STARGATE: An Undergraduate Experiment on the Feasibility of Direct-Current Electrical Discharge for Gridded Ion Thruster Applications

Claude Blue[1], Griffin Minter[2]
University of Alabama in Huntsville, Huntsville, Alabama, 35899, United States of America

Themistoklis Chronis[3]
University of Alabama in Huntsville, Huntsville, Alabama, 35899, United States of America

This paper reports on an ongoing study on the feasibility of utilising Corona Discharge and Visible Glow Discharge as alternative plasma production mechanisms in a Gridded Ion Thruster system. The STARGATE project has investigated and demonstrated the discharge properties of both negative and positive Corona and Visible Glow Discharges as they pertain to electric propulsion applications, tested initial prototypes, and is currently fabricating and preparing to test its first high-vacuum prototype.

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
PMD	=	Propellant Management Device
sccm	=	Standard Cubic Centimetres per Minute (unit of volume flow rate)
V	=	Volts (unit of electrical potential)
$\dot{V}$	=	Volume Flow Rate
VGDR	=	Visible Glow Discharge Reaction
V_B	=	Breakdown Voltage
$V_{cathode}$	=	Cathode Voltage
V_S	=	Sustaining Voltage
Vscreen	=	Screen Grid Voltage

I. Introduction

STARGATE is a proprietary, patent-pending, experimental gridded ion thruster concept developed by the STARGATE project team at the University of Alabama in Huntsville (UAH), as part of UAH's Electric Propulsion Club. The goal of the project is to investigate the feasibility of utilising the Corona Discharge Reaction (CDR) and

---

[1]Chancellor & Research Lead, UAH Electric Propulsion Club, AIAA Undergraduate Student Member

[2]STARGATE Project Permanent Team Member, AIAA Undergraduate Student Member

[3]Principal Investigator, Electric Propulsion Club, University of Alabama in Huntsville

Visible Glow Discharge Reaction (VGDR) as alternative methods of plasma production in a Gridded Ion Thruster (GIT).

II. Technology Introduction and Background

Gridded Ion Thrusters (GIT) are a family of electric propulsion systems that utilise gridded ion extraction and acceleration mechanisms, and have physically and functionally separated plasma production and ion extraction systems across multiple variants.[1] Plasma production systems included electron-emitting cathodes, induction-coupled plasma through radiofrequency ionisation and microwave ionisation systems.[2]

The STARGATE system is a plasma physics experiment that investigates the feasibility of direct current corona discharge (CDR) and visible glow discharge reaction (VGDR) as a new method of plasma production in a gridded ion thruster architecture.

A. Corona Discharge Reaction and Visible Glow Discharge Overview

CDR reactions have been observed before in spaceflight applications, though notoriously as a failure mode of improperly insulated high-voltage electrical systems, leading to electrical discharge within trapped pockets of gas and outgassing material, often causing catastrophic failure.[3]CDR and VGDR are phenomena that occur when a high voltage is applied between two electrodes, causing electrical breakdown and ionisation of the surrounding gas,[4,5] a neutral atom in the presence of a strong electric field is ionised by a primary trigger event such as a inelastic electron collision, which produces a positive ion and an electron. The positive ions are accelerated toward the negatively charged cathode, while the electrons are accelerated toward the positively charged anode. As the electrons accelerate, they gain sufficient kinetic energy to undergo further inelastic collisions with neutral atoms, causing further ionisation and generating cations and secondary electrons. This process produces an avalanche effect.

Corona discharge may occur in non-uniform fields at voltages below the Paschen breakdown voltage for the full electrode gap, whereas glow discharge corresponds to volume breakdown and self-sustained current across the gap. where secondary electrons from inelastic collisions are emitted but not in sufficient numbers to form a self-sustaining reaction across the electrode gap. Increasing the voltage across a CDR beyond the breakdown voltage produces enough secondary electron emission to "complete" the circuit, accompanied by a drop in apparent resistance across the discharge region. VGDR generates more strongly ionised plasmas than CDR and operates at higher currents with a lower sustaining voltage than the initial breakdown voltage.[6] Just as in electron bombardment ionisation, free electrons can repeat this inelastic-collision process, allowing for a self-sustaining electron avalanche effect.

