# Undergraduate Demonstration of a Hall Effect Thruster

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**Guys, we have to write an abstract at some point.**

## I. Nomenclature

| | | |
|---|---|---|
| $\vec{\mathbf{B}}$ | = | magnetic field |
| $\vec{\mathbf{E}}$ | = | electric field |
| $I$ | = | beam current |
| $n$ | = | particle density |
| $P$ | = | total power |
| $q$ | = | particle charge |
| $\rho$ | = | charge density |
| $r$ | = | cylindrical radial coordinate |
| $c_i$ | = | ionization rate coefficient |
| $V$ | = | operating voltage |
| $\vec{\mathbf{v}}$ | = | particle velocity |
| $\phi$ | = | azimuthal coordinate, counterclockwise |
| $z$ | = | axial coordinate, toward plume |

## II. Introduction

Traditional chemical rockets generate a large magnitude of thrust over a relatively short time scale, and thus find a common usage in launch vehicles, which require rapid acceleration for only minutes at a time. These chemical rockets, however, are inefficient in space, where large changes in velocity are often required and the mass of the fuel required to accelerate a spacecraft follows an exponential curve (as the rocket must accelerate all unburnt fuel as well as the spacecraft).

An alternative form of thrust is electric propulsion; rather than accelerating large molecules through combustion, electric thrusters generate individual ions that are accelerated to extremely high speeds by electric fields. These thrusters generate very low magnitudes of thrust (typically on the order of milli-Newtons), but require very less fuel mass and can continue to fire as long as a potential difference can be maintained, sometimes as long as thousands of hours. Ultimately, electric thrusters are capable of achieving large changes in velocity with much less fuel than a chemical rocket and opens doors to highly ambitious space missions, from outer-planet studies to asteroid redirection, and finally makes realistic the prospect of human spaceflight beyond lunar orbit.

The Hall Effect thruster (or Hall thruster) is one such method of electric propulsion that has various advantages over other ion thrusters. Gridded ion thrusters are conceptually simpler devices, but are inherently space-charge limited by nature of the design: positive charges build up between the two plates of a gridded ion thruster, preventing further positive ions from entering the region. As a result, the thruster becomes thrust density limited because when the space-charge limit is reached, no more propellant can be pushed through the thruster. Hall thruster plasma is quasi-neutral all the way through, enabling them to avoid this limit. This makes such thrusters more versatile in many use cases and is one of the reasons that we decided to focus this project on the building of a Hall thruster.

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# III. Motivations

This project is both student-initiated and student-led; we decided to undertake it out of an interest in space technology and a curiosity with the challenges of electric propulsion.

Initially, our goals for the project were to learn the physics principles behind electric propulsion, to develop computer modeling skills by modelling electric and magnetic fields, and to apply the theoretical physics from this study and from our classrooms to real thruster design decisions. By the end of the project, we had also developed skills in many fields beyond those we set out to study, including CAD modeling, design for manufacturing, and fabrication techniques and limitations, especially through interacting with real-world manufacturing facilities. This caused us to realize the potential application of projects like these for application-based educational purposes.

The core team consists of four undergraduate students from the Franklin W. Olin College of Engineering with academic advisement from applied physics professor Rebecca Christianson. Olin is a 4-year undergraduate school with around 350 students. It experiments with a project-based engineering curriculum in which students constantly apply the skills and techniques learned in a classroom to technology demonstrations, rather than exams. As part of this, Olin actively encourages independent studies and academic side projects, and awarded our team general engineering credit for this pursuit.

Braden Oh began the project as a second-year mechanical engineering student. He had experience with space systems engineering at MIT and NASA JPL prior to beginning the project, but no experience building or designing propulsion systems.

Justin Kunimune began the project as a fourth-year general engineering with a concentration in physics. He had prior academic experience with applied physics but no experience with space systems.

Lauren Anfenson began the project as a second-year electrical and computer engineering student. She had experience designing printed circuit boards for space instruments at NASA JPL prior to beginning the project, but also had no experience with propulsion systems.

Jonah Spicher began the project as a second-year electrical and computer engineering student. He had experience designing hardware for electric vehicles and formulating chemical rockets prior to beginning the project, but no experience with electric propulsion.

# IV. Literature Search

Identifying key resources that would give us a background in Hall thruster operation, both conceptually and quantitatively, was a critical starting point, as neither our team nor anyone else at Olin had previous experience with electric propulsion. We became aware of electric propulsion researchers at NASA JPL who directed us toward the book "Fundamentals of Electric Propulsion: Ion and Hall Thrusters,"[1] which was written by their colleagues Dr. Dan Goebel (JPL) and Dr. Ira Katz (JPL). This is a textbook-like publication that describes key operating principles and provides equations and explanations for both determining and relating critical design quantities such as the Larmor radius (see section VII.A).

A second avenue of literature search we performed was to seek out publications from other teams who had previously built demonstration Hall thrusters; we were aware of a graduate level class at MIT that had constructed electric thrusters in the past and wanted to know whether this was a common technology demonstration that has already-published literature. We discovered that this is likely not the case, as we could find only one technical report outlining such an attempt. Matthew Baird published a senior design thesis titled "Designing an Accessible Hall Effect Thruster"[2] while studying at Western Michigan University. This paper provided a walkthrough of Baird's high level equations (which matched equations provided by Dr. Goebel) and the design process for a simple Hall thruster. Most of the paper was specific to his particular design, and so we used the Baird paper as a case study in applying the methods from Dr. Goebel.

