**ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL**

# MINIATURE ELECTRICAL PROPULSION SYSTEM DESIGN FOR CUBE SATELLITES

**M.Sc. THESIS**

**Egemen ÇATAL**

**Department of Defense Technologies**

**Defense Technologies Programme**

**JULY 2022**

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**Thesis Advisor: Prof. Dr. Alim Rüstem Aslan**
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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

# NANO UYDULAR İÇİN
# MİNYATÜR
# ELEKTRİKLİ İTKİ SİSTEMİ TASARIMI

**YüKSEK LİSANS TEZİ**

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**TEMMUZ 2022**

Egemen ÇATAL, a M.Sc. student of ITU Graduate School student ID 514191041, successfully defended the thesis entitled "MINIATURE ELECTRICAL PROPULSION SYSTEM DESIGN FOR CUBE SATELLITES", which he/she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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**Date of Submission : 1 May 2020**
**Date of Defense : 1 June 2020**

***To infinity and beyond...***

## FOREWORD

For the foreword, 1 line spacing must be set. The foreword, written as a first page of the thesis must not exceed 2 pages.

The acknowledgments must be given in this section.

After the foreword text, name of the author (right-aligned), and the date (as month and year) must be written (left-aligned). These two expressions must be in the same line.

The foreword is written with 1 line spacing.

July 2022 Egemen ÇATAL
(Physics Engineer)

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## MINIATURE ELECTRICAL PROPULSION SYSTEM DESIGN FOR CUBE SATELLITES


### SUMMARY

1 line spacing must be set for summaries. For theses in Turkish, the summary in Turkish must have 300 words minimum and span 1 to 3 pages, whereas the extended summary in English must span 3-5 pages.

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# NANO UYDULAR İÇİN MİNYATÜR ELEKTRİKLİ İTKİ SİSTEMİ TASARIMI

## ÖZET

Özet hazırlanırken 1 satır boşluk bırakılır. Türkçe tezlerde, Türkçe özet 300 kelimeden az olmamak kaydıyla 1-3 sayfa, İngilizce genişletilmiş özet de 3-5 sayfa arasında olmalıdır.

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Özetlerin başında, birinci dereceden başlık formatında tezin adı (önce 72, sonra 18 punto aralık bırakılarak ve 1 satır aralıklı olarak) yazılacaktır. Başlığın altına büyük harflerle sayfa ortalanarak (Türkçe özet için) **ÖZET** ve (İngilizce özet için) SUMMARY yazılmalıdır.

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# 1. INTRODUCTION

## 1.1 Cube Satellites

A cube satellite, or cubesat, is a small satellite made up of 10cm x 10cm x 10cm sized cubes [1]. One cube module is called 1 unit or 1U for short. Typically 1U has no more than 1.33kg of mass [1] [2]. Depending on the mission the size of the cubesat may vary from 1U to 27U's. Due to this fact a cubesat can either be classified as a nano satellite (1-10kg) or a micro satellite(10-100kg) [3]. A cube satellite can include several subsystems such as an on-board computer(OBC), electrical power system(EPS), atttitude determination and control system(ADCS), batteries and necessary payloads to perform its mission. Additionally they can carry antennas to communicate with the ground station and solar cells to provide power to the subsystems and to recharge the batteries.

The concept of cubesat was jointly developed by Stanford University and California Polytechnic University in 1999. It was designed as a tool to help students and engineers to develop necessary skills for the design and operate satellites. Majority of the cubesat launches have been originated by academic institutions. Even though the concept of a cubesat is created as a tool for educational purposes recent advancements in electronics and sensor technology allow for more miniature components and expand the mission envelope for cubesats. Missions that could only be realized by large satellites such as high-resolution earth observation or complex scientific observations such as X-ray observation can now be performed by a cubesat.

Due to their low cost and ease of accesibility cubesats have become first ever satellites of some countries. Projects such as BIRDS by JAXA enables developed nations to partner with underdeveloped countries and produce their first space asset in the form of a cubesat [4].

As of 2022 more than 1600 cubesats have been launched into space [5]. Vast majority of cubesats have been launched into LEO with very few of them are actually deployed into deep space. NASA's *InSight* mission carried the first cubesats to leave LEO: MarCO-A and MarCO-B [6]. There are plans to deploy cubesats into lunar orbit with upcoming Artemis missions as well [7].

### 1.1.1 Cube satellite research at ITU

At Istanbul Technical University any research related to cube satellites is handled by Space Systems Design and Testing Laboratory(SSDTL) operating under department of aeronautics and astronautics. Ever since its establishment in 2007, 7 cube satellites have been designed by SSDTL and 6 of them have been launced into space to perform variety of tasks such earth observation,scientific missions or handling radio communications [8]. Among the satellites launched into space is ITUpSAT-1, a 1U sized cubesat; first of its kind ever designed by Turkey [9]. An image of flight model of ITUpSAT-1 is shown in figure 1.1.

