DEVELOPMENT OF AN ANNULAR MICRO-HALL-EFFECT THRUSTER AND HALBACH PERMANENT MAGNET ARRAYS IN HALL-EFFECT THRUSTERS

by

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A THESIS

Submitted in partial fulfillment of the requirements for the degree of Master of Science in the Department of Aerospace Engineering in the Graduate School of The University of Alabama

TUSCALOOSA, ALABAMA

2018
ABSTRACT

The research following began the initial steps in developing a micro-Hall-effect thruster for the use on a University of Alabama designed and built CubeSat. Additionally, the implementation of an asymmetric magnetic field utilizing a Halbach array of permanent magnets was computationally modelled and constructed. Facilities to support this research we’re not available at UA at the beginning of this effort, and were developed over the course of the research.

Results of the magnetic computational models found a large difference in the magnetic fields of the MHET ring magnet and Halbach array designs. The UA MHET ring magnet was successfully operated for a combined 20 hours of testing, at a range of 5 to 50 W of power over varying voltages and mass flows. Additionally, two ion current sweeps were taken using a Faraday probe and the data analyzed, with the result that the design that was swept was not magnetically correct and would need to be solved before continuing testing.

With a new design constructed, testing will continue to verify the magnetic field is correct and a nominal ion current sweep is achieved. Additionally, the operational window for the design, the lifetime, and thrust must all be tested before a thruster can be deemed flight ready for a UA CubeSat. Additionally, the Halbach array variant should also be tested and compared to the ring magnet design to look for novel operation and potentially useful results to implement into future Hall-effect thruster designs.
DEDICATION

This thesis is dedicated to my family, friends, and mentors that have supported me through all of my education, research, and the writing of this thesis.
### LIST OF ABBREVIATIONS AND SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔV</td>
<td>Delta V, Change in Velocity</td>
</tr>
<tr>
<td>W</td>
<td>Watt</td>
</tr>
<tr>
<td>mi</td>
<td>Initial Mass, kg</td>
</tr>
<tr>
<td>mf</td>
<td>Final Mass, kg</td>
</tr>
<tr>
<td>V&lt;sub&gt;ex&lt;/sub&gt;</td>
<td>Exhaust Velocity, m/s</td>
</tr>
<tr>
<td>I&lt;sub&gt;sp&lt;/sub&gt;</td>
<td>Specific Impulse</td>
</tr>
<tr>
<td>L</td>
<td>Plasma Length, m</td>
</tr>
<tr>
<td>w</td>
<td>Plasma Width, m</td>
</tr>
<tr>
<td>eV</td>
<td>Electron Volt</td>
</tr>
<tr>
<td>T</td>
<td>Tesla</td>
</tr>
<tr>
<td>B</td>
<td>Magnetic Flux Density, Gauss or Tesla</td>
</tr>
<tr>
<td>r&lt;sub&gt;e&lt;/sub&gt;</td>
<td>Electron Larmor Radius, m</td>
</tr>
<tr>
<td>m</td>
<td>Electron Mass, $9.10938356 \times 10^{-31}$ kg</td>
</tr>
<tr>
<td>e</td>
<td>Electron Charge, $-1.6021766208 \times 10^{-19}$ C</td>
</tr>
<tr>
<td>T&lt;sub&gt;eV&lt;/sub&gt;</td>
<td>Electron Temperature in eV</td>
</tr>
<tr>
<td>r&lt;sub&gt;i&lt;/sub&gt;</td>
<td>Ion Larmor Radius, m</td>
</tr>
<tr>
<td>M</td>
<td>Ion Mass, Xenon, $2.1801714 \times 10^{-25}$ kg</td>
</tr>
<tr>
<td>V&lt;sub&gt;b&lt;/sub&gt;</td>
<td>Beam Voltage, Volts</td>
</tr>
<tr>
<td>I&lt;sub&gt;i&lt;/sub&gt;</td>
<td>Ion Current, Amps</td>
</tr>
</tbody>
</table>
$n_i$  Ion Density, 1/m³
$V_d$  Discharge Voltage, Volts
$R$  Mean Channel Radius, m
$T$  Thrust, Newtons
$\langle \sigma v_e \rangle$  Ionization Reaction Rate
$n_n$  Neutral Density, 1/m³
$n_e$  Electron Density, 1/m³
$v_n$  Neutral Velocity, m/s
$\Gamma_n$  Neutral Flux into Plasma
$\lambda_i$  Mean Free Path of Ionization
$I_H$  Hall Current, Amps
Torr  133.3224 Pa = 0.01933677 psi
sccm  Standard Cubic Centimeter, 0.0983009 mg/s Xenon
$r_p$  Probe Radius
$\theta_p$  Probe Angle from Centerline
$j_b$  Beam Current Density
$I_a$  Anode Current, Amps
$V_a$  Anode Voltage, Volts
$m_a$  Anode Mass Flow, sccm
$I_K$  Keeper Current, Amps
$V_K$  Keeper Voltage, Volts
$m_c$  Cathode Mass Flow, sccm
$P_b$  Base Pressure
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_o$</td>
<td>Operating Pressure</td>
</tr>
</tbody>
</table>

AFIT  Air Force Institute of Technology
ACKNOWLEDGMENTS

Without the help of everyone in my life, I wouldn’t have been able to have the academic career I’ve had and grateful for.

First and foremost, I am thankful to Lt. Col. (Ret.) Dr. Richard Branam, the chairman of my thesis committee. During my undergrad, he was willing to allow me the responsibility of setting up the SPOT Lab when I knew nothing of electric space propulsion or vacuum technology. His guidance and teachings have been immeasurable in inspiring my passion for electric space propulsion, maturing technical and academic skills, and supporting me during this research effort. I would like to also extend a big thank you to the other two committee members of my thesis, Dr. Semih Olcmen and Dr. Subhadra Gupta, for taking the effort and time to review my thesis and share their thoughts.

Additionally, I cannot overstate the gratitude I feel for my parents, Holly and Bob Kendrick and Brian Hill, for the support they have given me the past 18 years of my education and the 6 years before that. Their guidance and financial support are what have brought me to this point in my life and I truly wouldn’t be here without them.

I also would like to thank my girlfriend, Sarah Black, for being my best friend and president of my fan club. She has been there to support me through all of my research when things don’t go according to plan, and pushing me to achieve everything she sees in me. I look forward to many more years of sharing and experiencing life together.
CONTENTS

ABSTRACT ................................................................................................................................. ii
DEDICATION .............................................................................................................................. iii
LIST OF ABBREVIATIONS AND SYMBOLS .............................................................................. iv
ACKNOWLEDGMENTS ............................................................................................................... vii
LIST OF FIGURES ..................................................................................................................... xii

1 INTRODUCTION ..................................................................................................................... 1
   1.1 Research Motivation and Concept Overview ................................................................. 1
   1.2 Problem Statement ......................................................................................................... 2
   1.3 Research Objectives ....................................................................................................... 3
   1.4 Document Overview ...................................................................................................... 4

2 BACKGROUND AND PREVIOUS RESEARCH ..................................................................... 6
   2.1 History and Use for Electric Space Propulsion ............................................................... 6
   2.2 Hall-Effect Thrusters .................................................................................................... 10
      2.2.1 History .................................................................................................................... 10
      2.2.2 Architecture ........................................................................................................... 12
      2.2.3 Design ................................................................................................................... 15
   2.3 Magnetic Field Design .................................................................................................. 23

3 METHODOLOGY .................................................................................................................. 28
   3.1 Magnetic Simulation ...................................................................................................... 28
A.2 Lessons Learned.............................................................................................................................. 102
LIST OF TABLES

Table 2-1 Comparison of Electric Propulsion Systems \(^5\) ................................................................. 9

Table 4-1 UA MHET Ring Magnet Operating Conditions ................................................................. 82
LIST OF FIGURES

Figure 1-1 NASA NEXT Ion Thruster\textsuperscript{6} ................................................................. 2
Figure 1-2 NASA Hall-Effect Thruster\textsuperscript{6} .................................................................... 2
Figure 2-1 Effective Exhaust Velocity vs Acceleration\textsuperscript{5} ........................................ 8
Figure 2-2 SPT-100 Thruster Model\textsuperscript{8} ..................................................................... 11
Figure 2-3 Hall-Effect Thruster Cross-Section\textsuperscript{10} .................................................. 15
Figure 2-4 Busek BHT-20 Cross Section ............................................................................. 17
Figure 2-5 UA Micro-Hall-Effect Thruster Cross Section ................................................... 18
Figure 2-6 Earlier Design UA Halbach MHET Full Cross Section ....................................... 19
Figure 2-7 Channel Plasma Density Cross Section in a Hall-Effect Thruster\textsuperscript{16} .......... 20
Figure 2-8 UA MHET Thrust and Ion Current vs Discharge Voltage .................................. 22
Figure 2-9 NASA-173Mv Hall Thruster Magnetic Field Lines\textsuperscript{16} .............................. 24
Figure 2-10 Colorado State University 1 kW Thruster Cross-Section\textsuperscript{17} .................... 25
Figure 2-11 Colorado State University Magnetic Screen Analysis\textsuperscript{17} ....................... 26
Figure 2-12 Halbach Magnet Array and Resulting Flux ......................................................... 27
Figure 3-1 Simplified Halbach Array Thruster Magnetic Model ........................................... 29
Figure 3-2 EMS Materials List .......................................................................................... 30
Figure 3-3 EMS Halbach Array Magnetization Direction .................................................... 31
Figure 3-4 Global Mesh Size vs. Axial Magnetic Field in Ring Magnet Thruster .................. 32
Figure 3-5 Meshed Thruster Model with (Left) and without (Right) Air Cavity ...................... 33
Figure 3-6 Data Points Overlaid Thruster Cross-Section ................................................. 34
Figure 3-7 MATLAB Plot for Magnetic Field ................................................................. 35
Figure 3-8 Red Vacuum Chamber .............................................................................. 36
Figure 3-9 Xenon Propellant Plumbing .................................................................... 38
Figure 3-10 Xenon Tank with Regulator .................................................................... 39
Figure 3-11 Propellant Feed System Diagram ......................................................... 40
Figure 3-12 Power and Electronics Server Rack ......................................................... 42
Figure 3-13 Faraday Probe Electrical Schematic ..................................................... 43
Figure 3-14 Faraday Probe Sweep12 ......................................................................... 45
Figure 3-15 Collector Voltage vs. Measure Current ............................................... 46
Figure 3-16 H6 HET ion current density vs. angular position12 .............................. 47
Figure 3-17 Rotation Stage Solidworks Model ............................................................ 48
Figure 3-18 Rotation Stage Prototype ....................................................................... 49
Figure 3-19 3-Axis Stepper Motor Drive Controller ............................................... 50
Figure 3-20 3-Axis Stepper Motor Drive Controller Electrical Schematic .............. 51
Figure 3-21 Laser Pointer Mounted on Rotation Stage ............................................ 52
Figure 4-1 UA MHET Ring Magnet Radial Magnetic Flux Density, 3 mm
Upstream of Exit Plane ............................................................................................ 54
Figure 4-2 UA MHET Halbach Array Radial Magnetic Flux Density, 3 mm
Upstream of Exit Plane ............................................................................................ 55
Figure 4-3 UA MHET Halbach Array Radial Magnetic Flux Density Across 0°
Cross-Section Inside Thruster Channel and Past Exit Plane ............................... 56
Figure 4-4 UA MHET Ring Magnet Radial Magnetic Flux Density Across
Cross-Section Inside Thruster Channel and Past Exit Plane ............................... 57
Figure 4-5 UA MHET Halbach Array Axial Magnetic Flux Density Across 0°
Cross-Section Inside Thruster Channel and Past Exit Plane ............................... 58
Figure 4-6 UA MHET Ring Magnet Axial Magnetic Flux Density Across Cross-Section Inside Thruster Channel and Past Exit Plane ........................................ 59

Figure 4-7 Ring Magnet Radial Magnetic Field .................................................................................. 60

Figure 4-8 Ring Magnet Axial Magnetic Field .................................................................................. 61

Figure 4-9 UA MHET Halbach Array Eight Azimuthal Sections ......................................................... 62

Figure 4-10 Radial B Field Across Inner Channel Wall ....................................................................... 63

Figure 4-11 Axial B Field Across Inner Channel Wall ......................................................................... 64

Figure 4-12 Radial B Field Across Middle of Channel ........................................................................ 65

Figure 4-13 Axial B Field Across Middle of Channel ......................................................................... 66

Figure 4-14 Radial B Field Across Outer Channel Wall ..................................................................... 67

Figure 4-15 Axial B Field Across Outer Channel Wall ....................................................................... 68

Figure 4-16 UA MHET Version 1 Rear View ...................................................................................... 70

