Plasma Diagnostics System Development for Permanent Magnet Hall Thrusters

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José Leonardo Ferreira [1], Ivan Soares Ferreira[2], Jean Carlo Santos[3], Rodrigo Miranda[4], Paolo Gessini[5], Gabriela Possa[6] and Lui T. C. Habl[7]
University of Brasília, Brasília, DF, 70910-900, Brazil

Abstract: This work describes the development of a permanent magnet Hall Effect plasma thruster and its diagnostic systems at University of Brasilia Plasma Physics Laboratory. In order to measure plasma characteristics and thrust parameters an Integrated Plasma Diagnostics System were constructed. Experimental results containing plasma flow velocity, thrust and specific impulse, together with working parameters of two types of permanent magnet plasma thrusters are given. These results are analyzed and compared with other Hall Thrusters performance parameters.

I. Introduction

THE Plasma Physics Laboratory of UnB (fig. 1) has been developing a Permanent Magnet Hall Thruster since 2003. The project consists on the construction and characterization of plasma propulsion engines based on the Hall Effect. Electric thrusters have been employed in over 220 successful space missions. Two types stand out: the Hall-Effect Thruster (HET) and the Gridded Ion Engine (GIE)[1]. The first, which we deal with in this project, has the advantage of greater simplicity of operation, a smaller weight for the propulsion subsystem and a longer shelf life. It can operate in two configurations: magnetic layer and anode layer, the difference between the two lying in the positioning of the anode inside the plasma channel.

[1] Professor, Plasma Physics Laboratory, leo@fis.unb.br
[2] Professor, Plasma Physics Laboratory, ivansoaresf@gmail.com
[3] Professor, Plasma Physics Laboratory, jeansantos@fis.unb.br
[4] Professor, Plasma Physics Laboratory, rmiracer@unb.br
[5] Professor, Department of Aerospace Engineering, paologessini@unb.br
[6] PhD Candidate, Plasma Physics Laboratory, gabriela.possa@gmail.com
[7] Undergraduate Student, Department of Aerospace Engineering, txaicalvoso@gmail.com

A Hall-Effect Thruster-HET is a type of plasma thruster in which the propellant gas is ionized and accelerated by a magneto hydrodynamic effect combined with electrostatic ion acceleration. So the essential operating principle of the HET is that it uses a J x B force and an electrostatic potential to accelerate ions up to high speeds. In a HET, the attractive negative charge is provided by electrons at the open end of the Thruster instead of a grid, as in the case of the electrostatic ion thrusters. A strong radial magnetic field is used to hold the electrons in place, with the combination of the magnetic field and the electrostatic potential force generating a fast circulating electron current, the Hall current, around the axis of the Thruster, mainly composed by drifting electrons in an ion plasma background. Only a slow axial drift towards the anode occurs.

The main attractive features of the Hall-Effect Thruster are its simple design and operating principles. Most of the Hall-Effect Thrusters use electromagnet coils to produce the main magnetic field responsible for plasma generation and acceleration. In this paper we present a different new concept, a Permanent Magnet Hall-Effect Thruster (PMHET), developed at the Plasma Physics Laboratory of UnB[2]. The idea of using an array of permanent magnets (see fig. 2a), instead of an electromagnet, to produce a radial magnetic field inside the cylindrical plasma drift channel of the thruster is very attractive, especially because of the possibility of developing a HET with power consumption low enough to be used in small satellites or medium-size satellites with low on board power.

Figure 1. Plasma Physics Laboratory of UnB. View of Vacuum Chamber and Diagnostic Systems.

Hall-Effect Thrusters are now a very good option for spacecraft primary propulsion and also for station-keeping of medium and large satellites. This is because of their high specific impulse, efficient use of propellant mass and combined low and precise thrust capabilities, which are related to an economy in terms of propellant mass utilization , longer satellite lifetime and easier spacecraft maneuvering in microgravity environment.

The first HETs were developed in the mid 1950's, and they were first called Closed Drift Thrusters. Today, the successful use of electric thrusters for attitude control and orbit modification on hundreds of satellites shows the advanced stage of development of this technology. In addition to this, after the success of space missions such as Deep Space One and Dawn (NASA), Hayabusa (JAXA) and Smart-1 (ESA), the employment of electric thrusters is also consolidated for the primary propulsion of spacecraft. This success is mainly due to three factors: reliability of this technology; efficiency of propellant utilization, and therefore reduction of the initial mass of the ship; possibility of operation over long time intervals, with practically unlimited cycling and restarts.

This thrusting system is designed to be used in satellite attitude control and long term space missions. One of the greatest advantage of this kind of thruster is the production of a steady state magnetic field by permanent magnets (fig.2) providing electron trapping and Hall current generation within a significant decrease on the electric energy supply and thus turning this 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 of permanent magnets Hall Thrusters PHALL I and II were already developed and tested with different permanent magnets systems.

From the first studies in Russia[3] (former USSR) soon it became clear that the closed electron drift current (Hall current) inside the source channel was generated by the crossed electric and magnetic (radial) field configuration inside the cylindrical channel. The radial magnetic field action on the circular Hall current inside the channel, combined with the electric field action on the ions, is believed to be the main physical process responsible for plasma acceleration. However a good understanding of the acceleration mechanism and the steady-state plasma dynamics is still missing, and many issues concerning the role of electron transport, plasma fluctuations and instabilities are still open[4].

II. Description of the Permanent Magnet Thrusters PHALL I and II.

Since 2004, two versions of PMHETs have been developed, with dimensions suited to its application for the attitude control and orbit modification of small satellites, such as those described in the Brazilian National Space

Activity Program (PNAE). A unique aspect of this thruster (named PHALL) development is the employment of permanent magnets, as opposed to the more commonly used electromagnets, which reduces the electrical power required for thruster operation. In earlier phases of the project, a first version of PHALL has been characterized, with figures of merit containing work parameters such as thrust and specific impulse, so that currently a second, enhanced version, with similar geometry and smaller diameter, is undergoing testing in our vacuum facility. A third version is being built and will be described in a subsequent paper. It is also important to notice this project has been receiving continuous collaboration from the Associated Plasma Laboratory of The Brazilian National Institute for Space Research (INPE) in all of its phases.

