Group 17
Electric Propulsion Thruster for Nanosatellites

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Acknowledgments

Shoutouts to people who helped us

List of Abbreviations

GEO Geostationary Orbit

MEO Medium Earth Orbit

LEO Low Earth Orbit

EP Electric Propulsion

CSA Canadian Space Agency

PPU Power Processing Unit

GIT Gridded Ion Thruster

HET Hall Effect Thruster

PCB Printed Circuit Board

CHT Cylindrical Hall Thruster

AHT Annular Hall Thruster

NOMENCLATURE

I_{sp} Specific Impulse [s]

Chapter 1

Project Overview

1.1 Introduction

1.1.1 Background

The first satellite, Sputnik 1, was launched by the Soviet Union on October 4, 1957. This event marked the start of the space race, leading to new technological, scientific, and political developments [15]. Since then, 23030 satellites have been launched [11]. Satellites orbiting Earth can be split into 3 catagories:

- Low Earth Orbit (LEO) : 160 km - 2,000 km
- Medium Earth Orbit (MEO) : 2,000 km - 35,786 km
- Geostationary Orbit (GEO) : 35,786 km

For decades interest lied in GEO satellites, with Syncom becoming the first GEO satellite in 1963 [16]. Being in geosynchronous orbit meant that satellites could stay at a specific position above Earth, allowing for constant communication with a specific area on Earth. This made these satellites ideal for communication and weather monitoring. However, GEO satellites have high latency due to their distance from Earth, making them less suitable for real-time applications.

Since then the most significant change in satellite technology has been the development of LEO satellites. Although they were first developed in the 1990s, these satellites have only really become widely used in the last decade. Companies like OneWeb and Starlink have launched constellations of LEO satellites to provide low-latency internet access across the globe [18]. These developments denoted a transition in the commercial communication satellite business from small numbers of large geostationary satellites towards constellations of hundreds of smaller lower satellites in low earth orbit.

Fueled by this new idea, the global space industry accelerates as the number of satellites launched annually continues to rise. Both governments and private entities are allocating significant resources to satellite research and development for applications such as communication, navigation, Earth observation, atmospheric characterization, and military purposes.

1.1.2 Project Motivation

With the increasing complexity of mission requirements, the need for more advanced satellite technologies has increased. Specifically, the need for efficient and reliable propulsion systems has become crucial for satellite operations. Satellites require propulsion for various reasons, including orbit insertion, station-keeping, attitude control, deorbiting at the end of their operational life, and formation flying. Additionally, as spent rockets, satellites and other space trash accumulate in orbit, the likelihood of collisions with debris has increased. Unfortunately, collisions create more debris creating a runaway chain reaction of collisions and more debris known as the Kessler Syndrome [12].

There are two main types of propulsion systems used in satellites: chemical propulsion and Electric Propulsion (EP). Satellites have traditionally used chemical propulsion systems, although there is now a huge shift towards EP systems with Space X's Starlink constellation being the largest adopter of EP technology.

Chemical propulsion uses a fuel and an oxidizer, converting energy stored in the chemical bonds of the propellants, to produce a short, powerful thrust, or what we see as fire. It's loud and exciting, but not all that efficient. Chemical propulsion is said to be "energy limited" because the chemical reactants have a fixed amount of energy per unit mass, which limits the achievable exhaust velocity or Specific Impulse [s] (I_{sp}).

Electric propulsion systems use energy collected by either solar arrays or a nuclear reactor to generate thrust by using electric, and possibly magnetic, processes to ionize and accelerate a propellant. It is a technology aimed at achieving thrust with high-exhaust velocities, which results in a reduction in the amount of onboard propellant required for a given space mission or space-propulsion application compared to other conventional propulsion methods. Reduced propellant mass can significantly decrease the launch mass of a spacecraft or satellite, leading to lower costs from the use of smaller launch vehicles to deliver a desired mass into orbit or to a deep space target. [9] It can reduce the amount of fuel, or propellant, needed by up to 90% compared to chemical propulsion systems, saving millions in launch costs while providing greater mission flexibility. [17]