An additional resource we sought out were present experts in electric propulsion. Two individuals who helped us greatly were Dr. Steve Snyder (JPL) and Prof. Manuel Martinez-Sanchez (MIT) who graciously fielded questions from us throughout the process. Our workflow involved reading literature, taking notes, making ballpark calculations to verify orders of magnitude, and then developing a list of questions and clarifications for things we did not understand. Each time we amassed a large number of questions, Drs. Snyder and Martinez-Sanchez met with us to answer them. Prof. Martinez-Sanchez also offered excellent feedback as a member of our design review committee, before we began manufacturing. We also relied heavily on MIT graduate student Bjarni Kristinsson, who interfaced between us and MIT's test facilities, gave us a hot cathode design, and provided excellent feedback as a member of our design review committee.

The final key piece of literature we relied upon was the Ph.D. thesis "Theoretical and Experimental Investigation of Hall Thruster Miniaturization"[3] by Dr. Noah Warner (JPL), which was recommended by Dr. Martinez-Sanchez. This paper was a full detailed design and analysis of a 9-mm Hall thruster developed by Dr. Warner while a Ph.D. student at MIT. Complete with dimensions and an assembly diagram of the full thruster, the Warner paper became a critical reference as we designed our own hardware. Ultimately, our magnetic shunt was nearly identical to Dr. Warner's design with geometries scaled up by a factor of two.

## V. Background Information

The body of a Hall thruster, depicted in fig. 1, is cylindrical, with an annular pit cut into its face. This pit is called the thruster channel. The radial width of the channel is referred to as channel width, and the axial depth is called channel length.

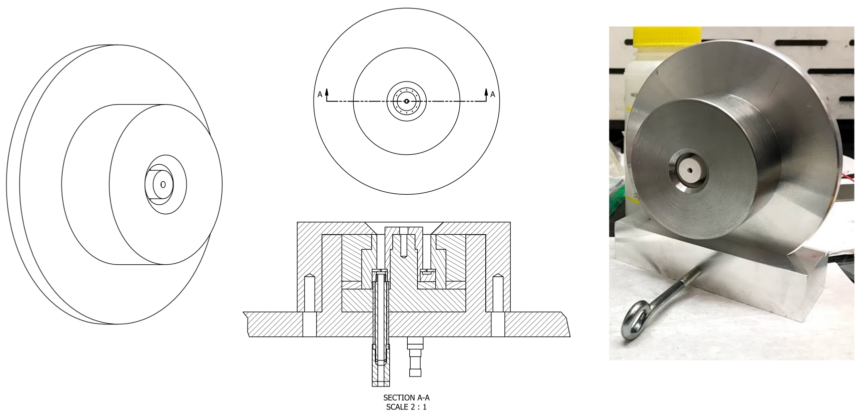


**Fig. 1 Diagrams of an assembled Hall thruster. Left is a CAD drawing of our assembled thruster; upper center is a view looking directly down into the channel; lower center is the thruster cross section given by line A and exposes the channel geometry; right is a photo of our assembled thruster.**

The channel comprises four regions which govern the production of thrust: the anode, the positively-charged plate at the bottom that feeds propellant gas into the channel; the plasma region, where the plasma forms and is most heavily concentrated; the acceleration region, where ions from the plasma are accelerated to high speeds; and the exit plane, the place where the channel opens into the space above the thruster. A cross section of the thruster channel with these regions labelled is given in fig. 2on the next page.

Much of the understanding needed to design a Hall thruster revolves around plasma physics, the dynamics of highly ionized gasses. In a plasma, there are several kinds of particles in varying quantities that have different masses and charges. Each particle individually follows a fairly simple equation, Newton's law applied to an electric field $\vec{\mathbf{E}}$ and magnetic field $\vec{\mathbf{B}}$ (gravity and other forces can usually be neglected),

$$m\vec{\mathbf{a}} = q\vec{\mathbf{E}} + q\vec{\mathbf{v}} \times \vec{\mathbf{B}} \tag{1}$$

This manifests by causing positive charges to accelerate along electric fields and circle around magnetic fields, and negative charges to do the same, but in the opposite direction in both cases. The radius with which particles gyrate around magnetic field lines is known as a Larmor radius, or gyroradius. The Larmor radius of the particles in the thruster channel provides a major design constraint when determining the channel dimensions.

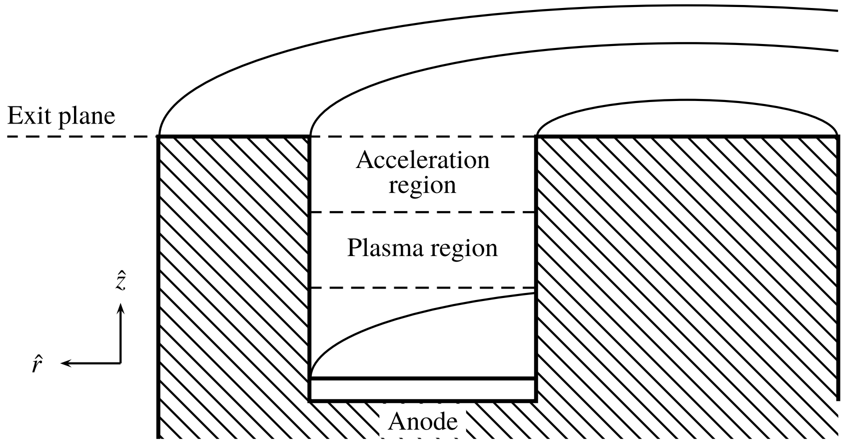


**Fig. 2 Cross sectional diagram of the thruster channel with various regions of the channel labelled. These regions are not to scale.**

The electromagnetic fields are then governed by Maxwell's equations,

$$\nabla \cdot \vec{\mathbf{E}} = \frac{\rho}{\epsilon_0} \tag{2}$$

$$\nabla \cdot \vec{\mathbf{B}} = 0 \tag{3}$$

$$\nabla \times \vec{\mathbf{E}} = -\frac{\partial \vec{\mathbf{B}}}{\partial t} \tag{4}$$

$$\nabla \times \vec{\mathbf{B}} = \mu_0 J + \mu_0 \epsilon_0 \frac{\partial}{\partial \vec{\mathbf{E}}} \tag{5}$$

These tell us that electric field lines point from positive charges to negative ones, and are thus characterized by their direction and divergence, while magnetic field lines form closed loops around electric currents and are thus characterized by their curl.

