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A Study of the Magnetic Field inside the Discharge Chamber of an Ion Thruster

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Abstract

One of the characteristics that ion thrusters are known for is its high efficiency. In the process of designing an ion thruster the study of the magnetic field alongside the discharge chamber is crucial to achieve optimal efficiency. This work shows the importance of taking into consideration the materials in the vicinities of the magnets as well as the expected intensity of the magnetitic field inside the thrusters in study. The procedures used to study the magnetic field in the open software used are described in this work. The thruster in study is an oversizing done of a previous one, so the desired results are to obtain the ones obtained for the original engine.

Keywords: Ion thruster, High efficiency, Magnetic field

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1. Introduction

The new era of space exploration is deeply linked with the rise of a new type of satellites, the CubeSats. CubeSats are a class of nanosatellites that use a standard size and form factor. This standard size is a cube of 10-centimetre edges, called unit or “U”, and it is possible to assemble units in groups of 2, 4, 6, 8 or 12. The rise of these satellites is based on the development of miniaturized technology. The development of the first CubeSat dates back to 1999 at California Polytechnic State University and Stanford University, with its purpose being solely educational. Even though nowadays there are a lot of CubeSats in space, the interest in them had a slow start. In the beginning they were seen by the scientific community as a simple tool used by universities to teach their students, it was only after the first scientific and technology demonstration missions that CubeSats started being seen in a different way. Once the scientific community understood the advantages related to CubeSats, the number of these satellites launched to space has grown exponentially. Due to their small size, the time needed to develop a CubeSat and the costs associated to the production and launch are much smaller when compared to the “traditional” satellites, which allowed access to space to a much wider range of users.

Since 1999 CubeSat were only launched for missions in Low Earth Orbit, LEO, but in 2018, Mars Cube One, MarCO [1], has shifted the paradigm. MarCO were the first CubeSats ever launched for an interplanetary mission. As missions for CubeSats got more ambitious, increasingly advanced technologies were required. One of the biggest challenges associated with space exploration are the propulsion systems. The first propulsion systems used for space exploration [2] were chemical systems and used liquid/solid propellant. These systems are highly inefficient, which led to the development of Electric Propulsion Systems, EPS. Contrarily to the chemical systems, EPS are characterized by its high efficiency and low trust. The concept of electric propulsion isn't recent, there are documents referring to it from as far as 1900 but at that time the existing technologies weren't matured enough so the research halted. After the mid of 19^{th} century the interest in this technology was reignited in the United States of America and in Russia with the first EPS models generating trust through electrothermic, electrostatic or electromagnetic processes. In the maturation process of this technology the mission SERT-1 (1964) [3] was crucial since it was a proof-of-concept mission for ion thrusters. After that, studies about ion thruster multiplied, speeding up the development process. In 1997 one of the most used ion thrusters was introduced, the Xenon Ion Propulsion System, XISP, which is still used to this day.

SpaceX is expecting to have a new satellite constellation, the Starlink project, by mid- 2020's, which will feature nearly 12000 satellites in orbit using electric propulsion systems [4]. The use of EPS has been growing every year, but these technologies aren't yet fully matured. When compared to chemical systems, EPS are still a young technology and since they operate for long periods, testing those systems takes a lot of time.

Table 1 shows the level of maturation of the different types of propulsion systems for small spacecrafts, as well as thrust and specific impulse.

Technology Readiness Levels [6], TRLs, is a method to assess the maturity of a space propulsion system. There are 9 levels in this scale, where level 9 corresponds to the most mature technology. The goal of the presented study is to analyse the magnetic field for a XISP model with 10-centimetre grids (Figure 1). As table 1 shows this technology has a TRL of 7, meaning that this thruster has already been tested in operational environments.

Ion propulsion thrusters produce thrust by accelerating ions by means of a purely electrostatic field, which is the potential difference created within the grids. The goal of the magnetic field's existence in these thrusters is to improve its performance. An ion thruster can be divided in 3 parts: the cathode, where the electrons are drawn from, the discharge chamber, where the ionization process occurs, and the ion optics, where the ions are expelled from the thruster.