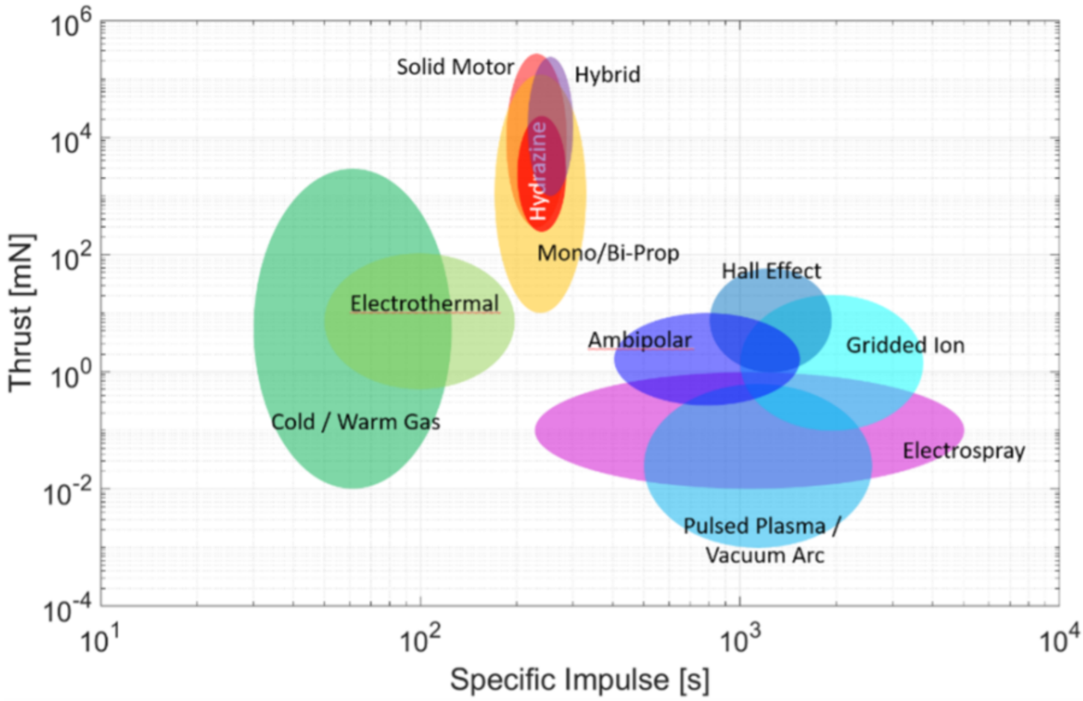

Figure 1.1: Typical small spacecraft in-space propulsion (thrust vs specific impulse) Chemical Thrusters shown in shades of red and Electric Thrusters shown in shades of blue[14].

1.1.3 Relevance

As the technology matures and becomes more widely adopted, we can see an increasing interest in the space and satellite industry by the goverment of Canada. The Canadian Space Agency (CSA) has been actively encouraging development in the industry through initiatives such as the ”Call for Ideas - Science and technology small payloads for space missions” [10]. The CSA also initated a ”Consultation on Changes to Licensing Requirements and Conditions of Licence on Space Debris Mitigation” [13], which aims to address the growing concern of space debris. It proposes mandating active propulsion systems, with redundancy, for all Non-Geostationary Satellite Orbit (NGSO) satellites operating at or above 400 kilometers. This can severley increase the system and integration complexity for small satellites. Hence, now more than ever, there is a need to develop modern, efficient, and reliable propulsion systems for satellites. This shows that the goverment of Canada is aware of the increasing importance of the space industry and is taking steps to ensure its growth and sustainability.

1.2 Capstone Outline

To tackle these issues this capstone project aims to explore the design, simulation, and prototyping of an electric propulsion system suitable for nanosatellites (1–10 kg). First a suitable method of electric propulsion will be selected based on mission requirements and compatibility with nanosatellite applications. The team will then design an electric propulsion module consisting of the key subsystems: a Power Processing Unit (PPU), a propellant storage and feed system, an ionization system.

The proposed design will evaluated using simulation softwares to assess performance metrics such as thrust, electrical performance, and orbital maneuvering potential. Finally, the team will develop a ground-based test stand prototype. While thruster testing may not be possible, this will lay the framework to measure and analyze critical parameters such as thrust, specific impulse, efficiency, and overall system stability under representative operating conditions.

