

# Polymers as fuel for laser-based microthrusters: An investigation of thrust, material, plasma and shockwave properties

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## Abstract

The micro-laser plasma thruster ( $\mu$ -LPT) is a micropropulsion device, designed for steering and propelling of small satellites (1–10 kg). A laser is focused onto a polymer layer on a substrate to form a plasma, which produces the thrust that is used to control the satellite motion. Three different polymers were tested to understand the influence of their specific properties on the thrust performance: poly(vinyl chloride) (PVC) as a low-energetic material, a glycidyl azide polymer (GAP), and poly(vinyl nitrate) (PVN) as high-energetic polymers. Different absorbers (carbon nanoparticles or an IR dye) were added to the polymer to achieve absorption at the irradiation wavelength (1064 nm). The influence of the material and dopant properties on the decomposition characteristics and the energy release were investigated by thrust measurements and ns-shadowgraphy. Mass spectrometry and time- and space-resolved plasma emission spectroscopy in air and vacuum were used to analyze the degree of fragmentation as function of the material properties. The kinetic energies of selected fragments were calculated from the spectra. GAP + C showed the best performance in all measurements at high fluences, while at low fluences PVN + C revealed the best performance.

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**Keywords:** Polymer; Micro-laser plasma thruster; Laser ablation

## 1. Introduction

The micro-laser plasma thruster ( $\mu$ -LPT) is a small propulsion device designed for the steering and propelling of small satellites (1–10 kg). There are special requirements on mass, volume and power for such a propulsion system, but the most important criterion is a low mass of less than 1 kg. Other requirements are a thrust of at least 75  $\mu$ N and 300 N s lifetime impulses [1,2].

Due to these demands, the  $\mu$ -LPT is driven by small powerful diode lasers, which emit in the near IR (920–980 nm) with an available power of 1–15 W and a pulse length from 100  $\mu$ s to the millisecond range [3]. This wavelength and pulse duration limit the material selection to materials with a low thermal conductivity, i.e. polymers [4,5].

The principle of a laser plasma thruster is illustrated in Fig. 1. A diode laser is focused on the fuel polymer through the substrate to form a plasma. The thrust produced by this plasma

is used to propel the satellite. The expansion of the plasma in a confined angle allows an application of this device without any nozzle, which might be difficult to design, fabricate and operate.

The fuel polymer is cast on a transparent substrate layer. Kapton<sup>TM</sup> has been selected as substrate due to its solvent resistance, physical toughness, outgasing properties [6], and the transparency in the near IR. The irradiation through the substrate has the advantage of protecting the laser optics from ablation products. Additionally an easy fuel supply and a high usage of the fuel polymer are possible with this tape design.

## 2. Experimental

### 2.1. Materials

Three polymers with different decomposition properties were studied. The chemical structures of all three polymers are shown in Fig. 2. Poly(vinyl chloride) (PVC) was used as a commercially available material, which has been studied previously [7,8]. Two “energetic” polymers, a glycidyl azide polymer (GAP Polyol obtained from Nitrochemie, Wimmis)

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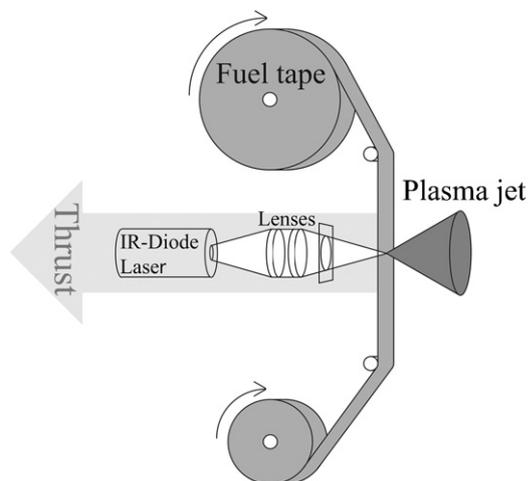


Fig. 1. Scheme of the  $\mu$ -laser plasma thruster.

and poly(vinyl nitrate) (PVN, synthesized as described in Refs. [9,10]) were used to study the influence of chemically stored energy. The decomposition temperature and the decomposition enthalpy of the three polymers are shown in Table 1.

