[FINAL YEAR PROJECT-MECH 502 : THE LEBANESE LINEAR PLASMA DEVICE]

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Acknowledgments:

There are several people to whom we must express our heartfelt gratitude for their assistance in so many ways as we endeavored to realize this project.

We are so grateful for our conscientious and meticulous advisors, Dr. Marwan Darwish and Dr. Ghassan Antar, who guided us through every step of the way and who gave invaluable advice that enabled us to enhance this report at every stage.

We thank our professors who shaped our lives and minds and made us the engineers we are today.

We thank staff personnel at the AUB physical plant, who provided us with much needed advice and contact information without which we could not have realized our design.

And most of all, we thank our parents who valued our education above all else. We could not have done it without their unquestionable support.
# Table of Contents

Acknowledgments: ........................................................................................................... 1

List of figures: ..................................................................................................................... 3

Introduction: ....................................................................................................................... 5

Abstract: .............................................................................................................................. 6

Project outline: .................................................................................................................... 7

Part 1: Bill of materials: ..................................................................................................... 7

Part 2: Identification of the missing material: ................................................................. 9

Part 3: Support structure .................................................................................................. 9

Stress analysis on critical points. ...................................................................................... 11

Introducing the stress analysis: ....................................................................................... 12

Free body diagram of the system as a whole. ................................................................. 13

2-dimensional analysis of the system stresses ................................................................ 13

Stress analysis at point A: .............................................................................................. 15

Stress analysis at point B: Normal stress on the leg ....................................................... 21

Stress analysis at point C: Middle Plate Calculation ..................................................... 22

Final Design ..................................................................................................................... 24

Manufacturing ................................................................................................................ 26

Pumping system ............................................................................................................... 27

The pumping system: ...................................................................................................... 27

The vacuum process: ........................................................................................................ 27

Choice of Pumps: ............................................................................................................. 28

Complete pumping System Design: .............................................................................. 29

First draft: ....................................................................................................................... 29

Updated draft: ................................................................................................................ 30

Part 5: the Coil Box ......................................................................................................... 33

Appendix A ...................................................................................................................... 36

Part 1) “Ethical and professional responsibilities” ......................................................... 36

Part 2) “Understanding in a social context” ................................................................... 37

Part 3) “Project as a Business Model” .......................................................................... 38

Appendix B .................................................................................................................... 39
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Nuclear Fusion explained</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>assembly 1</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>assembly 2</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>assembly 3</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
<td>rendering of support structure</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>Clamp that allows movement found on common desk</td>
<td>10</td>
</tr>
<tr>
<td>7</td>
<td>The design as drawn on PROE software</td>
<td>11</td>
</tr>
<tr>
<td>8</td>
<td>Side view of the support system</td>
<td>13</td>
</tr>
<tr>
<td>9</td>
<td>Upper view of the support system</td>
<td>13</td>
</tr>
<tr>
<td>10</td>
<td>I beam cross section</td>
<td>14</td>
</tr>
<tr>
<td>11</td>
<td>FBD at point A</td>
<td>15</td>
</tr>
<tr>
<td>12</td>
<td>Side view of a single I beam</td>
<td>16</td>
</tr>
<tr>
<td>13</td>
<td>Reaction forces of support</td>
<td>16</td>
</tr>
<tr>
<td>14</td>
<td>Free body diagram</td>
<td>19</td>
</tr>
<tr>
<td>15</td>
<td>Shear diagram</td>
<td>19</td>
</tr>
<tr>
<td>16</td>
<td>Moment diagram</td>
<td>20</td>
</tr>
<tr>
<td>17</td>
<td>I beam cross section</td>
<td>20</td>
</tr>
<tr>
<td>18</td>
<td>cross section 1 of the leg</td>
<td>21</td>
</tr>
<tr>
<td>19</td>
<td>solid area of leg</td>
<td>21</td>
</tr>
<tr>
<td>20</td>
<td>Middle plate free body diagram</td>
<td>22</td>
</tr>
<tr>
<td>21</td>
<td>Middle plate sheer diagram</td>
<td>23</td>
</tr>
<tr>
<td>22</td>
<td>Middle plate moment diagram</td>
<td>23</td>
</tr>
<tr>
<td>23</td>
<td>middle plate geometry</td>
<td>23</td>
</tr>
<tr>
<td>24</td>
<td>Longitudinal base long</td>
<td>24</td>
</tr>
<tr>
<td>25</td>
<td>Cross bar</td>
<td>24</td>
</tr>
<tr>
<td>26</td>
<td>I beam</td>
<td>25</td>
</tr>
<tr>
<td>27</td>
<td>Square holder</td>
<td>25</td>
</tr>
<tr>
<td>28</td>
<td>Support leg</td>
<td>25</td>
</tr>
<tr>
<td>29</td>
<td>Transverse base long</td>
<td>25</td>
</tr>
<tr>
<td>30</td>
<td>S holder</td>
<td>26</td>
</tr>
<tr>
<td>31</td>
<td>Full assembly of the support system</td>
<td>26</td>
</tr>
<tr>
<td>32</td>
<td>Effect of intermolecular distance on Pressure</td>
<td>27</td>
</tr>
<tr>
<td>33</td>
<td>Flow Regime Boundaries</td>
<td>28</td>
</tr>
<tr>
<td>34</td>
<td>Turbo Pump</td>
<td>28</td>
</tr>
<tr>
<td>35</td>
<td>Vacuum Pumping System Preliminary Design</td>
<td>29</td>
</tr>
<tr>
<td>36</td>
<td>Second draft of pumping system</td>
<td>30</td>
</tr>
<tr>
<td>37</td>
<td>third draft of pumping system</td>
<td>31</td>
</tr>
<tr>
<td>38</td>
<td>CF flange</td>
<td>32</td>
</tr>
<tr>
<td>39</td>
<td>KF flange</td>
<td>32</td>
</tr>
<tr>
<td>40</td>
<td>Coil Box</td>
<td>33</td>
</tr>
</tbody>
</table>
Figure 41: Center plates designed to hold the coils in place ......................................................... 34
Figure 42: Coil configuration, each three coil boxes will be supplied with one generator .................. 34
**Introduction:**
Nuclear fusion is nothing short than the holy grail of science. It promises to solve all our environmental and energy related problems and provide us with an abundant fuel supply for earth and beyond.

