Experimental Investigation of Wave-Plasma Coupling on the High Power Electrodeless Plasma Thruster in Princeton University

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Gregory D. Emsellem[1]
The Elwing Company, Irvine, CA, 92612, USA

Abstract: The High Power Electrodeless Plasma Thruster was tested at low power in Princeton University's Electric Propulsion and Plasma Dynamics Laboratory. These tests were oriented in order to obtain a greater understanding of the wave plasma coupling in this thruster. Total microwave input power ranged from 30 W to 1500 W. Measurements have been obtained for mass flow rate varied from 0.2 mg/s to 10 mg/s of various propellant including Argon, Helium, Air and Nitrogen. A high-sensitivity horizontal thrust stand designed for high-resolution thrust measurements of pulsed plasma thrusters has been slightly reconfigured to allow accurate steady state thrust measurement. The diagnostic package also includes spectroscopic measurement, thermal imaging and microwave forward and reflected power measurements. From this set of measurements it is established that the Electrodeless Plasma Thruster has the ability to operate efficiently over widely-varying power levels. Furthermore, at a given total power, thruster efficiency does not suffer during lower-specific-impulse/higher-thrust operation, demonstrating the effectiveness of the ECR ionization stage.

Nomenclature

A	=	Surface area of the thruster exit
α_{err}	=	mass flow rate measurement uncertainty
P_{lim}	=	maximum facility pressure level for accurate testing
R	=	ideal gas constant
v_{th}	=	thermal velocity
dm/dt	=	mass flow rate
M	=	molar mass of propellant
T	=	temperature

I. Introduction

EFFICIENT operation under a wide range of conditions is infrequently observed in most electric propulsion devices. Indeed efficiency is commonly quite low except for a few highly-optimized set of operating conditions. One of the key capabilities of the electrodeless plasma thruster is high performance operation over broadly-different operating regimes. This possibility stems from the double-staged nature of this technology, allowing each function, ionization and acceleration, to be independently optimized. At a given total power, the ability to maintain a high overall efficiency while the thrust is increased and the specific impulse is decreased is limited by the efficiency of the ionization function.

[1] Chief Technology Officer, research@elwingcorp.com.

In the electrodeless plasma thruster, the propellant is ionized by electron cyclotron resonance (ECR) in an original structure by applying a standing wave pattern to the plasma in a magnetic bottle topology. ECR by itself has been reported to be an extremely efficient ionization process with very low ion pair production costs. The magnetic bottle topology, *inter alia*, improves confinement of energized electrons hence further increasing the ionization rate for a given mass flow rate and ionization power input. These factors combine to form an ionization stage capable of efficient operation over a broad range of mass flow rates and ionization powers.

A highly-sensitive thrust measurement system, developed by Dr. Kurt Polzin, is used to gather accurate thrust data. This thrust stand, featuring a horizontal pendulum, has been optimized for high-resolution measurement of pulsed plasma thruster impulse bits. However, the thrust stand is readily modified such that it can use part of the thruster weight as a restoring force, thereby enabling the acquisition of steady state thrust. Thus configured, the thrust stand provides the additional advantage of adjustable thrust sensitivity.

Lastly, the microwave circuit providing power to the two thruster stages is designed and built using waveguides to provide power handling capability and choke flanges for contact-less power transmission. This microwave circuit is tunable and instrumented with directional coupler to establish coupling parameters. Thrust measurements and experimental scaling laws are presented and discussed.

II. High-Power Electrodeless Plasma Thruster Experimental Set-Up at Princeton University EPPDyL

The High Power electrodeless plasma thruster has been set-up in the Electric Propulsion and Plasma Dynamic Laboratory of Princeton University. The set-up comprised the Large Dielectric Pulsed Propulsion (LDPP) vacuum facility itself and associated controls, a variable sensitivity thrust stand and calibration apparatus, an infrared thermal imager along with the controls of the microwave power system and propellant flow control system. This set-up and all of these parts are described in the following sections.

A. The High-Power Electrodeless Plasma Thruster

The Electrodeless Plasma Thruster prototype is separated physically and functionally in two stages. An efficient ECR ionization stage provide a dense and cold plasma to the acceleration stage which increase the speed of the flow by applying a magnetized ponderomotive force(Fig. 1). This design is fully electrodeless and can accommodate a wide range of power and propellant, including dusty or chemically aggressive ones.

