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Mu2e Tracker assembly: from plane to station installation

Supervisor: Aseet Mukherjee

Co-supervisor: Mete Yucel

Summer Intern:

Leonardo Gozzini

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Abstract

The tracker is an important component of the Mu2e experiment at the Fermi National Accelerator Laboratory. The right assembly of it is a keypoint to achieve a good result in the experiment and, in this regard, needs adequate procedures and equipments. The purposes of this work are to study an important section of this assembly process, find out the main problems and suggest some feasible solutions, including also the conceptual design of the required lifting system.

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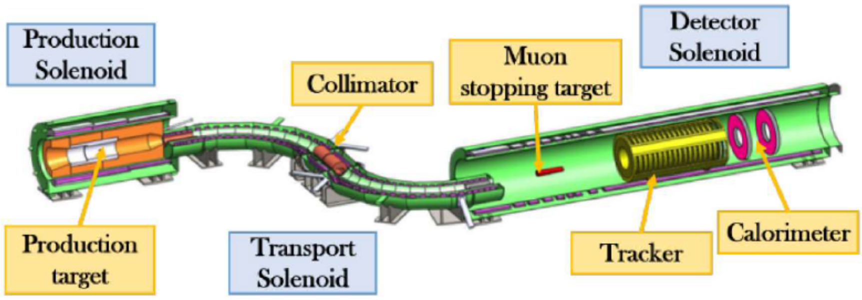


Figure 1: The Mu2e apparatus.

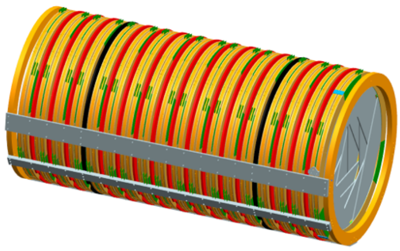


Figure 2: Mu2e Tracker: 18 stations (yellow coloured) plus structure.

1 Introduction

The goal of the Mu2e experiment is the search for the neutrino-less coherent conversion of a muon to an electron in the field of an aluminum nucleus. The layout of Mu2e experimental apparatus is showed in Fig.1.

The tracker is an important component of this experiment and its function is to provide the primary momentum measurement for conversion electrons. It must accurately and efficiently identify and measure 105 MeV/c electrons while rejecting backgrounds and it must provide this functionality in a relatively unique environment. In fact, it resides in the warm bore of a superconducting solenoid, evacuated to 10^{-4} Torr, providing a uniform magnetic field of 1 Tesla. For more information see [1].

The tracker (Fig.2) consists of 18 stations (Fig.3) equally spaced along 3 m with straws transverse to the beam line. Each station consists of 2 tracking planes, that are modularized structure made out of 6 panels (Fig.4). A single panel is made out of 96 straw-tubes with the following specifications: 5 mm diameter; 2x6.25 μm Mylar walls with a layer of adhesive in between, for a total thickness of 15 μm. The inner surface of the straw has a gold layer over an aluminum one to serve as the cathode, while the outer surface had an aluminum layer for additional electrostatic shielding and to improve the leak rate. The straws are filled with Ar-CO_2 gas mixture (80:20) at 1 atm differential pressure and they have a length varying from 34 up to 118 cm.

This work studies the assembly process from the completed plane to the station installation in the tracker frame.

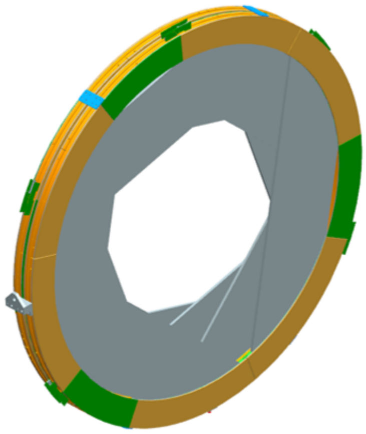


Figure 3: 3D view of a station.

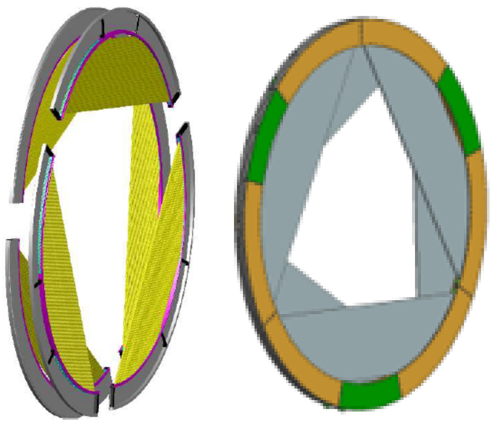


Figure 4: 3D views of a plane, before and after the assembly of six panels. The yellow areas on the left view and the grey ones on the right view are occupied by the straws.

The goals achieved in this work are:

1. Conceptual study of an handling solution for planes and stations, selecting off-the-shelf components and suggesting the design of custom made components.
2. 3D model of the cleanroom layout and the required lifting system, updated step by step basing on measurements and catalogue data.
3. Study of the cleanroom layout in order to: allow enough space of movement for the lifting system and the operators; reduce repositioning; take advantage of the lifting system movements that present the greatest precision.
4. Definition of a general outline for an efficient assembly procedure in accordance with the characteristics of the selected lifting system and the problem constraints.

2 Problem definition

2.1 Required steps

The procedure from plane assembly to station installation involves the following general steps:

1. Six panels are assembled in a plane;
2. Electronics is installed on both sides of the plane;
3. Two planes are assembled in a station. It is important to have an effective 60° rotation among the panels of first plane and those of second plane: to get that is sufficient to rotate one plane of 180°;
4. The station is stored;
5. The station is installed in the tracker frame.

2.2 Constraints

The main constraints of the problem influence the assembly procedure and the design of the handling/lifting system.

First of all, the components are very delicate and expensive: just think that the straw thickness is about 15 μm and the cost of a station is about one million $. Adding also that the space in the tracker frame is very limited, it is clear right away that a precise positioning system is required.

On the other hand, the assembly procedure has to be repeated only 18 times (18 are the station in the tracker). This small number of times makes the purchase of highly automated handling systems not convenient and force us to find cheaper solutions.

Plane and station are quite light (weight of the station is 100 kg) but rather large (the diameter is 1600 mm) and the cleanroom dimensions, in particular the vertical one, are limited. In fact, the assembly will take place in the cleanroom B at Lab.3 of the Fermilab Village, whose dimensions are shown in Fig.5. Hence,

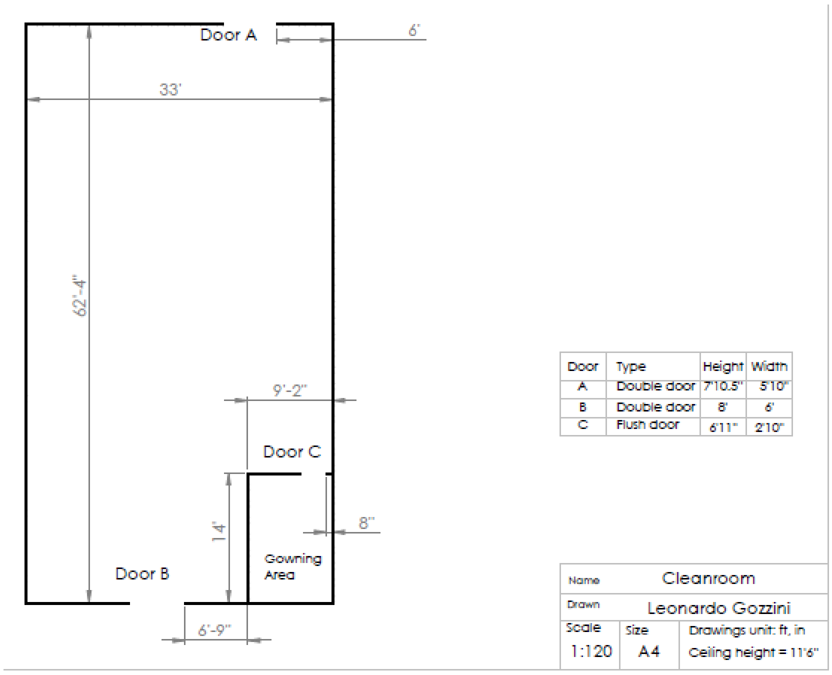


Figure 5: Plan view of Lab. 3 cleanroom B.

the handling system has to lift large components and move within a limited space.

