Hall Effect Thruster Prototype

Eduardo Duran Jr., Holly Herman, Luke Randhawa, Madz Schooley & Raj Sreenivasan

San Jose State University, San Jose, CA, 95112, United States of America

The objective of our senior design project is to design a Hall-Effect Thruster. The thruster will be small and intended for use of future space projects. Instead of missions using thrusters that run on fossil fuels our team will provide a reliable and greener alternative. Over the course of one semester the thruster design has been completed with future testing plans testing at JPL's electric propulsion laboratory using Xenon.

Table of Contents

I. Executive Summary

This report will be focusing on the development of an electric propulsion system, specifically aiming to design and build a Hall-Effect Thruster (HET) prototype. This is a senior design project with a primary objective for the prototype to be able to achieve ignition and functionally run with the correct plume, providing thrust for those 5 minutes. The secondary mission objective is to reach at least 300 Volts and 500 Watts during independent tests, while allowing the thruster during these tests to eventually reach maximum power and electrical potential.

The Hall-effect thruster is relatively small and is only 3 inches in diameter and weighs 1247 grams. The thruster is made of several key components including the magnetic housing, the magnets, the anode, the cathode, and the channel. The magnetic housing utilized steel and directed the magnetic field. The magnets were samarium cobalt which created the entire magnetic field for the thruster. The anode was made of 304 stainless steel and acted as a gas distributor as well as a positive electrode. The cathode provided electrons to produce and sustain the plasma. The cathode was given to our team by our advisor and mentor Dr. Dan Goebel. Lastly, the channel was made of boron nitride and provides a pathway for the propellant and the electrons to interact. The channel was also given to our team by Dr. Goebel. The thruster utilized a magnetic field that ranged from 350 Gauss in between two magnets and 200 Gauss in between no magnets. Using gas feeds xenon was pumped into the discharge chamber. There was no software used for the Hall-effect thruster, but implementing it in future work is feasible. The initial simulations ran perfectly and the magnetic field performed as expected. The thruster was tested at NASA JPL. The first two initial tests allowed the thruster to reach ignition and run for more than five minutes, achieving the first primary mission objective, but the plume of the thruster was ineffective. The thruster created plasma, but did not have a specific direction. The third test ran smoother as the team made adjustments to the magnetic field and placements of the magnets. The fourth test was the longest, having the thruster fire for around 30 minutes with no issues. The last test allowed the team to test the limits of our thruster because it was clear that it would be stable for a prolonged amount of time. The entire project was funded by the team independently. Our team made a GoFundMe and shared it with people of interest. The fundraising allowed us to cover all costs of the prototype built along with sheltering during our stay in Los Angeles for testing at JPL. There is some leftover funds from the GoFundMe and our team will transfer it over to the next team willing to improve this project.

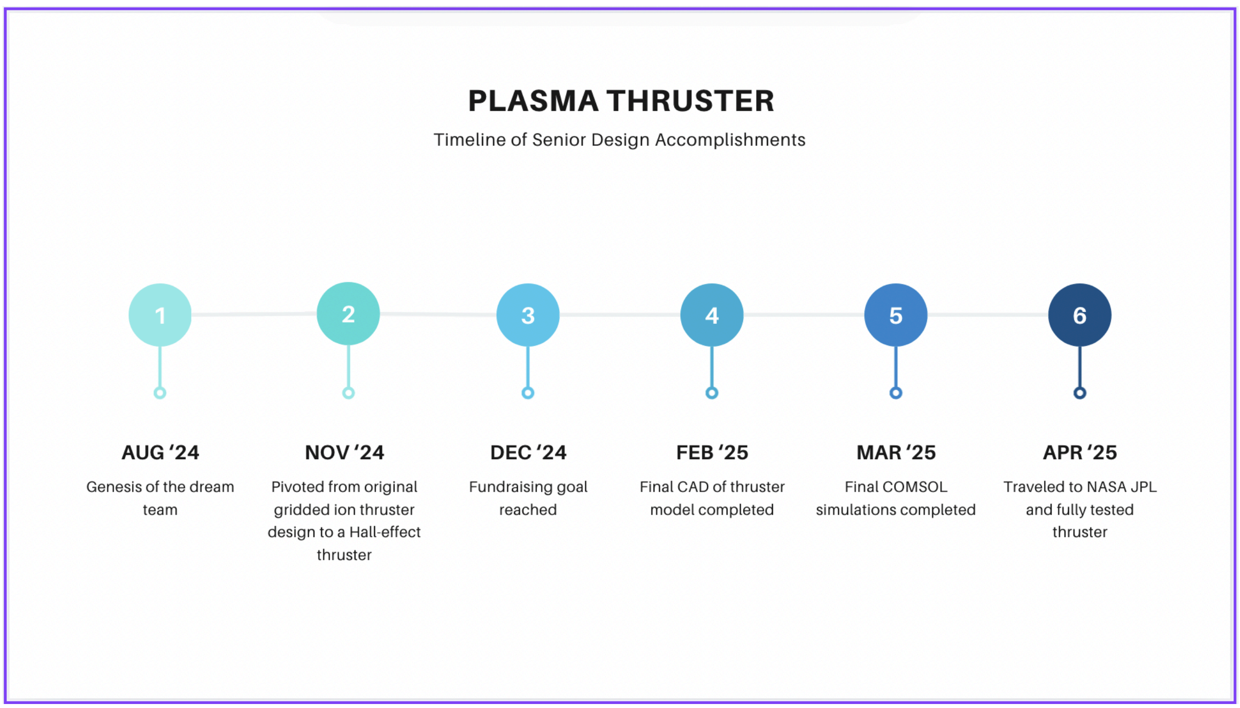

Fig 1. Timeline

The project in its entirety took place over the course of ten months. Beginning in August of 2024 on the first day of Fall semester, the five members of our team coalesced. Originally the goal was to create a different type of electric propulsion engine, a gridded ion thruster. The first few months were spent heavily reviewing literature on the subject of ion thrusters in general. As knowledge was gained on ion thrusters, it started to become clear that gridded ion thrusters were not the electric propulsion vessel that would be key to future space usage. Hall-effect thrusters were a more interesting, more feasible, and more heavily researched type of propulsion system, with some papers saying they would be integral to theoretical deep space missions. From November 2024 on, our team would be attempting to create a Hall-effect thruster instead of a gridded ion thruster. Several of the months of Fall semester were focused on fundraising. Specifically the team utilized a GoFundMe and social media to accomplish our fundraising goal; a goal that we were able to meet in December of 2024. As we transitioned into Spring semester, research as well as calculations continued to be worked on. During this time, the team used SolidWorks for CAD model and COMSOL for magnet field simulations. In February of 2025, the final design model of our thruster was finished. In March of 2025, all COMSOL simulations were run. With all preparatory requirements completed the team traveled to Southern California to NASA's Jet Propulsion Laboratory where 5 vacuum chamber tests were successfully completed.

The most notable achievement throughout this project was not only having our thruster fire correctly, but it also reaching 300 Volts and 500 Watts sustainably. The thruster performed incredibly well given that none of our team members have had any previous knowledge of electric propulsion systems. A couple of the challenges that our team was faced with was the channel not fitting inside of the magnetic housing and the thruster initially not performing correctly. The magnetic housing was too small to fit the channel because the tolerance was around a thousandth. Our team overcame this by baking the magnetic housing inside of the oven to expand the metal and allow it to fit the channel. The thruster did not perform well on the first test because the magnetic field was far too high, it was around 1000 Gauss. In order to overcome this our team decided to take out some magnets to lower the magnetic field to range from 200 to 350 Gauss. This allowed for the thruster to fire normally and have the correct plume afterwards.

II. Introduction

The Hall-effect thruster (HET), a form of electric space propulsion, stands as a remarkable technological innovation born in the Soviet Union during the Cold War. HETs are a type of ion propulsion device in which a stream of ions is accelerated by an electric field, with electrons trapped in a magnetic field to create a Hall current that maintains the propellant's discharge. This Hall-effect for which the thruster is named was discovered by Edwin Hall in 1879. An ion thruster utilizing this concept was first experimented with in the late 1950s and early 1960s and was pursued in parallel by American and Soviet engineers. The initial American designs suffered from efficiency problems, and by about 1970 the United States largely abandoned Hall thrusters in favor of more conventional gridded ion thrusters. However, in the 1990s Americans gained access to the Soviet's research, and their own development of HETs began. Today HETs are mainly used for satellite station-keeping, orbital inserting, and deorbiting. Station-keeping being the collective maneuvers used to keep a satellite a fixed distance away from another body, orbital insertion being maneuvers to put a body into orbit around a body, and deorbiting being maneuvers to remove a body from orbit.

The purpose of the project is to design a HET with the ultimate goal of integrating it into a cubesat. In order to achieve this goal, a prototype must be designed. Developing a prototype is a multipurpose endeavor. The design team had no previous experience at the start of the project and thus, designing a prototype served as a learning experience. It also served as hands-on experience to see how a HET's design can be improved. The prototype was developed with the primary goal of being able to reliably reach ignition. The secondary goal was stable, sustained ignition. It also had several constraints. One of the primary constraints of any student led project is the monetary budget. Testing the thruster also carried an additional constraint, being that the prototype had to be tested in a high temperature vacuum chamber (HTVC). The facility constraint was solved by gaining access to JPL's chambers and test equipment. Furthermore, the prototype also had design constraints that are typical of a HET. The primary of these constraints being that all the components needed to withstand high temperatures. There were additional constraints carried by the individual design needs of the components.

The prototype was designed in SOLIDWORKS, simulations were made using COMSOL, and the prototype was machined by the central shops at San Jose State University. The prototype was largely custom made, with only the permanent magnets, shaft collars, and ceramic shoulder washers being off the shelf components. The HET prototype had 2 major subcomponents, the magnetic circuit and the discharge channel. The magnetic circuit is the most critical component of a HET. The magnetic circuit consists of a magnetic housing and a set of permanent magnets. The circuit is meant to create a Hall current and form the thruster plume. If the magnetic field generated by the magnetic circuit is too high, it will magnetically shield the entire discharge chamber, which will prevent the electrons from an externally mounted cathode from striking the bottom of the discharge channel. If there are problems igniting, it typically lies with the design of the magnetic circuit. The discharge channel consists of an insulating channel wall, an anode, and a cathode. The channel wall acts as both a thermal and electrical insulator. It separates the plasma from the magnetic circuit. The anode acts as both the source of the accelerating electric field and a gas distributor. The cathode serves as the ignition source. It provides electrons to ionize the neutral propellant into plasma. It should be acknowledged that there are other methods to ignite a HET, such as using RF waves to ionize the propellant. While there are many variations of HETs, this HET was designed to be a 500W class thruster and designed to be able to withstand temperatures of 300 ℃.

The roles and responsibilities of the team are as follows, Eduardo Duran was the design engineer, responsible for testing, research, and design. Holly Herman was the team lead, responsible for mechanical design. Luke Randawa's was the simulation lead, responsible for research, software development, and simulations. Madz Schooley was the test engineer, responsible for testing and mechanical design. Raj Sreenivasan was the systems engineer, responsible for fundraising and system design.

III. Mission Objectives and Requirements

A. Mission Objectives

a. Primary

The primary mission objective for this project is to develop a working Hall-effect thruster for a CubeSat-class satellite that can fire for at least five minutes. The Hall-effect thruster's magnetic housing must be made of 1018 steel, the channel must be made of boron nitride, the anode must be 304 stainless steel, and the magnets must be samarium cobalt. After assembly the thruster must be able to run for at least five minutes without any interruptions and with the correct plume. The plume of the thruster must allow for the ionized gas to expand correctly in a cone shape, which will improve the specific thrust.

b. Secondary

The secondary mission objective for this project is to fire the Hall-effect thruster while reaching 300 Volts or higher and 500 Watts independently. The thruster must achieve ignition and remain stable throughout the 300 second test. The secondary mission objective limit tests the Hall-effect thruster and determines how much power and electric potential it has.

B. Mission Requirements

a. Functional

Create a functional HET which can achieve ignition and be able to be reignited to ensure the thruster can fire multiple times for at least two different power consumption trials. The thruster must be able to ionize xenon gas to be accelerated against. The thruster must confine the plasma and electron cloud into the channel to operate as a hall effect thruster.

b. Performance

The thruster must produce 30mN of thrust with a continuous burn time of 300 seconds. This sustained ignition must consume 500W of power throughout the entire duration of the burn in two different configurations. The first configuration is with 300V applied on the anode with a current draw of 1.66A to reach a total of 500W. The second configuration is with 250V applied on the anode with a current draw of 2A and again a total power consumption of 500W.

C. Constraints

a. Hypothetical launch interface, deployment, orbital parameters

We are constrained by the typical cube-sat deployment bus interface which would be deployed at a typical LEO parking orbit. The launch interface would be a typical cube-sat bus from a Falcon 9 launch vehicle. This cube-sat bus would be deployed from the Falcon 9 upper stage once it reaches a LEO parking orbit. The thruster's cube-sat would then be deployed from the bus at the appropriate time. The orbital parameters of the LEO parking orbit can be altered due to the thruster's inherent ability to change its own orbital parameters.

b. Regulatory

The only regulatory entities we must comply with are the FAA, SJSU safety, and JPL. We were constrained to stay within each of these regulatory agencies to ensure we would be allowed to design, build and test our thruster. The FAA regulates what we can send into space and gives us constraints on the lifestyle of our project. SJSU safety constrained us to stay within a safe working environment to ensure the safety of all the members involved in the project. JPL constrained us to be within the regulations and procedures they have for anyone to use their facilities and parts.

c. Budgetary and manpower limits

The budgetary constraint we have is that we must stay under the maximum finding we achieved. We were able to fundraise $2095.00. This allowed us to spend $1819.29 on all expenses accrued throughout the course of the project and stay within the budgetary constraints imposed by the success of our fundraising campaign. The manpower constraints we experienced were due to the maximum limit of the number of people within our senior project group. This ment we were limited to a max of five people with the maximum amount of time we could spend capped by the time limits of the class. This in total meant we had about ten months with five people maximum for manpower on our project.

d. Thermal, aero, loads, dynamics

The thermal constraints expected for us to experience are up to 500K from the plasma temperature within the channel. The aerodynamic loads we expect to experience are what would be expected during deorbiting, however we do not need to worry about these loads due to that portion of the lifestyle starting after our thruster will reach its end of life. Vibrational loads experienced will be due to the vibrations of the rocket getting our thruster to orbit. There are no dynamical constraints as our system is static and will not move in relation to anything on the spacecraft. Radiation constraints are significantly higher than the typical in space radiation due to our cathode producing a constant stream of high energy electrons. This however will only be an issue during firing of the thruster and the thruster is designed to withstand these loads for the duration of its lifecycle.

IV. Concept of Operations

A. Hypothetical scenarios for launch and deployment phase

Hall thrusters are mounted in satellites for station keeping and orbiting maneuvers. It is part of a larger system. A commercial satellite, from development to deployment, will take approximately 2-3 years to complete. The satellite will then be loaded onto a launch vehicle and then it will reach its insertion orbit. Once the satellite is deployed, the onboard propulsion system takes over and takes the satellite to its parking orbit. The onboard propulsion system would be an electric based propulsion system, like a hall thruster. The primary reason for choosing an electric propulsion system is because of their high ISP values (> 1000s). With a high ISP propulsion system, more mass can be distributed to other subsystems.The thruster would periodically fire in order to maintain its orbit. At the end of the satellite's life, the propulsion system would then be used to de-orbit the satellite.

B. Nominal operations

There are multiple nominal operation phases that the HET should endure, those being pre start up procedures with the objective of ensuring all systems are safe and within operational limits before ignition. This includes making sure the propellant system is pressurized to nominal xenon pressure, Power Processing Unit (PPU) performs self-checks and thermal sensors and electrical connections are verified. The next phase would be the cathode heater warm-up with the objective to prepare the cathode for plasma ignition. This includes heater voltage is applied to the cathode to reach thermionic emission temperature, duration: 1–3 minutes depending on cathode design and heater voltage and current monitored for anomalies. The third phase is the ignition sequence with the objective of initiating stable plasma discharge and neutralizing the beam. Including Xenon gas flow starts to anode and cathode, Anode voltage (typically 200–300 V) is ramped up; plasma discharge is established, cathode emits electrons to neutralize ion beams and the beam current and voltage stabilize at target levels. The fourth stage is a steady-state operation with the objective to maintain desired thrust level and collect performance data. This includes the thruster operating at steady discharge voltage and mass flow rate, adjusting the magnetic field to optimize thrust efficiency and test durations vary from minutes (performance mapping) to hours (endurance/stability tests). Last phase is the shutdown and post operation cooldown inspection, with the objective of safely shutting down all subsystems and ensuring the system has cooled and reviewed for anomalies. This includes anode voltage is ramped down to 0, Xenon flow is stopped, cathode heater is turned off last, passive cooldown in thermal vacuum chamber or ambient, inspect thruster for erosion, discoloration, or contamination and analyze performance metrics vs. expectations.

V. System Architecture Overview

A. Block Diagrams

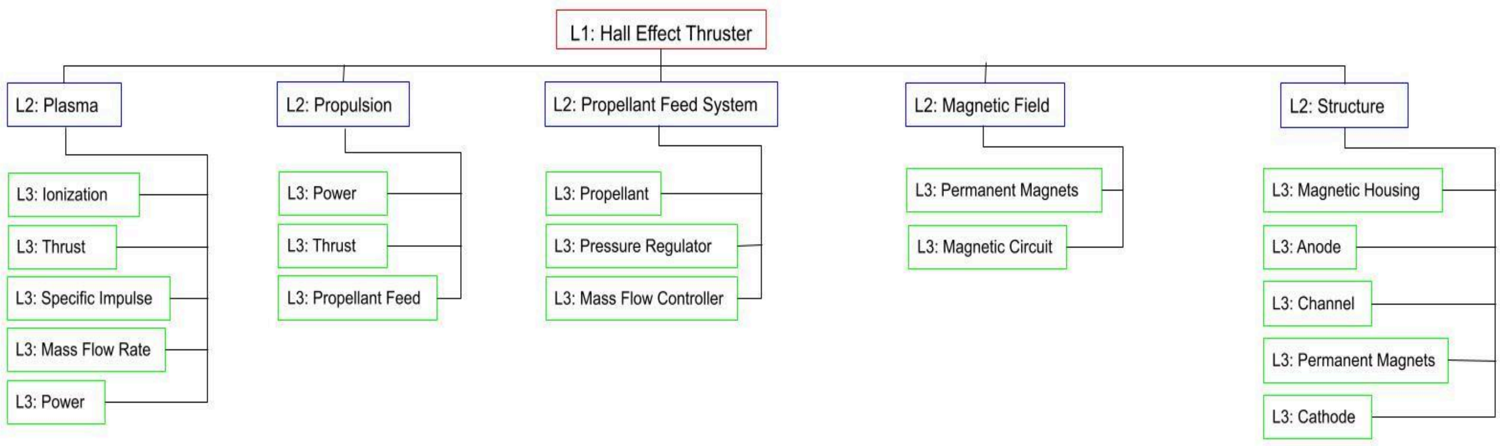

Fig 2. System Architecture Breakdown

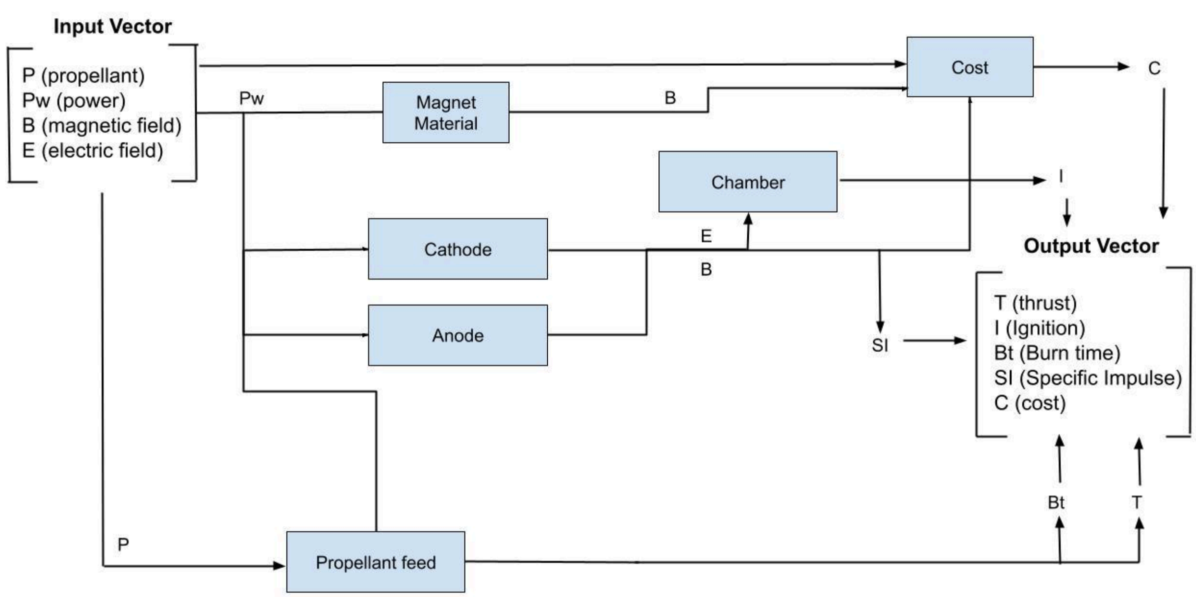

Fig 3. Block Diagram

B. Description

This block diagram represents a systems architecture breakdown tree of the different systems that makeup our Hall Effect Thruster. There are 5 major components that are known as L2 in this case, those being Plasma, Propulsion, Propellant Feed System, Magnetic Field and Structure. For each of these systems, there are subsystems that make them up that are known as L3 in this case. For Plasma it is made up of Ionization, thrust, specific impulse, mass flow rate and power. Propulsion is made up of power, thrust and propellant feed. The Propellant Feed System is made up of propellant, pressure regulator and mass flow controllers. The Magnetic field is made up of permanent magnets and the magnetic circuit. Lastly the Structure is made up of the magnetic housing, anode, channel, permanent magnets and the cathode.