1.3 Capstone Requirements

The requirements for the electric propulsion system are as follows:

- The propulsion system must be compatible with nanosatellite platforms in the 1–10 kg range
- The propulsion module should fit within a volume of 3U (30 cm x 10 cm x 10 cm) or smaller
- The system should be capable of producing a thrust level sufficient for orbit keeping of a nanosatellite at 200km altitude
- The total power consumption of the propulsion system should not exceed 500W
- The system should provide a I_{sp} greater than 500 seconds
- The propulsion system and PPU should not exceed a total mass of 3kg
- The propulsion system should utilize a propellant that is safe and easy to handle
- The design should include considerations for thermal management to ensure stable operation in space environments

1.4 Capstone Deliverables

The expected deliverables are as follows:

- A prototype electric propulsion module suitable for nanosatellites in the 1–10 kg range
- A design and prototype of a thrust test stand capable of accurately measuring low thrust levels
- CAD models, technical drawings, and electronic schematics associated with the system
- Simulation results validating key aspects of the propulsion system, including thrust and electrical performance

These outcomes will demonstrate the feasibility of implementing electric propulsion on nanosatellite platforms and provide a foundation for further development and testing

1.5 Development Plan

Explain dev plan here

Put image of gantt chart here

Chapter 2

Electric Propulsion Method Selection

To determine the baseline design for the EP system being developed, several EP technologies were evaluated for compatibility with the requirements. Some of the primary determining factors included:

- Thrust level
- Specific impulse
- Power requirements
- Propellant type
- System complexity
- Flight Heritage

While most of these requirements are already defined, the thrust requirement needs to be further refined.

2.1 Thrust Requirement

One of the reqirements was that "The system should be capable of producing a thrust level sufficient for orbit keeping of a nanosatellite at 200km altitude". To calculate the necessary thrust levels for maintaining a stable orbit at various altitudes, a python script was developed. The script considered atmospheric drag as the primary actor, while assuming all other forces such as solar radiation pressure were negligible. The drag force was calculated using the standard drag equation:

$$F_d = \frac{1}{2} C_d \rho A v^2 \tag{2.1}$$

where F_d is the drag force, C_d is the drag coefficient, ρ is the atmospheric density at the given altitude, A is the cross-sectional area of the satellite, and v is the orbital velocity.

The drag coefficient C_d was assumed to be 2.2, which is typical for small satellites. (Provide a reference for this) The cross-sectional area A was taken as the average surface area of the satellite. The atmospheric density ρ was estimated using the ... model, which provides values for densities of each element in the atmosphere at different altitudes. The orbital velocity v was calculated using the formula for circular orbits:

$$v = \sqrt{\frac{GM}{r}} \tag{2.2}$$

where G is the gravitational constant, M is the mass of the Earth, and r is the distance from the center of the Earth to the satellite.

As shown in fig 2.1, the script iterated over a range of altitudes and satellite sizes to compute the required thrust to counteract drag. The results were plotted to visualize the relationship between altitude, satellite size, and required thrust.