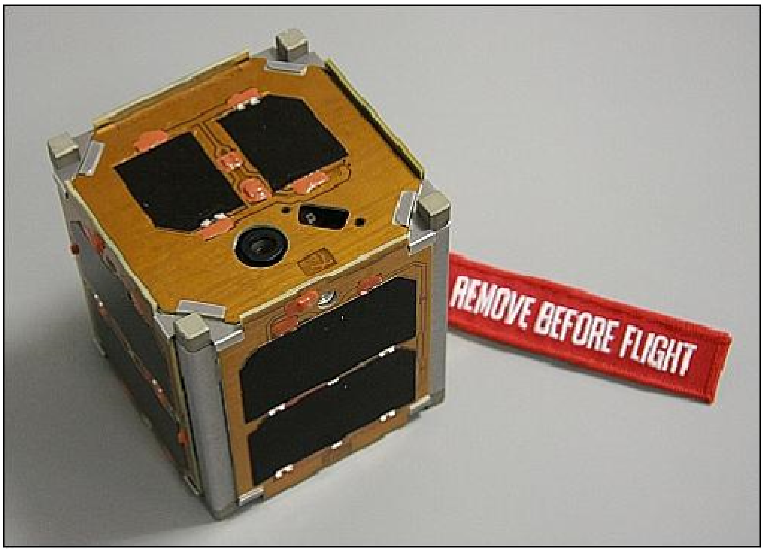



**Figure 1.1 :** 1U sized cubesat ITUpSAT-1 [9]

In addition to satellites individual research have been performed into subsystems such as an interface board, OBC, an EPS and ADCS [8] [10][**INTERFACE KARTINA ATIF BUL**]. To date no work have been done regarding the propulsion systems for cube satellites.

## 1.2 Spacecraft Propulsion Systems

A propulsion system is defined as a system that enables acceleration for a spacecraft. The contents of this section only includes propulsion systems that are used in space. Other systems such as launch vehicles are not included. Propulsion systems may be used to perform variety of tasks in space such as orbital maneuvering, station-keeping or attitude control.

A propulsion system generates thrust, typically expressed in units of newtons(N) that in turn changes the spacecraft's velocity. Thrust is given as the change in momentum with respect to time [11].

alters

$$T = \frac{d}{dt}(m_p v_{ex}) = \dot{m}_p v_{ex} \tag{1.1}$$

where $m_p$ is the propellant mass, $v_{ex}$ is the exhaust velocity of the departing propellant and $\dot{m}_p$ is the flow rate of the propellant.

In order to examine the performance and efficiency of the thruster the term "Specific Impulse" is used, denoted as $I_{sp}$. It is defined as the ratio of the generated thrust to the Earth weight of the flow rate of the propellant as shown in equation 1.2.

$$I_{sp} = \frac{T}{\dot{m}_p g} \tag{1.2}$$

Substituting the expression of $\dot{m}_p$ from equation 1.1 into equation 1.2 gives;

$$I_{sp} = \frac{v_{ex}}{g} \tag{1.3}$$

Using $v_{ex}$ for specific impulse calculations gives its unit in seconds(s). Higher specific impulse levels means higher efficiency. Ion thrusters, a member of electric propulsion family, has specific impulse values around 3000 seconds but provide low thrust as opposed to chemical thrusters such as monopropellant thrusters that has specific impulse levels as ~~low as 300~~ seconds but provide greater thrust [12] [13].

Based on their operating mechanism propulsion systems can be divided into two main groups as chemical and electric propulsion systems. This section includes general information regarding both types of systems to provide a basis for following sections.

### 1.2.1 Chemical propulsion systems

Chemical propulsion systems exploit the energy in the molecular bonds of the propellant. When the propellant is ignited these molecular bonds are broken and energy is released. Thrust is generated when this hot, expanding propellant is ejected from the spacecraft.

Many cube satellites are launched into space as secondary payloads. Limitations of secondary payloads regarding the stored chemicals and combustion within the satellite pose serious challenges. Although there are several systems currently under development, so far no cube satellite with a chemical propulsion system have been launched into space [13]. Depending on the type of the used propellant there are several types of chemical propulsion systems available: monopropellant, bi-propellant and solid rocket engines

#### 1.2.1.1 Monopropellant

#### 1.2.1.2 Bi-propellant

#### 1.2.1.3 Solid rocket engines

### 1.2.2 Electric propulsion systems

Electric propulsion systems provide thrust without igniting their propellants. They use the on-board electrical power supply to generate thrust. Compared to chemical propulsion systems they produce less thrust and higher specific impulse [14]. Due to their low thrust and high specific impulse output they are mainly used for space missions that require high $\Delta V$ and efficiency. Also due to the low thrust they are often subjected to long continuous use. EP systems can be further examined under three main groups: electrothermal, electrostatic and electromagnetic systems [11].

low thrust
propellant
use
efficient

#### 1.2.2.1 Electrothermal propulsion

**Resistojet Thruster**

Resistojet thrusters constitute the simplest approach for an electric propulsion system. Compressed propellant, either in liquid or gas state, is fed into the nozzle of the thruster. Within the nozzle area is located a heating element. This heating element is usually just a simple resistor that produce ohmic heating due to current flow. As the propellant passes through the heating area it heats up and expands. This expanded gas is then ejected from the spacecraft to produce thrust. A schematic of a resistojet thruster is shown in figure 1.2