C. Design Philosophy

The thruster itself is made to be modular, in order to be able to accommodate design changes and facility use. However, all of the parts were custom designed for our prototype specifically. This was due to scaling on our end with the vacuum chamber as well as making a custom design for the magnetic housing to accommodate our magnetic circuit, channel and anode. The magnets were COTS since we received them from Dan Goebel, however that was the only part of our prototype that wasn't custom.

D. Trade Study

The design team evaluated three key decision areas before freezing the Hall-effect thruster baseline. For each topic we identified the principal figures-of-merit (FOMs), screened realistic options, and ranked them using a 1-to-5 scale (5 = best) for every FOM. Scores are relative within each study—they are qualitative, not absolute performance numbers—and are drawn from vendor data sheets, published HET literature, and our own prototype‑specific constraints (≤ 500 W input power, CubeSat envelope, <$2 k cash budget).

Anode Design Study

Candidate geometry	Uniform gas distribution	Manufacturability	Power handling	Mass / volume	Heritage	Overall notes
Azimuthal ring with multi-hole manifold (baseline)	5 – 32 small 0.10-in holes yield <5 % flow non-uniformity	4 – single CNC turn + drilled pattern	4 – ring acts as heat sink	5 – widely used (Busek, SPT)	5 – widely used (Busek, SPT)	Best balance; easy to tune hole count / φ.
Single-slot "showerhead" plate	4	3 – shallow plunge cut; stress at slot ends	3 – plate heats at slot edges	4 – no feed stub	3	Simpler but less plume symmetry; risk of ion back-sputter on slot walls.
Porous sintered metal ring (diffusive)	**5**	2 – custom pressing & sinter	**5** – uniform heat dissipation	3	2	Superb uniformity; cost/time prohibitive for student build.
Swirl-inducing helical	3	2 – EDM or 5-axis	4	3	2	Promotes ionisation

inlet		required				path length; complexity outweighs gains at 500 W scale.

Table 1. Anode design study

Channel Material Study

Material	Dielectric strength	Erosion rate vs. Xe plasma	Thermal conductivity	Machinability & cost	Mass density	Heritage / TRL
Boron nitride (BN)	**5**	**5** – <0.5 µm/hr at 300 V	2 – low (20–30 W m^{-1} K^{-1}) keeps magnets cool	3 – diamond tooling, ~$1 k blank	3	Flight standard (SPT-100, BHT-200)
Aluminum-oxide (Al_2O_3)	4	3 – sputter ~2× BN	3	**4** – readily machined, low cost	4	Used in early US TALs; still common in lab thrusters
Hexagonal boron-nitride/SiO_2 composite (BN-SiO_2)	5	5 – similar to pure BN	3	2 – custom hot-press billet	3	High-end commercial units (e.g. SPT-140)
Silicon nitride (Si_3N_4)	4	4	**5** – 30–40 W m^{-1} K^{-1}	2 – hard grinding, costly	4	Limited HET testing; good for >5 kW
Graphite (isotropic)	2 – conductive	2 – high sputter	5	5	2	Attractive for TALs but short life & electrically conductive —poor for HET

Table 2. Channel material design study

Permanent Magnets vs. Electro-Magnets Study

Attribute / FOM	SmCo / NdFeB permanent magnets	Water- or air-cooled electro-magnet coils
Peak field at 4 mm gap	200–400 G (with steel return)	200–800 G (tunable)
Power draw	0 W	10–50 W for 500 G on 3-cm dia. yoke
Mass	Low – magnets only	Higher – copper coils + core + driver
Thermal load on channel	Lower (no I^2R) but Curie risk if >550 °C	Coil heat can raise channel temp; requires cooling
Field tunability in situ	Fixed once stacked (minor shim only)	High – adjust current from 0–100 %
Complexity / cost	Simple; <$120 for 100 SmCo bars	Driver electronics + wound coils ($200-$400)
Failure modes	Demagnetisation at high T; mechanical drop	Coil burnout, driver failure, EMI, vacuum insulation
CubeSat power budget impact	**None**	Significant for low-power bus
Flight heritage	SPT-100, BHT series, HEMPT	TALs and some high-power HETs (NASA-300M)

Table 3. Magnet design study

VI. Subsystem Design

A. Structures and Mechanisms

a. Material considerations

The next stage in narrowing the design space came from choosing the material for each of the components, depending upon the function of each component. Some further considerations when choosing our materials were budget and accessibility. The budget was $2,000 and as a student team, materials had to be commercially available.

b. Anode Design

The anode has two primary functions. The first is to hold an electric potential. The second is to distribute and disperse the propellant. As a requirement, the anode must be able to withstand a high temperature environment of +300℃. These requirements narrowed down the material choice to a common metal alloy. Upon investigating several options, it was found that a high temperature steel alloy would suit the needs of the design. A 304 stainless steel alloy was chosen due to its high temperature tolerance, for a relatively common alloy. When designing the geometry of the anode, inspiration was taken from other models. The anode acts as a gas distributor, as such, there were two main geometries that were designed. The first geometry is a distribution ring where the gas is allowed to flow and mix as it comes in from the propellant tanks.The next geometry that was designed were the ejection holes. The number, size, and orientation of the holes all had different effects on the thruster. 32 holes of size 0.10 inches in diameter were chosen. The smaller, more numerous holes allow for a more uniform gas distribution, which in turn leads to more uniform ionization. Lastly, the holes were oriented azimuthally to increase the path length the propellant travels. This would have the effect of increasing the ionization rate of the propellant.

c. Cathode

A cathode was chosen as the source of ignition because of its simplicity compared to RF wave generation.The cathode emits electrons to neutralize the ion beam and supplies electrons for ionizing the xenon. There are many choices that could be made for a cathode. For example, a simple heated tungsten filament could have worked. The primary difference between a heated cathode and a heaterless cathode is that a heated cathode uses thermionic emission to eject electrons. Whereas a heaterless cathode uses other methods such as electron bombardment from plasma to emit electrons. Off the shelf cathodes are typically prohibitively expensive for student led design teams. In the case of this project, a cathode was borrowed from the MaSmi thruster [6]. The MaSmi cathode is heaterless and uses Lanthanum Hexaboride as an electron emitter.

d. Discharge Channel

The discharge channel contains the electron cloud and xenon plasma. This insulates the magnets from the electrons and plasma in the channel which could severely damage them and cause them to lose their magnetism. Because of these requirements the channel material must have a high work function so that it will not rapidly degrade while the thruster is turned on. One of the best materials for this would be Boron Nitride which is what we decided to use because of its high work function. Another key aspect required for this material is a low thermal conductivity so that the magnets do not heat up to the temperature of the plasma contained within the channel. Boron Nitride also has an extremely low thermal conductivity, so it is also very well suited to this requirement.

e. Magnetic Circuit

The magnetic circuit must control the magnetic flux and be the base for everything to clamp onto. To control the magnetic flux created by the magnets to create a uniform magnetic field near the top of the discharge channel. To control the shape of the magnetic field a paramagnetic material, such as wrought iron, must be used. In order to be a base for everything to clamp onto, the material must be structurally sound so that it will not break under the loads required to clamp everything together. A large enough wrought iron base satisfies these requirements and will also allow for the manipulation of the magnetic flux needed to get the ideal magnetic field shape.

B. Propulsion

a. Power

In order to accelerate the plasma, we must apply a voltage to the anode and cathode. The voltage applied to the anode will in turn create a current through the plasma and draw power to generate thrust. The anode will be supplied with 300V and the current will be dependent upon the mass flow rate of the xenon gas. The cathode will be supplied with a voltage to initiate the electron generation then reduced to maintain a constant supply of electrons. This will also draw a current due to the xenon flowing through it and thus draw power.

b. **Thrust**

The thruster must act as a hall effect thruster and be current controlled by the mass flow rate. To operate as a hall effect thruster, the thruster must contain the electron cloud and xenon plasma in the channel before being accelerated against. In order to be current controlled by the mass flow rate we need to have a constant voltage applied to the anode and the current must then be able to be changed at a linear rate by adjusting the mass flow rate of xenon through the anode feed lines.

c. **Propellant Feed**

In order for the cathode to supply electrons and the plasma to be created, the propellant, xenon, must be supplied to both the cathode and anode. The propellant must be able to be supplied at a steady rate for the cathode and be able to be reduced once the cathode has been turned on. The anode must also be supplied with both a steady and variable flow of xenon gas.

C. Plasma

a. **Ionization**

In order to create a plasma, the xenon gas propellant must be ionized by an electron cloud. The xenon gas moves through the electron cloud at the top of the discharge channel which allows for a high chance of ionization to occur. The electron cloud is confined into the channel by the magnetic circuit. The electrons in the electron cloud are created by the cathode.

b. **Thrust**

The thruster must act as a hall effect thruster and be current controlled by the mass flow rate. To operate as a hall effect thruster, the thruster must contain the electron cloud and xenon plasma in the channel before being accelerated against. In order to be current controlled by the mass flow rate we need to have a constant voltage applied to the anode and the current must then be able to be changed at a linear rate by adjusting the mass flow rate of xenon through the anode feed lines.

c. **Specific Impulse**

The specific impulse of the thruster must lie within the range of 1000-2000 seconds. In order to accomplish this a hall effect thruster design is used. Hall effect thrusters have extremely high values for specific impulse due to the way the plasma is accelerated.

d. **Mass Flow Rate**

In order for the cathode to supply electrons and the plasma to be created, the propellant, xenon, must be supplied to both the cathode and anode. The propellant must be able to be supplied at a steady rate for the cathode and be able to be reduced once the cathode has been turned on. The anode must also be supplied with both a steady and variable flow of xenon gas.

e. **Power**

In order to accelerate the plasma, we must apply a voltage to the anode and cathode. The voltage applied to the anode will in turn create a current through the plasma and draw power to generate thrust. The anode will be supplied with 300V and the current will be dependent upon the mass flow rate of the xenon gas. The cathode will be supplied with a voltage to initiate the electron generation then reduced to maintain a constant supply of electrons. This will also draw a current due to the xenon flowing through it and thus draw power.

VII. Systems Engineering and Integration

A. Requirement Traceability

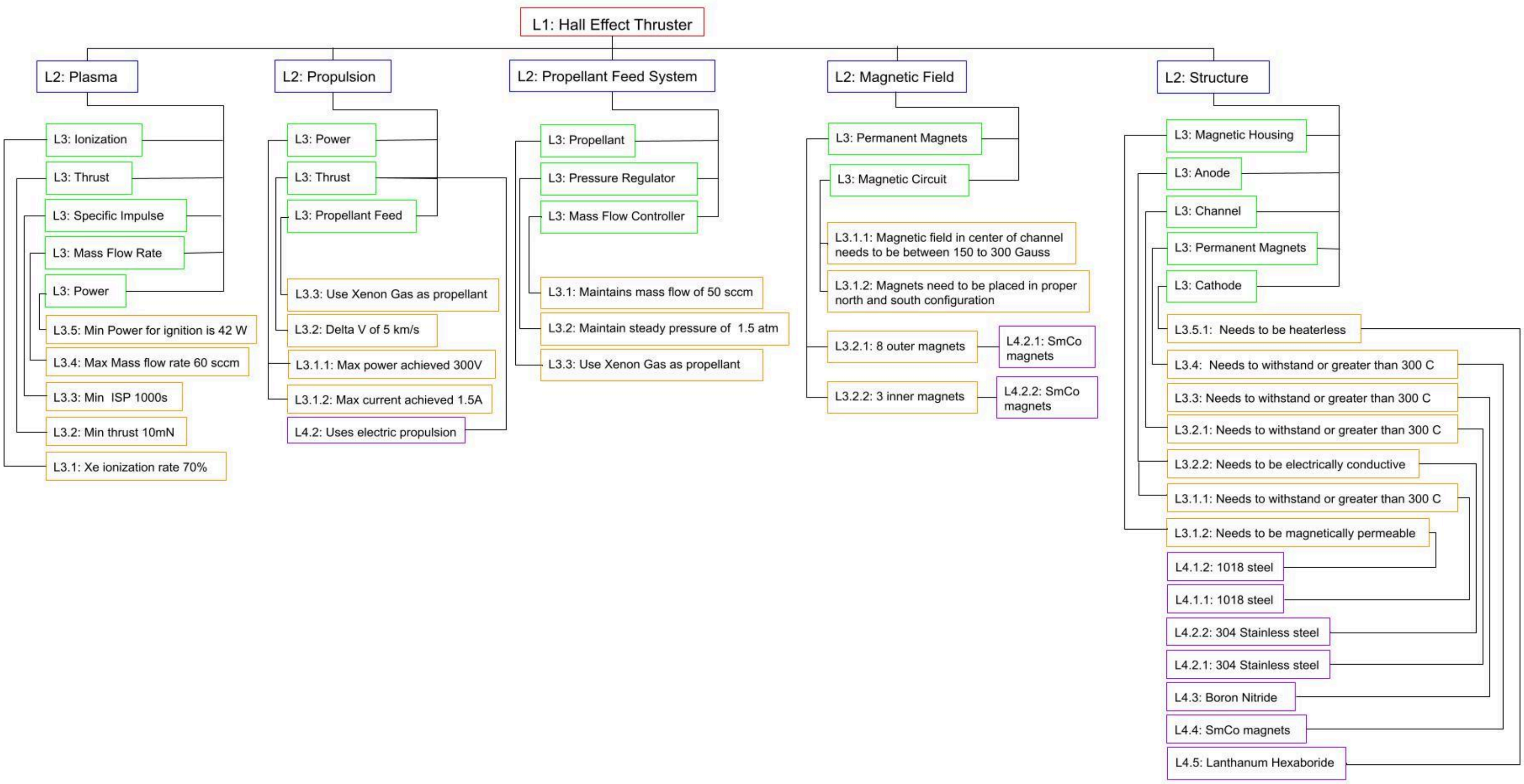

Fig 4. System Architecture Breakdown with Requirements

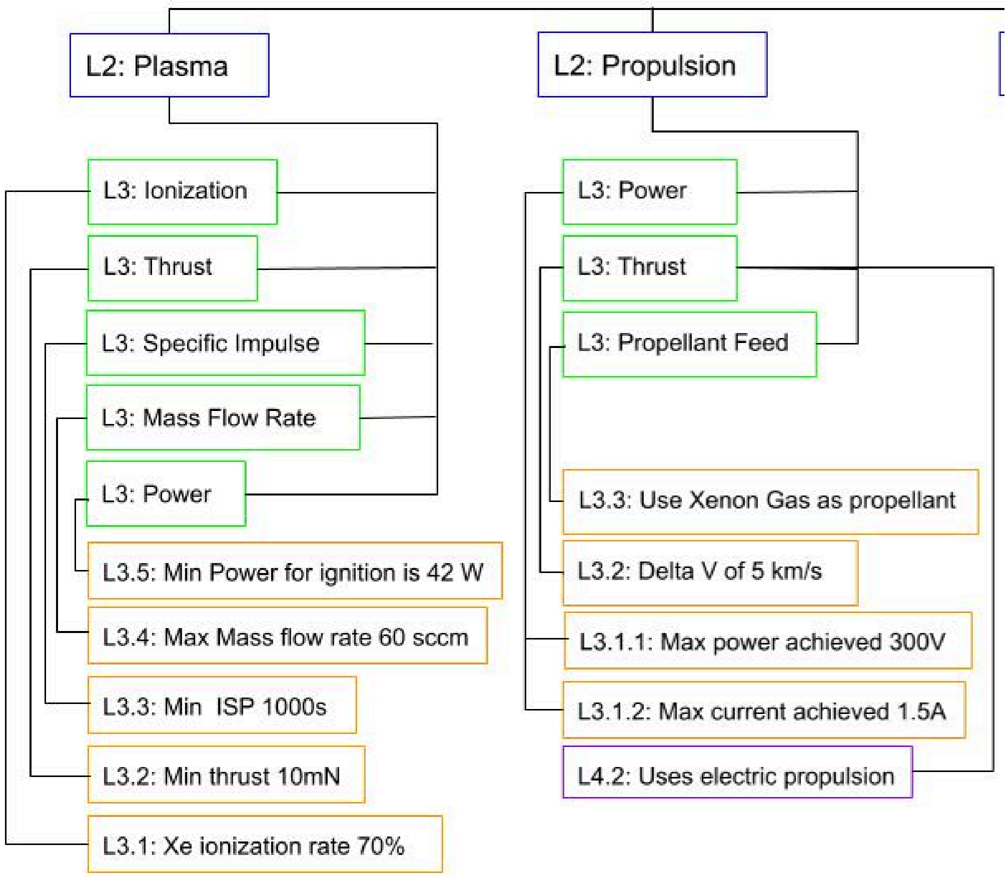

Fig 5. System Architecture Breakdown with Requirements of Plasma and Propulsion

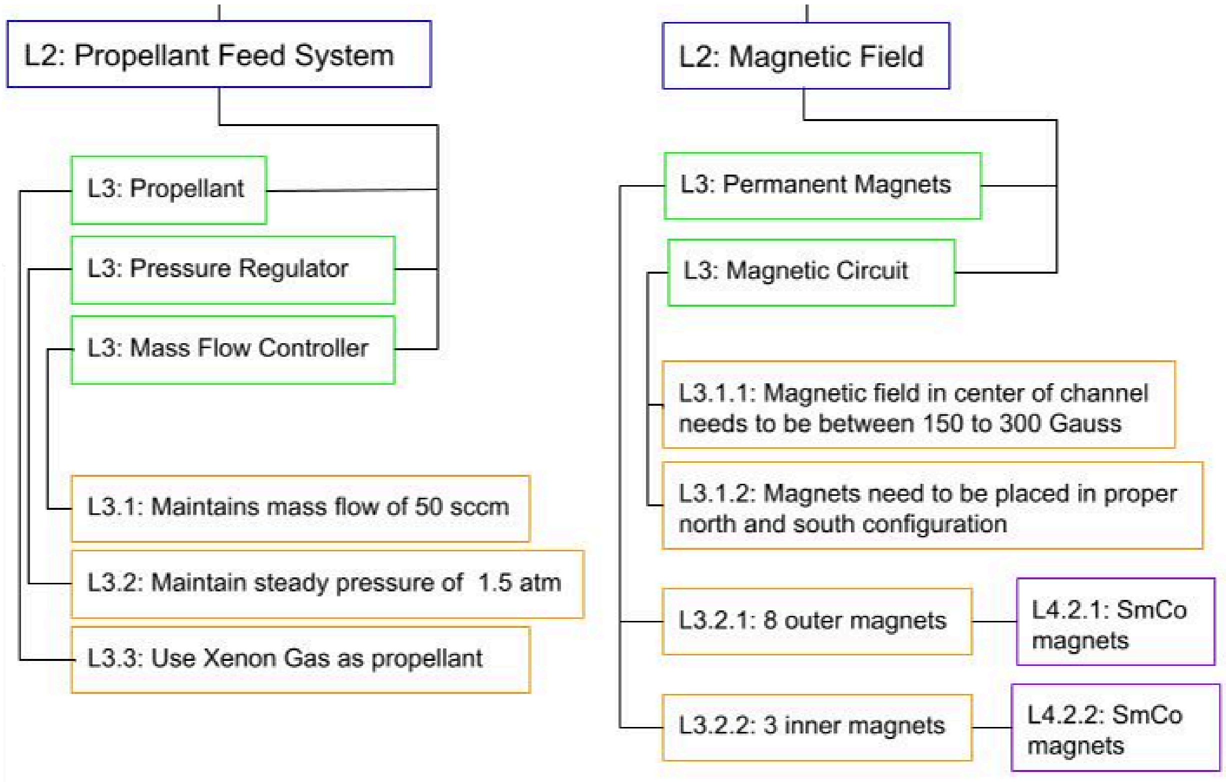

Fig 6. System Architecture Breakdown with Requirements of Propellant Feed System and Magnetic Field