CDR is most often associated with asymmetrical electrodes, such as pin-to-tube or pin-to-plate configurations, while VGDR is typically observed as a visible discharge between parallel plates. However, geometry alone does not determine whether the discharge is a CDR or VGDR; this is defined by the applied voltage and current. CDR can occur between parallel plates, though rarely, as it is most commonly found near sharp or irregular edges. Conversely, VGDR can be sustained with asymmetrical electrodes typically associated with CDR, as demonstrated in experiments discussed in later sections.

III. Concept Exploration

A. Comparison Between Negative and Positive Corona Discharge Reaction

In the negative CDR configuration, the pins are charged negatively, functioning as the cathode, and the plate is biased comparatively positively, functioning as the anode. In the positive CDR configuration, the plate is charged negatively, functioning as the cathode, and the pins are biased comparatively positively, functioning as the anode. See Figs. 1 and 2.

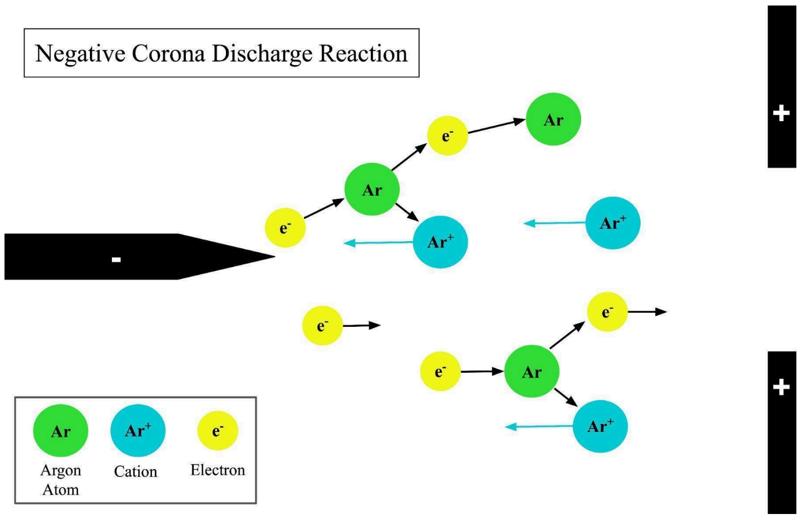

Figure 1. Negative Corona Discharge Reaction

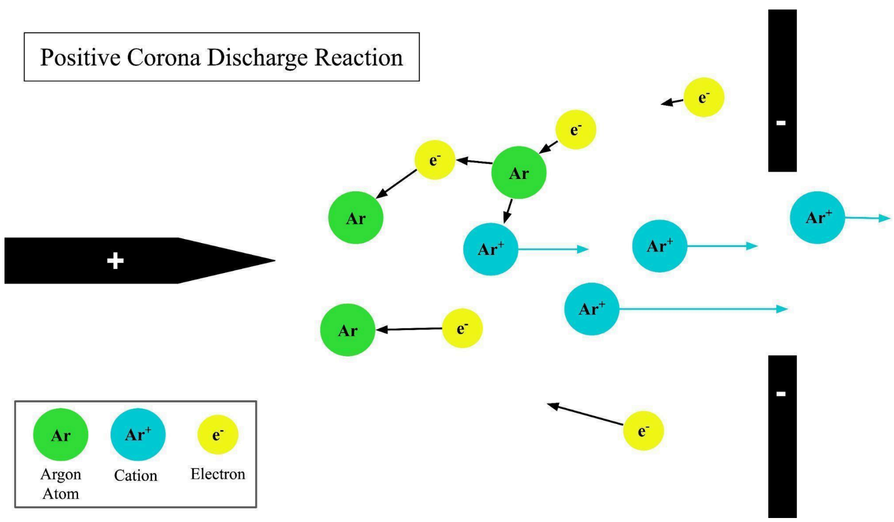

Figure 2. Positive Corona Discharge Reaction

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.

(a) Positive CDR Configuration. **(b) Negative CDR Configuration.**

Figure 3. Discharge at 5 Torr in the remaining air

An experiment is conducted in a low-vacuum testing chamber, at around 5 torr of air. In either corona discharge configuration, the field is strongest at the tip of the pin electrode where the discharge forms. As shown in Figure 3b, in the negative discharge configuration, with the pin charged as the cathode and the plate charged as the anode, the electrons flow from the pin to the plate, while the positive ions move in the opposite direction toward the pin, producing a discharge region that coats the tip of the pin in plasma. As shown in Figure 3a, in the positive discharge configuration, with the pin charged positively and the plate charged negatively, the electrons flow from the plate surface to the pin, while a stream of more concentrated plasma is formed from the pin tip to the cathode plate surface.

