DOI: 10.13009/EUCASS2019-962

Laser propulsion: preliminary definition of a demonstrator

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Abstract

Because of the increasing development of the space industry, the research for cheaper launch technology became critical. Indeed, the high cost of access to low earth orbit still limits many projects. Moreover, recent issues such as the removal of orbital debris or the rapid development of small satellites market is the opportunity for a new paradigm in space propulsion. In this context, the use of high-power pulsed lasers for space propulsion appears as a very promising solution. This technology is based on the laser ablation: the material is quickly heated, vaporized and the ejected mass creates thrust. Imagined first by Kantrowitz in 1972 [1], then applied by Myrabo in 1997 [2] with a lightcraft demonstrator, this technology evolved into various versions [3] [4] [5]. Laser ablation propulsion presents several advantages: the remote energy deposit enables distant sources, which limits the fuel mass and enables the use of large ground installations. This technology could also offer a viable solution within less than a decade to remove small orbital debris [6]. However, this technology is not mature enough yet to be deployed as several key technical issues remain, especially concerning the laser-matter interaction when applying numerous successive ablations. The aim of our work is to investigate on thrust parameters such as momentum coupling coefficient and specific impulse. Besides, the quantification of mass loss induced by ablation is a question addressed by this study. Our work is based on numerical estimation using the ESTHER code from CEA (the French Alternative Energies and Atomic Energy Commission), which makes it possible to simulate laser-matter interaction. The results are compared to existing experimental data from literature in order to determine the limits of this simulation. Later, it will be compared to dedicated tests foreseen at the end of 2019, early 2020.

1. Introduction

The use of the laser for propulsion has been considered for several years and made significative progress as the development of new sources enables more powerful irradiation. Several technologies have already been tested, but the most promising for now seems to be the laser ablation propulsion. Irradiation of matter with ultra-short pulses, even with a modest amount of energy, can generate local intensities above gigawatts per square centimeter, leading to a brutal vaporization of the matter and plasma. The small amount of matter is ejected with a very high velocity, generating thrust. Projects such as the Myrabo Lightcraft [7] show the feasibility of such a propulsion system for light vehicles and low altitudes. Even though the thrust generated for now isn't enough for space propulsion, but several progress has been made on sources, and modelling for understanding of the phenomenon. Indeed, a better modelling of the laser ablation is crucial to progress on the performances of the propulsion technology, and especially the parameters involved in flight performance.
This study is based on simulation results of the ESTHER code, developed by Combis et al. (CEA), which is a 1D Lagrangian code able to simulate laser matter interaction code and shockwave propagation. This code can compute several phenomena at the same time: laser matter interaction, plasma behaviour under lasers, mechanical behaviour (shock propagation) and thermodynamics parameter estimation (temperature, pression, density). The aim of this paper is to show the ability of Esther to compute the relevant parameter for the laser ablation propulsion: coupling coefficient, specific impulse and ablation efficiency. The material studied here is aluminium, since this material have already been studied with ESTHER for nanosecond lasers. Indeed, Esther can evaluate velocities of particles,

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pressure along the 1D model and phase change. Those quantities are the basis for the evaluation of the coupling coefficient, the specific impulse and the efficiency. In order to verify this, the result of this code will be compared to several existing data found in literature.

2. Laser Ablation Propulsion Principle

Laser Ablation Propulsion (LAP) is based on the short pulse laser (nanosecond to femtosecond) at very high peak intensity (several GW/cm²). The energy is firstly absorbed by free electrons, and then converted to heat by collisional process [8] [9].This heating changes the state of the matter from solid, to liquid and vapor. The ejection at high velocity of the mass generate thrust. Moreover, the mass ejected at high temperature generate a plasma plume that can interact with the laser if the impulse is ongoing [10]. The plasma absorbs a significative part of the energy: this phenomenon called plasma shielding can reduce the ablation efficiency.
For nanosecond wide pulses, the irradiation is still ongoing during ablation, and then subjected to plasma shielding since ionization occurs in the early stage of laser ablation, considering nanosecond time scale.

