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Pulsed Plasma Thruster Plume Analysis

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Abstract

Micro-Pulsed Plasma Thrusters (μPPTs) are a promising method for precision attitude control for small spacecraft in formation flying. They create an ionized plasma plume, which may interfere with other spacecraft in the formation. To characterize the ions in the plume, a diagnostic has been built that couples a drift tube with an energy analyzer. The drift tube provides time of flight measurements to determine the exhaust velocity, and the energy analyzer discriminates the ion energies. The energy analyzer measures the current on a collector plate downstream of four grids that repel electrons and ions below a specified energy. The first grid lowers the density of the plasma, therefore increasing Debye length. The second and fourth grids have a negative potential applied to them so they repel the electrons, while the third grid's voltage can be varied to repel lower energy ions. The ion energies can be computed by differentiating the data. Combining the information of the ion energies and their velocities identifies the ion masses in the PPT plume. The PPT used for this diagnostic is the micro-PPT developed for the Dawgstar satellite. This PPT uses 5.2 Joules per pulse and has a 2.3 cm^2 propellant area, a 1.3 cm electrode length, and an estimated thrust of 85μN [C. Rayburn *et al.*, AIAA-2000-3256]. This paper will describe the development and design of the time of flight / gridded energy analyzer diagnostic and present recent experimental results.

Introduction

Pulsed Plasma Thrusters (PPT) are small electromagnetic thrusters that are ideal for spacecraft attitude control and precise positioning needed for formation flying of satellite constellations. The thrusters also emit a plume of ionized gas that could interfere with the performance of the nearby satellites. The primary concern is that the ions in the plume will react with the other satellites surfaces, possibly clouding over solar cells or sensitive optical instruments. In order to characterize the risks of a thruster firing in the direction of other satellites, the plume components must be determined.

To determine the masses of the plume components a gridded energy analyzer combined with a time of flight measurements will be used. This paper will explain the experiment development, the purpose of each component as well some recent results.

Background

Pulsed plasma thrusters were first developed in the 1960's and placed on several spacecraft for attitude control. The first such craft was the Soviet Union's Zond 2 bound for Mars in 1964 when radio contact was lost. Other satellites such as the TIP/NOVA in 1981 used PPTs to makeup for the drag loss in altitude of its orbit.[1]

Pulsed Plasma Thrusters are a type of electric propulsion. The power to produce the thrust comes from the satellite's power supply, which is usually from photovoltaic cells. The power from the spacecraft's bus, typically 28 Volts, is used to charge a capacitor. The purpose of the power processing unit (PPU), seen in Fig. 1, is to charge the capacitor. When the capacitor is fully charged a spark plug embedded in the cathode is discharged. This discharge creates a small amount of material between the electrodes through which the current flows. This is important since the area between the electrodes is initially at a vacuum, which will not easily carry a current. Once there is a pathway, created by the sparkplug, the capacitor discharges across the electrodes creating a current.

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A PPT provides thrust in short small impulses by creating an electrical discharge across two parallel plates as described above. A solid bar of Teflon™ is used as the fuel. The Teflon™ is fed between the two plates by a coiled spring as can be seen in Fig. 1. The face or surface area between the electrodes of the Teflon™ ablates becoming a partially ionized gas. The ionized portion of the gas is accelerated through electromagnetic forces and the non-ionized portion is accelerated through gasdynamic forces. As the particles are accelerated out of the thruster they impart a small force on the spacecraft providing thrust.

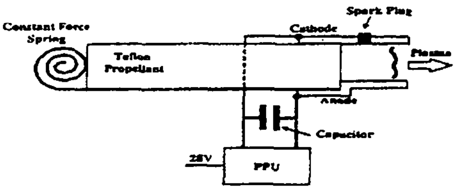

FIG 1. Schematic drawing of a spring fed Pulsed Plasma Thruster courtesy C. Rayburn[2]. The propellant is fed in between the cathode and anode by a coiled spring. The capacitor is charged by the power processing unit (PPU) and discharging the spark plug initiates the current across the electrodes.