Figure 4-17 UA MHET Version 1 Front View .................................................................................... 70

Figure 4-18 UA MHET Version 1 Cross-Section ............................................................................... 71

Figure 4-19 UA MHET Version 1 Successful Ignition ....................................................................... 72

Figure 4-20 UA MHET Version 2 Required Components ................................................................... 74

Figure 4-21 UA MHET Version 2 Fully Assembled ........................................................................... 74

Figure 4-22 UA MHET Version 2 Cross-Section ............................................................................... 75

Figure 4-23 UA MHET Version 2 Operating at 20 W ....................................................................... 76

Figure 4-24 UA MHET Version 3 Cross-Section ............................................................................... 77

Figure 4-25 UA MHET Halbach Array Cross-Section ...................................................................... 78

Figure 4-26 UA MHET Aluminum Halbach Array Spacer Assembly ................................................. 79

Figure 4-27 UA MHET Halbach Array Spacer Weak Side ................................................................. 80
Figure 4-28 UA MHET Halbach Array Spacer Strong Side with Spacer .................................................. 80
Figure 4-29 UA MHET Halbach Array Spacer Strong Side without Spacer ............................................ 81
Figure 4-30 UA MHET Ring Magnet Anode Voltage vs. Anode Current ............................................. 83
Figure 4-31 UA MHET Ring Magnet Anode Current vs. Time at 175V ............................................. 84
Figure 4-32 Vacuum Chamber Faraday Background Ion Current ....................................................... 85
Figure 4-33 Standard Deviation of Background Ion Current ................................................................. 86
Figure 4-34 Hollow Cathode Faraday Sweep Current ........................................................................ 87
Figure 4-35 UA MHET Ring Magnet Version 2 Faraday Sweep Ion Current ..................................... 88
Figure 5-1 HeatWave Labs LaB6 Crystal Thermionic Cathode ............................................................. 93
Figure 5-2 AFIT Torsion Balance with BHT-20 Integrated ................................................................. 94
Figure 5-3 X-Y-Theta Translation Stage Concept .................................................................................. 95
Figure 5-4 UA MHET Ring Magnet Design Flight Design ................................................................. 97
Figure A-1 Laser Pointer Perpendicular to Thruster Exit Plane ......................................................... 101
Figure A-2 Aligning Faraday Probe Height ......................................................................................... 102
Figure A-3 UA Hollow Cathode with Keeper Removed ........................................................................ 103
Figure A-4 Thermionic Cathode Installed in Faraday Test Setup ....................................................... 105
Figure A-5 CSU Cathode Installed in Faraday Test Setup .................................................................. 106
1 INTRODUCTION

1.1 Research Motivation and Concept Overview

Within the last decade, the space industry has become increasingly more privatized. Multiple new launch providers and satellite developers give customers from new markets a variety of choices to accomplish their mission. With privatization, more emphasis has been placed on performing the required mission with tighter budgets and schedules than with previous government programs. Industry and academia are attempting to meet many of these new constraints through the CubeSat Program. CubeSats are standardized micro-sized satellites typically under 10 kg, developed by Stanford and Cal Poly in 1999. CubeSats reduce the cost of entry for science experiments in space and can demonstrate new technology deemed too risky for larger, more expensive satellites. CubeSats’ main benefit is the free ride on commercial satellite launches. In recent years, more commercial and government missions have chosen CubeSats as the platform to perform their missions, allowing them to stretch their budgets further.

By the beginning of August 2017, only one CubeSat, developed by Purdue, has successfully launched and tested a CubeSat propulsion system. The ability to modify a CubeSat’s orbit is paramount as the space industry adopts CubeSats for a wider range of missions. Many missions require the CubeSat to deviate from the initial orbit it is placed in during its launch. Multiple propulsion companies (i.e. Aerojet Rocketdyne and Busek) are developing CubeSat propulsion systems or entire CubeSat buses for clients to purchase. The NASA iSat mission will demonstrate an iodine propellant Hall-effect thruster in space (Busek). Lockheed Martin’s
SkyFire mission plans to demonstrate an electrospray thruster. However, these systems have yet to be flown.\(^1\) With the cost of these commercial propulsion systems oriented for governmental and commercial budgets, most university CubeSat programs are unable to include one in their satellite designs. Universities unable to afford a commercial propulsion system are forced to either launch without one or develop their own system, as is the goal of B3Sat at the University of Alabama.

CubeSats need to maximize \(\Delta V\) of the propulsion system to be a viable mission option. Unfortunately, CubeSat standards prevent many conventional propulsion systems from being employed.\(^2\) Per the standard, propellants must be unpressurized and non-combustible during the entire launch sequence until deployment of the CubeSat. This restriction eliminates the use of bi-propellant engines, hydrazine thrusters, or increasing the propellant density (pressure) in the propellant tank above 100 Watt-hours. The most probable result is the employment of an electric propulsion device such as an ion thruster (Figure 1-1) or Hall-effect thruster (Figure 1-2).

\[\text{Figure 1-1 NASA NEXT Ion Thruster}^{\text{6}}\]

\[\text{Figure 1-2 NASA Hall-Effect Thruster}^{\text{6}}\]

1.2 Problem Statement

The University of Alabama Aerospace Engineering and Mechanics department plans to develop and launch a CubeSat with a propulsion device in the next five years. Currently, the University does not have an available propulsion device to use on the CubeSat, or the facilities to
test the propulsion device and CubeSat. To meet the five-year deadline, UA must develop vacuum facilities to test propulsion and CubeSats, as well as an electric propulsion device capable of operating on a CubeSat platform.

Maximizing propulsion capability ($\Delta V$ available) for the B3Sat precludes the use of traditional chemical propellants, leaving electric propulsion as the obvious choice. A Hall-effect thruster meets the mission requirements of the B3Sat CubeSat while still being simpler to design and test than an ion thruster. A Hall-effect thruster system operating in the micronewton thrust range ($100 – 200 \mu N$), while remaining under 100W of power, is to be designed, constructed, and characterized as the first step for flight certifying a University developed CubeSat propulsion system. Additionally, alternative magnetic field configurations are to be explored and tested to identify potential efficiency improvements when compared to traditional, industry standard configurations.

1.3 Research Objectives

The key objectives of this research focus on Hall-effect thruster development as well as:

1. Designing, constructing, and testing a sub-100W Hall-effect thruster.

2. Characterize the operating power and thrust range of the sub-100W, or micro-Hall-effect thruster.

3. Operate the micro-Hall-effect thruster continuously for 100 hours as an initial life test.

4. Implement Halbach magnetic arrays into the micro-Hall-effect thruster design and compare power, thrust, and life results to the original design.

The research greatly benefits from previous research on a 20W Hall-effect thruster developed by Busek with the designation BHT-20. Busek’s BHT-20 is a cylindrical-channel
Hall-effect thruster as opposed to the more traditional annular-channel thruster design. Struggles with efficiency using the cylindrical design led to the choice to return to a traditional annular design.

A non-traditional magnetic field configuration using permanent magnets arranged in a Halbach array was devised to replace the traditional radial field design found in commercial Hall-effect thrusters employing electromagnets. The Halbach array uses a modified cusp field to increase the field strength in one direction and reducing the strength in the opposing direction. The increased field strength is critical when designing micro-Hall-effect thrusters. The required magnetic field strength inside the thruster channel increases as the diameter of the channel decreases in order to enforce a smaller radius for the electron motion in the channel.

The complex motion of electrons and ions introduced by the asymmetric properties of the Halbach array requires complex computer simulations to best model the thrusters. Unfortunately, this effort was considered outside the scope of this research and will be accomplished in subsequent iterations of the design. Currently, the primary goal was to prove the Halbach array will improve performance. An engineering model was built to compare with the original model constructed with a more traditional magnetic field.

1.4 Document Overview

First, the fundamentals and history of electric space propulsion and the Hall-effect thruster are discussed (Chapter 2). An in-depth description of Hall-effect thruster design along with calculations for the micro-Hall-effect thruster used for this research are also provided. The development of the experimental setup required to perform this research follows the thruster discussion (Chapter 3). The lab was required to be built from the ground-up for this research. No facilities were available at the University of Alabama capable of performing the experiment.
Chapter 4 contains the experimental results of the research for both the traditional micro-Hall-effect thruster and the new Halbach array thruster. The paper ends with a summary and conclusions of the research drawn from the results (Chapter 5). This final section will also provide recommendations for future researchers who will continue the development of the micro-Hall-effect thruster and the potential further implementation of the Halbach array in it.
2 BACKGROUND AND PREVIOUS RESEARCH

This section provides a brief discussion of the history of electric space propulsion and the theory governing Hall-effect thrusters. The design of Hall-effect thrusters will be discussed, as well as the physics behind Halbach magnet arrays. The calculations used to design the UA micro-Hall-effect thruster will be reviewed, as well as the design integration of the Halbach magnet array into the outer channel wall.

2.1 History and Use for Electric Space Propulsion

Electric Space propulsion has a history that rivals modern chemical rocket propulsion. Robert H. Goddard was one of the first to mention the possibility of electric propulsion in his studies of chemical propulsion in the early 1900’s. However, the testing of electric space propulsion in space did not occur until 1964 with the test of SERT I (Space Electric Rocket Test), where a sounding rocket carried an ion thruster on a suborbital trajectory. In the years that followed, electric propulsion devices such as pulsed plasma thrusters (PPTs), ion thrusters, arcjets, augmented-hydrazine thrusters, and hall thrusters have either been tested on orbit or included in commercial satellite bus systems, providing the foundation of satellite propulsion today. A large increase in the use of electric space propulsion on orbit can be attributed to the advancement of electricity generation on orbit via solar panels in the 1990’s.

No one space propulsion system has yet been developed able to fully satisfy all stages of a mission’s requirements optimally. Chemical systems, such as liquid bi-propellant engines or solid rocket motors may be the best option for launch and perform well for large orbital
maneuvers with short timeframe requirements. Chemical systems prove to be less than ideal for missions requiring many orbit changes or adjustments (station keeping), though. For direct interplanetary missions, chemical propulsion is limited to inner planet missions only (use of gravity assist has enabled missions to the outer planets). Missions to outer planets in the solar system will require the use of high performance thrusters (electric propulsion) with higher levels of efficiency (specific impulse, I<sub>sp</sub>) in terms of mass savings. The effective exhaust velocity of a particle is directly related to the efficiency of a system in propelling a single atom, transferring the resultant momentum to the space system (Figure 2-1). Electrical systems offer effective exhaust velocities greater than four time that of a chemical system. The improvement results in a drastic reduction in thrust capabilities for electric propulsion systems. For launch vehicles, traditional chemical system thrust to weight ratios need to be greater than 1.0, allowing the vehicle to achieve orbit. This is not required for electric propulsion systems, where forces on the space vehicle are much lower. Electric propulsion systems are incapable currently of launching from Earth into orbit.
When examining the effective exhaust velocity further, its relationship to total system mass and $\Delta V$ produced can be better understood through Eq. (2-1), the Tsiolkovsky equation. The equation calculates the change in velocity of a system reducing its mass at a specific velocity. This change in velocity, $\Delta V$, directly translates to changes in orbits in space.

$$\Delta V = V_{ex} \ln \left( \frac{m_i}{m_f} \right)$$  \hspace{1cm} (2-1)

For a desired payload mass ($m_f$), the best way to increase the $\Delta V$ of the system is to increase the effective exhaust velocity, $V_{ex}$, reducing the total propellant needed to accomplish the mission. For a spacecraft mission (i.e. station keeping) requiring the same $\Delta V$ (i.e. 2000 m/s),
a liquid chemical system \((V_{ex} \sim 4000 \text{ m/s})\) will require more than four times as much propellant than a typical electric propulsion system \((V_{ex} \sim 20,000 \text{ m/s})\)

\[
\left( V_{ex} \ln \left( \frac{m_i}{m_f} \right) \right)_{CH} = \left( V_{ex} \ln \left( \frac{m_i}{m_f} \right) \right)_{EL} \rightarrow \frac{(m_p)_CH}{(m_p)_EL} = \frac{1 - e^{-V_{ch}/\Delta V}}{1 - e^{-V_{el}/\Delta V}} = 4.13
\]

Electric space propulsion has demonstrated extremely high efficiency but only offer limited thrust. With the exception of magnetoplasma dynamic (MPD) thrusters, a relationship can be seen in Table 2-1 Thrust provided by an electric propulsion system is inversely related to the specific impulse \((I_{sp})\).

