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A SIMPLE LABORATORY PULSED PLASMA THRUSTER FOR DIDACTIC PURPOSES: LEARNING THROUGH RESEARCH

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Abstract. *The traditional chemical propulsion technology relies on the internal energy stored in the molecular bonds of the propellant to produce thrust via a combustion reaction. On the other hand, electric thrusters rely on external power sources to accelerate the propellant with an electrical heater or by applying electric and/or magnetic body forces and, thereby, its thrust and exhaust velocity are only limited by the capacity and efficiency of such external power sources. One of the big advantages and innovations of the technology of space Electric Propulsion (EP) is that it enables missions that would not be otherwise viable, as the high specific impulse produced by EP allows a greater payload mass fraction in the spacecraft and/or a save in the amount of propellant (cost) necessary to accomplish the mission. Amongst the many types of EP thrusters is the PPT (Pulsed Plasma Thruster), which is mostly known for its outstanding robustness and simplicity. The PPT presents no mechanical moving parts and produces the thrust from pulsed electric discharges that ablate and accelerate a solid propellant (usually PTFE, Teflon®). The main objective of this work is to present the development of a PPT laboratory prototype for didactic purposes that will allow students to perform basic measurements and be introduced to EP technology research. The project will also aid the learning of fundamentals of plasma physics while providing a hands-on experience on space engineering development. The thruster will be designed to be as modular as possible to allow students to modify it. The work will be carried out at the Combustion and Propulsion Laboratory (LCP) of the National Institute for Space Research (INPE) in a high-vacuum space simulation chamber. As a main scientific goal, this work is the first step of the collaboration UnB-INPE to study the low-power regime of the PPT, which is still poorly understood.*

Keywords: *Pulsed Plasma Thruster, Plasma Physics, Electric Propulsion, Aerospace* **Engineering**

1. INTRODUCTION

In general there are basically two types of thruster technologies that are usually applied in space missions. The first and more traditional is chemical propulsion. This kind of technology is based on the acceleration of gases from combustion reactions via thermodynamic devices, like convergent-divergent nozzles. One of the biggest limitations of this kind of technology is that it is impossible to increase the maximum energy of the thrust unless the molecular structure of the propellant is modified. On the other hand, up to now, chemical thrusters are the only type of thrusters capable of producing the thrust level necessary for the first stage of launcher vehicles.

The second type is Electric Propulsion (EP) thrusters. This kind of technology has another approach to propulsion and focuses mainly on the elevation of the specific impulse (up to hundreds of thousands of seconds), sacrificing the thrust magnitude, ranging from a few μN up to 1N. In contrast the thrust of chemical thrusters can be as high as hundreds of kN or MN, but as a down side the chemical thrusters' specific impulse range from 100 to 450s. The main advantage in utilization of EP is the high efficiency of the propellant mass utilization (Jahn, 1968), in other words, it is possible to decrease the amount of propellant necessary to change some ΔV of a space vehicle, using the high specific impulse of EP. Furthermore, another important advantage of EP is that its maximum thrust energy is not limited by the molecular bonds of the propellant, what happens in the chemical thrusters, and only depends on the power output of the electric source, thus having virtually no limit (Turner, 2009).

Aboard space vehicles, EP has many important applications, that are similar to chemical thrusters but with different characteristics, advantages and disadvantages. As already has been said, the main advantage of EP is to produce high exhaust velocities and thus have a small consumption of fuel, and nowadays many companies and institutes of the space community choose to use EP thrusters aboard their spacecrafts. The main current applications are described by (Turner, 2009): *station keeping* – this is currently the main application of EP thrusters (even more in commercial satellites), that is because nearly every satellite needs intervention of a propulsion system to correct its orbit path and compensate the perturbations from the environment. Despite producing low thrust, EP thrusters produce just the amount of impulse necessary to maintain the space vehicle in its path with much less fuel consumption than when monopropellant thrusters are used; *transfer maneuver* – that is the application of the propulsion system to transfer the space vehicle from one orbit to another (usually from LEO to GEO). This application is not so frequent, because the period of time necessary to perform the transfer usually is much longer than when chemical thrusters are used. Despite that, many times EP is applied to transfers, again because of its low fuel consumption and thus it is possible to use small propulsion system aboard huge satellites; *interplanetary/lunar missions* – although the application of EP in these kind of mission was not so common until nowadays, some of the most important research institutes are currently doing great investments to develop new advanced EP thrusters to perform new interplanetary and lunar missions with high payload mass fractions.

