

Electric Propulsion Activities in Brazil

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Abstract: Electric Propulsion activities in Brazil have undergone a considerable expansion since 2007, when a previous review was published. Other institutions have joined the pioneering National Institute for Space Research (INPE) and the University of Brasília (UnB), new research groups have been established and new facilities have been and are being implemented. In this paper, we present the current situation, together with plans for the immediate future.

Nomenclature

T	=	thrust
I_{sp}	=	specific impulse
I_b	=	beam current
I_K	=	keeper current
I_D	=	discharge current
m	=	propellant mass
$\dot{m}_j$	=	propellant mass flow rate (j : M main discharge, H main cathode and N neutralizer)
U	=	accelerating voltage
U_D	=	discharge voltage
q	=	ion charge
g_o	=	standard acceleration of gravity (45° latitude, sea level), $9,81 \text{ m/s}^2$
E	=	electric field
B	=	magnetic field
e	=	elementary charge
j	=	current density
k_B	=	Boltzmann constant
P	=	pressure
P_c	=	critical pressure of PTFE
Q	=	heat flux
R	=	resistance
R_a	=	radius of discharge cavity
T	=	temperature
T_c	=	critical temperature of PTFE
T_s	=	propellant surface temperature
V_0	=	discharge voltage
V	=	velocity
Γ	=	ablation rate
v_0	=	average exhaust velocity
ν_{ei}	=	electron-ion collision frequency
σ	=	plasma conductivity
Φ	=	plasma potential

I. Introduction

ELECTRIC Propulsion (EP) has been a reality in Brazil for over thirty years.¹ The two institutions that were pioneers in this field, the National Institute for Space Research (INPE) and the University of Brasília (UnB) established, in 2010, the Brazilian Electric Propulsion Network (RBPE), in order to facilitate collaboration and foster a more rapid development of the field.

The INPE Associated Plasma Laboratory (LAP/INPE) has been developing gridded ion engines (GIEs) and Hollow Cathodes (HCs) since 1985.² Several models of GIE have been tested in a 1.2m-diameter vacuum chamber, and thrust measurements have been performed with a target-based system, together with various types of plasma diagnostics. HCs with inserts made of rolled tantalum foil and a mixture of oxides have shown good current emission characteristics, with performances more than satisfactory, at least for laboratory use. Since 2012, HC testing has been ongoing in a smaller (0.8m-diameter), dedicated vacuum chamber.

Pulsed Plasma Thrusters (PPTs) have been developed at INPE Combustion and Propulsion Laboratory (LCP/INPE) for over ten years, both with conventional and multiple-discharge configurations.^{3,4} These latter have been tested with the intent of decreasing the negative impact of late-time ablation on thruster performance. In order to

perform direct thrust measurements, a new torsional balance has been designed and is being implemented. In the next few years, a new Electric Propulsion Laboratory will be built at LCP/INPE, with a large (4m-diameter) high-vacuum facility, in order to extend capabilities into large thruster and lifetime testing.

The Plasma Laboratory (LP) at the Physics Institute, University of Brasília (IF/UnB) has been investigating Hall-Effect Thrusters (HETs) since 2001, developing different models of Permanent-magnet HALL thrusters (PHALLs).^{5,6} The use of compact versions of such thrusters on Brazilian space missions is envisaged for the coming years, beginning with small divergent cusp field Hall (DCFH) thrusters on CubeSats and Microsatellites. Helicon Double Layer type thrusters are also being investigated.⁶ The LP at IF/UnB is undergoing an expansion, with the acquisition of a new, 1.5m-diameter vacuum chamber.

More recently, EP research has been ongoing at UnB Aerospace Engineering Course, established in 2012. Low-power and non-traditional geometry PPTs, in collaboration with LCP/INPE and the University of Southampton, UK (UoS),⁷ small HETs (in particular CHTs, Cylindrical Hall Thrusters), in collaboration with IF/UnB and UoS,⁸ and novel types of GIEs (in particular RITs, Radiofrequency Ion Thrusters) have been investigated. Traditional geometries and novel models of HCs are being studied in collaboration with IF/UnB, LAP/INPE and UoS. These theoretical and numerical investigations have yielded, among other things, correlations extremely useful for the preliminary design of thrusters. In order to supplement such studies with experimental activities, an Electric Propulsion Laboratory, with a high-vacuum, 0.75m-diameter chamber, is being established at Aerospace Engineering, and a thrust measurement system will be built and installed inside the chamber, in collaboration with LCP/INPE.

Other institutions have started to develop EP research activities, like the Federal University of Santa Catarina (UFSC) and the University of São Paulo (USP). UFSC, in particular, is developing a new numerical code for advanced simulations of EP plasmas, in collaboration with UnB and Texas A&M University, and joined the RBPE in December 2015. USP is working on extending the application of the model developed by Keidar and Beilis⁹ to different PPT geometries and discharge configurations, including multiple discharges, in collaboration with LCP/INPE and UnB.

II. Electric Propulsion Research Groups

Starting at INPE in the 1980s, EP research and development activities have grown considerably in the last thirty years. Since 1997, the UNIESPAÇO Program of the Brazilian Space Agency (AEB) has been supporting research in the aerospace field, with the intent of integrating Brazilian universities in the National Space Activities Program (PNAE). In recent years, the UNIESPAÇO program has been expanded and strengthened, greatly contributing, among other things, to the growth of EP in Brazil. Currently, four major Brazilian institutions are involved in the field: INPE, UnB, UFSC and USP.