**Table 2-1 Comparison of Electric Propulsion Systems\(^5\)**

<table>
<thead>
<tr>
<th>Engine Type</th>
<th>Specific Power, (a) (W/kg) (estimated)</th>
<th>Thruster Efficiency, (n_t)</th>
<th>Specific Impulse, (I_{sp}) (sec)</th>
<th>Thrust (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistojet</td>
<td>333-500</td>
<td>0.8-0.9</td>
<td>280-310</td>
<td>0.2-0.8</td>
</tr>
<tr>
<td>Arcjet</td>
<td>313</td>
<td>0.33-0.35</td>
<td>450-600</td>
<td>0.2-0.25</td>
</tr>
<tr>
<td>Ion Propulsion</td>
<td>400</td>
<td>0.7</td>
<td>1400-4300</td>
<td>0.25-0.235</td>
</tr>
<tr>
<td>Hall</td>
<td>283</td>
<td>0.55</td>
<td>1650</td>
<td>0.088</td>
</tr>
<tr>
<td>MPD-steady</td>
<td>N/A</td>
<td>0.5</td>
<td>2000-5000</td>
<td>N/A</td>
</tr>
<tr>
<td>MPD-Pulsed</td>
<td>N/A</td>
<td>0.0068-0.009</td>
<td>836-1000</td>
<td>0.0003</td>
</tr>
</tbody>
</table>

For the purposes of a UA CubeSat propulsion system, volume restrictions severely reduce the total impulse \((\Delta V)\) available for the mission. Current orbit profiles put UA’s CubeSat in Low Earth Orbit (LEO), requiring the spacecraft to actively maintain their orbit due to aerodynamic drag. The Hall-effect thrusters are uniquely suited for this role (station keeping) due to their higher thrust density. The thrust density will allow the B3Sat CubeSat to maintain the LEO placed in at launch longer than CubeSats without a propulsion system, or overcome the drag found in LEO and achieve a new higher orbit around earth or another celestial body entirely.
2.2 Hall-Effect Thrusters

Hall-effect thrusters rely on applied radial magnetic field and applied axial electric field. In the thruster channel, the radial magnetic field is concentrated in a region near the exit plane, the furthest point from the gas inlet possible in the channel. The Hall-effect describes how the electrons are trapped in a circular motion ($\mathbf{E} \times \mathbf{B}$, perpendicular to both the electric and magnetic fields) around the azimuth of the thruster channel, prevented from escaping by the magnitude of the magnetic field. The applied electric field creates a voltage potential between the anode (bottom of the thruster channel) and cathode. Ions are created by the trapped electrons (direct impact) and then the resulting electrostatic force accelerates ions out of the channel.

2.2.1 History

In the 1960’s, research on Hall-effect thrusters started in the Soviet Union and the United States. After preliminary development was made on the Hall-effect thruster in the United States, it was decided to be less useful due to the thruster’s lower $I_{sp}$ performance.\(^6\) With this in mind, the United States focused on ion thrusters. In the Soviet Union however, development continued on the Hall-effect thruster, improving the thrust, efficiency, and $I_{sp}$ of their thrusters. In contrast to the United States, the USSR performed very little research on ion thrusters. To date, the Soviet Union has flown more than 100 Hall-effect thrusters in space on their satellites.

After the fall of the USSR in the 1990’s, the US became very interested in Soviet Hall-effect thruster technology. Researchers wanted to verify many of the claims of improved performance and thruster lifetime; $I_{sp} \sim 1600$ sec, 7,000 hours on the SPT-100, Figure 2-2.\(^7\)
The US has made significant advances in Hall-effect thruster research since the 90’s, resulting in the first few Hall-effect thruster systems flown by US satellites. Understanding of the plasma physics occurring in the thruster, as well as optimization parameters for a specific Hall-effect thruster size, have been advanced under US research efforts. The most recent advancements are being demonstrated on NASA’s Hall Effect Rocket with Magnetic Shielding (HERMeS) and High Voltage Hall Accelerator (HIVHAC) thrusters. NASA’s Human Exploration Directorate has determined that a 50-kW Solar Electric Propulsion (SEP) system would enable near term and future manned missions\(^9\), and these NASA programs are progressing manned space flight propulsion systems to achieve missions not possible previously.

Recent advancements with HERMeS and HIVHAC will eliminate the most limiting Hall-effect thruster shortcoming, life expectancy. The high velocity ions leaving the thruster have limited the lifetime by eroding the channel walls away. This erosion has forced NASA to consider other electric propulsion options that meet the 20,000+ lifetime hours needed by deep space missions. Magnetic shielding of the walls reduces the erosion of the Hall-effect thruster’s

---

**Figure 2-2 SPT-100 Thruster Model\(^8\)**
ceramic channel walls by nearly 1000-fold, Hofer et al.\textsuperscript{10}. The reduction in erosion eliminates channel life concerns, limiting Hall-effect thruster life to the life expectancy of the cathode, which is well understood and resolved. With this technical problem solved, Hall-effect thrusters are poised to be the primary choice for future human exploration and science missions in the US for the coming decades.

2.2.2 Architecture

When given a cross-section of a Hall-effect thruster, the number of components necessary for operation usually surprise most. Classified as a magnetostatic thruster, a static magnetic field is created in the channel of the thruster and require very few components to operate a Hall-effect thruster; anode/gas inlet, discharge chamber/channel, electromagnet circuit or permanent magnets, and cathode, Figure 2-3.

- **Anode/Gas Inlet:** Usually made of stainless steel, the anode is located at the bottom of the discharge channel. A gas line connects to the anode in one or more locations around the thruster channel. Propellant is dispersed evenly around the discharge chamber through gas flow control methods inside the anode. The anode potential is typically 200 to 400 volts for nominal operation. The potential between the anode and cathode accelerates the electrons into the channel. The magnetic field traps the electrons by imparting a Hall-effect force on them (ExB). The ions are propelled out of the channel by the potential created by the anode.

- **Discharge Chamber/Channel:** The discharge channel, in US designs, consists of an insulator, typically a ceramic like alumina or boron nitride. Ions are accelerated while still in the chamber (ionization occurs over a region in the channel). The wall material must be able to handle plasma over a range of temperatures, 10 to 20 eV,
while also resisting sputtering from ions. Most commercial thrusters use boron nitride as the to minimize wall erosion and performance degradation. With implementation of magnetic shielding, the resistance to ion sputtering becomes much less of a requirement, and in some cases the requirement of the material to be an insulator is not necessary.

- **Magnetic Circuit:** The magnetic circuit for a Hall-effect thruster features electromagnets and a ferromagnetic frame. The first component usually consists of copper wire wrapped around four (nominally) posts on the outside of the discharge channel (external magnet coil in Figure 2-2). An additional post with a similar copper coil is placed in the center of the thruster. The internal magnet is wired to generate the opposite magnetic field inside of the discharge channel (internal magnet coil in Figure 2-2). Current flows in opposite directions for the external and internal magnet coils and the generated magnetic fields are complementary. If the external magnet coil is oriented as a north pole (positive) on the exit plane, then the internal magnet coil at the exit will be the south pole (negative).

The ferromagnetic frame holds the electromagnets, anode, and discharge channel in position. The material is ferromagnetic, allowing the applied magnetic field to be shaped by following the geometry of the frame. The goal is to provide a uniform, radial magnetic field in the discharge chamber with a minimum number of external magnet coils.

- **Cathode:** The cathode provides the electrons that are used in the Hall-effect thruster channel to create the Hall current that ionizes the neutral propellant injected at the anode. The electrons are pulled toward the anode through the
potential difference between the anode and cathode, but are trapped in the radial magnetic field located near the exit plane of the thruster. The $\mathbf{E}\times\mathbf{B}$ field the electron experiences at the exit plane causes it to spiral azimuthally around the thruster channel near the exit plane, parallel to the anode face. The Hall movement continues until an electron impacts a propellant neutral, ionizing the neutral. Additionally, the cathode produces electrons that are injected into the Hall-effect thruster plume, neutralizing the ions in the plume to prevent a spacecraft potential that would attract the ions back to the spacecraft. This attraction back would result in a reduction in $\Delta V$ created by the system.
2.2.3 Design

The use of the Busek BHT-20 as a baseline design for UA’s micro-Hall-effect thruster greatly accelerated the development of UA’s MHET. The BHT-20 provided the channel length, channel radii, and magnetic field strength for the initial values in the design. The Busek BHT-20 (Figure 2-4) differs from the one used in this thesis; a cylindrical channel rather than the
traditional annular channel. Annular thrusters feature outer and inner magnetic circuits with opposing poles. Cylindrical thrusters do not have an inner magnetic circuit at roughly the same plane that annular thrusters do. The anode is used as a neutralizing point for the magnetic field of the channel for cylindrical thrusters, creating a radial magnetic field that slopes towards the anode. This design is more practical for small thrusters where the surface area to volume ratio of the plasma is higher than in annular thrusters, reducing thermal and electron losses to the channel walls. Additionally, design constraints limit the ability to implement an annular magnetic circuit in extremely small thrusters, and cylindrical channels is one possible solution to that problem.

With an outside channel radius chosen to match the BHT-20’s radius, the Larmor electron radius, \( r_e \), must be much smaller than both the length of the thruster channel and the channel width when using an annular design. Without this relationship, the electrons in the hall current at the exit plane of the thruster will either spiral into the channel walls on the outside or inside of the channel, or will spiral towards the anode and be lost, resulting in a lower thruster efficiency. This is directly related to the radial magnetic field in the channel, \( B \), found in Equation 2-2. The stronger the magnetic field in the channel, the smaller the electron radius. In larger thrusters, with power levels in the 1 kW range, the magnetic field can be smaller, and is in some cases preferred.

\[
r_e = \frac{1}{B} \sqrt{\frac{8 m}{\pi e^2} T e V} \ll L
\]  

(2-2)
When developing the UA MHET, the goal was to increase the efficiency of the thruster, which was less than required by the B3 CubeSat with a BHT-20. The major change between the BHT-20 and UA’s micro-Hall-effect thruster (MHET) was the inclusion of a center post and magnet. This conversion resulted in a traditional annular thruster channel with much more literature. The resulting geometry can be seen in Figure 2-5.
The capability to move the center post up and down the channel axially was incorporated while converting the thruster to the annular design. A moveable center post allows small changes to the magnetic field to tune the thruster to maximum performance. The exact location of the center post magnet is expected to have a significant effect on the plume and thruster operation. The center post was integrated into the center of the anode and gas line. The placement of the center post inside the gas line added complexity to the design to secure and center it in the channel. A retaining ring was added to hold the center post, Figure 2-6. Two sets of screws lock the center post axially and radially in the thruster channel through the retaining ring. One set independently centers the ring with the outside of the gas line. The other set of screws enter through holes in the gas line tube to clamp onto the center post. The introduction of
holes in the gas line required the use of o-rings and nuts to seal the holes from propellant leakage.

![Figure 2-6 Earlier Design UA Halbach MHET Full Cross Section](image)

The first step in sizing a Hall-effect thruster is to determine the electron and ion Larmor radii. The magnetic field strength is specifically chosen to match the Larmor radii to the thruster dimensions. Figure 2-7 is a cross section of a thruster channel with a generalized plasma density of width \( w \) and length \( L \). As propellant is supplied through the anode (width, \( w \)), it passes through the magnetized plasma in the shaded region (length, \( L \)). The propellant is ionized by electron-neutral impact in this plasma. The plasma density length of thrusters is designed to be
longer than the electron Larmor radius. The electrons have a greater chance of impacting a neutral before traveling to the anode, improving the thruster’s efficiency. Additionally, the electron Larmor radius is smaller than the width of the channel to avoid electron bombardment and erosion of the channel walls.

