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In-plume acceleration of leading-edge ions from a pulsed plasma thruster

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Abstract

Pulsed plasma thrusters are a form of electric propulsion for spacecraft. Their research has undergone recent growth due to an increasing interest in small satellites. However, their plasma plumes are transient and challenging to study due to the extremely short discharge time that lasts in the order of microseconds. The plasma plume is accelerated by a combination of electrothermal and electromagnetic forces. With electromagnetic acceleration, the ions are typically thought to be only accelerated within the thruster by the Lorentz force. Estimated downstream exhaust velocities have ranged widely from 5 to 60 km s^{-1}, with values on the lower end corresponding to electrothermal acceleration. However, we show here that the fastest leading-edge ions continue to accelerate in the plume even in the absence of electromagnetic forces. Pulsed plasma thruster plumes are composed of electrons and a mixture of ion species with different ionization levels. Due to this quasi-neutrality of the plasma plume with electrons featuring much larger velocities than ions, we suggest that the acceleration might be ambipolar in nature. The leading-edge ions eventually reach velocities in excess of 100 km s^{-1}, far greater than values typically associated with electrothermal acceleration. This indicates that care must be taken in the accurate measurement of the ion velocity in the plume. The ion plume may also be more energetic than previously believed. Furthermore, we also propose that simple extrapolation can be used to determine the actual exit plane ion velocity; this value can be used as accurate input data for future simulations.

Keywords: pulsed plasma thruster, ion acceleration, ambipolar diffusion, exhaust velocity

Introduction

Pulsed plasma thrusters (PPTs) are a form of electric propulsion for spacecraft [1–5]. They were first deployed in orbit on the Zond-2 spacecraft in 1964 [6] and are highly suitable for small satellites [7], especially with the recent discovery of promising alternative propellants [5, 8–10]. As suggested by their name, they operate in a pulsed mode triggered by a spark plug. A side-view image of a single pulse is shown in figure 1. As the pulse duration is in the order of microseconds, images with exposure times longer than this capture the entire discharge process. In a single PPT pulse discharge (i.e., one shot), energy stored in a capacitor is used to ablate propellant through the production of a discharge arc triggered by a spark plug [1–3]. This produces a plasma plume that is conventionally thought to be accelerated downstream between the electrodes due to the Lorentz force and ejected at a final exhaust velocity, thus providing thrust. However, the plasma plume of a PPT is composed of many different components

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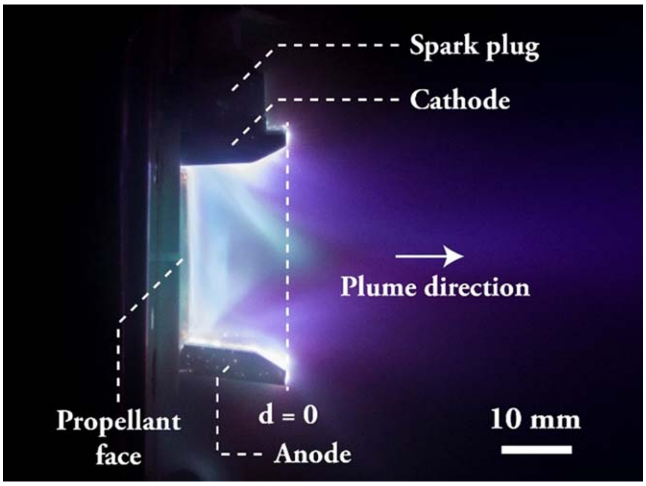

Figure 1. Side view of a single PPT pulse discharge.