A. National Institute for Space Research (INPE)

- **Associated Plasma Laboratory (LAP)**

INPE is one of the various institutes of the Ministry of Science, Technology, Innovation and Communications (MCTIC) of the Brazilian Federal Government. In the past four decades, INPE has been dedicated to a wide range of space activities involving various laboratories, in particular the Associated Plasma Laboratory (LAP), which was established in 1978, becoming the first associated laboratory of INPE in 1986. During the past two decades LAP has been recognized by the quality of various experiments and activities carried out in such diverse areas as: laboratory simulation of space plasma phenomena; isotopic enrichment; surface treatment of materials; fusion plasma research, with the development of a spherical torus and various plasma diagnostic techniques; electric propulsion.

In 1984 the laboratory started the PION (ion propulsion program) and in 2004 the PROPEL (electric propulsion program) was formally supported by AEB, both dedicated to the study of electrostatic propulsion and the development of Kaufman-type ion thrusters for auxiliary propulsion of satellites. These two programs have produced four prototype ion thrusters, with 5-cm (two models), 7-cm and 15-cm diameters. To this purpose, a complex infrastructure was established, comprising two high-vacuum facilities and a mechanical shop. The Ion Propulsion Group is currently composed of three senior researchers, specializing in plasma physics, chemical engineering and electronic engineering. Components like grids, hollow cathodes, magnetic confinement system, propellant feed system, were developed and built in-house. Diagnostic systems were also developed, such as Retarding Potential Analyzers (RPAs), Langmuir probes with software for operation and data processing and a pendulum target thrust balance. All data can be collected through a digital acquisition system.

The first demonstration prototype of ion thruster (PION-1), built in 1985, consisted of a 7-cm diameter by 14-cm long stainless-steel discharge chamber, a checkerboard magnetic assembly produced by ferrite permanent magnets, a pair of 30% transparency stainless steel grids masked down to a 3-cm exhausting section, and tungsten filaments as

primary electron emitters for both the main discharge and neutralizer. The performance tests were carried out in the first vacuum chamber using argon as propellant, with the flow set by needle valves (since there were no flow meters available at that time). The experiments comprised only the measurement of both the plasma density in the discharge chamber, using Langmuir probes, and the ion beam current, using a Faraday cup. Because of the poor overall performance, a maximum thrust of $2.7 \mu\text{N}$ was estimated for an accelerating voltage of 900 V, even generating plasma densities of order of 10^{16} m^{-3} . The thrust was estimated using the well-known thrust to beam current relationship, assuming a single charged ion beam (see Eq.1 in the Appendix). The second enhanced prototype (PION-2) was built in 1992. This model was designed using self-consistent analytical methods, for both the ion optics system and the discharge chamber. It consisted of a 5-cm diameter by 10-cm long stainless-steel discharge chamber, a ring cusp magnet assembly produced by samarium-cobalt permanent magnets, one coaxial oxide cathode (thermionic emitter), a pair of 45% transparency tantalum grids masked down to a 4cm exhausting section, and a surrounding mu-metal magnetic shield. The PION-2 was tested inside the larger vacuum chamber using argon as propellant and the diagnostics were the same ones as those used for PION-1. The differences in performance between these two models were remarkable. For a same level of plasma density generated in both prototypes, PION-2 produced higher argon ion beam currents (typically 20 mA), resulting in an estimated thrust level of $560 \mu\text{N}$ and an estimated specific impulse of 190 s (see Eq. 2 in the Appendix), at an accelerating voltage of 1000 V and a mass flow rate of $300 \mu\text{g/s}$. The low value obtained for the specific impulse comes from propellant leaks through the PION-2 joints, which were not properly sealed by any welding techniques but only assembled by fastening them with screws. Another limiting factor for a better efficiency of this prototype was the short lifetime of the oxide cathodes (no more than few hundreds of hours), because the materials used were not resistant enough to the ion bombardment. The cathode was usually damaged either by losing its oxide layer for low discharge currents, or, by melting its nickel basis for discharge currents exceeding 1 A. The third ion thruster prototype (PION-3) was designed by Particle in Cell numerical codes (PIC), aiming both at enhanced plasma generation and at efficient ion beam extraction. It consisted of a 16-cm diameter by 5-cm long stainless-steel discharge chamber, a ring cusp magnet assembly produced by a pair of AlNiCo ring permanent magnets, a pair of 50% transparency molybdenum grids, and a surrounding mu-metal magnetic shield. A rolled-tantalum-oxide-foil-insert hollow cathode was used for the main discharge and a dispenser insert hollow cathode was used as neutralizer, the latter being a commercial type one. The PION-3 was also tested in the larger vacuum chamber. Its preliminary performance parameters, with an estimated thrust of 4 MN, and a specific impulse of 1200 s at 500 V accelerating voltage, indicate that this prototype exhibits real possibilities to achieve higher thrust levels once some improvements were adopted, e.g., the elimination of propellant leaks. The fourth ion thruster prototype (PION-4), shown in Fig.1, consists of a 6-cm diameter by 16-cm long stainless-steel discharge chamber,

