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Demonstrative set-up for Propulsion Induced by High Power Pulsed Laser Irradiation

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Abstract
Ablative laser propulsion can be widely proposed in aerospace applications, including laser micro thrusters for spacecraft attitude, orbit control, debris removal, etc. The high-power HiLASE beamline facility (Dolní Břežany, Czech Republic) with BIVOJ (100J, 10ns, 10Hz, 1030nm) is used as a laser facility enabling high-energy, short-pulse, repetitive irradiation. As a demonstrator, a “Rail or V-shaped track” system was specially designed. Solid targets, namely hollow metal-coated polymer projectiles, are irradiated in single and multi-shot laser loading mode. As a propulsive answer, the velocity induced by the laser/matter interaction of the ablated targets is investigated offering perspective in this domain.

Keywords: High power pulsed laser interaction, HiLASE BIVOJ laser, Ablative laser propulsion, V-track Demonstrator

1. Introduction

Pulsed Laser Propulsion (PLP) is an advanced propulsion concept that can be used in a variety of fields with a wide range of applications. Firstly, proposed by Arthur Kantrowitz in 1972 [1], it provides thrust from external energy sources. It requires many technical challenges, such as target displacement/trajectory (i.e. deorbiting large numbers of space debris), target tracking, choice of target materials (i.e. improving the quality of combustion materials ejected into the already overloaded atmosphere) [2-4] including polymers that can be doped with different types of absorbers to achieve absorption at the irradiation wavelength [5,6] and coupling to high-energy laser sources [7-9].
To better understand the propulsion of matter by laser ablation, previous work has evaluated avenues using different high-power laser sources interaction with ‘model’ targets to create plasma jets [10-15]. For optimizing the performance of laser propulsion applications, it is required to provide effective data, as for instance the thrust that relies on the interaction between laser and material [14].
In the present work, it is proposed to apply PLP for the Low Earth Orbit (LEO) environment that is threatened by runaway collision cascades [16-19]. A “Rail or V-track” system demonstrator is specially designed to evaluate comparatively the efficiency of repeated laser bursts on moving objects. Solid targets are metal-coated hollow polymer spheres. The targets are irradiated in single-shot and multi-shot laser loading mode. The velocity induced by the laser/matter interaction of the ablated targets is evaluated as a function of various laser irradiation with BIVOJ facility.

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2. Experimental set-up and Materials

The experiment was conducted in the HiLASE laser center (Dolní Břežany, Czech Republic) with the BIVOJ laser system [20]. This source is a single beam, cryogenically cooled, multi-slab laser system delivering over 1kW of average power in 80J (for the present work), 10ns pulses at 10Hz, 1030nm wavelength. BIVOJ represents the world's first kW average power, diode pumped solid state laser.

According to preliminary results on materials integrity to repeated high power pulsed irradiation [21] polymer and aluminum were retained for evaluating the propulsive effect. The target should be light enough to move even with low thrust, such as a that generated by a single pulse on aluminum target. Therefore, ablation on hollow metal (aluminum)-coated polymer projectiles were tested during this experiment. Two sizes of spheres were used, the first with 40mm (approx. 3g) diameter and the second with 55mm diameter (approx. 7g) (see Section3).

The target was placed into a "V-shaped track" system. The track system was specifically designed for this experiment (4m length, atm pressure) and the direction of propagation of the laser was aligned parallel to the rail at the level of the projectile.
The aim is to estimate the velocity of a spherical target that can be induced by the laser/matter interaction for various energies and number of pulses in the BIVOJ regime, and also with a tilted V-shaped track (5.6°).

Figure 1 illustrates the experimental V-shaped setup on the BIVOJ line.

Figure 1: "V-shaped track" propulsion set-up installed at BIVOJ external users platform. a. "V-shaped track" 0° mode. b. "V-shaped track" 5.6° mode. c. Schematic of the environmental installation. Full spot size on target was between 30 and 40mm in diameter (without focalization).

