Design and Preliminary Experiments of the Prototype of a 500J Inductive Pulsed Plasma Thruster

IEPC-2019-A-174

Presented at the 36th International Electric Propulsion Conference
University of Vienna • Vienna, Austria
September 15-20, 2019

Xiaokang LI[1], Mousen CHENG[2], Bixuan CHE[3], Moge WANG[4], Xiong YANG[5]
College of Aerospace Science and Engineering, National University of Defense Technology, Changsha, Hunan, 410073, China

Abstract: Because of the non-electrode feature, the inductive pulsed plasma thruster (IPPT) is considered as a promising electromagnetic propulsion device with a long working life and good propellant compatibility. In this paper, we present a thruster prototype with a pulsed energy lever of 500J developed in our lab, which has a specially-designed planar inductive driving coil and an axisymmetric arranged capacitor bank, and is controlled by a pseudo-spark switch. A current monitor is used to obtain the histories of the coil current, and a photo-diode for the plasma radiation. The plasma radiation curves show that when the pressure is high, there are two peaks during the discharge. While the pressure decreases, the second peak becomes flat, which implies the current sheet is leaving away from the driving coil. While for a given gas pressure, the discharge becomes more intense when the voltage goes higher. As a preliminary estimate, nearly 80% of the total energy can be deposited in the plasma for this thruster prototype. Yet the effective acceleration of the plasma still needs more direct proofs.

Nomenclature

C	=	capacitance
dt	=	time step
E	=	energy
I	=	current
L	=	inductance
p	=	pressure
R	=	resistance
r	=	radius
T	=	period
V_0	=	initial capacitor voltage
η	=	ratio of energy deposited in plasma to total energy

I.Introduction

In an inductive pulsed plasma thruster (IPPT), a plasma current sheet is produced inductively by a pulsed current through a driving coil. The current sheet is then repelled by the Lorenz force interaction between itself and the coil. In this manner, the thruster could gain a mechanical impulse[1].

---

[1] Lecturer, College of Aerospace Science and Engineering, lxk0330@163.com.
[2] Professor, College of Aerospace Science and Engineering, mscheng@sina.vip.
[3] PhD candidate, College of Aerospace Science and Engineering, 15575936694@163.com.
[4] Associate Professor, College of Aerospace Science and Engineering, czzwwhrs@126.com.
[5] Lecturer, College of Aerospace Science and Engineering, yx12321@126.com.

Because of its non-electrode feature and the related good propellant compatibility, it is possible for IPPT to utilize water or carbon dioxide as the propellant, which can be gotten from the astronautics life support system or the local atmosphere of Mars. As a result, IPPT is considered as a promising electromagnetic propulsion device for deep-space mission to moon or Mars.

Initially developed by TRW corporation[2], IPPT now has several branches and is being researched worldwide[3-5]. In this paper, we present the design of a thruster prototype of 500J energy level developed in our research lab, which has a planar inductive driving coil and an axisymmetric arranged capacitor bank, and is controlled by a pseudo-spark switch. Then an experimental system is set up. A current monitor is used to obtain the histories of the coil current, and a photo-detector for the time-resolved signal of the plasma radiation. For the first stage, the discharge experiments for different propellant pressures and initial capacitor voltages are implemented.

II.Experimental setup

A. Thruster prototype

The thruster prototype is designed to operate at an energy lever of 500J. Eight capacitors of 1μF are connected parallel for energy storage. So while the capacitors are charged to 12kV, the total energy E could be 576J, according to $E=(1/2)CV_0^{\,2}$. In order to reduce the difference between each branch, especially the parasitical inductance introduce by the wiring, these eight capacitors are axisymmetrically arranged around the axis of the thruster.

The high voltage terminal of each capacitor is connected to a pseudo-spark switch (PSS), which allows a high current peak and very quick current change rate, and therefore is quiet suitable for this pulsed discharge case.

The other terminal of each capacitor is connected to a driving coil branch. The branch wire is a one-turn Archimedes spiral, with an outer radius r_2 of 25cm and inner radius r_1 of 10cm. The curve equation of each wire in polar coordinates is then expressed as:

$$r = r_1 + \left[(r_2 - r_1)/(2\pi)\right]\theta \tag{1}$$

The eight spiral wires are arranged axisymmetrically likewise, and compose a planar driving coil group. Then the whole coil group is fixed on an epoxy resin panel. The sketch of the driving coil group is shown in Fig. 1, while the electrical connection is shown in Fig. 2.

