Design and Development of a Low-Cost Ion Plasma Thruster for Plasma Generation and Analysis Studies

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Abstract– This study draws its inspiration from an ion-plasma generator design that uses direct current (DC) while integrating commercial off-the-shelf (COTS) components for easy assembly and modifications. Addressing the limited accessibility of plasma propulsion systems in university-level education especially for universities still establishing SST curricula centers on the high cost and complexity of ion thrusters, which restricts hands-on learning oppurtunities for Space Science Technology students interested in thruster development. Guided by design principles of simplification, cost-reduction and scalability, the low-cost scalable design is modified and tested for plasma observations, iming to provide modification experience and extend the study for fundamental principles of plasma generation, the basics of propulsion systems, and plasma-material interactions. The researchers utilized commercial ff-the-shelf (COTS) components and alternative materials such as a copper tape and aluminum spikes. Instead of a vaccum, prototype was implemented and tested in a room temperature laboratory condition, demonstrating successful plasma emission with observable inconsistencies due to ambient air ionization. Beyond the technical artifact, the study contributes to educational practice by offering a replicable model for teaching plasma physics and propulsion fundamentals, and to theory by formulating design principles for accessible space technology learning tools. Future studies will expand the design ncluding the modifications necessary for propellant usage and more testing in sophisticated environments, enhancing their educational value.

Keywords– *thruster, ion-plasma, cost-effective, electric, direct current, propulsion, rocket science, cathodes*

INTRODUCTION

As backbones of satellite and rocket technology, propulsion systems enable precise navigation and space maneuvers. Relying on the principles of physics and engineering, thrust is generated to lift it off from Earth, maintaining orbits and explore the cosmos. A propulsion system is differentiated through its onboard power. Two types of propulsion systems are classified: electric and non-electric. Onboard power is needed for regulation including termination and initiation of the processes. Encompassing propulsion technology, electric propulsion utilizes electrical power to harness propellant exhaust velocity. Despite its potential contribution in plasma observations and applications, it is unprecedented in educational environments due to its perceived complexity and high cost. Exposure to these systems in establishing academic setting remains rare due to its intimidating nature.

The high cost, complexity, and reliance on specialized materials prevent many universities from providing students with practical experiences in plasma generation and propulsion systems. While previous works have demonstrated miniature ion thrusters including the study of micro-ion thrusters and with the development and testing of a 3cm electron bombardment Micro-Ion Thruster (Wirz et al., 2001) and the pulsed plasma thruster on his study of a continuous plasma thruster using water vapor as a propellant for nanosatellite propulsion, these designs remain financially and technically inaccessible for most university laboratories (Boeva, 2014). To introduce a design suitable for laboratory modeling and demonstrations, a single component instead of building a whole thruster will be explored. One of the primary components of propulsion system for space explorations is the propellant. These chemicals are ionized in the thruster and then accelerated by the electrical field, creating a high-velocity stream of particles.

Since the researchers will build and operate an ion plasma thruster without using the propellant, one of the goals of this propulsion design is to generate and demonstrate the formation of the plasma. Using ambient air for propulsion systems as the working medium for plasma production simplifies the setup, making it more accessible for experimental observations (NASA, 2023). The usage of ambient still has the potential to help the researchers understand the basic mechanisms of a propulsion system. Using ambient air, instead of specialized propellants, provides a cost-effective and practical solution for educational propulsion experiments. It allows students to observe the fundamental processes of plasma generation and emission spectroscopy without the need for an expensive and complex vacuum environment.

One of the distinctive features of this research is the use of material innovation in developing the plasma generator. Traditional and sophisticated ion thrusters rely on components made of expensive thin copper plates or tedious copper plating procedures that require high-voltage exposure and equipments. This study introduces a practical and sustainable alternative by repurposing recycled aluminum cans that are malleable enough to be shaped into cathode spikes. These spikes will be coated with copper plates, which is a readily available and inexpensive material for conductivity. Educationally, the novelty of this approach directly reduces the barriers to engaging in complex space propulsion systems. Students can now study ionization and plasma generation instead of relying on theoretical instruction. In this way, the project not only advances hands-on learning in space science but also contributes a replicable material for interested researchers facing resource constraints.

