University of Pisa

Department of Industrial Engineering
Master of Mechanical Engineering

Mu2e experimetn integration

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Contents

1 Mu2e experiment overview

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). 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:

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

The signature of this process is a monoenergetic electron with an energy nearly equal to the muon rest mass. The best experimental limit on muon-to-electron conversion, $R_{\mu e} < 7 \times 10^{-13}$ (90% CL), is from the SINDRUM II experiment. Mu2e intends to probe four orders of magnitude beyond the SINDRUM II sensitivity, measuring $R_{\mu e}$ with a single-event sensitivity of 2.87×10^{-17}. To achieve this significant leap in sensitivity, Mu2e requires an intense low energy muon beam and a state-of-the-art detector capable of efficiently identifying, reconstructing and analyzing conversion electrons with momenta near 105 MeV/c [1].
The muon beam is created by making a proton beam strike a small tungsten production target, then the magnetic field created by the superconductive solenoids steer the muons in the correct direction towards the stopping target. Therefore, the experiment is composed by **(Figure 1)**:

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

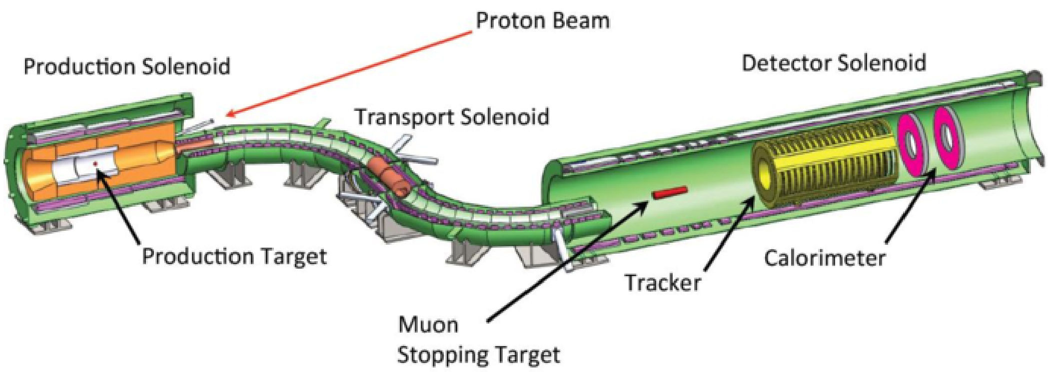


Figure 1: Mu2e experiment overview

2 STM stands design

In the first part of my work I have modeled some components of the Stopping Target Monitor (STM), which were already described in Mu2e documents, and I have realized the concepts of the stands which are going to support these parts.

2.1 Stopping target monitor overview

With reference to document [2], we are going to describe the STM system and its most important components.
The Stopping-Target Monitor (STM) system, consisting of photon detector plus shielding and collimation, must be designed to measure X-ray and/or γ-ray lines whose rate is proportional to the number of stopped muons. It must handle high photon rates and the radiation damage associated with photons and neutrons. Its energy resolution must be sufficient to see the muonic X-rays or γ-rays of interest for normalization. The baseline Mu2e stopping target material is aluminum. The Stopping-Target Monitor will consist of a high purity germanium detector (HPGe). The germanium detector is located at the most downstream end of the DS area, slightly offset from the DS solenoid axis to allow for a second (HPGe or $LaBr_3$) detector. A series of collimators and a sweeping magnet are designed to reduce background rates in the germanium detector and the Cosmic Ray Veto detector. The windows, shielding and collimators are, in order traveling downstream **(Figure 2)**:

1. The polyethylene at the end of the Muon Beam Stop (MBS) has an 9.2 cm radius hole on the axis of the DS solenoid to allow the STM signal photons to reach the STM detector.

2. The thin mylar vacuum window of the Instrumentation Feed-through Bulkhead (IFB) has a 9.7 cm radius.

3. The $\sim$3 feet thick concrete DS end-cap shield (ECS) (for the Cosmic Ray Veto, CRV) has a 11.0 cm radius hole along the solenoid axis.

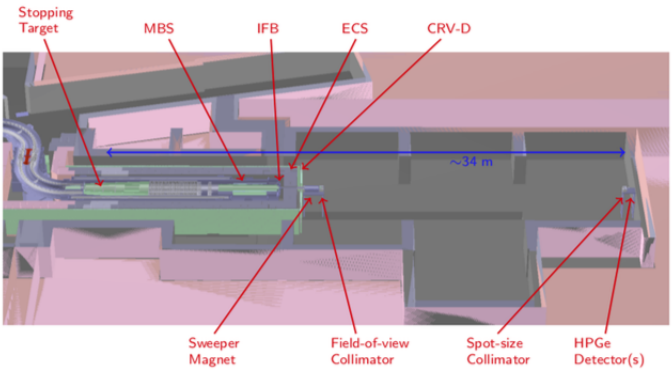
4. The rate requirements of the STM require that we cannot have a polyethylene absorber on the solenoid axis upstream of the sweeper magnet, which means muons will escape the DS into the air downstream of the DS. These muons then stop in the air, on the magnet, or on other materials downstream of the DS, decay, and the Michel electrons are often energetic enough to cause significant dead-time to the CRV. In order to reduce the rate to the CRV a cylindrical stainless steel shield around the beam axis and a wall in front of the magnet that shields the CRV from Michel electrons have been added. The cylindrical stainless steel shield is placed beginning at the downstream end of the CRV end-cap shielding. It has an inside radius of 11.0 cm and an outer radius of 16.0 cm (5.0 cm thick). This cylindrical shield extends from the downstream end of the ECS through the rectangular opening in the CRV and merges with the next element, a stainless steel wall.

5. The 10 cm thick vertical stainless steel wall with an 11.0 cm radius aperture along the DS axis which is the continuation of the cylindrical shield in the previous item. The purpose of the cylindrical shield and wall are to stop muons and absorb any muon decay electrons headed to the CRV. The height and width of this stainless steel wall are the same as the height and width of the sweeper magnet in order to prevent any Michel electrons originating inside the magnet from reaching the CRV.

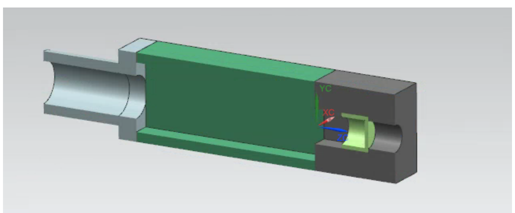
6. The STM would suffer from radiation damage if charged particles aren't swept away. In addition to radiation damage, the STM may not be able to sustain the extremely high rates. Therefore a 1 m long, 500 gauss permanent magnet is placed just downstream of the shielding wall in the previous item. Its outer dimensions are: 43.2 cm wide by 45.7 cm tall. The inner opening of the magnet is: 19.0 cm (7.5 in) wide by 35.6 cm (14 in) tall.

7. The STM detector must be able to see the entire stopping target, but the view all of the inner edges of the components along the beamline such as the MBS, IFB flange, sweeper magnet, etc has to be blocked. To accomplish this a 45.0 cm long lead collimator has been placed just downstream of the sweeper magnet. The collimator is 43.2 cm wide by 45.7 cm tall, with a 7.1 cm radius aperture in the downstream-most 15 cm (see Figure 8). Unfortunately there is a chance that some muons might make it through the sweeper magnet and hit this lead collimator resulting in a background line close in energy to our signal line (there are also background lines from W and Fe so tungsten and stainless steel each also have their disadvantages). To suppress that from happening, 15.0 cm (z) of the central region of this collimator has been lined with polyethylene to absorb any muons that may have made it through. The downstream edge of the polyethylene liner has a 2.0 cm thick polyethylene absorber to suppress the number of muons and neutrons escaping downstream. The inner radius of this collimator must be 6.52 cm to allow the STM to view the whole ST Stopping Target), but it will be 7.1 cm to allow for some misalignment. The other beam axis openings, such as the MBS, IFB flange, etc. were calculated assuming this 7.1 cm radius collimator and two 0.5642 cm radius spot- size collimators separated center-to-center in x by 7.62 cm (3.0 in).

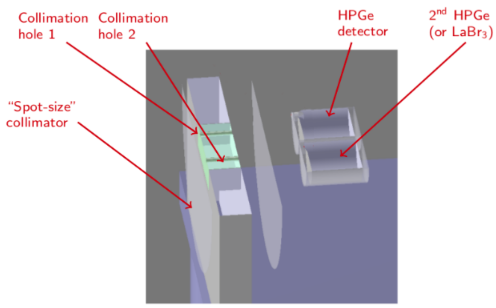
8. 5.08 cm (2 in) thick lead shielding will be placed around the HPGe crystal(s). Standard 2"x4"x8" thick lead bricks should suffice. The front wall of the shielding collimator, at a distance of about 34 inches (86.36 cm) from the end of the building, will be 15.24 cm (6") thick tungsten and will provide a $\sim 1cm^2$ "spot-size" collimation hole just in front of the HPGe. This collimator, combined with the collimator in item 7, allows the HPGe to see the entire stopping target but prevents it from seeing much else, such as the walls of the collimator, shield, and magnet described in items 1, 3, 4, 5, and 6, or the calorimeter or tracker. The 2 cm thick lead walls and roof of the shielding will suppress room background. There is no need for this shielding to have a back (downstream) wall, which will be the building concrete. Access to the detectors will be obtained by removing the necessary bricks.