A stainless steel cylindrical vacuum chamber (see fig. 1) with several flanged ports, for optical and instrumentation access, with Diam. = 0.5 m and Length = 2.0 m is used to test the PMHETs. A fore pump with pumping velocity of 35 m3/h and two diffusion pumps with velocity of 1500 l/s each are able to maintain 10-4 Torr to 10-5 Torr of working pressure in the vacuum chamber.

The first version of this thruster, called PHALL-I, has been completely characterized, so a total thrust of the order of 84 mN and a specific impulse of 1060 s was achieved[5]. PHALL-01 featured a rudimentary cathode made of tungsten filaments covered with barium oxide, in such a way that its efficiency has always been low. In addition, this thruster was sized to operate between 800W - 1250 W of electrical power, a value far greater than the available in small satellites as well. Thus, over the course of phase II of this project, a second version of this thruster was designed and built, in which are employed magnets made of neodymium-iron. This stage was also purchased a hollow-cathode with spatial qualification.

The PHALL-II plasma source (fig. 2b) is on its first tests of plasma propulsion and acceleration, where it is being studied, among others, the plasma interaction effects with the ceramic coating of the walls of PHALL II plasma source. PHALL II is going to be more efficient because it is using a hollow cathode as an electron source for gas ionization and ion beam neutralization. Nefe magnets have a higher Curie temperature and so are more suitable for space applications.

The PHALL I plasma source (see fig. 2a) is made of stainless steel with ionization channel covered by a thin ceramic layer of gypsum plaster type with a 2-mm thickness. It uses an array of permanent ceramic (ferrite) magnets. The anode ring is 2-cm wide and 1-mm thick made of stainless steel and positioned 3.8 cm from the exit of the channel. Behind the anode ring, the propellant gas is uniformly distributed in the Hall plasma source cylindrical channel by using an isolated copper circular tube with several small holes.

III. Experimental Operation of PHALL I and II

While continuing to pursue the development of Permanent-Magnet Hall Effect Thrusters (PMHETs), other lines of research could include work on lower-power, smaller-size PMHETs, for use on micro and nanosatellites, and on HETs employing alternative propellants. The use of argon, for example, would greatly decrease the costs of development and operation, with respect to xenon, while at the same time allowing an increase in the specific impulse.

In order to pursue these lines of research and development in an aggressive, efficient fashion, leading to flight qualification models over a period of five years of intense work, new high-vacuum facilities will be necessary. These will comprise larger vacuum chambers and pumping systems with much higher pumping speeds than actually

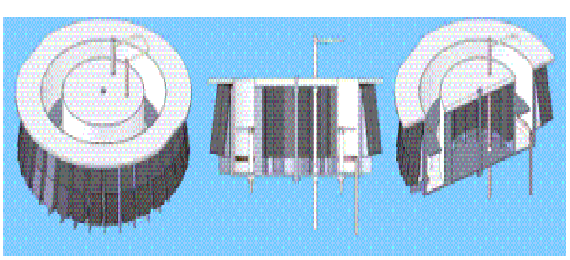
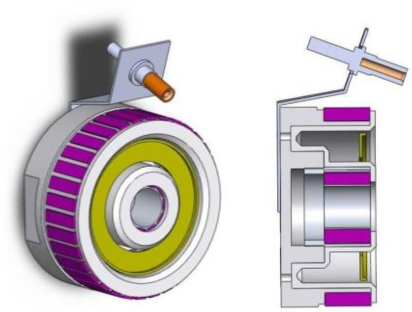
a)  b) 

Figure 2. PHALL I and PHALL II with its NeFe permanent magnets arrangement's. Dext= 15cm, Channel width= 25mm.

available in the Plasma Physics Laboratory , together with power supplies, vacuum gauges, other diagnostic instrumentation (in particular, a thrust measurement system) and various auxiliary equipment.
In the PMHETs a closed chain of electrons generated by a hollow cathode creates the so called the Hall current inside a cylindrical channel.

This circular Hall current is formed due to the interaction of electrons with a very peculiar geometry of combined crossed electric and magnetic fields (see fig. 3 and fig. 4 below). The presence of this current in the radial magnetic field region creates an intense J_{Hall} x B force, which accelerates plasma and thus promotes the thrust[6]. The role of the electric field in plasma acceleration has also to be considered but its contribution is still a matter of discussions. Among the advantages of this concept, the highlight is the absence of grids for ion extraction and acceleration, which increases the service life and reliability of propellant.

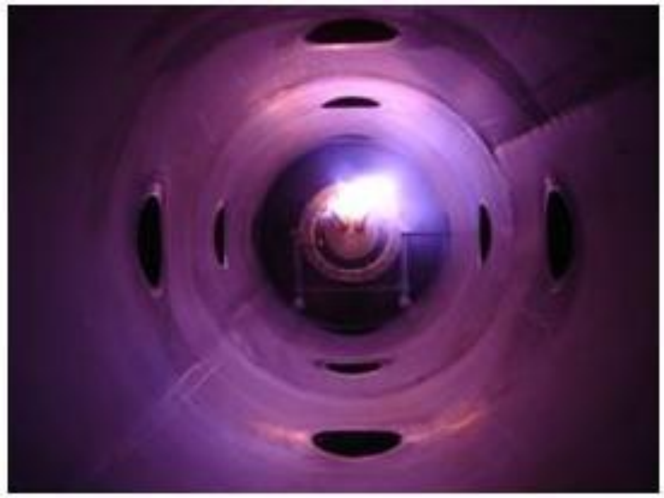


Figure 3. PHALL I on tests inside the vacuum chamber at UnB

The electrons that form the so-called Hall current inside the PMHET cylindrical channel appears as a circular luminosity ring, as shown on figure. The Hall plasma ring current and gas ionization are both obtained by an electrical discharge produced by electrons emitted from a hot cathode , made of a tungsten wire coated with Barium Oxide and heated with currents up to 9 A from a DC electrical power feed source. This current is necessary in order to make the hot cathode reach temperatures above 800 degrees Celsius and then provides a primary electron emission by thermionic effect.

PMHETs can be operated with an anode bias voltage going from 150 V to 700V because these potentials provide the necessary energy for the emitted electrons to perform argon neutral atoms ionization by inelastic collisions. This acceleration energy range is compatible to very well-known ionization cross section curves for noble gases ionization by collisions with electrons. The discharge plasma current for most of the experimental conditions ranged between 0.1 A to 1.5 A. The argon pressure in the vacuum chamber varies from 10-2 Torr to 10-4 Torr.