TABLE 1: Propulsion Systems for Small Satellites Source: [5]

Type of propulsion system	Product	Thrust	Specific Impulse (s)	TRL Status
Chemical	Hydrazine	0.5 - 30.7 N	200 - 235	9
	Cold Gas	10 mN - 10 N	65 - 70	Butane 9
	Alternative (Green) Propulsion	0.1 – 27 N	220 - 250	HAN 6, AND 9
	Solid Rocket Motor	0.3 – 258 N	187 - 300	CAPS-3 8, MAP 9
Propellant less	Solar Sails	0.25 – 0.6 mN	N/A	6 (85m^2), 7 (35m^2)
Electric	Resistojet	10 mN – 0.45 N	48 - 150	Micro Resistojet 5, Resistojet Propulsion System 9
	Variable Specific Impulse Magnetoplasma Rocket, VASIMR	N/A	3000 - 30000	4<
	Pulsed Plasma Thruster, PPT	1 – 1300 μN	500 - 3000	Teflon 7, Titanium 7
	Electrospray Propulsion	10 – 120 μN	500 - 5000	7
	Hall Effect Thrusters	10 – 50 mN	1000 - 2000	Xenon 7, Iodine 3
	Ion Engine	1 – 10 mN	1000 - 3500	Xenon 7, Iodine 4

Firstly, and although there are different ways of removing electrons from the cathode, the thruster in which this study is based on has a thermionic emitter which means that electrons are separated through a thermionic emission process [7]. Afterwards, when the electrons are already in the discharge chamber, they collide with the propellant, forming the ions that will be expelled, the phenomenon that makes it possible to expel the ions is the aforementioned potential difference created within the grids.

The magnets are depicted in the Figure 2 inside the discharge chamber as can be seen below in burgundy colour.

2. Case Study

There are different ways to study a magnetic field. One of which is through the

computation of the magnetic potential, ϕ_m, which can be derived from Maxwell's equation and Laplace's equation [8]. This allows to determine the magnetic field for a given distance and angle from a magnetic source.

$$\Phi_m = \sum_{k=0}^{\infty} \frac{m_k}{r^{k+1}} P_k(\cos\theta) \tag{1}$$

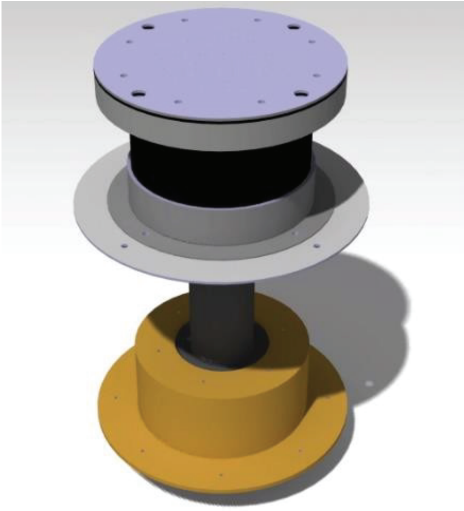

Figure 1: XISP model with 10-centimetre grids.

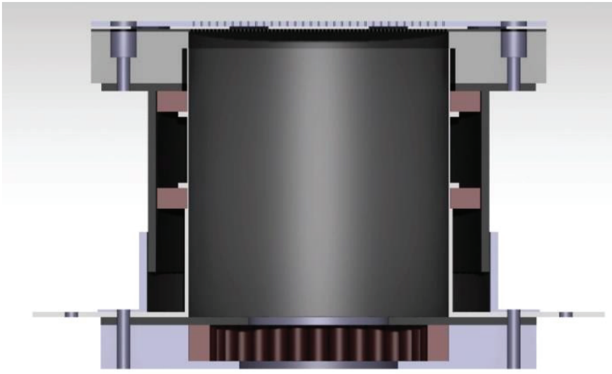

Figure 2: Interior display of the Discharge Chamber.