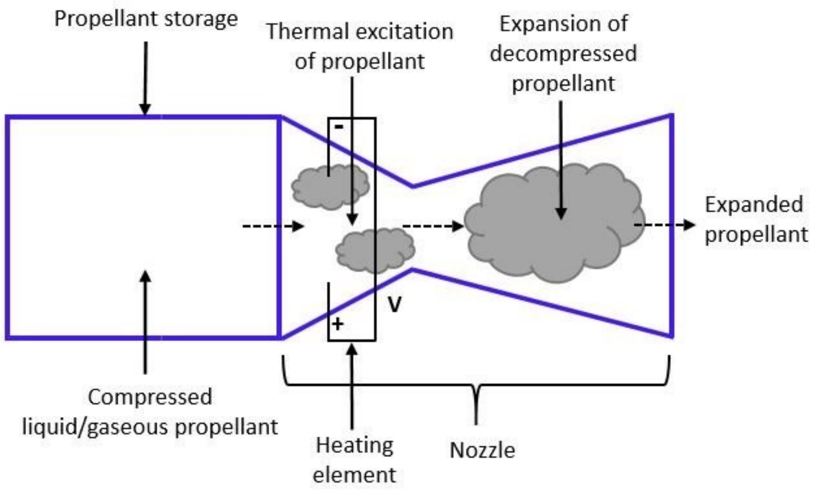



**Figure 1.2 :** Resistojet thruster schematic [15]

Even though they have a considerable flight heritage on regular sized satellites none have flown into space on board a cube satellite so far [13]. Several companies have developed or in the process of developing resistojet thrusters. CubeSat High Impulse Propulsion System(CHIPS) designed and developed by CU Aerospace is stated to provide specific impulse of 76 s and thrust of 31 mN with 25W of power consumption [16]. Busek company has developed a micro resistojet thruster that can provide 150s specific impulse and 30 mN at 15W input power [13]. Both of these designs share similar sizes and occupy approximately 1U volume.

Resistojet thrusters suffer from low efficiency obvious by their low specific impulse values. However considering their low power consumption and high thrust output they may be suitable for cubesat missions.

**Arcjet Thruster**

Similar to resistojets the aim of an arcjet thruster is to heat up the propellant and then eject the expanding propellant to create thrust. The method of heating up the propellant however, is different. Instead of a heating element an arcjet thruster consists of an anode, acentral cathode and injector. Prior the ignition high voltage, on the level of thousands of volts, is applied in between the cathode and anode. Ignition and arc forming occurs due to paschen-discharge [17] in the gap between the anode and cathode. Propellant injected into this gap is heated up and expanded. Expanded propellant is directed into the nozzle and thrust is generated. Working principle of an arcjet thruster is illustrated in figure 1.3

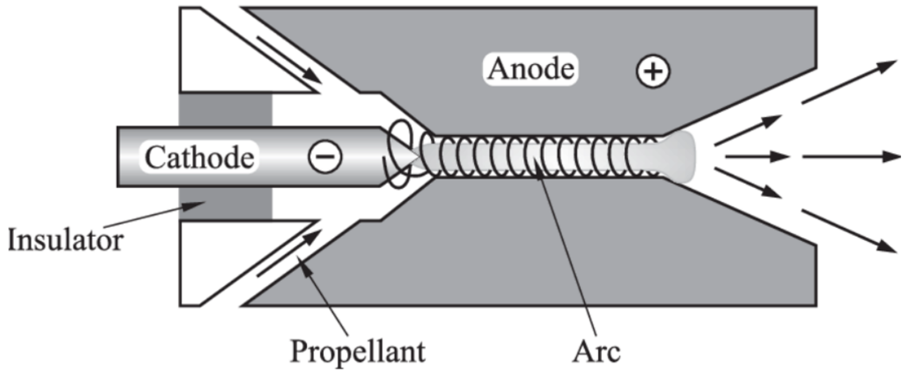



**Figure 1.3 :** Arcjet thruster schematic [18]

Plasma effects that occur because of the high current arc is neglectible since propellant is only weakly ionized. Specific impulse provided by the arcjets are recorded to be limited at approximately 700 s [11].

#### 1.2.2.2 Electrostatic propulsion

**Ion Thruster**

Ion thrusters, or sometimes called ion engines, utilize ions to create thrusts. These ions are supplied by the plasma generated and sustained within the thruster. In order to accelerate the ions a grid extraction system is used. This extraction system consists of two or three biased grids that create an electrostatic field. Any ion that encounters this electrostatic field is then ejected from the spacecraft. Depending on the mass of the used propellant ejected ions can reach speeds up to 1000 km/s [11]. They can provide $I_{sp}$ values up to 3500 s [14]. Since spraying only ions from spacecraft will cause spacecraft be rapidly charged a neutralizer mechanism is needed to preserve the neutrality of the spacecraft.

There are three main types of ion thrusters in literature. First one is called Kaufman type thruster, also known as electron bombardment thruster, mainly studied in the United States, another one is RF ion thruster originated and predominantly studied in Germany and lastly Microwave or Electron-Cyclotron Resonance(ECR) thruster studied in Japan [19] [20] [21]. . Main difference between mentioned types of ion thrusters is their individual methods to create and sustain plasma. All subtypes of ion thrusters share the same ion acceleration mechanism.

Working schematic of a Kaufman or electron bombardment ion thruster is shown in figure 1.4.

