STARGATE: An Undergraduate Experimental Gridded Ion Thruster Student Research Project

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This paper reports on the ongoing investigation regarding the feasibility of utilizing the Corona Discharge Reaction as an alternative plasma production mechanism in a Gridded Ion Thruster system. The STARGATE project investigated and demonstrated the difference between negative and positive Corona Discharge Reactions as it pertains to electric propulsion applications, as well as investigated the feasibility of utilizing the Corona Discharge Reaction for plasma production in its intended operating environment. The team has designed and fabricated an initial functional vacuum testing prototype and is pending initial test-firing.

Nomenclature

CDR	=	Corona Discharge Reaction
DC	=	Direct Current
d	=	Distance
GIT	=	Gridded Ion Thruster
HVPS	=	High Voltage Power Supply
Isp	=	Specific Impulse
Pa	=	Pascal (unit of pressure)
PPU	=	Power Processing Unit
PWM	=	Pulse Width Modulation
RC	=	Resistor Capacitor
sccm	=	standard cubic centimeters per minute (unit of volume flow rate)
μ	=	ion mobility
V	=	Volts (unit of electrical potential)
$\dot{V}$	=	Volume Flow Rate
Vaccel	=	Accelerator Grid Voltage
Vanode	=	Anode Voltage
Vcathode	=	Cathode Voltage
Vscreen	=	Screen Grid Voltage

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I. Introduction

STARGATE is an experimental gridded ion thruster undergraduate student research project at the University of Alabama in Huntsville (UAH) as part of UAH's Electric Propulsion Club, an independent student research organization. The goal of the project is to investigate the feasibility of utilizing the Corona Discharge Reaction (CDR) as an alternative method of plasma production in a Gridded Ion Thruster. The project facilitates the mission of the Electric Propulsion Club by lowering the bar of entry for undergraduate students to participate in the research and development of electric propulsion systems and technology.

To prove technology feasibility, the project seeks to fabricate and test a prototype to meet or exceed current capability demands for small satellite propulsion systems on the market. For the purposes of this project, these requirements can be taken as a sub-100W total power consumption, specific impulse ≥ 1500 seconds, and a total thrust of ≥1 mN (millinewton).[2] To accomplish this, the STARGATE project develops thrusters, Power Processing Units (PPUs), electrical test equipment, modelling software, control software, and other products through rapid and iterative prototyping to fulfill the project's goal-based requirements set by comparable market alternatives.

Several developmental prototypes will be produced to better help understand the system and technology. The initial concept feasibility prototype, "SG-1", was built to observe the behavior and properties of the Corona Discharge Reaction within the system. Currently, the SG-2_1 prototype is already built and is pending test-fire. It will serve as an initial functional vacuum testing prototype, and the next-generation SG-2_2 prototype is undergoing preliminary design. The knowledge, experience, and experimental data gained from these early rapid prototypes will serve to aid in the development of the final prototype.

This paper reports on the technology background of the CDR and its applicability for electric propulsion applications, results and findings from preliminary experimentation on the "SG-1" prototype, system overview of the current "SG-2_1" prototype, plans for testing, planned experiments, and future development and research goals of the project.

II. Technology Introduction and Background

Gridded Ion Thrusters (GIT) are among the most proven and efficient electric propulsion systems.[1] Adaptations and variations of the conventional GIT platform have begun to emerge in recent years to replace the hollow cathode by utilizing alternative plasma production systems, such as microwave and RF systems.[2] The STARGATE project proposes a possible alternative to the hollow cathode used for plasma production in a conventional GIT by using direct current electrical discharge, specifically the Corona Discharge Reaction (CDR).

The GITs have physically and functionally separated plasma production and ion extraction systems. Because of this, different methods of plasma production can be explored to create novel variations of the production modes seen in conventional GITs. For example, conventional GITs use electrons extracted from a hollow cathode for plasma production in a conventional GIT. The electrons extracted from the hollow cathode enter the discharge chamber where neutral propellant gas is ionized through inelastic collision with the electrons, producing a secondary electron. The secondary electrons can then go on to repeat the inelastic collision, creating an electron avalanche effect. This process is known as electron bombardment ionization, and it shares similar ionization reaction properties to the Corona Discharge Reaction (CDR).