However, this wasn't the approach used. For the presented case it is necessary to have in consideration the vicinity of the magnetic sources and the different materials around those spaces. To analyse the magnetic field, an open source software, Finite Element Method Magnetics, FEMM, was used. As the names suggests, this program uses the Finite Element Method to study different types of problems. It is possible to study magnetic or electrostatic problems in 2D, whether those problems are axisymmetric or planar. Every case is analysed through the mesh created by the program. Since FEMM takes in consideration the interactions of the magnetic field with the surrounding materials, a library is available with numerous different materials. Apart from this, it is possible to add new materials to the available library. Considering the nature of the problems for the FEMM's analysis to be successful, it is crucial that when a material is added to the list, its magnetic and electrostatic characteristics are as accurate as possible. For this study, MACOR, graphite and Carbon-Carbon composite were added to the library.

The magnets existing in the designed engine are permanent. Permanent magnets are materials where the magnetic field is generated by the internal structure of the material itself, meaning that, inside the operative conditions the material will keep its magnetic intensity. Due to this, the problem analysed in this document is a magnetostatics problem, a problem in which the fields are time-invariant. In this problem the *field intensity* (*H*) and *flux density* (*B*) must obey [9]:

$$\nabla \times H = J \tag{2}$$

$$\nabla . B = 0 \tag{3}$$

To present results FEMM utilises the following equation:

$$\nabla \times \left(\frac{1}{\mu(B)} \nabla \times A \right) = J \tag{4}$$

So that magnetostatics problems with a nonlinear *B*-*H* relationship can be solved.

In the general 3-D case, *A* is a vector with three components. However, in the 2-D planar and axisymmetric cases, two of these three components are zero, leaving just the component in the "out of the page" direction.

Product Set-up:

The Figure 3 only represents half of the thruster since FEMM can analyse axisymmetric problems. The analysed segment of the thruster is represented by the blue square in Figure 4. During the process to obtain the set up shown in Figure 3, it is necessary to define the material for each geometrical shape and the boundary conditions. The definition of the materials is what sets the parameters to use in (4). For example, the chosen magnets, SmCo30, have a coercivity of 817190 A/m, a linear B-H Relationship, a source current density of 0 MA/m^2 and a relative μ_r and μ_z of 1. Regarding the boundary conditions, there are 5 different possibilities: Dirichlet, Neumann, Robin, Periodic A and Antiperiodic. The one used was Dirichlet's one. In this type of boundary condition, the value of a potential A is explicitly defined. A was defined as 0 along the boundary, meaning that the magnetic flux will not cross the boundary.

FEMM has the ability to automatically create a mesh for every presented problem. This mesh represents the level of detail that the results will have. Having more points in the mesh means a more precise result. The automatically generated mesh has more points in the limits of each geometry, as a result, the distribution of points is not uniform alongside the problem. It is possible to refine the mesh, and with this tool the mesh becomes uniform alongside the defined boundaries. The automatically generated mesh for this study had 15583 points, but meshes with 4050, 11090, 40286 and 157499 points were also tested.