3 Lifting system

3.1 Main structure

For a preliminary idea of the main geometric constraints we assumed the dimensions shown in the Fig.6. In that figure, we specially considered the space needed to move planes/stations from a table to another one and the important constraint of the cleanroom ceiling height. In this regard, a gantry crane with adjustable height (Fig.7) has seemed the simplest solution that could fit this application. In particular, we studied two options: the first one is to re-use the FNAL gantry crane but the inside span is insufficient. Hence a new I-beam is needed together with a new engineering note. Moreover, to remove the rust, the structure has to be painted before it is moved in the cleanroom. The time estimate for all these operations is about 3.5 days.

On the other hand, we could purchase another gantry crane, saving time on painting and customizing the old one. For the new gantry crane, the cost is around 2.5 K$, the time to be assembled is about 1-2 days and it needs an internal engineering note too.

Not having a significant difference in time between the two options, that can justify the difference in price, we have decided to keep the cheaper solution design, i.e. the FNAL gantry crane, for the following study.

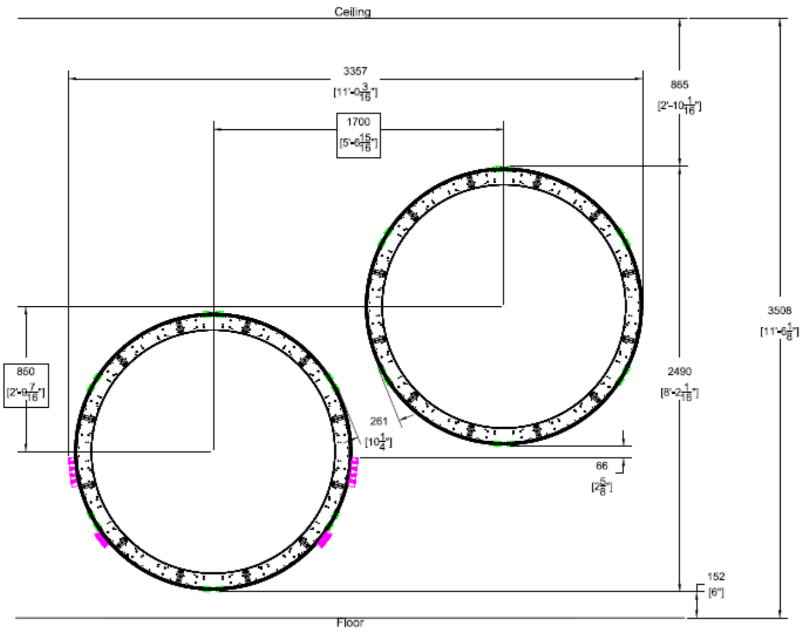


Figure 6: Preliminary geometric constraint for lifting system design.
Main unit: mm. Units in brackets: in, ft.

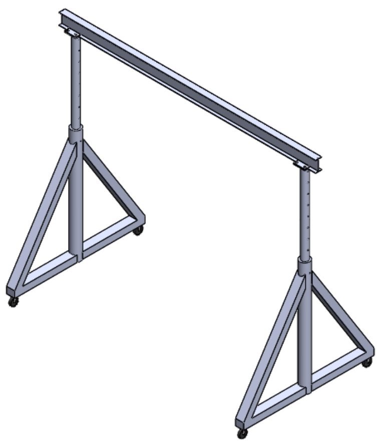


Figure 7: Gantry crane with adjustable height.

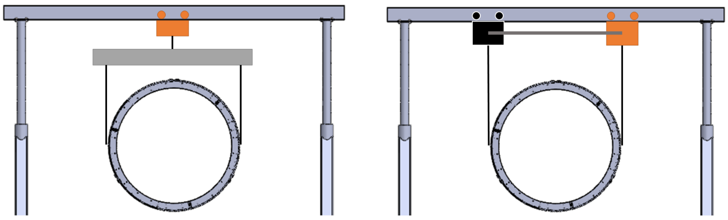


Figure 8: Two different solutions for the lifting equipment: *One trolley, one hoist, spreader bar solution* (on the left); *Two trolleys, two hoists solution* (on the right).

One trolley, one hoist, spreader bar solution	
Motorized trolley with electric hoist	4 K$
Spreader bar	0.8 K$
Total cost	4.8 K$

Table 1: Preliminary cost estimate of *One trolley, one hoist, spreader bar solution.*

Two trolleys, two hoists solution	
Motorized trolley with electric hoist	4 K$
Push trolley with electric hoist	3 K$
Total cost	7 K$

Table 2: Preliminary cost estimate of *Two trolleys, two hoists solution.*

3.2 Lifting equipment

We evaluated two common and simple solutions, sketched in Fig.8, for the lifting equipment to be mounted on the gantry crane:

1. *One trolley, one hoist, spreader bar solution*: the motorized trolley allows movements along the I-beam, while the hoist allows lifting/lowering of the spreader bar. The disadvantages of this option are: the risk of spin around vertical axis due to the twisting of hoist chain; the spreader bar encumbrances, that limits the vertical space for plane/station movements. Moreover, the presence of hoist right above the straws increases the risk to contaminate them due to oil leaks.

2. *Two trolleys, two hoists solution*: one trolley is motorized and the other one is pulled/pushed through a bar, that we will call *trolley bar*. The disadvantages of this option are: the more difficult control for two hoists, that have to work in parallel, and the higher cost due to the second trolley with hoist.

Tab.1 and Tab.2 show the preliminary cost estimate of the two solutions. Considering the necessity of precise positioning and the possibility to rotate plane/station over a table without crane repositioning, it is clear that the spin around vertical axis has to be avoided and the clearance between I-beam and plane/station plays an important role. For this reason, we have carried on the *Two trolleys, two hoists solution*.

4 Handling

The study about how to handle planes and stations starts from three main questions:

- Which movements we have to allow.
- Which points of connection on the components we can use.
- Which are the lifting system characteristics (We talked about that in the previous section).

Considering that:

- Planes are placed horizontal on granite tables and need to be rotate 180° to install electronics on both side.
- Station are installed vertically in the frame.

The handling system should allow to lift/lower components and rotate them at least 180°. Moreover, the vertical position should be guaranteed without uncontrolled rotations.

The main points of connection for planes and stations are three flanges located on the ring outer surface: two of them are designed to be connected with lifting brackets, while the third one, that we will call *third point*, is designed to be connected with a particular element, needed for the correct installation in the frame (for more information see [3]).

4.1 Preliminary solution

The simplest idea, showed in Fig.9, was to connect the two lifting brackets to chains, supporting the component weight and lifting it, and the third point to a rope, in order to control the rotation around x-axis. Moreover, a misalignment of about 60 mm between the lifting brackets axis and the COG axis was needed to maintain the rope stretched, avoiding uncontrolled rotations.

To not stress the main structure on one side only, for the rotation mechanism we also thought the use of two rope instead of one, connected to the third point. The Fig.10 explains the operation of this handling system: at first one rope is stretched and one rope is loose, but after 90° rotation, the situation is reversed.

This conceptual idea presented some problems not easy to solve:

- We could not control the station in vertical position with the third point at the bottom, that is the required configuration for a correct installation in the frame.
- High risk of sliding, and then damage, between component and granite table at the start and at the end of the lifting.