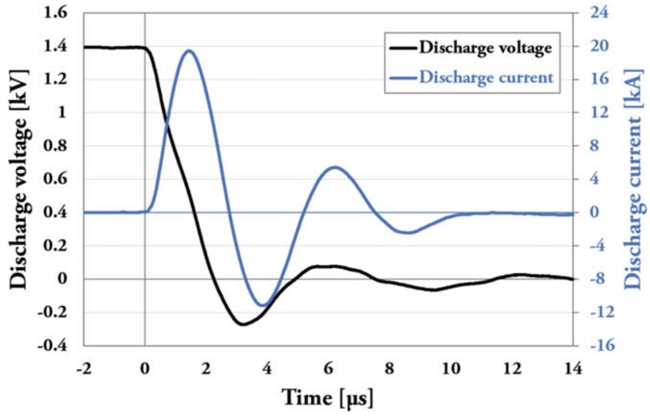

Figure 2. Example discharge voltage and current curves for an initial discharge voltage of 1.4 kV (9.8 J). The discharge exhibits a damped sinusoidal waveform typical of pulsed plasma thrusters. The period is ~5 μs and discharge completion occurs in ~10 μs.

such as electrons and ions of different elements with different ionization levels, thus resulting in a quasi-neutral plasma. We will show here that contrary to some inherent assumptions of a relatively constant plume velocity over several decades (arising from the use of limited arbitrary downstream measurement points [11–13]), the leading-edge (fastest) ions in the plasma plume continue accelerating outside the thruster. It is also likely that the entire plume experiences the same phenomenon as ambipolar forces will affect not only the leading-edge, but the entire plume.

The exhaust velocity of the plasma plume is the end result of a complex acceleration and plasma interaction process within a PPT. Calculations and plasma models that aim to accurately simulate these interactions will usually produce the exhaust velocity as one of the outputs. This can then be compared to experimental measurements for verification purposes. However, the experimental exhaust velocity of PPTs has previously been estimated to be in a wide range from 5 to 60 km s^{-1} [11–21]. It has been plagued with inaccuracies and challenges due to the transient nature of PPT discharges and insufficient knowledge regarding the discharge and acceleration processes. Several measurement methods have been used, including the use of high-speed cameras [14, 15], Doppler shifts [11, 16], time-of-flight (TOF) methods [11, 15–18], etc [12, 19–21]. Factors such as the shot-to-shot variations and discharge noise of a PPT further increase the difficulty in velocity measurements; occasional discrepancies have also been observed which hint at a non-constant ion velocity [13, 16, 18]. Here, we used a triple Langmuir probe and a Faraday probe for TOF velocity measurements outside a PPT over a distance range that is relatively large compared to the size of the PPT (over 10 times the electrode length).

Methods

The experimental PPT was equipped with an oil capacitor rated for a maximum voltage of 2 kV with a capacitance of 10 μF, corresponding to a maximum discharge energy of 20 J. The electrode length and spacing was 15 mm and 25 mm, respectively. An example of the discharge voltage and current of the PPT used in this study can be found in figure 2. The data recorder used was a Tektronix DPO3014. Langmuir probe currents were measured using a Tektronix TCP0030A. Faraday probe data was directly measured using the data recorder. The discharge voltages were measured using a Tektronix P5100 and the discharge currents using a Rogowski coil that consisted of a wound induction coil (~200 turns) and a resistor-capacitor integrator. The Rogowski coil had a calibrated sensitivity of $S = 9.75 \times 10^{-4}$ V A^{-1}.

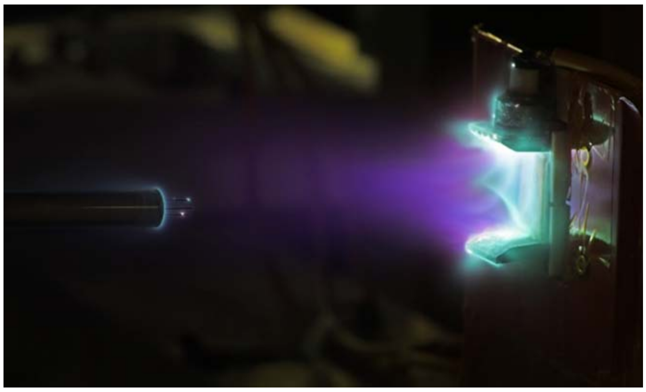

Figure 3. A triple Langmuir probe located in front of the pulsed plasma thruster during a single discharge. The probe is parallel to the plume along the central axis in front of the thruster. The dimensions of the probe and the experimental geometries are much larger than the estimated Debye length.