3. Parameters of the study

3.1. Coupling coefficient

Evaluation of a propulsion system implies the estimation of the thrust, which estimates the capability of a system to accelerate objects. This parameter is important to estimate the possible use of a propulsion system: high thrust will be used for earth to orbit mission or orbital manoeuvre, while low thrust is preferred for fine adjustment in the trajectory and orientation. As the LAP is concerned, the thrust is directly related to the intensity of the laser impulse. The coupling coefficient (Cm) estimates the thrust due to the ablation in respect with incident power. This coefficient evaluates the generated impulse compared to the laser energy of the pulse. This parameter can be expressed as:

$$C_m = \frac{F}{I} = \frac{J}{\mathrm{E}} = \frac{\int_0^\infty P(t).dt}{\Phi} = \frac{\int_0^\infty P(t).dt}{\int_0^\infty I(t).dt}$$

Where :
C_m : the coupling coefficient (N/W)
F : the thrust (N)
I : the laser intensity (W/m²)
J : the impulse (N.s)
E : the laser energy (J)
Φ : the fluence (J/m²)
P : the pressure
τ : the pulse duration

The aim here is to evaluate the pressure using Esther. The ablation pressure can be estimated on the elements where the velocity of the particle changes the direction of the velocity (i.e. the sign of velocity value changes). The impulse per surface unit is then the integration of the pressure over time.

3.2. Specific Impulse

Propulsion is based on the thrust generated using mass ejection. Most of the space propulsion systems have a limited amount of fuel or mass to eject. The specific impulse (Isp) estimates the efficiency of a propulsion considering the mass ejection. It’s the ratio of the impulse generated over the mass. High Isp mean a higher impulse with the same amount of mass ejected, which means ejected mass is used more efficiently. Isp can be defined by:

$$I_{sp} = \frac{J}{\mathrm{m_{ej}}\, g_0} = \frac{\int_0^\infty P(t).dt}{\mathrm{m_{ej}}\, g_0}$$

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With :
m_{ej} : the ejected mass
g_0 : the gravitation field constant

The point is to estimate the mass ejected, which can be done on several assumptions:

- Considering the limit with the inversion of velocity orientation
- Considering the limit as the vaporized matter
- Considering the limit as the liquid matter

These definitions of ejected mass are not equivalent. In order to get the lowest efficiency estimation, this study used estimation of the limit with the solid/liquid frontier (highest mass estimation, lowest Isp estimation). Here, the aim is more to evaluate the loss of mass than the amount of mass that contribute effectively to thrust. The mesh also has some importance, using a coarse mesh can over-evaluate the mass ejected. Here the mesh convergence was done in order to get a reproductive pressure.

3.3. Ablation Efficiency

All the laser energy is not converted into kinetic energy, and could be dissipated into heat, phase change or directly absorbed by the creation of plasma. In order to evaluate the loss of energy, the efficiency of the ablation represents the ratio between the kinetic energy of the exhaust and the incident laser energy, and can be expressed as :

$$\eta_{ab} = \frac{E_k}{E_l} = \frac{m_{ej} v_{ej}^2}{2E_{laser}} = \frac{g_0}{2} C_m I_{sp}$$

With :
E_k: the kinetic energy (J)
E_l: the laser energy (J)
v_{ej} : the velocity of ejected particles (m/s)

This parameter is crucial to evaluate an efficient ablation material. Moreover, this efficiency cannot exceed 100% if there is no other energy source than the laser. In the case of chemical reaction or electric powered acceleration of exhaust, the efficiency might be higher than 100%, considering this definition of efficiency.

4. Simulation set up

4.1. Mesh

The mesh is divided in 3 main regions: an ablation region with a fine mesh to accurately describe the mass ejection, a region with coarse mesh for the shockwave to propagate and avoid early reflection and finally a region with a bias mesh to connect the fine and the coarse region. This is illustrated in Figure 1:

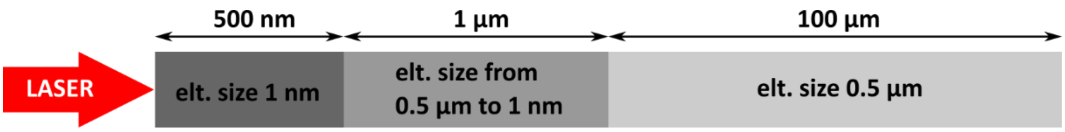

Figure 1 : Mesh strategy for the ETHER computation.

4.2. Laser parameter

The laser considered is a 532 nm laser, with a Gaussian time profile for the impulse. The laser is described by the pulse duration (width at 0.1% of the maximum value) and the fluence (energy per surface unit). The experiment plan was made using this using the following parameters:

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Table 1: parameters for simulation

	Min.	**Max.**	**Step**
Fluence (MJ/m²)	1	10	1
Duration (ns)	10	100	10

Those duration and fluence are representative of existing lasers, like Hephaistos platform in PIMM (Paris, France), or Bijov in Hilase (Prague, Czech Republic), even if the majority of the fluence tend to be on the lower limit. The simulation was done for a total time of 1 µs in order to ensure the end of the ablation and to get a correct estimation of total impulse.