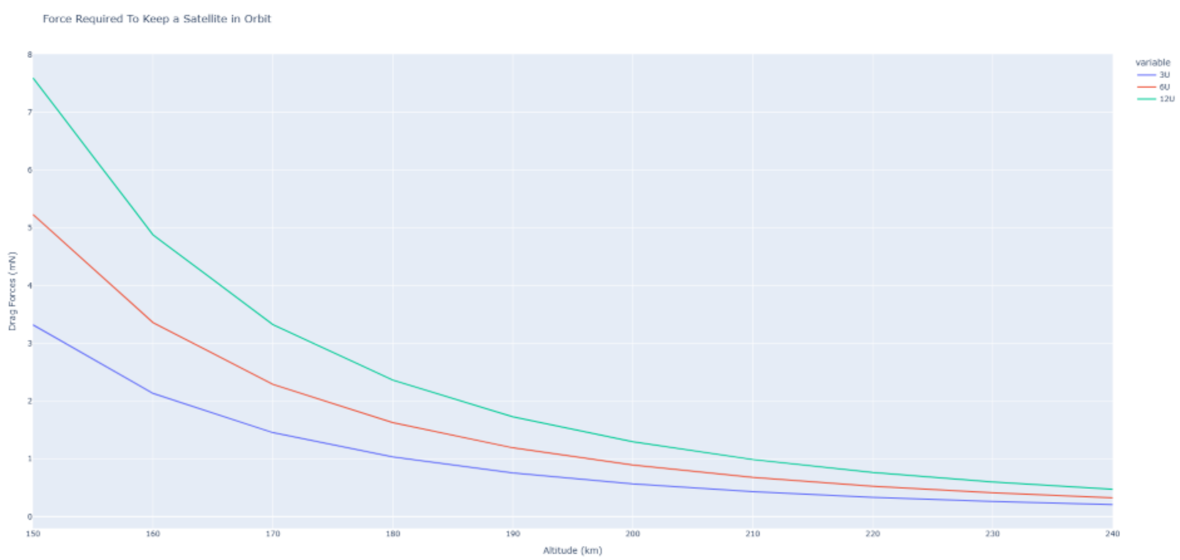

Figure 2.1: Drag Force vs Altitude for Various Satellite Sizes

Assuming that the drag force is the only force acting on the satellite, the required thrust to maintain a stable orbit is equal in magnitude and opposite in direction to the drag force. The results indicated that a thrust level of approximately ... mN would be sufficient for orbit keeping at 200km altitude for a nanosatellite in the 1-10 kg range.

Hence any force greater than this would be sufficient for orbit keeping and if sufficiently higher thrust levels were available, the system could also be used for orbit raising.

2.2 Propulsion Methods Considered

2.2.1 Gridded Ion Thrusters

2.2.2 Hall Effect Thrusters

2.3 Selection Results

Chapter 3

Hall Thruster Theory

Before diving into the design specifics of our Hall Effect Thruster (HET), it is essential to understand the fundamental principles that govern its operation. In comparison to other electric propulsion systems, such as ion thrusters, the construction of a HET may be relatively simple, but the physics involved to produce thrust is much more complicated, and less predictable. The dimensions of the discharge chamber, and the shape and strength of the magnetic field have a great impact on the performance, efficiency, and lifetime of the thruster.

Chapter 4

Conceptual Design

Over the years, many different designs and configurations of the HET have been developed and tested. While there may be many different variations of the thruster, they all share the same basic subsystems, with most concepts focussing on improving one or more of these subsystems. The following section will cover these major subsystems, and existing designs for each of them. This will provide a foundation for the conceptual design of our HET, and the reasoning behind the choices made in our design. The major subsystems of a HET are as follows:

- Magnetic Field System
- Cathode
- Anode and Propellant Feed System

This conceptual design phase will focus on the above subsystems, that will affect the thruster architecture. Other aspects such as propellant selection, material selection, and avionics will be discussed in the detailed design, as they are less likely to affect the thruster architecture and rather behave as supporting systems.

Many different types of HETs have been developed over the years, with each design having its own advantages and disadvantages. Before diving into the specific subsystems, we will first look at two of the more relevant thruster types:

- The Annular Hall Thruster (AHT)
- The Cylindrical Hall Thruster (CHT)

4.1 Hall Thruster Types

4.1.1 Annular Hall Thrusters

AHTs are the most common type of HET in use today. They feature an axisymmetrical annular discharge channel where tne propellant is ionized and accelerated. The magnetic field is generated by coaxial coil windings wrapped in and around the discharge channel or by permanent magnets. It consists on a high voltage metallic anode located upstream in the channel, and a cathode that is often located outside the channel.

