Development of an mobile electric propulsion demonstration for STEM outreach

Sarah E. Cusson,* Marcel P. Georgin, † Katherine Wolff,‡ Veronika Bayer,§ Kirsten Reid,¶ Catherine Budd,‖ Abigail Huff,** Kaelan Oldani,†† Nora Shapiro,‡‡ Benjamin A. Jorns,§§ and Alec D. Gallimore¶¶
University of Michigan, Ann Arbor, MI, 48109

The Plasmadynamics and Electric Propulsion Laboratory at the University of Michigan is developing a mobile-demonstration platform to bring advanced propulsion technologies into high school classrooms in the greater Ann Arbor area. Public outreach is critical to recruit the next generation of engineers and scientists as well as correct misconceptions about the engineering discipline. The development of the platform was structured such that a team of undergraduate women in aerospace engineering and aerospace-related fields designed and implemented the system. The team was split into three different sub-teams with one responsible for Hall thruster refurbishment, another for the design of the facility and the last for the design of the control system. Additionally, the team is developing a lesson plan to maximize the effectiveness of the presentation.

I. Introduction

A 2008 study conducted by the National Academy of Engineering showed that children and the public commonly held misconceptions or limited understanding of the engineering profession [1]. In response to these misconceptions, engineering outreach efforts continue to grow throughout the country focusing on attracting the attention of elementary and high school students to Science, Technology, Engineering and Math (STEM). This is critical as they are the workforce of the future. Although the K-12 curriculum is generally a favorable venue to address these issues, educators are just as likely to hold the same misconceptions and limited knowledge as the public[2]. Therefore, it is critical that scientist and engineers take an active role in engaging this audience.

Many studies have shown the efficacy of these efforts. Empirical evidence has shown that short-term engineering events have positive influences on attitudes towards engineering[2]. A study of a two-week outreach program for seventh-grade females showed that 18% of participants intended to pursue engineering in college as compared to 2.5% of the national average[3]. The College of Engineering at North Carolina State University conducted an outreach program at a high school resulting in four students in the class deciding to consider engineering who were previously not considering it as a degree program [4]. Finally, research has indicated that increased frequency of interaction with STEM industries, particularly for under-represented populations, is critical to enrollment in STEM fields[5]. Clearly, outreach is a critical component to informing the public and encouraging the next generation of engineers and scientists.

Extending beyond K-12 and undergraduate engineering studies, a corollary could be made to undergraduate engineers and graduate education. Research has shown that enrollment of US students in engineering

*Ph.D. Candidate, Department of Aerospace Engineering, and AIAA Student Member
†Ph.D. Candidate, Applied Physics Program, AIAA Student Member
‡Undergraduate Student, Department of Electrical Engineering, and AIAA Student Member
§Undergraduate Student, Department of Aerospace Engineering, and AIAA Student Member
¶Undergraduate Student, Department of Aerospace Engineering, and AIAA Student Member
‖Undergraduate Student, Department of Mechanical Engineering, and Non-Member
**Undergraduate Student, Department of Aerospace Engineering, and AIAA Student Member
††Undergraduate Student, Department of Aerospace Engineering and Engineering Physics, and AIAA Student Member
‡‡Undergraduate Student, Department of Aerospace Engineering, and Non-Member
§§Assistant Professor, Department of Aerospace Engineering, and AIAA Senior Member.
¶¶Dean of Engineering, College of Engineering, and AIAA Fellow.

graduate programs is declining[6]. Survey data indicate that undergraduates typically hold the preconceived notion that graduate school is simply an extension of their undergraduate degrees except with harder classes [7]. This misconception could lead to students not enrolling in these studies. An effective method for informing undergraduates about graduate school and research is undergraduate research experiences. Studies have shown that undergraduate research experiences lead to 74% of students having increased confidence in their understanding of science and research work as well as their ability to perform research[8]. Additionally, this experience provides clarification on career and education goals. The case is clear for the need to nurture informative decisions and an interest in STEM on both the undergraduate and graduate levels.

