Development and Performance of Permanent Magnet Hall Thruster

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Abstract: Electric propulsion is now a succeful method for primary propulsion of deep space long duration missions and for geosyncronous satellite attitude control. Closed Drift Thruster, so called Hall Thruster or SPT (Stationary Plasma Thruster) was primarily conceived in USSR (the ancient Soviet Union) and since then, it has been developed by space agencies, space research institutes and industries in several countries such as France, USA, Israel, Russian Federation and Brazil. In this work we present the main features of the Permanent Magnet Hall Thruster (PMHT) developed at the Plasma Laboratory of the University of Brasilia. The idea of using an array of permanent magnets, instead of an eletromagnet, to produce a radial magnetic field inside the plasma channel of the thruster is very significant. It allows the development of a Hall Thruster with power consumption, low enough to be used in small and medium size satellites. Description of a new vacuum chamber used to test the second prototype of the PMHT (PHALL II) will be given. PHALL II has an aluminum plasma chamber and is smaller with 15 cm diameter and will contain rare earth magnets. We will show plasma density and temperature space profiles inside and outside the thruster channel. Ion temperature measurements based on Doppler broadening of spectral lines and ion energy measurements are also shown. Based on the measured plasma parameters we construct an aptitude figure of the PMHT. It contains the specific impulse, total thrust, propellant flow rate and power consumption necessary for orbit raising of satellites. Based on previous studies of geosyncronous satellite orbit positioning we perform numerical simulations of satellite orbit raising from an altitude of 700 km to 36000 km using a PMHT operating in the 100mN – 500 mN thrust range. In order to perform these calculations integration techniques were used. The main simulation paraters were orbit raising time, fuel mass, total satellite mass, thrust and exaust velocity. We conclude comparing our results with results obtainned with known space missions performed with Hall Thrusters.

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I. Introduction

ELECTRIC propulsion is already recognized as a successful technology for long duration space missions (4). It has been used as primary propulsion system on earth-moon orbit transfer missions, comet and asteroids exploration and on commercially geosynchronous satellite attitude control systems. Electric propulsion is basically a technique of space propulsion which envolves the conversion of electrical power into the kinetic power or thrust of the exaust beam of ionized particles. The ability to obtain high exaust velocities with ionized particles enables plasma thrusters to perform high specific impulse mission in space (5). It is now a successful method for primary propulsion of deep space long duration missions and for geosyncronous satellite attitude control. Closed Drift Plasma Thruster, so called Hall Thruster or SPT (stationary plasma thruster) was primarily conceived in Russia in 1960 and the first sucessful space mission with a 60mN thrust was made by the Meteor satellite series in 1972 [1] Since then, it has been developed by space agencies and research institutes and industries in several countries such as France, USA, Japan and Brazil.

The main attractive feature of the Hall Thruster is its simple design and working principles. Most of the Hall thruster plasma sources are based on the use of an eletromagnet to produce the main magnetic field responsible for plasma acceleration and generation. In this paper we present a new conception. A Permanent Magnet Hall Thruster (PMHT) developed at the Plasma laboratory of the University of Brasilia. The idea of using an array of permanent magnets, instead of an electromagnet, to produce a radial magnetic field inside the cylindrical plasma drift channel of the thruster is very significant, specially because of the possibility of developing a Hall Thruster with power consumption low enough to be used in small and medium size satellites[2].

This work also describes the basic plasma diagnostic used to characterize the Hall plasma source such as plasma density, temperature space profiles and ion flow velocity (3). We are particulary interested in the developing of non perturbative plasma diagnostics to obtain plasma parameters inside the Hall thruster plasma channel. For this we implement a plasma spectrocopy system to perform ion temperature measurements based on Doppler broadening of spectral lines.

II. Hall thruster principles

A Hall thruster is a type of ion thruster in which the propellant is accelerated by an electric field. The essential working principle of the Hall thruster is that it uses an electrostatic potential to accelerate ions up to high speeds. In a Hall thruster, 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, where the combination of the magnetic field and the electrostatic potential force a fast circulating electron current around the axis of the thruster and only a slow axial drift towards the anode occurs. Besides the production of the plasma accelerating electric field, these electrons also have the functions of ionizing the propellant gas and neutralizing the ejected ions in the plasma plume.

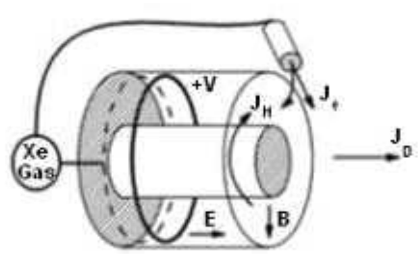

Fig. 1 Basic Components of Thruster operation J_H is the Hall Plasma current
And J_D is the accelerated drift plasma current.

