# High Frequency Burst Pulsed Plasma Thruster Research at the University of Southampton

### IEPC-2007-300

R. I. Marques†[1,2] , S. B. Gabriel‡[1], F. de S. Costa§[2].

[1]*University of Southampton, SO17 1BJ, United Kingdom*

[2] *Instituto Nacional de Pesquisas Espaciais, Cachoeira Paulista, SP, 12630-000,Brazil*

**Abstract: Pulsed Plasma Thrusters (PPTs) are long standing electric propulsion thrusters that are reliable, relatively simple and low cost. A main problem with PPTs is its low efficiency, typically between 3-8%. One of the main contributors for the low efficiency in PPTs is the sublimation of propellant that takes place after the main discharge. This late time ablation produces a low speed gas and macro particles that does not contribute significantly to produce thrust. The High Frequency Pulsed Plasma Thruster (HFB-PPT) aims at accelerating the late time ablation by employing additional discharges after the main discharge. This paper presents the research on HFB-PPT at the University of Southampton and the development and test of a rectangular HFB-PPT, the design of a coaxial HFB-PPT and the initial design of a low power HFB-PPT for use in the UniSat-5 satellite.**

## I. Introduction

The PPT was the first electrical thruster to be used in space, in 1964, with the Soviet space probe Zond 2. In the USA, the first PPT was used in the LES-6 satellite, launched in 1968. The augmented hydrazine thrusters, arcjets, ion and Hall thrusters were developed later (Burton & Turchi, 1998).

Pulsed plasma thrusters are electric thrusters that allow very precise maneuvers and present relatively simple construction, reliability, low cost and long lifetime. They can be used in satellites, space probes and other spacecrafts for orbit control and maintenance (LaRocca, 1966) (Guman & Nathanson, 1970) (Vondra, Thomassen, & Solbes, 1971) (Vondra & Thomassen, 1972) (Vondra & Thomassen, 1974), orbit transfer (Akimov, et al., 1997), drag compensation and flight formation (Ebert, 1989) (Janson, 1993) and attitude control (Meckel, Cassady, Osborne, Hoskins, & Myers, 1997)

Impulse is derived from a high voltage discharge applied on the surface of a solid dielectric, in general Teflon™ (PTFE – Polytetrafluoroethylene), causing its sublimation, dissociation and ionization. The generated plasma is then accelerated by the Lorentz force which results from the coupling of the electric discharge and the self-induced magnetic field (Burton & Turchi, 1998). A parcel of the sublimated propellant is not ionized, being accelerated only by thermal expansion (Vondra R. T., 1970); this portion is also known as late time ablation.

The High Frequency Burst Pulsed Plasma Thruster was designed specifically to minimize the effects of the late time ablation (LTA) on the performance of the PPT. It is, therefore, convenient to give further details about LTA.

Late time ablation is the sublimation of the propellant that takes place after a pulse discharge on the PPT and happens because the propellant surface remains hot after the main discharge, above the sublimation temperature. This causes a significant part of the propellant (~40% in some cases) to be ejected at very low speeds, compared to the speeds of electromagnetically accelerated propellant. This low speed material does not contribute significantly to the impulse generated by the PPT and therefore current PPTs use approximately only 60% of the propellant to produce usable thrust.

---

† PhD Candidate, Astronautics Research Group, and researcher at INPE/LCP, intini@soton.ac.uk
‡ Professor, Astronautics Research Group, sbg2@soton.ac.uk
§ Senior Researcher, Propulsion and Combustion Laboratory (LCP), fernando@lcp.inpe.br

In order to minimize the LTA effects a new PPT design was required. In 2004 a research was initiated at the University of Southampton in cooperation with INPE/LCP – Brazilian National Space Centre, Laboratory of Combustion and Propulsion (Pottinger, Gessini, Webb, Intini Marques, & Gabriel, 2006). The approach in the new design was to electromagnetically accelerate the late ablation by employing additional pulses after the main discharge occurs. However, if these additional pulses were to happen in the same set of electrodes, near the propellant surface, the propellant would receive more heat which would lead to more LTA. Therefore, the additional discharges should take place downstream, relatively far from the surface, in a separate set of electrodes. It was noted that a synchronization system was desirable to allow the secondary pulses to occur only after the main discharge occurred. Also, in order to match the mass flow rate of the LTA, relatively slow compared to the main discharge, there was a need for a switch system capable to generate several pulses in the extra pair of electrodes. This pulses, or secondary discharges, would be generated in high frequency bursts in an attempt to accelerate most of the LTA.

## II. The Basic HFB-PPT Design

Figure 1 shows the basic concept of the HFB-PPT in a rectangular geometry. The first set of electrodes (cathode 1 and anode 1) is responsible for the main discharge and the second set (cathode 2 and anode 2) is responsible for the secondary discharges. A spark plug is located in the cathode 1.

