FERMI NATIONAL ACCELERATOR LABORATORY

Mu2e Integration and Refinement of the 3D Integration Model

SUMMER INTERNSHIP

FINAL REPORT

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Abstract

The primary mission of the Mu2e Project is to design and construct a facility that will enable the most sensitive search ever made for the coherent conversion of muons into electrons in the field of a nucleus, an example of Charged Lepton Flavor Violation (CLFV). The discovery of this physics process would demonstrate the existence of physics beyond the Standard Model, the current description of the building blocks of matter and how they interact.

Discoveries beyond the Standard Model will help scientists answer some of the most fundamental questions about matter and our Universe. Were the forces of nature combined in one unifying force at the time of the Big Bang? How did the universe change from being dominated by energy and radiation remnants from the Big Bang to the one we see today with visible matter, including people and plants?

During my Summer Internship at Fermi National Accelerator Laboratory I had the chance to become familiar with the Mu2e apparatus and its subsystems, assisting Mu2e scientists and engineers to develop and refine the plans for installation and servicing of infrastructure of the Mu2e experiment.

The net result of the work is an improvement in the fidelity of the representation of the current Mu2e plan, facilitating Mu2e integration activities, reducing the potential for interferences or misunderstandings.

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1. Introduction

1.1 Project Overview

Mu2e proposes to measure the ratio of the rate of the neutrinoless, coherent conversion of muons into electrons in the field of a nucleus, relative to the rate of ordinary muon capture on the nucleus:

$$R_{\mu e} = \frac{\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)}{\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N)} \tag{1.1}$$

The current best experimental limit on muon-to-electron conversion, $R_{\mu e} < 10^{-13}$ (90% CL) is from the SINDRUM II experiment. With $3.6 * 10^{20}$ delivered protons Mu2e will probe four orders of magnitude beyond the SINDRUM II sensitivity, measuring $R_{\mu e}$ with a single event sensitivity of $2.87 * 10^{-17}$. Observation of this process would provide unambiguous evidence for physics beyond the Standard Model and can help to illuminate discoveries made at the LHC or point to new physics beyond the reach of the LHC [1].

1.2 Project Plan

To achieve this significant leap in sensitivity, Mu2e requires an high intensity, low energy muon beam coupled with a state-of-the-art detector capable of efficiently identifying, reconstructing and analyzing conversion electrons with momenta near 105 MeV/c while minimizing background from conventional processes. The muon beam is created by an 8 GeV proton beam striking a production target and a system of superconducting solenoids that efficiently collect pions and transports their daughter muons to a stopping target.

The scope of work required to meet the scientific and technical objectives of Mu2e is listed below.

- Modify the accelerator complex to transfer 8 GeV protons from the Fermilab Booster to the Mu2e detector while the 120 GeV neutrino program is operating. To accomplish this, the existing Recycler and Debuncher Rings will be modified to re-bunch batches of protons from the Booster and then slow extract beam to the Mu2e detector.

- Design and construct a new beamline from the Debuncher Ring to the Mu2e detector. The beamline includes an extinction insert that removes residual out-of-time protons.

- Design and construct the Mu2e superconducting solenoid system (Fig. 1.1) consisting of a Production Solenoid that contains the target for the primary proton beam, an S-shaped Transport Solenoid that serves as a magnetic channel for pions and muons of the correct charge and momentum range and a Detector Solenoid that houses the muon stopping target and the detector elements.

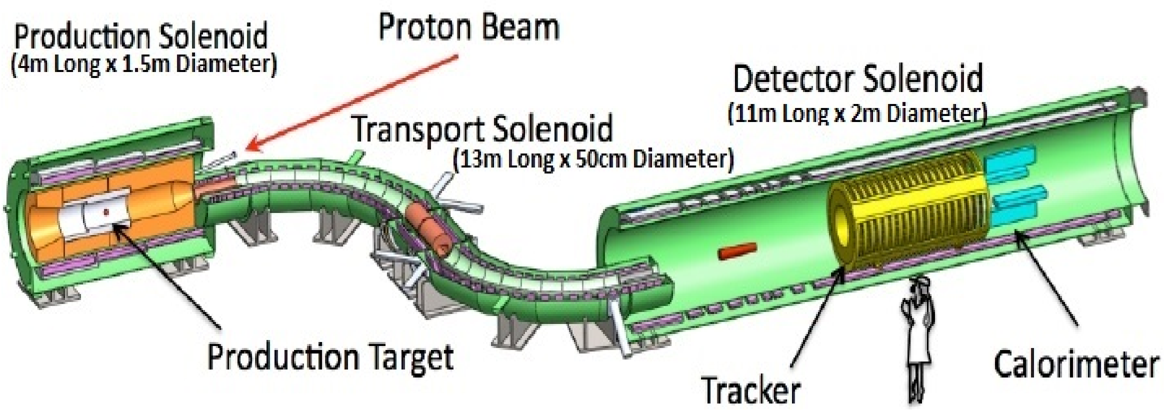


Figure 1.1: *Mu2e Detector*

- Design and construct the Mu2e detector consisting of a tracker (Fig. 1.1), a calorimeter (Fig. 1.1), a stopping target monitor, a cosmic ray veto, an extinction monitor and the electronics, trigger and data acquisition required to read out, select and store the data. The tracker accurately measures the trajectory of charged particles, the calorimeter provides independent measurements of energy, position and time, the cosmic ray veto identifies cosmic ray muons traversing the detector region that can cause backgrounds and the extinction monitor detects scattered protons from the production target to monitor the fraction of out-of-time beam.

- Design and construct a facility to house the Mu2e detector and the associated infrastructure (Fig. 1.2). This includes an underground detector enclosure and a surface building to house necessary equipment and infrastructure that can be accessed while beam is being delivered to the detector.

Figure 1.2: *Mu2e Facility*

2. Installation Plan

2.1 General Installation Plan

In a such complex project, every single steps of the installation process needs to be taken to account in a very detail way to prevent any kind of misunderstandings or errors and to not face delays and waste of money.

