PROGRESS ON THE DEVELOPMENT OF A PULSED PLASMA THRUSTER FOR THE ASTER MISSION

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Abstract: *ASTER is the first planed Brazilian deep space mission and it comprises the launch of a space probe to land on the main body of the triple asteroid 2001-SN263. To accomplish this mission the ASTER space probe will employ three types of propulsion systems: chemical thrusters (for launching the probe into Earth orbit), ion-thruster (to reach the asteroid orbit) and a pulsed plasma thruster (PPT) for attitude control. This paper focuses on the development of a PPT for the ASTER mission. The PPT is an electrical propulsion device that works by applying electric discharges on the surface of a solid propellant (PTFE – Polytetrafluoroethylene) that is sublimated, ionized and accelerated by the Lorentz force. The main mission requirements that guided the development of this PPT were: lifetime, total impulse, specific impulse, minimum impulse bit, maximum power available, limiting dimensions and volume, and maximum thruster weight. Preliminary design methods based on the literature and past experiences were used to calculate key PPT parameters in order to predict basic behavior and aid the design. The performance data are simulated using equation that models the current curves as a function of the electric resistance, inductance and voltage. The expected result is the calculation of the PPT parameters of a thruster that fulfills the requirements of the ASTER mission.*

Nomenclature

η_t	=	efficiency
I_{bit}	=	impulse bit
C_e	=	exhaust velocity
E_0	=	energy stored in the capacitor bank
C	=	capacitance
V	=	input voltage
L'	=	inductance gradient
i	=	electric discharge current
ε	=	total initial energy stored
R	=	resistance
F	=	thrust
f	=	frequency
A	=	area
L	=	inductance
t	=	operating time of the PPT
Δt	=	capacitor discharge time

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I. Introduction

A mission currently under investigation at INPE, known as the ASTER mission, involves sending a space probe to the triple asteroid 2001 SN263 to study the origins of the Solar System, asteroid-Earth collision protection mechanisms and the origin of life on Earth. This will be the first Brazilian mission into deep space (1).

The asteroid 2001-SN263, discovered in 2001, is part of a system identified in 2008 as triple, that is, a central body being orbited by two satellites. The existence of satellites orbiting an asteroid was discovered in 1994, when the asteroid *Ida* was identified as a binary system, and in 2005 it was discovered the asteroid *Sylvia* with two satellites forming a triple system. In 2019 the asteroid 2001-SN263, whose central body measures 2.8 km in diameter, will reach about 241 million kilometers from Earth and will be the target of the ASTER mission, which will launch a spacecraft in a partnership between Brazilian and Russian researchers with the intention of orbiting this asteroid and landing on its main body to collect data (1).

To keep a probe in orbit and correct attitude for a long period it is necessary to make small corrections and thrusters can be used to accomplish that. The pulsed plasma thruster (PPT) is an electric propulsion device that has been used for attitude control and orbit maintenance since 1964 in the Russian probe Zond 2. The PPT in its traditional rectangular shape has a solid propellant bar of PTFE located between two electrodes connected to a capacitor (2). A spark plug provides a small amount of plasma close to the surface of the PTFE, reducing the breakdown voltage of the dielectric material, causing an electric discharge on the surface of the solid propellant, which is sublimated, ionized and accelerated by the Lorentz force (3). As the extremity of the propellant is consumed in discharges, a spring makes the propellant advance towards the discharge chamber, repositioning it close to the spark plug (4).

The objective of this project is to develop a Pulsed Plasma Thruster for attitude control and station keeping for the ASTER probe. The main mission requirements that guide the development of this PPT are: lifetime, total impulse, specific impulse, minimum impulse bit, maximum available power, dimensions, volume, and maximum weight of the thruster.

Preliminary design methods based on the literature and past experiences were used to calculate key PPT parameters in order to predict basic behavior and aid the design. The predicted performance data was obtained using equations that models the current curves as a function of the electric resistance, inductance and voltage. The expected result is the calculation of the PPT parameters of a thruster that fulfills the requirements of the ASTER mission.

II. PPT characterization parameters

This section will present some parameters defined for characterization of a pulsed plasma thruster for performance comparison, including efficiency, specific impulse, thrust, total impulse and impulse bit.