The ionized portion of the plume is comprised of gas of charged ions and electrons. The electromagnetic force that accelerates the ions and electrons is given in eqn. (1) bellow:

$$F_{Electromagnetic} = (j \times B), \qquad (1)$$

where j is the current between the plates and B is the magnetic field induced by the current. This force can accelerate ions to high velocities, which will be measured by the time of flight analysis later on in this paper.

The gasdynamic force is created by a pressure difference between inside the thruster, where there is the gas from the ablated Teflon™, and the vacuum outside the thruster. Because the gas is expanding into a vacuum the plume will expand and accelerate out of the thruster as well as back-flowing onto the spacecraft.

There are many advantages for using PPTs; one is that they use an inert fuel Teflon™. Teflon is also non-toxic so fuel handling becomes a much simpler process. The fuel is fed into the thruster by a spring, which is the only moving part of a PPT system, reducing the risk of mechanical failure. Other propulsion systems involve a much greater complexity because they have a fuel tank, valves, cryogenics, seals and toxic fuels.[3] Not only will the system be less complex and less likely to fail by eliminating these components in a PPT system the overall mass of the system can be decreased.

Another great advantage for the PPT is the small impulse bit that the PPT can provide to the satellite. The electromagnetic impulse bit I_{bit} is defined by Burton and Turchi [1] by the following equation:

$$I_{bit} = \frac{1}{2} L' \int I^2 dt, \qquad (2)$$

where L' is the inductance gradient and I is the current. Another part of the impulse bit comes from the gasdynamic forces as well. This impulse bit is essentially how small the pulse of thrust the thruster can give in a second. The smaller the I_{bit} is the more precise the positioning possible for the formation of satellites. The impulse bit for this PPT is 56 μN-s.

At the University of Washington a small satellite, Dawgstar, was designed to be part of a three satellite constellation, ION-F, along with Virginia Polytechnic Inst. and Utah State satellites. The Dawgstar satellite will use micro-PPTs as the primary method of propulsion to keep the satellites in formation and translate between different formations.[2]

For the purpose of this research a PPT of the same design as the PPTs used on the Dawgstar satellite was used. A machine drawing of the Dawgstar thruster can be seen in Fig. 2. The fuel area is 2.3 cm^2 based on mission requirements for a 5.2 Joule thruster. The electrode length is 1.3 cm, which was determined by Rayburn [2] to be an optimal length to minimize electrode erosion, yet increase the thruster's specific thrust and specific impulse. The estimated thrust of this PPT is 85 μN[3]. This small thrust allows for the fine positioning of the satellite.

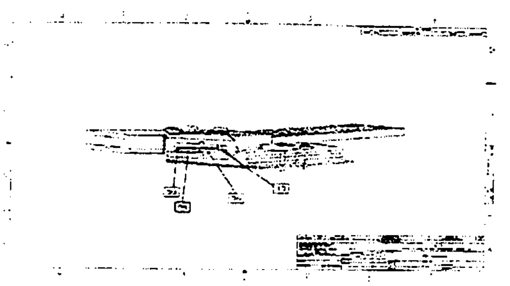

FIG 2. Machine drawing of a Dawgstar PPT looking down one of the exhaust planes.[2] The long bars extending back are the fuel bars.