In-space thruster tests with this geometry have demonstrated thrusts up to 280mN. They have exhibited power levels of up to 4.5kW, and specific impulses up to 2000s. [4] [5]

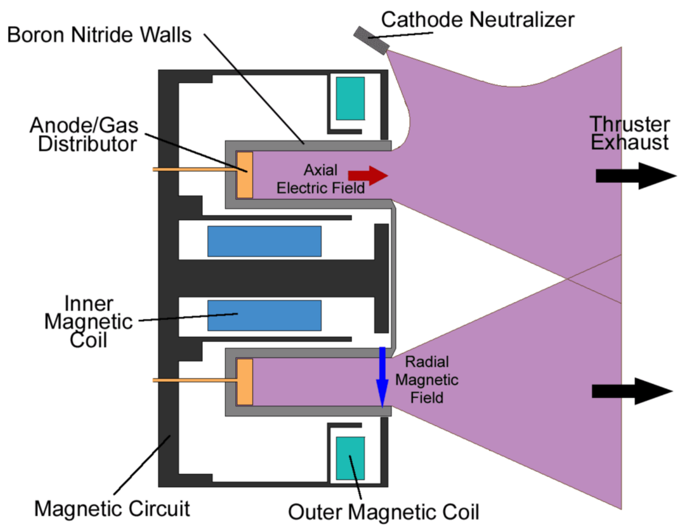

Figure 4.1: Annular HET

4.1.2 Cylindrical Hall Thrusters

One of the largest drawbacks when downscaling AHTs is the increase in surface area to volume ratio, which leads to higher wall losses and lower efficiency. The plasma tends to interact with the thruster channel walls, which results in heating and erosion of the thruster parts [1]. To combat this, CHTs, proposed at the Princeton Plasma Physics Laboratory were developed. As seen in figure 4.2, the ratio of the channel surface area to volume is reduced, limiting electron transport and ion losses [3]. These thrusters have also seen unusually high propellant ionization efficiencies, hence being able to operate at much lower discharge voltages and propellant flow rates [2].

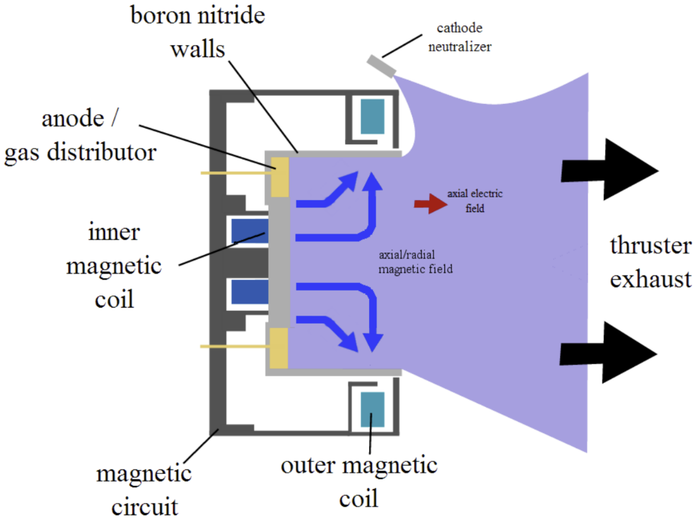

Figure 4.2: Cylindrical HET [7]

4.2 Propellant Feed System and Anode

storage tank feed plumbing injector

talk about anode

4.3 Magnetic Field Design

As described in section 3, the radial magnetic field in a HET traps electrons in an azimuthal Hall current, which allows for a strong axial electric field to be established. The methods of generating this magnetic field considered were:

- Electromagnetic Coils
- Radial Permanent Magnets
- Field shaping with a ferromagnetic core and permanent magnets

4.3.1 Electromagnetic Coils

Electromagnetic coils are the most common method of generating the magnetic field as seen in fig 4.1. They allow for the magnetic field strength to be adjusted bu changing the current flowing through the coils. However, they require a significant amount of power to operate, which is not ideal for smaller, lower power thrusters. Additionally, they generated heat which increases the design complexity as further thermal management will be required.

4.3.2 Radially Aligned Permanent Magnets

Another solution is to use ring shaped permanent magnets, placed near the exit plane of the thruster to generate the radial magnetic field as seen in fig 4.3. This method does not require any power to operate, and does not generate heat. However, the magnetic field strength cannot be adjusted without physically changing the magnets. Additionally, the custom radially aligned magnets can be expensive to purchase or manufacture.

4.3.3 Field Shaping with a Ferromagnetic Core and Permanent Magnets

The final method considered was to use a ferromagnetic core to shape the magnetic field generated by a set of smaller permanent magnets. This means that a material with high magnetic permeability is used to direct the magnetic field lines from the magnets embedded in the core to the desired locations in the thruster channel. An example of this method can be seen in fig 4.4. This method does not require any power to operate, and does not generate heat. Similar to the permanent magnet design proposed above, the magnetic field strength cannot be adjusted without physically changing the magnets.

