

Mass and Plasma Characteristics in the Current Sheet of a Pulsed Plasma Thruster

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Abstract: In the framework of the development of the pulsed plasma thruster ADD SIMP-LEX for the application on small satellite missions, the plasma created during the discharge was investigated by means of emission spectroscopy, Mach-Zehnder interferometry, a high-speed camera and induction probes. From the measurements, the assessment of the plasma properties was done, as well as a comparison with performance measurements on the same thruster. A special regard was put on the speed of the propagating current sheet, as being the main impulse-causing phenomenon. Further, the plasma composition and its properties were determined. To support the experimental results, the slug model was further improved and the propellant utilization computed. Results show a non-linear dependency of the current sheet speed on the discharge voltage, as well as a good agreement between the measurement systems. Plasma temperatures range from 20,000 to 30,000 K during the first few μs of the discharge. Together with a determined electron density of about 10^{23} 1/m^3 , measurements indicate a continuum plasma flow. This supports the use of the slug model, which showed that the capacitance and the voltage of the thruster have different effects on the propellant utilization.

Nomenclature

C	= capacitance
d	= width of electrodes
f	= fringe shift ratio

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h	= gap between electrodes
I	= discharge current
I_{bit}	= impulse bit
K_e	= specific refractive index
λ	= wavelength
μ	= propellant utilization efficiency
m_{bit}	= mass bit
n_e	= electron density
U	= discharge voltage

I. Introduction

The Institute of Space Systems (IRS) of the University in Stuttgart is working on several small satellite missions comprising Perseus and Lunar Mission BW1 sought to be technology demonstration missions for electric propulsion systems, including a pulsed plasma thruster named ADD SIMP-LEX¹. The development of ADD SIMP-LEX towards a thruster for the satellite missions was supported by national and international cooperation which was extended by an international collaboration with the University of Tokyo to enable better insight in the plasma physics and yield compatible experimental data. Today, the universities of Stuttgart and Tokyo are collaborating in research and development of this electric propulsion system².

Pulsed MPD thrusters, usually referred to as pulsed plasma thruster (PPT), are promising candidates for usage on board of small satellites due to the robust and simple design and the very low requirements in power consumption. They consist of a capacitor bank, a pair of electrodes, an ignition device and the, usually solid, propellant. Triggered by the spark plug, the energy stored in the capacitor is discharged across the propellant surface thereby ablating, dissociating and ionizing the material. This is then accelerated by electromagnetic force to form the thrust. Due to phenomena like late-time ablation, inefficient ionization and particulate emission, pulsed MPD thrusters often suffer from low thrust efficiency. A better understanding of the ablation processes, especially the ionization, might yield valuable information to improve the efficiency of the thruster, thus enabling more payload on the satellite.

Therefore, the properties of the current sheet propagation are assessed with the aim of finding an optimum condition, to evaluate the properties with regard to the general performance and to be able to use the results for modeling of the thruster.

II. Preceding research activities and motivation

Development of ADD SIMP-LEX towards its current design included a thorough parametric investigation of the performance with respect to the electrode geometry and the oscillation circuit design³⁻⁵. An optimum condition was found and yielded a pulsed plasma thruster that is shown in Figure 1.

ADD SIMP-LEX has a maximum of 4 capacitors with 20 μ F each, and a maximum applicable voltage of 1300 V. Ignition is done by a semiconductor spark plug. The PTFE propellant is side-fed in between the copper electrodes.

The main value to enable comparison between PPT is sought to be the thrust efficiency. However, little is known about the exact physics processes that determine this value for a certain thruster configuration. Various PPT configurations had been tested throughout the past decades in many countries. It is thus possible to plot the measured thrust efficiency for all these developments against the used bank energy disregarding the propellant material, the propellant feed, the geometry of the electrodes and of the oscillation circuit, et cetera. The resulting plot is shown in Figure 2⁶.

A significant difference in thrust efficiency can be seen for the same energy levels. Although, geometric and circuit parameters play an important role for the value (optimization of ADD SIMP-LEX leded a leap from around 10 % to 26 % at the same energy), a clear rising tendency for an increase in bank energy can be recognized.

The other main parameter for the performance is, thus, the energy level of the capacitors. That is, the

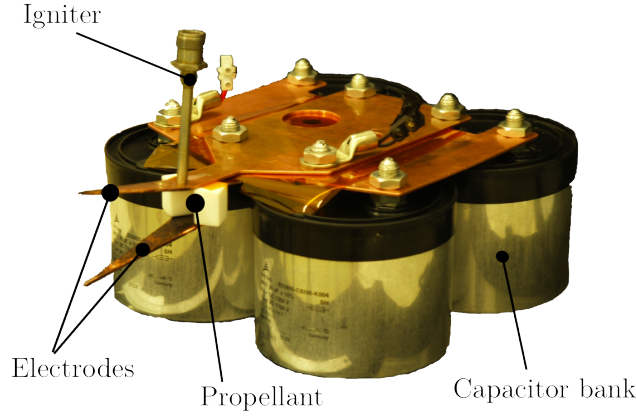


Figure 1. Setup of the engineering model of ADD SIMP-LEX.

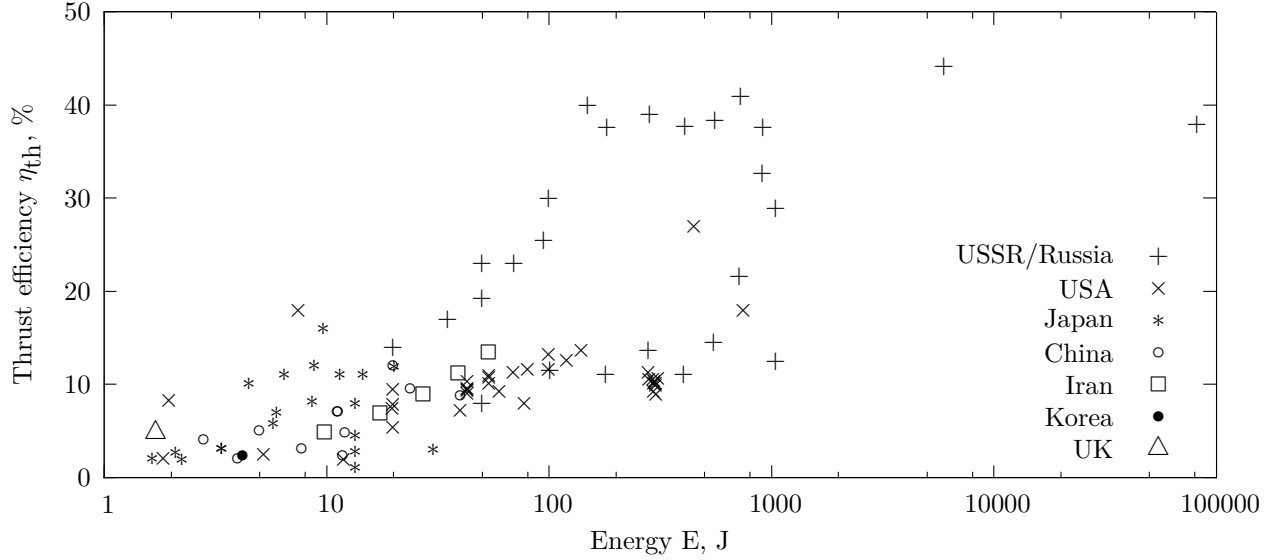


Figure 2. Thrust efficiency against bank energy for different PPT developments in the USSR/Russia, USA, Japan, China, Iran, Korea and UK⁶.

