Permanent magnet Hall Thrusters development and applications on future brazilian space missions

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Abstract. The Plasma Physics Laboratory (PPLUnB) has been developing a Permanent Magnet Hall Thruster (PHALL) for the Space Research Program for Universities (UNIESPAÇO), part of the Brazilian Space Activities Program (PNAE) since 2004. The PHALL project consists on a plasma source design, construction and characterization of the Hall type that will function as a plasma propulsion engine and characterized by several plasma diagnostics sensors. PHALL is based on a plasma source in which a Hall current is generated inside a cylindrical annular channel with an axial electric field produced by a ring anode and a radial magnetic field produced by permanent magnets. In this work it is shown a brief description of the plasma propulsion engine, its diagnostics instrumentation and possible applications of PHALL on orbit transfer maneuvering for future Brazilian geostationary satellite space missions.

1. Introduction
The Plasma Physics Laboratory of the University of Brasilia (PPLUnB) has been developing a Permanent Magnet Hall Thruster (PHALL) for the Brazilian Space Program since 2004 [1, 2]. Our project consists in designing a plasma source and construction/characterization of plasma propulsion engines based on the Hall current ionizing mechanism generated by the perpendicular electric and magnetic fields produced by the vertical electric fields of a bottom ring anode and the perpendicular radial magnetic fields produced by permanent magnets on the exit of a cylindrical annular channel. This thruster has to be studied in vacuum mimicking conditions and therefore we have to perform the tests inside a long and cylindrical vacuum chamber where we have attached a whole paraphernalia of plasma diagnostics and electric power systems for thruster excitation and characterization (Figure 1).

Electric propulsion is now becoming a very successful method for primary and secondary propulsion systems. It is essential for deep space long duration missions and for station keeping of geosynchronous satellites, where the thrusting system can be designed to be used on orbit maneuvering or on satellite attitude control in long term space missions.

One of the main advantages of our PHALL thruster is the production of a steady state magnetic field by permanent magnets providing electron trapping and electron Hall current generation with a significant decrease on the power consumed from the electric power supply. This advantage turns the PHALL thruster into a specially good option when it comes to space
usage for longer and deep space missions, where solar panels and electric energy storage on batteries is a limiting factor. Two prototype models, PHALL I and II, were already developed and tested with different types of permanent magnets (Figure 2).

Figure 1. General experimental setup with vacuum chamber and diagnostics for Hall thruster tests.

Figure 2. Hall thrusters developed at PPLUnB. a) PHALL I (External diameter of 30 cm); b) PHALL II (External diameter of 15 cm).
2. Physical characteristics of PHALL

Now we will describe briefly the general construction and characteristics of our Hall plasma source. The first prototype, the PHALL I (Figure 2.a) had long magnets that accompanied the length of the whole circular annular channel and were disposed at an angle at the inside and outside of the channel and used a tungsten wire at the top to initiate the discharge by thermionic electron emission. Later on this thruster was refined into PHALL II by using shorter magnets parallel to the channel walls thereby focusing the Hall current only at the channel exit and increasing the ion accelerating electric field between the anode and the virtual cathode (Figure 2.b and Figure 3). In PHALL II the tungsten wire was also replaced with a hollow cathode for electron emission, thereby improving efficiency and performance.

![Figure 3. PHALL II. On the left: with top hat dielectric protection, and on the right: showing the magnets without top protection.](image)

3. Diagnostics

Our Integrated Plasma Diagnostic System will now be detailed (Figure 4). This system contains several Langmuir probes that are used for plasma density and temperature measurements. We also use a Faraday Cup, Ion probes and a Spectrograph (Andor SR-750-B2, within 435nm to 700nm - line broadening measurements) to measure ion temperature and transport parameters inside the Hall current channel and the ejected plasma plume. In order to control the argon fuel purity a mass spectrometer is also planned to be used in the future. We are developing at this time a setup for detailed thrust and specific impulse measurements. We also research any relevant plasma physics phenomena that may significantly interfere on PHALL thruster performance due to the occurrence of instabilities inside and outside of the Hall current channel. In order to better understand the turbulence and plasma oscillations that occur during the thruster operation, we have a wide frequency range instability detection system based on a RF detection probe connected to a Spectrum Analyzer (Agilent CSA 100 khz-6 Ghz). Instabilities on the PHALL discharge current are monitored in a real time data acquisition system, based on a PCI-DAS 1602/12 board containing 16 analogic inputs, 24 digital channels operating within a 330 KHz sampling rate.