Experiments were conducted in a vacuum chamber with a diameter of 0.8 m and a length of 1.8 m. The chamber had a base pressure in the order of 10^{-4} Pa and operated at a pressure in the order of 10^{-3} Pa during thruster operation.

For Langmuir probe measurements, a triple Langmuir probe was positioned parallel to the plume and along the central axis in front of the PPT (see figure 3). The triple probe had wire diameters, spacings, and exposed lengths of 2, 7, and 4.5 mm, respectively. The probe material was pure tungsten. The Debye length was estimated using the triple Langmuir

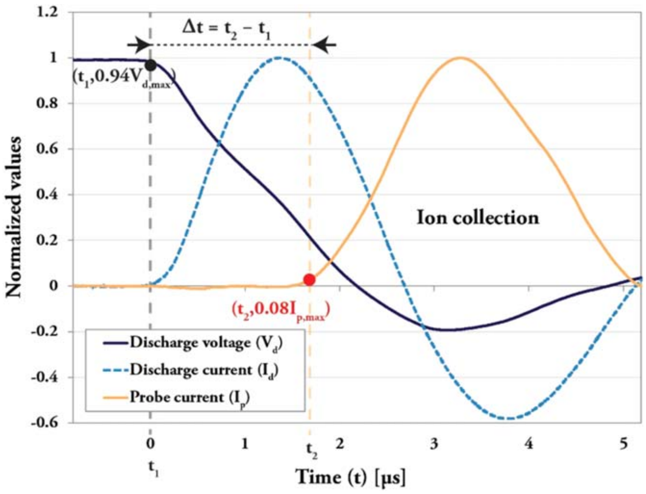

Figure 4. The time difference between discharge initiation and the onset of a recorded Langmuir probe signal used for time-of-fight measurements. The thresholds used for time measurements are shown. The discharge current is included only for reference purposes. This example corresponds to one actual TOF data point with a discharge voltage of 1.4 kV and a probe distance of $d = 50$ mm.

probe measurements to be in the order of μm or less, much smaller than the examined distances. The end of the PPT electrodes was considered to be $d = 0$ (i.e., zero distance from the thruster exit; see figure 1). The probe was used to record data in steps of 10 mm with a maximum of $d = 180$ mm. Different Langmuir probes with the same design were not observed to affect the recorded data.

The triple Langmuir probe is typically used for determining plasma parameters such as the electron temperature and density. A full background on the probe is beyond the scope of this letter but is widely available in the literature [13, 18, 22]. While there are three exposed wires on a triple probe, the two of interest here are biased with an applied voltage to repel electrons and are used to record the ion saturation current. Hence, the velocity of the fastest arriving population of ions can be estimated by simply using the time difference between discharge initiation and the initial onset of a signal recorded by the probe. A bias voltage of 74 V was used here and exhibited stable results. The third wire is floating with respect to the plasma, and can be used to record the arrival of electrons. However, as the electron velocity was found to be extremely high, our present instrumentation was not suitably accurate for a detailed study of the fastest electrons.

Results and discussion

The initial drop in voltage upon the initiation of a single discharge is shown in figure 4 along with the first signal curve recorded by the Langmuir probe. Units other than time are irrelevant for our purposes here; therefore, figure 4 shows the data normalized against the maximum of the recorded values within the displayed time range. When the probe was located further downstream, the signal curves are delayed to later times as expected (as there is further distance to travel). The ion collection signal therefore varies with downstream distance, with the greatest distances having signals that are delayed by half the period of the discharge. Due to this, it was possible to observe signals overlapping with various stages of a discharge. No significant cross-contamination or interaction between the discharge curves and the probe signals were observed. The probe behavior was consistent over the measured distance range.