IV. Designing The Experiment

A. Discharge Condition

The discharge mechanism is one of the most critical phenomena to understand when assessing the feasibility of DC discharge as a plasma production mechanism for GIT systems. According to Paschen's law, the breakdown voltage V_B is a function of the product of pressure and discharge distance, $p*d$. Assuming a fixed distance d in our experimental setup, the pressure at which the discharge chamber stabilises directly determines V_B, thus affecting the dividing line between CDR and VGDR.

In vacuum conditions, the discharge-chamber pressure of a thruster is a function of propellant inlet mass flow and exit area (i.e., the area and transparency of the accelerator grid), together with the effective pumping speed of the system. As the STARGATE system does not have a conventional hollow cathode, the thruster's discharge-chamber pressure is directly tied to the main plenum mass-flow rate $\dot{m}$; a higher mass flow corresponds to a higher discharge-chamber pressure and higher-pressure discharge conditions.

As this type of thruster is unprecedented, there is no reliable estimate for the amount of thrust it can generate, nor the corresponding flow rate needed for a specific impulse suitable for EP applications. For the purpose of experimentation, it is assumed that the ideal flow rate is the minimum flow at which an ionisation process can be sustained and ions extracted and accelerated at a measurable beam current. The Omega Instruments FMA-A2403 electronic mass-flow controller used for STARGATE thruster testing can output a minimum of 0.1 sccm and a maximum of 100 sccm. The goal of the experiment is to find the minimum viable flow rate at which a CDR (and, where possible, a VGDR) is sustainable and where ion density and beam current can be detected downstream.

As seen in Fig. 4, the VGDR exhibits hysteresis: there exists a "sustaining voltage" V_S between the dark (Townsend) and glow regimes at which the discharge, once ignited, can be sustained at a voltage lower than the breakdown voltage V_B when transitioning between CDR and VGDR.

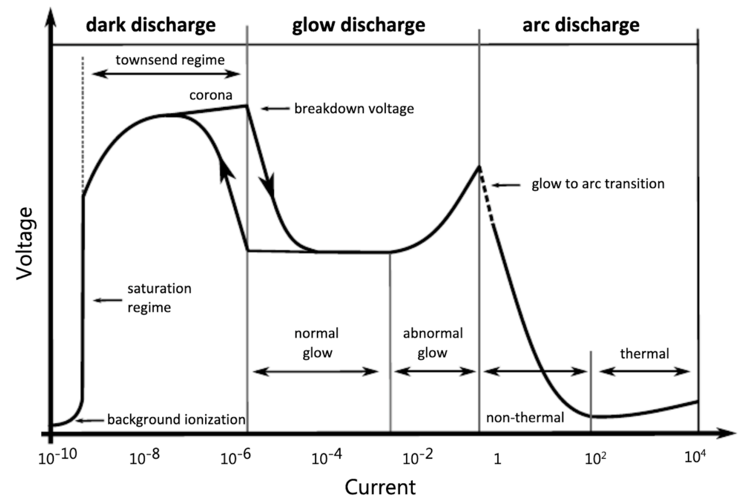

Figure 4. Discharge regime of DC Discharge[6]

B. Experimental Hypotheses

The STARGATE designs and testing campaign aims to answer four hypotheses:

Hypothesis 1: VGDR is required for sustained plasma ignition and operation of a GIT; a CDR does not produce sufficient plasma density or volume fill to yield a measurable, uniformly extractable beam current at the screen grid without transitioning to glow.

Hypothesis 2: At 100 sccm — where, depending on thruster geometry and grid transparency, the discharge-chamber pressure is of order 10^{-2} Torr— a VGDR can be initiated and sustained at applied voltages up to 2.8 kV with a discharge current of ~5 mA.

Hypothesis 3: As pressure is lowered at fixed discharge distance d and applied voltage V, and pd passes below the VGDR sustaining boundary, the discharge will revert to a corona discharge reaction localised near the high-field electrode, or extinguish.