4. Applications and developments for future Brazilian Space Missions

Future developments of our program will include an experimental PHALL lifetime test system assembly in a vacuum system with a much bigger volume and pumping speed capability. We will
compare these results with correspondent preliminary simulation results. We will also develop for the bigger chamber a new direct thrust and specific impulse measurement instrumentation system in order to obtain detailed performance characteristics of our PHALL thruster. We are also in the process of concluding a completely automated system for plasma diagnostic measurement which will provide all plasma characteristics and parameters in real time on the spot.

Finally, based on the measured parameters of the accelerated plasma, we are able to present an aptitude figure (see table 1 below) for PHALL I and PHALL II. It contains all working parameters such as the specific impulse, total thrust, propellant flow rate, electric power, efficiency and all parameters needed to foresee what type of space mission will be suitable for the thrusters we are developing.

| Table 1. Working parameters of PHALL I and PHALL II. |
|--------------------------------------------------|
| **PHALL-I** | **PHALL-II** |
| Thrust (mN) | 26.5 - 126.0 | 23.0 - 150.0 |
| Thrust power (N/m²) | 1.5 | 2.4 - 8.7 |
| Specific Impulse (s) | 803.5 - 1607.0 | 1500.0 - 2000.0 |
| Power (W) | 1250.0 | 500.0 - 1000.0 |
| Mass flow rate (mg/s) | 5.0 | 2.0 |
| Electrical efficiency (%) | 67.2 | 80.0 |
| Total efficiency (%) | 8.4 | 45.0 - 60.0 |

We show numerical simulations results for satellite orbit raising from an altitude of 700 km to 36000 km using a PHALL II operating in the 100mN - 500mN thrust range for two situations: in the first case, the satellite is in a circular orbit and is subjected to a continuous thrust tangent to the orbit. In the second case, the satellite is on an elliptic orbit with pericenter of 700 km and apocenter tangent to the geosynchronous orbit. However, in this case we have applied a continuously pulsed thrust with direction tangent to the orbit at the apocenter. The second situation resulted in a faster orbit transfer. In order to perform these calculations, integration techniques of spacecraft trajectory were used. The main simulation parameters
Figure 5. Maneuver time to send a spacecraft to geostationary orbit, from 700 km altitude circular orbit, using continuous thrust as a function of propellant mass flux (measured in laboratory for PHALL II) and of satellite mass.

were: orbit raising time, propellant mass, satellite mass, thrust specific impulse and exhaust velocity. Figure 5 shows the maneuver time to send a spacecraft to geostationary orbit, from 700 km altitude circular orbit, using continuous thrust as a function of propellant mass flux (measured in laboratory for PHALL II) and of satellite mass.

Figure 6. Propellant mass consumption as a function of the apocentral angular opening for various thrusts.
The numerical calculation of propellant consumption for orbital transfer maneuvering are
depicted in Figure 6. The propellant mass is calculated for pulsed thrust in the correspondent
apoapsis orbit angle opening. The time necessary for circularized orbit using pulsed thruster,
supposing satellite geostationary orbit crossing apocenter, with pericenter at 700 km altitude,
for several values of PHALL II total thrust is shown in Figure 7.

![Figure 7](image)

**Figure 7.** Time necessary for circularized orbit using pulsed thruster, supposing satellite
geostationary orbit crossing apocenter, with pericenter at 700 km altitude, for several values
of PHALL total thrust.

5. Conclusion
We have come a long way in our study of plasma propulsion of the Hall current type and have
progressed from PHALL I to II and are preparing even a third further improvement which will
be disclosed soon. We are developing contacts in order to try and send one of these to the outer
space for real life testing. Possible applications of PHALL on future Brazilian space missions
dedicated to geostationary satellite orbit maneuvering from low earth to geosynchronous orbit
is foreseen. PHALL experimental results and computer calculations have shown that Electric
propulsion with Hall thrusters can improve and give important contributions to future Brazilian
space program missions.

6. References
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