LASER PROPULSION – A NEW TECHNOLOGY FOR SPACE FLIGHT

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Abstract

In the last decades the principle of laser propulsion has been demonstrated by several laboratory experiments all over the world. The primary goal of these investigations was the development of alternative launch concepts for very small satellites (nanosats) from earth’s surface to low earth orbits (LEO). Unfortunately, it turned out, that the required laser power will not be available in near future.

The rapid progress in the field of solid-state laser technology triggered the development of powerful compact pulsed laser sources even for applications in zero gravity environments and space. Equipped with this new laser sources laser propulsion technology offers new concepts for position keeping and attitude control of satellites or satellite constellations in orbit. Beam control with active and adaptive optical systems enables long range or remote laser propulsion. A future step may be space missions with sampling probes to asteroids or small planets and the return on a tractor beam.

Today, the main objective is the development and evaluation of precise laser thrusters in the range from 0.1 µN to 1 mN. Alternative micro propulsion concepts are absolutely essential for many missions with precise attitude and orbit control. There is a growing demand due to geodesic missions measuring earth’s gravity (successors of CHAMP, GRACE or GOCE), x-ray astronomy with telescopes built out of 2 satellites with highly constant distance, and astronomical missions with arrays of telescopes in a synthetic aperture architecture (Darwin).

Due to its high precision and the simple (propellant) infrastructure laser propulsion is an ideal technology for micro thrusters. Precise adjustable thrust can be generated by laser induced ablation of metals or composites with pulsed laser sources. Solar pumped laser systems are an ideal technology for in orbit laser propulsion.

1. INTRODUCTION

Since the invention of laser propulsion by Arthur Kantrowitz in 1972 pioneering work in this area has been performed by a series of research groups worldwide [1],[2],[3],[4],[5],[6],[7]. For many years DLR investigated launch scenarios of small satellites [8]. However, the launch of nanosats (up to 10 kg wet mass) requires high power laser sources that still need significant development with respect to laser energy scaling and therefore are not available to the laser propulsion community.

In space, however, already existing lasers may be used as energy sources for the remote propulsion of small objects. Rezunkov et al [6] have already presented a laser propulsion engine exhibiting an optical assembly that provides a motion towards the laser source. A flexible combination of this concept with a conventional thruster device moving away from the laser source makes logistic applications possible. Power beaming for both acceleration and deceleration will allow for mail service in space or sample return missions to small planets or asteroids.

Micro propulsion is a new research topic at DLR. In recent years the launch of numerous satellites for gravitational research had to be postponed due to the lack adequate thrust devices [9]. These missions require for extremely low thrust and high stability. Ablative micro propulsion employing onboard microchip lasers and momentum less beam control is a promising technology for low thrust devices.

Figure 1 illustrates the different laser propulsion regimes and the corresponding laser sources, yielding an almost constant thrust to Laser power ratio, the impulse coupling coefficient c_m.

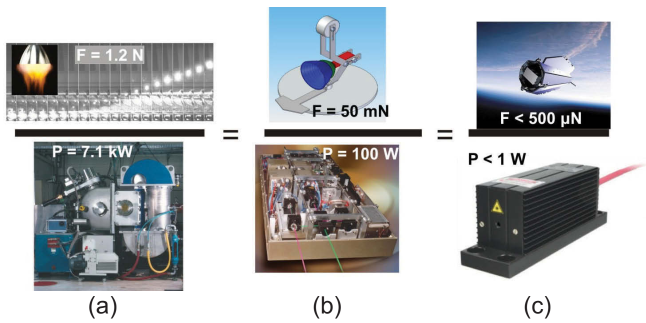

FIGURE 1. Laser propulsion research for different applications: (a) ground based launch of small satellites, (b) in space laser propulsion, and (c) ablative micro propulsion.

In the following the latest research activities at DLR in the different laser propulsion regimes will be briefly reported:

- Laser rocket experiments. From free flights to a remotely controlled thrust vector steering device integrated in a parabolic nozzle.
- Flight experiments with a parabolic thruster in an artificial 2D-zero gravity on an air cushion table.
- New investigations in the field of laser micro propulsion.