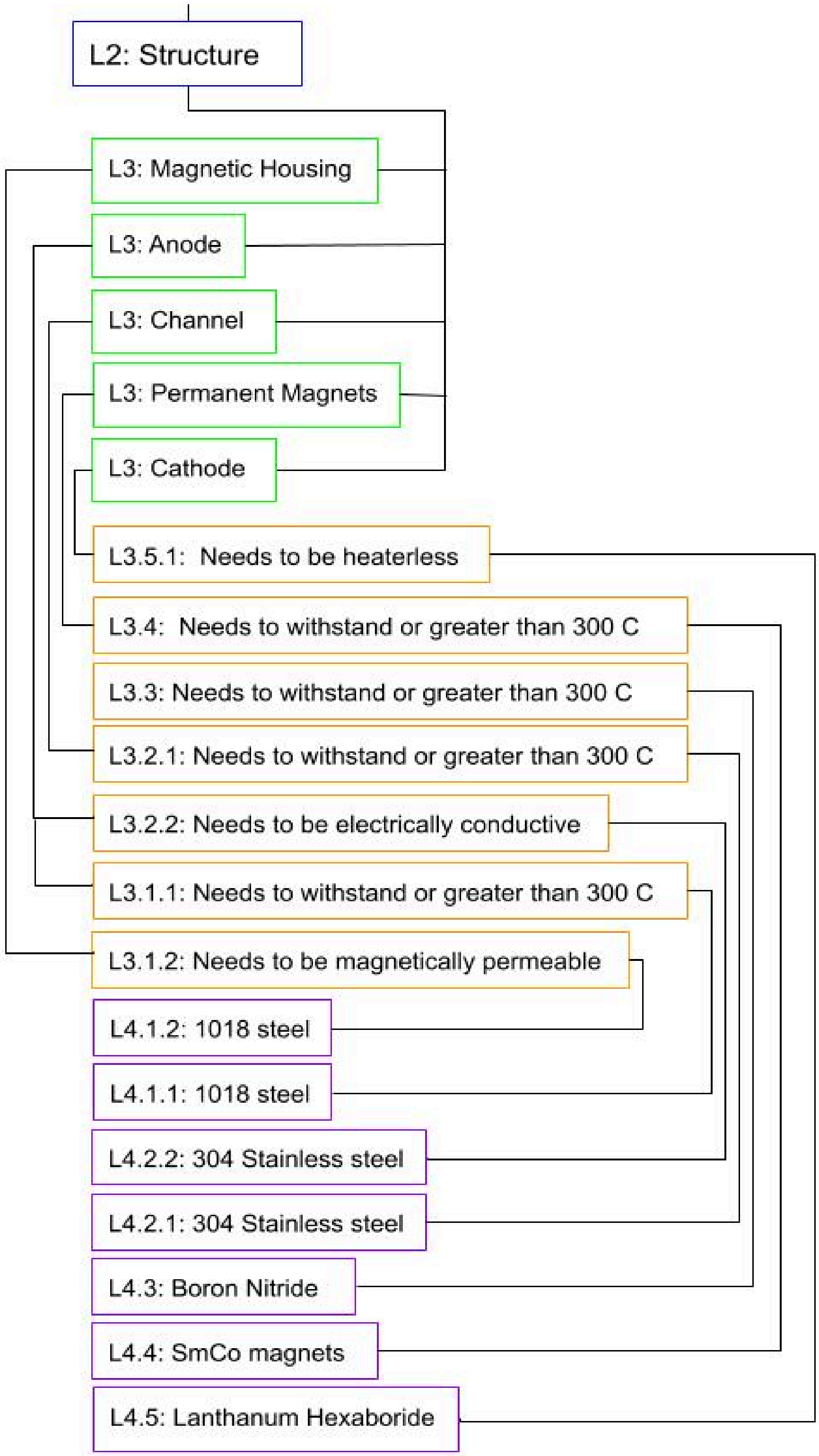

Fig 7. System Architecture Breakdown with Requirements of Structure

B. Mass, Power, Volume Budgets

HET Systems	Mass (g)	Volume (cm^3)	Power (W)
Structure	958.6	341.7	–
Thermal	221.4	129.6	–
Cathode	31.2	4.7	12.8
Anode	13.7	14.3	500
Magnetic Circuit	22.1	3.4	–
Total	1247	493.7	512.8
Margin	**25%**	**50%**	**25%**

Table 4. Mass, power and volume parameters

C. Risk Analysis

a. Risk identification

i. Thermal damaging to thruster itself
ii. Failure to operate
iii. Damaging the mass flow system through an unwanted reaction with the Xenon
iv. Budget constraints
v. Time

b. Risk matrix (likelihood vs impact)

Risk	Likelihood (1-5)	Impact (1-5)	Risk Level
i. Thermal damaging to thruster itself	3 (Possible)	5 (Catastrophic)	High
ii. Failure to operate	3 (Possible)	5 (Catastrophic)	High
iii. Damaging the mass flow system through an unwanted reaction with the Xenon	2 (Unlikely)	4 (Major)	Moderate
iv. Budget constraints	4 (Likely)	3 (Moderate)	High
v. Time	4 (Likely)	2 (Minor)	Moderate

Table 5. Risk Assessment

c. Mitigation and contingency plans

i. Selecting heat tolerance materials
ii. Need to check each subsystem - power, gas, etc
iii. Safety measurement procedures
iv. Find efficient ways to purchase materials that are cost effective. Try to put together some last minute fundraising if needed

v. Ensure giving enough buffer time to create a realistic schedule to mitigate wait time for materials to be shipped, building physical prototype, as well as travel time to testing facilities

d. What if scenarios

Degradation of channel wall

- Limited chance (1/100), will occur after significant amount of time firing
- Will cause catastrophic failure as magnets will get damaged and cause failure of the magnetic field, disabling our ability to produce thrust

Ignition failure

- Minimal chance (1/1000), may occur due to problems with the cathode, propellant, magnetic field or discharge instability
- Will prevent initial ionization of the propellant necessary for the thruster to function properly

Magnets become demagnetized

- Limited chance (1/100), may only occur if firing the thruster for too long.
- Will cause catastrophic failure as we will be unable to produce thrust

D. Reliability and Redundancy

a. Redundancy strategy

Subsystem	Redundancy Strategy	Rationale/Implementation
Plasma Generation	Cold redundant cathode (neutralizer)	The cathode is a single point of failure, where a second cathode can be electrically isolated and activated if the primary fails.
Propulsion Output	Functional redundancy through power profile tuning	Thrust stability issues may be mitigated via software-controlled tuning
Propellant Feed System	Dual solenoid valves or bypass path	Two valves in series or parallel for critical flow paths to maintain flow in case of blockage or valve failure.
Magnetic Field System	Use of permanent magnets (no active coils)	Permanent magnets eliminate the risk of coil burnout or driver failure. While not adjustable, they improve passive reliability and reduce power demand. May require careful thermal and magnetic design due to fixed field strength.
Structural Components	Passive robustness, not redundant	Structure is generally not redundant due to weight/cost constraints. Focus is on using materials with high margins and factoring in thermal loads.

Table 6. Redundancy strategy

b. Expected system reliability

Reliability for expected systems entail successful ignition and thrust generation, sustained performance under vacuum and thermal cycling, minimal erosion and stable plasma behavior over time as well as power and control electronics functioning without failure.

Subsystem	Expected Reliability	Rationale
Plasma Generation	0.85-0.90	Common issues are cathode wear, ignition instability and erosion of the discharge channel. This often requires tuning of ignition logic and current profiles. The cold start ignition has higher risk.
Propulsion Output	0.90-0.95	Once ignited the plasma tends to generate stable thrust. Failures can occur from erosion or long term thermal stress, however these are rare in short term tests.
Propellant Feed System	0.92-0.96	Pretty reliable when using xenon compatible hardware. The risks include flow sensor drift, regulator malfunction or small leaks that are caught during integration testing.
Magnetic Field System	0.88-0.93	Permanent magnets have the risk of possibly overheating and demagnetizing. Magnet placement is critical to maintaining plasma confinement
Structural Components	0.96-0.99	Very reliable. Includes discharge chamber, magnetic housing, anode rings, mechanical fasteners and mounting frame.

Table 7. Expected system reliability

VIII. Integration and Testing Plan

A. Assembly & integration procedure

To assemble the thruster, everything is assembled in a nesting doll fashion. Each part is placed within the next until everything is locked in place. The magnets are first magnetised to the magnetic circuit to create the magnetic field geometry. Next, the channel walls are placed within the channel of the magnetic circuit. The anode is then placed within the channel on top of the base of the walls. Shoulder washers are then put on the feed lines from the back and shafts collars are attached behind them to lock everything in place. The thruster is then placed inside the vacuum chamber and attached to the chamber interface. The cathode is next placed within the fringing magnetic field near the top of the channel. The insulation for the feed lines are hung over the feed lines before the swage locks are attached to the end of them. The connectors are then attached for the xenon gas propellant and sufficiently tightened. Electrical connectors are then attached to the feed lines. The vacuum chamber is then sealed and pumped down to 10^{-5} torr over the course of an hour. The electrical connections are then attached to power and testing can begin.

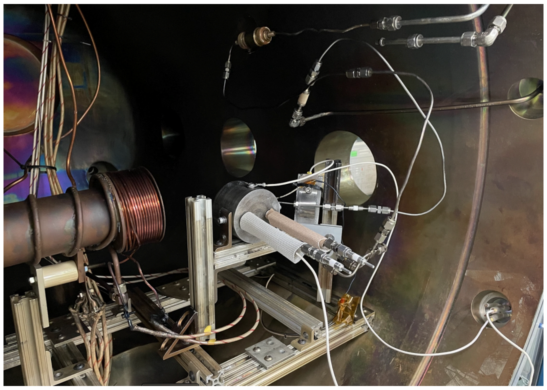

Fig 8. Thruster in vacuum chamber

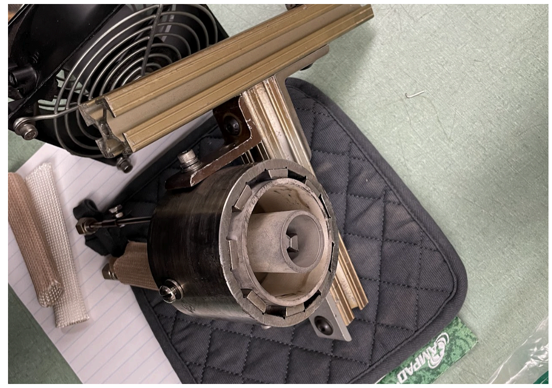

Fig 9. Thruster assembled

B. Interface verification and checklists

To ensure the thruster is properly integrated, a number of checks are made. First the magnets are checked that they are in the correct positions and orientations using a magnetic field sensor. The channel is ensured it is pushed down all the way via mechanical pressure, the anode is also checked in this way to assure it too is at the base of the channel. The shoulder washers and shafts collars are also ensured they are pushed up to the top they can go to ensure the thruster will not fall apart. The shaft collars are ensured they are tightened sufficiently using mechanical torque. The thruster is ensured it is attached by mechanical force as well. Each of the connections are ensured they are properly tightened by using mechanical torque.

C. Environmental test plans

The first tests to take place are the magnetic field testing and the thermal testing. The magnetic field testing allows for an analysis of how the magnetic field interacts and how well the simulation captures the field. The main objective for this test is to ensure that each magnet works and that the polarity is facing the correct direction. The thruster must also withstand lots of heat as it will be creating plasma while firing. The team utilized an oven starting at 100 ºF waiting for an hour then increasing the heat by 25 ºF in increments of 30 minutes until the oven reached a temperature of 425 ºF. After the preliminary tests the next test was to use a vacuum chamber and fire the thruster. The tests were run at NASA JPL in a vacuum chamber. The environment of the test should emulate space, meaning no air should be present. The thruster will be placed on a test stand and hooked up to the mass flow rate controller as well as the electrical wires and cathode. The chamber will then be pumped down, with the thruster inside, to remove air residing in it. Afterwards the cathode will be fired then the entire thruster. These tests will then lead to data that can be collected.

D. Functional testing and validation

The functional tests were run at NASA JPL in a vacuum chamber. The thruster will perform its duty in space, therefore the testing environment should emulate space. The thruster will be placed on a test stand and hooked up to the mass flow rate controller as well as the electrical wires and cathode. The chamber will then be pumped down, with the thruster inside, to remove air residing in it. The cryopump must remove gases using cold temperatures and must reach 0.026 Torr (3.33Pa) inside the chamber. After reaching 0.026 Torr the cryopump must be stopped so that it does not run at the same time as the mechanical pump. Afterwards the cathode will be fired for a few minutes to ensure stability. Then the thruster will fire when increasing the current. These tests will then lead to data that can be collected. The simulations and environmental tests run beforehand validate the results of the thruster tests. The environmental tests validated that our thruster could withstand the temperatures and had the correct magnetic polarity. The calculations were validated by the functional tests performed. The team had calculated that the thruster would reach a maximum voltage of 300 V and maximum power of 500 W independently.

E. Test schedule and facility use

At 11:00 AM on Thursday morning the team met with Dr. Dan Goebel at Nasa JPL. The team utilized the vacuum chamber provided by JPL. The vacuum chamber is custom built and has two cryopumps that allow for the chamber to reach 5×10^{-5} Torr, adjusted for Xenon. The chamber also has a gas feed that allows for the propellant to enter the thruster. After arriving at JPL we placed our thruster on the adjustable test stand built inside of the chamber and allowed for the crypumps to get rid of any gas residing in the chamber. Around 12:00 PM the chamber was fully pumped down and we were able to start testing. The facility utilized a mass flow controller to control the amount of Xenon flowing through the gas feed. The test ran for 10 minutes and the team decided to make adjustments to the thruster for better performance. The thruster was placed in the chamber again at 12:30 PM. The second test began at 2:00 PM and ran for around 20 minutes. The following day, Friday, allowed for the team to make corrections to the thruster and improve the thruster. The team met with Dr. an Goebel at 9:00 AM and redid the same process as day one. The first test on the second day took place at 10:00 AM and ran for 25 minutes before the team decided to make more adjustments to the insulation of the gas feeds. The second test began at 11:30 AM which ran for much longer, around 40 minutes. For the third test we decided to test the limits of the thruster and did not need to make any adjustments. The test began at 1:00 PM and ran for around 40 minutes as well. After completing the third test the second, and final day, of testing was complete.