As both the voltage drop and signal rise are not discrete jumps, it is not possible to determine an exact time for each. Instead, we used a percentage change as an indication of the times of interest. The data to be presented here uses a 6% drop in the voltage and an 8% rise in the probe signal, compared with the initial voltage and the maximum of the first probe signal curve, respectively (as shown in figure 4). The experimental parameters and analytical methods used here are extremely conservative in terms of sensitivity and were chosen to enable a wide range of distances to be examined. For example, with a discharge voltage of 1.7 kV, we were not able to use distances less than 40 mm due to noise and signal interference. Conversely, with a discharge voltage of 1.1 kV, signals at distances greater than 160 mm were too weak to be used reliably. We will focus our discussion on 1.4 kV, which enabled the largest distance range to be examined. In our experience, if measurements are optimized for a much smaller range, much more sensitive values such as a 1% change or less can be used. The variables to be balanced in such cases are the distance from the thruster, the probe's bias voltage, and the PPT's discharge voltage. Nevertheless, in our data, shot-to-shot variations and experimental errors still dominate the velocity estimation errors since the plume of the PPT varies slightly with each shot. Velocity measurements intended for precise thruster characterization can use a smaller distance range to obtain more accurate measurements; this letter instead aims to conclusively demonstrate a velocity trend over a larger distance range.

While the peak of the probe signal might be an obvious choice for TOF measurements (and has been used before), there are some factors that should preclude it from use. First, while it indicates the greatest collected ion saturation current and the associated time, we are not completely certain as to which stage of the discharge corresponds to its formation time. Second, the plasma plume of a PPT is composed of multiple ion species and different ionization levels, and the recorded probe current is a convolution of all these. These individual components will experience different acceleration forces due to their different charges and masses, even if they all experience Lorentz force acceleration. In the event that ion acceleration does not occur during plume expansion outside the thruster, it may be reasonable to assume that the overall spatiotemporal distribution of the collected ion saturation current does not change downstream. However, we will show here that such an assumption may be inappropriate. In addition, plasma diffusion during downstream propagation would also change the spatial distribution of plasma. Therefore, the only portion of the probe data that we can currently use

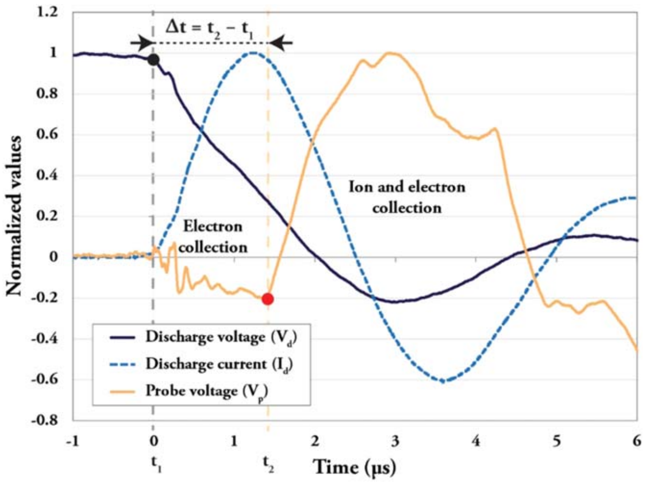

Figure 5. The time difference between discharge initiation and the onset of a recorded Faraday probe signal used for time-of-flight measurements. The data is normalized against the maximum of the recorded values within the displayed time range.