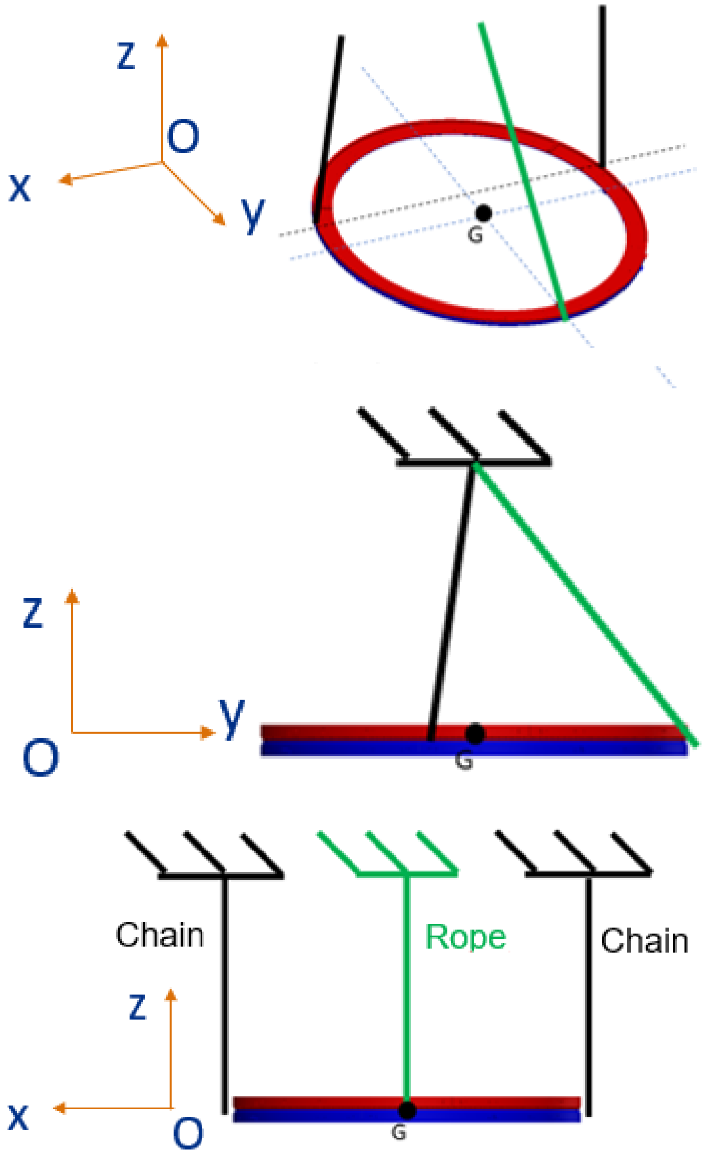


Figure 9: Sketches of the preliminary handling solution. The component showed is a plane and its colours are only to distinguish two sides.

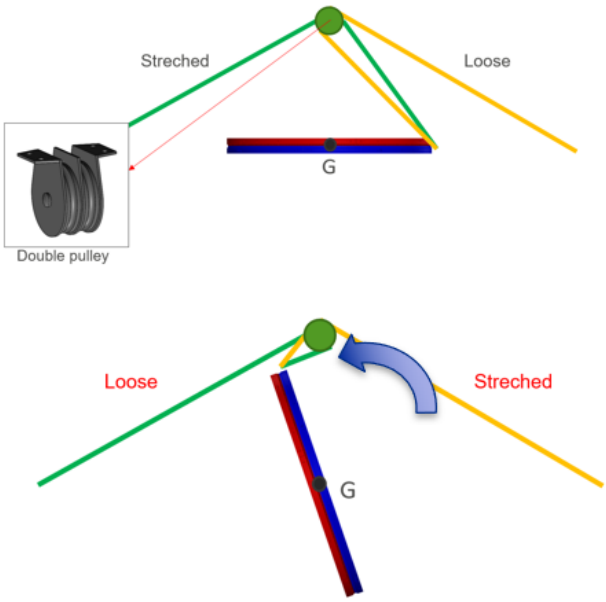


Figure 10: Sketch of the preliminary rotation mechanism. Only ropes are represented.

- The use of two ropes needed a double pulley installed on the trolley bar, that would have been located in the middle of the component, right above the straws. Hence, there was an high risk of damaging them, due to operator errors during the connection of the rope hook with the third point. Moreover, oil leaks from the pulley could contaminate the straws.

4.2 Wheel solution

The preliminary solution problems led us to find another option to handle plane and station, without radically change the main structure of the system.

The idea showed in the Fig.11, called *Wheel solution*, concerns in a wheel, connected to the third point, that makes the component able to roll over a surface. The wheel can be easily installed when the plane/station is horizontal and placed on spacers, stands or something similar. The synergistic use of chains connected to the lifting brackets and the wheel allows rotation up to 180° and vertical placing with third point at the bottom. Moreover, the choice of a rubber wheel can reduce shocks during the approach to the granite table.

To connect the wheel a flange adapter is needed. The Fig.12 shows the conceptual design of it, that is based on the following considerations:

- The flange adapter has to be usable both for plane and station, in order to reduce the number of required custom made components for the handling system. In this regard, it is noted that the locations of holes for the connection are different between plane and station.
- The shape has to take in account the presence of *ears*, that are electronic boards emerging from the ring outer surface. As showed in Fig.13, we

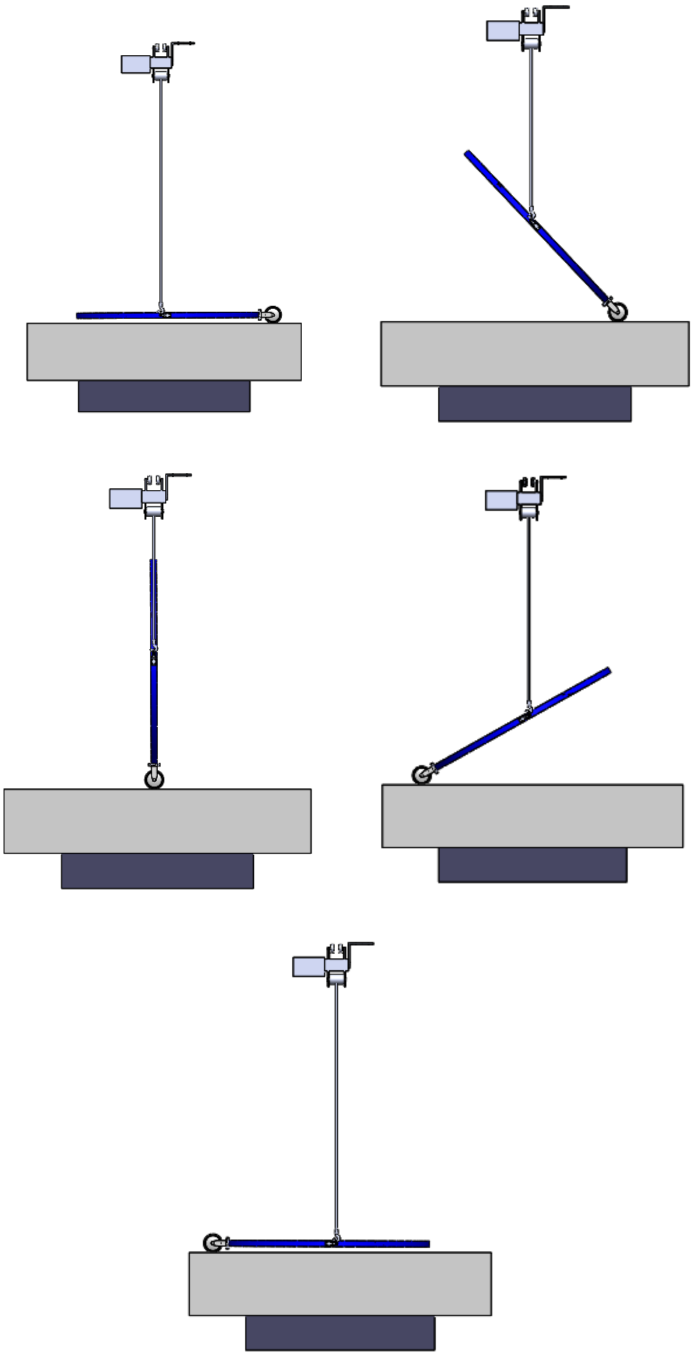


Figure 11: Functioning of the *Wheel solution.* A 180° rotation is illustrated in five steps.