3. Results and Discussion

3.1. Effect of intensity conditions – target 40mm, V-shaped track 0° (horizontal)

Defining the initial situation (as the origin in time and space, t0=0s for a distance Δdistance=0mm), the distance traveled by the propelled target is followed. At firing events, i.e. when the laser interacts with the target, the interaction behavior can also be observed by the high-speed camera.

Let's take the case of two irradiations, called **I1** and **I2**, with a target diameter of 40mm and without rail tilt, namely (**I1**: 10Hz_60pulses, energy on target 13J, intensity 0.188GW/cm^2) and (**I2**: 10Hz_30pulses, energy on target 16J, intensity 0.232GW/cm^2). Figure 2 illustrates the event for **I1** irradiation. The illustrations were selected to follow the target's path. Laser comes from the left; the laser interaction is visible by illuminating the target surface.

From the first laser interaction, a plasma expansion is visible. This signature indicates that the exhaust cloud is moving in the opposite direction to the target's forward movement. These ablation clouds (or plumes) have been observed in the work of [22,23]. The existence of these plumes and their density, or even their accumulation of presence with each shot, raises a question: would they lower the propulsion efficiency by absorbing partly laser energy of the following shots resulting in a lowered propulsive effect (by creating a kind of protective mask)? In this case, would the velocity decrease? By quantitatively representing the displacement of the target versus time, Graph 1, at this scale it does not seem that the impact of the particle cloud, induced by the previous shot, on a local acceleration/or a local velocity change is visible. Nevertheless, this open question remains to be considered and verified more in detail.

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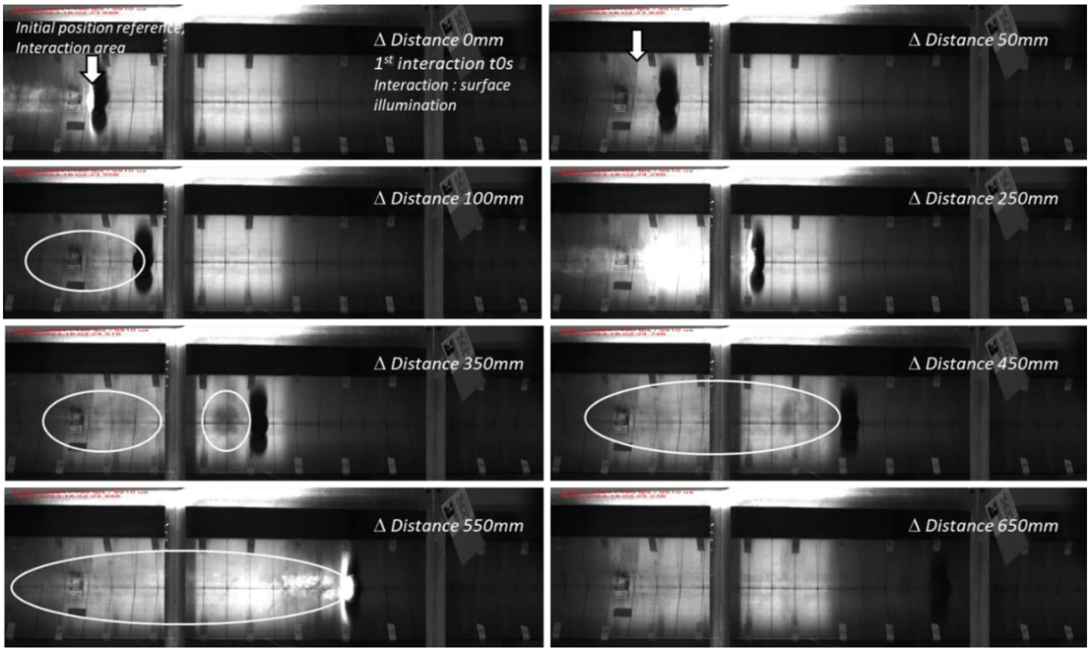
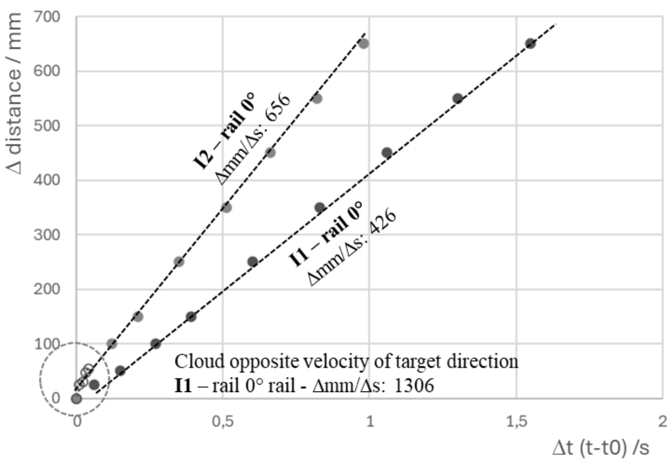


