Review On Laser Lightcraft Research At DLR Stuttgart

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Abstract. A review on 15 years research on remote laser propulsion with a parabolic thruster at DLR is presented. Mission scenarios were analyzed for nanosatellite launch to Low Earth Orbit (LEO) using a ground-based high energy laser as energy supply significantly optimizing the mass-to-payload-ratio. Experimental work was carried out using a home-made, electron-beam sustained CO_2 high energy laser in the 10 kW class with around 10 µs pulse length. The parabolic thruster was compared with the Lightcraft Technology Demonstrator in air-breathing mode as well as with Polyoxymethylene (POM) as an ablative propellant with respect to laser pulse energy and beam profile taking into account for standardization issues of ballistic pendula. Experiments showed good performance of pure air-breathing mode without propellant down to 200 mbar ambient pressure allowing for a drastic propellant reduction for the initial flight phase during dense atmosphere. The commonly used hydrodynamic point explosion model with a strong shock wave was analyzed with respect to the optimization of the impulse coupling coefficient in geometric scaling by the adaptation of nozzle diameter and length to the range of the applied laser pulse energy. The usage of ablative propellants like POM, inevitable in the vacuum of space, yields enhancement of impulse coupling under atmospheric conditions which can partly be attributed to combustion. Various polymer-metal composites were developed and analyzed in order to achieve a higher specific impulse, but failed due to material inhomogeneity. Started up with wire-guided flights, using only air as propellant in a laser-induced breakdown, the detonation reproducibility by means of an ignition pin on the axis of symmetry of the thruster was proven in the free flight experiments yielding an altitude up to 8 m, limited by the laboratory ceiling. Nevertheless, flight dynamic analysis of a tilted pin as steering gear and hovering experiments near ground level revealed crucial coupling of lateral and angular motion and the demand of spin-stabilization for a beam-riding flight. A review of related publications, in cooperation with US AFRL, University of Stuttgart and Nagoya University, is given as a compendium.

Keywords: Laser propulsion, Impulse coupling coefficient, High energy laser, Lightcraft, Raytracing, Laser-supported detonation, Flight dynamics, Thrust vector, Beam-Riding, Mission analysis, Nano-satellites, Laser-induced air breakdown, Standardization, Optical engineering.
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1. INTRODUCTION

Arthur Kantrowitz envisioned the ground-based launch of rockets into space by laser power in [36] and comprised the essentials of Beamed Energy Propulsion as a "4P-principle": Payload – Propellant – Photons – Period, emphasizing the simplicity of his visionary idea. Looking back at the research on ground-based laser propulsion at

DLR in the years 1998 – 2012, the outline of this paper attempts to follow this principle.

2. PHOTONS

A. The Big Bang

In 1998, laser lightcraft research at DLR Stuttgart was initiated by flight experiments with a simple parabolic thruster at the CO_2 high energy laser of the Institute of Technical Physics (ITP). First test runs were performed with the front reflector of a bicycle, later on a geometry fitting to the laser beam diameter was developed (beam ∅: 80 mm, nozzle ∅: 100 mm, nozzle height: 62.5 mm), well-known as the “Bohn bell”, named after W. Bohn, the former director of the institute.

After wire-guided demonstration flights up to 8 m altitude, the simplicity of the air-breathing laser propulsion concept using only light and air as propulsive energy sources experienced overwhelming resonance at DLR’s yearly main convention. Along with Myrabo’s experiments at US AFRL and his world-record flight up to 71 m altitude [37], a wave of national media interest and scientific enthusiasm at DLR pushed this new technology into the research portfolio of ITP.

B. The Multispectral High Energy Laser Testbed

Being developed since the 1980’s, the home-made pulsed electron-beam sustained high energy laser at ITP was found as an ideal prerequisite for laser lightcraft research. Designed for investigations on laser pulse energy scaling for a broad range of gaseous lasing media (Ar-Xe, CO, CO overtone, CO_2) and therefore wavelengths from 1.7 µm to 10.6 µm, its original dedicated usage was research on laser-matter interaction in the fields of industrial applications and for defense purposes against ballistic threats.

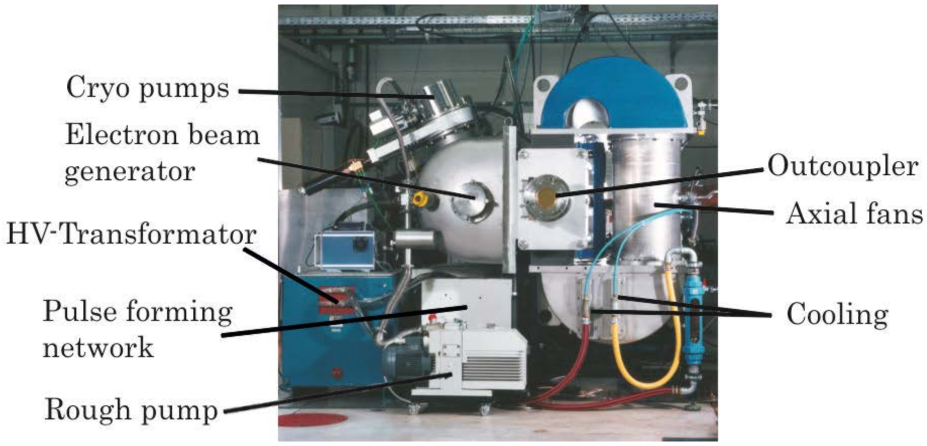


FIGURE 1. High energy laser at the Institute of Technical Physics of the German Aerospace Center (DLR) Stuttgart.

Lasing at 10.6 µm, pulse energies up to 450 J were achieved in unstable resonator mode. However, whereas this configuration with a ring-shaped beam profile in the near field was shown to be more appropriate for the outer ring focus of Myrabo's Lightcraft Technology Demonstrator (LTD), the parabolic DLR bell turned out to be operated slightly better with the top hat beam profile of a stable resonator [10], cf. Fig. 2. Data were taken from experiments with a mathematical pendulum. However, an extensive comparison with a physical pendulum from US AFRL was carried out as well.

