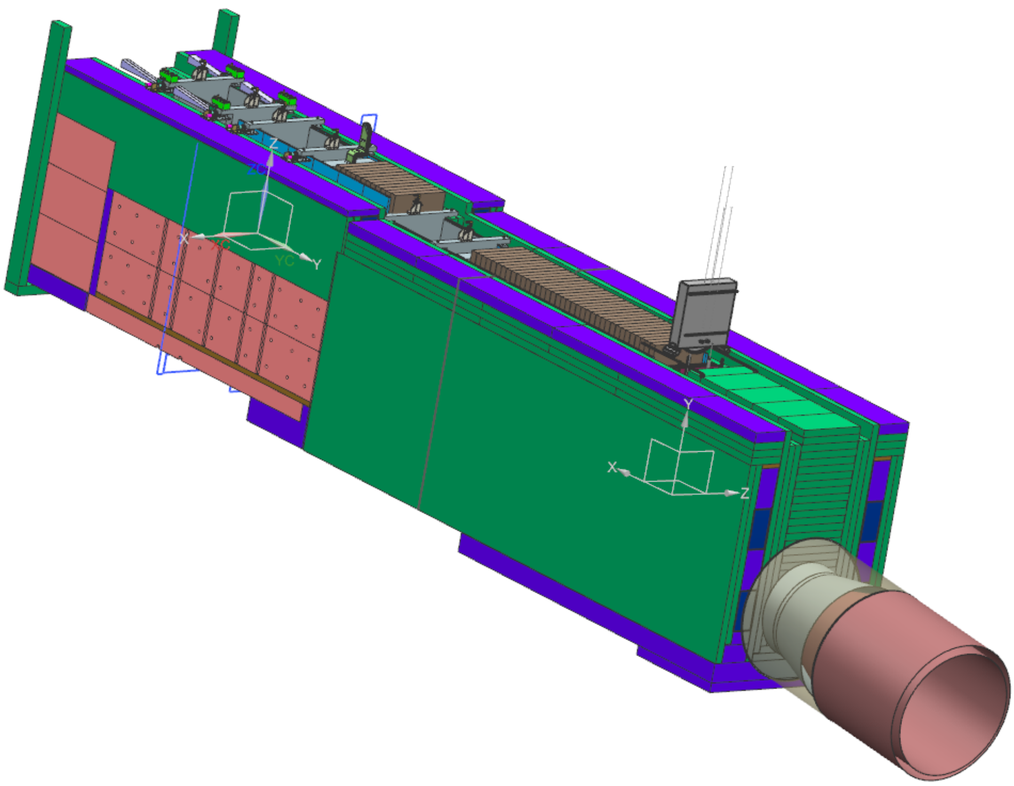
Fermilab

Design of an automated system for a removable decay pipe window for LBNF



Summer Internship 2016

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Chapter 1

Introduction

1.1 Deep Underground Neutrino Experiment

A game-changing particle physics experiment, with support from more than 800 scientists in 27 countries, aims to transform our understanding of neutrinos and their role in the universe.

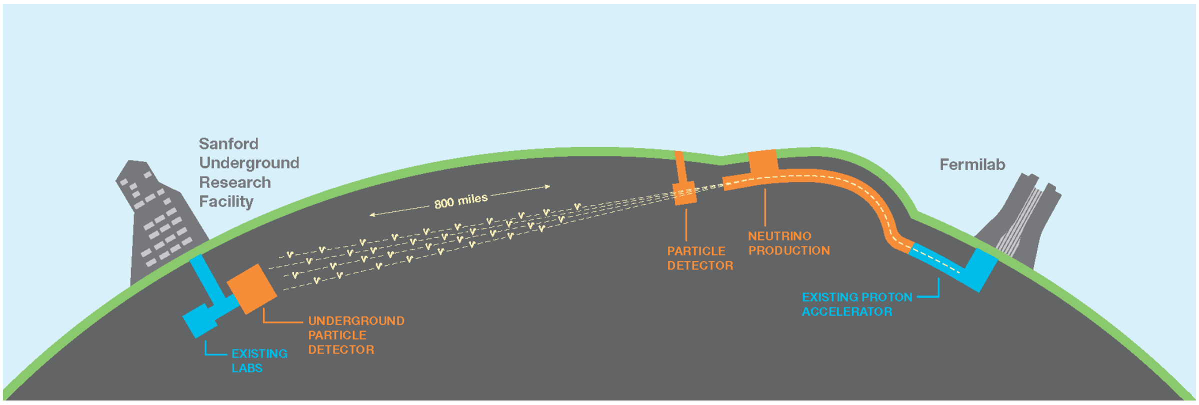


Figure 1.1: DUNE Experiment

1.1.1 Mysterious Neutrinos

Neutrinos are among the most abundant particles in the universe, a billion times more abundant than the particles that make up stars, planets and people. Each second, a trillion neutrinos from the sun and other celestial objects pass through your body. Although neutrinos are all around us, they interact so rarely with other matter that they are very difficult to observe. The latest developments in particle accelerator and detector technology make possible promising new experiments in neutrino science. The Deep Underground Neutrino Experiment collaboration, which comprises about 800 scientists from 27 countries, has proposed to build a world-leading neutrino experiment that would involve construction at both Fermi National

Accelerator Laboratory (Fermilab), located in Batavia, Illinois, and the Sanford Underground Research Facility (Sanford Lab) in Lead, South Dakota.

1.1.2 Why are neutrinos important?

Neutrinos may provide the key to answering some of the most fundamental questions about the nature of our universe. The discovery that neutrinos have mass, contrary to what was previously thought, has revolutionized our understanding of neutrinos in the last two decades while raising new questions about matter, energy, space and time. Neutrinos may play a key role in solving the mystery of how the universe came to consist of matter rather than antimatter. They could also unveil new, exotic physical processes that have so far been beyond our reach.

1.1.3 What do we know about neutrinos

Neutrinos are elementary particles that have no electric charge. They are among the most abundant particles in the universe.
They are very light. A neutrino weighs at least a million times less than an electron, but the precise mass is still unknown.
In nature, they are produced in great quantities in the sun and in smaller quantities in the Earth. In the laboratory, scientists can make neutrino beams with particle accelerators.
Neutrinos pass harmlessly right through matter, and only very rarely do they collide with other matter particles.
There are three types of neutrinos: electron neutrinos, muon neutrinos and tau neutrinos.
The laws of quantum mechanics allow a neutrino of one type to turn into another one as the neutrino travels long distances. And they can transform again and again. This process is called neutrino oscillation.
Understanding neutrino oscillations is the key to understanding neutrinos and their role in the universe.
The distance between Fermilab and Sanford Lab is 800 miles (1300 kilometers). This is ideal for examining neutrino oscillations with the proposed Deep Underground Neutrino Experiment. Scientists also would use DUNE to look for neutrinos coming from the explosion of a star—a supernova—to discover the formation of a black hole.