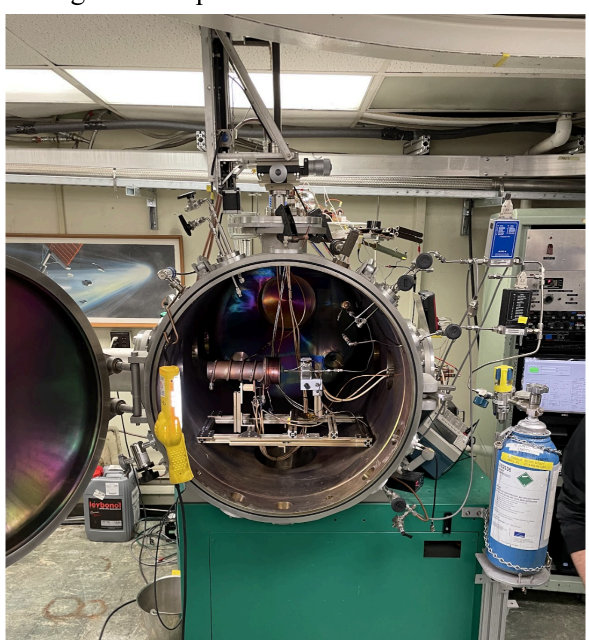

Fig 10. NASA JPL Vacuum Chamber

IX. Results and Discussion

A. Test Results

a. Test 1

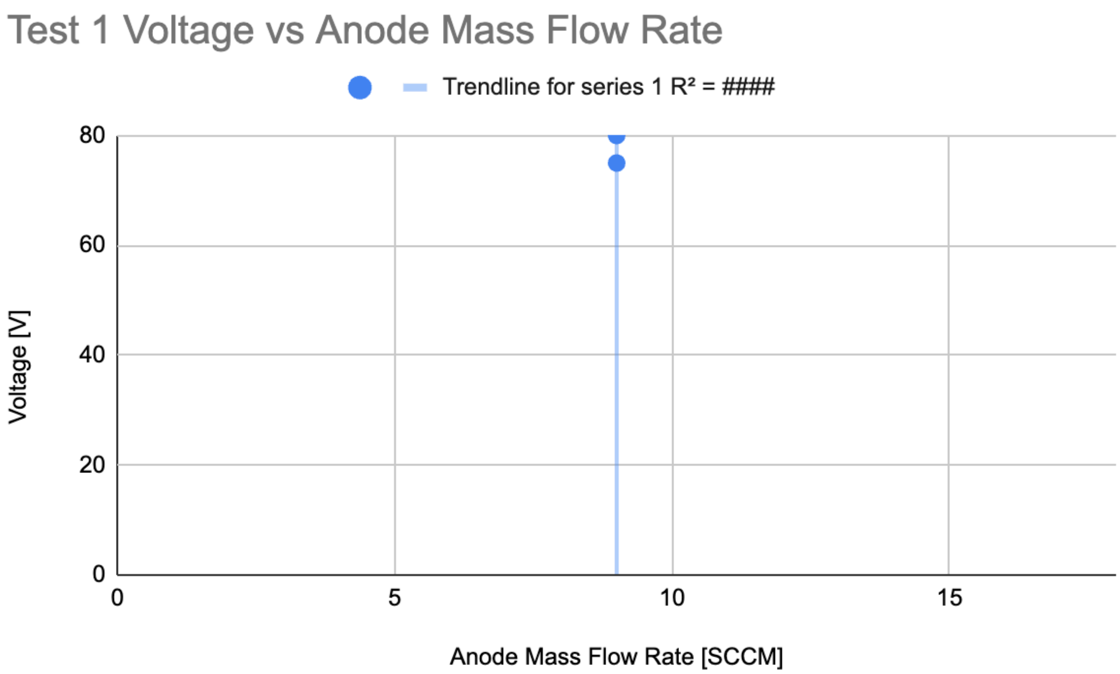

Fig 11. Test 1 Anode: Voltage vs Mass flow rate graph

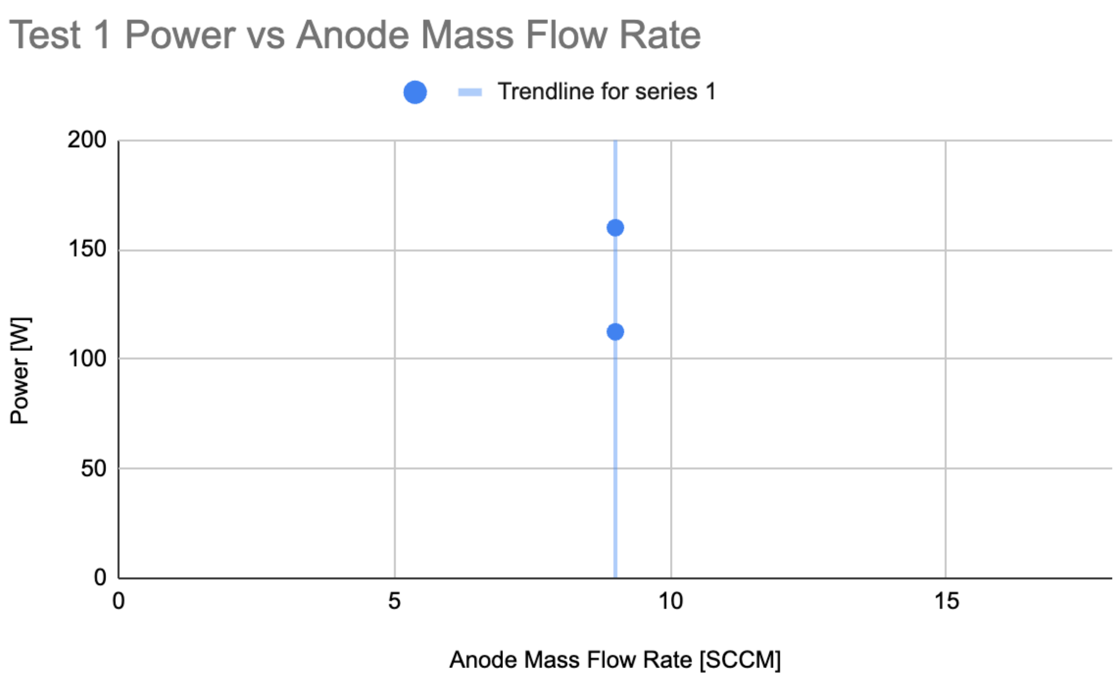

Fig 12. Test 1 Anode: Power vs Mass flow rate graph

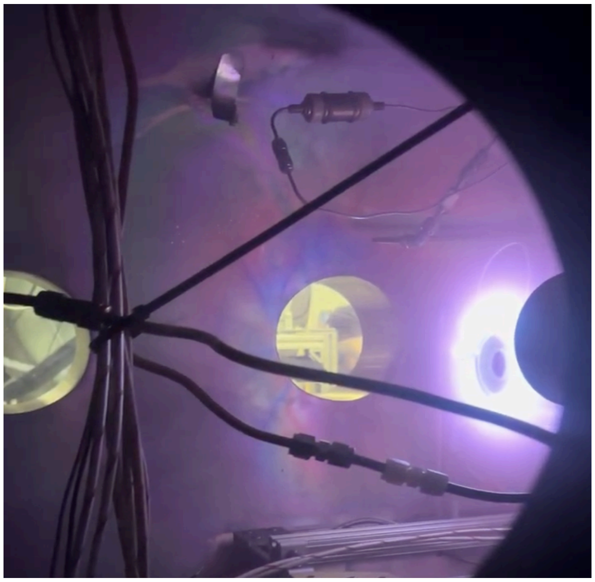

Fig 13. Test 1 image 1

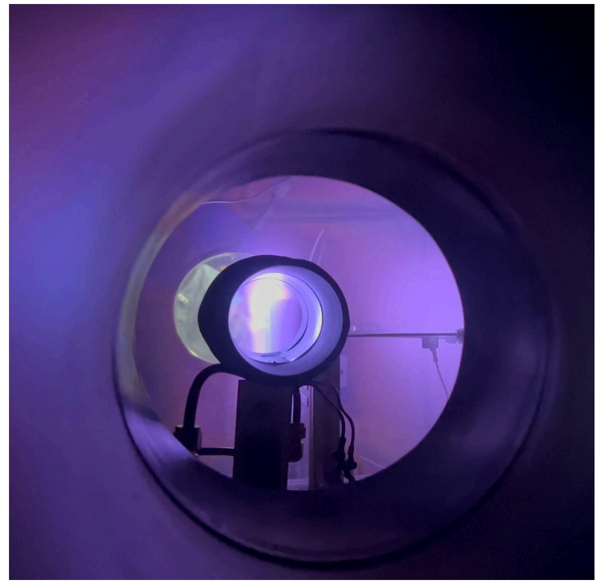

Fig 14. Test 1 image 2

Test 1 consisted of a 1000 gauss (1kG) magnetic field in the channel. This effectively created a magnetic shield for the channel. This meant that the electrons from the cathode could not penetrate the channel. What is seen in fig. 13 is the plasma forming around the channel opening. While the thruster had successfully generated plasma, it was not forming the characteristic plume of a Hall thruster. Further, the voltage was being controlled manually, and not by the volumetric flow rate of the propellant. This is another aspect that qualifies a thruster as a hall thruster.

b. Test 2

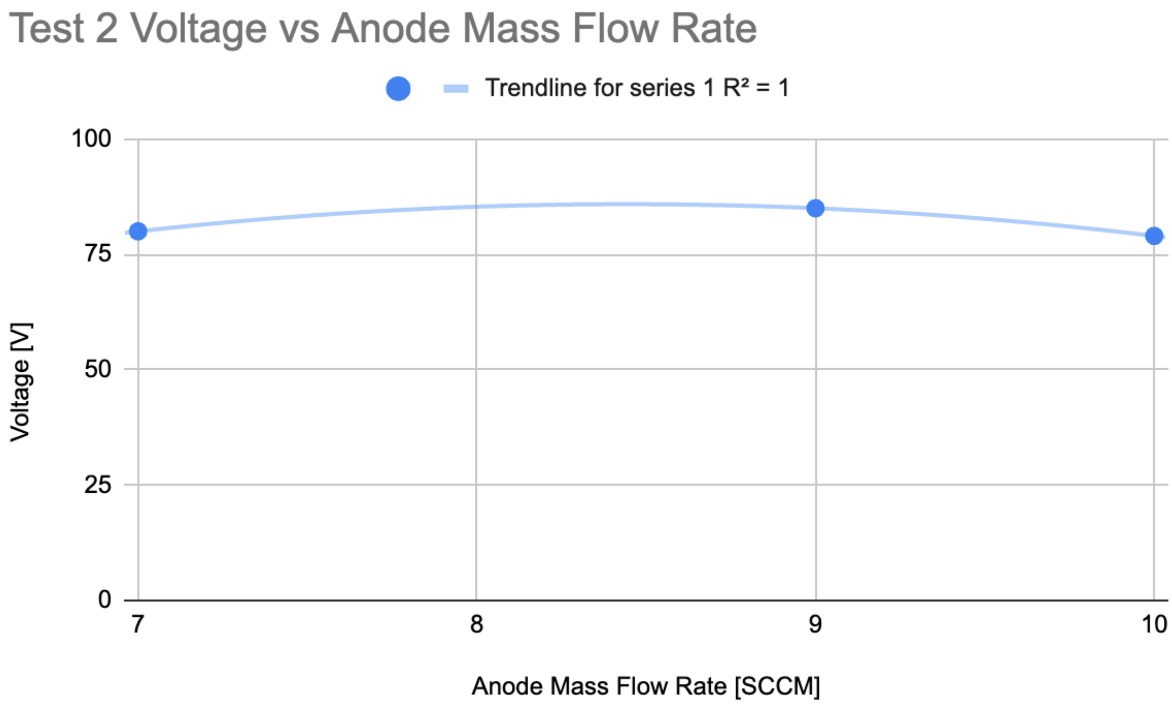

Fig 15. Test 2 Anode: Voltage vs Mass flow rate graph

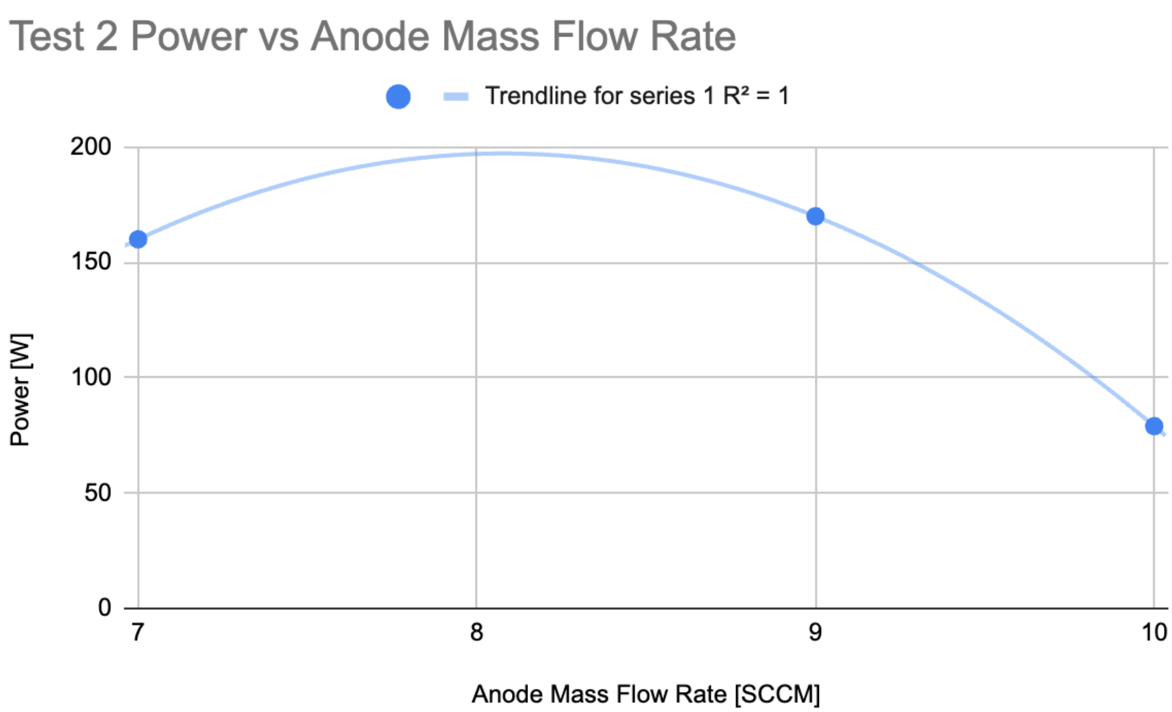

Fig 16. Test 2 Anode: Power vs Mass flow rate graph

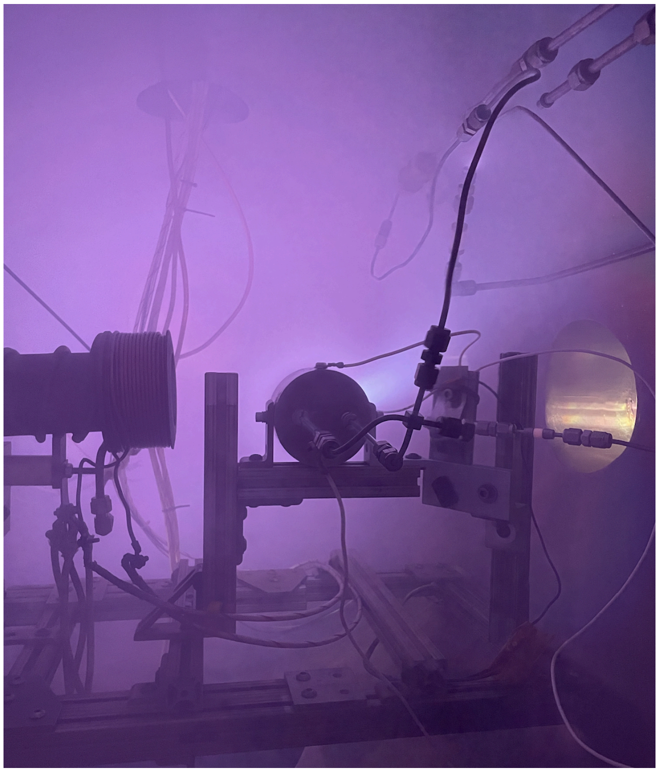

Fig 17. Test 2 image 1

Fig 18. Test 2 image 2

Test 2 fixed the problem of the high flux magnetic field. Half of the magnets were taken out to decrease the strength of the field. There were some other issues. The thruster was not sealed properly and plasma began to spray through the gaps in the thruster. This led to a plasma fog that created an electrically conductive medium in the chamber. There was no plume formation, and the feed lines were not electrically insulated. The combination of the plasma fog and lack of feed line insulation led to arcing to the feed lines and the chamber itself.

c. **Test 3**

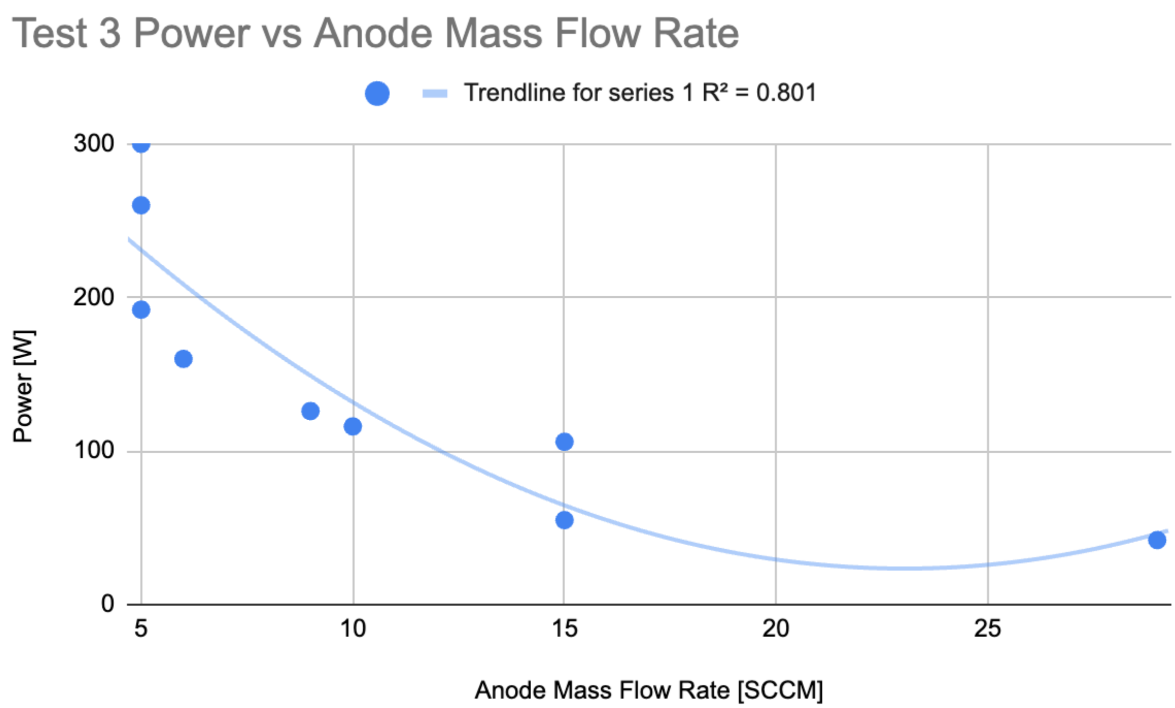

Fig 19. Test 3 Anode: Power vs Mass Flow Rate

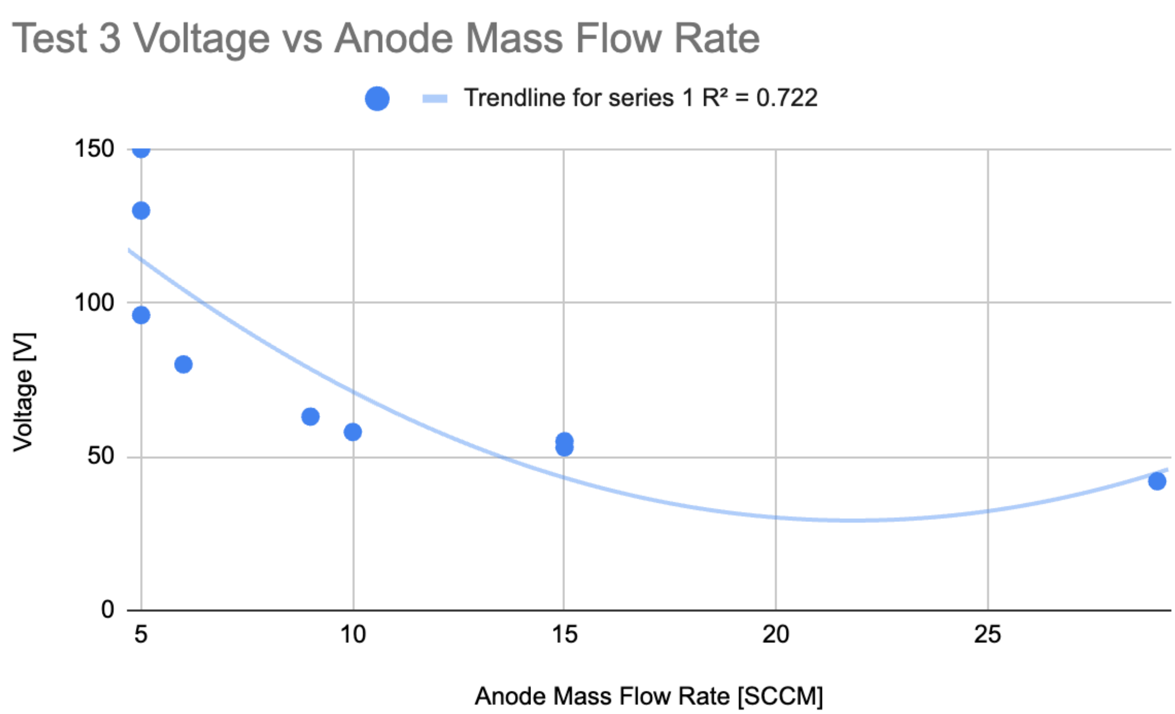

Fig 20. Test 3 Anode: Voltage vs Mass Flow Rate

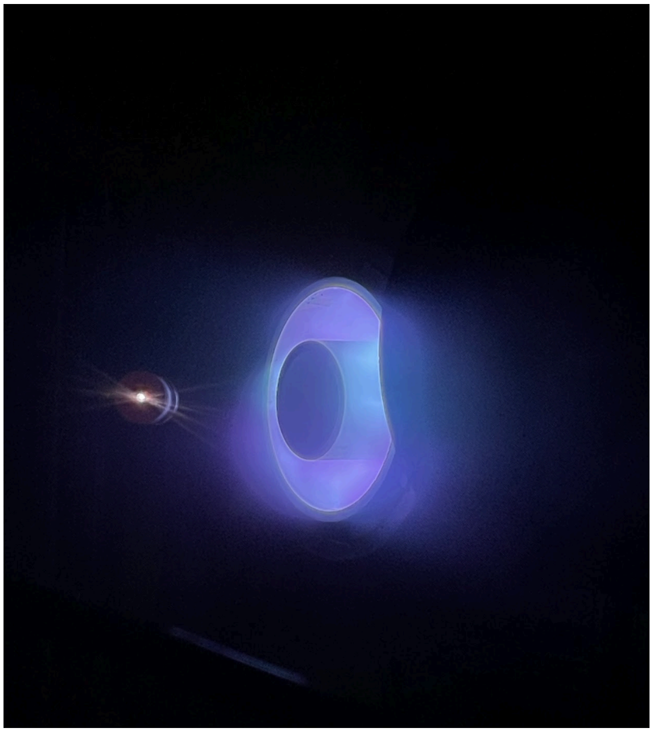

Fig 21. Test 3 image 1

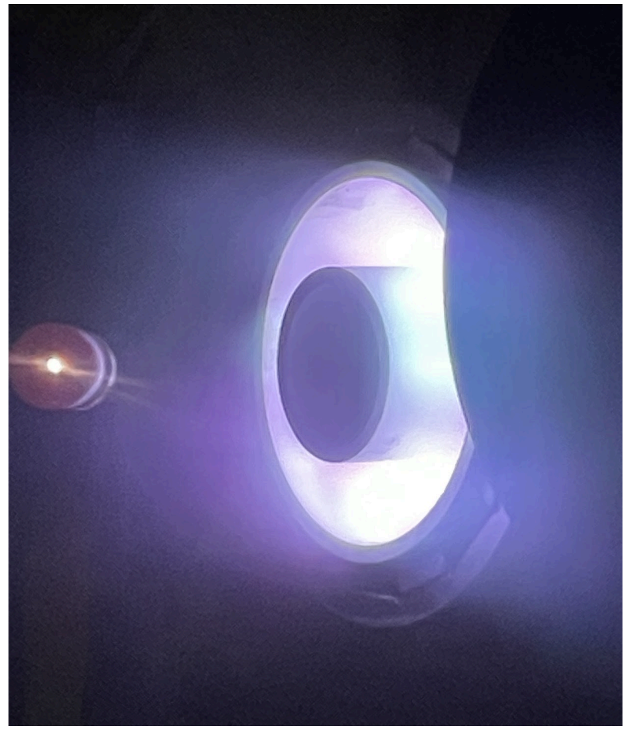

Fig 22. Test 3 image 2

In order to fix the issues of arcing in test 2, the feed lines were electrically insulated.Test 3 required the chamber to be flooded with 30 SCCM of propellant. This was done in order to achieve ignition. This was the first that was a technical success. A plume was formed, It exceeded the 300W mark at which point commercial Hall thrusters are sold, and the voltage was controlled by the volumetric flow rate to the anode. The voltage is controlled by the mass flow rate through the Anode, while maintaining the discharge current at a fixed value. As the volumetric flow rate was decreased the resistance in the channel increased. This is a result of the decreasing amount of conductive plasma. Due to voltage oscillations in the chamber, the thruster was extinguished.