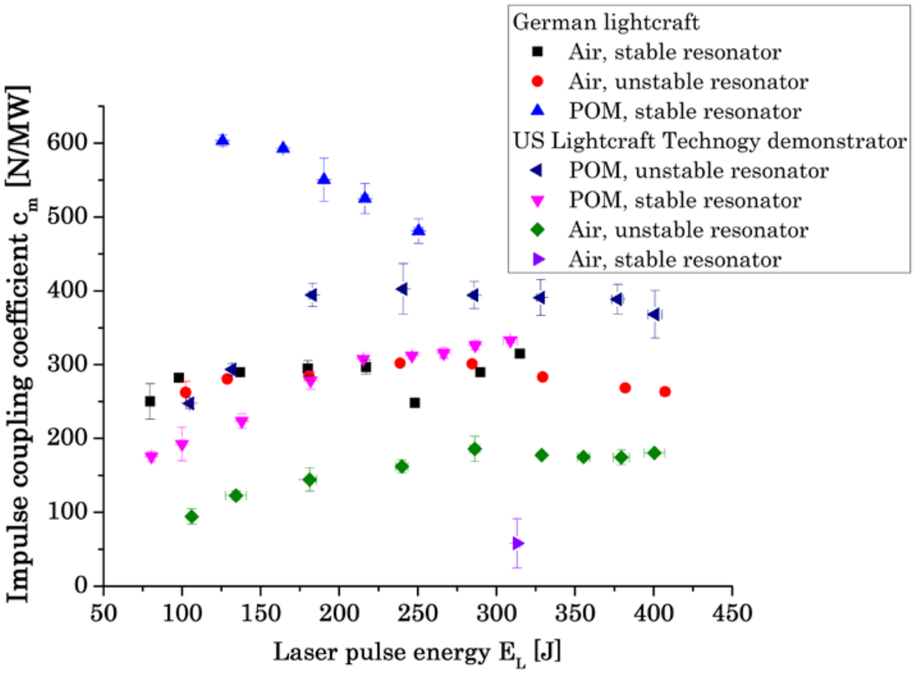


FIGURE 2. Dependency of the impulse coupling coefficient on pulse energy, beam profile and usage of ablative propellant (see below) for the German parabolic lightcraft and the US Lightcraft Technology Demonstrator.

Circulation and optional cooling of the laser medium allowed for an upper repetition rate of 100 Hz yielding the maximum average laser power of 15 kW [8]. However, in principle the laser could operate as a 50 kW system given a suitable electrical power supply.

The laser pulse length was in the range of 2 to 12 µs, depending on pulse energy and the selected capacitors of the pulse forming network, exhibiting a characteristic short spike and a broad tail [23]. Due to its high Fresnel number in stable resonator configuration, N_f = 105, numerous laser modes are excited and the beam quality is rather poor, $M_x^2 \approx 71, M_y^2 \approx 81$.

Experimental laser lightcraft research was finished at the end of 2010, followed by final free flight demonstration experiments in 2011, among them at ISBEP 7, and concluding data analysis in 2012.

C. Laser-induced Air Breakdown in a Parabolic Nozzle

The technical term "Lightcraft" is associated with Myrabo's LTD. However, following his original definition as "[…] any flight platform, airborne vehicle, or spacecraft designed for propulsion by a beam of light – be it microwave or laser. […]" in [44], we extend the usage of "laser lightcraft" to the common understanding to any laser-driven vehicles being powered by a ground-based laser. Hence, the Bohn bell is denoted as DLR's parabolic laser lightcraft.

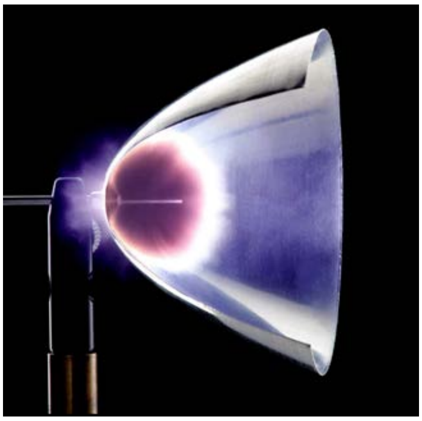
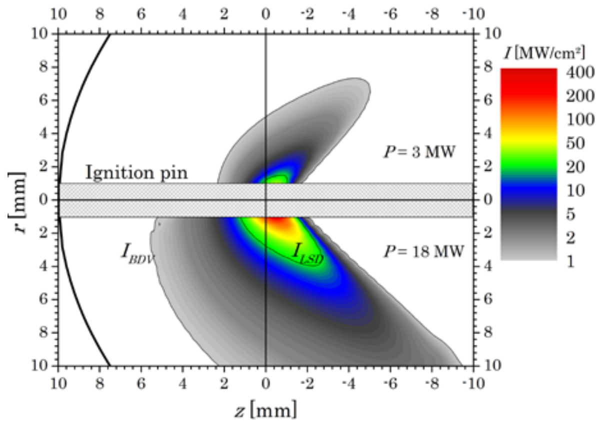
(a)  **(b)** 

FIGURE 3. (a) Cross-section of the parabolic laser lightcraft and (b) intensity distribution from raytracing with the intensity threshold of laser-induced breakdown of air above a metal surface, I_{BDV}, and approximate required intensity for LSD wave propagation, I_{LSD}.

As a parabolic reflector, it exhibits a double function which simplifies the propulsion concept: The parabolic reflector works both as an optical element to focus the incoming laser radiation and as a nozzle for gas expansion. Focused CO_2 laser radiation yields air breakdown for intensities beyond 1.5 GW/cm^2 in clean air, but near to metallic surfaces, the breakdown threshold is lowered by several orders of magnitude down to 1 MW/cm^2 [45]. Hence, irregular detonations at the reflector wall may occur [9, talk]. Therefore, a metallic ignition pin on the axis of symmetry was implemented [9] and patented [35] providing for reproducible plasma ignitions in the focus. This concept was adapted, e.g. in [46], and grants for reliable momentum coupling in free flight experiment, being supported by findings from high speed image recordings [4].

Laser-induced air breakdown yields a dense and hot plasma sphere which expands in a laser-supported detonation wave (LSD wave), later on in a laser-supported combustion wave (LSC). Exhaust velocities in the range of 500 – 700 m/s by laser probe detection of changes of the refractive index in the air at the thruster exit [9]. However, estimation of exhausted air mass is difficult and, with respect to repetitive operation, $I_{sp} \rightarrow \infty$ since air refresh causes $\Delta m \rightarrow 0$.

D. Momentum Coupling

Basically, momentum coupling can be calculated in a first approach on the basis of Sedov's theory of a strong explosion [38] with the principle of self-similarity. As a more rigorous method, Ageev et al. proposed to take into account for atmospheric counter-pressure [39] on the foundation of tabulated data of the generalized impulse $J^{(1)}$ [40]. Introducing the dynamic radius R_0 of the explosion, $R_0 = \sqrt[3]{E_0 / p_0}$ of the detonation energy E_0 under the ambient pressure p_0, the generalized coordinate ξ_0 of the apex, $\xi_0 = R / R_0$, and the geometric parameter $\kappa = 1 + (4R/D)^{-2}$, with R as the focus length and D as the nozzle diameter, the impulse coupling coefficient can be written as

$$c_m(\xi_0, \kappa) = \frac{4 \cdot \pi}{c_0} \xi_0^2 (\kappa^2 - 1) J^{(1)}[\xi_0 \cdot \kappa] \tag{1}$$

with c_0 being the velocity of sound in the ambient gas. This expression should allow for optimization of the thruster geometry with respect to the given laser pulse energy range and beam diameter.