Both PVN and PVC are solvent cast from dilute (5–10 wt.%) polymer solutions, and are linear polymers with a well defined softening temperature of 30–45 °C for PVN [11], and a melting temperature ranging from 175 to 212 °C for PVC [12]. GAP is a crosslinked polymer and shows therefore no signs of softening or melting. The crosslinker is added to the 70 wt.% polymer solution prior to tape casting the polymer on a Kapton<sup>TM</sup> substrate.

As all three polymers do not absorb in the near IR, absorbers had to be added. For all three polymers, carbon nanoparticles were added to the polymer prior to casting the polymers. In the case of GAP an IR-dye (Epoline 2057) was also used as absorber to understand the influence of the absorber and its distribution in the polymer film [8]. The amorphous carbon nanoparticles with a nominal size of 15 nm tend to agglomerate and form clusters with diameters of up to 15  $\mu$ m [13]. The IR-dye on the other hand is uniformly distributed on a molecular level throughout the polymer film.

The polymers will be referred to in this paper with the abbreviation of the polymer and by indicating the dopant by “+C” for carbon and “+IR” for the IR-dye.

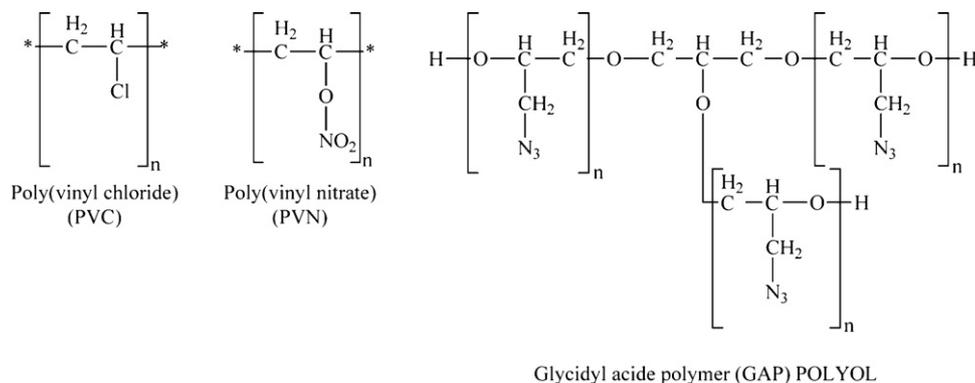


Fig. 2. Chemical structures of PVC, PVN and GAP Polyol.

## 2.2. Experimental setup

For the spectroscopy and shadowgraphy experiments the fundamental wavelength ( $\lambda = 1064$  nm,  $\tau = 6$  ns) of a Nd:YAG laser (Brillant B from Quantel) with a supergaussian beamprofile with some hotspots was utilized. The shadowgraphy measurements were performed under ambient conditions at fluences below the plasma formation threshold. The experimental setup is described in detail in [8]. The mass- and plasma emission spectroscopy were performed in a UHV chamber at a pressure of  $8 \times 10^{-6}$  Pa. The sample was mounted on a xyz-manipulator (see Fig. 3), with the sample normal directed at the mass spectrometer. The manipulator was used to create a matrix of measurements spots in the polymer with two laser pulses per position on the sample. The spatial resolution of the plasma emission spectroscopy was achieved by moving a double slit system parallel to the symmetry axis of the expanding plasma. Two slits arranged at 90° with a width of 1 mm were used in a distance of 15 cm to the plasma. The light passing the two slits was then focused on an optical fiber, coupled to the spectrometer (Acton 500) and a gated ICCD camera (Princeton Instruments). The time resolution was achieved by delaying the trigger signal between the external trigger of the laser and the trigger signal to the ICCD-camera.

