Prototype Design and Manufacturing Method of an 8 cm Diameter RF Ion Thruster

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Abstract— Among the various types of plasma thrusters developed over the last few decades for in-space propulsion applications of satellites and spacecrafts, Hall effect thrusters and ion engines are the most studied ones. The work at Bogazici University is concentrated on radio frequency ion thrusters. In this paper the design and manufacturing methods of the BURFIT-80 (Bogazici University Radio Frequency Ion Thruster-80) are explained. The BURFIT-80 is an experimental ion thruster and will be tested in the vacuum chamber at Bogazici University. The Ion Thruster has a cylindrical discharge chamber having an inner diameter and outer of diameter of 80 mm and 88 mm respectively, with a length of 72 mm. A double grid system with 91 holes is implemented. Preliminary calculations suggest that the thruster will generate thrust in the range of 2 to 6 mN. A discussion on material selection and manufacturing methods is presented for the production of the prototype.

Keywords—electric propulsion, radio-frequency ion thrusters, ion thruster design

I. INTRODUCTION

The two main plasma thrusters in use today are Ion thrusters and Hall effect thrusters. These thrusters ionize the propellant gas then eject these ions after accelerating them by the electrostatic force to generate thrust. The advantage of plasma thrusters is that the average exhaust velocity of the particles being thrown out of these thrusters is much greater than chemical thrusters, meaning that their specific impulse (Isp), ~1750 seconds for Hall Thrusters and >3000 seconds for ion thrusters, is much higher compared to the Isp of chemical thrusters, <450 seconds [1].

There are three main types of ion engines, differentiated by the main mechanism for ionization of the propellant gas. The first type is called the electron-bombardment ion engine (or Kaufman type ion engine). In this type of ion engines an internal cathode provides the electrons for the ionization of the propellant. In the second kind, called Radio-Frequency (RF) ion thrusters, the propellant gas is ionized by the rf energy generated by a low frequency rf voltage supplied to an antenna. This can be achieved through wrapping a chamber containing the propellant gas, with an rf coil. In the third kind, called microwave ion engine, a microwave antenna is used to deliver microwaves into the discharge chamber that are used

for the ionization of the propellant gas [2].

The Russians were the first in using electric propulsion on their satellites for station keeping purposes. The Soviets have used over 238 Hall Thrusters on more than 48 spacecraft [3,4]. The Japanese have launched and successfully operated the first ion thruster in 1995 [2]. The United States has used the ion thruster commercially first in 1997, which was the Hughes Xenon Ion Propulsion System (XIPS) [5] and then in 1998 on the first NASA deep-space mission, using the NASA Solar Electric Propulsion Technology Applications Readiness (NSTAR) ion thruster [6]. Both the XIPS and the NSTAR are Kaufman type ion engines. Work on RF Ion Engines has been performed mostly by the Germans, mainly EADS Astrium GmbH. Their Radio frequency Ion Thruster (RIT) designs have been used on satellites such as EURECA and ARTEMIS [7].

A. Radio-Frequency Ion Engines

An RF Ion Thruster can be considered to be composed of three main parts: the discharge chamber, an axisymmetric dielectric chamber, where the formation of plasma takes place, the grids, where the ions are accelerated and spewed out from the thruster to generate thrust and the electronics and the electrical connections, such as the rf coil wound around the discharge chamber to create the plasma, or the electrical connections to the grids to create the voltage difference that accelerates the ions. The thruster is then encased by a metallic structure to eliminate electron collection from the space plasma [2]. This encasing also helps in achieving structural integrity and shields the electromagnetic radiation generated by the rf coil from reaching the environment. A neutralizer cathode is affixed to the thruster in order to neutralize the net charge of the beam of ions that generate the thrust. A simple schematic of an rf ion thruster can be seen in Fig. 1.

The ions generated in the discharge chamber of an RF Ion Engine are accelerated as they pass through the grids of the thruster and create the thrust that is desired from the engine. These grids are basically parallel plates with apertures for the ions to flow through and a voltage difference to increase the kinetic energy of these ions. The grids are called in the downstream direction: the screen grid, accelerator grid and decelerator grid (if used). Three grid systems provide variable thrust, variable Isp and a longer service life, however they complicate the design. The grids should be designed to