In an effort to continue inspiring the next generation of STEM personnel as well as provide undergraduate students exposure to graduate research, the Plasmadynamics and Electric Propulsion Laboratory (PEPL) at the University of Michigan is developing a demonstration platform for STEM outreach. The demonstration specifically uses the technology the laboratory focuses on: electric propulsion. Electric propulsion devices use electric and magnetic fields to accelerate a plasma (an ionized gas) and produce thrust. They are a cutting-edge and cost-effective method for maneuvering in space. Electric spacecraft propulsion is a game changing technology that enables new and more ambitious missions in space. Electric propulsion (EP) devices have been used to maintain commercial and military satellite orbits for over four decades. More recently, advancements in these technologies have made them appealing to government space agencies for deep space exploration and even transport to Mars.

Historically, PEPL has been involved in outreach in a variety of ways. The lab has been involved with the Rocket Scientist for a Half-Day (RSHD) program, where elementary school students from the Ann Arbor community come tour the laboratory and receive an introduction to advanced propulsion. In addition to RSHD, we also give laboratory tours to communicate our research to industry partners, government officials, and visiting students and programs. Most recently, we have started participating in the Summer College Engineering Exposure Program (SCEEP) hosted by the UM Center for Engineering Diversity (CEDO). While these tours primarily consist of a guided walk through, discussion of our work and small scale demonstrations, a major missing component to these outreach programs is a vivid demonstration of the technology in action. This is largely due to the expense and complexity of setting up and running experiments for tours. In addition, laboratory tours can only reach a limited number of personnel. On-site outreach typically targets groups that are already interested and knowledgeable about engineering.

In order to overcome the limitations of current outreach efforts, we designed the demonstration platform to be mobile, compact and cost-effective. Previous groups have used this model for effective outreach in the aerospace field[9]. This will enhance our ability to communicate how electric propulsion technology works as well as highlight the technology development the United States government is actively funding. The goal of this project is to combine a presentation on electric propulsion and a demonstration of an active EP device in a vacuum chamber. The demonstration employs the PEPL-70 Hall thruster, the first Hall thruster developed at PEPL, to show how the technology works.

To provide research experience to undergraduate students, we structured the project such that an undergraduate team of engineers designed and built the system. Specifically, we targeted women in aerospace and aerospace-related fields to join the team. Only about 15% of the aerospace engineering graduate students at the University of Michigan and 10% of the graduates from PEPL are women[10]. Therefore, we took this opportunity to promote interest in advanced propulsion among female students. This project provides a unique experience for undergraduates to operate an electric propulsion device, a task typically reserved for doctoral students. Undergraduates of the Women in Aeronautics and Astronautics (WAA) were recruited to complete the project. WAA is an organization at the University of Michigan specifically “dedicated to fostering a sense of community among women in fields related to aviation and space, improving diversity within the department of aerospace engineering, and helping members build both personal and professional connections in the aerospace industry."

This project was multifaceted with each component outlined here and discussed in more detail below. First, we present the goals of the project. Next, we discuss the refurbishment of the electric propulsion system.

Then, we present the design and implementation of the mobile vacuum system. Subsequently is a discussion of the control system and its interactive nature to enhance outreach capabilities as well as the plan for the outreach presentation. We then discuss the structure and budget of the project. Finally, we outline lessons learned as well as potential plans and enhancements to the system.

II. Goals

At the outset of the project, we developed a set of over-arching goals to better define the development. These goals were stated as:

- Provide the students involved with professional experience in public speaking, STEM outreach, and leadership in the STEM fields.
- Develop an outreach tool for UM's leading plasma science and engineering programs.
- Provide the public a vivid and functional example of how UM and its industry partners are developing advance propulsion technology to support the nation's endeavors in space.
- Support women in astronautics related fields at UM through a unique opportunity to get hands on experience with advanced space propulsion.

With these goals in mind, we present the implementation of the project.

III. Hall Thruster Refurbishment

A subset of the undergraduate researchers responsible for the completion of the project were working to refurbish the PEPL-70, a 600 W Hall thruster. This part of the project was critical as we must have an operating thruster to show the community in order to properly communicate the technology. Additionally, seeing advanced technologies operate tends to garner excitement and inspiration not acquired by simply talking about said technology. This thruster was chosen for two reasons: (1) it is the first Hall thruster ever developed by PEPL and (2) it is a low power Hall thruster making the requirements for other subsystems less demanding.