A. Corona Discharge Reaction Overview

The CDR is a phenomenon that occurs when a high electric potential is applied between two electrodes, causing electrical breakdown and ionization of the gas that surrounds it.[3,4] For the CDR to be initiated, a neutral atom in the presence of a strong asymmetrical electric field is ionized through a random natural event such as being struck by a high energy particle, producing a positive ion and an electron. Since the ionized atom is in the presence of a strong electric field, the positive ions accelerate toward the negatively charged cathode, and the electrons accelerate toward the positively charged anode. As an electron accelerates, it gains enough kinetic energy for an inelastic collision with a neutral atom to cause ionization, creating a positive ion and a secondary electron in addition to the primary electron. Just as in electron bombardment ionization, both free electrons can repeat this inelastic collision process, allowing for an electron avalanche effect. Both the CDR and the electron bombardment ionization initiated by a hollow cathode rely on the electron avalanche process, which suggests the feasibility of using the CDR as an alternative method of plasma production in a GIT.

B. Concept Feasibility

High voltage electrical discharge and breakdown of gasses, such as the Corona Discharge Reaction, can occur in low-pressure to rarefied gas conditions. This has been observed as a failure mode on spacecraft, and similar reactions are being experimented with emerging pulsed plasma thruster designs. Most research surrounding the CDR in space-related environments and applications is aimed at mitigation and prevention.[5] Because CDRs have been observed in extremely low-pressure environments inside spacecraft, it suggests the feasibility of deliberately causing the CDR to be used as a source of plasma production for electric propulsion applications.

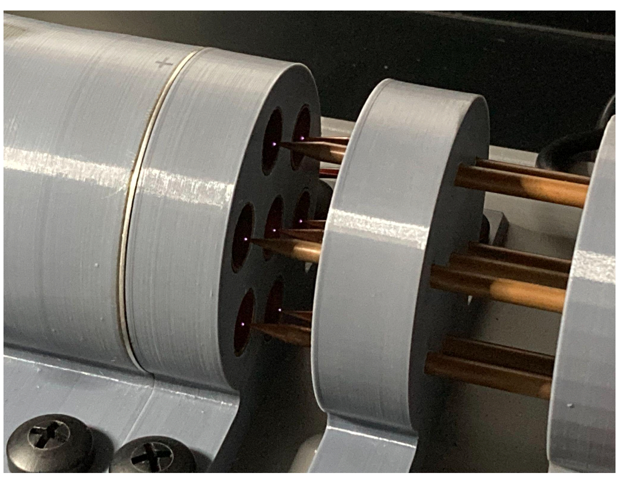
III. Initial Experimentation

A. Initial Concept Feasibility Prototype (SG-1)

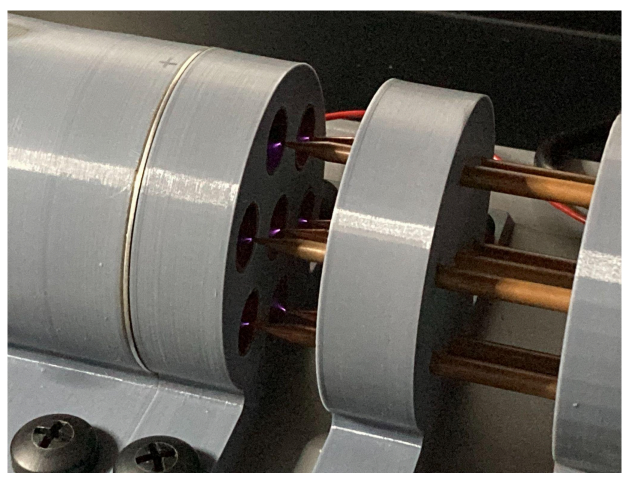
To better understand the properties of the Corona Discharge Reaction, an initial experimentation device was devised to facilitate experimental testing. The initial experimentation device is referred to as the "SG-1" prototype. The SG-1 is a simplistic prototype allowing for the demonstration, adaptive testing, and detailed observation of the CDR. SG-1 consists of 7 matching pairs of electrodes and utilizes a single adjustable negative 8.5kV output High Voltage Power Supply (HVPS). It is tested in the atmosphere and utilizes atmospheric air as a propellant gas. The electrodes for the SG-1 prototype use a variation of the pin and tube discharge configuration and are machined from copper. The electrical discharge occurs between the point of the pin electrode(s) to the interior surface of the tube electrode. Utilizing the SG-1 prototype, both the positive and negative corona discharge configurations were tested.

B. Comparison Between Negative and Positive Corona Discharge Reaction

In the negative corona discharge configuration the pins are charged negatively functioning as the cathode, and the tubes are biased comparatively positively functioning as the anode. In the positive corona discharge configuration, the tubes are charged negatively functioning as the cathode, and the pins are biased comparatively positively functioning as the anode.



(a) Negative CDR Configuration.



(b) Positive CDR Configuration.

Figure 1. SG-1 test firing under negative (a) and positive (b) corona discharge configurations.