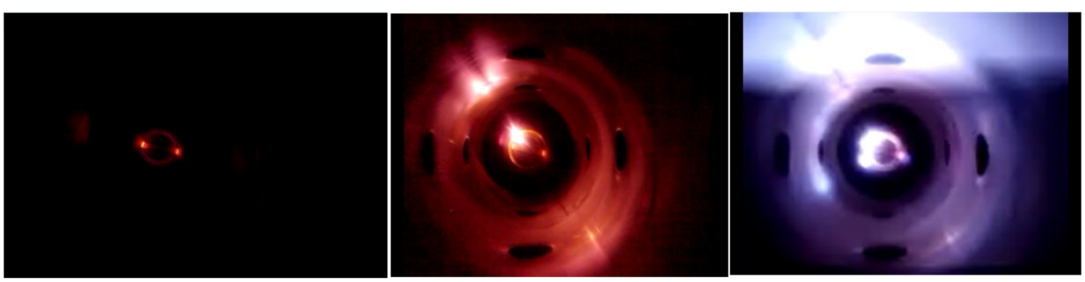


Figure 4. Preliminary tests with PHALL II showing the formation of the Hall current in a double cathode working regime

IV. Plasma Diagnostics System Development for PMHETs

HETs are today widely employed in attitude control and orbital maneuvering of medium and large satellites. Despite the great use of these thrusters, some problems of these engines remain outstanding and require further improvements. This is the case of the Hall plasma source discharge dynamics always connected with the production and propagation of plasma instabilities in the Hall current channel.

Since its beginning PHALL project faces scientific and technological problems. Thus, in order to optimize these thrusters, it is necessary to perform Plasma Diagnostics with a good temporal resolution. In previous phases of this project, the first working model PHALL-I was developed to the point of having its figures of merit well established. In this phase of the project, we are going to develop additional instrumentation required not only for basic plasma diagnostics such as Langmuir probes and Faraday cups but also for direct measurement of thrust parameters with optical balances.

In order to increase our diagnostic ability we need better instrumentation, with higher resolution and reliability. In this project, we will be developing dedicated instrumentation, equipped with electronic acquisition cards signal accommodation to control plasma characteristics probes, electrical sources and various actuators. We named this system "Integrated Diagnostics Workbench (BID)", and it will become a permanent infrastructure of LP - IF/UnB that can be used in tests of different types of plasma or ion thrusters[7].

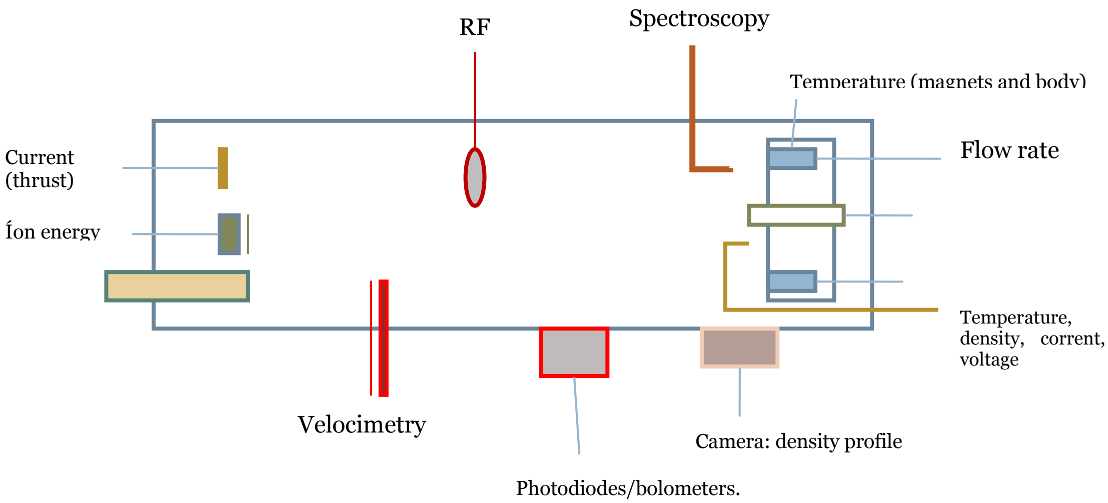


Figure 4. Integrated Diagnostic Workbench - BID

A major development of this phase of the project is the Integrated Diagnostics Workbench (BID), with which it is possible to perform complete diagnostics of plasma sources, including those used for propulsion. In this work basic plasma basic diagnostics used to measure Hall Plasma Source of PHALL I and II working characteristics are shown on fig. 5 below.

Several plasma diagnostics techniques are used inside and outside the HET, operating inside the vacuum chamber as shown in Figure 8. The measurement of plasma characteristics and flow were made by using a movable Langmuir probe, an ion collector probe, a Faraday cup type ion energy analyzer and gas flow meters . The cylindrical Langmuir probe (0.25 mm x 3.5 mm) can be oriented parallel or perpendicular to the thruster axis in order to provide plasma density, plasma potential and temperature spatial profiles. The probe size was designed to minimize perturbations of the plasma. We obtained the plasma density, temperature and distribution function using the Druyvensteyn method[11], which consists of taking the second derivative of the characteristic curve (I x U) measured with the Langmuir probe. The ion energy flow was measured with an ion energy analyzer, also called Faraday cup.