d. Test 4

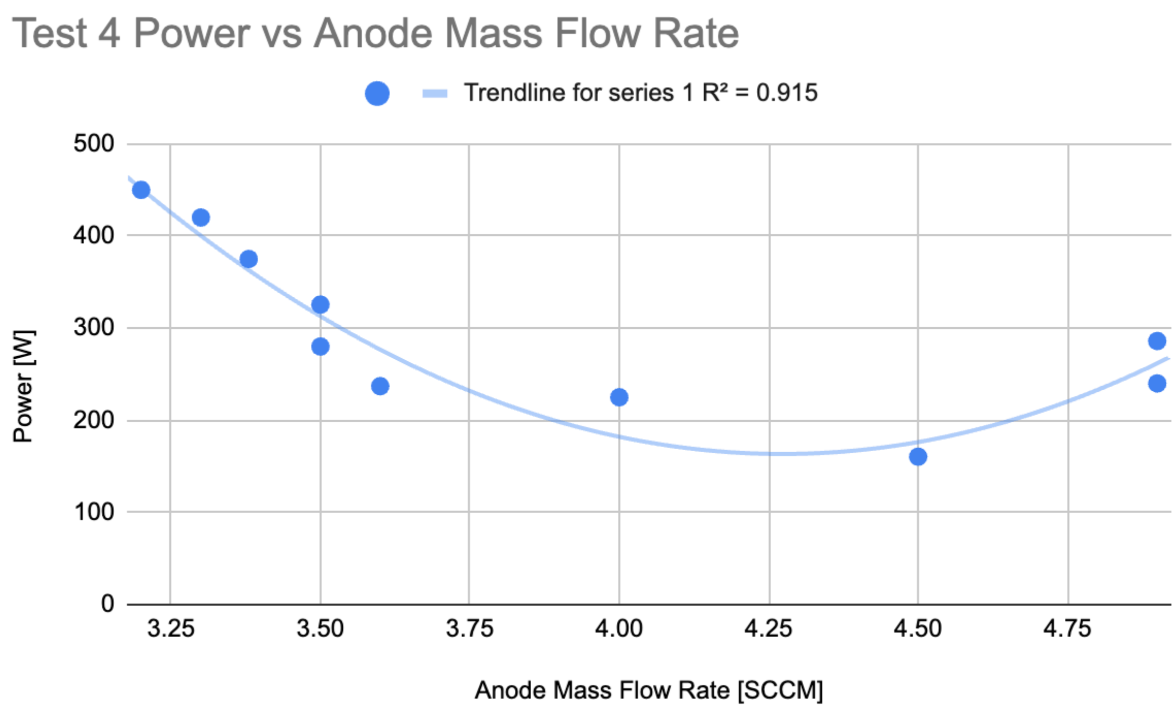

Fig 23. Test 4 Anode: Power vs Mass flow rate graph

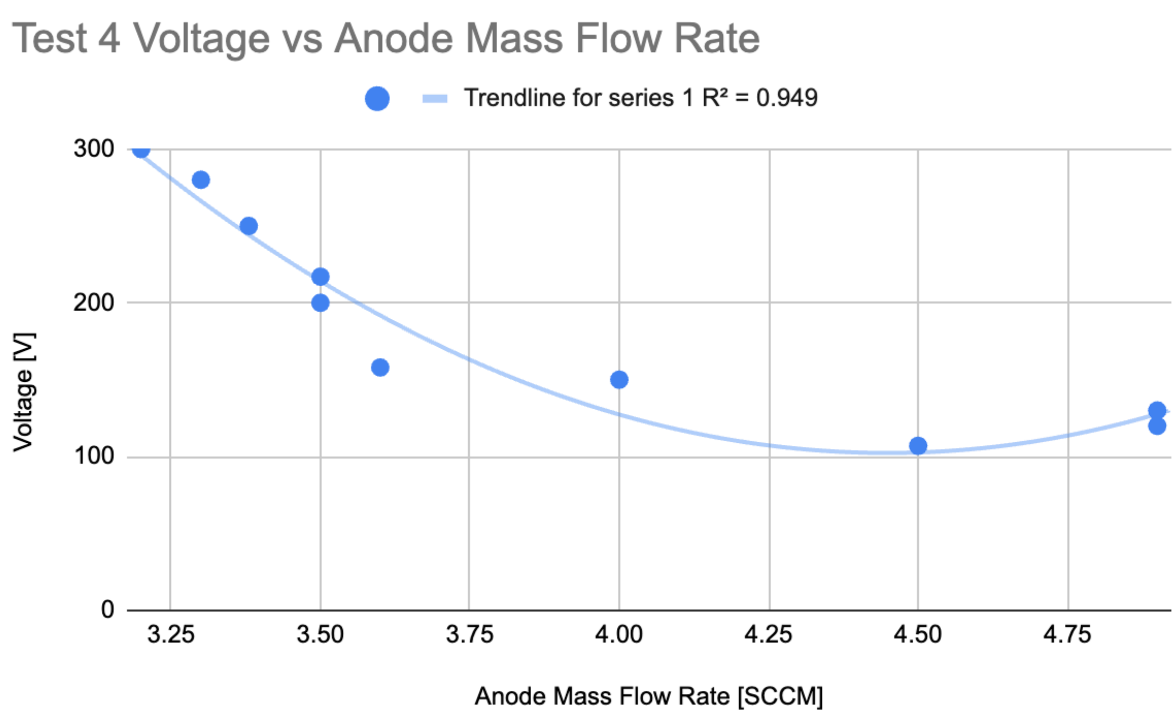

Fig 24. Test 4 Anode: Power vs Mass flow rate graph

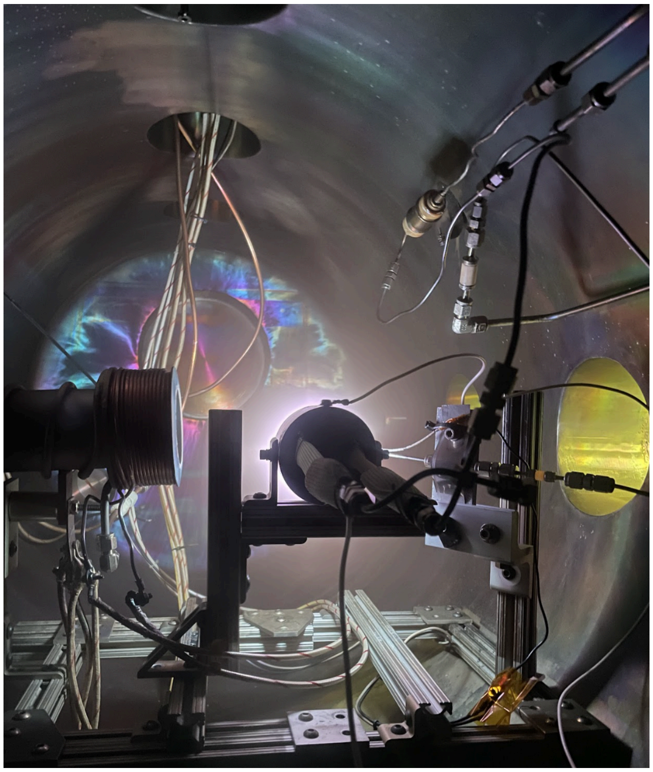

Fig 25. Test 4 image 1

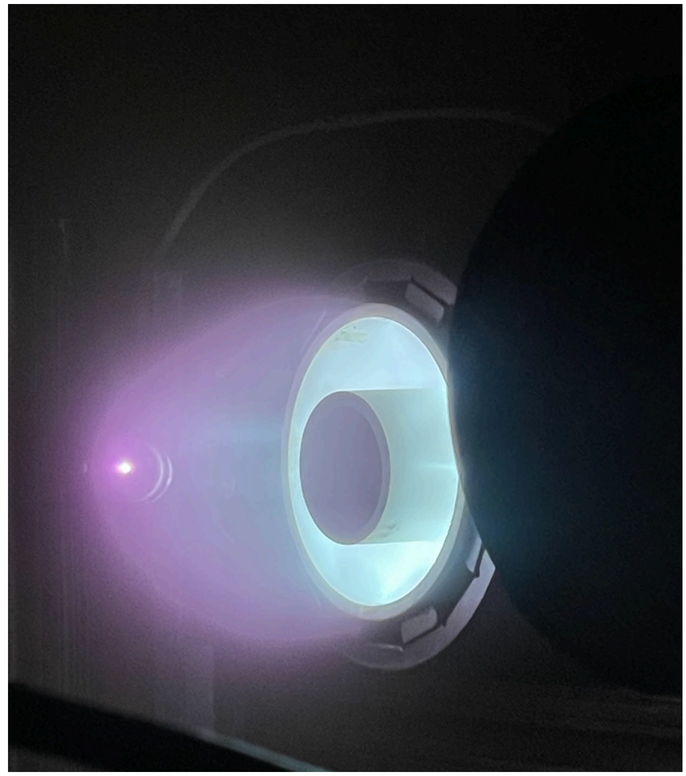

Fig 26. Test 4 image 2

Test 4 reached ignition at a much lower volumetric flow rate, 4.9 SCCM. Keeping in mind that volumetric flow rate is directly proportional to the conductivity of the chamber. Ignition was easier to achieve for a number of reasons. The thruster was left in vacuum overnight. This meant that the Boron Nitride had outgassed many of its impurities. An impurity meaning the channel was submerged in an oxygen rich atmosphere. Further, the magnets had undergone several thermal cycles in 200+ ℃ environments. This reduced the magnetic field strength of the magnets. The combination of these events allowed for a healthier hall thruster. This can also be seen by the color of the plasma discharge. A healthy hall thruster, using Xenon, burns a light blue. This can be seen in figure 26. This test was also the longest duration at 30 min of sustained burn. The thruster reached a stable 450W at 300V.

e. Test 5

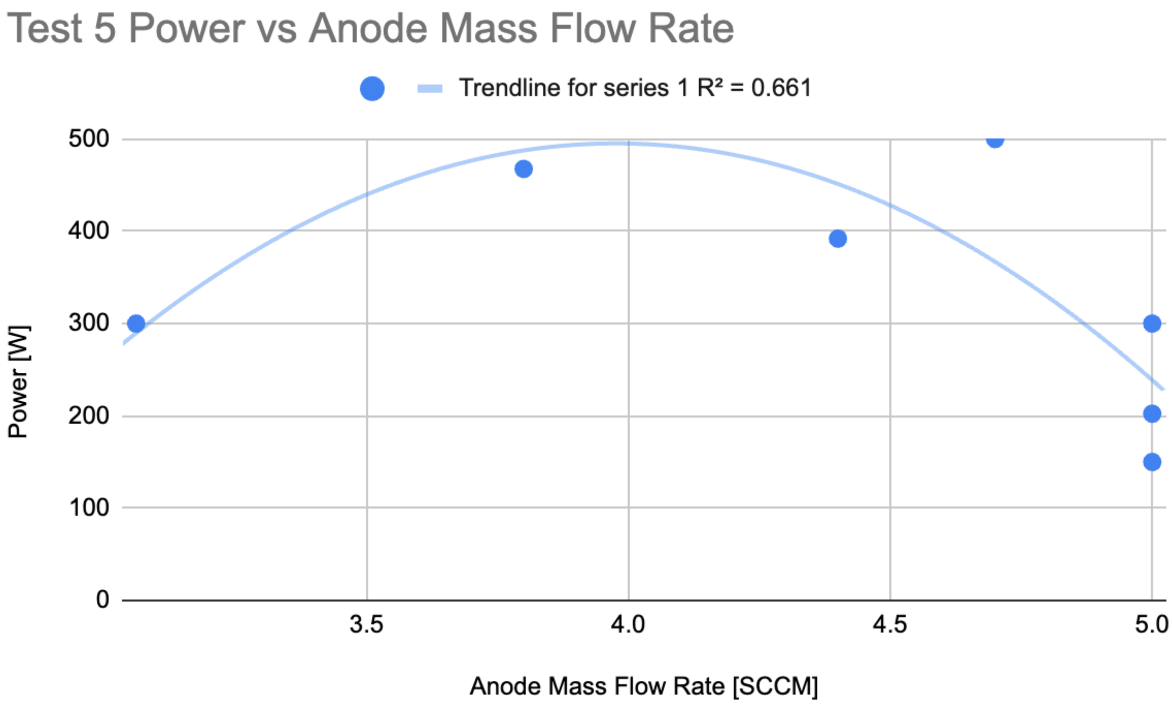

Fig 27. Test 5 Anode: Power vs. Mass flow rate graph

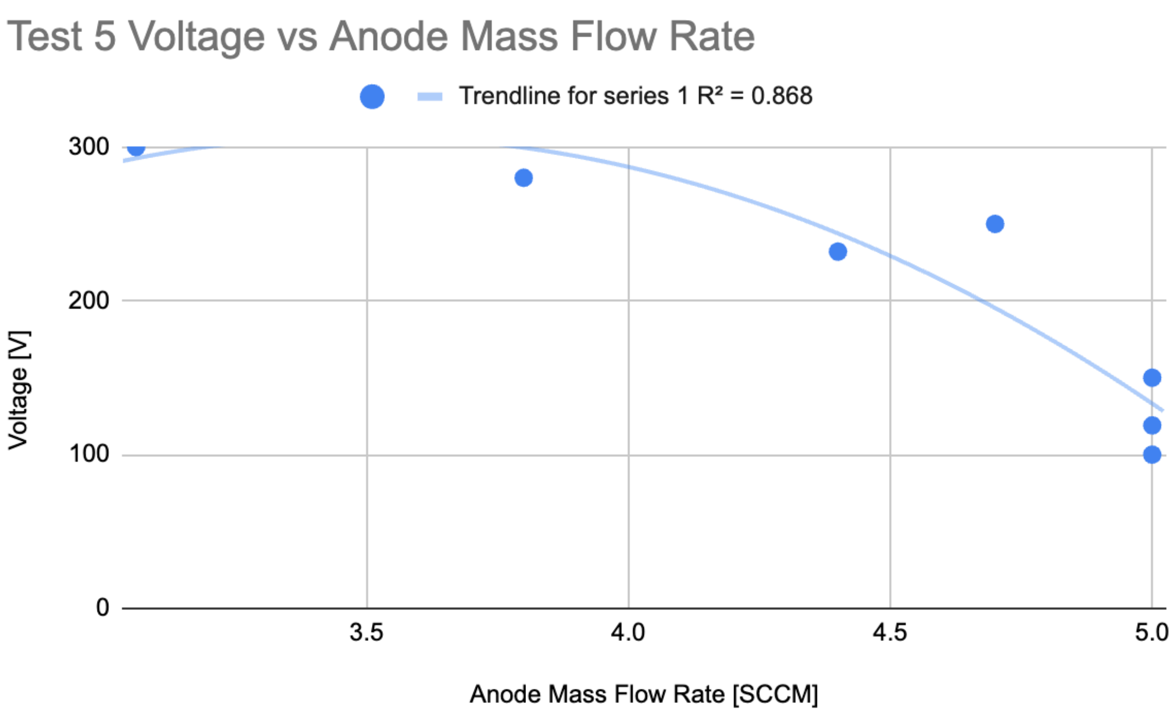

Fig 28. Test 5 Anode: Voltage vs. Mass flow rate graph

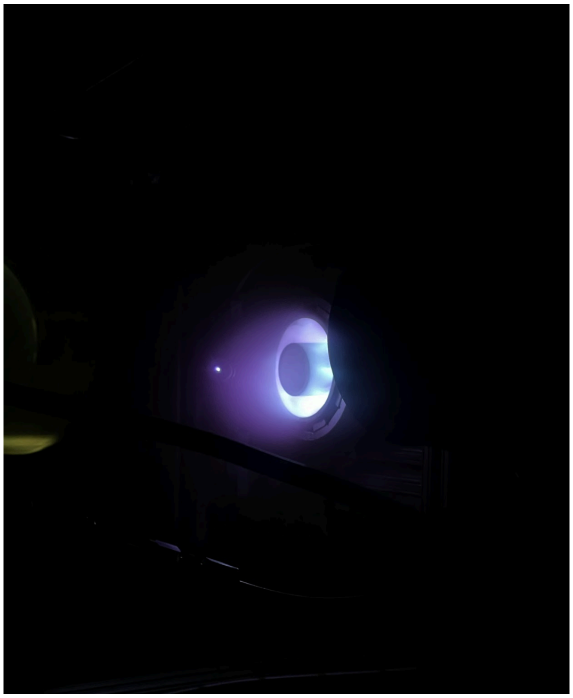

Fig 29. Test 5 image 1

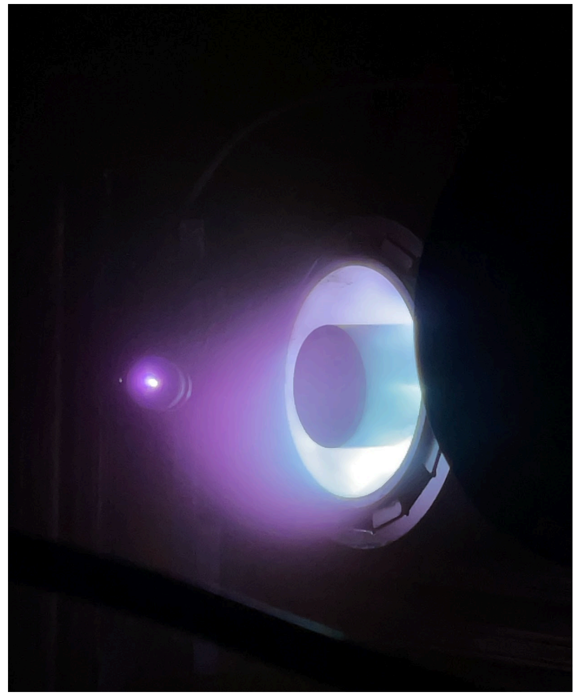

Fig 30. Test 5 image 1

Test 5 was the highest power output test. The thruster achieved 500W at 250V. The test was stopped due to a break in the channel that had reduced the thrusters thermal resistance.