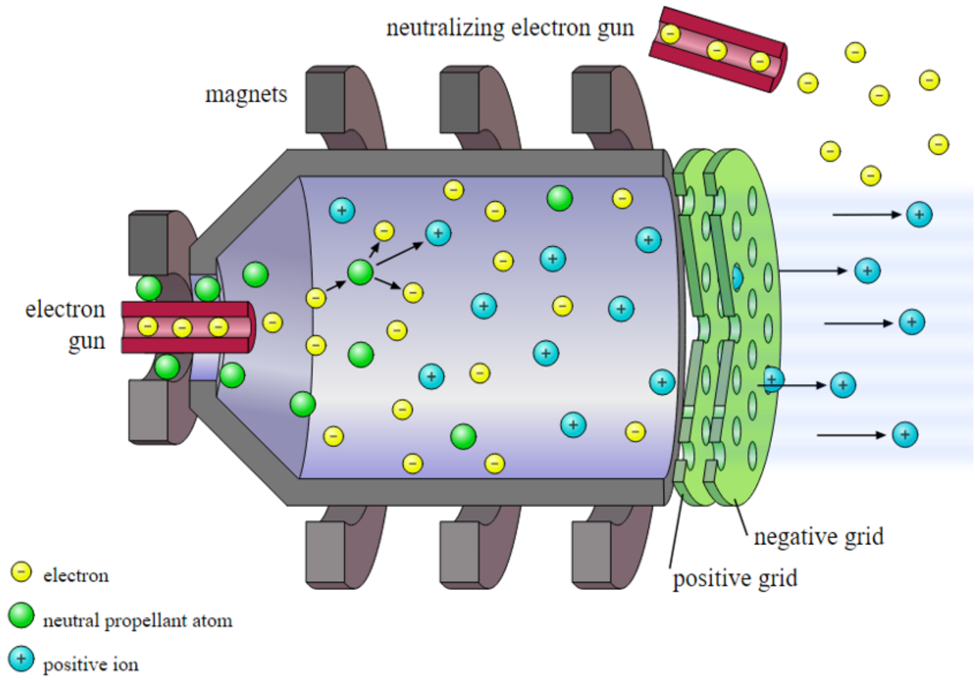



**Figure 1.4 :** Kaufman type ion thruster schematic [22]

Electrons needed to ignite the plasma are pumped via an electron gun into the cylindirical discharge chamber. From same location neutral propellant is also fed into the chamber. Energetic electrons from electron gun collide with neutral propellant atoms and suffer elastic collisions. Through these collisions a valance electron from the neutral propellant atoms is ripped off. As a result an electron and an ion is obtained from the neutral atom in addition to the initial colliding electron. Energy acquired from the broken bond and presence of ions ignite the plasma and chain reaction resulting from increased density of electrons in the enviroment sustain the plasma [11].

A pair of grids are located at the end of discharge chamber. Grid closer to the plasma is named as screen grid and is positively biased wheras the grid positioned away from the plasma is positively biased and named as acceleration grid. Electrostatic field created by the pair of grids accelerate the ions present in the plasma and create thrust [19]. Accelerated ions form an ion beam at the downstream of accelerator grids. Remaining electrons inside the plasma are drawn to walls which act as anodes. Magnets are used to create suitable magnetic fields to increase the amount of time electrons spend in the discharge chamber before evacuated to the anode and thus increase the chance of plasma ignition [20].

Same amount of electron density received at the anode walls of the thruster is injected into the extracted ion beam in order to keep the spacecraft neutral.

For RF ion thruster the plasma is formed by using a helical antenna wrapped around the discharge chamber. A diagram of such device is shown in figure 1.5.

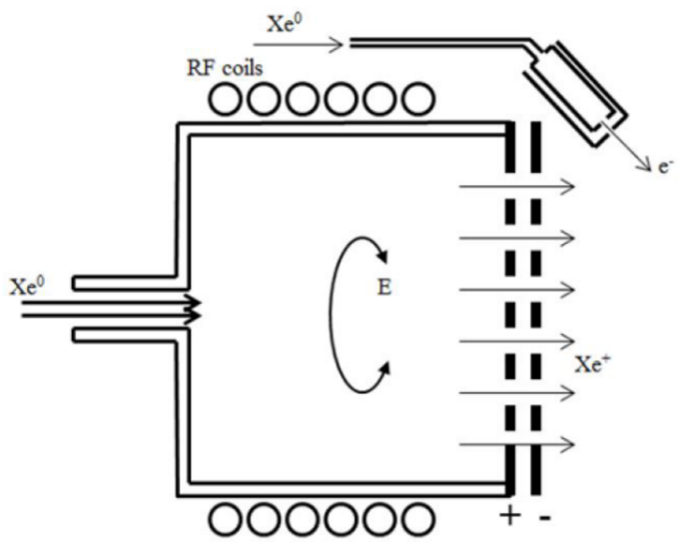



**Figure 1.5 :** RF Ion Thruster Schematic [19]

RF ion thrusters are cathodeless designs. Free electrons needed for plasma ignition can be retrieved from the neutralizer thruster chamber by reverse polarizing the grids. When an RF signal is broadcasted to the discharge chamber it acts as a solenoid and creates an axial magnetic field and perpendicular azimuthal electric field. Electrons inside the chamber start to display a tangential motion within the chamber under the influence of broadcasted signal and get energized. At this point a propellant is introduced to the discharge chamber. Electrons with high energy inside plasma collide with neutral propellant atoms and create a plasma. Depending on the power levels supplied by the RF antenna the resulting plasma can either be low density capacitively coupled plasma(CCP) or high density inductively coupled plasma(ICP). In CCP mode voltage from the helical coil is capacitively coupled to the chamber walls and create strong enough electric field to break down the propellant [23]. During the ICP mode RF energy is coupled to the free electrons through magnetic induction [21]. RF signal is typically in the range of 1-13.56MHz [24]. The same two or three grid accelerator system used in Kaufman thrusters is used to accelerate and eject the ions from the device to create thrust. Main advantages of the RF ion thruster is that it utilizes a simple design and the helical coil is not in contact with plasma and thus have a longer life time.

~~Microwave Electrothermal(MET) or~~ Electron-Cyclotron Resonance(ECR) thrusters utilize high frequcency (>1GHz) microwave(MW) signals to create a free floating plasma and heat the propellant. Working schematic is shown in figure 1.6.

