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Laser Propulsion

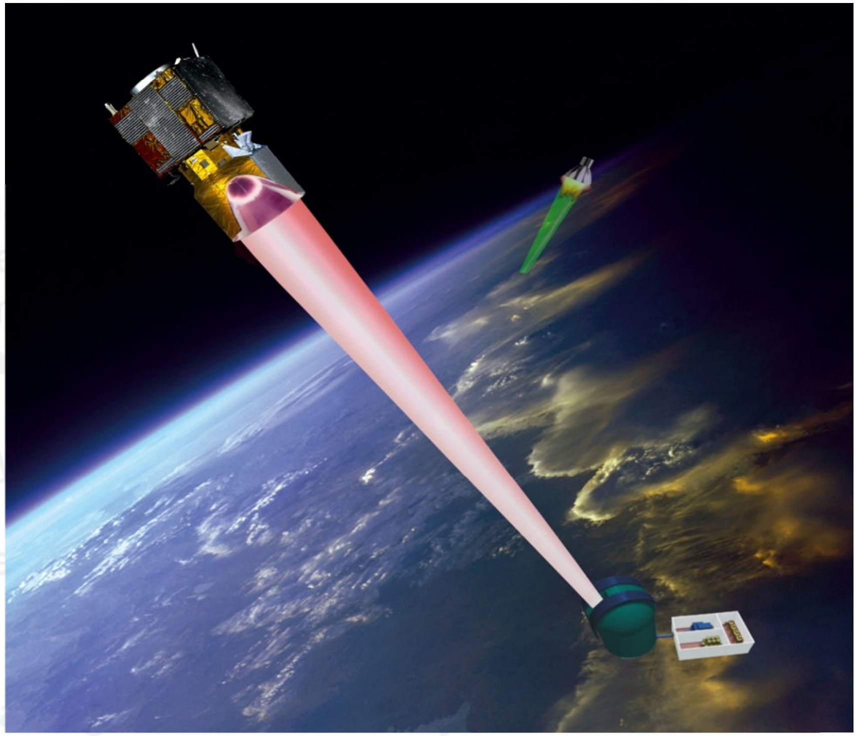
Lectures on Unconventional Space Propulsion

Part 1: Introduction

IRS Institute of Space Systems, University of Stuttgart
February 10, 2023

Dr. Stefan Scharring

Institute of Technical Physics,
German Aerospace Centre (DLR)



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1980 People who have a vision should turn to a doctor. (Helmut Schmidt, German chancellor)

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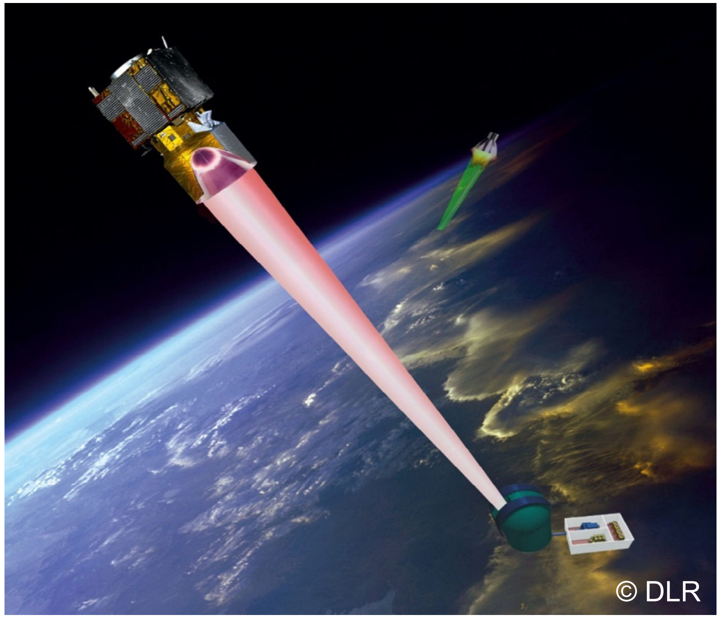
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IRS Institute of Space Systems, University of Stuttgart
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Institute of Technical Physics

Learn more

Head of Institute: Prof. Dr. Thomas Dekorsy

Laser systems for:

Aeronautics

Flight instruments

Space

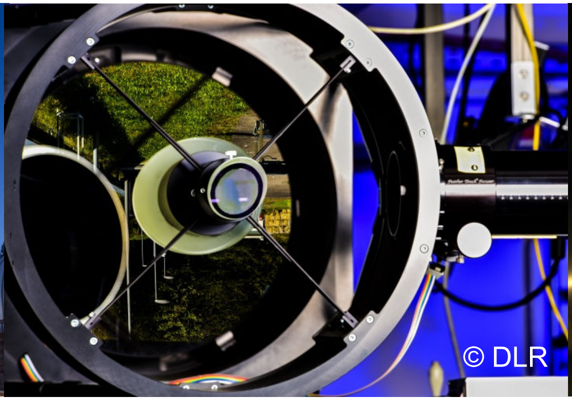
Detection and characterization of space debris

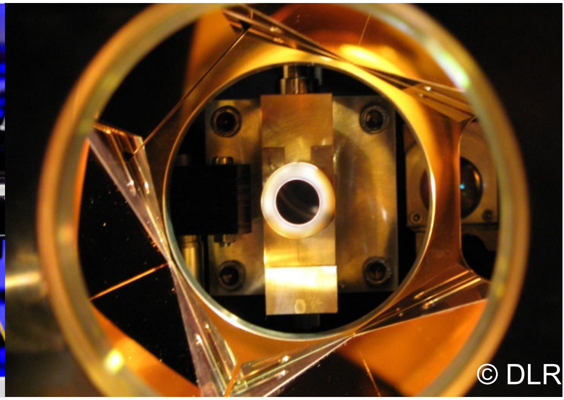
Security

Standoff detection

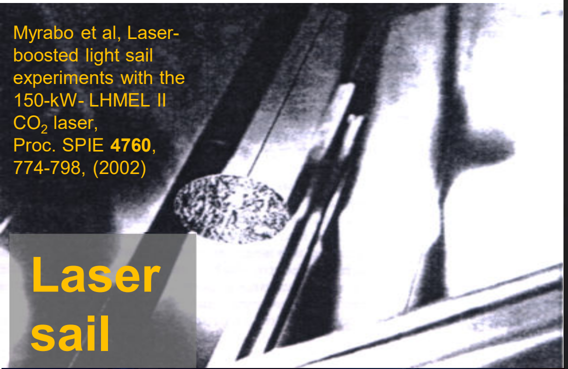
Defense

Long-range laser effectors





Laser Applications: Science, Vision and Fiction


Myrabo et al, Laser-boosted light sail experiments with the 150-kW- LHMEL II CO_2 laser, Proc. SPIE **4760**, 774-798, (2002)

Laser sail


Laser power beaming

Image credits: Ascending Technologies


Laser cutting

Image credits:
Quander Metall- und Lasertechnik


Eye surgery

Image credits: Dr. med. Inken Lamcke, Femto- Lasik – PRK


Photon rocket

Image credits: Bundeshandelsschule Völkermarkt

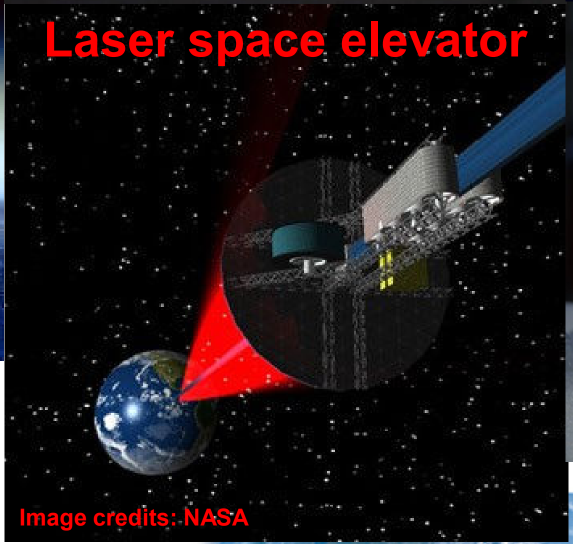

Laser space elevator

Image credits: NASA


Light saber

Image credits: Sandra_M_H, Pixabay


Image credits: Anua22a

Death ray

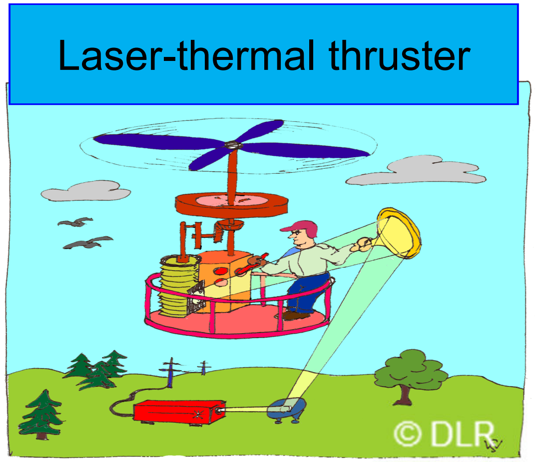
Definitions and Examples

Laser Thruster

Thruster in which laser energy contributes substantially and indispensably to kinetic energy.

Lightcraft (in the broader sense)

Thruster based on electromagnetic radiation (laser or microwave)



Laser-thermal thruster

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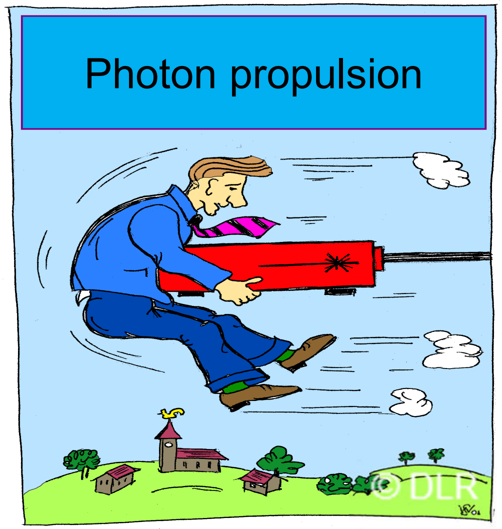

Photon propulsion

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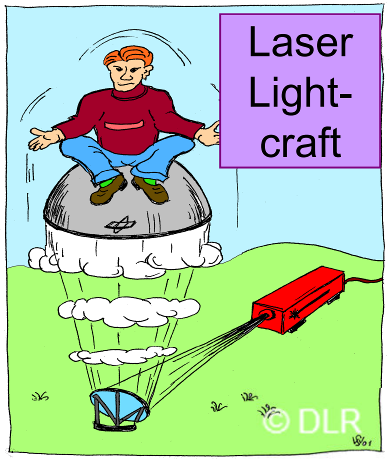


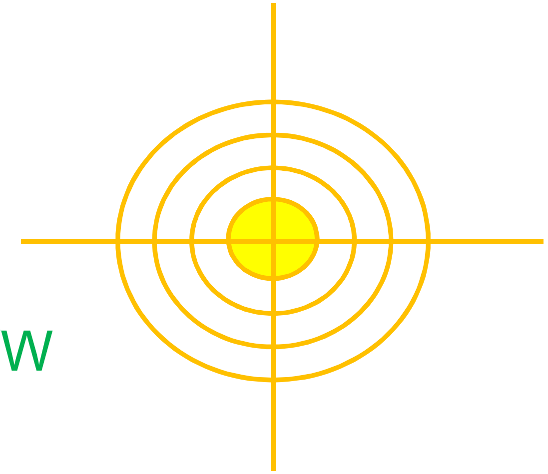
Laser Light-craft

© DLR

Lightcraft (in the narrower sense)

Thruster based on detonations induced by a remote laser source

Experiment No. 1: Thrust from photon pressure



- Can you exert thrust to a wall using a laser pointer?
  If so, how much?
  - Momentum coupling from photon pressure: ~ 5 nN/W
  - Laser pointer power: < 1 mW
  - Exerted thrust: ~ 5 pN

- How can you increase the thrust?
  - Increase laser power
  - Create a focal point
  - Compress irradiation

} → induce material reaction + recoil

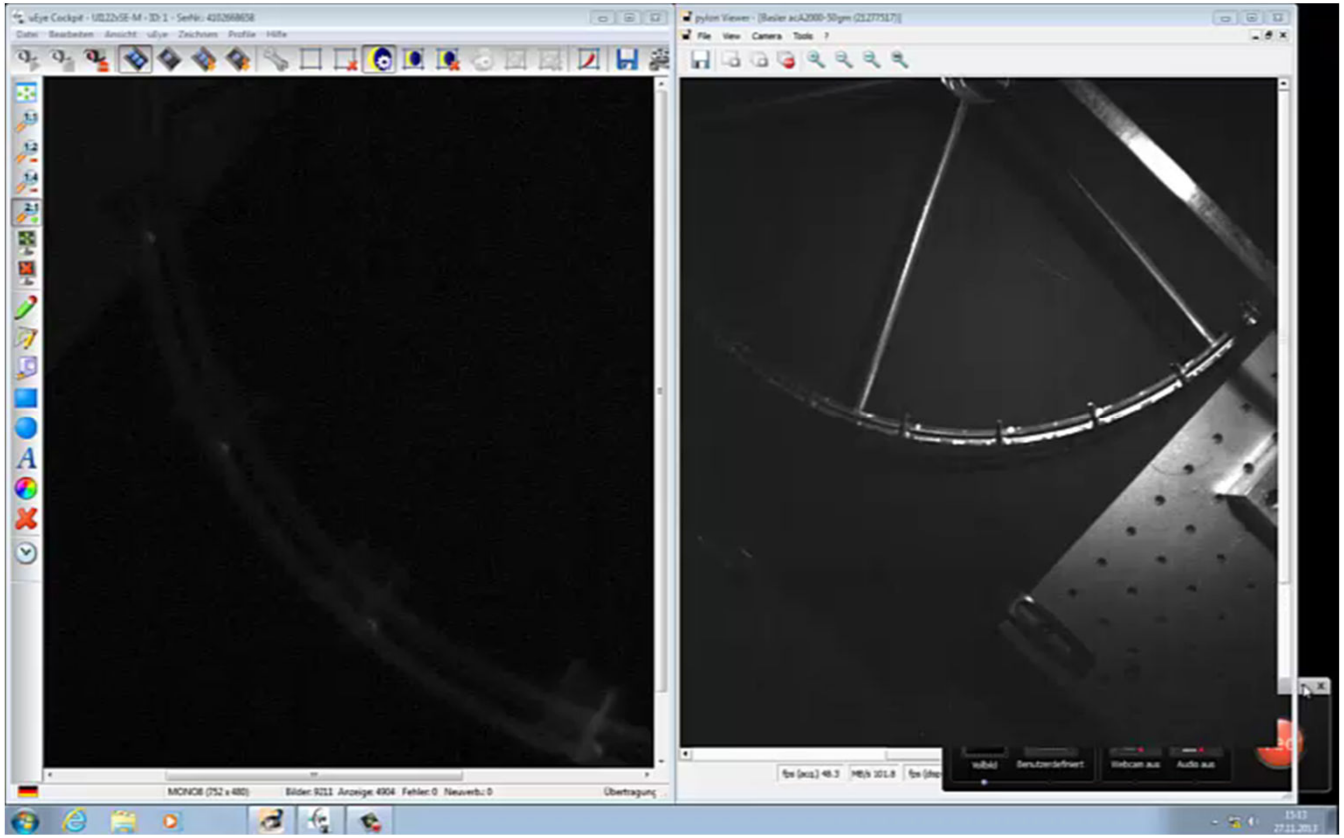
Experiment No. 2: Thrust from laser-induced material ablation