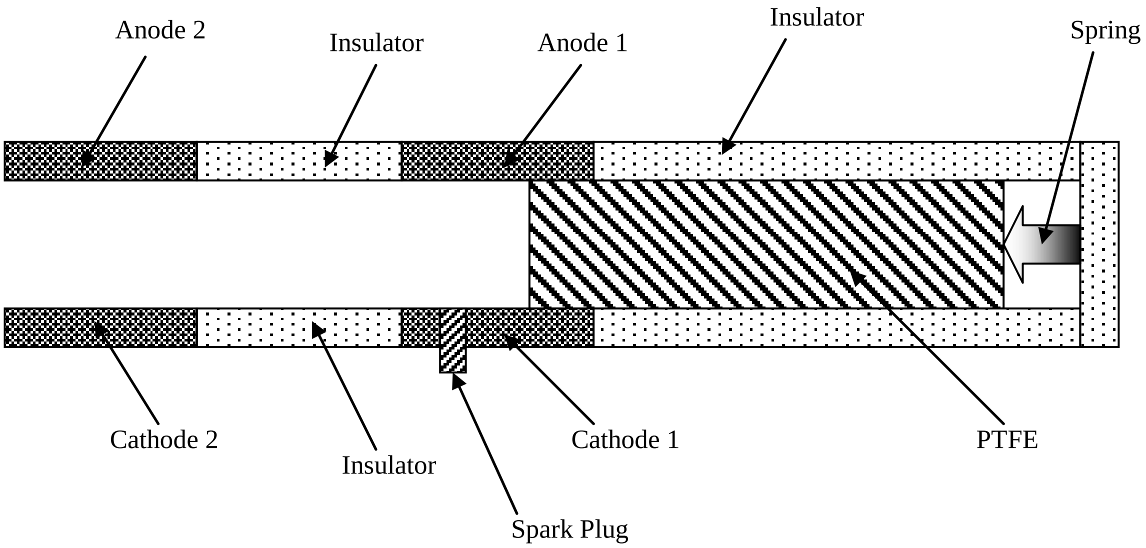


**Figure 1. HFB-PPT discharge chamber concept.**

The circuitry of the HFB-PPT is an important part of the design, since the switching system is responsible for generating the high frequency pulses. Figure 2 shows a block diagram of the HFB-PPT circuitry, where separate switches are employed to allow the discharges to be controlled.