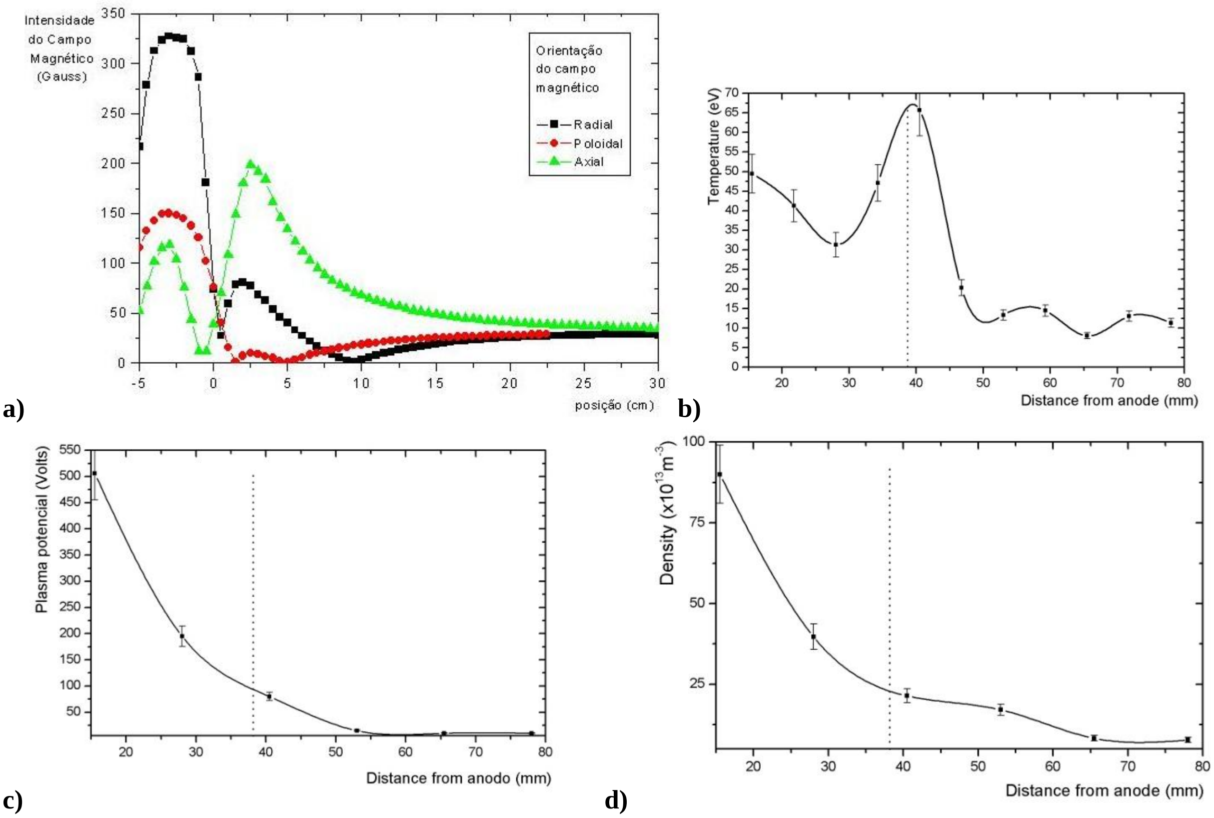


Figure 5. Magnetic fields space profiles (a), plasma temperature (b), plasma space potential profiles (c) and plasma density (d) of PHALL I.

The above figure shows the three component magnetic field measurement inside the Hall current channel made by magnetic probes of PHALL I. The radial component can be as high as 250 Gauss and the axial z component forms a small magnetic mirror. We believe that this effect is contributing to a better primary electron confinement inside the channel and to the increase of the gas ionization efficiency. Langmuir probes are used for plasma potential, density and temperature measurements. In the highest pressure conditions, the electron plasma density and temperature space profiles inside the plasma source channel are respectively in the range of 2.0 - $2.5x10^{10}$ part/cm^3 and temperature from 30eV to 120eV (see fig. 10). Plasma potential measurements show that inside the plasma source channel the anode determines the plasma potential. Outside the channel, the potential decreases mainly due to the plasma neutralization made by the thermionically emitted electrons. It was also observed that plume expansion creates density gradient. The total thrust and plasma acceleration is measured using ion probes and an ion energy analyzer(Faraday Cup).

The computer controlled plasma diagnostics system BID, an Integrated Plasma Diagnostic System. This system contains Langmuir probes 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 measured ion temperature and transport from Hall current channel to the plasma ejected plume. In order to control argon plasma fuel purity a quadrupole mass spectrometer, a Leybold Transpector 1-300 UMA, is used. Thrust and Specific Impulse measurement system will also be described on this work. Important to notice plasma physics phenomena, that may significantly interfere in PHALL performance 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´s operation, we propose and test a wide frequency range instability detection system based on a RF (radio frequency) detection probe connected to a Spectrum Analyzer (Agilent CSA 100 khz-6 GHz) is used. Instabilities on the PHALL discharge current is also monitoring 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 the near future we expect to develop life tests systems for these thrusters in larger vacuum systems with bigger volume and pumping speed capability. A direct thrust and specific impulse measurement instrumentation it is also been considered.

In order to control argon plasma fuel purity a quadrupole mass spectrometer Leybold-Transpector (1-300 UMA) is used. A Spectrograph (Andor SR-750-B2, within 435nm to 700nm) line broadening measurements are used to measured ion temperature and transport from Hall current channel to the plasma ejected plume.We are using a non-intrusive diagnostics in our second prototype, such as spectroscopy devices. We are studying the ion dynamics in the plasma channel t by measuring ion temperature using plasma spectroscopy techniques such as Doppler line broadening of argon spectral lines It is based on the well known line broadening of spectral lines caused by several atomic processes inside the plasma. The visible spectrum of the argon plasma (fig. 12) was measured using Andor SR-750 monocromator,equipped with 1200lines/mm grid, resolution below 0.02 Å.

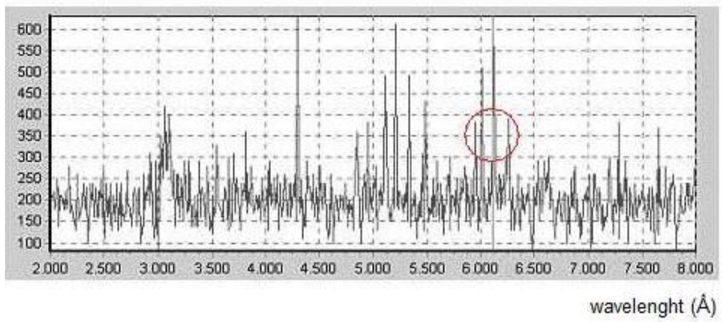


Figure 6. Argon plasma spectrum from the hall plasma current channel region, Photon pulsed measured in a photomultiplier tube.