In either CDR configuration, electrons flow from the negative electrode (cathode) to the positive electrode (anode). In the negative CDR configuration, electrons flow from the cathode pins to the anode tubes, allowing for electron collision and the production of cations. However, cations produced by the negative CDR configuration are attracted back to the cathode pins, as shown below in Fig. 2. In the positive CDR configuration, electrons flow from the cathode tubes to the anode pins, and cations created by electron collision are attracted towards and through the cathode tubes opposite of the path of electron collision and in the direction of thruster exhaust, as shown in Fig. 3.

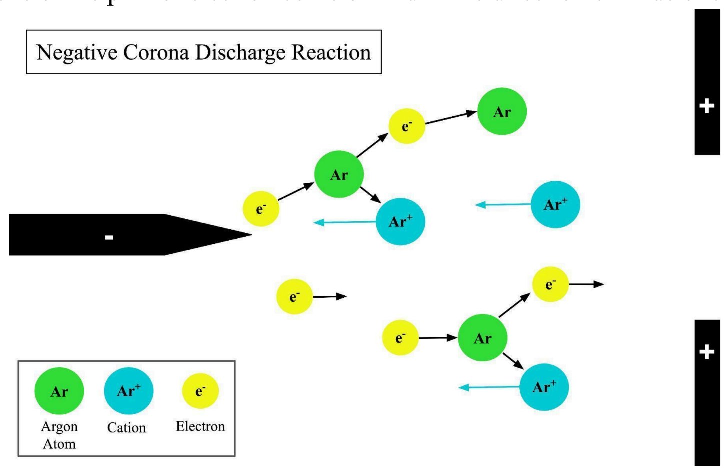


Figure 2. Negative Corona Discharge Reaction

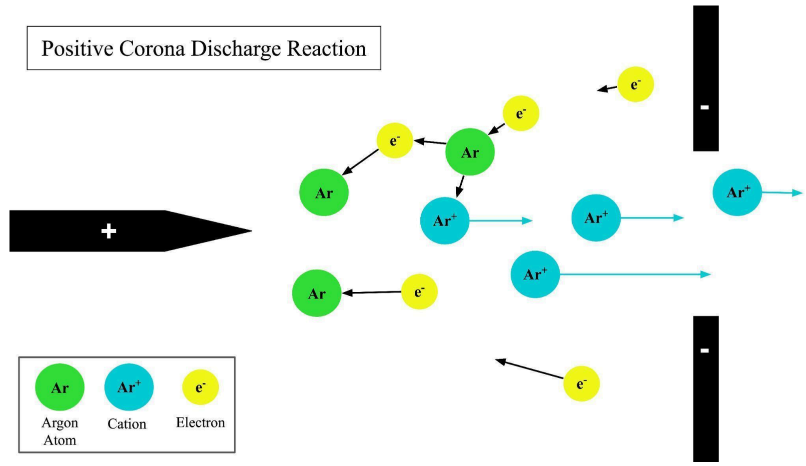


Figure 3. Positive Corona Discharge Reaction

In both configurations, the SG-1 prototype is able to create thrust through ionic wind. As shown in Fig. 1 above, the positive CDR configuration produces a more intense, stable, and consistent electrical discharge compared to the negative CDR configuration. As a result, the positive corona discharge configuration produced a stronger ionic wind. It should be noted that the STARGATE system as it is intended to be applied for spaceflight applications does not utilize ionic wind to produce thrust, instead utilizing ion grids for ion extraction and acceleration as it is a GIT derived design, therefore the thrust produced by ionic wind in the atmosphere with the SG-1 prototype has little to no correlation to performance characteristics in a vacuum or space environment.

IV. Ongoing Experimental Prototype (SG-2_1)

The STARGATE project is currently in Phase II. The goals of Phase II are primarily to fabricate experimental prototypes, gather experimental data, and observe the performance properties and capabilities of the system. Phase II is not aimed at fulfilling any performance requirements. The first of many planned Phase II prototypes is the Initial Functional Vacuum Testing Prototype or "SG-2_1" which serves to help the team understand the behavior of the CDR in extremely low pressure to rarefied argon gas operating conditions,[6] and the compatibility of a gridded electrostatic ion extraction and acceleration mechanism with the CDR plasma production system.