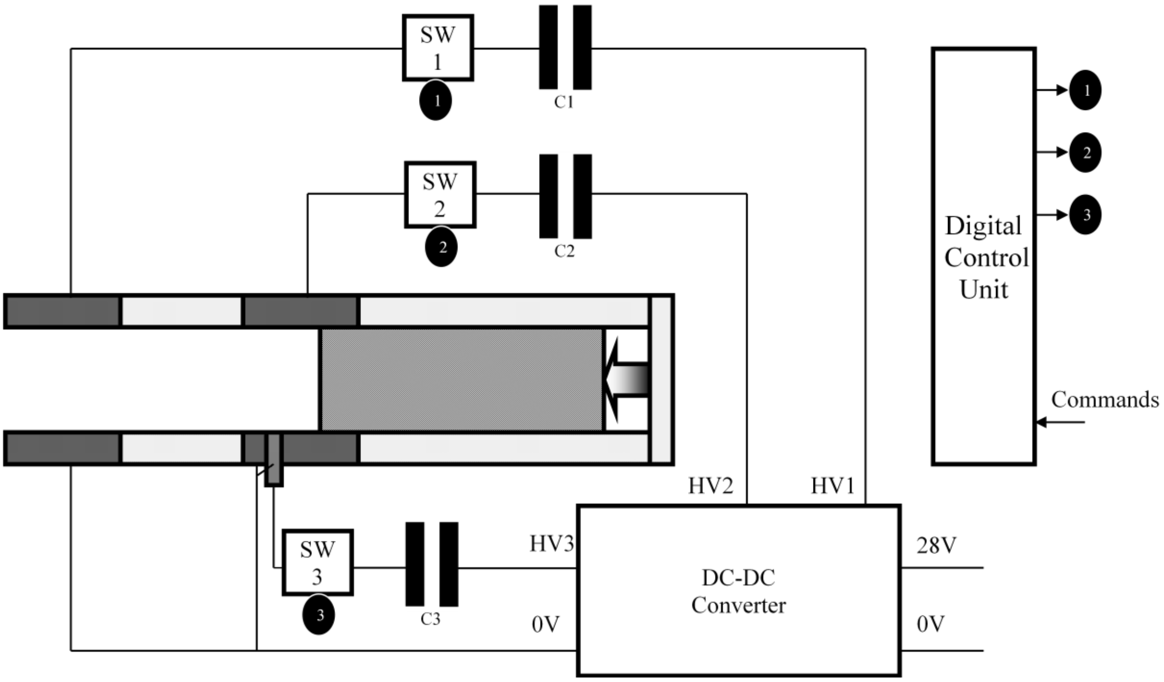


**Figure 2. HFB-PPT circuitry block diagram.**

At the beginning of the cycle all capacitors are charged with its nominal voltages. The Digital Control Unit (DCU) sends a command signal to the switch number three SW3, which controls the capacitor number three C3, the spark plug capacitor. The DCU also sends a signal to SW2 to let the capacitor C2 discharge, after the spark plug ignited. Thus a regular PPT cycle is finished. The novelty of the HFB-PPT starts from this point on. After a predetermined amount of time, with the intention of accelerating the LTA, the switch SW1 receives ON/OFF signals. These signals can be either only one single ON signal or a burst of ON/OFF signals with different time intervals between them or at a fixed frequency – this frequency can reach ~1 MHz hence the name of the thruster.

Based on the cycle above, some of the switches may seem unnecessary at first, like the SW2. However, since this is a development platform, the SW2 can be used when the voltage applied on capacitor C2 is greater than the breakdown voltage for the main discharge's electrodes. In this case the spark plug circuit would not be used for the main discharge. There is also the possibility of triggering the spark plug after the main discharge to help the LTA being accelerated by the second pair of electrodes downstream.

## III. Rectangular Prototype

A rectangular HFB-PPT prototype was built and preliminary tests were carried out. Figure 3 shows a computer model of the discharge chamber of the rectangular prototype. Figure 4 shows the built prototype inside the vacuum chamber. The prototype follows the basic concept with angled secondary electrodes and has glass walls to allow visualization of the discharges.

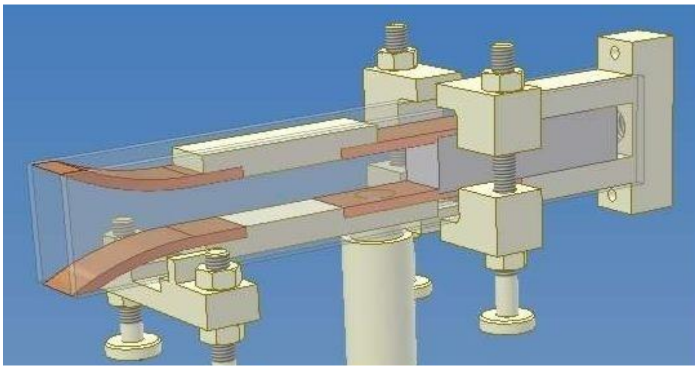


**Figure 3. HFB-PPT with a rectangular geometry**

An open loop control system was chosen as a first approach to control the discharges. As this was a laboratory prototype it was our intention to make the control circuit as flexible as possible. Therefore, it was used a small flight computer running a proprietary operating system and a developed software in 'C' language. This system would allow us to program detailed discharge bursts to investigate the impact on efficiency. Figure 3 shows a block diagram of the HFB-PPT with the digital control unit. In this configuration three switches are employed to control the discharge of three capacitors.

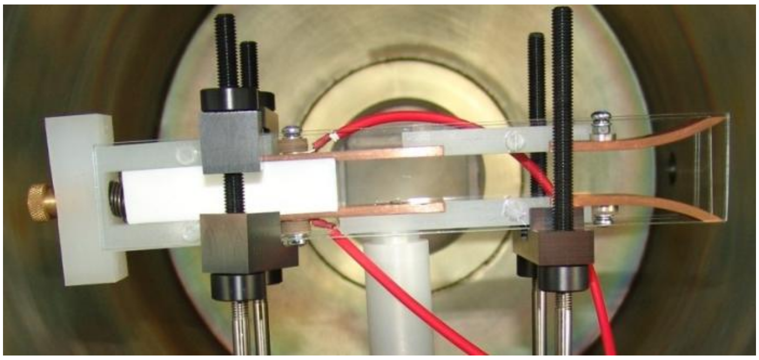


**Figure 4. HFB-PPT prototype inside the vacuum chamber.**

In a first phase of characterization of the HFB-PPT it was used a 110 µF capacitor for the main discharge and a 4700µF capacitor for the secondary discharge. The high capacitance of the secondary discharge was chosen to investigate maximum lengths of secondary discharges. Three different main discharge voltages were used: 1 kV, 1.5 kV and 2 kV; and fourteen different secondary discharge voltages: 0, 3.75, 7.5, 15, 30 35, 50, 75, 100, 150, 200, 250, and 300 V. Importantly, a single second pulse was employed in all cases and there was no added delay between the first pulse and the second pulse. The intention with these tests was to observe how the currents and voltages of the secondary discharge behave with single pulse and *zero* delay in the DCU to serve as a base for the next tests. The low voltages applied to the secondary discharges were used to investigate the time of flight and the effects of the first discharge on the secondary discharge. In this mode the HFB-PPT operates like a two-stage solid pulsed plasma thruster.