Hall thrusters use a crossed an electric and magnetic field to ionize and accelerate propellant. The electrical discharge in this system consists of two main parts: an anode and a cathode. The cathode is the electron source for the thruster. The electrons are emitted from the cathode and move towards the anode. A magnetic field is then applied in the radial direction which impedes the motion of the electrons towards the anode. The electrons are trapped along the magnetic field lines since their Larmor radius is much smaller than the characteristic length scale of the device. Gas is then injected through the anode and is ionized through electron-impact ionization. The axial electric field then accelerates the ions. The cathode also acts as a source to neutralize the flow of ions.

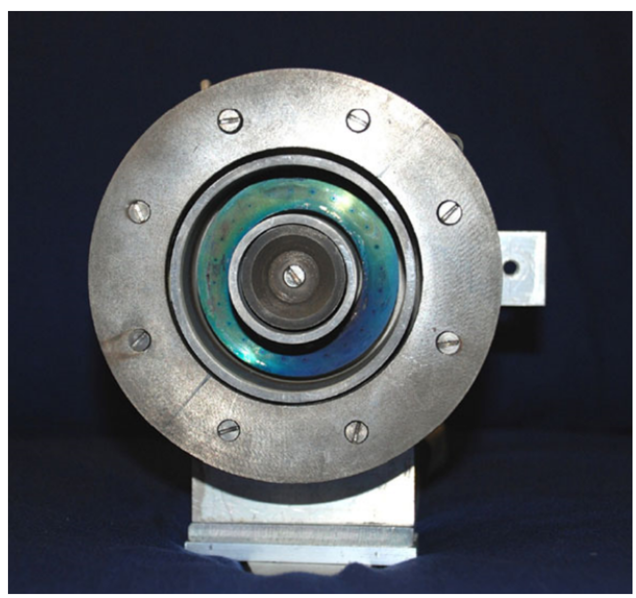


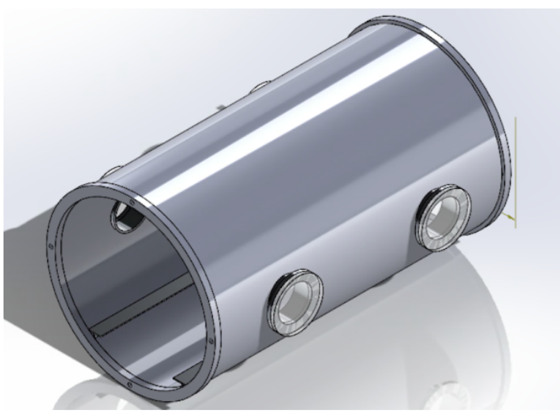
Fig. 1 The PEPL-70 Hall thruster to be used for the outreach project.

Figure 1 shows the PEPL-70 Hall thruster. This thruster shares design heritage with the Russian SPT-70 and SPT-100 thrusters. To refurbish the thruster, there were three main projects: confirmation of electrical and magnetic field configuration, selection of a cathode, and implementation of the system into the vacuum facility.

The electrical configuration of the thruster was assessed to make sure proper isolation and connectivity was present. The magnetic field was modeled using MagNet v7.7 simulation software and confirmed via 2-axis measurements of the field. Most state of the art Hall thrusters use a hollow cathode[11]. Hollow cathodes offer long lifetimes and minimal heating requirements. However, they are quite complicated, expensive, and require additional gas flow. Their advantages were not critical for this application. Additionally, the gas flow required for them would raise the pressure in the chamber higher than desired. Therefore a simpler solution was implemented: a filament cathode which emits electrons upon heating. The main drawback is high light emission due to the required temperature of the filament to emit sufficient current. In order to alleviate this issue, the students implemented a heat shield in order to try to lower the required current as well as block the light from line of sight vision. Once the cathode was finalized, we integrated the full system into the facility.

The undergraduate students in this section of the project were exposed to many opportunities for learning not typically seen in the classroom. They learned about electric propulsion and basic plasma physics, magnetic modeling, model verification, and high vacuum experiments.

IV. Vacuum Facility



(a) Three dimensional rendering of the final design of the vacuum facility.

(b) Picture of full implementation of the vacuum facility.

Another subset of the undergraduate researchers was responsible for the creation of the vacuum facility. The vacuum chamber design was limited by several different factors that contributed to size, material selections, and components selections as well as their integration within the system. The primary design constraints were that the entire system must be able to run off a single 120 V_{AC} plug, the chamber needed to have multiple viewing opportunities for the students and all external electrical and vacuum hardware needed to fit compactly on the cart provided. All these constraints were driven by the intended place of use of the unit: a classroom in a school. Generally, school classrooms only have wall outlets (120 V_{AC}), and we wanted to be able to quickly roll the entire unit into and out of the classroom. Additionally, the facility needed to be able to able to hold high enough vacuum to run the thruster (approximately 10^{-4} Torr). Safety considerations, such as a plexi-glass enclosure, were also made for the demonstration.