2. THE LASER ROCKET

A special form of thermal propulsion is the repetitively pulsed laser plasma propulsion. In this application very high laser intensities are used to break down matter on a short timescale. This mechanism creates a plasma of very high initial pressure and temperature and initiates a blast wave. The impact of this blast wave on a vehicle structure produces an impulse that pushes the vehicle forward. The mechanism functions in all media and can be utilized in all kinds of propulsion engines. The initiation of a breakdown in a natural ambient medium (i.e. the air) makes it possible to do without on-board propellant.

DLR has developed repetitively pulsed e-beam sustained multiple wavelength lasers of particularly high powers and excellent pulse reproducibility. This laser has been used for all the laser rocket experiments.

2.1. Flight experiments

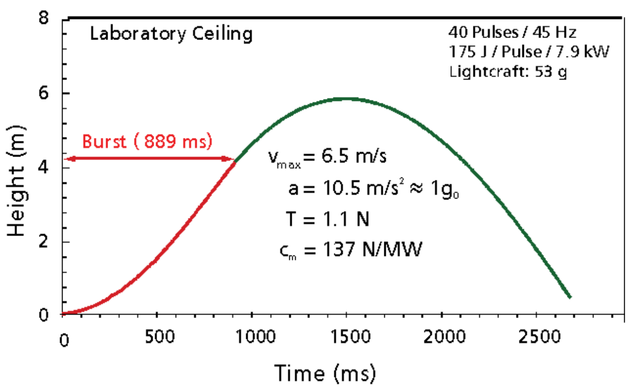

FIGURE 2. Typical flight history of a vertical ascent.

A simple parabolic thruster has been manufactured from aluminum having a height of 62.5 mm, a diameter of 100 mm, and a mass of 17 grams. The inside of the paraboloid is polished for high reflectivity. The mass of the vehicle was varied up to 55 g by attaching metal rings. The laser beam from the stable resonator had a diameter of 95 mm at the launch position and a flat energy distribution over the cross-section. The beam divergence was 3.7 mrad. Vertical ascents to the 8 m high ceiling of the laboratory could be demonstrated with various repetition rates and pulse energies [10].

The height vs. time history has been recorded by a laser range finder with accuracy better than 1 mm. Fig. 2 is an example of a typical flight curve. The differentiation of the curve during the boost phase yields a terminal speed of 6 m/s and a maximum acceleration, a, of 10.5 m/s^2 or a little more than 1 g_0 (Earths acceleration). After termination of the laser radiation the vehicle continues to climb and then falls down again. The maximum thrust, T, in this example was 1.05 N. Higher accelerations, as well as hovering type flights have been demonstrated for different pulse frequencies, pulse energies and vehicle masses.

2.2. Pendulum experiments

The important figure of merit for the performance of a laser rocket is the impulse coupling coefficient. It is a measure of the momentum imparted on the thruster per Joule of laser energy. Practical units are Ns / MJ = N / MW. From the simple balance of forces (neglecting friction effects) a value of cm = 133 N/MW can be deduced for instance from the flight curve of the example shown in fig. 2. However, c_m can be measured directly by suspending the thruster on a thin string as a pendulum and by finding the initial velocity after one laser pulse, i.e. by measuring the displacement of the pendulum.

The coupling coefficient is found to depend on the pulse energy as well as on the intensity distribution of the laser beam. A maximum value of about 300 N/MW is measured at a pulse energy of 275 J followed by a linear decline for higher pulse energies.

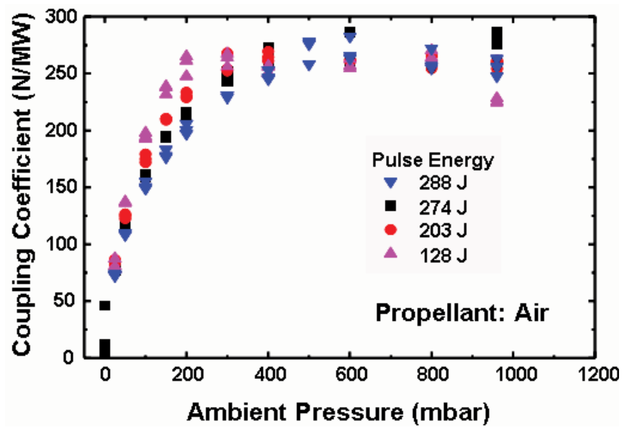

FIGURE 3. Coupling coefficient at reduced air pressure.

