Charge tracing for determining electrical facility effects on electric spacecraft propulsion systems.

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ME/AE 4800
Mechanical/Aerospace Engineering Project

Charge Tracing for Determining Electrical Facility Effects on Electric Spacecraft Propulsion Systems

Group 23

Joseph Backe
Tyler Bye

April 20, 2021
Electric Propulsion Systems are the future of deep space travel. Since its design in 2016 Western Michigan University has been testing a Hall-Thruster from a previous Senior Design Group. One issue with Electric Propulsion Systems is tracing where the electrons go after being used to ionize propellant for spacecraft acceleration. Induced magnetic fields on Earth alter the electron paths found in the vacuum of space.

One solution is the EP TEMPEST. The EP TEMPEST is an electron tracer designed by the Air Force Research Laboratory. The goal of this project is to design an electron tracer like the EP TEMPEST but on a smaller scale.

The design of an electron tracer would consist of the use of SolidWorks to create a visual model of the electron tracer and COMSOL Multiphysics® to simulate the conditions within the electron tracer while a thruster is running.
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Disclaimer

This project report was written by students at Western Michigan University to fulfill an engineering curriculum requirement. Western Michigan University makes no representation that the material contained in this report is error-free or complete in all respects. Persons or organizations who choose to use this material do so at their own risk.
<table>
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<td>AFRL</td>
<td>Air Force Research Lab</td>
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<tr>
<td>ALPE</td>
<td>Aerospace Lab For Plasma Experiments</td>
</tr>
<tr>
<td>ECR</td>
<td>Electron Cyclotron Resonance</td>
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<tr>
<td>HET</td>
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1. Introduction

1.1 Introduction to Project

Currently, space measurements of electric-propulsion systems have digressed significantly from measurements taken on earth and numerical simulations. Some factors for interaction with Hall-Thrusters are well understood whereas others are either poorly understood or completely unknown. [4,10]

To understand these differences, the Air Force Research Lab designed a confinement cage that operates within a vacuum chamber. The confinement cage is an electrically floating Faraday cage. The cage has segmented and isolated conductive panels to take measurements for total and distributed plume current flux. [4,10]

The measured current in this chamber was nearly zero as to be expected. Minimal current can be linked to ions and electrons leaking through porous walls. The confinement cage could be a useful tool to explore interactions between vacuum chambers and electric-propulsion thruster plumes. [4,10]

1.2 Motivation

In 2016 a Senior Design Group at Western Michigan University designed a Hall-Thruster shown in Figure 1. This Hall-Thruster is currently being used for research in the Aerospace Lab for Plasma Experiments at Western Michigan University.

Current measurements taken on Earth for electric-propulsion systems do not accurately reflect the conditions in the vacuum of space. It is currently unknown where electrons go after being used to ionize propellant for spacecraft acceleration. When testing an electric propulsion system on Earth there is also interference from magnetic fields that would not exist within space [4,10]. An inability to track electrons decreases the efficiency of electric-propulsion across the board.

The Air Force Research Lab has designed and built an electron tracer named the EP TEMPEST. ALPE would like a senior design group to design an electron tracer similar to the EP TEMPEST, but on a smaller scale.
1.3 Project Plan

The first step was to understand on a rudimentary level how EP TEMPEST worked. This included how a Hall-Effect-Thruster operated, magnetic field interactions, and how the EP TEMPEST geometry affects ions and electrons within the containment field, specifically the beam dump. Understanding these topics allowed building materials, key parameters, and instrumentation to be chosen for the confinement cage.

After conducting this research a SolidWorks model for the cage was designed. Images of the Air Force Research Lab’s existing EP TEMPEST and members of the project were heavily consulted in understanding how to design a confinement cage for this project.

While building the model in SolidWorks, instrumentation such as ion gauges, cables, and controllers needed to be ordered. Several companies were consulted, Duniway, Kurt J Lesker, Instrutech, and LDS Vacuum, with questions concerning: controllers, ion gauges, and connecting cables. After much talk with these companies, it was decided that the cables would need to be built independently of a distributor to meet feedthrough specifications into the vacuum chamber. This meant research into cables and pin configurations to build a cable that would meet the specifications for both our controller and the purchased ion gauges.
After finishing a SolidWorks model the confinement cage required simulation. A two-dimensional cross-section was created for simulation. The simulation took place within COMSOL Multiphysics® to determine if the proposed design met the key parameters of a confinement cage, ideally minimal net current and minimal induced magnetic fields.