This method also allows for the use of smaller, more common magnets which are cheaper and easier to source.

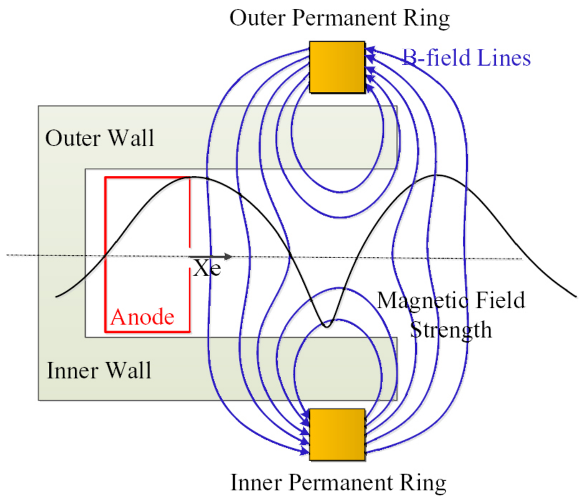

Figure 4.3: Magnetic Field concept using radially aligned permanent magnets near the thruster exit plane [6]

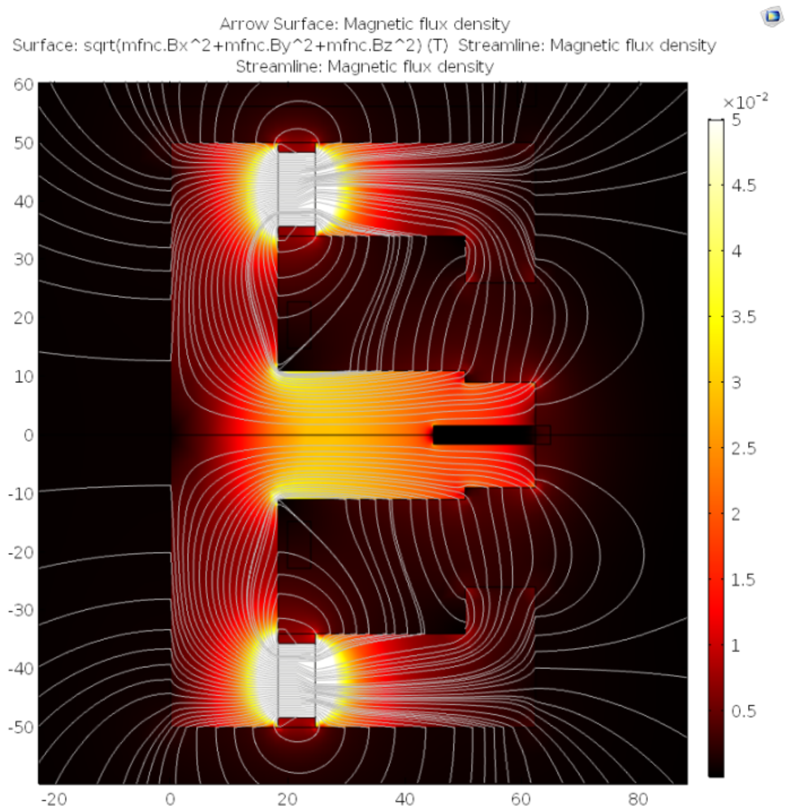

Figure 4.4: Predicted magnetic field lines using a ferromagnetic core and permanent magnets (seen in bright yellow/white) [8]

4.4 Cathode Placement

4.5 Final Concept

The final basic geometry of our final concept is shown in figure 4.5. It is important to note that the render does not include all components such as the propellant feed system and propellant diffuser, and that the design may very well change as we move through the design process. However, it does the job of conveying some of the design goals and choices that have been made. The final concept will consist of the following features:

1. Magnetic Field System - will consist of a ferromagnetic core with permanent magnets to create the required magnetic field topology. This will reduce power consumption and avionics system complexity
2. Cathode - will be centrally mounted on the thruster axis allowing for a more compact design
3. Ring anode - simple and well understood design
4. Propellant feed system - will consist of a pressure vessel, custom propellant diffuser, and supporting hardware. May become to primary conductor to the anode.