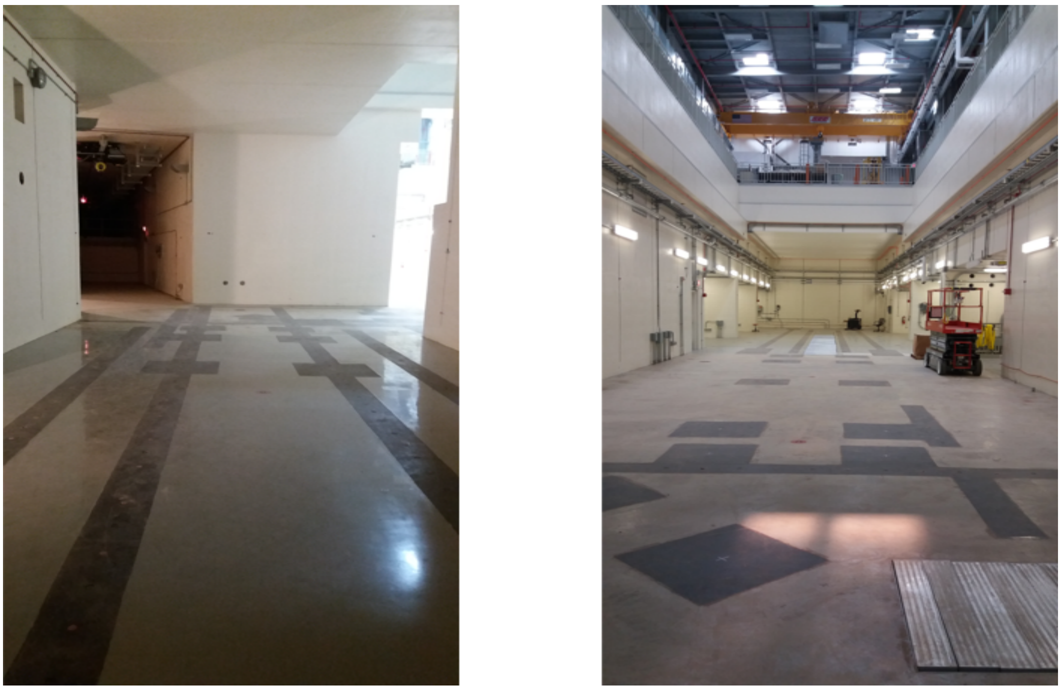


Figure 2.1: *Experimental Area. Left: PS Area, Right: DS Area*

Starting with a relatively empty experimental hall (Fig. 2.1), it is needed to install some subsystems inside the Mu2e facility before facing the main installation of the Solenoids:

1. Cryogenic transfer lines are installed: down the pipe chase, PS and TSu transfer line along the west wall, DS transfer line along the south wall and TSd transfer line in the TS trench

2. Solenoid insulating vacuum piping and pumps installed.

3. Muon Beamline vacuum pumps & piping (in remote handling room and mechanical alcove).

4. Install cooling lines, calibration lines, gas lines, electrical and data services in the DS trench.

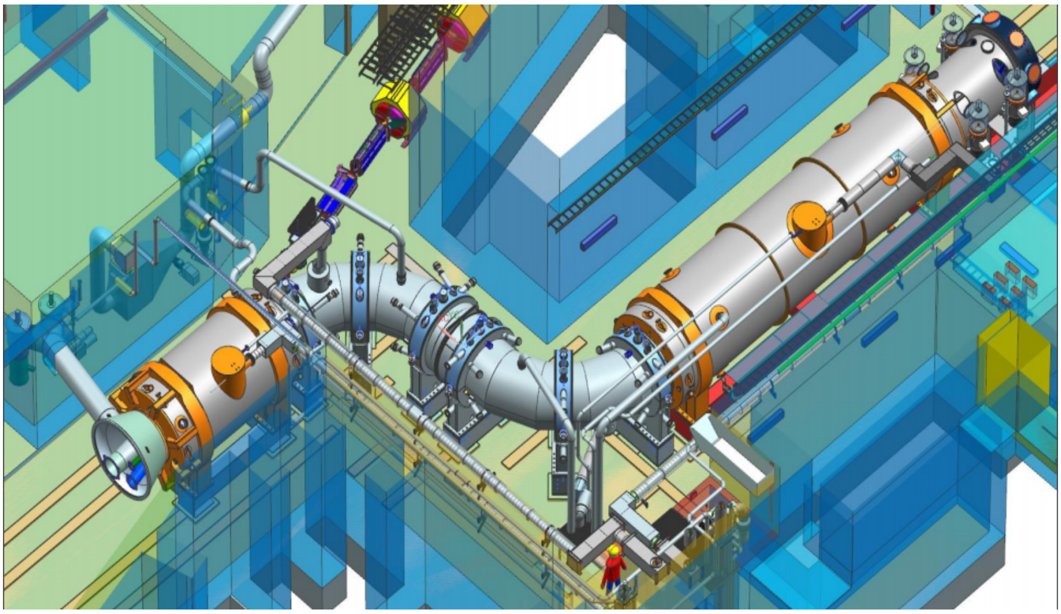


Figure 2.2: *Mu2e Experiment without Shielding*

The current installation plan for the Solenoids (Fig. 2.2) is based on the programmed schedule in which the PS is delivery last and includes the following key points:

1. The Heat & Radiation Shield (HRS) is lowered through the TS hatch. It is translated north, west, and north into the Remote Handling room. The PS support frame is located under the PS hatch

2. The DS is lowered through the DS hatch and aligned parallel to the DS trench.

3. The TSu is lowered through the TS hatch and translated north.
4. The TSd is lowered through the TS hatch and translated east. The TSd mates with the DS. The TSd is then translated a few inches north to center it in the DS and mate with the TSu.
5. The Production Solenoid is lowered through the PS hatch using an external crane. It mates to the PS support frame sitting below.
6. The PS is translated to the east but 1m away from the TSu.
7. The HRS is translated south out of the Remote Handling Room. Then aligned and inserted into the PS.
8. The PS with HRS is translated east to mate with the TSu.
9. Cryogenic Transfer lines are connected to the solenoids.
10. Insulating vacuum piping is connected to the solenoids.
11. Instrumentation lines are connected.
12. Hard interconnects between solenoids are installed.

In case of the PS will be delivered as first, there is an alternative plan and it will use the building cranes instead of an external crane.[1]

2.2 PS installation

Regarding this installation plan, my work involved developing and improving of the PS installation phase through the PS hatch using an external crane (Fig. 2.3):

- Verify there is room to install the PS Solenoid down the PS Hatch with the PS Hatch blocks also staged on nearby hardstand.