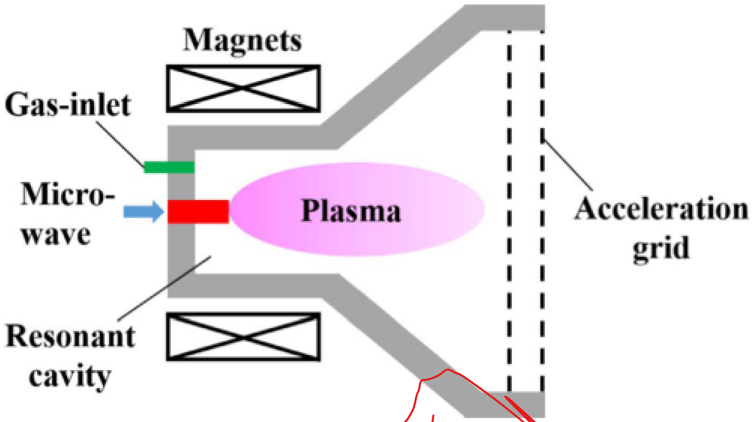



**Figure 1.6 :** Schematic of Microwave ~~Electrothermal~~ Thruster [25]

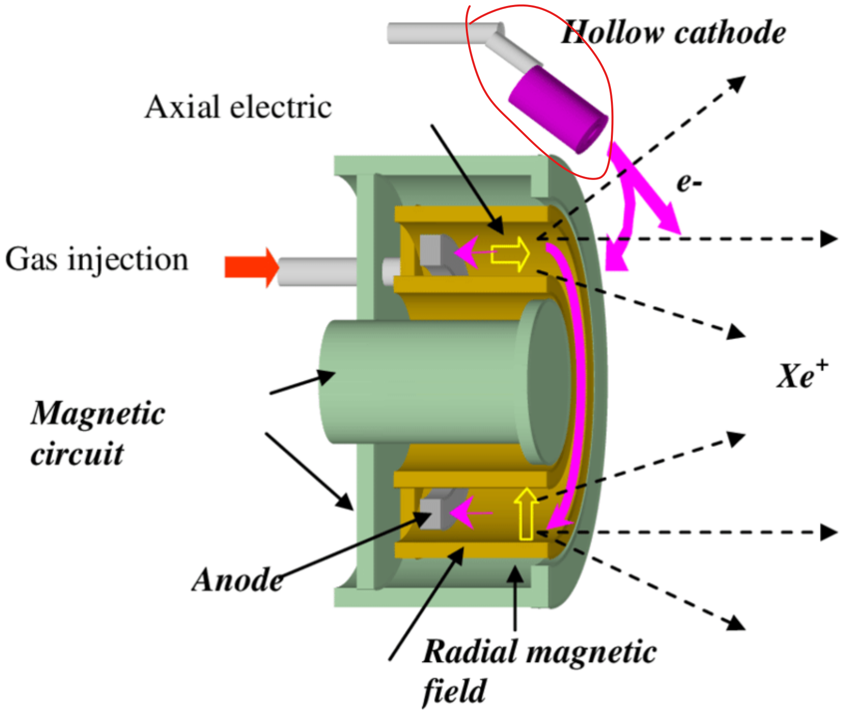
In a MET microwave signals are broadcasted into the resonance cavity and a standing wave is formed. Free electrons present in the enviroment and propellant are coupled to the electric field and become ionized. These energetic electrons then collide with neutral propellant atoms to create a plasma similar to other types of ion thrusters. Once the plasma is ignited in the cavity region it can sustain itself by producing more free electrons and collisions.

Main propellant type for ion thrusters are noble gasses such as Xenon, Krypton, Argon. Some non-noble gasses such as Mercury or Iodine have been used as well. Noble gasses are chemically inert and thus are safe to store. In addition they pose no risk of contamination for sensitive spacecraft surfaces such as solar panels or optics. Xenon have been predominantly used ~~to~~ in electric propulsion ~~purposes~~ systems due to its high atomic mass (131 amu) and higher thrust output but it ~~requires more power to~~ ionize Xenon when compared to other types of noble gasses. In addition due to its rarity Xenon is considerably expensive. Other types of noble gasses such as Argon or Krypton have gained popularity. With atomic masses of ~~31~~ 40 amu and 83 amu for Argon and Krypton ?

respectively they provide less thrust than Xenon but their wide availabilty make them more appealing [14].

**Hall Thruster**

Hall thrusters, like ion engines, use ions to create thrusts. They employ magnetic circuits to trap electrons and collide trapped electrons with neutral propellant to create ions. Created ions are expelled from the ~~spacecraft~~ thruster by utilizing the electric field created by the same magnetic circuit used to trap the electrons. A working schematic of a typical hall thruster is shown in figure 1.7.




baslca resin ball

**Figure 1.7 :** Schematic of Hall Effect Thruster [26]

An electron source, in the case of figure 1.7 a hollow cathode, is used to provide electrons. An anode is used to attract the electrons to the ~~circular~~ annular coaxial channel within the thruster. Once electrons are within the channel they are trapped due to radial magnetic fields created by specifically located magnetic circuits. Electrons inside the channel begin to exhibit tangential motion around the thruster axial axis. During this motion they incur a current called Hall current, hence the thruster's name. A neutral propellant is injected into the channel. Propellant atoms collide with energetic electrons inside channel and are ionized. Created ions are accelerated and subsequently ejected from the thruster by an axial electric field, perpendicular to the magnetic field created by the magnetic circuit. Some of the electrons originated from the cathode is used to neutralize the created ion beam.

