127th ASEE Annual Conference
June 21-24, 2020 | Palais des congrés de Montréal | Montréal, Canada

Paper ID #29672

(Student Paper) Undergraduate Demonstration of a Hall Effect Thruster: Self Directed Learning in an Advanced Project Context

Braden K. Oh, Olin College of Engineering

Braden Oh is a second-year mechanical engineering student at Olin College of Engineering with an interest in space technology. Previous work of his has included CubeSat systems engineering through the NASA CubeQuest Challenge and software systems verification and validation for the Perseverance Mars rover at the NASA Jet Propulsion Laboratory.

Justin Haruaki Kunimune, Olin College of Engineering

Justin Kunimune (/dstn kunmune/) is a nuclear engineering student at the Massachusetts Institute of Technology who recently graduated from the Olin College of Engineering. He is professionally interested in nuclear fusion energy. He is hobbially interested in map projections, language construction, and historical cosmological models.

Jonah Spicher, Olin College of Engineering

As a third year electrical engineering student at Olin College of Engineering Jonah Spicher is interested in space propulsion methods and advancing engineering education.

Lauren Anfenson, Franklin W. Olin College of Engineering

I'm a current undergraduate at Olin College pursuing a degree in Electrical and Computer Engineering. Previous electrical hardware intern with NASA JPL and Microsoft, current Sketch Model Fellow with the Massachusetts Museum of American Bird Art.

Dr. Rebecca Christianson, Draper Labs

Undergraduate Demonstration of a Hall Effect Thruster: Self Directed Learning in an Advanced Project Context

Abstract

Here we demonstrate a self-directed project for undergraduate students that uses the design of a Hall effect thruster (HET) as a way to introduce fundamental physics concepts in lieu of traditional coursework. HET is a type of electric propulsion engine that uses orthogonal magnetic and electric fields to create a plasma that ionizes a propellant, which is then accelerated by a strong electric field to create thrust. The HET is used for many modern space applications, from station-keeping on small satellites to long-term travel to faraway asteroids.

Electric propulsion, and specifically the HET, integrates many concepts that are fundamental in an undergraduate education such as electricity and magnetism (E&M), material properties, thermal analysis, and laboratory experimentation. However, the HET is rarely studied below the graduate level. As such, we present a path of feasibility for an undergraduate electric propulsion project building a small, low-power HET, both as a novel vehicle for engaging with introductory physics concepts and as a case study of an advanced self-directed project at the undergraduate level.

In this paper we detail our process for developing a fundamental understanding of electric propulsion and demonstrate how to apply that learning to the design, manufacture, and test-fire of a small, low-power HET. Participants learned principles of E&M by modeling the magnetic field and channel, material properties and thermal analysis by designing the thruster components, and laboratory experiment by testing the thruster. We were able to complete this project with limited resources and within a single academic semester; to accommodate the constraints of integrating this project into undergraduate coursework, our HET was built with under $600 and using machinery found in a standard machine shop. Whereas typically a central concern in project based learning is ensuring a student begins a project with most of the skills needed to complete it, this paper outlines an extreme counterexample. We demonstrate that by taking advantage of student motivation, projects requiring skill sets far beyond those possessed by students at the beginning of the project can be both feasible and highly educational. Our hope is that readers of this paper will be able to use the design and construction of a low-power HET or similar projects in their own education as an applied way to learn fundamental physics while also customizing this project structure to address individual students' learning goals.

1 Introduction

Over the course of a single semester, from September to December of 2018, we—a group of four undergraduate students—undertook a project that considered HETs not only as a means of electric propulsion, but as a tool to learn introductory concepts that HET operating principles are based on, such as force and momentum, heat transfer, and E&M. We identified the HET as a potentially apt candidate for an educational self-directed project out of mutual interest in the subject, and because it encompasses many of the topics covered in more traditional introductory physics courses. The HET seemed challenging due to its complexity and rarity at the undergraduate level, and intriguing due to its modern applications. It also provided an excellent opportunity to link disparate physics and engineering topics together, such as using equations for particle motion in electromagnetic fields to determine physical dimensions of the thruster.

Project-based learning has become a popular method for improving engagement in physics and engineering education,[1,2,3] particularly with respect to providing a capstone experience for students to apply what they've learned in a class. However, such projects are rarely initiated, designed, and completed by students, despite the demonstrated efficacy of self-direction.[4] The structure of this project was novel in that it was not intended as a show of understanding of concepts we had already been taught, but as a context in which to teach ourselves the concepts needed to complete the project. Instead of being a supplement to an introductory physics course, the goal of this project was to serve as an alternative to such a course.

As Olin College is relatively new and electric propulsion is a niche field, we were limited in the resources we had available to us. There is no electric propulsion research lab, no faculty with specific expertise in space propulsion, relatively limited machining capacity (our machine shop houses CNC mills and manual lathes), and we were given no official funding by Olin. As a result, it was advantageous for us to optimize our design for simplicity of manufacturing as well as cost. This lack of resources also pushed us to seek outside sponsorship, which was a key component of the success of this project as well as an opportunity to learn how to acquire resources independently.

Initially, the scope of the project was to learn physics principles behind electric propulsion, to develop computational modeling skills, and to apply the theoretical physics from this study (supplemented by material from the standard engineering curriculum) to real thruster design decisions; we did not originally plan to actually build such a thruster. As the project progressed, however, we developed skills in many fields beyond those we initially set out for, including CAD modeling, design for manufacturing, fabrication techniques, and interaction with external manufacturing facilities. We also gained experience with performing a literature search, as, out of necessity, we sought out and compiled sources of information on electric propulsion, and we eventually interfaced directly with experts in the field. Progress on the research and design moved faster than we anticipated, and we were able to fully manufacture and test an HET by the end of the semester.

This process convinced us of the potential of projects like these for application-based education; because it was self-driven, we were intrinsically motivated to learn all of these concepts out of necessity. In this paper, we aim to provide clarity for the process of designing and building a small, low-power HET as a self-directed project.