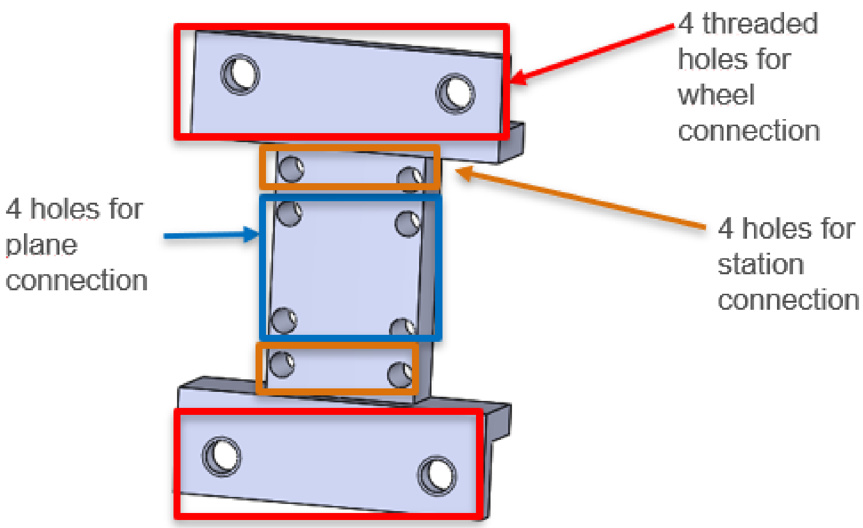


Figure 12: Flange adapter conceptual design and role of each group of holes.

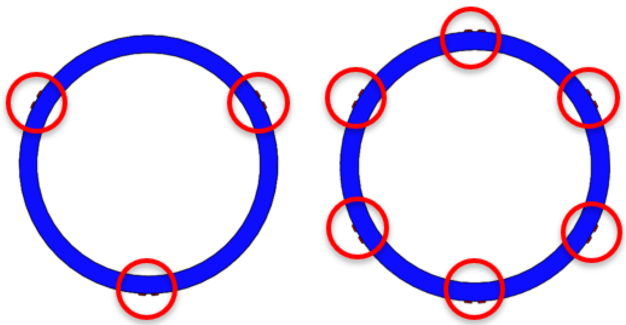


Figure 13: 3D view of ears on the plane (left) and on the station (right). The red circles highlight their location.

have 3 couples of ears at 120° each other on the plane and, reminding that a station is made of two planes relatively rotated 180°, 6 couples of ears at 60° each other on the station. The Fig.14 confirms the right sizing of the flange adapter in order to avoid touches with these electronic components.

5 Oscillations

5.1 Problem definition and considerations

This section is dedicated to the main problem of the selected lifting system: the oscillations. In fact, the use of chains leaves the lifted component free to rotate in any direction, as showed in Fig.15. In this regard, the *Two trolleys, two hoists solution* was selected to limit the oscillations around vertical and z-

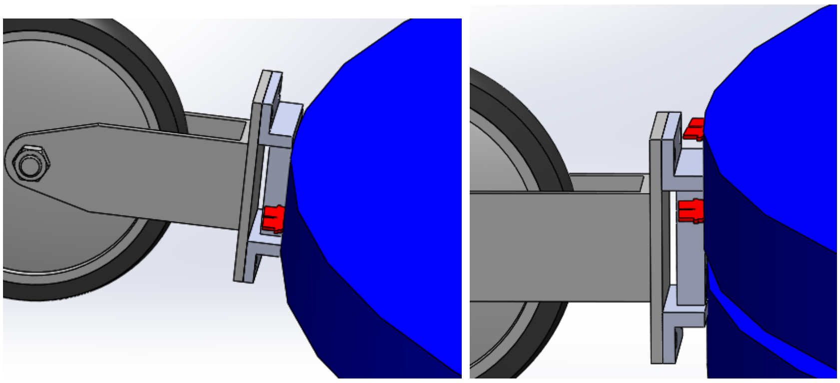


Figure 14: 3D views of the two wheel connections: wheel-plane (on the left); wheel-station (on the right). Ears in red.

axis, but it does not affect the oscillation around the I-beam axis and the lifting brackets axis. The study about this problem starts by understanding which the strongest constraints on oscillations are, in order to define a conceptual design of a locking or damping system. In this sense, the hardest positioning of the assembly procedure is the station installation in the tracker frame, that has the following specifications (Fig.16):

- The station is lifted up to about 1 m from the floor, that is the height needed to avoid collisions with the stave, and lowered up to about 150 mm. In this regard, a locking/damping mechanism, connected to the gantry crane, should follow the station for a stroke of about 850 mm.
- The bronze ring - station gap is 33 mm.

Moreover, we have to consider that:

- The limited space under the station impedes to remove any locking/damping system during the installation.
- When the tracker will be installed in the detector solenoid, any locking flanges or damping system on the top of station has to be removed. That position, considering the tracker dimension (3x1.8x1.8 m), is hard to reach.

Starting from these considerations, we decided to focus the attention on a locking system easy to remove. The damping mechanism option was discarded because the amplitude of oscillation during the station movements is hard to estimate and then the correct damping too. Moreover, the allowable amplitude of oscillation is very small: to get an idea, an amplitude higher than 2° around the lifting brackets axis, is enough to hit the bronze rings. The Fig.17 briefly explains this latter consideration.

So the conceptual design for the locking system consists of:

- A telescoping column with a locking groove at the end to follow the station lifting and lock rotations around vertical, lifting brackets and I-beam axis. Fig.18.
- A larger distance between trolleys to reduce oscillation around z-axis. Fig.19.

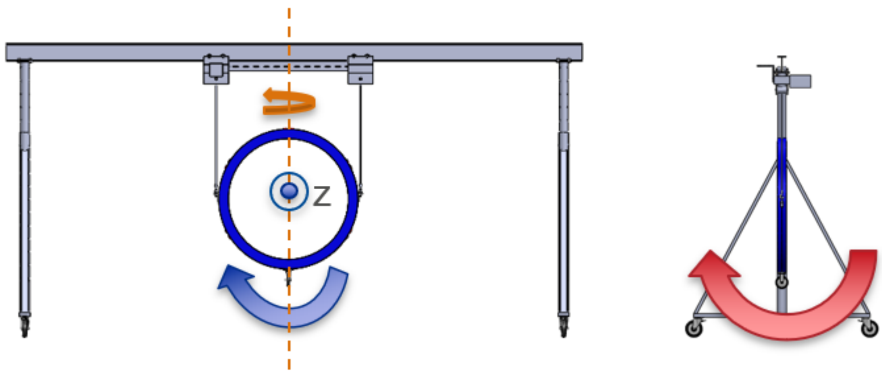


Figure 15: Possible system oscillations.

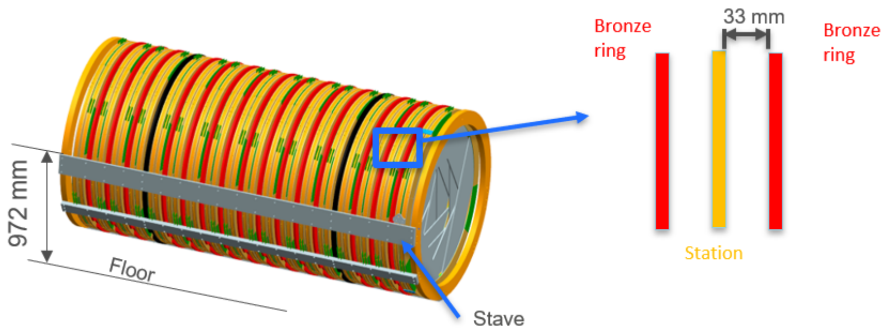
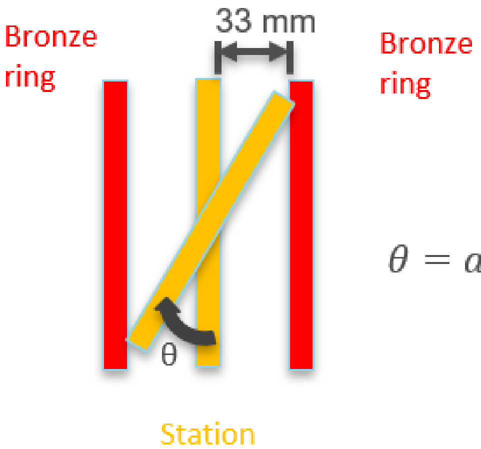


Figure 16: Geometric constraints on stations installation.



$$\theta = arctan\left(\frac{33mm}{810mm}\right) = 2.3^{\circ}$$

Figure 17: Simple estimate on the station rotation constraint around the lifting brackets axis.