All mass spectrometric measurements have been performed with an electrostatic quadrupole plasma (EPQ) Analyzer (Series 1000, from Hiden Analytical) which allows to measure masses in the plasma, which is very dense compared to vacuum conditions normally necessary for mass spectrometric measurements.

The mass spectrometer was kept at a constant distance of 3 cm from the sample surface with the nozzle in the center of

Table 1

Solvents used for casting the GAP, PVN and PVC films and decomposition properties of the three polymers

Polymer	Solvent	Decomposition temperature (°C)	Decomposition enthalpy (J/g) <sup>a</sup>
GAP	Ethyl acetate	249	−2053
PVN	Acetone	204	−3829
PVC	Cyclohexanone	241, 288, 383	−418

<sup>a</sup> Measured by DSC, using carbon doped samples of the polymer.

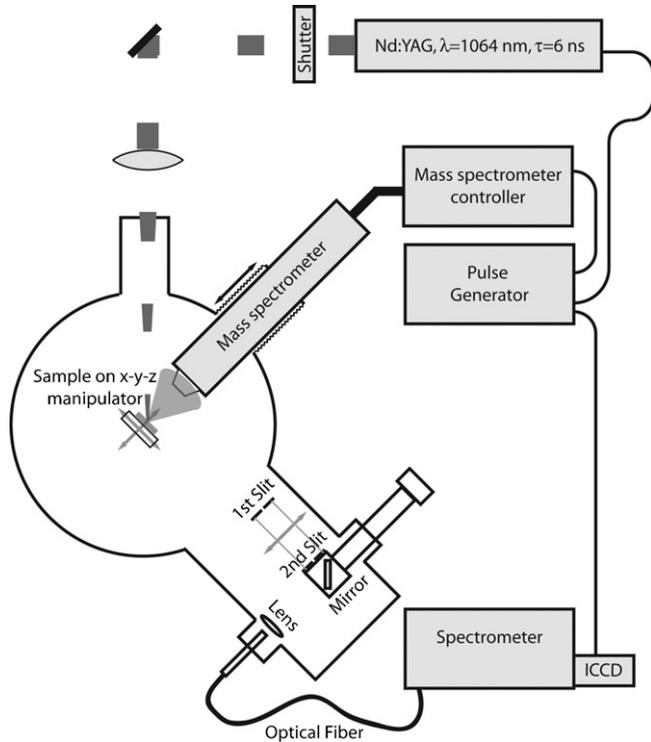


Fig. 3. Experimental setup for the mass- and plasma emission spectroscopy measurements.

the expanding plasma. The mass spectrometer was triggered 14  $\mu\text{s}$  prior to the laser with an accumulation time of 2 ms for each pulse. For each mass or energy spectrum, 10 pulses were averaged.

### 2.3. Thrust measurements

The target momentum of the polymers was measured with a torsion balance as described in [7] to analyze their performance in a  $\mu$ -LPT. From the target momentum, the momentum coupling coefficient,  $C_m$ , was calculated according to

$$C_m (\text{dyn/W}) = \frac{m \Delta v}{W} = \frac{F}{P} \quad (1)$$

where  $m \Delta v$  is the target momentum produced during the laser ablation through the ejection of material,  $W$  the induced laser pulse energy,  $F$  the thrust, and  $P$  is the incident power. The specific impulse  $I_{sp}$  is the second important parameter for thrusters and is defined as

$$I_{sp} g (\text{cm/s}) = v_E = C_m Q^* \quad (2)$$

$Q^*$  is the specific ablation energy (incident power/mass ablation rate),  $v_E$  the exhaust velocity, and  $g$  is the acceleration due to gravity.