2 Project outline

2.1 Team formation

The core project team consisted of three undergraduate sophomores and one undergraduate senior, with academic advisement from an Associate Professor of Applied Physics, Rebecca Christianson. Olin College is a 4-year undergraduate school with a focus on project-based engineering curriculum, in which students constantly apply the skills and techniques learned in a classroom to technological demonstrations, rather than exams. All four students had some experience with introductory physics, but none had studied advanced topics relevant to electric propulsion, such as plasma physics. Olin College recognized and encouraged this project as an independent study, and awarded our team general engineering credit for this endeavor.

The team was deliberately assembled to be multidisciplinary, with areas of expertise including electrical engineering, modeling and simulation, mechanical engineering and manufacturing, and physics. The disciplines that are useful to have represented on a team will vary with the end goal of the project—for example, we were planning on mechanically designing a thruster, so we made sure to include someone who had experience in mechanical design. If when recreating this project one wants to put more emphasis on, for example, producing optimized models of the thruster's parameters, mechanical design may not be an interest that needs to be represented on the project team. When forming or self-selecting teams for a project, it is important to identify the main disciplines that are integral to the completion of the project and make sure that interest in each of those disciplines is represented on the team.

2.2 Goal setting and deliverables

In the very early stages of this project we found it useful to have a discussion about individual learning goals and interests. This allowed us to identify what each team member wanted to get out of the project in order to shape our end goals to accommodate those wants; this helps foster the self-motivation that is required for success in a project that has a high learning differential for all involved. We decided on the scope, scale, and deliverables for our own project. This freedom ensured that we only pursued goals that were realistic and of direct interest to us. This control is important for students to have in a project of this scale because it ensures continued engagement; if we ever found ourselves disengaged with our goals, we allowed ourselves the freedom to discuss changing these goals as a group.

When setting the desired deliverables for the project based on the interests of the team members, we came up with a set of tiered goals. This let us set minimum viable product goals that would satisfy the interests of everyone involved, while also giving us the flexibility to change our scope and extend our learning depending on how the project progressed. At the least, we would all come out of this experience with an understanding of the fundamental operating principles of HET through readings, group discussions, and modeling. The extension of that was moving into designing specifications for our own thruster and incorporating those constraints into our models. Our stretch goal was to manufacture, assemble, and test the designed thruster. These goals can (and should) be changed to suit the individual needs, interests, and commitment level of one's team. We do, however, think it is vital to build this flexibility into one's initial goal setting to account for the inevitable unpredictability of a team project and to keep motivation high as the interests and needs of the team change.

While customization of goals and deliverables is important for student engagement and motivation throughout the course of the project, if this model is to be used as a project-based approach to teaching fundamental physics, there are certain subjects that must be learned by the participants, such as mechanics and E&M. These concepts naturally arose from seeking a fundamental understanding of the thruster we were designing and building, which is a large part of why we found the HET to be an ideal project topic. We dedicated the first three weeks of the project to meetings focused on learning with the entire team. We would choose a topic or set of problems for each of our two weekly meetings, and work through them as a group, recording questions that we had as they arose and using those unknowns to structure the content we covered in the next meeting. This ensured we all had a shared knowledge base before we focused on our specific interests for the remaining weeks.

2.3 Timeline

The timeline for this project was constrained within one academic semester, between September and December. This timeline changed a few times over the course of the semester, but ultimately was broken into three ’phases’ that were representative of the tiered deliverables we had set at the beginning of the project:

> **Weeks 1-3: Building a theoretical background –** work through chapters in Fundamentals of Electric Propulsion by Dan Goebel and Ira Katz to understand the math needed to model the function of a Hall thruster. Deliver a ‘problem set’ at the end of week 3 that demonstrates a basic understanding of the physics involved in electric propulsion.
>
> **Weeks 3-6: Begin computational modelling –** choose parameters for the design of a Hall thruster (diameter, channel depth, magnet strength and positioning, etc) and begin developing a mathematical model of the design.
>
> **Weeks 6-10: Specialize –** Some team members have a higher interest in the mechanical design and fabrication of the thruster and would like to begin hardware manufacturing for a preliminary prototype. Others have a higher interest in computer modeling and would like to continue developing a high-fidelity magnetic model as well as explore the plume environment.

This timeline worked as a general structure, but ultimately, the actual process was not as cleanly partitioned. It was helpful to have the first three weeks set aside as time for the team to focus on building up a shared theoretical background, as well as compiling questions that we had and identifying potential future risks to our future modeling and designing process. Building this background, however, bled into every aspect of the project, as the application of our learning to the design of the thruster continuously brought gaps in our knowledge to light. For example, when in the later weeks of the project it came time to select the magnets that we would use in the thruster, we scheduled an additional team meeting dedicated to learning the properties of magnets and how we might physically—as opposed to in simulation—shape the magnetic field.

The ‘Specialize’ phase was where most of the schedule’s flexibility was built in; we were still unsure when making this schedule if we were going to reach the manufacture and testing of the HET we designed. So, 'Specialize' turned into a catch-all period that could be used for whatever needed to happen to advance the project. For our team, this meant dedicating a lot of time to the manufacturing and assembly of the thruster as well as making arrangements for testing, since our design was mostly completed at the end of the modeling phase. Of course, this distinction was not firm, and certain aspects of the design (such as the cathode) were finalized quite late in the process. This portion of the timeline was designed to let us complete whatever the specific goals of the project were. These might be different for different projects and different groups.

2.4 Resource acquisition

Identifying key resources—both intellectual sources on HET operation and physical sources of materials and manufacturing capabilities—was a critical starting point as neither our team nor anyone else at Olin College had previous experience with electric propulsion, and our project had no official funding. The process of identifying and acquiring these resources was a valuable learning opportunity that is nearly impossible to achieve in conventional projects, where needed resources are typically known and provided to students before the project starts.

