3rd International Symposium on Beamed Energy Propulsion, Troy, New York, October 2004 (keynote)

Will your children ride a laser beam into orbit? Would you want them to?

– Realistic applications of ablative laser propulsion –

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Abstract. This presentation is about laser space propulsion (LSP), a subset of beamed energy propulsion. After outlining a brief history of the topic and reviewing terminology, we will survey applications which have been suggested and identify those which appear to be highly realistic. It is our contention that most of these, in the near future, will be unmanned and occupy a unique technological niche where LSP based on laser ablation can show strong advantages to the current inhabitants of the niche. Examples are micropropulsion, lifting space vehicle components off the planet, launching completed space vehicles into interplanetary trajectories, and deep space propulsion. There are also military niches, and certain advantages for fs pulses, based on recent work in the fs regime. Perhaps the most exciting application is using LSP to assemble spacecraft in orbit at low cost. We will discuss the three reasons for this anticipated cost benefit.

EARLY DEVELOPMENTS IN LASER PROPULSION

The earliest reference to photon propulsion is in a 1953 paper by Eugen Sänger [1] published in 1955, well before the demonstration of the laser [2], and probably about the time that Charles Townes thought of it. In the paper, it is shown how one can circumnavigate the universe in 20 years. However, this and related papers by Marx and Möckel [3,4] a decade and more later did not consider laser ablation propulsion, but rather rockets driven by the reflection or absorption of photons. This is essentially the laser-driven photon sail problem. Even in total reflection, the momentum coupling coefficient, the ratio of coupled momentum to laser pulse energy W,

$$C_m = m\Delta v/W = F/P \tag{1}$$

is limited to 6.7E-9 N/W, but specific impulse I_{sp} is as large as it can be, 3.1E7 seconds. Ablation efficiency $\eta_{AB} = g_o C_m I_{sp}/2 = 1$.

These facts mean that, as an example, to accelerate a 1-tonne object at 1 Earth gravity, 1.5 TW of optical power is required. Möckel did not shrink from this, envisioning a 1TW, 1-km diameter xray laser beam with 1Å wavelength impinging on a 1-km diameter sail to propel a spacecraft to α-Centauri in 10 years [4].

Sänger's *Aero Digest* paper [5] is notable for its optimistic conclusion, which provides an encouraging backdrop for this paper:

> *No, we do not have to resign and humbly fold our hands in our laps. The infinite universe is small enough to be open to the initiative of every one of us, open to its ultimate boundaries, everything accessible to human beings.*

ABLATIVE LASER PROPULSION

In 1971, Kantrowitz was first to suggest the more practical approach for the near term of using expensive laser power to heat a propellant sufficiently to produce a vapor or plasma jet for thrust [6], which is the principle of ablative laser propulsion. Shortly thereafter, Möckel also considered a laser-heated hydrogen gas exhaust [7]. This approach is practical simply because the specific impulse I_{sp} characteristic of laser-heated plasma temperatures