![Channel Plasma Density Cross Section in a Hall-Effect Thruster](image)

**Figure 2-7 Channel Plasma Density Cross Section in a Hall-Effect Thruster**

Expected electron temperatures \( (T_{eV}) \) in the ionization zone are in the range of 25 to 30 eV. The samarium cobalt ring magnet used in the BHT-20 can produce a magnetic field strength of 0.1 tesla at the middle of the thrust channel. The expected electron Larmor radius is just 0.2 mm, (0.007 inches), using Eq. 2-2. As designed, the thruster will meet the plasma region length \( L = 18.3 \text{ mm (0.720 inches)} \) and width \( w = 3.75 \text{ mm (0.1475 inches)} \).

\[
r_e = \frac{1}{B} \sqrt{\frac{8}{\pi e^2 T_{eV}}} \ll L
\]  

The channel length needs to also be much less than the ion Larmor radius, Equation (2-4), to maximize the ion mobility through the magnetized plasma region and out of the thruster channel. The longer channel length allows the ion to be accelerated out of the channel.
via the electric field rather than getting trapped in the magnetic field. A typical ion energy for this thruster is 300 eV (anode voltage potential). The ion Larmor radius \( r_i \) is 28.6 cm (11.25 inches) with the same samarium cobalt ring used in the electron Larmor radius equation which is much larger than the channel width and length.

\[
r_i = \frac{1}{B} \sqrt{\frac{2M}{e^2} V_b} \gg L \tag{2-4}
\]

To predict the thrust performance, ion current passing through the channel area \( A_c \) needs to be estimated. The discharge voltage of the thruster \( V_d \) can be varied to adjust operation of the Hall-effect thruster, as in Equation (2-5) with the Hall current. A thruster of this size can produce an ion density of 8.0E16 m\(^{-3}\) at the exit plane.\(^{13}\) The thrust is linearly proportional to discharge voltage, Equation (2-6). The thrust of the UA MHET over a variety of discharge voltages is expected to vary from 125 to 175 \( \mu \)N, Figure 2-8, which is similar to the measured BHT-20 performance. The variance of the calculated thrust can be calculated by taking the derivative of Equation (2-6) with respect to each variable, Equation (2-7). The expected variation on the discharge voltage, \( V_d \), is \( \pm 3V \); mean radius, \( R \), is \( \pm 0.025 \) mm; channel width, \( w \), is \( \pm 0.025 \) mm; and \( n_i \) is \( \pm 1.0\)E16.

\[
I_i = n_i e \sqrt{\frac{2e V_d}{M}} 2\pi Rw \tag{2-5}
\]

\[
T = I_i \sqrt{\frac{MV_d}{2e}} = (2\pi Rw) n_i e V_d \tag{2-6}
\]

\[
\Delta T = (2\pi Rw)n_i e \Delta V_d + (2\pi Rw)\Delta n_i e V_d + (2\pi R\Delta w)n_i e V_d + (2\pi \Delta Rw)n_i e V_d \tag{2-7}
\]
Finally, the length of the plasma, $L$, must be long enough ensure high efficiency in ionizing the neutral atoms (propellant utilization). To ensure high propellant utilization, the ionization region of the plasma needs to be large enough to ensure neutral atoms replenish the ions being accelerated out of the thruster. The empirically determined ionization reaction rate $\langle \sigma v \rangle$ provides the needed insight into neutral density in the ionization zone for a Maxwellian electron distribution, Equation (2-8), which can be found in appendix E of *Fundamentals of Electric Propulsion*.$^{16}$

$$ \frac{dn_n}{dt} = -n_n n_e \langle \sigma_i v_e \rangle \quad (2-8) $$

The flux of the neutrals entering the plasma (boundary condition) (Equation (2-9)), can be modeled to provide neutral density in the plasma, Equation (2-11).

$$ \Gamma_n = n_n v_n \quad (2-9) $$
\[
\frac{d\Gamma_n}{\Gamma_n} = -\frac{n_e (\sigma_i v_e)}{v_n} \, dz
\]

\[
\Gamma_n(z) = \Gamma(0) e^{-z/\lambda_i}
\]

(2-10)

(2-11)

\( \Gamma(0) \) refers to the neutral flux upstream of the plasma, injected from the anode. In this equation, \( z \) is the coordinate in the axial direction and \( \lambda_i \) is the mean free path of ionization (Equation (2-12)), the average distance a neutral atom will travel before colliding with an electron. As the electron density \( (n_e) \) increases, the mean free path will decrease, increasing the chance a neutral atom is ionized.

\[
\lambda_i = \frac{v_n}{n_e (\sigma_i v_e)}
\]

(2-12)

The design goal is to ensure less than 1% of the neutrals exit the plasma region \( (L) \) without ionizing, Equation (2-13). The necessary plasma length \( L \) to reach 99% ionization is achieved at a length of 4.6 times the mean free path. For 95% ionization, a length of 3 times the mean free path would be necessary.

\[
\frac{\Gamma_{exit}}{\Gamma_0} = 1 - e^{-L/\lambda_i}
\]

(2-13)

\[
L = -\lambda_i \ln(1 - 0.99) = 4.6\lambda_i
\]

(2-14)

For this research, the neutral velocity is approximately 10 m/s, and the ionization coefficient is 7.61E-15 m^3/s at a temperature of 5.0 eV. The plasma length is expected to be 1.64 mm (0.065 inches) long, Equation (2-15).¹⁴ The 10:1 channel length to plasma length ratio allows the design to reduce the magnetic field near the anode (plasma to demagnetize).

\[
L = \frac{v_n V_d w e}{I_H (\sigma_i v_e) B} = 1.64 \text{ mm}
\]

(2-15)

2.3 Magnetic Field Design

Asymmetric magnetic fields in the thruster channel (i.e. Halbach array or cusp field) are not studied much in contemporary research efforts. An axisymmetric magnetic field in a Hall-
effect thruster channel is well understood on the impacts towards both ionization and thrust performance and an optimized magnetic field can result in a thruster with upwards of 60% efficiency. Before the advent of magnetic shielding\textsuperscript{15}, magnetic field topology was fairly uniform in thruster channels, with the radial magnetic field peaking near the exit of the thruster channel and decaying in strength as it approaches the anode, as shown in Figure 2-9.

![Figure 2-9 NASA-173Mv Hall Thruster Magnetic Field Lines\textsuperscript{16}](image)

Modern thrusters utilize a magnetic circuit featuring ferromagnetic material magnetized by electromagnetic posts on the inside and outside of the thruster channel, Figure 2-10. The post material, usually an iron alloy, amplifies the applied magnetic field and creates a uniform radial field in the channel. Additionally, this magnetic circuit’s shape allows the magnetic field to turn towards the channel, reducing the axial field in the channel, “Pole Pieces” in Figure 2-10. When the electromagnets are powered, magnetic field strength increases in the “Pole Pieces”. Magnetic field lines develop between the inside and outside pole pieces of the thruster channel, creating the axisymmetric radial field. Also, “Magnetic Screens” are used to shield most of the
thruster channel from the magnetic field generated by the pole pieces, Figure 2-10. These magnetic screens shape the magnetic field to ensure the Hall-effect in the plasma is maximized at the exit plane.

![Diagram of Thruster Cross-Section](image)

**Figure 2-10 Colorado State University 1 kW Thruster Cross-Section**

Optimization of the magnetic field can dramatically improve the performance of the thruster, Figure 2-11. A resulting magnetic field without a screen produces a magnetic field (lines of constant magnetic field strength, Figure 2-11, extending from the exit plane of the thruster to the bottom of the channel, a. in Figure 2-11. A magnetic screen varies the magnetic field most in the channel (gap between the pole pieces and screen, c. Figure 2-11). As the gap increases, the magnetic field more closely resembles the nominal field with no screen, d. Figure 2-11. The UA MHET is designed using a ring magnet, therefore no screen or pole pieces needed. With a ring magnet, the radial field is symmetric and does not benefit from a pole piece. The Halbach array version could benefit from a pole piece to average the strength, but is not included in this research. A magnetic screen and additional pole pieces will be considered in future designs.
A Halbach magnet array can produce an asymmetric magnetic field in the UA MHET.

The magnets for the Halbach array are located around the outside of the thruster channel in this design implementation. In the 1980s at the Lawrence Berkeley National Lab, Klaus Halbach developed a magnet arrangement to increase the magnetic flux on one side of the magnets, while reducing the field strength on the opposite side, Figure 2-12. The most public use of Halbach arrays is in fridge magnets. Fridge magnets can be placed on the fridge with one side, but easily falls off if flipped onto its opposite face. This is achieved using a linear Halbach array. Halbach arrays allow the design to strengthen radial magnetic fields in the desired locations and directions of a Hall-effect thruster. The design for this research oriented the magnets in a circumferential pattern around the thrust channel in place of the ring magnet in the traditional UA MHET design. However, the Halbach array produces a complex 3D field, requiring a 3D electromagnetic solver to model the radial, axial, and azimuthal field.
Figure 2-12 Halbach Magnet Array and Resulting Flux
3 METHODOLOGY

This chapter describes the computational magnetic models and experimental setup used to design and test the two micro-Hall-effect thruster designs. The magnetic simulation program is explained, along with the models used to compare the magnetic fields between the ring magnet and Halbach array, as well as what results will be pulled from the data. Facility and equipment used in the experiments have been described, including setup and operating procedures.

3.1 Magnetic Simulation

The ring magnet thruster and the Halbach array thruster magnetic configurations were modeled. Detailed models were developed in SOLIDWORKS for production, and the models were simplified for magnetic simulation, mainly removing bolt fidelity and the stand component. An add-in for SOLIDWORKS called Electromagnetic Simulation Software (EMS) by EMWorks® was used to solve for the magnetic fields in both thrusters.

3.1.1 Computational Models

The majority of Hall-effect thrusters rely on axisymmetric magnetic fields which requires only a 2D electromagnetic solver. Hall2De, developed by JPL, calculates the axisymmetric magnetic field. Additionally, Hall2De computes basic plasma performance of the thruster with that specific magnetic field configuration. Once an asymmetric field is added, such as a Halbach array, Hall2De is no longer an option. EMWorks® directly interfaces with the SOLIDWORKS model streamlined the analysis cycles during design. To modify the thickness of one component of the thruster, re-mesh the model, and re-run an analysis was possible within
two hours. Additionally, EMS offered direct exporting of nodal results when supplied with coordinates, allowing plots to be easily made in MATLAB®.

When designing the thrusters, the two different configurations shared the same thruster channel, anode and center post. As a result, the magnetic models for both thrusters share a majority of components between them.

![Figure 3-1 Simplified Halbach Array Thruster Magnetic Model](image)

To reduce mesh complexity and solver time for unnecessary solution fidelity, the flight model was simplified. The simplified model used cylinders for bolts, Figure 3-1, the mounting plate was trimmed to the same outer diameter of the other thruster parts, and the centering ring for the center post was not included. For the model to mesh properly, the space between each magnet needed to be captured properly by the mesh spacing. Otherwise, zero thickness mesh elements would be created between each magnet in the array, resulting in errors during analysis.
Additionally, an air cavity encompassing the model was necessary for solving the magnetic field in empty space between parts, such as within the thruster channel.

Once the model dimensions are finalized, the EMS add-in is initialized, and the remainder of the analysis is set-up in the add-in. First, material properties are applied to all components in the assembly, including the air cavity. These material properties are in addition to the material properties applied in the SOLIDWORKS model. The assembly part list would provide materials applied to all parts, with the materials in bold, Figure 3-2.

Figure 3-2 EMS Materials List
Permanent magnets have a magnetization direction. Aligning the magnetization with the intended direction is the basis of the Halbach array. Specific magnetic fields are being designed when employing a Halbach array. For this research, the magnetization direction of the SmCo magnets are aligned in three primary directions (Figure 3-3): axially toward the anode, axially away from the anode, and circumferentially (specific to the neighboring magnet). This Halbach array employed four magnets (red in Figure 3-3) axially, with north magnetic pole pointed away from the anode, out of the page in Figure 3-3. Four magnets are aligned with magnetic north pointed axially towards the anode, into the page (blue magnets in in Figure 3-3). Eight SmCo magnets are diametrically magnetized specifically so the north pole (magnetization) can be directed towards the neighboring red magnet, along a line connecting the two magnets’ centers (magnetization vectors, labeled x, show the magnetic field circumferential orientation). The pattern is repeated four times to provide a relatively continuous Halbach magnetic field.

![Figure 3-3 EMS Halbach Array Magnetization Direction](image)

The Halbach array model is easily discretized for computational analysis after applying the materials and magnetization directions. The computational meshes are generated using the
same settings. The grid generation produces tetrahedral elements with side length ~ 1 +/- 0.001 mm (0.04 +/- 0.00004 in.). To ensure sufficient representation of the magnetic field, the model uses at least 145 mesh elements along the diagonal for each part. With the importance of the magnetic field within the thruster channel, the channel wall part in both models is meshed with an element size of .305 mm (0.012 in).

The magnetic simulation was run at a selection of mesh settings to verify the convergence of the results with respect to a decreasing global mesh size, Figure 3-4. The ring magnet model was run with and without the mesh control applied at the channel wall, from 4.445 mm to 1 mm global mesh size. The center of the thruster channel at the exit plane was the location of the data extraction for the comparison. The variation in the magnetic field strength is reduced with respect to global mesh size when a mesh control tolerance is applied to the channel wall.

![Figure 3-4 Global Mesh Size vs. Axial Magnetic Field in Ring Magnet Thruster](image_url)
Figure 3-5 provides a comparison of the mesh model with the air cavity present on the left, and without on the right. With the model meshed, the simulation can be run and the results analyzed.

![Meshed Thruster Model with (Left) and without (Right) Air Cavity](image)

3.1.2 Interpreting Results

The direct comparison between both the radial and axial magnetic fields of the Halbach array and ring magnet thrusters is the most important aspect of the simulation, and requires exportation of the data from both models to graph alongside each other. First, desired data points must be imported into the EMS add-in to create an Excel compatible text file. A MATLAB script was created that discretizes the geometry of the model into a manageable amount of data points.