Based on the equation for the Doppler broadening becomes $\Delta\lambda_D = 7.16\times10^{-7}\left(\frac{T_i}{M_i}\right)^{\frac{1}{2}}$, in angstroms, we can estimate the ion temperature (fig. 13).

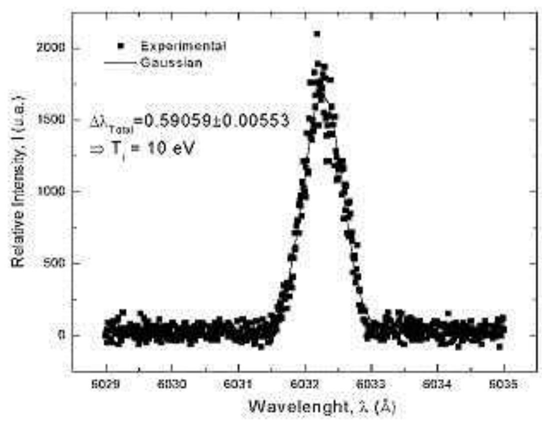


Figure 7. Argon spectrum line (6032 Å) plot after treatment used to measure the ion temperature. This peak was chosen from the spectrum showed at fig. 14.

From the point of view of plasma physics research on electrical thrusters, it is important to notice a basic phenomenon that may significantly interfere in the permanent hall thruster performance. It is the occurrence of severe plasma instabilities that can occur inside and outside the Hall current channel. In order to better understand the turbulence and plasma oscillations that occur during the thruster´s operation, we propose   a wide frequency range   instability detection system based on a RF (radio frequency) detection probe connected to a Spectrum Analyzer (Agilent CSA 100 khz-6 GHz) is used. Instabilities on the PHALL discharge current is also monitoring 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.

Figure 8- Views of BID equipments at the Plasma Physics Laboratory of UnB

With the BID we are going to use two personal computers(see fig.), both with PCI-GPIB and also with GPIB-USB converters. This interface is used to control and read data from bench Digital Multi-meters (4 are used in total) and electrical power supplies. Pressure monitoring of the vacuum system is done by measured coupled to a central signal processing unit which communicates with computers via the serial ports.

On the data acquisition system an acquisition card is used9see fig.8). The card PCI-DAS1602/12 Measuring Computing, sound cards (with 96 kHz sampling rate) and the NI USB-6008 Board are on this system. These plates are used to act in some analog sources of electric power and gas flow controller. On the other hand, are linked to room signal circuitry for reading in real time of the discharge current, discharge voltage, the current in the cathode, and collected at current up to 3 electrostatic probes, or energy analyzers. With this configuration it is possible to act via software in propellant and obtain data from different parts of the beam and plasma channel.

The Optical Spectrograph is a Andor Shamrock model SR 750 B2, which is interfaced via USB ports. This is up to 3 attached spectrograph optical fibers, with which it is possible to estimate the temperature and the velocity of ions (via Doppler shift) at various points of the plasma channel or accelerated beam, also synchronously with the current measures and Langmuir probes. The user interface was initially built in C/C++, with the aid of free softwares like QT. However, given the complexity of the system, including large numbers of instruments from different manufacturers, we opted for an interface built with NI Labview, with which it is possible to collect the data, perform a pre-processing and acting on the system.

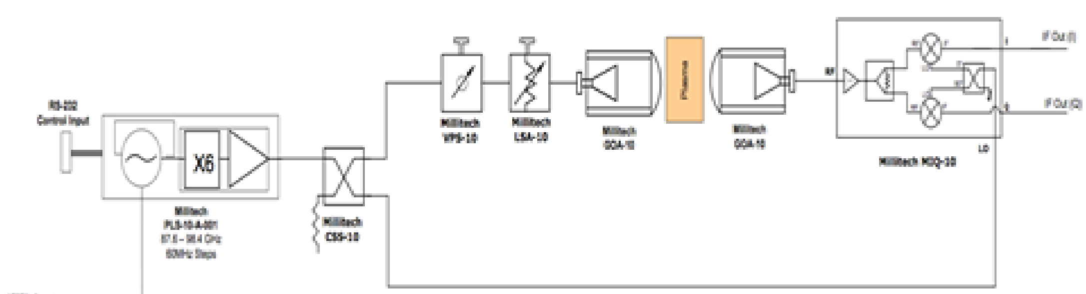


Figure 9- Microwave interferometric system for plasma plume plasma parameters control

In order to monitor the Hall Plasma Thrusters plume a new diagnostic system is proposed(see fig. 9). A multi-channel microwave plasma diagnostic system is to be used to measure plasma density distribution and fluctuations in the plasma plume is going to be measured by an interferometer multi antenna system operating at 90 GHz . This system is going to be assembled inside the vacuum test system (see figure below).

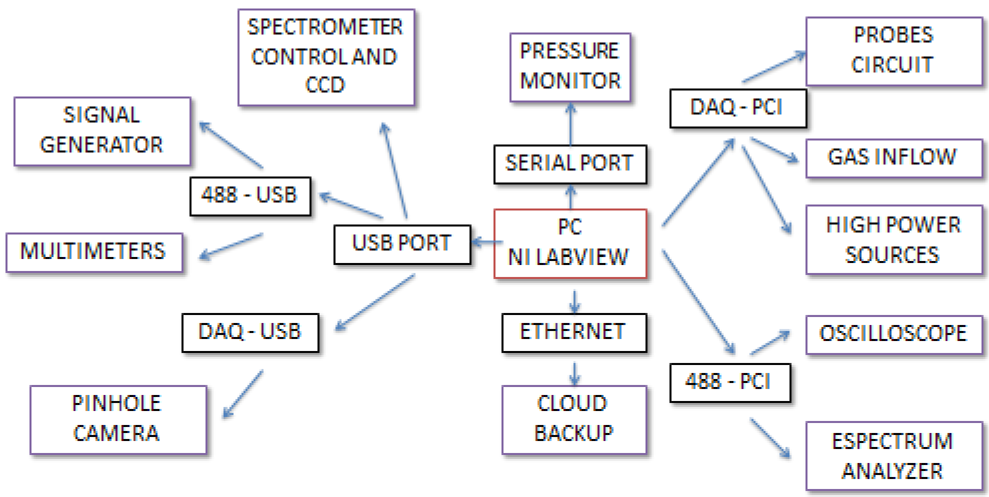


Figure 10. Schematics of the BID system interrelationship.