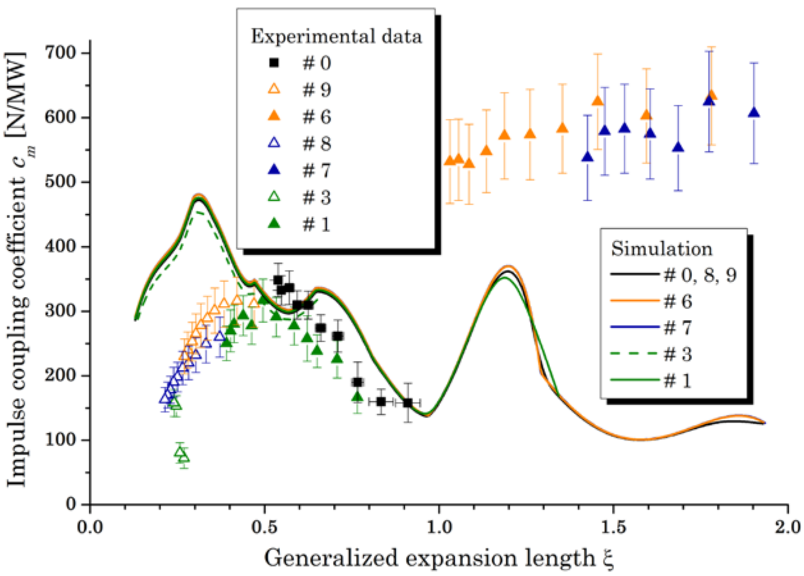


FIGURE 4. Impulse coupling coefficient c_m: Experimental data for various nozzle geometries, cf. Table 1, vs. simulation results from hydrodynamic point explosion theory with counter-pressure. Similar to the definition of the generalized coordinate of the apex, ξ_0, the generalized expansion length is given by $\xi = R_1 / R_0$ where $R_1 = \kappa \cdot R$ is the expansion length of the nozzle, measure from the focus to the rim of the nozzle exit.

Whereas for the standard Bohn bell and for down-scaled nozzles at moderate pulse energies [20] a rather good agreement between simulation and experiment is found [4,24], cf. nozzle # 0 and # 1 in Fig. 4, impact experiments with nozzles on a piezo sensor revealed large discrepancies from the calculation results for other geometries. Maintaining the same ratio of R/D with respect to the Bohn bell for nozzle # 8 and # 9 very low impulse coupling coefficients have been recorded though an optimization was expected from the simulation results. On the other hand, for long nozzles c_m exceeded even 600 N/MW which is a factor of up to 4 higher than the theoretical value. These differences can be associated with neglected phenomena of LSD wave propagation during the long laser pulse deviating from the (spatial and temporal) point explosion approach which is not sufficient for a comprehensive optimization of the nozzle geometry

TABLE 1. Focus length *R*, nozzle diameter *D*, and nozzle length *L* of the investigated nozzle geometries together with the range of pulse energies in the experiments.

Nozzle ID	R [mm]	D [mm]	L [mm]	E_{min} [J]	E_{max} [J]
0	10	100	62.5	43 ± 5	208 ± 14
1	2.7	30	22	2.8 ± 0.3	21 ± 2
3	2.7	20	8.8	6.6 ± 0.7	9.3 ± 1.0
6	5	100	125	33 ± 4	171 ± 20
7	3.7	100	180	32 ± 4	177 ± 21
8	3.7	38	24	35 ± 4	180 ± 21
9	5	48	30	35 ± 4	181 ± 21

As nearly any kind of space propulsion, laser propulsion is subject to Ziolkowski's rocket equation and especially is not unchained from the additional mass of onboard propellant demanding in turn for supplementary thrust and propellant. However, the mass-to-payload ratio is dramatically diminished (see below) since air breakdown allows for a propellant-less flight in the lower, dense atmosphere. Experiments at a ballistic pendulum in a pressure chamber revealed the large range of pure air-breathing laser propulsion without significant changes of impulse coupling down to 200 mbar, which allows for an ascent of the craft up to 20 km while cm decreases down to 50% of its original value [12]. In this region, the high atmospheric drag usually consumes a lot of propellant in conventional rocketry.

Recent considerations [34] show that for higher vehicle velocities it should be considered, that conservation of energy and momentum yield a reduction of impulse coupling according to

$$c_{m,v} = \frac{c_{m,0}}{1+\left(v/u\right)^2} \tag{2}$$

following [47], where v is the vehicle velocity and u is the velocity of the exhaust jet.

3. PROPELLANT

A. Detonation of Ablative POM

Polyoxymethylene (Polyacetal, POM, Delrin®) is polymerized from Formaldehyde yielding POM homopolymer whereas it should be noted that a co-polymer modification of POM exhibiting slightly deviating characteristics of impulse coupling under laser ablation exists as well [29]. As a volume absorber with a high absorption coefficient α = 6740 ± 240 cm^{-1} [41] at λ = 10.6 µm, it is a propellant with a wide-spread usage in related laser propulsion work, e.g. in the focal ring of the LTD [37]. Similarly, propellant rods of 8 – 12 mm ∅ were inserted at the thruster symmetry axis yielding fluences up to 90 J/cm^2, as derived from raytracing in good accordance with profilometry data after ablation [29], depending on rod diameter, nozzle shape and pulse energy.

The symmetric configuration of the ablative target inside the thruster does not allow for an interpretation of the (additional) momentum as a result from recoil of the ablative jet. In fact, following Ageichik et al. in [42], detonation and delayed burning of POM and its constituents deliver additional energy, E_{det} = 2.69 J/mg and E_{db} = 16.1 J/mg [43], for the explosive process that would be induced by air-breakdown due to E_L only otherwise. Hence, explosion theory according to Eq. (1) can be extended on the usage of ablative propellants, as described in detail in [34].