The ablation efficiency parameter  $\eta_{AB}$  is defined as the efficiency of the conversion of the laser energy into exhaust kinetic energy:

$$2\eta_{AB} (\%) = C_m v_E \quad (3)$$

## 3. Results and discussion

### 3.1. Plasma emission spectroscopy

Time and space resolved plasma emission spectra of Balmer  $H_{(\alpha)}$  line at 656.6 nm have been recorded for an irradiation fluence of 25  $\text{J cm}^{-2}$ . The temporal position of the maximum intensity for each distance from the sample surface was used to calculate the propagation velocity of the excited hydrogen along the central axis of the plasma plume (see Fig. 4).

The fastest hydrogen was observed for GAP + C and PVC + C, followed by GAP + IR and PVN + C. The expansion velocities are compared in Table 2.

### 3.2. Mass spectroscopy

The fragmentation of the polymers upon near-IR laser irradiation has been studied by mass spectrometry and a higher fragmentation for the energetic polymers has been observed [14]. For all polymers one of the main decomposition products was positively charged carbon ( $\text{C}^+$ ). The kinetic energies of the  $\text{C}^+$ -ions were measured with the mass spectrometer and the energy spectra are shown in Fig. 5 for an irradiation fluence of 23  $\text{J cm}^{-2}$ . The expansion velocity of the selected species was

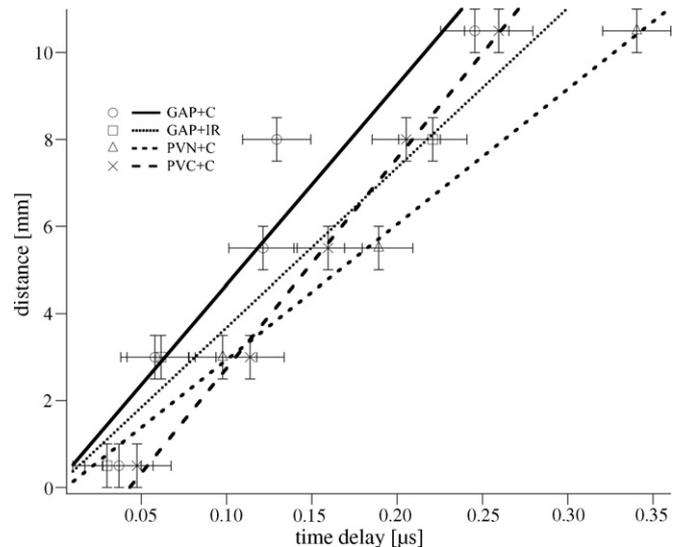


Fig. 4. The distance vs. time delay for the detection of the maximum intensity of the Balmer  $H_{(\alpha)}$  peak at 656.6 nm. The irradiation was performed with a fluence of 25  $\text{J cm}^{-2}$  at 1064 nm.

Table 2

Expansion velocities for the shockwave,  $\text{C}^+$ -ions and hydrogen from the Balmer  $H_{(\alpha)}$  line

Polymer	Shadowgraphy (m/s)	Mass spectrometry (m/s)	Plasma emission (m/s)
GAP + C	710	28,600	46,000
GAP + IR	850	29,300	36,700
PVN + C	1080	25,100	31,100
PVC + C	630	25,900	48,300

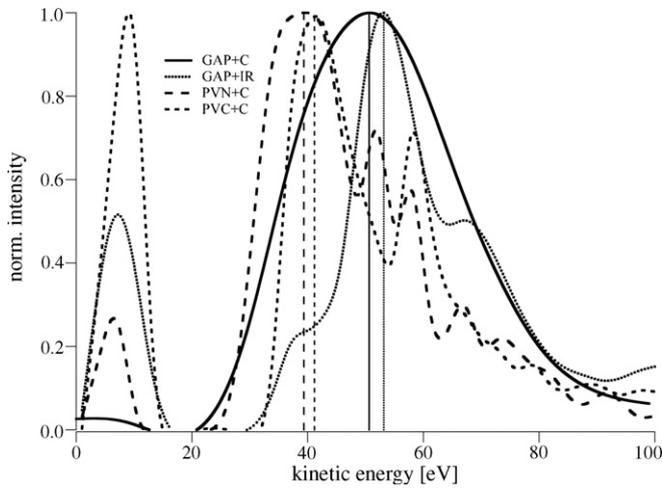


Fig. 5. Kinetic energy vs. the normalized intensity of the  $C^+$ -ions at a irradiation fluence of  $22.6 \text{ J cm}^{-2}$ . The velocities shown in Table 2 are calculated from the kinetic energies with the highest intensity.