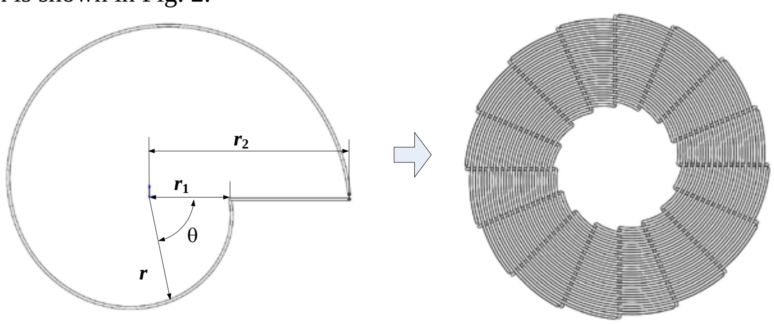

Figure 1. Schematic of the single branch and the driving coil group

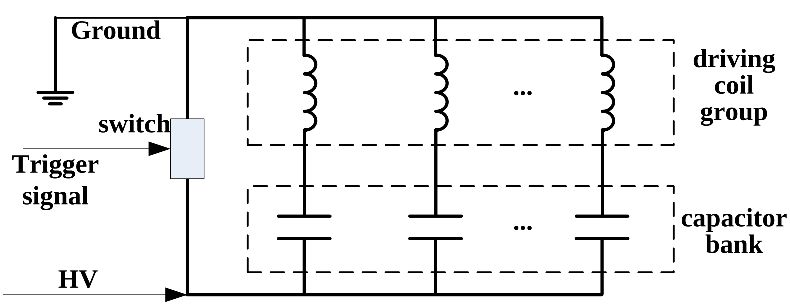

Figure 2. Schematic of the electrical connection of the thruster prototype

The propellant is supplied from a tower-like injector which is connected to a gas cylinder. For better propellant constrain, a cylinder collar is added in front of the driving coil group. Then all the modules, including the collar, the driving coil group and its panel, the pseudo-spark switch, the capacitor bank, are assembled together and fixed on a framework to make the thruster prototype, as shown in Fig.3.

Measurements with a LCR meter shows that in the unload case when no plasma is generated, the total introduce of the discharge circuit L is 498nH, including the introduce of the driving coil group L_c 378nH, while the total capacitance C of 8.1uF, and total resistance R of 0.016Ω. Therefore, as a RLC circuit, the natural period of the discharge circuit is about 12.6μs, according to $T = 4\pi L\sqrt{C} / \sqrt{4L - R^2 C}$.

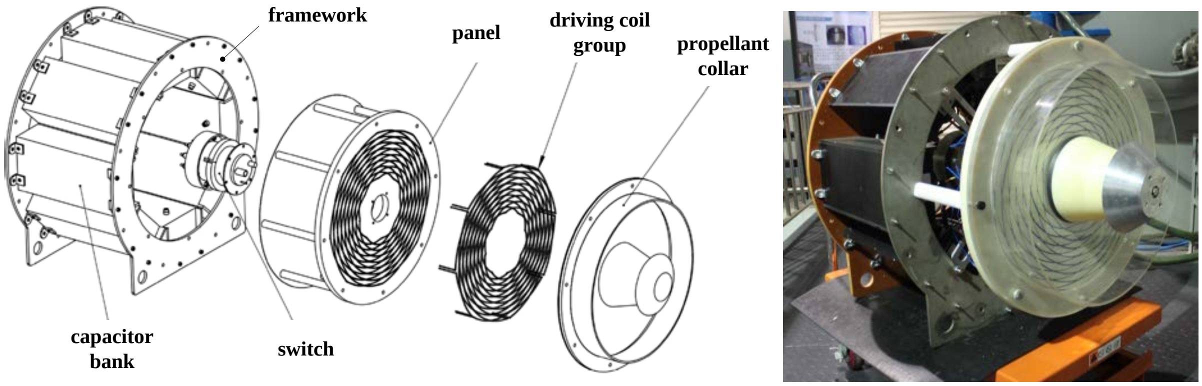

Figure 3. The components and assembly structure of the thruster prototype

B. Control and measurement system

The capacitor bank of the thruster is charged by a high-voltage power source (HV PS), of which the output voltage is adjustable. After the capacitor is charged to a preset voltage, the pseudo-spark switch is triggered by a signal from the controller. Then the switch is closed and a pulsed current will flow through the discharge circuit.

During the discharge, a current monitor (Pearson Model 5046) is used to obtain the histories of the coil current, and a high voltage probe (Tektronix P6015A) is used for monitoring the capacitor voltage. Additionally, a photo-diode (Thorlasbs DET10A) is adopted to obtain the time-resolved signal of the plasma radiation. All the data are acquired by an oscilloscope (Tektronix DPO4034).