Hypothesis 4: The ideal operating condition is one in which the flow rate is adjusted so that the pressure corresponds to the VGDR sustaining regime ($p*d \approx$const. for V_S); it is hypothesised that, for the same applied power, this yields higher ion density and measurable beam current than CDR operation (to be verified via discharge-loss and beam-current measurements).

VI. SG-3

Following initial experimentation with earlier experimental prototypes, as well as additional consideration for testing in high vacuum conditions, the SG-3 prototype was developed as the initial high vacuum testing article.

A. General Overview

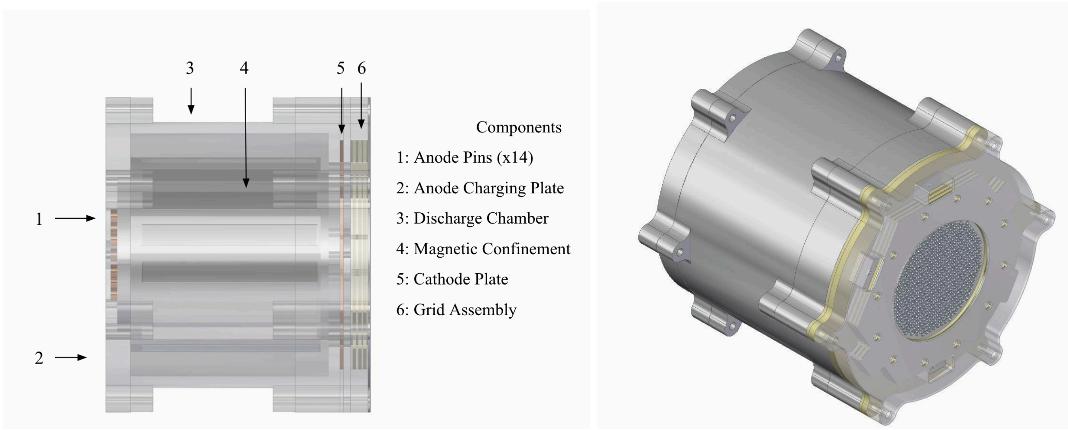

Figure 5. SG-3 Prototype Overview

The SG-3 Prototype is designed for testing in a high-vacuum environment; therefore, its components are fully ASTM-E595 Compliant. The shell of the thruster is machined from 6061 aluminium and has an inner diameter of 110 mm. The discharge chamber is composed of a COTS alumina ceramic tube, 10mm thick with a 60mm inner diameter, 100 mm long. The Anode pin array is housed inside the assembly, while the cathode plate is mounted to the grid structure. A line cusp (barrel) magnetic confinement assembly is on the outside of the discharge chamber, composed of 16 permanent magnets in a circular array, each spanning the entire length of the effective discharge area at 22.5° in alternating polarities. This is intended to provide magnetic confinement to the thruster, in an attempt to lengthen the effective electron path of travel to compensate for the long mean free path of the reaction environment. Such a configuration is necessary for sustained discharge in extremely rarefied discharge conditions.[1]

B. Ion Optics

The SG-3 ion extraction system employs a three-grid architecture, with apertures arranged in a hexagonal array, it is fabricated from 304 stainless steel primarily due to the low cost nature, and machined on an enclosed CNC machine, with drillbit replacement every 115 holes drilled to maintain a uniform size. A sacrificial aluminium plate is placed beneath the stainless steel stock used both as a fixture, and to reducing breakout burring and simplifying post-processing without distorting aperture geometry. After drilling, the plate is finished through an electropolishing process using an electrolyte solution consisting of 10% dionised water, 75% Phosphoric Acid (H_3PO_4)and 15% Sulphuric Acid (H_2SO_4). Then is further treated with an acid passivation process using a 33.5% Nitric Acid (HNO_3) solution.