The BID interfaces and connection systems shown on fig. 10. It is now be available at the Plasma Physics Laboratory for rapid characterization of ion thrusters or for small plasma sources. It should be used even within the context of the University, in the diagnosis of plasma sources of accelerated innovative design, as is the case today of the Plasma Diagnostic System Development for HET control.

A part that hadn't yet been developed in the project was the control of driving, that is, a system that allows the stable operation of the propellant insertion for a long period of time, based on the continuous monitoring of a variable, such as thrust, and real-time performance on the system, correcting any possible failure.

The approach chosen for the control has been monitoring the discharge current, since the thrust is proportional to this current and, moreover, it is not necessarily monitored by telemetry from the spacecraft. Note that the acting in discharge current helps prevent the problems of transit-time instabilities and of low frequency oscillations, which obviously decrease the lifetime of propellant, and even cause problems on electric power source.

The control used was Proportional-Integral-type differential (PID), whose construction is quite simple, because it can be all done based on an analog electronics. Using resistors, inductors and capacitors of high power, build a circuit in the form of a high-pass filter with cutoff frequency in the range of 40 KHz. Thus, it was observed the removal of large amplitude oscillations, especially those coming from transit-time instabilities. To prove the actions of control, moved the propellant flow within an order of magnitude, and the discharge current remained virtually unchanged, except for the high-frequency fluctuations that are always present and are not harmful to possibly source of plasma.

V. Study of Plasma Oscillations and Instabilities

With the new acquisition cards used on the BID, with the acquisition of signals with a sampling of up to 330 kHz in one of the plates, it was possible to monitor the temporal evolution of the discharge current, in sync with the current of the cathode, which allows us a better understanding of the phenomenology of the discharge which produces plasma. Preliminary analysis of the data, it was possible to identify three components that make up the discharge current, which must be connected to the primary, secondary electrons and ions. In further analysis we want to check the phase and frequency of these three components, and thus shape the physics underlying their existence.

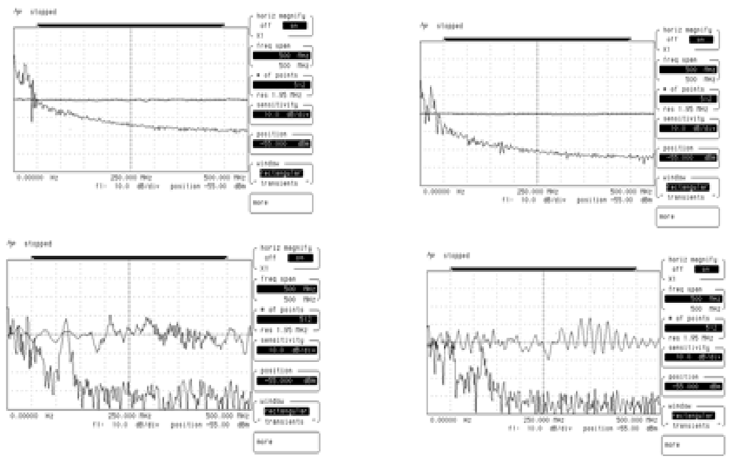


Figure 11 – Spectrum analyser showing typical spectral paterns of the Plasma instabilities inside the PHALL cylindrical channel.

Another way to investigate plasma oscillations, especially those which may have an impact on the use of thruster in space applications, was made with the use of frontal picture of propellant. Even with the low resolution of images, typically 640 x 480 pixels, and with sampling of 15 frames per second, it was possible to detect the current disturbances in training Hall with frequencies of 3 Hz and wavelength on the order of the impeller RADIUS PHALL-I. These oscillations change not only the thrust module, but also the direction of the thrust over time, such that it is safe to assume that the propellant produces low-amplitude vibrations in the ship with the same frequency characteristic.

In addition, we will analyze these signals and characterize plasma oscillations using nonlinear techniques such as the discrete wavelet transform and the Hilbert-Huang transform. These techniques allow filtering noise, decomposing a signal into orthogonal modes, and extracting the information of instantaneous phase and frequency of each mode. These results can improve the detection of plasma instabilities in the data acquired from our experiments and their comparison with results from numerical simulations." the thrust over time, such that it is safe to assume that the propellant produces low-amplitude vibrations in the ship with the same frequency characteristic.

VI. Hall Thruster Plasma Experimental Research with Computer Simulation Assistance

In Hall thrusters the propellant is injected inside the acceleration chamber and is ionized by collision with electrons. The same electric field that produce the discharge used to ionize the propellant accelerate the ions along the acceleration chamber. The electrons from the discharge are also used to neutralize the ions that are ejected from the acceleration chamber and form the plume. The magnetic field inside the acceleration chamber is strong enough to magnetize the electrons but not the ions. In this way the electrons are trapped and form a current perpendicular to the magnetic field (Hall current). In order to investigate the interaction of the electron beam with the propellant, the behavior of the ions in the acceleration chamber, the stability of the hall current, the characteristics of the plume and the effects of different configurations of magnetic and electric fields on the performance of the thruster we will use numerical simulations. We intend to use mainly particle in cell (PIC) and hybrid codes in order to catch the fast oscillations that can lead to instabilities inside the thruster. The code used at the moment is a 2D PIC code (OOPIC) developed by TECH-X corporation. This code allows the study of plasma and its beams of charged and neutral particles in the presence of external and magnetic fields. The code also allows the application of different boundary conditions and presents electrostatic and electromagnetic solutions.

