Hall plasma thruster development for micro and nano satellites

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Abstract. Hall thrusters are one of the most successful electric thrusters for space application that has been developed until now. The Plasma Physics Laboratory of the University of Brasilia (UnB) has been developing a Permanent Magnet Hall Thruster (PHALL) for the Brazilian Space Program since 2004. Recently we have achieved important experimental results satisfying our initial goals of generating a force above 40 mN with powers around 620 W. We will discuss in this article possible applications of this thruster to nano and microsatellites with powers above 50 W. Meanwhile, a complete description is given of our present and future installations where the new thruster will be tested; taking advantage of our new 1.5 m diameter vacuum chamber (the old chamber had 0.5 m in diameter), which intends to test our thruster in the most realistic conditions, including mounting and testing on a 3U CubeSat structure, which is where we intend to start testing our thruster in a real mission in space.

1. Introduction
Electric propulsion is proving to be a very successful method for primary and secondary propulsion systems of satellites and spacecrafts. It is an essential technology for station keeping of several existing and future geostationary satellites. Since their historical beginning in the sixties, most of the Solar System missions were based on gravity assisted trajectories, which depended heavily on planet orbit positioning relative to the Sun and the Earth. The consequence of such dependence was always the narrowing of the mission launch window. Future in situ exploration of small bodies of the Solar System will require less dependence on gravity assisted manoeuvering and will need new high precision and low thrust navigation methods. Hayabusa I and II are sample return missions to NEOs – Near Earth Objects. They are good example of successful deep space missions dedicated to explore near earth asteroids to study primitive leftover building blocks of the Solar System formation. Such missions could be accomplished with the usage of low thrust trajectories with spacecraft’s propelled by plasma thrusters.

2. Hall thrusters for micro and nano satellites
Permanent Magnet Hall Thrusters (PHALL) have been developed at the Plasma Physics Laboratory (PPL) at the University of Brasilia since 2004 [1-7], as part of a space activity program held by the Brazilian Space Agency (AEB). Now, applications of compact versions of PHALL on future Brazilian space missions are needed and foreseen for the coming years, beginning with the use of small Divergent Cusp Field Hall (DCFH) Thrusters on CUBESATS (5-10 kg, 1-5 W) and Microsatellites (50-100 kg, 10-100W). Brazilian (AEB) and German (DLR) space agencies and related research centers are now developing a new rocket system dedicated to small satellite launching known as the VLM -
Microsatellite Launch Vehicle. This capability could provide, in the near future opportunities to test on space several types of plasma thrusters. One of the main advantages of PHALL thrusters is the production of a steady state magnetic field by permanent magnets providing electron trapping and Hall current generation with a significant decreased load on the electric power supply. The development of more compact version of PHALL is foreseen future applications on CubeSats and microsatellites in order to extend their lifetime on space.

3. Latest PHALL II-C Results
Our latest version of the anelaar Hall type thruster using permanent magnets to save power and using a hollow cathode for the electron source is PHALL II-C (Figure 1). We have performed several plasma measurements on this thruster resulting in the compressed data given in Table 1 for two different total applied powers.

| Total Power (W) | Anode Power (W) | Cathode Power (W) | Force (mN) | Power / Force (W/mN) | Specific Impulse (s) | Electric Efficiency (%) |
|-----------------|-----------------|-------------------|-------------|----------------------|----------------------|------------------------|
| 350.4 W         | 200.4           | 150               | 24.92       | 14.60                | 1979.88              | 57.19                  |
| 620.6 W         | 470.6           | 150               | 41.39       | 14.99                | 2286.22              | 75.83                  |

These results reveal important PHALL technology maturation by achieving for the first time our proposed goal of generating a thrust force above 40 mN at 620 W (Figure 1) with a very good specific impulse of 2286 s, as desired for the expected application in space missions using small satellites. We are currently in the process to perform low power measurements in order to verify system performance.

Based on these successful results reached with PHALL II-C, we believe we will be able to develop a more compact and efficient plasma thruster nicknamed PHALL III. This will allow not only its use on microsatellites with small size and limited electric power consumption, but also the necessary performance improvements for future Brazilian spacecraft on long term space missions.