Electric propulsion reduces the propellant mass for space missions because plasma thrusters can generate higher exhaust velocities than those reached by chemical rockets. Today, space propulsion systems based on plasmas are renewing the space mission planning because the propellant is a substantial part of the space vehicle mass. It corresponds to 55% - 65% of the mass in most of geostationary satellite missions and 70% to 80% in planetary missions. In low earth orbit missions, mass reduction factors from 2 to 3 can be reached due to the higher efficience of gas ionization and plasma charged particles acceleration method. Althought plasma thrusters devices have low thrust compared to chemical rockets, the specific impulses are higher, typically I_{sp} = 10000 s. I_{sp}= U / g , where U is the exhaust velocity of charges (typically 5 x 10^4 m/s) and *g* gravity acceleration constant. The Hall conductivity component of the conductivity tensor (σ_H) are associated with the Hall current $\vec{J}_H$ and with the radial magnetic field $\vec{B}$. Thus the acceleration of a plasma fluid element is given by: $\frac{d\vec{U}}{dt} = \frac{\vec{J} \times \vec{B}}{n}$.

Others important features are the increase of maneuvering time for station keeping and easier control of satellite locations on space which increases the satellite life time [3]. In this work, we show the results of a new closed drift thruster with a one-staged magnetic field layer made by permanent magnets. With this new arrangement it is possibe to save about 200W in energy consumption, while keeping the same thrust obtained by the SPT family. The main advantage of the SPT is its comparative low power consumption (0.1 to 1.0KW) with respect to its total thrust capability (0.1N to 10N), allowing its use as primary propulsion system for long space missions, because it can produce higher plasma flux density. It is also important to point out that with the absence of polarized grids, the probability of undesired effects caused by ion sputtering decreases.
A.

III. Plasma source description

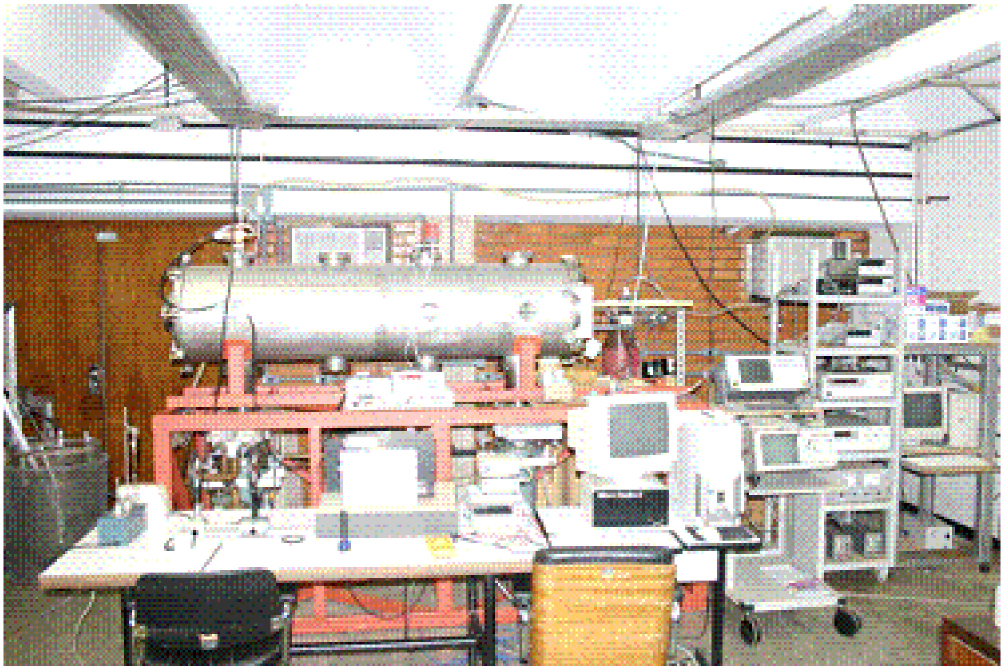

Figure 2- PHALL vacuum test chamber and equipments for plasma generation and diagnostics

A stainless steel cylindrical vacuum chamber with several access flange windows with Diam. = 0,5m Length = 2,0m is used to test the PMHT. A fore pump with pump velocity of $35m^3$ /h and two diffusion pumps with velocity of 1500l/s each are able to maintain 10^{-4}torr to 10^{-5}torr of working pressure in the vacuum chamber. The Hall plasma source chamber is made of stainless steel with ionization channel cover by a thin ceramic layer within 2mm thickness (see also fig. 6). The anode ring is 2cm wide and 1mm thick, and is made of stainless steel and it is positioned 3.8cm from the exit of the channel. Behind the anode ring, the propellant gas is uniformly distributed in the Hall plasma source chamber by using an isolated copper circular tube with several small holes [5].

The PMHT can work with a single cathod and requires low number of components to be controlled which means easier access and maintenance of the plasma source components. The Hall thruster schematics of the plasma source and circuits with its basic components can be seen on fig. 2, it shows a cross section view of the thruster with permanent magnet locations, anode ring, thermionic cathode, gas feed tube, electrical supplies and plasma diagnostics. The plasma is generated by a discharge between the anode ring and a negatively polarized directed heated cathode. This simple thermionic cathode is made of [2].a 5.5cm long and 2mm thick tungsten wire cover by BaO in order to increase electron emission. By using this type of cathode it is possible to move it and choose its best position outside the ionization channel.