Demonstration experiment from the EU study „CLEANSPACE“ at DLR – Institute of Technical Physics

Laser:
- Average laser power: 33 W
- Laser pulse duration: 3 ns
- Laser pulse power: 94 MW
- Wavelength: λ = 1064 nm

Focus:
- Target: aluminum
- Size: 3 mm diameter
- Intensity: 190 MW/mm²
- Fluence: 4.7 J/cm²

Thrust: 700 µN
- Momentum coupling: c_m = 21 µN/W



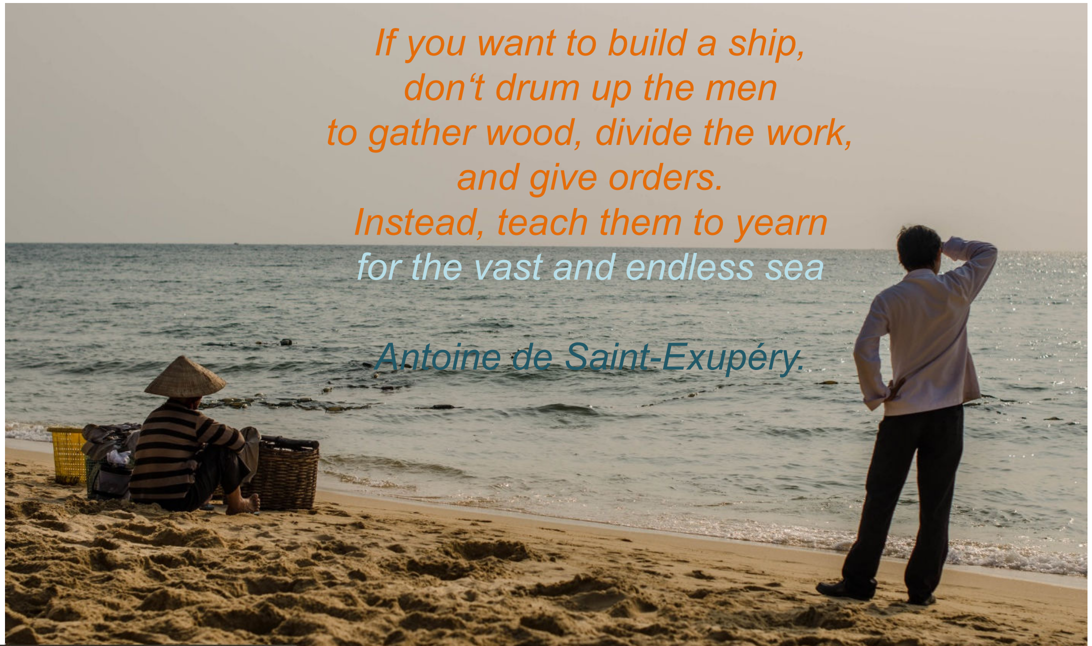
Motivations for Laser Propulsion

Upload propulsion power in the order of ***MW***

Reduce propellant consumption down to ***< 1 %***

Precise satellite positioning at a level of ***nm - µm***

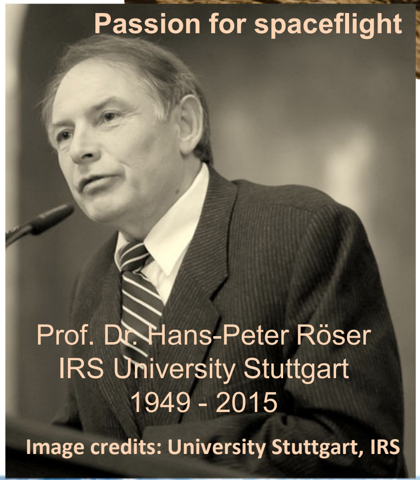
Detect and remove space debris in the size range ***cm - dm***



If you want to build a ship,
don't drum up the men
to gather wood, divide the work,
and give orders.
Instead, teach them to yearn
for the vast and endless sea

Antoine de Saint-Exupéry

Image credits: Mariyan Dimitrov



Passion for spaceflight

Prof. Dr. Hans-Peter Röser
IRS University Stuttgart
1949 - 2015

Image credits: University Stuttgart, IRS

Outline

Part I. Introduction
Part II. Lasers
Part III. Power beaming propulsion
Part IV. Laser launchers
Part V. Laser-ablative propulsion
Part VI. Spacecrafts' debris propulsion

Laser-matter Interaction Phenomena and Propulsion Principles

Part I. Introduction

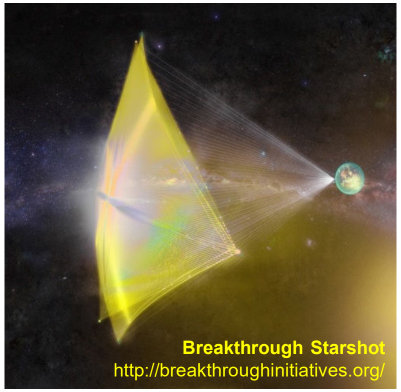
Part II. Lasers

Part III. Power beaming propulsion
- Absorption and/or reflection
  → Laser photon propulsion
- Absorption and conversion
  → Laser photovoltaic propulsion
- Heating and ionization
  → Laser-thermal propulsion

Part IV: Laser launchers
- Detonation and combustion
  → Laser Lightcraft

Part V: Laser-ablative propulsion
- Material ablation

Part VI. Spacecrafts‘ debris propulsion
- Material ablation

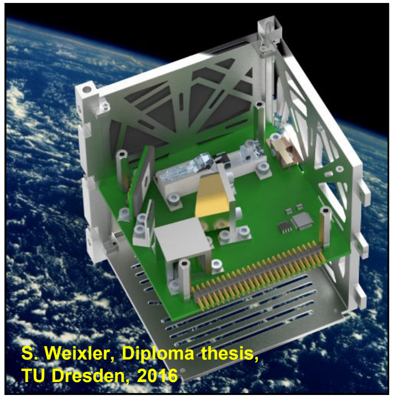


Breakthrough Starshot
http://breakthroughinitiatives.org/

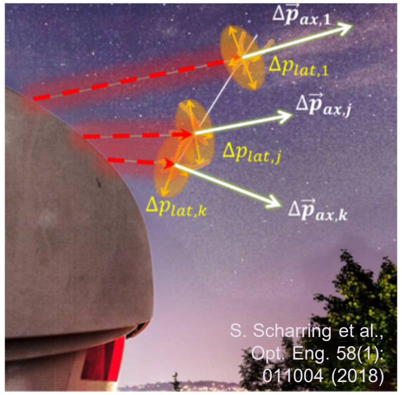
© Steinsiek, EADS Space Transportation Systems, 2003

J. Coopersmith et al., A Strategic Roadmap for Commercializing Low-Cost Beamed Energy Propulsion Launch Systems, AIAA Space 2016

Laser Lightcraft Technology Demonstrator



S. Weixler, Diploma thesis, TU Dresden, 2016



S. Scharring et al., Opt. Eng. 58(1): 011004 (2018)

THE Figure of Merit in Laser Propulsion

- Impulse (Momentum) coupling coefficient c_m

$$c_m = \frac{F}{P_L} = \frac{\Delta p}{E_L}$$

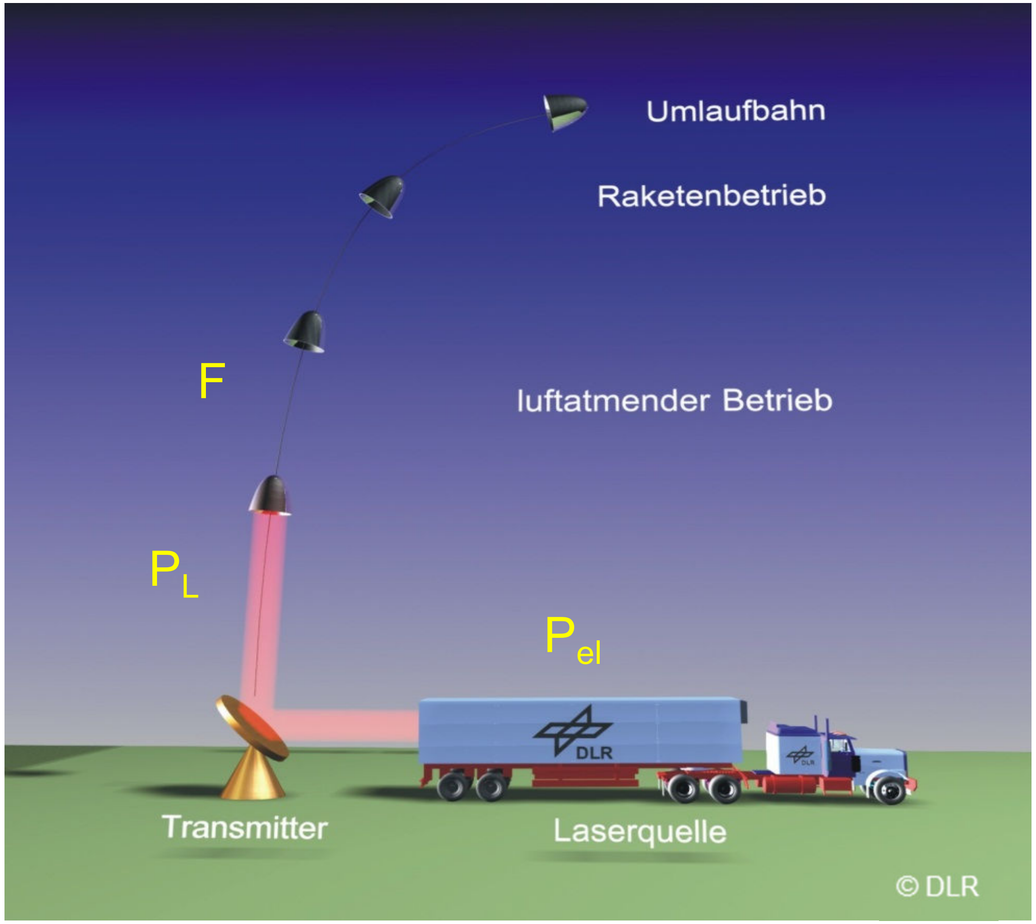
F: thrust
P_L: average laser power
Δp: imparted momentum
E_L: laser pulse energy

- *System* momentum coupling coefficient $c_{m,sys}$

$$c_{m,sys} = \frac{F}{P_{el}} = \eta_{eo}\frac{F}{P_L}$$

= Thrust/power ratio in electric propulsion

- Efficiency of electro-optical energy conversion η_{eo}



A brief History of Laser Propulsion

1953	E. Sänger	Concept for photon rockets
1967	G.A. Askarian	Experimental proof of laser-ablative momentum
1972	A.Kantrowitz	Concept for ground-based laser propulsion
1989	Metzger	Concept for laser-based removal of space debris
1995	Liukonen	Laser-propelled free flight in the laboratory
1997	Myrabo	Laser-propelled outdoor free flight
1998	DLR	Start of laser lightcraft research at DLR
2000	Myrabo	World record flight, 71 m altitude
2002	Phipps	Concept for laser-ablative micro propulsion
2006	Bae	Concept for photonic intra-cavity propulsion