$$I_{sp} = (2kT/m_E)^{0.5} g_o << c/g_o, \qquad (2)$$

so that C_m, which is constrained by the relationship

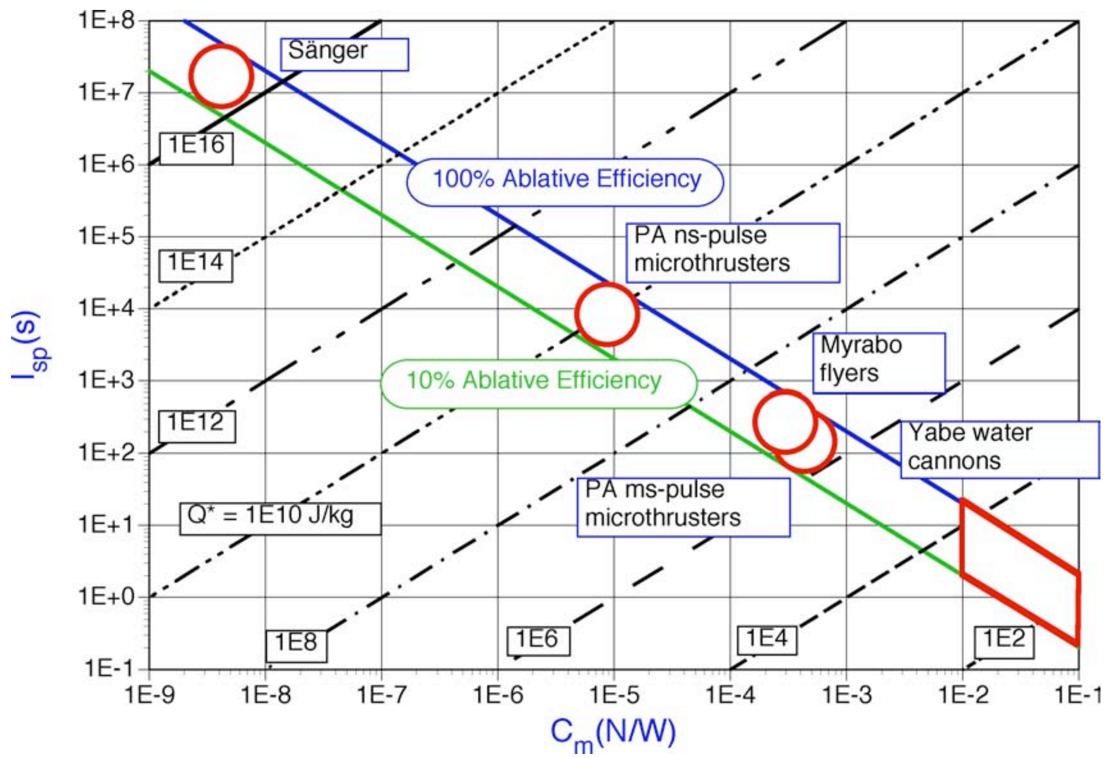

Figure 1. Specific impulse vs. momentum coupling coefficient for several types of photon-powered flyers. Lines of constant energy investment are shown.

$$C_m I_{sp} = 2\eta_{AB}/g_o, \quad (3)$$

is orders of magnitude larger than in the case of photon propulsion, so that lasers with practical power levels can propel useful payloads in relatively short-duration missions [Figure 1]. In the Figure, we show lines of constant specific energy density Q*, where

$$I_{sp} = (Q^*/g_o)C_m \quad (4)$$

in order to compare the immense energy investment ($E = mc^2$!) in a light-speed exhaust with that of, for example, water cannons [8]. Other references for the data in the Figure are: Myrabo [9], Photonic Associates (PA) ns-pulse microthrusters [10], Yabe [11] and PA ms-pulse microthrusters [12].

Missions are of short duration on the scale of Sänger's dreams because ablation fuel lifetime τ_{AB} of mass M with laser power P is

$$\tau_{AB} = 2\eta_{AB}M/(PC_m^2) = 2\eta_{AB}M/(FC_m) \quad (5)$$

and decreases sharply with increasing C_m and thrust F.

PRESENT COSTS OF LIFTING MASS TO LOW EARTH ORBIT

Table 1: Present Day LEO Launch Costs to Low Earth Orbit (LEO)

Launch System	Minimum Cost (k$/kg)
Rockot	10
Shuttle	12
Athena 2	12
Taurus	20
ISS, commercial	22
Pegasus XL	24
Long March CZ-2C	30
Athena 1	41

The way we now send things to space is very expensive. Present day costs of raising mass from the Earth's surface into low Earth orbit (LEO) with chemical rockets is more than $10,000/kg [Table 1]. This cost, equivalent to the cost of gold, dominates all other considerations relating to spaceflight, limiting what we consider to be possible. But it need not be so.

EXPECTED COSTS WITH LASER LAUNCHING

Phipps and Michaelis[14], taking advantage of an innovative conceptual design for a very large pulse energy laser system appropriate for launching large payloads

[15], showed that there is an optimum set of parameters for laser space propulsion which can reduce the cost of lifting mass to LEO nearly 100-fold from its current level. Figure 2, based on the costs derived in that work, emphasizes that rapid launch is one of the main reasons for the reduced cost. When a curve for 0.01/day launch frequency (typical of the Shuttle) is added to the original graph, it is seen that cost is even greater than current costs (50k$/kg vs. $400/kg for 5 per day).