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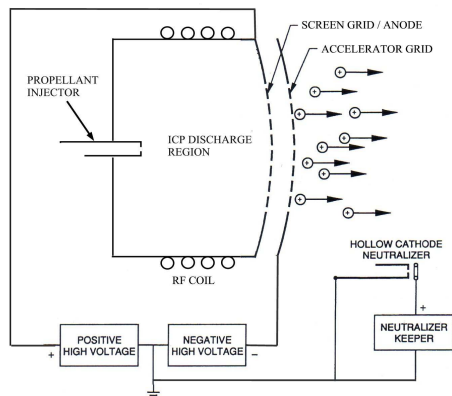E-mail: murat.celik@boun.edu.tr
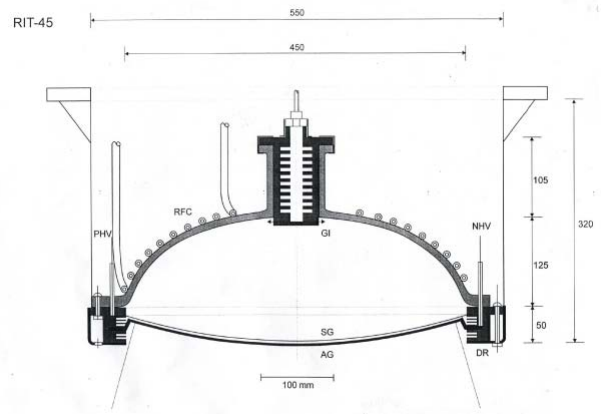
Fig. 1: Basic schematic of an RF Ion Thruster [7]

maximize ion transparency and minimize neutral atom loss to increase the mass utilization efficiency of the thruster [2]. Ion Optics studies the effects of the design of the grids have on the performance of the thruster. The designs may vary regarding the size of the apertures, the thicknesses of the grids and the distance between the grids. Since the study of ion optics is not one of the objectives of this paper, the design of the grids will be influenced by previous works performed on the subject [8,9,10,11,12].

II.   DESIGNS OF EXISTING RF ION THRUSTERS

A.   The RIT

The RIT's have been under development by the Germans at the University of Giessen and Astrium GmbH [10]. The RIT family consists of many Radio-Frequency Ion Thruster Designs named according to their chamber diameters. The designs regarding to the RIT-10 and RIT-15 were analyzed diligently for the purpose of this paper as they were the most concrete examples of RF Ion Thruster's that are being used today. The schematics of the RIT-XT and the RIT-45 can be seen in Fig. 2 and Fig. 3.

It was observed that for the discharge vessel, a part required to be a dielectric material, a shift towards alumina ceramics was made due to its more suitable mechanical
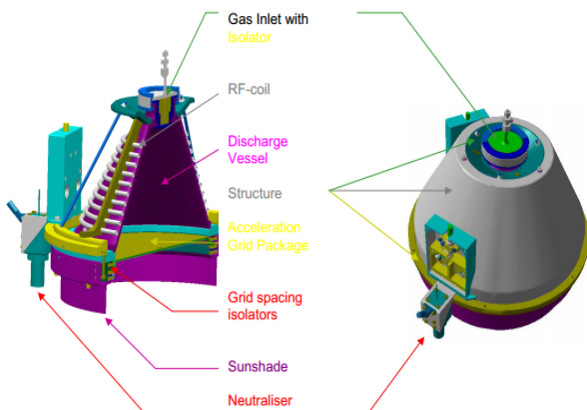

Fig. 2. The RIT-XT [8]

Fig. 3: The RIT-45 [12]

properties and flexibility in design compared to quartz [11]. The shape has also evolved from a cylindrical shape to a conical one and finally a hemi-spherical design [10,11,12]. There is an isolator that isolates the grounded gas feed from the plasma. This part also acts to direct the flow of the Xenon gas, so that the gas does not directly flow through the discharge chamber and out the grids before being ionized.

Different parameters for the rf-coil exist such as the number of windings of the coil around the chamber and the frequency of operation. While copper is used mainly for the coils, the number of windings change depending on the length of the chamber. The frequency of the rf-sources range from 880 kHz to 1 MHz.

For the grids, different materials have been used for the last 40 years, including carbon-carbon material, graphite, molybdenum and INVAR [10,11,12]. These materials all have excellent thermal properties, especially, very low thermal expansion coefficients.

A casing is used to shield the rf-field from radiation to the environment also to protect the parts safe from sputtering materials. The materials used for this purpose include aluminum, and stainless steel [10,12].

B.   The MiDGIT

The Electric Propulsion Group of Qinetiq and the University of Southampton have worked on a novel rf ion thruster called the "Miniaturized Differential Gridded Ion Thruster" (MiDGIT). The MiDGIT achieves precise thrust levels on the order of µN through the differential control of two ion beams extracted from both sides of the thruster [13]. The schematic of the MiDGIT is shown in Fig. 4.