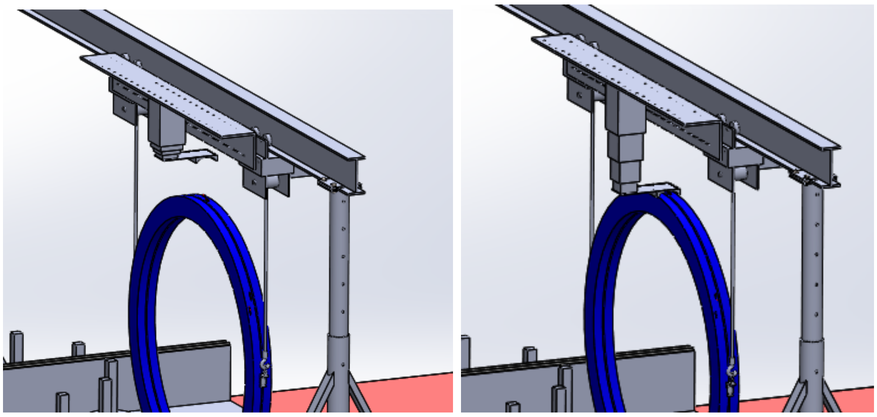


Figure 18: Functioning of the locking system, actuated by a telescoping column.

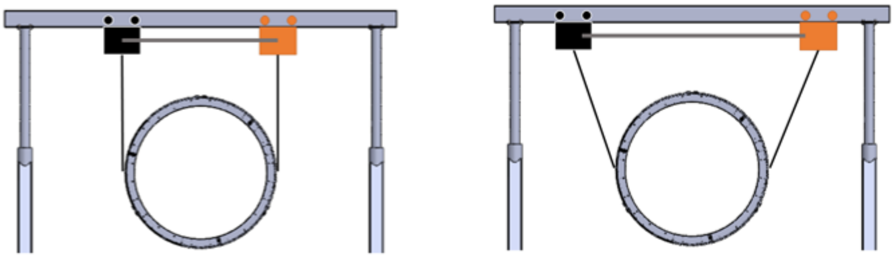


Figure 19: Previous sketch of the *Two trolleys, two hoists solution* (on the left) and sketch of the same solution with a larger distance between trolleys (on the right).

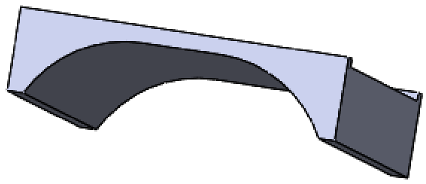


Figure 20: 3D view of the locking groove.

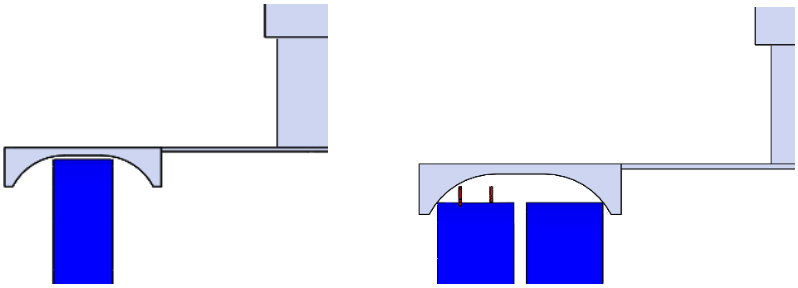


Figure 21: Functioning of the locking groove with planes (on the left) and stations (on the right).

5.2 Locking groove conceptual design

The conceptual design for the locking groove takes in account similar considerations of the flange adapter design, in particular:

- Usability both for plane and station.
- Avoid contacts with the ears, that in this case are present only during the station handling.
- Centering should be facilitated by the groove profile.

In Fig.20 and Fig.21 are showed a 3D view of the locking groove and its operation with planes and stations. This is only a preliminary sizing of the locking groove and further developments are needed. For example:

- Optimize the groove profile to have the best locking.
- Look for a soft material for the groove inner surface that can absorb shocks but that wears little, to avoid contaminating the cleanroom.

6 Cleanroom layout

6.1 Problem definition

In parallel with the lifting/handling system design, the work concerned also the study of cleanroom layout. In particular this task started from five main questions:

Figure 22: Current picture of the cleanroom.

1. What are the cleanroom dimensions?
2. What is there currently inside?
3. What are its dimensions and locations?
4. What will have to be there inside at the beginning of the assembly procedure?
5. How to place them efficiently?

To answer these questions, the cleanroom has been inspected, measurements of it and the necessary equipment have been taken and a 3D model of the layout have been made, in order to study a more efficient one and check the geometric constraints of the lifting system during the entire tracker assembly process.

6.2 Cleanroom inspection

From the cleanroom inspection we observed that inside there are:

- The two granite tables needed for the assembly of planes and stations.
- An inner cleanroom, for which it is decided only a relocation inside the room and not a removal.
- Some unnecessary equipment that will have to be removed.

In addition to these components we will have the storage and the frame, whose details of exact sizes are currently work in progress. The Fig.22 shows a picture of the cleanroom during the inspection.

6.3 Proposed layout

The principles followed during the layout study on the 3D model are:

- Allow enough space of movement for the lifting system and the operators.

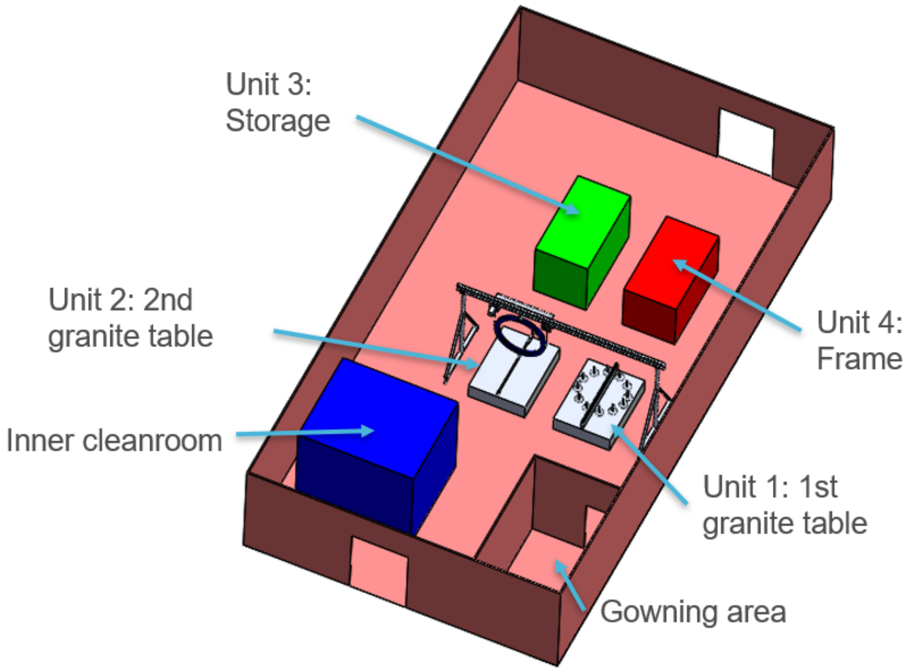


Figure 23: Proposed layout of the cleanroom.

- Reduce repositioning.
- Take advantage of the lifting system movements that present the greatest precision of positioning.