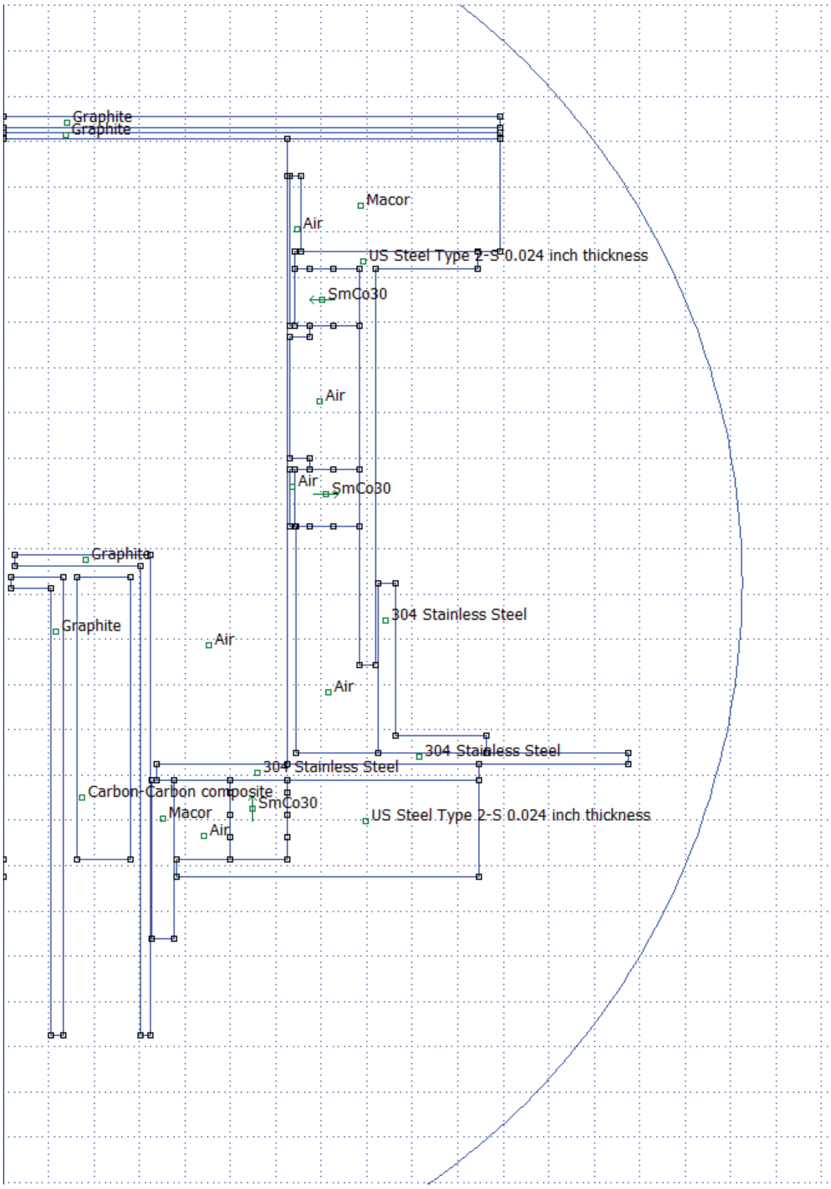

Figure 3: FEMM representation of XISP model with 10-centimetre grids.

When filling in the problem definitions, and considering that the problem is axisymmetric, the default precision of $1 \cdot 10^{-8}$, was changed to the highest value possible, $1 \cdot 10^{-16}$.

3. Results

The purpose of this study is to check if the generated magnetic field of the designed thruster, which is an in oversizing of, Dr. Bondar's one [8] is as similar as possible to its predecessor's.