The research seeks to design, build, and test an ion-plasma generator that is downsized for accessibility, especially to university students who aim to understand the mechanisms of the propulsion system for possible plasma observations and analysis interconnected with the propulsion system, rocket science and its principles. Plasma remained; moreover, the researcher aims to reduce the cost of constructing a spacecraft's engine so that university students will have more access to space technology. The working principles of anion plasma engines will be explored through the representation of its main components. Due to the vastness of this study, the researchers will cover only an ion plasma thruster without propellants such as xenon to make it viable. However, the design is modifiable and can be subjected to improvements and innovations, making it suitable for future studies and focuses can be applied to various studies such as magnetohydrodynamics, plasma-material behavior and confinements, understanding the basics of propulsion and many other rocket science observations and analysis.

A. *Addressing Global Barriers in Space Science Education*

Beyond their academic motivation, the research seeks to respond to broader global concerns which surround accessibility, inclusion, and sustainability in science and technology. Across many developing nations and academic institutions still developing programs in propulsion, aerospace, and space engineering, access to advanced laboratory facilities and specialized materials remains limited, reflecting the global disparities in space science capacity noted by the United Nations Basic Space Science Initiative (Mathai et al., 2015). Inducing educational division, students are intimidated by complex technologies that appear to be unattainable. This approach also promotes the democratization of space science education, which echoes global actions by UNESCO and the United Nations Office for Outer Space Affairs (UNOOSA) for inclusivity to STEM access and space related education. In the long term, projects like this contribute to building local capacity for scientific innovation, encouraging students and researchers to pursue studies that align with the Sustainable Development Goals (SDGs), particularly Goal 4 (Quality Education) and Goal 9 (Industry, Innovation, and Infrastructure). Through the development of educational models that are both scalable and sustainable, the study not only supports the future of space technology education in the Philippines but also contributes to the global movement advocating for equitable participation in space exploration and scientific discovery.

METHODOLOGY

Following the Educational Design Research (EDP) framework, researchers implemented analysis, design, implementation, and evaluation phases for the plasma generator. This model is adapted from an ion plasma thruster design licensed under a Creative Commons Public Domain Dedication (CC0), permitting modification and use for educational purposes (Gigazine, 2023) This will be a more accessible entry point for students, especially in Space Science Technology programs, encouraging exploration and experimentation of the commonly intimidating propulsion systems. One of the desired features includes the simplification of the ion-plasma generator. By starting with a less complex design, the elements exempted can still be integrated in future iterations to enhance the generator's functionality. This approach encourages the students to understand the foundational concepts first, providing a solid groundwork for more complex experiments. The model highlights the main components of an ion thrust plasma engine which include the following: **Ion Source, Power Supply, Control System**.

A. *Theoretical basis and Equations*

The operation of the low-cost ion plasma generator is governed by the principles of plasma formation and ion acceleration. Although this study did not focus on performing comprehensive measurements of thrust or plasma parameters, a mathematical foundation is presented to explain the mechanisms of plasma generation and the theoretical basis of ion acceleration. As described by Paschen's Law, plasma is generated when the applied electric field exceeds the breakdown voltage of air (NASA, 2020).

Similarly, the principle of ion acceleration can be explained by the rocket thrust equation, expressed as $F = \dot{m}v_e$ (Lutheran Pioneers, n.d.).

1. Plasma Formation

Plasma is formed when their is ionization of neutral gas under the influence of a sufficiently strong electric field. In order for a discharge to happen between the two set up of electrodes of distance d, the applied voltage must exceed the breakdown voltage of air demonstrated by Paschen's Law (Chen and Chang, 2012).

$$V_b = \frac{B \cdot p \cdot d}{\ln(A \cdot p \cdot d) - \ln\left[\ln\left(1 + \frac{1}{\gamma_{se}}\right)\right]} \tag{1}$$

Where:

- V_b = breakdown voltage (V),
- p = pressure of the gas (Pa),
- d = distance between electrodes (m),
- A, B = gas-specific constants (for air, $A \approx 112.5$ (1/m · Pa), $B \approx 2737$ V / (Pa · m)),
- γ_{se} = secondary electron emission coefficient.