The magnetic field of interest is inside the thruster channel from the anode to the exit plane. The lensing magnetic fields can diverge the plume. To see the lensing magnetic fields results past the exit plane are analyzed. Inside the channel, 25 axial points between the anode and exit plane, and five radial points between the inner channel wall and the outer channel wall are created. Additionally, for the Halbach array, the azimuthal variation in the field is needed, so the same 25 axial and five radial channel points is swept in an 8-point, 45° arc at 5.625° intervals.
from 0° to 45° to capture the repeating pattern of the Halbach array. Past the exit plane, the radial data points capture the center of the thruster to the outside edge of the ceramic exit plane in 17 data points. Also, the axial data points extend 50% the channel length past the exit plane, which is captured by 12 data points, Figure 3-6.

![Data Points Overlaid Thruster Cross-Section](image)

**Figure 3-6 Data Points Overlaid Thruster Cross-Section**

To see how the magnetic field strength changes throughout the chamber, radial and axial magnetic fields are compared along the depth axis for each of the three radial locations within the channel, Figure 3-7. The ring magnet and all azimuthal sections of the Halbach array show the most variation toward the outer radius of the channel radius.
3.2 Experimental Setup

In conjunction with the computational magnetic field simulation, experimental data is acquired through operation of both micro-Hall-effect thrusters. Operating ranges for power, as well as Faraday probe data for plume characterization, are both used to compare the two magnetic configurations of the Hall-effect thrusters.

3.2.1 Vacuum Facility

The experimental work performed for this paper occurred in the Space Propulsion Observation and Testing (SPOT) Lab. The lab features three large vacuum chambers, all of which can perform the experiments required for this project. All tests for this paper were performed in the red vacuum chamber located in the SPOT Lab.
The red chamber (Figure 3-8 is 1.5 m diameter x 2.4 m long) achieves a base pressure of 0.1 mPa with the current pumping equipment installed. Multiple ConFlat flanges are available along each side of the vacuum chamber, allowing for viewing windows, propellant feedthroughs, and power and instrumentation connections.

![Figure 3-8 Red Vacuum Chamber](image)

**Figure 3-8 Red Vacuum Chamber**

To begin the pump down procedure, all ports are tightened to prevent atmospheric leaking, and the door is closed and clamped shut. The roughing stage of the pump down is performed by a Leybold D65BCS pump, reducing the pressure in the chamber from atmosphere to the crossover pressure (~100 Pa). At crossover, the turbomolecular pump (Leybold Mag W 1500 CT) begins to spin, taking the chamber down to 0.1 mPa. This turbo pump is mounted on
one end in the horizontal position with a gate valve to allow the pump to continue operation if the chamber needs to be opened. Nominal operation of the turbopump is 600Hz at a base pressure 0.1 mPa. At base pressure, the turbo pump is capable of pumping 1100 l/s of N₂, providing operating pressures between 6.0 and 7.0 millipascals while the Hall-effect thruster is operating. All pressure measurements from atmosphere to base pressure were taken using a Leybold PTR 90N cold cathode ionization vacuum gauge.

### 3.2.2 Propellant Feed System

Two gas lines for the xenon (Figure 3-9) are required; one for the cathode and the other for the MHETs. Xenon used for this research was 99.999% purity (Linde containing 200L). The gas flow was regulated using MKS mass flow controllers. The regulator used on the xenon tank has VCR fittings on all ends, shown in Figure 3-10, a type of crushed gasket fitting that provides an extremely small leak rate, and the CGA fitting connecting the VCR regulator to the xenon tank utilizes a Viton o-ring to further reduce the leak rate of xenon from the system, as well as the chance of allowing oxygen into the propellant lines.
Downstream of the regulator are two MKS GE50A mass flow controllers, one rated for a full range of 50 sccm of xenon and the other 10 sccm. The controllers have a controllable range of 2-100% of their rated full range, with an accuracy of 1% for a set value in the 20-100% of the rated full range and an accuracy of 0.2% of the rated full range for 2-20% of their rated full range. For example, the 50 sccm controller is capable of controlling xenon from 1.0 sccm to 50
sccm, with an accuracy of 0.5 sccm when setting values of 10-50 sccm, and an accuracy of 0.1 sccm when setting values of 1.0 to 10 sccm.\textsuperscript{21}

![Xenon Tank with Regulator](image)

**Figure 3-10 Xenon Tank with Regulator**

In Figure 3-11, a diagram of the propellant feed system as set up for the experiments is shown. Upstream and downstream of the mass flow controllers are shut-off valves allowing isolation of the entire propellant system from the vacuum chamber. The shutoff valves make it possible to calibrate the mass flow controllers for the zero-set point. All connections between the regulator, valves, mass flow controller, and gas feedthrough located on the chamber are made with VCR fittings and flexible steel bellows lines. Rated to 4.0E-11 sccm/s leak rate, VCR fittings provide leak-free connections in the propellant lines. Once inside the vacuum chamber, Swagelok compression fittings are used on Teflon tubing to connect the propellant lines from the gas feedthrough inside the vacuum chamber to the cathode and MHETs. Swagelok compression fittings provide a suitable connection inside a vacuum where oxygen is no longer a concern. The
Teflon lines provide electrical isolation from the red vacuum chamber with respect to the cathode and MHETs.

![Propellant Feed System Diagram](image)

**Figure 3-11 Propellant Feed System Diagram**

### 3.2.3 Power System

A bank of rack-mounted Matsusada, TDK-Lambda, and Spellman power supplies provided the power for the cathode, thrusters, and various plasma diagnostics equipment. The cathode used in the experiments requires up to 1300V and 1.3A for the keeper used to ignite the plasma and produce electrons. After ignition, the voltage drops to a nominal 30V operating condition. This power requirement is satisfied by two 650V/1.5A TDK-Lambda power supplies placed in series. For the thruster anode, operating voltages are anywhere from 150V to 300V and current needs are as much as 200mA. Additionally, up to 800V can be required for ignition, depending on the coupling between the cathode and anode. Operating voltage then drops to the nominal 150-300V operating range once current is achieved on the anode supplied by a Spellman 3600V/350mA power supply.
As shown in Figure 3-12, the server rack cart contains all the electronics used to power and record the thruster and chamber data. Located in the bottom half of the rack are the Matsusada power supplies, as well as the Spellman power supply for the anode. Additionally, the two TDK-Lambda power supplies are located on a shelf on the top half of the rack. Above the Spellman is a Keithley 6517B picoammeter, used for plasma plume diagnostics. Above the Keithley is a clear breakout panel. Connections from left to right for: the power supplies located below the breakout panel include; two rows of input connections allowing up to 20 power outputs to a vacuum chamber through a power feedthrough; two sets of diodes used to protect the power supplies from reverse current from the plasma generated in the cathode and MHET; multiple BNC breakouts to allow for plasma diagnostic instruments to be connected. At the very top of the rack is an MKS 947 controller to power and set desired mass flows for the two MKS GE50A mass flow controllers.
3.2.4 Faraday Probe

The Faraday probe used for this research measures the ion current density in the Hall-effect thruster plume, providing the divergence of said plume. Plume divergence is an efficiency loss due to the lensing effects of the magnetic field. Optimizing the magnetic field can reduce this loss in the thrusters though. Reducing the divergence angle will increase the measured thrust along the center axis of the thruster, and therefore increase the specific impulse ($I_{sp}$).
The Faraday probe was constructed by Plasma Controls. Faraday probe systems typically consist of a collector plate, an aperture, a guard (body), a power supply and an ammeter. The collector disk can be set to a positive or negative voltage potential with the purpose of measuring the number of high-energy, positively charged particles impacting the surface. Some Faraday approaches set the aperture potential to the same value as the collector plate. Our approach sets the body and aperture to a negative bias to repel elections in the plasma (introducing error in the measurement). Current is measured by putting a resistor in line and measuring the voltage drop across the resistor or by using a calibrated ammeter. The currents measured are usually in the μA range, requiring a large resistance such as 4 MΩ. For these experiments, a Keithley 6517B picoammeter, capable of measuring down to 2pA, is used instead of a resistor.

![Faraday Probe Electrical Schematic](image)

*Figure 3-13 Faraday Probe Electrical Schematic*
The guard is usually biased negative to repel electrons in the plume that may give incorrect ion current measurements. Additionally, the Faraday probe guard reduces the low energy charge-exchange ions in the plume from interfering with the measurements. In the case of an aperture being used, the collector disk would be biased positive to contribute to the removal of the low energy ions in measurements. For the purposes of these experiments, no aperture is used, exposing the collector disk directly to the plume.

Both the collector disk and the guard body were biased to -30V to repel electrons and attract ions. The guard current is not measured, and biased using a 60V Matsusada power supply. Connections for the Faraday probe consist of one BNC connector located on the rear of the probe. In this case, the center pin is used for the collector disk, and the shield is used to bias the body/guard. A supplied cable from Plasma Controls splits the single BNC to two BNC cables where the shields are grounded, and the center pins of each contain the collector disk and guard voltages/currents. The majority of the length of this splitter cable is configured with the guard bias voltage on the shield.

Discussed in greater detail in the following section, a translation system is used to move the Faraday probe through the plume of the hall thruster, usually in a 180° arc a set radius from the center of the Hall-effect thruster shown in Figure 3-14, and the beam current density for each point on the arc can be found using Equation (3-1).
Initially, a voltage sweep on the collector plate is necessary to determine ion saturation voltage. One location on the arc is chosen, and with the guard voltage steady, the collector voltage is swept from a positive voltage to a negative voltage, and the current is recorded. Negative measured current indicates that electrons are being measured. Ideally, a collector voltage will be chosen in the linear portion of the measure ion current sweep (Figure 3-15).

\[
\mathbf{j}_B = \frac{I_{\text{measured}}}{A_{\text{aperture}}} \left( \frac{A}{\text{cm}^2} \right)
\]  

(3-1)
Once a voltage value was chosen, -30V in this case, the Faraday probe was swept across the face of the Hall-effect thruster in a 180° arc at a constant radius. Current values were measured at 1° intervals, 1 value per degree step. After converting the measured current across the arc using Equation (3-1), a plot can be produced similar to Figure 3-16.
Figure 3-16 H6 HET ion current density vs. angular position\textsuperscript{12}

Additionally, the Faraday data can be numerically integrated to estimate the total ion current through a theoretical half-sphere shell at a given radius assuming the thruster plume is axisymmetric. An asymmetric thruster, like the Halbach array, will require a full half-sphere sweep to characterize the total ion current. For the ring magnet thruster, the total beam current can be estimated by numerically integrating Eqn. (3-2).

\[ I_b = \int_{S_0}^{S_f} j_b dS \]  

(3-2)

3.2.5 Rotation Stage

To properly measure properties of the thruster plume, the plasma probes must be oriented towards the center of the thruster body and rotated about the thruster exit plane. A rotation platform was developed to move the Faraday probe, or any other probe desired, in a constant radius arc with the central axis pointing towards the thruster.
The rotation stage used a slewing ring, which is a rotational bearing, mounted to a 120:1 worm gear in addition to the aluminum housing that the Empire Magnetics stepper motor is also mounted to, Figure 3-17. The stepper motor is mounted to one side of the rotation stage housing, and its rotor is passed into the housing where it is coupled with a shaft that the worm of the worm gear system is attached. This shaft continues to the opposite side of the housing where it seats into a bearing, not shown in Figure 3-17, to support loads applied during operation.
The Empire Magnetics stepper motor used in the prototype rotation stage features a step resolution of 1.8°, which translates to 200 steps per 360° turn. With the addition of the 120:1 worm gear system, each 1.8° of the stepper motor can be further divided into 120 steps, giving a final expected resolution of 0.015° at the probe mounting surface of the rotation stage. This level of resolution needs to be verified. Preliminary tests have shown rotational stage accuracy of 1°.

To control the stepper motor in the rotation stage, a motor driver system interfaces with both the stepper motor and LabVIEW. The SMD-761X line of drives features an ethernet connection, stepper motor encoder inputs, and small form factor, that allows all three to be mounted in a 19” server rack box as shown in Figure 3-19.
A 48VDC power supply provides up to a total of 13A to all three SMDs. A front switch allows power to both the 12VDC and 48VDC power supplies, starting the system. Three parallel leads are provided for each SMD from the 48VDC power supply. Six parallel leads are provided from the 12VDC power supply to the 6 limit switch input circuits that connect to the three SMDs. Limit switches are currently not implemented in the rotation stage, but this feature allows minimal design changes to the box for the limit switches that will be necessary for the full X-Y-Theta translation stage.
Figure 3-20 3-Axis Stepper Motor Drive Controller Electrical Schematic

On the rear panel of the server box, (Figure 3-20), three sets of the following connections are provided, one for each SMD: One stepper motor output 6-pin Molex connector, connecting the four power outputs and one ground from the SMD to the stepper motor; two limit switch 2-pin Molex connectors, connecting the two limit switches for each translation axis, and the one for the rotation axis plus one extra connector; the Ethernet port connecting port on the SMD.