This behavior occurs because the costs of personnel and facility amortization,

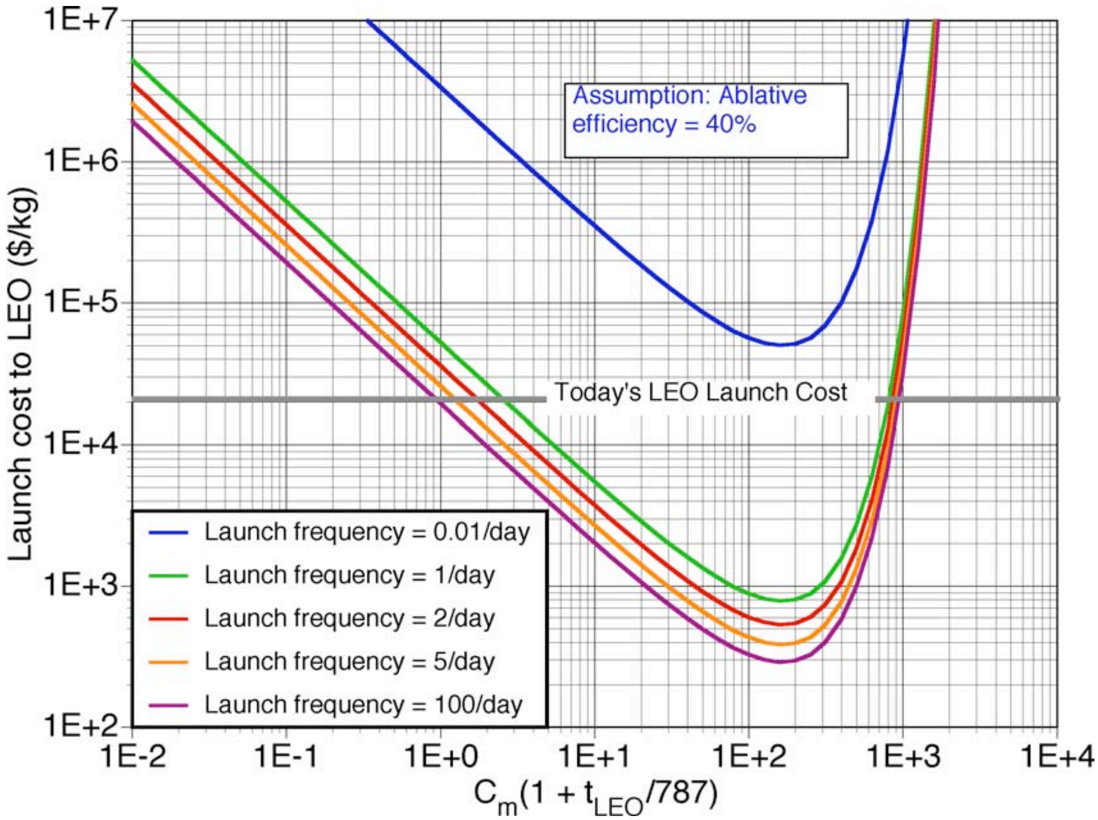

Figure 2. Cost of laser launching 10 tonnes to LEO using a repetitive-pulse deuterium-fluoride laser, figure adapted from ref. 17 to illustrate the importance of launch frequency.

which depend linearly on time, easily outweigh the cost of consumables when launches are infrequent.

The results are reasonable even for more modest laser power scenarios. With optimum flight profiles, it costs about 100MJ/kg to put mass into LEO [13], and several kg can be delivered using ablative propulsion with a 20-kW laser [16]. Present energy costs are about 3¢/MJ at retail on the ground. Accordingly, it ought not cost a great deal more than $3/η per kg to reach LEO where η is the product of all efficiencies intervening between the wall plug and the kinetic energy of the laser-ablation rocket exhaust. That this cost can be as little as $300/kg makes sense even if η is as small as 1%.

The point is that laser launching is uniquely adaptable to a high launch frequency, while chemical rocket launches, even given extensive development, have not shown that capability. However, either chemical or laser technology could probably be inexpensive if it could achieve several launches per day, and probably corresponds to a $50,000 ticket per passenger to LEO [17].

APPLICATIONS OF LASER PROPULSION

So many interesting application studies in this field have occurred that only a cursory review is possible here. Many of these have benefited from careful physics study of the laser-plasma interaction [18-20], leading, for example, to the double-pulse illumination scheme [21]. Others [e.g., 22,23] have considered tasks such as near-Earth object (NEO) deflection which will be a long time coming, to say the least.

Launching to low earth orbit (LEO) and beyond

Myrabo [24] described, developed and flew a laser-driven aerospike flyer or "Lightcraft" which can potentially operate in both air-breathing and vacuum modes. This flyer has a very specific design featuring light concentration near the rim of a frisbee-like shape that provides thrust from laser supported detonations in air or from ablation of solid material placed near the ring focus. A version of this flyer has flown to altitudes of 71m using a ≈20kW laser[25]. Bohn [26, 27] has reported flying a wire-guided parabolic device to a height of a few m in the laboratory. This device could be a first stage for a LEO-insertion vehicle. Whether it could go all the way to orbit without also destroying the crucial part of the reflector located near the ring focus due to UV radiation from the plasma formed there has yet to be demonstrated.