energy itself is comprised of two independent parameters - the capacitance of the main capacitors and the discharge voltage during the pulse. The variation of each of these parameters does have a different effect on the performance outcome of the thruster. Figure 3 shows the same performance data as a function of bank capacitance and applied voltage.

The data show two general tendencies. First of all, for a raise from a very low capacitance (1 to 10 μF) to a medium capacitance (10 to 100 μF), the thrust efficiency tends to increase slightly in general. An increase in capacitance beyond 100 μF yields a strong performance gain. Regarding the voltage, it can be seen that for small voltages (< 1000 V), the thrust efficiency in general is quite low. Between 1000 and 2000 V, depending on the capacitance, the thrust efficiency appears to increase exponentially whereas for voltages beyond 3000 V, the performance starts to level off. An increase in energy is then not related to any further gain in thruster performance efficiency.

The same effect on the performance could also be verified by experiment on ADD SIMP-LEX. Measurements of impulse bit and mass bit yielded clear tendencies as a function of the current action integral $\Psi = \int I^2 dt$. Figures 4(a) and 4(b) show the experimental results for a variation in capacitance and voltage. Note that a higher voltage is related to a higher current action integral⁷. For the impulse bit, the empirical estimation proposed by Solbes⁸ has been added for the assumption of a constant electrode geometry (Constant) as well as for the assumption of a mean electrode geometry (Mean).

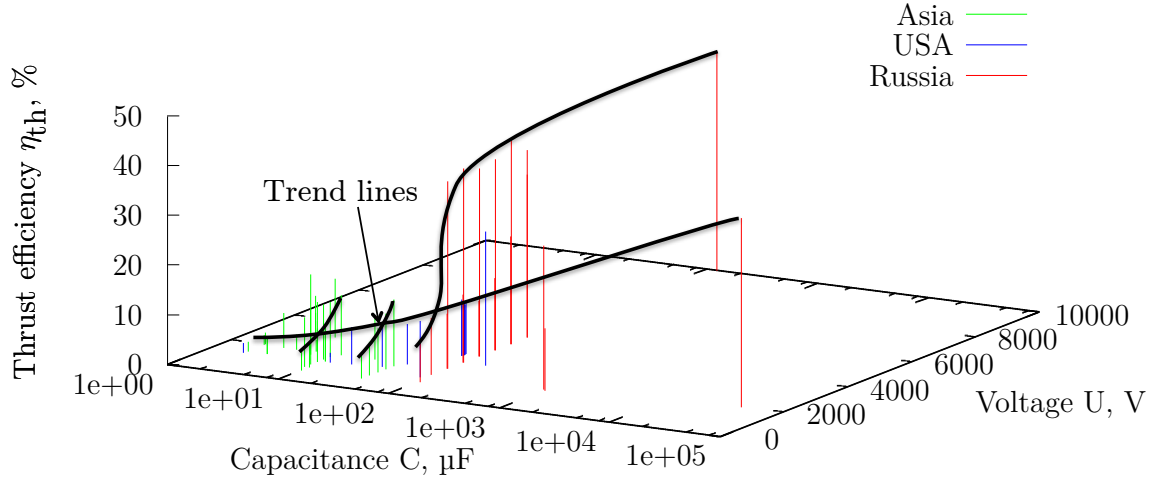
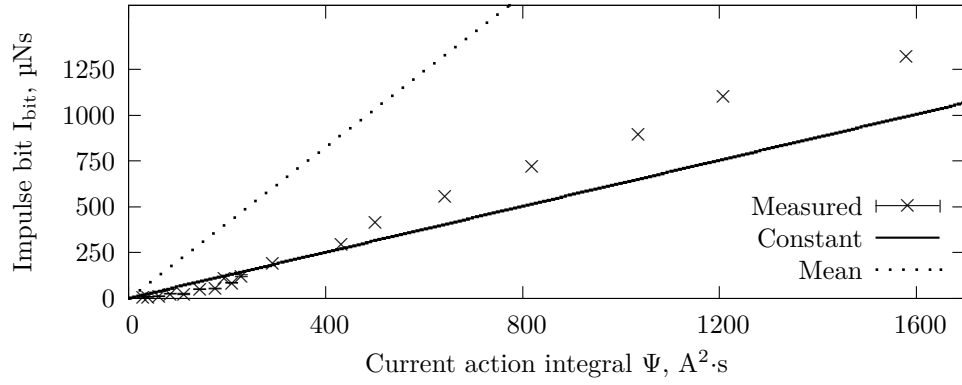
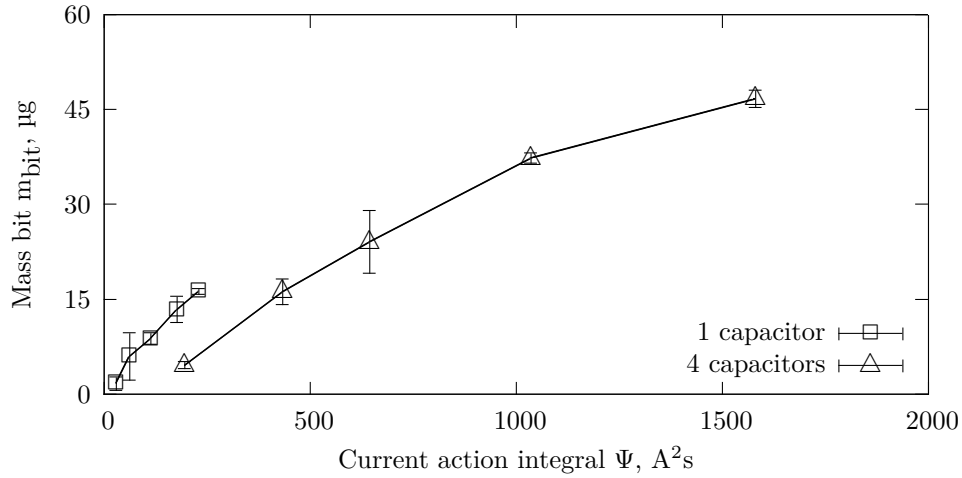


Figure 3. Thrust efficiency as a function of capacitance and discharge voltage for different PPT developments.