Under atmospheric conditionss, reaching the breakdown voltage produces cascading electron collions which produces free electrons and ions that sustains the plasma discharge. This principle will explain the visible plasma emission when high voltage goes through the aluminum copper tape electrodes.

2. Ion Acceleration and Thrust Principle

After the plasma formation, ions within the discharge will be accelerated by the applied potential difference. The basic epression for thrust produced by ion acceleration is:

$$F = \dot{m}v_e \quad (2)$$

Where:

- F = thrust (N),
- $\dot{m}$ = mass flow rate of ions (kg/s),
- v_e = exhaust velocity of the ions (m/s).

The exhaust velocity is related to the accelerating voltage by:

$$v_e = \sqrt{\frac{2qV}{m}}$$

Where:

- q = charge of the ion (C),
- V = accelerating potential (V),
- m = mass of the ion (kg).

The expression explains how exhaust velocity increases with higher accelerating voltage and lighter ion mass. Since the prototype utilizes ambient air as working medium instead of a dedicated and conventional propellant (e.g. xenon), the plasma discharge is expected to be unstavble and thrust will be immeasurable. Nevertheless, the mechanism illustrates how ion acceleration underlines the functionality of electric propulsion systems.

Although this study did not conduct direct thrust measurement, these equations provided other students with a mathematical baasis to connect observed plasma dischrages with theoretical propulsion concepts. This theoretical basis complements the physical prototype in ensuring that the educational intervention not only demonstrates plasma visually but also reinforces the underlying physics and mathematical modelling essential in space propulsion.

3. Materials and Components

The ion plasma generator will be constructed using accessible, low-cost and modifiable components to maximize educational value. These materials will be deliberately chosen and tested to balance cost-effectivity, availability and functionality while demonstrating plasma generation. The main components are as follows:

a. 3.7V 2500mAh Lithium Polymer Battery – used as the primary power source.

b. DC 3–6V to 4kV–400kV Step-Up High Voltage Transformer Module – for voltage amplification to achieve plasma breakdown.

c. 3-pin toggle switch – for circuit control and safety.

d. Aluminum cans – cut and shaped into pointed cathode spikes, serving as a sustainable alternative to copper rods.

e. Copper tape – applied as plating to both electrodes for enhanced conductivity.

f. 3D-printed nozzle and electrode holder – designed in CAD (SolidWorks) to house electrodes and stabilize plasma discharge.

g. Wiring, insulating tape, and Styrofoam base – for safe mounting and electrical insulation.

4. Procedures

Since this research utilized Educational Design Research (EDR), it will follow the tyical design-development-testing cycle.

4.1 Design Conceptualization

The researcher's reviewed the conventional copper plating method which is not accessible to students with the primary reason of its expense with the necessary components. An electroplating setup is not just a battery and a breaker but requires DC power supply with precise voltage and current control as well as specialized plating tanks and filtration systems. Moreover, this plating method requires copper sulfate solution and while students can purchase small, pre-made kits which are often more expensive per unit. Therefore, the inaccessibility is less about the fundamental concept and more about the practical application. The modified design will develop and replace expensive copper electrodes with aluminum spikes covered in copper tape, maintaining conductivity while reducing cost.