Once the stepper motor is connected to the controller box and the ethernet cord is plugged in for the rotational stage SMD, the rotation stage is commanded to a specific angle using the LABVIEW® program.

A laser pointer attached to a mounting on the rotation stage facilitated alignment of the center of rotation for the rotation stage with the thruster centerline, centering the Faraday probe with the centerline of the thruster, Figure 3-21. For more information on the Faraday probe setup and alignment, please refer to A.1.
Figure 3-21 Laser Pointer Mounted on Rotation Stage
4 RESULTS AND DISCUSSION

In this section, the magnetic simulation results are introduced and discussed. Axial and radial magnetic fields at multiple locations in the channel are shown and compared between the Halbach array and traditional ring magnet.

4.1 Magnetic Simulation Results

Provided with an educational license of the EMWorks® add-in EMS for Solidworks®, the performance of the SmCo ring magnet was modeled and compared with the novel Halbach array. Both magnet configurations provided viable solutions for a Hall-effect thruster. The radial magnetic flux density inside the thruster channel 3. mm upstream of the exit plane shows how the two configurations differ; Figure 4-1 for the ring magnet thruster, Figure 4-2 for the Halbach array thruster.
Figure 4-1 UA MHET Ring Magnet Radial Magnetic Flux Density, 3 mm Upstream of Exit Plane
Both thrusters have the same channel dimensions. With the ring magnet, resultant fields exist throughout the channel in greater intensity than with the Halbach array, which is to be expected. The Halbach array axial length is over just a third the axial length of the ring magnet. The radial peak strength is nearly identical between the two 3 mm upstream of the exit plane. However, the radial field geometry is azimuthally irregular in the Halbach array design, and some locations in the channel contain a weaker radial field than the corresponding location for the ring magnet design.

Looking at the axial cross-section of both thrusters, the radial magnetic field is more concentrated 3 mm upstream of the exit plane at 0° for the Halbach array thruster, Figure 4-3. For the ring magnet thruster configuration, downstream of the exit plane, a radial field magnitude
roughly double that of the Halbach array (-0.014 Tesla vs. 0.32 Tesla) can be seen, Figure 4-4. Additionally, a radial field magnitude near the anode is ten times greater (0.1 Tesla vs. -0.014 Tesla) for the ring magnet configuration when compared to the Halbach array. This larger radial field will lens the plasma off axial, reducing the efficiency of the thruster.
Figure 4-4 UA MHET Ring Magnet Radial Magnetic Flux Density Across Cross-Section Inside Thruster Channel and Past Exit Plane

For the same axial cross-section for both thrusters, but looking at the axial magnetic field, the axial field strength is greatly reduced overall throughout the channel and downstream of the exit plane for the Halbach array thruster compared to the ring magnet thruster, Figure 4-5 and Figure 4-6.
Figure 4-5 UA MHET Halbach Array Axial Magnetic Flux Density Across 0° Cross-Section Inside Thruster Channel and Past Exit Plane
A better comparison can be made with discrete points in the channel chosen for each thruster design. On the inside wall, the middle of the channel, and the outside wall, data points are taken from the anode to the exit plane, and extending to $1.5L$ (length of the channel) past the exit plane. Zero on the x-axis of the following plots indicates the exit plane of the thruster, where the ceramic channel wall ends. For reference, the radial and axial magnetic fields at all three radial locations for the ring magnet thruster is provided, Figure 4-7 and Figure 4-8.
Figure 4-7 Ring Magnet Radial Magnetic Field
For the next six graphs, the radial and axial magnetic fluxes are plotted for the ring magnet and four out of eight radial locations for the Halbach array. Eight azimuthal locations are necessary to capture the repeating pattern of the Halbach array. These locations are at a 5.625° interval, from zero to 45°, corresponding to the middle of one axial Halbach magnet azimuthally to the middle of the opposing magnetization axial Halbach magnet, Figure 4-9. Four radial locations are chosen for the graphs to reduce clutter while articulating the change in the fields azimuthally.
Figure 4-9 UA MHET Halbach Array Eight Azimuthal Sections
The ring magnet design has a stronger magnetic field near the anode than any radial location of the Halbach array, Figure 4-10. The magnetic field strength correlates to an increase in the plasma length inside the channel, which impinges the plasma on the anode, causing wear and reducing overall thruster efficiency. Peak magnetic field strength occurs at ~3 mm upstream of the exit plane inside the thruster channel. The magnetic field strength for the Halbach array is weaker at every radial location compared to the ring magnet. At 0°, the Halbach strength is roughly 80% that of the ring magnet, (-0.09 Tesla vs. -0.11 Tesla). At 45°, the strength is approximately 45% of the peak values found on the inner channel wall (-0.05 Tesla vs. -0.11 Tesla). The orientation of the Halbach array magnet at that location has the same magnetization as the center post magnet, much like trying to touch the south poles of magnets together.
Downstream of the peak (3 mm), both the Halbach array radial locations and ring magnet slopes towards zero are similar although the starting points for the Halbach slopes are smaller in magnitude than the ring magnet.

![Axial B Field Across Inner Channel Wall](image)

**Figure 4-11 Axial B Field Across Inner Channel Wall**

The ring magnet thruster design generates a stronger axial magnetic field along the inner channel wall, peaking at nearly the same strength as the radial field, Figure 4-11. The axial magnetic field will accelerate the electrons along the axis of the thruster toward the anode, reducing their potential for ionizing the neutral propellant, reducing efficiency of the thruster. The Halbach array has a peak further downstream from the anode ($z = -5$ mm, $B \sim 0.02$ Tesla, force on electrons in $+z$ direction) than the ring magnet’s peak and a complementary peak of opposite magnetization very close to the exit plane location ($z = -2$ mm, $B \sim -0.02$ Tesla, force
on electrons in -z direction). The force exerted on the electrons in opposite direction creates a trap at \( z = -3.5 \) mm in the channel, increasing the loiter time in the channel and therefore the thruster efficiency.

![Radial B Field Across Middle of Channel](image)

**Figure 4-12 Radial B Field Across Middle of Channel**

For the ring magnet, a peak exists near the anode \((z = -15 \) mm, \( B \sim 0.06 \) Tesla). The peak near the exit plane has the same strength with opposite magnetization \((z = -3 \) mm, \( B \sim -0.1 \) Tesla), Figure 4-12. This peak near the anode is very poor for operation and efficiency, as it can lead to leak currents from the exit plane containing the hall current to the anode. The peak radial magnetic field strength for the Halbach array design is evidence of the expected better performance over a ring magnet \((z = -0.1 , B \sim -0.1 \) T). The Halbach array has a favorable magnetic field for \(0^\circ\), but not for the remaining radial locations, where the reduced radial
magnetic field strength \( \Phi = 28.1^\circ, z = -3. \text{ mm}, B = -0.01 \text{ Tesla} \) can potentially cause a loss of Hall current. As the radial magnetic field is reduced, the Lorentz force \( F = q(E + v \times B) \) holding the electrons in the Hall current is reduced, which allows greater axial movement of the electrons across the axial magnetic field. The hall current and plasma can be hypothesized to have a dead zone for thruster operation, where electrons are lost to the environment, or spiral directly towards the anode. Another hypothesis is the alternating axial field in the channel will create a closed loop for the Hall current, in which the electrons oscillate back and forth azimuthally in the channel as they cross weak magnetic field zones.

![Figure 4-13 Axial B Field Across Middle of Channel](image)

The ring magnet generates a strong axial field inside the channel \( z = -12.5 \text{ mm to -5 mm}, B = -0.08 \text{ Tesla} \). The magnetization is opposite for the channel region than at the anode and exit.
plane, Figure 4-13. As previously discussed, this large axial field will result in thruster inefficiencies or poor operation. Other thrusters have employed magnetic screens to counter strong axial magnetic fields. For the Halbach array design, the opposing magnetization peaks is prominent. Peaks can reach approximately the same strength as the ring magnet peak located at the exit plane, as in the case of the 45° radial location. However, these peaks are roughly 50% weaker than the peak field strength experienced along the channel with the ring magnet axial magnetic field.

![Radial B Field Across Outer Channel Wall](image)

**Figure 4-14 Radial B Field Across Outer Channel Wall**

The ring magnet configuration features a peak near the anode of approximately the same value, but of opposite magnetization, for the same design downstream close to the exit plane, Figure 4-14. For the Halbach array design, the magnetic field near the outer wall of the channel
exhibits a wide range of directions and strengths. At its peak, the Halbach array design produces a magnetic field strength near the exit plane approximately 0.03 Tesla higher than that of the ring magnet design. As the radial locations move from 0° to 45°, the radial field is still the same direction as the ring magnet, with peaks approximately 75% that of the peak ring magnet radial magnetic field strength. At about 30°, the magnetization of the radial magnetic field flips, and is approximately 66% that of the ring magnet radial magnetic field strength. This flipping of the field for the Halbach array seems to suggest a reversal of the Lorentz force direction on the electrons across the outer wall of the channel.

![Axial B Field Across Outer Channel Wall](image)

**Figure 4-15 Axial B Field Across Outer Channel Wall**

Like at the middle of the channel, the ring magnet exhibits a peak magnetic field strength near the anode. A zone of zero field strength occurs just downstream. Continuing downstream,
the magnetization of the axial magnetic field for the ring magnet configuration flips before flipping again at \( z = -3 \) mm and peaking at the same strength as the anode peak. For the Halbach array, large variations exist across the axial depth and radial locations. Positive and negative magnetization are found at different axial locations for each radial location. These peaks are less than 50% of the peak for the ring magnet configuration found in the channel.

For the Halbach array design, the effect the potential dead zones or closed loop hall currents that exist can only be hypothesized. A narrow range of axial magnetic field strong coupled with the radial field will create an oscillatory effect for the electrons trapped in the hall current. Conventional Hall-effect thrusters’ electrons spiral around the channel azimuthally, slowly moving upstream towards the anode until it collides with a propellant neutral and ionizes the neutral. In the case of the Halbach array, the electrons will spiral back and forth in a small section of the azimuth, slowly moving away or towards the anode depending on the axial magnetic field direction and strength. Eventually, the electrons will be pulled towards the anode via the Lorentz force exerted from the electric field.

4.2 UA MHET Thruster Development

The original design of the thruster is an extremely compact design, shown in Figure 4-16, Figure 4-17 and Figure 4-18. The main concern for this design was the inability to mount the thruster without directly attaching to the ceramic channel or propellant supply tube, running the risk of either fracturing the ceramic walls or magnet, Figure 4-16. Attaching the mounting structure to the propellant line in this design will also raise the structure potential to that of the anode, which causes other design problems for the spacecraft, Figure 4-17.
Figure 4-16 UA MHET Version 1 Rear View

Figure 4-17 UA MHET Version 1 Front View
Additionally, the lack of an axial retainer on the anode/propellant line combination allowed the anode to freely move up and down the channel, usually being pulled into a specific location axially by the center post magnet and ring magnet interaction, Figure 4-19. The channel geometry from the original design can result in the anode impinging on the ionization zone and magnetized plasma downstream from the anode. A insulative, high temperature spacer was placed between the centering ring holding the center post in place and the back of the anode, keeping the anode at the designed location at the bottom of the channel.

Figure 4-18 UA MHET Version 1 Cross-Section
Initial operations (two combined hours) provided some immediate issues needing to be addressed. The first thing noticed was the depth of the hall current, depicted by the torus of blue plasma, Figure 4-19, in the channel. The plasma stops approximately 3 mm upstream of the exit plane, creating a concern for the channel walls. As ions accelerate out of the thruster from the plasma zone, the chance to impact the walls increases the further in the channel the particle is ionized. The ion impacts cause wall erosion, changing the shape of the exit plane, and thereby changing the operating conditions of the thruster. Ultimately, the result is a drastic reduction in life expectancy. Many commercial thrusters design the magnetic field to move the hall current as close as possible to the exit plane, reducing the amount of erosion on the walls from ion bombardment.

Additionally, start-up required roughly 800V applied to the anode to establish plasma generation. As the anode draws a current, nominal operation would see the current limited by the circuit and the anode voltage drop. Operating in current limited operation allows the voltage to oscillate as necessary. The thruster in this current limited operation resulted in large variations in
the resulting operating voltage and never could operate steadily. Steadier operation of the thruster was achieved with literature review suggesting industry practice operates Hall-effect thrusters using voltage limits.