A. Efficiency

The efficiency η_t is defined as the ratio between the kinetic energy of the exhaust gases and the energy stored in the capacitor bank (2).

$$\eta_t = \frac{I_{bit} * C_e}{2 * E_0} \tag{1}$$

$$E_0 = \frac{1}{2} C * V^2 \tag{2}$$

Here, I_{bit} is the impulse bit, C_e is the exhaust velocity of the gases, E_0 is the energy stored in the capacitor bank, C is the capacitance of the capacitor bank and V is the voltage at which the capacitor bank is charged.

B. *Impulse bit*

The impulse delivered by the thruster per pulse due to electromagnetic acceleration of the propellant in a PPT, called impulse bit, can be estimated from the discharge current (3):

$$I_{bit} = \frac{1}{2} L' \int i^2 \, dt = \frac{1}{2} L' \frac{\varepsilon}{R_{total}} \tag{3}$$

Here, L' is the inductance gradient (in µH/m) and i is the electric discharge current, ε is the total initial energy stored in the capacitor and R_{total} is the equivalent total resistance.

C. Thrust

The thrust force F is produced by a propulsion system acting on the vehicle. It is the reaction of its structure due to mass ejection at high speed. If the PPT is operating at a fixed frequency f, it is possible to get the equivalent thrust through the impulse bit (4).

$$F = f \cdot I_{bit} \tag{4}$$

Here, f is the fixed frequency of the operating PPT.

III. Mission requirements

This thruster was designed for a specific mission and several key mission parameters guided our project. The main parameters considered were dimensions, maximum total mass, maximum power available, total impulse, specific impulse and impulse bit.

It will take a minimum of 4 thrusters for attitude control of the ASTER probe. Each thruster must have the maximum dimensions of 15×10×7(cm). The maximum mass of each thruster, including the electronics, capacitors and propellant shall not exceed 1.5 kg. The PPT power will be provided by a solar panel and was set to a maximum of 20J/pulse, which is equivalent to 20W for each thruster operating at 1Hz. The estimated total impulse to operate the probe and make orbital and attitude corrections is 20Ns with a specific impulse greater than 1000s and the impulse bit is estimated at 300 µNs. The PPT will be connected to the power supply through a 24Vdc bus, with a maximum available power of 122W. The connection interface with the probe will be via a DB9 electric connector.

Table 1 – PPT Thruster Mission Requirements

Requirement	Value
Maximum Dimensions	15×10×7 (cm)
Total Mass	1.5 kg
Total Impulse	20Ns
Specific Impulse	1000s
Impulse bit	300µNs
Maximum power available	22W

IV. Thruster design

This section will present the design of the thruster divided in three parts: discharge chamber, spark plug and electric circuit of the PPT. The project will be based on achieving the highest propellant use efficiency while meeting the mission requirements.

A. Discharge Chamber Design

The discharge chamber is where the plasma is produced and accelerated. It consists of two electrodes, a bar of solid propellant, and a spring that makes the propellant advance towards the discharge chamber as the propellant is consumed. Based on the values of specific impulse and available energy in the capacitor it is possible to define the area of the face where the propellant discharge will occur using a semi-empirical relation derived by Guman (3).

$$I_{sp} = 320 \cdot \left(\frac{E_0}{A}\right)^{0,6} \quad (5)$$

Based on the values of mission requirements for total impulse and specific impulse and using Eq. (5), for a rectangular propellant bar, the face area subjected to the discharge was found to be $3cm^2$, with dimensions of 1.5 cm x 2 cm x 5 cm. The electrodes will be stainless steel 10 cm long, 1.5 cm width and 0.4cm thick.

B. Spark plug design

The discharge is initiated using a device that is similar to a very small PPT. (4). Such a device is located on the cathode with an electrode inside connected to a high voltage source. The spark plug will be rectangular, as shown in Fig. 1, and produces an arc near the surface of the propellant (5).

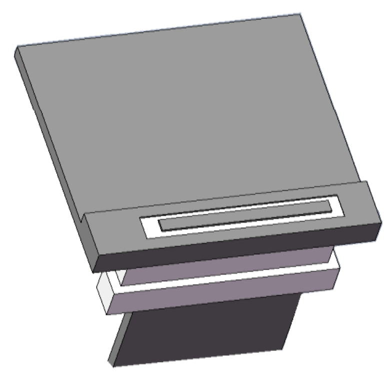

Figure 1: Spark plug.

C. Design of electronic circuit.

The electronic circuit comprises a main capacitor for discharge and one for the spark plug, a transformer and a power supply. The main capacitor has a capacitance of 40μF, and with a voltage of 1kV it stores 20J.