Figure 1 Electrode Holder

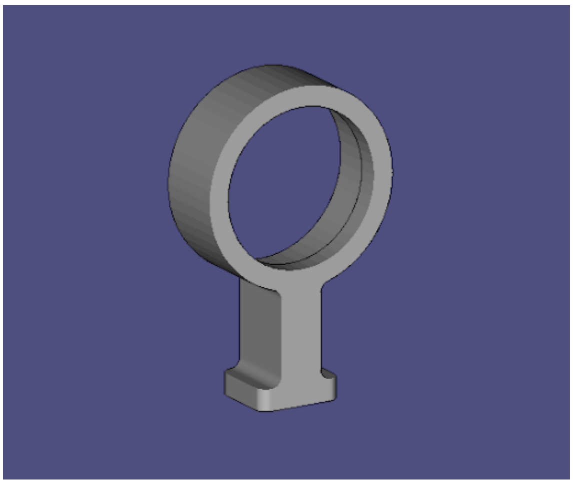


Figure 2 Mount

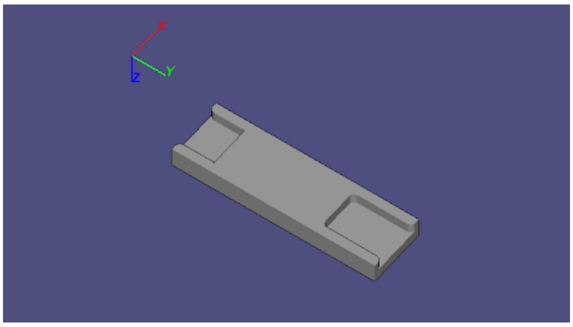


Figure 3 Nozzle

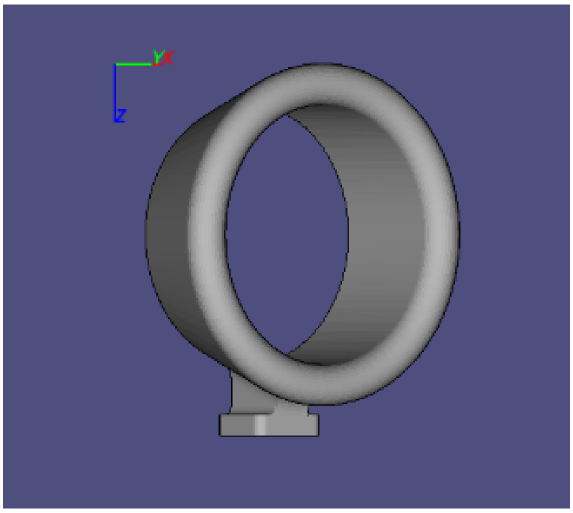
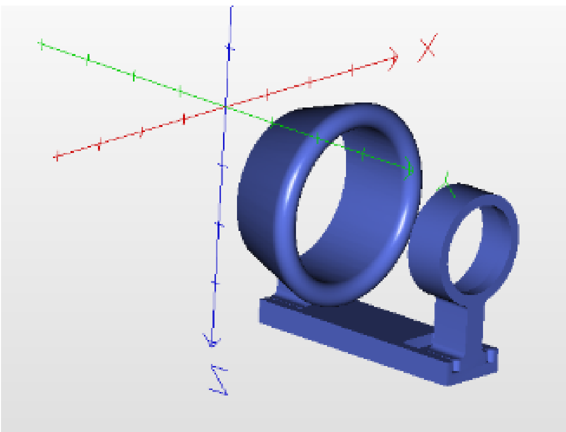


Figure 4 Front Circuit Design



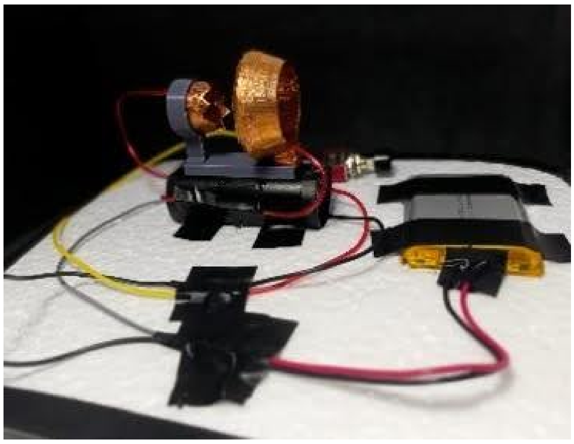
4.2 Prototype Construction

The electrodes was developed by utilizing malleable aluminum soda cans shaped into aluminum spikes. To ensure conductivity, the researcher's used copper tapes to to cover the aluminum surface. Since a 3D printer is available to cater the development of the nozzle and electrode holder, it drastically reduced the cost and time associated with creating a custom design. Moreover, a platform or a holder was also 3d printedd to hold the cathode (spike electrode) and anode (hollow tube) to create a discharge region.