We began our search for academic resources with the textbook "Fundamentals of Electric Propulsion: Ion and Hall Thrusters" by Dr. Dan Goebel and Dr. Ira Katz,[5] which was recommended to us by electric propulsion researchers we met through personal networking. It explains key operating principles of HET and provides equations and explanations for critical design quantities such as the Larmor radius (see section 3.1).

In addition to this more general reading, we searched the scientific literature to determine if there were any publications by other teams who had previously built demonstration HETs similar to the one we intended. We were able to locate two such papers: Matthew Baird's senior thesis "Designing an Accessible Hall Effect Thruster"[6] and Dr. Noah Warner's Ph.D thesis "Theoretical and Experimental Investigation of Hall Thruster Miniaturization". Both papers presented detailed descriptions of their authors' design processes, which served as invaluable roadmaps for our team. Many of our design decisions were ultimately taken directly from these publications (see section 3).

We quickly developed questions that could not be easily answered by Goebel's book or Baird's and Warner's theses, though. Because they were written for graduate students with more background knowledge than we had, reading them gave us an accelerated but incomplete understanding of electric propulsion and all the physics it depends on. We therefore sought out present experts in electric propulsion to field specific questions. By further pushing on our networks, we met JPL's Dr. Steve Snyder, MIT's Dr. Manuel Martinez-Sanchez and MIT graduate student Bjarni Örn Kristinsson, all of whom helped us greatly throughout the process. Each time we amassed a large number of questions, Drs. Snyder and Martinez-Sanchez met with us to answer them. Dr. Martinez-Sanchez and Mr. Kristinsson offered feedback as members of our design review committee before we began manufacturing. After the design review, Mr. Kristinsson also provided us a hot cathode design and interfaced between us and MIT's test facilities.

For material resources, we turned to local companies. The most expensive components of our

HET were those constructed of boron nitride, which can normally only be purchased in bulk. On our advisor's suggestion, we reached out to a local space propulsion company, Busek Co., to inquire about having some donated to us. They were receptive to the idea, and gave us all of the stock we needed for free.

We received a similar donation from a manufacturer, which we met through our personal networks. This company manufactured the iron sheath and casing of our HET out of stock they provided. This saved us multiple weeks of manufacturing at Olin College's machine shop facilities, and made it possible for us to complete the thruster before the end of the semester. Interfacing with them also gave us useful experience in both designing for manufacturing and composing technical drawings, subjects that none of us had extensively studied in our prior classes.

Rather than being impeded by our lack of resources, we used it to our advantage to learn how to seek them out. The process of resource acquisition gave us first-hand experience of the willingness of professionals to donate time and resources to a student project, while also teaching us a variety of skills that are difficult to teach in traditional classes and technical projects, like how to effectively communicate these requests and present our project convincingly to industry professionals. The unexpected availability of resources we had thought unobtainable was one of the factors that enabled us to progress so much farther than we had thought we would.

3 Hall effect thruster development

Traditional chemical rockets generate a large magnitude of thrust over a relatively short time scale by combusting fuel at moderate speeds. This works well for launch vehicles, where high thrust is necessary, but only needed for minutes at a time. Rockets also use inefficient chemical energy, which requires more fuel mass for the same amount of thrust, which makes them ill-suited for space, where vehicle mass becomes a critical design parameter.

An alternative form of thrust is electric propulsion; rather than accelerating molecules through combustion, electric thrusters ionize individual atoms that are then 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 substantially less fuel mass per unit impulse and can fire for much longer than chemical rockets—sometimes thousands of hours. Ultimately, electric thrusters are capable of achieving large changes in velocity with much less fuel than a chemical rocket, opening doors to highly ambitious space missions—from outer-planet studies to asteroid redirection—and finally making the prospect of human spaceflight beyond lunar orbit realistic.

The HET is one such method of electric propulsion that has various advantages over other ion thrusters. In particular, because the plasma they produce is quasineutral throughout the thruster rather than positively charged, HETs avoid inherent thrust density limits that other ion thrusters face.[5] This allows HETs to eventually reach higher thrusts than gridded ion thrusters, and is one of the reasons that we decided to focus on the HET.

An HET, depicted in figure 1, produces plasma by releasing neutral propellant into an annular channel. An axial electric field pulls free electrons from space (often generated by a separate

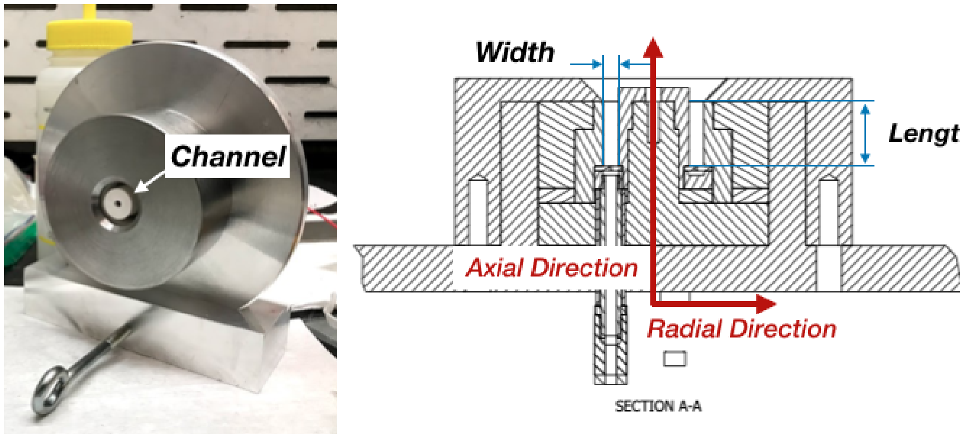

Figure 1: Labeled diagram of our assembled HET. Left is a photo of our assembled thruster. Right is a CAD drawing of a channel cross section. The channel is the annular cavity in the center of the thruster. The channel width is the width of this cavity in the radial direction. The channel length is the depth of the channel in the axial direction.

cathode) into the channel, where they become trapped by the strong radial magnetic field. These electrons collide with the neutral propellant, generating positive ions, which are accelerated out of the channel at high speeds by the electric field. Additional electrons from the cathode join the ions to neutralize the resulting plasma plume.