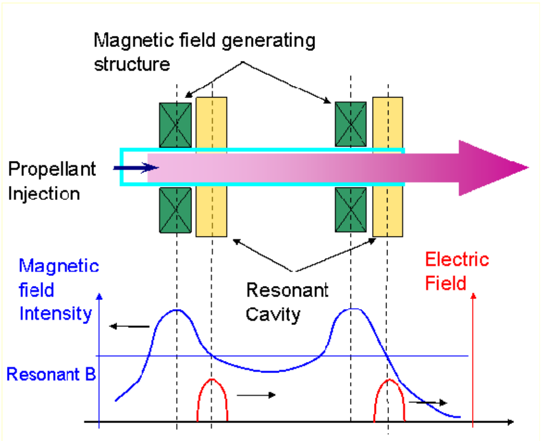

Figure 1. Overview of the basic structure of the electrodeless thruster. *The magnetic structure creates an axial magnetic field featuring a magnetic bottle and a diverging field suitable for ponderomotive force acceleration.*

Figure 2. The High Power Electrodeless Plasma Thruster on test bench at ONERA. *Each resonator (golden cylinders) is attached to one of the microwave tuning element (black rectangles in front). The thruster is producing a plasma beam in the small glass vacuum vessel at the right.*

In this specific thruster the same frequency, in the S-band, is used on both stages, thus simplifying greatly the power supply design. The magnetic field is created by a complex permanent magnet assembly. The permanent magnet assembly do not require any electrical power for magnetic and does not create any resistive heat load, it is also much lighter and have a much reduce fringing field than an equivalent assembly using coils or electromagnets.

The microwave is created by two complex resonators which are fitted with tuning elements. These tuning elements provide each stage with four degree of freedom, allowing for fine adjustment of the microwave circuit. The structure of this thruster provides the non-uniform static magnetic field and high frequency electromagnetic field required for both the ECR ionization stage and the ponderomotive acceleration stage. These stages are separated by a local maximum in the magnetic field intensity, which hence take the topology of a magnetic bottle around the ionization stage hence increasing its efficiency.

This thruster has previously been operated on a bench set-up at ONERA, where it was exhausting into a small vacuum test section while the body of the thruster was surrounded by atmospheric air (Fig. 2). During these tests, thrust was measured by a target pendulum and qualitatively seems much larger than the thrust produced by the cold gas at the same mass flow rate.

One of the goals of the present set up is to accurately measure the performance (thrust and specific impulse) of this thruster under a wide range of operating conditions and propellants.

B. EPPDyL Large Dielectric Pulsed Propulsion facility configuration for steady state testing

The Large Dielectric Pulsed Propulsion (LDPP) facility has been set-up in its current state in 1998 by the efforts of Dr. K. Polzin and Dr. T. Markusic. It comprises a large fiberglass vacuum chamber, a pumping system and a thrust stand along with associated control systems.

The spacious vacuum chamber is cylindrical approximately 7.5 m long and 2.5 m diameter, it is made of fiberglass and is fitted with about two dozens openings for optical access and feed-through. It is attached to the pumping system through a 1.2 m diameter, 90° elbow which also contain a system of baffles. These baffles, which can be cooled by liquid nitrogen from a cryo-stat, are designed to reduce the back-streaming of diffusion pump oil into the vacuum chamber; a major source of mass bit uncertainty for pulsed plasma thrusters. However, the effect of diffusion pump oil on a steady state device is very temporary (time for the plasma to vaporize and decompose the oil film) and does not affect the measured thrust after so they were not used for the test of the High Power Electrodeless Plasma Thruster.

The pumping system is composed of two Stokes mechanical pumps, a Roots blower and a 20 kW Consolidated Vacuum Corporation diffusion pump. The pressure is monitored by four separated gauges : a set of two thermocouple gauges for pressure above 10 mTorr, and two cold cathode gauges for higher vacuum.

The use of a diffusion pump allows continuous testing over extended period of time unlike the periodic downtime of cryopumped system required to regenerate the cryogenic heads.