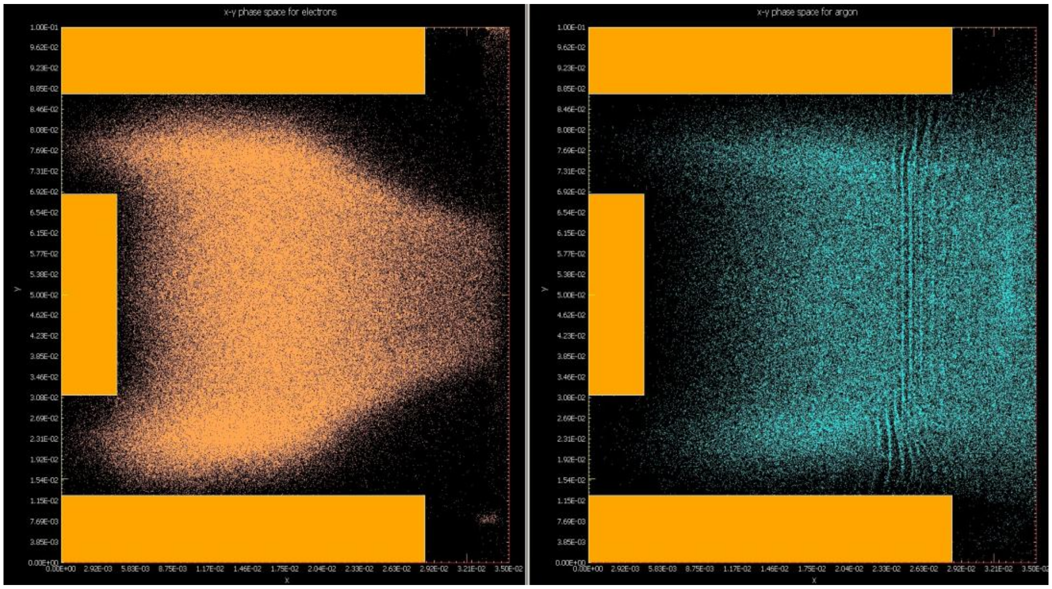


Figure 12. Electrons (left) and argon ions (right) x-y phase space inside the acceleration channel of a hall thruster.

Figure 12 shows the x-y phase space for electrons (left panel) and for argon ions (right panel) inside the acceleration channel of a hall thruster. The simulation is performed using a 2D PIC code (Oopic pro). The walls of the hall thruster, shown in orange on the figure, are considered as made of a dielectric material. On the top right corner there is a cathode emiting electrons, which are attracted by two anodes located on the left side between the dielectric walls. The voltage between the cathode and the anodes is 350 V. When the electrons leave the cathode they are accelerated in direction of the anodes. In their way the electrons colide with a neutral argon background producing argon ions and secondary electrons. A background magnetic field trap the electrons increasing the transit time of the electrons between the cathode and the anodes, forming a hall current perpendicular to the plane of the figure.

VII - Comparative Performance of PHALL family with Known Plasma Thrusters

Table I –Comparative performance parameters measured in PHALL I and expected for PHALL II.

	PHALL I	PHALLII(preliminary)
Thrust (mN)	26.5 – 84.0	13 – 42
Thrust density (N/m^2)	1.5	2.4 – 8.7
Specific Impulse (s)	803.5-1060	1500 – 2000
Power (W)	1250	500 -900
Mass Flux (mg/s)	5.0	2.3
Electrical Efficiency (%)	67.3	80
Total Efficiency (%)	8.4	45 – 60

PHALL-I operation at low power always resulted in a very poor ionization efficiency, often less than 10%, well known in the literature. Thus, low-powered thrusters, but appropriate to the proposal of the PNAE should be designed with smaller dimensions.

Thus, the PHALL-II was designed to have a body covered by machinable ceramic from a block of MACOR with cocoons on the outside surface for placement of permanent magnets. It has a floor area 40% smaller than the

PHALL-I, which implies, in principle, the same reduction in need for electric power for operation, that is, now is on the order of 900 W, to an operation with efficiency of approximately 55%.
In PHALL II the inside walls of the plasma channel have reduced dimensions, which admittedly reduces the loss of plasma for the walls, and increases efficiency for low-power operation. Still with the same purpose, the anode in this propellant is well positioned closer to the channel's output, in a setting that is known as Anode Layer. In terms of the problem of the ceramic coating, this propellant is used alumina ceramic plates, bolted to the structure. The plates are alumina and MACOR.

In spite of some criticism from the scientific community, especially regarding to heat dissipation, which could be happening during PHALL-I and PHALL-II operations, we believe it doesn't affect seriously the permanent magnets. However, some important aspects of the construction of the thruster needed to be solved. The lack of flexibility of the magnetic circuit of PHALL family introduces a strong limitation on the thruster performance. New ideas are been proposed and they will be object of analysis in future works.

From the results obtained for the figure of merit of PHALL I and II we can say they are having a relative successful performance on the laboratory level. Table III(below) concerning the performance of PHALL family compared with successful and space mission proved plasma thrusters such as SMART-1 DS 1 and Hayabusa Microthrusters.

Table II -Comparative performance parameters of PHALL family with performance of some Electric Thrusters already used on solar system space missions.

Mission and Thruster	Target	Thrust (mN)	Specific Impulse (s)	Power Consumption (W)
Smart – 1 (Snecma PPS1350 G)	Moon	68	1640	1190
DS1 (30 cm NASA ion engine NSTAR)	1992KD, Borrely comet	91	3100	2300
Dawn (30 cm NASA ion engine NSTAR)	Ceres & Vesta	91	3100	2300
Hayabusa (4x JAXA micro10 ion thruster)	Itokawa sample return	8	3200	350
PHALL – I	-----	85	1083	1000
PHALL – II		40	1800	800

VIII - Direct Thrust Measurement System

In order to characterize the performance of a thruster, by far the most important step is an accurate measurement of the thrust it would produce in as wide as possible a range of operating conditions. To this purpose, a simple and robust measurement system will be implemented inside the chamber on the Gama Campus (Aerospace

Engineering), while that on the Darcy Campus (Institute of Physics) will be mostly devoted to investigation of the plasma parameters inside the thruster and in the near plume. The HET will be mounted on a pendulum stand, the deflection of which will be calculated by reflecting a laser beam off a mirror mounted on the stand and measuring the displacement of the laser spot, at a certain distance, with a photo sensor.

It has being primarily conceived at the University of Southampton and developed at Associated Plasma Laboratory (LAP) at The Brazillian National Space Research Institute (INPE). In the below figure the vacuum system used for plasma thruster life tests of LAP INPE is shown. is a schematic of the system was developed at LAP/INPE.