Four distinct regimens were observed during the tests, delimited by increasing the second discharge voltage. These regimens were discussed elsewhere (Marques, Gabriel, & Costa, 2007) and will be shown here in a more concise form.

### A. First Regimen

With very low voltages applied to the secondary electrodes, between 0 V and 50V (depending on the main discharge voltage), yields an oscillatory secondary discharge current approximately $90^o$ out of phase with relation to the main discharge. The length of the discharge is approximately the same as the main discharge. Interestingly, a significant current was measured even when the secondary capacitor was initially completely discharged and at the end of the discharge there was a residual voltage in the capacitor, directly proportional to the main discharge voltage.

### B. Second Regimen

At intermediate voltages, between 30 V and 75V (depending on the main discharge voltage), a mainly positive secondary discharge current is observed, with a reduction on the phase difference to the main discharge current. The length of the discharge is considerably longer than the first regimen, with a long tail after the main discharge is over.

### C. Third Regimen (transition)

With the capacitor of the secondary discharge charged between 75 V and 100 V it is observed a transition regimen with two clear phases. The first phase is oscillatory and presents a higher peak, mainly positive current discharge . The second phase is a very distinct long tail that starts after the main discharge, resembling a critically dumped circuit.

### D. Fourth Regimen

The fourth and last regimen has a completely positive secondary discharge current and resembles the current shape of a critically damped circuit, although it also has a not so pronounced oscillating phase during the main discharge. The length of the secondary discharge is much longer than the main discharge.

### E. Other measurements

It was also measured the length of the secondary discharge, delay with respect to the primary discharge and maximum current. Figure 5 shows all four regimens and the results of these measurements. Figure 6 shows the HFB-PPT firing, during tests.

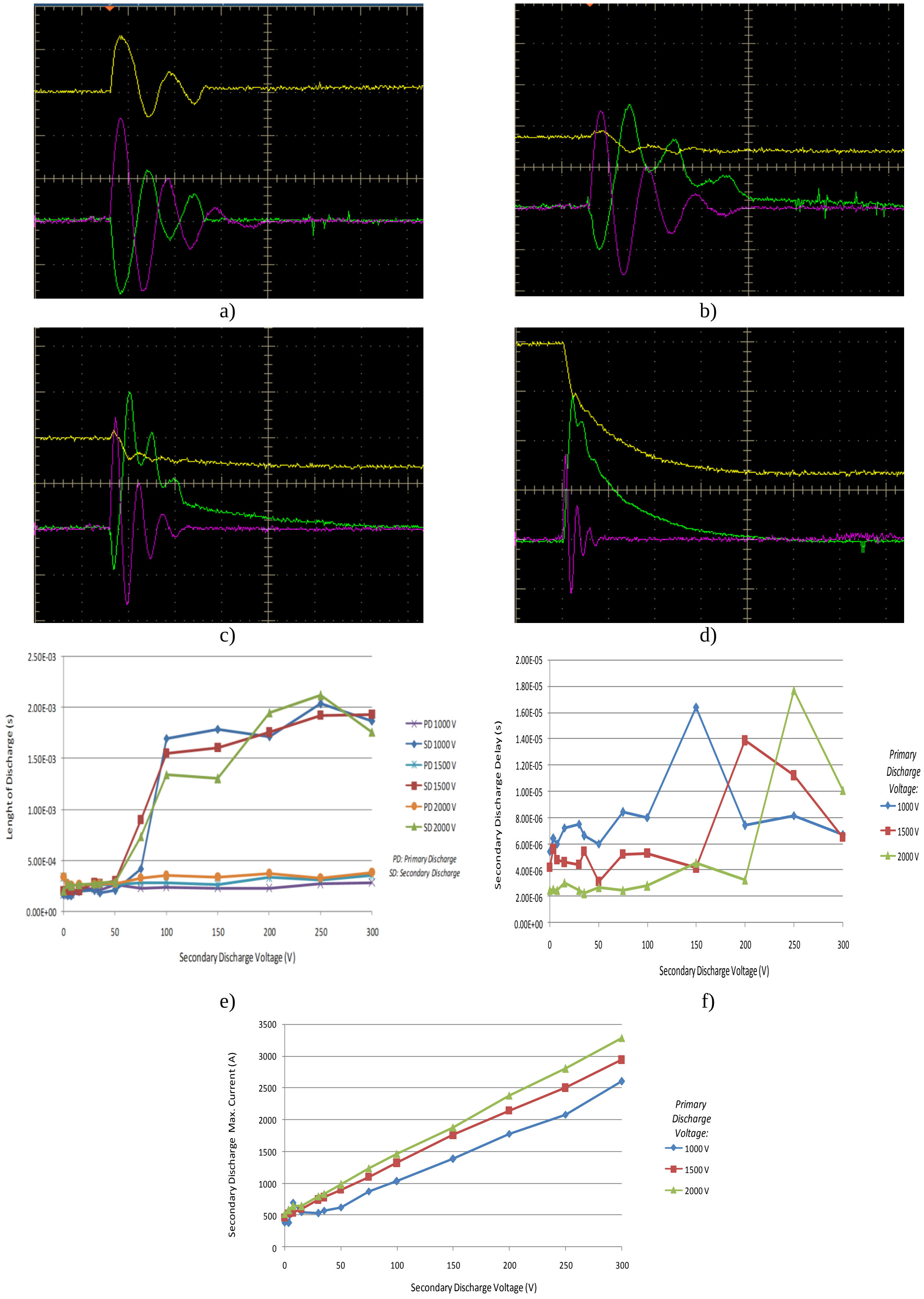
### F. Conclusion of the Preliminary Tests with the Rectangular Prototype