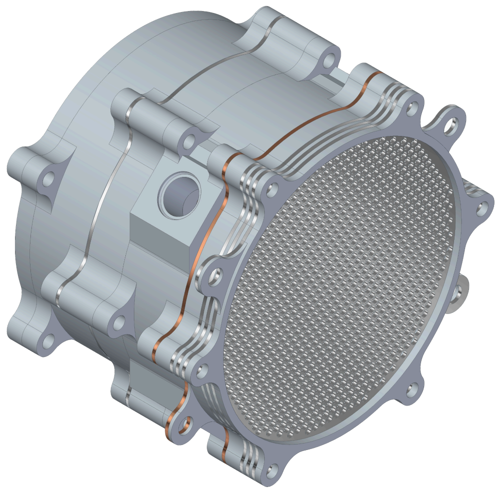


Figure 4. SG-2_1 Prototype V4.3 Isometric View

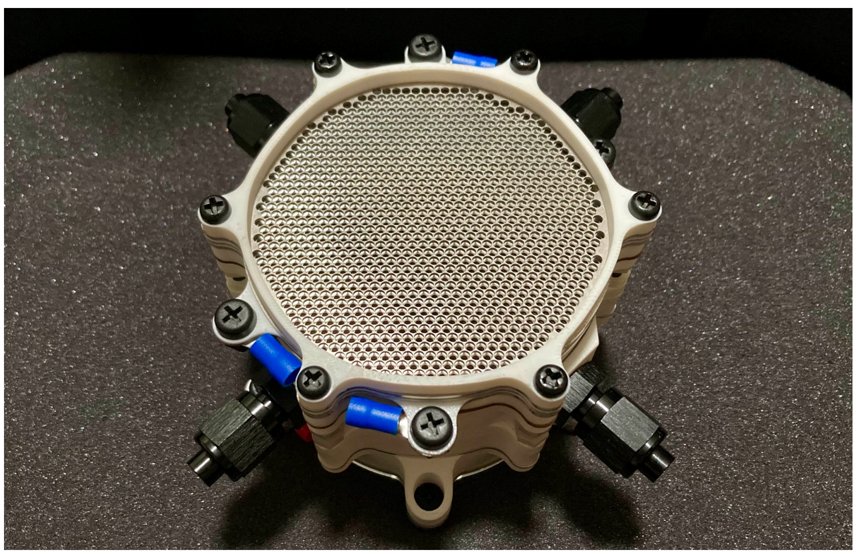


Figure 5. SG-2_1-C V5.1 Prototype

A. SG-2_1 Prototype System Overview

The SG-2_1 prototype utilizes a positive Corona Discharge Reaction system for plasma production. The plasma production system consists of 14 positively charged anode pins, and a singular negatively charged cathode plate with 14 apertures that are coaxially aligned with the cathode pins and separated by a discharge distance as shown in Fig. 5 and 6. Just as on the SG-1 prototype, electrons flow from the cathode plate toward the anode pins, ionizing the propellant gas atoms during its course of travel through inelastic electron collision. Due to the properties of positive corona discharge as described above, electrons travel in the opposite direction of the thruster exhaust. Cations produced by the ionization reactions are drawn toward the cathode plate and are electrostatically extracted and accelerated by the ion extraction grids through the cathode plate apertures.

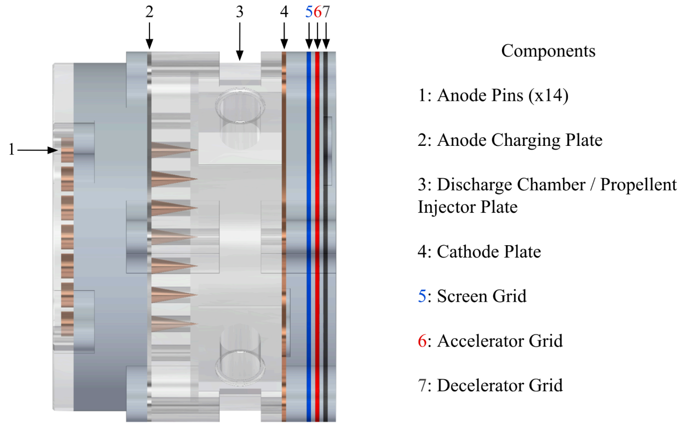


Figure 6. SG-2_1 Prototype Overview

B. Discharge Conditions

The discharge distance between the anode pins and the cathode plate is 20 mm. The relatively long discharge distance is due to the prototype being expected to operate in rarefied gas conditions,[6,7] allowing for a greater effective area of discharge to compensate for the longer mean free path and lower collision frequency of the propellant gas. The effective internal volume of the discharge chamber is also minimized to increase the discharge chamber pressure.