### 1.3.1 Decision Matrix

<table>
<thead>
<tr>
<th></th>
<th>Cost</th>
<th>Weighted Cost</th>
<th>Ease of Design</th>
<th>Weighted Design</th>
<th>Vacuum Chamber Criterion</th>
<th>Weighted Vacuum Criterion</th>
<th>Compatibility With Existing Technology</th>
<th>Weighted Technology Compatibility</th>
<th>Score</th>
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<td>10</td>
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<td>5</td>
<td>25</td>
<td>4</td>
<td>20</td>
<td>67</td>
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**Figure 2: Decision Matrix**

Figure 2 contains an image of a decision matrix that summarizes key decisions that have been made for the duration of the project. When designing anything cost is always a key factor, however parameters such as meeting the criterion to work in a vacuum chamber and compatibility with current market technology proved to be more important than cost or ease of design.

The final decisions made are as follows: ion gauges will be purchased from a vendor, one available controller will be used and the other controller will be purchased from a vendor, the purchased ion gauges will be hot glass ion gauges, cables that will be used to connect the ion gauges to the controllers will be designed instead of purchased.

### 1.4 Hall-Effect Thruster Background

HETs are one of a few different types of ion thrusters being researched currently for deep space travel. The main components of a hall thruster include a cathode, anode, electromagnets, a backplate, and a channel. Each of these components is vital for the thruster to properly function. The anode design is very important because this is where the plasma starts to generate from where the electric field and the magnetic field cross, thus accelerating the ions out the ceramic channel providing thrust in the opposite direction. The electromagnetic coil provides the magnetic field that is crossing the channel diameter while dipping down within the channel to provide a more concentrated thrust plume. The preferred gas that is used within these thrusters is Xenon gas due to its ability to easily ionize and relatively high mass compared to other inert
gases. HET are quite promising for its thrust capabilities once the space vehicle has already exited the Earth’s atmosphere. The plume of ions exiting the thruster should neutralize shortly after discharge with the electrons discharging separately. This brings the total electric flux of the system theoretically to zero [6,9].

This is important to understand due to the inability to ground any electrical system in space. Regarding this senior design project, understanding what happens to the particles after each leaves the thruster is vital to understanding how efficient the system will be in practical use [6,9].

1.5 Confinement Cage Background

In space, the electric attraction between an ion and electron will keep the electrons near the thrust axis. In a vacuum chamber, the electric attraction between the ion and electron is not as strong. Ambient pressures and plasma plume density are higher here. This allows a conduction path leading to the chamber walls that would not exist in space. [4,10]

The purpose of the confinement cage is to monitor plume currents and interactions while thruster operation is maintained to determine how the ion stream interacts with the earth’s environment and how this causes performance to differ from that of space. [7]
2. Component Designs

2.1 Vacuum Chamber

*Figure 3: Large Chamber Solidworks Assembly*

The Constraints of the design relating to dimensioning and overall size of the design of the project refer to Figure 3 shown above. This is the large vacuum chamber available in the ALPE lab. The chamber has a length of 68.19 inches and an inner diameter of 41 inches. The square support has a cross-section with a length of 30.97 inches. The overall design must fit within the length and diameter of the chamber for optimal testing. It should slide and fit within the 8020 strut railings providing support for the design.

Using the only design available at this time provided by the AFRL a smaller design was created for smaller testing by Universities with less allocation and funding for vacuum chambers. The design must also be large enough to fit the Western Hall Thruster currently being used for research purposes and other thrusters currently being designed by students in the lab. Currently only HETs have been tested in this type of apparatus, but hopefully in the near future ECR thrusters and more can have the opportunity to further research on electron discharge in-ground vacuum chambers.
2.2 Strut

Due to the design constraints listed above. The design must fit within the large vacuum chamber located in the ALPE on-campus laboratory. The decision was to change the six-ring design formerly used by AFRL into a two-ring design. Ring one would be 26 inches in length with a hexagonal design. The hexagonal design would have six strut pieces measuring 30.31 inches at its widest point and 27 inches tall. These dimensions stand true for the two ring design with the only difference being the length of 36 inches.

The strut chosen was 8020 strut with one-inch by one-inch square T slot design. This was due to an abundance of the material available within the ALPE laboratory.

2.3 Honeycomb Mesh

As shown in Figure 5, the Honeycomb mesh design was purchased from McMaster-Carr and is identical to the mesh used by AFRL in their design with the part number 9635K4. To make the device as close to the original as possible, parts that could be identical were kept as such. The cell size is ½ inches in size and ¾ inches in thickness.
Each piece was cut to size to fit within the 8020 strut square openings differing for each ring. Although the mesh will not support any load besides its own weight it can hold a maximum capacity of 165 lbs./sq. in.