determined from the energy with the highest intensity (vertical lines in Fig. 5). The highest velocity was observed for GAP + IR, followed by GAP + C. For PVN + C and PVC + C a similar lower velocity for the  $C^+$  was observed (see Table 2). In comparison to the velocities from the emission measurements, velocities that are consistently lower by a factor of 1.2–1.8 are obtained. One possible explanation for this is the experimental design, i.e. emission spectroscopy is a non-invasive measurement method, whereas the mass spectrometer and the nozzle can have an influence on the plasma and its expansion, as they are in direct contact with the expanding plasma. Another possible reason could be the fact that in the energy measurements with the mass spectrometer, ions are measured, while the Balmer  $H_\alpha$  line corresponds to neutral hydrogen. We have not yet established whether in our experiments the ions and neutrals have the same velocities.

To allow a comparison of these two methods, more experiments with the same species have to be performed.

### 3.3. Shadowgraphy

Shadowgraphy was applied as fast, non-vacuum method to test the different polymers, where the shockwave velocity is used as indicator for the thrust performance of the polymer.

The expansion velocity of the shockwave has been calculated  $1 \mu\text{s}$  after the laser pulse (vertical line in Fig. 6). The highest expansion velocity has been observed for PVN + C, followed by GAP + IR, GAP + C and PVC + C (see Table 2). This result corresponds well to the decomposition enthalpies of the polymers. PVN, the polymer with the highest decomposition enthalpy, has the fastest shockwave, while for PVC the lowest shockwave velocity and decomposition enthalpy was measured. It is noteworthy to emphasize that the shadowgraphy measurements are performed in air and at much lower fluences than the spectroscopic and thrust measurements.

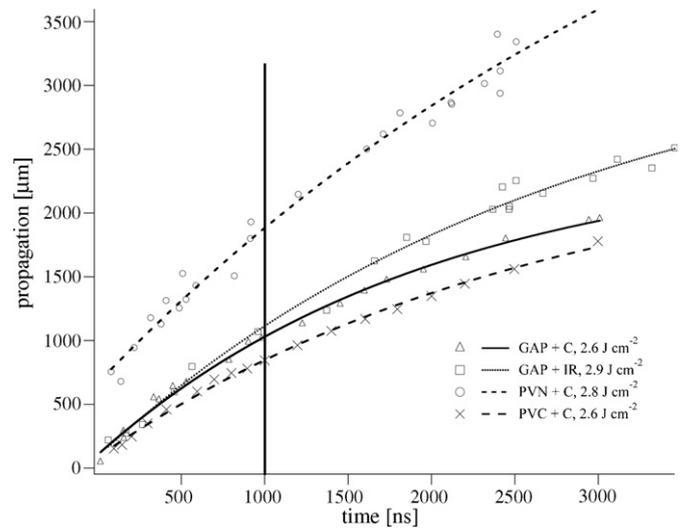


Fig. 6. The shockwave velocity obtained from shadowgraphy measurements. The vertical line indicates the  $1 \mu\text{s}$  time delay, for which the velocities are listed in Table 1.

### 3.4. Thrust measurements

The polymers will eventually be rated for their thrust performance, which origins most probably from a combination of volume explosion from the polymer decomposition, Coulomb repulsion and impulse from larger, fast traveling fragments.