A. Work Breakdown Structure (WBS)

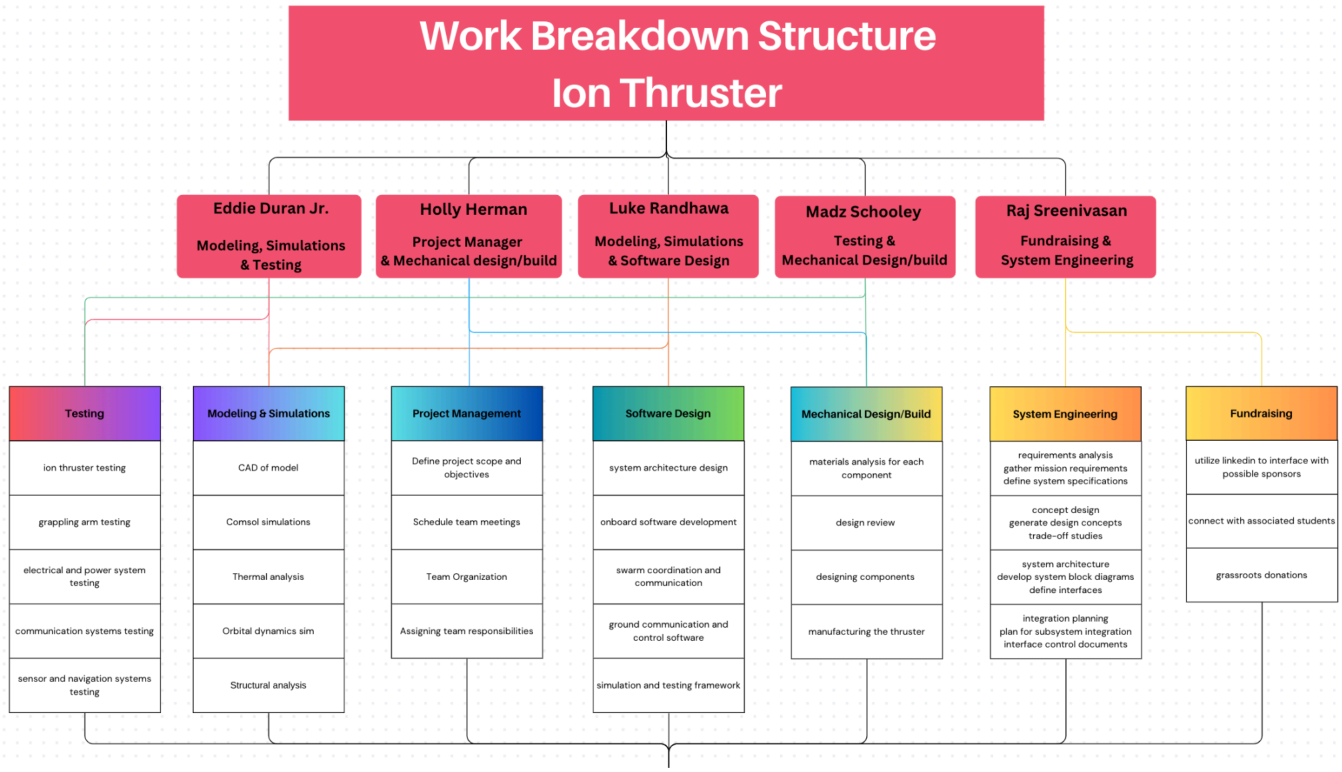

Fig 31. WBS part 1

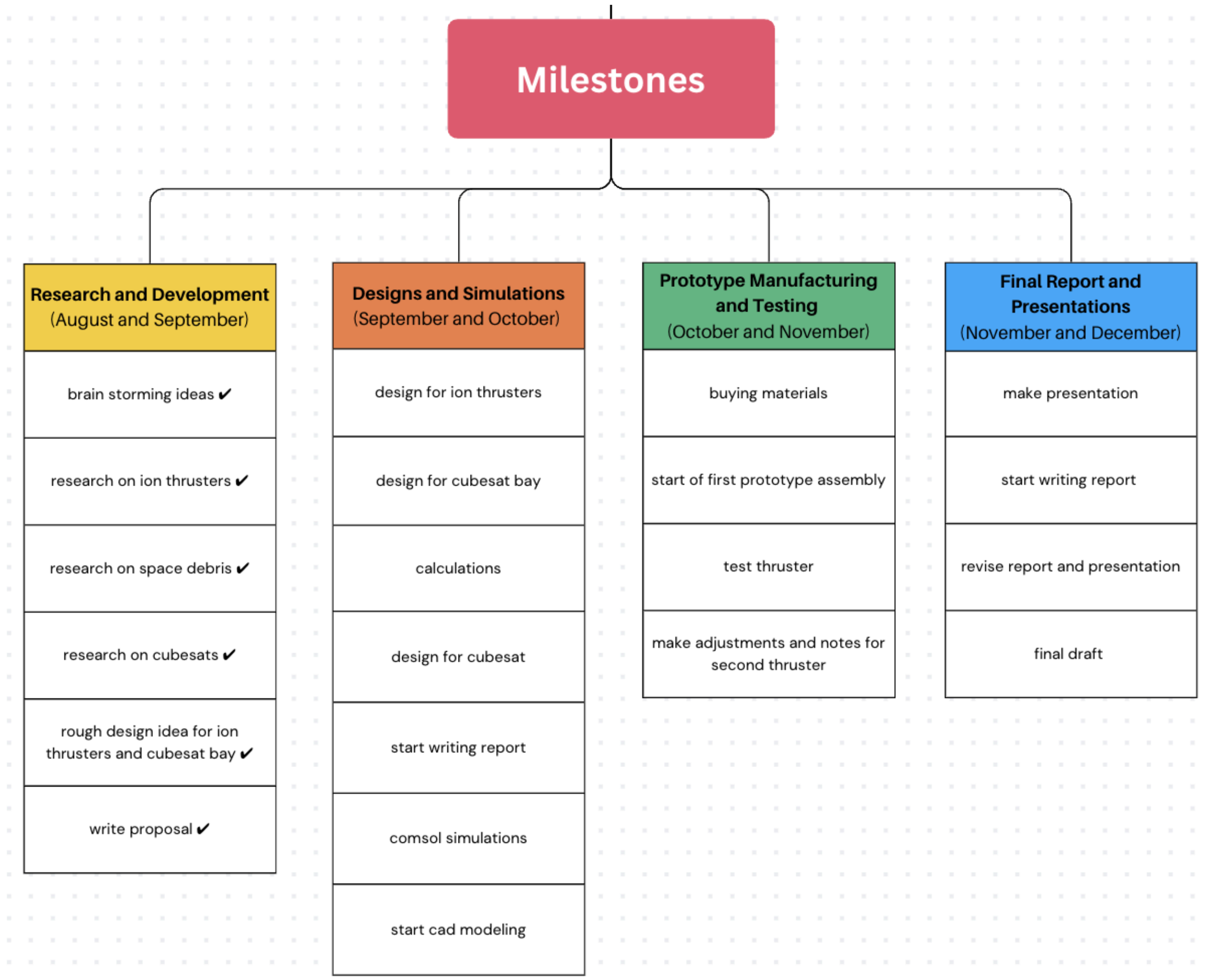

Fig 32. WBS part 2

B. Cost Estimate

a. COTS part costs

Item	# of Units	Subtotal
Clamping Two-Piece Shaft Collar	3	$61.11
Electrical-Insulating Ceramic Sleeve Washer	5	$21.40
Tubing: Seamless, 304 Stainless Steel, 1/8 in	1	$53.29
Dremel EZ406 EZ MTL STARTER KIT 6PC	6	$19.97
Travel Lodging	1	$1,217.22
Travel Gasoline	1	$302.39
3M WET+DRY 1/3SHEETS 6000	10	$8.08
CFT 1/4 SHEET SANDING 60#	20	$8.98
VENOM 50-CT HUY DTY NITRI	50	$17.98
SmCo Bar Magnet 26RE163208*	100	$116.00
Lanthanum Hexabromide Hollow Cathode*	1	$2,995.99
AISI 1040 Carbon Steel Magnetic Housing*	1	$400.00
304 Stainless Steel Anode*	1	$280.00
Boron Nitride Channel*	1	$1,100.00
1 kg of Xenon gas*	2.5	$2,125.00
Actual Total		$1,710.42
Theoretical Total		$8,727.41

Fig 33. Itemized Cost Index

* denotes costs not accrued

The total cost to us for the project was $1710.42. This was within our budget as we had roughly $2,000 available. However, the theoretical total was much higher at $8727.41. If we had to purchase everything at list price (including cathode, channel, xenon), the cost would be much higher. The major savings came from the donated cathode ($3,000) and channel ($1,100), and by using provided xenon gas. We included a cost margin of 20% in early estimates, but actual spending came in under that margin. Unspent funds ($300) will be transferred to the next team if this project continues. Future improvements could reduce costs: for example, custom fabricating the anode or using alternative propellants, though xenon was already the least reactive choice. We note that for flight, xenon per kilogram is expensive, but the fuel mass for CubeSat station-keeping is small.

C. Schedule

a. Gantt Chart

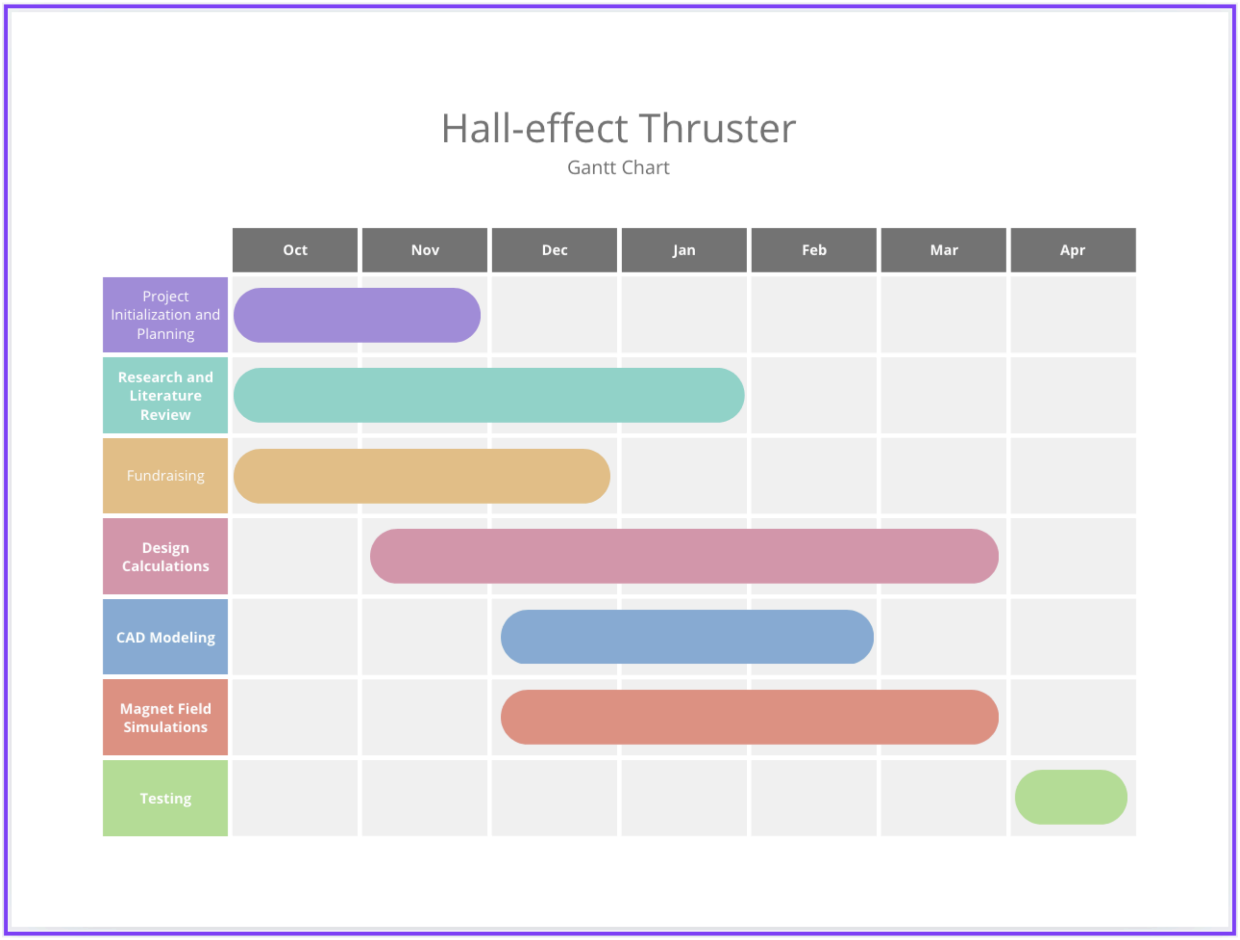

Fig 34. Gantt Chart

b. Critical Path Identification

Sequence	Work Package	Window in Chart	Dependency Logic
1	Project Initialization & Planning	Beginning Oct to end Nov	Launches the WBS, sets funding targets, and finalises scope documents that must exist before any procurement or design starts.
2	Research & Literature Review	Beginning Oct to end Jan	Generates the equations, state-of-practice data, and component short-lists that feed

			directly into design calculations. Planning can end, yet Research must still run until the first design sprint can draw on mature inputs.
3	Design Calculations	Beginning Nov to end Mar	Begins only after enough literature insight is banked (mid-Dec). Outputs channel dimensions, magnet spacing, power budgets—prerequisites for CAD and simulations.
4	CAD Modeling	Beginning Dec to end Feb	Consumes the preliminary numbers from Design Calculations in real time; every late design iteration ripples straight into CAD.
5	Magnetic Field Simulations	Beginning Dec to end Mar	Runs concurrently with CAD but requires an up-to-date solid model for each iteration. It therefore inherits the same finish-by date to keep pace with CAD release.
6	Testing	Apr	Cannot begin until **all three** upstream design streams (Calculations, CAD, Simulations) produce a frozen hardware configuration that

			is fabricated and leak-checked.

Table 8. Critical Path Identification

Because design calculations, CAD modelling, and magnet-field simulations all terminate around a similar time and each is a requisite for "Test-Readiness," any slip in one pushes the others—and the April test slot at JPL has no later alternative this academic year. Fund-raising, while lengthy (Oct → Dec), is not on the critical path once enough seed money is banked to place the long-lead component orders; the remainder can finish in parallel with design.

X. Conclusion and Future Work

This senior design project successfully fulfilled its objectives: we built and tested a Hall-effect thruster in a CubeSat-like configuration and demonstrated its operation. Key design features include a steel housing with integrated permanent magnets, a boron-nitride channel, and an independent xenon feed. The thruster was capable of continuous burns longer than the 5-minute target and achieved stable operation at 300 V, 500 W (exceeding our secondary goal). In fact, the longest test burn lasted ~30 minutes without interruption, showing robust stability.

We encountered and overcame several challenges. The tight fit of the channel in the housing was resolved by thermal expansion during assembly. The magnetic field was initially too strong; by selectively removing magnets, we achieved a more efficient plume shape. Managing high voltage and vacuum safety, as well as coordinating on-site testing at JPL, required diligent planning.

Currently, the thruster hardware is built and has been fired successfully under test conditions. All planned performance tests were completed. Remaining work for future teams could include quantifying thrust (with a calibrated thrust stand), adding flight-like power processing, or extending life tests. Additionally, integrating the thruster into an actual satellite bus (with ADCS, comms, etc.) would be the next step toward a full mission.

Interdisciplinary collaboration was crucial – mechanical, electrical, and plasma expertise all contributed. Early prototypes (using 3D-printed channels or simplified circuits) helped identify problems before final assembly. We learned that real-world prototyping often diverges from theory (e.g. magnetic field tuning). Rigorous scheduling and budgeting kept the project on track.

Several avenues remain open for refinement. Quantitative thrust measurement, via a calibrated micro-newton thrust stand, would translate discharge data into true specific impulse and efficiency values. A dedicated, radiation-tolerant PPU could replace laboratory supplies, bringing the subsystem closer to flight readiness. Life-testing beyond 30 min would validate channel erosion rates, cathode longevity, and magnet thermal margins. Development of a heaterless cathode, such as lanthanum hexaboride based cathode. On the mission-integration front, the thruster should be mated with a CubeSat avionics stack to verify electromagnetic compatibility, attitude-disturbance torques, and power-sharing.

Finally, the team gained valuable experience: nearly all members started with little to no propulsion background but finished with practical skills in vacuum testing and high-voltage systems. In sum, the Hall-effect thruster project has transitioned from concept to functional prototype while meeting every technical requirement within the allotted schedule and budget. Its successful 30-minute, 300-V/500-W burn demonstrates both mechanical integrity and plasma stability, validating the underlying design methodology. The work has generated a tangible asset for SJSU's aerospace program, enriched student skills, and positioned future cohorts to push deeper into flight-ready electric propulsion.

Continued investment, principally in thrust metrology and flight-grade electronics, could unlock the yet further milestones.

XI. References

[1] A. A. Shagayda, "On Scaling of Hall Effect Thrusters," in *IEEE Transactions on Plasma Science*, vol. 43, no. 1, pp. 12-28, Jan. 2015, doi: 10.1109/TPS.2014.2315851.

[2] A. Bapat, P. B. Salunkhe and A. V. Patil, "Hall-Effect Thrusters for Deep-Space Missions: A Review," in *IEEE Transactions on Plasma Science*, vol. 50, no. 2, pp. 189-202, Feb. 2022, doi: 10.1109/TPS.2022.3143032.

[3] Dressler, R., Chiu, Y.-H. and Levandier, D. (2000) 'Propellant alternatives for Ion and Hall Effect Thrusters', *38th Aerospace Sciences Meeting and Exhibit* [Preprint]. doi:10.2514/6.2000-602.

[4] Eckhaus, A.J. *et al.* (2024) 'Student-led design, construction, and testing of a permanent magnet hall thruster on argon propellant', *AIAA SCITECH 2024 Forum* [Preprint]. doi:10.2514/6.2024-1955.

[5] Goebel, D.M., Katz, I. and Mikellides, I.G. (2024) *Fundamentals of electric propulsion*. 2nd edn. Hoboken, NJ: Wiley.

[6] Conversano, R. W., Gobel, D. M., Hofer, R. R., Matlock, T. S., and Wirz, R. E., "Development and initial testing of a magnetically shielded ...," *IEEE Xplore*