Without using the liquid nitrogen cooled baffles the best base pressure obtained during this short testing campaign was approximately 3.5 x 10^{-5} Torr. Tests were performed to evaluate the steady state pressure levels obtained while continuously injecting propellant to feed the thruster. Following the accepted practice we used the Equation 1 to confirm these vacuum levels are compatible with high accuracy testing.

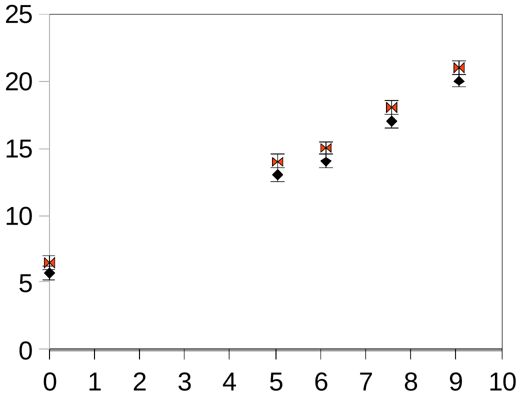

Figure 3. Steady state pressure in SSLP at various mass flow rate. *The pressure is displayed in 10^{-5} Torr unit and the mass flow rate in mg/s Red and black mark display the small but measurable difference between the pressure at the end of the vacuum chamber and at the pump inlet.*

$$P_{\lim} = \frac{\alpha_{err} R T \dot{m}}{A M_{prop} v_{th}}$$

Precisely it allowed verifying that on all the useful range of the mass flow meter controlling gas injection in the thruster, the expected flux of residual gas into the thruster would remain less than 5 % of the injected gas flow (Fig. 3). Hence this facility effect would be comparable to the error in the mass flow rate measurements, which in our tests was about 6.5%.

The LDPP provides vaccum level allowing testing of the High Power electrodeless plasma thruster over the whole range of mass flow rate delivered by the mass flow controller, for all three gases used : Helium, Argon and Air.

C. Diagnostic set up

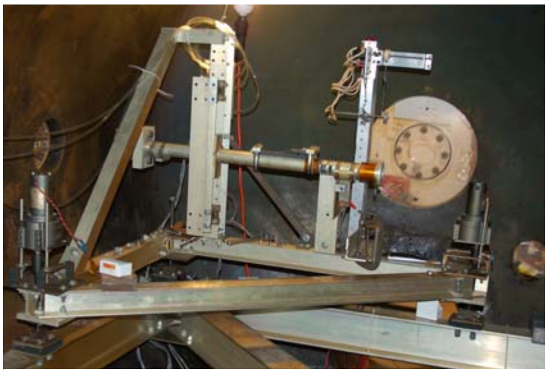

Figure 4. LDPP thrust stand. *The horizontal arm rotate around the vertical axis on the left side of the picture. The motor at the lower left corner and on the right side of the picture allow adjusting the orientation of the thrust stand axis. Behind the armthe vertical support of the thrust calibration system is visible*

The diagnostic package consisted of the thrust stand, an infrared thermal imager and a spectrometer.

The LDPP thrust stand has been designed to measure impulse created by pulsed plasma thruster. It is characterized by a high and adjustable sensitivity and is able to carry a thruster of large mass, up to 50 kg. It consists of a horizontal pendulum arm freely rotating around flexural pivot, with a counterweight to compensate the vertical bending. The position of the arm is measured without contact by a Linear Voltage Differential Transducer. The position signal is used to drive a negative feedback loop which apply small magnetic field to a magnetic core in order to dampen the oscillation. Impulse bit are measured by analyzing the damped sinusoidal signal. The thrust stand is calibrated by the use of a small hammer which allows measuring directly the applied force through a piezoelectric detector.

This set-up needed to be modified to be able to measure steady state thrust. If used in this set-up a steady state thrust, irrespectively of its intensity, would result in an ever increasing deflection angle, until the limit angle of the flexural pivot are reached, and would not allow measuring the value of the thrust. Previous test using the LLDP to measure steady state thrust, solved this problem by adding some elements introducing controlled stiffness coefficient when flexed. However it was decided to try and modify the thrust stand without adding any elements that would also bring inevitable friction.