(a) STM building view



(b) Upstream components

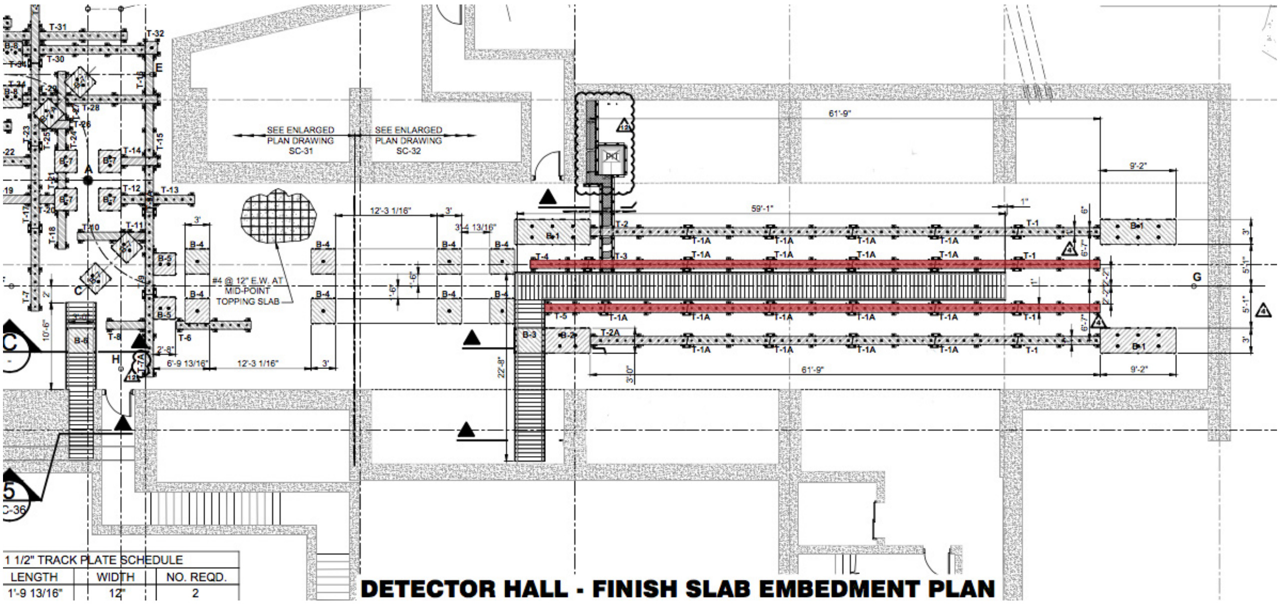


(c) Downstream components

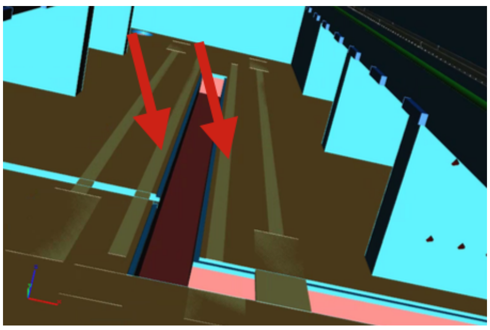
Figure 2: STM components

2.2 STM Upstream stand requirements

- Support the upstream STM components (shield for CRV, sweeper magnet, lead collimator, polyethylene liner and absorber); their total weight is of 4811 lbs.
- The stand has to be mobile to allow the movement and repositioning of the upstream components of the STM, during the maintenance of the tracker and calorimeter.
- It has to be made out of non-magnetic material, because of the proximity with a strong magnetic field.
- It has to facilitate the alignment of the components.
- The legs of the stand have to rest on the two inner floor plates **(Figure 3)**.



(a) Rails from drawing



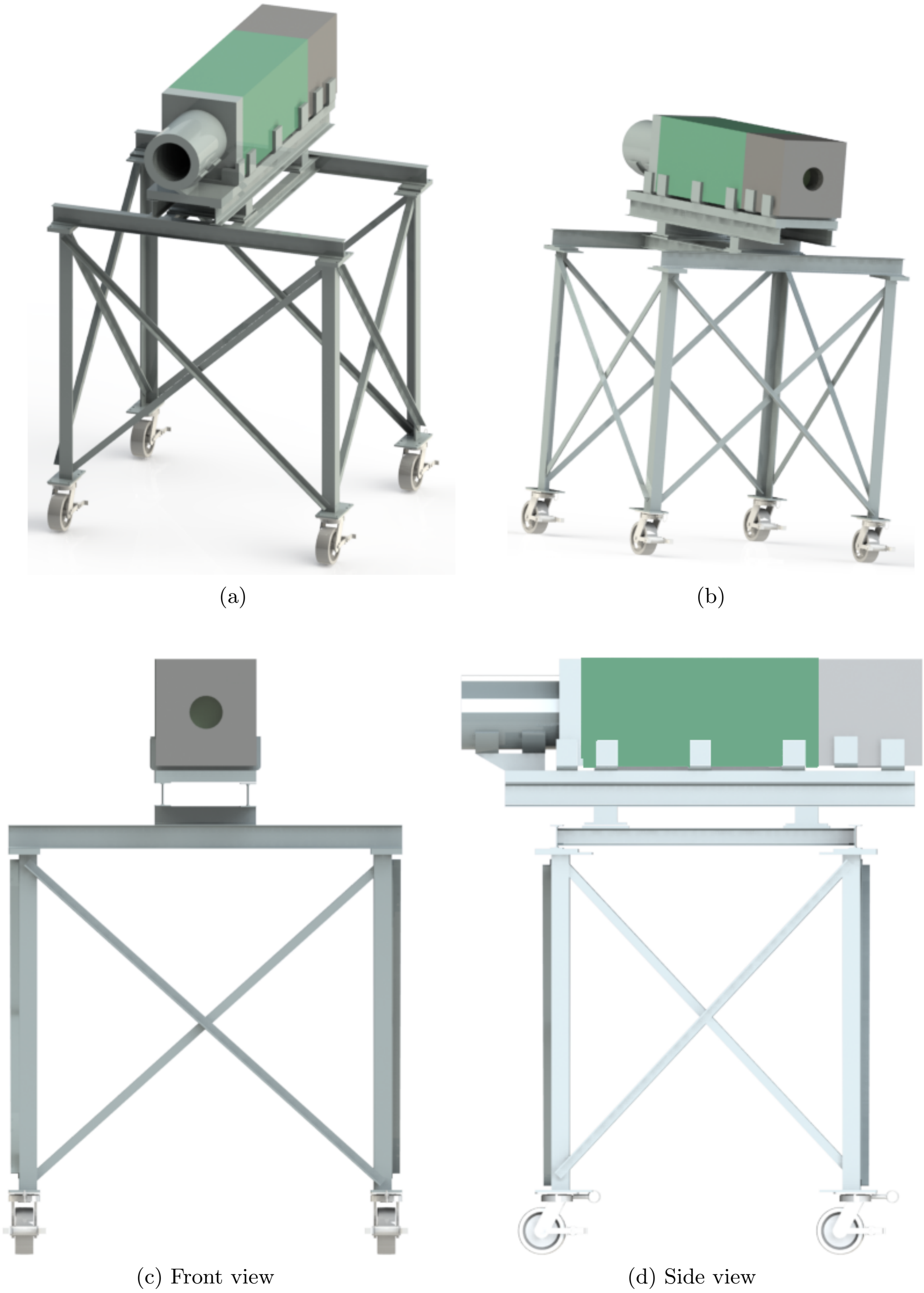
(b) Rails from NX model

(c) Rails from a picture

Figure 3: Rails

2.3 Upstream stand concept

2.3.1 Realized concept



(a) (b)

(c) Front view (d) Side view

Figure 4: STM upstream realized concept

The solution realized consists of an aluminum frame where the beams are welded to each other. On the top of the frame there are two longitudinal beams that support a table. The two blocks visible in **Figure 4** are a schematic representation of the alignment systems that has to be put between the frame and the table. After that, on the table we find four stands, one for each upstream STM component (cylindrical stainless steel shield, rectangular stainless steel wall, sweeper magnet and lead collimator). These stands have to support the compontents and at the same time allow the link with the table. Also these stands are only a schematic representation of the alignment systems between each compontent on the table. The length of the four legs of the frame is chosen to make sure that the distance between the floor and the axis of the STM upstream components is 91.042", considering the height of the four wheels chosen and the heights of the aligment systems mounted between the stand and the components on the top. After that, we have chosen the dimensions of the cross-section of the four legs to avoid the buckling instability due to the weight of the STM components which amount to 4800 lbs ($\sim$ 2200 kg). We have considered that each leg has to support a quarter of the total weight of the components. The used material is aluminum 6061 ($E = 69.9GPa$), according to the fact that we have to avoid structural steel because it is a magnetic metal. Using a Factor of Safety (FS) of 5 and considering an instability process that gives us $\mu = 0.7$ **(Figure 5)**, from the eulerian relation:

$$F_{max} = \frac{\pi^2 E J_{min}}{(\mu L)^2} \quad (1)$$

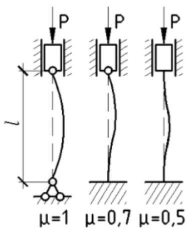


Figure 5: μ value depends on the conditions of end support of the column

we obtain the J_{min} necessesary to avoid the buckling. Starting from that value we have choosen the L shaped beam legs from an American catalogue with the imperial system dimensions, to be consistent with the other dimensions of the building that are given in feet and inches. We have added the other cross beams to increase the stiffness of the structure. The selected beams are shown in **Figure 6**.