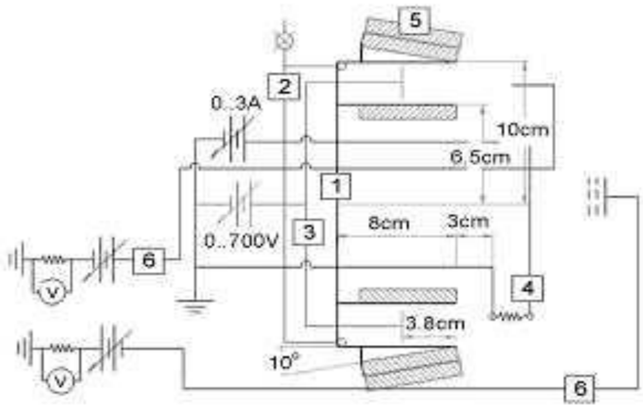

Figure 3 - Hall Thruster plasma source and circuits schematics.

Electric and magnetic fields geometry are key issues in the permanent magnet Hall thruster design. The shape of these fields controls ion trajectories and the acceleration zone [2]. Although a desirable magnetic field can be obtained by adjusting permanent magnet relative positions around the channel, a computer simulation study of possible magnetic field geometries was performed using Finite Element Method Magnetics. The best magnetic field design was chosen from these studies, it shows computer simulated magnetic field lines of the Hall thruster for two concentric circles with 76 permanent magnets bars (16 on the internal cylinder) with 6.0cm length and cross section of 1.0cm x 2.0cm. The radial component of the magnetic field for several distances from the source axis is shown on fig. 4 (right). The magnetic field space profile along the channel has a maximum value of 350 gauss, near the channel exit and 0.5cm from the external wall. At the center of the channel a magnetic field gradient $\frac{dB}{dz} > 0$ was obtained with this magnet arrangement. It is important to point out that in this arrangement, other magnetic field components (axial and poloidal) are also present in the thruster channel. They may contribute to the generation of better plasma conditions in the ionization channel and higher plasma drift flux and the Hall current in the plasma source channel [6].

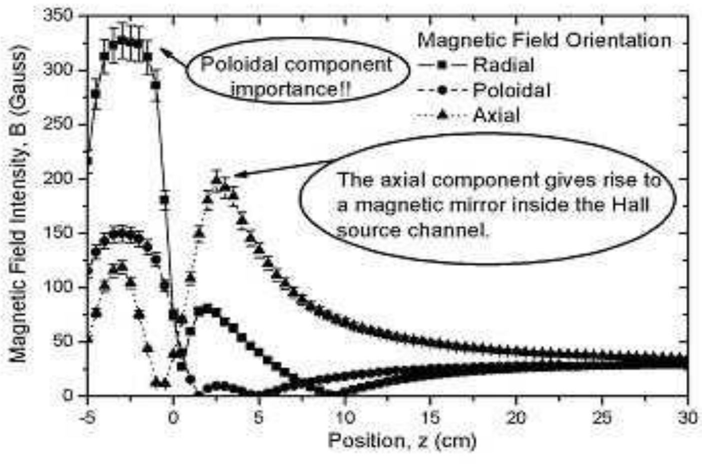

Fig. 4 – Space profile of radial, poloidal and axial components of the magnetic field.

In the proper operating regime, the electron Hall conductivity parameter is larger than unity and the electron Larmor radius ($R_L \approx 4mm$) has to be small compared to the typical channel depth L ($L \approx 38mm$), in order to magnetize only the electrons. On the other hand, the Larmor radius of the much heavier ions ($R_{Li} \approx 100mm$) is larger than the channel dimension. For this reason, they are weakly affected by the magnetic field This main condition to establish the magnitude of the magnetic field and of the channel size is given by: $R_{Li} > L > R_{Le}$ [1].

So far, the space industry has built Hall thrusters whose magnetic fields are produced only by electromagnets. In this work, we present the main features of the Permanent Magnet Hall Thruster (PMHT) developed at the Plasma Laboratory of University of Brasilia (LP). The idea of using an array of permanent magnets, instead of an electromagnet, to produce a radial magnetic field inside the plasma channel of the thruster is very significant. It allows the development of a Hall Thruster with power consumption low enough to be used in small and medium size satellites. Our first constructed Hall Thruster (PHALL I) has a stainless steel chamber with 30 centimeters of diameter (see fig. 5). Its magnetic field is produced by two concentric cylindrical arrays of ferrite permanent magnets: 32 bars in the outer shell and 10 bars in the inner (see fig. 6). The magnetic field in the middle line of the plasma source's channel is 200 Gauss.