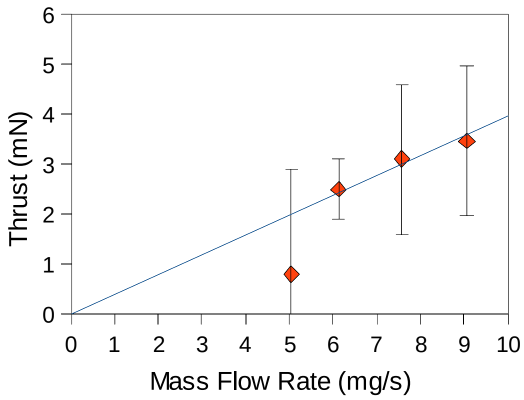

Figure 5. Cold thrust measurements at various argon mass flow rate. *The thrust measured by the thrust stand is represented by the red data points along with their uncertainty. The blue line represents the cold thrust calculated from theory.*

The solution found was to slightly tilt the axis of rotation of the thrust stand away from vertical. In this way the circle described by the thrust stand extremity is no longer horizontal but present a lower point, which when set-up correctly correspond to the position of the thrust stand when the thruster does not produce any thrust. As the thrust stand rotate around its axis, a fraction of the thruster weight acts as a restoring force. This force increase as the thruster is pushed away from the lowest point of its trajectory, just as a regular vertical pendulum. The fraction of the weight serving as restoring force is controlled by the axis angle with vertical, enabling a high and controllable sensitivity measurement. A higher angle of inclination creates in a larger restoring force for a given angular rotation.

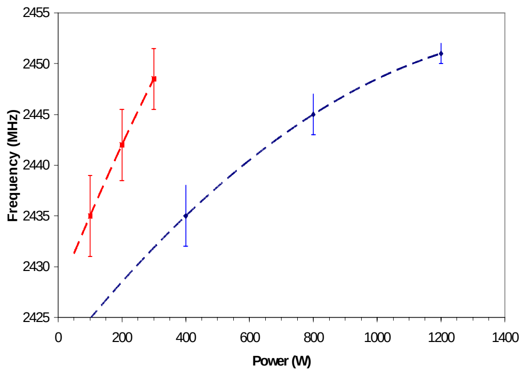

Figure 6. Microwave generators frequency variation requested power output. *The frequency accuracy of the generators are excellent for a given power output. However, the spectrum shift and reach the nominal frequency at the nominal power output of each generator.*

Similarly, the thrust calibration procedure had to be changed. An in-situ thrust calibration apparatus was installed and attached to the thrust stand. This apparatus simply consist of a small electric motor which permit to pull the thrust stand with a controlled force by suspending small calibrated lead weight on a string attached to the thrust stand via a pulley to redirect the force in the horizontal plane.

Using very small angle, the thrust stand has demonstrated the ability to attain a resolution of 170 mV/mN. The noise level being usually 40 mV, it results that the thrust stand can resolve thrust level larger than 2 mN. All these figures where measured when the thruster weight was 19 kg. This very high accuracy allowed distinct measurement of the cold thrust produced by argon mass flow (Fig. 5).

The thruster temperature was measured remotely by using a FLIR infrared camera with a sensitivity of 0.2 K in the range of -50 C and 250 C. However the infrared thermal imager needs to receive thermal infrared radiation from the thruster in order to provide temperature measurement. Glass and polycarbonate windows do not transmit the infrared band used by the camera. So a ZnSe infrared window was installed on the side of the LDPP, granting permanent temperature measurement of the thruster.

Last, an optical access aligned with the vacuum vessel axis and the thruster axis allowed to measure spectrum from the plasma created inside the thruster. It has been determined that this electronic self contained spectrometer has an effective resolution of 2nm. However measuring spectrum emitted by the plasma with various propellant and at various power level allowed to identify the emitting species.

Last the set of microwave diagnostic comprise a microwave network analyzer, a free field detector for safety and one reflected power measurement for each microwave power generator.

III. Experimental results

The high power electrodeless plasma thruster has been tested at power level ranging from 30 W to 1500 W of 2.45GHz using mass flow rate going from 0.2 mg/s to 8 mg/s. These tests have been performed with Helium, argon and air as propellant.

We will first review the results obtained from the microwave measurements which have important consequences on the tests, then we will quickly review the thermal and spectroscopic measurements.