Developing our HET required major design decisions in five main areas: the magnetic field, the channel, the anode and electric field, the cathode, and materials. The magnetic and electric fields determine how electrons behave within the channel, the dimensions of the channel determine the amount of plasma generated and the chance of its particles colliding with the walls or anode prematurely, and the cathode provides an initial source of high-energy electrons to aid in thruster ignition. Naturally, the materials used throughout also have various effects on efficacy, and chance of failure by cracking, demagnetizing, or eroding.

Our thruster was heavily based on the HET designed and built by Noah Warner,[7] scaled up by a factor of two due to concerns regarding our ability to manufacture the amount of detail Warner's thruster necessitated. This greatly simplified the design process. There were, however, still many parameters that we needed to verify or select. Where learning about the basic principles of HET operation synthesized research skills and scientific understanding, the process of designing a system both to meet design constraints and to be within the capabilities of manufacture synthesized skills and techniques from many of our previous classes.

3.1 Magnetic field design

Since we could not afford the annular permanent magnets that Warner used, and we were unsure about how the change in scale would affect the field strength, we needed to partially redesign the magnetic field. Designing the shape and strength of it required us to learn about Maxwell's equations as well as finite element modeling.

The magnetic field has four major constraints:

1. The field must be radial. A strong radial field combined with the axial electric field ensures that electrons entering the channel experience azimuthal drift and become trapped within the channel. If the magnetic field has too weak of a radial component, electrons will rapidly fall into the anode, inhibiting the thruster's ability to ionize propellant.

2. The field must peak in strength at the exit plane. This allows the thruster to trap electrons just as they enter the channel and results in a concentration of electrons just below the exit plane. If the field strength is too uniform in the axial direction, or if it peaks elsewhere in the channel, the electrons will not concentrate highly enough to cause sufficient collisions with neutral propellant.

3. The field must be strong enough to trap electrons. To this end, the field must be strong enough to ensure that the electron Larmor radii are significantly smaller than the length of the channel. If the field is too weak, highly energetic electrons will escape the ionization region. This results in a higher rate of collisions between electrons and the channel walls, reducing the number of electrons available for propellant ionization.

4. The field must be weak enough to not trap ions. The field must be weak enough to ensure that the ion Larmor radii are significantly larger than the length of the channel. If the field is too strong, ionized propellant will become trapped in the ionization region rather than accelerating outwards, and the thruster will generate no thrust.

Constraints 1 and 2 are typically achieved in one of three ways: electromagnets, a radially-aligned permanent magnet, or axially-aligned permanent magnets with a "shunt" that controls the strength and direction of the magnetic field near the exit plane. Due to the high current draw of electromagnets and the high price of radially-aligned magnets, we, like Warner, decided to use the magnetic shunt. An initially non-magnetic shunt, depicted in figure 2, experiences a ferromagnetic response to the permanent magnets embedded within it. This guides the magnetic field to be both radial and peaking in strength just below the exit plane by a geometry that draws the magnetic field radially through a lip in the outer edge of the channel and across the channel into a core inside the channel. Our shunt geometry was identical to Warner's[7] but for the scale factor. Unlike Warner, we were unable to afford an annular permanent magnet and so decided to use multiple cylindrical ones. Since we were unsure what effect this, in addition to our thruster's larger scale, would have on the orientation and magnitude of the magnetic field in the channel, we turned to computer models. We decided to use COMSOL Multiphysics® simulation software for this.

In order to create a reliable model, we needed to first understand the basic principles and limitations of finite element analysis, then familiarize ourselves enough with the COMSOL® software's interface to use it. The resulting model is shown in figure 3. By experimenting with different numbers, sizes, and strengths of permanent magnets, we found that six magnets with diameters 6.35 mm, thicknesses 3.18 mm, and magnetizations 10.4 kG, which we knew we could purchase off the shelf, resulted in a predicted peak magnetic field strength of 28.0 mT in the channel. This was on a similar order as the magnetic field of Warner's[7] and Baird's[6] thrusters, so we deemed this design sufficient. The actual peak strength was measured by a handheld Hall probe to be between 22.5 mT and 25.6 mT. This task yielded not only a useful model of our thruster's magnetic field and a lesson in the limitations of analytic solutions, but for many of us, an introduction to electromagnetic computer modeling in general.

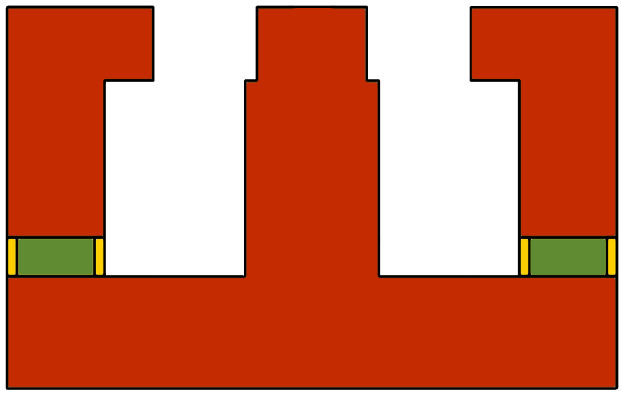

Figure 2: Cross section of the magnetic shunt. The iron shunt is depicted in red, the SmCo disk magnets are depicted in green, and the aluminum retaining ring is depicted in yellow.