The final note to be gathered from this revision of the thruster, literally, was the operating window. This thruster is designed with a nominal power consumption of 20 W, with the ideal operating window to be within 5-30 W. While working on the operating procedures for this version of the thruster, the thruster was found to work in some fashion at 4 W, and up to 30 W. A problem was discovered while operating in voltage limited mode above 40 W. The anode current runaway was possible when current protection was not properly enabled on the anode power supply. Operating at 200 V and 40 W of power translates to 0.200 A of anode current. The hall thruster exhibited no limit on the current it could pull however, and the current continued to increase at an accelerated pace until anode power consumption reached 100 W, well outside the predicted window. The entire thruster began to glow a soft orange. The thruster was turned off, but not before the SmCo magnets were demagnetized.

The next revision of the UA MHET ring magnet design offered many improvements allowing for easier mounting and assembly of the thruster, reuse of some components from the original design, and the ability to share an outer channel wall and center post with the Halbach array design. The design revision can now be arbitrarily mounted to any plate that has the required bolt hole mounting pattern, Figure 4-20. The new mounting bracket attached to the thruster (Figure 4-21) allows for easy height adjustments and a build cycle (designed, water jet cut, and bent into a 90° angle) of less than 30 minutes.
The ease of assembly and mounting made testing set ups far easier, with the thruster centerline at the same height as the centerline for the hollow cathode. Two sets of four M3 bolts
hold the thruster together at the thickest gray, aluminum section encompassing the thruster outer channel at the middle. While this design was constructed and operated, Figure 4-23, and was the last unit to collect data, the axial mobility as well as the angular variability of the center axes for the center post and outer channel wall made it imperative to modify the design again. The operational data and Faraday sweeps indicated that these problems needed to be corrected before useful data would be acquired.

Figure 4-22 UA MHET Version 2 Cross-Section
The final version of the UA MHET to be built resolved the issue of axial mobility of the anode for the ring magnet design, as well as the resulting axis misalignment between the center post and outer channel wall. Both problems were believed to have impacted the data acquired for the second iteration of the ring magnet UA MHET. The anode is axially stable and the center post is properly centered in the channel. Additionally, the ring magnet was moved forward towards the exit plane to move the plasma forward in the channel towards the exit plane and reduce the potential for channel erosion. The first change is a modification to the propellant supply tube and anode. While the original was a single integrated piece, these aspects have been separated into two pieces, allowing machining to be far simpler, as well as increase the diameter for support surfaces during assembly. The propellant supply line outer diameter increased from 9.525 to 12.7 mm. With the change in the propellant supply tube and anode assembly, centering support plates were made for the forward and back surfaces of the assembly, locking the assembly in place axially and leaving no circumferential movement of the center post with respect to the outer channel wall.
To incorporate the Halbach array into the version 3 ring magnet design, we reused as many parts as possible, essentially hot swapping the Halbach array for the ring magnet. By designing two new parts, the thruster design could operate using the same hardware with the only difference being the magnets (Figure 4-24). The ring magnet and the two gray aluminum spacers on the outside radial cylindrical surface holding it in place are replaced at the same location by two new gray aluminum spacers that fill in the gap around the outer channel wall left by the ring magnet, Figure 4-25. The aluminum spacer closest to the exit plane was machined with a 3.175
mm wide by 3.175 mm deep recess for the 16 SmCo Halbach array magnets to sit flush with the top surface of the spacer.

Figure 4-25 UA MHET Halbach Array Cross-Section

Axially magnetized SmCo 3.175 mm diameter by 3.175 mm long rod magnets are readily available, however diametrically magnetized ones of the same dimension are unavailable in small quantities. Vendors require a large minimum order, well outside the budget of this experiment. A source was found though at the cost of a longer lead time. The “Halbach array spacer” was completed using cyanoacrylate glue as the adhesive to hold the 16 SmCo magnets in their position, Figure 4-26.
Assembly was very complicated and required a lot of trial and error. The cylindrical shape of the magnets allowed them to freely spin in location and left much to be desired when holding a magnet during installation. Magnetic viewing film was used to visually verify a theoretically stronger side of the Halbach array was in fact stronger than the weaker side. An aluminum spacer was placed over the exposed Halbach array to ensure both sides of the array were visualized from the same distance. The film covering the weak side, or side closest to the anode, showed no discernable magnetic field above the static normally within the film, Figure 4-27. However, in Figure 4-28, the strong side of the Halbach array was easily discernable even with the spacer. Without the spacer, the repeating Halbach pattern found in the computational models is visible, Figure 4-29.
Figure 4-27 UA MHET Halbach Array Spacer Weak Side

Figure 4-28 UA MHET Halbach Array Spacer Strong Side with Spacer
4.3 Thruster Operating and Faraday Sweep Data

All the data collected for the following was done with the CSU heaterless cathode and revision 2 of the UA MHET ring magnet design. While operational data was taken over a large range of anode voltages and mass flows, this data will not be reported. The thruster design interfered with repeatable operating voltages with corresponding currents. The anode and center post moving with respect to the outer channel walls created an extremely asymmetric channel and magnetic field. The second revision was tested for approximately 20 hours, in which its plume was swept twice with a Faraday probe. Table 4-1 provides the operating conditions that produced the data provided throughout the rest of this section.
Table 4-1 UA MHET Ring Magnet Operating Conditions

<table>
<thead>
<tr>
<th>Operating Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anode Mass Flow</td>
<td>1.5 sccm Xenon</td>
</tr>
<tr>
<td>Anode Voltage</td>
<td>155 – 180 V</td>
</tr>
<tr>
<td>Anode Current</td>
<td>100 – 130 mA</td>
</tr>
<tr>
<td>Cathode Mass Flow</td>
<td>3 sccm Xenon</td>
</tr>
<tr>
<td>Cathode Voltage</td>
<td>60 V</td>
</tr>
<tr>
<td>Cathode Current</td>
<td>1 A</td>
</tr>
<tr>
<td>Base Pressure</td>
<td>1.8E-05 Torr</td>
</tr>
<tr>
<td>Operating Pressure</td>
<td>2.1E-04 Torr</td>
</tr>
</tbody>
</table>

While operating the thruster for Faraday sweep, the anode voltage was set to 175 V and the current was allowed to fluctuate, Figure 4-31. This fluctuation is commonly seen in Hall-effect thrusters with varying frequency and amplitude and is a function of the “breathing-mode” operation of a thruster. Additionally, the anode voltage power supply could not control the voltage to a tight window. As a result, the voltage also fluctuated between 170 and 178 V, resulting in a large range of anode voltage and current values, Figure 4-30. At a nominal voltage of 175 V and 120 mA for the current, the revision two of the ring magnet design was operating nominally at 21 W, expected power level for a thruster this size. When igniting this thruster, a large anode voltage is required to start the thruster, upwards of 800 V. In order to prevent a power spike in which the current rises uncontrollably when the operating voltage drops from 800 to a more traditional 200 V, the current is limited to 100 mA. When ignition occurs for the thruster and the anode current begins to rise, the anode will be limited to 100 mA and the voltage will drop to a corresponding level, approximately 155 V. Once operation has started, the desired anode voltage can be set and the current limit removed, switching the thruster to a voltage limited operation.
Figure 4-30 UA MHET Ring Magnet Anode Voltage vs. Anode Current
While operating this thruster at a nominal 175 V and approximately 120 mA, Faraday sweeps in a 150° arc were performed. Shortly before the thruster was turned on however, the Keithley 6517B was zeroed and then connected to the Faraday probe in the chamber to measure the background ion current noise before sweeping with cathode and thruster on, Figure 4-32. The background has no correlation between arc angle of the Faraday probe and the applied voltage at the probe collector. The lack of correlation between voltage and current allows for all the measured currents at a particular arc angle for the voltage sweep to be considered part of a population and statistically analyzed. The Keithley 6517B is reported to have a bias of 0.2% + 5E-13 Amp at the 2E-8 Amp. Using Equation (4-1), the error is calculated using the Keithley bias and standard deviation of the data at each arc angle and report as error bars in Figure 4-33.
Again, there is no discernable correlation between arc angle and background ion current. With this assumption, all data measured for background ion current was averaged to 1.02E-08 Amps with a standard deviation of 6.22E-09 Amps. Additionally, these values are two orders of magnitudes smaller than the cathode current, which is itself an order of magnitude lower than the thruster current. All of this leads to a conclusion to not subtract the background current from any measured values.

\[
\text{Error} = \sqrt{\text{Bias}^2 + \sigma_{\text{STDDev}}^2}
\]  \hspace{1cm} (4-1)

Figure 4-32 Vacuum Chamber Faraday Background Ion Current
After the background ion current noise was measured, the cathode was ignited and the ion current was measured, as shown in Figure 4-34. Subtracting the background from the hall thruster sweeps gives a more complete picture of thruster operation. This sweep was completely nominal with the expected current level and distribution. Although the peak is shifted 10° from 90° to 80°, it is entirely possible that the angles recorded were incorrect. Regardless of what the angle values are, the peak should be considered center of the cathode and thruster when calculating plume divergence and other useful statistics. The limits of rotation on the rotation stage prevented the Faraday probe from continuing to rotate left of the peak, but it can be expected that a large degree of symmetry between the right side with its larger dataset and the
left side. It is highly desirable to extend the arc to the full 180° used in many publications to verify the large drop-off in ion current on the edges of the sweep.

![Cathode Current Sweep](image)

**Figure 4-34 Hollow Cathode Faraday Sweep Current**

With the cathode sweep complete, the UA MHET ring magnet version two thruster was turned on and set to the values discussed above and a Faraday sweep was performed, shown in Figure 4-35. For this test setup, the cathode centerline was placed directly above the hall thruster centerline. So, in this case, the 80° mark that was the peak for the cathode should have also been the thruster’s peak ion current. However, it is easily discernable that this is not the case for this this specific version of the thruster.
An ion current distribution like above is highly irregular, as traditional annular thrusters have a distribution as discussed in 3.2.4. This distribution is what lead to the assertion that the axial mobility of the anode and the misalignment of the axes between the center post and outer channel wall. If the channel was not symmetrical, with the center post leaning to one side, the plume will be shaped abnormally due to the changed magnetic field, which would explain why the peak ion current measured closer to zero. Without taking the shape of the distribution into account, the magnitude of the thruster ion current, in the $10^{-5}$ A range, is exactly what was expected to be measured, which is a positive sign that if the distribution is fixed in the third version of the ring magnet design that the thruster will have a comparable ion current to the Busek BHT-20 the UA MHET is based off of, or even higher.

**Figure 4-35 UA MHET Ring Magnet Version 2 Faraday Sweep Ion Current**
5 CONCLUSION AND RECOMMENDATIONS

5.1 Research Conclusions

This research successfully developed and tested a UA designed Hall-effect thruster, designed and constructed the first Halbach magnet array Hall-effect thruster, and developed the facilities necessary to facilitate electric space propulsion research on the University of Alabama campus. Multiple vacuum chambers were refurbished and brought online through various pumping methods. At the beginning of the research schedule, the black vacuum chamber was SPOT Lab’s first large vacuum chamber to achieve pressure levels for propulsion testing, on the order of 1.E-5 Torr. In this chamber, the first Hall-effect thruster to be tested at UA, the Busek BHT-200, was successfully operated. Additionally, this chamber was the first chamber for UA’s MHET design to be operated. To support this testing, power systems were installed alongside data acquisition equipment needed to record thruster operating and plume data. When it was necessary for the research to move to a new vacuum chamber, SPOT’s other large vacuum chamber was refurbished and fitted with pumping equipment that allowed an order of magnitude lower than black chamber, at 1.E-6 Torr. While working with the red chamber, a cost-effective rotation stage was developed to facilitate plume measurements for this research with the Faraday probe, as well as future plume diagnostics with other probes available to the lab.

For UA’s first MHET, an annular Hall-effect thruster design was derived from Busek’s BHT-20 thruster, and was developed with a permanent magnet to simplify the electrical circuit for a thruster of such a confined size. This design became the first UA designed Hall-effect
thruster to be ignited and operated, totaling 2 hours of operational time. This design was refined twice during this research, with plans for a third to resolve additional issues and concerns for a flight version of the design. The second version of UA’s first MHET would accrue approximately 20 hours of operational time, allowing thruster operational procedures to be developed for UA to be used for future designs. Additionally, many lessons were learned that would be applied to a third version of the thruster design, although this third version has yet to be tested at the time of writing. With the second version UA MHET ring magnet design, initial operating values were benchmarked for the power range to be expected from a thruster of this size, with a nominal 21 W of power used for the majority of the 20-hour operational time. Along with operational data, the first Faraday sweeps were taken of both the hollow cathode and UA MHET thruster, which identified problems in geometry and construction in the second version design that needed to be addressed before progressing further in the research. Regardless, the Faraday sweeps showed promising ion current values for the thruster design, as well as reinforced that plume diagnostic equipment and procedures were working according to industry standards and will provide valuable data for the remaining portions of this research as well as future research projects.