Eugen Sänger

Image credits: DLR

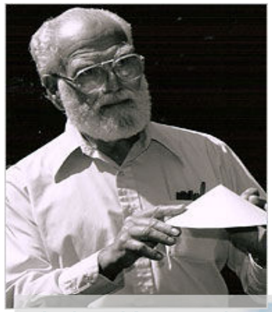

Arthur Kantrowitz

Image credits: New York Times


Leik Myrabo

Image credits: Apogee Books

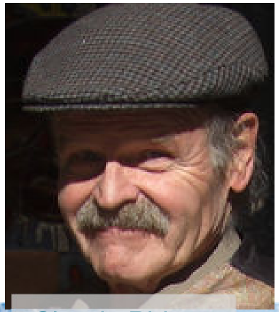
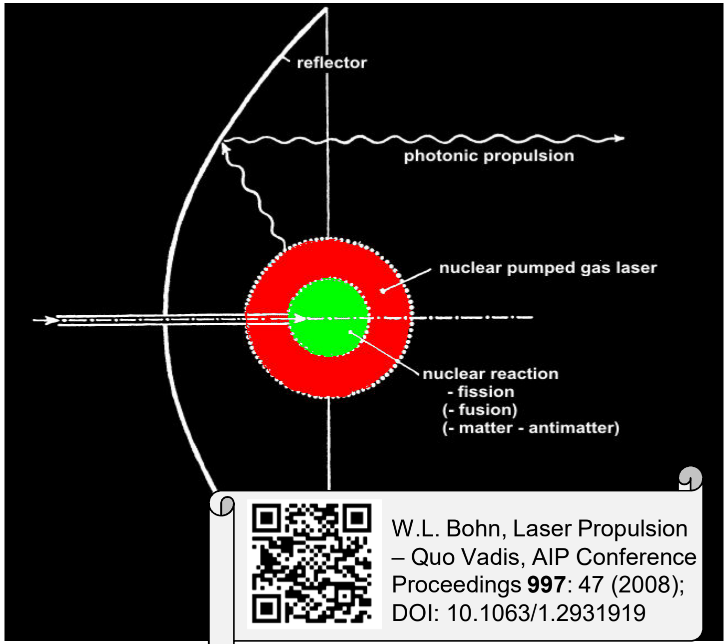
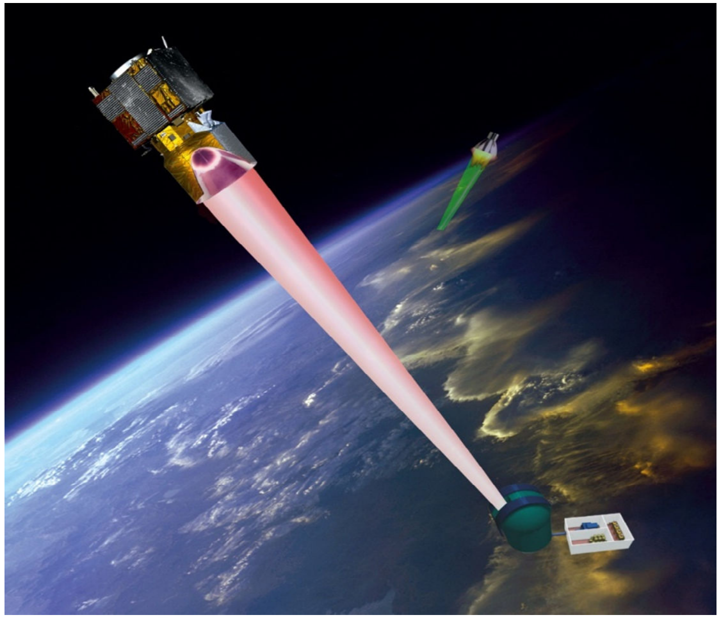

Claude Phipps

Image credits: Photonoic Associates, LLC



W.L. Bohn, Laser Propulsion – Quo Vadis, AIP Conference Proceedings **997**: 47 (2008); DOI: 10.1063/1.2931919

A.N.Pirri et al., Laser Propulsion, AIAA Paper 72-719, DOI: 10.2514/6.1972-719



Laser Propulsion

Lectures on Unconventional Space Propulsion

Part 2: Lasers

Light **A**mplification by **S**timulated **E**mission of **R**adiation

IRS Institute of Space Systems, University of Stuttgart
February 10, 2023

Dr. Stefan Scharring

Institute of Technical Physics,
German Aerospace Centre (DLR)

No Light Amplification by Stimulated Emission of Radiation? but Light Saving (from Absorption)

Parallel Mirrors

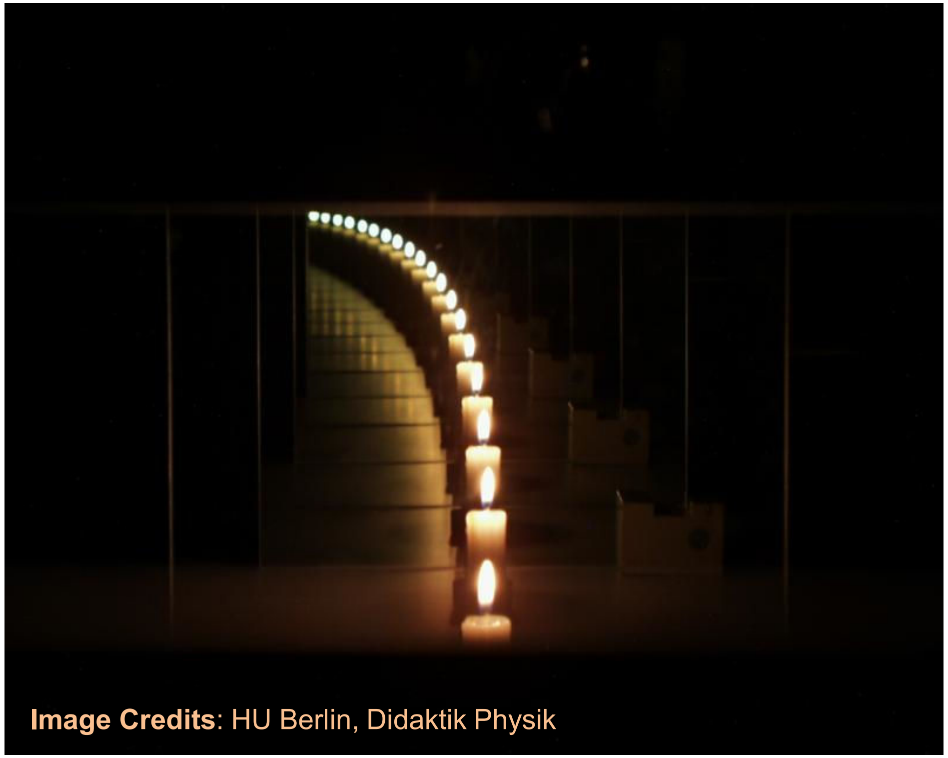


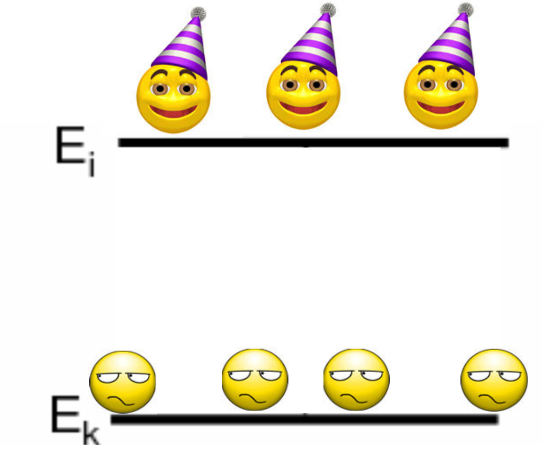
Image Credits: HU Berlin, Didaktik Physik

Scaling

Image Credits:
AFP/THOMAS COEX

Light Amplification by **Stimulated** **Emission** of **Radiation**

$$E_{rot} = 1/2 \cdot M \cdot \omega^2 \cdot R^2$$



Discretized (quantized) energy levels

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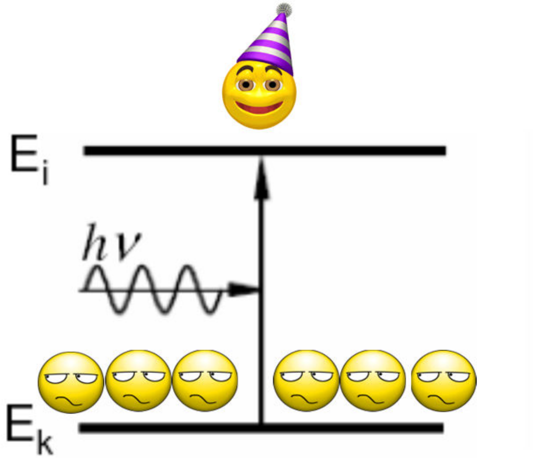
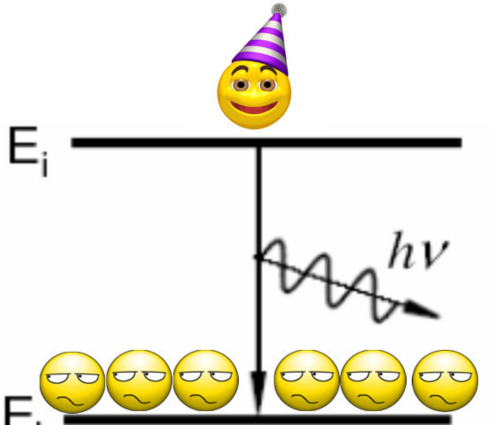
Image Credits: Deutscher Schaustellerbund

Continuous transitions between different energy levels

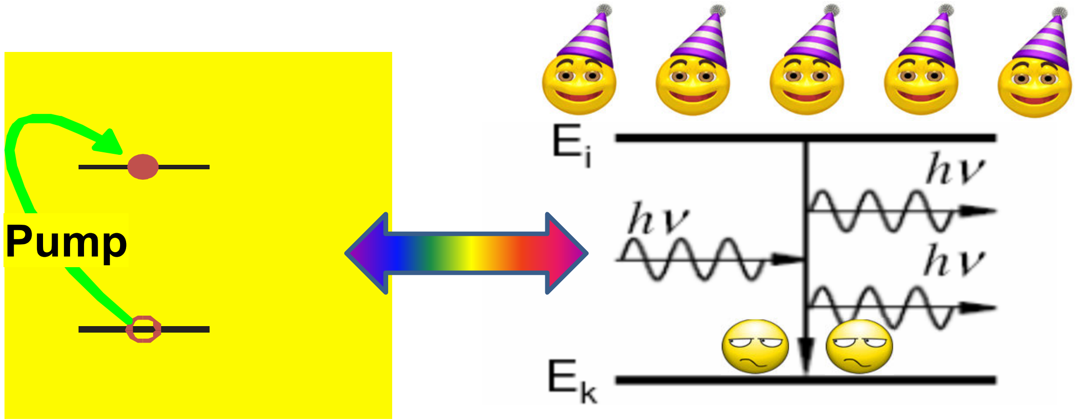
Light Amplification by **S**timulated **E**mission of **R**adiation



Absorption

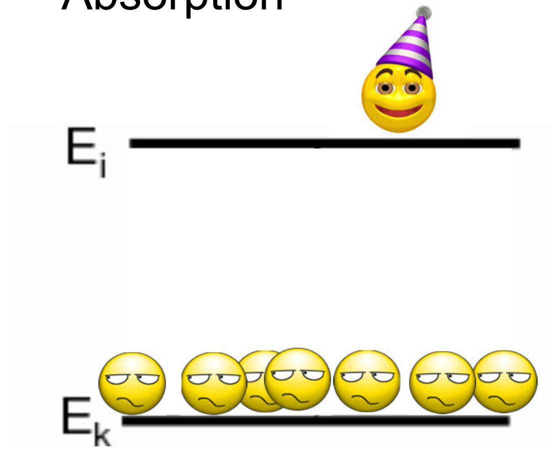


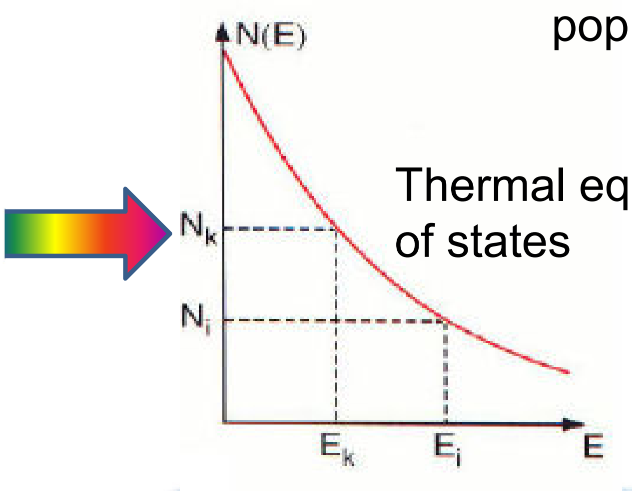
Spontaneous emission



Generation of population inversion

Stimulated emission





Thermal equilibrium of states

Population of energy levels

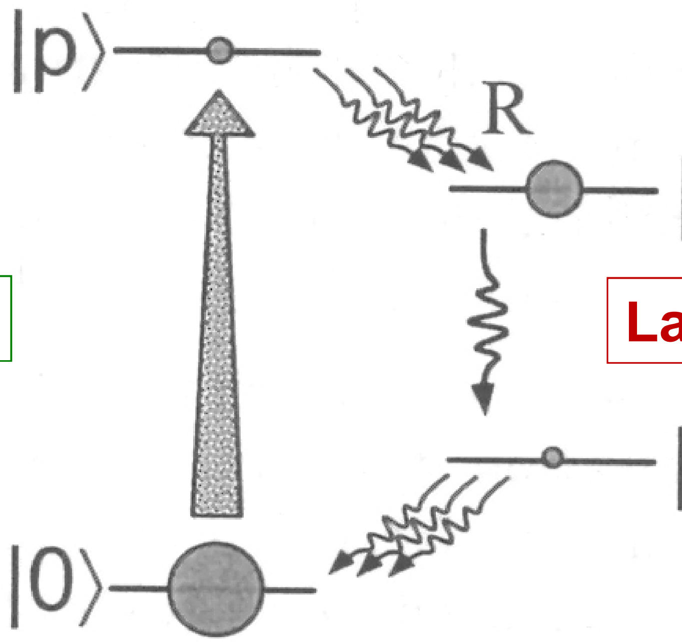
$$\frac{N_i}{N_k} = \frac{g_i}{g_k} e^{-(E_i - E_k)/kT} = \frac{g_i}{g_k} e^{-h\nu/kT}$$