XII. Appendix

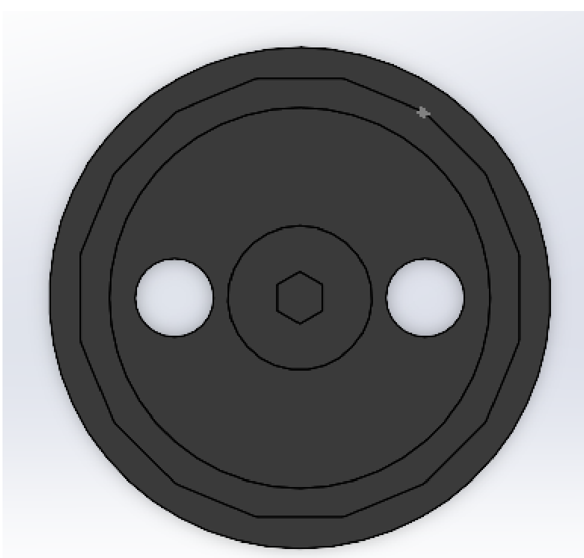

Fig 35. CAD top view of Magnetic Housing

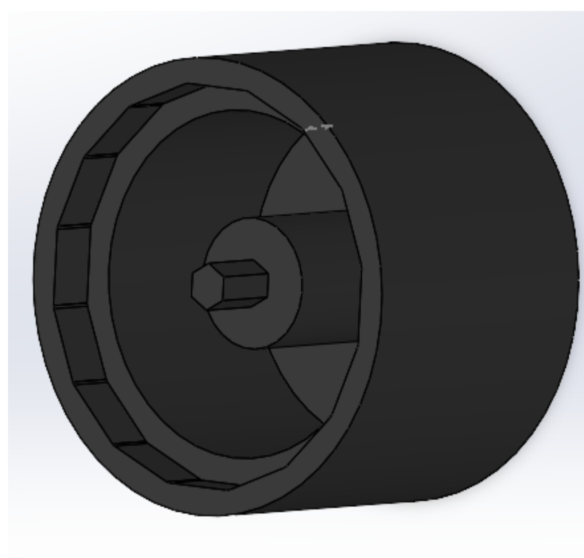

Fig 36. CAD side view of the Magnetic Housing

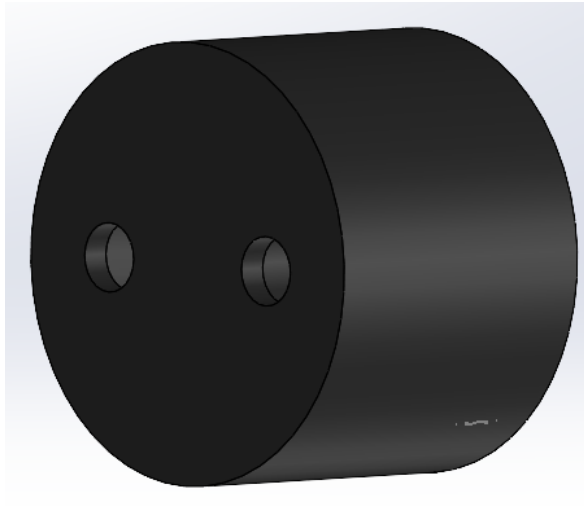

Fig 37. CAD back side view of the Magnetic Housing

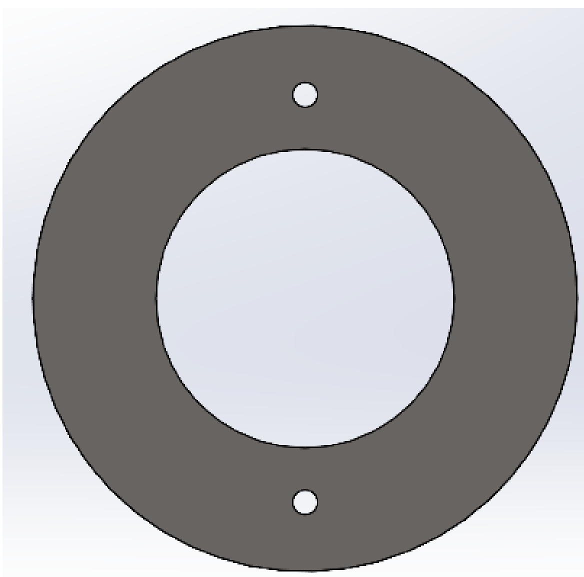

Fig 38. CAD back side view of the Back Plate Anode

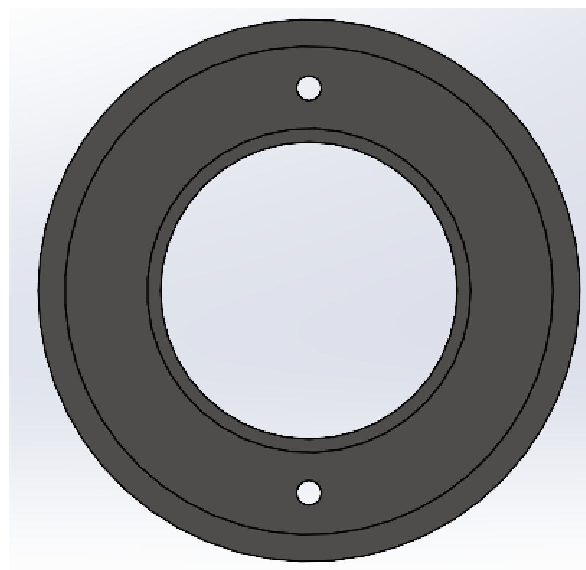

Fig 39. CAD front side view of the Back Plate Anode

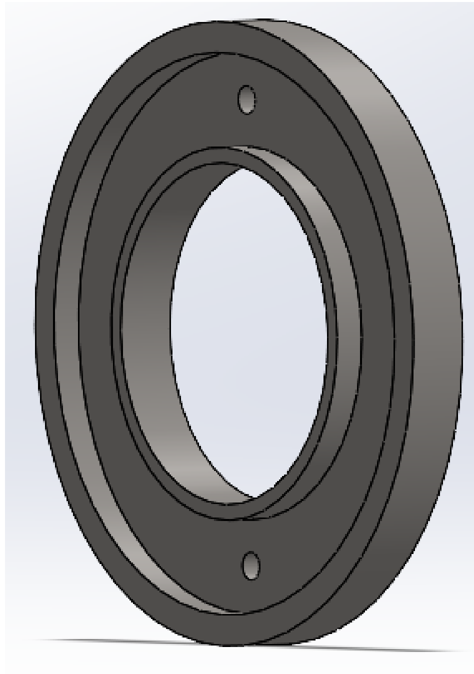

Fig 40. CAD front side view of the Back Anode Plate

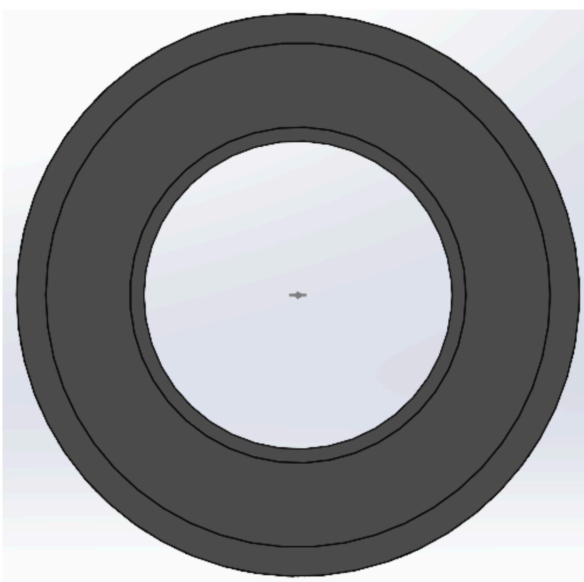

Fig 41. CAD front view of Front Anode Plate

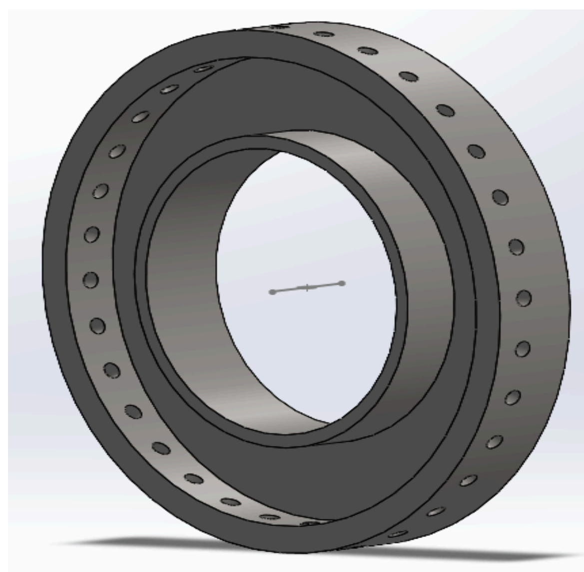

Fig 42. CAD side view of Front Anode Plate

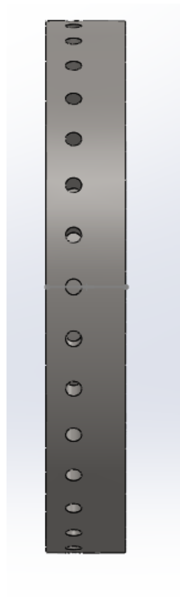

Fig 43. CAD side view of Front Anode Plate

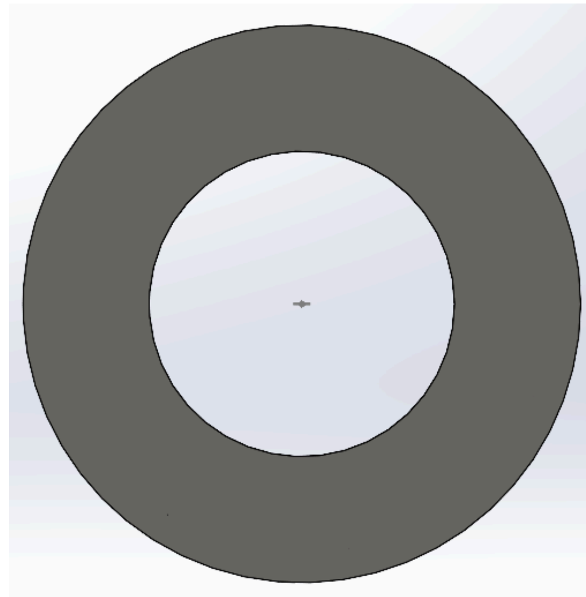

Fig 44. CAD back view of Front Anode Plate

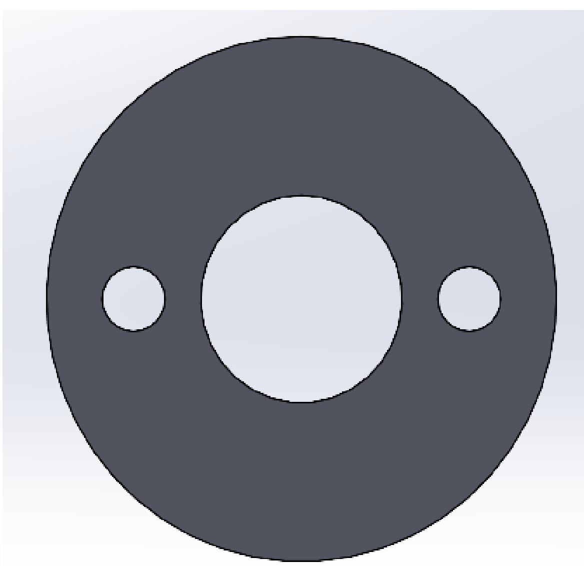

Fig 45. CAD back view of Channel

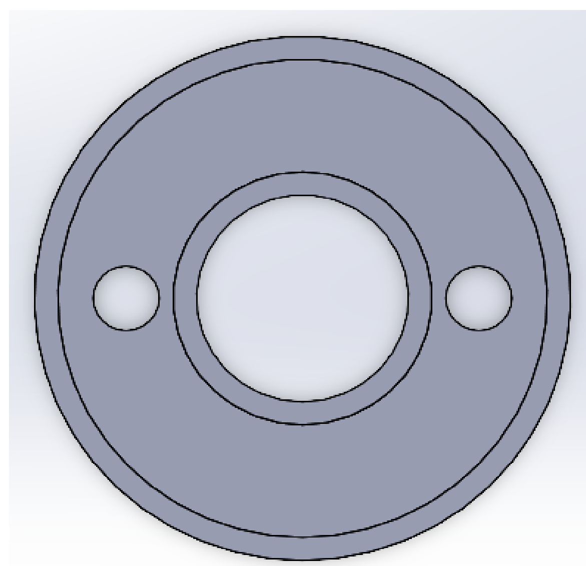

Fig 46. CAD front view of Channel

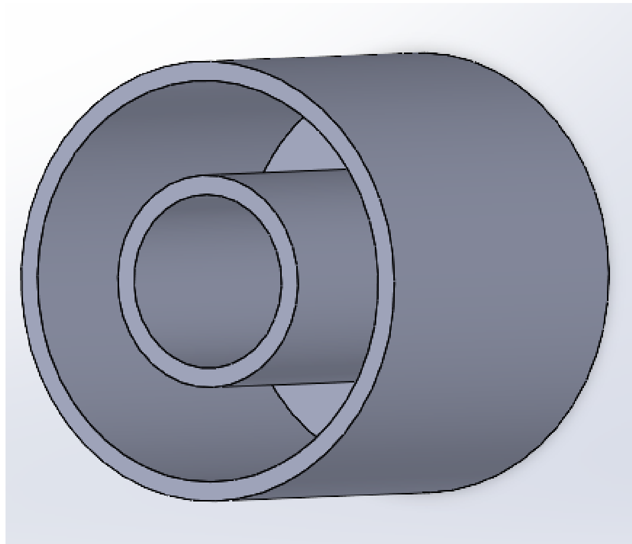

Fig 47. CAD side view of Channel

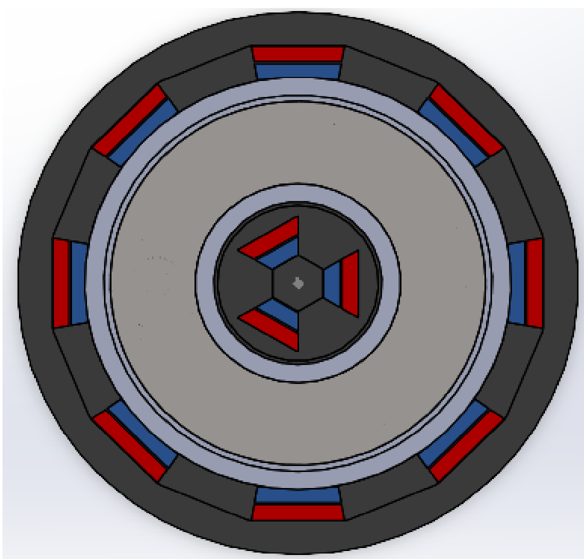

Fig 48. CAD front view of full assembly

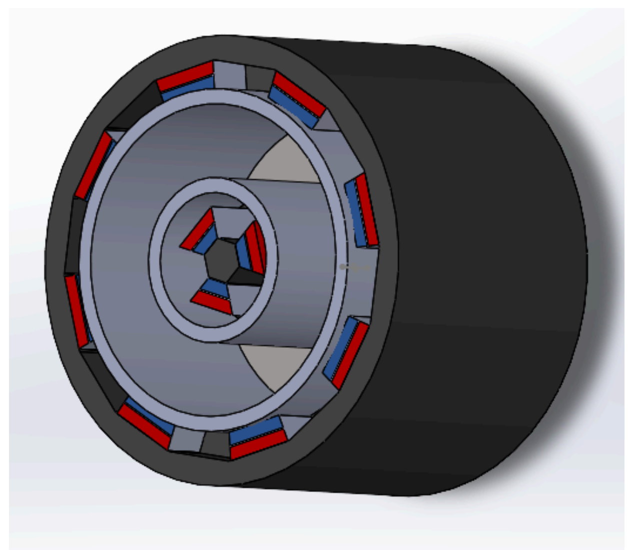

Fig 49. CAD side view of full assembly

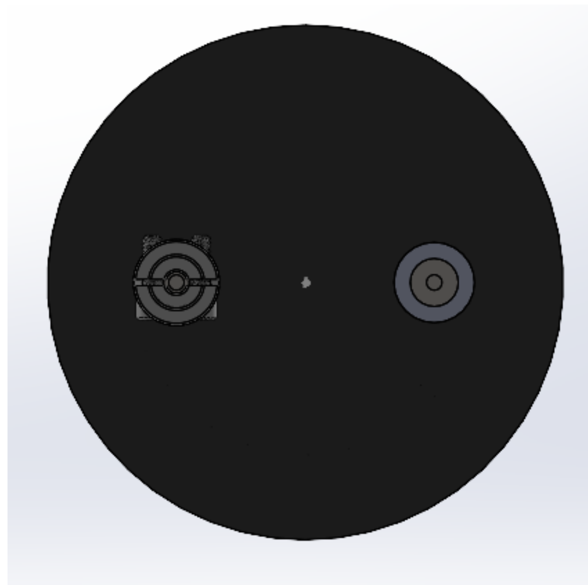

Fig 50. CAD back view of full assembly

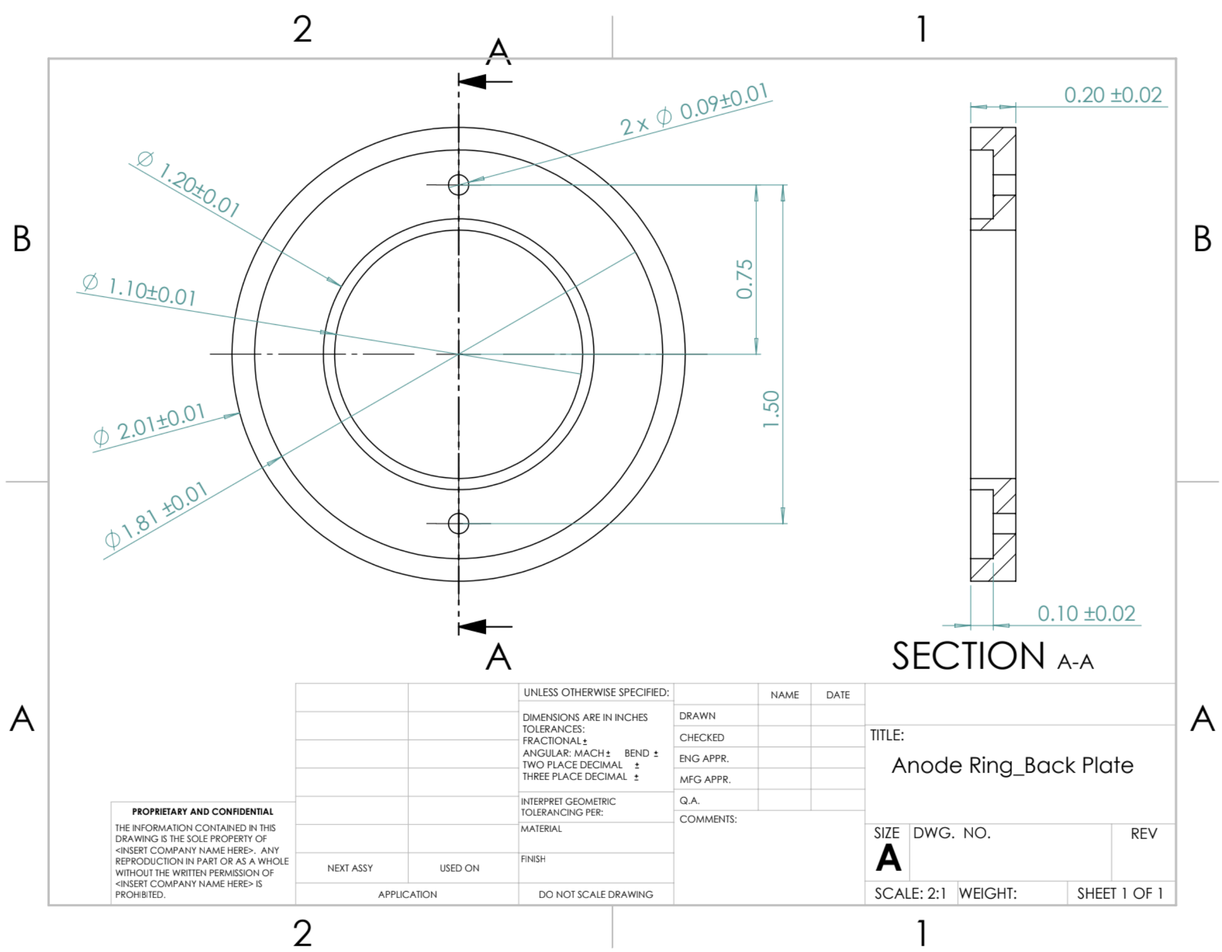

Fig 51. Anode Ring Front Plate GD&T

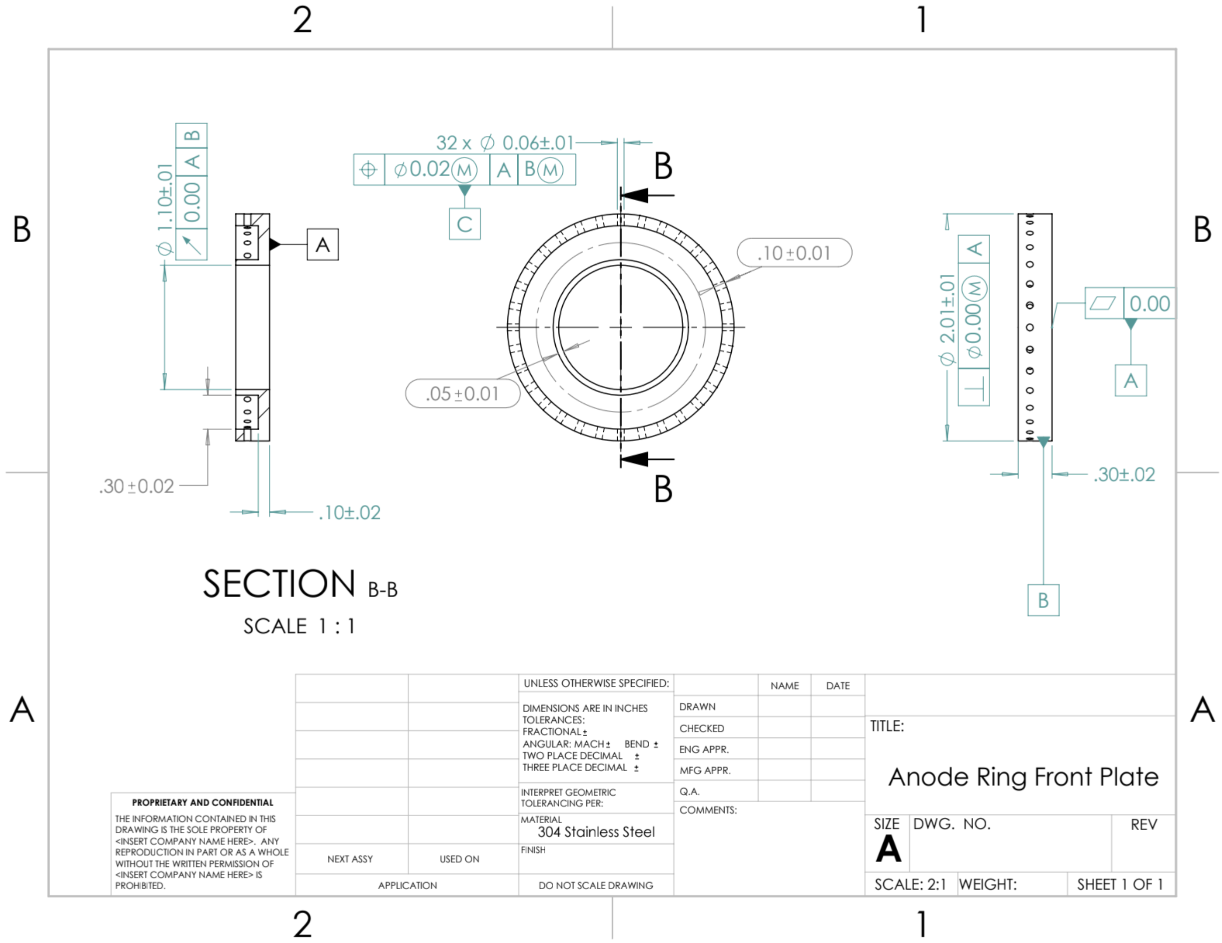

Fig 52. Anode Ring Back Plate GD&T

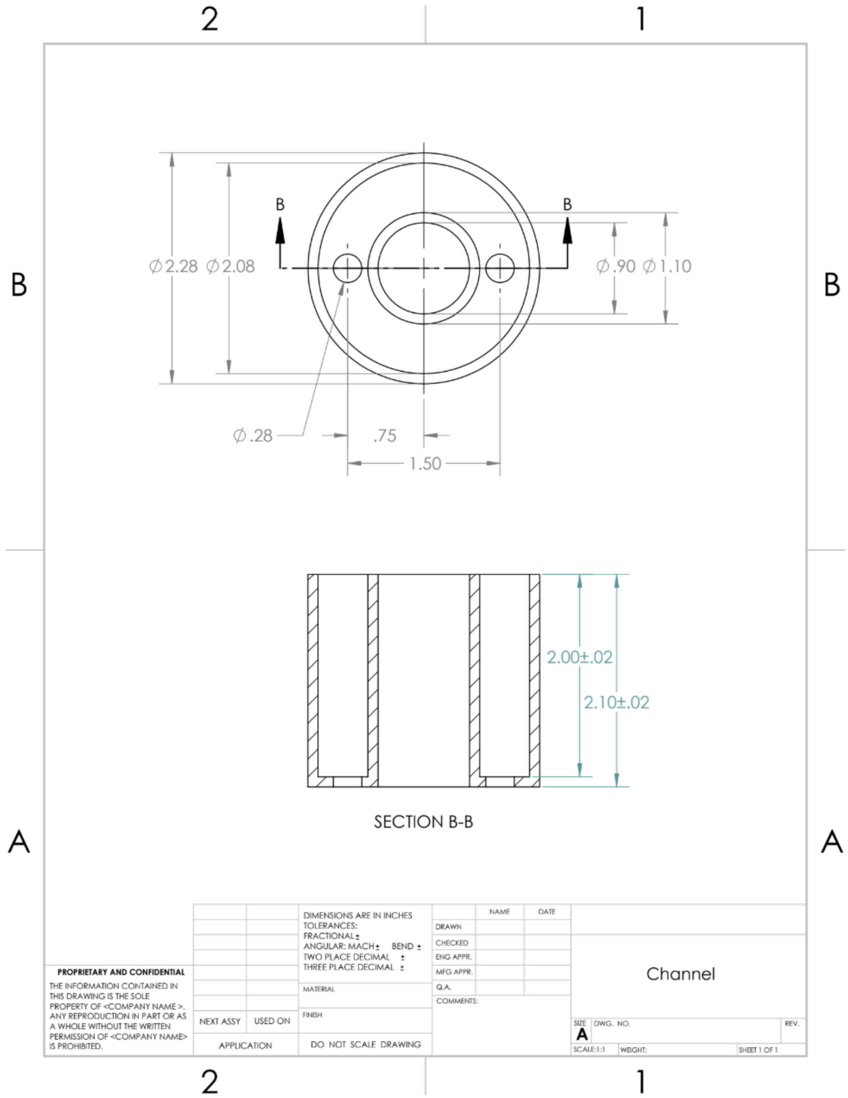

Fig 53. Channel GD&T

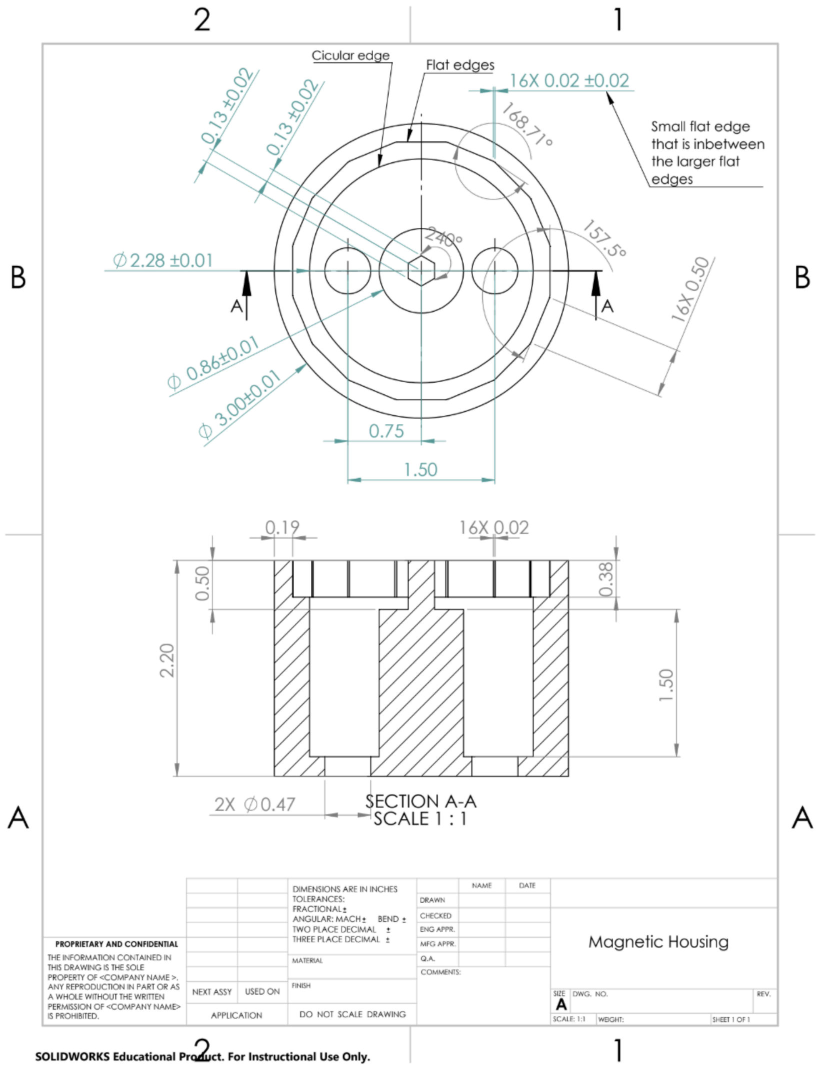

Fig 54. Magnetic Housing GD&T

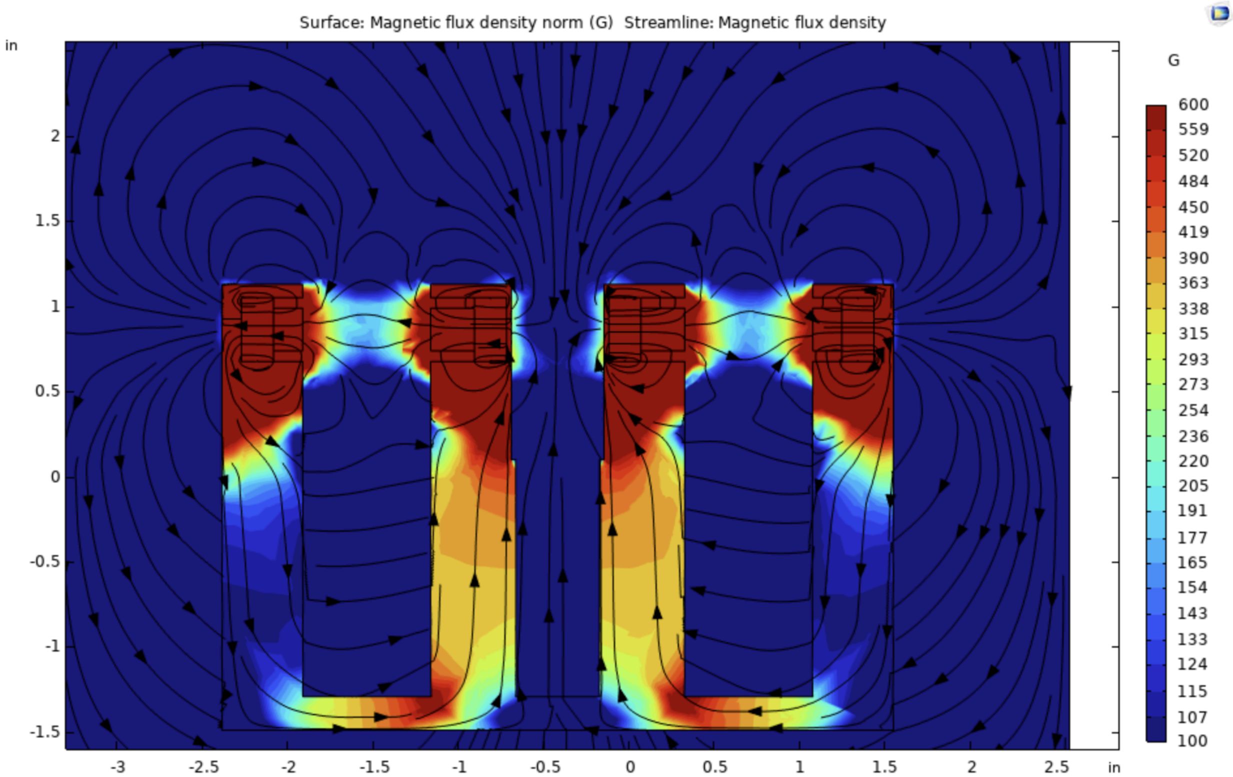

Fig 55. Side Full of Magnetic Field

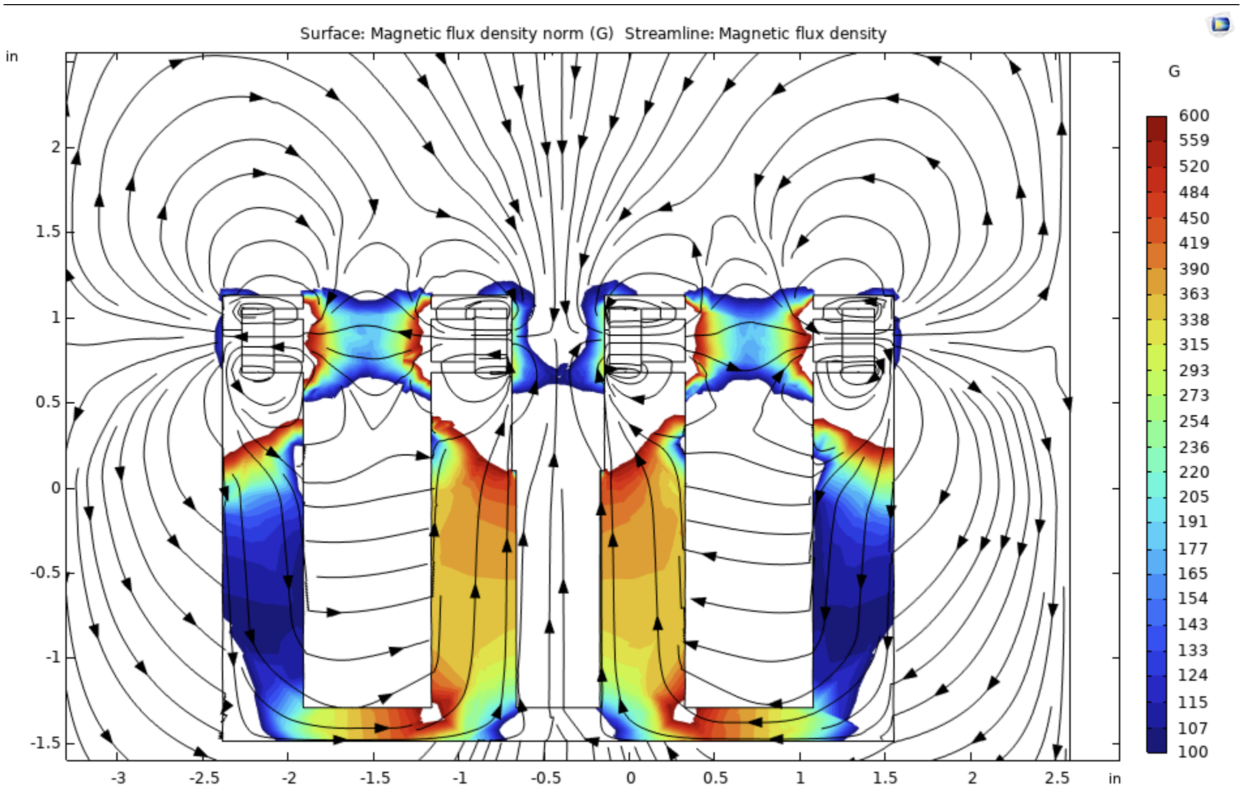

Fig 56. Side Clip of Magnetic Field

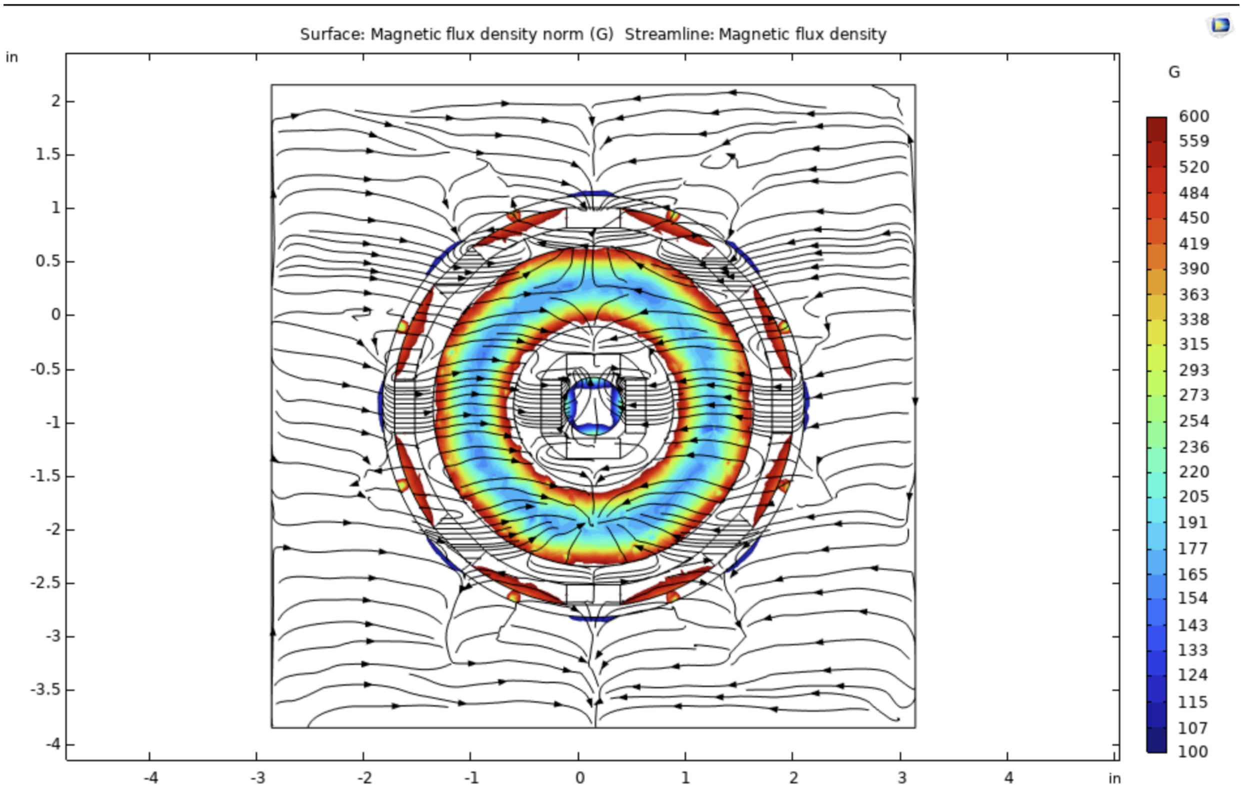

Fig 57. Top clip of Magnetic field

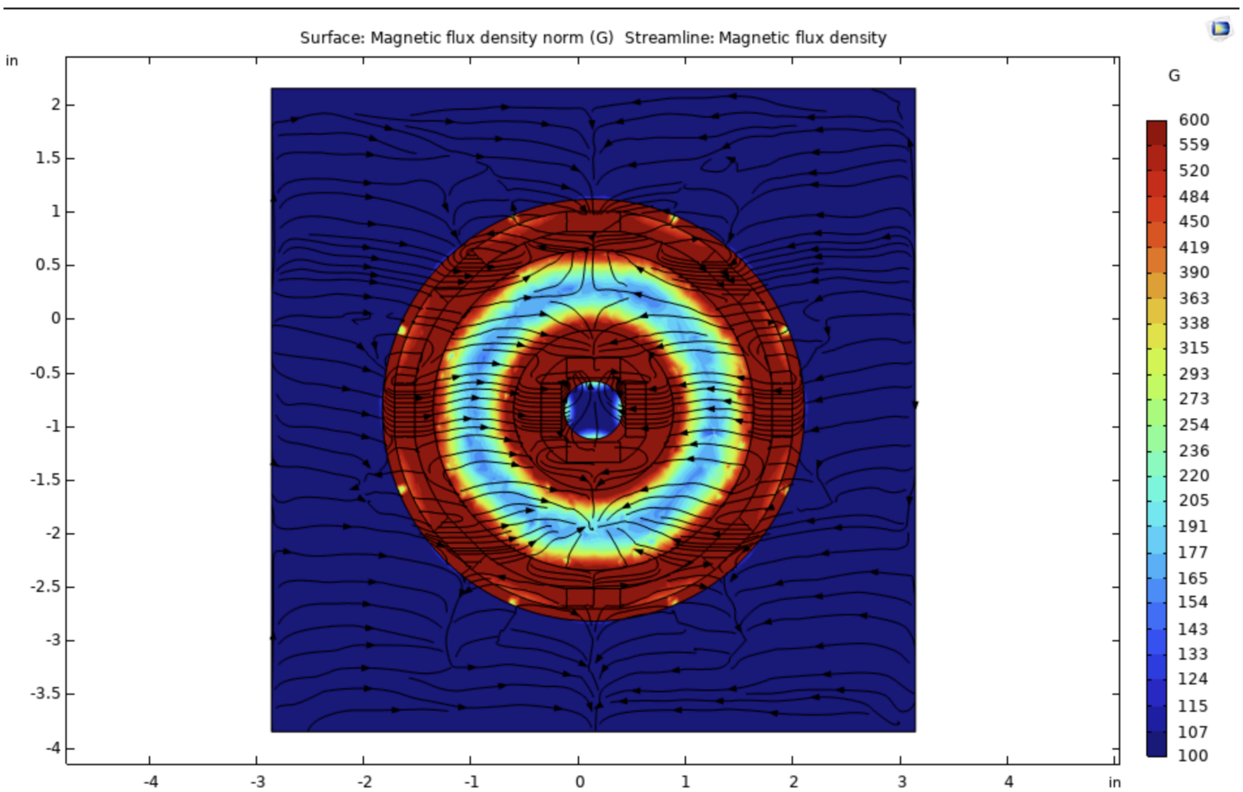