4.3. Material Parameters

The parameter used here is aluminium, considerers as pure (no alloy). This material was validated in terms of ablation pressure by Bardy et al. [11], at least for nanosecond wide pulses. The equation of state used here is the SESAME for the vaporization part, which is based on tabulated properties. The plasma stage is described using a SCAALP model, based on a single atom of aluminium.

5. Results

5.1. Result on Cm

Results on Cm are presented in Figure 2.

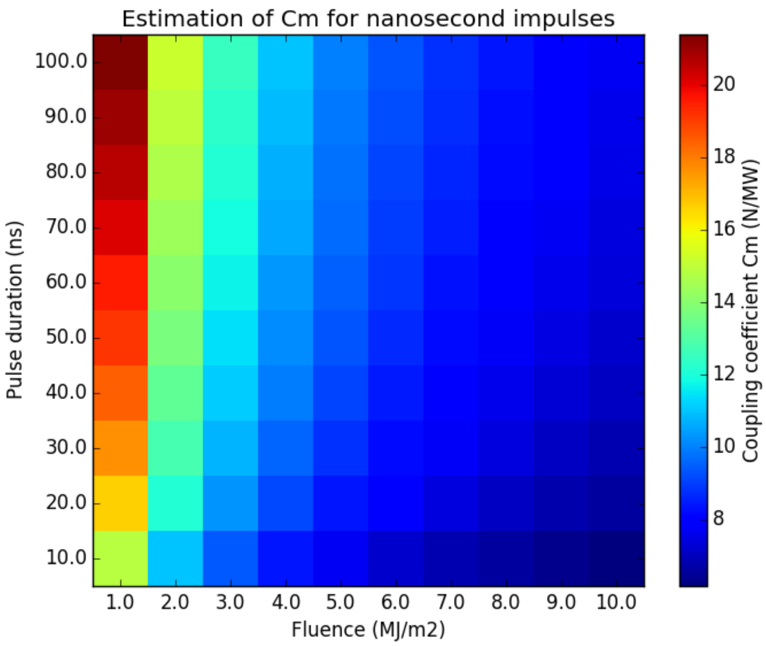

Figure 2 : Cm estimation using ESTHER for a fluence range from 1 to 10 MJ/m², and a pulse duration from 10 to 100 ns

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The Cm tends to be higher for low intensities (long duration, low fluence). This trend was highlighted by several numerical studies [12] [13] and experimental studies [14] [15], which tend to validate the computation. Mesh convergence was done for this computation on Cm estimation first, but it is not the determinant parameter for mesh convergence.

5.2. Result on Isp

Results on Isp are presented in Figure 3.

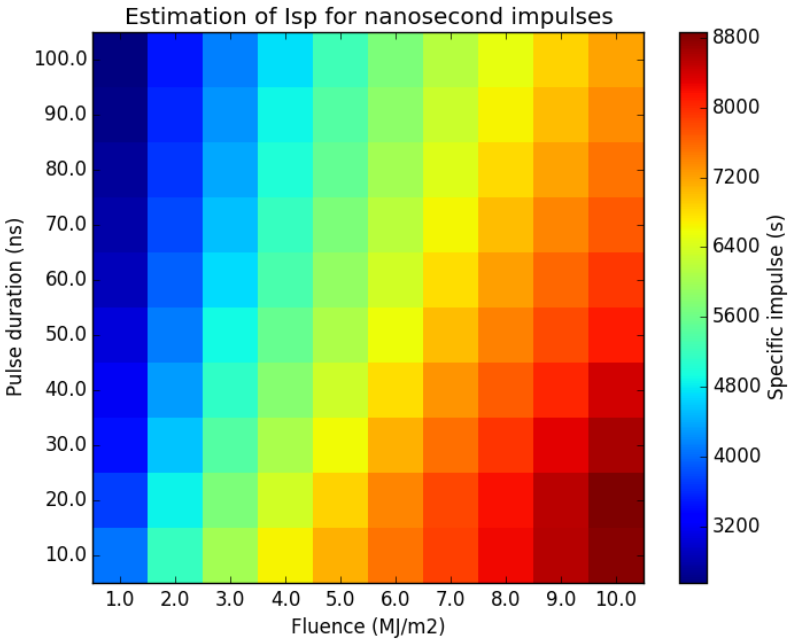

Figure 3 : Isp estimation using ESTHER for a fluence range from 1 to 10 MJ/m², and a pulse duration from 10 to 100 ns

The Isp is higher for high intensities (short duration, high fluence). This trend was highlighted by experimental studies and numerical studies [16], which tend to validate simulations. The mesh convergence was done on ejected mass criteria (and so Isp) which is the determinant criterium. Mesh convergence on mass ejection ensure a converted result in Cm too. The accurate description of mass ejection requires a mesh with a constant size, where small elements discretize finely the ablated layer. Notice that Isp results are strongly dependent on mass estimation.