An alternative cone-shaped flyer design has been discussed which would launch from 35km altitude to LEO. The flyer was 0.95m diameter, with a length-to-diameter ratio of 1.0. Simulated flights in a model atmosphere with realistic drag coefficients delivered 6.12kg to LEO in 690 s with a 1MW laser driver. The delivered mass ratio was $m/M = 0.32$ [16].

The laser -powered heat exchanger concept [28] offers a creative way to bypass many of the technological problems which have delayed the actual realization of laser propulsion to LEO. Neither concept has been built and flown.

Advantages of laser launch to LEO are many, and this application is believed by its proponents to offer a quantum shift in access to space. It is at least as practical as Forward's space elevator concept, although technical difficulties may put both of them further in the future than their proponents would like. These advantages include:

a) Drastically reducing the cost of unmanned exploration of the solar system by permitting assembly of larger space vehicles on orbit from many small ground-based launches.

b) In ambient atmosphere, offering the possibility of optimally efficient propulsion by adjusting C_m and I_{sp} on the fly to match gravity and atmospheric density [29].

c) In vacuum, offering the possibility of I_{sp} values well beyond those available from chemical propulsion for larger delivered mass ratio over interplanetary distances, possibly competing in the future with ion thrusters and other high I_{sp} electric propulsion systems [10].

d) The cost of energy and of energy converters on the ground is extremely small compared to the situation in space, where a component such as a valve or a turbine costs as much as the same mass of gold on Earth, just by being in space, without even considering the usual highly inflated development and space qualification costs. Meanwhile, for Moon-based or space-based stations, nuclear or solar concentrators look good, economically speaking, when compared to the cost of hoisting and combining chemical fuels to such sites.

e) Femtosecond pulses can offer some advantages by reducing the size of transmitting apertures required to achieve plasma formation at large range in space, because of the lower fluence threshold for short pulses [30, Figure 3].

ORION

Phipps has suggested clearing near-Earth space debris in the 1–10-cm size range by pushing them into an orbit whose perigee intersects the atmosphere[31, 32]. To do this, Δv of only 100m/s is required so that, even with a 1-m beam diameter at the higher altitudes (up to 1500km) for which the ORION system was designed, it is possible to clear near-Earth space in two years with a modest laser power. The name, suggested by NASA personnel, was previously used for a sail driven by the flux of repeated nuclear detonations [33]. A complementary proposal by Schall [34] to locate the debris de-orbiting laser station in space also has great merit. This is because orbital velocity allows it to sweep out an equal volume of space per unit time with a much smaller aperture, because the detection problem is in some ways easier, and because the vector relationship between the laser propagation and debris velocity vectors is more appropriate.

Craft Propelled by water cannon phenomenon

Yabe has suggested and demonstrated laser propulsion of small objects in the laboratory with applications ranging from propelling aerostats for atmospheric monitoring to passenger airplanes to nanobots in the human bloodstream [11, 35-37]. Very large C_m approaching 0.1 N/MW is attained by causing the laser-produced vapor to eject liquid, usually water. Very small I_{sp} must correspond to such C_m values (Figure 1), meaning that long-duration missions are only possible when the liquid is continually resupplied. These applications occupy a very interesting range of the I_{sp} vs. C_m diagram.

Planetary defense

Serious consideration has been given to laser deflection of asteroids large enough to be “epoch ending” [23, 37, 38]. Two crucial disadvantages relative to laser deflection exist for the alternative of NEO deflection using nuclear weapons: a) dangerous NEO’s will, by definition, be discovered on first approach leaving small reaction time and moving toward Earth at speeds that may require a total Δv of order

60km/s from the propulsion system carrying the nuclear weapon, and b) retargeting after a failed deflection attempt is very expensive. However, the laser power required to do the deflection for an epoch ending NEO is astronomical and several GW are required to deflect even a 40-m-diameter asteroid.