The first regimen is largely dependent on the main discharge and considerable current was observed even when the capacitor was initially discharged. The second regimen has an offset, directly proportional to the secondary discharge voltage. The third regimen shows a relatively pronounced discharge tail after the main discharge and the fourth regimen shows a very long discharge tail after the main discharge.

After the main discharge is over, there is no more plasma being produced upstream and the propellant starts to produce the LTA. It was hypothesised that the current flowing in the secondary electrodes, at this point, would supposedly be flowing in the LTA. A more in-depth analysis will be carried out to validate this assertion.

Tests measuring the length of the discharge showed that by increasing the secondary discharge voltage the duration of the secondary discharge was also increased. However, for a given main discharge voltage, there is a maximum length of the secondary discharge. This characteristic supports the hypothesis that the secondary current discharge would be flowing on the LTA, as there is a limited amount of LTA for a given main discharge voltage. In fact, a residual voltage was measured in the secondary capacitor for secondary discharge voltages above 200 V.

The maximum delay observed at different secondary discharge voltages indicates the transition of the secondary discharge from an oscillatory mode, with the first part negative, to a completely positive discharge. This transition occurs at different voltages, depending on the main discharge voltage. When there is 0 V applied on the secondary discharge capacitor, a current on the secondary electrodes is generated by the main discharge with the first bit negative. To overcome this first negative bit and initiate the positive only discharge mode it is necessary to have increasingly higher voltage applied on the secondary discharge capacitor as the main discharge voltage is increased. The voltages that correspond to the maximum delays can be seen as the voltages above which the discharge is completely positive. A finer change in the secondary discharge voltages is required to analyze exactly where the peak occurs and the behaviour in its vicinity.



a) b) c) d) e) f) g)

**Figure 5. Example of discharge for regimens 1(a), 2(b), 3(c) and 4(d), length of secondary discharge (e), delay between the first discharge and second discharge (f), and maximum current of secondary discharge (g), as a function of the secondary discharge voltage.**

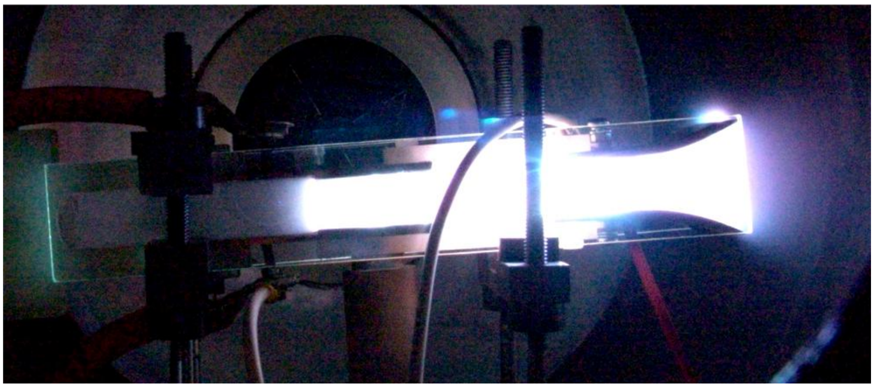


**Figure 6. HFB-PPT firing.**

## IV. The coaxial geometry

While the long rectangular geometry tested provided a convenient way of observing the discharges, after long tests, a significant amount of carbon deposits were found on the inner surface of the glass walls. After a certain number of discharges, these carbon deposits were preventing the current from flowing on the (dielectric) propellant surface, due to its much higher conductivity. Although the rectangular geometry was still going to be investigated, other geometries were studied and a coaxial geometry was found to be suitable.