[1]For more details about the backup plan and the Detector installation see "R. Rucinski / Mu2e Installation" [2]

- Creation of new parts to represent a 350 Ton Crane and a Placeholder for a Flatbed Truck Trailer for the PS.
- Restaging of Concrete PS Hatch Blocks in the model to facilitate the PS installation operation.
- Positioning and organization of all these elements in the Global Integration Model.

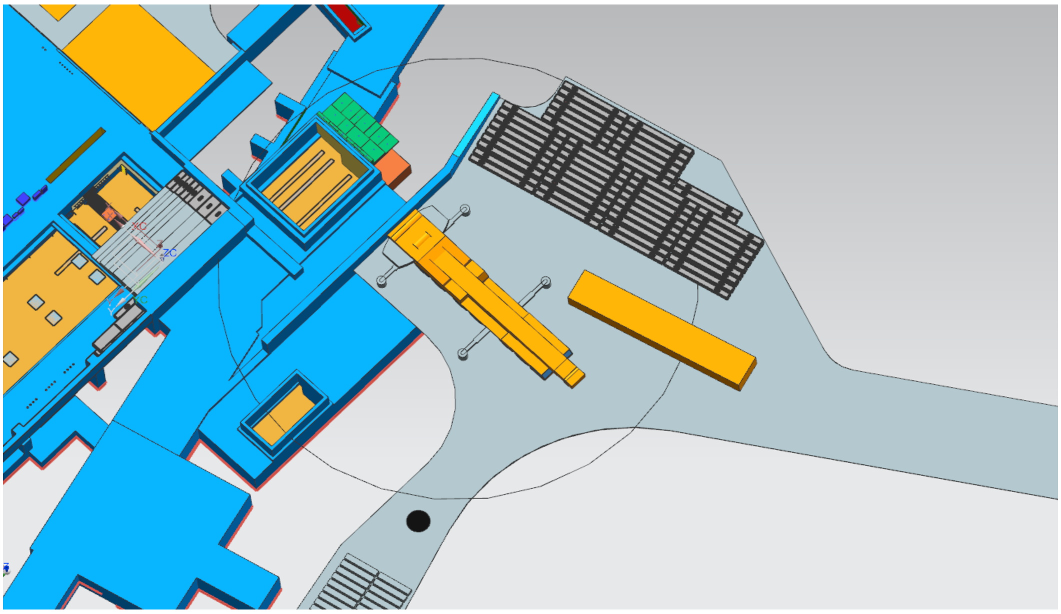


Figure 2.3: *PS installation*

After the installation of all the experiment elements, according with the MARS radiation simulations (Fig. 2.4), the hatches need to be sealed with shield blocks. Moreover supplemental earth berm shielding must be added along the north wall and a total of 19' of concrete must be placed in the PS drop hatch [3].

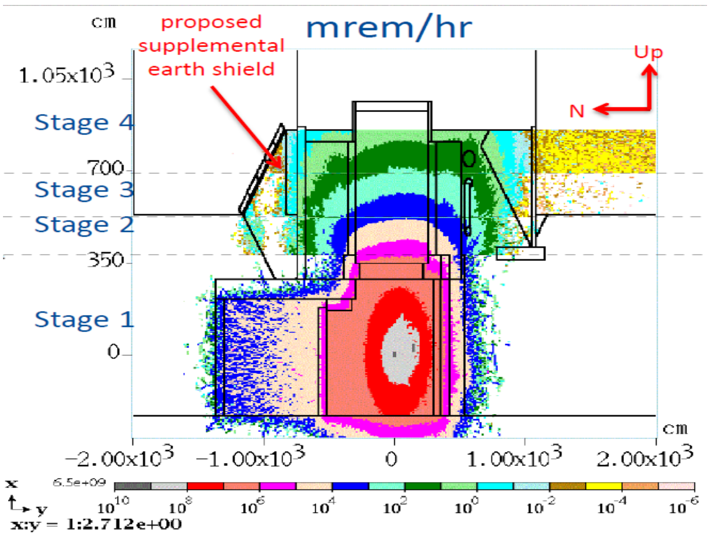


Figure 2.4: *MARS Radiation Simulations North Wall*

So I managed the creation and position of the concrete blocks for the 5 hatches [4], considering the real installation process, taking account for clearance and tolerance using Excel spreadsheets analysis and keeping in mind the future needs of the experiment maintenance, as well as the creation of a placeholder for the supplemental earth berm (Fig. 2.5).

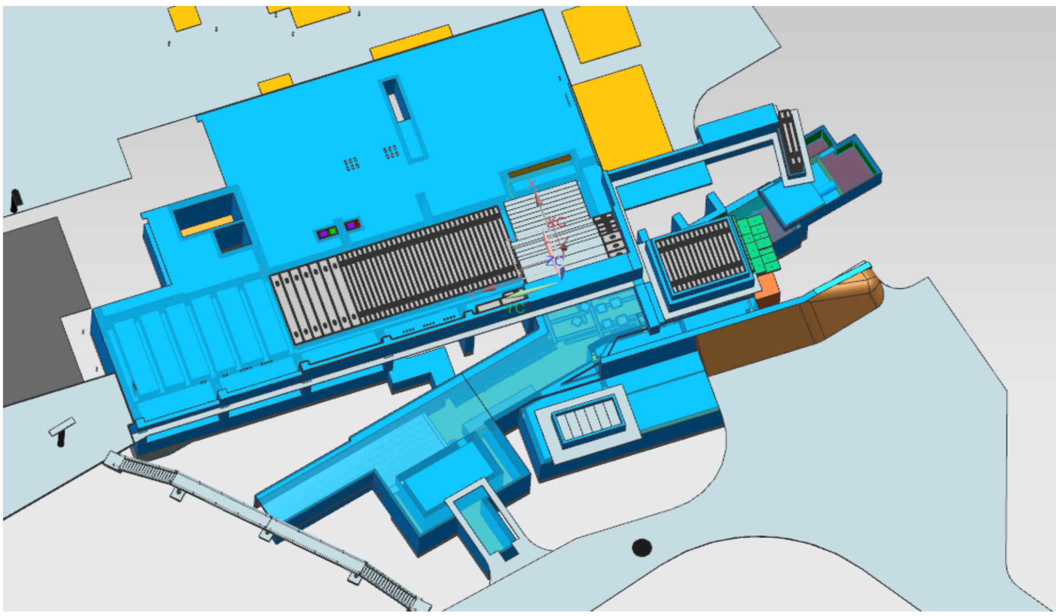


Figure 2.5: *PS installed with sealed hatches*

3. Muon Beamline Shielding

3.1 Upstream Muon Beamline Shielding

The Upstream External Shielding of the Muon Beamline (Fig. 3.1) surrounds the Production Solenoid and isolates the primary proton beamline from the Detector Solenoid hall while shielding the Cosmic Ray Veto (CRV) from radiation generated at the production target located in the PS and resulting from the secondary beam transported by the upstream Transport Solenoid (TSu).