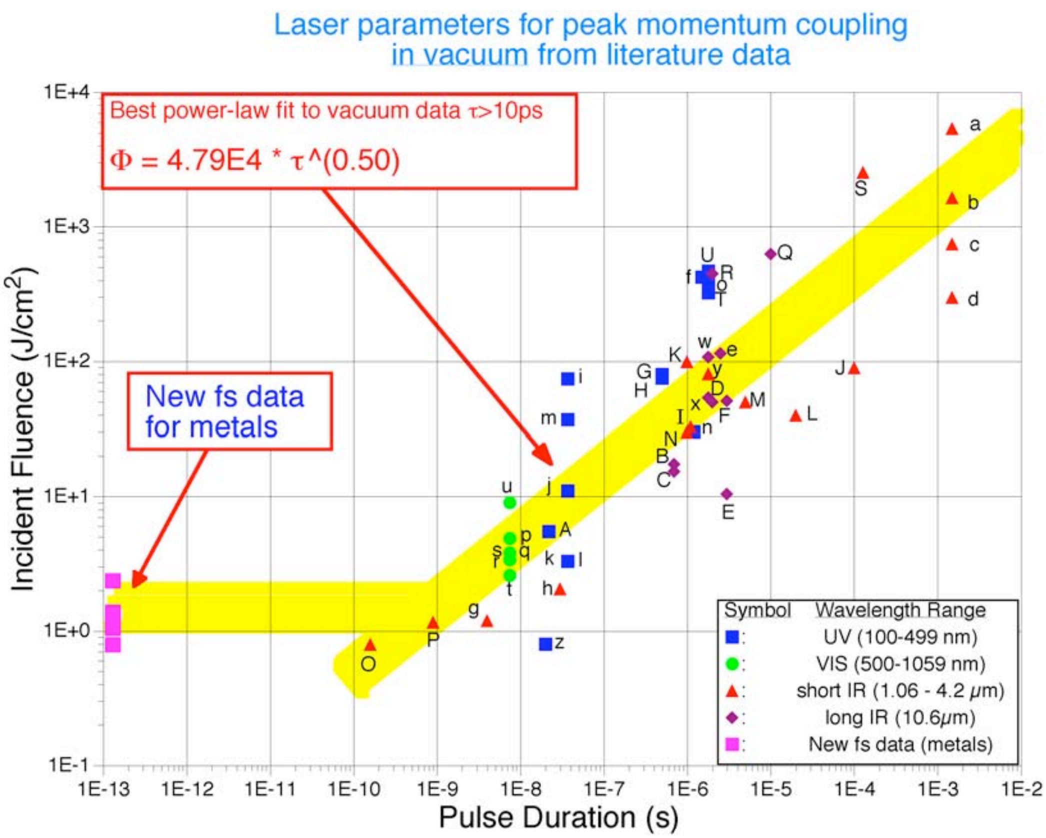

Figure 3. Fluence required for optimum coupling and plasma formation on a target in vacuum is a minimum across the entire range from 100fs to 100ps.

Military applications

Unfortunately, wheels will always be used for gun carriages as well as vegetable carts, and driving passive hypervelocity kinetic energy devices in space warfare from orbit or the Moon is potentially highly effective against predictably placed targets. There is a serious question whether such applications will be cost-effective compared to conventional kinetic energy weapons.

Laser microthrusters

Laser microthrusters differ from most of the other applications in that an onboard laser, rather than a remote source of beamed energy, produces an ablation jet which provides attitude control and stationkeeping for micro- and nanosatellites [10, 39]. The work is being funded because it can demonstrate practical advantages against competition in a well-bounded niche. The niche for these small motors is thrust less than 1mN and power less than 1kW with typical values 100μN and 10W electrical. This is a nearterm application which may be the first one to actually fly in space. Two versions are being developed with high C_m and high I_{sp}, respectively (Figure 1, Figure 4). A future development path exists in which much higher-power versions of the latter devices may be able to compete with high-I_{sp} electric propulsion devices such as ion engines. The devices have stimulated advanced research in target materials [40, 41].

Figure 4. Jets from the ms-pulse (left) and ns-pulse microthrusters in vacuum [see, e.g., 12]. The ns-pulse jet was demonstrated in tests with a spinning laptop hard drive diskk, and operated for 4 hours.

Laser orbital transfer vehicles

Several authors (for example, [42] and [43]) have suggested using medium-power lasers to drive laser orbital transfer vehicles (LOTV's) from LEO to GEO orbits via ablative propulsion.

Laser propulsion is especially well suited for large Δv and long-duration missions, and can be competitive in the future with ion engines and Hall thrusters, despite the added inefficiency of converting prime power to laser light. In the first place, this conversion step is now 20% efficient, even for ns-duration repetitive-pulse lasers, because of advances in diode-pumped fiber laser oscillators [44]. Second, the same I_{sp} values that have been demonstrated for the ns-pulse microthrusters (of order 20k seconds) are equally possible with higher power lasers, and these are better matched to Δv's for interplanetary transfer orbits than the far smaller I_{sp} values possible with chemical thrusters. The larger delivered mass ratio which results far outweighs the lower energy conversion efficiency. This application is underappreciated currently, but should receive greater interest in the near future.

Other useful applications include LEO reboost or re-entry for existing satellites which which were not designed with, or have run out of, maneuvering fuel [22].