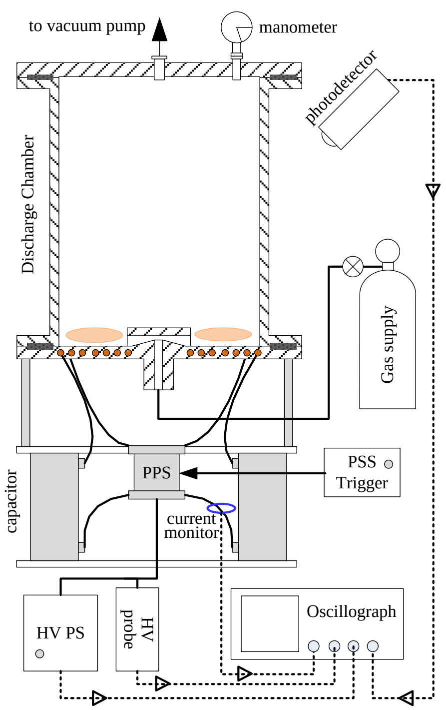

Figure 4. Schematic of the experimental system

Figure 5. Typical discharge photograph for the test

C. Vacuum system

For the first stage, the end of the thruster prototype is connected to a small transparent discharge chamber, which is then connected to a vacuum system, supported by a set of pumps. The pressure of the small discharge chamber is measured by a high-precision capacitance manometer (CERAVAC CTR 101 N).

The schematic of the whole experimental system is shown in Fig. 4. The discharge experiments for different propellant pressures and initial capacitor voltages are implemented. The typical long-exposure image of the inductive discharge is shown in Fig. 5.

III.Results and Discussion

A. Experiments for different propellant pressures

First, the effects of the propellant pressure on the discharge characteristics are tested. For a given capacitor voltage of 13.2kV, discharge experiments are performed with the gas pressure from 10Pa to 80Pa. The typical plasma radiation histories are shown in Fig. 6.

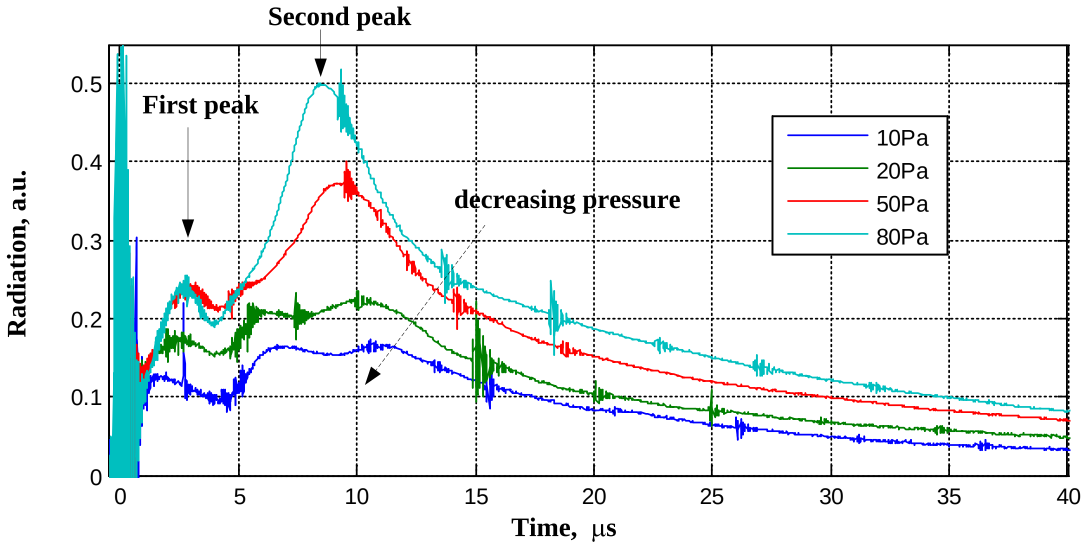

Figure 6. plasma radiation histories for different pressures (V_0=13.2kV)

From the radiation curve, an interesting phenomenon can be observed when the pressure is high (in this case p>50Pa). The plasma radiation curves show that there are two peaks during the discharge, and the second peak rises relatively slow and always has a higher value than the first one.

According to the time these appears, these two peaks seem to coincide with the first two maximum amplitudes of the current. They are thought to be dominated by the thermal effect leaded by resistance dissipation when the current flows through the plasma. Basically, if the plasma is not effectively accelerated, the energy accumulated will become heat, and then be released in the form of radiation. In this way, a higher second radiation peak takes place.