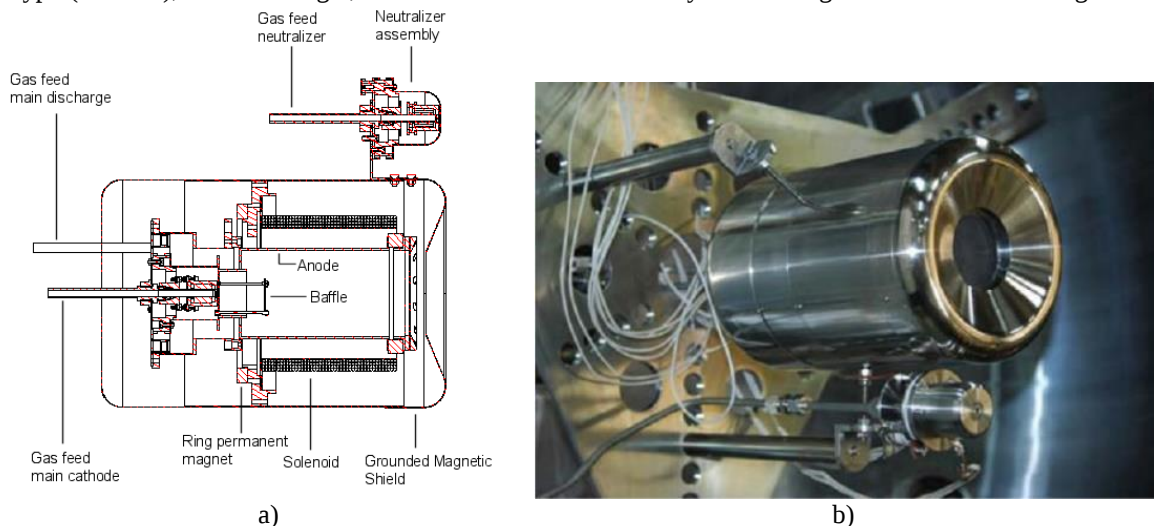


Figure 1. Schematic diagram of the 5-cm ion thruster PION-4 (a) and the thruster mounted inside the vacuum chamber (b).

with a pair of 50% transparency tantalum grids masked down to a 5 cm exhausting section. Its magnetic assembly consists of a solenoid and an AlNiCo ring permanent magnet radially magnetized. This setup allows a more flexible and precise adjustment of the magnetic containment volume of electrons, since the magnetic field strength will be

dictated by the solenoid current. A mu-metal magnetic shield surrounds the discharge chamber. The performance of the PION-4 was investigated with an RPA and a pendulum target thrust balance.¹⁰ The beam ion current was measured at the axial position. In order to calculate thrust, two different types of charge distribution were assumed: rectangular and triangular. The triangular distribution yielded thrust values closer to those actually measured with the target balance, as shown in Fig. 2. Table 1 shows the main performance parameters of PION-4 at full throttle.

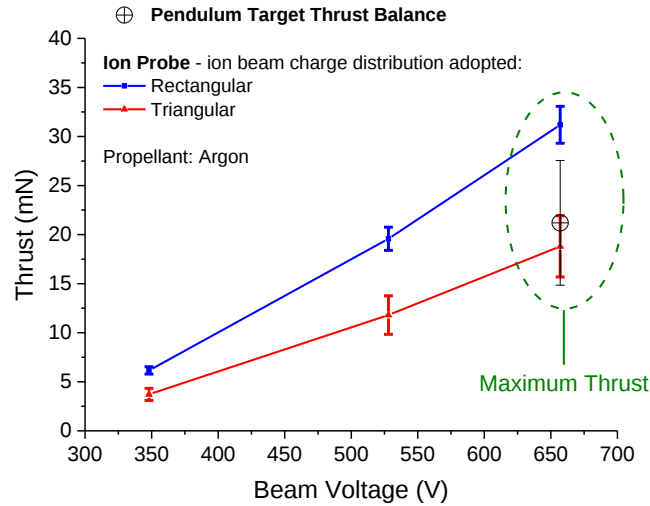


Figure 2. Thrust as a function of the ion beam acceleration voltage for the PION-4 ion thruster.

Table 1. PION-4 main performance parameters.

Thrust (mN)	Specific Impulse (s)	Thrust to Power Ratio ($\mu\text{N/W}$)	Propellant
20	5000 s	19,8	Argon

As mentioned above, the LAP ion thrusters started running with tungsten filaments, which were replaced by oxide cathodes, and presently they are equipped with rolled-tantalum-oxide-foil hollow cathodes. All these cathodes were entirely developed and built at LAP. One of the several models of hollow cathode, shown in Fig. 3, consists of a 5-mm diameter by 40-mm long, 0.3-mm-wall thickness tantalum tube, with a cold pressed 1-mm diameter orifice tungsten tip. The insert consists of a 5-turn rolled tantalum foil painted with a thin layer of mixed carbonates, (Ca, Ba, Sr) CO_3 , which are converted to oxides by heating the insert up to 900°C. The cathode heater comprises a boron nitride body machined in the shape of a revolver cylinder, with holes through which a coiled tungsten filament is passed, as shown in Fig. 3a. This heater dissipates 90 W to heat the cathode up the carbonate to oxide conversion temperature.

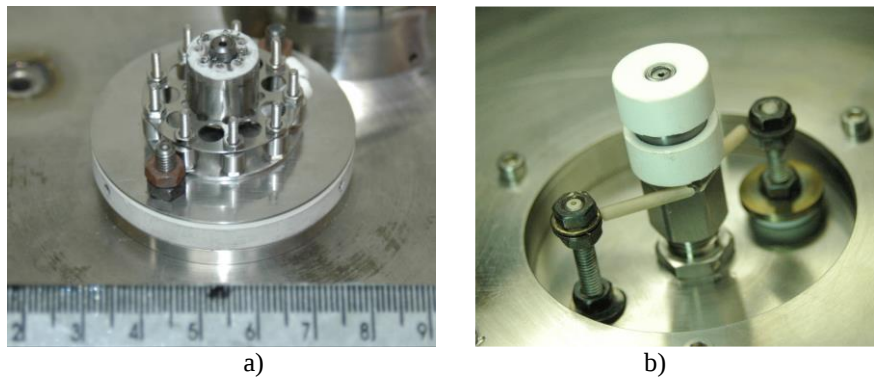


Figure 3. Rolled-tantalum-oxide-foil hollow cathode: heater cartridge (a) and full assembly.