(a) Impulse bit measurement results with empirical prediction for constant and mean electrode geometry.



(b) Mass bit measurement results.

Figure 4. Thrust performance of ADD SIMP-LEX for a variation in voltage and capacitance.

From the measurements, the thrust efficiency was easily deduced yielding the results displayed in Figure 5.

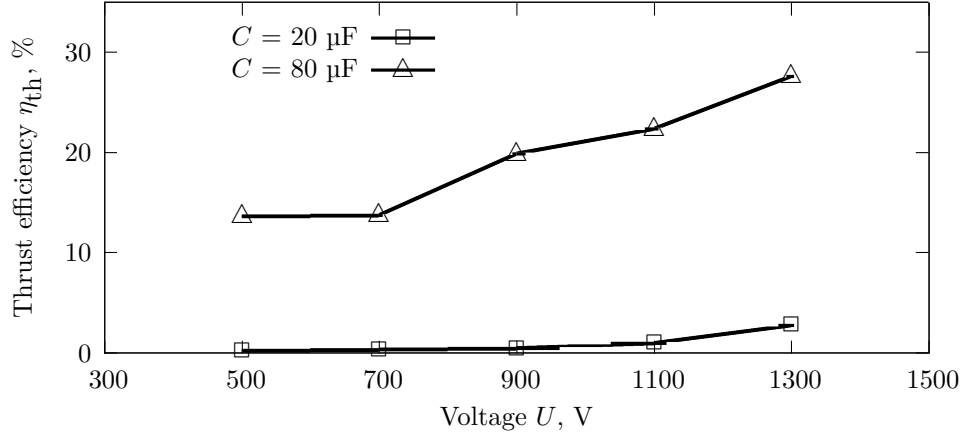


Figure 5. Thrust efficiency for variation in capacitance and voltage for ADD SIMP-LEX.

The results of the thrust efficiency for ADD SIMP-LEX confirm well the tendencies that were observed in Figure 3. The increase in capacitance lead to a significant leap in the thrust efficiency independent of the discharge voltage. An increase in voltage, however, yielded but a small increase. In order to understand why this change happens in the performance, a determination of performance values related to the discharge and the plasma was sought necessary. While the discharge behavior was studied before^{5,7}, a deeper insight in the plasma properties remained compulsory. This paper tries to fill the gap, and to enable a better understanding on the influences on the PPT performance and physics.

III. Determination of plasma front velocity

An assessment of the velocity of the plasma front (i.e. current sheet) was considered to enable an understanding of the influence of voltage and capacitance on the plasma velocity. As the velocity is one of the main contributing effects in the resulting thrust performance, an understanding can yield valuable conclusions about the plasma behavior. Four different measurement systems were used in order to determine the velocity. A high-speed camera and emission spectroscopy are thereby making use of optical emission of the excited plasma particles whereas induction probes are using the electromagnetic behavior of the discharge to detect the current sheet, and the interferometry uses the density gradients in order to identify the position of the plasma front.

III.A. High-speed camera

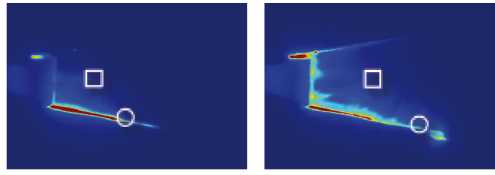
A high-speed camera system was used to trace the illumination of the plasma flow during discharge for a variation in voltage and capacitance. The camera system is described elsewhere^{9,10}. Exemplary pictures together with the traced points for a configuration with 500 V and 80 μF are shown in Figure 6

From the tracing a velocity was determined for permutations in voltage and capacitance. However, current sheet canting, a strong variation in brightness, et cetera, reduce the accuracy of the measurements.

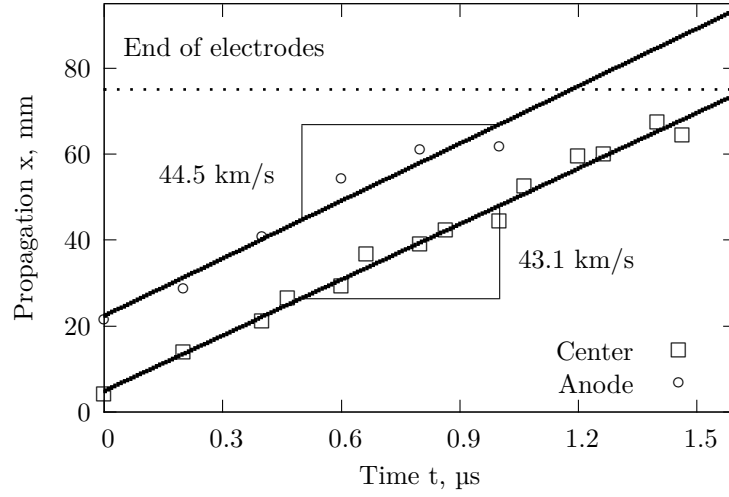
III.B. Induction probes

Induction probes were used to determine the passage of the current sheet indicated by an intersection of the magnetic field, i.e., the integrated signal output, as was done previously on the older design of the PPT¹¹. The design of the induction probe can be found for example in¹⁰. Figure 7 shows a typical output of the induction probe located on the central axis of the discharge space with a distance of 20, and 40 mm respectively, from the exit plane of the propellant.

The difference in the timing of the intersection then yields the velocity of the current sheet for the different configurations. However, for cases with 1 capacitor ($C = 20 \mu\text{F}$), the signal-to-noise ratio was not sufficiently high to derive a precise value.



(a) Exemplary trace points (Top: Cathode, Bottom: Anode, Left: PTFE; Plasma flow to the right)



(b) Tracing positions

Figure 6. Current sheet displacement histories for 500 V ($C=80 \mu\text{F}$).