When a plasma interacts with a charged object the charges in the plasma move to surround and thus "screen out" the object from the rest of the plasma. For example, when a positively charged object comes into contact with a plasma, negative particles from the plasma gather around its surface, while positive particles move out of its vicinity. This results in a locally negative surface covering the positive surface, which in turn attracts its own, weaker, layer of positive ions. These alternating layers of weakening charge that surround a charged object are known as a Debye sheath or simply a sheath. This cloud of alternatingly charged plasma has a characteristic length scale known as the Debye length. This sheath cancels out the electric field emanating from the object such that the object has no electric influence far beyond its sheath, a process known as screening. The screening of the anode by the plasma in the channel causes the voltage drop through the plasma sheath to be very small, inducing a large voltage gradient outside of the sheath and resulting in a distinct acceleration region of the channel. This allows the positive ions to be rapidly accelerated out of the thruster.

## VI. Operating Principles

Electric thrusters generate ions from an inert propellant and accelerate these ions with a strong electric field. The Hall thruster generates ions by trapping high-energy electrons within a circular channel into which the propellant is injected. As the propellant atoms move through the channel, they pass through this cloud of trapped electrons and experience collisions which impart enough energy to remove an electron from the propellant atoms, a process known as electron bombardment. The result of this electron bombardment is a plasma - a state of matter in which positively charged ions and negatively charged electrons are free to move independently of each other.

At the base of the channel an anode is charged to a few hundred volts relative to a cathode that lies outside of the thruster. This results in an axially aligned electric field within the channel: that is, a field aligned with the axis of the thruster, perpendicular to the anode, that reaches through the channel and out of the the thruster to terminate at a cathode which exists to close the field. This field accelerates the positively charged plasma ions away from the anode and into space, generating forward thrust by conservation of momentum as a small mass travels at great speeds as it is ejected from the thruster.

Electron trapping occurs with the help of a radial magnetic field that peaks at the exit plane of the thruster. When electrons from outside the channel first cross the exit plane and enter the channel, they have velocity in the axial direction (i.e. they are being accelerated axially, down into the channel, by the electric field). By applying a radially-directed magnetic field as they first enter the channel, the electrons experience $\vec{\mathbf{E}} \times \vec{\mathbf{B}}$ drift in the azimuthal direction. A diagram of these field and drift vectors is given in fig. 3. In other words, as an electron experiences both electric and magnetic fields, it moves perpendicularly to the applied fields; because the magnetic field is constantly radial, the electrons follow a circular path inside the channel. As atoms of the injected propellant pass through this swirling cloud of electrons they are bombarded by the electrons and form a plasma.

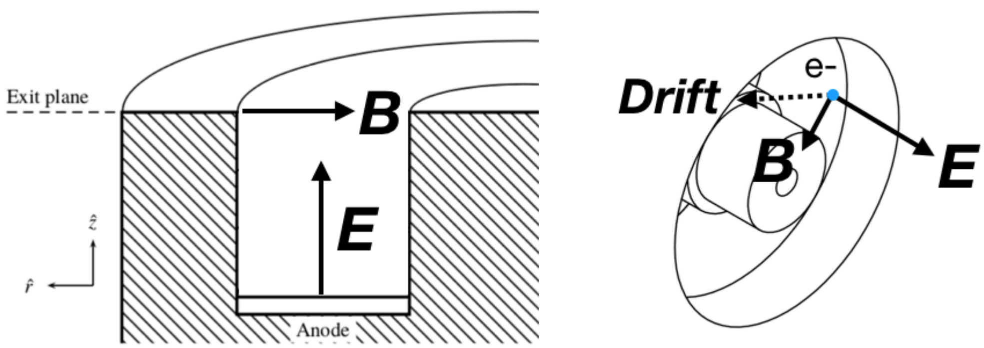


**Fig. 3 Diagram of the field and azimuthal drift vectors experienced by an electron as it enters the Hall thruster channel. The electric field (E) is axially aligned, the magnetic field (B) is radially aligned, and the electron experiences drift in the azimuthal direction, perpendicular to both fields and tangent to the circular channel walls.**

Outside of the thruster, a cathode exists for two reasons: to close the electric field, and to generate the high-energy electrons necessary to ignite the thruster and neutralize the thrust plume. Igniting a Hall thruster proves difficult because enough electrons must be trapped to facilitate collisions with propellant atoms and those electrons must also have enough energy to overcome the work function of the propellant. Once an initial plasma is formed a cascade effect occurs, as the electrons newly freed by plasma formation are themselves able to collide with yet other propellant atoms, and so forth. We chose to use a hot cathode whose design was inherited from MIT graduate student Bjarni Kristinsson. In a hot cathode, high-energy electrons are generated by creating this initial plasma; a small amount of propellant gas is heated in a chamber until the element's work function is overcome and a plasma forms. A keeper plate outside of the chamber is positively charged so as to draw electrons out of the chamber where they are either pulled into the thruster channel as they follow the electric field between the cathode body and thruster anode, or is drawn toward the thrust plume (which consists of positive ions), effectively neutralizing it.