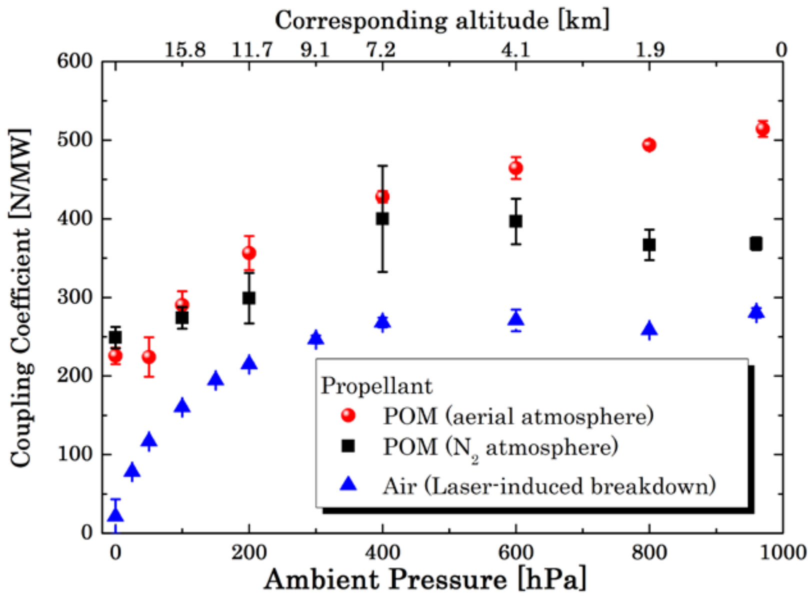


FIGURE 5. Experimental results from a ballistic pendulum inside a pressure chamber: Coupling coefficient for a parabolic lightcraft with and without POM as an ablative propellant under various atmospheric conditions (ambient air and inert nitrogen atmosphere).

As an experimental proof, detonation and combustion have been distinguished in comparative experiments under air and inert atmosphere, resp., cf. Fig. 5.

In vacuum, I_{sp} using POM amounts less than around 300 s [12,19] which is insufficient aiming for a single-stage ground-based launch to LEO demanding for a specific impulse of 600 – 800 s. Hence, as a link to research on pure laser ablative propulsion, experiments with flat targets were undertaken in greater detail.

B. Laser-ablative Propulsion with Flat Targets

Since surface absorbers like metals yield a high specific impulse under laser ablation, it has been attempted to increase the velocity of the ablative jet by doping volume absorber targets (POM, epoxy resin) with metallic powder (Al, Mg) of grain diameters in the range of 15 to 30 µm. However, local hot spots were formed in the target material under laser irradiation acting like a piston for the metallic grain "bullets" [14]. This resulted in presumably inhomogeneous ablation of a metallic high speed jet and a still slow part of polymeric bulk material, but not in a significant increase of I_{sp} [14,16], cf. Fig. 6.

Meanwhile, this problem has been solved using Polytetrafluoroethylene (PTFE, Teflon®) yielding a high I_{sp} = 754 ± 40 s, as reported by Pakhomov [48], where the realization of variable, homogeneous mixtures of PTFE and ammonium perchloride (high c_m, low I_{sp}) was successfully proven for the scope of a constant momentum mission [49] with variable exhaust velocity and constantly optimized propulsion efficiency, cf. [47].

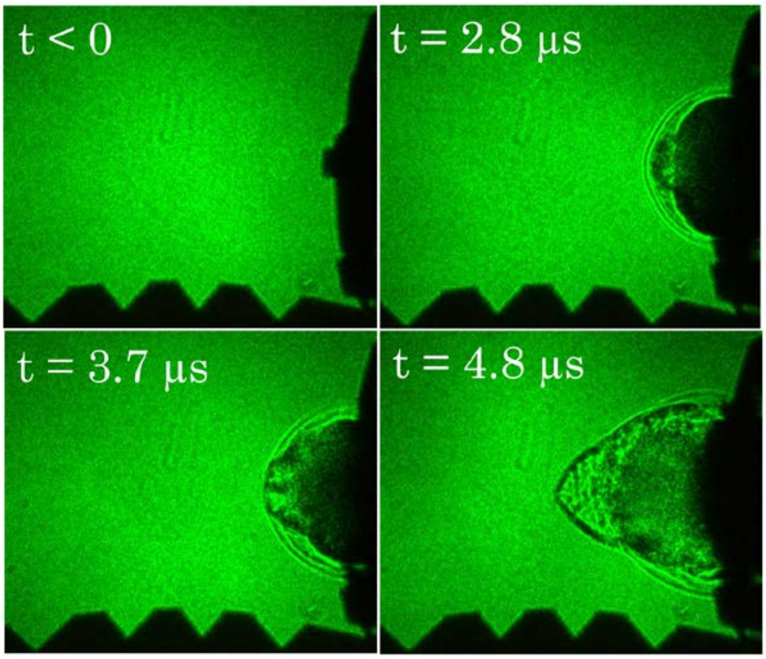


FIGURE 6. Schlieren recordings from laser ablation at 150 J of a flat POM target with 20 % dopant of aluminum grains at 35 mbar residual pressure. After the formation of a shock front with 3.8 km/s and a slowly expanding plasma front (dark), a material fraction, presumably aluminium grains, penetrates the shock front with a high velocity (8.1 km/s).

Shadowgraphy methods and laser probe experiments with a hole in the target also have clearly shown the detrimental effect on c_m of shielding by the laser-induce absorption wave in front of the target. Based on findings on the absorption wave inside a parabolic Microwave thruster [50], however, we assume that under certain conditions the absorption wave might have a beneficial effect on the imparted momentum, namely on the propagation path of the expanding plasma from the propellant rod towards the nozzle walls during heating by the long laser pulse. This assumption is supported by the above mentioned findings on high c_m for long nozzles with laser pulses of around 10 µs.

C. Scaling and Standardization Issues

Comparability of scientific results and their scalability in various areas of research and development is an important issue for the scientific community. Hence, a cooperation with Nagoya University was initiated comprising scientist exchange visits with collaborate work on standardization issues in laser propulsion [7,23], ablation of POM at flat targets [28] with respect to target area scaling [27] considering a broad range of pulse energies from various laser systems, cf. Fig. 7. Pulse energy scaling was investigated as well for the usage of POM propellant in miniaturized nozzles at moderate pulse energies [29].