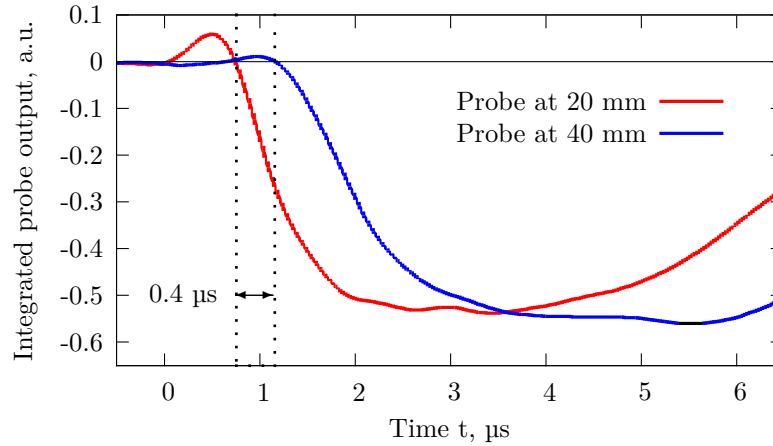


Figure 7. Determination of plasma front velocity from induction probe signals.

III.C. Emission spectroscopy

Measurements of the emitted light were conducted by means of a LTB Echelle spectrometer where the focal point was moved from 10 to 70 mm downstream on the center axis of the discharge space to trace the evolution and propagation of the species. The experimental setup is reported, in e.g.,¹². A typical spectrum, recorded for $U = 1300 \text{ V}$ and $C = 80 \mu\text{F}$ is shown in Figure 8.

Most lines in the spectrum were linked to either ionized species of Carbon (C^+ , C^{++}) or Fluorine (F^+), as are marked in the Figure. Small emission from copper was also recorded implying a minor erosion of the electrodes. However, no significant emission from either atoms or molecules was detected.

Tracing the emission of the different species throughout discharge time and focal point position yields a

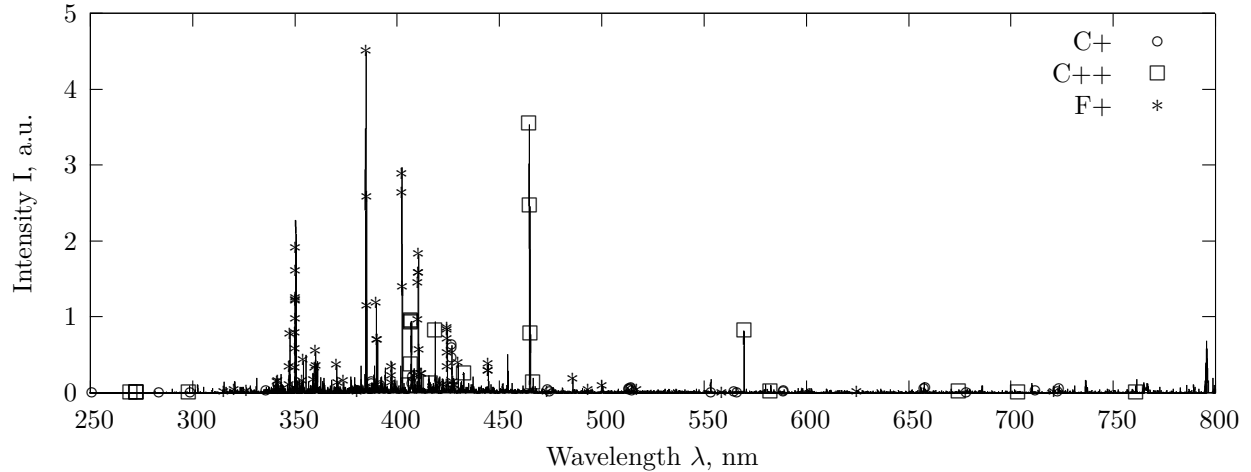


Figure 8. Exemplary spectrum for the plasma flow of ADD SIMP-LEX.

picture of the intensity propagation and, thus, the velocity of the plasma. Figure 9(a) shows the normalized emission intensities for the strongest spectral lines of the 3 main species to be found in the PTFE plasma (C+, C++, F+) as a function of discharge time and focal point position. The peaks of the intensity distribution are connected to visualize the movement. For the sake of visibility, the peaks are projected into a two-dimensional plot in Figure 9(b).

From the propagation of the peak intensity, a velocity can be derived, as indicated in Figure 9(b). However, as intensity of the emission decreases quickly with a reduction of the energy level (either capacitance or voltage), the determination of the velocity is defied for the typical exposure time of 200 ns of the spectrometer. However, application of emission spectroscopy can yield further valuable information about the plasma flow which will be explained in the next Section. One important point to notice is that the velocity of all three species agrees well with each other, showing no significant difference for a variation in molecular weight and/or charge.

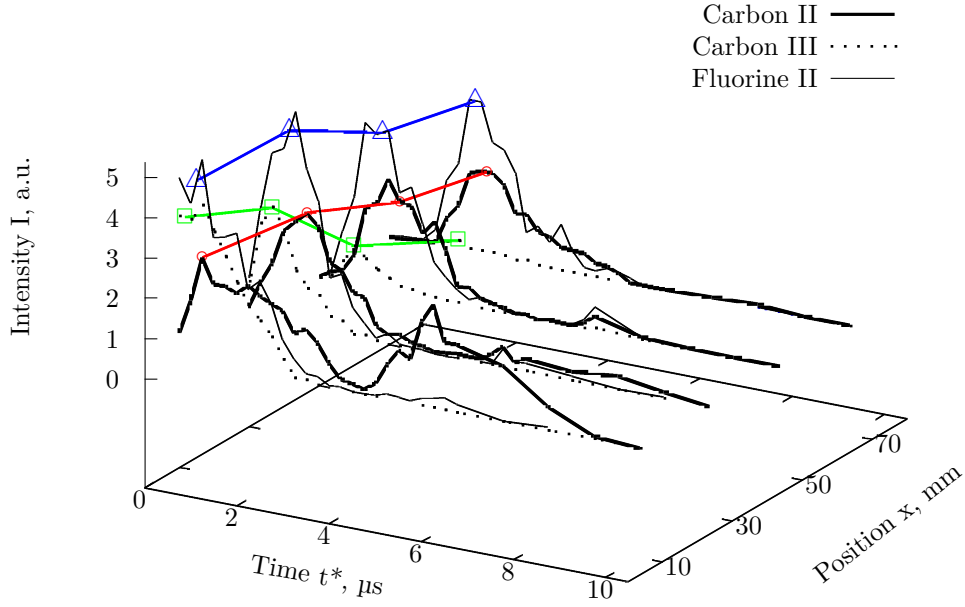
III.D. Mach-Zehnder interferometry

Application of a Mach-Zehnder interferometry setup was done as shown in Figure 10 using the same high-speed camera as used in III.A. Two lasers with a wavelength of 633 nm (red), and 532 nm (green) respectively, were used to create the interference pattern.