During the ascent of a spacecraft from the ground through the atmosphere to outer space the density of the air drops exponentially to zero. Therefore, the surrounding air eventually ceases to be useful as the propellant and, as in conventional rocketry, on-board fuel must replace it. The decline of the thrust with reducing air pressure has been investigated by suspending the pendulum with the thruster inside a vacuum tank and measuring the impulse at various tank pressures and pulse energies. The result is shown in fig. 3 and led to the remarkable experience that, depending on the pulse energy, the coupling coefficient does not change notably down to pressures of 200 to 500 mbar. Therefore, altitudes of about 11 km can be reached in the air-breathing operation mode without loss in performance and 20 km and even more, if a certain loss in thrust is admitted. However, a loss in thrust is associated with an increase in necessary total laser energy for reaching the same altitude. The result is of significance, since it allows a substantial reduction of necessary on-board fuel in exchange for in-creased payload. The flight through the atmosphere is particularly fuel consuming due to the added force of air drag, which increases with the square of the flight velocity.

Additional propellant may increase the performance during atmospheric flight, however. It is indispensable during propelled flight at high altitudes and in the vacuum of space. Delrin, a plastic material that vaporizes without producing soot, has been selected as a first choice. Cylindrical Delrin rods of 8 and 10 mm diameter and 17 mm in length have been inserted into the thruster. The laser light irradiates the pin on the circumference and evaporates material in radial direction. The intensity distribution on the pin surface varies with the diameter of the pin.

It has been observed that Delrin substantially increases the cm-value at all pressures. In vacuum the coupling coefficient amounts to about 250 N/MW. As the air pressure rises c_m in-creases steadily, displaying no leveling off. In contrast, the operation with surrounding pure nitrogen exhibits a simple displacement of the air curve by a practically constant value. The difference between the two curves is attributed to a release of combustion energy from a reaction of Delrin vapor with the oxygen in the air. In this case and at the proper pulse energy a maximum coupling coefficient of 610 N/MW has been found, compared to 400 N/MW in vacuum. The combustion effect suggests optimum propulsive conditions if either the performance of a chemical propellant is enhanced by laser energy or laser propulsion is augmented by a chemical reaction.

2.3. Laser-matter interaction

The efficiency of the ablation of solid polymers for the production of impulses under various conditions has been studied intensively for CO2 laser pulses of pulse lengths between 12 and 15 µs. Flat samples have been irradiated with fluence values ranging from 22 to 150 J/cm^2 [11][12]. The values cover the region designated optimum for the attainable coupling coefficient [13]. Measurements of the laser power arriving on the sample surface as a function of the incident laser pulse energy have indicated severe energy losses in front of the target. The source for these losses not only reduces the arriving energy in magnitude but also shortens the length of the efficative pulse on the target surface [12]. It is well known, that in experiments with pulsed laser ablation a breakdown of the air or of ablated material in front of the target occurs by Inverse Bremsstrahlung and launches a laser supported detonation wave that moves away from the surface. In this wave much of the laser pulse energy may be captured, preventing further ablation and hence the production of impulse by conservation of momentum.

The proof of the existence and the knowledge of the position of an emerging laser absorption wave in front of the surface are imperative for the understanding of the obvious losses of laser energy. It was found that the fraction of energy that is not absorbed in front of the target surface is inversely proportional to the applied pulse energy. The length of the penetrating energy pulse is also shortened with increasing pulse energy. In the limit, only the initial spike energy can penetrate to the target surface.