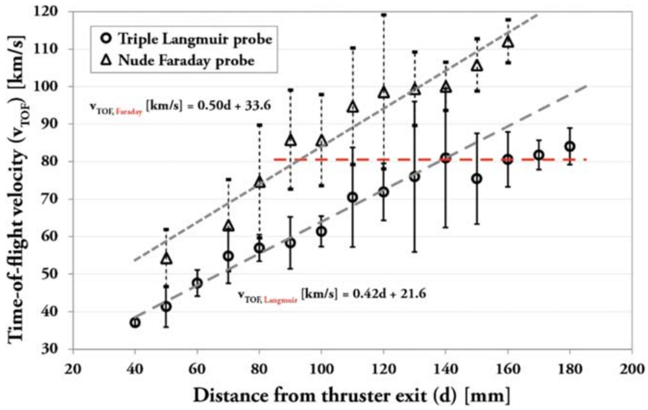

Figure 6. Time-of-flight velocity as a function of downstream distance outside the thruster.

reliably is the arrival time of the fastest ion species (leading-edge velocity), which we assume is created at or very close to the onset of the discharge. Any error due to this assumption will decrease with increasing downstream distance (since the assumption error would be constant while the time difference would increase).

In contrast to Langmuir probes, Faraday probes are far more susceptible to noise, thus introducing significant errors in the determination of the onset time and TOF velocity. They are used here only for validating the reasonability of the Langmuir probe results. The Faraday probe had a diameter of 4 mm and no bias voltage (nude probe). The probe recorded a negative voltage upon the almost immediate arrival of fast electrons after the start of a discharge. The probe onset time was defined as the time when the probe began to record a significant positive trend in the voltage, indicating the more delayed arrival of ions. The examined distance range (50–160 mm) was slightly smaller than for the Langmuir probe due to susceptibility to discharge noise and different physical constraints for the Faraday probe. Furthermore, for unknown reasons, measurements at 60 mm exhibited significant noise and variability, and are thus omitted. An analogous example of figure 4 for the Faraday probe can be seen in figure 5. Since the probe is unbiased (nude probe), it collects both electrons and ions. The electrons produce a negative signal almost immediately after discharge initiation, but the onset time data is noisy due to the high velocity of the electrons and the temporal proximity to the discharge initiation. The arrival of ions produces an increase in the probe signal, and is used as the arrival time of the leading-edge of ions for TOF velocity determination. As the arrival of ions is rather abrupt, the collection of electrons should not affect the identification of the arrival of the leading-edge.

The measured TOF velocities of the leading-edge ions are shown in figure 6. Data is shown for discharge voltages of 1.4 kV. Each data point is the average of 5 shots with the error bars showing 2 standard deviations. While several discharge voltages were similarly tested over a similar distance range, no significant difference in velocity was observed as a function of the discharge voltage in the 1.1–1.7 kV range.

It is immediately clear at first glance that there is a clear increase in the velocity with the distance from the thruster exit, even when shot-to-shot differences (error bars) are taken into consideration. The linear fit for the Langmuir probe data indicates that the extrapolated velocity at $d = 0$ is approximately 22 km s^{-1}. This is in agreement with measurements of the inter-electrode plasma plume velocity that we previously obtained using magnetic probes. The Faraday probe data appear to lie on a different curve fit (i.e., there is a systematic increase in the recorded velocity). This may be due to the collection of both electrons and ions and the different probe conditions. The diameter of the Faraday probe is larger than that of the Langmuir probe, resulting in collection from a greater surface area. As the plasma plume of a PPT is canted, this larger surface area may better capture the true leading-edge of the plasma plume, i.e., while the probes are positioned along the centerline, plasma plume canting means that the global leading-edge is not exactly along the centerline. However, while the errors of the Faraday probe data are much larger (especially closer to the thruster), it still serves to support a clear increase in the velocity with distance.