The proposed solution for the layout is showed in the Fig.23. As we can see from that figure, the assembly process keypoints are called units and go from the first granite table, where we have the plane assembly, to the frame, that is located close to the exit door, in order to facilitate its removal from the cleanroom at the end of process.

To use mainly hoists and trolley movements, that are motorized and then more precise, instead of gantry crane movement, that is manually actuated, it is decided to place some units in parallel. This solution, together with the idea to leave almost 3 ft of clear space around tables, storage and frame, requires a 22 ft I-beam for the gantry crane.

7 Assembly procedure

The work ends showing the defined assembly procedure, the main found out problems and explaining how we suppose to solve them.

The criterion used to define each step of the procedure is arbitrary and, in this case, only to focus the attention on some important issues faced during the work.

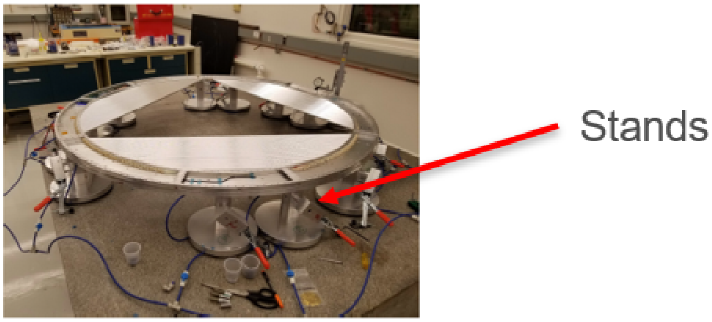


Figure 24: Picture of the plane placed on vacuum stands.

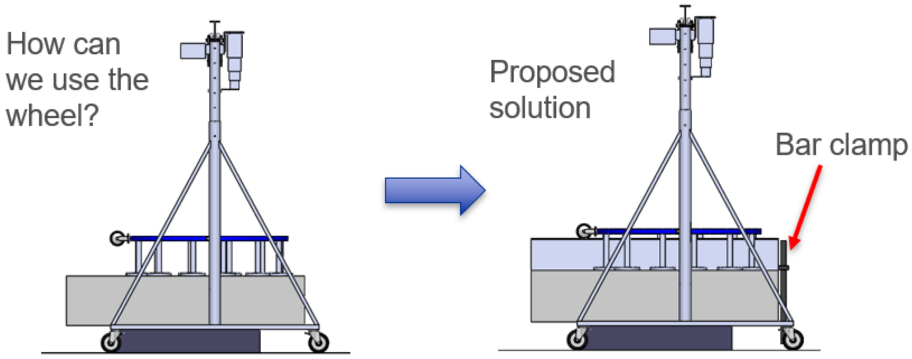


Figure 25: Stands problem and conceptual solution.

7.1 Step 1

The plane is assembled on a first granite table and electronics is installed on the top side.

7.1.1 Stands problem and conceptual solution

The vacuum stands on the table, showed in Fig.24, are needed for plane assembly but obstruct the use of the wheel and the possibility to rotate the plane in order to install electronics on the other side. For this reason, we thought about a support passing through the stands and having a groove on the top to allow the installation of a C-channel, useful as a guide for the wheel. The support shape is based on a simple rectangular hollow section and the groove can be easily obtained milling the top of the beam. For a correct positioning of the support and then the C-channel, a bar clamp is needed. Fig.25 and Fig.26 show this conceptual solution.

7.1.2 Plane lifting brackets conceptual design

Two conceptual designs for the plane lifting brackets, needed also for next steps, are showed in Fig.27. They are based on the existing station lifting brackets

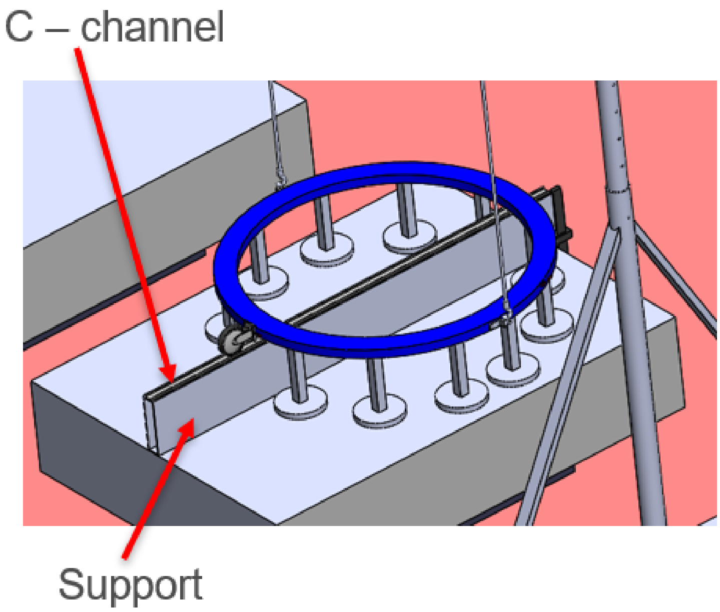


Figure 26: 3D view of the conceptual solution for the stands problem.

design. These components have to allow the connection to hook and 180° of plane rotation, so we decided to investigate the use of two off-the-shelf components: the hoist ring and the shackle. Depending on the hook orientation, we considered that the *Shackle solution* can reduce more the risk of contact between plane and hook. For this reason, that is the solution implemented in the 3D model.

7.2 Step 2

This step is divided in 4 phases, showed in Fig.28:

1. The plane is placed vertical on the first granite table.
2. The locking mechanism acts and then the plane is lifted up.
3. The motorized trolley moves the plane to the other granite table. The plane is lowered and the locking mechanism is disengaged.
4. The plane is placed horizontal and the electronics is installed on the other side.

7.3 Step 3

7.3.1 Electronics installation and station assembly problem

In the third step, we have the previous plane on the second granite table and a second plane ready on the first granite table. This configuration, showed in Fig.29, has some important problems, because the presence of the first plane on

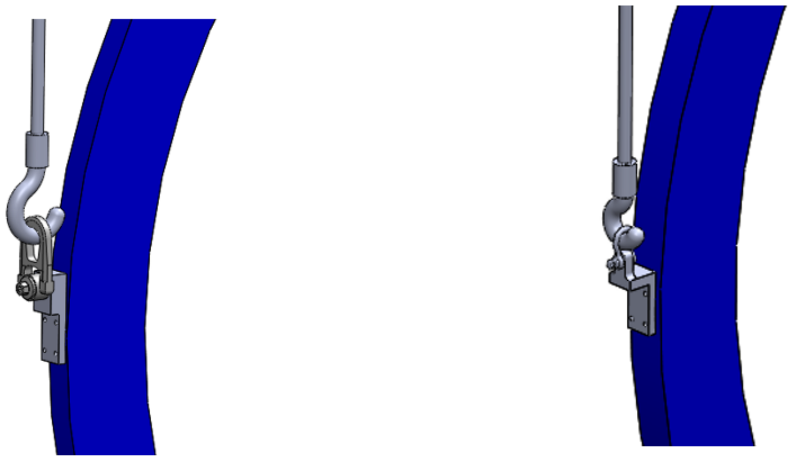


Figure 27: Two conceptual design for the plane lifting brackets: *Hoist ring solution* (on the left) and *Shackle solution* (on the right).