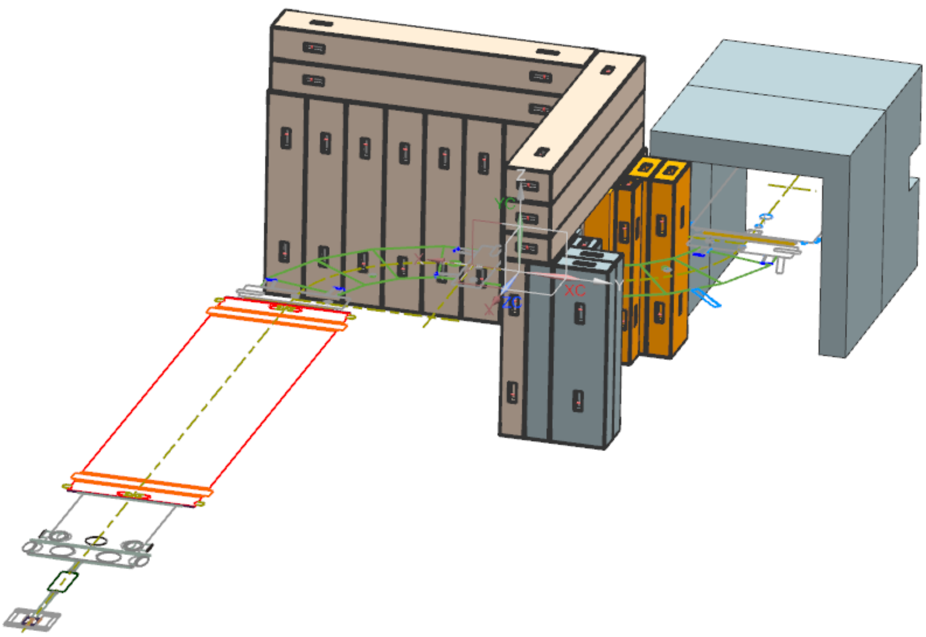


Figure 3.1: *Upstream Muon Beamline Shielding*

The primary purpose of the Upstream External Shielding is to shield the Mu2e detectors, reducing the rate of neutron and gamma background impinging on the CRV to an acceptable level. This shielding also serves to isolate the primary proton beamline from the downstream muon beamline, dividing the lower level of the Mu2e Experiment Hall into two independent zones.

The West Wall Shielding completes the coverage of the relief in the west wall through which the cryo and vacuum services will be routed from the alcove below the Solenoid and Power Supply Room to the PS and TSu, and provides additional shielding of the Mu2e detectors from the radiation emerging from the primary proton target located in the PS.

The Upstream Shield is composed of 28 blocks for a total weight of 308 tons, with the main goals of:

- The rate incident upon the Cosmic Ray Veto must be suppressed to a low enough level to support efficient operation of the CRV, so that potential sources of background due to incident cosmic rays can be identified and suppressed by the CRV.
- Isolate the primary proton beamline from the Downstream muon beamline, dividing the Mu2e Experiment Hall into two different zones to reduce rates in CRV and control flow of activated air.

3.2 Downstream Muon Beamline Shielding

The Downstream External Shielding (Fig. 3.2) is constructed of concrete, boron loaded concrete and high density (barite) concrete blocks, and will be completely external to the TSd and DS cryostats. The current configuration of this shielding is primarily composed of reinforced concrete T blocks assembled into two independent (but mated) sections. The “Downstream Cave”, which surrounds the body of the TSd and DS, and the “End Cap Shielding”, which serves to enclose the downstream end of the muon beamline vacuum space. The upstream open end of this shield will be placed against the downstream end of the TSu External Shielding.

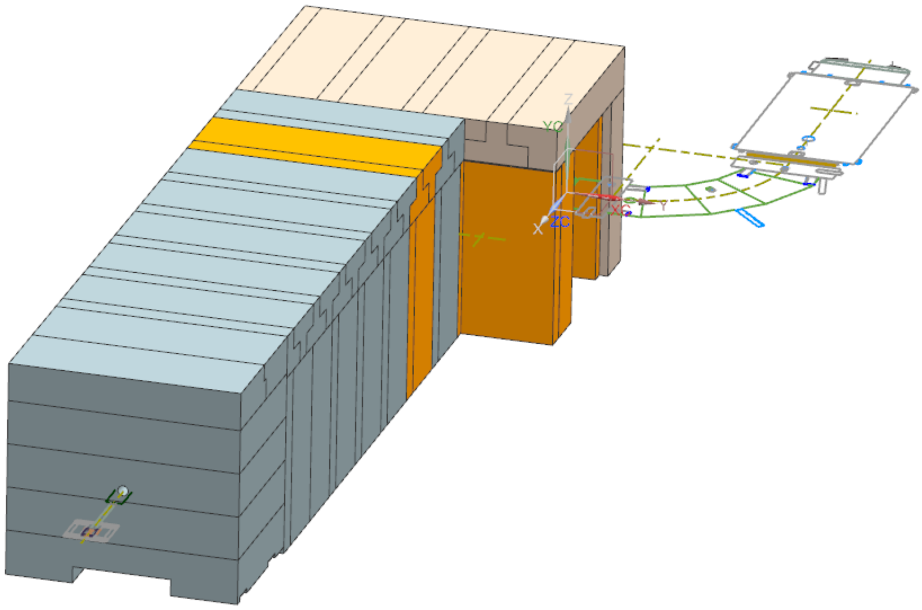


Figure 3.2: *Downstream Muon Beamline Shielding*

The Downstream Shield is composed of 84 individual blocks, with a total weight of 800 tons, with the main goals of:

- Reduce the neutron and gamma background incident upon the Cosmic Ray Veto (CRV) Counters.
- Allow a line of sight to the muon stopping target monitor and reduce the neutron and gamma background incident upon the muon stopping target monitor.
- Provide a base for support CRV modules .
- Reducing radiation dose rates in the detector hall.