### 2.4 Fine Mesh

![Stainless Steel Wire Cloth](image)

*Figure 6: Stainless Steel Wire Cloth [1]*

The fine mesh shown in Figure 6, was purchased from McMaster-Carr. It is the same mesh product used by AFRL in their design with part number 9319T159. The mesh has an opening size of 0.02 inches, an open area of 37%, and a wire diameter of 0.013 inches. The mesh is cut to specification to cover the inside of the confinement cage.

### 2.5 Back Wall

![Ring 1 with Back Wall Pictured](image)

*Figure 7: Ring 1 with Back Wall Pictured*
The back wall is the location where the preferred thruster will be attached and tested. Two vertical strut beams can be adjusted for the optimal placement of the thruster in the horizontal direction. On the vertical beams, a backplate is mounted for adjustment in the vertical direction. The back wall is technically a connection to the first ring in terms of circuitry. Theoretically, no charged particles should escape and go towards the back wall, but there are mesh inserts in case this does occur.

2.6 Beam Dump

![Beam Dump Diagram](image)

The beam dump is where the thruster plume of escaping ionized Xenon particles and free electrons are moving towards. The angled hexagonal shape is to prevent particles from refracting off of the wall and going back in the direction of the thruster exit. The angle of the beam dump is approximately ten degrees into the apparatus. It is made of the same mesh materials as the two ring assemblies as well as using the same 8020 strut as the frame of the system. The hexagonal hole left in the beam dump is covered with an
acrylic transparent material that a camera lens can fit into for testing purposes on the thruster.

2.7 Ring Separation Insulator

![Figure 9: Ring 2 with Insulator Pictured](image)

The ring separation insulator is designed identical to the dimensions of the outside hexagonal dimensions of the rings. Each insulator is identical to the other for manufacturing purposes and construction simplicity. The insulation ring is designed as six separate rectangular members that cover each ring end completely to avoid current leakage between the separate partitions. G-10 fiberglass material selection provides ample insulation between the rings and avoids any gaps to prevent leakage from escaping charged particles from the cage system.
2.8 Confinement Cage

*Figure 10: Confinement Cage Within Vacuum Chamber*

*Figure 11: Confinement Cage Isometric View*
3. Testing

3.1 Experiment Setup

The experiment was conducted in COMSOL Multiphysics®. Due to the symmetrical nature of the cage, a two-dimensional cross-section of the confinement cage was constructed within COMSOL Multiphysics® as seen in figure 12. Material properties were added to the corresponding sections consisting of Aluminum and air. Possibly to the deficit of the simulation, most of the cross-section was given the material properties of aluminum. In actuality, the three-dimensional model is going to have a large amount of air. The conductance of air is significantly lower than aluminum. The Electrostatics and Electric Current tool packages were used to simulate electric conditions within the cross-section.

The Electrostatics toolbox was used to simulate the electric potential across the cross-section. Grounds were placed at the beam dump (left end of figure 12) and the back wall (right end of figure 12). An electric potential of 250V [2] was applied for the HET based on previous anode potential from previous senior design groups.

The Electric Current toolbox was used to simulate the current density across the confinement cage. Grounds were applied in the same positions as the Electrostatics toolbox and the same potential was applied. In the calculations for electric current, a negligibly sized square was placed to create the potential in the simulation.
3.2 Results

3.2.1 Electric Potential

The expected electric potential would be higher around the HET as the propellant is ionized and electrons are accelerated by the more electrically dense protons. As you leave the area surrounding the thruster electrons are neutralized. This would cause a decrease in potential the further you move from the cage.
The results from COMSOL Multiphysics® show exactly that. Around the area where the HET is simulated maximum potentials of 250 V are shown. As you leave the thruster area and approach the idealized grounds the electric potential decreases. This validates both the two-dimensional cross-section assumption and the use of a confinement cage for HET testing.

### 3.2.2 Electric Current

In space, the current density of an ion stream must be zero. As aforementioned the testing on Earth does not lead to these ideal conditions even within a vacuum chamber. The above
results show minimum current density at any point within the confinement cage. This gives a net current of essentially zero. When the units of the current density are taken into consideration compared to the actual size of the cross-section the results are incredibly low. The current density is in A/m² with results ranging from $10^{-17}$ to about $10^{-7}$ and the areas of the sections are less than a few hundred square inches.

### 3.2.3 Electric Field

![Electric Field of Cross-Section](image)

The magnetic fields within the simulation range from $10^{-24}$ to $10^{-4}$ V/m. The upper boundary appears very high. However the lengths within the simulation cage are on the order of 5 inches. The magnetic fields at these points are relatively weak when the length of the section is taken into consideration.