In the experiments employing Schlieren Photography with nanosecond exposure times we could show the formation of surface plasma along with the deposition of energy into a target sample (fig. 8). The plasma expands to a maximum distance of 12 mm from the surface. In a gaseous environment the plasma expansion launches a strong shock wave with Mach no. ~6. From the velocity of the shock wave and the assumption of a quasi one-dimensional expansion process, an approximate expansion velocity of the material cloud of ablation products can be deduced. As the released gas or vapor expands, an absorption wave spreads out. This is where most of the incident pulse power is subsequently absorbed. The addition of heat into the off-flowing matter can be one reason why the velocity, observed as the shock velocity, does not decrease over an extended time, as would be expected for a multi-dimensional expansion. The circular shape of the density gradients, as seen in the Schlieren pictures, does suggest a 3-dimensional expansion, although probably not in the full half-space. Shock velocities in the range of the applied pulse energies of 150 J (fluence 75 J/cm^2) were not higher than 2.5 km/s for plain POM. Only POM samples blended with a certain amount of metal powder showed an unusual behavior with material escape velocities in excess of 8 km/s.

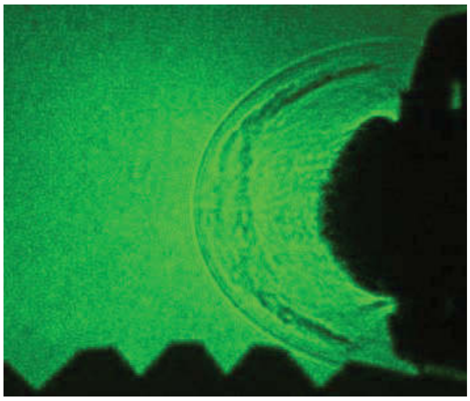

FIGURE 4. Typical Schlieren Picture at a pulse energy of 150 J.

In summary, we must conclude from the results, that a CO_2 laser with pulse lengths of several microseconds in combination with polymers as propellant is not an ideal laser for beamed energy propulsion. The pulse length should be much shorter than the characteristic time for the build-up of an absorption wave, which is less than 1 µs. Energy that is absorbed in such an absorption zone serves only to increase the expansion rate of the zone itself and has no effect back on the target. Pulsed laser ablation rockets that gain their momentum only from the release of matter directly at the target surface probably work only efficiently for either low energy pulses at a relatively high pulse rate (kHz) or with sub-microsecond pulse lengths. For pulsed high-power CO_2 lasers these conditions are not easy to achieve and require special development efforts.

2.4. Remotely controlled laser rocket

A simple configuration to control the ignition of a laser-supported detonation that can be used for a thrust vector steering device for a parabolic nozzle has been developed at DLR. Free flights of laser-driven thrusters were mainly reported from the spin-stabilized Lightcraft Technology Demonstrator (LTD) of Leik Myrabo, among them the world-record flight with an altitude of 71 meters [2]. In the case of spin-stabilization, however, the question arises how steering issues, e.g. orbit insertion, could be addressed. Nevertheless, the occurrence of unwanted lateral and angular velocity components due to limited back-driving forces raises the question of appropriate countermeasures. While the possibilities of varying the beam position at the nozzle aperture are limited, an onboard solution has been found which offers additional steering potential for stability enhancement and orbit insertion [18].

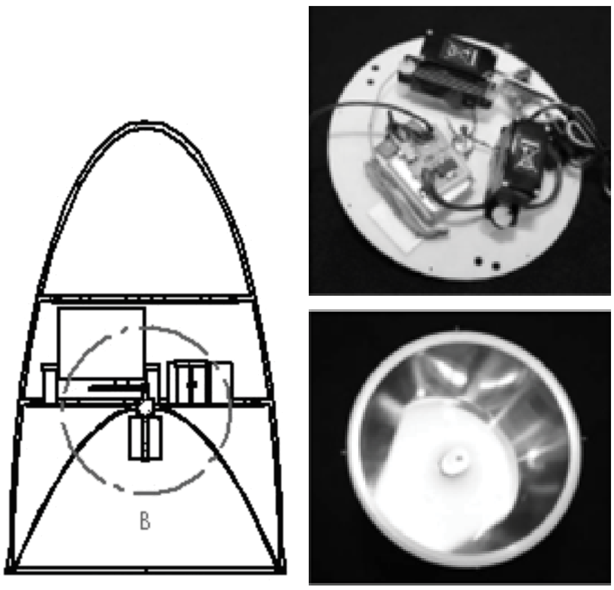

FIGURE 5. Conceptual sketch of the laser-driven rocket with a parabolic reflector/nozzle and a steering unit (lower platform) as well as components of the prototype.