The vacuum facility chosen is 4 ft long and 2 ft in diameter. The support structure/cart for the facility uses castors to make the facility mobile. The structure under the chamber is fully enclosed in plexiglass allowing the different components to be visible by students but ensure safety. The facility has four newly designed viewports to allow the audience to observe the thruster operating. Figure 2a shows a 3D rendering of the final design and Figure 2b shows the chamber with the acrylic viewports, mounted on the cart. A new endcap for the facility was designed to mount the turbo pump. A large viewport along with a protective glass barrier were created for the end cap to allow full view of the discharge.

The facility uses a mechanical pump (Varian Triscroll 300) and small turbo pump (Varian Turbo-v70) to bring it to vacuum as well as a pressure gauge to visibly see how much lower than atmosphere these devices operate (typically eight to nine orders of magnitude). The team also designed the flow control system necessary for delivering gas to the thruster. The system uses a needle valve to control the flow rate, a regulator, and a bottle of high pressure krypton. This design removes the necessity of an actively controlled flow controller. Again, the students gained experience in computer-aided design, high vacuum systems, and structural engineering.

V. Control System

The final subset of undergraduate researchers was responsible for the development of the control system. Power supplies and propellant flow control are required to regulate the electrical current to the system and the mass flow of propellant. We intended the control system to be interactive and intuitive by creating a user interface that is simple to use and understand. The students determined the best possible computer and screen for the application. A picture of the screen mounted to the chamber can be seen in Figure 3. It is a touch screen, with the intention of having an interface with buttons and calibrated dials available for the high school students to view various plots as they learn about the system.

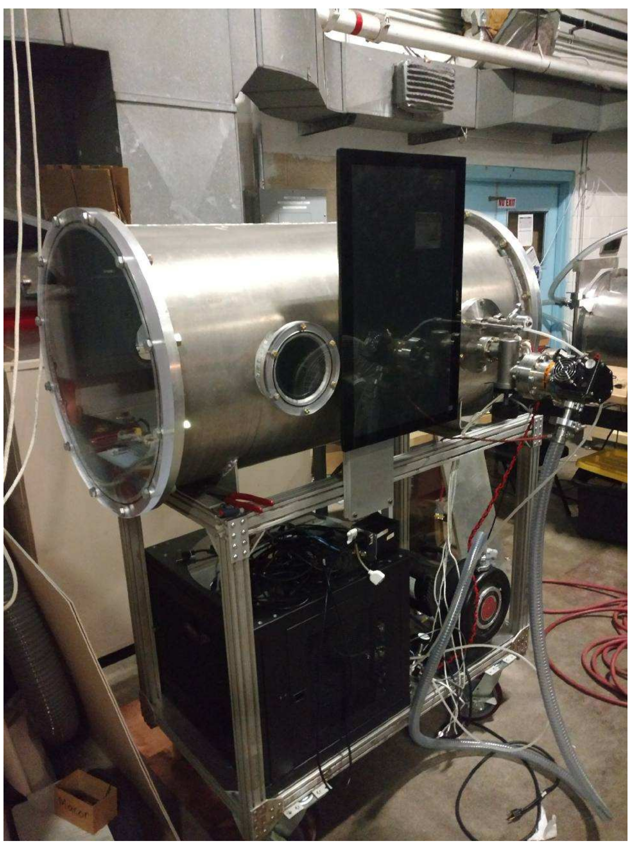


Fig. 3 A picture of the system with the interactive data acquisition screen mounted to the facility.

The team also determined all required power supplies for operating the thruster as well as connecting these power supplies to the facility. The power supplies are connected to two LabJacks which then connect to the computer for the system. The touch screen connects to the computer and displays a LabVIEW interface to run each of the power supplies. The students developed the entire LabVIEW code to operate the system. This included operating each power supply in the required sequence for thruster operation, collecting data from the thruster, and displaying this data in an intuitive way for interaction with the audience. The main skills that each student on the controls team gained were programming LabVIEW, developing hardware requirements to enable full integration as well as proper installation and sizing of power supplies and cabling.