1.2 The LBNF neutrino beamline at Fermilab

1.2.1 What is LBNF?

The proposed Long-Baseline Neutrino Facility would use Fermilab's particle accelerators to create neutrinos and send them through the earth to a new, large, cutting-edge neutrino detector located almost a mile underground at the Sanford Underground Research Facility. The neutrinos would travel the 800 miles from Illinois to South Dakota straight through the earth—no tunnel is needed for these particles.

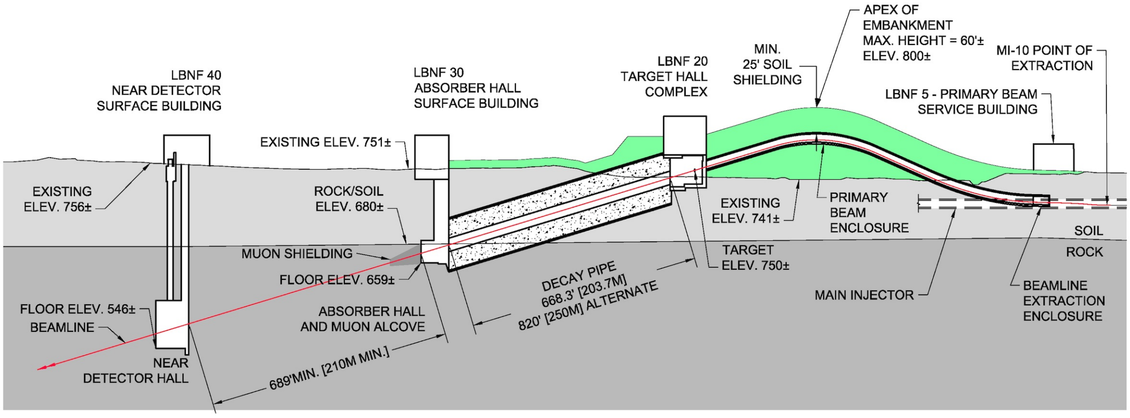


Figure 1.2: LBNF

1.2.2 The LBNF neutrino beamline at Fermilab

At Fermilab, scientists have operated neutrino-producing facilities for more than 30 years. The LBNF neutrino beamline would steer protons from Fermilab's Main Injector accelerator up a small hill (see graphic below) and then point the beam into the ground, toward the Sanford Lab. The protons would smash into a piece of graphite. The particles that emerge from these collisions would go into a 680-foot-long tunnel and generate neutrinos that travel in the same direction as the protons. Scientists would also build a state-of-the-art underground hall for the near detector of the Deep Underground Neutrino Experiment. The detector would measure the composition of the neutrino beam as it leaves the Fermilab site. Traveling at close to the speed of light, the neutrinos would leave the Fermilab site at a depth of about 200 feet, continue straight through the earth and arrive at the Sanford Lab in South Dakota within a fraction of a second. Because neutrinos can travel through rock and all other matter, no tunnel would be necessary for this 800-mile trip.

Chapter 2

Project

One of the most important parts in the LBNF is the target hall. This project is focused mainly on the decay pipe window of the target hall.

2.1 Requirements

The aim of the decay pipe window is to keep the whole amount of Helium inside the target hall, achieving a minimum leak rate. Due to this, we can make some considerations and have a list of requirements:

- The decay pipe Helium pressure is positive and amounts to 5 psig (0.34 bar);
- The beam operates at 2.3 MW;
- The window diameter is 1.5 m;
- In order to have the best behavior, previous analysis suggested a curved shape for an aluminum window, with a central part made of beryllium;
- Due to the highly radioactive environment the operators cannot interact with the target hall components: the window has to be completely remotely removable and positioned;
- Leak rate of Helium has to be less than $0.01\frac{\text{std}}{\text{cc}}$;
- The usage of an elastomeric seal system is not possible due to beam-on dose rates.