A study was the carried out to design a coaxial HFB-PPT. In this design the electrodes are concentric and a spark plug is in the centre of the discharge chamber. To allow for the second set of electrodes the coaxial design needed a conical section, where the secondary electrodes would be mounted. To minimise the occurrence of carbon deposits, the conical section had an angle of $45^o$ with its main axis. Above this angle the plume densities are very low (Eckman 1999) and the deposits would also be minimised. Figure 7 shows a two-dimensional view of the HFB-PPT with coaxial geometry and Fig. 8 shows perspective view and a cut of the HFB-PPT.

From the centre of the thruster outwards there are five electrodes. The first is the anode of the spark plug, the second is the cathode of the spark plug. Between these two electrodes there is a PTFE hollow cylinder, what makes the spark plug essentially a coaxial PPT (Marques & Costa, 2003) (Marques & Costa, 2004) (Marques, 2004). The third electrode is the anode 1. In this design the cathode 1 is not a separate electrode; instead the cathode of the spark plug is used.  Between the electrodes two and three is the propellant, a conical shaped spring-fed PTFE. The fourth electrode is the anode 2, placed in the conical section of the HFB-PPT. The cathode 2 is a rod placed in the axis of the thruster, suspended by three other rods and aligned with the anode 2.

In this concept the spark plug discharge triggers the main discharge. The cathode 2 (central rod) and anode 2 are responsible for generating additional discharges to accelerate the LTA.

A prototype of the coaxial design will be built and tested in the near future.