They contain a simple design compared to ion engines but magnetic and electric fields needs to be optimized to provide an efficient operation. Their $I_{sp}$ and efficiency values are somewhat less than other types of electorstatic propulsion systems but their thrust levels are significantly higher [11].

#### 1.2.2.3 Electromagnetic propulsion

**Pulsed Plasma Thruster(PPT)**

Capacitors and spark igniters are used to create a discharge through a series of impulse bits. Solid, liquid or gas propellant can be used. If the used propellant is solid then this discharge ablates and removes small parts of the propellant. Same discharge also partially ionizes the propellant. Ionized propellant is then accelerated by Lorentz forces [13].

PTFE is traditionally used as solid propellant [27]. Thrust levels are limited to the frequency of the charged capacitor. Spark igniter can limit the lifetime of the thruster. Their advantage is low power use. They can generate moderately high $I_{sp}$ values up to 800 s with $80\mu$N with only 10W of power [14].

**Magnetoplasmadynamic(MPD) Thruster**

In MPD thrusters a propellant is ionized by using arcs generated by high currents. Ionized propellant is accelerated by electromagnetic forces such as Lorentz force to generate thrust. Since Lorentz force $J \times B$, where J is the current density and B is the magnetic flux density, utilize both current and magnetic field MDP's require greater power compared to other types of electric propulsion systems. At the same time they provide higher thrust (>1N) and higher $I_{sp}$ values (>5000 s) [28]. Working schematic of an MPD is shown in figure 1.8

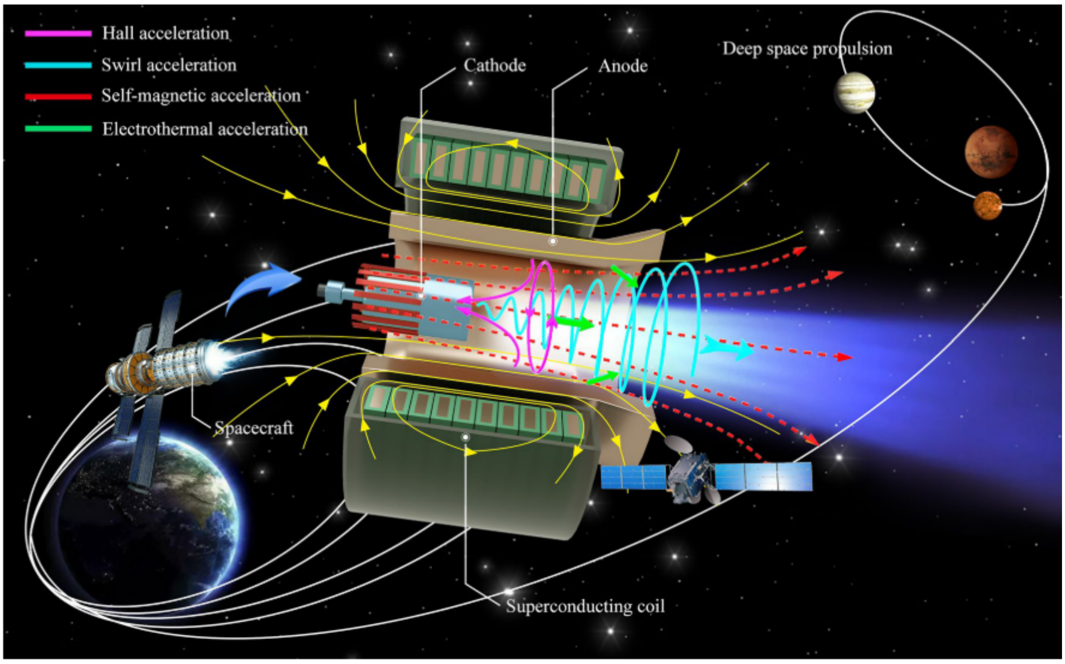


**Figure 1.8 :** Working principle of a MPD thruster [28]

## 1.3 Thesis Purpose and Overview

Cube satellites offer very limited power budgets and volume limitations due to their small sizes. For an electric propulsion system to work properly it should be both compact and power efficient. Considering these factors for this thesis study an RF ion thruster is selected to be built.

düzelt

RF ion thrusters does not include complex parts such as an electron source or magnets to confine the plasma. Their design simply consists of a plasma generator; an RF antenna wrapped around a discharge chamber and a pair of biased grids. Regardless of their simplicity they offer the highest $I_{sp}$ among the electric propulsion systems and are renowned for their scalability [29].

Another reason for RF ion thruster choice is the significant accumulation of know-how regarding their structure and testing at Bogazici University Space Technologies Laboratory(BUSTLab). Testing equipment within the BUSTLab such as the vacuum chamber, DC power sources, matching network tuner and RF signal generator are best suited for RF ion thruster operations [30].

# 2. BACKGROUND

## 2.1 Basic Plasma & RF Thruster Physics

30 km/s

RF ion thruster accelerates charged particles called ions up to 1000 km/s to produce thrust [11]. Accelerated ions are sourced from the plasma generated and sustained within the thruster. Before elaborating further on the thruster systems a basic understanding of plasma physics is required.