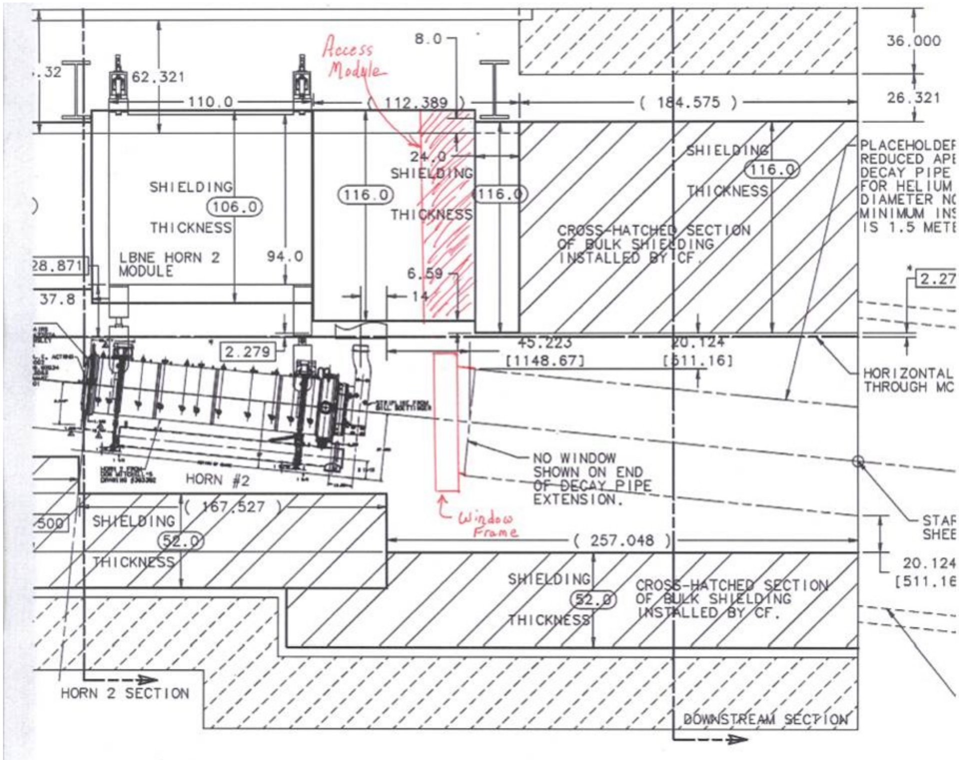


Figure 2.1: Target Hall 2D scheme

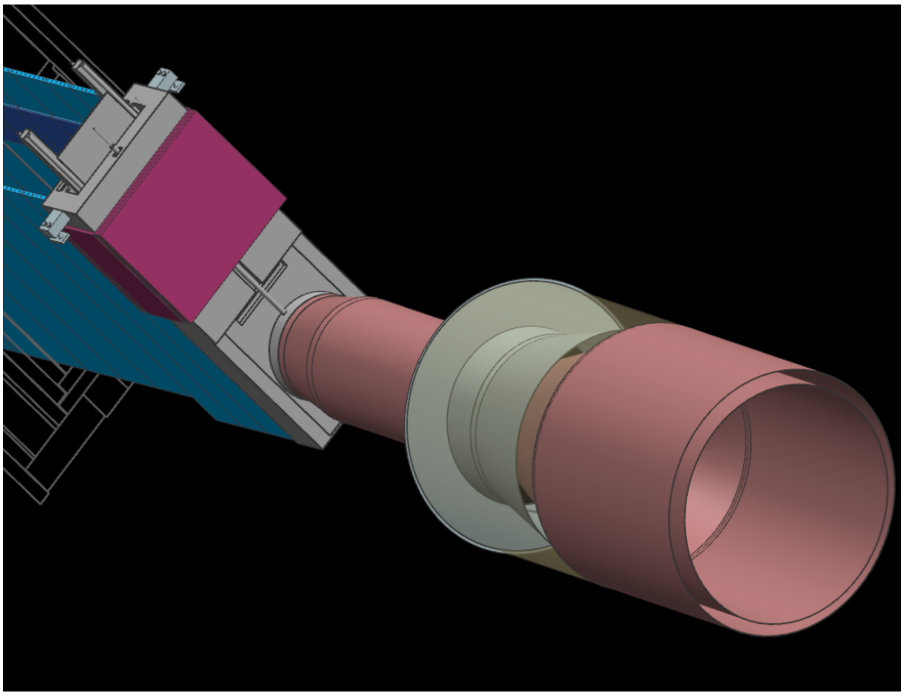


Figure 2.2: Target Hall

2.2 Seal System

From the requirements section, it is known that the required leak must be less than $0.01\frac{\text{std}}{\text{cc}}$. The usage of an elastomeric system is not possible. The choice will be a metal seal with a great sealing power. In particular, the system chosen is the Helicoflex Seal.

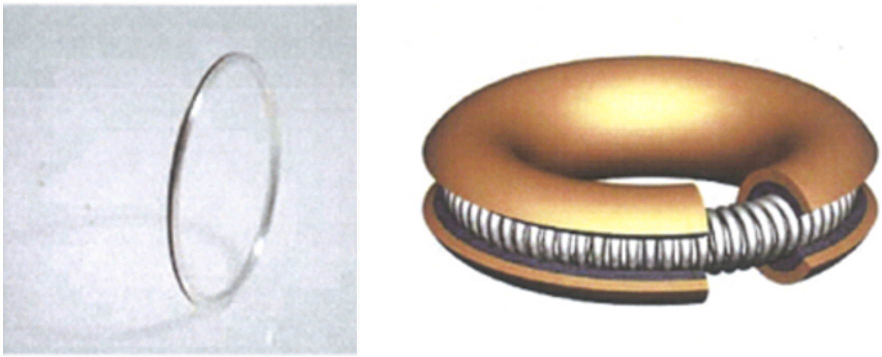
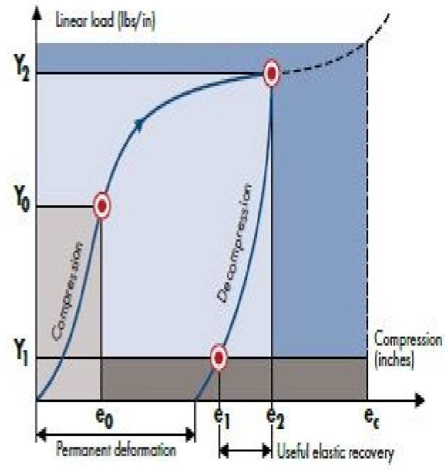


Figure 2.3: Helicoflex Seal System

The Helicoflex seal system allows a leak rate of $10^{-6}\frac{\text{std}}{\text{cc}}$, which is far better than the requirements. But, as we can see from the datasheet below, the pressure required in order to actually achieve the seal is very high: choosing a system with 0.276 inch cross section, the required load is 1542 $\frac{\text{lbs}}{\text{inch}}$. Doing some calculation, we can easily see that the required load amounts to 286,000 lbs (or 1.27MN). If we compare this number to the Helium internal pressure, we can see that it amounts to more than 20 times this one (about 13,000 lbs). The next chapters will analyze some ways to achieve this load.

DEFINITION OF TERMS

- Y_0 = load on the compression curve above which leak rate is at required level
- Y_2 = load required to reach optimum compression e2
- Y_1 = load on the decompression curve below which leak rate exceeds required level
- e_2 = optimum compression
- e_c = compression limit beyond which there is risk of damaging the spring



Jacket Material	HELIUM SEALING Cross Section	e_2	e_c	Y_2 lbs/inch	Y_1 lbs/inch	Pu68°F PSI	Pu-Θ392°F PSI	BUBBLE SEALING Y_2 lbs/inch	Y_1 lbs/inch	Pu68°F PSI	Pu-Θ392°F PSI	Max Temp °F
Aluminum	0.063	0.024	0.028	857	114	7250	N/A	514	114	5075	N/A	302
	0.075	0.028	0.033	914	114	7540	N/A	571	114	5800	N/A	302
	0.087	0.028	0.035	942	114	7685	N/A	600	114	5800	N/A	356
	0.098	0.028	0.035	999	114	7975	725	657	114	6090	725	428
	0.118	0.031	0.039	1056	143	7975	1450	742	114	6525	1450	482
	0.138	0.031	0.039	1085	143	7975	2030	799	114	6815	2030	482
	0.157	0.035	0.043	1142	143	8700	2465	857	114	7250	2465	536
	0.177	0.035	0.047	1199	143	8700	2900	914	114	7540	2900	536
	0.197	0.035	0.055	1256	171	9135	3190	971	143	7975	3190	572
	0.217	0.035	0.063	1313	171	9425	3480	1028	143	8265	3480	608
	0.236	0.039	0.071	1399	200	9715	3625	1113	171	8700	3625	644
	0.276	0.039	0.087	1542	228	10150	4060	1171	200	9425	4060	644
	0.315	0.039	0.102	1656	286	10440	4640	1285	228	9860	4495	680

Dimensions in inches

Figure 2.4: Datasheet

Chapter 3

Previous Solutions

In order to achieve the required load for the seal system, in the last three years were developed different solutions. Here it is possible to walk through two of the most important concepts designed and understand what their major drawbacks are.

3.1 Wedge Loading

By the usage of some pressured wedge, the purpose of this method was to obtain a load using deformation. Each wedge was compressed inside the space in order to obtain as much pressure as possible from the one closest to the window. The wedges require high loads to compress the seal and concerns about how the wedges separate after exposure to the beam and the corrosive, activated air, have not been satisfactorily addressed.