As there are no commercial standard pipe fittings for 5 mm-diameter tubes, both the connector and the ferrules must be developed and machined specially for sealing the cathode body. The cathode full assembly is shown in Fig.3b. Experimental tests revealed that it can operate at currents in the range of 3 A to 10 A for long time periods, and at 18 A for short time periods. The discharge behavior of these hollow cathodes with rolled tantalum foil inserts, operating with xenon, was investigated. Plume, transition and spot mode were observed for different combinations of varying discharge current and mass flow rate, as shown in Fig. 4. Plasma parameters in the plume were measured with a cylindrical electrostatic probe, by varying its position from the cathode orifice to the anode (94 mm away from the cathode tip) in 5-mm steps. This was done only for plume and spot mode discharge conditions, as the transition mode is unstable, resulting in large oscillations of the probe current values. In plume mode, the minimum distance between the probe and the cathode orifice was kept to 5 mm, so as not to excessively perturb the discharge. In spot mode, such minimum distance was 2 mm, as for shorter distances the current collected by the probe would exceed the current limit of the voltage supply. Three cathode configurations were investigated, with different orifice diameters: 0.5 mm, 0.7 mm and 1 mm. Figure 5 shows the voltage-current discharge characteristics for different values of mass flow rate,

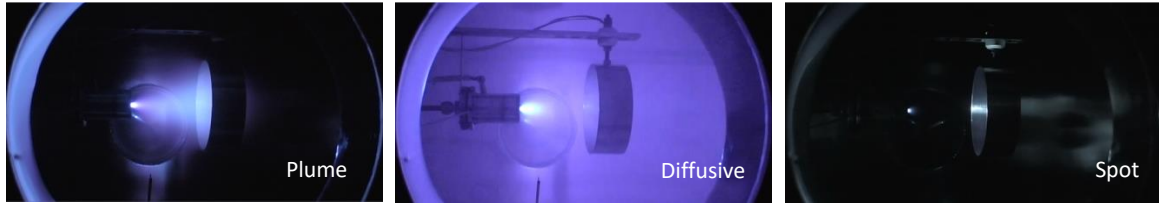


Figure 4. Hollow cathode discharge modes.

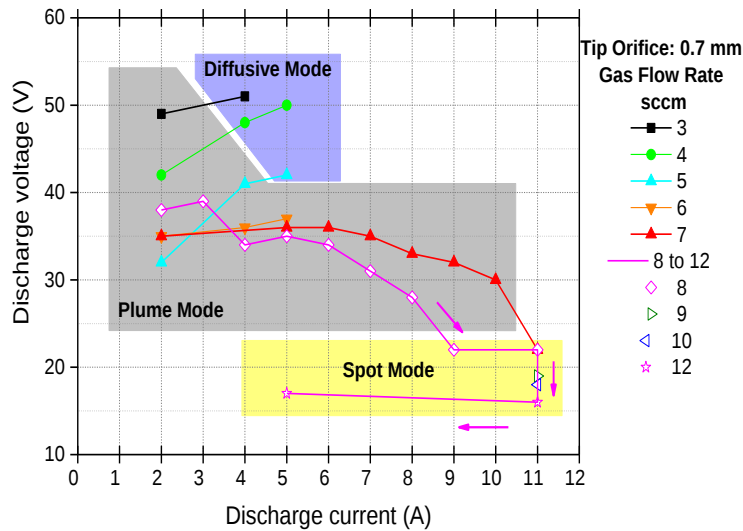


Figure 5. Discharge modes for the hollow cathode with 0.7 mm orifice.

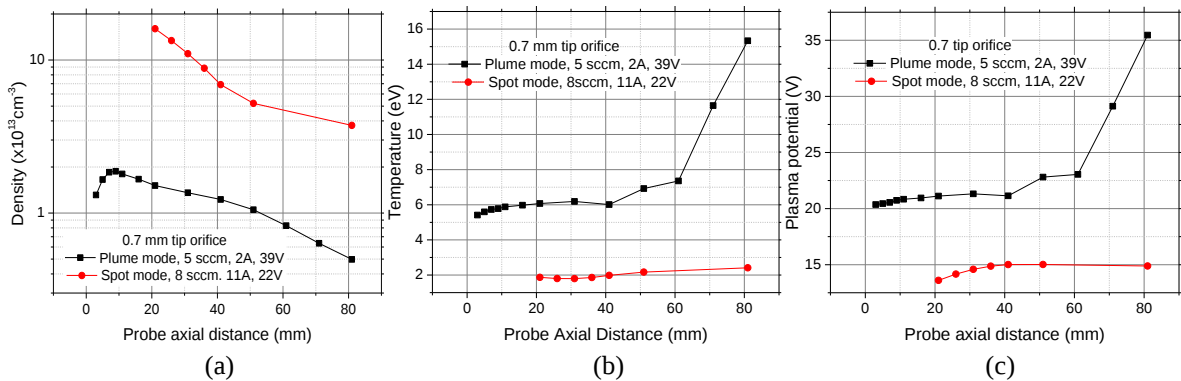


Figure 6. Plume and Spot modes plasma parameters for the hollow cathode with 0.7 mm orifice. Electron density (a), electron temperature (b) and plasma potential (c).

with different discharge regimes indicated, for the 0.7-mm orifice diameter hollow cathode. Plasma parameters are shown in Fig. 6, for plume and spot mode, with mass flow rates of 5 sccm and 8 sccm, respectively. The anode is placed 94 mm in front of the cathode tip, located at 0 mm.