The most general definition of EP is given by (Jahn, 1968): "The acceleration of gases for propulsion by electrical heating and/or by electric and magnetic body forces". This definition encompasses many types of propulsion systems, like Resisto-jets, Arc-jets, Hall-Effect Thrusters, and many others, that are way beyond the scope of this work. Thereby, to better develop the objectives of this text, all efforts will be made to clarify only the concepts around the Pulsed Plasma Thruster (PPT) technology, that due to its outstanding simplicity and robustness was the first EP thruster used in a real space mission, in 1964 aboard the soviet probe Zond 2 (Burton and Turchi, 1998).

The operation of such thruster concept, described in details by (Vondra, 1974), is based on an electronic circuitry that stores energy in a capacitor bank and cyclically discharges it producing pulsed high voltage arcs (some thousands of Volts) on the surface of the solid propellant (usually PTFE), causing its vaporization, dissociation (known as the ablation process) and ionization. Part of the resulting gas is accelerated by the effect of the Lorentz force and other part by thermal expansion - resulting in the generation of thrust.

Currently exists three main types of PPT geometric configurations described in the literature (Burton and Turchi, 1998), each of them greatly influencing both the performance of the thruster and its complexity of implementation aboard the spacecraft:

- **Breech-fed** (Figure 1a): It is the oldest configuration. The thruster is fed by just one rectangular propellant bar that is located between two parallel electrode plates. As the PTFE is being consumed, a spring pushes the bar ahead, so that the propellant remains always between the electrodes.
- **Side-fed** (Figure 1b): This configuration is similar to the first one, but the thruster is fed by two propellant bars located at opposite sides of the parallel rectangular electrodes.
- **Coaxial** (Figure 1c): In this configuration, the propellant is a cylinder with an axial hole, so that the electrodes are located coaxially. Usually the cathode is located at the center of the cylinder and the anode externally.

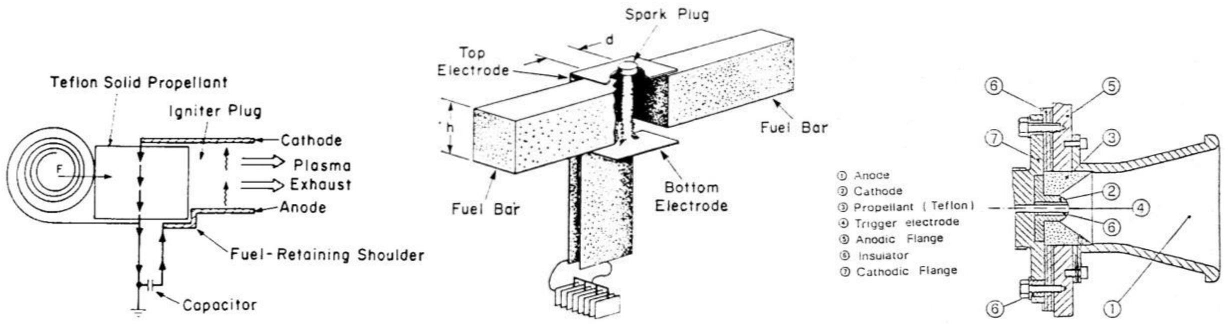

Figure 1. (Gessini *et al.*, 2005) a) (Left) Breech-fed PPT; b) (Center) Side-fed PPT; c) (Right) Coaxial PPT.