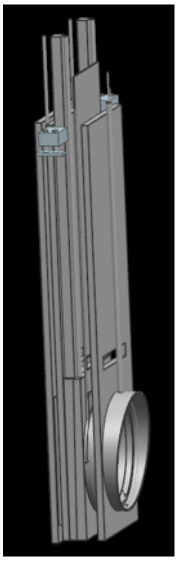


Figure 3.1: Wedge Loading

3.2 Autoclave with Rotating Ring

This proposed method is based on the quick-actuating closure method used in most industrial autoclaves.

- Rotating ring is rotated using hydraulics, again located above ground
  - Rotating ring sits on the decay pipe flange
  - Advantage is that the seal does not experience the rotation
  - Links allow for linear piston motion, allows rotation which will protect from extra loads are the rods
  - Use double acting cylinders (one rod is pulling while the other pushes)
- Beryllium window is mounted onto a circular frame.
  - Circular frame has wedges to match rotating ring on outer diameter
  - Circular frame has hook(s) near the top so that the raising/lowering of the window is controlled
  - Circular Frame slides up and down the positioning frame.
- Positioning frame guides the circular frame/window.
  - Vertical rods help alignment of circular frame with rotating ring
  - Positioning frame aligns the window with respect to the rotating ring by rotating around the hinge on the bottom

The torque required to rotate the autoclave ring is very high, and the amount of travel, while fine for elastomers, is insufficient for the metal seal.

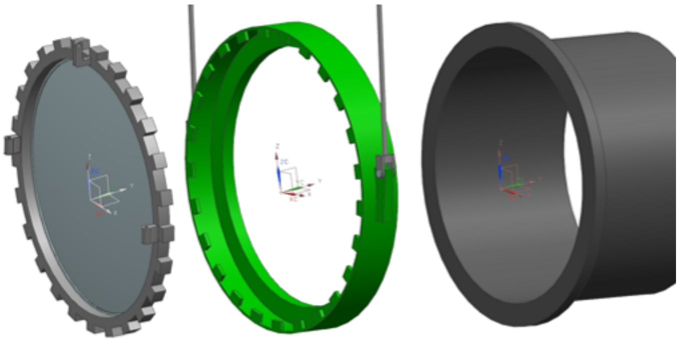


Figure 3.2: Autoclave with Rotating Ring

Chapter 4

Bolt Solution

Due to the failure of the previous systems, the first efforts of the project are focused on the choice of a new way to apply the required load. Following the seal manufacturer's suggestion, it turned out that one possible solution can be a flange. Through the usage of bolts we can apply the required load. The problem of asymmetries in the load distribution can be overwhelmed by the huge number of bolts required (as we will see in the next section).

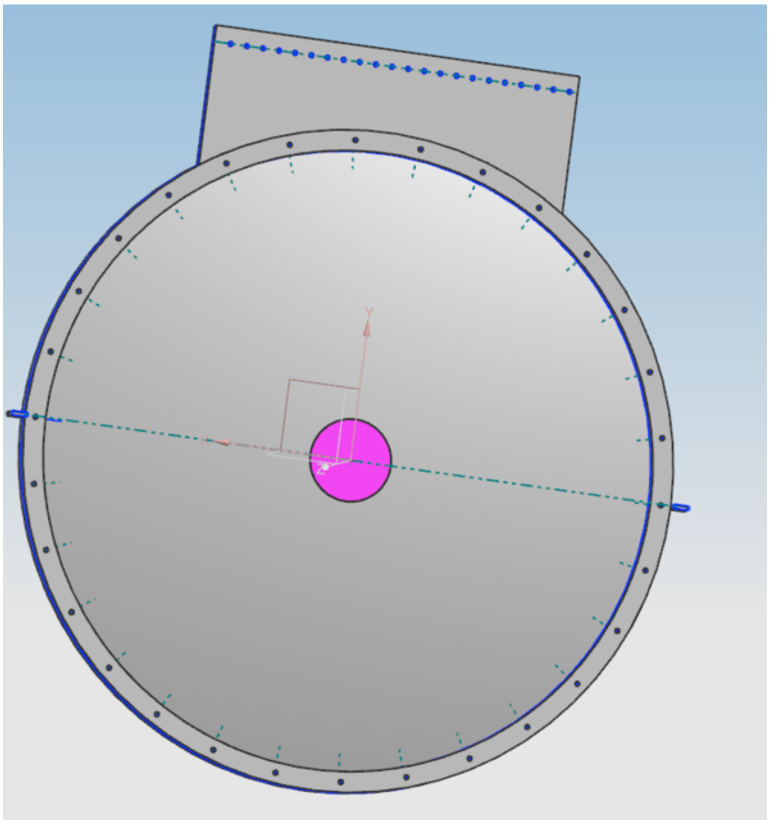


Figure 4.1: First Concept with Flange

4.1 Bolt Choice

During the choice of the bolt type and number, we have to be careful of at least three major parameters:

- Load applied;
- Corrosion in a highly radioactive environment;
- Size.

The size chosen for the bolts is M12.
Taking a glance at the behavior in a highly radioactive environment, it is possible to notice that one of the materials with the most important corrosion problems is steel. Thus, it is not possible to use it. Two choices are possible:

- Stainless steel;
- Titanium.

While stainless steel is lighter, titanium has a far higher proof load strength, which results in a higher tightening force applied. The choice for this application is Titanium HEX HEAD M12. Stainless steel was not chosen because of the low strength and potential for galling.

Figure 4.2: Titanium HEX HEAD M12

4.2 Torque

In order to obtain the required load on the seal system, it is necessary to apply a proper torque on the bolts. This torque can be calculated by using the bolt parameters.
Using these information we can calculate the torque required (applying a safety factor η of 4.5).The load applied by each bolt can be easily calculated by:

$$F_i = k \cdot S_p \cdot A_t = 65.6\text{kN} \tag{4.1}$$

Calculating the torque:

$$T = 0.2 \cdot F_i \cdot d = 176\text{Nm} \tag{4.2}$$

It is possible to calculate the number of bolts required with this safety factor:

$$n = \frac{F_r}{F_i} \cdot \eta = 80 \tag{4.3}$$

Bolt parameters

Density	4420kg/m^3 (276lb/ft^3)
Young's Modulus	110GPa (16 x 10^6 psi)
Yield Strength	828MPa (120 x 10^3 psi)
Ultimate Tensile Strength	1030MPa (149 x 10^3 psi)
Compressive Strength	960MPa (139 x 10^3 psi)
Shear Modulus	43GPa (6.24 x 10^6 psi)
Ductility	10% elongation at break
Poisson's Ratio	0.34
Hardness	36 Rockwell C
Strength-to-Weight Ratio	187 kNm/kg
Stiffness-to-Weight Ratio	24.9 Mnm/kg
Bolt type	M12
PL Strength	792MPa
Stress Area	92,1 mm^2

Figure 4.3: Bolt Parameters

Chapter 5

Window Replacement System

One of the easiest way to tight all the bolts is to carry a robot inside the target hall. It will tight them using an impact wrench appositely chosen. Two choice are possible:

- Tailored Designed Robot
- Commercial Robot

During the project both the conceptual designs were developed in order to understand which can better fit our needs.