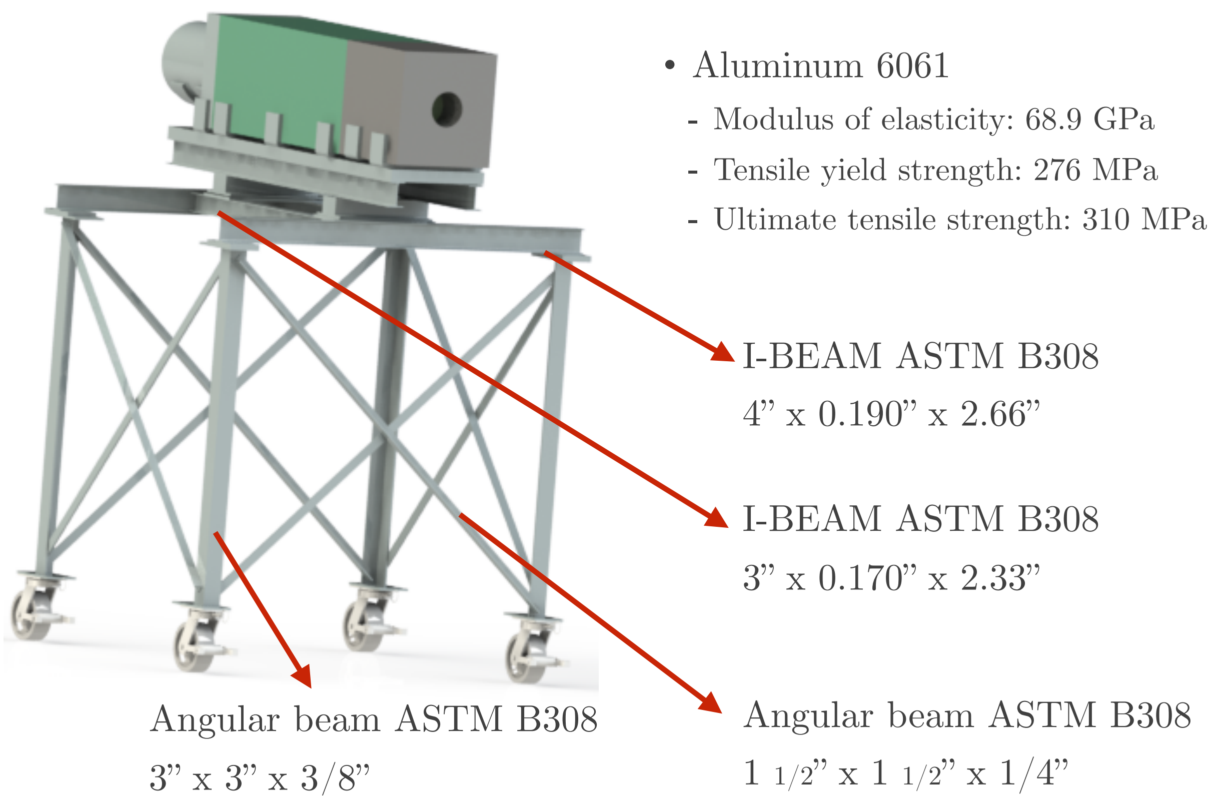


Figure 6: Used beams shapes

2.3.2 Selected wheels

Because of the fact that we need to easily move the STM upstream components during the maintenance, we opted for four wheels, chosen from McMASTER-CARR catalogue **(Figure 7)**. Each wheel can support 2520 lbs, so, assuming again that each wheel has to support a quarter of the total weight of the components, we have a $FS \sim 2$ on each wheel. The chosen wheels have got also a swivel with brake and swivel lock, that allows us to stop the stand and to move it both in parallel or perpendicularly to the beam line direction.

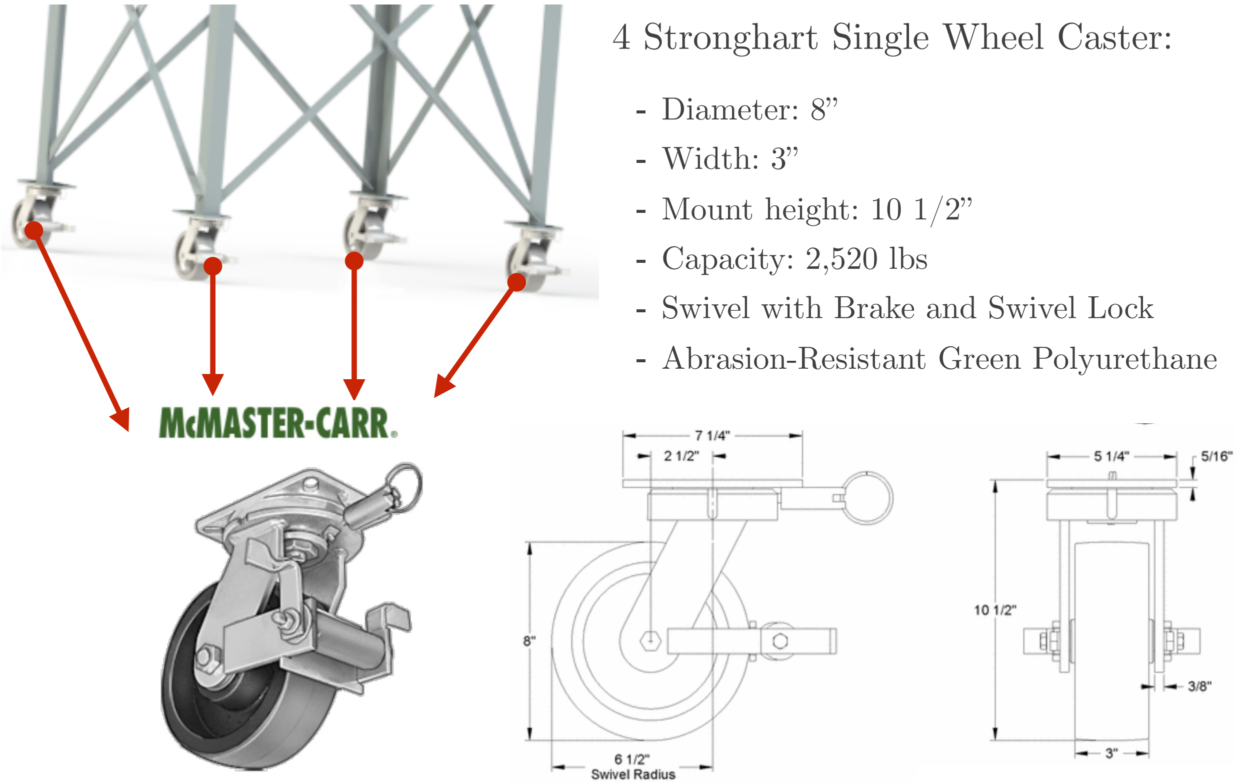


Figure 7: Chosen wheels

That solution allows the table with the shield for CRV, the sweeper magnet and the collimator to be moved in the plane, to allow other maintenance operations. This will avoid the need to pick up the table when it is just sufficient remove it from the beam line **(Figure 8)**.

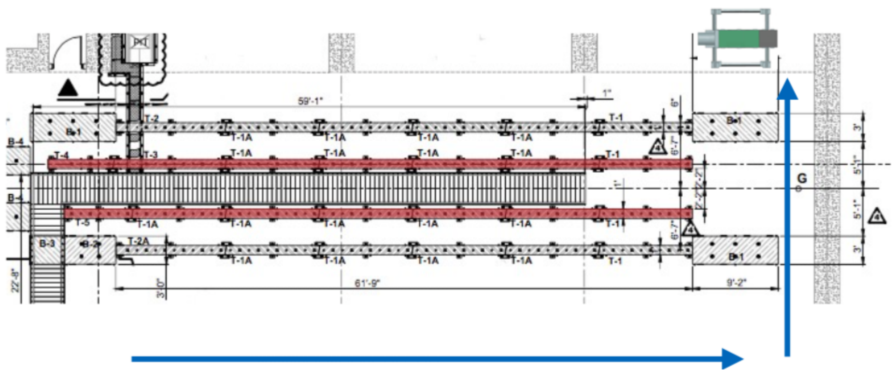


Figure 8: Moving operation

2.3.3 Alignment of the components

The fact that we have put different alignment systems, one between the frame and the table and one between each components on the table and the table itself, allows us to split the alignment operation in two steps:

- **Relative alignment of the parts on the table**: the system realized allows the relative alignment of the shield for CRV, sweeper magnet and the collimator, so that this internal alignment operation does not have to be repeated every time the stand is moved **(Figure 9)**.

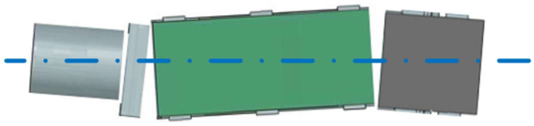


Figure 9: Relative alignment of the part on the table

- **Alignment between the table and the beam line**: once realized the alignment of the individual elements on the table, this one can be mounted on the stand and aligned to the beam line through the alignment system mounted on the stand. This second alignment is faster than the one made before and this will reduce the time due to the realignment after the maintenance operations **(Figure 10)**.

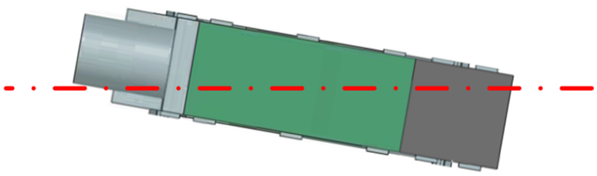


Figure 10: Alignment between the table and the beam line

2.4 STM Downstream stand requirements

- It has to support the tungsten wall with the two 5.642 mm radius collimation holes, the two photon detectors and the lead background shield.
- It has to allow to build the shielding with common $2'' \times 4'' \times 8''$ lead bricks.
- It has to allow to remove the bricks for maintenance on the two detectors.
- It can't be too long, in z direction, because the space upstream of the tungsten wall is necessary for the moving of the upstream train during the maintenance **(Figure 11)**.
- The stand has to be referred to the ground, so it can't be fixed to the east hall wall.
- It has to allow the operation of alignment.