Figure 2: Propulsion event on an aluminum-coated polymer target (40mm in diameter). **I1** irradiation: 10Hz_60pulses, energy on target 13J, intensity 0.188GW/cm^2). Rail 0°. View from the top of the V-shaped rail. Laser comes from the left. The ablation clouds are shown in the circles.



Graph 1. Propulsion event on a 40mm in diameter polymer target. **I1**(13J, 0.188GW/cm^2) and **I2** (16J, 0.232 GW/cm^2) irradiations. Distance traveled vs. time. Note: Open symbols, **I1** irradiation cloud velocity with acceleration in the opposite direction

The two experimental conditions **I1**(13J, 0.188GW/cm^2) and **I2** (16J, 0.232 GW/cm^2) show the propulsive effect on a light 40mm diameter spherical polymer target rolling with friction on the V-shaped rail. The target displacement is increasing with time. However, **I1** condition with about 19% less intensity on target gives about 35% lower speed compared to **I2** irradiation. It is emphasized that the coupling coefficient and thus the thrust is not a linear function of the intensity.

Nota: We note that in the experimental conditions of **I1**, tentatively, the propagation speed of the most visible (dense) part of the ablation cloud was estimated (announced value taken positive but is negative if we consider the target direction); and it shows a speed three times higher than that of the ball movement. propagation of fine (lightweight) particles. The ablation cloud propagation is hindered by the ambient air molecules (a kind of 'frictionless' in the air) but the particles from the plume are fine (lightweight) particles and thus have larger speed than the target with, moreover, a velocity distribution.

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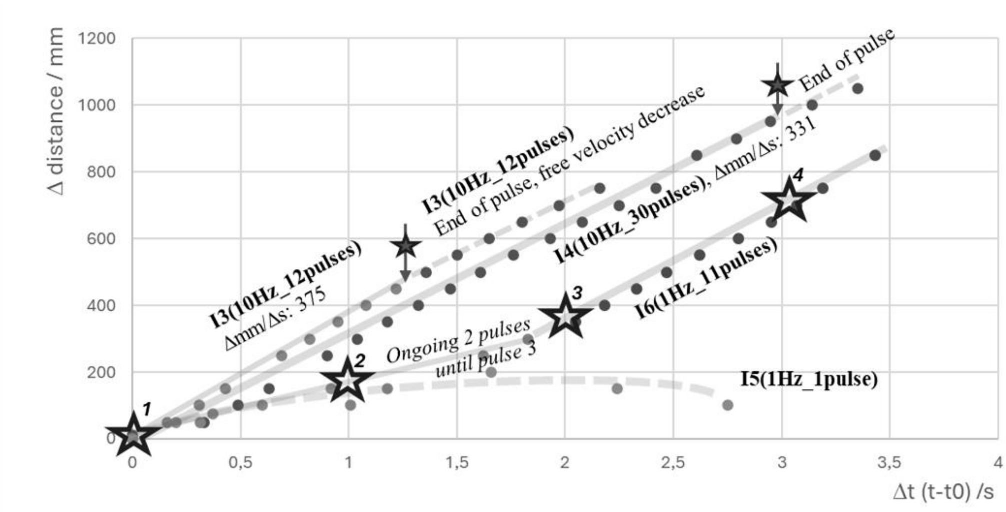
3.2. Effect of V-shaped track inclination – target 55mm