Experimental Apparatus

Drift Tube and Vacuum Chamber

A PPT needs to operate in vacuum conditions. To get these vacuum conditions in a laboratory a vacuum chamber, along with a pump to pump out the air inside the chamber are necessary. The vacuum chamber, used in this research is about 1 meter high and 87 cm in diameter, which is a volume of just about 600,000 cubic centimeters. The chamber is evacuated by a two pump system. A Duo Seal Vacuum Pump rough pump is used to get the pressure inside the tank down to approximately 100 mili-Torr. The pressure is indicated by Convectron Pressure gauge down to a pressure of 1x10-4 Torr. Once below this pressure an ionization gauge is necessary to measure the pressure. The second pump is a 10" diffusion type pump with a liquid nitrogen cooling trap from the Aero Vac Corporation. This pump is capable of evacuating the tank down to pressures below 5×10^{-9} Torr. A picture of the pump system and vacuum chamber can be seen in Fig. 3.

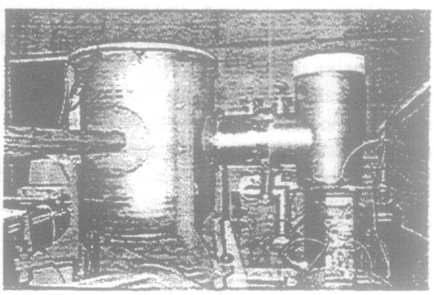

FIG 3. The tank and vacuum setup of experiment. The tank is the large stainless steel vessel on the left. On the right is the diffusion pump and on the floor in the background is the rough pump.

In order to determine the energies of the ions in the plume of a PPT their velocities need to be measured. The drift tube allows time for the faster particles and the slower particles to separate their arrival at the end of the drift tube. This is important because the instrument measuring the arrival of the ions can only sample 100 Mega samples per second. By spreading out the arrival time the instrument can distinguish arrivals of separate particles. The time it takes for a particle to travel a given distance in the direction of travel is all that is needed to measure its velocity.

The PPT is placed inside of a vacuum chamber shown in Fig. 3. The PPT is bolted to a test stand in such a way that the thruster fires down a long drift tube. The drift tube is 3.2 meters long and 3.5 inches in inner diameter with 1/4" thick walls. The actual distance that the particles travel before hitting the collector plate inside the gridded energy analyzer (GEA) is 3.68m.

Before the energy analyzer is a collimator plate, which is a plate with a 3.6mm hole in it. The purpose of this collimator is to make sure all of the velocities are in the same direction as the length of the tube. The collimator will reject particles with velocities not in line with the tube. This is necessary because one of the assumptions for the analysis of the GEA is that all the particles hit the collector plate perpendicular to the plate. At the inlet of the pipe is another collimator with a 3.6mm hole in it as well. Figure 4 shows a schematic of the vacuum chamber, thruster location and drift tube. Figure 5 shows a picture of the experimental apparatus.

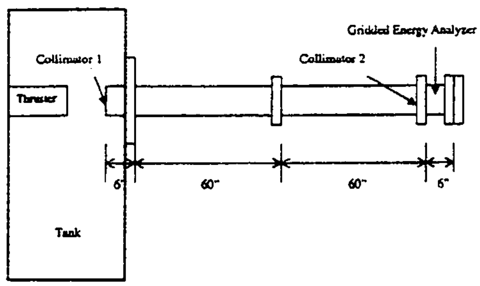

FIG 4. A schematic of the vacuum tank and drift tube. Collimator 1 is located at the entrance of the drift tube right after the thruster; the second collimator is right before the gridded energy analyzer at the other end of the tube. The cap on the end of the drift tube is an insulating flange with an electrical feed-through for the GEA.

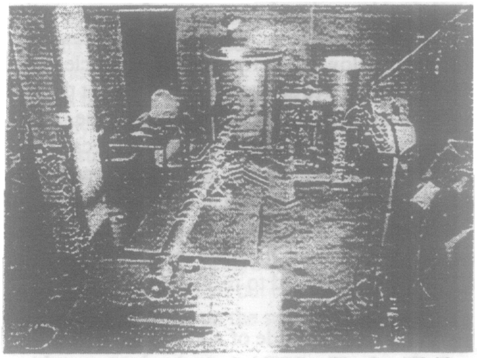

FIG 5. Picture of the vacuum chamber, drift tube and pump system.