5.1 Tailored Designed Robot

While designing the robot we have to be careful about some key factors:

- Space: we have only 17 inches available;
- Weight: having a lighter robot means to save space;
- Corrosion is not a problem: we are acting in a beam-off configuration.
- Aligning the center of the robot with the window, we can use only 2 DOF, one on the angular coordinate and one in the depth.

Some possible solutions for saving space can be:

- Two joints: one rotational and one primastic;
- Curve profile;
- Hydraulic or pneumatic impact wrench;
- Socket head bolts: this will require less precision from the robot.

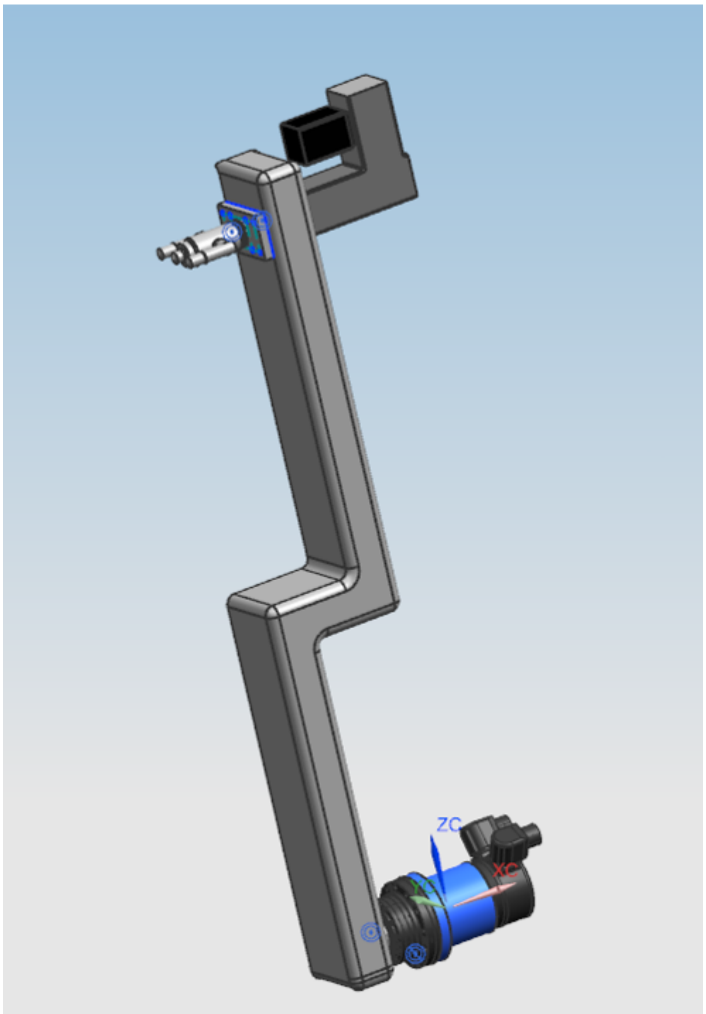


Figure 5.1: First Design

5.1.1 Motors

Focusing on saving space, the choice of the motor was based on high torque to weight ratio and small dimensions. We chose those two motors:

- Lynx Drive 20C with Harmonic Drive technology: the Harmonic Drive technology uses a strain wave gear in order to give a 1:160 ratio using a very tiny component;
- Parallel linear actuator: by positioning the motor of the linear actuator on the upper part, it is possible to save space in the depth coordinate.

Figure 5.2: Lynx 20C and Parallel linear actuator

5.1.2 Torque Reducing

We adopted two solution for the torque reduction:

- Aluminum hollow body: this allows to reduce weight and consequentially the motor size;
- Supporting pins: these two pins will transfer the torque to the window structure instead of charging the robot motors.

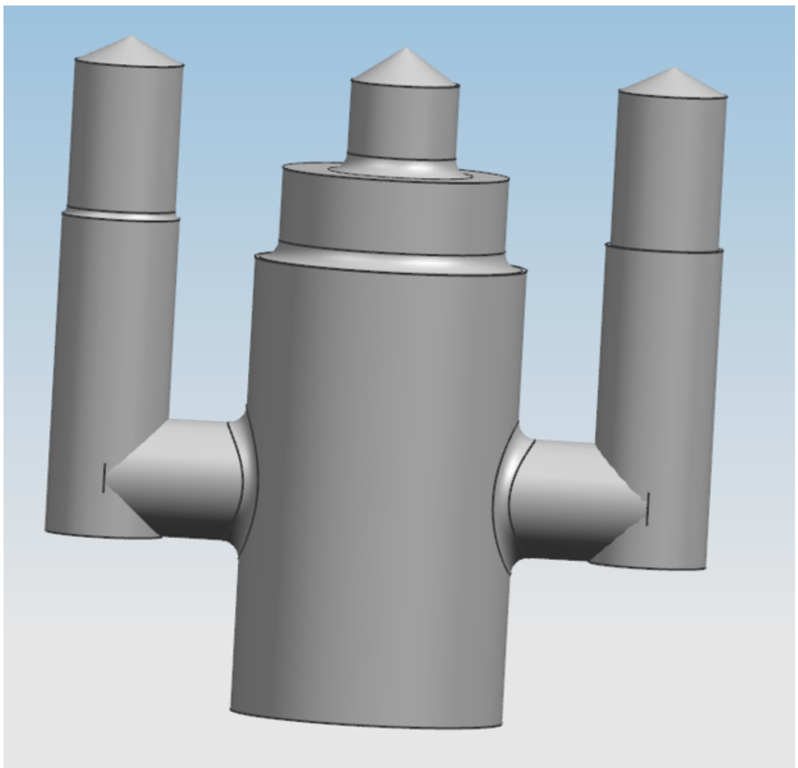


Figure 5.3: Impact wrench example with supporting pins

5.2 Commercial Robot

Choosing a commercial robot our needs will be slightly different than choosing a tailored designed one. We want it to be:

- Light;
- Versatile;
- Small;
- Compatible workspace;
- With high payload to weight ratio.

It is possible to notice that a requirement of versatility has been added. This can be motivated by thinking at this application: the window will be removed once a year, thus the best choice would be to have the robot ready for other tasks for the rest of the year.