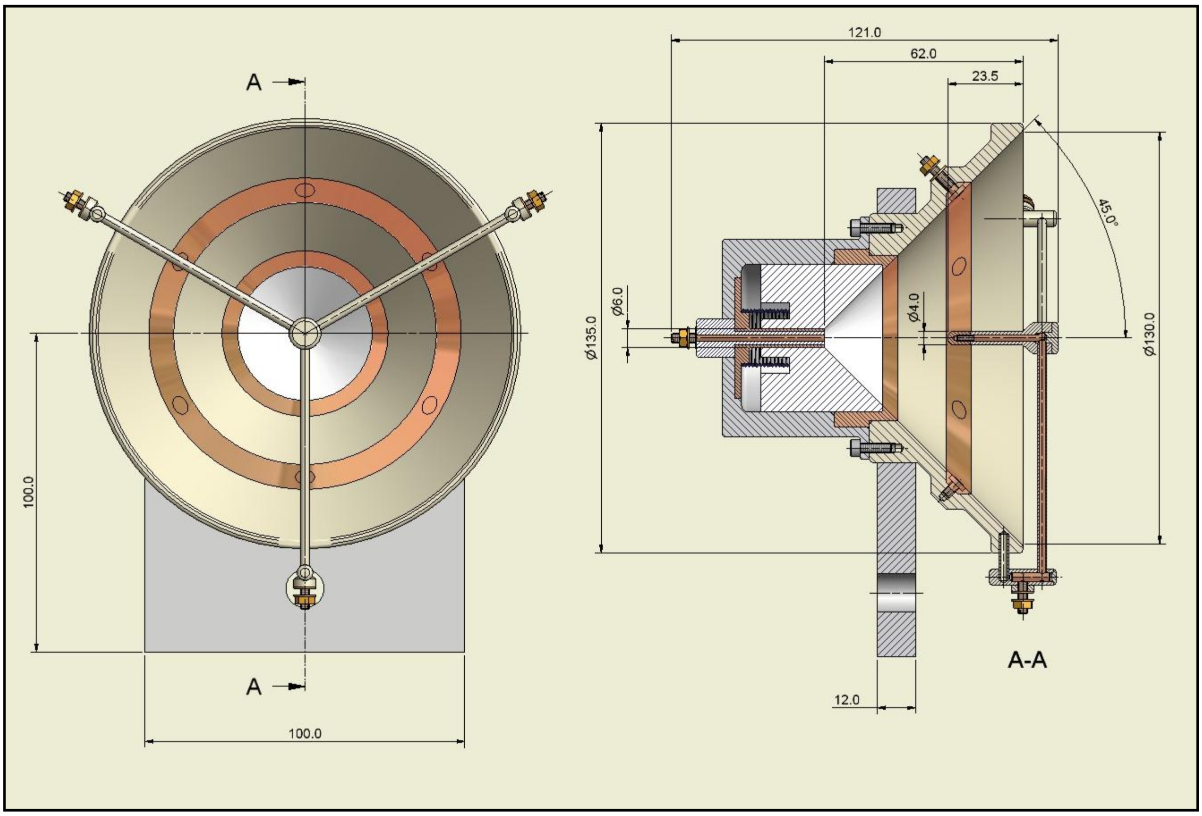


**Figure 7. HFB-PPT Coaxial Design.**

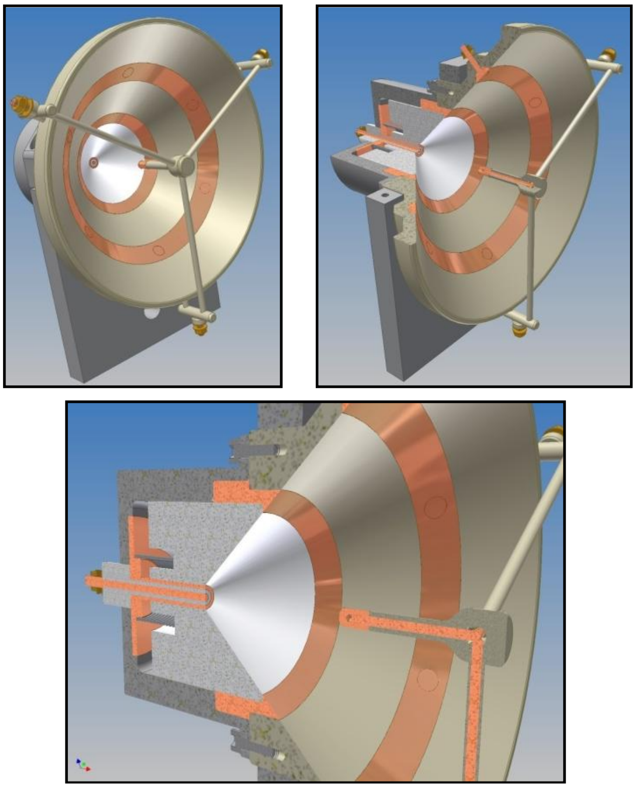


**Figure 8. HFB-PPT Coaxial design. Perspective and cut views.**

## V. UniSat-5 HFB-PPT

The series of satellites UniSat (University Satellite) are developed by the Gruppo di Astrodinamica dell'Universitá degli Studi "La Sapienza University of Rome" (GAUSS). These satellites are designed to carry scientific experiments on-board. The first satellite of the series was the UniSat-1 (Clark, 2000), launched in 2000, followed by UniSat-2 in 2002 and UniSat-3 in 2004. The UniSat-4 was not successful due to a failure in the launcher, a DNEPR-1, in 2006. The UniSat-5 is due to be launched in 2008 and is expected to carry two low-power HFB-PPTs.

This new HFB-PPT had a power limitation of 10 W and a maximum total mass of 1 kg. A rectangular geometry was studied and a prototype is being built at the University of Southampton. Figure 9 shows a diagram of the HFB-PPT for use in the UniSat-5. It comprises a rectangular discharge chamber with a 20mm x 5 mm x 45 mm PTFE propellant bar and a $45^o$ angled nozzle where the secondary electrodes are assembled. The spark plug is mounted on the cathode 1. In this design three separate capacitors will be used for the spark plug, main discharge and secondary discharge. These capacitors will be charged in parallel. The discharge initiation will be triggered by voltage breakdown on the spark plug gap.