The thrust measurements reveal the best performance for GAP + C as fuel polymer with  $\eta_{AB}$  of up to 368%. GAP + IR reveals also a  $\eta_{AB}$  value, which exceeds 100% (see Table 3). This means that more energy is released in the form of thrust than deposited in the polymer by the incident laser pulse, suggesting that the  $\mu$ -LPT with GAP as fuel can be described as a hybrid thruster utilizing chemical-stored and laser energy. For PVC + C and PVN + C  $\eta_{AB}$  values are observed that are significant lower. This was expected for PVC + C, as only a small amount of energy is stored in the polymer.

PVN has the highest decomposition enthalpy of  $-3829 \text{ J/g}$ , but shows the worst performance of all polymers in all experiments at high fluence, i.e. mass-, plasma emission spectrometry, and the thrust measurements. Only in the shadowgraphy measurements the fastest shockwave was observed for PVN + C. One possible explanation for this surprising behavior could be related to the material properties of PVN, as it is a thermoplast with a softening temperature of  $30\text{--}45 \text{ }^\circ\text{C}$ . When this temperature is reached during the

Table 3

Thrust data for all for polymer-absorber systems at optimized experimental conditions, i.e. maximum  $\eta_{AB}$  value

Polymer	$I_{sp}$ (s)	$C_m$ ( $\mu\text{N/W}$ )	$v_E$ (m/s)	$\eta_{AB}$ (%)
GAP + C	867	865	8502	368
GAP + IR	256	1574	2510	198
PVN + C	137	310	1343	21
PVC + C	159	635	1559	49

decomposition process, the polymer starts to flow and later to melt. For the evaluation of the thrust measurements, the ablated mass has to be determined. The thermal effects such as melting or the observation of fibers on the surface [14] may result in an overestimation of the ablated mass, which will yield a lower momentum coupling coefficients and efficiencies (Eqs. (1) and (3)). The mass spectra presented in Ref. [14] also reveal the presence of solvent in the polymers film. The remaining solvent acts as inert mass during the ablation process, which will not contribute to the thrust.

The thrust data corresponds quite well with the mass spectrometry measurements, where the fastest  $C^+$  fragments were obtained for GAP with both dopants, followed by PVC and finally PVN. This indicates that  $C^+$  plays an important role for the thrust and is probably more important than the influence of neutral hydrogen (plasma emission measurements).

### 3.5. Discussion

Only a qualitative correlation can be established between the different methods. GAP + C shows a good performance in all experiments, while GAP + IR reveals good results in the thrust and mass spectrometry measurements, but the velocity of the hydrogen measured by plasma emission spectroscopy is much lower compared to GAP + C and PVC + C. It has to be considered that until now, only a single line in the emission spectra (Balmer  $H_{(\alpha)}$ ) and only one mass in the mass spectrometer ( $C^+$ ) have been investigated in detail. It is possible, that thrust, which is the sum of different effects, can only be explained by a combination of different measurements.

The longer pulse lengths and shorter irradiation wavelength in the thrust measurements may also have a significant influence on the ablation process. The longer pulse length could increase the influence of the thermal side effects, such as melt ejection, and may therefore result in the worse performances of the thermoplasts, PVN and PVC.

For a quantitative correlation the thrust measurements have to be performed with the same experimental conditions, i.e. pulse length and irradiation wavelength.

## 4. Conclusions

The best overall performance from the studied polymers is observed for GAP + C, but only a qualitative correlation can be established between the different spectroscopy methods and the measured thrust. GAP + C clearly indicates the importance and possibility of the utilization of the chemical energy stored in the

polymer, as 3.7 times more energy was released as thrust than deposited by the laser pulse. Energy could also be gained from decomposing GAP + IR, while PVN, the polymer with the highest decomposition enthalpy, exhibits the worst performance in all experiments at high irradiation fluences. This is probably caused by the thermal properties of the polymer, i.e. the ejection of molten polymer, which is lost for the decomposition process and a pronounced amount of remaining solvent in the polymer film.

An ablation efficiency of  $\sim 50\%$  was achieved for PVC + C, which is not surprising, as only a small amount of energy is gained from the decomposition of the polymer.

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