3.3 Checks and Changes

About the nominal configuration, the following tasks were been performed to refine the models:

- Evaluate the position of the main part of the assembly to verify of compliance of the stay clear zone and the alignment of the blocks.

- Correction of the various precast concrete Blocks type: Normal Concrete, Boron Loaded Concrete and High Density (Barite) Concrete.
- Designation and color of the Blocks to reflect the current project plan, adding the material types and density property so the weights are properly estimated.
- Adjustment of the blocks in the model, deleting useless lifting features, repositioning in the correct way for the lifting operations and creating new ones.
- Reorganization of the subassembly through the creation of new ones.
- Check for and address interferences with the other elements in the model: Solenoids, Cryo system and Building.

3.4 Configurations Release

To have a freeze configuration that respect the requirements and then to improve it in the next step, I managed the release of the Downstream and Upstream Muon Beam Shielding configuration. The release process (Fig. 3.3) consists in an internal Fermilab process that allow to save the configuration. Passing through the process the assemblies and parts are controlled by a checker and an approvers so I had to prepare all the pieces to have the desired level of detail and to respect all the Fermilab release policy's rules.

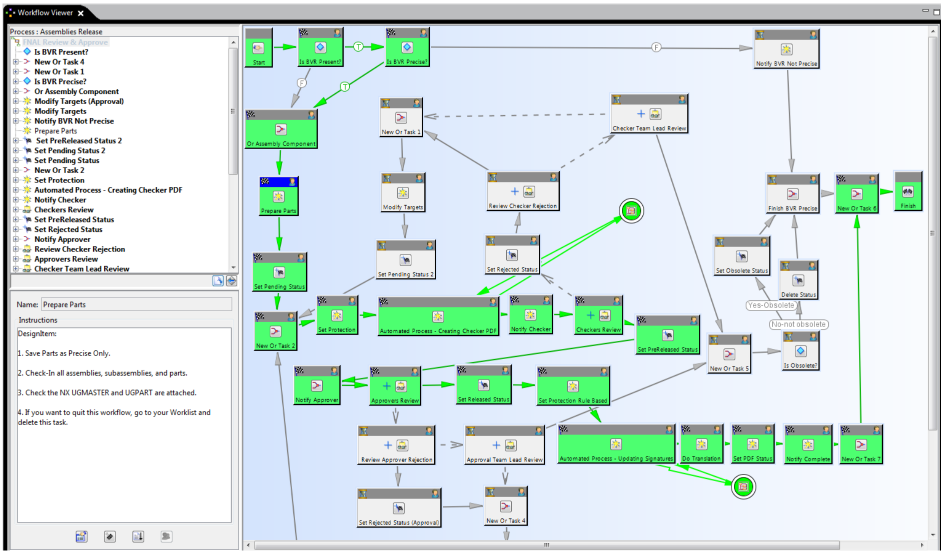


Figure 3.3: *Release Workflow*

3.5 Updated Versions

In the continuous process of improving of the configuration, I updated the model (Fig. 3.4) to take account of the installation process, the tolerance of the blocks and to reduce the overall costs.

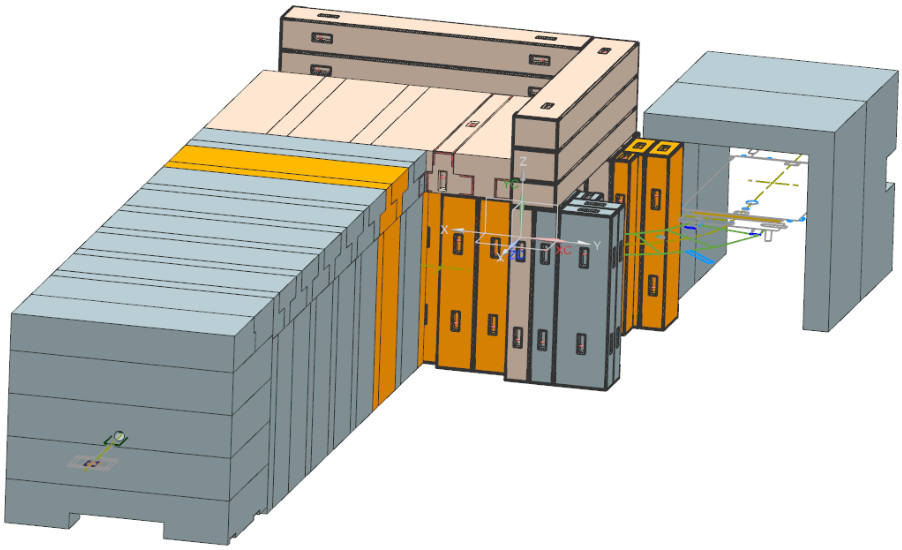


Figure 3.4: *Updated Shield*

Since the location of the downstream cave is constrained on the upstream end by the upstream external shielding and on the north, west and south sides by the solenoids and on east side by the north south DS trench, and the intent is to minimize line of sight cracks, the tolerances on the blocks and the spacing between blocks must be carefully controlled to accommodate these various constraints. The plan is to build in an intentional gap between neighboring block surfaces to account for the tolerances. Since the blocks are T blocks, this will result in local thinner regions in the shielding, but will not generate line of sight cracks (with the exception of the cracks between the side walls and the top blocks).

The side walls of the shielding must be installed after the solenoids are already in place, so they will all need to be installed from the outside of the solenoid envelope, and will be positioned close to the solenoids without contacting them.

The concrete blocks include steel reinforcing bars and steel angles to protect the block's edges. The default plan is to employ normal carbon steel reinforcement bars. Stainless steel reinforcement bars will only be used if demonstrated to be necessary due to magnetic field constraints.