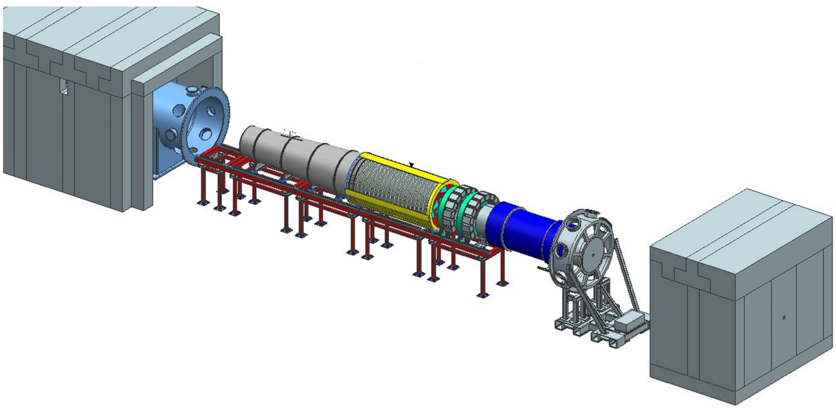
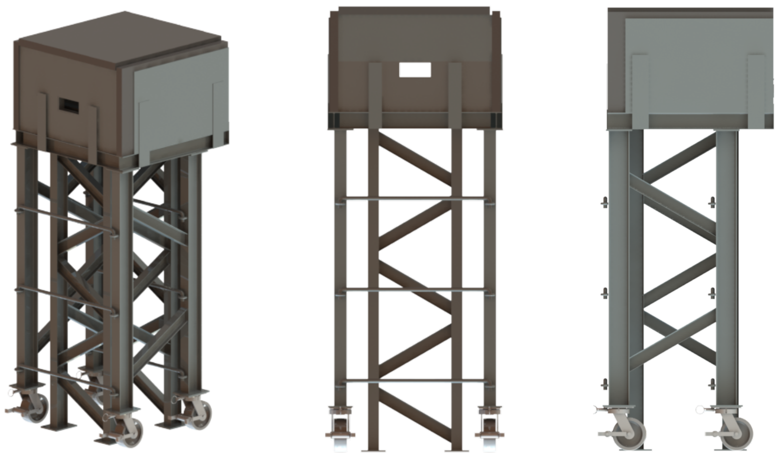


Figure 11: Maintenance operation

2.5 Downstream stand concept

2.5.1 Realized concept



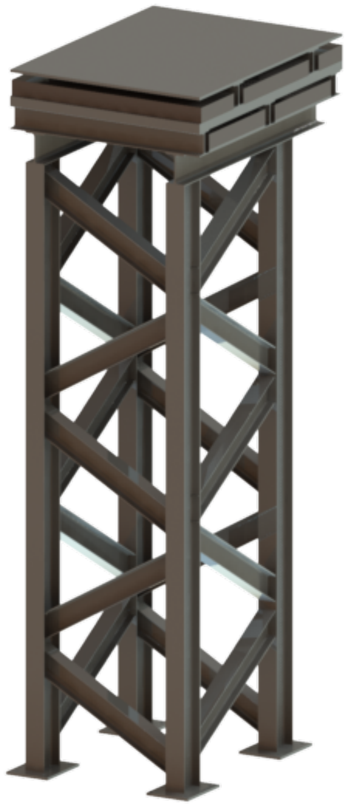
(a) (b) Front view (c) Side view

Figure 12: STM downstream realized concept

The solution realized is made of two parts: the internal one is bolted to the floor and so it is fixed, the external one is supported by four wheels and so it can be easily removed. The shield made out of common $2'' \times 4'' \times 8''$ lead bricks is split in two different parts. The bottom of the shield is supported by the fixed internal stand while the external one bears the lateral and frontal walls and the roof of the shield.

2.5.2 Solution realized-fixed part

The fixed part has the role to support the bottom of the lead shield and, on the top table, it has to support also the tungsten wall with the two collimation holes and the two photon detectors, with their alignment systems. Because of that it has to be very stiff and that justifies the use of so many cross beams. The two downstream legs are not at the corners of the table beacuse we have to leave some space between them and the east wall of the building, to allow the passage of pipes, cables and other.



Total weight of steel:
606 lbs

Total weight of lead:
980 lbs

Figure 13: Fixed part

2.5.3 Solution realized-mobile part

The mobile part has the role to support most of the lead shield. Because of the great weight of the this shield we have to choose the dimensions of the four legs to avoid the buckling instability. So, as we have already done for the STM upstream stand, starting from the length of the legs that let us to align the collimation holes with the muon beam line (in a direction orthogonal to the floor), we have chosen the section of the legs in way that the their J_{min} gives us a FS of 5 again **(Formulae 1)**. The wire frame of the mobile part is also welded, except for the part of that which bears the roof that, in this first concept is just laid on the below wireframe. In a second design of the stand it would be a good choice use bolts to link this one with the rest of the structure.

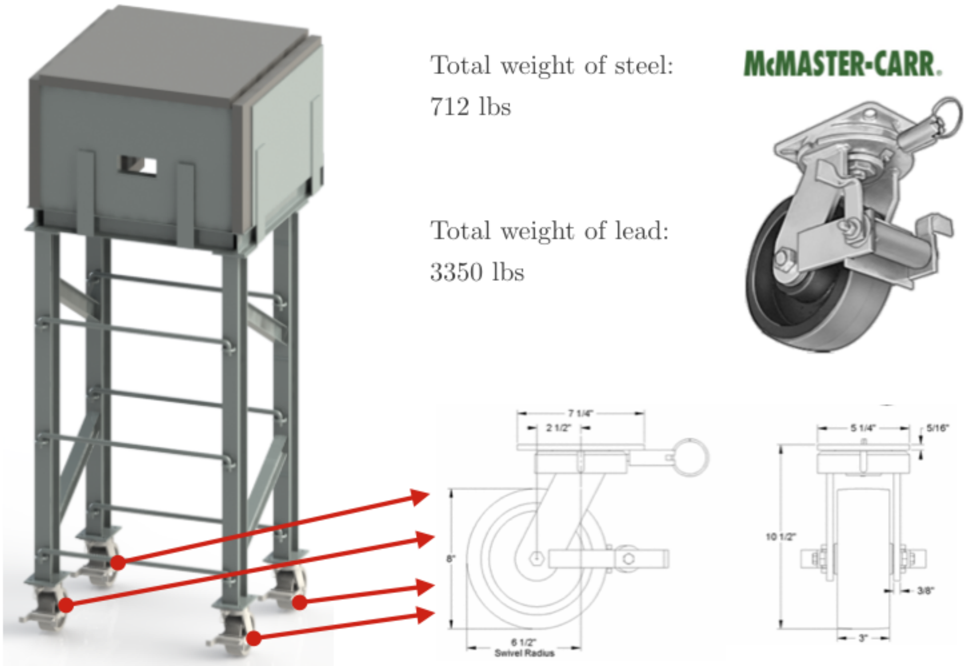


Figure 14: Mobile part

2.5.4 Used material and beams

2.5.5 Advantages of the realized solution

- The fixed stand, which is the one that supports the tungsten wall and the two detectors, includes few lead bricks. This reduces the weight of this part of the structure so that it is subjected to less deformation, allowing a better alignment of the pieces on it.
- The removable shield allows the maintenance operation without removing the bricks one by one. This operation in fact would be too long and it would be a waste of time. Furthermore, the

placement of the bricks one by one, once the maintenance is finish, could affect the alignment of the holes in the tungsten wall and the photon detectors.

- The fact that the shield can be easily removed allows to gain more space along z (muon beam line direction) during the upstream maintenance operation, which is important to allow the parts to be extracted from the upstream shielding.

3 Refinement of the Teamcenter model

In this second part we are going to show the refinements that have been done to the 3D CAD model of the Mu2e building and the features added to that. To do that work we need to access to Teamcenter, where every part and assembly of the Mu2e is located. From here we had to modify existing components and add, following the right procedure, the new features under the requested subassembly and with the requested part name. Sometimes we have also created several copies of the same compontent, located in different positions, inside or outside the Mu2e building, to allow their display in Lifecycle viewer, which is a tool that allows all the people who are working on Mu2e to see the 3D CAD model of the structure, without opening the CAD Software NX9, which requests appropriate skills.

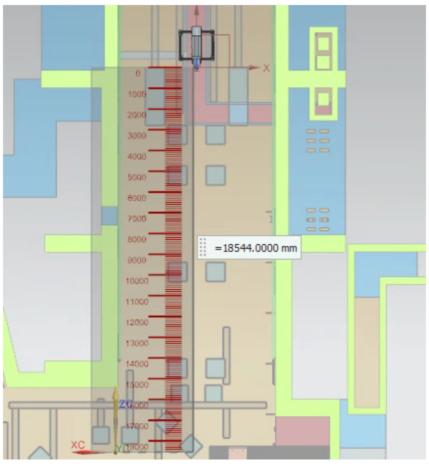
3.1 Inner refined and added features

3.1.1 Place the Upstream and Downstream components of STM in Teamcenter building model

We put inside the Teamcenter model the Upstream and Downstream components of the Stopping Target Monitor, locating them in the right x-y-z position, according to document Mu2e-doc-6453 **(Figure 15)**.