Constraints 3 and 4 are met by fixing the anode voltage and by setting the channel size to be between the resulting Larmor radii. The relationships between Larmor radius, field strength, and operating voltage are given by the following equations, provided by the Goebel book:[5]

$$r_e = \frac{1}{B}\sqrt{\frac{8m_e kT_e}{\pi e}} \tag{1}$$

$$r_i = \frac{1}{B}\sqrt{\frac{2m_i V_b}{e}} \tag{2}$$

where r_e and r_i are the Larmor radii of an electron and ion respectively, B is the magnetic field strength, m_e and m_i are the masses of an electron and ion respectively, k is Boltzmann's constant, T_e is the electron temperature, and V_b is the potential drop that the ions are accelerated across. To perform these calculations we relied upon the following values: 2.80×10^{-4} T for B, as predicted by the magnetic field model; 350 V for V_b, a value chosen to be in the same area as was used in Baird's thruster,[6]; and 35 eV for T_e, as Goebel stated that one tenth of the operating voltage is a reasonable estimate for electron temperature.[5]

Using these values, we computed $r_e = 0.83$ mm and $r_i = 61$ cm as the maximum and minimum allowable lengths of our channel. While both of these proved to be much more forgiving than the more practical constraints of what we thought we could manufacture, the computation was a valuable exercise in computing and designing for theoretical constraints. Given these reasonable design parameters, we were content with the strength of our magnetic field and continued with the design process.

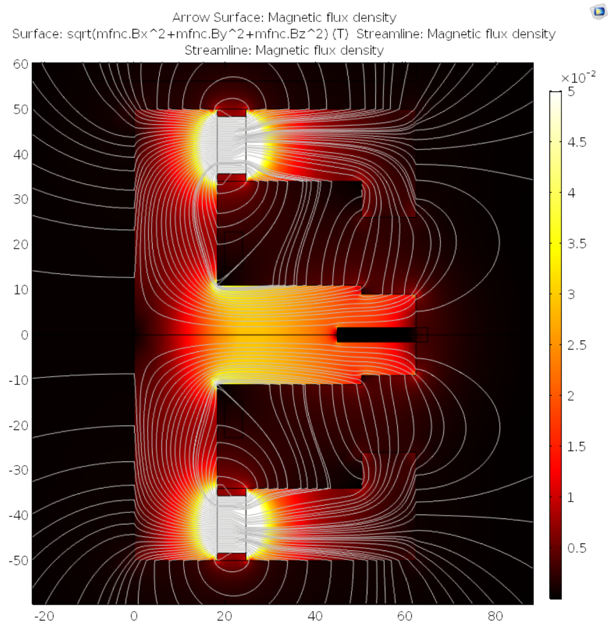

Figure 3: Predicted magnetic field inside the shunt. Lines are magnetic streamlines, and color is total magnetic field strength. There is no predicted or measured azimuthal magnetic field.

3.2 Channel design

The magnetic field design tied strongly into the design of the channel. Since we were unsure of how to scale Warner's channel dimensions to our thruster, we needed to compute the theoretical constraints on the channel length before building it.

The channel geometry was designed with four major considerations in mind:

1. The channel length should be significantly longer than the neutral mean free path length. The neutral mean free path is the average distance a neutral particle will travel before experiencing an ionizing collision with an electron. If the channel length is too shallow, neutral propellant will exit the channel without ever being ionized, resulting in greatly reduced thrust.

2. The channel length should be significantly longer than the electron Larmor radius. If the channel is too shallow, gyrating electrons will quickly reach the anode and reduce the number of electrons available for propellant ionization.

3. The channel length should be significantly shorter than the ion Larmor radius. If the channel is longer than the ion Larmor radius, ions will circle back into the channel instead of escaping and no thrust will be generated.

4. The channel geometries should fall within a range of reasonably manufacturable dimensions and tolerances. Olin College has manufacturing capabilities geared towards large projects (e.g. racing vehicles) rather than small ones, and too small of a geometry would prove difficult to manufacture in-house.

To meet the first constraint, we first estimated the neutral mean free path length using the following equation provided by Goebel:[5]

$$\lambda = \frac{v_n}{n_e \langle \sigma_i v_e \rangle} \tag{3}$$

where λ is the mean free path, v_n is the velocity of the neutral particles, n_e is the electron density, and $\langle \sigma_i v_e \rangle$ is the ionization reactivity coefficient assuming Maxwellian electrons. We did not know enough about our propellant supply or the dynamics inside the channel to precisely calculate v_n, n_e, or $\langle \sigma_i v_e \rangle$. However, we were able to make educated estimations for each.

For the neutral speed, we used the thermal speed of the propellant gas. The flow rate, which would determine the average neutral speed through the channel, would likely be much lower as thermal speeds are usually much higher than fluid speeds. However, this high estimate was easier to compute, and gave us a more conservative channel size. Assuming the propellant was at room temperature, this speed would be

$$v_n \approx v_{\text{th}} = \sqrt{\frac{2kT}{m_{\text{Ar}}}} = 350\,\text{m}\,\text{s}^{-1} \tag{4}$$

For the electron density, we assumed the electrons to be an ideal gas at standard pressure and the aforementioned estimated temperature of $35\,\text{eV} = 4.1 \times 10^5\,\text{K}$. This corresponds to a number density of $1.8 \times 10^{22}\,\text{m}^{-3}$. This was on a similar order of magnitude to electron densities described in Goebel.[5]

The ionization rate could be determined only through empirical tables. We found one such table published by Chung et al.[8] The closest temperature tabulated was $32\,\text{eV}$, with a corresponding ionization rate of $3.112 \times 10^{-14}\,\text{m}^3\,\text{s}^{-1}$.

With these values in place, the mean free path came out to $\lambda = 630\,\text{nm}$. Given that this is much smaller than the previously computed electron Larmor radius of $830\,\mu\text{m}$, as long as constraint 2 is met, constraint 1 is automatically met as well, ensuring that nearly all of the propellant ionizes before leaving the channel.

Though its resolution was ultimately insignificant, the mean free path calculation was another valuable learning experience that would not arise from ordinary coursework. Typically, when such exercises are done in a classroom, it is made clear to the students which equations to use and which values to plug into them. In practice, things are rarely so clear. The self-directed nature of this project forced us to search for applicable approximations and data tables, taught us how to proceed in problems so fraught with uncertainty, and gave us a chance to see values as numerical quantities with real consequences rather than abstract theoretical symbols.