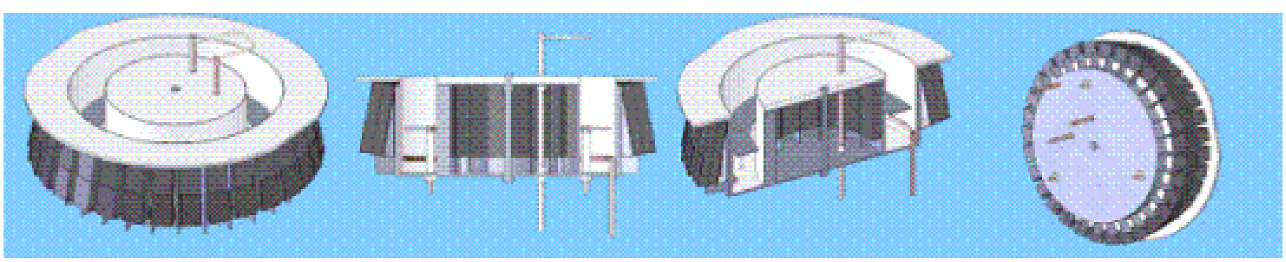

Figure 5 -PHALL I with various views of the plasma channel, tungsten wire cathode emitter, Anode, gas feed and magnet assembling.

IV. Experimental results with the PMHT

The electrons that form the so called Hall current at the open end of the Thruster were obtained through thermo-ionic emissions from a tungsten wire covered with Barium Oxide, which is heated with currents up to 9 Amps. The electric potential applied to the anode ranged from 100 to 600 Volts.

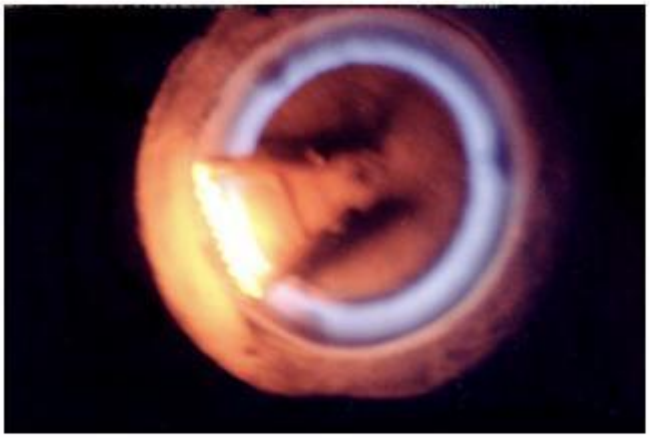

Figure 6 – Plasma and Hall current channel formation during PMHT operation

The PMHT can be easily operated with anode bias voltage going from 150Volts to 700Volts. The discharge plasma current for most of the experimental conditions ranged between 0.1 to 1.5A in argon gas pressures varying from 10^{-2}torr to 10^{-4}torr. A calibration curve of mass flow gas feeding to the PMHT was used to determine the propellant feeding (typically 10^{-5}Kg/sec) [2]. In this paper, we call the 0.1A discharge the low thrust regime, and the 1.5A discharge (with 150 to 200Volts), the higher thrust operational regime. The tungsten wire covered with BaO hot cathode works with temperature of 900^{o}C emitting 1A/cm^2 of primary electrons to generate the discharge.

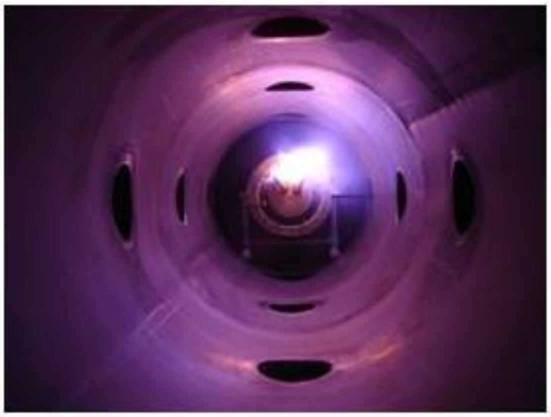

Figure 7 PMHT operating at the New Vaccum Test Chamber.

Plasma diagnostics inside and outside the source were made by using a movable Langmuir probe and an ion energy analyzer. The cylindrical Langmuir probe (0.25mm x 3.5mm) can be oriented parallel or perpendicular to the thruster axis in order to provide plasma density, plasma potencial and temperature space profiles. The probe size was designed to minimize pertubation on the plasma. We obtained the plasma density, temperature and distribution function using the Druyvensteyn method, which consists on 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.