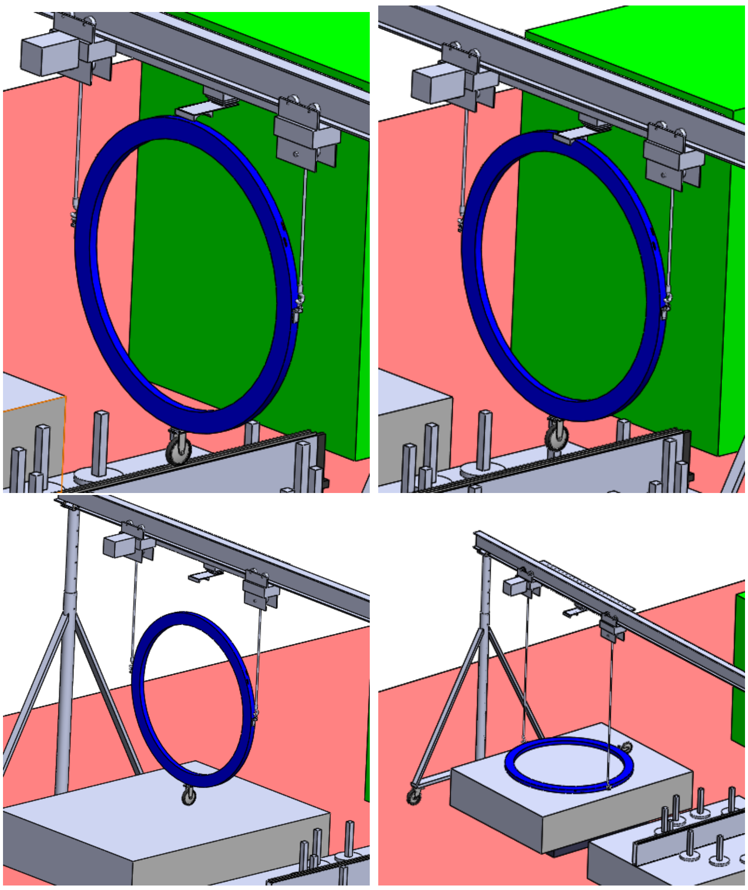


Figure 28: From the upper left corner to the lower right corner: phases of the second step in chronological order.

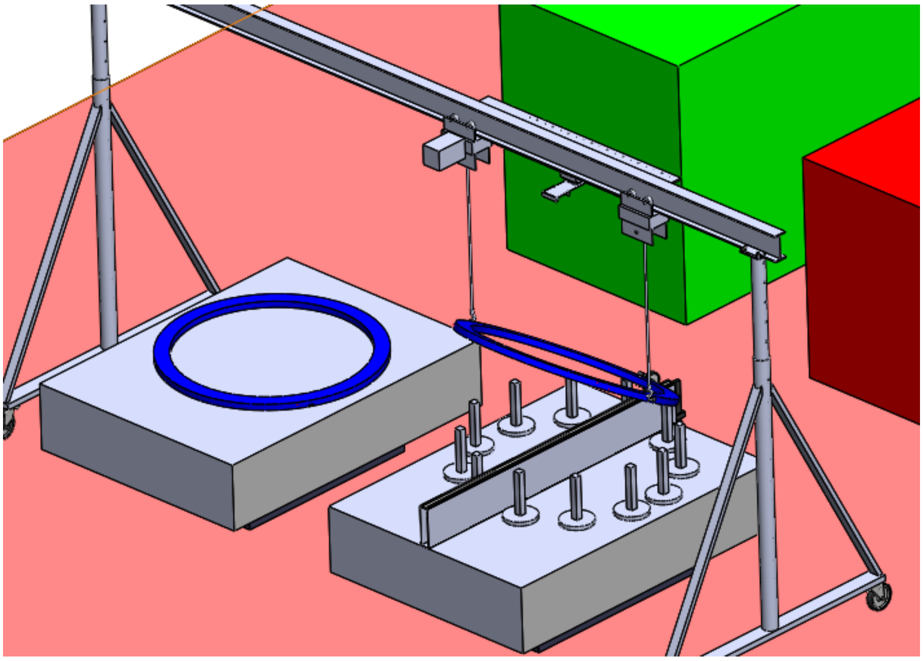


Figure 29: Configuration at the beginning of the third step.

the second granite table impedes to rotate the second plane in order to install electronics on the other side. Moreover, the station assembly requires a precise positioning of the second plane over the first one and a system to guarantee that is required.

7.3.2 Conceptual solution

The simplest idea could be the use of another table to complete electronics installation on the second plane, but it would take space in the cleanroom and require other gantry crane movements, reducing the efficiency and the precision of process. Furthermore, this idea does not solve the problem of a correct station assembly.

In this regard, our conceptual solution solves both problems on the second granite table. As we can see in Fig.30, using a C-channel above the first plane, the second one is lowered in the middle of channel and then, using only the hoist motor (that is more precise than to move the gantry crane manually), is placed horizontal. To start the required rotation for the horizontal positioning, a small inclination of the plane is needed: this can be obtained by an operator who pushes or pulls the wheel flange.

When the plane is horizontal, safe stops for the wheel are needed. In this regard the support, showed in Fig.31, has a step on one side and a ramp on the C-channel side. The latter in order to reduce shocks during the wheel rolling from C-channel to support.

At this point, the C-channel is between two planes and impedes the station assembly. Hence, to remove it safely, the idea is to slide it sideways, as showed in Fig.32.

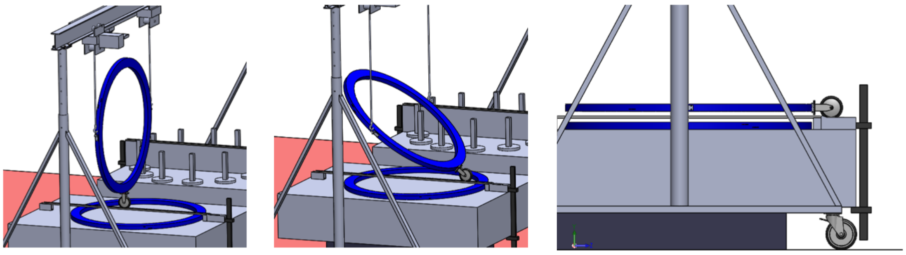


Figure 30: From left to right: horizontal positioning of the second plane.

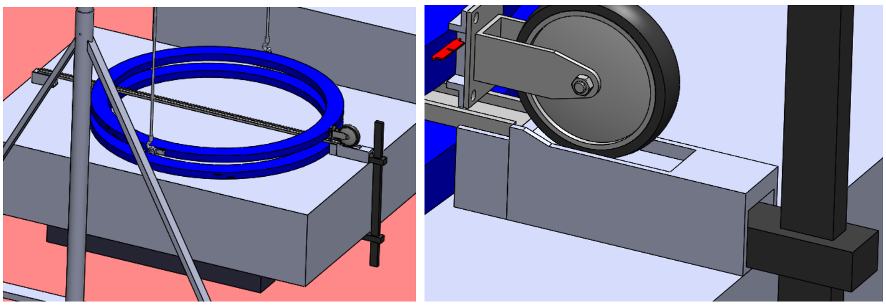


Figure 31: 3D view of the conceptual solution for the third step and detail of the support with the required safe stops.

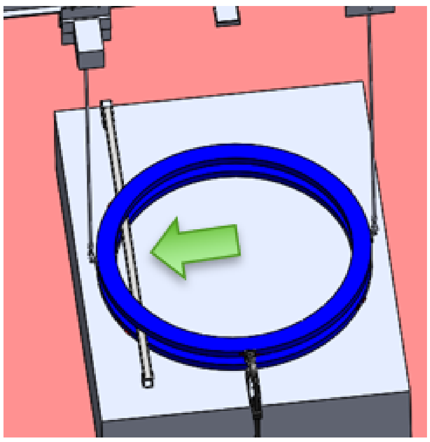


Figure 32: Proposed solution to remove the C-channel.

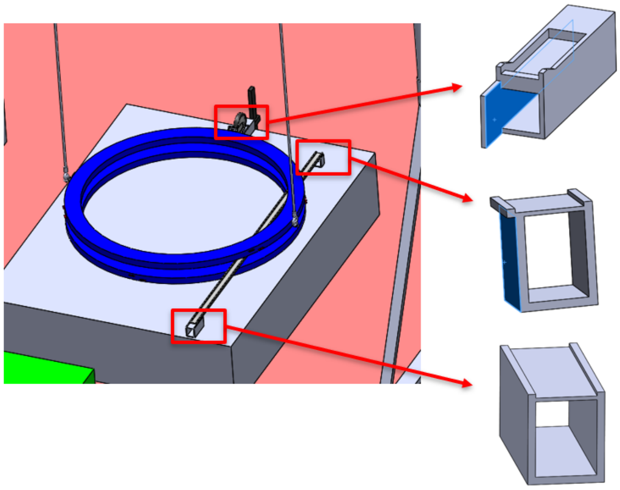


Figure 33: Conceptual designs of the required supports for the third step. From top to bottom: *Fixed support*, *Removable support 1*, *Removable support 2*

7.3.3 Supports conceptual design

The proposed solution is made of the C-channel and three supports, whose shapes are important to guarantee appropriate references. As showed in Fig.33, the *Fixed support* is locked on the granite table by a bar clamp and presents an appendix required for the connection with the close removable support (*Removable support 1*). On the other side of the table, the correct positioning of the *Removable support 2* is guaranteed by the groove where C-channel is placed.

