IAC-24,C4,IP,14,x86797

STARGATE: An Undergraduate Experimental Electric Propulsion Student Research Project

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Abstract

This paper reports on the ongoing investigation regarding the feasibility of utilising the Corona Discharge Reaction as an alternative plasma production mechanism in a Gridded Ion Thruster. 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 investigating the feasibility of utilising the Corona Discharge Reaction for plasma production in the intended operating environment. The project has designed and fabricated an initial functional vacuum testing prototype and is pending test-firing.
Keywords: Electric Propulsion, Gridded Ion Thruster, Corona Discharge Reaction, Small Satellite, Undergraduate Research

Acronyms/Abbreviations
Corona Discharge Reaction (CDR)
Direct Current (DC)
Distance (d)
Gridded Ion Thruster (GIT)
High Voltage Power Supply (HVPS)
Specific Impulse (*Isp*)
Pascal (PA, a unit of pressure)
Power Processing Unit (PPU)
Resistor Capacitor (RC)
Standard Cubic Centimetres per Minute (sccm)
Volts (V)
Volume Flow Rate ($\dot{V}$)
Accelerator Grid Voltage (Vaccel)
Anode Voltage (VA node)
Cathode Voltage (Vcathode)
Screen Grid Voltage (Vscreen)

1. Introduction

STARGATE is an experimental electric propulsion undergraduate student research project at the University of Alabama in Huntsville (UAH) as part of the UAH Electric Propulsion Club. The goal of the project is to investigate the feasibility of utilising 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 research and development of electric propulsion systems and technology.

In order to prove the feasibility of the technology, the project seeks to eventually fabricate and test a final prototype that can meet or exceed current capability demands for small satellite propulsion systems on the market. In order to accomplish this, the STARGATE project develops hardware, software, and other products through rapid and iterative prototyping in order to fulfil the project's goal-based requirements. These requirements are to create a Gridded Ion Thruster utilising the CDR for plasma production, with a sub-hectowatt (<100W) total power consumption, capability of specific impulse ≥1500 seconds, and a total thrust of ≥1 mN (millinewton) [2].

To eventually produce a final prototype capable of meeting these requirements, several nonperformance prototypes will be produced to better help understand the system and technology. The initial concept feasibility prototype, "SG-1", was built in order to observe the behaviour and properties of the Corona Discharge Reaction within the system. Currently, the SG-2_1 prototype is being developed and is pending test-fire. It will serve as an initial functional vacuum testing prototype. 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.

2. Technology Introduction and Background

Gridded Ion Thrusters (GIT) are among the most proven and efficient electric propulsion systems. Adaptations and variations of the conventional GIT platform have begun to emerge in recent years that replace the hollow cathode by utilising alternative plasma production 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, electrons extracted from a hollow cathode are used 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).

2.1 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 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 such that inelastically colliding with a neutral atom ionizes the neutral, creating a positive ion and a secondary electron, in addition to the primary free 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.

2.2 Corona Discharge Reaction Overview

The Corona Discharge Reaction can occur in low-pressure conditions, as this has been observed in failure mode with regard to its effects on spacecraft. Most research surrounding the CDR in space-related environments and applications is often aimed at mitigation and prevention [5]. But because CDRs are possible and 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.

3. Initial Experimentation

3.1 Initial Concept Feasibility Prototype (SG-1)

In order to better understand the properties of the Corona Discharge Reaction, an initial prototype was devised to facilitate experimental testing. The prototype is referred to as the “SG-1” prototype. The SG-1 prototype allows for the demonstration, adaptive testing, and detailed observation of the CDR. The SG-1 prototype is a simplistic contraption consisting of 7 matching pairs of electrodes and utilising a single -8.5kV output High Voltage Power Supply (HVPS). It is tested in the atmosphere and utilises atmospheric air as 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. Utilising the SG-1 prototype, both the positive and negative corona discharge configurations were tested.

3.2 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 biassed positively functioning as the anode. In the positive corona discharge configuration, the tubes are charged negatively functioning as the cathode, and the pins are biassed positively functioning as the anode.