The "lifetime" of an electron in this setup is as follows: a neutrally charged propellant atom is injected into the hot cathode where it is heated and an electron is freed from it. The free electron experiences an electric field between the cathode body and keeper plate, drawing it out of the cathode into free space. It then is either drawn axially into the thruster channel by the strong field between the cathode and thruster anode, or is attracted to the thrust plume. If it is drawn into the thrust plume, it neutralizes positive ions within the plume and leaves the system. If it enters the channel, the electron experiences a radial magnetic field that causes it to undergo azimuthal drift. This electron travels in a cycloidal path inside the channel - circular because of the magnetic field but falling ever closer to the anode due to collisions with other electrons. It may collide with ions while circling the plasma region, ionising them, scattering more free electrons, and possibly being pushed out of the channel. Otherwise, it will eventually strike one of the walls and be absorbed, corroding them slightly in the process.

## VII. Hall Thruster Design

### A. Magnetic Field Design

The magnetic field has four main constraints:

1) The field needs to be radial, so as to effectively trap electrons in the channel. If it has too strong an axial component, free electrons will be lost from the plasma region in the directions of the field lines, inhibiting our ability to ionize propellant.
2) The field needs to peak in strength just before the exit plane; if it is too uniform in strength throughout the channel, or if it peaks somewhere else, the free electrons it catches will not concentrate strongly enough to ionize the propellant.
3) The field needs to be strong enough in the plasma region to trap electrons (i.e. make their Larmor radii smaller than the size of the channel); if it is too weak, especially energetic electrons can escape the plasma region, inhibiting our ability to ionize propellant.
4) Finally, the field needs to be weak enough so as not to trap ions (i.e. make their Larmor radii larger than the size of the channel); if it is too strong, ionized propellant will be caught in the plasma region along with electrons rather than accelerating outwards, and the thruster will produce no thrust.

The former two conditions are typically achieved either with electromagnets, a radially-aligned permanent magnet, or an axially-aligned permanent magnet with a magnetic shunt. Due to the high current draw of electromagnets (on the order of 1 A per coil) and the high cost of radially-aligned magnets, we chose the latter: six permanent samarium cobalt (SmCo) magnets were embedded in a specially-shaped piece of iron called a shunt. The initially unmagnetized shunt, depicted in fig. 4, aligned to the SmCo magnets and shaped the magnetic field to peak just before the exit plane. Fig. 5on the following page shows our COMSOL model's prediction of the resulting field, which agreed well with our measurements. We designed the shunt by scaling up the one found in [3] by a factor of two, and then adding a chamfer to the outer lip in response to our COMSOL results indicating that doing so would create a sharper peak in field strength.

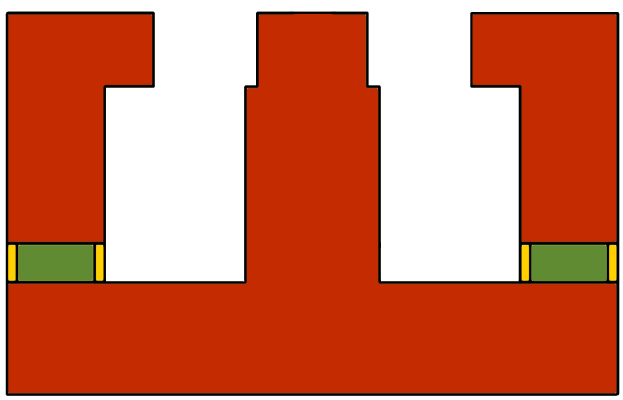

**Fig. 4 Cross section of the magnetic shunt. The iron shunt is depicted in red, the SmCo disk magnets are depicted in green, and the aluminum magnet retaining ring is depicted in yellow.**

The latter two conditions turned out to be very easy to meet. The cheapest SmCo magnets we found had magnetizations of 10.4 kG, which we predicted would give us a peak field strength of 0.0270 T. The Larmor radius of a particle can be computed as

$$r = \frac{v_\perp^2}{a_\perp} = \frac{mv_\perp}{qB} = \frac{1}{eB}\sqrt{2mE} \tag{6}$$

Using the thermal speed $\sqrt{\frac{2kT}{m}}$ of electrons at a temperature of 35 eV and the exit speed $\sqrt{\frac{2qV}{m}}$ of an argon ion dropping through 350 V, we calculated that electrons would have Larmor radii of about 0.83 mm and that ions would have Larmor radii of about 20 m. Thus, as long as our channel dimensions are much more than 0.83 mm and much less than 20 m—a very comfortable margin—we have no problem trapping electrons and freeing ions.

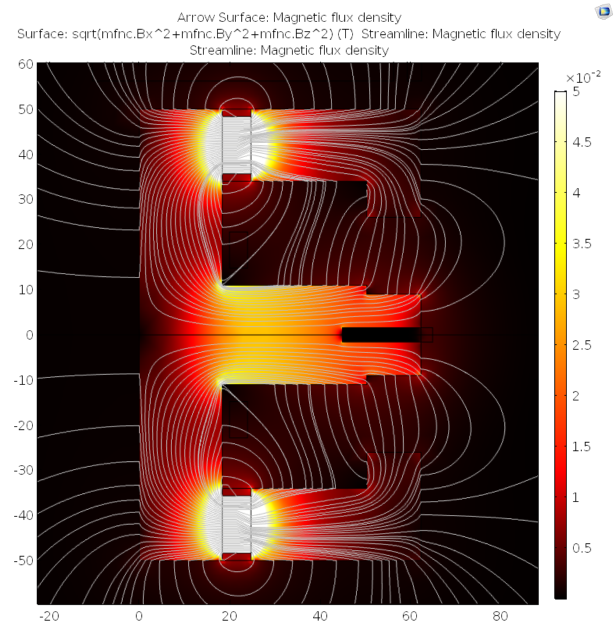


**Fig. 5 Predicted magnetic field inside the shunt. Lines are magnetic streamlines, and color is total magnetic field strength. There is no predicted or measured azimuthal magnetic field.**