Another observation that can be made from figure 6 is that the acceleration of ions recorded by the Langmuir probe appeared to slow down at distances greater than ~140 mm in the small chamber. The horizontal line in figure 6 is the average value of TOF velocities from $d = 140$ to 180 mm (81 km s^{-1}). It is intended to be a visual guide and is not a curve fit. To check for facility effects, we briefly examined a distance of $d = 235$ mm in a significantly larger vacuum chamber with a diameter of 3 m and a length of 5 m. In the larger chamber, the TOF velocity at $d = 235$ mm was found to be 120 km s^{-1} (standard deviation = 8 km s^{-1}). This is far greater than the values shown in figure 6 and also corresponds well with an extrapolation of the linear fit, suggesting that the in-plume acceleration phenomenon is independent of the chamber size. However, the chamber size may still affect the maximum velocity attainable by the ions, possibly due to faster electrons being absorbed by the chamber wall. This would disrupt the quasi-neutrality of the plasma plume. It is also important to note that the Faraday probe data does not seem to indicate such a threshold. The reason for this is currently unclear but may be due to small changes in the threshold distance caused by small changes in the thruster location between different probe experiments. It may also be due to the unbiased state of the probe producing a more quasi-neutral local plasma.

On some other electric propulsion thrusters such as ion thrusters, the energy of the ions does not change significantly with downstream distance [23]. However, in a PPT, electrons and a mixture of ion species with different ionization levels are formed together during the discharge process [14, 16, 17]. It is reasonable to expect all these different components to experience different acceleration forces, resulting in a quasi-neutral plasma plume. In particular, the electrons should exhibit a far greater velocity than the ions, leaving behind a positively charged population of ions. It is possible that ambipolar diffusion or a similar mechanism may act during the expansion of the plasma plume to accelerate the ions outside of the thruster [24, 25]. If so, we can expect fast light-weight electrons to be well-constrained along the centerline due to the self-induced magnetic field of the PPT, meaning that off-centerline ions should not exhibit such an acceleration phenomenon, as suggested by the results of Gatsonis *et al* [13]. Similar ion acceleration observations have also been made for other thrusters [24] and in some expanding plasmas [26]. However, contrary to stationary plasma plumes where the energy increase during expansion is several eV at most, PPT plasma plumes are intrinsically non-stationary due to their pulsed nature, resulting in the formation of plasma 'packets'. Therefore, the leading-edge ions will experience a vacuum environment directly ahead of them, resulting in more effective acceleration by the electric field. Furthermore, the effect on trailing-edge ions should be opposite to that on leading-edge ions; they should decelerate rather than accelerate. A broadening of each plasma packet can be expected as the plume travels downstream, with the average effect on the overall packet being smaller than for the leading-edge (there should be a smaller increase in the mean velocity). In fact, this broadening can be qualitatively observed with downstream Langmuir probe data but is unable to be accurately quantified as the leading and trailing-edge of successive plasma packets tends to merge with downstream distance.

It must be noted that because figure 6 shows the TOF velocity from the thruster to the position of the probes, it is equivalent to the average velocity over a given distance; the instantaneous ion velocity will be even higher. By comparing TOF data from $d = 100$ and 150 mm, we estimate the instantaneous velocity of the leading-edge ions to be in the order of 100–200 km s^{-1} at this distance. A more accurate estimation is not possible with our present setup due to shot-to-shot variations and compounding experimental errors. While the TOF velocity presented here only represents the leading-edge of the plume, in future work, quadruple Langmuir probes can also enable the measurement of the mean ion velocities [13]. Clearly, a thorough understanding of the complete plasma expansion process of a PPT still requires further work.

The findings presented here have several important implications. The most obvious is that the measured exhaust velocity is strongly dependent on the downstream measurement distance. This may have partially resulted in the wide range of exhaust velocities that have previously been reported. It is necessary to obtain measurements from at least two distances that are sufficiently far apart to distinguish differences in velocities. Curve fitting can then be used to extrapolate the data to obtain the exhaust velocity at the thruster exit. This extrapolated velocity will be the actual exit plane plasma velocity rather than an arbitrary downstream velocity.