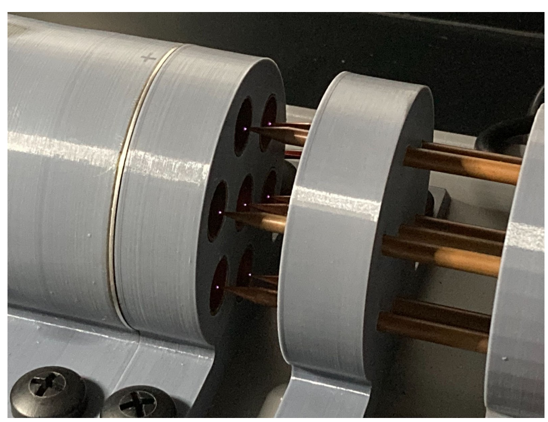

Figure 1. SG-1 test firing under a negative corona discharge configuration

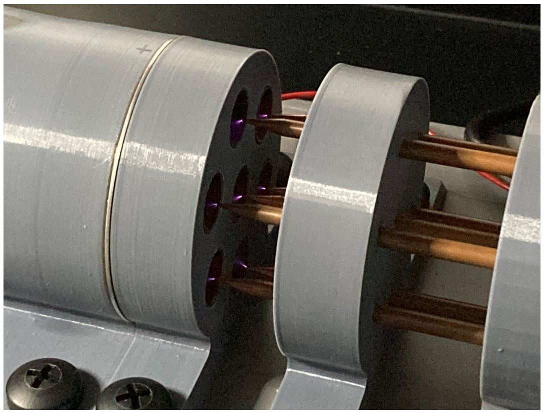

Figure 2. SG-1 test firing under a positive corona discharge configuration

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 (see Fig. 3). 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 exhaust (see Fig. 4).

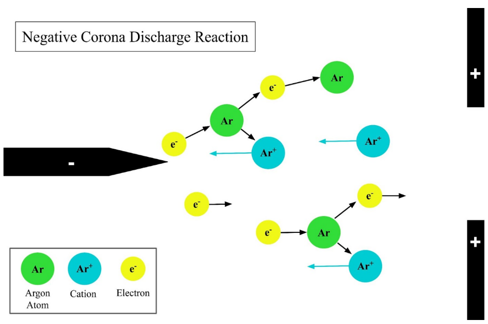

Figure 3. Negative Corona Discharge Reaction

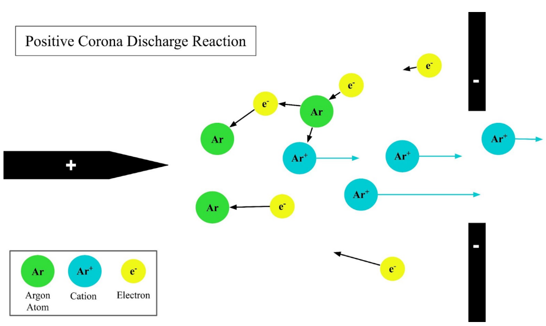

Figure 4. Positive Corona Discharge Reaction

In both configurations, the prototype is able to create thrust through ionic wind. The positive CDR configuration produces more intense electrical discharge compared to the negative CDR configuration (see Fig. 1 and 2). As a result, the positive corona discharge configuration also produced stronger ionic wind. It should be noted that although both configurations of the prototype are able to produce thrust, the thrust is produced in the atmosphere and through ionic wind. The thrust effect on the SG-1 prototype has no correlation to the performance capabilities of this technology as it is applied in its intended operating environment.

4. Ongoing Experimental Prototype (SG-2_1)

The STARGATE project is currently in Phase II. The goals of Phase II are primarily to fabricate prototypes, to gather experimental data, and to observe performance properties and the capabilities of the system. Phase II is not aimed at fulfilling any performance requirements. The first of many planned Phase II prototypes is an initial functional vacuum testing prototype called "SG-2_1". The SG-2_1 prototype serves to understand the behaviour 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.

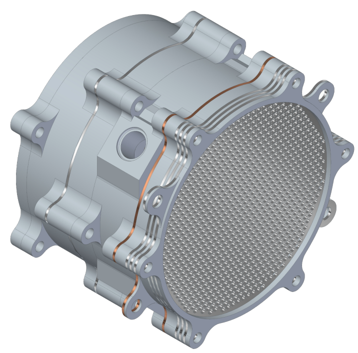

Figure 5. SG-2_1 Prototype V4.3 Isometric View

4.1. SG-2_1 Prototype System Overview

The SG-2_1 prototype utilises 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 (see Fig. 6 and 7). Just as on the SG-1 prototype, electrons flow from the cathode plate towards 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, electron collisions happen in the opposite direction of the thruster exhaust.