Gridded Energy Analyzer (GEA)

The collector plate is part of the gridded energy analyzer (GEA). Upstream of the collector plate are four grids, see Fig. 6 for a schematic of the GEA. The first grid serves to reduce the density of the plasma entering the analyzer, therefore increasing the Debye length. Debye length is a plasma parameter given as,

$$\lambda_D = \sqrt{\frac{\varepsilon_0 k T_e}{ne^2}}, \qquad (3)$$

where T_e is the electron temperature, n is the number density of the electrons, e is the charge on an electron, ε_0 is the permittivity of free space and k is Boltzsmann constant.

A general rule of thumb given by Hutchinson [4] is that the grids should be spaced at about $4\lambda_D$. The effect of increasing the Debye length is that the grids can be spaced further apart. If the grids are too close they have a greater probability of arcing across the grids.[4] The transmission percentage of the first grid is 50%. The second grid is at a negative potential voltage to repel the electrons; the transmission percentage is 85%. The third grid repels ions below a set energy level that can be varied by changing the voltage applied to the grid; this grid also has a transmission of 85%. The last grid with a transmission of 85% is also at a negative potential to repel the secondary electrons created by ions colliding with the previous grids.

Between each grid is an insulator to help prevent arcing across the grids. The grids are each connected to a ring of stainless steel for mounting to the housing. A copper ring is used to provide a connection to the wires that supply their potential. The housing is made of stainless steel with an opening of 0.745 inches. The collector plate is made of stainless steel and is 1 inch in diameter. However due to the grids having transmissions of less than a 100% the effective collection area is 87.52 mm^2.

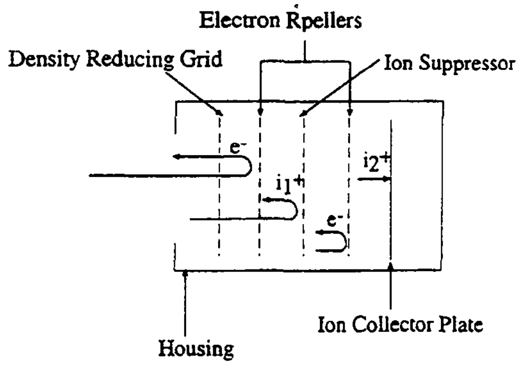

FIG 6. Gridded Energy Analyzer schematic. The first grid reverses some of the ions and electrons. The electron repelling grids repels the electrons, e-. The ion suppressor repels ions, i_1^+, below a specified energy. The ions above the set energy, i_2^+, then hit the collector plate.

The original design of the experiment used a variable power source to supply the grids with their respective potentials. Initial results showed that the experimental measurements were dominated by electromagnetic interference. A large portion of this interference was coming from the power source so an alternative source was found.

The alternative power source came from 45 Volt batteries connected in series in a voltage divider circuit. The electrical schematic is shown in Fig. 7. By varying the resistance on R1 the voltage applied to the grid can be changed. The negative grids are at the same potential as each other and supplied also by a 45 Volt battery. The voltage applied to the positive grid is varied using the same type of potentiometer and measured using a multimeter. The multimeter is removed when the thruster is fired to reduce the electromagnetic interference contamination.

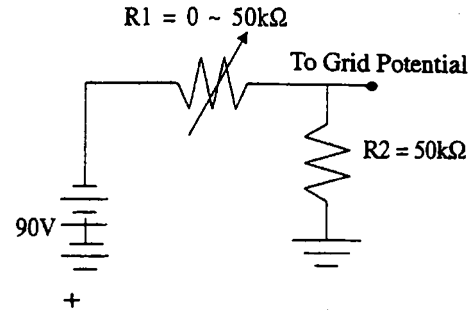

FIG 7. Schematic of the potentiometer battery system used to vary the voltage on the repelling grids of the gridded energy analyzer.