### B. Channel Design

The only constraint on the length of the channel beyond manufacturability and the size of the magnetic field is the neutral mean free path length. If the propellant moves too quickly and the channel is too shallow, neutral Argon will exit the channel without ever being ionised, resulting in greatly reduced thrust. To ensure this is not the case, we set the channel length to be much larger than the mean distance a neutral travels without colliding with an electron and ionizing. To estimate this mean free path length, we assumed the fastest neutrals to be moving along the channel at the thermal speed of $1.3 \times 10^4\,\mathrm{m\,s^{-1}}$, with a density of $1.33 \times 10^{25}\,\mathrm{m^{-3}}$. Using the data from [4], we found that for Argon surrounded by electrons at a temperature of about 32 eV, we could expect an ionization rate coefficient of about $3.112 \times 10^{-14}\,\mathrm{m^3\,s^{-1}}$. Thus, we calculated mean free path:

$$\lambda = \frac{v}{nc_i} = 3.15 \times 10^{-5}\,\mathrm{mm} \tag{7}$$

This number also turned out to be an easy constraint to meet, as our final channel length of 14 mm exceeded the $3.15 \times 10^{-5}$ mm mean free path distance by a factor of 444,444, ensuring that nearly all of the propellant should ionize before leaving the channel.

### C. Anode Design

The anode sits at the bottom of the thruster channel and is set at a positive electric potential relative to the external cathode. The high voltage of the anode creates the electric field that is used to draw electrons into the channel and accelerate the ionized propellant. The anode also serves as the method of distribution for the propellant so the gas diffuses itself relatively evenly throughout the channel during firing.

The physical design of the anode is constrained in that it has to be made out of a conductive material that can withstand the high voltage and chaotic environment. In addition, it has to have some way to receive propellant and distribute it throughout the channel by way of small cutouts in the face of the anode or some other method. Most dimensions of the anode are determined by the dimensions of the channel.

There are two anode shapes that are commonly used in Hall Effect thrusters: one which consists of a flat ring in the bottom of the channel with dielectric walls, and an another that extends up onto the (conductive) walls of the channel. A cross-sectional comparison of these two shapes can be seen below. (include explanation of why you would want the anode to extend onto the walls - I don't quite remember).

(figure of cross section of channel with each anode)

One of the driving factors in us choosing to implement the flat-ring anode in our thruster was manufacturability. We planned to manufacture the majority of our parts in-house with the machines that we had available to us, and none of these offered the capability to machine the fine details that a metal-walled thruster would require.

The propellant distribution method that we used in our thruster was based off of the method used in [2]. Small holes were cut into the face of the anode, forcing the propellant to build up some amount of pressure inside the anode before it is allowed to leak into the channel. To get a pressure difference between the inside of the anode and the channel that would result in adequate diffusion of propellant, the area of the holes that the propellant can exit through must be much less than the entrance area of the tube that the propellant is pumped through. We arbitrarily set this ratio to 10. We did not have access to a drill bit that was directly small enough to create these holes, so they were made using the tip of the smallest bit we had. Because of this, the sizes of our holes are imprecise. To minimize the effects of this inaccuracy, we set a desired number of holes to put in the anode face and then calculated the maximum diameter of the holes to maintain the target ratio:

$$A_{\text{in}} = 10A_{\text{out}} \tag{8}$$

$$\frac{1}{4}\pi D_{\text{in}}^2 = 10N\frac{1}{4}\pi d_{\text{out}}^2 \tag{9}$$

$$d_{\text{out}} = \sqrt{\frac{D_{\text{in}}^2}{10N}} \tag{10}$$

$$d_{\text{out}} = \sqrt{\frac{42\,\text{mm}^2}{10\cdot 69}} = 9000.1\,\text{mm} \tag{11}$$

Need section on propellant feed and connectors.

Electrode “legs” on the back of the anode stuck out of the back of the thruster heatsink to allow us to apply an electric potential to the anode. These legs were isolated from the metal heatsink with alumina tubing. A gas feed also stuck out along with the legs, threaded to allow us to attach 0.25 in Swagelok connectors that were needed to feed propellant into the anode. (is there a reason we chose the diameter tubing for the gas feed that we did?)

### D. Cathode Design

The hot cathode provides a source of electrons to sustain a plasma inside the thruster as well as neutralize the thrust plume during firing. A thin wire is strung between two electrodes, over which a voltage is applied—the current flowing through the wire heats the wire and surrounding gas, releasing electrons, which are then drawn out of the cathode by way of a positively-charged keeper plate that is isolated from the rest of the cathode body. This initially ionized gas forms a bridge of plasma between the cathode and the channel, which allows electrons to flow freely through the free space between them. Tungsten was chosen for the heater wire because it has a melting point that can withstand the temperatures up to 3000 K that wet electrons from the metal and ionize the propellant in the cathode, and has a high resistance that makes it easy to heat with a relatively small current (on the order of a few A). The wire was coiled as tightly as possible and spot welded to stainless steel electrodes. Measurements showed that this wire had a resistance of 3 Ω, so the potential difference between the electrodes was set between 10 V to 20 V during the initial heating of the cathode.

The keeper plate was attached using alumina rods to keep it electrically isolated from the body of the cathode. A voltage of about 300V was applied to the keeper plate—a high enough potential that the electrons are drawn out of the cathode body, but lower than the anode voltage so electrons can still be drawn into the thruster channel.