Another important implication is that there is obviously a large surplus of energy present within the plasma that is not taken into account if only the ion exhaust velocity at the exit is used to calculate the efficiency of a PPT. This suggests that there is a large proportion of energy present in the electrons (likely in the form of thermal energy), which is subsequently transferred to the ions in the process of reaching an overall equilibrium. The eventual mean velocity of ions and electrons in the plume should be equal at an infinite downstream distance. It is also important to note that an ambipolar effect should also result in a decrease in the electron temperature with downstream distance (as the ion temperature and mean ion velocity increase correspondingly). While the electron temperature can be directly estimated using a triple Langmuir probe, we observed that the error currently precludes accurate quantification with a high spatial and temporal resolution, especially as the leading-edge data also experiences noise from the discharge onset (the electron temperature calculations rely on voltage measurements). This may be rectified in the future with the use of current-mode triple Langmuir probes. Although the leading-edge ion velocity represents a significant increase in the ion energy (the velocities correspond to several hundred eV), it is currently unclear how the rest of the plume behaves. However, as mentioned previously, the trailing-edge is likely to experience a contrasting deceleration and the increase in the mean velocity is expected to be less than for the leading-edge.

The relationship between the electrons and the ions will be quite complicated since the thruster does not operate in a steady-state mode. This means that at the end of a pulse, there will be an end to the supply of new electrons in the plume. To further complicate matters, the PPT plume also consists of multiple ion species with different ionization levels. As the electron velocity is too high to measure accurately using our present TOF method, and it is difficult to deconvolute the probe signal based on the ion species, future plasma plume simulations will likely be needed to better understand the interactions within the PPT plume. The new information presented here will be helpful in directing such future work towards a more comprehensive understanding of the plasma plume physics.

Conclusions

The plasma plume of a PPT is typically thought to be accelerated between the electrodes due to electromagnetic and electrothermal acceleration. Of these, the velocity due to electromagnetic acceleration is several times higher than that due to electrothermal acceleration. Once the plasma is ejected from the thruster, these acceleration mechanisms are no longer present. In the absence of any other acceleration mechanisms, the plume should then have a constant exit velocity (the gas expansion velocity can be ignored as it is significantly slower than the plume exit velocity). Calculations and plasma models that aim to simulate the complex acceleration and interaction processes will usually produce the exhaust velocity as an output. This can then be compared with experimental values for verification. However, we show here using experimental measurements that the leading-edge of the plasma plume continues to accelerate outside the thruster. Langmuir probe and Faraday probe measurements both show an increase in the velocity with downstream distance. As the plasma plume of a PPT is in fact a quasi-neutral plasma composed of energetic electrons and ions of multiple elements with different ionization levels, we suggest that this acceleration is due to ambipolar diffusion as the electrons will have a significantly greater velocity than the ions due to their lower mass. These electrons will have non-zero residual thermal energy upon exiting the thruster. In order to obtain the actual exit velocity, it is then necessary to measure the ion velocity at several downstream distances. This can then be used to simply extrapolate and determine the actual velocity at the thruster exit.