VI. Outreach

This demonstration is designed to engage high school students and undergraduates and generate interest in aerospace engineering, plasma science, and advanced propulsion. This outreach project aims to develop a demonstration that can be used to communicate the exciting field of plasma science and engineering to local high school students and establish new programs in which the mobile system will be transported and set up in the classrooms. During each visit to a high school, there will be three stages to each lesson plan: an initial presentation,

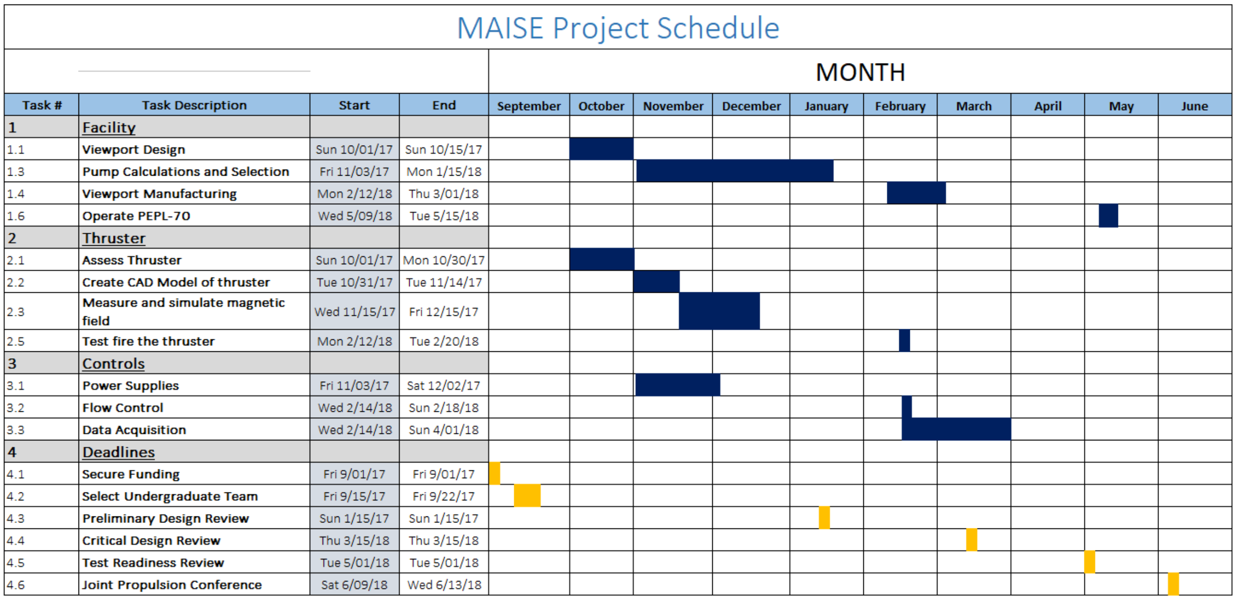


Fig. 4 Gantt chart for the project including a selection of each team's tasks as well as all the major milestones and deadlines.

a demonstration of the technology with interactive capabilities, and a question and answer session. The presentation aims to cover a wide variety of topics including a discussion of what engineering is and a discussion of the different types of engineering before moving into a more detailed section about our specific technology. This part of the presentation will include a discussion on in-space propulsion options, "what is a plasma", the history of electric propulsion and PEPL, the advantages of EP for deep-space missions and an overview of how a Hall thruster works. Additionally, we hope to develop an animation that will complement the demonstration showing a physical picture of what the students are viewing. This presentation will culminate in the operation of the Hall thruster, beginning with a step through of the lighting procedure. As the thruster is turned on, students in the audience will observe changes in the discharge parameters and be able see the thruster generate a plasma through viewports in the vacuum chamber. Additionally, they will be able to toggle through charts on the touch screen. After all students have seen the demonstration, the presenters will take any questions from the audience ranging from questions about engineering in general to questions about Hall thrusters. The undergraduate students on the team will be the presenters.