4.3 Electrical Integration

A 2000mAh lithium polymer battery (Li-Po) was connected to the step-up transformer, which is a DC 3v-6v to 4000k-40000V power module generator, which boosted the voltage required for ionization. A toggle switch was installed to regulate current flow and provide operator safety. The wiring was insulated and secured on a styrofoam base to minimize risks of short-circuiting.

Figure 5 Circuit Design



4.4 Testing and Plasma Generation

The assembled thruster was operated in ambient air and voltage adjustments were made incremently to identify breakdowns threshold consistent with Paschen's Law. Plasma glow dischrages were visually observed at the sharp cathode tips which validated functionality. However, issues such as occasional sparking and overheating was documented, attributed to the electrodes geometry and air breakdown variability.

RESULTS AND DISCUSSION

A. *Ion Thruster Unit*

The fabricated ion thruster unit has successfully demonstrated the generation of plasma under the conditions of ambient air. With the toggle switch on, high voltage is applied through the copper-plated spikes and a visible plasma cloud of bluish-purple tinge is produced, confirming that there is ionization with the surrounding gas molecules. The plasma plume was sustained but only for short intervals, typically ranging from 5-10 seconds, before the intermittent sparking. Moreover, the high voltage and Li-Po battery (2000 mAh) reliably provided sufficient voltage to sustain ionization. The researchers observed that plasma stability is sensitive to spike geometry and that poorly sharpened cathodes resulted in fluctuations of the plume.

With the observed limitations and implications identified for future modifications and improvements, the study identified gas breakdown sensitivity, electrode geometry, and overheating as a limitation that aligns with the prior finding that miniaturized, nonvacuum plasma systems face instability issues (Nakagawa et al., 2019). However, the ability to generate plasma in ambient air is consistent with the educational goals of this study. A video demonstration of the prototype developed ion-plasma thruster in operation has been provided as supplementary material (Devero & Santos, 2025).

Figure 6 Plasma Observation

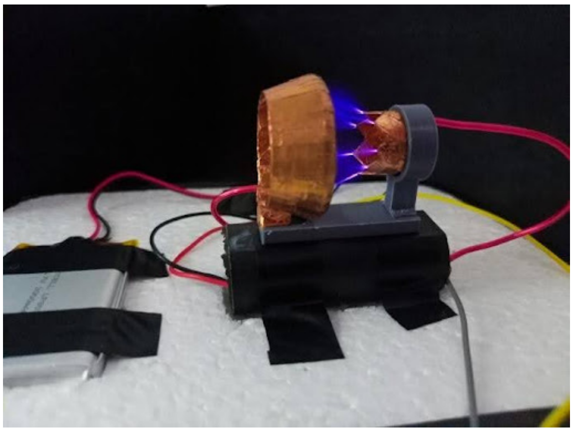
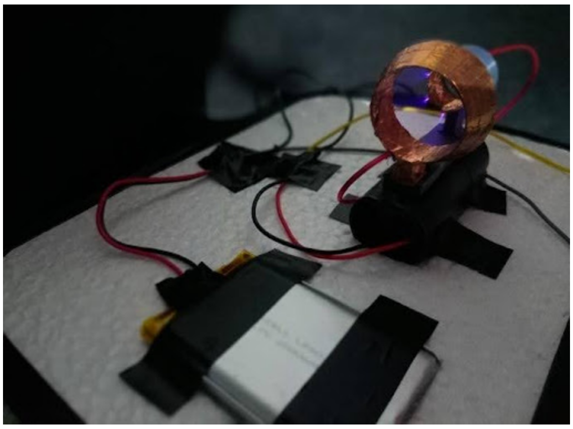


Figure 7 Faint Plasma



This comparison shows that despite prototype cannot match the efficiency and sustainability of the commercial thrusters, it provides cost-effective, accessible entry point for educational and laboratory demonstrations. It is also empahsized that the primary objective of this initial research was not to achieve optimized performance metrics or conduct comprehensive thrust measurements, but rather validate a working design capable of generating plasma under specified conditions. The study deliberately focused on the accessibility and demonstrability, ensuring that the device could be assembled from low-cost, commercially available components while still functioning as a tangible proof of concept. With the establishment of a baseline design that has demonstrated the production of plasma, the study laid the groundwork for future enhancements and experimental iterations. It is a prototype intentionally made to be modular and modifiable, which will allow subsequent researchers to introduce upgrades such as higher power voltage, reined electrode geometries and materials or even and integrated propellant flow systems once budget and laboratory resources permit. In this way, the current design serves as a scalable platform that can evolve into more advanced ion-thruster research set-ups.