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References

[1] Burton R L and Turchi P J 1998 Pulsed plasma thruster *J. Propulsion Power* **14** 716
[2] Jahn R G 1968 *Phys. Electr. Propulsion* (New York: McGraw-Hill)
[3] Schönherr T 2016 *Encyclopedia of Plasma Technology* ed J Shohet vol 2 , pp 1452–61(New York: Taylor and Francis)
[4] Zhang Z, Ren J, Tang H, Ling W Y L and York T M 2017 An ablative pulsed plasma thruster with a segmented anode *Plasma Sources Sci. Technol.* **27** 015004
[5] Glascock M S, Rovey J L, Williams S and Thrasher J 2017 Plume Characterization of Electric Solid Propellant Pulsed Microthrusters *J. Propulsion Power* **33** 870–80
[6] Kazeev M N, Kozubskiy K N and Popov G A 2009 Victor Khrabrov–Pioneer of the first space electric propulsion system development and space tests *31st Int. Electric Propulsion Conf.* IEPC-2009-2235
[7] Levchenko I *et al* 2018 Space micropropulsion systems for Cubesats and small satellites: from proximate targets to furthermost frontiers *Appl. Phys. Rev.* **5** 011104
[8] Szelecka A, Kurzyna J, Daniłko D and Barral S 2015 Liquid micro pulsed plasma thruster *Nukleonika* **60** 257–61
[9] Ling W Y L, Schönherr T and Koizumi H 2017 Characteristics of a non-volatile liquid propellant in liquid-fed ablative pulsed plasma thrusters *J. Appl. Phys.* **121** 073301
[10] Ling W Y L, Schönherr T and Koizumi H 2017 Discharge characteristics of an ablative pulsed plasma thruster with non-volatile liquid propellant *Appl. Phys. Lett.* **111** 014101
[11] Guman W and Begun M 1978 Exhaust plume studies of a pulsed plasma thruster *13th Int. Electric Propulsion Conf.* AIAA-78-704
[12] Gatsonis N A, Zwahlen J, Wheelock A, Pencil E J and Kamhawi H 2004 Pulsed plasma thruster plume investigation using a current-mode quadruple probe method *J. Propulsion Power* **20** 243–54
[13] Gatsonis N A, Byrne L T, Zwahlen J C, Pencil E J and Kamhawi H 2004 Current-mode triple and quadruple Langmuir probe methods with applications to flowing pulsed plasmas *IEEE Trans. Plasma Sci.* **32** 2118–29
[14] Koizumi H, Noji R, Komurasaki K and Arakawa Y 2007 Plasma acceleration processes in an ablative pulsed plasma thruster *Phys. Plasmas* **14** 033506
[15] Nawaz A and Lau M 2011 Plasma Sheet Velocity Measurement Techniques for the Pulsed Plasma Thruster SIMP-LEX *32nd Int. Electric Propulsion Conf.* IEPC-2011-248
[16] Thomassen K I and Vondra R J 1972 Exhaust velocity studies of a solid teflon pulsed plasma thruster *J. Spacecr. Rockets* **9** 61–4
[17] Markusic T E and Spores R A 1997 Spectroscopic emission measurements of a pulsed plasma thruster plume *33rd Joint Propulsion Conf. and Exhibit, Joint Propulsion Conf.* AIAA Paper 97-2924
[18] Gatsonis N A, Eckman R, Yin X, Pencil E J and Myers R M 2001 Experimental investigations and numerical modeling of pulsed plasma thruster plumes *J. Spacecr. Rockets* **38** 454–64
[19] Myers R, Arrington L, Pencil E, Carter J, Heminger J and Gatsonis N 1996 Pulsed plasma thruster contamination *32nd Joint Propulsion Conf. and Exhibit, Joint Propulsion Conf.* AIAA Paper 96-2729
[20] Bushman S S and Burton R L 2001 Heating and plasma properties in a coaxial gasdynamic pulsed plasma thruster *J. Propulsion Power* **17** 959–66
[21] Zhang Z, Ren J, Tang H, Ling W Y L, York T M and Cao J 2018 Direct investigation of near-surface plasma acceleration in a pulsed plasma thruster using a segmented anode *J. Phys. D: Appl. Phys.* **51** 395201
[22] Eckman R, Byrne L, Gatsonis N A and Pencil E J 2001 Triple langmuir probe measurements in the plume of a pulsed plasma thruster *J. Propulsion Power* **17** 762–71
[23] Zhang Z, Tang H, Zhang Z, Wang J and Cao S 2016 A retarding potential analyzer design for keV-level ion thruster beams *Rev. Sci. Instrum.* **87** 123510
[24] Longmier B W *et al* 2011 Ambipolar ion acceleration in an expanding magnetic nozzle *Plasma Sources Sci. Technol.* **20** 015007
[25] Keidar M and Beilis I I 2013 *Plasma Engineering: Applications from Aerospace to Bio- and Nanotechnology* (New York: Academic) p 136
[26] Biloiu I A, Scime E E and Biloiu C 2008 Ion beam acceleration in a divergent magnetic field *Appl. Phys. Lett.* **92** 191502