VII. Structure and Budget

In this section we discuss the structure of the project team as well as the budget. There were three teams of undergraduate students working on the project. The students completed their work at PEPL under the supervision of two graduate students and a faculty mentor. The role of the faculty mentor was to make high level and large budgetary decisions to ensure the success of the project. The role of the graduate students was to use their experience with electric propulsion testing to assist in the design and the construction of the demonstration and to give feedback on the design. Each subteam (facility, thruster and controls) had a "lead member". This member was responsible for communicating any questions and issues of the team to the graduate students. Additionally, the lead member was responsible for debriefing the entire team (all undergraduate and graduate students) about any progress or issues on a bi-weekly basis. We found that this structure worked well since not all students had the same schedule and were often working at different times.

In addition to the bi-weekly check-ins, we had "major" milestone reviews. We had three reviews for the project: a preliminary design review (PDR), a critical design review (CDR) and a test readiness review (TRR). The goal of the PDR was for each team to present its anticipated design, while receiving feedback from the team about potential problems and roadblocks prior to purchasing any materials. The purpose of the CDR was to assess the current status of each team in their design and implementation prior to full system integration. Finally, the TRR was used to set the goals of the initial testing of the system and determine any additional tasks necessary. A Gantt chart of the project was put together to ensure each team remained on the desired timeline. A subset of this chart can be seen in Figure 4.

The total budget for the project was $20,000. The majority of this cost was budgeted for the vacuum pump. Other budgeted items included gas required to run the thruster, a feed system, flanges for the vacuum chamber, a control system and power supplies. The main structure for the vacuum chamber was loaned by PEPL.

VIII. Lessons Learned

While the project was a success overall, there are always lessons learned and ways to implement that could improve the process. Specifically, at the beginning of the project (September to December), the pace of work was significantly slower than desired. While some of this was likely due to the need to get "up to speed" from the students, it also appeared that a lack of accountability and reporting structure was at fault. As such, starting after December, the graduate students implemented bi-weekly meetings (discussed above). At each of the meetings, the students had to present their progress. This increased the accountability and the ability to discuss major issues. Once these meetings were implemented, progress began to proceed more quickly. Additionally, if starting over, we would implement a single undergraduate lead into the project. We would still have each sub-team with a lead and then one lead for the entire project. This would have simplified communications for the graduate students as they would only have had a single point of contact and questions/issues would have only presented themselves a single time. Additionally, there would have been a member of the team with a full system view able to help integrate all the teams together more seamlessly.

Finally, we are at a point in the project where a natural restructuring will occur. Since the construction of the project is completed, the future will focus on science communication, outreach and smaller projects within the facility. Therefore, we will have students dedicated to presentation development, students dedicated to communications, and students dedicated to improvements and future changes to the system, with an overall team lead.

IX. Discussion of Future Work

In order to continue to enhance this effectiveness of the demonstration, we aim to implement two additional features. One of them is a "deflection paddle". A deflection paddle would visibly show the audience the thrust that the thruster is producing. A mock-up of this can be seen in Figure 5. The second feature is an

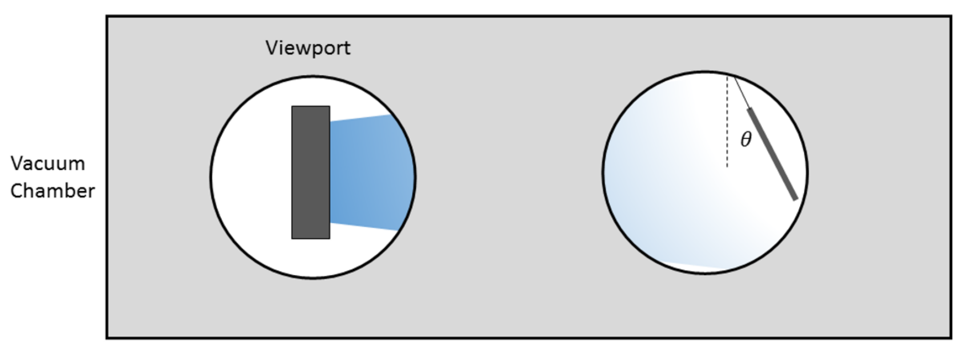


Fig. 5 A mock-up of the deflection panel implemented in the vacuum chamber.

auditory demonstration. Hall thrusters are very oscillatory by nature. We could measure these oscillations and then convert them to sound such that the students can "hear" the Hall thruster operating. Both of these elements will be implemented into the system in the near future. Finally, when not in operation at a high school, we hope that the system will be a platform for undergraduate students to continue to do research on advanced propulsion.

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