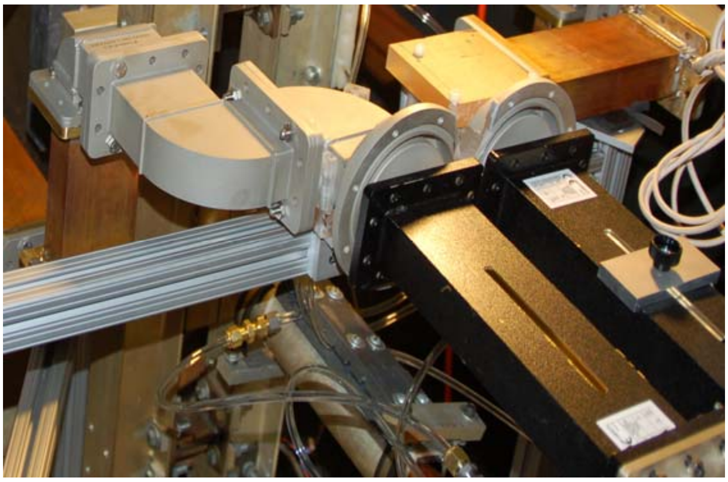

Figure 6. View of the close range antennae on the thrust stand. *The clear colored close range antenna is distinguished by its deep groove and circular rim. The distance between the thruster feed and the antenna is comprised between 10 and 30 mm.*

A. Microwave circuit results and modifications

Initially, for simplicity the thruster two stages where connected to the microwave power generator by coaxial cable of type LMR-400. These semi-flexible cables are designed for transporting high power radio signals with low loss.

This initial set up generated three important problems. The first problem came from the cable stiffness which was strongly lowering the thrust stand sensitivity. Moreover the cable would heat quickly, while the temperature increase was only about 0,3 C/min, it resulted in changes of stiffness that would amount to applied forces on the thrust stand many time larger than the expected thrust. Last it was found that the coaxial connectors used at the feed-through would systematically arc at power level lower than 100W. This resulted in very high reflected power, no power transmitted to the thruster and quick destruction of the feed-through.

It was then decided to design an all waveguide circuit to feed power to the thruster. However, waveguide are rigid so would have barred any possibility to measure thrust as the thrust stand arm would have not been able to move anymore. So a mean to contactlessly transmit microwave power had to be designed.

Two close range antenna have been designed, based on choked flange used in very high power microwave radar.

B. Thermal measurements results

The thermal measurement made with the infrared camera showed no sign of definite heating on the thruster. We observed a very slow warming of the waveguides components when the circuit was tuned for low reflected power. At high reflected power the heating rate was somewhat increased but still remained very slow, less than 20 C in over three hours at average power of 600 W. It nonetheless happened that when parasitic discharge took place in the waveguides, due to high background pressure, then the temperature of the waveguide increased quickly approximately 2-4 C over ten minutes.

C. Spectroscopic measurements

The spectrum measured where coherent with operating parameters. The lines observed were always only the one of the propellant used. We did not observe any line from Aluminum, alumina, silicium oxide or silicium. This was especially clear in testing performed with Helium.

It seems that the overall measured light intensity varied linearly with absorbed power. More specifically it seems that at a given forward power level, the light intensity decreased when the measured reflected power increased.

IV. Conclusion

All these observations coalesce to indicate that the microwave tuning is the single most important parameter. These experimental observation also seems to confirm that the thruster operate with very limited power transferred from the plasma to the thruster structure either in form of heat or of erosion.

We also discovered that a power as low as 30W was enough to obtain plasma formation in the thruster and validated the possibility to transmit microwave power at close range without contact and without significant losses. Similarly the thruster has already successfully demonstrated the capability to be started without any specific initiation device or procedure. The thruster also has exhibited a great stability with regard to operating conditions, the same conditions producing reliably the same behavior.

Last it was shown that with minimum procedural modification LDPP thrust stand was able to measure steady state thrust as low as a millinewton. Similarly it was proven that this facility can operate the electrodeless plasma thruster over an extended range of mass flow rate even without using the cryo-cooled baffles.

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Last, the Elwing Company wants to thanks our investors for their ever renewed support and interest.

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