Cations produced by the ionization reactions are then drawn toward the cathode plate and are electrostatically extracted and accelerated by the ion extraction grids through the cathode plate apertures.

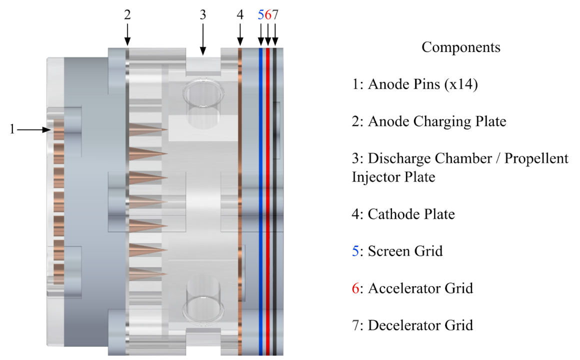

Figure 6. SG-2_1 Prototype Overview

4.2 Discharge Conditions

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

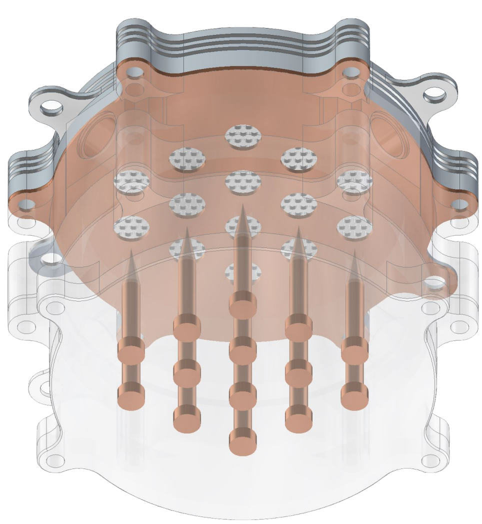

Figure 7. SG-2_1 Discharge View

4.3 Propellent Injection

The SG-2_1 prototype and all subsequent planned STARGATE project prototypes utilise argon gas as propellant, primarily due to the low cost and ease of handling, in addition to other common reasons noble gases are used as EP propellant. 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 requires only 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 (see 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 tubing and AN 4 fittings.

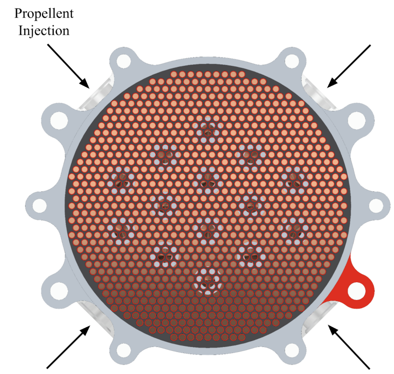

Figure 8. SG-2_1 Exhaust View

4.4 Power Processing Unit (PPU)

The SG-2_1 prototype utilises 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. HVPSs capable of different outputs 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. 12). The system is then further broken up into modular subsections, to allow the system to grow as project demands widen in scope.

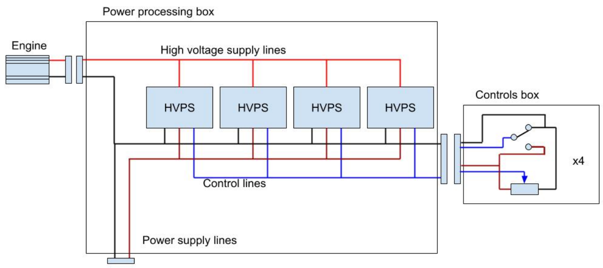

Figure 9. Simplified High Voltage PPU schematic

The basic layout of the PPU can be seen in Fig. 9. The SG-2_1 prototype utilises four variable output enclosed DC-DC converting HVPS made by Analog Technologies, 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 in the future, though 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 heatsinks.

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.

4.5 Ion Extraction System

The SG-2_1 prototype utilises a three-grid ion extraction system, consisting of a screen grid, accelerator grid, and a decelerator grid, an example of which can be seen in Fig. 10. 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 aluminium. The screen grid has 963 holes, which are 2.2 mm in diameter, and have a transparency of 72.8%. The accelerator grid has 963 holes of 1.6mm in 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.