5.2.1 UR5

After the examination of various robot catalogs, it has been chosen the robot called UR5 from Universal Robot. We can notice four important details:

Technical specifications UR5 — **Item no. 110105**

We accept no liability for any printing errors or technical changes.

6-axis robot arm with a working radius of 850 mm / 33.5 in

Weight:	18.4 kg / 40.6 lbs		
Payload:	5 kg / 11 lbs		
Reach:	850 mm / 33.5 in		
Joint ranges:	+/- 360°		
Speed:	All joints: 180°/s. Tool: Typical 1 m/s. / 39.4 in/s.		
Repeatability:	+/- 0.1 mm / +/- 0.0039 in (4 mils)		
Footprint:	Ø149 mm / 5.9 in		
Degrees of freedom:	6 rotating joints		
Control box size (WxHxD):	475 mm x 423 mm x 268 mm / 18.7 x 16.7 x 10.6 in		
I/O ports:		Controlbox	Tool conn.
	Digital in	16	2
	Digital out	16	2
	Analog in	2	2
	Analog out	2	-
I/O power supply:	24 V 2A in control box and 12 V/24 V 600 mA in tool		
Communication:	TCP/IP 100 Mbit: IEEE 802.3u, 100BASE-TX Ethernet socket & Modbus TCP		

Figure 5.4: Technical specification

- The robot is very light: it weights only 18.4 kg;

- The payload is 5 kg, this is important for the impact wrench choice;
- Workspace 850mm: it fits our application;
- Joint ranges: 360°. This is reflected on a very high versatility and in a perfect configuration for this application.

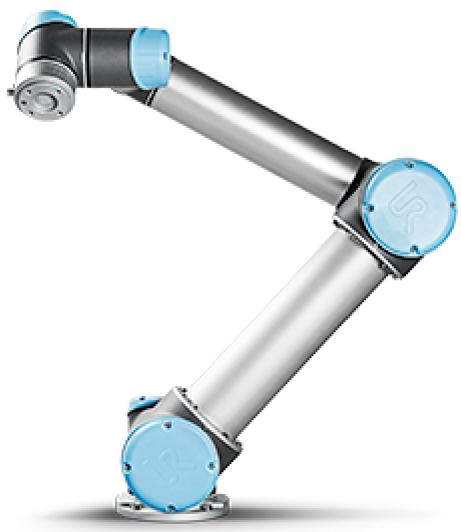


Figure 5.5: UR5

5.3 Our Choice

When choosing the best options we need to evaluate some pros and cons:

Tailored Designed Robot

Pros:

- No need for adaptability;
- Developed in Lab;
- Optimized for this task.

Cons:

- Need for testing;
- Costs;
- More human resources needed;

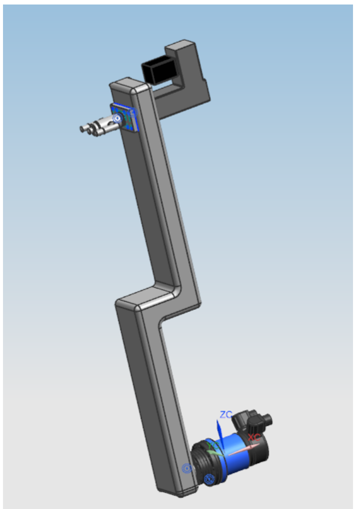


Figure 5.6: Tailored designed robot

- Cannot be reused for other applications.

Commercial Robot

Pros:

- Versatile (can be reused);
- Already tested;
- Cheaper;
- Fewer human resources needed.

Cons:

- Not optimized;
- Need to adapt to this task.

Judging from these consideration, we decided to adopt a **Commercial Robot** .

5.4 Impact Wrench

The requirements for the impact wrench will be:

- Weight: must be less than 5 kg;
- Size: smaller than 30 cm;
- Torque: Max Torque must be greater than 176 Nm;
- Torque: Remotely controllable.

We chose to adopt this impact wrench from Bosch:

Pneumatic 1/2

The most important data

Max. tightening torque	310 Nm
No-load speed	7000 1/min

Part number: 0 607 450 629

Technical data

Max. tightening torque	310 Nm
No-load speed	7000 1/min
Direction of rotation (R = right; L = left)	R/L
Air consumption under load	8,5 l/s/cfm
Weight as per EPTA	2,3 kg
Bit holder	1/2" external square
Connecting thread	1/4"-NPT
Hose inner diameter	10 mm

Figure 5.7: Impact Wrench Technical Specification

5.4.1 Automation

By not choosing an automatic impact wrench, we had to find a way to automatize it. We adopted a system that was already actuated in the lab, that simply pushes the ON button and regulates the tightening torque by regulating the air pressure. In order to switch between "front" and "reverse" regulation, we chose to use a stepper motor with a small leverage flanged on it.