Despite being the oldest EP concept applied to a space mission, the operation performance and characteristics of the PPT are not deeply understood until nowadays, especially the Coaxial type, that has been the focus of much investigation recently (Aoyagi, 2009), mainly due to its potential to have better performance characteristics compared to the other geometries (Gessini *et al.*, 2013a). One of the biggest obstacles in the study of these thrusters is the difficulty in achieving a precise mathematical modeling of the ablation process and mechanics of the exhaust fluid, which would give the tools for the researchers to approach the optimal PPT configuration. Among many other problems to achieve the model, is that the ionized gas resulting from the ablation process has no particle uniformity, since it is derived from the break-up of large polymer molecules, and has in its composition ions, electrons, neutral particles and molecules of different sizes (Popov *et al.*, 2001). The difficulty greatly increases when the regime of operation is restricted to the low-power discharges (less than ten Joules), where the performance of the thruster becomes less predictable and it cannot be fitted in the usual semi-empirical trend curves (Gessini *et al.*, 2013b). In this regime, the design of the thruster turns out to be very complex and requires extensive testing to achieve predictions of its operation characteristics.

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This work describes the design of a modular coaxial PPT that will operate in the low-power regime, with discharge energies less than 5 Joules, designed to serve as an experimental workbench for the students in the research project. They will have the opportunity to change the configuration of the system, understand its working characteristics, from an experimental point of view, and all the plasma physics phenomena involved, greatly aiding in the learning process of all Electric Propulsion technology concepts. Ultimately this workbench will allow them to perform research works to better understand the PPT operation characteristics inside the low-power realm, allowing them to have a first scientific experience in space technology. All the specifications and design characteristics of the proposed system will be shown, as well as the facilities where the thruster will be installed and tested in the future, that are located at the LCP (Combustion and Propulsion Laboratory) of INPE (National Institute for Space Research), located in the city of Cachoeira Paulista, SP.

2. LOW-POWER REGIME

The design of PPTs, as described by (Guman, 1975), is mostly based in following semi-empirical laws to predict and improve its performance. Much work has been done to fit analytical functions to the experimental data in order to achieve some universal law that could help in the reaching of the optimal PPT configuration. Some of the most used semi-empirical relations are given by (Gessini and Paccani, 2001). Among the various relations, the linear dependency of the impulse-bit on the discharge energy dominates, due to its simplicity and the amount of available data in the literature to confirm it. The relation is given by:

$$I_E = \frac{I_{bit}}{E} \; [{}^{\mu Ns}/_{J}] \tag{1}$$

Where I_E corresponds to the specific thrust, I_{bit} gives the impulse-bit, that is the impulse generated by the PPT at each pulse, and E corresponds to the discharge energy that ablates and accelerates the propellant. It is important to note that in the above relation the specific thrust will remain constant over all the regime of operation, thus usually in the literature this relation is represented graphically by a linear plot, with the energy on the horizontal axis, as an independent variable, and the impulse-bit on the vertical axis.

Using this relation it is possible to review the experimental data available in many works to determine values of I_E to each geometric configuration of the PPT and thus achieve approximated laws to predict the performance of the thruster, even before it is built. Reviews of this kind are given by works like (Gessini *et al.*, 2013a) and (Molina-Cabrera, 2011). Observing such studies is possible to note that for nearly all the data available the coaxial geometry presents higher specific thrust when compared to the breech-fed and side-fed geometries. The Figure 2a demonstrates this performance behavior for energy discharges from 0 to 80 J and the Figure 2b for energies from 0 to 10 J, showing that performance appears to be seriously degraded at low energies for the breech-fed and side-fed configurations, but not for the coaxial one.