The PPU allows for a range of adjustments for the bias applied to the ion extraction system. The screen grid can be biased up to 1500 V. The accelerator grid can be biased up to −500 V. The decelerator grid is grounded and serves as the common ground of the system, as well as the ground reference point for the neutraliser. The potential difference between the screen grid and the accelerator grid can be as high as 2000 V. This prototype is designed with a nominal operating condition in which the components are biased according to the following trend, as shown in Fig. 6: V_{Anode} at +4000 V, $V_{Cathode}$ at +1200 V, resulting in a discharge voltage of 2.8 kV across the electrodes. The screen grid V_{Screen} is biased slightly more negative than $V_{Cathode}$, at +1100 V, in order to establish a downstream electric field for positive ion extraction into the acceleration region. The accelerator grid V_{Accel} is biased to −250 V. Each component toward the exhaust end of the thruster, excluding the decelerator grid, is biased more negatively than the component immediately upstream. This establishes a monotonic decrease in electric potential in the downstream direction, allowing positive ions generated in the discharge region to drift toward progressively more negative electrodes and be accelerated toward the exhaust.

The SG-3 grids are hexagonal and feature locking tabs on four of the six sides. Three locking tabs serve purely as geometric alignment features to prevent grid rotation; the fourth doubles as a charging tab. This tabbed locking scheme, the hexagonal shape fitted in a hexagonal housing, and 12 alumina ceramic M4 fastening screws are used to secure the stack in place. The grid stack is housed within a MACOR housing, which fully encloses the rims of the grids. The grid spacers are also fabricated from MACOR, CNC cut from 1mm thick stock. The grids each have 551 apertures, arranged in a hexagonal array. The screen grid is 0.8mm thick with holes of 2.1mm diameter. The accelerator grid and decelerator grid have holes of 1.6mm and 2.0mm diameter, respectively.

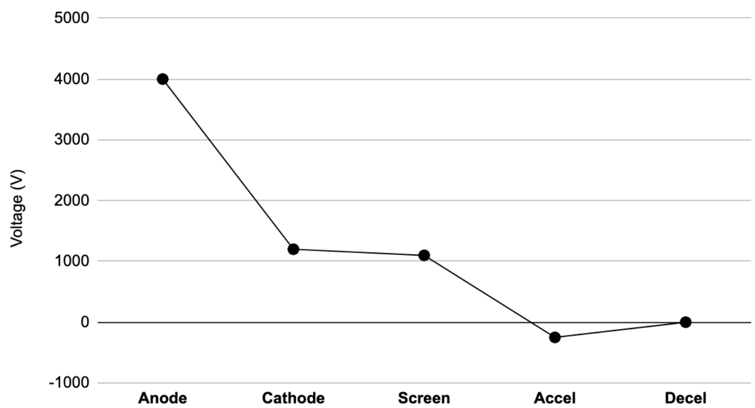

Figure 6. Voltage Bias of SG-3 Prototype Components

C. Neutraliser

A thermionic hot filament cathode neutralizer assembly, as shown in Figure 7, is developed for the SG-3 prototype. This particular neutraliser assembly design is inspired by a similar system deployed on the ThrustMe NPT30-I2 Iodine GIT.[7]