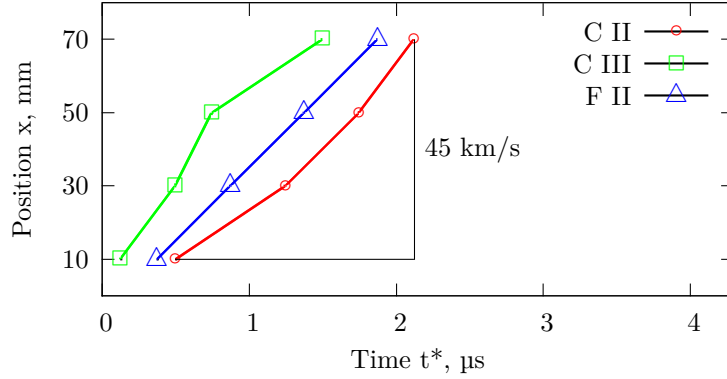
Due to changes in the refractive index of the plasma during the discharge, the interference pattern fringes vary, and, hence, plasma and a pertinent plasma front can be detected by the differences in the pattern. For the measurements, 4 sections of the discharge space were illuminated and measured. The sections were selected in order to enable an easier analysis, a sufficiently high laser intensity at the camera, and a minimum in time for experiment and evaluation of the pictures. The measured areas are as in Figure 11.

Limitation of this method is the small change in refractive index in case of an electron density of less than 10^{23} 1/m^3 . Thus, for a later moment in discharge time, a fringe shift might not be visible anymore. For the measurements, a typical exposure time of 250 ns was used for the camera. Intensity of the laser light and the resulting signal-to-noise ratio was then sufficiently good. An exemplary image for area 1 for a reference measurement without plasma and a actual measurement with plasma are shown in Figure 12.

From the propagation of the fringe shifts, a plasma front velocity was determined similarly to the measurements with the direct visualization by high-speed camera (compare Figure 6). A decrease in voltage yielded smaller fringe shifts throughout the discharge, implying smaller electron densities. Thus, for voltages below 900 V, no determination of the velocity was feasible. A reduction of the capacitance, however, still enabled a detection although decreased slightly.



(a) Spectral intensities for characteristic wavelengths of C^+ , C^{++} and F^+ over time and position on the x-axis.



(b) Peak intensity for the 3 traceable species in time and position (projection).

Figure 9. Results of the application of emission spectroscopy on the plasma flow of ADD SIMP-LEX.

III.E. Comparison of determined front velocities

By means of the four measurement systems explained above, the velocity of the plasma front was determined for a variation in capacitance and voltage. Figure 13(a) and 13(b) show the results for the configurations investigated (within the limitations mentioned in the experimental description).

Comparison of the measurement methods shows good agreement of the velocity value, especially in case of the higher energy level with $C = 80 \mu\text{F}$ (Figure 13(b)), save the deviation of the HSC value for 1300 V. As mentioned above, the current sheet canting is very strong in this case, making the tracking slightly more prone to uncertainties. Although a certain error due to noise lies within the results, on average a concave progression is visible, suggesting that the current sheet velocity forms a maximum around a voltage of 900 V.

This maximum is different to what would have been expected by the performance, thus, suggesting that the

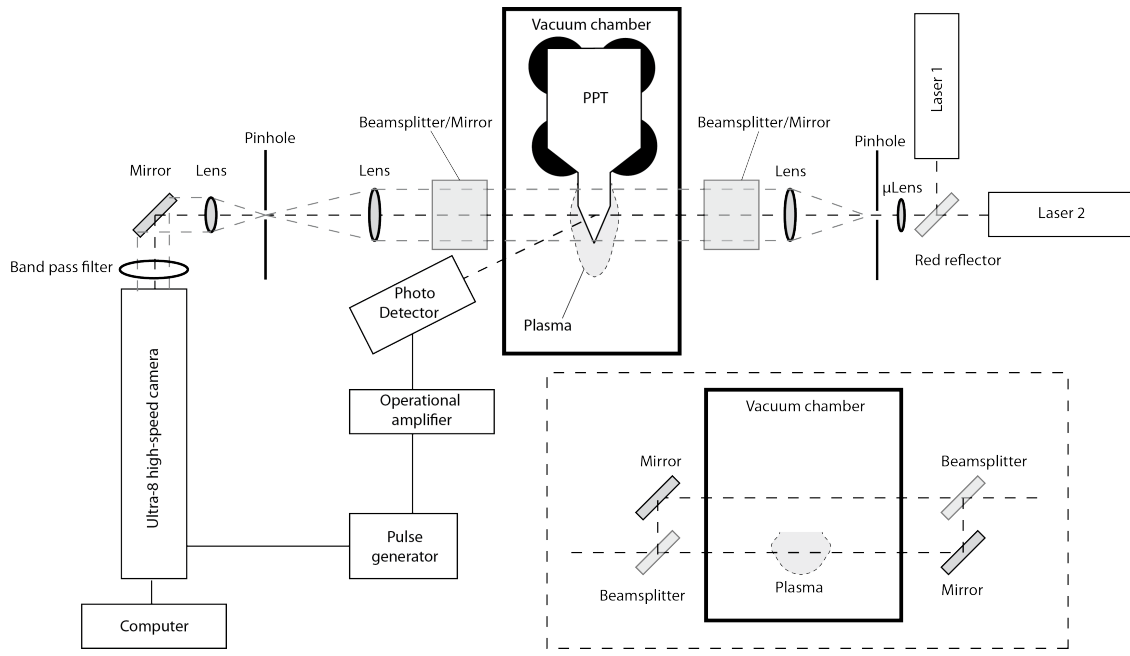


Figure 10. Experimental setup for application of Mach-Zehnder interferometry on ADD SIMP-LEX.

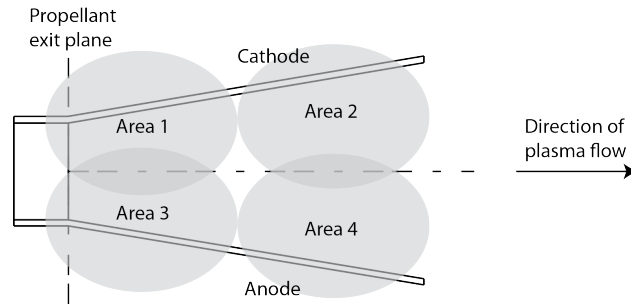


Figure 11. Measured sections of the PPT discharge space.