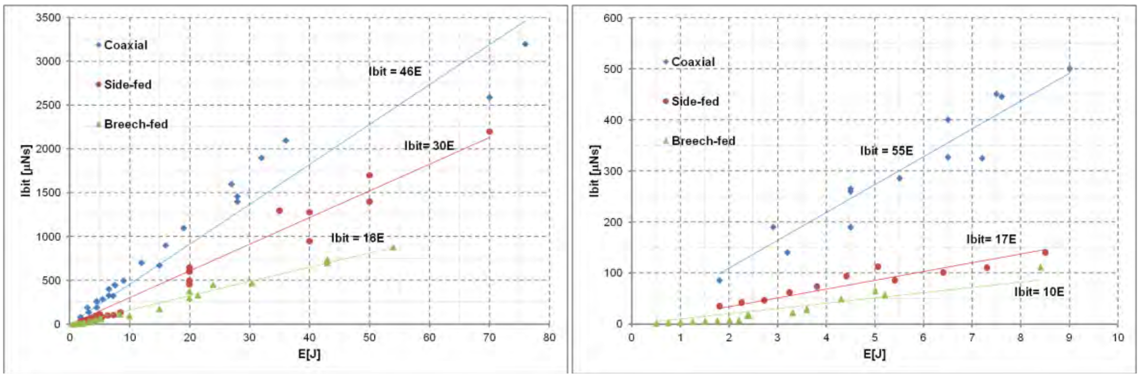

Figure 2. (Gessini *et al.*, 2013a) a) (Left) I_{bit} vs. E (0J,80J); b) (Right) I_{bit} vs. E (0J,10J).

Therefore, considering the global better performance of the coaxial geometry of the PPT, and also considering the present trend of researching the operation characteristics of such geometry (Aoyagi, 2009), the authors decided to perform their studies based on this geometric configuration of PPT.

Nevertheless, exploring other experimental data available in the literature for low-power operational regimes, like in (Uezu *et al.*, 2005) and (Lau *et al.*, 2011), it is possible to observe that a wide data scatter starts to occur in its performance characteristics, even for geometries that appear to be quite similar, like the ones from the cited references. In Figure 3, when only very low-power discharges are considered, it is possible to observe the hard data deviation from the linear approximation presented previously.

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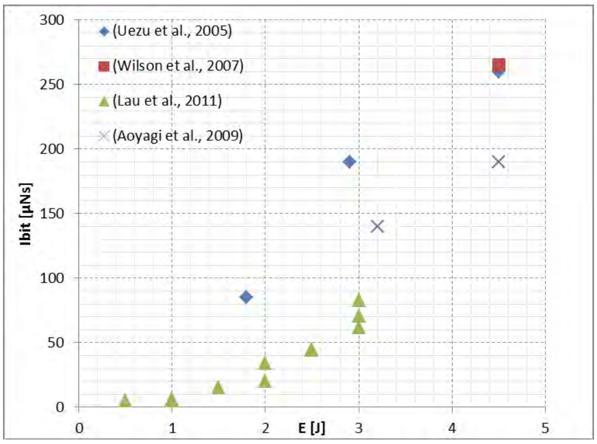

Figure 3. Demonstration of the Coaxial PPT performance at very low energy levels.

With that, it is quite reasonable to consider that the linear relation between the impulse-bit and discharge energy stops to be valid for values below 5 J. To better understand this strange performance behavior of low-power PPTs the authors decided to perform their experiments at the energy levels between 0.5 and 5 J. This will allow future works to perform the characterization of the performance trends of PPTs in these regimes and ultimately to propose new semi-empirical relations to be used in this energy interval. These new relations would give important tools to the space community to achieve optimal configurations for PPT micro thrusters for applications aboard nano and microsatellites, mostly, but not only, for their station keeping (Coletti *et al.*, 2011).

The present work is the beginning of a new line of research, a collaboration between the University of Brasília (Aerospace Engineering and the Physics Institute) and the Combustion and Propulsion Laboratory of the National Institute of Space Research (INPE), which should allow us to shed light on both points, namely the non-linearities at low discharge energies and the relatively better performance of coaxial PPTs.

3. THRUSTER PRELIMINARY DESIGN

The design of a PPT is a multidisciplinary complex task, as it is necessary to optimize several mechanical and electrical parameters to modify the plasma and thermal phenomena in order to achieve an acceptable performance. Some of these parameters are: propellant geometry, electrode characteristics, electronic configuration, spark-plug (igniter) design and even the presence of a thermal nozzle (Coletti *et al.*, 2011).

3.1 Propellant geometry

It is possible to design PPTs with widely different geometries. The most common, however, are the breech-fed, side-fed and coaxial. The present work, as already said, will use the coaxial geometry owing to its superior performance characteristics and the new current trend to study it.

The coaxial PPT, in a simplified vision, consists of a tubular PTFE (Teflon®) propellant tube, with an anode made of conducting material, usually brass, at its bottom, and at the other end of the propellant tube (where the plasma is exhausted), the cathode, which may have or not a divergent thermal nozzle in order to increase its performance when the thermal effects are non-negligible. Figure 4 shows the coaxial PPT configuration presented by (Uezu *et al.*, 2005).