**What is nuclear fusion?** Nuclear fusion happens when multiple atoms having the same charge fuse together and form a heavier atom. This process can either consume or produce energy depending on the atoms involved and the weight of the final output.

![Diagram of nuclear fusion](image)

**Figure 1** Nuclear Fusion explained

The advantages of nuclear fusion are:

- Ample fuel supply (to give you a perspective, 50 cups of sea water can hold as much energy as 1 ton of coal)
- No risk of a nuclear accident
- No air pollution or CO\(_2\) generation
- No high level nuclear waste
But the problem with nuclear fusion is in getting two atoms similarly charged close to each other, because they will tend to repel each other due to their same charge. But once they are close enough the nuclear force will take over and complete the fusion process.

The major obstacle in fusion technology is plasma turbulence that greatly reduces the efficiency of the system and makes it energy consuming rather than producing.

AUB is undertaking the project of building the first Lebanese Linear Plasma Device (LLPD) that will be used to study turbulence in the plasma and ways to optimize the process.

**Abstract:**

The department of physics in collaboration with the faculty of engineering and architecture is building the LLPD which is basically a cylinder like vacuum chamber where the plasma will be created and the flow studied in order to simulate problems faced in the actual fusion power plant.

This project is very important because it will allow AUB and Lebanon to partake in the global effort for fusion development. And since the device will be unique in the region (including Israel) and it will have unique characteristics worldwide, then it will further solidify AUB’s role at the forefront of intellectual innovation and technological development.

The mechanical engineering team will handle:

- The support structure
- The pumping system (gas in, gas out)
- The system assembly

The milestones of the project are:

- ✓ Understand the problem: vacuum, support
- ✓ Make CAD (or equivalent) drawing of the whole setup
- ✓ Identify missing components
- ✓ Design the pumping system
- ✓ Design the support structure
- ✓ Design the coil box
- ✓ Assemble the system
Project outline:
The project is mainly divided into three main parts each in its turn divided into sub-divisions.

Part 1: Bill of materials:
This part is where the team had to visit the plasma lab at the physics building at AUB campus to identify the available parts for the system. Dr. Antar showed briefly how the system must be assembled and the available parts and left the team to identify the possible arrangement and realize the missing material to be ordered.

Table 1 in appendix B describes the parts of the pumping system. Table 2 in the appendix B describes the needed gaskets for the system, stating them clearly. Those gaskets have their CAD drawings online; we will obtain them after ordering the parts.

- CAD drawings: are the professional drawings of the system that are required to proceed

This includes:

1- Drawing the system to be build using PRO-E software:
   a- To accomplish this part, measures of all the parts have to be taken accurately
   b- Some of the CAD drawings of the flanges were found on the web
   c- The remaining had to be drawn to scale and sub-assembled
      Note: some parts were standard made for linear plasma devices while other parts were custom made.
2- Those drawings have to be realized on PRO-E software using the right materials and drawing techniques.
3- An assembly of all the parts has been made for further analysis.

Note that this drawing and realization of the system will vary based on future analysis; that is the system assembly might be changed based on the performance of the system. Therefore the drawing of the parts must include certain variables to be modified if needed. We also went ahead and made several configurations of the linear device. Below are some of the configurations.
Figure 2: assembly 1

Figure 3: assembly 2

Figure 4: assembly 3
Part 2: Identification of the missing material:
To assemble the linear plasma device the system must include all the needed parts and their complements; that is the flanges are to be assembled linearly separated by gaskets (O-rings) to insure proper functioning of the system and foremost safety.

Research was made to ensure the missing parts are ordered properly. O-rings presentation found in appendix B served as a good reference to choose the Gaskets. A table of required gaskets is also found in appendix B.

Bolts: there are approximately 400 bolts used in the system. A table is included in appendix B to elaborate on the specifications.

Part 3: Support structure
This structure is the base of our project. The linear plasma device will be held on a base support structure that will be mobile for modifying the arrangement of the parts. Several support structures were discussed in the meeting with the members as well as with the lab technicians to check the availability of manufacturing them at the shops.

Step 1: weighing all the parts available at the lab to have an overall weigh that will help in analyzing the support structure.

Step 2: force, shear, stress and bending diagrams analysis have to be made to ensure a safety factor when working on the structure. This analysis is still being processed.

Step 3: a rough drawing has to be made for the structure. Basically two rails will lie on a rectangular support. Mobile arms are clamped to the rails. Clamps are welded on the arms to hold the flanges in place.

The support structure looks as follows
The blue part is the support structure that we intend to construct. This image is taken from the internet and serves just as an example. As for the design of the real support structure and its drawings they are still not ready.

While brainstorming for the support structure we focused mainly on having a mobile support structure so we can modify the position of the parts as we test the system. We therefore used the support structures of common furniture to have a wider vision:

Below is an example of a system we looked at:
Stress analysis on critical points.
The stress analysis in the design we chose is a useful tool in selecting the correct and safe dimensions of the support structure. In what follows are the critical points we analyzed while designing the support structure.

![Figure 7: The design as drawn on PROE software](image)

The main points in the system to be analyzed for proper dimensioning are points shown above: A, B & C.