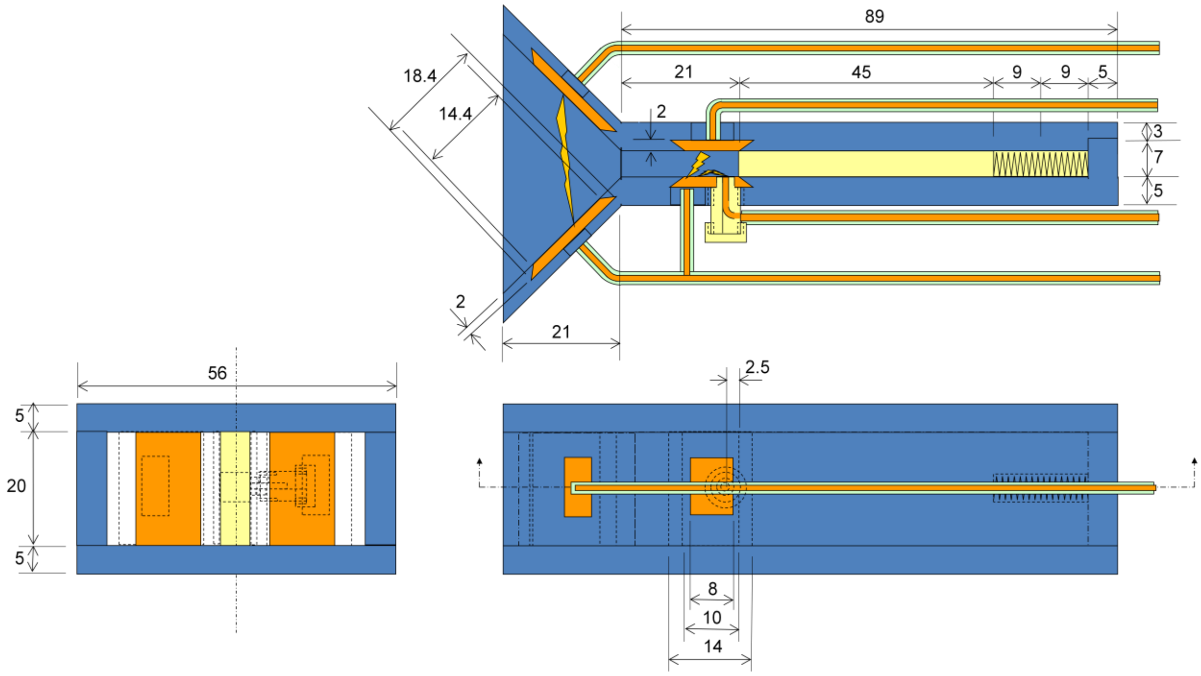


**Figure 9. Diagram of the HFB-PPT for the UniSat-5.**

## VI. Acknowledgments

The first author acknowledges CNPq – Conselho Nacional de Desenvolvimento Científico e Tecnológico – part of the Ministry of Science and Technology of Brazil, for granting a PhD scholarship and also thank for Mike Street from EDMC at the University of Southampton.

## VII. References

Akimov, V., Nagel, I., Ogloblina, I., Antropov, N., Pokryshkin, A., Popov, G., et al. (1997). Analysis of PPT Potentialities in Solving the Satellite Orbit Control Tasks. 25th International Electric Propulsion Conference.

Burton, R. L., & Turchi, P. J. (1998). Pulsed Plasma Thruster. *14* (5).

Clark, S. (2000, August 26). *Breaking News*. Retrieved September 5, 2007, from SpaceFlight Now: http://spaceflightnow.com/news/n0008/25dnepr/

Ebert, W. L. (1989). Operational Noval Spacecraft Teflon Pulsed Plasma Thruster System. AIAA.

Guman, W. J., & Nathanson, D. M. (1970). Pulsed Plasma Microthruster Propulsion System for Synchronous Orbit Satellite. *7* (4).

Janson, S. W. (1993). The On-Orbit Role of Electric Propulsion. AIAA.

LaRocca, A. V. (1966). Solid propellant electrical thrustors for attitude control and dift correction of space vehicles. San Diego: AIAA, 5th Electric Propulsion Conference.

Marques, R. I. (2004). *Desenvolvimento de um Propulsor de Plasma Pulsado.* São José dos Campos: INPE - Instituto Nacional de Pesquisas Espaciais.

Marques, R. I., & Costa, F. S. (2004). Propulsores de Plasma Pulsado: Configurações. Histórico e Estudo da Variação de Massa (in Portuguese). *10th Brazilian Congress of Thermal Sciences and Engineering (ENCIT 2004).* Rio de Janeiro: ABCM.

Marques, R. I., & Costa, F. S. (2003). Pulsed Plasma Thruster Development. *17th International Congress of Thermal Sciences and Engineering, COBEM 2003.* Sao Paulo: ABCM.

Marques, R. I., Gabriel, S., & Costa, F. S. (2007). Preliminary Results of a High Frequency Burst Pulsed Plasma Thruster. *43rd Joint Propulsion Conference and Exhibit.* Cincinnati: AIAA.

Meckel, N. J., Cassady, R. J., Osborne, R. D., Hoskins, W. A., & Myers, R. M. (1997). Investigation of Pulsed Plasma Thrusters for Spacecraft Attitude Control. Cleveland, OH: IEPC.

Pottinger, S. J., Gessini, P., Webb, D., Intini Marques, R., & Gabriel, S. (2006). Electric Propulsion Research at the University of Southampton. *Journal of the British Interplanetary Society (JBIS)* .

Vondra, R. J., & Thomassen, K. I. (1974). Flight Qualified Pulsed Electric Thruster for Satellite Control. Lake Tahoe, Nevada: Journal of Spacecraft.

Vondra, R. J., & Thomassen, K. I. (1972). Performance Improvements in Solid Fuel Microthrusters. San Diego, CA: AIAA 10th Aerospace Sciences Meeting.

Vondra, R. T. (1970). Analysis of Solid Teflon Pulsed Plasma Thrusters. *Journal of Spacecraft and Rockets , 7* (12), 1402-1406.

Vondra, R., Thomassen, K., & Solbes, A. (1971). A Pulsed Electric Thruster for Satellite Control. *59* (2).