During early laser thruster research at DLR, irregularities in detonations were found. These were ascribed to the high breakdown threshold of air (1.5 GW/cm^2 at 10.6 µm wavelength) compared to the low breakdown threshold (1 MW/cm^2) in metal vapor close to a metallic surface [9]. Impurities on the reflector wall would also lower the ignition threshold, leading to a plasma detonation close to the mirror surface, but not in the focus. To provide for a lowered ignition threshold in the focus, a metallic ignition pin was introduced at the axis of symmetry (and patented [15]). This device allows for thrust vector steering by tilting the ignition pin and thus shifting the origin of the detonation. The effects of this pin and of a propellant rod in the same configuration were investigated. A theoretical analysis of the components of impulse coupling and the corresponding forces as well as a detailed description of the experimental setup can be found in [16].

A design model of a laser-driven rocket with a remotely controlled steering gear was constructed, as shown in Fig. 5 [17]. Inside the rocket we used a more robust reflector (1 mm thickness, 35.2 g mass) to prevent it from deformation. It was mounted in the lower part and connected to the steering unit in the center part. Two digital servos were placed on the steering platform perpendicular to each other enabling a tilt of the ignition rod in the nozzle by an angle of up to 10° in the x-y-plane. The remotely controlled servos were powered by LiPo batteries. The transmitter was operated from the operating desk. An additional payload can be placed at the upper platform of the rocket. The overall mass amounts to 154 g without payload.

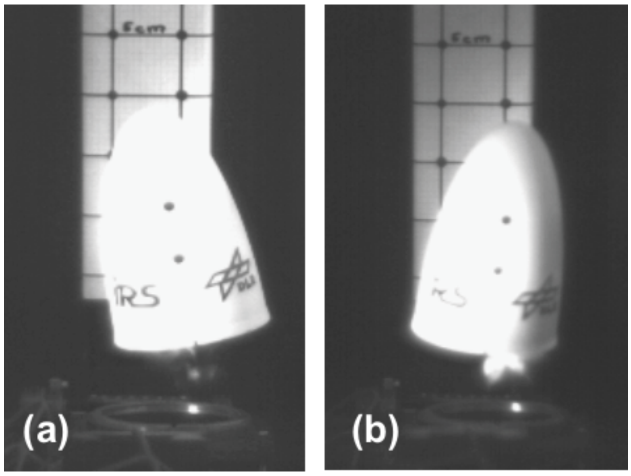

FIGURE 6. High speed recording of laser pulse # 6 with positive (a) and negative (b) inclination.

First test flights with an average laser power of 3.2 ± 0.3 kW and 3.1 ± 0.3 kW, demonstrated the practical feasibility of thrust vector steering by changing the ignition configuration. The performance of the steering unit was not significantly affected by the strong accelerations during the laser pulse.

The laser power was sufficient to lift the thruster. Nevertheless, in the temporal course of the laser burst, the rocket descends again. Since the propagation path of the laser beam is aligned to vertical, in a first approach this effect has been ascribed to the reduced rate of energy entering the nozzle with increasing inclination angle and lateral offset of the inlet. The energy losses have been modeled by a ray-tracing algorithm, only yielding a 10 % reduction of $c_{m,eff}$ [18].Thus, the decrease during the flight is supposed to be due to significant changes of the intensity distribution on the propellant rod under inclined illumination. These topics will be the subject of further research.

3. LASER PROPULSION IN WEIGHTLESSNESS

The exploration of in-space laser propulsion in artificial weightlessness is a first step to space-borne applications of laser propulsion. First ideas employing the drop tower facility in Bremen have been reported in [19] but had to be postponed due to limited budgets. An alternative approach is the investigation of energy scaling in 2D artificial weightlessness on an air cushion table by scaling down the dimensions of a parabolic nozzle and, in parallel, the pulse energy of a CO_2 high energy laser [20].