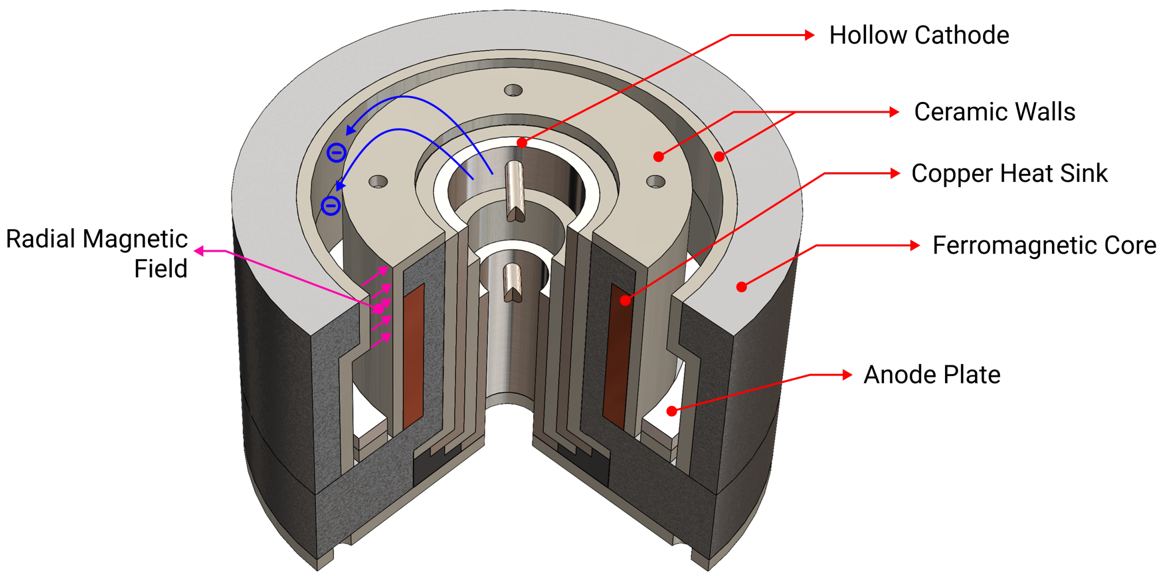

Figure 4.5: Final Concept Diagram

Chapter 5

Design Development

5.1 Propellant Selection

5.2 Channel Wall Material Selection

5.3 Avionics

To control and operate the thruster we require an avionics subsystem that can provide power, control signals, and data acquisition. For this several Printed Circuit Board (PCB)s may need to be designed such as the PPU, and a seperate low power control board. Accompanying, this electrical system a real time software control system will be needed to operate the thruster, and monitor its performance.

5.3.1 Electrical System

block diagrams reference to existing designs explanation of the goal of the system how it will be run from soalr panels etc

5.3.2 Software

reference to existing use of real time system in rockets Exaplin the RTOS and using MCU peripherals like PWM How this choice of software architecture will help achieve the final goals Explain that low power feature will be used to minimize power consumption in space

Chapter 6

Testing

6.1 Testing in Vacuum

Talk about chamber and testing considerations

6.2 Test Stand

explain existing methods

why you chose yours

touch on initial concept

change dues to chamber sizes

final concept

data acquisition needed

6.3 Test Software

Exaplain ideas considered, why unity

6.3.1 Software in the Loop Testing

Explain what the purpose of this is, how you plan to do it (aka. testing software through simulated data)

6.3.2 Hardware in the Loop Testing

Explain what the purpose of this is, how you plan to do it (aka. testing software through real data from the test stand)

6.4 Test Electronics

If Applicable

Chapter 7

Prototypes and Results

Chapter 8

Closing Remarks

Chapter 9

Project Management

Appendix A

List of Figures

Here you can include additional figures, tables, or explanations.

Appendix B

List of Tables

Detailed derivations go here.

Appendix C

Engineering Drawings

Appendix D

Code Snippets

```
for i in range(10):
    print(i)
```

Bibliography

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