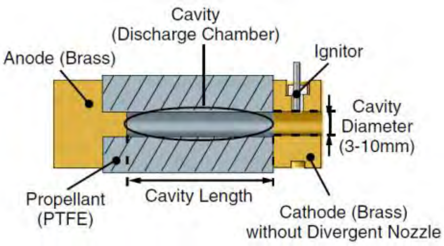

Figure 4. (Uezu *et al.*, 2005) Coaxial PPT diagram.

For the sake of simplicity, in this first preliminary design, the present work will use a design similar to the ones that are presented in (Uezu *et al.*, 2005) and (Lau *et al.*, 2011), with no application of a thermal nozzle. For a near future work a nozzle of this type may be employed in order to study the thermal characteristics of the new PPT.

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Considering that and the didactic purpose of this research, the thruster will have a variable propellant cavity length that may go from 10mm up to 50mm, with baseline at 30mm. The cavity diameter, for now, will have a fixed value of 5mm, but with possibilities of future variation.

3.2 Electrode characteristics

The electrode geometry, obviously, is coaxial as well. Although not mandatory, the anode is usually designed to remain at the closed end of the PPT (where no exhaust flow occurs) and the cathode at the nozzle end. The electrodes in the PPT have the function to create a potential difference between them and thus, with the help of an igniter, provide a high voltage discharge on all the exposed surface area of the propellant. This discharge ablates the material, dispersing it inside the cavity, ionizing it and finally accelerating it by the acting Lorentz force. This process generates the thrust.

The material used to construct the electrodes, when the application of the thruster is a real space mission, usually is an alloy like copper-tungsten that presents very low erosion rates, allowing the thruster to function for the entire mission (Coletti *et al.*, 2011).

For merely experimental laboratory prototypes simpler materials like brass are usually employed. This material presents reasonable electrical characteristics and erosion rates that allow experiments for sufficient amount of time (Uezu *et al.*, 2011). Therefore, to keep the simplicity of the prototype, the present work will employ brass to construct the electrodes, with the future possibility to change them to evaluate new kinds of materials and develop other options for space applications.

3.3 Eletronic configuration

The electronic hardware of the PPTs, responsible for producing the pulsed high voltage on the electrodes, is usually composed by a Power Processing Unit (PPU) that receives the DC low voltage input (few volts) from the spacecraft and produces the high voltage output (a few thousands of volts). This conversion usually is made by a Switched-mode DC converter that uses a high frequency switch to convert DC voltages, one of such PPUs is described by (Shin *et al.*, 2005). These devices usually have digital electronics parts to control and interface the thruster with the rest of the spacecraft or the laboratory computers. Figure 5 shows the scheme of a proposed PPU developed by (Shin *et al.*, 2005).

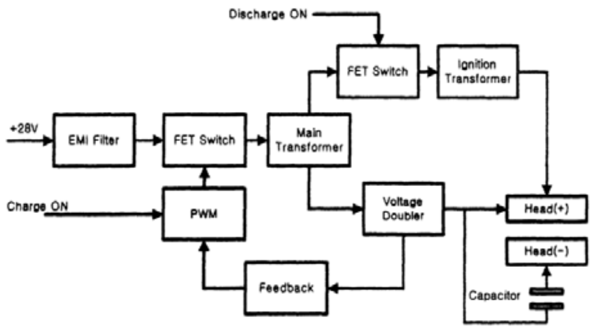

Figure 5. (Shin *et al.*, 2005) Power Processing Unit scheme.

Another essential part of the PPT's electronic hardware is its capacitor bank. This bank has the function to store charge at high voltage and release it creating the discharge on the electrodes of the PPT. The necessity of such capacitor arises because the DC converter, in order to maintain the same operational power, is only able to increase the voltage of the output if there is a reduction on the magnitude of the current. Therefore, applying the high voltage for a sufficient time to the capacitors, it is possible to achieve the necessary amount of energy to make the discharge inside the PPT.