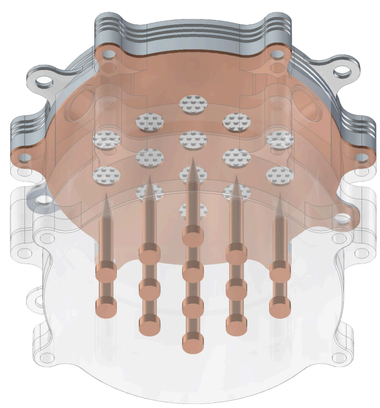


Figure 7. SG-2_1 discharge view

C. Propellent Injection

The SG-2_1 prototype and all subsequent planned STARGATE project prototypes utilize argon gas as propellant, primarily due to the low cost and ease of handling, in addition to other common reasons noble gasses are used as EP propellant.[1] Unlike a conventional GIT which has separate propellant flow control for the hollow cathode and main plenum, the STARGATE system's lack of a hollow cathode means it only requires one propellant flow into the main assembly. Propellent gas is supplied directly into the discharge chamber at the discharge region through four lateral injector inlets around the circumference of the thruster positioned 90 degrees from each other as shown below Fig. 8. Propellant flow is controlled by an electric mass flow controller capable of outputting a volume flow rate ($\dot{V}$) of 1-100 sccm. Propellent gas will be injected into the discharge chamber using 3/16 inch outer diameter tubings and AN#4 fittings.

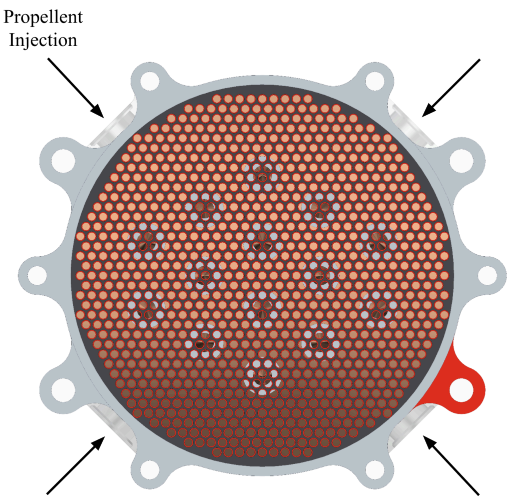


Figure 8. SG-2_1 Exhaust View

D. Power Processing Unit (PPU)

The SG-2_1 prototype utilizes a scratch-built Power Processing Unit (PPU) to supply low-voltage and high-voltage power, as well as control signals to the entire prototype. The PPU consists of a programmable benchtop power supply, four separate DC-DC High Voltage Power Supplies, and an HVPS output controller.

Electrical power to the entire system is supplied from a North American standard 120V AC electrical outlet through a programmable benchtop power supply. The power supply is used to regulate input voltage and current to four separate high-voltage power supplies connected in parallel. Electronically adjustable HVPSs are connected to the anode assembly, cathode plate, screen grid, and accelerator grid. The decelerator grid serves as the common ground of the whole system. For the purpose of systems engineering and safety protocols, the high-voltage portions of the PPU and low-voltage portions of the PPU are treated as separate subsystems. The high voltage PPU is designated with “EN-4” and low voltage PPU components are designated with the “EN-5” prefix (see Fig. 13). The system is further broken up into modular subsections, allowing the system to grow as project scope widens.

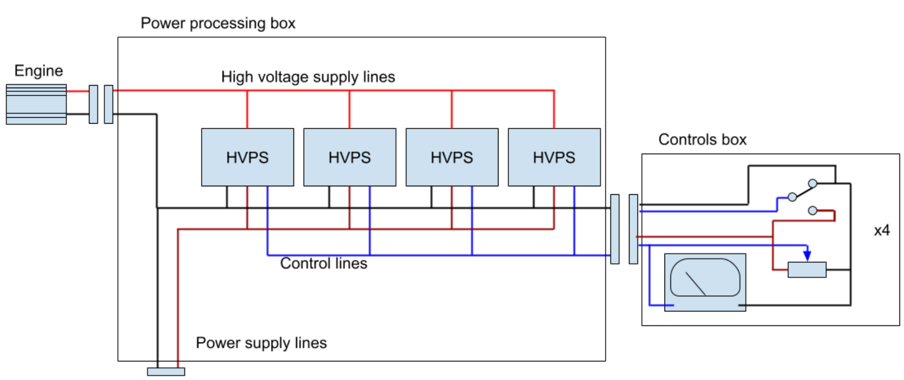


Figure 9. High Voltage PPU (EN-4)

The basic layout of the PPU can be seen in Fig. 9. The SG-2_1 prototype utilizes four variable output enclosed DC-DC converting HVPS made by Analog Technologies,[8] each of which is controlled by a proportional analog input signal, as well as including a “soft” shutdown input. The control pins are connected to a standard connector that can be used to interface with the controls box. The controls box currently consists of four 10k ohm low tolerance potentiometers and four persistent shutoff switches, one for each HVPS, and a momentary four-way switch to control all four HVPSs simultaneously. There are currently plans to replace the analog control system with a digital control system utilising an Arduino microcontroller to help with test automation. The analog system was chosen to minimise the risk of software errors and simplify circuitry for early testing.