Plasma is defined as combination of positively charged ions, negatively charged electrons and neutral particles. Densities of charged ions and electrons are assumed equal. This equilibrium state is referred as "quasi-neutrality" [14]. Thus on a macroscopic scale plasma is considered to be charged neutrally. This neutral state is violated under two conditions. One of the conditions is when the plasma is studied near its boundary regions. In such regions due to interaction with the thruster walls a *sheath* is formed in which the densities of positively and negatively charged particles vary. Second condition occurs when the plasma is examined in microscopic scales. In microscopic scales there are regions in which the neutrality is broken [31]. The size of such regions are approximated by a certain lenght called *Debye lenght*. Effects of plasma sheaths, their occurance and relation to Debye lenght will be discussed in chapter 2.1.1.

Since plasma has a certain amount of electric conductivity it can be affected by magnetic and electrical forces [32]. General behaviour of electric and magnetic fields generated by plasma is compatible with Maxwell's equations ~~which are provided in equations 2.1, 2.2, 2.3 and 2.4~~ [33].

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0} \tag{2.1}$$

$$\nabla \cdot \mathbf{B} = 0 \tag{2.2}$$

$$\nabla \times \mathbf{E} = -\frac{\partial B}{\partial t} \tag{2.3}$$

$$\nabla \times \mathbf{B} = \mu_0 \left( \mathbf{J} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right) \tag{2.4}$$

flux ?

In which **E** is the electric field vector, **B** is the magnetic field vector, $\rho$ is the plasma charge density, $\varepsilon_0$ and $\mu_0$ are permittivity and permeability of vacuum respectively and **J** is the current density [11]. Plasma charge density $\rho$ is defined as;

$$\rho = \sum_n q_s n_s = e(Zn_i - n_e) \tag{2.5}$$

where $q_s$ is the charge state and $n_s$ is the number density of an arbitrary species named $s$. e is the electron charge, Z is the charge state, $n_i$ is the ion density, $n_e$ is the electron density. Current charge density **J** is formulated by the equation [11];

$s$ or italics

$$J = \sum_s q_s n_s \upsilon_s = e(Zn_i \upsilon_i - n_e \upsilon_e) \tag{2.6}$$

in which $\upsilon_s$, $\upsilon_i$ and $\upsilon_e$ are the velocities of the species s, the ion and the electron, respectively. Electric field **E** occuring in the ion thrusters is given as [32];

$$\mathbf{E} = -\nabla \Phi \tag{2.7}$$

where $\Phi$ is the electric potential. ~~Value of~~ **~~E~~** ~~is~~ negative since **E** always points in the ~~direction of motion~~.

Motion of a charged particle within the thruster can be described by equation 2.8

$$\mathbf{F} = m\frac{d\mathbf{v}}{dt} = q(\mathbf{E} + \upsilon \times \mathbf{B}) \tag{2.8}$$

Which is defined as the Lorentz force equation [11]. In the case of magnetic field **B** in axial direction of the thruster with no electric field **E** the motion of particles can be found from equation 2.8.

$$\begin{aligned} m\frac{\partial v_x}{\partial t} &= qBv_y \\ m\frac{\partial v_y}{\partial t} &= -qBv_x \\ m\frac{\partial v_z}{\partial t} &= 0 \end{aligned} \tag{2.9}$$

Taking one more time derivative of equation 2.9 results;

$$
\begin{aligned}
a = \frac{\partial^2 v_x}{\partial t^2} = \frac{qB}{m}\frac{\partial v_y}{\partial t} \\
a = \frac{\partial^2 v_y}{\partial t^2} = -\frac{qB}{m}\frac{\partial v_x}{\partial t}
\end{aligned}
\tag{2.10}
$$

Substituting partial time derivative values from equation 2.9 into equation 2.10 yields;

$$
\begin{aligned}
\frac{\partial^2 v_x}{\partial t^2} = -\left(\frac{qB}{m}\right)^2 v_x \\
\frac{\partial^2 v_y}{\partial t^2} = -\left(\frac{qB}{m}\right)^2 v_y
\end{aligned}
\tag{2.11}
$$

Equation 2.11 shows that particle displays a~~n~~ harmonic oscillation with a certain frequency defined as cyclotron frequency $\cancel{w}_c$; $\omega_c \leftarrow$ omega

$\omega_c$

$$\cancel{w}_c = \frac{qB}{m} \tag{2.12}$$

Orbit size of this circular motion can be found by observing this circular motion displayed in figure 2.1.

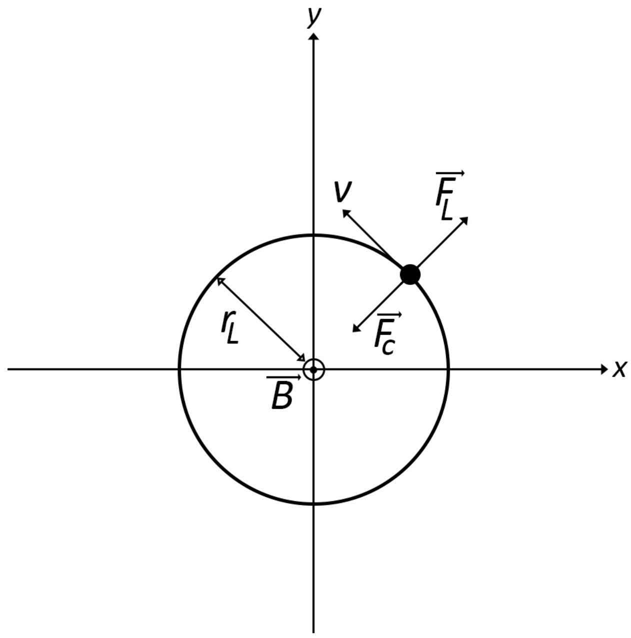



**Figure 2.1 :** Motion of a particle in a uniform axial magnetic field

Charged particle shown in figure 2.1 will act under the influence of a Lorentz force;

$$\mathbf{F} = q\mathbf{v} \times \mathbf{B} \tag{2.13}$$

Same particle will also feel a centripetal force;

$$\mathbf{F_c} = \frac{mv^2}{r_L} \tag{2.14}$$

For a constant uniform motion equations 2.13 and 2.14 must be equal.