To go further in demonstration, the influence of inclination of the V-shaped track on the propelling abilities for given laser energy conditions is investigated.

i- V-shaped track 0°

In this section, different experimental conditions were selected by keeping constant the energy on target to 27J which corresponds to a constant and intensity of 0.217GW/cm^2 and employing polymer spheres with a 55mm diameter. In Graph 2 the displacement of the target on the rail is shown versus time, for four different irradiations conditions, namely (**I3**: 10Hz_12 pulses), (**I4**: 10Hz_30 pulses), and (**I5**: 1Hz_1 single pulse), (**I6**: 1Hz_11 pulses).



Graph 2. Propulsion events on a 55mm in diameter polymer target at a constant energy of 27J and intensity of 0.217GW/cm^2. Distance traveled vs. time.

Similar to the descriptions presented for the 40mm target, the trends are linear for 10Hz frequencies. The speeds Δmm/Δs remain fairly close to each other. The curve for the **I3**(10Hz_12pulses) condition indicates a constant tendency velocity during the pulsed-irradiation followed by a decrease in the velocity after the end of the irradiation due to friction. For the **I6**(1Hz_11pulses) condition, laser shots are spaced further apart in time compared to 10Hz conditions.

It can be seen, for the **I6**(1Hz_11pulses), that the movement of the target consists in a series of translations lasting 1s (the interval between subsequent pulses). Each 1s-translation between two laser pulses occurs at a velocity that is almost constant (since the displacement versus time is close to linear). However, each new pulse increases the velocity of the target since the slope of the position versus time increases incrementally after each second. This is due to the residual speed of the target (due to previous pulse) when a new pulse impinges on it: during 1s the rate of kinetic energy losses (friction) is low enough not to stop the ball on the rail. This can be seen from the irradiation **I5** on Graph 2 related to the action of a single pulse on an initially immobile target. In this case, the target stops only after about 3s. Therefore, 1s after the pulse, the target has a residual velocity. We also note that the speed (slope of the data points for the single shot irradiation for **I5**) is almost constant during the first second.

Importantly, the comparison between 1Hz and 10Hz shows a much better efficiency for the 1Hz regime: a much lower number of pulses are needed to reach the same distance. For example, after four pulses, the target is about 700 mm from the reference position in the case of irradiation with 11 pulses at 1Hz while it is only about 100 mm in the cases of the 10Hz regime. This non-intuitive behavior could be explained by the screening of the laser beam by the target ablation plume. During 1s, the ablation cloud can expand in ambient air sufficiently to become mostly transparent to the next pulse. In the 10Hz regime, however, the clearing of the ablation plume on the path to the target is far from complete before the next pulse reaches the target, resulting in a significant absorption ahead of its surface and a loss of propulsion efficiency.

The fact that there are larger losses (due to screening of the laser) in the 10Hz regime compared to the 1Hz regime can be viewed by comparing the evolution of the speed pulse after pulse (the slopes of the data in Graph 2). In the 1Hz regime the speed increases pulse after pulse which means a global acceleration of the sphere, i.e. a global positive forward thrust that is overcoming the losses due to air friction on the rolling sphere. On the contrary, for the 10Hz

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irradiations, the speed is almost constant over the 12 or 30 shots series (1.1s and 2.9s, respectively) which expresses a zero acceleration and thus, globally, a balance between the thrust imparted by the laser pulses and the losses.

ii- V-shaped track 5.6°

Let us take the case of the **I7**(10Hz_30pulses, energy 27J and intensity 0.217GW/cm^2) with the rail inclined by 5.6 degrees. Figures 3a-b illustrate the events.