Fig 58. Top full of Magnetic Field

Test	Voltage [V]	Current [A]	Cahode [sccm]	Anode [sccm]	Notes:	Watts [W]
1	75	1.5	5	9	Magnetic field at 1k Gauss (too high)	112.5
1	80	2	5	9	0 Gauss at anode ---> good	160
2	79	1	5	10	- pulled out 3 center magnets (w/all inner magnets) - In between channel 300-400 Gauss - At end of channel 700 Gauss - pulled out 8 outer magnets and 3 center magnets: 8 outer and 3 in the center total - 350 Gauss in between 2 magnets 200 Gauss with gap/ no magnets	79
2	80	2	8	7		160
2	85	2	3	9	better shape, but plasma is still everywhere	170
3	42	1	30	29	- Tightening the feedline to the cathode ----> Failed run because magnetic field too high to strike at first. Then flooded the chamber with gas	42
3	55	1	5	15		55
3	53	2	5	15		106
3	58	2	5	10		116
3	63	2	5	9		126
3	80	2	3	6		160
3	96	2	2	5		192
3	130	2	2.7	5		260
3	150	2	2.7	5	-lots of oscilation and went out at 150 v -got really hot	300
4	120	2	2.6	4.9	turned it back on after test 3	240
4	130	2.2	2.5	4.9		286
4	107	1.5	2.5	4.5	less dispursion/ more uniform	160.5
4	150	1.5	2.5	4	start of instability/more collisions flickering	225
4	158	1.5	2.5	3.6	No flickering. Stable	237
4	200	1.4	2.5	3.5	current controlled	280
4	217	1.5	2.5	3.5		325.5
4	250	1.5	2.5	3.38		375
4	280	1.5	2.5	3.3		420
4	300	1.5	2.5	3.2	Inside of channel turning red, afterwards it got too hot and started to outgas/voltage dropping	450
5	100	1.5	2.5	5	Much more stable ---> most likely killed the inner magnetic field	150
5	119	1.7	2.5	5		202.3
5	150	2	2.5	5	Oscilation level 40 v	300
5	250	2	2.5	4.7	Oscilation level 150 volts peak to peak (turning on and off) ---->current oscilating 70-80% (current shifted to a different mode which is normal)	500
5	232	1.69	2	4.4		392.08
5	280	1.67	2	3.8	Started getting too hot and voltage went down after (outgasing)	467.6
5	300	1	1.8	3.06	300 v case at 300W 500 Gauss in between and 300 in deadspot	300
5						0

Fig 59. Test results