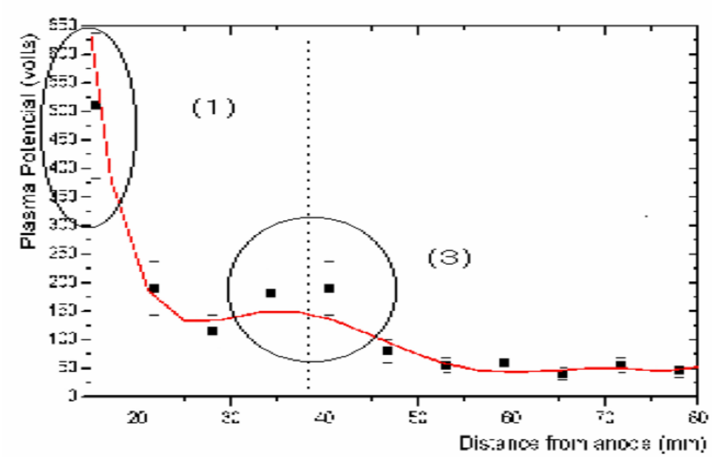

Figure 8- Langmuir probe space profiles of plasma potential inside and outside the plasma channel of PMHT

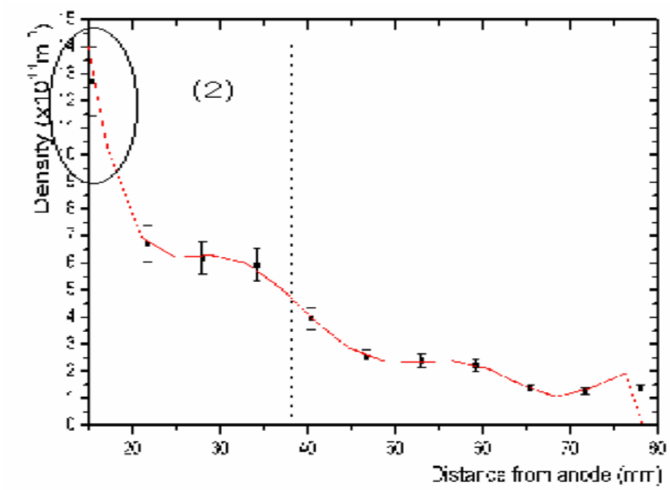

Figure 9- Langmuir probe space profiles of plasma density inside and outside the plasma channel of PHALL I

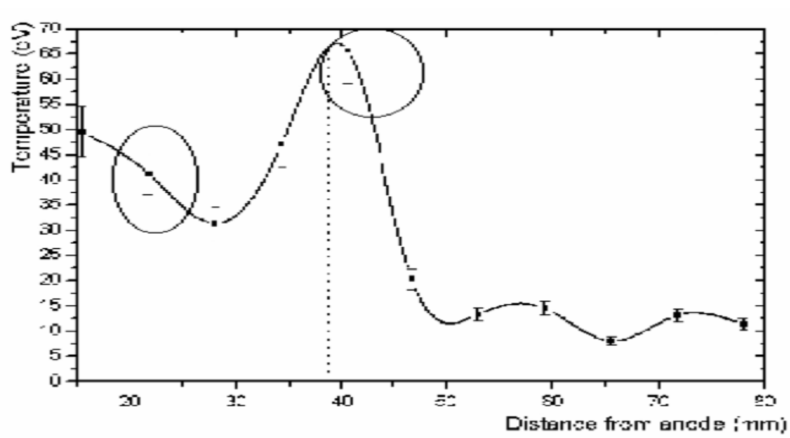

Figure 10- Langmuir probe space profiles of plasma temperature inside and outside the plasma channel of PHALL I

Under the influence of the axial electric and radial magnetic fields, the electrons drift in the azimutal direction (azimuthal Hall current). Due to collisions, electrons diffuse across the magnetic field towards the anode (axial electron current) and ionize by impacts the working gas atoms emerging form the anode. The axial dependence of the electron mobility depends on the magnetic field profile. This is the main physical mechanism to determine the axial space plasma potencial drop associated with the exausted plasma beam current [4].

The distribution function F can be determined from the retarding potential of the probe (U) [2]:

$$F(U) = \frac{\sqrt{8m}}{e^{\frac{3}{2}} A} \frac{d^2 I_e}{dV_{ap}{}^2}$$

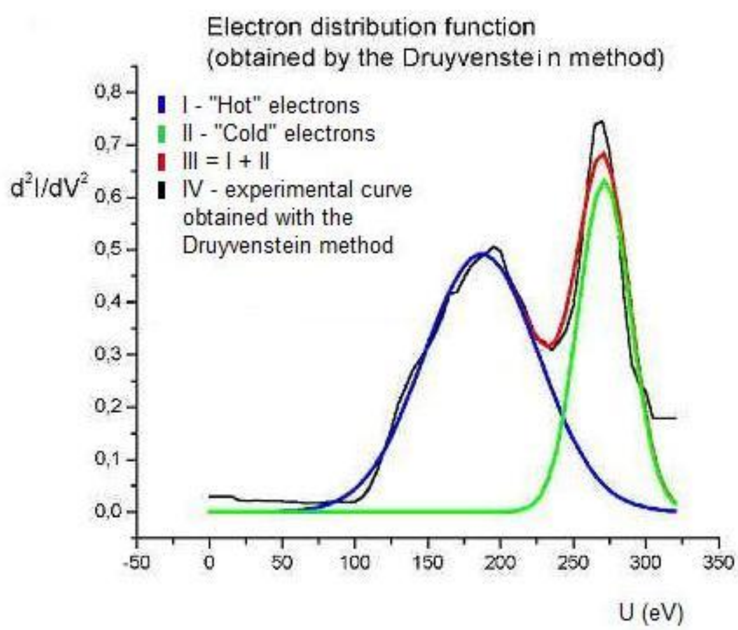

Fig.11 – The two-electron temperature plasma.