Constraints 2, 3, and 4 were met by choosing a channel depth of 16 mm and a channel width of 3.26 mm. We judged these to fall within the manufacturing capabilities of our machine shop, and the depth satisfied the aforementioned limits of the Larmor radii and ion mean free path.

3.3 Anode design

The physical design of the anode was constrained only in that it must be made from a conductive material that can hold a high voltage and can withstand exposure to the energetic plasma. Most dimensions of the anode are determined by the dimensions of the channel. Our anode design was complicated by our decision to incorporate the propellant injection system, as many HETs do.

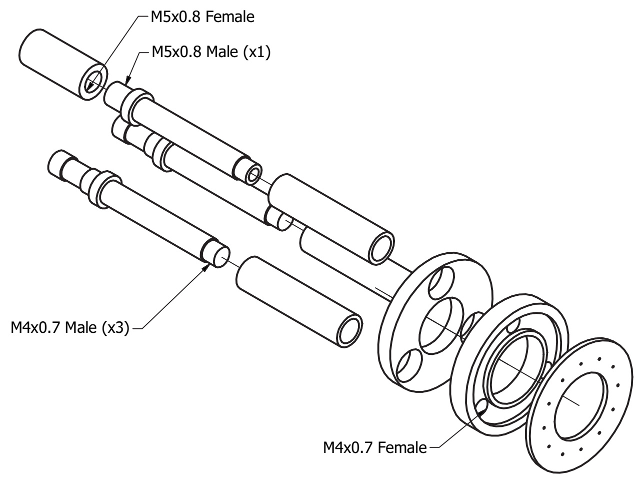

Figure 4: An exploded diagram of the anode, with the direction of propellant flow down and to the right.

Our anode consisted of a disk set at the bottom of the thruster channel held at a high positive electric potential relative to the external cathode. The high voltage of the anode generated an axial electric field that both drew electrons into the channel and accelerated the ionized propellant out.

It also injected propellant into the channel in a method similar to that of the Baird thruster,[6] which in turn resembles the method used to distribute air evenly across an air hockey table. A thin steel disk with 12 holes drilled through its face, shown in the lower right of figure 4, was laid atop a thicker steel disk with a channel carved into its surface. Gaseous propellant was fed into this anode channel underneath the thin disk by means of a small pipe, and the propellant expanded to fill the volume of the anode channel.

3.4 Cathode design

The hot cathode provides a source of electrons to sustain a plasma inside an HET as well as to neutralize the thrust plume during firing. At the center of the cathode is a cavity into which a small amount of propellant gas is injected. A thin wire inside this cavity is strung between two electrodes across which a voltage is applied. The resultant electrical current heats the wire, which in turn ignites a plasma in the surrounding propellant, generating positive ions and free high energy electrons. These electrons are then drawn out of the cathode and into the thruster channel.

We did not design our own cathode, as we were fortunate enough to have a design suggested to us by a graduate student with experience in the field. However, we did make some modifications to the design to align with our manufacturing capabilities. The operating principles behind the cathode are slightly more complex than the rest of the thruster, so this saved time and allowed us to focus on manufacturing.

3.5 Materials

At the start of this project, our team had no experience with serious mechanical design, and so this project provided a multitude of opportunities to develop those skills. Materials were selected on a case by case basis to support the necessary function of each part.

The HET components were primarily composed of six materials: boron nitride (BN), stainless steel (SS303), iron (ST42-S), samarium cobalt (SmCo), and aluminum (2014 T-6), with the anode legs insulated with alumina (aluminum oxide). The cathode components were composed of scrap aluminum, mild steel, and tungsten filament.

The thruster walls were manufactured from BN, a ceramic material which has the unusual property of being fairly thermally conductive while remaining electrically insulative. BN is a specialty material that is expensive and difficult to acquire; our BN stock was donated generously by Busek Co. This material would electrically isolate the plasma in the channel from the grounded thruster assembly while remaining able to conduct heat away from the channel and into the rest of the thruster. This property is important because the thruster must be fired inside a vacuum, within which the primary mode of heat flow is conduction between thruster components. Thermally conductive channel walls allow hardware in contact with the channel to conduct heat away as rapidly as possible, reducing thermal expansion and keeping the magnetic components cool enough to hold their magnetizations.

The magnetic field focused by the shunt was generated by six permanent SmCo magnets purchased off-the-shelf from CMS Magnetics. We selected SmCo for its high Curie temperature, necessary to ensure continued operation while firing.[9] In order to hold these magnets at precise locations within the shunt, we designed a 2014 T-6 aluminum retaining ring with six slots to house the magnets. We selected aluminum for this retaining ring because aluminum has an extremely weak ferromagnetic response. Using a ferromagnetic material such as ST42-S for the retaining ring would have amplified the magnetic field in the negative axial direction and, according to our model, would have severely decreased the magnetic field strength in the ionization region of the channel.

Calculations were done for each of these components to account for the expected thermal expansion of our design. As a result, none of the more fragile ceramic components were cracked after firing the thruster.

Material selection comprised one of the more tedious parts of the design process, but it was also important. Each material that we chose allowed us to investigate the applications of a different kind of metal or ceramic, and to study a different material property. Because material selection is such a crucial part of many engineering projects that is often overlooked in classes where a choice between wood and aluminum is sufficient, this part of the project was especially pedagogically valuable.

4 Testing

At the end of the semester, the MIT Space Propulsion Laboratory generously allowed us to use their testing facilities. The thruster was placed in a vacuum chamber and, over the course of three days, activated under various conditions. As shown below, the thruster successfully fired. Early in the testing process, the wire used in the heating coil of our cathode burnt out due to high currents. This meant that the plasma was ionized by free electrons in the chamber rather than the plasma bridge we expected from the cathode. This supply was much less reliable, and so as charge built up and was depleted, the thruster pulsed on and off at a frequency of about 5 Hz.