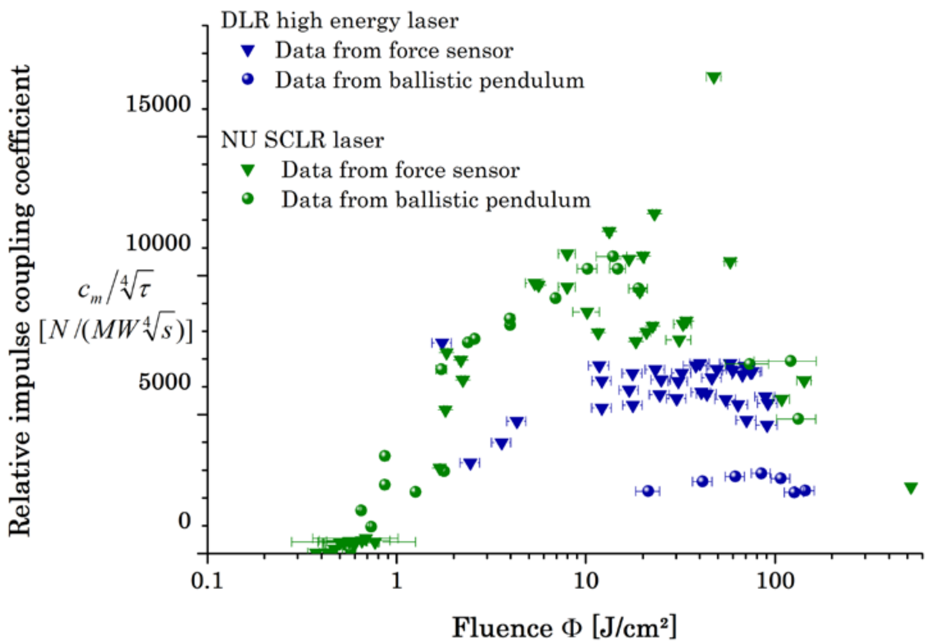


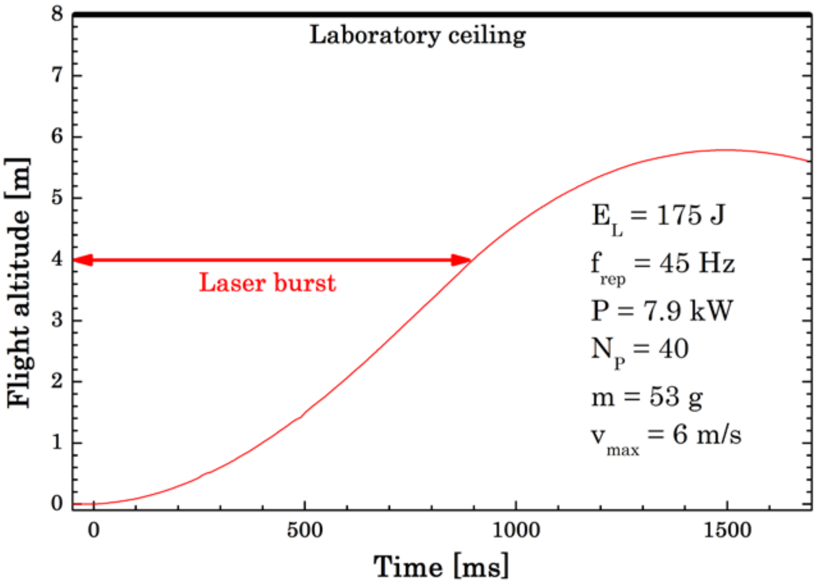
FIGURE 7. Comparison on experimental data of the impulse coupling coefficient of POM under ambient air. The scaling factor $\sqrt[4]{\tau}$ takes into account the different pulse lengths τ (DLR: 7.2 – 10 µs, NU: 1.4 – 1.5 µs) affecting momentum coupling in the vaporization regime (photothermal model [51]).

This work on scaling in laser ablative propulsion marked as well a turning point in our research strategy from ground-based laser propulsion towards our present work on laser ablative micropropulsion.

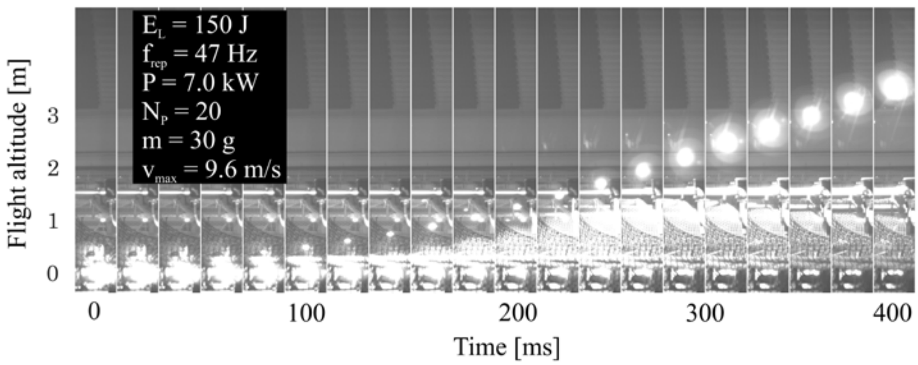
4. PAYLOAD

A. Flight Dynamics

Transportation of expensive payload from ground to orbit demands for a reliable propulsion technology. The initial point of wire-guided demonstration flights leaves the unanswered question of what would happen without a wire. It was the leading question in [34] if this propulsion concept could basically be space-proven, if “space” was extended from 1D to 3D? In fact, this 3D extension is even not met by spin-stabilization itself yet and, moreover, spinning might demand for additional de-spinning devices with the corresponding structural mass. In order to obtain a “light” craft, however, the inherent beam-riding characteristics of the parabolic thruster were examined, i.e. the question whether and to which extent the laser beam not only acts as an energy source (like a catenary line in railways) but as well as a guiding track yielding restoring lateral forces and rotational momentum, resp., in order to keep track with the laser beam propagation path.



(a)



(b)

FIGURE 8. (a) Temporal evolution of the flight altitude of a parabolic lightcraft in a wire-guided experiment and (b) frames from high-speed recording of 20 subsequent plasma detonations in a free flight experiment.

Though numerous free flights up to the laboratory ceiling were reported as well [4], success or failure of those demonstration experiments was subject to a remarkable uncertainty. Hence, stereoscopic high speed analyses of the lightcraft’s motion in pulsed free flights were conducted [6], especially under an adapted hovering setup with adjusted laser power by real-time control for the laser pulse train [30]. In spite of thorough alignment of the lightcraft at the launchpad, the maximum hovering time of

0.36 seconds was not exceeded. Nevertheless, ground trajectories, cf. Fig. 9, as well as studies on angular motion clearly pronounced the existence of restoring lateral forces and angular momenta.

In a comparative study [52], Kenoyer et al. stated that in contrast to the LTD, the Bohn bell simply would exhibit too weak restoring forces and momenta. This is not the case. Whereas in this work only the dependency on lateral offset was investigated, in our approach it was possible to derive experimental data of lateral $c_{m,lat}$ and rotational c_L impulse coupling *fields* depending on lateral and angular offset simultaneously. Roughly summarized, strong restoring lateral forces are present when the craft is inclined towards the beam center. With the opposite orientation, however, repulsive force components are found. Similar results are reported for the partial action of restoring angular momenta.