Minimal magnetic fields are induced within the confinement cage. This models the non-existent magnetic fields that the HET would encounter in space.
4. Future Improvements

COMSOL Multiphysics® is a program that neither member is familiar or comfortable with. Much of the simulation was designed by watching tutorials and trial runs. In the future, a more sophisticated and refined model in COMSOL Multiphysics® would give better results to the group building the confinement cage. One thing to note is that the model is basically a solid piece of metal. In actuality, there is going to be air in the confinement cage. The conductance of air is much lower than aluminum. Results may be exaggerated to the group’s deficit in this simulation.

Determine if the beams in the vacuum chamber would affect the circuitry of the confinement cage. This was not considered beforehand and there was not time to run a simulation.

The University does not have particle tracing within their COMSOL Multiphysics® license. It was originally planned to include electron tracing within the final results. Unfortunately, these resources were not available. Having particle tracing as part of the simulation would further help in the building of the confinement cage.
5. Constraints

The entirety of this project was executed during a global pandemic. All meetings and discussions were conducted through WebEx. The software was accessed via remote login. Time that would not have been taken during a semester in person was taken due to computer malfunction.

Due to COVID-19 protocol access to the lab and university was limited. Only one student was able to go into the lab throughout the semester as the schedule opened up. Many times there was time spent waiting for someone in the lab to email specifications as neither member was in the lab at the time.

The University did not have particle tracing in their COMSOL Multiphysics® license. One part of the previously planned simulation had to be removed due to this.
6. ABET

1. Is this project useful outside of the United States? Describe why it is or not—provide Details.
   This project would be useful outside of the United States. The project does not further a company's ability to mainstream a product. It is a research and design project that has the intent of furthering electric propulsion research at Universities.

2. Does your project comply with U.S. and/or international standards or regulations? Which standards are applicable?
   We believe the project complies with U.S. standards. It was originally done by the Air Force Research Lab and is now moving towards University application. Specific standards are unknown to us currently.

3. Is this project restricted in its application to specific markets or communities? To which markets or communities?
   This project is restricted to the research sector concerning electric propulsion.

4. If the answer to any of the following is positive, explain how and, where relevant, what were your actions to address the issues?
   N/A
7. Conclusion

When testing the model design in COMSOL Multiphysics® a current flux close to zero and minimal to non-existent magnetic fields were desired. The simulation results show that there is a minimal current density throughout the entirety of the cross-section. Having a minimal current density throughout the entirety of the cross-section shows two things. The first is that the net current is approximately zero. The second is that the current leakage is approximately zero. The simulation results also show minimal magnetic fields within the cross-section. These are three key parameters for the confinement cage. As they are all met the design for the confinement cage is validated through the simulation.
8. Acknowledgements

The knowledge and support needed to complete this project was immense. A special thank you goes out to:

- Dr. Kristina Lemmer - Faculty Mentor
- Nagual Simmons - Industry Mentor
- Mike Holmes - Industry Mentor
- Lee Honors College - Sponsor
- Dr. Bade Shrestha - AE 4800 Professor
- Cristine Thomas - Administrative Assistant and Scholarship Award Liaison
- Christopher Boucher - COMSOL Multiphysics® Tutorials
- The many students within the ALPE lab who responded to emails concerning controller parameters and vacuum chamber information
9. References


10. Appendices

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Figure 16: Modified Gantt Chart of Actual Project Timeline
Appendix B - Technical Drawings

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Figure 44: Current Density of Large Ring
Figure 45: Current Density of Small Ring
Figure 46: Current Density of Large Mesh
Figure 47: Current Density of Small Mesh
Figure 48: Electric Field of Beam Dump
Figure 49: Electric Field of Large Ring
Figure 50: Electric Field of Small Ring
Figure 51: Electric Field of Large Mesh
Figure 52: Electric Field of Small Mesh
## Appendix D - Budget

### Figure 53: Budget

<table>
<thead>
<tr>
<th>Item (Part Number)</th>
<th>Category</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stipend</td>
<td>Labor</td>
<td>$1,500.00</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>$1,500.00</strong></td>
</tr>
</tbody>
</table>

### List of Expenses

<table>
<thead>
<tr>
<th>Item (Part Number)</th>
<th>Category</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire Mesh (85385T105)</td>
<td>Materials</td>
<td>$135.36</td>
</tr>
<tr>
<td>Pressure Sensors (PN2294)</td>
<td>Materials</td>
<td>$868.00</td>
</tr>
<tr>
<td>Progressive Ring Fitting (E40261)</td>
<td>Materials</td>
<td>$22.00</td>
</tr>
<tr>
<td>Honeycomb Cores (9635K4)</td>
<td>Materials</td>
<td>$247.02</td>
</tr>
<tr>
<td>Misc. Parts</td>
<td>Materials</td>
<td>$226.62</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>$1,500.00</strong></td>
</tr>
</tbody>
</table>