	SUPPORT RIB, 95.25mm X 95.25mm X 12.7mm 6061-T6 ALUMINUM	16
7	FCC051574	PLATE, STAND BASE TO TRACK, 12" X 6" X 1", 6061-T6 ALUMINUM	4
6	FCC051573	STAND LEG, 6" X 6" X 1/2"WALL X 36.11"LG TUBE, 6061-T6 ALUMINUM	4
5	FCC051568	LONG SUPPORT C, 6" X 6" X 1/2"WALL X 67.40"LG TUBE, 6061-T6 ALUMINUM	2
4	FCC051565	CROSS SUPPORT, 6" X 6" X 1/2"WALL X 33.37"LG TUBE, 6061-T6 ALUMINUM	2
3	FCC044950	PLATE, JACK GUIDE, 272mm X 2.4" X 2" 6061-T6 ALUMINUM	8
2	F10044102	COVER PLATE, BOTTOM WELDMENT, EXT STAND	4
1	F10043004	PLATE, FRAME INTERFACE	4

FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY

NAME: EXTERNAL STAND, UNIT C, BOTTOM WELDMENT

DRAWING NUMBER F10041527
SIZE A1 SCALE 1:10 SHEET 1 of 1 REV -

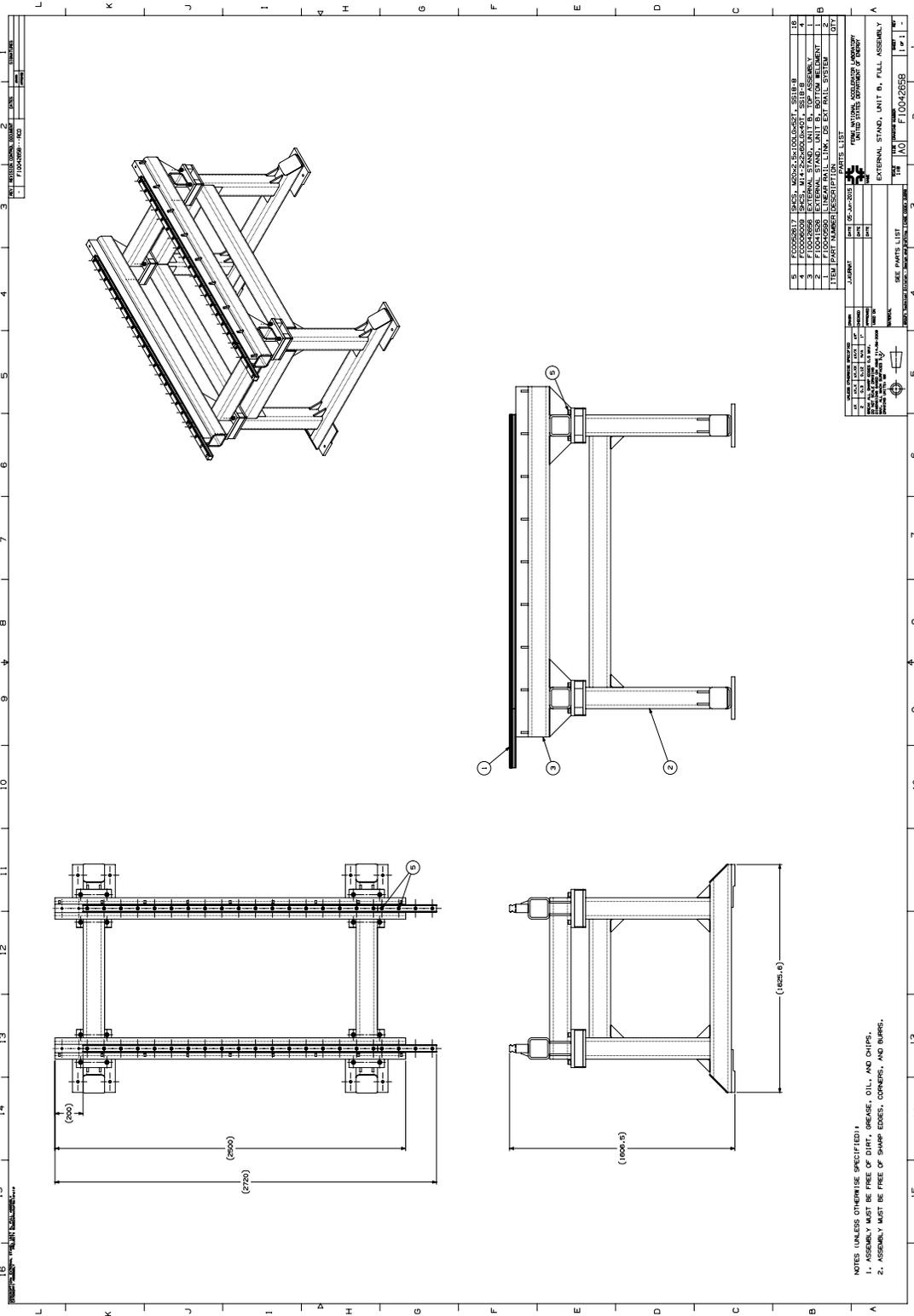DRAWN J.KURNAT DATE 11-May-2015

SEE PARTS LIST

NOTES (UNLESS OTHERWISE SPECIFIED):
1. WELDMENT MUST BE FREE OF DIRT, GREASE, OIL, AND CHIPS.
2. WELDMENT MUST BE FREE OF SHARP EDGES, CORNERS, AND BURRS.
3. APPROXIMATE WEIGHT OF WELDMENT: 465 kg

REV REVISION CONTROL DOCUMENT
- F10041527--RCD

NOTES (UNLESS OTHERWISE SPECIFIED):
1. ASSEMBLY MUST BE FREE OF DIRT, GREASE, OIL, AND CHIPS.
2. ASSEMBLY MUST BE FREE OF SHARP EDGES, CORNERS, AND BURRS.

PARTS LIST

ITEM	PART NUMBER	DESCRIPTION	QTY
1	F10040569	LINEAR RAIL, DS EXT RAIL END	2
2	F10040616	EXTERNAL STAND, UNIT C, TOP WELDMENT	1
3	FC0006009	SHCS, M14x2x60LGx40T, SS18-8	38

FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY

EXTERNAL STAND, UNIT C, TOP ASSEMBLY

DRAWING NUMBER F10042659

SIZE A1 SCALE 1:5 SHEET 1 OF 1 REV -

DRAWN J.KURNAT DATE 05-Jun-2015

SEE PARTS LIST

(2420)
(1272)
(463.1)
2X 200

NOTES (UNLESS OTHERWISE SPECIFIED):
1. ASSEMBLY MUST BE FREE OF DIRT, GREASE, OIL, AND CHIPS.
2. ASSEMBLY MUST BE FREE OF SHARP EDGES, CORNERS, AND BURRS.

(2420)

(2840)

(1825.6)

(1806.5)

FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY

EXTERNAL STAND, UNIT C, FULL ASSEMBLY

F10042860

SEE PARTS LIST

ITEM	PART NUMBER	DESCRIPTION	QTY
1	F10042860	LINEAR RAIL LINK, US EXT RAIL SYSTEM	2
2	F10041527	EXTERNAL STAND, UNIT C, BOTTOM WELDMENT	1
3	F10040959	EXTERNAL STAND, UNIT C, TOP ASSEMBLY	1
4	FC0009566	SHCS, 3/4-16x4.0x2.T, SS18-8	16
5	FC0008008	SHCS, M14-2x2x60Lx40T, SS18-8	4

PARTS LIST

DATE 05-Jun-2015