As an approach to explain these phenomena, a sectorial impulse component model based on raytracing was set up [6], but it is recommendable to include the temporal evolution of laser-matter interaction by FEM methods, as depicted in [53], into this simulation for a better understanding.

Looking at the flight performance, these phenomena result in a butterfly effect with respect to alignment at the launch position and the corresponding flight duration which is expected to stay in the range of a few seconds even for high-precision alignment [31,34].

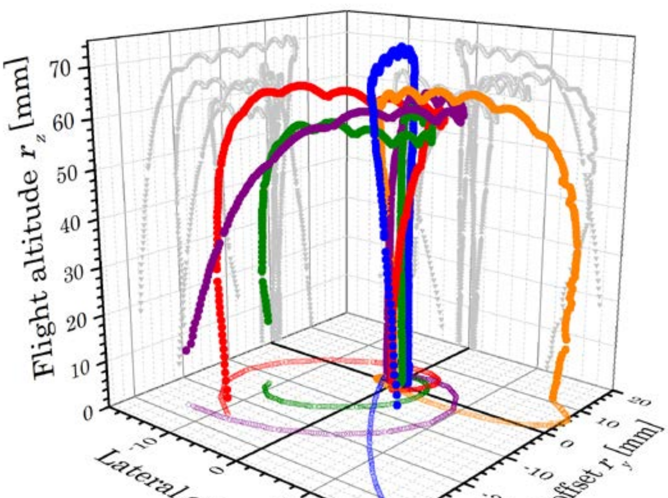


FIGURE 9. Trajectories of a parabolic lightcraft in hovering free flight experiments, 5 test runs, color-coded. Solid color data represent the spatial trajectory, ground trajectories are indicated by the hollow symbols. Grey: projections into the *x-z* and *y-z* plane, resp.

The dynamic tilt of the ignition pin by a certain angle α was proposed in [35] as a device for steering and orbit insertion. Its usage for dynamic flight stabilization was tested as well.

The intention of this concept was to move the center of detonation alongside the inclination of the pin. Experimental work on momentum coupling [32] revealed, however, that in fact the detonation center moves to the opposite side of the center of the intensity distribution on the pin, cf. Fig. 10.

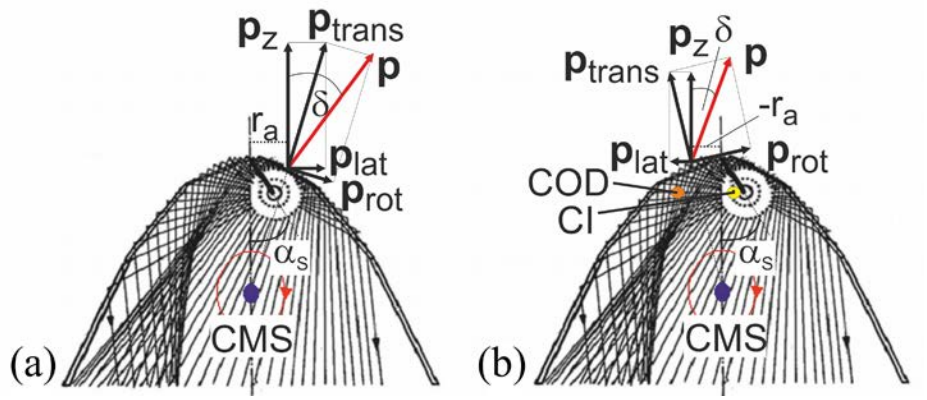


FIGURE 10. Shock wave propagation inside the lightcraft with an ignition pin tilted by the inclination angle α_S: (a) Expected momentum components following [35] and (b) experimental results, cf. [22]. CI: Center of intensity, COD: center of detonation, CMS: center of mass, δ: Thrust angle. Vector analysis of the impulse components (lateral – *lat*, coaxial – *z*, translational – *trans*, and rotational – *rot*) from free flight experiments has shown that the point of attack is found on the opposite side of the ignition pin ($\text{sgn}\, r_a = - \text{sgn}\, \alpha_S$).

Nevertheless, it has been successfully demonstrated that steering of a laser-driven rocket is feasible [4]. A flight demonstrator was developed comprising a 2D steering unit with remote access by a quartz receiver above the nozzle and an upper unit for payload was provided yielding an overall mass of 154 g [32]. Test flights with a light-weight payload were performed as well.

For various tilt angles α the corresponding fields of $c_{m,lat}$ and c_L have been investigated in pulsed free flights [34]. Flight simulations based on these results show, however, that the compensation of both angular and lateral displacement for a stable flight is not likely to be realized by this simple device. Furthermore, even if these motions were compensated in the instantaneous plane of inclination of the craft, e.g. the *x*-*z* plane, any lateral offset in the perpendicular plane, i.e. the *y*-*z* plane, would lead to lateral and angular motion there at the same time that would not be compensated. Therefore, alternative ideas for beam-riding stabilization are sketched in [31, 34].

B. Concept Studies

Beyond all technological roadblocks, among them flight stabilization and the availability of suitable high power laser as the biggest ones, it is worthwhile to keep in mind the great potential of remotely beamed laser propulsion for the future and to consider that both the invention of laser and the beginning of space rocketry lie only two generations back in the past. Aiming for knowledge for tomorrow, a broad horizon of potential technological developments in the future should be kept in mind in scientific work, since the fundamentals of lasing and of propulsion by photons were envisioned even long before the technological realization of the first laser.

Therefore, it is reasonable to take a look at mission scenarios that recall why remote laser propulsion is such an attractive propulsion technique, cf. e.g. [54]. As a main advantage of laser propulsion, no staging is required. Hence, no debris would be left in the orbit. In contrast, the energy source remains on ground and would soon again be ready for the next mission.

In [13], Eckel and Schall reported flight simulation results for various conditions of atmospheric drag. The required minimum laser power *P*, for a ground-based satellite launch to orbit can be calculated according to [13] using

$$P = 0.5\, m_f a_0 v_j \exp\left[\frac{\Delta v}{v_j}\right] \tag{3}$$

where m_f is the final mass in orbit, a_0 the initial acceleration at launch, v_j the exhaust velocity and Δv the required velocity increment for orbit insertion, cf. Fig. 11.

Using the fundamental rocket equation, a remarkable fraction of propellant mass to the overall mass at launch can be deduced which is in the range of 0.39 to 0.92. For typical satellite launch the propellant fraction is expected to amount around 0.75. This would constitute a significant technological quantum jump compared with the mass of Sputnik-I (83.6 kg) and its launch vehicle (280 tons).

However, simulations have shown that – as a rule of thumb – for the launch of 1 kg payload to LEO 1 MW average laser power would be required [3,13] which would demand for large efforts in technological development and financial funding [18].