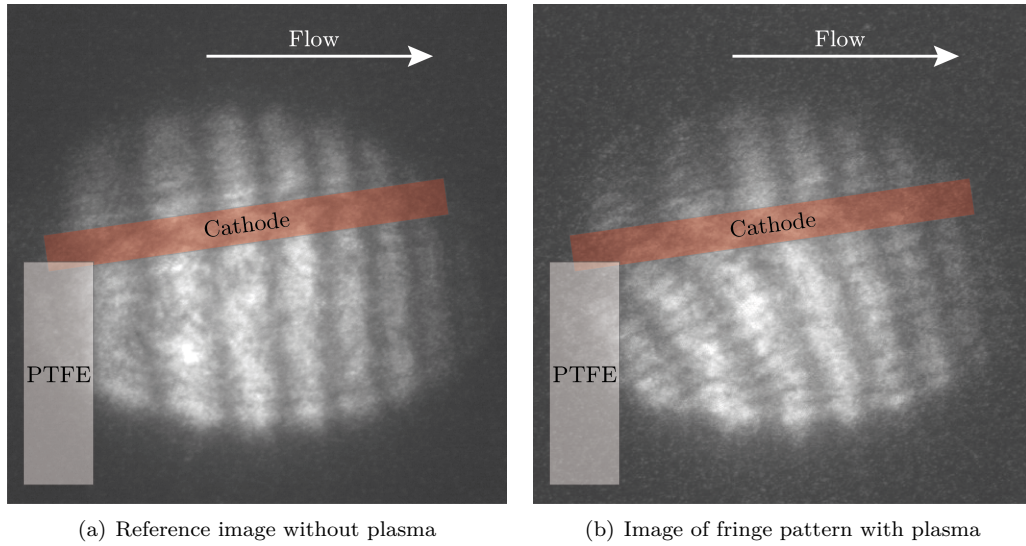
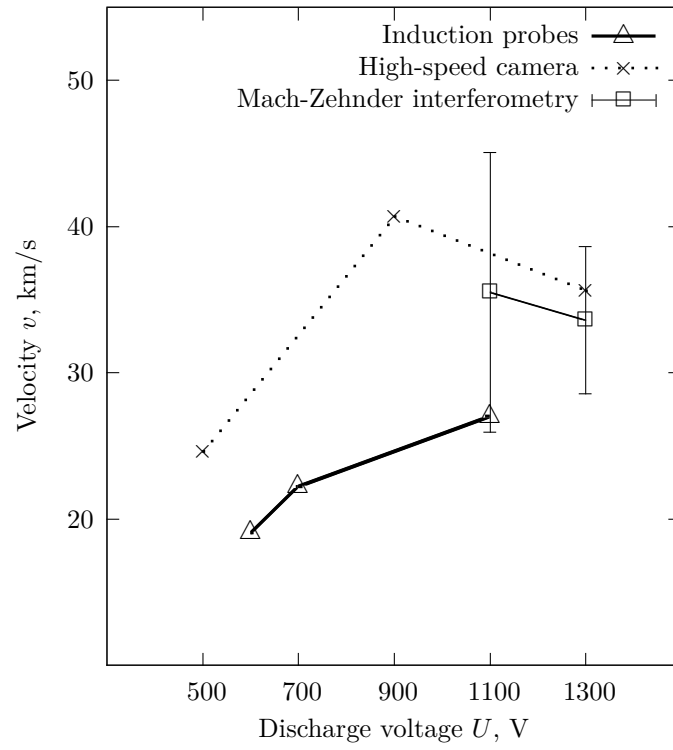
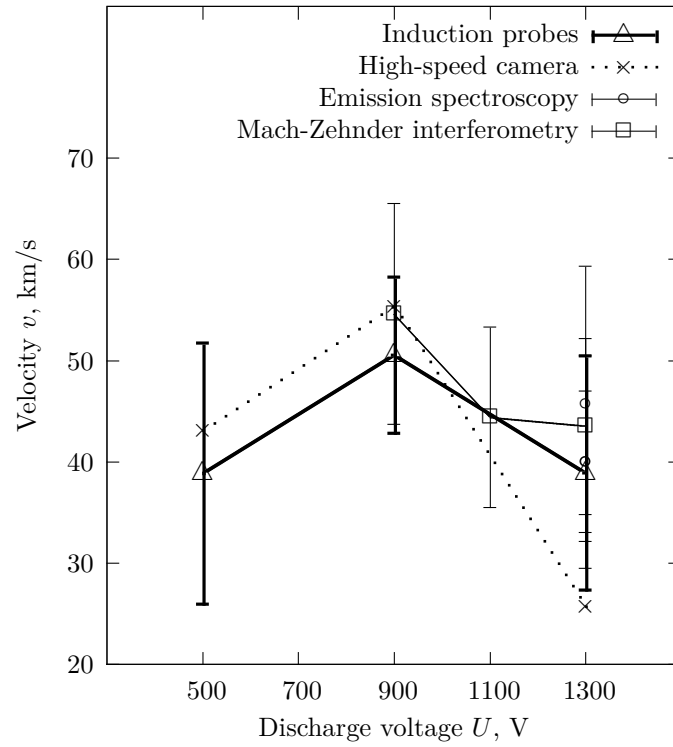


Figure 12. Example image for interferometry measurements at area 1 for $C=80 \mu\text{F}$, $U=1300 \text{ V}$.



(a) Comparison of plasma front velocities for $C = 20 \mu\text{F}$.



(b) Comparison of plasma front velocities for $C = 80 \mu\text{F}$.

Figure 13. Plasma front velocity as a function of voltage and capacitance.

thrust efficiency is not directly linked to the plasma front velocity. Especially, the increase in capacitance that yielded a huge impact in performance seems to have only little effect on the plasma velocity.

IV. Determination of specific plasma parameters

With the measurement of emission intensity and the associated line profiles by emission spectroscopy, as well as from the fringe shift patterns found in the application of the Mach-Zehnder interferometry, several values related to the plasma flow were determined.

By means of the Boltzmann plot, applied on the intense emission lines, the electronic excitation temperature of the ions during the first part of the discharge was determined to be around 22,500 K in average over discharge time and focal position¹². A Voigt fitting was applied to the strong emission lines, in order to enable a determination of the electron density via Stark broadening. The mean electron density determined is $9.4 \times 10^{22} \text{ 1/m}^3$.

The fringe shift patterns indicate a inhomogeneous distribution of the electron density with higher values close to the electrodes. Figures 14(a) throughout 14(i) show the fringe shift patterns for the configuration and timing of the strongest shifts. Figure 14(j) shows the concurrent discharge voltage as reference.