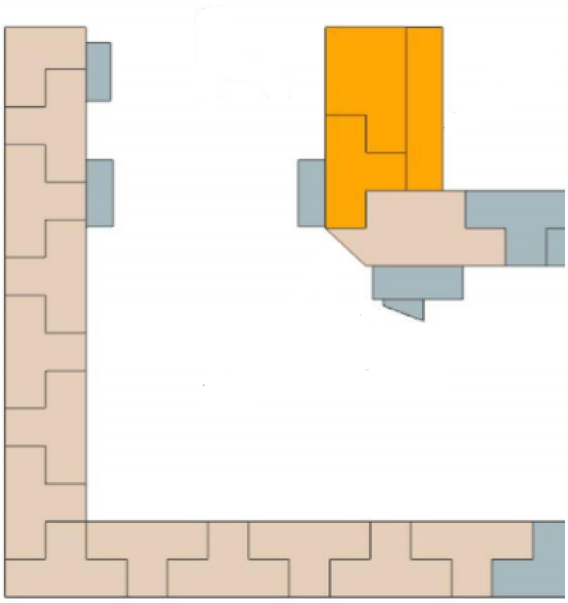


Figure 3.5: *Detail of the old Downstream Shielding (as viewed from above)*

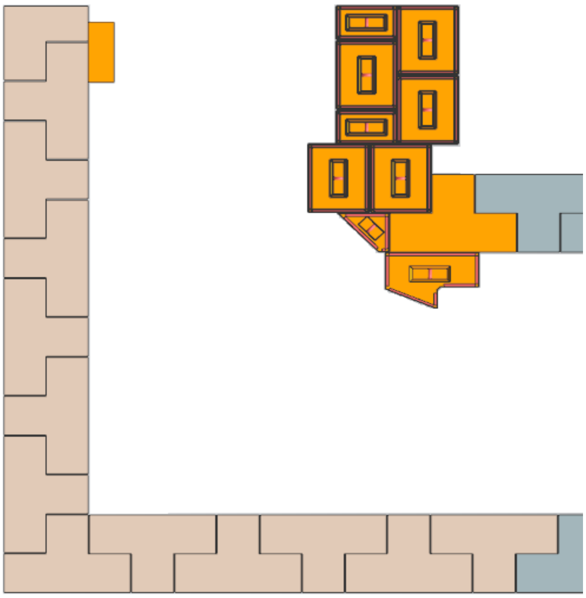


Figure 3.6: *Detail of the new Downstream Shielding (as viewed from above)*

It is very unlikely that a sufficient quantity of blocks in appropriate sizes will be available from the Fermilab stock to address these shielding needs and conform to the specialized space and size constraints. So, due to these space constraints in the building, as well as the specialized sizes of the blocks involved, new blocks will need to be procured. I also changed some blocks to reduce the number of new shape blocks and to use more standard Fermilab blocks as possible.

Moreover a series of solutions are proposed to facilitate the installation process, as the one shown below in (Fig. 3.7), where two blocks were replaced with a single integrated block, improving the stability of the assembly, which needs to be installed near the solenoid without damaging that element.

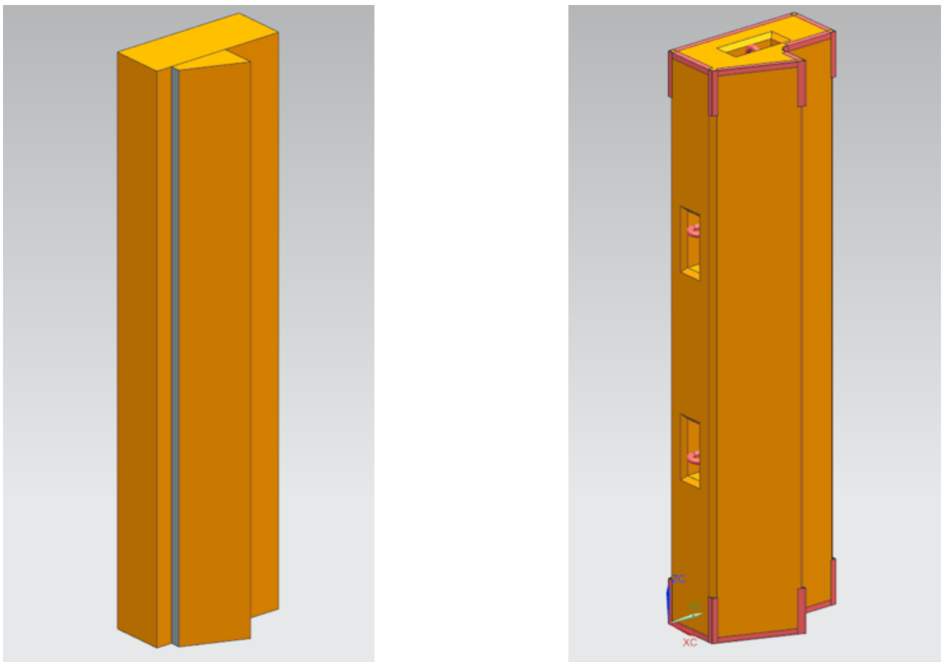


Figure 3.7: *Example of integration. Left: Old Version, composed of two individual blocks. Right: Updated Version, realized as a single blocks.*

4. Radiation Safety

The Radiation Safety Improvements WBS item contains the tasks required for the design and implementation of the Radiation Safety upgrades that are required to maintain the level of radiation protection required by the Fermilab Radiological Control Manual.

As we already have seen the Upstream and Downstream shield, as well as the General Concrete Structure and the hatches are used to contain the radiation level when the Experiment will be running. I had to face also other radiation issue proposing some solutions to this problems.

4.1 Shielding Primary Beamline

Due to proximity of proton beamline to Mu2e building, which transports proton to the production target, there is the need to install 16 foot shielding along the primary beamline in the north west corner of the high bay. [5]

So, after taking measurements in the actual building of the constraints and available spaces and note obstructions, based on the Civil Drawings of the current supposed position of the shielding blocks, I proposed and implemented a solution in the Cad model (Fig. 4.1) to provide the necessary shielding: due the tilted line of the Proton Beamline with respect to the Building the number of the blocks required decreases going from west to east side. [6]