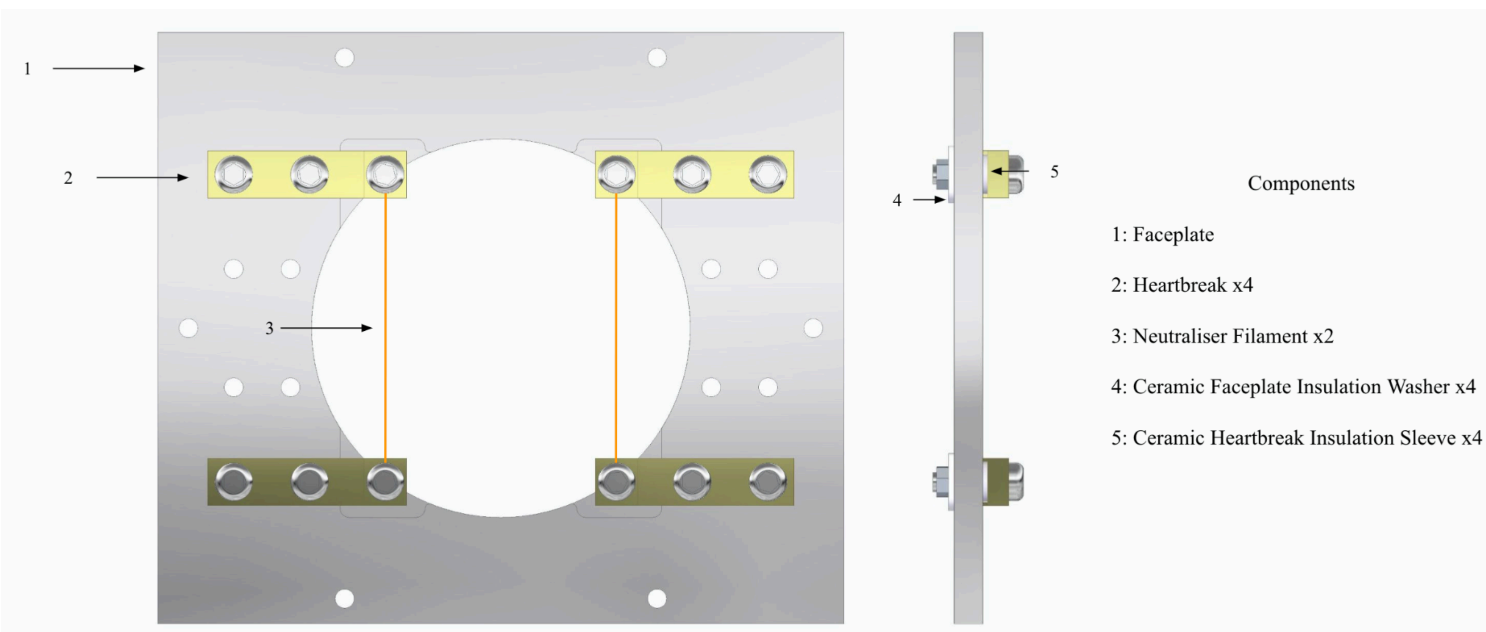

Figure 7. SG-3 Neutraliser Assembly

This SG-3 neutraliser assembly, informally referred to as the *"Lightbulb"* assembly, consists of two tungsten filaments mounted on either side of the neutraliser face plate. The filaments are supported by four brass heat breaks, which are secured to an aluminium mounting plate. Ceramic fittings are utilised at each interface to provide thermal insulation and to limit conductive heat transfer to the face plate.

When electrical current is applied to the tungsten wires, the filaments are heated to incandescence, causing thermionic emission of electrons, hence the designation *"lightbulb."* These emitted electrons are directed into the ion beam plume exiting the thruster, where they combine with the positive ions to neutralise the overall charge of the exhaust.

The *"Lightbulb"* design was selected for its simplicity in initial prototype testing. In contrast to hollow cathode neutralisers, it does not require a dedicated propellant feed or precise flow-matching with the main discharge plenum. While this approach is generally regarded as less than ideal for long-duration operation or adaptability, it is a sufficient system for early testing, and similar thermionic filament neutralisers have been successfully employed in flight systems. The neutraliser assembly is secured with six trimmed steel standoff nuts located at the edge of the thruster exhaust. By varying the length of the standoff nuts, the position of the filaments relative to the discharge plume can be adjusted.

D. Startup Sequence

The startup sequence of the SG-3 thruster begins with activation of the neutraliser assembly until a filament reaches visible incandescence, or equivalently, until the thermionic electron emission rate is sufficient to support discharge initiation. The neutraliser is electrically isolated and referenced to the decelerator grid, which serves as system ground.

Once the neutraliser is operating, the screen grid is biased positive relative to the decelerator grid in order to draw emitted electrons upstream through the grid assembly and into the discharge chamber. After sufficient electron injection is established, the discharge voltage between the anode and cathode is applied to initiate breakdown. Alternatively, a UV laser may be directed through the grid assembly to stimulate the initial ionisation event.

VII. SG-3 Prototype Experiment Plan

The SG-3 prototype will be tested once the test chamber is built and the vacuum gauge is calibrated. Initial testing will confirm a glow discharge and measure beam current downstream of the thruster in the intended operating condition of the prototype. Once the glow and beam current are confirmed, large-scale testing will be scheduled, involving plume diagnosis, full-spectrum Faraday probe data, and thrust measurement.

A. Planned Experiments

The prototype will be used to conduct a series of experiments during test firing in order to collect experimental data throughout the process. Two primary categories of data will be gathered: plasma properties and beam current density. CDR and VGDR reactions in low-pressure regimes are not well documented, particularly with regard to the potential for sustained reaction after initial ignition and breakdown as chamber pressure is gradually reduced.