B. Design Validation and Significance

The study's primary contribution lies in validating that a low-cost, modular ion plasma generator can reliably produce plasma using accessible materials and basic laboratory tools. Although not intended for thrust measurement or long-duration operation, the prototype serves as an effective educational model that allows students to observe plasma discharge, breakdown voltage, and ionization phenomena in real time. This tangible exposure helps bridge the gap between theoretical learning and experimental understanding of electric propulsion systems. Table 1 presents the cost analysis of the materials used in the prototype, emphasizing affordability and transparency. The total fabrication cost was approximately PHP 1,100, using commercially available and recycled materials such as aluminum cans and copper tape. This cost efficiency validates the study's design principle that plasma phenomena can be demonstrated in educational laboratories without highbudget requirements or vacuum facilities.

CONCLUSION

Plasma emission was visually observed through the cathode spikes, which emitted a faint bluish glow when the applied voltage exceeded the air breakdown threshold. The plasma plume displayed short bursts of stability before fading, confirming successful air ionization but highlighting challenges in maintaining consistent discharge. Instability, overheating, and occasional sparking were noted as limitations arising from the absence of a vacuum and the irregular geometry of the aluminum spikes. These results align with Nakagawa et al. (2019), who reported similar instability in non-vacuum, miniaturized plasma systems

A. Limitations and Future Work

The plasma produced by the prototype was intermittent and sensitive to electrode geometry and environmental conditions. The absence of a controlled vacuum environment and limited voltage regulation contributed to performance inconsistencies. Future iterations of the design will focus on refining electrode shape, improving insulation, integrating voltage control, and incorporating a small propellant system to achieve more stable plasma behavior. These enhancements will support more advanced measurements of ion acceleration and thrust, expanding the design's research and instructional value.

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Table 1 Cost Table Transparency

Material	Quantity	Unit Cost (₱ / $)	Total Cost (₱ / $)
Li-Po Battery (3.7V, 2500 mAh)	1	₱350	₱350
Step-up Transformer (3–6V to 400kV)	1	₱500	₱500
Toggle Switch	1	₱50	₱50
Aluminum Cans (recycled)	2	–	–
Copper Tape (roll)	1	₱120	₱120
3D-printed Nozzle & Housing	1	–	–
Wiring & Insulation	–	₱80	₱80
Total Estimated Cost	–	–	**₱1,100**

Table 2 Comparison of the developed thruster with existing ion thruster technologies

Feature	Present Study (DC, Ambient Air)	Conventional Ion Thrusters (e.g., Xenon-fed, RF/MW)
Cost of Fabrication	₱1,356 (low-cost, COTS-based)	₱20,000+ (specialized materials, vacuum systems)
Propellant	Ambient air	Xenon, Krypton, or water vapor
Operating Medium	Open-air, no vacuum chamber	Vacuum chamber required
Voltage Range	20–30 kV (DC discharge)	200–1000 V (RF/MW systems)
Plasma Stability	5–15 s (intermittent)	Sustained minutes–hours
Target Application	Educational, demonstration	Satellite propulsion, high ΔV maneuvers

Table 3 Experimental observations and operating parameters

Parameter	Value / Observation	Notes
Input Battery Voltage	3.7–6.0 V (Li-Po)	Stable discharge at 3.7 V
Output Voltage	∼20–30 kV	From module specs
Plasma Duration	5–15 s sustained	Sparking observed >15 s
Current Draw	∼150–200 mA	Load dependent
Spike Overheating	After ∼15 s	Due to ion bombardment

tributed indirectly to the success of this study. Their encouragement and the resources provided created an environment that made the completion of this work possible.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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