Magnetic Field Design for a Strongly Improved PHALL Thruster

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Abstract. In this article, we are going to go through some steps that we took in the refining of engineering work related to the development of a permanent magnet Hall thruster. The use of permanent magnets in these thrusters is mainly related to the decrease of used power for propulsion, especially important for low power thrusters as for micro-satellites. The advantage of our chosen configuration is that the magnetic field can be used either perpendicular or parallel to the thruster channel walls, whereas in the last case the generated erosion forces are strongly reduced by at least three orders of magnitude. We are going to show how each magnetic field configuration affects the generated plasma and consequently the generated propulsion force and efficiency.

1. Introduction

Since 2004, the Plasma Physics Laboratory (LFP) of University of Brasilia - UnB is developing high efficiency Hall Effect Plasma Thrusters (PHALL) using permanent magnets [1-5]. These types of thrusters are now currently being used for commercial and scientific space missions for satellite attitude and orbit control and for long duration space missions in the solar system. In order to simulate the vacuum conditions of the space environment, high vacuum systems are used at LFP, in order to test the thrusters in conditions similar to those that are encountered in space, where they will work.

These thrusters have an anode in the form of a metallic ring that is inside a ceramic annular channel. A vertical ion accelerating electric field is generated between this anode and a virtual cathode made of an electron Hall current generated upwards to the anode in a region where the electric and magnetic fields are mutually perpendicular. The electrons are strongly magnetized by this magnetic field and follow a circular unidirectional path determined by the ExB fields. Ions are accelerated towards this virtual cathode and are ejected from the thruster at high velocity generating a reaction thrusting force.

Generally, the used magnetic fields are perpendicular to the vertical annular ceramic walls of the thruster, generating also a strong erosion process of the protective thruster material in a relatively short time frame severely limiting the lifetime of the thruster. This occurs because the electrons are also strongly directed along magnetic field lines towards the walls, leading the ions to follow their path by electrostatic attraction. However, there is a new and much better magnetic field configuration known as “magnetic shielding” where the magnetic fields are parallel to the vertical walls and significantly increase the lifetime of our thrusters for long duration space missions.
We will show for the first time how we have used ferromagnetic materials in order to control the magnetic field intensity of permanent magnets, which also allow for a decrease of the magnetic field to the desired intensities while helping at the same time to strongly making these fields much more uniform. In this way, we can engineer the shape of the thruster’s magnetic fields in order to allow the correct and controlled development of Hall currents along uniform lines of perpendicular ExB spaces. When the magnetic shielding configuration is used we are able to generate a circular Hall current just outside the exit channel of the annular thruster therefore avoiding most of the contact and interaction between the generated plasma and the ceramic walls increasing dramatically the thruster’s working lifetime and operational usefulness.

2. Magnetic Field Simulation Results for B Field Perpendicular to Wall and their Effects on Plasma Current

Initially, the intensity of the magnetic field $B$ at the center of the internal channel of the PHALL II-A, where the plasma discharge occurs, was around 700-900 Gauss (Figure 1) in the whole vertical length of the 35.5 mm magnet height. This configuration caused a strong magnetization of both ions and electrons (which inhibited the generation of propulsive forces) generating a plasma torus (Figure 2). This magnet configuration had a strong gradient and non-uniformity of the $B$ field along the internal channel of PHALL due to the aluminum support (non-ferromagnetic) structure that was initially used.

This initial result shows the need to use magnetic fields of specific magnitudes that can magnetize the electrons but not the ions. Magnetic fields in the order of 100 Gauss satisfy the conditions for length scales in the order of 10 mm. In practice, conventional Hall thrusters with powers in the order of kilowatts use magnetic fields with average peak magnitude around 100-300 Gauss at the center of the annular channel, with a depth and width around 25 mm.

For this propulsion system to work we have to use conditions where the Larmor radius of the electrons ($r_e$) is substantially smaller than the dimensions of the annular channel ($L$), which itself has to be substantially smaller than the Larmor radius of the ions ($r_i$) in such a way that the ions are not magnetized and can be ejected from the thruster in order to generate a useful propulsive force [6]. These relations are explicit in Equation 1 (where $v_e$ and $v_i$ is the electron and ion velocity respectively, $e$ is the electron elemental charge and $B$ is the magnetic field magnitude) and Table 1.

$$r_e = \frac{m_e v_e}{e B} < L < r_i = \frac{m_i v_i}{e B}$$  \hspace{1cm} (1)

Table 1. Magnetic field intensity and Larmor radius for ions and electrons depending on applied magnetic field.

| Magnetic Field Strength (Gauss) | $r_i$ (mm) (1000 K) | $r_e$ (mm) (eV) | (1) | $r_e$ (mm) (10 eV) |
|-------------------------------|---------------------|-----------------|-----|-------------------|
| 1                             | 5500                | 40              | 120 |                   |
| 100                           | 55                  | 0.4             | 1.2 |                   |
| 1000                          | 5.5                 | 0.04            | 0.12|                   |

This ion magnetization problem was solved by replacing the initial long magnets (10x10x35.5 mm) with other shorter and smaller magnets (10x10x10 mm, Figure 3) and by replacing the initial aluminum support for the magnets with a different support with a material of ferromagnetic nature (Figures 3 and 4). By simply decreasing the magnet length and using these shorter magnets with no ferromagnetic support we can generate immediately lower fields (100-500 Gauss) than before (700-900 Gauss), but 500 Gauss (Figure 3) is still too high for our purposes (Table 1). By adding the ferromagnetic support into the mix this solution allows for the necessary decrease of magnetic field intensity inside the channel to levels where only the electrons are magnetized (100-300 Gauss) as desired, and on the other side it also allows for a higher uniformization of magnetic field lines inside the channel (Figures 4 and 5).
Figure 1. Initial magnetic field configuration of PHALL II-A with no ferromagnetic material (magnets with length of 35.5 mm): a) 3D structure of magnets, b) Magnetic field line map for lines with 700 (green), 800 (yellow) and 900 (red) Gauss.