The experimental procedure will assess prototype performance across a range of volume flow rates ($\dot{V}$) and voltage potential differences. The prototype will be tested at flow rates ranging from 0.1 to 100 sccm. From 1 to 5 sccm, the flow rate will be increased in 0.1 sccm increments, and from 10 to 100 sccm in 5 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 to 2800 V in 50 V increments.

Plasma properties will be measured at each flow rate and voltage interval to identify the "extinguishing flow rate," defined as the point at which chamber pressure becomes too low to sustain a discharge or produce any detectable beam current. Measurements of beam current density will only be collected once optimal operating conditions are established based on the initial plasma property characterisation experiments.

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 localised nature of the CDR phenomenon. Langmuir probe data will be used to calibrate optical measurements of the CDR plume density, utilising an Abel inversion to "unwrap" the axially symmetric plume in cylindrical coordinates, in a process similar to techniques used in diesel injection studies.[8] 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,[9,10,] greatly simplifying the testing setup. 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.

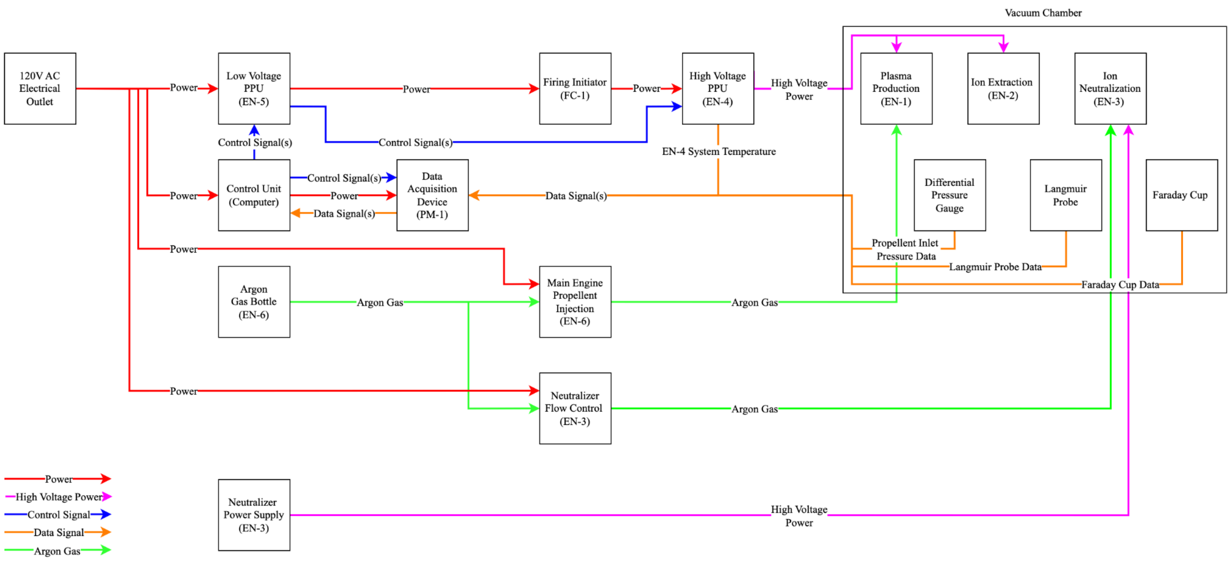

Figure 8. System Interaction Diagram for Test-firing

VIII. Future Development Goals

The SG-3-A prototype is currently under development. The original SG-3 prototype was designed within the manufacturing capabilities of the university machine shop rather than for optimised performance. Once credible data demonstrates that the technology is feasible, steps will be taken to improve the prototype, optimise the device for both thrust and specific impulse, and study the unique effects of grid erosion and lifetime limitations posed by high-voltage DC discharge.

The present ion grid was designed according to general design criteria and published guidelines[11], but due to practical limitations in materials and manufacturing, no attempt has yet been made to optimise the grid geometry. While the design is consistent with common ion optics practices, it is less than ideal in operation. In addition, the current grid design does not account for thermal expansion or buckling under compressive stress caused by constrained thermal expansion. PEEK is less than ideal for grid mounting hardware due to its properties as a plastic and its relatively low melting point relative to expected ion optics temperatures. While it is acceptable for early, low-power laboratory prototypes because of its machinability and availability, it becomes unsuitable for higher-power operation or extended runtime. Materials such as MACOR and other high-temperature, low-outgassing dielectric materials are currently being prototyped.