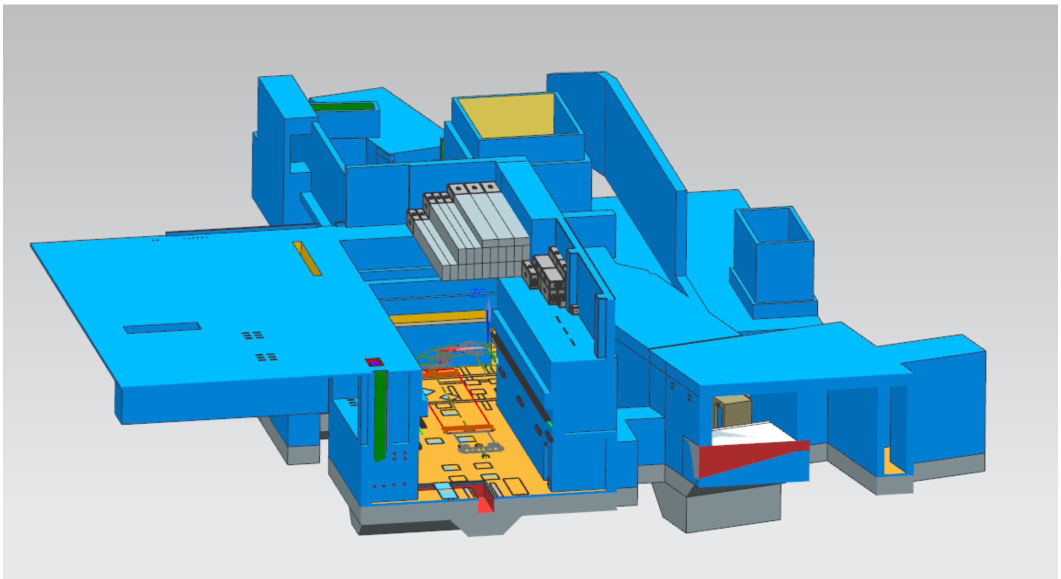


Figure 4.1: *Shielding Primary Beamline (the grey blocks in the center of the image represent the shield block pile)*

4.2 Activated Air Barrier

The major source of airborne radioactivity due to beam operations for the Mu2e experiment is from primary/secondary beam passing through the air volume between the Production Solenoid and the Proton Target Beam Absorber.

The Production Solenoid Room will be under negative pressure relative to the outdoor environment and to the Detector Solenoid area to prevent activated air infiltration to those areas.

To achieve this negative pressure during beam operations will require: PS hatch closed and sealed, remote handling room shield door closed, PS area isolated from DS area via isolation wall, West wall relief sealed, PS area isolated from M4 beamline via isolation barrier, numerous penetrations all sealed, Extinction Monitor area isolated, the entrance collimator aperture will have a sealed window and M4 beamline penetrations also sealed.

The activated air should then pass through the HEPA filter and then to the Proton Beam Line, and finally it will arrive out from the building after an appropriate decay time [7].

For all of that, I proposed the following first sealing solution: as we can see in (Fig. 4.2) where the Air Barrier is highlighted in red and the HEPA Duct in yellow.

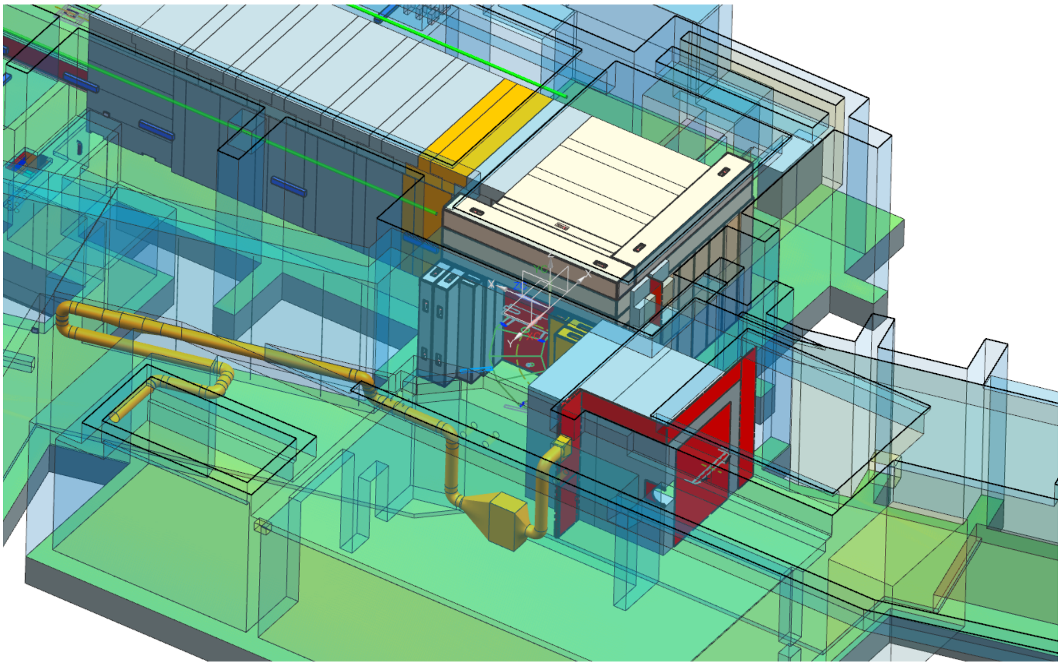


Figure 4.2: *Activated Air Barrier (air barriers shown in red, HEPA duct system shown in yellow).*

5. General Support

To help with integration of inputs from various teams, I made some adjustments and added some other elements to better reflect the current plans, and to implement stay clears in the model to facilitate future developments.

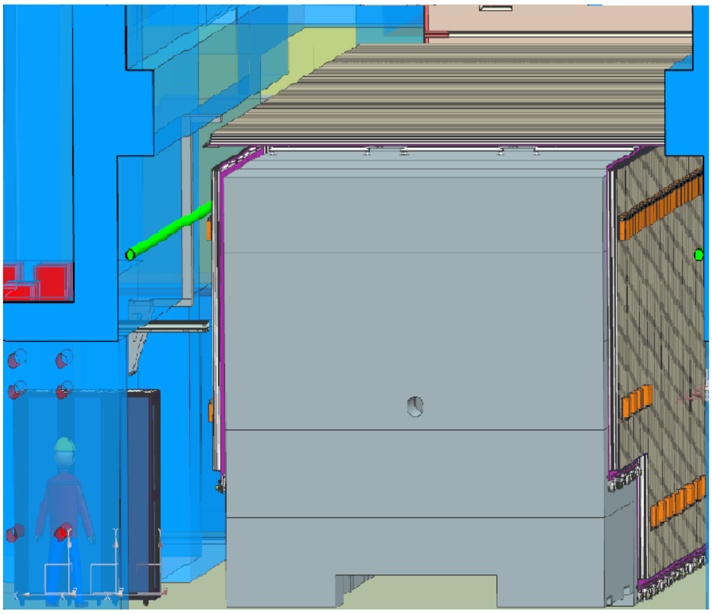
5.1 CRV Team Support

Cosmic-ray muons are a known source of potential background for muon-to-electron conversion experiments like Mu2e. A number of processes initiated by cosmic-ray muons can produce 105 MeV particles that appear to emanate from the stopping target.