- **Point A**: this point represents the upper surface contact of the cross sectional bar with the I beam. Analysis at this point will guide us in calculating the proper size of the I beam and choosing the safest feasible design.

- **Point B**: this point represents the lower surface contact between the I beam and the hollow square beam that will be the leg of the support system. Analysis at this point will guide us in selecting the appropriate surface area of contact to hold the weight.

- **Point C**: this point represents the mid-section of the cross sectional bar that holds the upper support of the system. Analysis at this point guides us to check the thickness needed preventing any bending of the bar.
Introducing the stress analysis:
The first step in this section includes a full computation of the weight of the system excluding the support structure. Below is a table that shows the different part weights:

Table 1: Weight of device parts

<table>
<thead>
<tr>
<th>PART</th>
<th>Weight (KG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>16</td>
</tr>
<tr>
<td>B</td>
<td>11</td>
</tr>
<tr>
<td>C</td>
<td>24</td>
</tr>
<tr>
<td>D</td>
<td>6</td>
</tr>
<tr>
<td>E</td>
<td>2</td>
</tr>
<tr>
<td>F</td>
<td>4</td>
</tr>
<tr>
<td>G</td>
<td>2</td>
</tr>
<tr>
<td>H</td>
<td>6</td>
</tr>
<tr>
<td>I</td>
<td>5</td>
</tr>
<tr>
<td>J</td>
<td>9</td>
</tr>
<tr>
<td>K</td>
<td>18</td>
</tr>
<tr>
<td>L</td>
<td>19</td>
</tr>
<tr>
<td>Gate valve</td>
<td>30</td>
</tr>
<tr>
<td>Manual valve</td>
<td>15</td>
</tr>
<tr>
<td>Turbo pump</td>
<td>25.5</td>
</tr>
<tr>
<td>O-rings</td>
<td>15</td>
</tr>
<tr>
<td>Bolts + nuts</td>
<td>10.5</td>
</tr>
<tr>
<td>Instruments</td>
<td>30</td>
</tr>
<tr>
<td>Watch glass</td>
<td>8</td>
</tr>
<tr>
<td>Blind end</td>
<td>10</td>
</tr>
<tr>
<td>TOTAL</td>
<td>266</td>
</tr>
</tbody>
</table>

The parts listed from A to L are the main tubular parts that make up the system shown in the above figure.

The nuts and bolts calculations were done to approximate values using a website.

**BOLT AND NUTS:**
The system consists:

- 360 HEX bolts.
- Diameter 0,332 inches
- Maximum length: 2.2 inches
- Threaded length: 1 inch
- + their corresponding nuts

The weight of the bolts and the nuts were computed using [http://www.portlandbolt.com/bolt-weight-calculator.html](http://www.portlandbolt.com/bolt-weight-calculator.html)

So based on the above mentioned calculation our stress analysis will be considered at the points A, B and C.
Free body diagram of the system as a whole.

2-dimensional analysis of the system stresses.

Figure 8: Side view of the support system

Figure 9: Upper view of the support

Figure 9: The areas marked with red color are the areas of stress concentration.

Figure 8: The arrows labeled 1 till 6 are the forces that act on each of the 6 points of contact of the system. P and Q are the distances between the supporting arms of the system.

Note that all the steel will be of the type HEA 100 chosen from the following table:
Table 2: HEA steel types and associated characteristics

<table>
<thead>
<tr>
<th>HEA</th>
<th>Dimensions</th>
<th>Static Parameters</th>
<th>Section Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Depth (mm)</td>
<td>Width (mm)</td>
<td>Web Thickness (mm)</td>
</tr>
<tr>
<td>100A</td>
<td>96</td>
<td>100</td>
<td>5</td>
</tr>
<tr>
<td>120A</td>
<td>114</td>
<td>120</td>
<td>5</td>
</tr>
<tr>
<td>140A</td>
<td>133</td>
<td>140</td>
<td>5.5</td>
</tr>
<tr>
<td>160A</td>
<td>152</td>
<td>160</td>
<td>6</td>
</tr>
<tr>
<td>180A</td>
<td>171</td>
<td>180</td>
<td>6</td>
</tr>
<tr>
<td>200A</td>
<td>190</td>
<td>200</td>
<td>6.5</td>
</tr>
<tr>
<td>220A</td>
<td>210</td>
<td>220</td>
<td>7</td>
</tr>
<tr>
<td>240A</td>
<td>230</td>
<td>240</td>
<td>7.5</td>
</tr>
<tr>
<td>260A</td>
<td>250</td>
<td>260</td>
<td>7.5</td>
</tr>
<tr>
<td>280A</td>
<td>270</td>
<td>280</td>
<td>8.5</td>
</tr>
<tr>
<td>300A</td>
<td>290</td>
<td>300</td>
<td>8.5</td>
</tr>
<tr>
<td>320A</td>
<td>310</td>
<td>300</td>
<td>9</td>
</tr>
<tr>
<td>340A</td>
<td>330</td>
<td>300</td>
<td>9.5</td>
</tr>
</tbody>
</table>

Our calculation will take into consideration the beam selected having the following dimensions:

- \( h_w = 80 \text{ mm} \)
- \( t_f = 8 \text{ mm} \)
- \( t_w = 5 \text{ mm} \)
- \( b_f = 100 \text{ mm} \)

Linear mass: \( \text{Mass}/L = 16.7 \text{ kg/m} \)

Section = 21.2 cm²

Figure 10: I beam cross section

\[
A = b_f \cdot (h_w + 2\cdot t_f) - h_w \cdot (b_f - t_w) = 2000
\]

\[
x_c = b_f \cdot 2 = 50
\]

\[
y_c = h_w + t_f \cdot 2
\]

\[
= 44
\]

\[
l_x = b_f \cdot (h_w + 2\cdot t_f)^3 - (h_w)^3 \cdot (b_f - t_w) \cdot 12
\]
Iy = 2.tf.(bf)3 + hw.(tw)3/12
= 1,334,166 mm^4

Ixy = 0
= 0

Ip = bf.(hw+2.tf)3 -(hw)3.(bf-tw)12+2.tf.(bf)3+hw.(tw)3/12
= 4,653,633 mm^4

We will take a modulus of elasticity E = 200 GPA.