Feedback on the HVPS system is supplied through voltmeters reading both the input and output voltage on the HVPS units, as well as status lights to indicate power and shutdown states of the HVPSs. Thermal monitoring of the HVPSs is provided through two thermocouples, and thermal regulation is provided through the use of heat sinks mounted to the HVPSs and PC fans to increase airflow over the heat sinks.

With this PPU configuration, the applied voltage of the plasma production system on the prototype can be adjusted by raising or lowering the anode voltage. The PPU can supply up to 2800V of electrical potential to the plasma production system. Breakdown voltage of the propellant depends on many factors, including inlet pressure, chamber pressure, and chamber temperature. The adjustment capabilities of the PPU allow the plasma production system to function in a wide range of operating conditions.

E. Ion Extraction System

The SG-2_1 prototype utilizes a three-grid ion extraction system, consisting of a screen grid, an accelerator grid, and a decelerator grid. For simplicity of fabrication, and due to this prototype having no specific performance requirements, all grids are flat faced, and made from 1mm thick 6061 aluminum. The screen grid has 963 holes, which are 2.2 mm in diameter, and has a transparency of 72.8%. The accelerator grid has 963 matching holes of 1.6mm diameter and a transparency of 38.5%. The decelerator grid is identical to the screen grid. The distance between the screen grid and the accelerator grid as well as the distance between the accelerator and the decelerator grid can be adjusted by an interchangeable spacer. The default experimental setup uses a 1mm spacer for both distances.

The screen grid is biased to 1100V and can be biased to up to 1500V. The accelerator grid is biased to -250V and can be biased up to -500V. The decelerator grid is grounded and serves as the common ground of the system. The potential difference between the screen grid and the accelerator grid is 1350V. Components are biased following a negative trend excluding the decelerator grid as shown in Fig. 10. This means each component towards the exhaust end of the thruster is biased more negatively than the component before, which allows for the flow and acceleration of positive ions towards the exhaust end of the thruster.

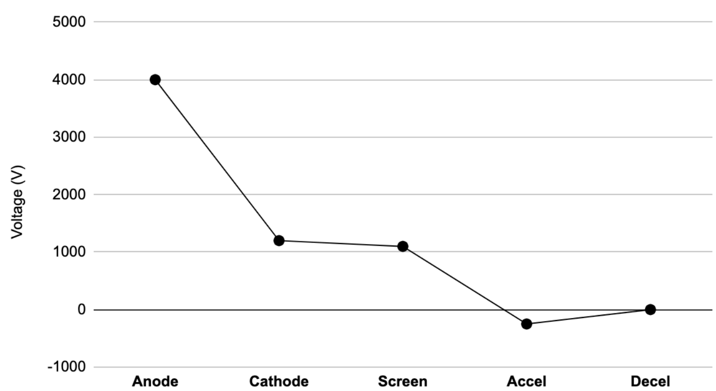


Figure 10. Voltage Bias of SG-2_1 Prototype Components

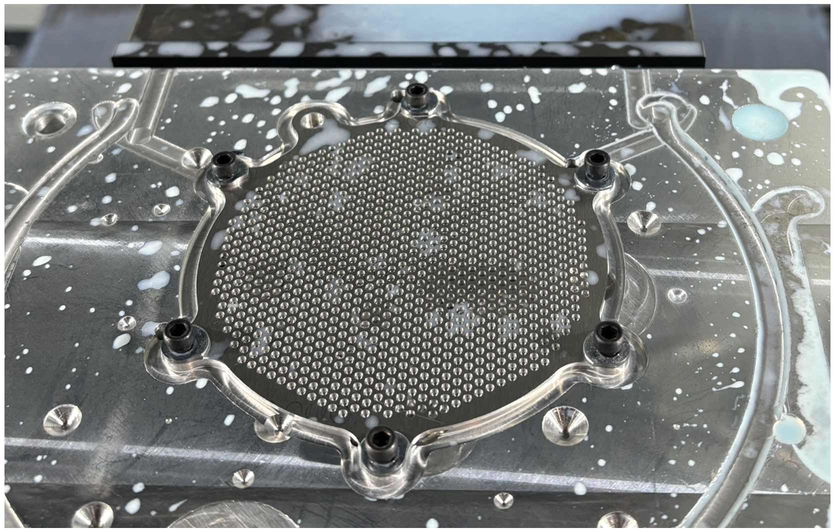


Figure 11. Accelerator Grid Being Machined

The design of the ion extraction systems on the SG-2_1 prototype is not yet optimized and is intended to accomplish the most basic functionalities of the system,[9] however, the system allows for a degree of flexibility and adjustability if needed.