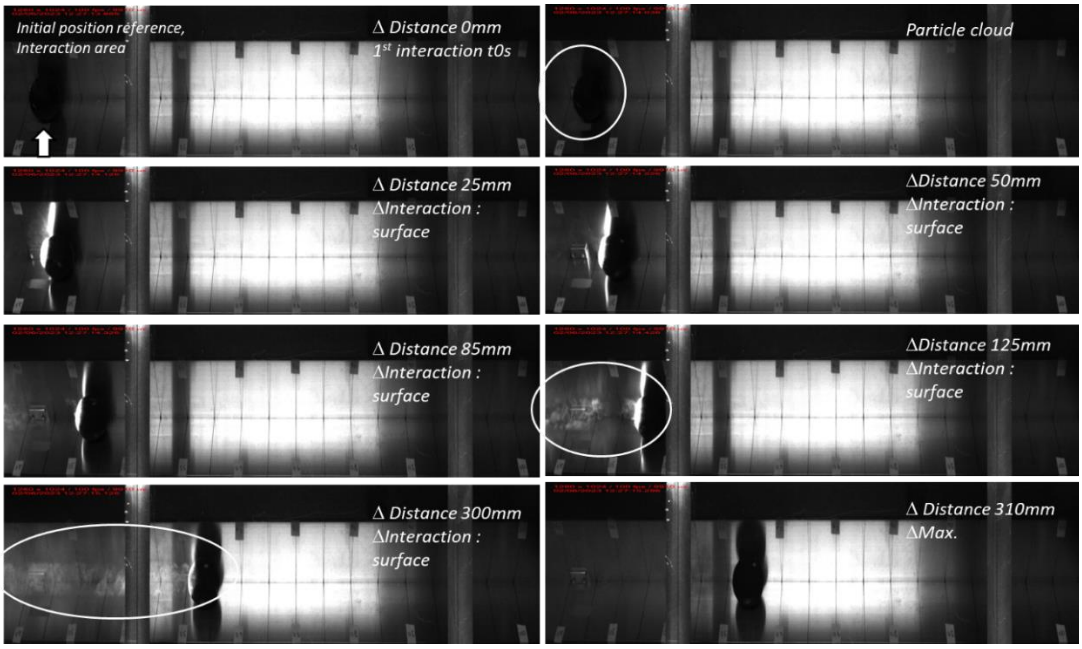

Figure 3-a: Propulsion event on an aluminum-coated polymer target (55mm in diameter). **I7**(10Hz_30pulses, energy 27J and intensity 0.217GW/cm^2) – 5.6° rail. First ascent.