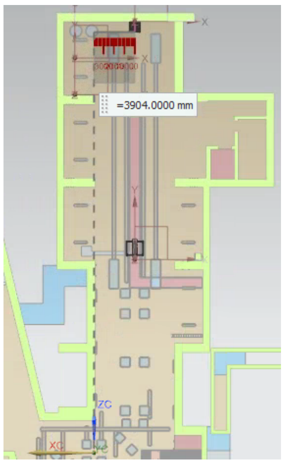
Component	$z^{\mathrm{min}}_{\mathrm{mu2e}}$ (mm)	$z^{\mathrm{max}}_{\mathrm{mu2e}}$ (mm)	x_{offset} (mm)	design r (mm)
Stopping Target	5470.95	6271.05	0.0	75.0
MBS hole	17156.0	17308.4	0.0	92.0
IFB window	17320.9	17321.1	0.0	97.0
IFB flange	17321.0	17421.0	0.0	97.0
ECS hole	17627.3	18542.3	0.0	110.0
CRV-D	18761.0	18872.8		
CRV shield cylinder	18544.0	18963.0	0.0	110.0
CRV shield wall	18963.0	19063.0	0.0	110.0
Sweeper magnet	19064.0	19978.4	0.0	
Collimator (field-of-view)	19985.4	20435.4	0.0	
Collimator (field-of-view, poly)	20135.4	20285.4	0.0	71.0
Collimator (field-of-view, coll)	20285.4	20435.4	0.0	71.0
Collimator (spot-size) hole1	40487.6	40640.0	40.6	5.642
Collimator (spot-size) hole2	40487.6	40640.0	40.6	5.642

(a) Mu2e-doc-6453 Table



(b) Locatation of Upstream STM stand in Z coordinate

(c) Locatation of Upstream STM stand in X coordinate



(d) Locatation of Downstream STM stand in Z coordinate

Figure 15: Place the Upstream and Downstream components of STM in Teamcenter building model

3.1.2 Storage of the STM components during maintenance

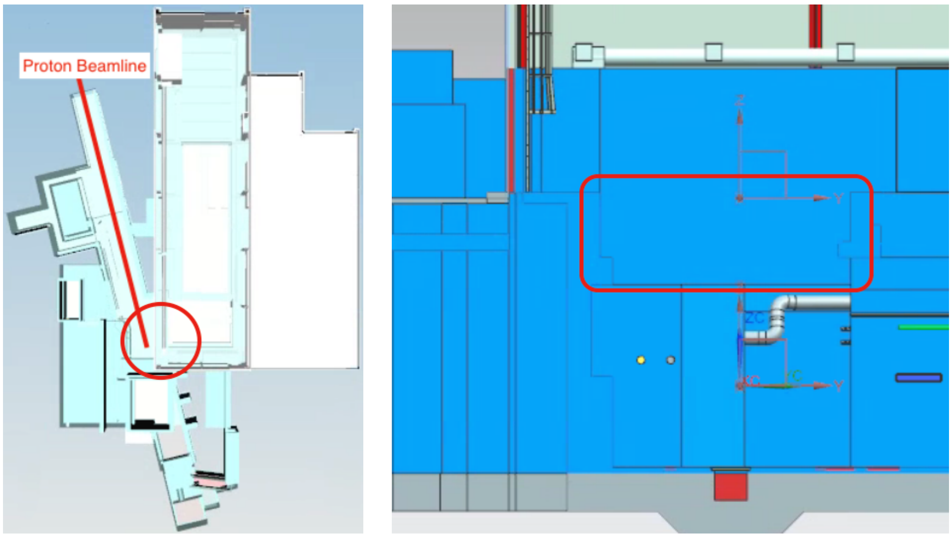
During the maintenance operation on the Upstream components of the muon beam line, we need to pull out the detector train **(Figure 11)**. To do that we have to remove the Upstream STM components, that stand in front of the end cap shielding, and we have also to remove the mobile lead shielding of the Downstream STM compontents **(Figure 14)**. So in the CAD model we created a copy of these two parts and we have placed them in the North-East corner of the lower floor of the building, where they are supposed to be stored **(Figure 16)**. Doing that, people who are going to open the model, even with Lifecycle Viewer, immediately see where these compontents are going to be stored and also learn that that space is already taken.

(a) STM storing operation (b) Stored STM components

Figure 16: Storage of the STM components during maintenance

3.1.3 North West Shield Block Pile

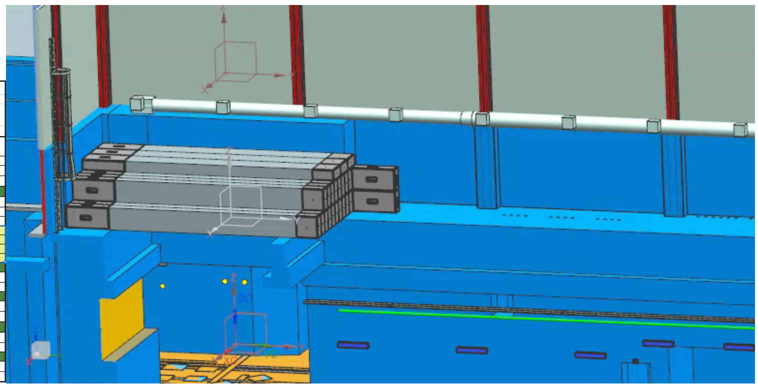
Looking at **Figure 17a** we can see that the proton beamline, which is covered and shielded by the earth, in correspondence of the red circle isn't covered any more because of the TS Hatch visible in the red rectangle in **Figure 17b**, necessary for the building of the TS concrete shielding and the PS itself. So to continue the shield provided by the earth until this point, we have to add a block pile which replace the earth function. Therefore we have added this feature, following the instruction given in the appropriate spreadsheet **(Figure 18a)**. We have to pay attention to the fact that only the yellow underlined blocks are the ones that constitute the North-West shield block pile, the other blocks are necessary for other hatches in the building. The D and E blocks were already available in NX Fermilab common library while the SP26 are special ones (SP prefix stands for special), not existing in the library yet, so we modelled them like simple boxes with the right dimensions written on the spreadsheet.



(a) Muon Beamline (b) DS Hatch

Figure 17: North West Shield Block Pile

Date	**10/02/16**	Rev 5			
Shield Block Count					
Location	Number of Blocks Required	Block Type	Block Dimensions (Ft.)	See Sketch	Equivalent Shielding
Mu2e Detector Hall					
Detector Hatch	48	*G*	1.5 x 3.0 x24	SECTION S4	6 feet
	47	*G*	1.5 x 3.0 x24	SECTION S4	6 feet
TS Hatch					
Bottom Layer	20	*SP23H*	1.5 x 3.0 x 23 w/ haunch	SECTIONS 2, 3 &4	6 feet
2nd layer	20	*SP23*	1.5 x 3.0 x 23	SECTIONS 2, 3 &4	6 feet
3rd, 4th & 5th layer TS Hatch	23	*SP26*	1.5 x 3.0 x 26	ALL SECTIONS	16 feet
3rd, 4th & 5th layer West	23	*D*	1.5 x 3.0 x 6	ALL SECTIONS	16 feet
3rd, 4th & 5th layer East	23	*E*	1.5 x 3.0 x 3	ALL SECTIONS	16 feet
Far East	2	*D*	1.5 x 3.0 x 6	ALL SECTIONS	16 feet
PS Hatch	90	*H*	1.5 x 3.0 x 18	SECTION S3	18 feet
Remote Handling Hatch	48	*SP9*	1.5 x 3.0 x 9	SECTION S2	12 feet
Extinction	4	*H*	1.5 x 3.0 x 18	NOT SHOWN	6 feet
Beamline Hatch	30	*C*	3.0 x 3.0 x 6	NOT SHOWN	16.5 feet
	6	*D*	1.5 x 3.0 x 6	NOT SHOWN	16.5 feet



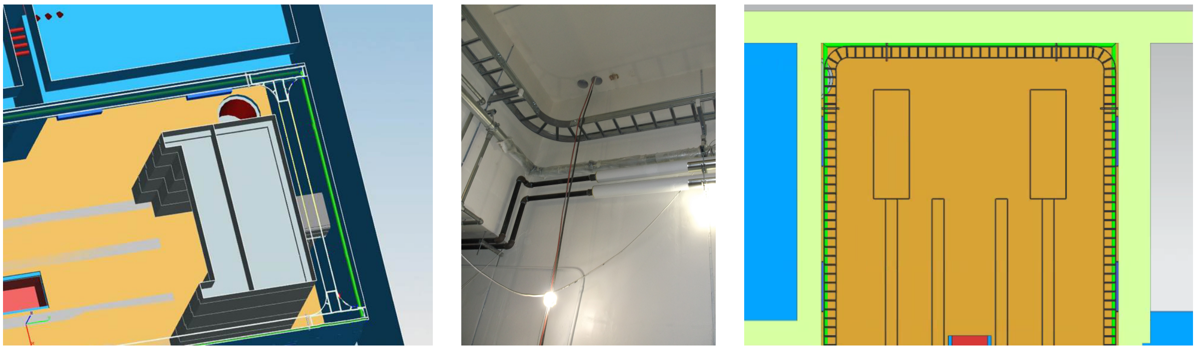
(a) Blocks spreadsheet (b) Added blocks pile

Figure 18: Added feature

Looking at the realized model we noticed that the two D blocks on the East most side (on the right in **Figure 18b**) are in a strange and unusual postion and maybe they aren't necessary. We pointed out this fact at one of the meetings.

3.1.4 Cable trays around East end of detector hall

The existing model, which was the one shown in **Figure 19a**, had the cable trays around the East end of the detector hall ending with a T-shape part, linked to the East wall. However the **Picture 19b**, taken from the already existing Mu2e building, shows a different solution for these trays. So we have changed the CAD model to make that as similar as possible to the real one **(Figure 19c)**. The round corner trays that we use to replace the T-shape ones were aready in NX Fermilab common parts, so we didn't need to model them.