F. Neutralizer System

A thermionic hot filament cathode neutralizer assembly as shown in Figure 12 will be used for SG-2_1 prototype testing instead of a hollow cathode neutralizer. This particular neutralizer assembly design is inspired by a similar system deployed on the Thrust-Me NPT30-I2 Iodine GIT.[10]

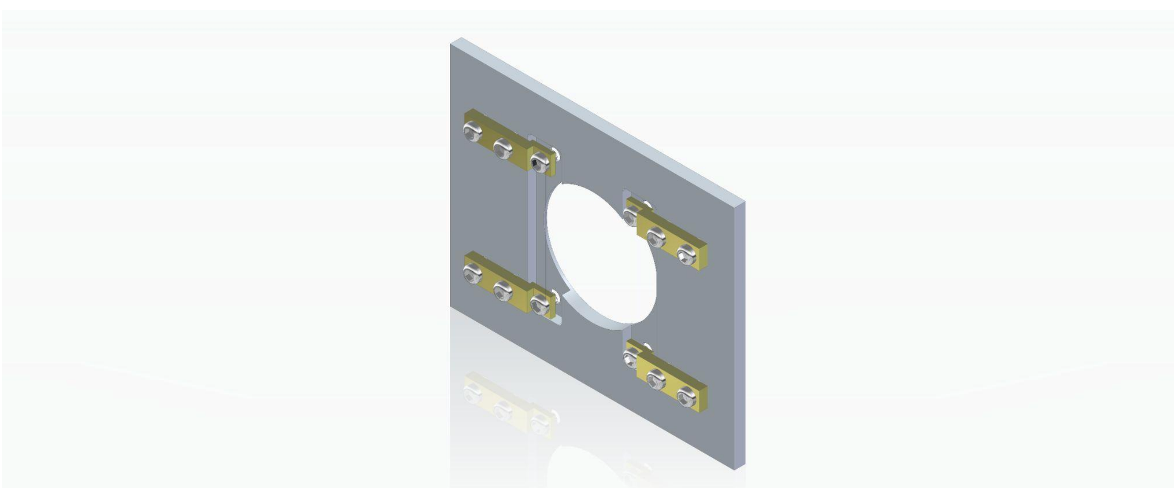


Figure 12. SG-2_1 Neutralizer Assembly

The SG-2_1 neutralizer assembly consists of two tungsten wires mounted to either side of the neutralizer assembly, held by four brass heat breaks attached to an aluminum mounting plate with ceramic fittings for thermal insulation. Electrical current applied through the tungsten wire filaments causes it to heat up and electrons to boil off, which will collide with the plume ions emitted from the thruster and neutralize the ions.

This neutralizer design is utilized due to its simplicity for initial test-firing purposes, as it eliminates the need for the setup and operation of a hollow cathode neutralizer. A similar system was successfully flight-proven on the Thrust Me NPT30-I2 thruster, indicating the potential viability of similar systems being used in future thruster prototypes instead of a hollow cathode neutralizer.

V. SG-2_1 Prototype Experiment Plan

Test-firing on the SG-2_1 prototype is currently being conducted at the University of Alabama in the Huntsville Electric Propulsion Club Research Lab. Once all prototype subsystems have been functionally validated, a comprehensive test is planned to be conducted at the NASA Marshall Space Flight Center.

A. Planned Experiments

The prototype will be used to conduct several experiments throughout its test-firing and to gather experimental data during the process. The project plans to gather two major types of data from the prototype: plasma properties and beam current density.

Planned experimentation procedures involve assessing prototype performance at various volume flow rates ($\dot{V}$) and voltage potential differences. The prototype will be tested at $\dot{V}$ from 1-100 sccm, in 10 sccm increments. While $\dot{V}$ is held constant at each interval, the voltage potential difference between the anode (Vanode) and cathode (Vcathode) will be varied from 50 - 2800V at 50V intervals. Data regarding plasma properties will be measured at each interval, however, data regarding beam current density will only be gathered at the optimal thruster operating conditions as determined by pending previous experimental data with the prototype.

B. Instrumentation

A Langmuir probe positioned downstream of the thruster and used to gather data pertaining to plume plasma properties from which information on plasma potential, electron temperature, and electron density can be derived.