A large amount of electromagnetic interference (EMI) is generated by the PPT. The goal is to reduce the amount of EMI interference to the signal. Several changes were made to the initial set up of the experiment to reduce the noise. The cable length from the analyzer to the oscilloscope was reduced and many connections were soldered with coaxial cable reducing the use of alligator clips.

The current on the collector plate is monitored using a Tektronix 420A oscilloscope. The oscilloscope is set to trigger off of the EMI pulse caused by the discharge across the electrodes. The scope is set to record at a sampling rate of 100 Mega-samples a second. At this rate the time between samples is only 10 nanoseconds. The scope controlled by a DOS program that can be found on the Tektronix web site; this program's purpose is to set-up the scope and save the data through the GPIB interface card on the computer. The program then saves the data from the scope into a file. The data stored are the time and current from the collector plate. A Matlab program can then read the file and generate a plot of the current to the collector plate.

Data Analysis

The data analysis begins with basic kinetic energy of the ions. The basic kinetic energy equation for a charged particle is given below,

$$qV = \frac{1}{2}mv^2, \qquad (4)$$

where q is the charge on the particle, V is the voltage applied to the respective repelling grid (ions or electrons), m is the mass of the particle and v is the velocity of the particle. To find the voltage necessary to repel a particle the equation can be solved for the voltage,

$$V = \frac{1}{q}\frac{1}{2}mv^2, \qquad (5)$$

However, the mass and charge of the ions are unknown.

The collection plate sees a voltage, but the data is analyzed through the oscilloscope, which involves a 1MΩ resistance thus the observed collector plate data is in current form. Current is equal to voltage divided by resistance (V=IR). The collector plate current is plotted as a function of time an example can be seen in Fig. 9. From this plot, the flight time of the fastest ions can be determined. The time of flight is the time from the sharp EMI pulse to the point when the current rises sharply into the curve as indicated in Fig. 9. The maximum current rise can also be determined from this plot by zooming in on the peak of the curve.

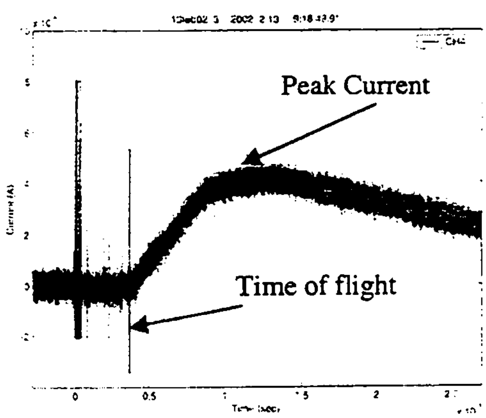

FIG 9. Example plot of the current on the collector plate as a function of time. The arrival time of the fastest ions is indicated as well as the peak current. The positive grid is set to zero and the negative grid is set to 44 V.

The next step in the analysis is to differentiate the data. For this process all five of the plots at each potential will be averaged. Then the highest potential's curve will be subtracted from the next highest potentials curve. A new curve will be formed and from this new curve a new maximum current will be determined. These new maximum currents can be plotted versus the voltages applied to the grid. This new function is like the change in current with respect to the change in voltage. From this and the velocity distribution function of the ions the mass of the ions can be determined.

Experimental Results

The first step of the experiment is to determine the voltage that the negative grids need to be to repel all of the electrons. To calculate the potential necessary to repel the electrons the kinetic energy equation given in Equation 5 is solved for voltage, assuming the fastest electrons to be 60 km/s and using the electron mass and charge. The result is that the voltage necessary to repel the electrons is 10V. Since there may be electrons faster than 60 km/s, the voltage applied to the negative grid is set to a value above 40V; this will ensure that no electrons hit the collector plate. An example of the signal acquired with only the electron repelling grids on to 40V can be seen in Fig. 9. This is the signal for only the ions hitting the collector plate.