- **Combustion and Propulsion Laboratory (LCP)**

In 2002 at INPE Combustion and Propulsion Laboratory (LCP/INPE) a research effort was initiated to study pulsed plasma thrusters (PPTs). In 2003 three thrusters were designed, built and tested. These PPTs had a coaxial geometry, copper electrodes and used Teflon® (PTFE) as a propellant. In 2004 a new research was initiated, in collaboration with the University of Southampton, aimed at increasing the PPT propellant efficiency by applying additional discharge(s) on the surface of the propellant, after the main discharge has occurred. In order to minimize the well-known late-time ablation (LTA) issue a new PPT design was conceived. The approach to solve this problem was to try to electromagnetically accelerate the LTA by employing an additional pulse (or pulses) after the main discharge occurs. However, if these additional pulses were to occur in the same set of electrodes, near the propellant surface, the propellant would receive more heat which would lead to more LTA. Therefore, the additional discharges should take place downstream, relatively far from the surface, in a separate set of electrodes.^{1,3,11}

It is clear that a synchronization system has to be used to allow the secondary pulse (or pulses) to occur only after the main discharge occurred. Also, it is desirable to have a switch system capable of triggering several pulses in the extra pair of electrodes in order to investigate the effects of the timing and different pulse patterns in the performance of the thruster, which is therefore denominated, in its general form, High-Frequency-Burst-PPT (HFB-PPT) or, in its simpler version, Two-Stage PPT or Double-Discharge PPT (DD-PPT). Research has been focused on studying the mechanisms that influence efficiency, concentrating on three main areas. First, the distribution of energy amongst the two-stages.¹² Then, the variation of the geometry of the electrodes of the second stage.¹³ Finally, actually measuring the thrust using a direct measurement, torsional thrust balance, calibrated with an optical system.¹⁴ Figures 7 and 8 show the thrusters and their plumes. Figure 9 shows the thrust balance developed at LCP/INPE.

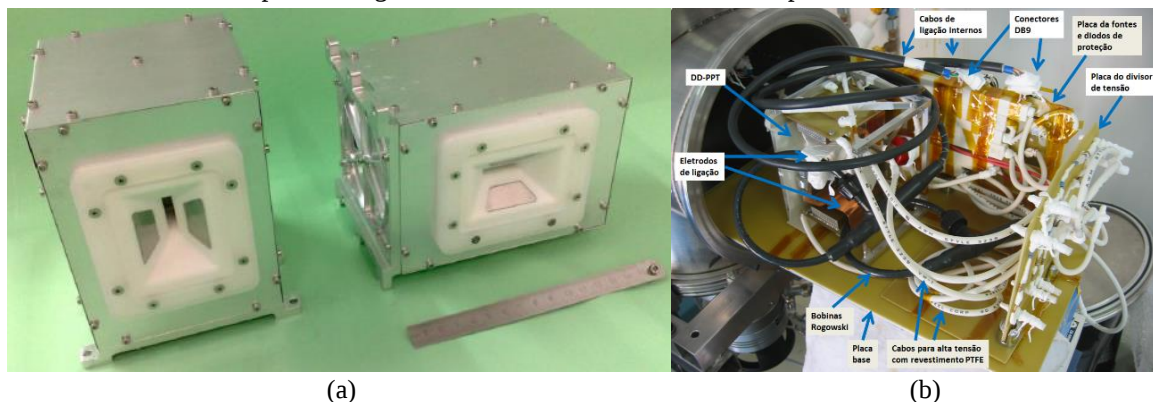


Figure 7. The DD-PPT X1 used to test energy distribution amongst the two stages (a) and the same in the vacuum chamber facility, connected to a power supply (b).



Figure 8. DD-PPT X1 (a) and DD-PPT X2 (b) being tested.

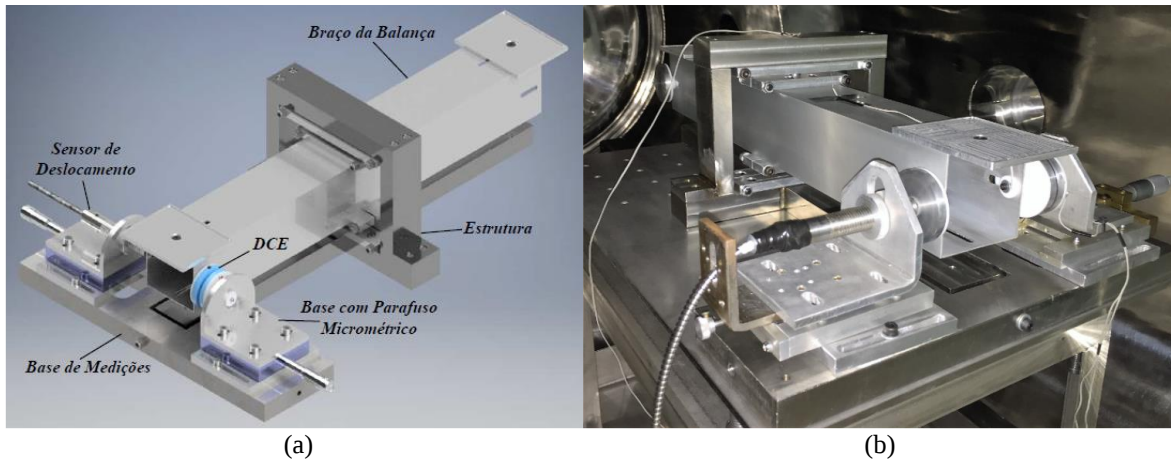


Figure 9. Direct Measurement torsional thrust balance with optical calibration system.