4. Future PHALL III Design
PHALL III (Figures 2 to 4) is being designed with a DCFH (Divergent Cups Field Hall) like model and foreseen to be used in future CubeSats and on microsatellites, including possible applications in
geostationary attitude control systems and on low thrust trajectory missions to the Near-Earth Asteroids region. We are using a particular new permanent magnetic field design for PHALL III (Figures 2, 3.a) and 4), together with computer simulations (Figures 4 and 5), using a particle-in-cell methodology [7] that predicts thrust performance characteristics and erosion lifetime expectations for these types of thrusters (Figure 5).

![Figure 2. Expanded view of PHALL III internal structure.](image)

![Figure 3. PHALL III a) Ferromagnetic structure to accommodate permanent magnets b) Complete setup upper view.](image)

![Figure 4. Comsol simulations showing PHALL III with white arrows for the magnetic field vectors in a) Direct configuration with magnets aligned magnetically, and b) Cusped configuration with magnets opposed magnetically.](image)
5. Our new test facility for testing nano to small satellites in a space environment

Our old vacuum chamber (Figure 6) used until now for the testing of the PHALL thruster in a space environment is made of non-magnetic 304L steel and has 2 meters in length by 50 cm in diameter. It has a total pumping capacity of 3,900 l/s using three diffusion vacuum pumps of the type Edward's Diffstak B34831977 with a pumping velocity of 1,300 l/s per unit and a Edward's E2M80 Rotary Vacuum mechanical pump capable of pumping until $10^{-3}$ Torr. The diffusion pumps start functioning after the pressure of $10^{-3}$ Torr and are capable of achieving a final working pressure of around $10^{-7}$ Torr.

The problem in using this vacuum chamber for testing Hall thrusters is that its diameter is very small and interacts strongly with the plasma plume of the thruster altering the plasma structure and density in relation to space conditions. In this way it will be extremely important for future tests to be performed in our new and bigger vacuum chamber.

![Figure 6](image)

**Figure 6.** Expanded view of PHALL III internal structure.

Our new vacuum chamber (Figures 7, 8) has a diameter of 1.5 m by 2.5 m in length, allowing to decrease possible interactions with the plasma plume both in the radial direction and linear direction due
to its larger diameter and length. This facility will use a mechanical pumping system formed by a Drystar 80/EH500 plus a DryPump GV80, with a pumping velocity of 400 m³/h, together with two turbo molecular pumps of the type STP-iXA2206C each with pumping velocities of 2,200 l/s on par with other two Edward’s STP-iXA4506C higher capacity turbo molecular pumps each with a pumping velocity of 4,300 l/s, where the chamber is prepared to receive in the future even more pumps or cryo-pumps to increase the total pumping capacity even more.

These new dimensions together with the higher pumping capability of around 13,000 l/s allow us to perform long duration tests of Plasma thrusters with higher discharge currents and powers in operating conditions similar (within possible) to those found in real space operating environments for nano and micro-satellites. In this way we will be able to elevate the current TRL 3/4 towards the desired TRL 5/8, where the next level or TRL 9 is the maximum TRL (Technology Readiness Level) where a technology is tested in real operating conditions, which in our case will be in space.

Our short term goal is to test a complete CubeSat type structure using a Hall thruster together with all space ready components in our new vacuum chamber, suspended by a vertical arm that will be connected to a force sensor in order to measure directly the force developed by our thruster in the most real possible application that we can create here on Earth (Figure 9).

Figure 7. Drawing and dimensions (mm) of the new vacuum chamber.

Figure 8. Images of the new vacuum chamber a) frontal view b) backwards view.
6. Conclusions
We at PPL have been able to come a long way since the start of our PHALL project in 2004 being able to generate gradual and step improvements (that depended on the received financial support) on PHALL in such a way that we have advanced at the present towards a Hall engineering model with a TRL of 3/4. We are developing currently two PHALL versions; PHALL III will be directed towards the nano or CubeSat segment and the second version will be used in micro-satellites and have a higher power. We are now immersed in the details of the PHALL III new and more compact design with a view for complete CubeSat testing in our new vacuum chamber, so that they can be used in future space vehicles of the Brazilian Space Program.

7. References
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