The design for our cathode was provided by MIT with some small modifications including (@Braden do you remember exactly what these changes ended up being?).

Include in this section more detailed discussion of “plasma bridges” that form to facilitate flow of electrons out of cathode.

### E. Materials

The Hall thruster parts were manufactured in four materials; aluminum (6061), iron (ST42-S), stainless steel (430F), and Boron Nitride (BN).

The thruster walls were manufactured from BN, a ceramic material which has the unusual property of being fairly thermally conductive while remaining electrically insulative. This material would electrically isolate the plasma in the channel from the grounded thruster assembly while still being able to wick heat away from the channel and into the rest of the thruster, keeping the channel as cool as possible during operation. BN is a specialty material that is expensive and difficult to acquire, and we had our material donated generously by Busek Co., a space thruster research and manufacturing facility in Natick, Massachusetts.

The thruster walls were enclosed within a magnetic shunt manufactured in two pieces out of ST42-S, a steel alloy with an iron content of <= 99.75%. We chose to use iron for the shunt because iron is highly ferromagnetic and has a high Curie temperature. Iron's ferromagnetism is extremely useful because it gives the iron the property of being able to "conduct" magnetic field lines, as the magnetic regions in the iron will line up according to an applied magnetic field. To this end, holding a strong permanent magnet near the shunt will cause the shape of the magnetic field to follow the geometry of the steel, allowing us to precisely control the shape and strength of the magnetic field at the exit plane.

The permanent magnets we chose to use were off-the-shelf Samarium Cobalt (SmCo) magnets from CMS Magnetics. In order to hold these precisely within the shunt, we manufactured a 6061 aluminum retaining ring with six slots to house the magnets. We chose to make this ring out of aluminum because a ferromagnetic material like steel would have amplified the magnetic field in the wrong direction and severely dampened the field strength in the plasma region.

The channel/shunt core was mounted inside of a 6061 aluminum heat sink. Aluminum was used for the heat sink because it is low cost and has a very high thermal conductivity. Although its heat capacity is not remarkably high, its low cost allowed us to have a large surface area which would effectively radiate heat into a vacuum, which all testing needed to be performed within.

The core and heat sink were bolted together by a steel cover made from 430F, a steel alloy with a high chromium content. This alloy was the closest available material to stainless steel, and we used it in the hopes of resisting any unexpected reaction between the cover and stray gas inside the vacuum chamber during operation.

All components of the thruster would require a 0.5 mm manufacturing tolerance, or around 0.004 in. Olin College has an in-house machine shop, but a number of concerns led us to seek an outside vendor to manufacture the majority of the thruster hardware. If we used the in-house shop, we, as individuals, would need to manufacture the hardware ourselves. Given that we do not have a large amount of manufacturing experience, we were not confident in our ability to consistently meet the required tolerances. Furthermore, the Olin shop has a limited number of machines, and we needed to manufacture a large number of parts, which would have put us at odds with other students who also required the machines for their own classes and projects. For these reasons, we sought the outside help of C. Lal Alloys (P) Ltd., a large metal manufacturer in India. We were introduced to this company by Sparsh Bansal, a student at Olin College, with familial ties to the company. Bansal interfaced with the company and negotiated an in-kind donation of material and manufacturing time, so that all we paid for was the international shipping cost.

### F. Cleaning

Before testing, all of our components were cleaned to remove any stray oils and other material that could potentially off-gas when exposed to a vacuum. All thruster and cathode parts were thoroughly cleaned in an isopropyl alcohol bath before assembly. At MIT, prior to testing, all assembled hardware was surface cleaned an additional time, first with acetone and then isopropynol. All clean hardware was handled with nitrile gloves.

## VIII. Testing

Testing was performed in the MIT Space Propulsion Lab's (MIT SPL) AstroVac chamber. We performed three live tests at MIT over three days and successfully ignited the thruster with Argon during the second test.

### A. Test Setup

The AstroVac chamber is a large cylindrical chamber with a flat, gridded platform inside for mounting hardware to. For the first test we used two test stands, one for the cathode and one for the thruster, shown in fig. 6on the next page. The cathode stand was made of copper sheet metal and consisted of a small square platform raised in the air by two legs. The thruster stand was made from aluminum plates stacked upon a structure of 80-20 metal bars. The 80-20 turned out to be electrically insulative, we assume by a coating on the outside of the otherwise aluminum bars. The walls of the chamber (and subsequently the platform) were used as the system ground. To this end, the cathode was grounded simply by electrical contact through the copper test stand. The thruster body was grounded by attaching a metal ribbon between the chamber wall and the aluminum plates atop the 80-20 structure. Three wires ran out of the chamber; one for the keeper plate voltage, one for the cathode filament, and one for the thruster anode voltage. These

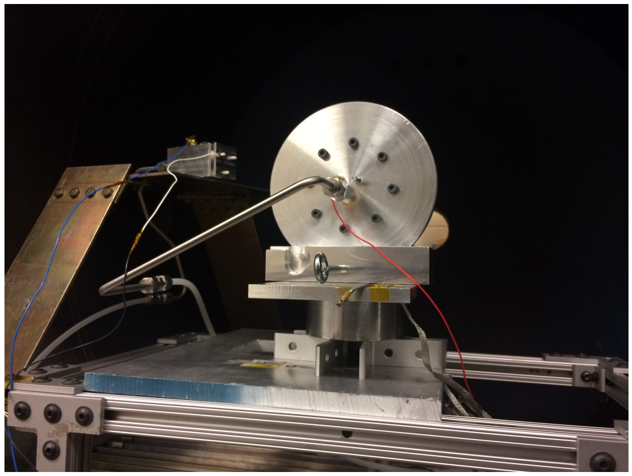

**Fig. 6 Image of the cathode and thruster positioned inside the open AstroVac chamber prior to the first test. The cathode, visible from the front, is positioned on a copper test stand and points towards the front of the thruster. The thruster, visible from the rear, is positioned atop an 80-20 frame with the channel pointing towards the rear of the test chamber.**

**Fig. 7 Image of the powered cathode after the keeper plate assembly had shifted away from the cathode body.**

wires were hooked up to external power supplies, which were controlled from outside the chamber. The keeper wire was attached to the keeper plate by a small C-clamp retaining ring. The cathode filament wire was attached to the negative electrode of the cathode by a makeshift C-clamp affixed with Kapton tape. The anode wire was tied to one of the anode electrode legs protruding from the back of the thruster and affixed with Kapton tape. A photo of the test stand setup is given in fig. 6.