Willing to measure the plasma beam energy profile, we used a plane moveable electrode known as the ion “Faraday cup”, which allows the measurement of the drifting plasma flux current space distribution and the correspondent ion energy [7]. The ion probe was positioned 35cm from the acceleration channel exit. It was fixed with an experimental arrangement that allowed radial and angular movements permitting measurements of the total beam current and the PMHT Thrust due to the accelerated plasma. The energy spectrum obtained from derivation of the ion energy analyser characteristic curve (E= 300 eV) correspond to thrust measurements of the ion collector on the order of T= 86 mN.

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 (3000 to 8000 Å) of the argon plasma (fig. 12) was measured using a Czerny-Turner monocromator (Spectra-Pro 750),equipped with 1200lines/mm grid, resolution below 0.05 Å, a photomultiplier tube, a fiber optic array fitted inside a cylindrical stainless steal tube with o ring seal to allow the fiber optic adjustement inside the vaccum chamber.

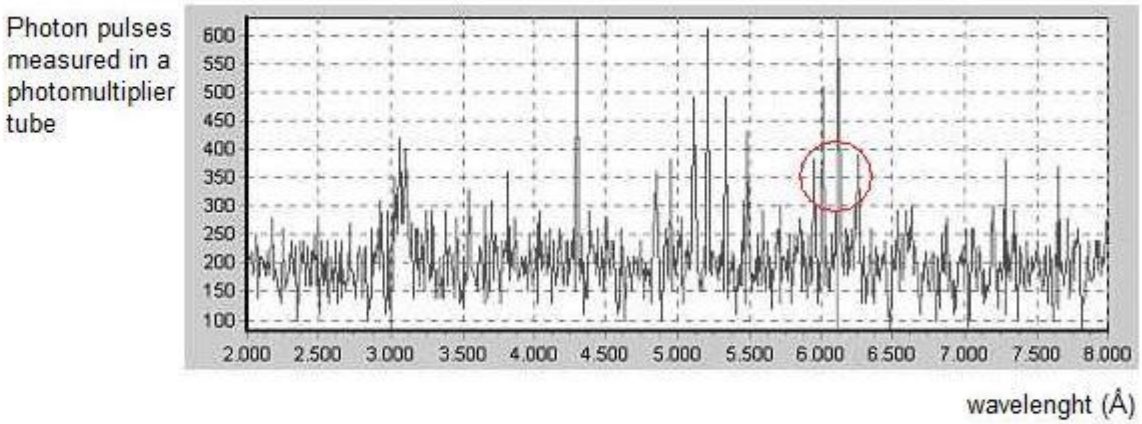

Fig. 12 - Argon plasma spectrum from the hall plasma current channel region.

Based on the analysis of the experimental conditions in the plasma Hall current channel, we were able to determine the appropriate statistical model to be applied on the interpretation of the measured spectral lines. Collisional ionization and excitation, charge exchange and radioactive recombination are the predominant processes that affect the radiation emitted by the plasma, and a model which includes these phenomena is satisfactorily suitable for this experimental conditions. The broadening of spectral lines is one of the consequences of the several perturbative effects on the atomic systems caused by these processes.

Line broadening can be driven by several mechanisms such as Stark and Zeeman effects when strong electric and magnetic fields are applied to the plasma. High pressures can also produce collisional line enlargement; nevertheless, inside the Hall plasma source, the Doppler Broadening of spectral lines is one of the predominant characteristics of the thermal particle motion.

In order to evaluate the ion temperature of the plasma, the Doppler broadening of the plasma radiation was measured. This method is based on the difference between the wavelength emitted by a moving ion and the wavelength that would be detected if the ion were at rest. This broadening is given by $\Delta\lambda_D = \lambda_0 \frac{v_i}{c}\gamma\cos(\theta)$ where $\gamma = \left[1 - \left(\frac{v_i}{c}\right)^2\right]^{-1}$ and θ is the angle between v_i and the detector "target line".

If we consider the Maxwell velocity distribution, the measured intensity of the $\Delta\lambda_D$ broadened spectral line – which emerges as a typical gaussian distribution – is expressed by $I(\lambda) = I_0 e^{-\left(\frac{\lambda}{\Delta\lambda_D}\right)^2}$ (in atomic units).

In this calculation, we assume that $v_i = \left(\frac{2k_B T_i}{m_i}\right)^{\frac{1}{2}} << c$ and consider only the radiation emitted by the ion moving towards the detector (forward or backward). Therefore, 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. With this equation, we can estimate the ion temperature (fig. 13).