Maxwell Boltzmann distribution

N: Population number

g: Degeneracy of energy level

Pumping and Lasing



Pump level

External energy supply

metastable

Laser energy levels

sparsely populated

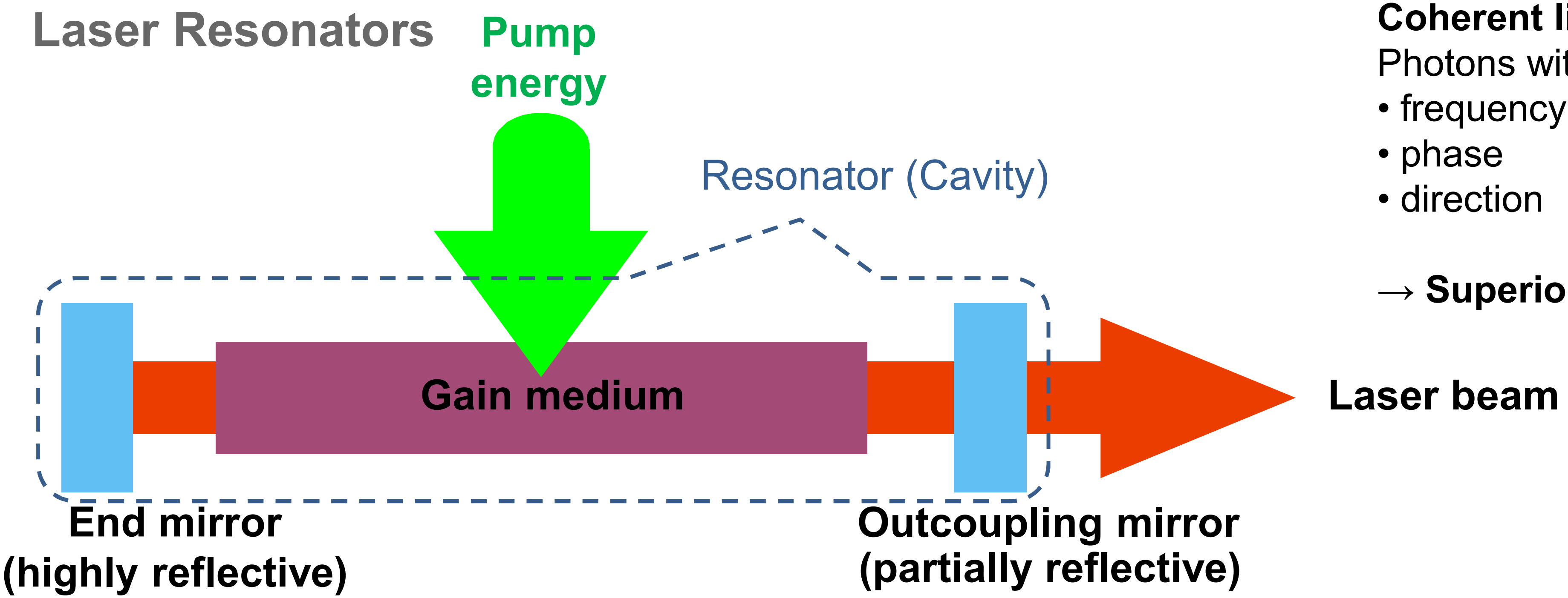
Ground state

Pump mechanisms:

- Electron collisions
- Collisions between molecules
- Chemical reactions
- …

D. Meschede, Optik, Licht und Laser,
Teubner-Verlag 1999, Leipzig

Laser Resonators



Coherent light

Photons with indentical
- frequency
- phase
- direction

→ **Superior focusability**

Image Credits: HU Berlin, Didaktik Physik

Small-signal gain >> absorption

↓

Licht amplification („Photon avalanche“)

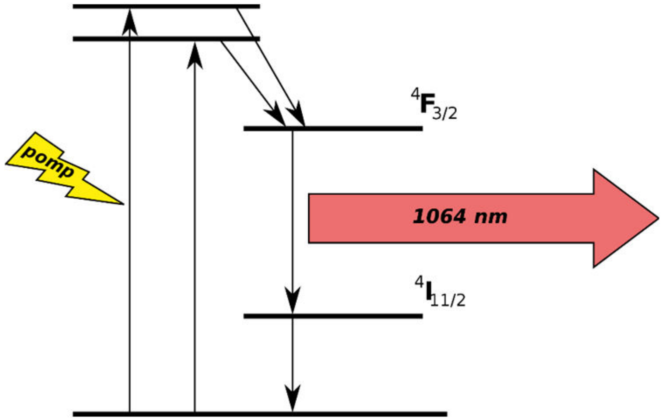
Solid-State Lasers (SSL)

Laser-active ions (e.g., Neodymium, Ytterbium, Holmium)
+ host material (e.g. glass, crystal, polymer)

Example: Nd:YAG
(Neodymium-doped Yttrium aluminum garnet, Nd:$Y_3Al_5O_{12}$)

Pump mechanisms:

- Gas-discharge lamp
- Laser diodes



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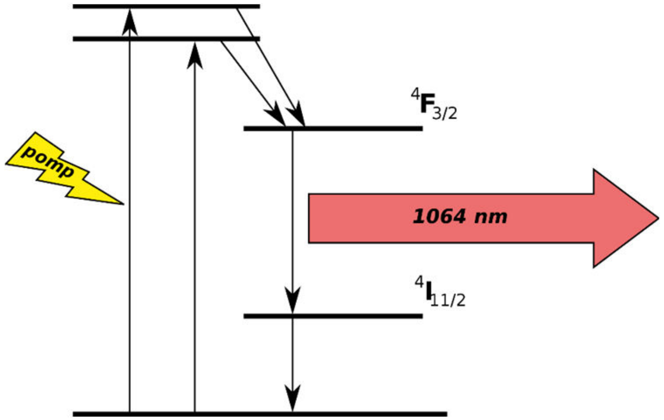


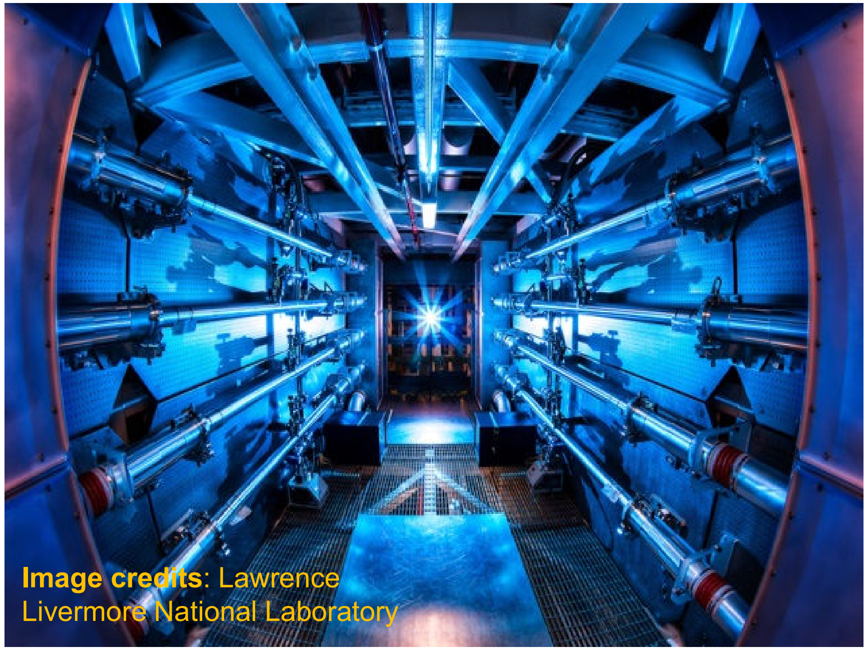
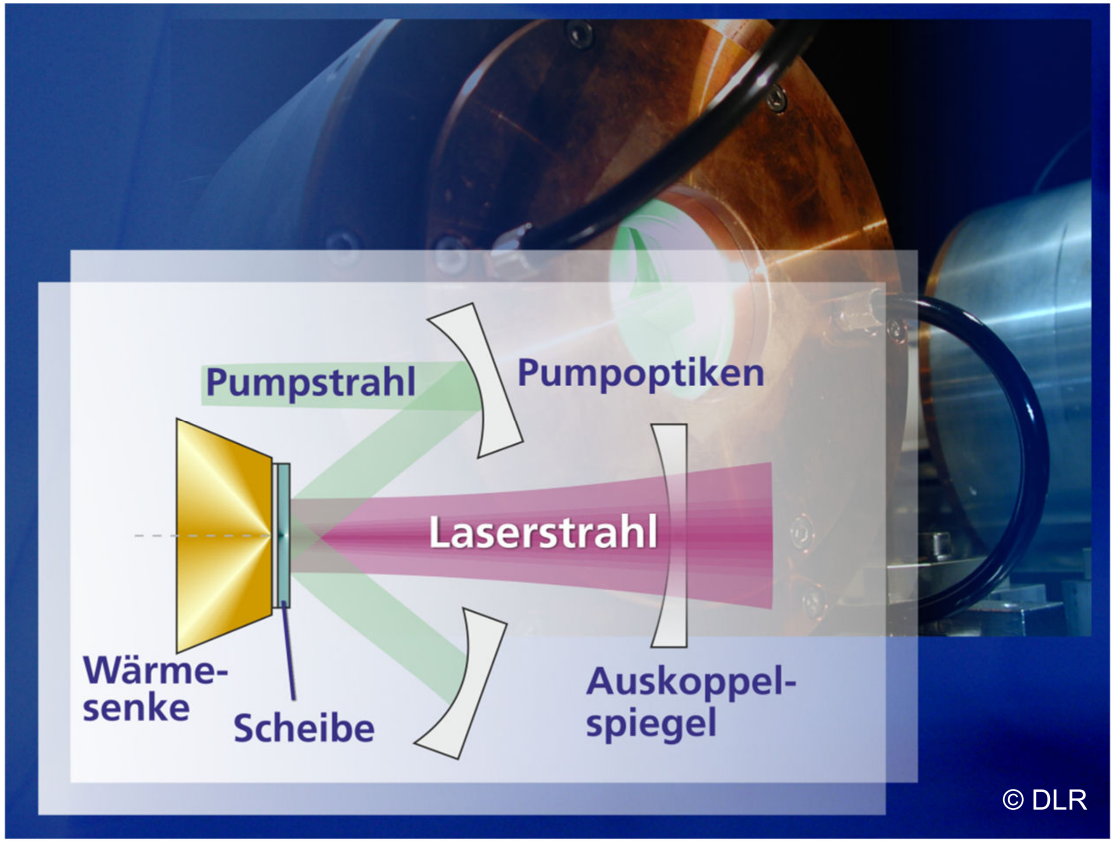


Image credits: Lawrence Livermore National Laboratory

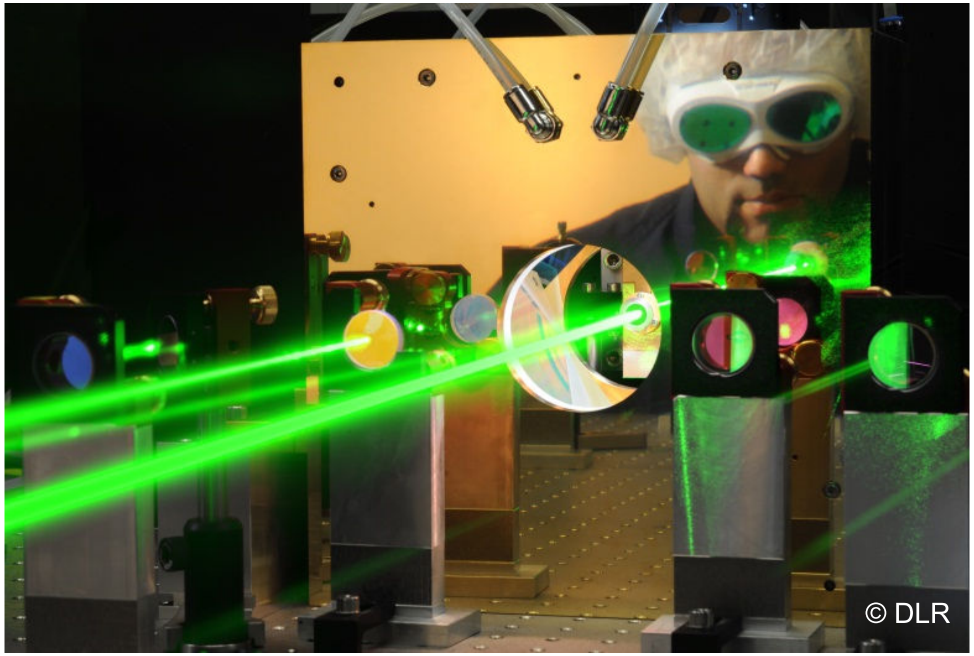
National Ignition Facility:
Experiments on inertial confinement fusion
192 beamlines of Nd:phosphate lasers
(18.8 kJ each, single pulse)