Ideally, sets of Langmuir probe data will also be gathered at multiple points in the thruster discharge chamber, in proximity to anode pins nearest to and farthest from the propellant inlet as well as within the inter-electrode gaps due to the extremely localized nature of the CDR phenomenon. However, gathering Langmuir probe data inside the discharge chamber presents significant engineering and logistical challenges, and might not be feasible in the short term.

To observe the functionality of the ion extraction system, a Faraday cup will be used to measure ion beam current density directly downstream of the thruster. The objective of the Faraday cup for testing this prototype is to verify that a gridded ion extraction system is compatible with a CDR plasma production mechanism. The Faraday cup as used in this experiment, is not used to profile the entire thruster plume but simply to confirm that ions are being extracted and accelerated. As a result, data can be gathered with the Faraday cup fixed at a single point in space, and does not require the Faraday cup mechanism to have an active alignment or translational motion apparatus.[11,12] Beam current density will be measured both with the ion extraction system powered on and powered off. If the ion extraction system functions properly and is compatible with the CDR plasma production mechanism, then the beam current density while the ion extraction system is on should be vastly greater than when the ion extraction system is off.

Figure 13. System Interaction Diagram for Test-Firing

VI. Future Development Goals

The SG-2_2 series of prototypes will succeed the current SG-2_1 series, incorporating lessons learned from previous iterations, as well as more advanced features intended to improve performance, efficiency, and operational durability.

Materials for the structure of the SG-2_2 series of prototypes will be selected to comply with the ASTM E595 outgassing test for space and simulated space environments. The use of high voltage discharge also necessitates that the STARGATE system utilises a fully dielectric discharge chamber and thruster casing. Extensive materials testing, selection, and qualification testing are currently underway to find a material that best suits these needs.

A possible unique feature of the STARGATE system is that the corona discharge reaction could produce ions with much higher energies than in other types of gridded ion thrusters if it operates at a high breakdown voltage. While higher energy ions could lead to enhanced performance capabilities, it also accelerates grid erosion and limits the thruster's lifespan drastically, exacerbating an issue that is already the most common limiting factor in the lifetime of gridded ion thrusters. Experiments are being planned in which different grid materials and geometry will be tested with the Corona Discharge Plasma Production mechanism to study effects and phenomenon with grid erosion.

Magnetic confinement mechanisms are critical systems in Gridded Ion Thrusters as they increase thruster efficiency drastically by extending the mean free path of electron travel in rarefied gas and increasing collision frequency while operating in a rarefied gas discharge condition. The SG2_2 systems will incorporate a ring cusp magnetic confinement mechanism.

Phase III of the STARGATE project, using data, information, and experience gathered from Phase II, will create prototypes aimed at meeting the project's goal-based requirements. The feasibility of the technology will be proven if Phase III can fulfill all project goal-based requirements. If Phase III is successful, the project scope may be expanded to include in-space testing and viability assessment for real-world implementation.

VII. Conclusion

The STARGATE project is an undergraduate student research effort to assess the feasibility of the Corona Discharge Reaction as an alternative plasma production method in a Gridded Ion Thruster (GIT). The feasibility of the technology is suggested by the incidental occurrence of CDR in low-pressure spacecraft environments and the fact that both the hollow cathode of a conventional GIT and the corona discharge reaction produce ions through electron bombardment ionization and electron avalanche. Initial experimentations demonstrated the difference between positive and negative corona discharge reactions as applicable to the STARGATE system. Ongoing experimentation seeks to demonstrate the feasibility of producing positive corona discharge in a low-pressure to rarefied operating environment. Ongoing experiments will also gather data pertaining to plume plasma properties under different propellant volume flow rates and applied voltages. Additionally, the ongoing experiments will test the functionality and compatibility of the ion extraction systems with the CDR plasma production mechanism by gathering data on the ion beam current density.

Testing of Phase II STARGATE prototypes is currently underway. Future extensions of the project as part of EPC's mission include the building of our own Langmuir probe, the fabrication of an inverted pendulum thrust stand, and the development of a flow visualization system. Should the technology prove to be feasible, it may provide an alternative solution for sub-hectowatt thrusters used in small satellite propulsion applications.

Acknowledgments

The STARGATE project team would like to offer our acknowledgment and our sincerest gratitude to the University of Alabama in Huntsville College of Science, College of Engineering, Office of the Vice President for Research and Economic Development, Office of Technology Commercialization, as well as to Blue Origin, and NASA Marshall Space Flight Center for their ongoing support of the project. Special thanks go to Dr. Themistoklis Chronis of the UAH Physics Department for his ongoing advice, guidance, and assistance with the project.

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