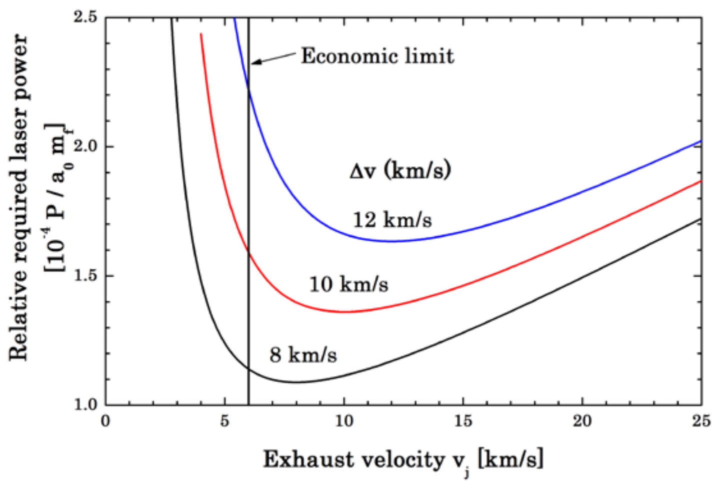


FIGURE 11. Required laser power *P* with respect to initial acceleration a_0 at launch, final mass m_f in orbit and required various velocity increments Δv for LEO.

Working with available laser sources, in-space missions, e.g. for logistic purposes in space or sample-return from asteroids, might be attractive in the mid-term [55]. Downscaling laser pulse energy and nozzle size, a corresponding Earth-bound experiment in a drop tower was proposed in [20]. Experimental work, however, was carried out in the 2D artificial weightlessness of an air cushion table [33] showing the proof-of-concept [24].

5. PERIOD

A. Conclusions

Laser lightcraft experiments in Germany have illustrated the great innovative potential of this propulsion technology. Research on thruster configuration, the usage of ablative propellant and flight dynamics provide for a sound base of knowledge for future developments in the BEP community. However, keeping in mind the original vision of a ground-based launch of nano-satellites by laser light, available laser power would only cope with “atto-satellites”. At the present state, however, a ground-based launch of nanosatellites seems to stay an academic scenario to be left not addressed by technological solutions for the next several decades.

B. Outlook

Therefore, future work should in the mid-term focus on mission scenarios in space where Earth’s gravity does not have to be compensated by laser power.

At DLR, these considerations have led to the finalization of laser lightcraft research after 15 years in 2012 and the kick-off in 2009 for research and development on laser-ablative micropropulsion as a potential short-term application of laser propulsion.

6. PEOPLE

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7. PUBLICATIONS

A deeper insight in laser lightcraft research at DLR can be found in the following publications:

A. Book Chapters

1. W. Schall, and H.-A. Eckel, and W. Bohn, “Laser Propulsion Thrusters for Space Transportation”, In: Laser Ablation and its Applications Springer Series in Optical Science, Springer, 2006.

2. H.-A. Eckel, and W. Schall, „Laser Propulsion Systems“, In: Advanced Propulsion Systems and Technologies, Today to 2020, *Progress in Astronautics and Aeronautics* **223,** pp. 357–406, AIAA, 2008.

B. Journal Papers

3. W. Schall and H.-A. Eckel, “Pulsed Laser Propulsion Experiments”, *Space Technology* **24**, pp. 129–135, 2004.
4. S. Scharring, D. Hoffmann, H.-A. Eckel, and H.-P. Röser, “Stabilization and steering of a parabolic laser thermal thruster with an ignition device”, *Acta Astronautica* **65**, pp. 1599–1615, 2009.
5. C. Phipps et al., “Review: Laser-Ablation Propulsion”, Journal of Propulsion and Power **26**(4), pp. 609–637, 2010.
6. S. Scharring, H.-A. Eckel, and H.-P. Röser, Beam-Riding of a Parabolic Laser Lightcraft, *International Journal of Aerospace Innovations* **3**(1), pp. 15–31, 2011.
7. S. Scharring et al., “Experimental Determination of the Impulse Coupling Coefficient - Standardization Issues”, *International Journal of Aerospace Innovations* **3**(1), pp. 33–43, 2011.

C. Conference Proceedings

8. G. Renz et al., “Pulsed CO_2-laser with 15 kW average power at 100 Hz rep-rate”, *Proc. of SPIE* **3092**, pp. 114–117, 1997.
9. W.O. Schall et al., “Lightcraft Experiments in Germany”, *Proc. of SPIE* **4065**, pp. 472–481, 2000.
10. W.O. Schall et al., “Comparative lightcraft impulse measurements”, *Proc. of SPIE* **4760**, pp. 908–917, 2002.
11. W.O. Schall, H.-A. Eckel, and W. Riede, “Laser Propulsion Experiments with High-Power Pulsed CO_2 Laser”. *Proc. of SPIE* **5120**, pp. 618–622, 2003.
12. W.L. Bohn, and W.O. Schall, “Laser Propulsion Activities in Germany”, *AIP Conf. Proc*. **664**, pp. 79–91, 2003.
13. H.-A. Eckel, and W.O. Schall, “Concept for a laser propulsion based nanosat launch system”, *AIP Conf. Proc.* **702**, pp. 263–273, 2004.
14. W.O. Schall, J. Tegel, and H.A. Eckel, “Ablation Performance Experiments with Metal Seeded Polymers”, *AIP Conf. Proc.* **766**, pp. 423–432, 2004
15. W.O. Schall, “Propulsion by laser power”, *Proc. of SPIE* **5777**, pp. 993–998, 2005.
16. H.A. Eckel, J. Tegel, and W. Schall, „CO_2 Laser Absorption in Ablation Plasmas“, *AIP Conf. Proc.* **830**, pp. 272–283, 2006
17. H.A. Eckel, J. Tegel, and W. Schall, “Absorption waves produced by CO_2 laser ablation”, *Proc. of SPIE* **6261**, 62610E, 2006
18. W.L. Bohn, “Laser Propulsion – Quo vadis”, *AIP Conf. Proc.* **997**, pp. 47–55, 2008.
19. S. Scharring, H.-A. Eckel, and H.-P. Röser, “Flight Analysis of a Parabolic Lightcraft – Ground-based Launch”, *AIP Conf. Proc.* **997**, pp. 304–315, 2008.
20. S. Scharring et al., „Spaceborne Lightcraft Applications – an Experimental Approach“, *AIP Conf. Proc.* **997**, pp. 295–303, 2008.
21. S. Scharring, H.-A. Eckel, and H.-P. Röser, “High speed analysis of free flights with a parabolic thruster”, *AIP Conf. Proc.* **1230,** pp. 77–88, 2010.
22. S. Scharring et al., “Remotely Controlled Steering Gear for a Laser-driven Rocket with a Parabolic Thruster”, *AIP Conf. Proc.* **1230,** pp. 89–100, 2010.
23. J. Sinko et al., “Measurement issues in pulsed laser propulsion”, *AIP Conf. Proc.* **1230**, pp. 125–136, 2010.
24. S. Scharring et al., “Flight experiments on energy scaling for in-space laser propulsion”, *AIP Conf. Proc.* **1230,** pp. 326–337, 2010.
25. H.-A. Eckel and S. Scharring, “Tailoring Laser Propulsion for Future Applications in Space”, *AIP Conf. Proc.* **1278**, pp. 677–688, 2010.
26. S. Scharring et al., “Laser Propulsion Standardization Issues”, *AIP Conf. Proc.* **1278**, pp. 780–788, 2010.
27. J.E. Sinko et al., “CO_2 Laser Ablation Area Scaling and Redeposition on Flat Polyoxymethylene Targets”, *AIP Conf. Proc.* **1278**, pp. 538–547, 2010.
28. J.E. Sinko et al., “Update on CO_2 Laser Ablation of Polyoxymethylene”, *AIP Conf. Proc.* **1278**, pp. 548–557, 2010.
29. S. Scharring et al., “Review on Japanese-German-U.S. Cooperation on Laser-Ablation Propulsion”, *AIP Conf. Proc.* **1402,** pp. 47–61, 2011.
30. S. Scharring, H.-A. Eckel, and H.-P. Röser, “Beam-Riding Analysis of a Parabolic Laser-Thermal Thruster”, *AIP Conf. Proc.* **1402,** pp. 115–131, 2011.
31. S. Scharring, H.-A. Eckel, and H.-P. Röser, “Beam-Riding Simulation and Diagnostics for Beamed-Energy Vehicles”, submitted for these proceedings, 2014.