Figure 2. Plasma torus due to strong magnetization of both ions and electrons.

Figure 3. Magnetic field configuration of PHALL II-B with no ferromagnetic material reducing the size of magnets (squares of 10x10x10 mm): a) 3D structure of magnets, b) Magnetic field line map for lines with 100 (dark green), 200 (light green), 300 (yellow), 400 (orange) and 500 (red) Gauss.

In this case, by using the ferromagnetic material only on the inside of the external magnet ring (Figure 4 and 5.a)), then the field becomes uniform also only on the external half of the channel (Figure 5.a)) and if we use this ferromagnetic material also on the external face of the internal magnet ring then the field will be uniform along the whole channel (Figure 5.b)). This uniformity of the magnetic field is extremely important for the correct generation of the Hall current inside the channel of the thruster and the subsequent generation of force.
Figure 4. Disassembled PHALL II-B with partial ferromagnetic structure for magnets: a) perspective view, b) upper view.

Figure 5. 3D structure of magnets and ferromagnetic material with magnetic field line map (100 – green, 200 – yellow, and 300 – red, Gauss) for the PHALL II-B magnetic field configuration with the magnetic field perpendicular to the vertical wall of the channel (square magnets of 10x10x10 mm) with ferromagnetic material: a) only on the inside of the external ring, b) plus the outside of the internal ring.

In experiments, we have observed directly the influence of magnetic field line uniformity in the Hall current generated plasma discharge. When the magnetic field lines are uniform only on the external half of the channel, then the Hall current only appears in that partial space (Figure 6.a)), but when all the channel has uniform magnetic field lines then the plasma of Hall current occupies all the available channel space (Figure 6.b)) increasing the generated propulsion force and efficiency.
Figure 6. Generated Hall current when: a) magnetic field lines are uniform only on the external half of the channel, and b) magnetic field lines are uniform across the whole channel.

3. Magnetic Field Simulation Results for B Field Parallel to Wall

As we mentioned, the use of this new magnetic field configuration using magnets (10x10x10 mm) has the additional advantage of them being able to be used either in the normal magnetic field configuration (Figures 1, 3 and 5) with the field perpendicular to the wall, or in a second configuration with the field parallel to the wall (Figure 7), known as “magnetic shielding” configuration, and avoiding in this way the strong erosion processes that occurs in the normal magnetic field configuration, significantly increasing the lifetime of the thruster. In this case, also in accordance with the results of the previous section, the magnetic field inside the channel becomes completely uniform when we use the ferromagnetic material both on the inside of the external ring and on the outside of the internal ring (Figure 7.b)).

Figure 7. 3D structure of magnets and ferromagnetic material with magnetic field line map (100 – green, 200 – yellow, and 300 – red, Gauss) for the PHALL II-B magnetic field configuration with the magnetic field parallel to the vertical wall (“magnetic shielding”) of the channel (square magnets of 10x10x10 mm) with ferromagnetic material: a) only on the inside of the external ring, b) plus the outside of the internal ring.
Until the present moment, experiments have been made only with the magnetic field perpendicular to the wall (Figure 6.b)) with powers up to 800 W. A representative performance of our thruster at 450 W generates 36.4 mN of thrust with 2247 s of specific impulse. In the near future experiments will be performed also in the “magnetic shielding” configuration.

4. Conclusions
Initially, the intensity of the magnetic field at the center of the channel of PHALL II-A, where the discharge occurs was around 700-900 Gauss with 35.5 mm height magnets, producing a very strong magnetization of both ions and electrons (which inhibited the production of any propulsive force) generating a plasma torus. This problem was solved by replacing the long magnets (10x10x35.5 mm) by other smaller and shorter magnets (10x10x10 mm) and replacing the initial Aluminum support for the magnets by a different support with a ferromagnetic nature, which allows for a strong reduction of the magnetic field intensity in the propulsion channel to levels where only electrons are magnetized (100-300 Gauss) on one side, and on the other side it also allows for a much better magnetic field line uniformity inside the channel. In this case, by using the ferromagnetic material only on the outside ring, then the field becomes uniform only on the external half of the channel. But if we use this ferromagnetic material on both the inside and outside magnet rings, then the magnetic field becomes uniform in the whole channel. This uniformity of the magnetic field is extremely important for the correct generation of the Hall current in the thruster channel and consequently important for the generation of thrust.

The implantation of this new magnetic field configuration has the additional advantage of these magnets being able to be used both for the usual magnetic field configuration with the magnetic field perpendicular to the walls, and also able to be placed in a second different configuration with the magnetic fields directed parallel to the walls, known as “magnetic shielding” configuration, which is able to avoid by at least three orders of magnitude the strong erosion of the walls associated with Hall thruster operation and increasing in a very significant way the lifetime of these thrusters. These aspects will be tested in the near future.

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5. References
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