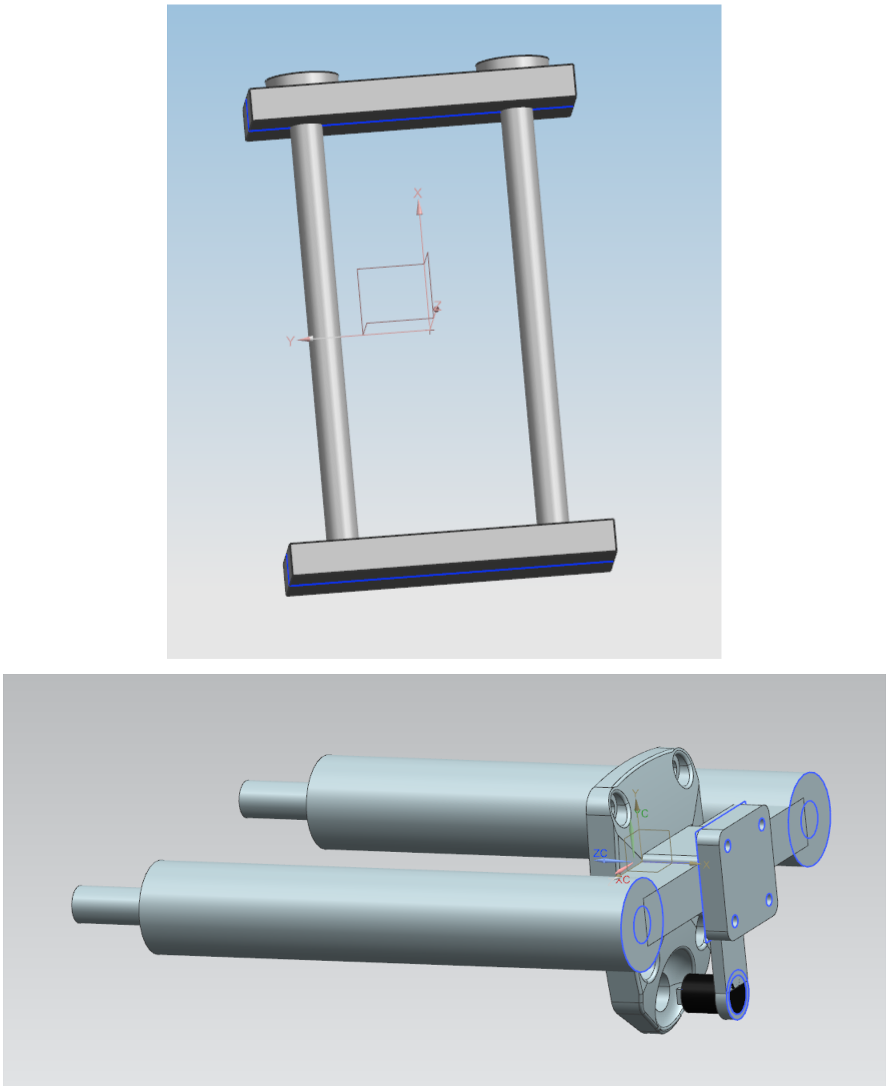


Figure 5.8: Automation mechanism and link

5.4.2 Link

The link between the two parts must have two parts to be flanged (one for the robot and one for the impact wrench). As written before, it must have two supporting pins to be inserted inside two bolts. This will discharge the torque to the structure instead of charging the robot.

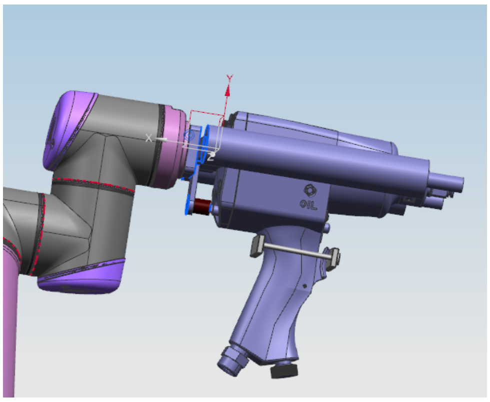


Figure 5.9: Complete system

5.5 Lifting Tools

The entire structure of the window has to be pulled up and down remotely. Taking advantage of the gravity, it is possible to use threaded rods with a system that allows to lock the window with the rods and to leave it. Two blocks come inside the window and rotate in order to lock inside it and carry it. Upside, the whole structure is moved on wheels.

When removed, the whole window is radioactive. The interaction with humans is not possible. The window will be placed inside a steel shield with 5 cm of thickness. Here there are some pictures of the structure:

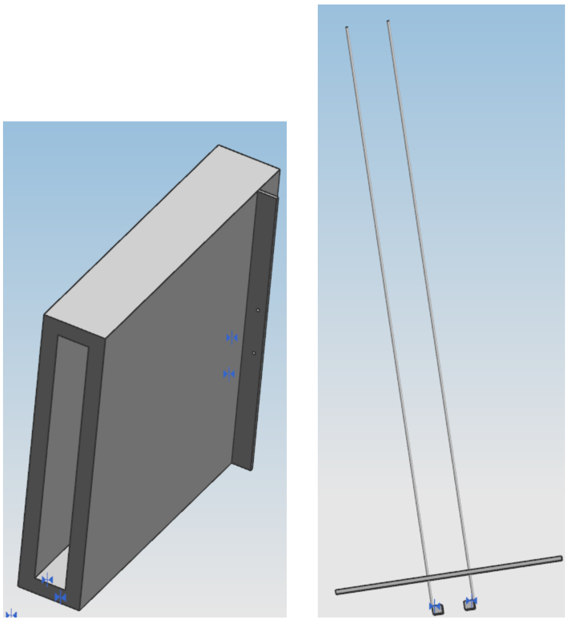


Figure 5.10: Shield and carrying tool

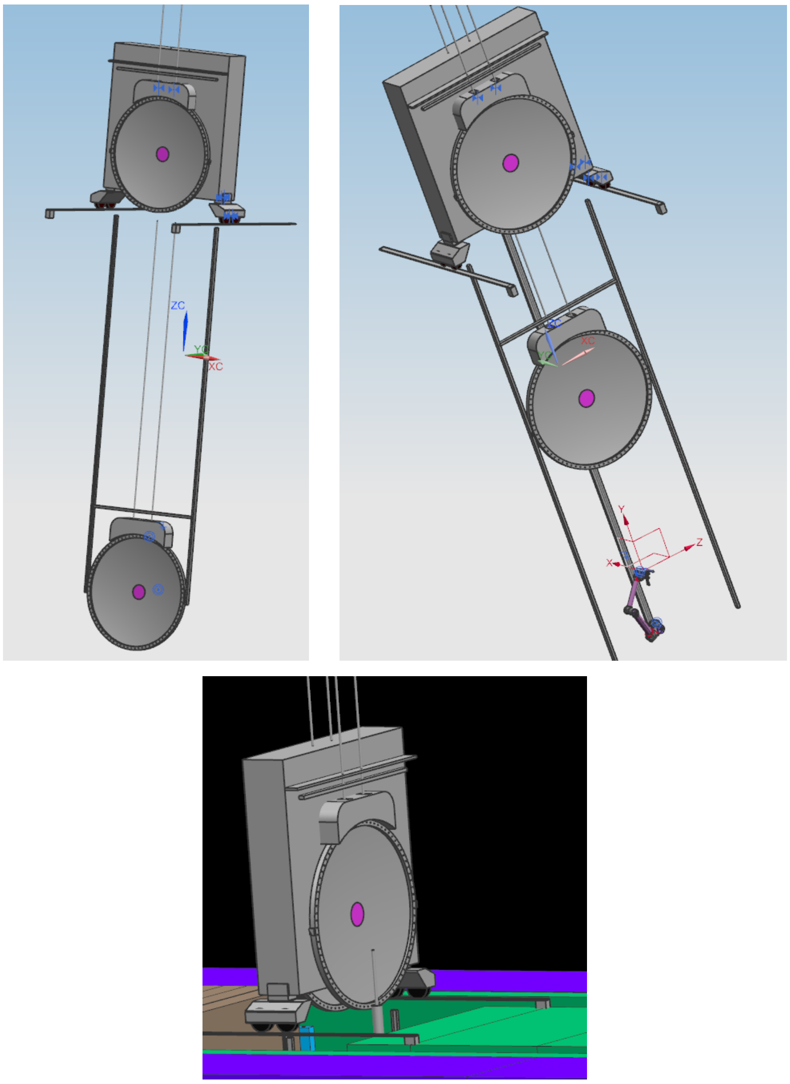


Figure 5.11: Some views of the window replacement system

5.6 Air Lock

When the window is opened, without a proper system, all the helium will be wasted. This system is called "AirLock". An airlock is a device which permits the passage of objects between a pressure vessel and its surroundings while minimizing the change of pressure in the vessel and loss of air from it. The lock consists of a small chamber with two airtight doors in series which do not open simultaneously. The airlock will be opened two times: at the beginning of the operation and at the ending.