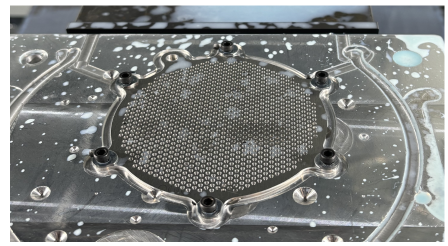

Figure 10. Accelerator Grid Machining

The screen grid is biassed to 1100V and can be biassed to up to 1500V. The accelerator grid is biassed to -250V and can be biassed up to -500 V. 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 biassed following a negative trend excluding the decelerator grid as shown in Fig. 11. This means each component towards the exhaust end of the thruster is biassed more negatively than the component before, which allows for the flow and acceleration of positive ions towards the exhaust end of the thruster.

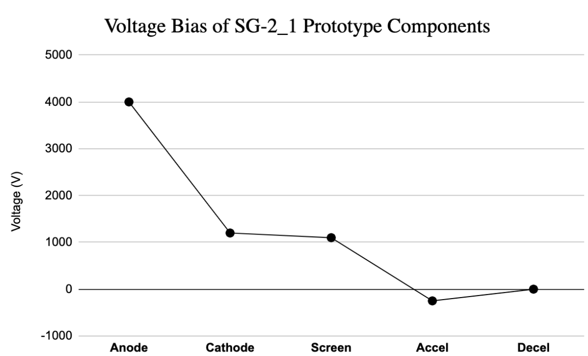

Figure 11. Voltage Bias of SG-2_1 Prototype Components

The designs of the ion extraction systems on the SG-2_1 thruster are far from optimised and are intended to accomplish the most basic functionalities of the system [9], however, the system also allows for a degree of flexibility and adjustability if needed.

5. SG-2_1 Prototype Experiment Plan

Test-firing on the SG-2_1 prototype is due to begin in October of 2024, starting with small-scale testing at the UAH Charger Advanced Propulsion and Power (CAPP) laboratory. Once all systems and components of the prototype are functionally validated, a comprehensive systems test firing may be conducted at the NASA Marshall Space Flight Center.

5.1 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 the prototype performance at different volume flow rates ($\dot{V}$) and voltage potential differences. The prototype will be tested at different $\dot{V}$ from 1-100 sccm, changing in 10 sccm increments. While the $\dot{V}$ is held constant at each interval, voltage potential difference between the anode and cathode 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.

5.2 Instrumentation

A Langmuir probe positioned inside the discharge chamber will be used to gather data pertaining to discharge plasma properties from which information on plasma potential, electron temperature, and electron density can be derived.

Ideally, sets of Langmuir probe data will be gathered at multiple points in the 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 localised nature of the CDR phenomenon. However, gathering Langmuir probe data at more than one location can vastly increase the logistical challenges with test-firing, 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 [10,11]. 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 beam current density while the ion extraction system is on should be vastly greater than when the ion extraction system is off.