For several thruster geometries, laser heating of the plasma in a shockwave front during the laser pulse has been approximated according to the hydrodynamic model of a point explosion with counter-pressure [21]. It was adapted by V. P. Ageev for laser propulsion with various thruster geometries [22]. Different nozzles have been constructed. Each nozzle was fixed to an adjustable mounting assembly on a puck for hovering on the air cushion table. Details on this setup, the corresponding measuring technique, and the data analysis are described in [18],[20],[23],[24].

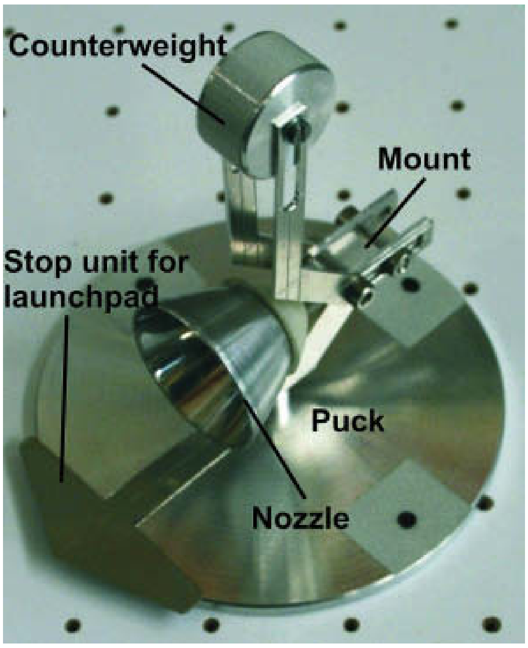

FIGURE 7. Laser propulsion nozzle, mounted on a puck with tracking markers. A counter-weight to adjust the center of mass is placed on top.

Air breakdown in single pulse experiments as well as laser ablation investigations have been carried out. For low pulse energies, the data are in quite good agreement with theoretical values. However, at higher pulses energies, the experimental findings were much lower than the theoretical predictions. This effect can be attributed to energy loss due to internal vibrations of the flyer. Though only a sparse database of theoretical values had been computed, even predicted local maxima in the course of c_m seem to be verified by the experiment, however, within the range of the corresponding error bars and with a lateral shift of the experimental data graph.

The single pulse experiments have been repeated with a rod of POM mounted on the symmetry axis of the nozzle. POM ablation from a circular focal zone enhanced the momentum by a factor of 2 to 3, as already found for large parabolic nozzles in this ablation geometry [8]. At higher pulse energies, however, this effect seems to be limited. Again, this effect may be ascribed to energy losses in structural vibrations of the puck at high pulse energies.

Finally we compared our results with data from experiments using a vertical launch setup. Due to gravity, the limit of detection was higher than at the air cushion table, even with the larger mass of the puck. Since the small, lightweight nozzles exhibited only poor beam-riding abilities, an extensive comparison of multiple-pulsed flights between the two different setups was not possible.

A more detailed discussion of all the different experiments in artificial 2D-weightlessness is given in [23].

4. ABLATIVE MICRO PROPULSION

Alternative thruster technologies are required for missions involving micro spacecrafts or station-keeping on very low, but precise thrust levels. Especially scientific missions for mapping the Earth's magnetic or gravity fields and for the detection of gravitational waves, e.g., CHAMP, GRACE, GOCE, MICROSCOPE or LISA [26], require new thruster concepts. These concepts should also provide for long term reliability and high efficiency. Lasers have proven their long term reliability in many applications, e.g., in industry or medicine. Depending on the laser power, pulsed laser ablation of metals or polymers reveals a broad range of impulse bits and corresponding average thrust, as defined by the momentum coupling coefficient [27],[28].

As a first step towards laser micro propulsion, experiments using a highly repetitive $Nd:YVO_4$ laser are in preparation. The goal during this first phase is to identify and characterize suitable materials for laser ablation. For this purpose, a high accuracy thrust stand is under development.

The resulting data will also be used for the selection of a laser source to be optimized for space applications by tailoring laser pulse length and shape with respect to repetition rate, fluence on target and a suitable wavelength for ablation.