The approximate capacitance necessary to perform the discharges in PPTs that are similar to the one that this work is discussing is defined by (Uezu *et al.*, 2011) to be inside the interval from 6 to 14 μF. The exact capacitance used in the experiment depends on the configuration of the power source and the desired energy discharge.

3.4 Spark-plug (Igniter)

The spark-plug is the device responsible for the initiation of the discharge inside the PPT. This subsystem has the function to facilitate the main discharge to occur by increasing the charge density inside the cavity by early ablating some small amount of propellant. The design of this igniter plays an important role in the performance of the PPT and precision and efficiency defines in part the quality of the main discharge (Pottinger and Scharlemann, 2007).

The design of the traditional spark-plug, which will be used in the present prototype, is very similar to the actual thruster. This subsystem is composed by a pair of electrodes and an amount of propellant between them. To produce the

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ablation a high voltage (even higher than the main discharge) is applied to the electrodes. The reason that this ablation occurs with no previous charge density inside the cavity is that the gap between these electrodes is very small, compared to the main ones.

The research to achieve better spark-plug designs is one of the main fields within PPT technology. Some of the main problems to be solved in the spark-plug design are related to the erosion phenomenon that limits the thruster life-time and the efficiency of this early discharge (Pottinger and Scharlemann, 2007).

4. FACILITIES

The facility where the prototype will initially be tested is located at the Combustion and Propulsion Laboratory (LCP) of the National Institute of Space Research (INPE), in the city of Cachoeira Paulista, São Paulo.

The main items of the facility are:

- Stainless steel high vacuum chamber, with volume of approximately 37,000 cm³.
- Turbo-molecular pump, Leybold TURBOVAC 150V 50000 rpm, with pumping capacity of 145 liters per second (with operational pressure below 10^{-10} mbar).
- Mechanical pump, Leybold TRIVAC B D8B, two stages, with pumping capacity of 8m³/h.
- Pressure sensor Edwards Pirani 501.
- Pressure controller Balzers TP6300 Total Pressure Controller.
- Controller of the turbo-molecular pump, Leybold TURBOTRONIX NT 150/360 VH.

The above described facility is shown in Figure 6.

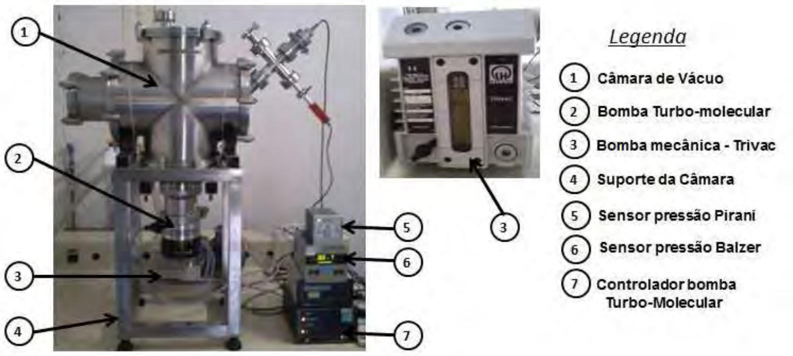

Figure 6. PPT Facility of LCP/INPE.

5. CONCLUSIONS

This work presents a preliminary view of the project that will be conducted as a collaboration between the University of Brasília and the National Institute of Space Research. Initially, this project will be aimed at the construction of a Coaxial PPT prototype with didactic motivations. This prototype should give students working on the project a first experience in Electric Propulsion technology research and facilitate the study of the physical phenomena involved, mainly the ones related to the plasma physics.

As presented, the PPT performance shows a hard data scatter when the energy discharge regime is restricted to the low-power levels. Therefore, this work also proposes the study of PPTs inside this regime. This proposition will give the opportunity for the students and the researchers that, at the same time that the didactic objectives are underway, there is a prospect for them to really produce new scientific data.

This project is a first step in the collaboration of INPE and UnB to study the PPT performance at low energy regimes and therefore design new micro thrusters for application onboard Cubesats and other nano and microsatellites.

This new trend of micro thruster research is in accordance with the beginning of development of nano and micro satellites that is occurring at several Universities of Brazil. Currently this development is ongoing at ITA and just beginning at UnB.

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