If the pressure is lower than 50Pa, the second peak is becoming flat and indistinctive. It is thought as a sign that the current sheet is leaving away from the driving coil, and the coupling effect between the circuit and the plasma is weaken. Considered a pressure too low may not allow the generation of current sheet, there should be an optimal pressure exists, where the energy is most effectively used for plasma acceleration.

B. Experiments for different initial capacitor voltages

Then the effects of the initial voltage on the discharge characteristics are tested. For a given propellant pressure of 10Pa, discharge experiments are performed with the capacitor voltage from 8.4kV to 15.2kV. The typical results are shown in Fig. 7. It can be seen that while the voltage increases, the plasma radiation show an upward tendency. This is inevitable, because of the higher total energy. So the ratio of deposited energy in plasma to the initial total energy is needed to evaluate the discharge.

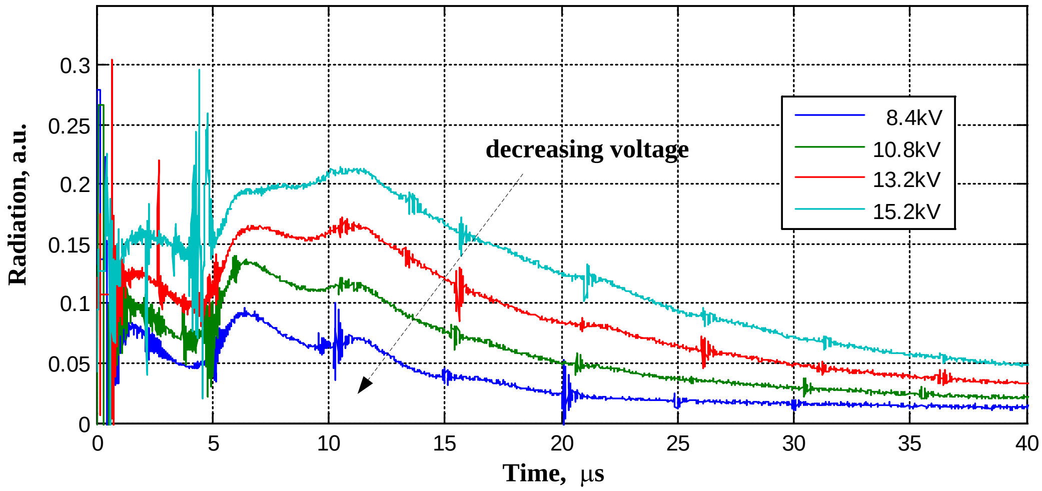

Figure 7. plasma radiation histories for different initial voltages (*p*=10Pa)

C. The ratio of deposited energy

Given the size of the circuit and its oscillation period, the energy loss in the form of electromagnetic wave is very small. So the total energy stored in the capacitor bank E_{tot} is mainly transferred to two parts, the resistive dissipation in the circuit E_{dis} and these deposited in plasma E_{pla}. And E_{pla} is then transferred to the inter energy and the kinetic energy of the plasma.

So as a preliminary estimate for E_{pla}, we can use

$$E_{pla} = E_{tot} - E_{dis} \tag{2}$$

where the resistive dissipation energy in the circuit can be calculated by integrating the I^2R_0 over time:

$$E_{dis} = \int_0^\infty I^2 R_0 \cdot dt \tag{3}$$

Here R_0 is the circuit resistance.

Hereby we can get the ratio of deposited energy in plasma to the total energy stored in capacitors:

$$\eta = E_{pla} / E_{tot} = 1 - \left(\int_0^\infty I^2 R_0 \cdot dt \right) / E_{tot} \tag{4}$$

According to Eq.4, the ratio can be obtained for different initial voltages, as shown in Fig. 8, where V_0=0kV represents the unload case. It can be seen that nearly 80% of the initial energy is transferred to the plasma. However, it must be noticed that only part of the deposition energy can finally be transferred into the plasma kinetic energy. So, further researches are still needed to insure the effective acceleration of the plasma.

From another point of view, if the energy is effectively transfer to the plasma, the characteristics of the driving circuit will change, due to the mutual inductance effect between it and the plasma current sheet. A simple RLC lumped circuit model is adopted to confirm that. It is found that the apparent inductance and resistance changes significantly whenever the plasma is generated. For example, in the case of voltage of 13.2kV and pressure of 10Pa, the curve-fitting gives that the inductance L becomes about 322nH, while the resistance R 0.068Ω. Compared with the unload case when no plasma is generated (where L=498nH, R=0.016Ω and C=8.1µF), the circuit inductance is reduced to about 65% and the resistance becomes over four times of the former, implying the remarkable mutual inductance effect and energy exchange.