A new vacuum chamber, with 1-m diameter e 2-m length, has been purchased and is being installed (see Fig. 10). Much larger experimental facilities are being planned, which will allow investigating higher power devices and also the life-testing of electric thrusters for use in actual space missions.



Figure 10. The new 1-m diameter vacuum facility at LCP/INPE.

B. University of Brasília (UnB)

• Plasma Laboratory (LP) – Physics Institute

José L. Ferreira and his group started investigating electric thrusters by testing their first Hall thruster prototype in 2001 in the Plasma Laboratory (LP) at the Physics Institute (IF), University of Brasilia (UnB). This prototype consisted of a 28-cm diameter by 4-cm long stainless-steel discharge chamber with a 3.5-cm large ionization channel insulated by a thin ceramic cement layer within 2mm thickness. The anode consisted of a stainless-steel ring seizing 2cm wide and 1mm thick, located 3.8-cm from the exit of the channel. Behind the anode ring the propellant gas could be uniformly distributed in the Hall plasma source chamber by using an insulated copper circular tube with several small holes. The magnetic field was generated by a ring composed of several ferrite permanent magnets surrounding the discharge chamber. A movable tungsten filament painted with a layer of carbonates (Ba, Ca, Sr) CO_3 was used as primary electron emitter. The plasma diagnostics inside and outside the source were carried out by using both a movable Langmuir probe and an ion energy analyzer. This Hall thruster, shown schematically in Fig. 11a and assembled on the work bench in Fig. 11b, could produce an estimated thrust of 85 mN and an estimated specific impulse of 1080 s in high discharge current mode, and 26 mN and 900s in low discharge current mode, both ones using argon as propellant. The extracted plasmas for high and low current modes are shown in Fig 11c and 11d, respectively, during testing in a glass bell jar.

The second prototype of Hall thruster adopts the same concept of its predecessor, except by the following: a smaller discharge chamber with diameter of 15.5 cm, the replacement of the internal insulator by a sintered alumina case, the

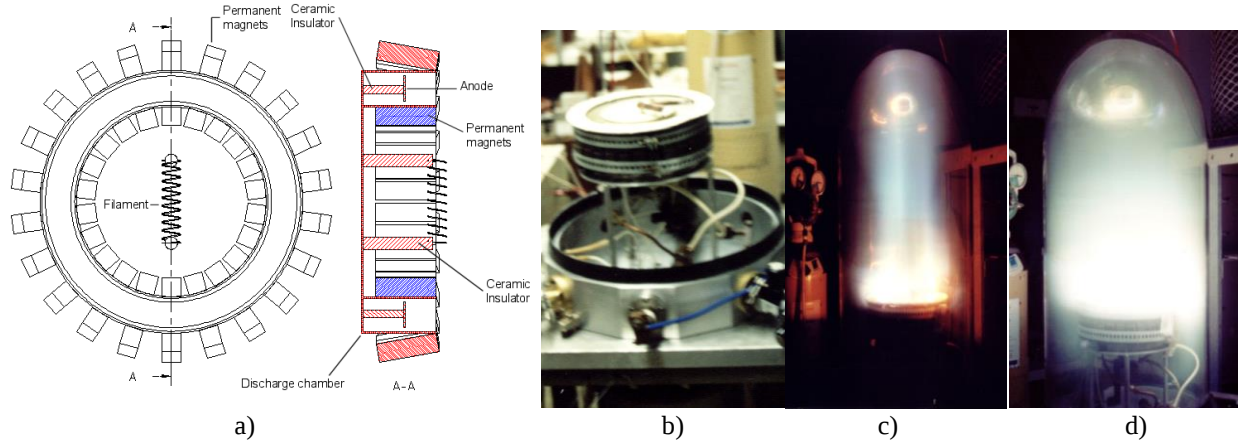


Figure 11. The first prototype of Hall thruster at UnB: schematics (a), assembled on the work bench (b), and firing in both low and high current modes (c) and (d), respectively

replacement of ferrite permanent magnets by NdFe permanent magnets, and the use of hollow cathodes instead of tungsten filaments for plasma generation. The plasma diagnostics involves, besides those ones mentioned above, a Doppler line broadening equipment developed as an evasive technique for the ion temperature measurement. The development of this Hall Thruster is funded under the UNIESPAÇO program of the Brazilian Space Agency (AEB).