To suppress this type of background , the cosmic ray veto is needed and it consists of four layers of long extruded scintillator strips, with aluminum absorbers between each layer. The scintillator surrounds the top and sides of the Detector Solenoid (DS) and the downstream end of the Transport Solenoid (TSd) (Fig. 5.1). The strips are 2.0 cm thick, providing ample light to allow a high enough light threshold to be set to suppress most of the backgrounds. Aluminum absorbers between the layers are designed to suppress punch through from electrons. The scintillation light is captured by embedded wavelength-shifting fibers, whose light is detected by silicon photomultipliers (SiPMs) at each end (except those counters closest to the TSd) [8].

For the Cosmic Ray Veto team, we made the following elements:

- Add supports blocks for CRV-U panels
- Creation and position of a CRV Patch Panel
- Generate Placeholders for the CRV trunk cable routing



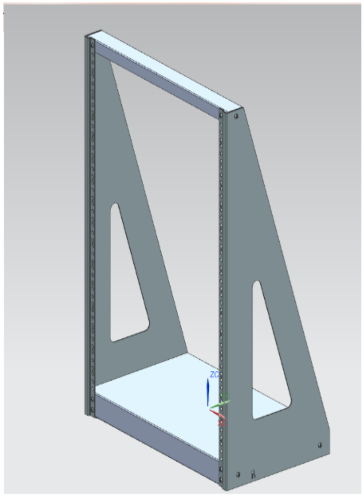


Figure 5.1: *Left: CRV mounted above Shield. Right: CRV Patch Panel*

5.2 Tracker Team Support

The racks for the Tracker were repositioned to improve the routing of the cables.

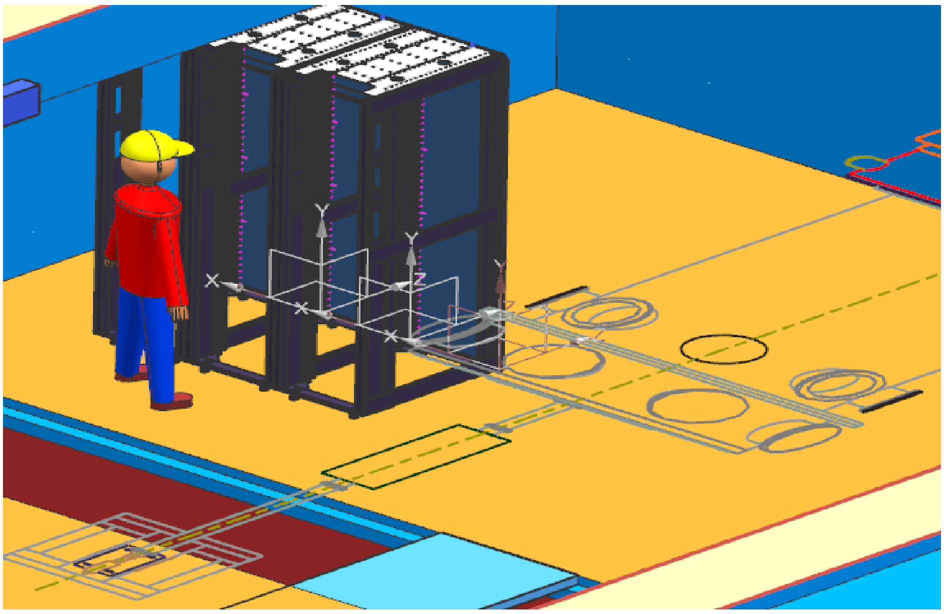


Figure 5.2: *Tracker Racks*

5.3 Pedestrian Bridge

To increase the fidelity of the model to facilitate planning for staging and installation of shield blocks, I created a model of the pedestrian bridge as it is in the Civil Drawings and as it was built.

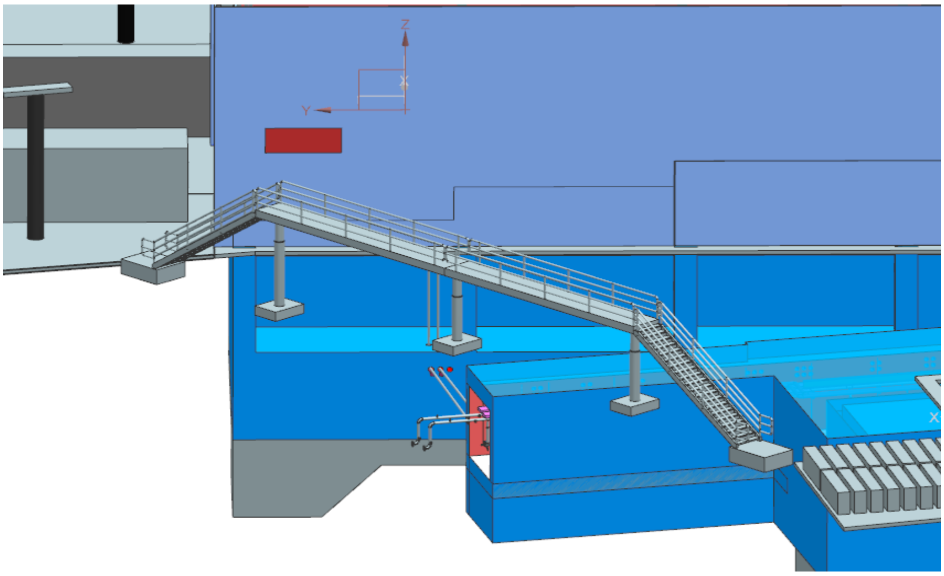


Figure 5.3: *Pedestrian Bridge*

Figure 5.4: *Actual Pedestrian Bridge*

6. Conclusions

This paper presents my work, the reasons behind it and how it fits inside the Mu2e Experiment at Fermi National Accelerator Laboratory.

The result is a step forward in the design of the Mu2e plan, facilitating Mu2e future integration activities, reducing the potential for interferences or misunderstandings.

During the Summer Internship, I had to face a large number of problems, from technical to organization ones, with the necessity to find a quick and good solution in the shortest possible amount of time to respect the deadlines and to get the job done. I had the chance of learn notions about Particle Physics and how the Accelerators works as well as face Engineering problems related to Civil and Mechanical Engineering, control of Radiations and safety in general.

Moreover I have participated in the Technical Meetings and discussions, having a taste of the participation in a big project, divided in groups with a common goal and that work hard to achieve it.

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