Another observation that can be seen from the plots in Fig. 9 is the high frequency interference in the signal. In order to create a clearer plot of the collector voltage a numerical filter is applied to the data. The filter is applied both forward and backward in order to eliminate any phase shift produced by the filter. An example of the same data found in Figure 9 after filtering is found in Figure 10. All of the data from the collector plate is filtered before analysis.

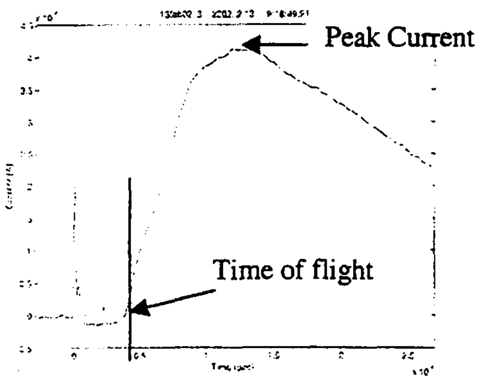

FIG. 10. Filtered data of the collector current for negative grid voltage 44 V and zero positive voltage. Also noted are the peak current and flight time.

Conclusions

The time that the fastest ions take to get to the collector plate is the time between the large EMI pulse and the beginning of the rise in voltage on the collector plate. From this, the fastest ions velocity can be determined knowing that they traveled 3.68 meters. The time of flight was about 50 microseconds, which leads to a velocity of 73.6 km/s. The range of fastest ions for all of the voltages on the positive grids was from 66μs to 38μs, which corresponds to velocities between 55 km/s to 105 km/s respectively.

As with the negative grids to make sure all of the electrons are being repelled, the positive grid can be increased to the point that few ions are getting through. Since the mass and charges are unknown this value was determined experimentally. The positive grid is slowly increased until the signal reaching the collector plate is minimized. This occurred at voltages above 150 volts. The small signal acquired means some high-energy ions are passing through the grids, even at 199 Volts a small amount of ions do hit the collector plate. To get a complete set of data the negative voltage was set to 43 volts and the ion-repelling grid was set to 5 volts. The voltage was increased in five volt increments until 150 volts, taking five shots at each voltage. A plot of the current on the collection plate as the voltage is increased to the ion-repelling grid can be seen in Fig. 11.

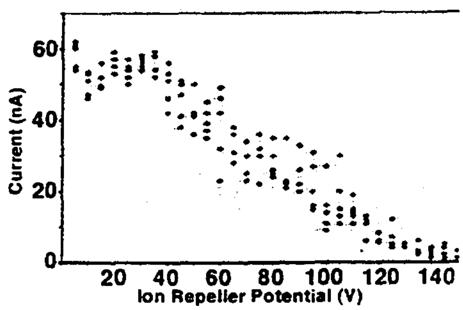

FIG 11. Collection plate current decreases as ion repeller potential is increased. This makes sense since fewer ions are reaching the collector plate at the higher voltages.

Reducing the EMI interference in the signal as well as taking an average of the data will improve accuracy and allow differentiating of the data.

Future Work

In most situations in space the thruster will not be firing directly at another spacecraft, but at an angle. Therefore the next experiment to perform would be the same experiment only with the thruster firing down the drift tube at an angle. Other experiments performed on PPTs have involved triple Langmuir probes measuring density and temperature of the electrons present in the plume. The Langmuir probe was positioned at several locations: 10, 15, 20, 30, and 45 degrees off the axis in the plane perpendicular to the electrodes and at 10, 20 and 30 degrees in the plane parallel to the electrodes.[5] A similar test can be performed using the GEA to analyze the ion's mass velocities and relative angular density distribution. A comparison between the GEA's on-axis results and of the angular results will show how the plume ion characteristics change as the plume expands. From this comparison mission planners can do their best to reduce the plume interactions with other satellites in the constellation, by firing the thrusters in relatively safe directions.

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