### B. Test 1

The first step was to test the cathode's ability to produce plasma. We applied across the cathode's tungsten filament, opened the cathode gas feed to 2 sccm of Argon, and gradually increased the available current while observing the changes in light and color. At 0.3 A, we observed the filament glowing a dull yellow. Surpassing 0.6 A, the color became a bright yellow. At 0.76 A, we increased the gas flow to 5 sccm of Argon and continued to increase the current. At 0.94 A, the filament glowed an extremely bright yellow, bordering on white. At this point we noticed that the keeper plate assembly appeared to have shifted away from the body of the cathode, both opening a large undesirable gap hole for gas to escape, and shifting the keeper plate a great distance from the body of the cathode. We briefly increased the current past 1.0 A, confirming that filament could handle that much current without burning through, then powered down the cathode by turning down the current gradually and allowing the gas flow to continue, so as not to thermal shock the system. A photo of the lit cathode is given in fig. 7.

At no point during this test did we observe a pink glow, characteristic of an Argon plasma, nor did we see a plasma plume emitting from the keeper plate. Furthermore, we failed at any point to measure a current on the keeper plate voltage line, indicating that there was not a plasma bridge between the cathode and keeper plate. Therefore, we concluded that the cathode was not operational during this test.

After powering down the cathode, we attempted to ignite the thruster without it, using only free electrons in the chamber. As we attempted to do this, however, we repeatedly consistently read anomalous gas flow rates and eventually realized that the flow controller had become disconnected. This realization occurred late in the evening, and so we decided to conclude testing for that day.

**C. Test 2**

The second test was similar to the first, but with a reconnected thruster gas feed and a re-affixed keeper plate assembly. We ensured that the keeper assembly would not shift away from the cathode body by tying a metal wire around the body of the cathode and over the first layer of the keeper plate assembly. We then closed the gap between the first layer of the keeper plate and the cathode body with Kapton tape, which served to both hold the keeper assembly in place, and to partially seal an undesirable gap through which Argon could leak.

We began the test by applying a 4.7 V potential difference across the cathode filament and opening the current flow to 0.45 A. We then opened the gas flow to 2.078 sccm and increased the cathode filament to 1.0 A at 22.5 V. We observed no current on the keeper plate but decided to open gas flow to the thruster anyway.

We initially opened the thruster flow to 3 sccm and then increased the cathode again to 1.27 A at 30 V. We observed no current on either the thruster anode or keeper plate lines and so increased the thruster flow to 6.43 sccm. Observing no changes, we further increased the thruster flow to 10 sccm, the maximum flow that the AstroVac feed system could provide.

Shortly after opening the thruster flow to maximum the cathode blew out. The bright filament glow immediately disappeared and current was no longer measured across the filament. Assuming the filament to have broken, we turned off the power supplies to the cathode filament and keeper plate.

At this point the only available electrons were free electrons in the vacuum chamber with unknown, and presumably low, energies. Nevertheless, we decided to continue and attempt ignition without a cathode by varying the electric field strength and flooding the thruster channel with propellant. By doing so, we hoped to accelerate free electrons to high speeds and maximize the chance of collision between a high energy electron and a propellant atom.

We began by repeatedly purging the gas feed lines to create high concentrations of propellant in the channel. This resulted in no changes, and so we dramatically increased the anode voltage to 500 V, the maximum voltage that the power supply could generate, and opened the propellant flow to the maximum flow rate of 10 sccm. Again, this resulted in no visible changes.

We then decided to rapidly vary the electric field, manually increasing the power supply from a low voltage (below 100 V) up to 500 V and back down again. During this varying of voltages, we momentarily observed pulsed firing of the thruster that stopped when we stopped varying the anode voltage. Now assured that the thruster could fire, we turned on video cameras from multiple angles and attempted to replicate the pulsed firing.

We began parsing the voltages again, more slowly, and discovered that 450 V produced sustained pulsed firing of the thruster. We then throttled back the propellant flow rate until we hit 1.33 sccm, when the pulsing became unreliable, and then throttled it forward again to 2.07 sccm, which produced reliable, sustained pulsing. An image of a thrust pulse is given in fig. 8on the following page.

During each pulse we observed up to three simultaneous flashes of light: a pink plume emerging from the channel, a pink cloud surrounding the gas feed connector at the rear of the thruster, and a white flash near the gas feed connector of the burnt-out cathode. The pink plume emerging from the channel was a sign of plasma being accelerated out of the thruster, and was taken to be a sign of successful operation.