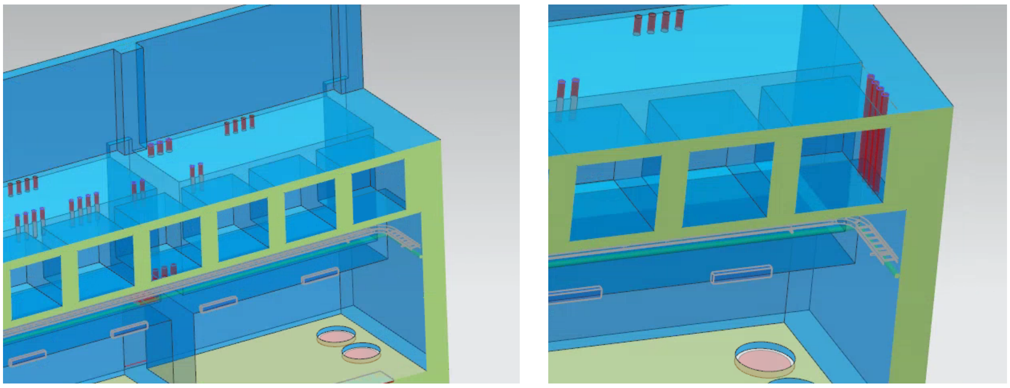


(a) Old cable trays (b) Picture from Mu2e building (c) Updated cable trays

Figure 19: Cable trays around East end of detector hall

3.1.5 Penetrations

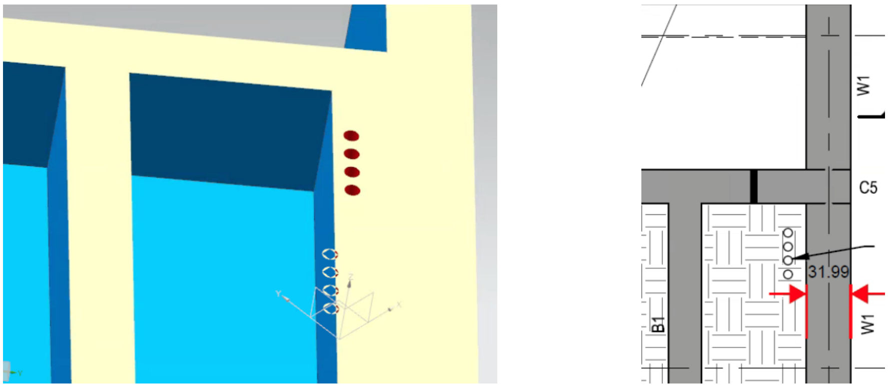
The red features already existing in the model **(Figure 20a)** are all penetrations that allow the connection between the upper and the lower floor. The four penetrations visible on the right in **Figure 20b** were not present in the model, so we added them.



(a) Existing penetrations (b) Added penetrations

Figure 20: Penetrations

Looking at the realized model we noticed the difference between the thickness of the East wall in the CAD model respect to the one in the drawing **(Figures 21a and 21b)**. The CAD model shows a thicker wall. We pointed out this fact to the engineers allowed to modify the walls of the building.

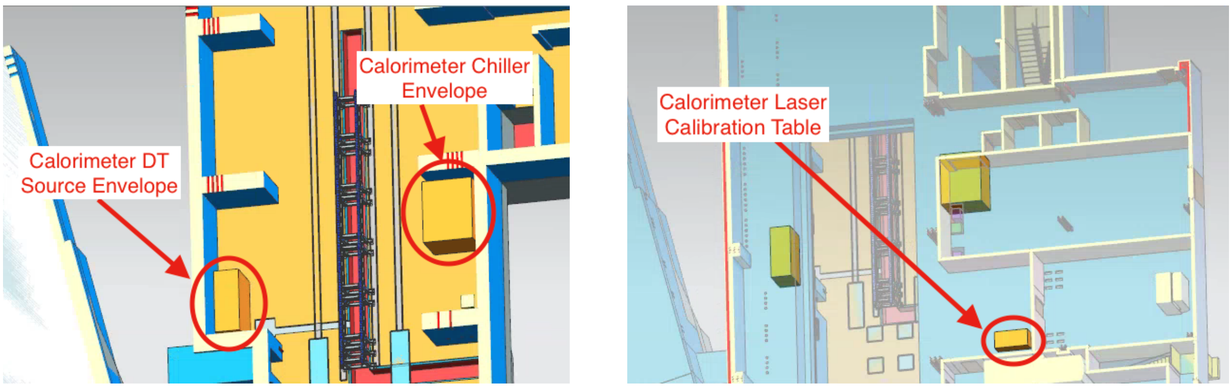


(a) CAD model (b) Drawing

Figure 21: Penetrations: difference between CAD model and drawing

3.1.6 Placeholders for calorimeter infrastructures

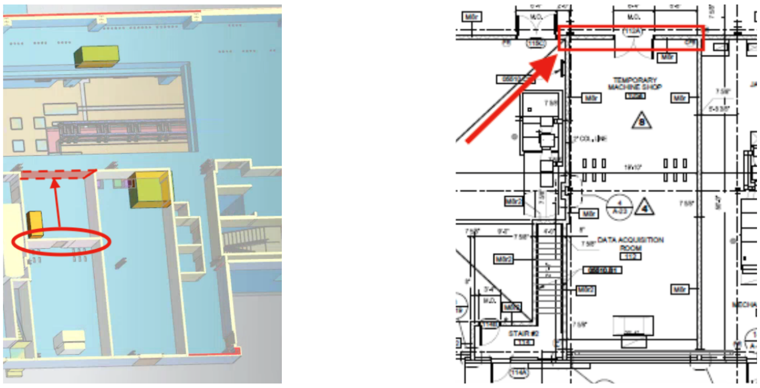
Likewise the process we made for the storage of the STM components in **3.1.2**, we created boxes and we located them in the places where there will be the calorimeter DT source and chiller envelopes and the calibration table. The models of these compontents don't exist yet but, once they will be done, they will replace the orange box in the model, so that at the end they will be already in the right positions with the right orientations.



(a) Calorimeter DT source and chiller envelopes (b) Calorimeter laser calibration table

Figure 22: Placeholders for calorimeter infrastructures

During the location of the placeholder for the calorimeter laser calibration table we noticed that the North wall of the DAQ room was not in the proper position, according to the civil drawing **(Figures 23a and 23b)**.



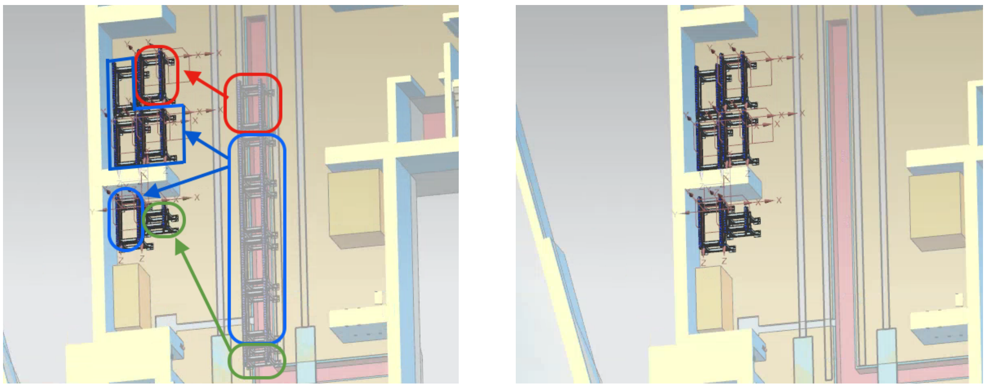
(a) DAQ room North wall in CAD model

(b) DAQ room North wall in drawing

Figure 23: Placeholders: difference between CAD model and drawing

3.1.7 Detector train - Parking location for external rails

Like shown in **Figure 11**, during the maintenance to the upstream components, if we want the access to the detector train, we need to remove the end cap shielding (the right one in the picture) and we have to bolt the external rails (the dark red ones in the picture) to pull out the detector train on these ones. When we don't need the access to the detector train we need a place, not to far from the beam line, to store these rails. So we created a copy of each of the six parts of the rails (1 A-Type rail, 4 B-Type rails and 1 C-Type rail) and we placed that where it is supposed to be stored **(Figure 24)**.



(a) Storing process

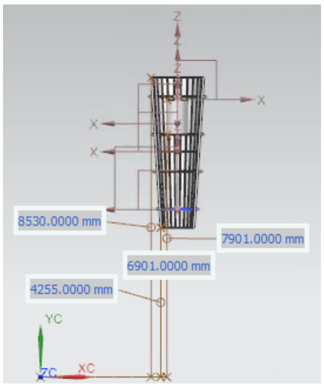
(b) Stored external rails

Figure 24: Storage location for external rails

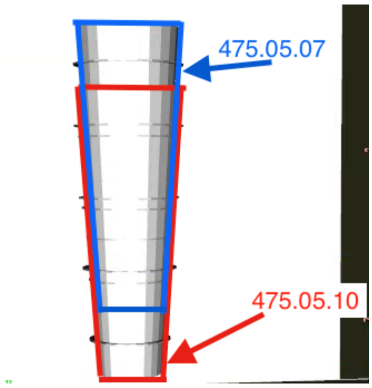
3.1.8 Other inner features refined

We have also improved and corrected other inner features in the Teamcenter CAD model.

Outer and inner proton absorbers (OPA and IPA) We placed the outer and inner proton absorbers in the right positions, according to the Mu2e documents, and in the right folder in Teamcenter model hierarchy. In **Figure 25** we can see the components in the right postion (the blue one) and the components in the old and wrong location (red one) and also the number of the folder where they have been put.



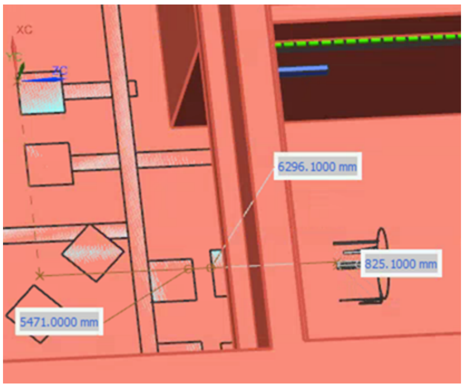
(a) OPA and IPA refined position



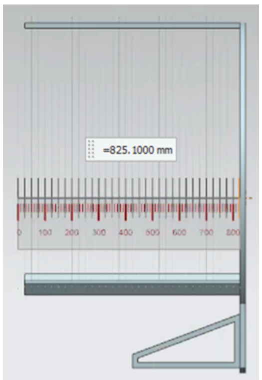
(b) OPA old and new postion

Figure 25: OPA and IPA location refinement

Stopping Target Location Like for OPA and IPA, we checked the position of the stopping target and we have placed that in the proper position, according to Mu2e documents, inside the 3D CAD model on Teamcenter **(Figure 26a)**. Measuring the distance between the first and the last disk of the



(a) Stopping Terget position

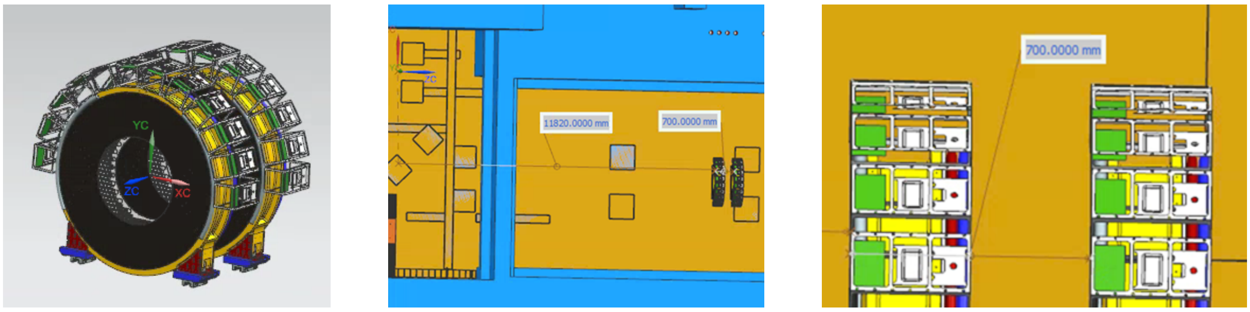


(b) Distance between first and last disk

Figure 26: Stopping Target refinement

Stopping target, we noticed that it was different from the one reported in Mu2e documents: it has to be of 800.10mm instead of the 825.10mm shown in **Picture 26b**.