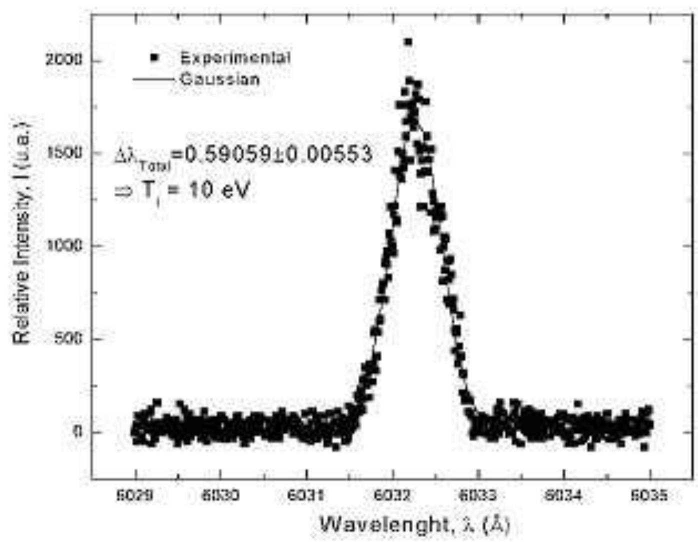

Fig. 13 – Argon spectrum line (6032 Ǻ) plot after treatment used to measure the ion temperature. This peak was chosen from the spectrum showed at fig. 14.

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 - 2.5×10^{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 plasma acceleration is measured using an ion energy analyzer. The drifting ion energy distribution function is proportional to $\frac{dI}{dV}$ and a derivation of analyzer characteristic curve was made by a computational code.

In spite of low frequency oscillations found in the ion probe measurements, we calculated the total thrust of the PMHT. The results from the ion collector current are placed in the interval of 18mN to 39mN indicating that the PMHT is working with 27% of efficiency - as expected for this first experimental model. If the total thrust is calculated from the input power in the Hall discharge, the maximum thrust goes from 44mN to 86mN. Hence, our PMHT has only 43% of the maximum thrust that can be obtained from this discharge. These values can at least be scaled up to the thrust values of the existent SPT.

With PHALL I we obtained the following performance parameters: Maximum thrust available of 126 miliNewton, maximum specific impulse of 1607 seconds and an electric efficiency of 67.2 percent; on the other hand, we had a very low ionized mass rate, of approximately 6 percent. We associate this low ionization to the type of cathode used on this first prototype. We also show the expected parameters for a second prototype of the PMHT (PHALL II) (see table I). The new plasma source is smaller (Diameter = 15 centimeters), has a hard aluminum body and a magnetic field will be produced by neodymium-iron magnets.

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

	PHALL1	PHALL2 (expected)
Maximum expected thrust (mN)	126	126
Average measured thrust	84,9	120,0

(mN)		
Thrust density (N/m²)	4,68	< 6,0
Maximum specific impulse (s)	1607	1607
Measured specific impulse (s)	1083	1600
Ionized mass ratio(%)	3,3	~30
Propellant consumption (Kg/s)	$6{,}0 \times 10^{-6}$	$1{,}0 \times 10^{-6}$
Energy consumption(W)	350	250 – 350
Electrical efficience (%)	33,9	60
Total efficience(%)	10,12	50,0

V. Numerical simulation study of satellite orbit maneuver with PMHT

Finally, based on the measured parameters of the accelerated plasma, we present an aptitude figure for the PMHT. It contains 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. We perform numerical simulations of satellite orbit raising from an altitude of 700 km to 36000 km using a PMHT 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, constant 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 applied 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 were: orbit raising time, propellant mass, satellite mass, thrust specific impulse and exhaust velocity.

In spite of absence of hollow cathodes we compare PHALLI (see table I) with other laboratory Hall Thrusters whose magnetic fields are produced by electromagnets. PHALL I is able to produce the same thrust and specific impulse with lower energy consumption but magnet assembling and spurious magnetic fields elimination can be improved. Figure 15 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) and of satellite mass. Figure 15 shows numericalcaculation of propellant consumption for orbital transfer maneuvering. The propellant mass is calculated for pulsed thrust in the correspondant apocentral orbit angle openning. Figure 16 shows the time necessary to circularized orbit using pulsed thruster, supposing satellite geostationary orbit crossing apocenter, with pericenter at 700 km altitude, for several values of PHALL total thrust.