One of the main advantages of PHALL thruster is the production of a steady state magnetic field by permanent magnets providing electron trapping and Hall current generation with a significant decrease in the electric power required. This advantage turns 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 PHALL II, were developed and tested with different types of permanent magnets. Plasma characteristics of these two acceleration systems are measured by several plasma diagnostics systems based on BID, an Integrated Plasma Diagnostic System. This system contains Langmuir probes that are used for plasma density and temperature measurements. Faraday Cup, Ion probes and Spectrograph (Andor SR-750-B2, within 435nm to 700nm) line broadening measurements are used to measure ion temperature and transport from Hall current channel to the ejected plasma plume. In order to control argon fuel purity a mass spectrometer is also planned to be used. Thrust and Specific Impulse measurements will also be shown. Important to notice relevant plasma physics phenomena investigation that may significantly interfere on PHALL performance. It is the occurrence of instabilities that can occur 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 propose and test 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 PHALL discharge current is monitored using 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. In order to prepare PHALL for near future Brazilian space missions, several developments are being made. Computer simulations based on a particle in cell (PIC) method have been carried out on a new computer based workstation integrated system. The main performance parameters of PHALL I and PHALL II, operating with argon, are summarized in Table 2.¹⁵

Table 2. PHALL I and PHALL II main operating parameters.

	PHALL I	PHALL II
Thrust (mN)	25-125	25-150
Specific Impulse (s)	800-1600	1500-2000

Up to the present, experimental investigations have been carried out in 0.5-m diameter, 2-m long vacuum chamber, pumped down with a combination of rotary and diffusion pumps. A new vacuum system is currently being assembled, which will allow performing PHALL lifetime testing, after further development, and in general the testing of a wide range of devices. This new system comprises a 1.5-m diameter vacuum chamber, shown in figure 12, pumped down



Figure 12. The new 1.5-m diameter vacuum facility at the Plasma Laboratory (LP), IF/UnB. to a high vacuum by using turbomolecular pumps. A direct thrust measurement system is being developed and will be installed in this new chamber.

- **Advanced Space Propulsion Laboratory (ASP Lab) - Aerospace Engineering**

A high vacuum chamber is being set up on the UnB Gama Campus, where the Aerospace Engineering Course was established in 2012. It constitutes the first experimental facility of the new Advanced Space Propulsion Laboratory (ASP Lab) and is shown in Fig. 13. With a 30-inch diameter, 50-inch length (75cm×125cm) and a 2000 l/s pumping speed, provided by a mechanical pump and a turbomolecular pump, it is well suited for low-power propulsion investigations.



Figure 13. The ASP Lab new vacuum chamber, with a 2000 l/s turbomolecular pump mounted below it. Preliminary to experimental work, which will include thrust measurements, carried out with a torsional balance similar to that developed at LCP/INPE¹⁴, theoretical investigations have characterized PPT performance through extensive analysis of experimental data available in the literature, yielding new semi-empirical relations extremely useful for initial thruster design. This was especially needed for the low-power operating regime, where existing relations did not accurately describe PPT behavior for all discharge configurations,⁷ and allowed some interesting insight into preliminary thruster design.¹⁶

In a similar fashion, performance data analysis of existing thrusters yielded semi-empirical relations that were employed in the preliminary design of low-power Cylindrical Hall Thrusters (CHTs).⁸ This work was partially carried out in collaboration with the Princeton Plasma Physics Laboratory (PPPL), UoS and the LP group at IF/UnB.

In connection to the lines of research described above, CubeSat/Nanosat propulsion system studies were carried out, investigating the use of PPTs^{17,18} and CHTs.⁸

Experimental work on Radiofrequency Ion Thrusters (RITs) was carried out by an exchange student at Justus Liebig University Giessen, Germany, in collaboration with ArianeGroup.¹⁹

HC investigations will entail acquiring and testing models developed at LAP/INPE, as soon as the high-vacuum facility is operational. Novel configurations (in particular, but not limited to, multi-channel and multi-electrode HCs) with LaB₆ emitting inserts are being studied in collaboration with UoS. Initial designs have been performed and models will be tested shortly. Besides their use as electron emitters, HCs are being considered for employment as standalone devices (Hollow Cathode Thrusters – HCTs), a line of research that was pioneered by Gessini, with the first actual thrust measurements of a modern, noble-gas HC,^{20,21} and successively by Grubisic^{22,23} and Frollani^{24,25}, all at UoS.

C. Federal University of Santa Catarina (UFSC)

- **Aerospace Engineering – Joinville**

The Kinetic Theory of Gases has the objective of describing the gas dynamics at the molecular level using the particle distribution function. The modeling of particle interactions can lead to different equations for the distribution function, the Boltzmann equation the most prominent.

Several numerical techniques can be used to discretize the Boltzmann equation. The Gas Kinetic Method²⁶ (GKM) is a finite-volume approach that solves the macroscopic continuity, momentum and energy equations obtained from appropriate averages of the Boltzmann equation. However, instead of evaluating fluxes from the macroscopic equations, an algebraic description of the fluxes at cell interfaces is obtained from the solution of the Boltzmann equation under some simplifying assumptions, in addition to the use of special interpolation procedures with shock-capturing features. GKM has the ability to correctly represent physics of the Knudsen number transition regime because of its independence from constitutive relationships. Current implementations of GKM have typically omitted the body force term, choosing instead to incorporate this term directly at the macroscopic level. This does not allow for the body force to affect the evolution of the distribution function. Our approach is to consider a simplified version of the body force term in which the non-equilibrium distribution function is approximated by the equilibrium distribution. Albeit not exact, we argue this is a reasonable approximation. The set of macroscopic equations is identical, however the algebraic flux expressions are still tractable. At the microscopic level of description, the Boltzmann distribution, hence the fluxes, will be affected by the body force term. Until now we have considered a Lorentz force field term given by $F = (\nabla \times B) \times B$. We are currently evaluating these different implementations with respect to computational cost and numerical accuracy under a set of benchmark problems.