Thermal Management?
- Heating
- Expansion
- Gradients of refractive index

SSL Geometries: Thin Disk Laser



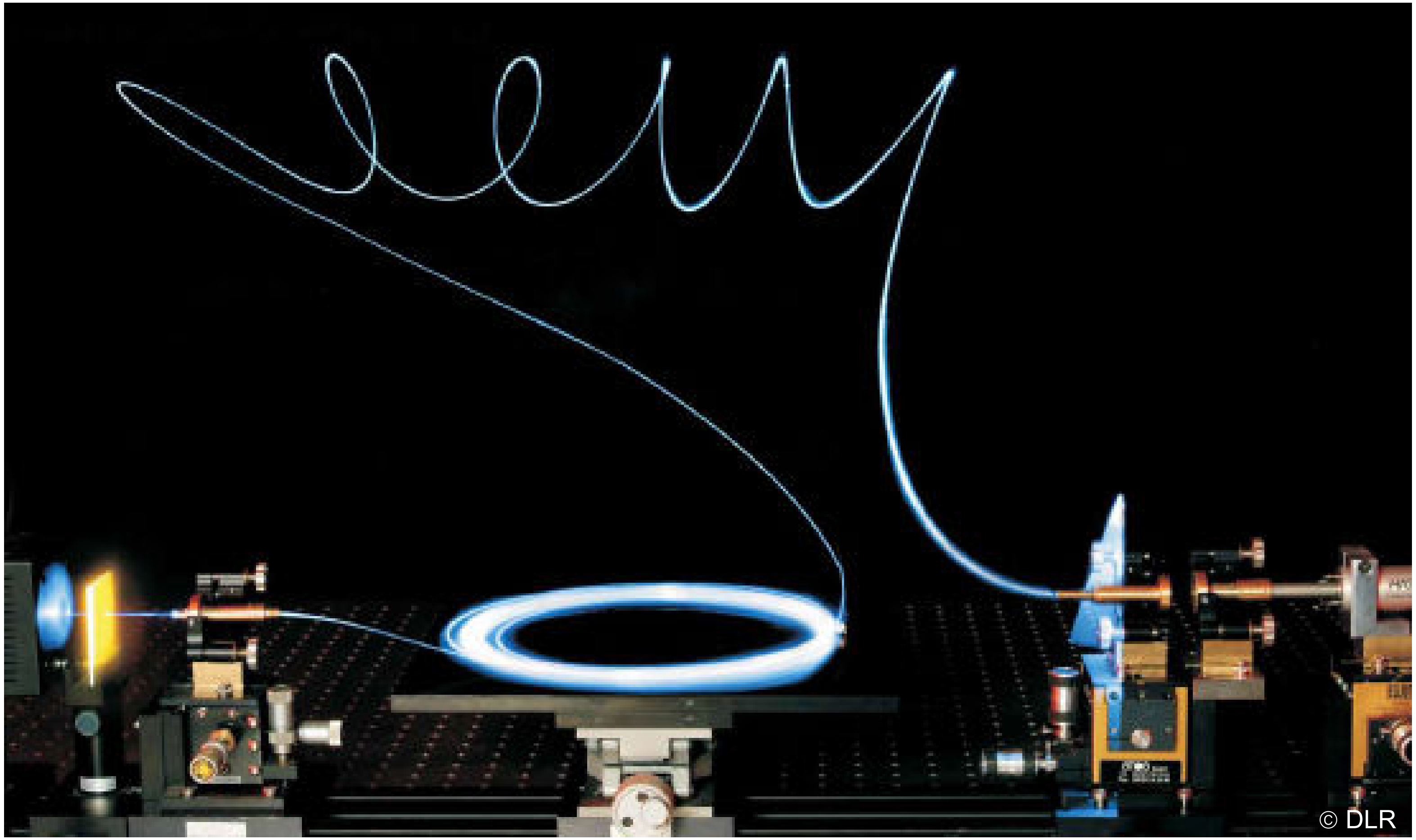
© DLR



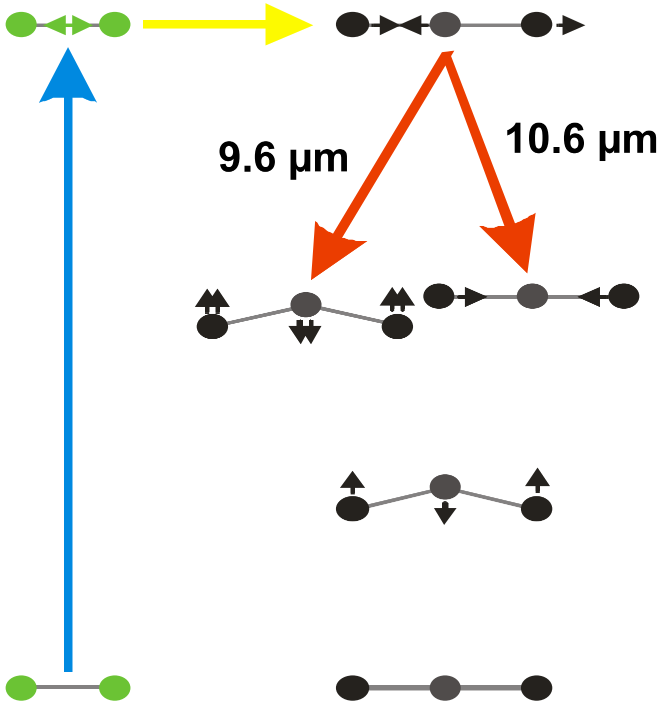
© DLR

- Joint invention of DLR-TP / IFSW Uni Stuttgart
- Crystal disk, 100 – 200 µm thin, e.g., Yb:YAG
- Pump modules: Laser diodes
- Continuous wave (cw) operation at the kW level
- Good power scalability
- Pulsed operation possible (ns, ps, fs)
- High beam brilliance (Power x beam quality)

SSL Geometries: Fiber Laser


© DLR

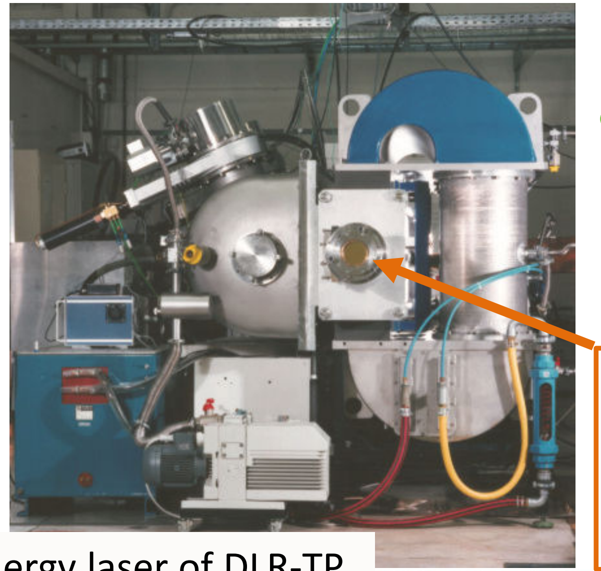
CO_2 Laser Example



Pump mechanisms:
Electrical discharge
Vibrational excitation of N_2 molecules by electron collisions

Energy transfer N_2 ⇨ CO_2
Laser emission at $\lambda = 9.6$ and $10.6\ \mu m$
Relaxation to ground state ⇨ heat

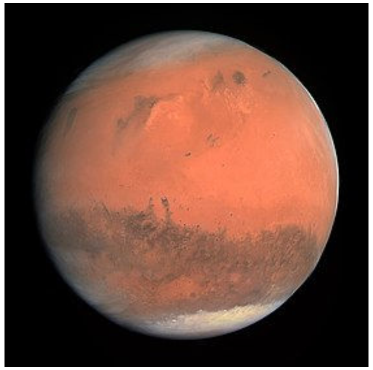
Advantages:
Homogeneous profile of the refractive index
Cooling by gas recycling or
Admixing of helium



λ = 10,6 µm,
τ = 7 – 10 µs, E_L = 30 – 210 J
f = 0 – 50 Hz, $\bar{P}$ = 0 – 7,5 kW
d ≈ 80 mm, ϑ ≈ 13 mrad

Former CO_2 high energy laser of DLR-TP

Natural CO_2 Laser



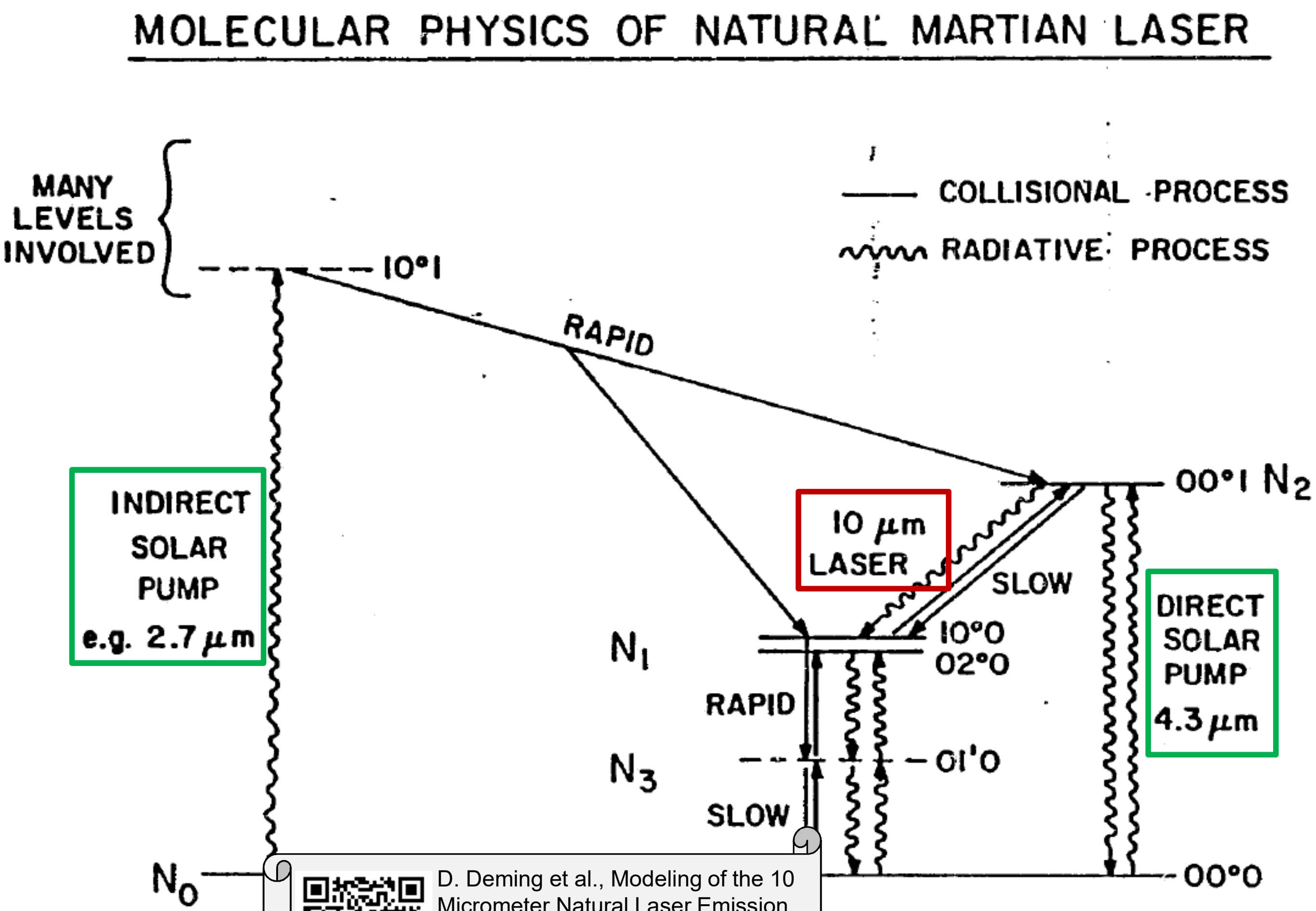
Emitted laser power:

($\lambda = 9.4\ \mu m$ and $10.4\ \mu m$ combined):

Mars: $P = 1.6\ \mu W/cm^2$

Venus: $P = 5.6\ \mu W/cm^2$

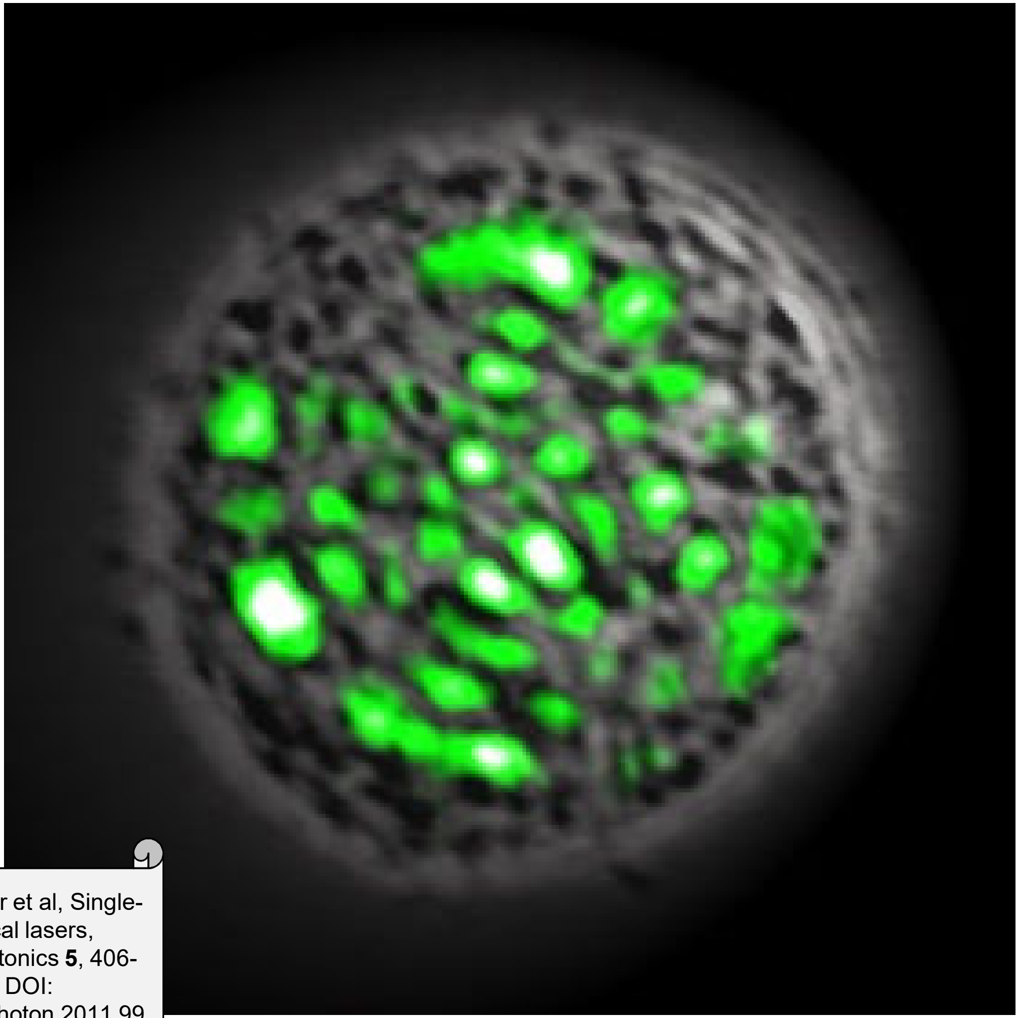
D. Deming et al. Observations of the 10-µm natural laser emission from the mesospheres of Mars and Venus, *Icarus* **55**(3): 347 (1983), DOI: 10.1016/0019-1035(83)90107-0



D. Deming et al., Modeling of the 10 Micrometer Natural Laser Emission form the Mesospheres of Mars and Venus, Icarus **55**(3): 356 (1983), 10.1016/0019-1035(83)90108-2

„Bio Laser“

- Single cell of a jellyfish placed in a resonator setup
- Optical pumping by laser pulses
  ns, nJ, blue
- Laser gain medium: GFP
  (green fluorescent protein)
- Laser emission: $\lambda = 516\, nm$ (green)
- Cell survives even after long-time laser emission.