The MiDGIT has a transverse gas feed through the middle of the discharge chamber and grids at both sides of the discharge chamber. The discharge chamber of the prototype was made of alumina with an outer diameter of 38 mm and a length of 70 mm. The inner diameter was optimized to 28 mm. Two rf Induction coils were wound around the discharge chamber in series with a pitch of 3.2 mm and 6 turns. The screen grid was made from molybdenum and the accelerator
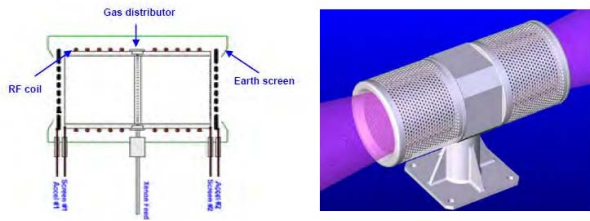
Fig. 4: The schematic of the MiDGIT Thruster [13,14]

grid from graphite. Each grid consisted of 55 apertures in the breadboard model [13,14].

C. The MRIT

The Miniature RF-Ion Thruster (MRIT) was designed and developed at the Pennsylvania State University. Different from the aforementioned ion thrusters, the discharge chamber for this thruster was made from MACOR. A 13.56 MHz RF source was used for ionization and two chemically milled molybdenum grids were used. The MRIT was to be tested on the LionSat satellite [15]. The laboratory testing setup diagram of the MRIT is shown in Fig. 5.

III. THE BURFIT-80 ION THRUSTER

RF Ion Thrusters hold a few advantages over the designs of other ion thrusters. The absence of an internal cathode extends the service life of an RF ion thruster as the erosion of the internal cathode sets the service life of a Kaufman type ion engine. Also the absence of a magnetic structure enables ion thrusters to be miniaturized more easily [2].

The objective and the subject of this paper was to design and investigate the manufacturing methods of an RF Ion Engine and then manufacture and finally conduct a parametric study of the Ion Engine in the vacuum chamber at Bogazici University. The results of this study will then be compared to the values from the computer generated model of Emre Turkoz [16].

A. Preliminary Design

In the preliminary designs of the BURFIT-80 (Bogazici University RF Ion Thruster), the proposed thruster has an 80 mm diameter discharge chamber, and double grid design consisting of 91 apertures. The 3D CAD models are generated in SolidWorks. The very first generated design of the BURFIT-80 Ion Thruster is shown in Fig. 6.
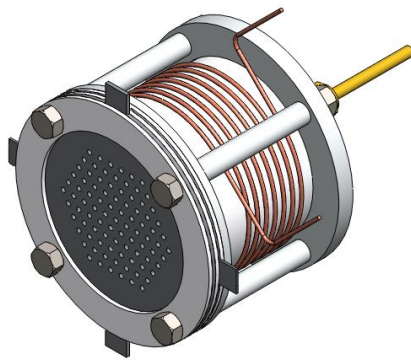

Fig. 5: The laboratory testing setup of the MRIT [15]

Fig. 6: The BURFIT-80 Ion Thruster

1) The Discharge Chamber

The discharge chamber of an RF Ion Thruster is where the plasma is generated. The chamber is axisymmetric; it can be cylindrical, conical or even hemispherical. The chamber must be dielectric so that the rf-field can penetrate the walls of the chamber. Dielectric materials such as quartz or alumina are widely used in discharge chambers [2].

Factors that affect the design and material selection of the chamber include better rf energy coupling of the propellant gas (Xenon will be used) and the vibrational stresses that may arise during the launch of the space vehicle. In literature, examples of conical designs exist that claim better rf energy penetration [17,18]. Optimized designs now point towards hemispherical discharge chambers that can also better withstand vibrational shocks during launch [12]. As this prototype thruster will not face vibrational stresses, and it is much easier to model a cylindrical discharge chamber rather than a conical one, the discharge chamber is shaped as a cylindrical crucible.

Due to availability, alumina has been selected as the material since alumina crucibles are widely available on the market. The outer diameter of the crucible is 88 mm and the crucible has a wall thickness of 4 mm. A hole with a diameter of 12 mm will be drilled to the back of the crucible as the gas inlet. Other machining procedures are avoided as alumina is a very hard material and has very poor machinability.

2) The Grids

A double grid system is implemented in order not to complicate the designs with the addition of the decelerator grid. The study of ion optics in previous work [8,9,10,11,12] influenced the design of the grids.