Figure 5: Our completed HET, viewed with the plume pointing to the right and towards the camera. Several extraneous plasma clouds are visible.

As figure 5 shows, the plasma is clearly present inside the channel, shown by the distinctive purple ring in the image on the right. There are two other sources of light. We believe that the purple glow emanating from behind the thruster was caused by a cascading effect as the ionization reaction in the channel propagated backwards through the propellant, which leaked out of our tube connections. The bright blue glow was likely caused by arcing, as electrons jumped from the negatively charged cathode gas feed to the grounded base plate.

5 Discussion

Typically, student driven projects are used to teach or cement individual concepts, and are often used as a sort of synthesis at the end of a unit or semester. This tends to work well, with the goal of establishing an adaptable understanding of the concepts being used. These projects, however, are often kept fairly small and short in order to prevent students from taking on overly ambitious tasks. This limitation is enforced under the assumption that upon hitting a significant roadblock, students will become frustrated and give up, learning nothing in the process. We disagree with this assumption. Given an engaging enough project, the desire to complete it can be enough to move past most pitfalls. It is rare to find a project engaging enough to thoroughly motivate students that is small enough to fit into the previous category.

Our recommendation is that projects be given much more stake in physics and engineering education. Large amounts of content can be covered by a team of students excited to tackle an open ended project. An example syllabus demonstrating how traditional classroom content can be replaced with such projects is given in appendix A.

Our project, though ambitious, was extremely educational and exceeded our expectations, both in terms of results and academic usefulness. We found that by continuously setting goals and working towards them, we were able to move past obstacles which might have stopped us relatively quickly had we not been deeply invested in the overall success of a project. Engineering applications are exciting, and this is the fundamental drive behind many students' involvement in engineering in the first place. By harnessing that directly, students could develop the thorough, practical understanding of subjects that comes with project based learning for much wider swaths of content.

5.1 Student reflections

5.1.1 Team member, sophomore, electrical and computer engineering

"The most valuable part of this project to me was how it forced us to network and source help from places and people outside of Olin College. The 'cold email' is always a nerve-wracking skill to practice, but it ended up connecting us with professional engineers in space propulsion who provided us with invaluable guidance.

A lot of the learning that came out of this project was not just technical details about plasma physics and electric propulsion, but about how to break down seemingly intractable problems, compile resources, and manage a multi-disciplinary project with multiple people. The focus of this project, for me, was very much on learning *how* to learn."

5.1.2 Team member, senior, engineering with a concentration in physics

"I was very surprised by how much we were able to accomplish in one semester. We kept saying 'we probably won't get much further than designing it,' and then 'there's no way we'll finish building it,' and then we just kept pushing further, partially because of all of the kind help we got from grad students and professionals, and partially because of the rate at which we kept learning new things. We also got very lucky with all the support we received. This project would have gone very differently if professionals hadn't been so willing to help us (or worse, if we had been too afraid to ask)."

5.1.3 Team member, sophomore, electrical and computer engineering

"The gap between where we were at the start of the project and where we were at the end was really shocking to me. We ran into several concepts we had never even heard of, and this sort of roadblock could have shut the whole project down. Fortunately, we were set on keeping momentum, which often meant seeking out help when a problem was outside of our capabilities, and that habit of constantly asking for advice from experts frequently kept us moving through very difficult portions of the project. We sought out and received a lot of help, but the drive behind the project was us, which made it really exciting to see the thruster light up at the end."

6 Conclusion

In one semester and with very few resources, our team of four undergraduate students built and tested an HET. We studied concepts we had never seen in class, searched out resources that we thought we needed, worked with external vendors and manufacturers, and finally tested the completed thruster to moderate success. The thruster fired, generating a plasma plume, but a cathode malfunction early in the process caused a rapid pulsing effect as charge built up and was released. This result was both exciting and disappointing, but secondary in importance to the rest of the project.

The chief outcome was that after a semester long project, our team came to understand the science behind HETs well enough to design one. This process covered many fundamental physics concepts which might otherwise be taught in an undergraduate E&M course as well as introductory plasma physics, materials science, and mechanical design and fabrication. We endeavored to understand these subjects because they were necessary to complete a project we initiated and organized. The personal investment in the project proved to be more than enough motivation to tackle a problem far outside the scope of projects traditionally used to assist in teaching physics. This suggests that this approach—being less cautious about overloading students and more focused on fostering excitement about interesting science—could be effective more generally. Project based learning moves in this general direction, but our recommendation is that more substantial portions of curriculum could be ceded to student-directed projects. Contrary to the belief that student led projects might succumb to disorganization and roadblocks, we demonstrate that enthusiasm can provide an incentive structure necessary to ensure the effective acquisition of skills and knowledge.

7 Acknowledgments

The authors would like to thank Bjarni Örn Kristinsson (MIT) for his highly appreciated involvement and assistance throughout the project. We would also like to extend a special thanks to Prof. Paulo Lozano (MIT) for opening the doors of his Space Propulsion Lab at MIT and allowing us to use his laboratory and vacuum chamber for testing. Furthermore, we would like to thank Prof. Manuel Martinez-Sanchez (MIT), Dr. Steve Snyder (JPL), Dr. Dan Goebel (JPL), and Dr. David Oh (JPL) for their time and willingness to accept questions as the project progressed, as well as Dr. James Szabo (Busek) for advice regarding propellant types and boron nitride manufacturing techniques. We would also like to acknowledge Sparsh Bansal (Olin College) and C. Lal Alloys Pvt. Ltd. for donating the material and manufacturing time for many of our thruster components and for serving as consultants as we iterated upon our mechanical design. We are also extremely grateful to Busek Co. for donating the boron nitride stock necessary to manufacture the channel walls.