D. Academic Theses

32. D. Hoffmann, “Development and validation of a design model with remotely controllable steering gear for flight experiments on pulsed laser thermal propulsion”, Diploma thesis, University of Stuttgart, 2008.
33. E. Wollenhaupt, „Experimental studies on the scaling of laser-thermal propulsion“, Diploma thesis, University of Stuttgart, 2009 (in German).
34. S. Scharring, Impulse analysis of air-breathing pulsed laser-thermal propulsion with a parabolic reflecting nozzle for space applications, PhD thesis, University of Stuttgart, 2013 (in German), http://elib.uni-stuttgart.de/opus/volltexte/2013/8360/

E. Other

35. W.O. Schall, E. Zeyfang, W. Riede, and W. Mayerhofer, “Propulsion device and method of generating shock waves”, Patent DE 100 17 343 C2, filed 7 April 2000 (in German) and US 2002/0047673 A1, filed 6 April 2001.

REFERENCES

36. A. Kantrowitz, “Propulsion to Orbit by Ground-Based Lasers”, *Astronautics and Aeronautics* **10**(5), pp. 74–76, 1972.
37. L.N. Myrabo, “World Record Flights of Beam-Riding Rocket Lightcraft: Demonstration of ‘Disruptive’ Propulsion Technology”, AIAA paper 2001-3798.
38. L.I. Sedov, “Similarity and Dimensional Methods in Mechanics”, Academic Press, New York, 1959.
39. V.P. Ageev et al., “Laser air-breathing jet engine”, *Soviet Journal of Quantum Electronics* **7**, pp. 1430–1437, 1977.
40. D.E. Ochozimskij et al., “Calculation of a Point Explosion with Respect to Counterpressure”, Akademia Nauk SSSR, 1957 (in Russian).
41. J. Sinko, “Vaporization and Shock Wave Dynamics for Impulse Generation in Laser Propulsion”, PhD thesis, University of Alabama in Huntsville, 2008.
42. A.A. Ageichik et al., „Detonation of CHO Working Substances in a Laser Jet Engine“, *Technical Physics* **54**, pp. 402 – 409, 2009.
43. Yu. A. Rezunkov et al., „Laser Fine-Adjustment Thruster for Space Vehicles“, *AIP Conf. Proc.* **1230**, pp. 309–318, 2010.
44. L. Myrabo and D. Ing, “The Future of Flight”, Bean Enterprises, New York, 1985, cited in [37].
45. H.M. Musal Jr., “Pulsed Laser Initiation of Surface Plasma on Metal Mirrors”, *Nat. Bur. Stand. (US) Special Publication* **620**, pp. 227–237, 1981, cited in [34].
46. J. Chen et al., “Air-breathing mode laser propulsion with a long-pulse TE CO_2 laser”, *Chinese Optics Letters* **8**(8), pp. 771–772, 2010.
47. G.P. Sutton and O. Biblarz, “Rocket Propulsion Elements”, 7. ed., John Wiley and Sons, New York, 2001.
48. A.V. Pakhomov and K.E. Mahaffy, “Binary Solid Propellants for Constant Momentum Missions”, *AIP Conf. Proc.* **997**, pp. 266–279, 2008.
49. C.W. Larson, F.B. Mead Jr., and S.D. Knecht, “Laser Propulsion and the Constant Momentum Mission”, *AIP Conf. Proc.* **702**, pp. 216–227, 2004.
50. Y. Oda et al., “An observation of plasma inside of microwave boosted thruster”, *AIP Conf. Proc.* **702**, pp. 399–406, 2004.
51. J. Sinko and D. Gregory, “Models For Laser Ablation Mass Removal And Impulse Generation In Vacuum”, *AIP Conf. Proc.* **1230**, pp. 193 – 203 (2010).
52. D.A. Kenoyer, I.I. Salvador, and L.N. Myrabo, “Beam-Riding Behavior of Lightcraft Engines with $\approx 1\ \mu s$ Pulsed TEA CO_2 Laser, *AIP Conf. Proc.* **1402,** pp. 93–105, 2011.
53. T.-S. Wang, Y.-S. Chen, J. Liu, L.N. Myrabo, and F.B. Mead Jr., “Advanced Performance Modeling of Experimental Laser Lightcraft”, *J. Prop. Pow*. **18**, pp. 1129–1138, 2002.
54. C.R. Phipps, “Will your children ride a laser beam into orbit? Would you want them to? – Realistic applications of ablative laser propulsion”, *AIP Conf. Proc.* **766**, pp. 11–22, 2005.
55. Yu. Rezunkov and A.V. Pakhomov, “Perspective In-Space Laser Propulsion Demonstrator Mission”, *AIP Conf. Proc*. **702**, pp. 205–215, 2004.