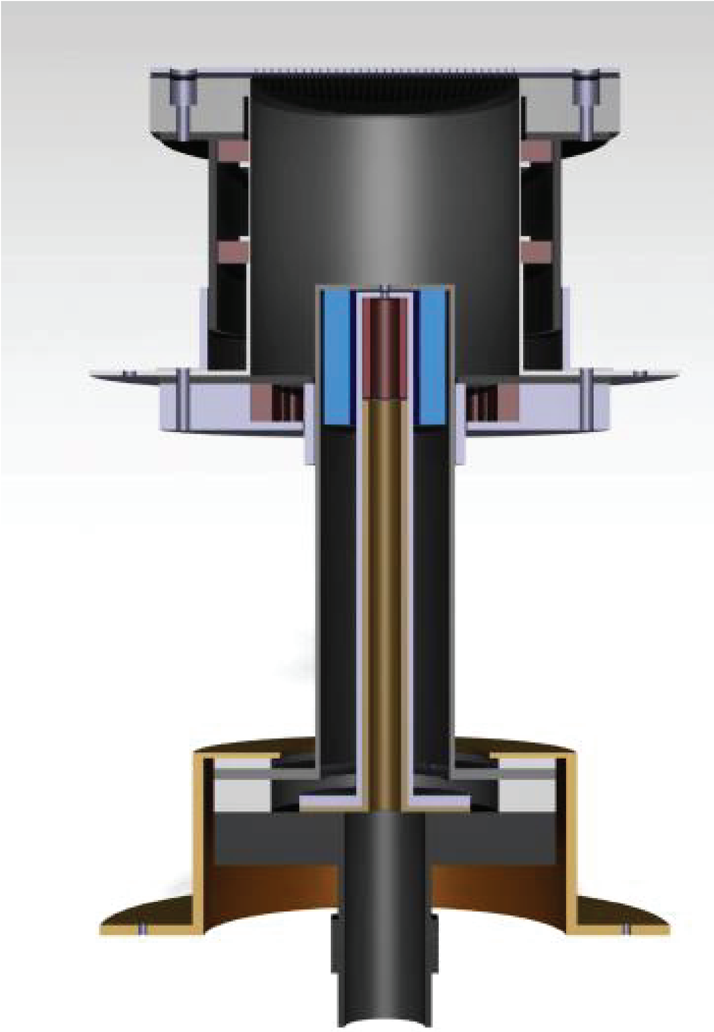

Figure 4: Interior display of the XISP model with 10-centimetre grids.

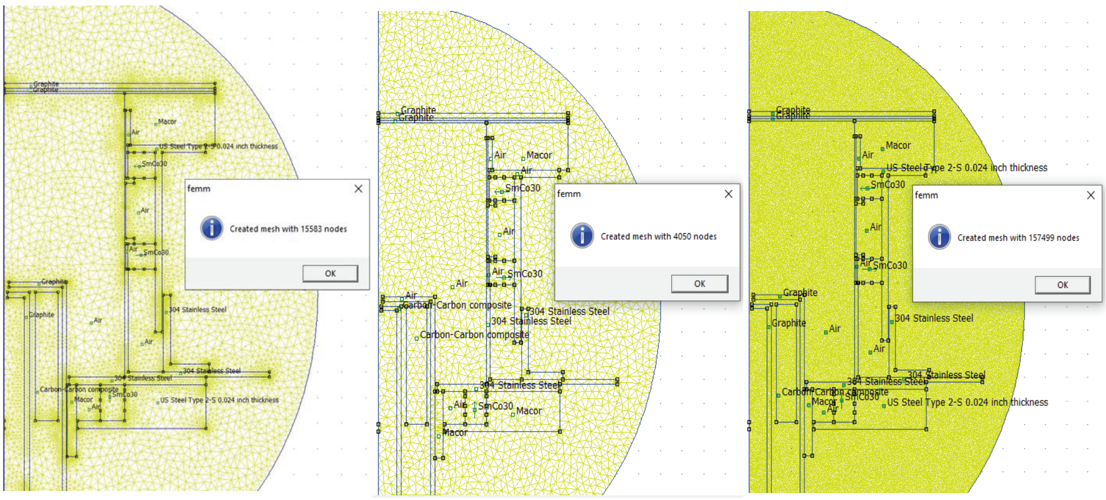

Figure 5: Automatically generated mesh, mesh with 4050 points and mesh with 157499 points.

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In a first approach of the oversizing, the option was to only change the diameter of each piece and try to keep the same thickness as the one used for the original thruster.