**Stress analysis at point A:**

Free body diagram:

The force shown on the figure P1 is the force acting on the I beam coming from the weight of the system. Since we have 6 identical points in the system (6 identical legs holding the cross bars to the I beams) then the force P1 is identical to forces P2, P3, P4, P5, P6 and are equal to the total weight divided by 6:

P1 = P2 = P3 = P4 = P5 = P6 = Weight/6

= 266/6

= 44.3 kg
Now considering 1 l beam to analyze.

![Diagram of a single I beam](image)

**Figure 12: Side view of a single I beam**

Forces P1, P3, and P5 are identical and are equal to 44.3 kg.

Force of weight = mass x gravity.

\[
F = 44.3 \times 9.81
\]

\[
F = 435 \text{ N}
\]

[http://www.engineeringcalculator.net/cross_section_properties.html](http://www.engineeringcalculator.net/cross_section_properties.html)

A free body diagram showing all the reaction forces on the Beam:

![Free body diagram](image)

**Figure 13: Reaction forces of support**

P1, P3, and P5 are the forces exerted by the weight of the system on the support and are known quantities.

R1, R2, and R3 are the three reaction forces exerted by the support to resist the weight and are unknown.
Based on Newton’s laws of motion, the equilibrium equations available for a two-dimensional body are:

\[ \sum \vec{F} = 0 \]: The vectorial sum of the forces acting on the body equals zero. This translates to

\[ \Sigma H = 0 \]: the sum of the horizontal components of the forces equals zero;

\[ \Sigma V = 0 \]: the sum of the vertical components of forces equals zero;

\[ \sum \vec{M} = 0 \]: The sum of the moments (about an arbitrary point) of all forces equals zero.

In statics, a structure is statically indeterminate when the static equilibrium equations are insufficient for determining the internal forces and reactions on that structure. This is the case in our system; we have 3 unknowns to be solving using two equations.

\[ \sum \vec{F} = 0 \]

This equation yields: (taking the positive direction upwards)

\[ R_1 + R_2 + R_3 - P_1 - P_3 - P_5 = 0 \] equation 1

\[ \sum \vec{M} = 0 \]

This equation yields: (taking the positive direction counter clockwise)

\[ R_2 (L/2) + R_3 (L) - P_3 (P) - P_5 (P+Q) = 0 \] equation 2

Using the singularity function to develop a third equation and solve the system:

\[ q = R_1 < x - 0 > ^1 - 1 + R_3 < x - L/2 > ^1 - 1 + R_5 < x - L > ^1 - 1 \]

\[ V = \int R_1 < x - 0 > ^0 + R_3 < x - L/2 > ^0 + R_5 < x - L > ^0 + C1 \]

\[ M = \int R_1 < x - 0 > ^1 + R_3 < x - L/2 > ^1 + R_5 < x - L > ^1 + C1x + C2 \]

\[ \Phi = \int M/El = 1/El (R_1/2 < x - 0 > ^2 + R_3/2 < x - L/2 > ^2 + R_5/2 < x - L > ^2 + C1x^2/2 + C2x + C3 \]

\[ Y = \int \Phi = 1/El (R_1/6 < x - 0 > ^3 + R_3/6 < x - L/2 > ^3 + R_5/6 < x - L > ^3 + C1x^3/6 + C2x^2/2 + C3x + C4 \]

Solving the equations by hand or on MATLAB software to get 3 equations with 3 unknowns:
The next step after finding the reaction forces is to draw the shear and bending moment diagram of the system.

Next is to find the point of maximum moment.

Compute at that point the yield stress.

Find the safety factor.

Check if the safety factor is suitable.

If it is keep the 10cm wide I beam; if not recalculate using a wider beam.

In the following calculations R2 is eliminated to make the problem a 2 unknowns and 2 equations.

\[ \sum F \text{ along } y=0 \]
\[ -P_1-P_3-P_5+R_1+R_3= 0 \]
\[ R_1+R_3 = 435 \times 3 \]
\[ R_1+R_3 = 1305 \text{N} \]

\[ \sum M \text{ on } R_1 =0 \text{ (taking clockwise as the positive direction)} \]
\[ P_3(p)+P_5(p) +P_5(L) -R_3(L) =0 \]
\[ R_3(L)= P_3(p)+P_5(L) \]
\[ R_3= \frac{(P_3(p)+p_5(L))}{L} \]
\[ R_3= 435 \times 4 + 435 \times 2.8 / 4 \]
\[ R_3= 740 \text{N} \]
\[ R_1=565 \text{N} \]

2) Shear and moment diagram:
Figure 14: Free body diagram

Figure 15: Shear diagram
Figure 16: Moment diagram

\[ M_{\text{max}} = \frac{P_{ab} l}{4} = \frac{(435 \times 1.2 \times 2.8)}{4} = 356.4 \text{ N.m} \]

Figure 17: I beam cross section

\[ I = 4,653,633 \text{ mm}^4 \]

\[ \sigma = \frac{Mc}{I} = \frac{365.4 \times 4.8}{4,653,633} = 3.77 \text{ MPa} \]