The grids are planar molybdenum sheet metal. They are not dished even though dishing is preferred in order to keep the apertures aligned after thermal expansion occurs in the grids and to preset the direction of possible buckling under thermal expansion [2]. The apertures are circular in shape and are packed in a hexagonal pattern. There are a total of 91 holes. The grids are shown in Fig. 7 and Fig. 8.

The holes in the screen grid are 2.2 mm in diameter and the grid is 0.5 mm thick. The accel grid on the other hand is 1 mm thick, with apertures having a diameter of 1.3 mm. The
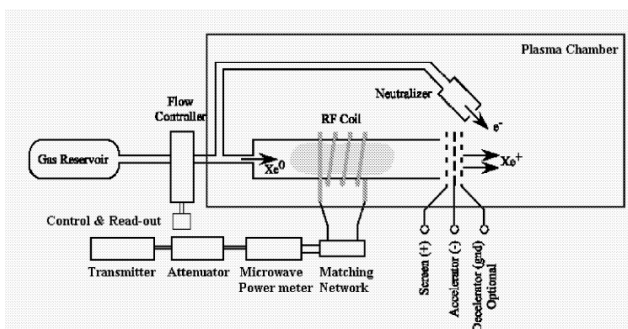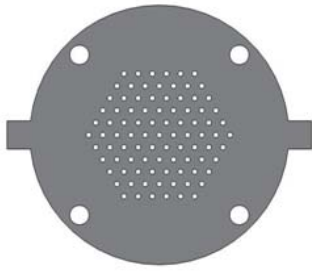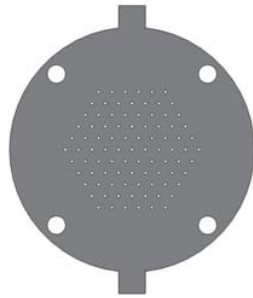
Fig. 7: The Screen Grid

Fig. 8: The Acceleration Grid

grid spacing is 0.7 mm. The apertures will be created through laser micro machining. The dimensions have been influenced by previous work on the RIT's. The relevant data are summarized in Table 1.

The resulting limiting ion beam current density is 30.65 mA/cm^2 from the Child–Langmuir equation [2], and this results in an ion beam current of 0.1 A for the thruster.

The screen grid contains arms extending in the horizontal axis and the accel grid has arms extending in the vertical axis. These arms are where alligator clips will be attached to supply the voltage to the grids. The arms are placed on perpendicular axes in order to provide sufficient space to attach the clips. The grids contain 4 large holes. These holes are where the bolts will pass through in order to hold the grids firmly to the alumina chamber. Since the bolts are made of steel, hence conductive, the bolts will pass through MACOR rings in order to prevent contact with the molybdenum grids. Also larger MACOR rings will be used in between grids in order provide the spacing between the grids.

3) Gas Inlet

The gas will be fed through a 1/8" stainless steel pipe, connected to the "flow isolator" through a Swagelok fitting. The flow isolator serves two functions. First of all, it is an insulator so that it will insulate the neutral gas feed from the charged plasma. Secondly, it serves to direct and slow down the flow so that unionized Xenon atoms do not directly flow straight through the discharge chamber and out the grids. Fig. 9 shows the complete gas inlet structure consisting of the Swagelok fitting and the flow regulator. The flow regulator
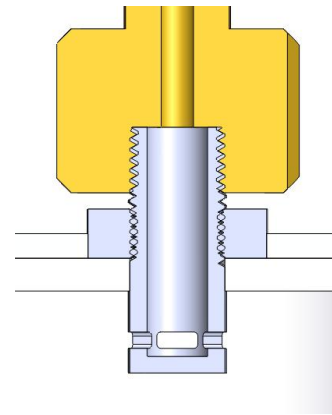

Fig. 9: Swagelok Fitting and Flow Regulator

will be manufactured from MACOR, as MACOR has excellent machinability compared to other ceramics.

The Flow regulator has threads on its end. These threads will be used to fix the regulator firmly to the crucible and connect the Swagelok. The end of the flow regulator will be wrapped in Teflon tape to prevent any leakage. The flow regulator is shown in Fig. 10 inside the discharge chamber with the grids removed.

4) The Aluminum Structure

Aluminum will be used to provide the structural integrity of the ion thruster and hold the parts together. The structure consists of a back plate having a seat to place the aluminum crucible and 4 holes. The front plate will provide a platform to place the grids. A MACOR ring will be placed between the screen grid and the platform to insulate the remaining structure, and 4 struts for holding the platform, connecting the back plate. The struts will contain internal threading on both sides so that the bolts can be directly attached to the struts. Aluminum was chosen due to its availability, low price and light weight. A cross-section of the structure with the grids attached is shown in Fig. 11.