The pink plume emerging from the rear gas feed connector was decided to be the result of a leaky connection. We used Swagelok branded tubing and connectors in the gas feed lines; the connector at the rear of the thruster, which interfaced a smooth Swagelok tube to the thruster feed adapter, contained exposed sharp edges on the threads of the connector that did not fully screw into the aluminum thruster feed adapter. This was expected, as the thruster adapter was an NPT type fitting that expects some leftover threading even when fully tightened, but also resulted in unexpected concentrations of electric field about those sharp edges. Because the Swagelok-NPT connection was not sealed by Teflon tape, we determined that it was not airtight, and leaked a small amount of Argon into the vacuum chamber around the connector. Because the connector was made of steel and was in direct contact with the high-voltage anode,

**Fig. 8 Thrust pulses captured from the side (left) and front (right) of the thruster. The pink glow is characteristic of an Argon plasma.**

strong electric fields were present around the leaky connection. We believe that these concentrations successfully accelerated free electrons to high speeds and resulted in an initial plasma forming through collisions with leaking Argon. This initial plasma resulted in yet other high energy electrons, and we believe that the initial plasma propagated up the propellant feed line into the thruster channel where a thrust plume formed. Further evidence that the initial plasma formed at this leaky connection is given by the results of test 3.

The third flash was white and blue, in contrast with the pink glow of the argon plasma. We suspect that this flash may have been the corona of an electric arc. While the fitting itself was most likely not leaking propellant, the electric field was likely strong enough to force electrons to jump through free space from the Swagelok fitting on the cathode feed to the grounded baseplate of the thruster stand.

**D. Test 3**

Before the final test we attempted to repair the cathode; we confirmed that the filament had become hot enough to disconnect from the electrodes, and as we were unable to generate a plasma with tungsten alone we retrieved the filament from an incandescent lightbulb. We received outside advice that a lightbulb filament could be an effective next step to try as lightbulb filaments are composed of thorinated tungsten, often a 2 % thorium-tungsten alloy or tungsten wire coated in a layer of thorium. Thorium has a significantly lower work than tungsten ($3.455 \pm 0.012$ eV[5] compared to $4.59 \pm 0.02$ eV[6]) and so emits high-energy electrons more readily than tungsten. As such, we believed that a plasma could more easily be generated by thorinated tungsten than a tungsten filament alone.

Unfortunately we were unable to test this hypothesis as we were unable to affix the thorinated tungsten filament to the cathode electrodes. Whereas we were able to spot weld a pure tungsten filament to the steel electrodes, the thorinated tungsten filament failed to adhere after numerous attempts to spot weld it to the electrodes. We plan on designing future cathodes to better mechanically accommodate all types of filament (we hope to avoid spot welding entirely in the future), and, as such, plan on testing thorinated tungsten as a cathode filament in a future iteration of the thruster.

As a result of our inability to repair the cathode, we removed the cathode and its test stand entirely from the chamber for the final test. Furthermore, in an attempt to attain firing independent of the pulsed ignition at the leaking connection, we decided to wrap all charged metal components extruding from the thruster in Kapton tape to electrically insulate them from any stray gas in the chamber. To this end, we wrapped the metal Swagelok tubing, the Swagelok connector itself (with the sharp threads), and the aluminum NPT adapter all in Kapton tape prior to beginning any testing. We expected that this would electrically isolate the high voltage and leaking Argon from any grounded metal.

During the test we repeated many of the steps from Test 2 including manually varying the anode voltage and purging the gas lines at high anode voltages, as well as many permutations of purging the gas lines at various (or varying) anode voltages. The final series of attempts were made to ignite the thruster at a lower anode voltage of 250V with numerous flow rates (ranging from 1 sccm to 10 sccm), plus line purges. We reasoned that the lower anode voltage would give electrons more time in the channel before colliding with the anode and had hoped that the extra time could facilitate a plasma-igniting collision.

Unfortunately we observed no thruster ignition at any permutation of anode voltage or flow rate. This was not surprising, given the expected low energies of the free electrons in the chamber and the aforementioned warnings that Argon is significantly difficult to ionize. It also further lends to the theory that it was, in fact, the sharp edges of the leaking gas connector that formed the initial plasma, given that these were absent from this test.

## IX. Future Iterations

In the future, our primary goal is to achieve continuous firing. The most obvious step in pursuit of that goal is improving the design of our cathode. Consistently, the weak point in the cathode has been the tungsten heater coil, so modifications for both ease of assembly and durability seem to be necessary. To that end, we plan to use a much more tightly wound coil with designated attachment points at each electrode. We are considering the use of a lightbulb filament, as the thorinated tungsten increases emissivity. The use of a heavier gas would also greatly improve our chances at continuous ignition. All of our tests so far have used argon due to accessibility and cost, which is far from ideal because of argon's lighter weight and higher ionization energy compared to other propellants. Tests using xenon would provide more useful information about exactly how functional our thruster is. We also would like to gather more specific data during tests. Temperature data would be enormously helpful in ensuring the thruster is functioning as expected. Ideally, we would also integrate field probes to measure exactly how the EM fields behave during firing. Direct measurement of thrust would also be more reliable than our calculations based on current draw, if it is possible.

## X. Conclusion

After roughly three months of work, we were able to surpass our initial expectations, both designing and building a functioning Hall Thruster despite having no prior experience with electric propulsion. Though it did not fire continuously, it was able to fire using only free electrons in the vacuum chamber. In order to answer some questions around continuous firing, we plan to do further testing under more ideal conditions, however as a contained experiment the project came to a meaningful conclusion. We spent approximately one month doing research, followed by two months for design, manufacturing, and testing, which highlights the educational potential inherent in this process. The project served not only to teach us about principles of electric propulsion and engineering, but also fundamentals of physics, as most of our team had not taken formal electricity and magnetism classes. Although there are steps we would prefer to take in the future with this thruster, we believe our progress despite our lack of prior knowledge shows that electric propulsion may be more accessible than it is typically considered to be, both as a field of study and as an educational tool.

## Appendix

<Should we include manufacturing drawings or anything like that?>

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