D. The thruster design

The thruster final design has dimensions of 15cm × 9cm × 6cm, and a mass of 0.8kg (without capacitors). The capacitors used are for testing only and are non-flight models, therefore not optimized for a reduced mass. Fig. 2 shows a cross section view of the thruster with the legend of the figure shown on Table 1.

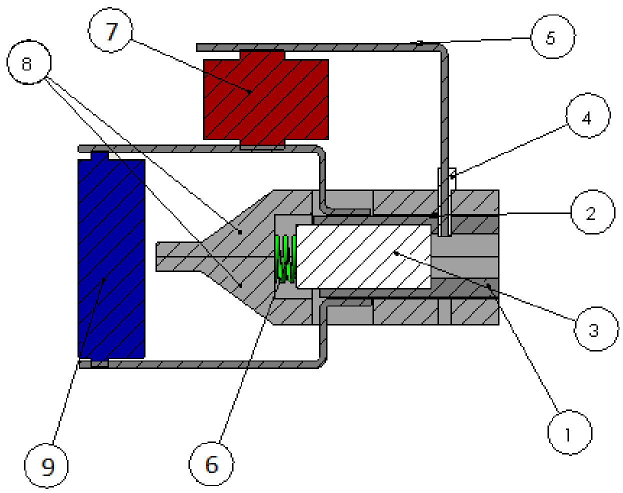

Figure 2: Cross section view of the thruster.

Table 1: Thruster parts description

Number	Description
1	*Anode*
2	*Cathode*
3	*Propellant*
4	*Spark plug propellant*
5	*Spark plug electrode*
6	*Spring*
7	*Spark plug capacitor*
8	*Insulating Structure*
9	*Main discharge capacitor*

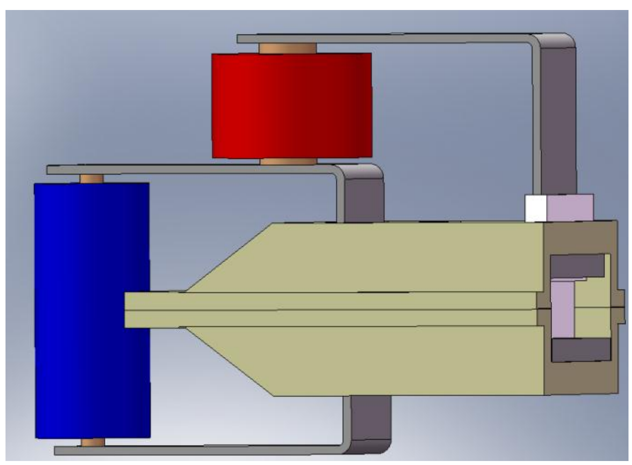

Figure 3: Perspective view of the thruster.

V. Simulation

As an approximation, a PPT was modeled as an RLC circuit to predict its performance parameters using previous works (7). Current curves were obtained using Eq.(6) from Ref.(7):

$$i = -\frac{V_0}{L} * e^{-\alpha t} * \frac{1}{\omega_1} * sen(\omega_1 * t) \tag{6}$$

where,

$$\alpha = \frac{R}{2 * L} \tag{7}$$

$$\omega_1 = \left[\left(\frac{1}{CL}\right) - \left(\frac{R}{2L}\right)^2\right]^{1/2} \tag{8}$$

A linear regression was used to set the resistance value of the electric circuit, based on data from other pulsed plasma thrusters derived from references 4 and 7.

Figure 5 shows a graph of both the actual values and the linear regression. The equation for the linear regression found was:

$$R = 0.053 - 8.3 \times 10^{-4} * \varepsilon \tag{9}$$

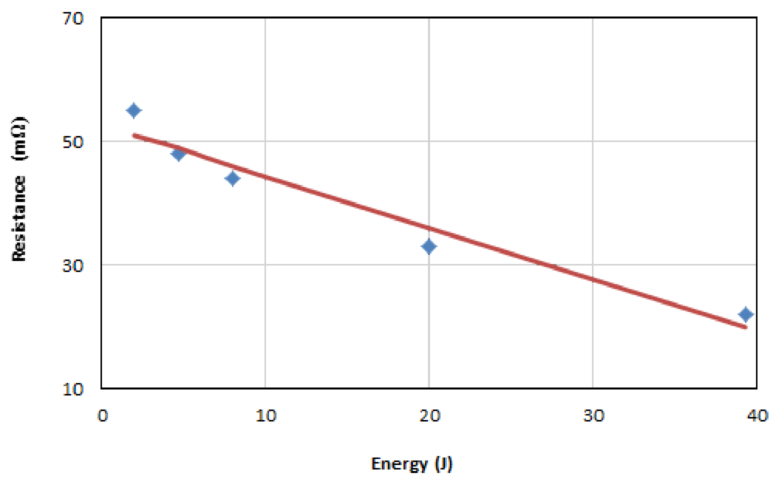

Figure 4: Graph of resistance as a function of energy. Blue curve represents the actual values and the red curve show the linear regression.

For energy of 20J the linear regression expression gives a resistance of 36 mΩ.
The inductance gradient of rectangular shape electrodes is given by (8):

$$L' = \mu_0 * \frac{h}{w} \tag{10}$$

$$\mu_0 = 4\pi * 10^{-7} \tag{11}$$

Where h is the distance between the electrodes and w is the width of the electrodes. The values of the geometric parameters for our case are h = 2cm and w =1.5cm.

The inductance is calculated by integrating the inductance gradient (4).

$$L = \int L' * dl \tag{12}$$

$$L = L' * l \tag{13}$$

For an inductance gradient of 1.67µH/m and a length l of 10 cm, the resulting inductance is 167nH. Figure 5 shows the calculated PPT current discharge.

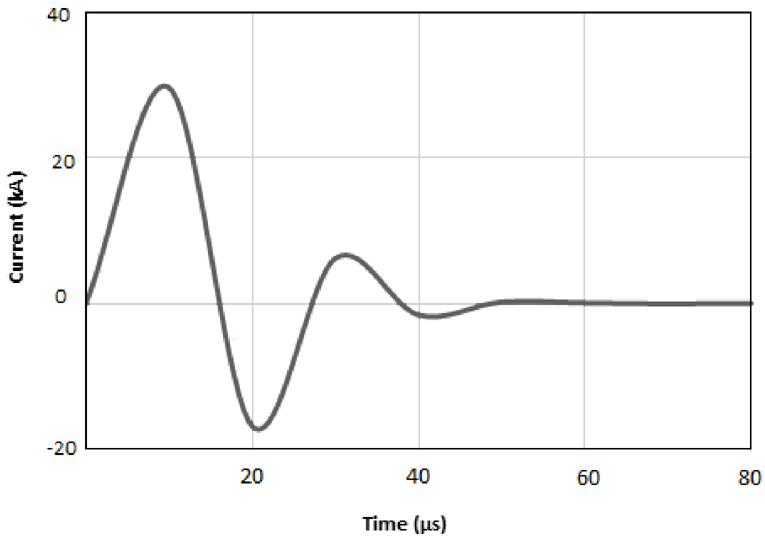

Figure 5: Calculated PPT discharge current.

The discharge current of the PPT is a good indicator of the performance of the thruster. It is known that the impulse bit due to electromagnetic acceleration can be estimated by Eq.(3).

Knowing that this PPT operates at a frequency (f) of 1Hz it is possible to calculate the equivalent thrust F through Eq.(4). Table 2 shows the calculated parameters.

Table 2: Calculated Parameters for the ASTER PPT

Parameters	Value
I_{sp}	1000s
C	40µF
R	36 mΩ
L	167 nH
ε	20 J
L'	1.67 µH/m
I_{bit}	464 µNs

VI. Conclusion

In this work we calculated the basic parameters of a pulsed plasma thruster for the ASTER mission, a probe that is planned to be used for the first Brazilian deep space mission expected to be launched in 2017. Preliminary design methods based on the literature and past experiences were used in order to predict basic behavior and aid the design. The results were shown to fit the mission requirements.

The propellant ablation area was calculated considering the requirements on a specific impulse of 1000s from a capacitive discharge of 20J. Analyses were carried out to estimate the resistance and the inductance of the thruster in order to simulate the behavior of the current curve and therefore calculate the impulse bit, estimated at 464 µNs.

The thruster dimensions are 15cm × 9cm × 6cm and its weight is 0.8kg (without capacitors) what adequately fulfills the requirements of the mission. Future work will be to build and test the designed PPT in order to compare the predicted performance parameters with the calculated values to ensure it conforms to mission requirements.

Acknowledgments

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