5.3. Result on efficiency

Result of efficiency is presented in Figure 4.

DOI: 10.13009/EUCASS2019-962

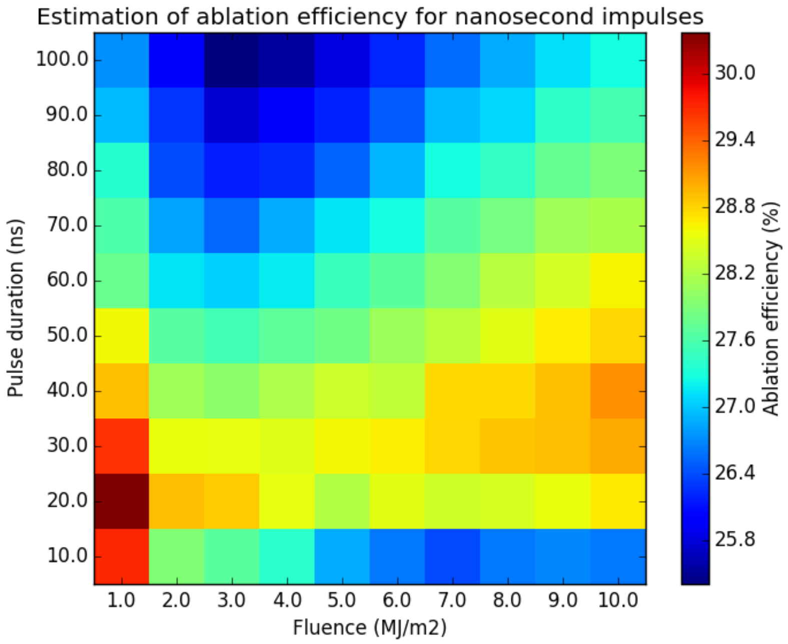

Figure 4 : Ablation efficiency estimation using ESTHER for a fluence range from 1 to 10 MJ/m², and a pulse duration from 10 to 100 ns

The efficiency is directly related to Cm and Isp. The efficiency is around 28% between a maximum efficiency of 30% and a minimum efficiency of 25%. The repartition within the experiment plane is difficultly interpretable, but considering assumptions made, the efficiency could be considered as constant. Another way to display the efficiency is to plot every case by Isp vs. Cm on a log-log scale, as shown Figure 5:

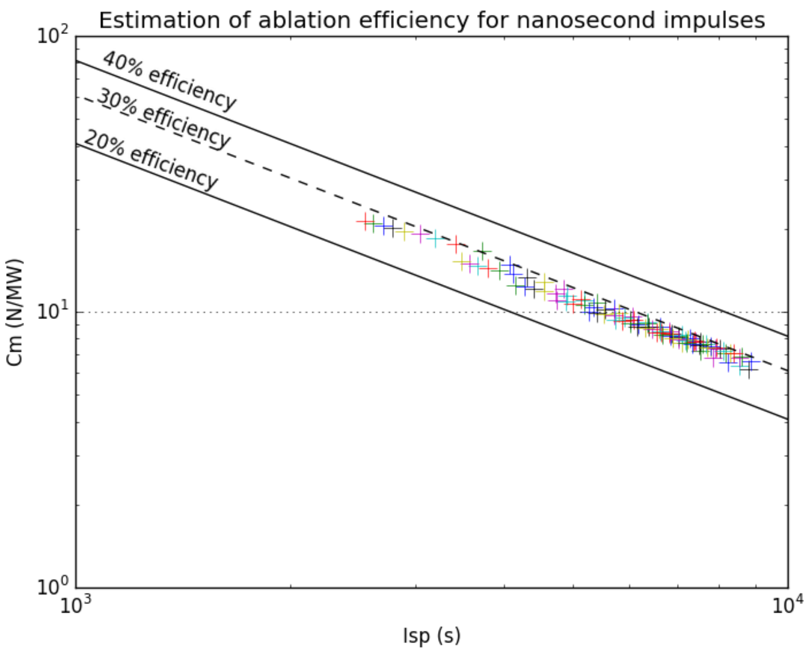

Figure 5: Isp vs. Cm for every case computed, comparison with iso-efficiency lines.