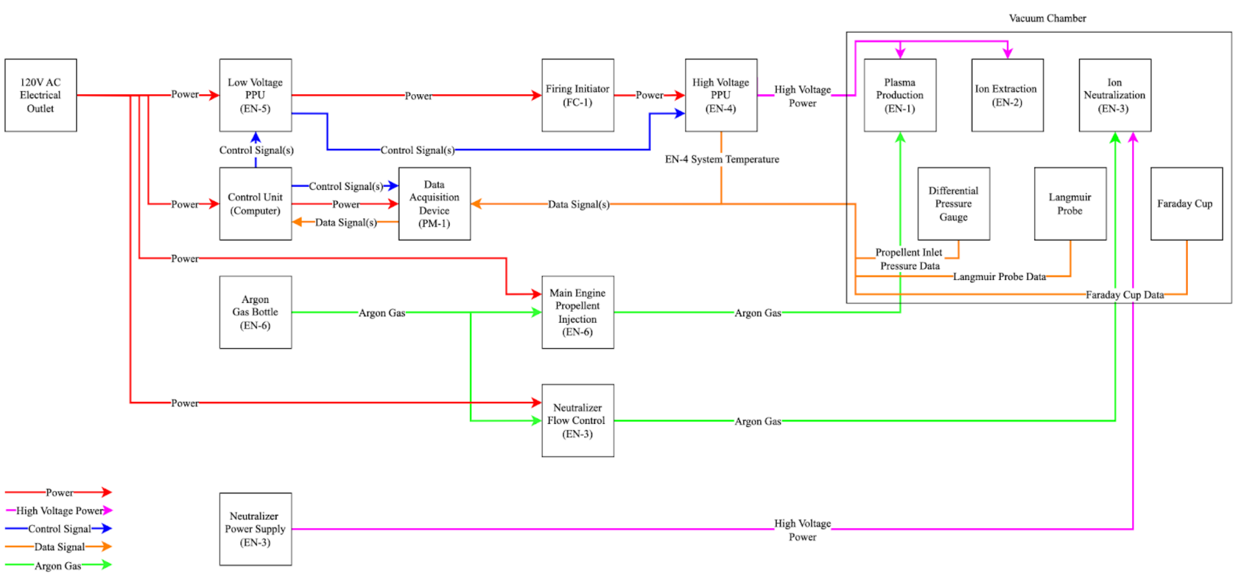

Figure 12. System Interaction Diagram for Test-firing

In addition to gathering data on plasma properties and beam current density, further Phase II prototype development will incorporate additional instrumentation to better understand the operating conditions and performance properties of the system to facilitate future prototype design and fabrication. This will include integrating a differential pressure sensor to measure inlet pressure at one of the propellant injector points as well as using both conventional and specialised cameras to photograph the thruster exhausts.

6. 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 nessecitates 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, excasbertaing 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.

Future extension of the STARGATE project within the UAH Electric Propulsion Club (EPC) will facilitate a series of sister projects for the development of our own experimental tools for electric propulsion systems testing. Among the projects proposed are to build a Langmuir probe, fabricate an inverted pendulum thrust stand, and develop a flow visualisation system. Building a Langumire probe will provide a critical tool and valuable learning experience, as well as vastly simplify future test-firing logistics by eliminating the need to borrow or purchase one. The Langmuir probes will be used for all future STARGATE project prototypes and other projects in the EPC, as well as other plasma physics research projects at UAH. The design for a NASA-Glenn style inverted-pendulum thrust stand is currently underway and will be fabricated in the near future for testing thrust capabilities of the STARGATE system and other EPC projects [12].

A flow visualisation system has been proposed for implementation on future STARGATE and EPC prototypes. Flow visualisation systems have been traditionally used in aerodynamic applications in order to observe phenomena such as boundary layers or shock waves in relatively high-speed flow. However, this technology can possibly be adapted for visualising EP exhaust properties, such as beamlets and cold flow. Whereas Schlieren optics was the initial consideration when looking into flow visualisation, shadowgraph optics may also be a feasible option [13]. The primary differences between both systems are complexity and scalability. Shadowgraph optics are currently considered favourable in both regards. Currently, both systems are being considered for possible implementation on future prototypes.

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 fulfil 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.

7. Conclusion

To date, the STARGATE project has proven as an invaluable resource for introducing and widening access to ion propulsion and plasma physics to undergraduate students. Additionally, CDR has been demonstrated as a potentially feasible ion production method through in-atmosphere prototypes, the occurrence of CDR in low-pressure spacecraft environments, and the fact that both the hollow cathode on a conventional GIT and the corona discharge reaction produce ions through electron bombardment ionization and electron avalanche.

Experiments have demonstrated the difference between positive and negative corona discharge reactions as applicable to the STARGATE system, with ongoing experiments seeking to demonstrate the feasibility of producing positive corona discharge in a low-pressure to rarefied gas discharge conditions, gather data pertaining to discharge plasma properties under different propellant volume flow rates and applied voltages, and 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. Multiple projects are also under way to support these activities, such as building a Langmuir probe, the fabrication of an inverted pendulum thrust stand, and the development of a flow visualisation system. Should the technology prove to be feasible, it may provide an alternative solution for sub-hectowatt thrusters used in small satellite propulsion applications.

Acknowledgements

The STARGATE project team and the UAH Electric Propulsion Club would like to acknowledge and offer 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, and the UAH Charger Advanced Propulsion and Power (CAPP) Laboratory; as well as the American Astronautical Society for their ongoing support.

Special thanks go to Dr. Themistoklis Chronis of the UAH Physics Department, Dr. Jason Cassibry, Dr. Gabriel Xu, and Jon Buckley of the UAH Mechanical and Aerospace Engineering Department for their ongoing advice, guidance, and support for the project.

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