References

[1] Reno Barry. Electric motorboat drag racing: A hands-on physics project that motivates students from start to finish. *The Physics Teacher*, 46(5):267–268, 2008. doi: 10.1119/1.2909742. URL `https://doi.org/10.1119/1.2909742`.

[2] Jay S. Huebner, Alice S. Fletcher, Julia A. Cato, and Jennifer A. Barrett. Micro-rockets for

the classroom. *American Journal of Physics*, 67(11):1031–1033, 1999. doi: 10.1119/1.19167. URL `https://doi.org/10.1119/1.19167`.

[3] Dita Nur Syarafina, Jailani, and Ririn Winarni. The application of problem based learning to improve students' self-efficacy. *AIP Conference Proceedings*, 2014(1):020024, 2018. doi: 10.1063/1.5054428. URL `https://aip.scitation.org/doi/abs/10.1063/1.5054428`.

[4] M. P. Silverman. Self-directed learning: A heretical experiment in teaching physics. *American Journal of Physics*, 63(6):495–508, 1995. doi: 10.1119/1.18080. URL `https://doi.org/10.1119/1.18080`.

[5] Dan M. Goebel and Ira Katz. *Fundamentals of Electric Propulsion: Ion and Hall Thrusters*. JPL Space Science and Technology Series. Jet Propulsion Laboratory, 2008.

[6] Matthew Baird. *Designing an Accessible Hall Effect Thruster*. Senior thesis, Western Michigan University, 2016.

[7] Noah Zachary Warner. *Theoretical and Experimental Investigation of Hall Thruster Miniaturization*. PhD thesis, Massachusetts Institute of Technology, 2007.

[8] H.-K. Chung, M.H. Chen, W.L. Morgan, Y. Ralchenko, and R.W. Lee. Flychk: Generalized population kinetics and spectral model for rapid spectroscopic analysis for all elements. *High Energy Density Physics*, 1(1):3 – 12, 2005. ISSN 1574-1818. doi: https://doi.org/10.1016/j.hedp.2005.07.001. URL `http://www.sciencedirect.com/science/article/pii/S1574181805000029`.

[9] K. Takasumi, P. Dent, J. Liu, M. Marinescu, and M. Walmer. New grade of temperature compensated samarium cobalt permanent magnets and design considerations. In *2009 IEEE International Vacuum Electronics Conference*, pages 565–566, April 2009. doi: 10.1109/IVELEC.2009.5193470.

Appendix

A Example syllabus

Below is the outline of the learning process of the described project formatted as a class syllabus, to illustrate how student-driven projects like it can serve as a substitute for traditional guided coursework. Note that this timeline does not describe the initial plans or goals of the involved students or advisor, but the end result of the students working at their own pace and adopting near-term goals that seemed interesting and achievable. Any application of this structure to another project would need to incorporate flexibility for its students to similarly choose their own goals and deadlines. The deterministic structure portrayed here is used only to allow comparison of this project to a more traditional class that might have filled a similar educational role.

A.1 Learning objectives

1. Basic Theory

- Mechanics
    - Thrust, rocket equation
- Electricity & magnetism
    - Lorentz force, Maxwell's equations, electric and magnetic fields, and magnetic materials

2. Engineering principles
    - Finite element analysis
    - Thermodynamics
        - Heat transfer
    - Magnetism
        - Modelling magnetic fields, types of magnets
    - Hall thruster scaling laws
3. Assembly and testing
    - CAD
    - Manufacturing
        - Lathe, CNC mill, interfacing with outside manufacturers
    - Material Science
        - Selecting and modelling thruster materials

A.2 Resources

- *Fundamentals of Electric Propulsion: Ion and Hall Thrusters* by Ira Katz and Dan M. Goebel
- *Introduction to Electrodynamics* by David Griffiths
- *Designing an Accessible Hall Effect Thruster*, senior thesis by Matthew Baird
- *Theoretical and Experimental Investigation of Hall Thruster Miniaturization*, PhD thesis by Noah Warner

A.3 Schedule

A.3.1 Phase 1: Basic Theory

The first three weeks or so should be dedicated to team planning and gaining a basic understanding of Hall Effect thruster operating principles and the physics that describes them. Learning goals should be discussed among team members to determine areas of focus and potential outcomes of the project. To check understanding of thruster operating principles, students work through problems in *Fundamentals of Electrical Propulsion* and *Introduction to Electrodynamics*, recording questions as they arise. The team should be able to describe, in detail, how the thruster generates thrust, from electron generation at the cathode to ejection of ionized propellant.

- One team meeting per week to work through textbook problems and compile questions
- One advisor meeting per week to ask questions and get guidance
- Contact with outside experts as needed

A.3.2 Phase 2: Design and Modelling

Once the team has determined that they have a decent grasp of the fundamentals, the next phase applies that understanding to the design and modelling of a Hall Effect thruster. The deliverables of this phase include calculated thruster dimensions and models of the magnetic and electric fields in the channel. This phase should also include several formal 'design reviews' with the project advisor and other interested faculty, focused on validating the physics behind the thruster's design.

- One team meeting per week to update each other on progress and make sure we are on track
- One advisor meeting per week

A.3.3 Phase 3: Assembly and Testing

Having completed a minimal thruster model and worked out dimensions, the final phase focuses on assembly and testing of the thruster. This is where calculated thruster dimensions are turned into a CAD model, logistics of propellent injection are worked out, materials are selected, and the thruster is assembled! Somewhere in this process there should be at least one formal design review with the advisor and other faculty, focused on validating the manufacture and assembly of the thruster.

- Meetings scheduled irregularly, as needed
- Team members branched off and worked on what they were interested in

A.4 Deliverables

- 1 "problem set" of answered questions from Fundamentals of Electric Propulsion and Introduction to Electrodynamics
- COMSOL tutorial simulations
- COMSOL model of thruster magnetic field
- Thruster design and dimensions
- Two design reviews with advisor + other faculty (physics-focused)
- Second design review with advisor + other faculty (manufacturing-focused)

- Final models + thrust calculations
- Built thruster