CHALLENGES AND CONCLUSIONS

Avoid the "snicker factor"

The main challenge that must be faced by workers in the field of ablative laser propulsion is developing enough nearterm useful applications to avoid the "snicker factor" for the whole field. This factor describes public reaction to an idea for which the cost-to-perceived benefit ratio is very large, which seems more like science fiction than reality, which does something that is already being done reliably, or which does something that most people would not wish to do, or do not see as an urgent problem.

For example, even though multi-GW lasers can be built for the cost of a few days of our involvement in Iraq, the snicker factor for NEO deflection is too large for such a proposal to even get initial funding because the technological goal is so far from current capability. The same statement applies to pushing automobiles around city streets with streetcorner lasers (automobiles work). The ORION idea is a very good one, but will not receive significant funding until an astronaut onboard the Space Station is killed by debris, if then. No one will want to ride a laser beam into orbit for quite a long time, however many papers are published, until the credibility of laser-driven craft can benefit from a history as long as that of rockets.

These thoughts lead one to start small, in order to start at all, and to build credibility in a gradual fashion through demonstrated performance in well-bounded operating niches that are sparsely populated, and where the laser option is obviously competitive, and to not shrink from seeking publicity for truly interesting achievements.

The Lightcraft program is doing that very effectively. However, its ultimate application is still far in the future so that funding agencies have not yet viewed major funding as an urgent priority. We sincerely hope that will change.

One dreamer's story

Unfortunately, it is useless to try to demonstrate success on small NEO's (their combination of low flux, high speed and small cross-section gives vanishing probability for seeing and acting on one), so the ORION idea was conceived. This concept featured a need (7% chance of an astronaut death on the Space Station in a decade from this cause), reasonably high flux, small enough range that detection is possible, and moderate laser power (20 kW). Yet, even at this reduced level, the buy-in cost of $100M was viewed as a deal breaker by cash-strapped NASA, and active attempts were made to kill the idea.

The first significant funding for our concepts was achieved for applications at a laser power level of 1W, in a niche with few other inhabitants (e.g., the pulsed plasma and the field emission electric propulsion microthrusters) in which no technology had yet established convincing credibility and chemical rockets did not work well. At the same time, the micro-LPT did not threaten well-established technologies at larger power levels, such as ion engines and Hall thrusters.

Conclusion

Ablative laser propulsion is a vital technology which must be pursued. It can be a tipping point to getting us off the planet. But we must have realistic applications which have the potential of competitively occupying a unique niche. Its economics are good for three reasons:

1) Laser propulsion devices are apparently uniquely amenable to high duty factor, which is economically essential [Figure 2]

2) It offers tuned and variable I_{sp} and C_m during flight, in parameter ranges unavailable to chemistry

3) For applications featuring lasers on the ground, the cost of energy and of energy converters is extremely small compared to the situation in space, while for Moon-based or space-based stations, nuclear or solar concentrators are economically attractive.

REFERENCES

1. E. Sänger, "Zur Theorie der Photonenraketen", in *Probleme der Weltraumforschung (IV. Internationaler Astronautischer Kongress, Zurich, 1953)* p. 32, Biel-Bienne, Laubscher, (1955)
2. W. L. Bohn, "Propulsion by Light: A Tribute to the German Pioneer Eugen Sänger," *Proc. High Power Ablation IV,* SPIE **5448** (2004) pp. 45-51
3. G. Marx, "Interstellar Vehicle Propelled by Terrestrial laser Beam," *Nature*, **211**, 22-3 (1966)
4. W.E. Möckel, "Propulsion by Impinging Laser Beams," *J. Spacecraft and Rockets* **9**, no. 12, p. 942-4 (1972)
5. E. Sänger, "Flight Mechanics of Photon Rockets," *Aero Digest*, pp. 68-73 (1956)
6. Kantrowitz, *Astronaut Aeronaut..* **9**, no. 3, 34-35 (1971)
7. W.E. Möckel, "Comparison of Advanced Propulsion Concepts for Deep Space Exploration," *J. Spacecraft and Rockets* **9**, no. 12, p. 863-8 (1972)
8. T. Yabe, C. Phipps, M. Yamaguchi, R. Nakagawa, K. Aoki, H. Mine, Y. Ogata, C. Baasandash, M. Nakagawa, E. Fujiwara, K. Yoshida, A. Nishiguchi and I. Kajiwara, "Microairplane propelled by laser driven exotic target," *Applied Physics Letters,* **80**, no. 23, pp. 4318-4320 (2002)
9. L. N. Myrabo, M. A. Libeau, E. D. Meloney, R. L. Bracken and T. B. Knowles, "Pulsed Laser Propulsion Performance of 11-cm Parabolic 'Bell' Engines within an Atmosphere," *Proc. High Power Ablation IV,* SPIE **5448** (2004) pp. 450-464
10. C. R. Phipps and J. R. Luke, "Advantages of a ns-pulse micro-Laser Plasma Thruster", in *Beamed Energy Propulsion, APS Conference Proceedings* **664**, American Institute of Physics, Melville, NY (2003), pp. 230-9
11. T. Yabe, C. Phipps, R. Nakagawa, M. Yamaguchi K. Aoki, C. Baasandash, H. Abe, N. Yoshida, Y. Ogata, M. Nakagawa, E. Fujiwara, K. Yoshida, A. Nishiguchi, K. Ochi and I. Kajiwara, "Numerical and Experimental Analysis of Laser-Driven Rocket and Micro-Airplane", *Proc. 2nd International Conference on inertial Fusion Sciences and Applications, Kyoto Japan,* Elsevier, Paris (2002)