Calorimeter disks orientation and location We have adjusted the calorimeter rings position and relative distance and we have also put them in the model in the proper orientation **(Figure 27)**, in fact before doing that they were flipped in the 3D CAD building.



(a) Calorimeter disks orientation (b) Calorimeter disks position (c) Calorimeter disks position

Figure 27: Calorimeter disks refinements

3.2 Outer refined and added features

In this part we are going to show the outdoor features added to the 3D CAD model. These features are important to understand the space we have around the Mu2e building, because that space will be necessary to store the huge number of shielding blocks that are inside the building during operations of the beam line. The first problem that we have found when we started this part was that the civil drawings, that are the ones that describe the outdoor features, are given in geographical coordinates North and East of a coordinate system with the origin in the conventional origin of Fermilab **(Figure 28)**. To link the coordinates given in this reference system to the one of the Mu2e CAD model,

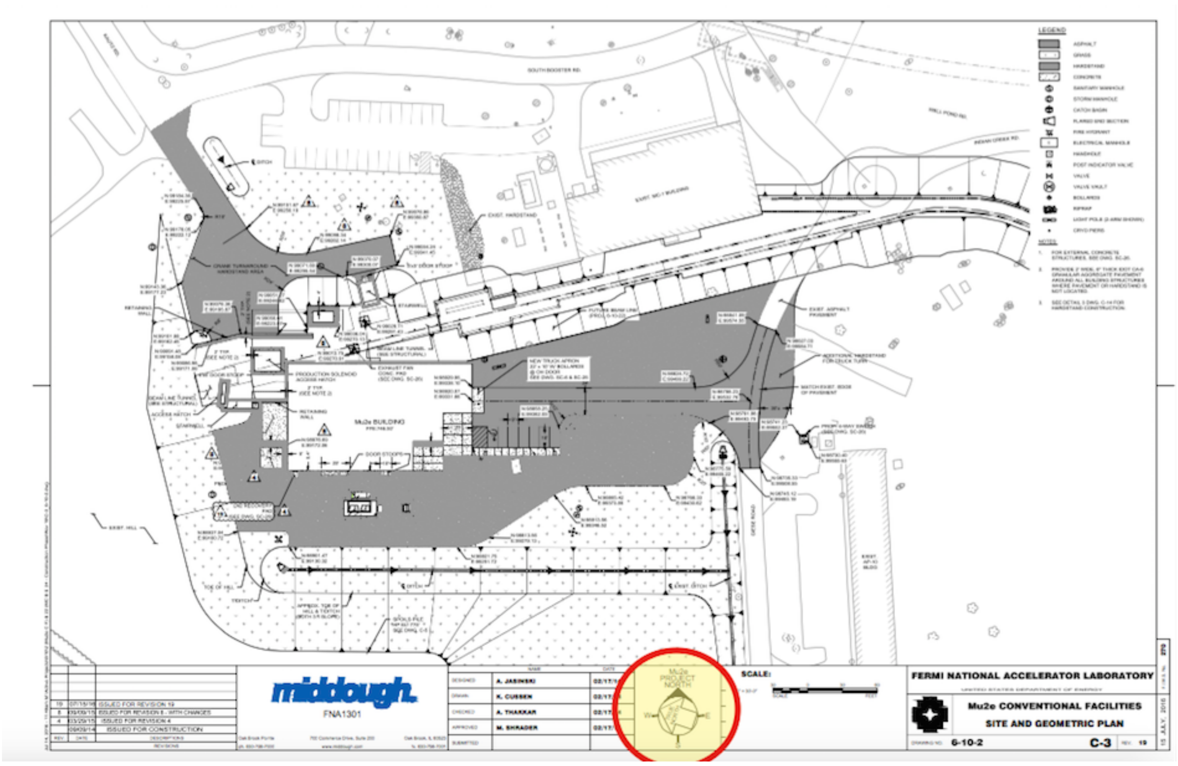
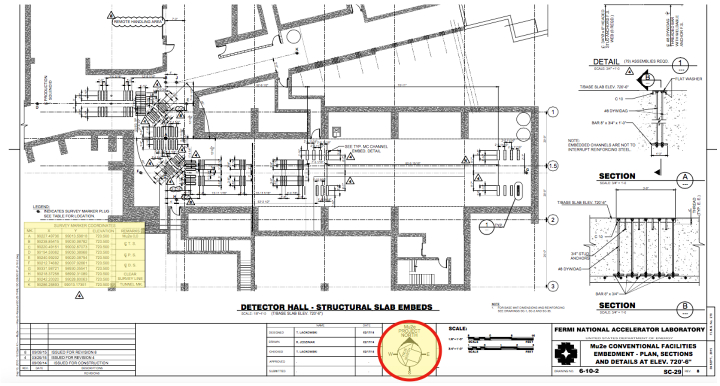


Figure 28: Civil drawing of the outdoor feature of Mu2e building

we have used the table in drawing SC-29 **(Figure 29a)**. In this table the X and Y coordinates are respectively the East and North coordinates of the points, given in feet, in Fermilab coordinate system. So knowing the postions of some particular points (for example in the **Table 29b** the Mu2e Origin) in both Fermilab and Mu2e coordinates systems, we created a simple spreadsheet where, giving as inputs the East and North coordinates of each point in feets, we obtain as outputs the x and y coordinates of the same point in CAD model reference system and in mm **(Table 30)**.



(a) Drawing SC-29

SURVEY MARKER COORDINATES				
MK.	X	Y	ELEVATION	REMARKS
A	99227.49736	99013.59818	720.500	Mu2e 0,0
B	99238.85415	99030.98782	720.500	℄ T. S.
C	99220.49151	99002.87073	720.500	
D	99194.59362	99050.38968	720.500	℄ P. S.
E	99240.99202	99020.08794	720.500	
F	99212.74682	99007.92861	720.500	℄ D. S.
G	99331.98721	98930.05541	720.500	
H	99218.37258	98992.31089	720.500	CLEAR
J	99242.20320	99028.80063	720.500	SURVEY LINE
K	99286.26893	99013.17351	720.500	TUNNEL MK.

(b) Zoom on table on SC-29

Figure 29: Structural drawing

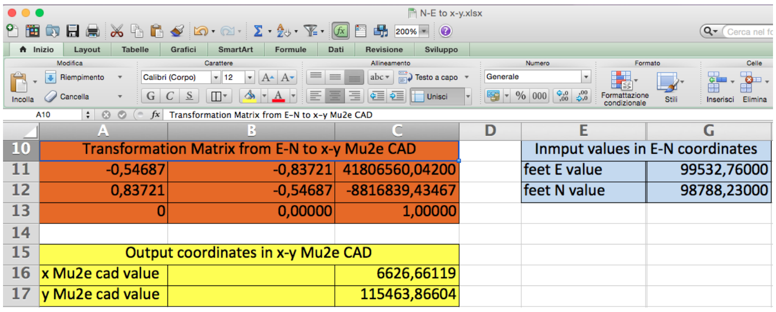
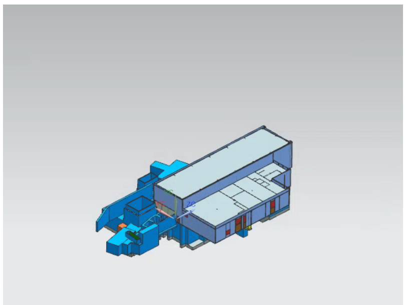


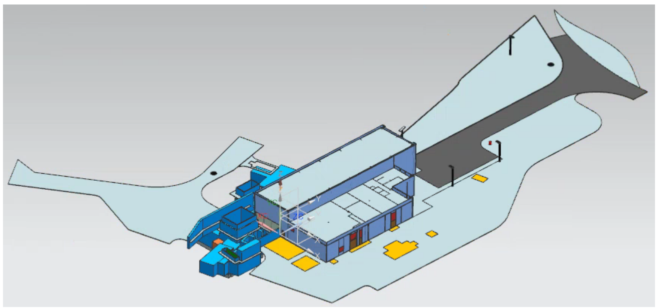
Figure 30: Spreadsheet to convert E-N coordinates in x-y ones

3.2.1 Hardstands, road, bollards, drains and tube trailer

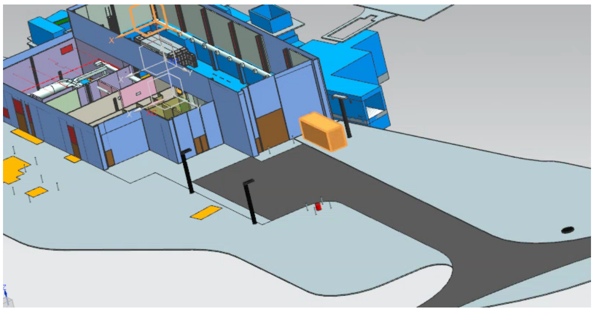
So, starting from the model of the building shown in **Figure 31a**, we have added all the external features visible in **Figure 31b**, the bollards and the tube trailer which is the orange box in **Figure 31c**. Again, the tube trailer has not been realized but we have just placed in the model a box with the dimensions equal to the ones of the tube trailer, so that everyone is going to watch the 3D CAD model immediately understands that the space is already taken. For the dimensions of the orange pads we have used the dimensions shown in document SC-26 **Figure 31d)**.