IV.Future Work

After that, the whole prototype is put into a large vacuum chamber for the second stage research. The preliminary tests have proven the discharge reliability (shown in Fig.9), and our next work will focus on the mechanical impulse measuring and operating in a repeated mode.

V.Conclusion

A thruster prototype of 500J energy level was developed in our research lab, which has a specially-designed planar inductive driving coil and an axisymmetric arranged capacitor bank, and is controlled by a pseudo-spark switch. The preliminary discharge experiments for different propellant pressures and initial capacitor voltages were implemented.

The plasma radiation curves show that when the pressure is high, there are two peaks during the discharge. While the pressure decreases, the second peak becomes flat, implying the current sheet is leaving away. In the other hand, for a given gas pressure, the discharge becomes more intense while the voltage goes higher. As a preliminary estimate, nearly 80% of the total energy can be deposited in the plasma for this thruster prototype. Yet the effective acceleration of the plasma still needs more direct proofs.

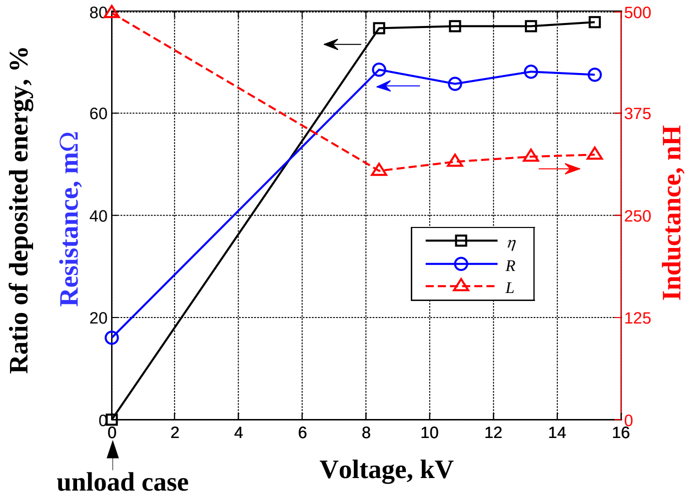

Figure 8. plasma radiation for different initial voltage (*p*=10Pa)

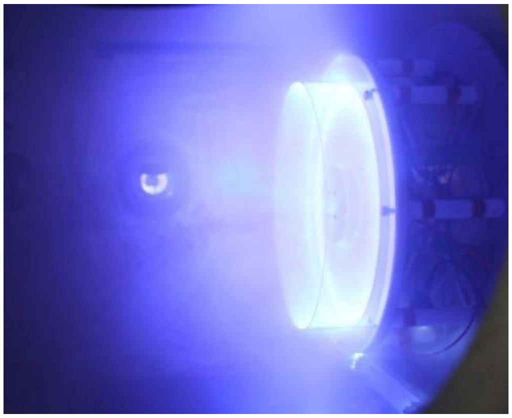

Figure 9. the discharge when the whole prototype put in a large vacuum chamber

Acknowledgments

The research work is supported by the National Natural Science Foundation of China (Grant No.51306203) and the Hunan Province Natural Science Foundation of China (Grant No. 2018JJ3592).

References

[1]Polzin K. A., Comprehensive Review of Planar Pulsed Inductive Plasma Thruster Research and Technology", Journal of Propulsion and Power, Vol.27, No.3, 2011, pp.513-531.

[2]Dailey C. L., Lovberg R. H, "The PIT MkV Pulsed Inductive Thruster", NASA CR 191155, 1993.

[3]Polzin K. A., "Faraday Accelerator with Radio-frequency Assisted Discharge (FARAD)", Ph.D. Dissertation, Department of Mechanical and Aerospace Engineering, Princeton University, 2006.

[4]Hallock A. K., Martin A. K., Polzin K. A., "Single- and Repetitive-Pulse Conical Theta-Pinch Inductive Pulsed Plasma Thruster Performance", IEEE Transactions on Plasma Science, Vol.43, NO.1, 2015, pp.433-443.

[5] Che B. X., Cheng M. S., Li X. K., et al., "Physical mechanisms and factors influencing inductive pulsed plasma thruster performance: a numerical study using an extended magnetohydrodynamic model", Journal of Physics D: Applied Physics, 51, 2018, 365202.