12. C. R. Phipps and J. R. Luke, "Micropropulsion using a Laser Ablation Jet," *Journal of Propulsion and Power*, **20**, no. 6 (2004, to appear)
13. C. R. Phipps, J. P. Reilly and J. W. Campbell, "Laser Launching a 5-kg Object into Low Earth Orbit," *Proc. High Power Ablation III,* SPIE **4065** (2000) pp. 502-510
14. Phipps and M. Michaelis, "Laser Impulse Space Propulsion", *Journal of. Laser and Particle Beams* **12** no. 1, pp. 23-54 (1994)
15. C. R. Phipps, "Conceptual Design of a 170-MJ Hydrogen Fluoride Laser for Fusion", *Laser and Particle Beams,* **7**, 835 (1989)
16. C. Phipps, J. Reilly and J. Campbell, "Optimum Parameters for Laser-launching Objects into Low Earth Orbit", J. Laser and Particle Beams, 18 no. 4 pp. 661-695 (2000)
17. G. Woodcock, "Space Transportation Vehicles for Space Tourism," Beamed Energy Technology Workshop, Advanced Space Transportation Program, NASA Marshall Space Flight Center October 3-4, 1996, pp. 98-106
18. N. Pirri, M. J. Monsler and P. E. Nebolsine, *AIAA Journal* **12**, no 9, 1254-1261 (1974)
19. J. T. Kare, ed., *Proc. 1987 SDIO Workshop on Laser Propulsion*, LLNL CONF-8710452, Lawrence Livermore National Laboratory (1990)
20. A. V. Pakhomov, M. S. Thompson and D. A. Gregory, "Albative Laser Propulsion: A Study of Specific Impulse, Thrust and Efficiency," *AIP Conference Proceedings* **664**, First International Symposium on Beamed Energy Propulsion 2002, A. V. Pakhomov, ed., American Institute of Physics, Woodbury, NY (2003) pp. 194-205
21. D. H. Douglas-Hamilton, A. Kantrowitz and D. A. Reilly, "Laser Assisted Propulsion Research," in *Progress in Astronautics and Aeronautics*, **61**, K. W. Billman, ed., AIAA, New York, pp. 271-8 (1978)
22. C. R. Phipps and M. M. Michaelis, "Space Propulsion Concept using High Energy, Pulsed Laser Ablation", *Proceedings of the Physics of Nuclear Induced Plasmas and Problems of Nuclear Pumped Lasers Conference, Obninsk, Russia, 26-29 May, 1992*
23. C. R. Phipps, "Lasers can play a rôle in planetary defense" in *Proc. Planetary Defense Workshop,* Lawrence Livermore National Laboratory, Livermore, CA May 22-6, 1995
24. L. N. Myrabo, "A Concept for Light-powered Flight," *AIAA/SAE/ASME 18th Joint Propulsion Conference,* Cleveland, OH, 21-23 June 1982
25. L. N. Myrabo, "Brief History of the Lightcraft Technology Demonstrator (LTD) Project," *AIP Conference Proceedings* **664**, First International Symposium on Beamed Energy Propulsion 2002, A. V. Pakhomov, ed., American Institute of Physics, Woodbury, NY (2003) pp. 49-60
26. W. L. Bohn, *Proc. SPIE Symposium on Advanced High Power Lasers and Applications, Institute for Laser Engineering, Osaka* SPIE **3885** (1999), pp. 48-53
27. W. L. Bohn, "Laser Lightcraft Performance," *Proc. High Power Ablation II,* SPIE **3885** (2000) pp. 48-53
28. J. T. Kare, "Laser Powered Heat Exchanger Rocket for Ground-to-orbit Launch," *J. Propulsion and Power* **11** no. 3, pp. 535-543 (1995)
29. S. Uchida and M. Bato, "Characterization of liquid propellant for improved LOTV mission," *AIP Conference Proceedings* **664**, First International Symposium on Beamed Energy Propulsion 2002, A. V. Pakhomov, ed., American Institute of Physics, Woodbury, NY (2003) pp. 214-222
30. C. R. Phipps, "Measurements of Laser Impulse Coupling at 130 fs," *Proc. High Power Ablation V,* SPIE **5448** (2004) pp. 1201-1209
31. C. R. Phipps, "LISK-BROOM: A laser concept for clearing space junk," in *AIP Conference Proceedings* **318**, Laser Interaction and Related Plasma Phenomena, 11th International Workshop, Monterey, CA October, 1993, George Miley, ed. American Institute of Physics, New York (1994) pp. 466-8