Steel \( Sy = 250 \times 10^6 = 250 \text{ Mpa} \)

\[ n_d = \frac{Sy}{\sigma} = \frac{250}{3.77} = 66 \]
Stress analysis at point B: Normal stress on the leg

Normal stress = 435 N

Area of support = $S^2 - s^2$

Normal stress = \( \sigma = \frac{F}{A} = \frac{435 \text{ N}}{S^2 - s^2} \)

The side $S$ of this leg will be taken as

$S$ (out) = 8 cm

$S$ (in) = 7.4 cm
Thus a thickness of 3 mm per side

Based on the calculation:

Normal stress $\sigma = 0.470 \text{ MPa}$

Steel $\text{Sy}=250 \times 10^6 = 250 \text{ Mpa}$

$$n_d = \frac{\text{Sy}}{\sigma} = \frac{250}{0.47} = 531$$

**Stress analysis at point C: Middle Plate Calculation**

![Middle plate free body diagram](image)

*Figure 20: Middle plate free body diagram*
Figure 21: Middle plate sheer diagram

Figure 22: Middle plate moment diagram

\[ M_{\text{max}} = \frac{P}{4} \]
\[ M_{\text{max}} = \frac{(435 \times 0.5)}{4} \]
\[ M_{\text{max}} = 54.375 \text{ N.m} \]

Figure 23: Middle plate geometry

\[ b = 50 \text{ cm} = 0.5 \text{ m} \]
After performing the stress analysis on the critical point of the system and checking for a satisfactory factor of safety we moved ahead in creating the part according to our specified dimensions:

\[ \sigma = \frac{Mc}{I} \]
\[ I = \frac{bh^3}{12} \]
\[ I = \frac{0.5 \times 0.02^{12}}{12} = 3.33 \times 10^{-7} \]
\[ \sigma = \frac{Mh/2}{I} \]
\[ \sigma = \frac{54.375 \times 0.01}{3.33 \times 10^{-7}} = \frac{54.375 \times 0.01}{3.33 \times 10^{-7}} \approx 1.63 \text{ MPa} \]

\[ Sy = 250 \times 10^0 = 250 \]

\[ \frac{250}{1.63} = 153 \]

**Final Design**

After performing the stress analysis on the critical point of the system and checking for a satisfactory factor of safety we moved ahead in creating the part according to our specified dimensions:

Find below an inventory of the parts designed to be manufactured:

**Part name:** Longitudinal base long (red in the assembly picture)

**Quantity ordered:** 4

**Part description:** holds the vertical legs together

![Longitudinal base long](image)

**Figure 24: Longitudinal base long**

**Part name:** Cross bar

**Quantity ordered:** 3

**Part description:** lies on the 2 I Beams and hold a wooden support

![Cross bar](image)

**Figure 25: Cross bar**
Part name: I beam
Quantity ordered: 1 pair
Part description: is supported by vertical legs and holds the crossbars

Part name: square holder (green in the assembly picture)
Quantity ordered: 16
Part description: is welded on the vertical leg and holds the longitudinal and transverse holding legs

Part name: leg
Quantity ordered: 6
Part description: holds the I beams and the longitudinal leg supports.

Part name: transverse base long
(red in the assembly picture)
Quantity ordered: 6
Part description: holds the vertical legs together
Part name: S holder (yellow in the assembly picture)

Quantity ordered: 6

Part description: holds the wooden upper support

FULL ASSEMBLY

Manufacturing

The manufacturing of those parts is not feasible at AUB due to the busy shops and the relative time needed for manufacturing.

We contacted a design company called ACID design and production that guided us to their workshop. We have agreed on manufacturing all those parts at this fabrication shop for the cost of 1991 $ (including VAT and transportation to AUB on the 28th of May 2011)
Pumping system

The pumping system:
The pumping system is needed to accomplish two goals:

1. Create a near perfect vacuum (high vacuum) with a pressure of $10^{-9}$ Torr.
2. Inject hydrogen gas at a steady flow rate into the vacuum chamber to be ionized and turned into plasma.

The vacuum process:
The pump-down process is the process of pumping the air out of the chamber; it can be broken down into 3 phases:

A. The viscous phase (or the roughing phase): this is when the air molecules are still tightly packed and close to each other, so if we remove some molecules from the vacuum chamber then the remaining molecules will be redistributed to occupy the empty space; this is what is perceived by a pressure gradient. In this phase any positive displacement pump will be suited for the job.

B. The molecular phase: the flow is said to be molecular when the average distance between the molecules (also known as the mean free path) becomes greater than the dimensions of the vacuum chamber, therefore the molecules are more likely to hit the walls of the chamber than each other. Which means that we do not have flow caused by pressure differential anymore; and if we continue using a positive displacement pump then our removal rate will depend on air

Water vapor at high vacuum:

Once we get to $10^4$ Torr in our pumpdown process we will suddenly realize that water vapor has become the predominant gas, consisting 99% of all the molecules still present in the system. This water vapor has always been there, but because of the polar nature of the water molecule it will tend to form weak bonds with the walls of the chamber and with other water molecules. Subsequently the pumpdown speed of this phase will be controlled by the speed of desorption of water vapor, which happens at a slow rate. Therefore the only way to traverse this region is either to wait long enough for desorption to finish or accelerate the process artificially.

Figure 32: Effect of intermolecular distance on Pressure
molecules wandering by chance into the pump and out of the system. This is why we need a new type of pumps, high vacuum pumps which we will address later in more detail.

C. **The transition phase**: in this phase the flow can neither be characterized as viscous nor molecular, it is a very complex phase that normally requires special consideration, but by the way our system is designed we managed avoid the complexities of this phase by using both the molecular pump and the roughing pump at the same time thus avoiding the need for complex piping.