5) RF Coil

14 gauge copper wire is selected for the RF coil. It is wound directly on the alumina chamber. It has 7 turns over 35 mm. A MACOR apparatus will be fit between the aluminum strut and the alumina chamber to stabilize the rf coil. An rf

TABLE I.   GRID PARAMETERS OF THE RIT'S

Ion Thruster	Screen Grid		Spacing (mm)	Accel Grid		Chamber Diameter (cm)	Reference
	Thickness (mm)	Hole Diameter (mm)		Thickness (mm)	Hole Diameter (mm)		
RIT-Artemis	2.00	4.0	0.8	2.0	2.4	10	[10]
RIT-Evo	0.30	1.9	0.7	1.0	1.2	10	[10]
RIT 15	2.00	4.0	1.0	2.0	2.0	15	[11]
RIT 15 LP	0.30	1.9	0.6	1.2	1.2	15	[11]
RIT 15S	0.35	2.2	0.9	1.2	1.4	15	[11]
RIT-XT	0.25	1.9	n/a	1.2	n/a	22	[8,10]
RIT-45	0.55	4.0	1.6	2.7	2.5	45	[12]
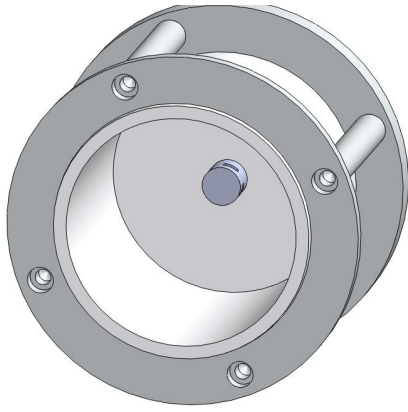
Fig. 10: The Flow Regulator and the Discharge Chamber

frequency of 13.56 MHz is proposed due to the availability of the equipment.

B. Preliminary Results of the 0D Model

A 0D analytical model was generated to model the inductively coupled plasma inside the discharge chamber [19]. This model predicts the thruster performance by evaluating the design of the thruster according to the mean energy spent on the ionization of each neutral Xenon atom, which is called the discharge loss per ion. By supplying the model the geometry of the discharge chamber, preliminary results of the relation between the discharge losses versus the mass utilization efficiency were generated and are shown in Fig. 12.

For the given parameters of 80 mm chamber diameter, 72 mm chamber length, 0.1 A beam current and a coil impedance of 50 Ω, the average discharge loss was calculated as 417 eV/ion. The beam current is directly related to the thrust to be generated, and therefore it is held constant. The beam current desired to be generated with this geometry is relatively low, so a smaller ion current is supplied to the RF coils which results with a weaker ion confinement and high wall recombination loss. This high discharge loss per ion result is due to the fact that the shape of the discharge chamber was not optimized to decrease discharge loss.
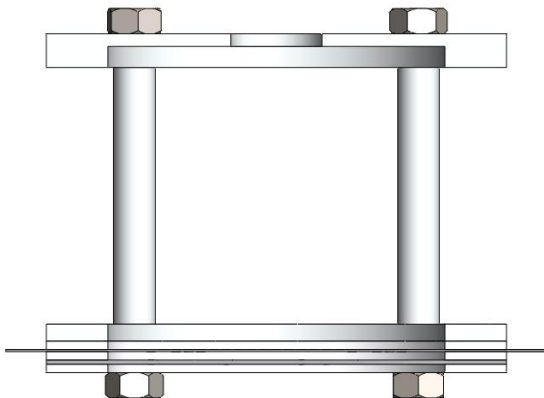

Fig. 11: The Aluminum Structure and the Grids

Fig. 12: Preliminary 0D Analytical Model Results for the BURFIT-80

IV. CONCLUSIONS AND FUTURE WORK

The proposed prototype design and the manufacturing methods of the BURFIT-80 were discussed. The BURFIT-80 is proposed to have a cylindrical discharge chamber made of alumina with an inner diameter of 80 mm and length of 72 mm, and consist of a double grid system with 91 holes. Preliminary calculations suggest a thrust in the range of 2-6 mN, and a limiting ion beam current of 0.1 A. Using the 0D Analytical Model on the geometry of the discharge chamber, an average discharge loss of 417 eV/ion was calculated.

Future work on the subject will include performing a manufacturability analysis on the designs, and investigate and improve the designs and finally to manufacture a prototype. After the prototype is made, propulsion tests will be performed in a vacuum chamber and the results of the test will be compared with the computer models.

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