M.C. Gather et al, Single-cell biological lasers, Nature Photonics **5**, 406-410 (2011), DOI: 10.1038/nphoton.2011.99

Laser Light: Properties

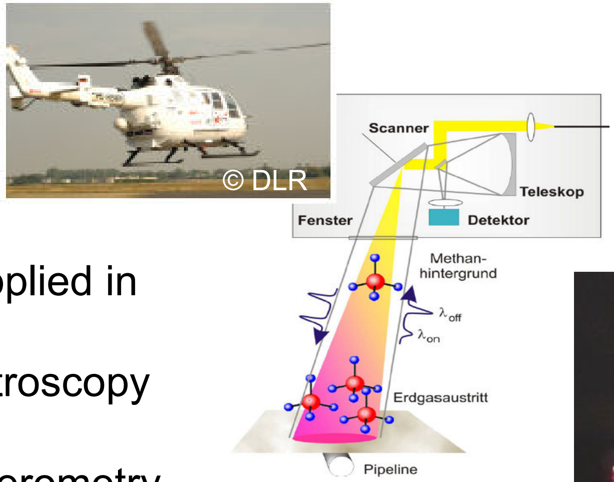
- Coherence: Photons sharing the same…
  - … frequency →
  - … phase →
  - … direction →
- Laser pulses →

  („focusing on the time-scale“)

- … can be applied in
  - … spectroscopy
  - … interferometry
  - … power beaming and

    … high-intensity focusing
  - … local material modifications

    and ablation



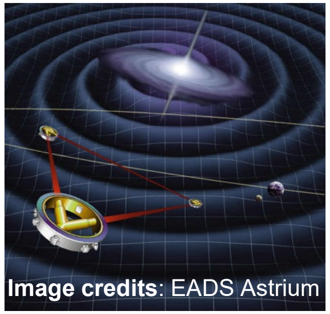


Image credits: EADS Astrium


Image credits: Ascending Technologies


Image credits: Quander Metall- und Lasertechnik


Image credits: Dr. med. Inken Lamcke, Femto- Lasik – PRK

Focusability

Sun

- Archimedes heat ray
- Defeat of the Roman fleet
- Syracuse, 212 BC

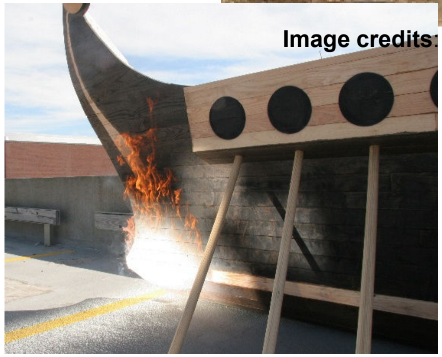
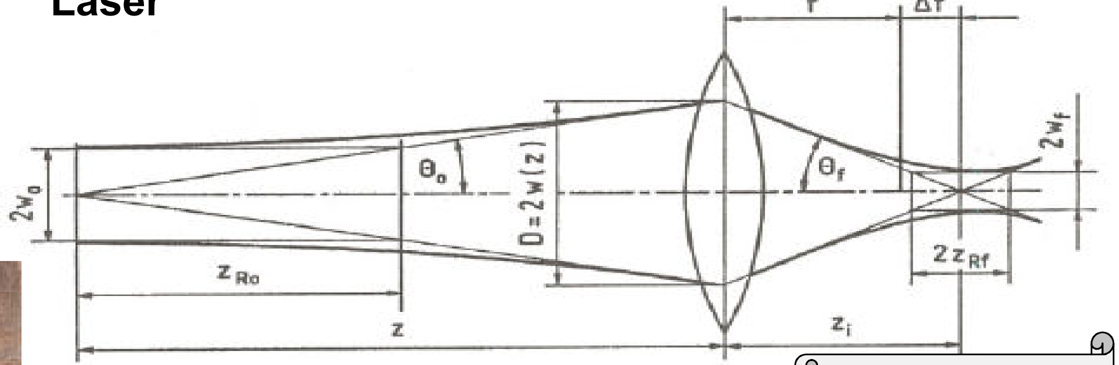


Image credits: Massachusetts Institute of Technology

Laser



H. Hügel, Strahlwerkzeug Laser, Teubner-Verlag 1992, Stuttgart

Beam parameter product:

$$w_0\Theta_0 = w_f\Theta_f = \frac{\lambda \cdot M^2}{\pi}$$

λ: Laser wavelength

w: Beam radius

Θ: Divergence angle

M^2: Beam quality parameter

Laser Operating Range

$$R = c_{opt}\sqrt{Str}\,\frac{D \cdot d}{\lambda}$$

λ: Laser wavelength

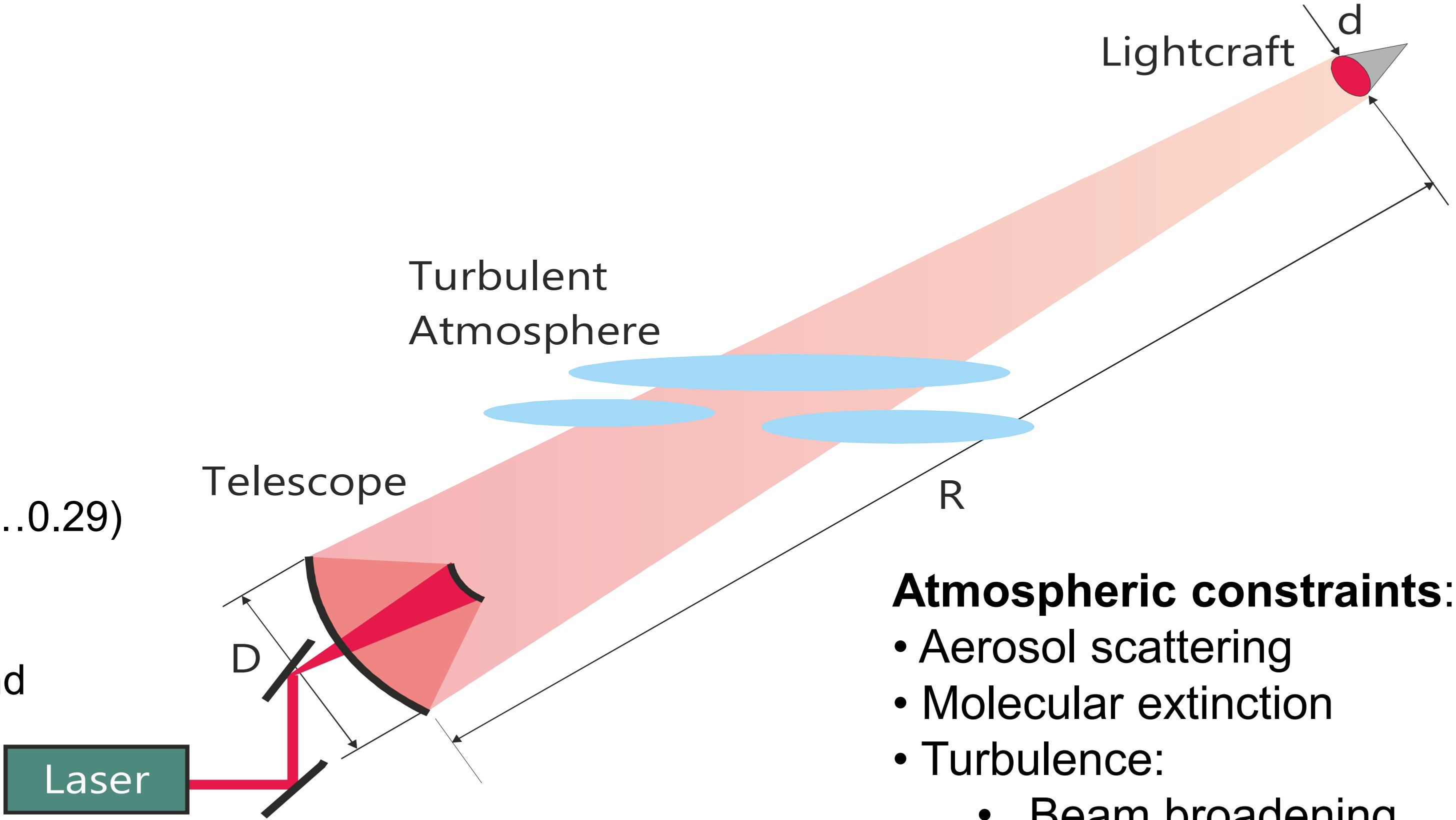
D: Transmitter diameter

d: Receiver diameter

c_{opt}: optical correction factor (0.22…0.29)

Str: Strehl number

- typically 0.3 – 0.5
- incorporates beam quality and
- optical components



Atmospheric constraints:

- Aerosol scattering
- Molecular extinction
- Turbulence:
  - Beam broadening
  - Beam wander
- Thermal blooming

Example: D = 5m, d = 1m, Str = 0.5

Laser	λ, µm	R, km
CO_2	10,6	137
COIL	1,32	1103
Nd:YAG $2f$	0,53	2736

H.-A.Eckel et al., *Concept for a Laser Propulsion Based Nanosat Launch System*, AIP Conf. Proc. **702**, 263 – 273 (2004), DOI: 10.1063/1.1721006

Laser Propulsion

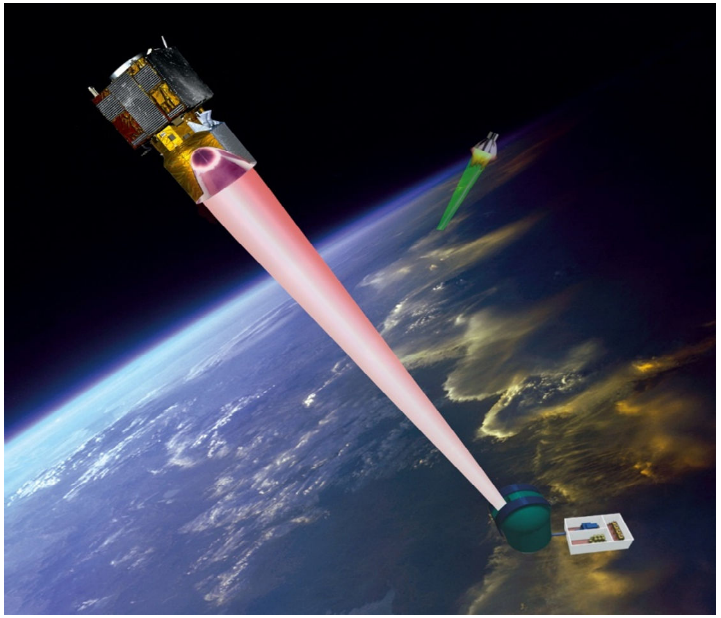
Lectures on Unconventional Space Propulsion

Part 3: Power Beaming Propulsion

IRS Institute of Space Systems, University of Stuttgart
February 10, 2023

Dr. Stefan Scharring

Institute of Technical Physics,
German Aerospace Centre (DLR)



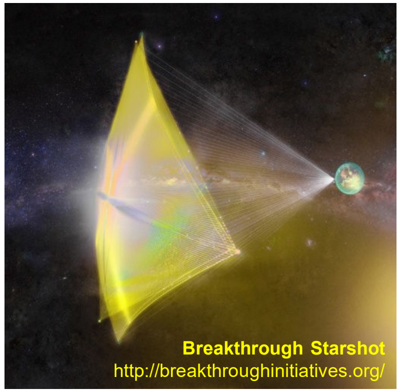
Outline

Part I. Introduction

Part II. Lasers

Part III. Power beaming propulsion

- Absorption and/or reflection
  → Laser photon propulsion
  → Intra-cavity photon propulsion
- Absorption and conversion
  → Laser photovoltaic propulsion
- Heating and ionization
  → Laser-thermal propulsion



Breakthrough Starshot
http://breakthroughinitiatives.org/

© Steinsiek, EADS Space Transportation Systems, 2003

J. Coopersmith et al, AIAA Space 2016

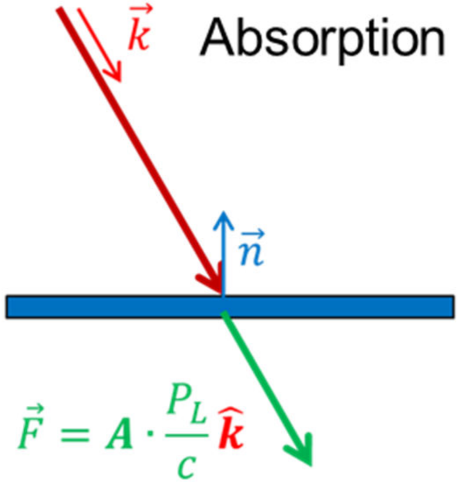
Part IV: Laser launchers

Part V: Laser-ablative propulsion

Part VI. Spacecrafts‘ debris propulsion

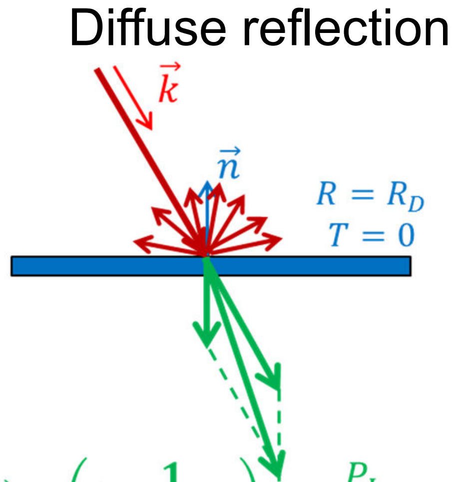
Photon propulsion: Main interaction mechanisms…

$$E_{Photon} = h\nu \qquad m_{Photon} = 0 \qquad p_{Photon} = \frac{h\nu}{c}$$

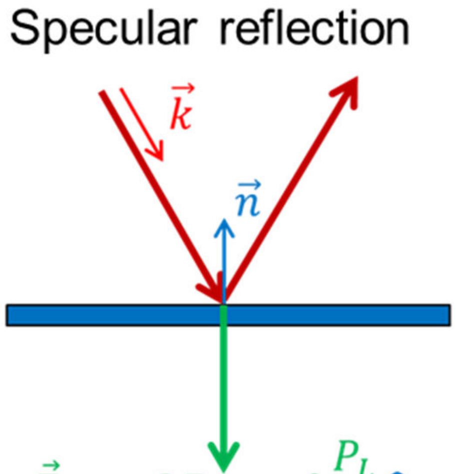


$$\vec{F} = A \cdot \frac{P_L}{c}\hat{\boldsymbol{k}}$$

$$c_m = A \cdot 3.3\ nN/W$$



$$\vec{F} = \left(\hat{\boldsymbol{k}} - \frac{1}{2} \cdot \hat{\boldsymbol{n}}\right) \cdot R_D \frac{P_L}{c}$$