$$q\mathbf{v} \times \mathbf{B} = \frac{mv^2}{r_L} \tag{2.15}$$

where $r_L$ is the *Larmor radius* and is the radius of the particle's circular motions, formulated as $\frac{mv}{qB}$.

not correct

Same magnetic field **B** ~~also creates an electric field~~ **E**. Direction of this electric field is perpendicular to the magnetic field. If the direction of the magnetic field is assumed as axial then the electric field direction becomes tangential.

### 2.1.1 Sheats At The Boundaries Of The Plasma

Earlier in the chapter 2.1 it was mentioned that the quasi-neutral stance of the plasma is broken along the plasma boundary in regions called sheaths. Since ion acceleration grids exploit the sheath at the edge of the plasma a solid understanding of sheath behavior is very important to model and design the ion thruster.

After the initial ignition of plasma created ions and free electrons will be lost due to interaction with the containing walls. Since electrons have much higher velocities compared to ions they will exit the plasma in larger quantities. Over time this imbalance creates a negatively biased container walls with respect to the plasma. This negative charge attracts ions from the plasma and repel the electrons, causing a non-neutral region on the border of plasma. These regions in which the plasma loses its neutrality is called a sheath [34].

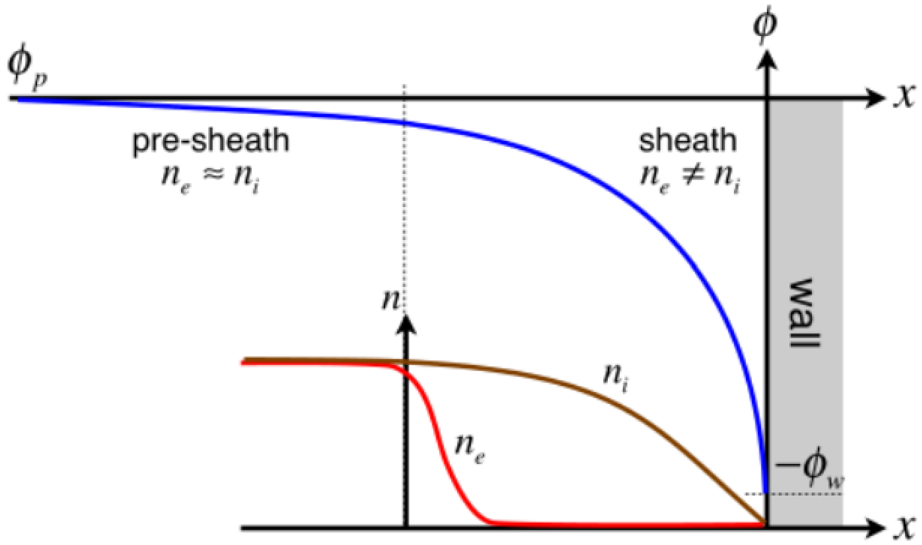



**Figure 2.2 :** Potential and species density change near plasma boundary [34]

Figure 2.2 shows how the species densit~~y~~ies and potential is changing while approaching the plasma boundary. As particles get close to the wall negative potential $-\phi_w$ attracts ions and repels electrons causing a charge inbalance. The thickness of this sheath region is given in the order of Debye lenght $\lambda_D$ [11]. Thanks to the shield that occurs the remainder of plasma maintains its potential $\phi_p$.

## 2.2 General RF Ion Thruster Design Parameters

Design of an RF ion thruster can be divided into two sections.

### 2.2.1 Discharge Chamber

### 2.2.2 Ion Optics

### 2.2.3 Thrust

### 2.2.4 Specific Impulse

### 2.2.5 Power Consumption

### 2.2.6 Efficiency

### 2.2.7 Neutralizer

# 3. MINIATURE RF ION THRUSTER DESIGN

## 3.1 Design Parameters

### 3.1.1 Sizing

## 3.2 Plasma Generation System

## 3.3 Ion Extraction System

# 4. EXPERIMENTAL SETUP

## 4.1 Experimental Setup & Methodology

## 4.2 Input Parameters

## 4.3 Firing Tests

### 4.3.1 Firing Test No. 1

### 4.3.2 Firing Test No. 2

### 4.3.3 Firing Test No. 3

# 5. RESULTS & DISCUSSION

## 5.1 Plume Diagnostics

## 5.2 Comparison

## 5.3 Efficiency Calculations

# 6. CONCLUSION AND FUTURE WORK

# 7. APPENDIX A: CHILD-LANGMUIR EQUATION

# 8. APPENDIX B: RF SYSTEM DESIGN

# 9. APPENDIX C: FARADAY CUP

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**APPENDICES**

**APPENDIX A.1 :** RF system design
**APPENDIX A.2 :** Faraday cup

# APPENDIX A: CHILD-LANGMUIR EQUATION

## APPENDIX B: RF SYSTEM DESIGN

## APPENDIX C: FARADAY CUP

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PHOTO

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2020