Further developments are needed for this conceptual design, for example:

- Find a solution to have low friction between supports and granite table, and then allow an easy removal of the C-channel.
- Design the mechanism or the tool to pull/push sideways the removable supports.

7.4 Step 4

In this step the station is:

1. Assembled and connected to the chains and the wheel
2. Vertical rotated
3. Locked
4. Lifted up
5. Moved to the storage

Fig.34 illustrates the above phases.

The storage design is currently work in progress, but we want that, when the station is stored, an operator removes the wheel from the third point and

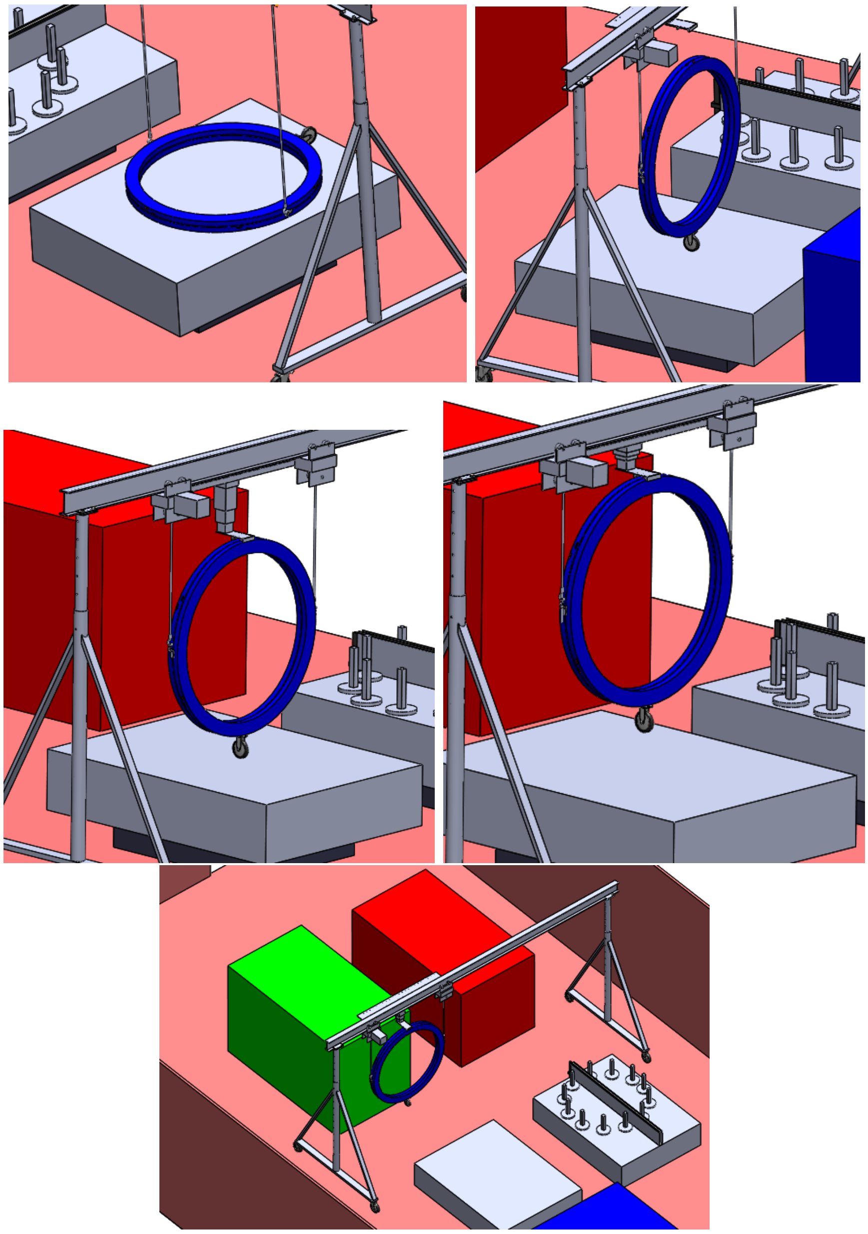


Figure 34: Phases of the fourth step in chronological order.

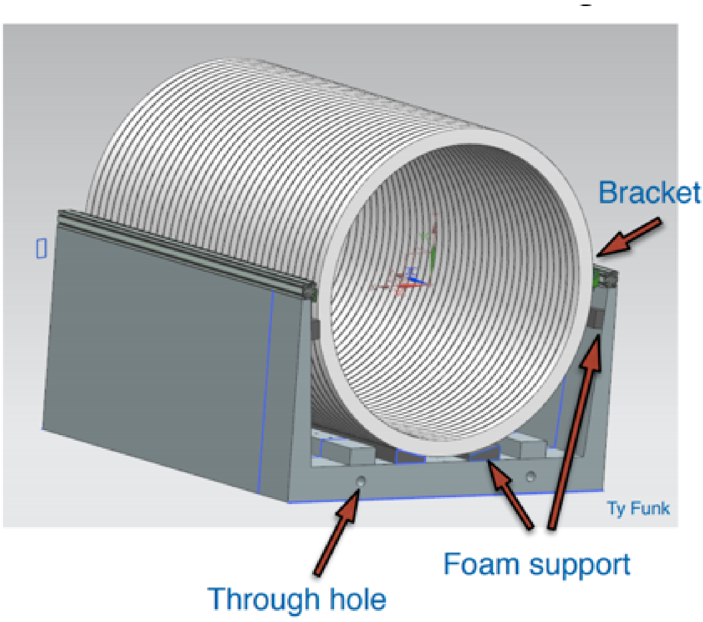


Figure 35: Conceptual designs of the storage. From [2]

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installs the required component for the tracker frame. To get an idea, Fig.35 shows the conceptual design of the storage.

7.5 Step 5 and Step 6

These two steps need more information about storage and frame design, so they are only described at a general level and showed in Fig.36.

7.5.1 Step 5

The station is moved from the storage to the frame.

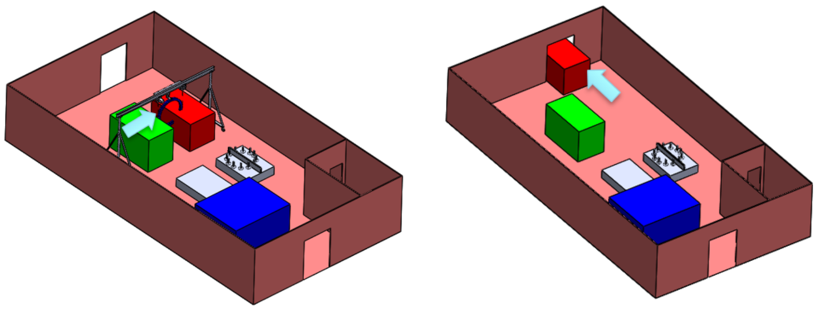

Figure 36: Fifth step (on the left) and sixth step (on the right).

7.5.2 Step 6

When the frame is completed, it is put on casters and brought out of the clean-room for the next installation in the detector solenoid.

8 Conclusions

The natural developments of the work are:

1. Detail the final steps of the procedure. In this regard, more geometric data on the storage and the tracker frame are required.

2. Finalize the selection of off-the-shelf components needed and update step by step the 3D model to check all the geometric constraints.

3. Finalize the design of custom made components and manufacture them.

4. Assemble the entire system and test the process with mock-up plane and station.

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