$$\vec{F} = -2R\cos\vartheta \frac{P_L}{c}\hat{\boldsymbol{n}}$$

$$c_m = 2R\cos\vartheta \cdot 3.3\ nN/W$$

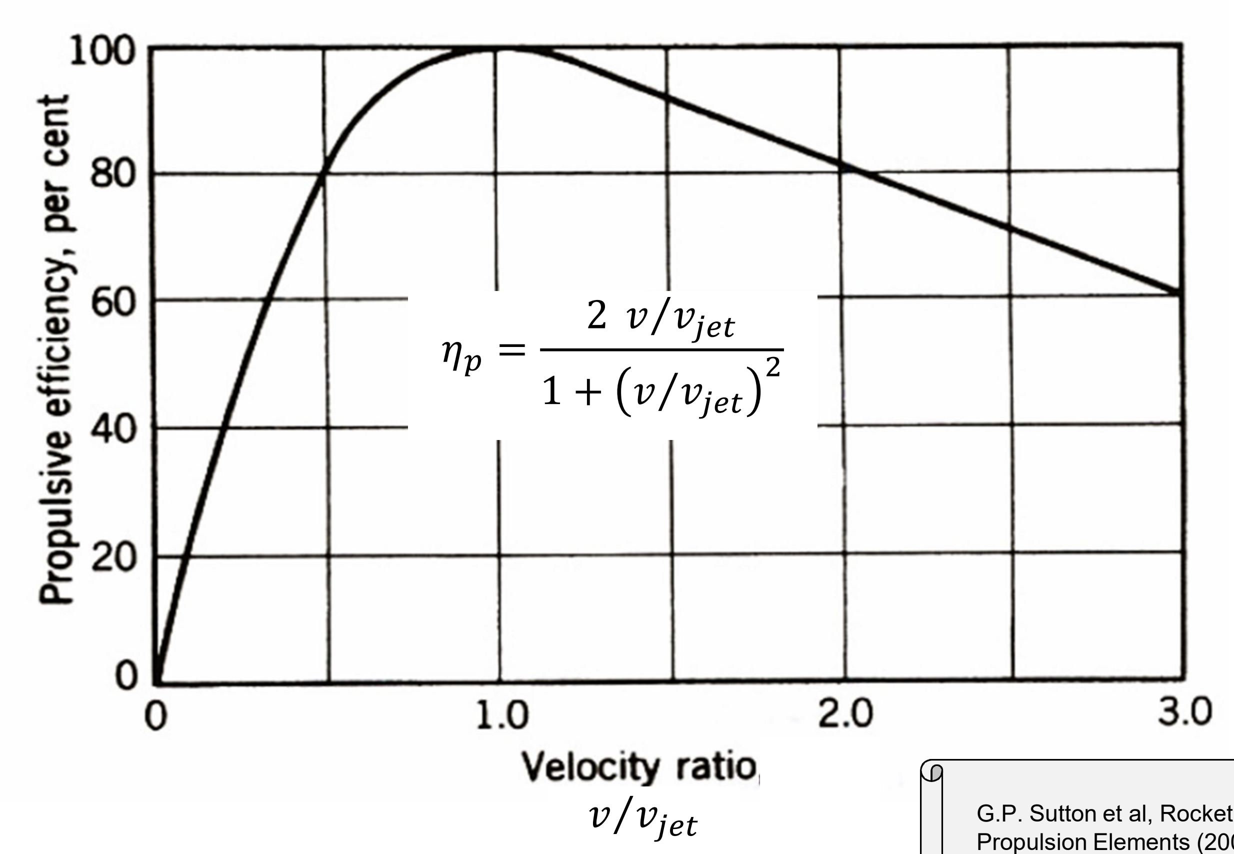
$$A + R + R_D + T = 1$$

$$\downarrow$$

$$\vec{F} = \frac{P}{c}\left[(A + R_D)\hat{k} - (R_D/2 + 2R\cos\vartheta)\hat{n}\right]$$

Photon propulsion: … and its potential

$$\boldsymbol{c_m \approx 0.000000005\ N/W}$$



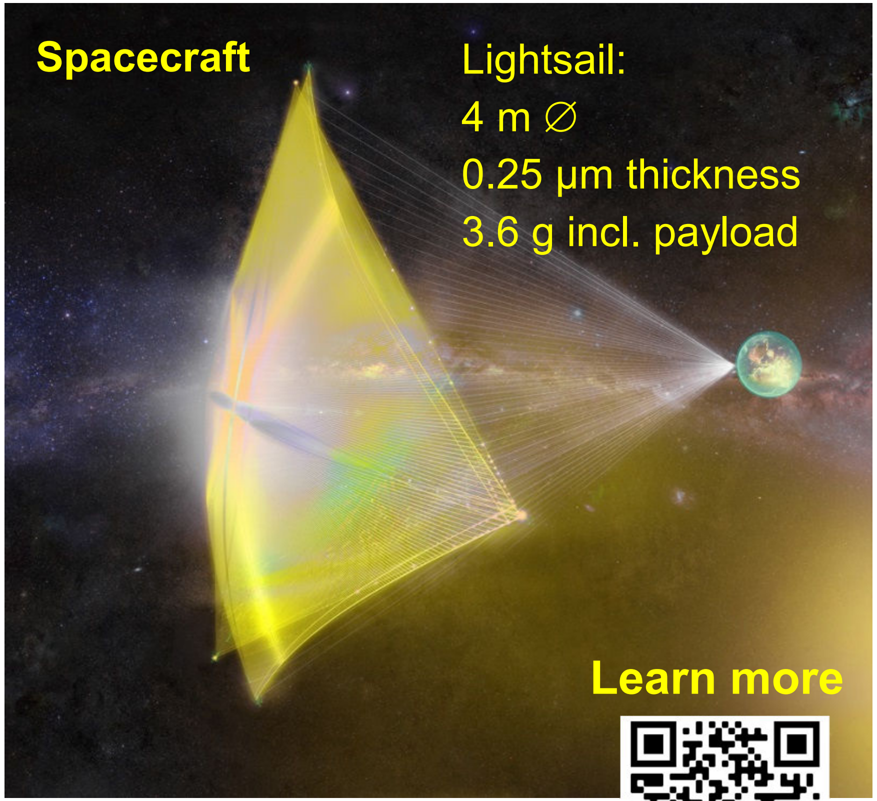
$$\eta_p = \frac{2\ v/v_{jet}}{1 + \left(v/v_{jet}\right)^2}$$

G.P. Sutton et al, Rocket Propulsion Elements (2001)

- High efficiency at relativistic speeds!
- Example for v = 0.25 c travel velocity:

$$\eta_p = \begin{cases} 47\% & v_{jet} = c \\ 0.03\% & v_{jet} = 5\,km/s \end{cases}$$

Breakthrough Starshot…



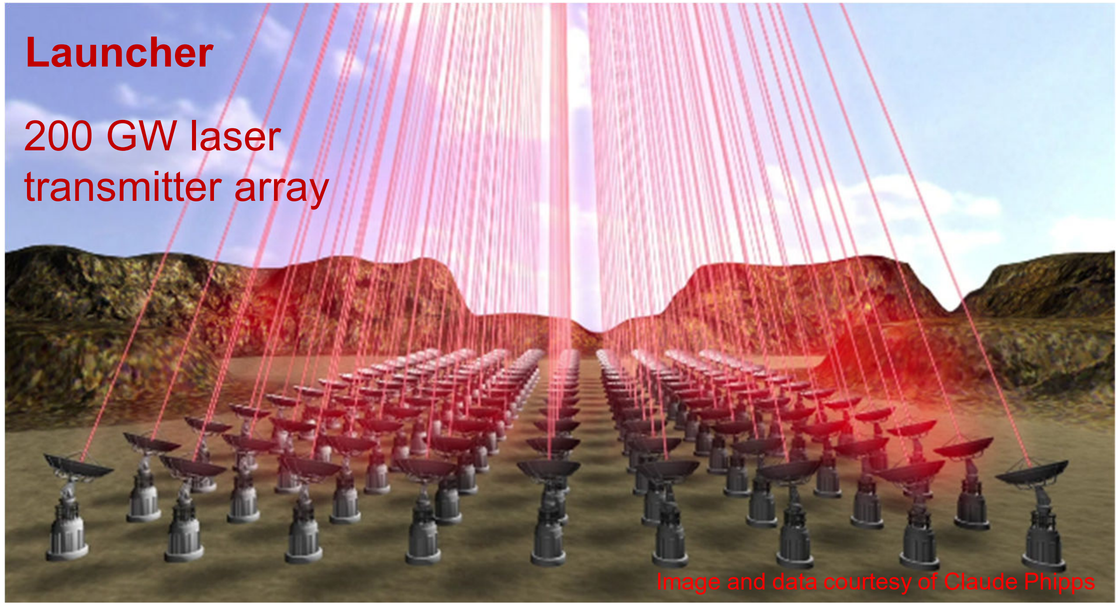
Spacecraft

Lightsail:
4 m ∅
0.25 µm thickness
3.6 g incl. payload

Learn more

Mission

- Destination α Centauri
- Propulsion: Photon pressure
- Acceleration: 9 minutes, 15000 G, to 0.2 c (near Mars)
- Funding: initially 100 M$; intended: 40 B$, 40 years



Launcher

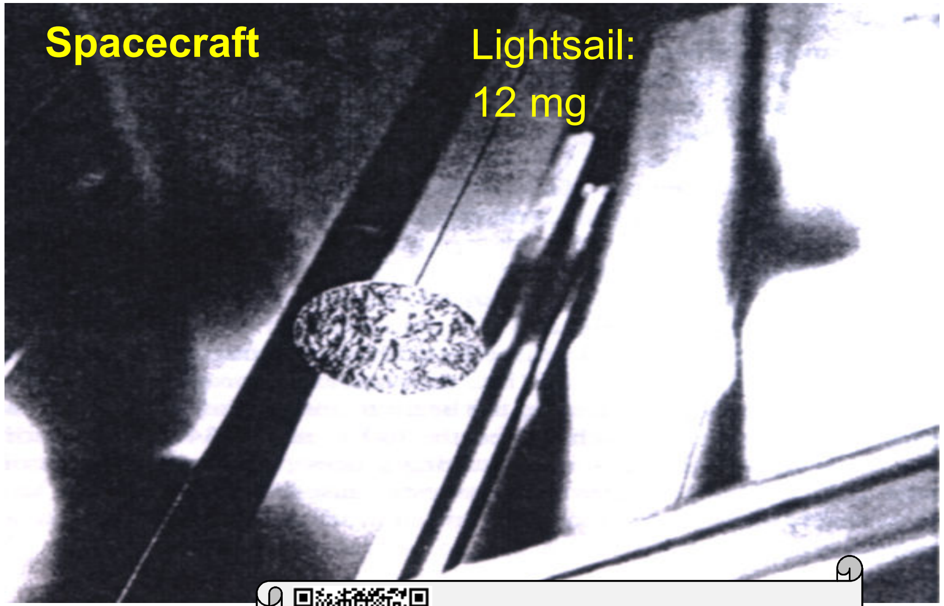
200 GW laser transmitter array

Image and data courtesy of Claude Phipps

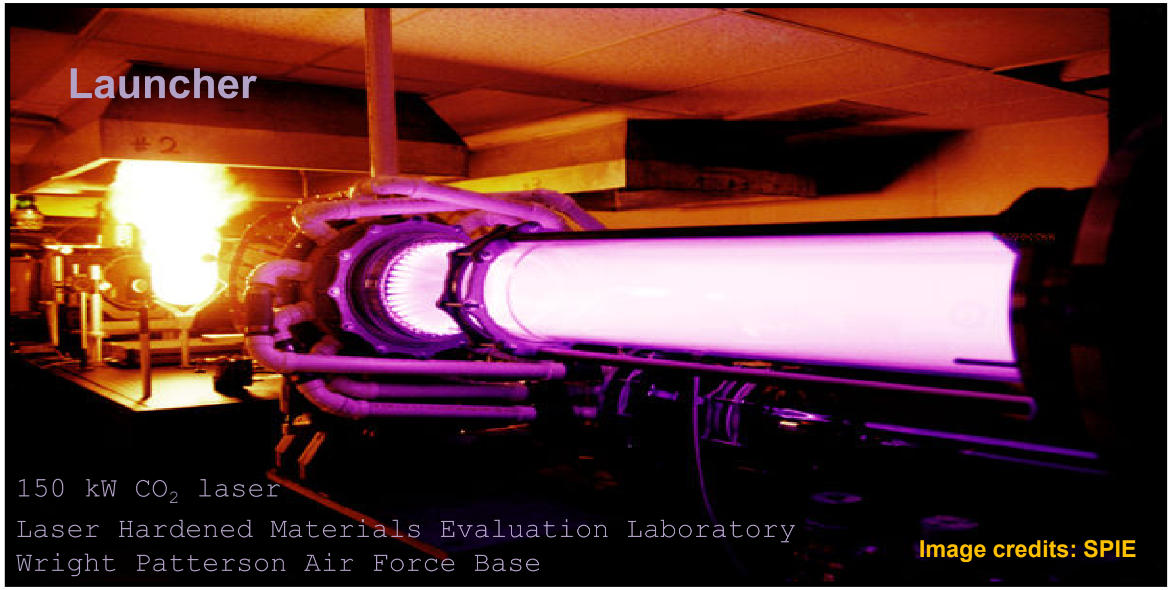
… and its proof of principle

Mission

- Hovering in Earth‘s gravity field at 10 cm altitude
- Propulsion: Photon pressure
- Hovering duration: 0.5 seconds



Myrabo et al, Laser-boosted light sail experiments with the 150-kW- LHMEL II CO_2 laser, Proc. SPIE **4760**, 774-798, (2002), DOI: 10.1117/12.482034