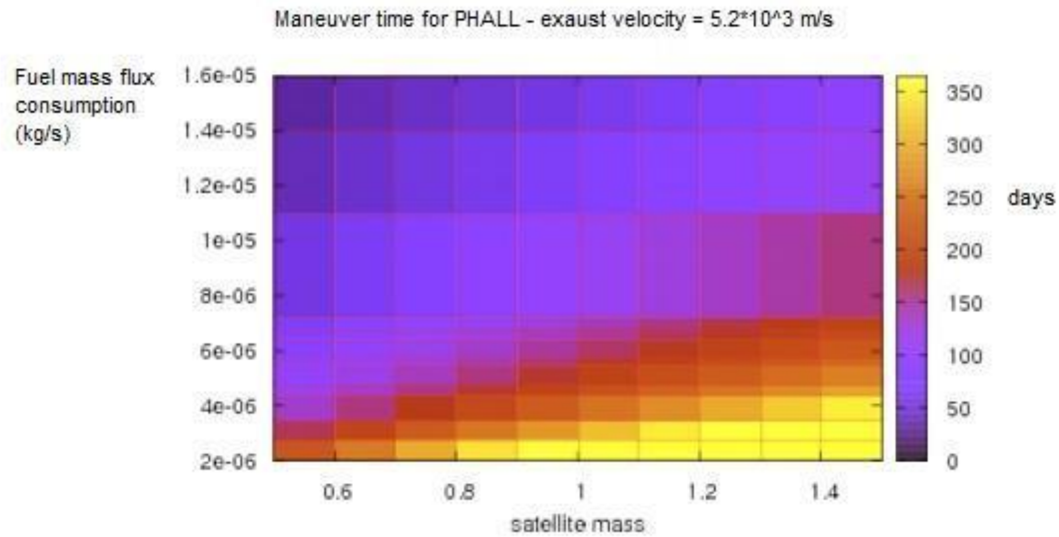

Figure 15 - Maneuver time to send a spacecraft to geostationary orbit, from 700 km altitude circular orbit, using continuous thrust as a function of propellant mass flux (measured in laboratory for PHALL) and of satellite mass.

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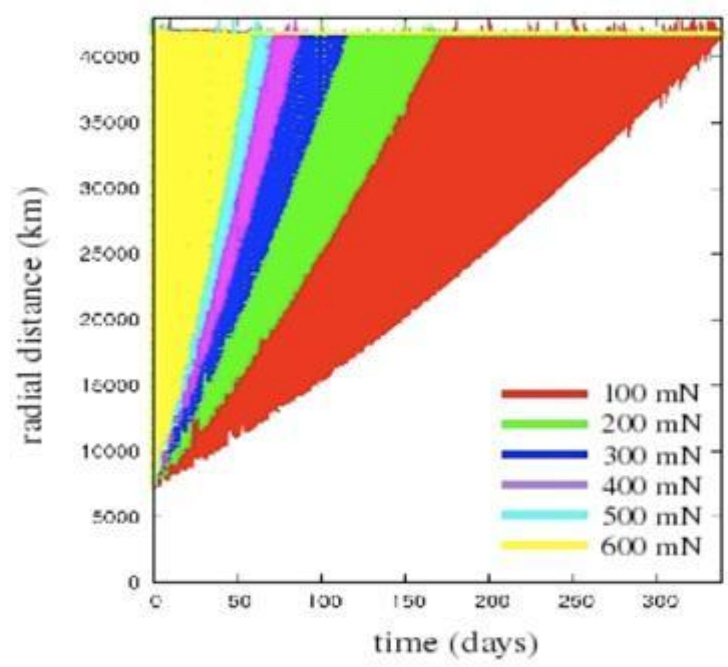

Figure 16- Time necessary to circularized orbit using pulsed thruster, supposing satellite geostationary orbit crossing apocenter, with pericente rat 700 km altitude, for several values of PHALL total thrust

VI. Conclusion

A new conception of closed drift Hall thruster using permanent magnets was developed. The results obtained on the magnetic field geometry and strength, the plasma density temperature, the thrust measured by ion collector probe and ion energy analyzer are motivating results to forthcoming tests. Ion temperature measurements are showing a strong influence of the electric field on ions inside the acceleration zone. We estimate a non mawellian velocity distribution function for these ions. . Even though, the Doppler broadening is a very adequate method of obtaining the ion characteristics for it is a non-intrusive technique. A two electron temperature plasma inside the acceleration channel was also measured using the Druyvensteyn method. These measurements are evidence of an anomalous plasma transport process being going on in the transition region between the Hall current channel and the acceleration zone[7]. These results are matching with plasma instabilities detected by the ion collector probe. .In spite of the use of simple materials easily found on brazillian industrial market and the utilization of Argon instead of Xenon, the new PMHT Hall thruster allows the study of the PMHT characteristics and performance using several diagnostics technics. Althought The quadrupole mass spectrometry indicate a high purity 99,95% Argon plasma the relatively high working pressure of 5x 10^{-5} mbar shows the necessity of a better vaccum pumping system and a bigger volume vaccum system. A computational study of satellite maneuvering using the PMHT was successfully conducted. These studies indicates that Permanent Magnet Hall Thrusters are a good candidate for spacecrafts performance control in long time space missions.The possibility of extra economy on satellite energy consumption due to the use of permanent magnets is one of the main advantages of this new design for Hall Thrusters.

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