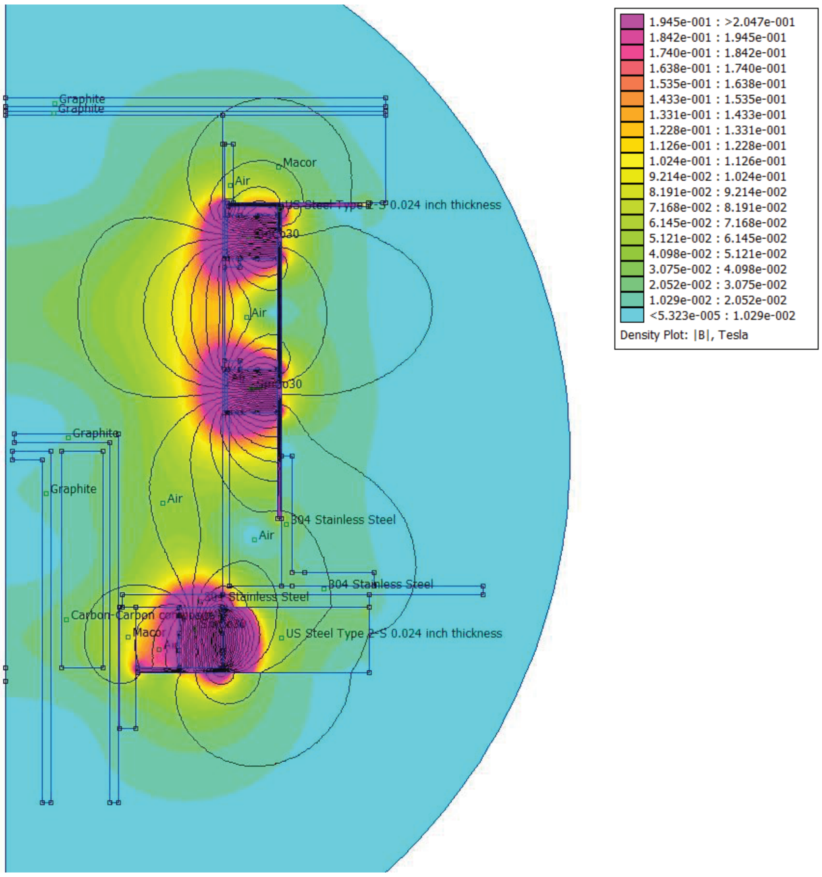

Figure 6: Results obtainned with 1 centimetre of thickness.

”The results obtained with this configuration weren’t the ones expected. It is possible to observe that the intensity of the magnetic field is higher than the one presented on Dr. Bondar’s results. This problem happened due to the reduced thickness of some pieces in the engine, which are shown in the image below.

To solve this problem, the thickness of those pieces was increased. The original thruster was designed for an active grid of 3 centimetres and this study is for a thruster with an active grid of 10 centimetres, so the diameter of each piece was increased by 3.33 times the original size. The same principle was used with the thickness of both pieces, but to simplify the manufacturing process they were only increased by 3 times their original size, changing from 1 millimetre to 3 millimetres of thickness.

This result is according to what was expected, which leads to the conclusion that the thickness of 3 millimetres is enough. All the images shown above were obtain in FEMM after analysing the problems with a mesh of 157499 points. As explained in the case study the results were tested for different meshes to understand the influence it had on

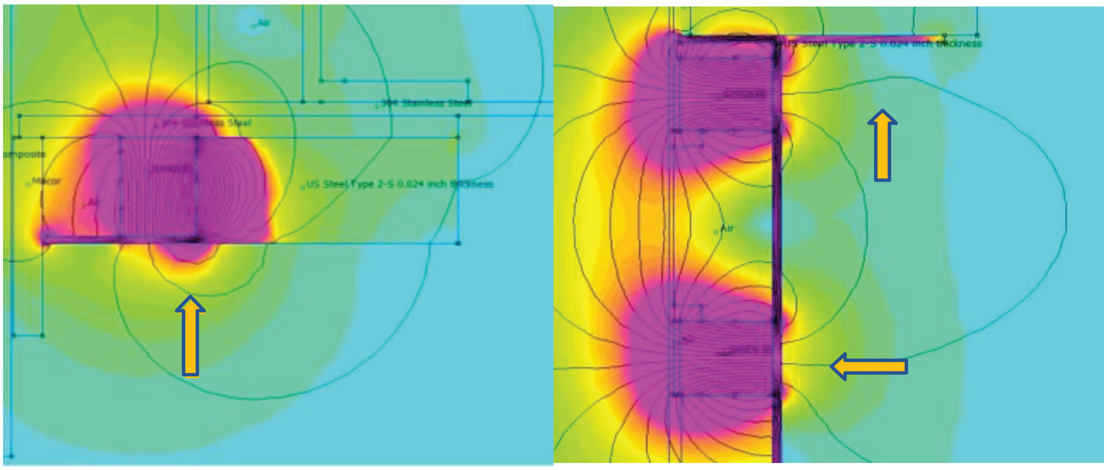

Figure 7: Critical areas with 1 cemtimetre of thickness.