This show the different cases are close to the 30% efficiency line and represent the actual range of Isp and Cm. The results are clustered on a segment on the line at iso-efficiency, with a concentration of the points on the bottom of the segment (Cm under 10 N/MW and Isp above 4000 s).

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6. Discussion

First, this simulation study shown coherent Cm value in the literature, as well as some Isp values. The efficiency of 30% is difficultly comparable with data in literature for aluminium, but seems to be a reasonable value because it’s under 100% and seems coherent with values from Phipps et al. 2010 [13] presented in Figure 6.

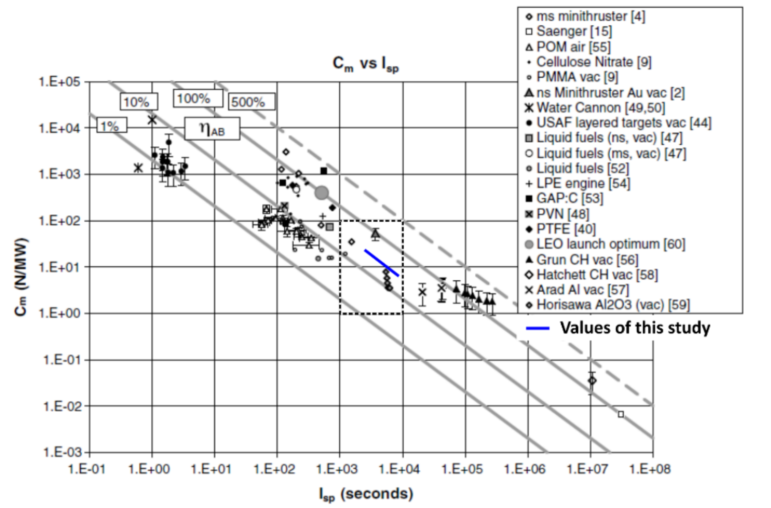

Figure 6 : Comparison of this study results with other values found in review of Phipps et al. 2010 *[13]*.

Those results are close to the result of Horisawa et al. [17], based on experimental evaluation of aluminium oxides for nanosecond lasers. Moreover, the efficiency is close to results from Arad et al. [18], based on picosecond aluminium ablation. Those similarities are encouraging but require more investigations especially for shorter pulses. Another interesting fact is the decrease of the Cm and the increase of Isp with an increasing intensity. This was modelled by Sinko et al. [16], and shown experimentally by Schall et al. [15].

The variation of (± 2.5% of efficiency) is a significant variation, but regarding assumptions made during this study, it is difficult to interpret those results. In terms of the order of magnitude, the efficiency can be considered as almost constant. Another interesting fact is high efficiency can be reached using modest fluence, which is encouraging because most of the available sources cannot reach high fluence.

The main limit of this study is the mass estimation because of the strong assumption made for simulation: the definition of the ejected mass and the mesh. Both of those parameters are crucial in the Isp estimation, and thus efficiency. Moreover, this is a unidimensional simulation, the parameter estimated does not consider the plasma plume shape influence. The real phenomenon might present lower efficiency than the one presented on this study.

7. Conclusion

This study shown the possibility of ESTHER to estimate the efficiency of a LAP for nanosecond ablations. The value computed in this study were underestimated compared to the reality, at least for a 1D assumption. Those values are in accordance with several values in literature. Efficiency values are coherent considering the assumptions made: efficiency is lower than 100%, and close to existing values.
The next step of this study is to do the same type of computation for other pulse duration: picosecond and femtoseconds. A wider range of fluence should be investigated too, especially concerning low values of fluence in order to confirm the feasibility for less powerful sources, more representative of existing laser sources. Computation for other materials, such as polymers could be interesting because of the high Cm observed on some polymers such as POM.
An experimental campaign should follow the numerical study to compare the numerical results to validate or not the simulation. The Cm values are close to the one in literature, but the ablated mass estimation requires more investigations.

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8. Acknowledgement

This work is part of a partnership between CEMEF, CNES, PPRIME with the help of CEA. CNES funds the preliminary design phase of a laser pulsed LEO vehicle, as well as test campaigns conducted in 2017, 2018 at X, and foreseen in 2019 (test facility to be confirmed). CEMEF funds the independent expertise and aftermaths realized by Photonic Associates, LLC. CEA made available the ESTHER Code, used for this study.

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