The implementation of the propulsion concept includes research on momentum-less beam control and tests on technological reliability (Fig. 8). Additionally, SEM and time resolved imaging of the plasma plume will be applied for analysis of reproducibility and directionality of the ablation jet.

In addition to experiments on long term stability of the micro thruster, an experiment under realistic conditions (microgravity, vacuum) is planned to be carried out at the ZARM drop tower at the University of Bremen in order to demonstrate the feasibility and maturity of this technique.

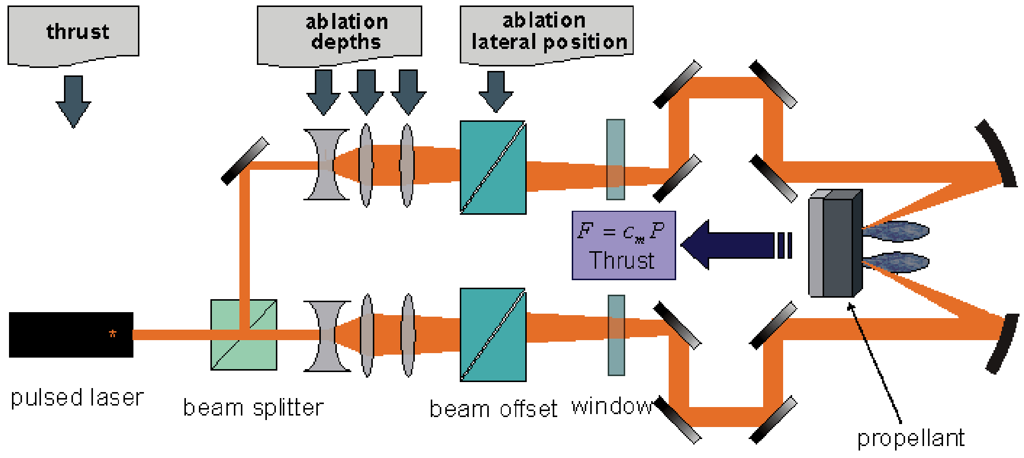

FIGURE 8. Concept of a laser ablation micro propulsion device with momentum-less beam control.

5. CONCLUSIONS

Despite many worldwide efforts in research the laser propulsion community has not been able to establish a satellite launch project. This has to be attributed to the lack of suitable laser sources. There are two alternatives to evade this gap. Researchers may stick to small scale experiments studying limited aspects of future propulsion projects or investigate laser propulsion in a zero gravity environment. In the latter case lower thrust levels are required and therefore sufficient laser sources are available.

DLR still has research activities in both fields. For the satellite launch scenario we investigated the feasibility of thrust vector steering of a laser rocket by variation of its ignition configuration. Direction, magnitude, and point of action of the thrust vector are dependent on various parameters, a situation which demands a more detailed analysis. A tilted configuration of a propellant rod inside the thruster induces lateral and angular momentum. A detailed analysis led to the introduction of a virtual center of the detonation. The remote control of the steering device allows for stabilization of the flight and is a prerequisite for a closed loop flight control based on optical tracking.

As a first step to the zero gravity regime the high speed analysis of pulsed horizontal “flights” of a parabolic thruster on an air cushion table allowed for measurement of the impulse coupling coefficient with respect to three degrees of freedom. The results for translational momentum coupling in a single pulse experiment correspond with theoretical values as well as with averaged data from multiple pulsed flights. The lower velocity increment per pulse compared to vertical flights allows for a detailed analysis of several subsequent pulses on a stretched timescale.

The air cushion table experiments proved to be a useful substitute for in-space propulsion. However, they were performed in ambient air and motion in weightlessness was only achieved for three degrees of freedom instead of six. As already shown with the free flights in 2000 by Leik Myrabo [2], experiments for demonstration purposes have the greatest impact when the experimental scenario is close to reality.

Another approach to the investigation of laser propulsion in space is laser ablative micro propulsion. Since there is a strong demand for thrusters on the µN to mN level, the development of space proof laser sources and laser-driven micro thrusters will become an increasing activity at DLR. A micro propulsion demonstration experiment in microgravity, as already proposed in [19], is under preparation.

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