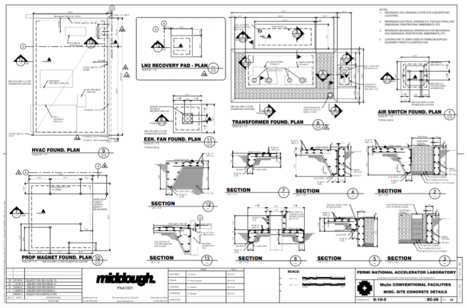
(a) Existing model



(b) Hardstands, road, light poles and drains added



(c) Bollards and tube trailer added

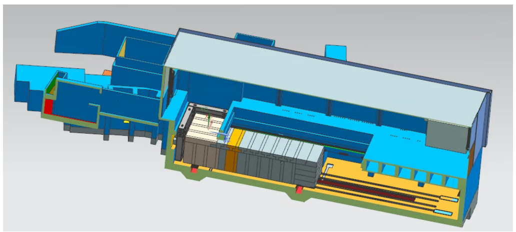


(d) Document SC-26

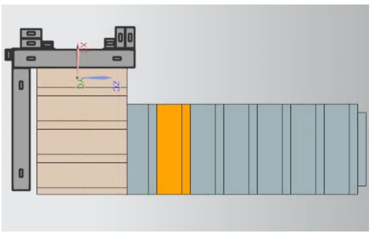
Figure 31: External features added

3.2.2 Plan Staging of shield blocks

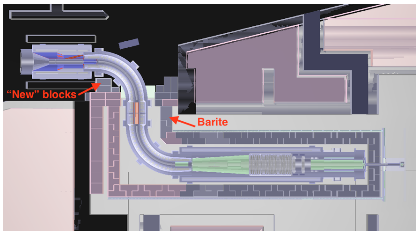
Once added the model of the outdoor features we had the possibility to start the placement of the huge number of concrete blocks that are inside the Mu2e building and used as shield. First of all we need to find the right location for the blocks that shield the Transport Solenoid (TS) and the Detector Solenoid (DS). These blocks are shown in **Figures 32a 32b 32c**.



(a) View from a building section



(b) View from a building section



(c) View from a building section

Figure 32: TS and DS concrete blocks

The stacking sequence that we have chosen is shown in **Figure 33**. The sequence has been chosen taking in account the order that has to be followed to build the shielding around the Transport and Detectos Solenoids, written in document Mu2e docdb 1371 v6.

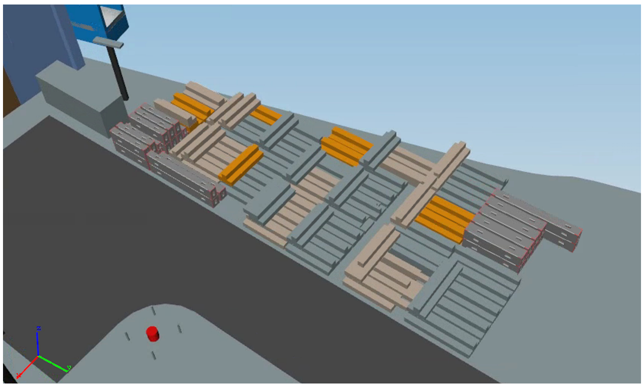
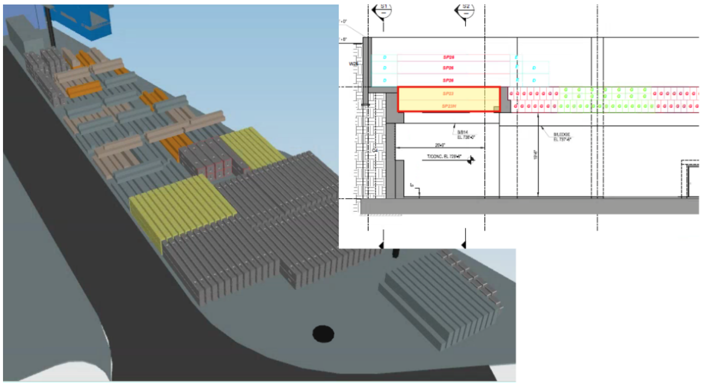
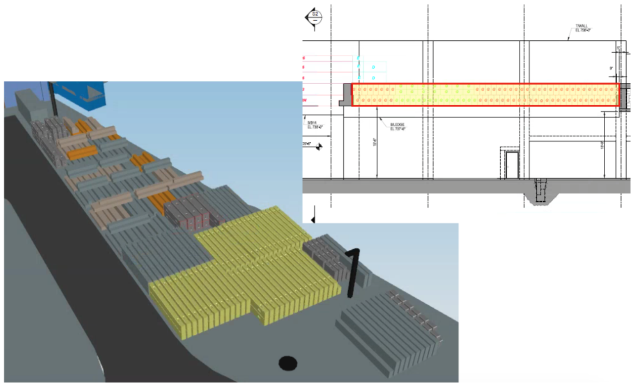


Figure 33: Stacking sequence chosen

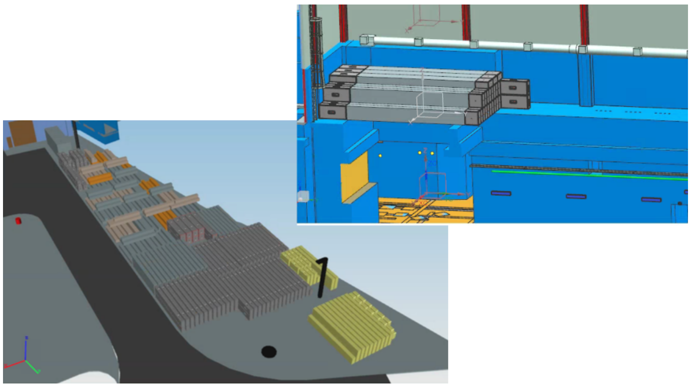
Done that, there were many other blocks to place: the TS Hatch Blocks **(Figure 34a)**, the DS Hatch Blocks **(Figure 34b)**, the North West Shield Block Pile, that we have added before in **Subsection 3.1.3** and shown in **(Figure 34c)**, the PS Hatch Blocks **(Figure 34d)**, the Remote Handling Hatch Blocks **(Figure 34e)** and the Extinction Hatch Blocks **(Figure 34f)**.



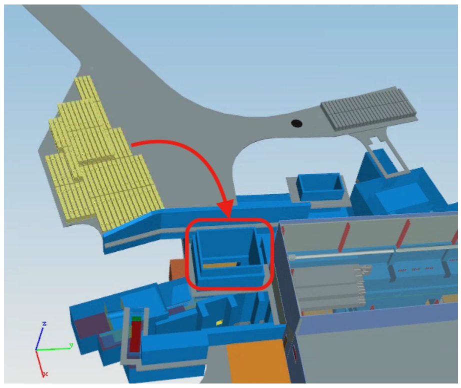
(a) TS Hatch Blocks



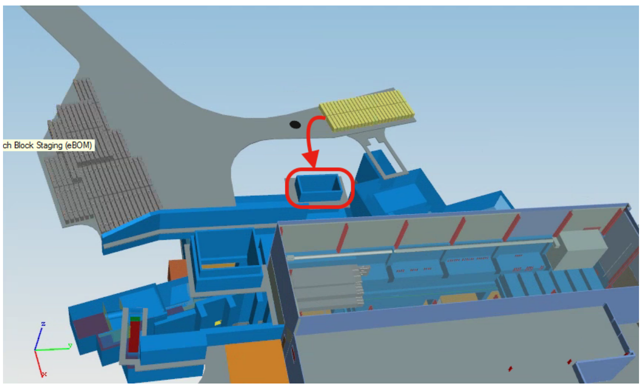
(b) DS Hatch Blocks



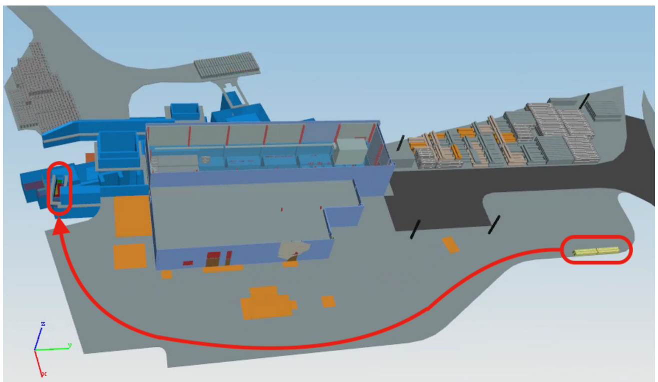
(c) North West Shield Block Pile



(d) PS Hatch Blocks



(e) Remote Handling Hatch Blocks



(f) Extinction Hatch Blocks

Figure 34: Other added blocks

4 Future improvements

Even if many features have been added and refined, there are still many parts that have to be realized and located in the 3D CAD model of the building, to obtain a better representation of the structure which allows everyone working on the Mu2e project, also people who have never worked with NX, to have an immediate view of the spaces of the building.

References

[1] *Mu2e Technical Design Report (TDR)*, Mu2e Document 4299-v15, 03/23/2015.

[2] A. Palladino, J. Quirk, J. Miller, *Mu2e Stopping-Target Monitor baseline design*, Mu2e document 6453, Boston University, 06/09/2016.