### Choice of Pumps:

The hardest choice is choosing the right molecular pump for the process, once this is done then we choose a suitable roughing pump that can support the molecular pump.

- **Molecular pump**: the molecular pump starts working at the pressure of $10^{-3}$ Torr, its main gas load does not come of the air inside the chamber (because that’s taken care of in the roughing phase of the pumpdown) but instead the main gas load will come from water molecules desorbing from the surface of the chamber. The molecular pump provided for us is a TURBO pump that is capable of achieving a pressure of $10^{-9}$ Torr and needs a backup pressure of $10^{-3}$ Torr.

- **The roughing pump**: needs to reach $10^{-3}$ Torr quickly and maintain that pressure to support the turbo pump. The pump also needs to be oil free to avoid contamination of the plasma that will jeopardize the experiments conducted. From an analysis of the
available pumps we concluded that a screw rotor oil free pump is our best choice. A summary of the available widely used pumps is presented below:

Complete pumping System Design:

First draft:

Figure 35: Vacuum Pumping System Preliminary Design

The Roughing pump characteristics are:

- Manually controlled pumping speed with high maximum speed.
- Able to reach and maintain a stable pressure of 1 mTorr.
- Oil free.
- Low maintenance.
- 1 in diameter input.

Therefore two Pumps are possible:

1. Two or more diaphragm pumps in series (possibly combined in a single device with multiple stages)
2. Vacuum screw rotor pump.
Good points to be kept:

- The pump down will be happening through 2 paths simultaneously, through the turbo pump and through a separate pipe. This has several benefits, it allows maximum conductance and allows the turbo pump to smoothly take over the molecular pump-down region, while avoiding complex piping. At the transition pressure of 1 mTorr, the roughing line will automatically stop the flow by using an automatic pressure control switch valve.

What needs to be changed?

- We don’t need digital pressure sensors, the analog ones work just fine alone.
- Although the choice of material for the pipes works, we can make the design simpler by using only Stainless steel pipes and discarding the Viton pipes.
- This current design needs to be connected to vacuum chamber by 2 openings, taking an extra 1 opening unnecessarily which can be used for measuring instruments. Therefore the updated design needs to use 1 opening only.
- It cannot be seen how the pumping system is connected to the vacuum chamber
- Instead of a screw rotor pump to pump in hydrogen, we can use what we already have which is a flow controller and a flow meter. Plus we need to add a second hydrogen input.

Updated draft:

Figure 36: Second draft of pumping system
Choice of pump: We previously establish that we needed an oil free roughing pump capable of reaching and maintaining $10^{-3}$. After carefully reviewing the options available at the market we concluded that the oil free pumps can either be diaphragm pumps or a rotor pump. But the problem with diaphragm pumps is that they don't reliably reach the target pressure. And the rotor pump is too expensive. Therefore we will opt for a vane pump, but it should be coupled with an oil trap to prevent oil from leaking into the system that could be disruptive to the plasma creation process.

Connection type: we determined the appropriate connection type between the components which is summarized in the following diagram.

Figure 37: third draft of pumping system
**CF flange and KF flanges:** These are vacuum flanges connecting the vacuum chamber and tubing.

![Image of a CF flange and KF flange](image)

**Figure 38: CF flange**

**Figure 39: KF flange**

- We added a pressure reducer connected to the hydrogen tank to control the flow when subjected to large pressure differences.

**Bill of material for the pumping system:** The bill of material for the pumping system is included in appendix B.
Part 5: the Coil Box

We worked on the design of the coils boxes. In fact each of the coils will have a box in order to support it, and to cool it. The coils are used to generate a constant magnetic field in order to control the plasma and accelerate it. Each box is made from aluminum because it is not affected by the magnetic field.

The diameter of the coil is considered as 1.6 cm. In each box the coil will loop 24 times, and form 2 sets with 12 loops each.

Note that the coil is well insulated.

The box is dimensions are 8cm for the height, 90cm for the length and 90cm for the width.

The upper and lower plate is linked by 8 hollow beams on the sides.

In order to design one of these boxes, we took several factors into consideration. In our design we have 2 inlet on the front plate and one outlet for the water on the back side plate as shown in the figure below in order to make sure that all the coil is cooled by water (of 25 C temperature).

![Coil Box Diagram](image)

Figure 40: Coil Box

We also have one inlet for the coil on the front side plate and one outlet on the back side plate.

The upper and lower plates are linked by a cylindrical plate in the middle as shown in figure above.

Inside we have 8 similar plates placed as shown in the figure blow.
The Plates are designed to allow the coil to loop 24 times and allow the water to circulate around the coils in order to cool it.

We are currently working on the heat transfer calculations; since the coil will generate heat; we have to do some heat calculations in order to know how much water we need in order to cool the coils, the temperature, the mass flow rate, the type of insulation the pump used and other important characteristics for the design.

After finishing all the necessary calculations and design, we are going to start manufacturing the boxes in the Engineering shops.

**Coil configuration:**

Each coil box should be able to provide 500 Tesla. But to minimize the cooling load and make sure the coils are safe, we are using two coils (with 250 Amperes) in each instead one. Each 3 coils will be supplied with one generator.

![Coil configuration](image)

**Figure 42: Coil configuration, each three coil boxes will be supplied with one generator**

\[ A = 7^2 - 2^2 \times \pi = 36.43 \text{ mm}^2 = 3.643 \times 10^{-5} \text{ m}^2 \]

\[ R = \rho_{\text{copper}} \frac{\ell}{A} = 1.68 \times 10^{-8} \times \frac{30}{3.643 \times 10^{-5}} = 0.0138 \Omega \]
For a single coil box we have: \( R_{eq} = \frac{R}{2} = 6.9 \times 10^{-3} \Omega \)

Therefore \( V_{\text{coil box}} = R_{eq} \times I_{\text{max}} = 3.45 \text{ V} \)

The voltage that needs to be supplied by the power supply is \( V_{\text{total}} = 10.35 \text{ V} \).