32. C. R. Phipps, H. Friedman, D. Gavel, J. Murray, G. Albrecht, E. V. George, C. Ho, W. Priedhorsky, M. M. Michaelis and J. P. Reilly, "ORION: Clearing near-Earth space debris using a 20-kW, 530-nm, Earth-based, repetitively pulsed laser", *Laser and Particle Beams*, **14** (1) (1996) pp. 1-44

33. J. C. Nance, "Nuclear Pulse Propulsion," *IEEE Transactions on Nuclear Science,* **NS-12**, no. 3, 177-182 (1965)

34. W. O. Schall, "Removing small debris from Earth orbit", *Z. Flugwiss. Weltraumforsch.,* **15**, 333 (1991)

35. S. Miyazaki, T. Yabe, T. Ohkubo, C. Bassandash, K. Taniguchi, A. Mabuchi, D. Tomita and Y. Ogata, "Laser Propulsion using Metal-free Water Cannon Target," *AIP Conference Proceedings*, Third International Symposium on Beamed Energy Propulsion 2004, A. V. Pakhomov, ed., American Institute of Physics, Woodbury, NY (2005)

36. T. Yabe, C. Phipps, K. Aoki, M. Yamaguchi, R. Nakagawa, Y. Ogata, M Shiho, G. Inoue, M. Onda, K. Horioka, I. Kajiwara and K. Yoshida, "Laser-driven vehicles - from inner-space to outer-space", *Applied Physics* **A77** 243-49 (2003)

37. C. R. Phipps, "Laser Deflection of NEO's," *Report of the NASA Near-Earth-Object Interception Workshop, January 14-16, 1992,* Los Alamos, NM, John D. G. Rather, Chair, Los Alamos National Laboratory Report LA-12476-C

38. C. R. Phipps and M. M. Michaelis, "NEO-LISP: deflecting near-earth objects using high average power, repetitively pulsed lasers" , Inst. Phys. Conf. Ser. **140** section 9, pp. 383-7, ICP Publishing, Bristol 1995

39. C. R. Phipps, J. R. Luke and J. Marquis, "Diode Laser-based Microthrusters: A New Alternative for High I_{sp}, Long-life Engines," paper AIAA-2000-3477, 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Huntsville, AL July 18, 2000

40. T. Lippert, M. Hauer, C. R. Phipps and A. Wokaun, "Fundamentals and applications of polymers designed for laser ablation", *Applied Physics* **A77**, 259-64 (2003)

41. L. Urech, M. Hauer, T. Lippert, C. Phipps, E. Schmid and A. Wokaun, I. Wysong, "Designed polymers for laser-based microthrusters – correlation of thrust with material, plasma and shockwave properties," *Proc. High Power Ablation V,* SPIE **5448** (2004) pp. 52-64

42. C. R. Phipps, "Modification of Earth-satellite orbits using medium-energy pulsed lasers," in *Proceedings of the Ninth International Symposium on Gas Flow and Chemcial Lasers, Crete, Greece,* C. Fotakis, C. Kalpouzos and T. Papazoglou, eds., SPIE volume **1810**, SPIE, Bellingham, WA (1992)

43. V. E. Sherstobitov, N. A. Kaliteevskiy, V. I. Kuprenyuk, A. Yu. Rodionov, N. A. Romanov, V. E. Semenov, L. N. Soms and N. V. Vysotina, "Computer simulaton of a solid-state laser system for propulsion of a space 'tugboat' from LEO to GEO," *AIP Conference Proceedings*, Third International Symposium on Beamed Energy Propulsion 2004, A. V. Pakhomov, ed., American Institute of Physics, Woodbury, NY (2005)

44. F. diTeodoro, J. P. Koplow and S. W. Moore, "Diffraction-limited, 300-kW peak-power pulses from a coiled multimode fiber amplifier," *Optics Letters* **27**, no, 7, pp. 518-520 (2002)