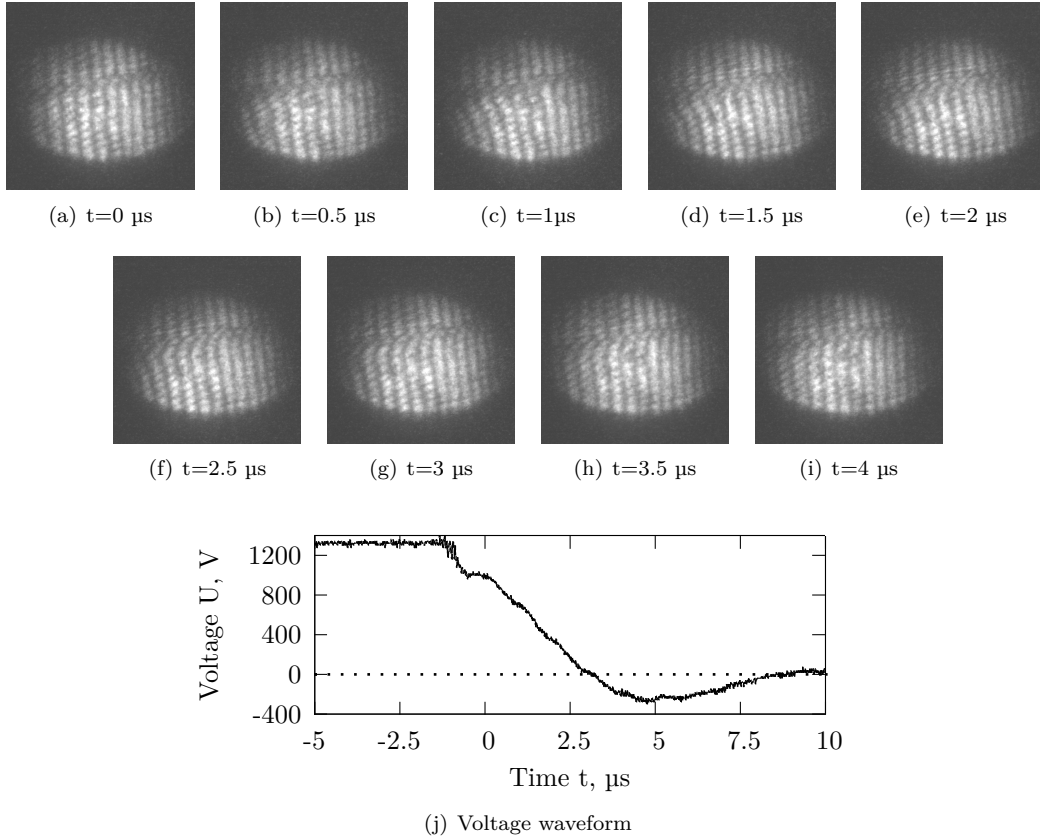


Figure 14. Fringe shift patterns measured for $U = 1300 \text{ V}$, $C = 80 \text{ μF}$, area 1.

By application of two lasers, and by measuring the fringe shift for both experiments at the same position, the electron density can be calculated by:

$$n_e = \underbrace{\frac{8\pi^2 c^2 m_e \epsilon_0}{e^2}}_{C_1} \frac{f_1 \lambda_1 - f_2 \lambda_2}{d_p (\lambda_1^2 - \lambda_2^2)}, \quad (1)$$

with λ_i being the wavelength of the lasers, f_i the fringe shift ratio (displacement by thickness) and d_p the plasma beam thickness through which the lasers travelled. From the calculation it was shown that there is no significant difference in the result for the electron density whether or not applying a two-laser system. By using only one laser, the electron density is:

$$n_e = \frac{f\lambda}{d \cdot K_e}, \quad (2)$$

with K_e being the specific refractive index of electrons derived from:

$$K_e = \frac{\lambda^2}{C_1}. \quad (3)$$

Thus, it can be assumed that neither neutrals nor ions contribute to the fringe shift. Latter because the specific refractive index of ions is several orders of magnitudes lower than the one of ions, former because a very high density would be required to yield a significant fringe shift. In any case (two laser or one laser), a electron density in the flow is determined to be:

$$n_e = \mathcal{O}(10^{23}) \, 1/m^3, \quad (4)$$

confirming the results of the emission spectroscopy. With the Saha equation under the negligence of neutral particles (i.e., local degree of ionization is 1), an electron temperature of about 22,500 K is determined. This matches very well with the electronic excitation temperature derived from the Boltzmann plot thus indicating a LTE. These values agree well with other experimental studies^{13,14} as well as the prediction of the plasma composition by modeling¹⁵

Deriving the mean free path¹⁶ from these plasma parameters yields values for the simple ions to be around 0.7 μm . With a characteristic length of 33 mm, the mean distance between the electrodes, the resulting Knudsen number is $\mathcal{O}(10^{-5})$. Thus, a continuum flow can be expected for the first plasma in the PPT discharge. This would, hence, limit the applicability of numerical models. Especially, as the plasma properties are likely to be different for the second breakthrough as well as for other energy settings or thruster configurations. However, it supports the application of models for a continuum plasma flow, like, e.g., the slug model, which will be used in the following Section.

V. Improvement of slug model to predict propellant utilization

The slug model is an easy prediction tool to analyze the performance of a certain PPT configuration¹⁷. It was extended and improved in previous research¹⁸ to reflect better the observed phenomena. The improvement of the model for the magnetic field and the change in inductance as suggested^{4,11} was improved in terms of convergence, stability and computation speed⁹. The computed magnetic field distribution was backed up by measurements with the induction probe described earlier in this paper.

For a further improvement of the model, the Lorentz force term was replaced by a direct computation:

$$F_L(x_p) = \int \vec{j} \times \vec{B} \, dV \approx \int_{x_p-\delta}^{x_p} \int_{-d(x)/2}^{d(x)/2} \int_{-h(x)/2}^{h(x)/2} \frac{I}{d(x)\delta(x)} \cdot \underbrace{\frac{B_y(x, y, z)}{I}}_{\text{from computation}} \cdot I \, dz dy dx. \quad (5)$$

Thus, the Lorentz force will be changing with the position of the slug. Further, it will be dependent on the current distribution and the slug thickness. For an exemplary thickness of 10% of the position, the Lorentz force as a function of slug position is plotted in Figure 15.

One can see that the computed Lorentz force is increasing towards the end of the electrodes as they narrow down.

In a further change of the slug model, mass of the slug is assumed not to be equal to the ablated mass bit. A propellant utilization efficiency μ is defined as the ratio of accelerated mass m_{acc} (total mass of all slugs in the model) and the experimentally determined mass bit m_{bit} :

$$\mu = \frac{m_{acc}}{m_{bit}}. \quad (6)$$

Instead of using the mass bit to determine the plasma propagation, one can use the determined plasma front velocity in order to derive the propellant utilization. To do so, an iterative computation loop is created. An initial utilization efficiency yields a certain propagation speed. Comparison with the experiment adjusts the propellant utilization, until a certain ratio converges. The resulting efficiencies for the thruster configurations investigated are shown in Figure 16.