Knowledge gained from SG-3 thruster testing will allow us to determine the relationship between thruster performance and plume properties at varying flow rates and applied potentials to the plasma production mechanism. These results will provide clearer insight into the characteristics of the CDR/VGDR reaction and directly inform future design iterations.

IX. Conclusion

The STARGATE project is an undergraduate research effort to assess the feasibility of the Corona Discharge Reaction (CDR) and the Visible Glow Discharge Reaction (VGDR) as alternative plasma production methods in a Gridded Ion Thruster (GIT).

Initial experiments demonstrated the difference between positive and negative corona discharge reactions in the STARGATE system and showed plume formation. Previous experimental prototype indicated initial feasibility of the discharge geometry, as well as validating the PPU design. The SG-3 prototype is currently being constructed to assess the feasibility of producing VGDR at low to rarefied pressure and its suitability for electric propulsion applications, and to understand plume and beam-current profiles of such a system in relation to thruster performance and characteristics. The experimental programme defined herein, ignition at higher flow, step-down to identify extinction and reversion to CDR, determination of sustaining voltage at the lowest viable flow, plume characterisation, and thrust quantification, provides the measurements needed to evaluate the stated hypotheses.

There is currently no indication that this approach could or could not be feasible for spaceflight applications, as this approach has largely remained unattempted. However, it has already proven to be a valuable teaching experience and may prove very valuable as a future teaching kit for understanding the fundamentals of EP and GIT operation. Further work will complete the test matrix, report discharge loss and beam current across regimes, and, if warranted, explore operating-mode refinements to extend VGDR sustainment at lower pressure.

Acknowledgments

The STARGATE project team would like to offer our acknowledgement and sincerest gratitude to the Alabama Space Grant Consortium (ASGC), the University of Alabama in Huntsville College of Science Department of Physics and Astronomy, as well as the UAH Office of Technology Commercialization and the Office of the Vice President for Research and Development, for their continued support and funding of our ongoing research.

References

[1] D. M. Goebel, I. Katz, and I. H. Mikellides, *Fundamentals of Electric Propulsion,* 2nd ed., John Wiley & Sons, Hoboken,
New Jersey. 2024.

[2] R. E. Wirz, "Miniature Ion Thrusters: Review of Modern Technologies and Mission Capabilities," IEPC, 2015-275, 2015

[3] "Spacecraft High-Voltage Paschen and Corona Design Handbook," NASA, NASA-HDBK-4009, 2016

[4] M. E. Ellion, "A Study of Electrical Discharge in Low Pressure Air," NASA Jet Propulsion Laboratory, 32-678, 1965

[5] R. Benocci, M. Urbano, and L. Mauri, "Study of a positive corona discharge in argon at different pressures," European Physics Journal D., 37, 115–122, 2005

[6] M. Radmilovic-Radjenovic, B. Radjenovic, M. Klas, A. Bojarov, and S. Matejcik, "The Breakdown Mechanisms in Electrical Discharges: The Role of the Field Emission Effect in Direct Current Discharge in Microgaps," Acta Physica Slovaca vol. 63 No. 3, 105 – 205, 2013.

[7] D. Rafalskyi, J. M. Martínez, L. Habl, A. Aanesland, "Development and In-Flight Testing of an Iodine Ion Thruster," ThrustMe, Small Satellite Conference, SSC21-XI-04, 2021

[8] A. Parker, S. A. Reggeti, J. A. Bittle, and A. K. Agrawal, "Limitations of cetane number to predict transient combustion phenomena in high-pressure fuel sprays," Combustion and Flame 251, 2023.

[9] V. Hugonnaud, S. Mazouffre, D. Krejci, "Faraday cup sizing for electric propulsion ion beam study: Case of a field-emission-electric propulsion thruster," AIP Publishing, 92,084502, 2021

[10] D. L. Brown, M. L. Walker, J. Szabo, W. Huang, and J. E. Foster, "Recommended Practice for Use of Faraday Probes in Electric Propulsion Testing," Journal of Propulsion and Power, 582-613, 2017

[11] M. Sangregorio, K. Xie, N. Wang, N. Guo, and Z. Zhang, "Ion engine grids: Function, main parameters, issues, configurations, geometries, materials and fabrication methods," Chinese Journal of Aeronautics 1635-1649, 2018