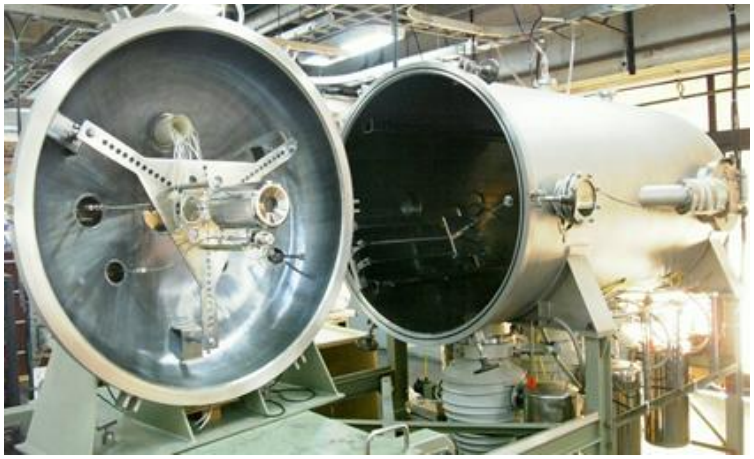
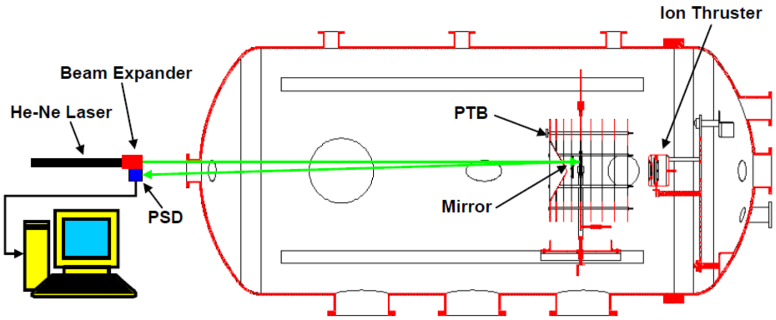


Figure 13. Vaccum test chamber for ion thursters at LAP INPE, 1,5m of diameter and 3,0m of length

The direct thrust measurement system developed at LAP/INPE is shown on figure 14 below. It consists of an indirect thrust measurement system, where the deflection of a pendulum target balance measure the ion beam thrust form the ion beam ejected form in the Electrostatic Ion Thruster (PION). The vacuum chamber size diameter is 2.5m and it has -3 m in length. Its pumping system, reach 10000l/s and laboratory is equipped with many power supplies, plasma diagnostics and all other equipment necessary for small plasma thursters life tests..



. **Figure 14. Direct thrust measurement system for PHALL II and III to be installed at The Plasma Physics Laboratory of IF UnB**

Therefore, in the present project funds are required to buy a high-vacuum pumping system for the new chamber at the Plasma Physics Laboratory, and a new chamber (1.5 m in diameter and 3.0 m in length) with high-vacuum pumping system for the Plasma Physics Laboratory of UnB. In order to completely characterize the performance of several types of advanced HETs, the implementation of new vacuum facilities will be necessary. The system currently operating in the Plasma Physics Laboratory comprises a small (0.5 m x 2 m) vacuum chamber and 3 diffusion pumps, backed by a rotary pump, providing a pumping speed of a few thousand l/s. This is barely sufficient for preliminary measurements, unless very small thrusters are being tested. For a complete characterization of the thrusters, including plume and thrust measurements, bringing them to the level of advanced engineering models, ready for life testing and subsequent flight qualification, larger vacuum chambers and more powerful pumping systems will be necessary. The Plasma Physics Laboratory has already procured funds to purchase a new, larger vacuum chamber. This bigger vacuum system facility it is planned to have 40.000 l/s that will allow to perform direct thrust measurement and life tests of medium size Permanent Magnet Hall Thrusters with 50 mN of total thrust.

VII. Conclusions

A new concept of closed-drift Hall-Effect Thruster using permanent magnets developed at UnB is described. The results obtained for the magnetic field generated by permanent magnets are similar to the values used in other types of HETs such as the SPTs. However, permanent magnets do not only generate the main radial magnetic field: other components also play important roles, such as the axial mirror-type field for electrons that helps to generate and maintain the Hall current inside the channel.

Concerning limitations of the magnetic circuit of PHALL I and PHALL II, a new version with an innovative permanent magnet assembly is been proposed, PHALL-III. The body of this new Permanent Magnet Hall Thruster plasma source is machined in a billet of ceramics (Alumina), which has good structural rigidity, since they were left 10 mm thick walls, and high thermal conductivity, which allowed connecting the body to heat sinks. The magnets are positioned away from the body of the propellant, and connected to a magnetic circuit formed by magnetic steel plates. So the configuration of the magnetic field in the plasma channel is very similar to that of Hall effect thrusters that use coils as a source of magnetic field, and also, given the form of installation of permanent magnets, you can vary the intensity of the magnetic field without however be necessary to change all magnets or build a new plasma source structure. We expect new future versions of PHALL will be tested on BID as soon as the experimental tests of PHALL-II is completed.

Several plasma diagnostics systems were successfully developed and integrated by BID. The measurement plasma and thrusters parameters were compatible with the expected values. Non perturbative plasma diagnostics with more complex techniques such as Doppler broadening spectroscopy, mass spectrometry and plasma turbulence detection with RF probes are now being used to give a complete set of plasma parameters and performance characteristics of the PHALL I and II.

To improve plasma diagnostics system analysis and plasma behavior on the various regions of PHALL plasma sources, it is necessary to improve the computer simulation capabilities of the laboratory in order to successfully accomplish the objectives proposed on Permanent Magnet Thrusters development it is necessary to acquire/develop of 3D hybrid code and 3D PIC code in the near future. The use of 3D codes requires an increase in the computational power necessary to perform the calculations. For this reason it will be necessary the use of HPC clusters. A HPC cluster consists basically of a master node, a network switch and compute nodes. The compute nodes perform the calculations and are controlled by the master node. All the communication between the compute nodes and the master node is done via the network switch using infiniband or normal ethernet connection. We propose the acquisition of a HPC new computer cluster for 2014 fiscal year.

PHALL I and II operation gave us the opportunity to obtain, for the very first time, characteristics and performance parameters of a Permanent Magnet Hall-Effect Thruster. The main feature of these thrusters is the possibility of extra economy of satellite electric power consumption due to the use of permanent magnets. This is the main advantage of this new design for PMHETs, as power in space is, in general, severely limited.

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