Finally, the UA MHET ring magnet design was modified for the purpose of this research to replace the SmCo ring magnet with a Halbach SmCo magnet array. The purpose was to create an asymmetric magnetic field for the thruster channel while eliminating a large amount of axial magnetic field in the channel, as predicted by numerical simulations. With the use of EMS by EMWorks, magnetic models were developed for the UA MHET ring magnet design as well as the newly design Halbach array variant, and the results were compared. While the ring magnet provided an axisymmetric radial magnetic field in the channel and the field was found to be
stronger on average compared to the much smaller Halbach array, a significantly larger residual axial magnetic field was found along the length of the thruster channel, which was close to zero for the Halbach array. Although the Halbach array design has not been tested at the time of this writing, the design has been finalized and the components assembled, allowing testing to begin when a vacuum chamber becomes available in the SPOT Lab. The operation of this thruster is uncertain due to the asymmetric radial magnetic field, but the author is hopeful that successful ignition will occur and interesting operational parameters will be observed. Regardless of the current design, future iterations of the thruster could utilize the Halbach array to reduce stray magnetic fields in the channel as well as utilize weaker magnets with better thermal properties.

5.2 Research Significance

This research began the development necessary for the UA B3Sat CubeSat propulsion system. A Hall-effect thruster was designed, constructed, and tested on the UA campus, and has the potential to be the first successful Hall-effect thruster operated on a CubeSat. This would provide a large amount of publicity to the university in the aerospace community, as well as expand the universities capabilities in space research. The design has progressed significantly, and a flight version of the thruster could be produced within the next year contingent upon thrust and efficiency results gathered in the coming months.

Additionally, successful operation of this design on orbit for UA’s CubeSat allows the opportunity to expand the number of vehicles that could use this design. The University of South Alabama has expressed interest in acquiring a unit, contingent upon performance, for their own CubeSat program. While larger thrusters normally have 1500 s of $I_{sp}$, if the UA MHET possessed only 500 s of $I_{sp}$, the operational windows for CubeSat missions in orbit would greatly increase,
allowing for a wider variety of science to be performed and technology to be demonstrated at a reduced cost.

5.3 Recommendations for Future Work

Recommendations for future work has been broken down into sub-categories for clarity and to provide focus areas that the SPOT Lab, B3Sat, and this research should pursue to expand capabilities or produce valuable data.

5.3.1 Cathodes

For CubeSats, hollow cathodes are a poor choice for on-orbit electron production for electric propulsion thrusters. Electric propulsion thrusters capable of fitting and fully operating on a CubeSat are usually very low power, anywhere from 5 to 50 W. At these power levels, electron currents necessary for operation are way below the normal current level generated with hollow cathodes, especially using an Lanthanum Hexaboride insert. Additionally, two electrical circuits may be necessary to operate, with a keeper and heater, although not the case for all hollow cathodes, as seen with the CSU variant. Finally, the most important factor is that hollow cathodes consume propellant. On multiple kW thrusters requiring 10’s of amps of current from hollow cathodes, only five to ten sccm is necessary to operate these cathodes, while the thrusters may consume over 100 sccm or propellant. And hollow cathodes are the only device capable of such a large current production. For a CubeSat, if the hollow cathode consumes 25% of the propellant that the thruster itself does, that is 25% less ΔV created. Also, another mass flow controller is needed, and the supporting feed system.

A better option for a thruster of this size is to use a thermionic cathode, as attempted during this research. However, using a material with a lower work function, such as LaB6,
electron currents required by the thruster can be generated directly from the material by heating it with a few W of power. One of many options available is from HeatWave Labs, which is a compact LaB6 crystal design shown in Figure 5-1. With a thermionic cathode like this, mass can be saved, propellant mass for the thruster increased, and enables the ability to operate the propulsion system on iodine, as an iodine compatible cathode is no longer needed.

![Model 102248-01 Ø2.0mm](image)

**Figure 5-1 HeatWave Labs LaB6 Crystal Thermionic Cathode**

### 5.3.2 Thrust Stand

While progress on SPOT Lab’s torsional thrust balance, similar to the one in Figure 5-2, is nearing completion, it is still imperative to state the need for a thrust stand for the lab to measure thrust levels at the micronewton level in the case of this thruster, as well as larger values for higher power thrusters that may be developed by the lab. Without this capability, thruster development from the lab and publications related to propulsion research are stunted. Thrust data is considered the most important date to be collected from electric propulsion thrusters, and is used to calculate efficiencies and specific impulse, all necessary values for flight thrusters to be qualified. Specifically, truly useful conclusions about the UA MHET ring design and the Halbach array variant cannot be made until thrust measurements are taken.
5.3.3 Translation System

While progress has been made on a X-Y-Theta translation system has been made with the development of the rotation stage for this research, much left to be finished to provide the SPOT Lab with complete plume diagnostic capabilities. A system like the design shown in Figure 5-3, with a sliding gantry for both an x-axis and y-axis utilizing a stepper motor with lead screw, supported in an 80/20 extruded aluminum frame, would provide a cost-effective solution when combined with the already developed rotation stage for the lab. When utilizing stepper motors not vacuum rated, the cost for this system reduces drastically at the increased risk of stepper motor failure.
Figure 5-3 X-Y-Theta Translation Stage Concept

With an X-Y-Theta translation stage, Spot Lab’s full suite of plasma diagnostic probes can be utilized to their full potential. Currently, only the Faraday probe can be mounted on an arm on the rotation stage due to weight concerns. Additionally, if the radius of the arc for the Faraday probe needs to be changed, the vacuum system must be vented to atmosphere, the radius changed, and the system pumped down and started again, an extremely tedious process, consuming multiple days, while the X-Y-Theta stage can accomplish this in less than an hour. If lateral sweeps of the Faraday probe perpendicular to the exit plane are desired, this is not possible with a rotation stage, and instead a linear traverse of some sort is needed to accomplish. Other probes, such as the ESA, ExB, or combined probe also require lateral and radial sweeps at various distances from the thruster are too heavy for a cantilevered arm on the rotation stage and required a full translation stage to support the probe masses.

Due to budget constraints, commercially available vacuum rotation platforms/stages were not an option for this experiment, however they may be a good option for future experiments performed in the lab. Most of these stages feature a stepper motor combined with a worm gear to increase the rotational resolution, and this was the basic design that the lab developed one also
follows. A very rough looking but functional prototype was constructed for this research. If this design is to be used in the future, it is recommended that the aluminum housing be milled out of a single block of aluminum, and a much smaller, more appropriately sized stepper motor be used.

5.3.4 Micro-Hall-Effect Thruster

Initial results suggest that the magnetic field of the ring magnet design can be improved in future iterations by shortening the length of the ring magnet if it minimally impacts the radial strength near the exit plane of the thruster. Shortening will reduce the axial magnetic field found along the axial depth of the channel, resolving a problem area and increasing the flight readiness of the design. Another option is to include magnetic screens along the length of the channel to reduce stray axial and radial fields near the anode.

The next crucial step of the MHET design for flight requires the removal of the centering ring for the center post and the corresponding o-rings and centering screws. Additionally, magnetic shielding should be investigated for increased channel life, and therefore mission throughput. Also, the magnetic screens previously mention should be properly sized and included, as well as retaining the axial mobility of the center post for magnetic field tweaking for the final flight design. Unnecessary weight found on the engineering designs must be removed and the design optimized for installation on a CubeSat.

Referring to Figure 5-4, many of these design upgrades can be seen. The channel length has been halved to 7.9375 mm while still allowing room for the plasma to demagnetize. The exit plane also contains a chamfer commonly found on magnetically shielded thrusters. This will work in conjunction with an axially moveable center post to optimize the radial magnetic field for magnetic shielding. Additionally, magnetic screens have been implemented along the length of the channel to reduce axial and radial magnetic fields near the anode.
The anode features a two-piece design with a screw in gas feed line that is separate from the center post. This two-piece design also allows for different anode materials to be utilized, for example a carbon anode to work with iodine propellant. The overall dimensions of the thruster are 19 mm in diameter and 25.4 mm long.

Figure 5-4 UA MHET Ring Magnet Design Flight Design
REFERENCES


2 Staff Reports, “New 'CubeSat' propulsion system uses water as propellant,” The Exponent [online], http://www.purdueexponent.org/campus/article_49da9480-7d10-11e7-a07f-33ad7c082187.html


APPENDICES

A.1 Faraday Probe Setup and Alignment

The rotation stage was set perpendicular to the thruster exit plane, allowing the laser to shine directly at the thruster, at which point the thruster was moved laterally until the center of the laser aligned with the thruster centerline, Figure 0-1. Once aligned, the rotation stage was then set to an angle off perpendicular, moving the laser pointer off of the thruster centerline, Figure 3-21. At this point, the thruster was moved along the centerline until again aligned with the laser. This procedure places the center of the thruster exit plane directly above the axis of rotation for the rotation stage.

Figure 0-1 Laser Pointer Perpendicular to Thruster Exit Plane
The rotation stage is again set to perpendicular to verify the laser shines at the thruster centerline. The Faraday probe is then mounted on the arm, and the laser pointer is turned around to align the height of the probe with the center of the thruster exit plane, Figure 0-2. The distance between the Faraday probe and the thruster exit plane are set and the probe is ready for data capture.

![Figure 0-2 Aligning Faraday Probe Height](image)

**A.2 Lessons Learned**

MHET:
At one moment for an anode current of 0.080 A, the anode voltage average may be 170 V, but as the current is increased then brought back down to the same 0.080 A, the anode voltage average may be 140 V. This created a lot of confusion, and with further literature review and consultation of some industry experts, it was determined that both the start-up procedure mentioned, as well as the current limited operation, were both incorrect. While the reason behind
the start-up requirements was still to be determined, the current limited operation was resolved with more success.

Cathode:

Numerous setbacks involving hollow cathodes and vacuum systems prevented a smoother schedule than what occurred. A six-month scheduled slip happened right at the beginning of the thesis in attempts to achieve stable hollow cathode operation, which was not the focus of these experiments. Power systems failed and fried some electronics in the process, vacuum systems were in the first few months of operation and operating pressure left much to be desired with many leaks to be found. Additionally, the hollow cathode heater itself suffered multiple failures, a redesign\textsuperscript{22}, and then a return to the original design once more funds were allocated. This return was due to the prohibitive expense of the heaters, roughly $500 each.

![UA Hollow Cathode with Keeper Removed](image)

**Figure 0-3 UA Hollow Cathode with Keeper Removed**
The heaters are a tantalum wire encased in an alumina insulator with an outer sheath of tantalum. One end of the heater welds the center tantalum wire and sheath together. The heater is then coiled tightly around the cathode tube near the orifice to heat the insert, as shown in Figure 0-3, to a high enough temperature to begin producing electrons to ionize the propellant passing through it. Once this coil is wrapped around the tube, it cannot be unwrapped after the heater has been used. The insulation embrittlement and will break/short the heater if unwrapped. Additionally, if the heater is improperly wrapped around the tube, a temperature differential may arise, thus causing a short in the heater. Using a mandrel of slightly smaller diameter than the cathode tube, to coil the heater tightly, proved to correct the problem (standard practice at JPL, Dan Goebel). The heaters are known to spring slightly larger than the tube used to wind them. A tight fit for the heater on the cathode tube eliminates the temperature differential problem. The cathode operated nominally for months before failing due to heater impact. A thermionic cathode was attempted, using a tungsten wire as an electron source, Figure 0-4. The wire was extremely unsuccessful as the hall thruster failed to ignite after powering the thermionic cathode with nearly 23 A at 400 W, creating a near blinding light inside the vacuum chamber requiring tinted sunglasses to observe operation.
An available heaterless cathode (Colorado State University) enabled continued exploration of the micro Hall-effect thruster. The heaterless cathode used a large gas flow and high keeper voltage to ignite, at which point the gas flow is throttled back to a more reasonable level. This cathode was successful in operating the revision 2 of the UA MHET ring design. The Faraday sweep setup can be seen in Figure 0-5. This cathode was used for the thruster operating and Faraday sweep data taken and presented in the following section. Unfortunately, the successful operation of this cathode with the third revision of the ring magnet UA MHET design was not attempted. This was due to the vacuum chamber used for these experiments suffered from a leak of unknown origin that would not be resolved until after the author had left UA. It is believed that the CSU cathode would operate nominally with the third revision, which solved the anode axial mobility and center post misalignment.
Figure 0-5 CSU Cathode Installed in Faraday Test Setup