Chapter 6

Complete Design

Now we can take a look at the whole structure mounted inside the target hall.

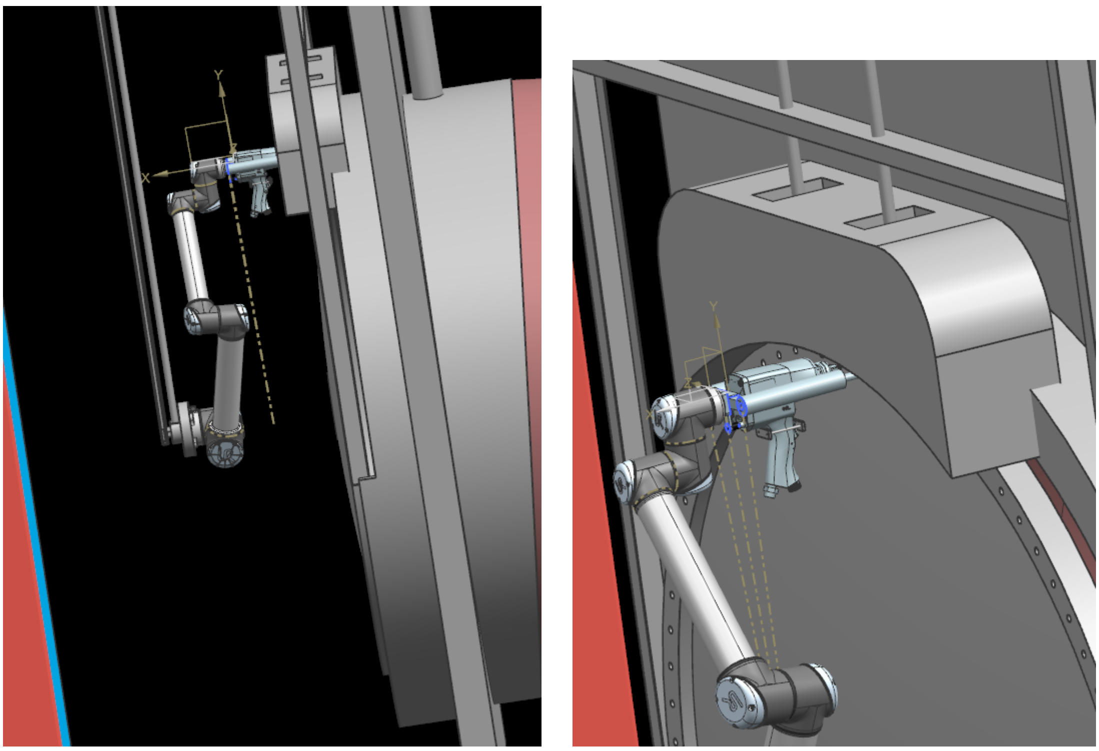


Figure 6.1: Robot in action

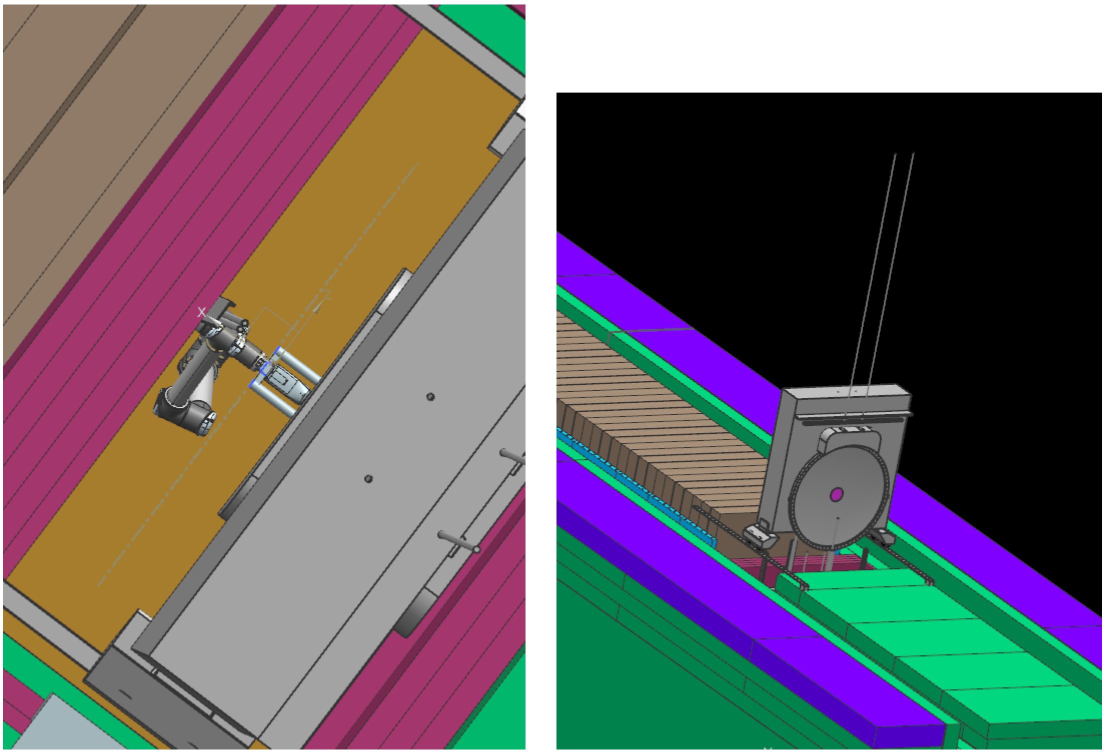


Figure 6.2: Two more views of the entire structure

Chapter 7

Conclusions and Further Steps

This project is meant to be a preliminary design of the window replacement system. Starting from zero, we developed an entire conceptual design from which the dimensioning and prototyping work can start.

There is much work to do in the control part too. Our idea is that the control must be obtained through a vision system which enables both the robot and the operator to track the task status.

The robot and the impact wrench have to be purchased and the other tools have to be built and after a proper session of testing this design can be the solution of this problem.

7.1 Acknowledgments

I have to thank Dave Pushka for this amazing experience and for being not only a supervisor, but also a friend and a mentor.
I'm grateful also to Giorgio Bellettini, Emanuela Barzi, Simone Donati, Vaia Papadimitriou, Cory Crowley and the Italian group, for being a constant support throughout the whole program.