The current passing through each coil is: \( I_{\text{coil}} = 250 \text{ A} \)

The heat generated by each coil is \( Q = R \times I_{\text{coil}}^2 = 862.5 \text{ W} \)

Therefore each coil box, having 2 coils will generate \( Q_{\text{box}} = 1725 \text{ W} \).

And since we estimate a maximum of 15 coil boxes \( Q_{\text{max}} = 25875 \text{ W} \) which is well within the cooling capabilities of the heat exchanger provided for us.

\[ m(\dot{m}) = \frac{Q}{C_p \Delta T} \]

- \( m(\dot{m}) = 618.82 \text{ grams/sec} \)
- \( m(\dot{m}) = 0.61882 \text{ L/s} \)
- \( m(\dot{m}) = 37.1292 \text{ L/min or Lpm} \)

Our heat exchanger supplies 30 to 78 Lpm. (note that the water will be supplied in parallel to all the coils)
Appendix A

Part 1) “Ethical and professional responsibilities”

This project, when it was first presented to our group, presented a lot of technical difficulties and obstacles that we had to solve and get around. For emerging engineers such as ourselves, it usually feels that the most important and vital objective of any project is to overcome the technical needs and henceforth the project will be basically completed. However, and this may sound a bit prescient, it never ends with just the physical and mathematic solutions. As with everything else in life, there is no black and white, just shades of grey, and the field of engineering is no different. We do not live in isolation from the rest of society, and issues that might sound redundant when we’re going full throttle in our workplaces, such as philosophy, religion, ethics, and law, are actually of grave importance to our success and failure. We are constantly faced with decisions in the workplace (and life in general) that can define career and life paths. Each decision we make, will produce ripples in the very fabric of society that can have endless consequences. Therefore, we have established a set of general guidelines and structures, rather using the “rules” or “law”, which sounds altogether more severe. These guidelines include the “Order of Engineers Code of Ethic” and the ASME guidebook as well. Now, as I have pointed out and from what we learned, no project can come close to being considered completed if it doesn’t go through a rigorous ethical examination, not by anyone other than its innovators. So going through the “Order of Engineers Code of Ethic”, we have found that most guidelines were committed to not through conscious action, but rather through our normal behaviorally patterns, since most of these ethical codes were gained in life, and henceforth applied in engineering. A basic example of this perfunctory ethical behavior is the following article: “Engineers shall perform services only in the areas of their competence.” Obviously, it goes without saying that we are working in a field that is very much own. There is also the example of not causing someone harm on purpose. The point we’re trying to make is that some ethical constraints need not be even considered if the engineer is a sane and fully functioning member of society. Any discrepancy in that and the problem extends beyond just
the realm of engineering and becomes a fully-fledged social problem. Now that we covered slithers of examples that poses no challenge, lets us go into something much more “challenging” shall we say. When, at the beginning, we were discussing the advantages reaped by producing such a wonderful and exciting project, the professor told us that this could be useful in our future careers. Now this might sound like an exciting prospect for us in the group, but there is a catch, one that occurred to us simultaneously with the compliment: what if in the foreseeable future, a company offered us well-paid, lofty positions, to work on a project highly relevant to the one we are working on now. What then? What if the company told us they wanted to see the documents we produced in the university, do we allow such a breach? Even though it will probably help our careers, it will produce a massive ethical dilemma: the freedom and right to thought. The following is the general article that deals with this train of ethical thought: “Engineers shall not disclose, without consent, confidential information concerning the business affairs or technical processes of any present or former client or employer, or public body on which they serve.” Therefore as you can see, the nature of this project, which very different and in general much more advanced than our previous example, can cause some gigantic ethical dilemmas. The larger the ambition of the project, the bigger the ripple it causes in society.

Part 2) “Understanding in a social context”
This is a wonderful issue to discuss, and in my humble opinion, the whole purpose of this project. To put it in an extremely simple, “non-technical” way: our project produces clean renewable energy. Now you may have heard about our little issue with the depleting fossil fuel reservoirs, and thus the huge energy crisis that awaits us in the not so distant future. At every level, from high-school science fairs, to international crisis meetings, everyone is discussing the energy topic, and of course the topics surrounding it as well, from pollution, to the advantages and disadvantages of nuclear energy and who should have it in the first place, and several other topics intertwined under the main heading of “energy”. It can truly be considered one of the paramount issues facing the international society. Therefore the search for clean, renewable energy is at its most fervent, and we are working on one of the scenarios that might eventually
be the solution to our problems. Our project, the “plasma vacuum chamber” can be described quite simply as a machine that turns air into energy. Now, this is a very child-like and simple description to our project that masks the intricate process that is undergoing, but in essence this is its purpose, and this is of course how it will be presented to the masses. This project will be able to produce and clean, renewable energy and if rough estimates are taken into consideration, at prices and costs much, much lower than producing energy in say a fossil-fuel based power plant. Therefore, we might say proudly, that we as engineers are working for the greater good of all of humanity, and while our efforts might barely affect the society in greater sense, the idea that we contributed to the improvement of the quality of man’s life is truly satisfying.