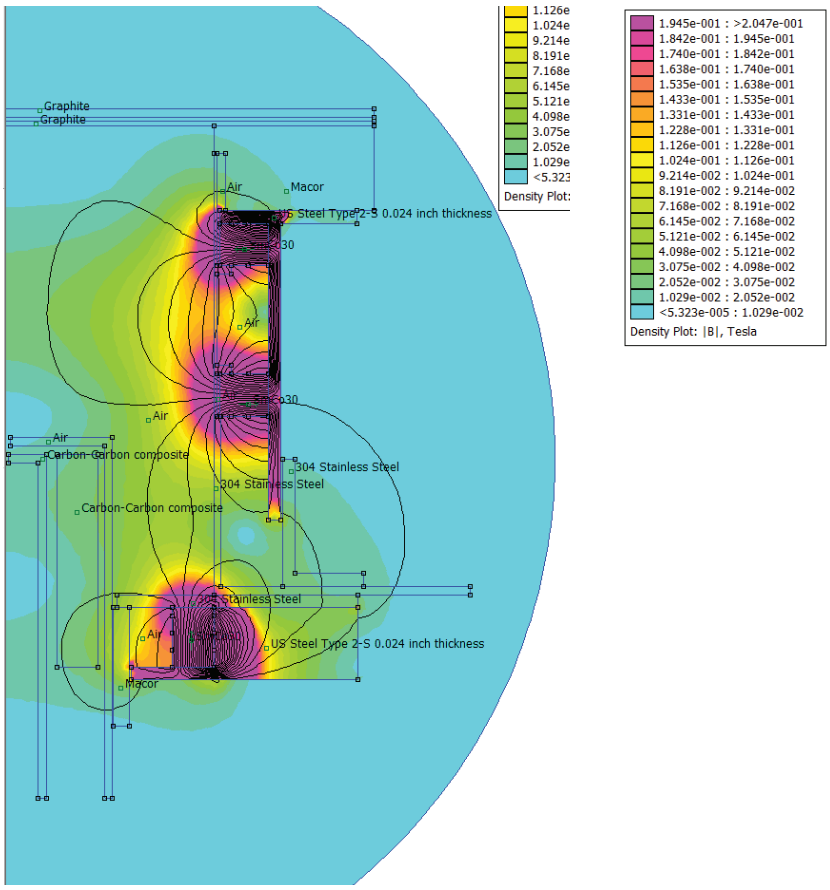

Figure 8: Results obtainned with 3 centimetre of thickness.

the final results. Since there were no noteworthy differences between the results, only the results with the most precise mesh were presented.

With the analysis of the result it is possible to conclude that the goal of this study was achieved. Through FEMM's colour scale is possible to analyse the magnetic field in the thruster. When approaching the centre of the engine the magnetic field intensity is much lower than closer to the magnets. This low strength diverging magnetic field in the centre of the discharge chamber is designed to prevent the over-confinement of the plasma and maintain a uniform ion beam density profile.

Although the results were satisfactory, there were some differences in relation to Dr.

Bondar's study. Those differences are solely related to the presentation of the field lines.

The first one is regarding the lines existent to the right side of the engine in the original thruster's study, this happens since the display option used in Dr. Bondar's work was around 50 field lines while for the present work, only 30 were used. This option is based on the simplification on the result's analysis.

The second one is the field lines' distribution across the magnets. In the original study the distribution in the magnets isn't uniform, contrary to the present work where the distribution was uniform.

Both these differences are only related to the way the results are presented and both are defined in a FEMM tool named "contour plot". For the present study, and regarding the "contour plot" definitions, the results were presented with a number of contours of 30, a lower bound of -0.00164 and an upper bound of 0.00247.

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