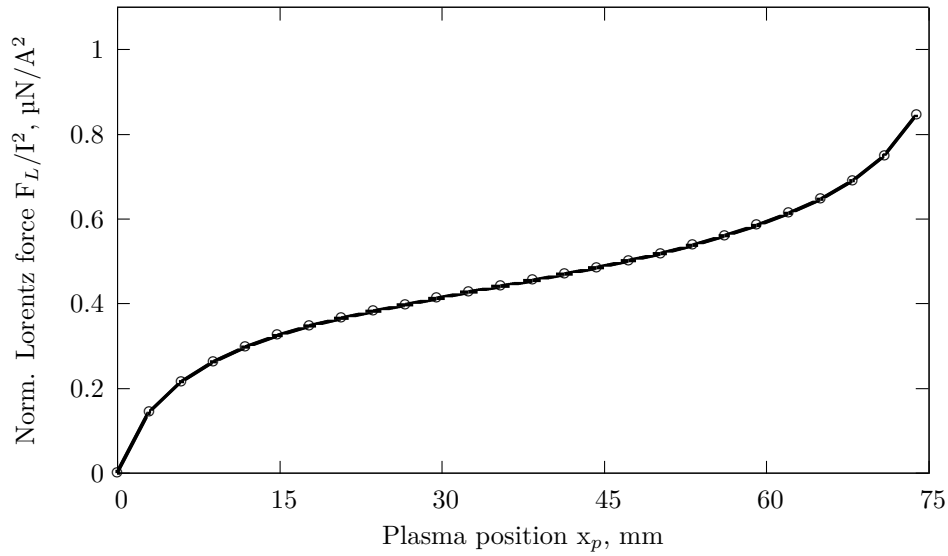


Figure 15. Lorentz force as a function of plasma position directly computed from the magnetic flux density.

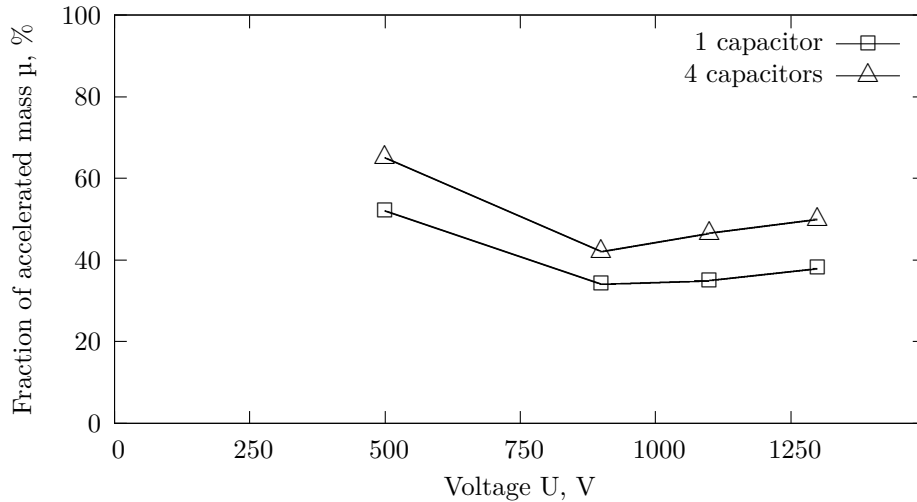


Figure 16. Fraction of accelerated mass as a function of capacitance and voltage.

From these values, it can be derived that a change in voltage has a significant effect on the accumulation of mass in the plasma front. The higher plasma front velocity at around 900V yields a lower mass fraction in the acceleration process, thus, only increasing the total impulse bit marginally. The tendency and the absolute values are similar for the difference in capacitance. Therefore, the voltage seems to be the main influencing parameter. A change in capacitance appears to have only little effect on the resulting mass fraction. Again, this proves that a change in energy can have a very different effect on the performance depending on the electric parameter varied.

By the slug model, it is further possible to derive the total impulse bit of the slugs in order to represent better the experimental values, instead of using the rough estimation formula found by Solbes. In doing so, one obtains the values as shown in Figure 17.

It is obvious that the tendency fits better the experimental values than the estimation formula, thus, justifying the changes and improvements done in the modeling process.

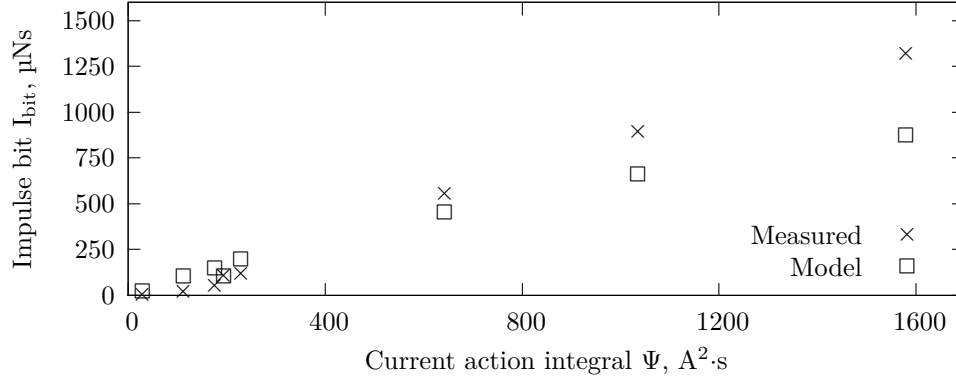


Figure 17. Experimental data and results of modified slug model for the impulse bit as a function of current action integral.

VI. Conclusions

With the discharge voltage and bank capacitance having a different effect on the performance, an increase in energy can yield different changes in the thrust parameters. Thus, even at the same energy level, the balance between capacitance and voltage is important for the discharge process of the PPT, and its resulting plasma characteristics.

From experimental investigation of the plasma front velocity, similar effects as for the thrust efficiency could not be seen. Instead a concave non-linear function of the discharge voltage was determined. Change in capacitance only yielded a small change in the velocity value. Observation with spectroscopy and interferometry suggests that the electron density decreases rapidly for lower voltages, and only slightly for a change in capacitance. Ablation is strongly affected by the variation of both energy parameters. Experimental data suggest that the ablation process is more efficient for a higher capacitance producing a smaller mass bit for the same current action integral. Hence, a less strong late-time ablation is expected. This idea is backed up by the computation of the propellant utilization efficiency by means of an extended and improved slug model. The results show a general increase of the efficiency with higher capacitance, whereas the voltage effect seems to saturate. This could eventually lead to the stagnation of the thrust efficiency as found in the literature review.

The use of the slug model was justified by deduction of the Knudsen number for the plasma flow in the order of 10^{-5} suggesting continuum flow.

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