Part 3) “Project as a Business Model”
As optimistic as we sound in the previous part about the applicability and practicality of the “Plasma Vacuum chamber” we must also sound a note of caution. The designs and plans are far from the finished article, and it will require further advancement in technology to be able to fully perfect the machine. Especially considering that arguably the machine’s most vital component, the electric field, is still rough and rarely produces the effect that engineers seek in such machines. Therefore, with our efforts, instead of producing the finished article, we are paving the way for future generations, who will have more advanced technologies at their disposals, to perfect our work. In the engineering world, results cannot be attained just by one trial, one experiment, or one attempt to innovate. It is a gradual process where various engineers pool in their efforts and talents to slowly but surely attain the results that are desired. Even then, the work of engineer is never over. We must always seek to improve, modify and ultimately perfect our designs, for the greater good of humanity.
# Appendix B

## Table 3: Bill of material of pumping system

<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity</th>
<th>Critical dimension</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MAIN VACUUM LINE</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roughing pump</td>
<td>1</td>
<td>input diameter = 1 in.</td>
<td>refer to diagram</td>
</tr>
<tr>
<td>Stainless steel connection pipe</td>
<td>1</td>
<td>Diameter = 1 in. Length = 20 in.</td>
<td>this can be ignored if the 3 way valve fits directly to the roughing pump</td>
</tr>
<tr>
<td>3 way vacuum valve</td>
<td>1</td>
<td>Diameter = 1 in.</td>
<td>suitable for pressure of 1 m Torr</td>
</tr>
<tr>
<td>Stainless steel connection pipe</td>
<td>1</td>
<td>Diameter = 1 in. Length = 20 in.</td>
<td></td>
</tr>
<tr>
<td>Turbo Pump</td>
<td>1</td>
<td>input diameter = 10 in. Output diameter = 1 in.</td>
<td>able to reach 10^-9 Torr.</td>
</tr>
<tr>
<td>Reducer</td>
<td>1</td>
<td>10 in x 8 in</td>
<td>suitable for High Vacuum</td>
</tr>
<tr>
<td>Butterfly Valve</td>
<td>1</td>
<td>Diameter = 8 in.</td>
<td>suitable for High Vacuum</td>
</tr>
<tr>
<td>T-connection</td>
<td>1</td>
<td>8 in main line. 1 in secondary line</td>
<td>suitable for high vacuum (this is used to connect the secondary vacuum line to the first)</td>
</tr>
<tr>
<td>Gate valve</td>
<td>1</td>
<td>Diameter = 8 in.</td>
<td>suitable for high vacuum</td>
</tr>
<tr>
<td><strong>SECONDARY VACUUM LINE</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stainless steel connection pipe</td>
<td>1</td>
<td>Diameter = 1 in. Length = 20 in.</td>
<td>suitable for High Vacuum</td>
</tr>
<tr>
<td>Automatic switch valve</td>
<td>1</td>
<td>Diameter = 1 in.</td>
<td>suitable for High Vacuum</td>
</tr>
<tr>
<td>Stainless steel connection pipe</td>
<td>1</td>
<td>Diameter = 1 in. Length = 20 in.</td>
<td>suitable for High Vacuum (connects to the T-connection in the main vacuum line)</td>
</tr>
<tr>
<td><strong>HYDROGEN INPUT</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow controller</td>
<td>2</td>
<td>Outer Diameter = 1.33 in.</td>
<td></td>
</tr>
<tr>
<td>Flow meter</td>
<td>2</td>
<td>Outer Diameter = 1.33 in.</td>
<td>suitable for High Vacuum</td>
</tr>
<tr>
<td>Stainless steel connection pipe</td>
<td>1</td>
<td>Diameter = 1.33 in. Length = 15 in.</td>
<td>suitable for High Vacuum</td>
</tr>
<tr>
<td>Pressure relief valve</td>
<td>1</td>
<td>Outer Diameter = 1.33 in.</td>
<td>atmospheric to high vacuum</td>
</tr>
<tr>
<td><strong>MEASUREMENT INSTRUMENTS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Analog thermal Conductivity gauge</td>
<td>2</td>
<td>Outer Diameter = 1.33 in.</td>
<td>accurate above 1 mTorr</td>
</tr>
<tr>
<td>Analog Ionization gauge</td>
<td>1</td>
<td>Outer Diameter = 1.33 in.</td>
<td>accurate below 1 mTorr</td>
</tr>
</tbody>
</table>
Table 4: Gasket requirements

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Description</th>
<th>Outer Diameter (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>24 holes flange</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>6 holes flange</td>
<td>2 3/4</td>
</tr>
<tr>
<td>1</td>
<td>24 holes flange</td>
<td>10</td>
</tr>
<tr>
<td>1</td>
<td>20 holes flange</td>
<td>8</td>
</tr>
<tr>
<td>6</td>
<td>6 holes flange</td>
<td>2 3/4</td>
</tr>
<tr>
<td>6</td>
<td>20 holes flange</td>
<td>8</td>
</tr>
<tr>
<td>1</td>
<td>20 holes flange</td>
<td>8</td>
</tr>
<tr>
<td>1</td>
<td>8 holes flange</td>
<td>4.5</td>
</tr>
<tr>
<td>2</td>
<td>8 holes flange</td>
<td>4.5</td>
</tr>
<tr>
<td>2</td>
<td>8 holes flange</td>
<td>4.5</td>
</tr>
<tr>
<td>2</td>
<td>16 holes flange</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>6 holes flange</td>
<td>2 3/4</td>
</tr>
<tr>
<td>1</td>
<td>20 holes flange</td>
<td>8</td>
</tr>
<tr>
<td>1</td>
<td>24 holes flange</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>24 holes flange</td>
<td>10</td>
</tr>
<tr>
<td>1</td>
<td>16 holes flange</td>
<td>6</td>
</tr>
<tr>
<td>1</td>
<td>24 holes flange</td>
<td>10</td>
</tr>
<tr>
<td>1</td>
<td>20 holes flange</td>
<td>8</td>
</tr>
</tbody>
</table>