D. University of São Paulo (USP)

- **Aeronautical Engineering – São Carlos**

The activities being carried at USP São Carlos are mainly concerned with simulation and mathematical modelling. The mathematical modelling used here for the PPT is based on Keidar and his colleagues' work⁹ where the plasma region is dissected into 3 sub regions as shown in Fig. 14: Knudsen layer, a hydrodynamic non-equilibrium layer, and a plasma bulk layer. The Knudsen layer is a kinetic non-equilibrium layer with a thickness of a few mean free paths of the plasma. The hydrodynamic non-equilibrium layer is a collision-dominated region, but the translational temperature of electrons and heavy particles are different. The outer boundary located between hydrodynamic layer and plasma bulk is the surface where all species reach thermal equilibrium.

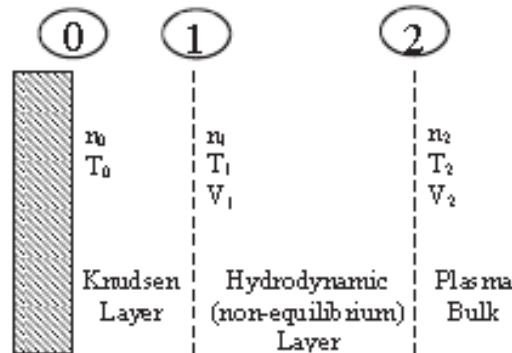


Figure 14. The triple-section division of the plasma region.

As a first step in this model, the number density, temperature and velocity at interface 1 are calculated from the following set of equations (1), given the experimental data of number density and temperature at interface 0. This would allow the calculation of the ablation rate.

$$\begin{aligned}
P &= P_0 \exp\left(\frac{T_1}{T_0}\right) = n_0 k_B T_0 \\
V_1 &= \left[\left(\frac{2kT_1}{m} \right) \left(\frac{T_2 n_2}{2T_1} - n_1/2 \right) / (n_1 - n_1^2/n_2) \right]^{0.5} \\
\Gamma &= m V_1 n_1 = n_1 \left[\left(\frac{2kT_1}{m} \right) \left(\frac{T_2 n_2}{2T_1} - n_1/2 \right) / (n_1 - n_1^2/n_2) \right]^{0.5}
\end{aligned} \tag{1}$$

Below are the equations (2) for the calculation of plasma acceleration: conservation equations of mass, momentum, and energy respectively. R_a is the cavity radius, Q_J is joule heating, Q_r is radiation loss, and Q_F is particle flux respectively. After obtaining the equilibrium pressure and electron temperature, the degree of ionization and plasma composition can be calculated by the Saha ionization equation. This model assumes full dissociation of the Teflon particles. Solved simultaneously with the above equation of the ablation rate, the acceleration derived from the electromagnetic effect can be obtained once we determine V_2 in the next section, the plasma bulk.

$$\begin{aligned}
A \left(\frac{\partial \rho}{\partial t} + \partial(\rho V) \right) &= 2\pi R_a \Gamma(t, z) \\
\rho \left(\frac{\partial V}{\partial t} + V \frac{\partial V}{\partial z} \right) &= - \frac{\partial P}{\partial z} \\
\frac{3}{2} n_e \left(\frac{\partial T}{\partial t} + V \frac{\partial T}{\partial z} \right) &= Q_J + Q_r + Q_F
\end{aligned} \tag{2}$$

Plume modelling based on a hybrid code of Direct Simulation Monte Carlo (DSMC) method and Particle-In-Cell method (PIC) was applied by Keidar et al. In this model, the quasi-neutrality of plasma in the plume is assumed. Ions and neutrals are treated as particles, whereas electrons are treated as a fluid. Particle collisions are treated by DSMC and the interaction of charged particles with electromagnetic field is treated by PIC. The electron distribution is derived by the electron momentum conservation equation (3) and Maxwell's equations.

$$e N_e (\mathbf{E} + \mathbf{V}_e \times \mathbf{B}) = -\nabla P_e - N_e v_{ei} m_e (\mathbf{V}_e - \mathbf{V}_i) \tag{3}$$

Then, the magnetic transport equation becomes

$$\frac{\partial \mathbf{B}}{\partial t} = \frac{1}{(\sigma \mu)} \nabla^2 \mathbf{B} - \nabla \times \left(\frac{\mathbf{j} \times \mathbf{B}}{e N_e} \right) + \nabla \times (\mathbf{V} \times \mathbf{B}) \tag{4}$$

By introducing Eq. (4) into Maxwell-Faraday's equation and equation before it, the electric field and magnetic field are obtained. Then, the ion dynamics can be solved.

This model is intended to be applied to the PPT constructed by Rodrigo I. Marques^{3,11} at LCP/INPE. There, Marques had been working on a two-stage PPT, where he added a second spark discharge as a mechanism to accelerate LTA particles, a phenomenon well known for causing efficiency losses in the thruster.

In addition, our current project expects to deliver an optimization study using the genetic algorithm developed by Alvaro Abdalla at USP. This shall evaluate different possible thrusts at different possible charge densities of the discharge current as well as physical dimensions of the thruster.

III. Conclusion

A brief history and the current situation of EP activities in Brazil has been presented. Despite the still modest number of players, and an involvement of the private sector that is only at the beginning, the field has undergone a considerable growth, and perspectives for the immediate future are encouraging.

Appendix

Thrust:

$$T = I_B \sqrt{\frac{2mU}{q}} \quad (1)$$

In this paper, the thrust has been estimated assuming singly-charged ion beams.

Specific impulse:

$$I_s = \frac{T}{\dot{m}g_o} \quad (2)$$

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