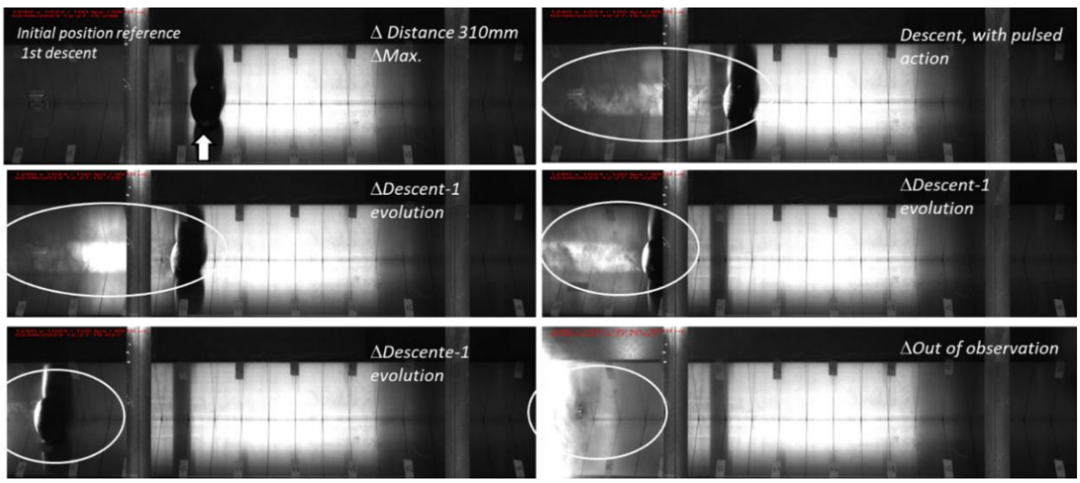

Figure 3-b: Propulsion event on an aluminum-coated polymer target (55mm in diameter). **I7**(10Hz_30pulses, energy 27J and intensity 0.217GW/cm^2) – 5.6° rail. View from the top of the V-shaped rail. Laser comes from the left. First descent. The ablation clouds are shown in the circles. They scatter part of the beam.

As before, each laser/matter interaction is visible by the illumination of the surface of the target with creation of a cloud of ablated particles. The target position reaches a first maximum, then begins the first descent despite the further incoming pulses. The descent passes through the zero point (reference position) until reaching the lower stop of the rail (outside the camera observation field). Then the target begins a second ascent/descent, as well as a third after passing through the zero point again and reaching the lower stop (Graph 3). The uphill movements generally appear to be faster than the downhill ones; however, the values remain fairly close in these conditions.

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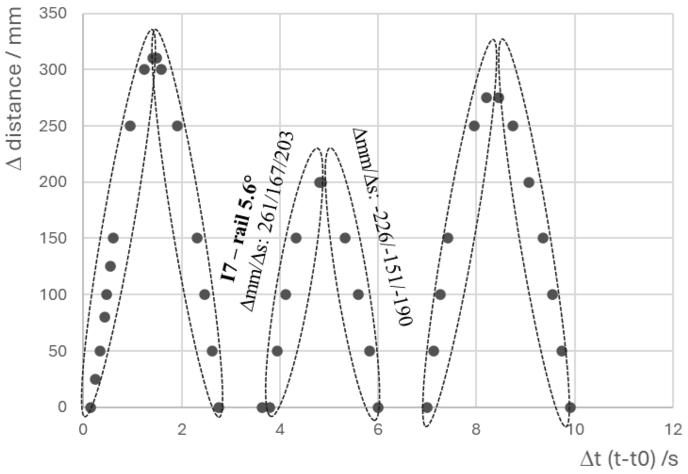

Graph 3. Propulsion event on a 55mm in diameter polymer target and V-shaped track. **I7**(10Hz_30pulses, energy 27J and intensity 0.217GW/cm^2) – 5.6° rail. Distance traveled vs. time.

Conclusion

The present work reports the first results on a direct technique for determining the ablation thrust by implementing a rail system for guiding spheres propelled by laser irradiation. The high power HiLASE beamline facility (Prague, CZ) with BIVOJ (100J, 10ns, 10Hz, 1030nm) is used as allowing both high energy and repetition rate of a short pulsed irradiation.

Those results show clearly an influence of the repetition rate and the number of pulses of the LAP performance on several aspects. In particular, it is illustrated that in ambient atmosphere conditions and for our coated spheres, irradiations close to 0.2 GW/cm^2 by 10 ns nanosecond laser pulses fired at 10Hz are less efficient than at 1Hz due to the significant screening of the beam by the ablation products.

Additionally, we have to keep in mind that the ablation plume density depends on the material and at the same time the ablation can, in our case, remove completely the coating leaving apparent the polymer in some places which would in turn change the performance of ablation depending on where the laser hits the surface of the targets (polymer part vs. aluminum part).

Our ongoing work will attempt to look at the influence of the shape of the laser beam, and damage of surface.

As an extended work, the use of other laser conditions is in our perspective.

Acknowledgements

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