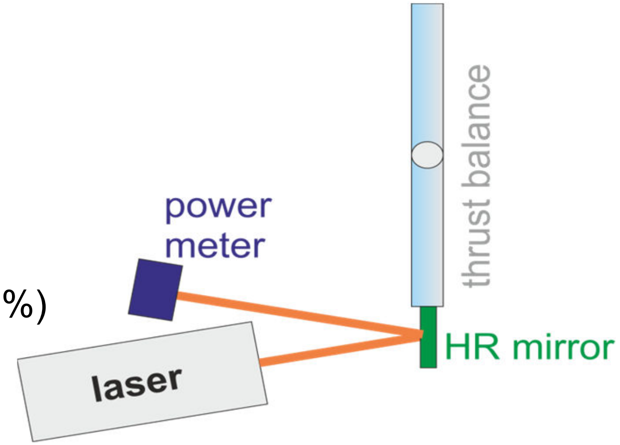
150 kW CO_2 laser
Laser Hardened Materials Evaluation Laboratory
Wright Patterson Air Force Base

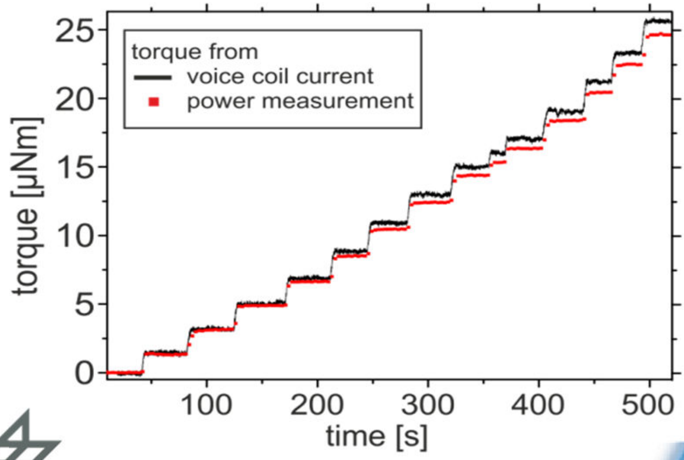
Image credits: SPIE

Digression: Thrust Balance Calibration using Photon Pressure

Extra-cavity

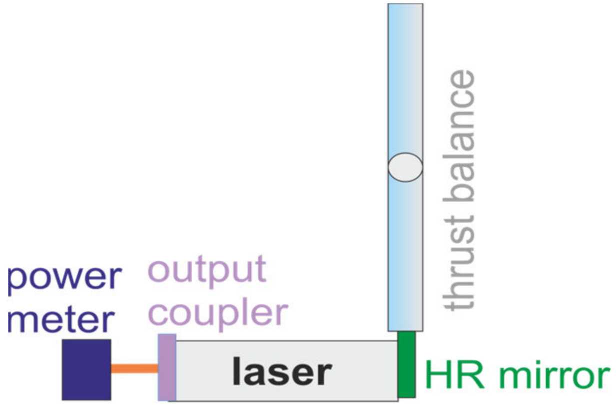
- Laser:
  1 kW thin disk laser
- HR =
  highly reflective (99.98%)
- Incidence angle: 10°

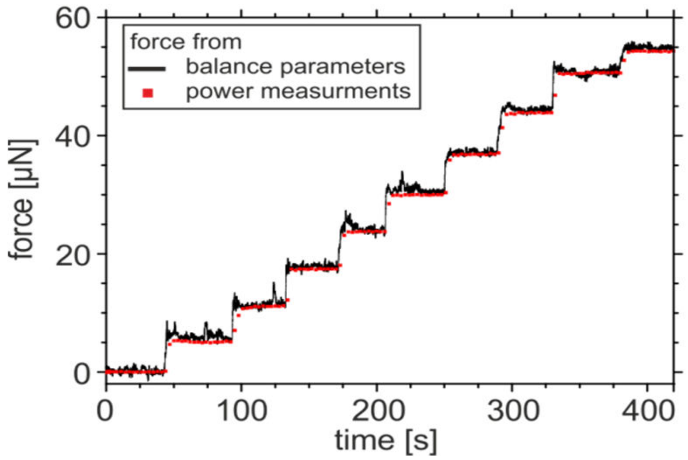




Intra-cavity

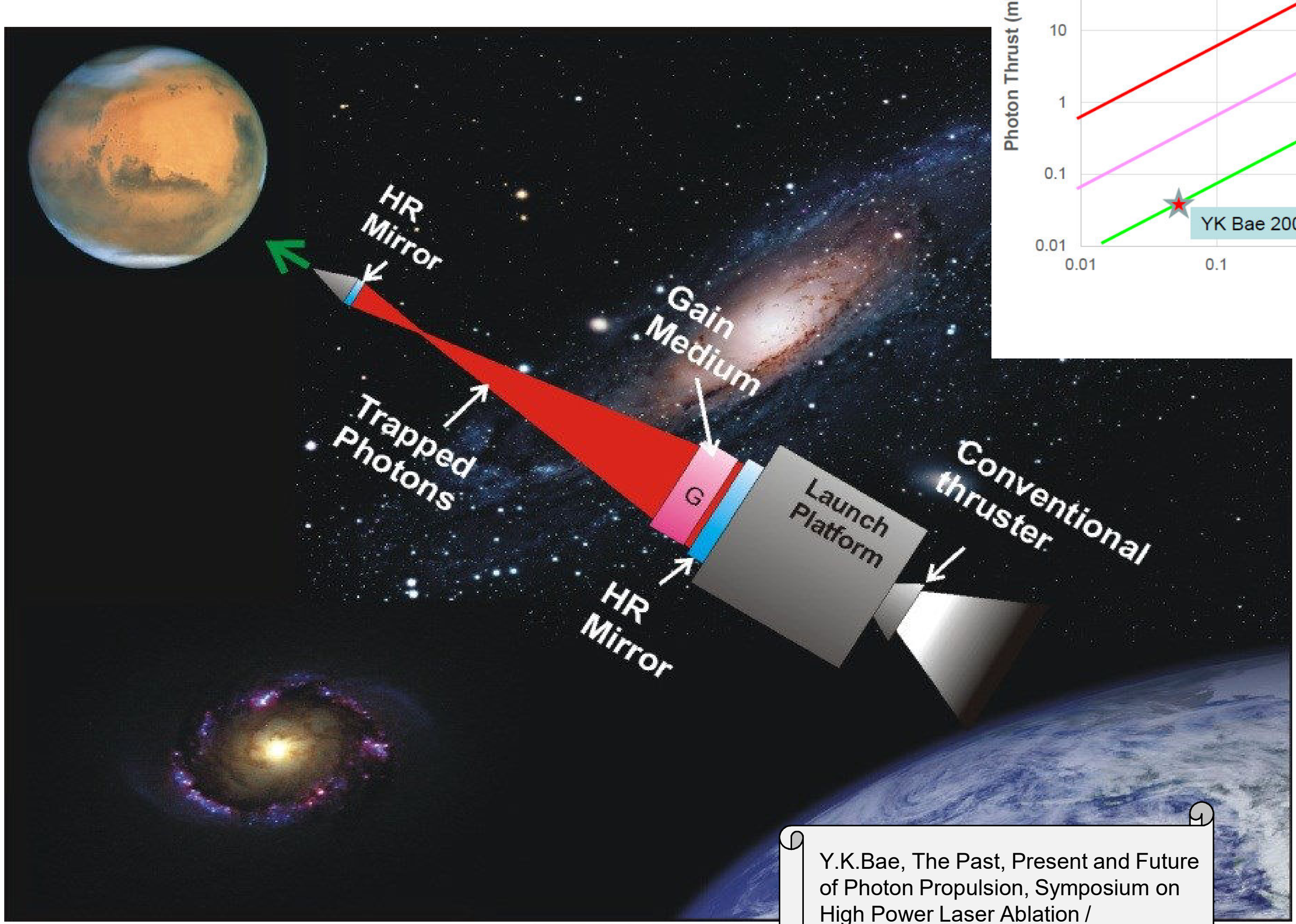
- Output coupler:
  2.4% transmittance



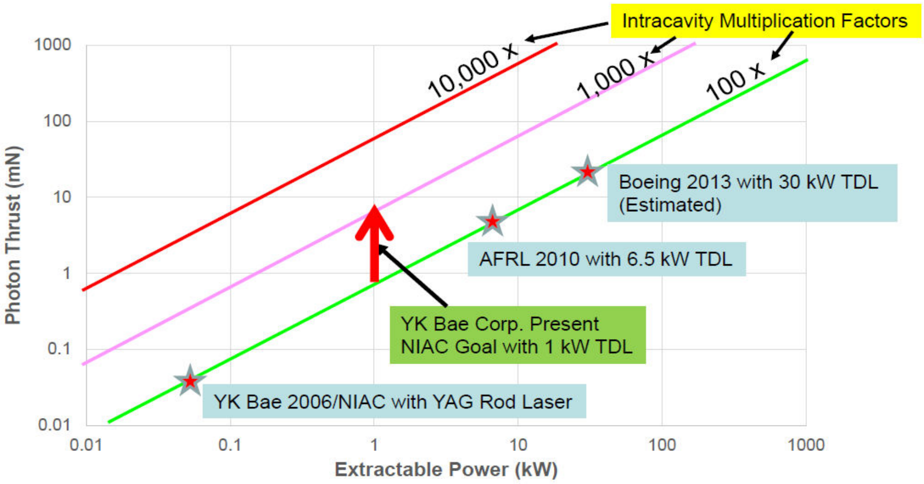


S. Karg et al., Laser Propulsion Research Facilities at DLR Stuttgart, Symposium on High Power Laser Ablation / Beamed Energy Propulsion 2014

Intra-cavity Photon Propulsion

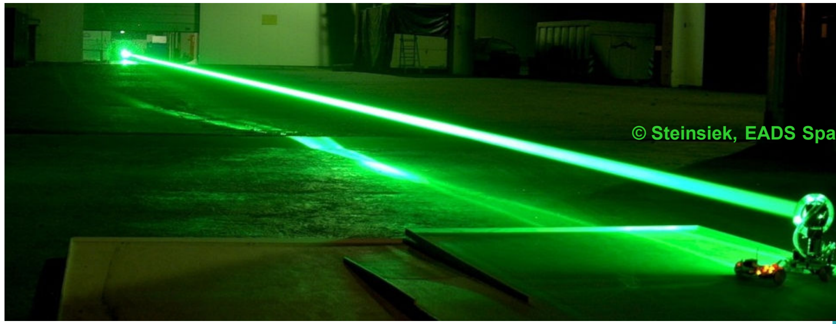


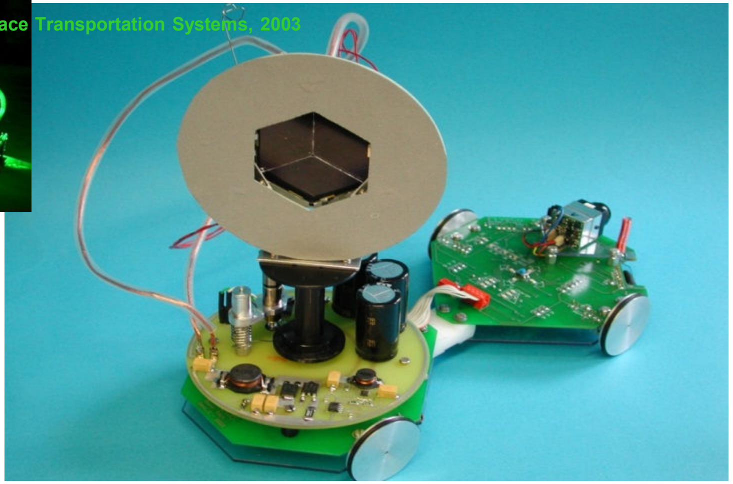
Y.K.Bae, The Past, Present and Future of Photon Propulsion, Symposium on High Power Laser Ablation / Beamed Energy Propulsion 2014



TDL: Thin Disk Laser

Laser-powered propulsion in shadowed areas





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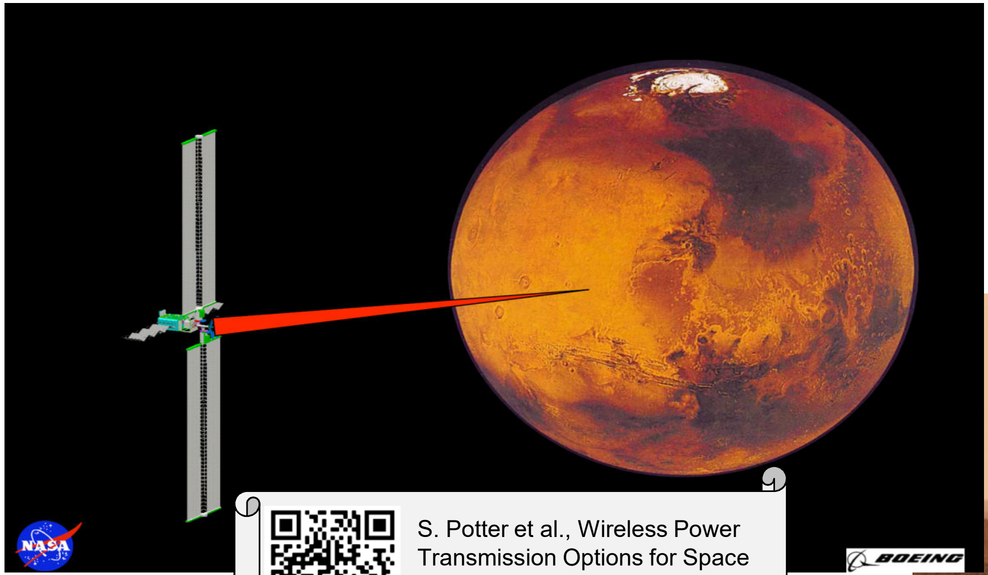
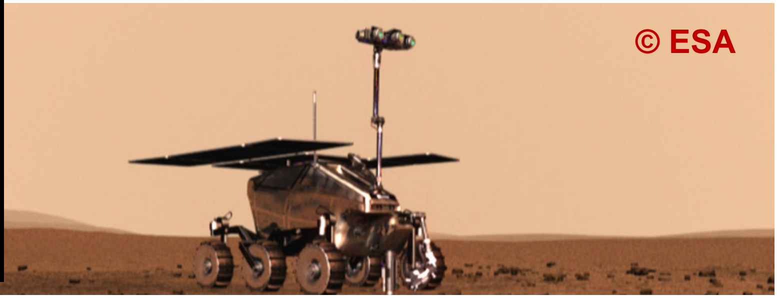


S. Potter et al., Wireless Power Transmission Options for Space Solar Power, State of Space Solar Power Technology, 2008



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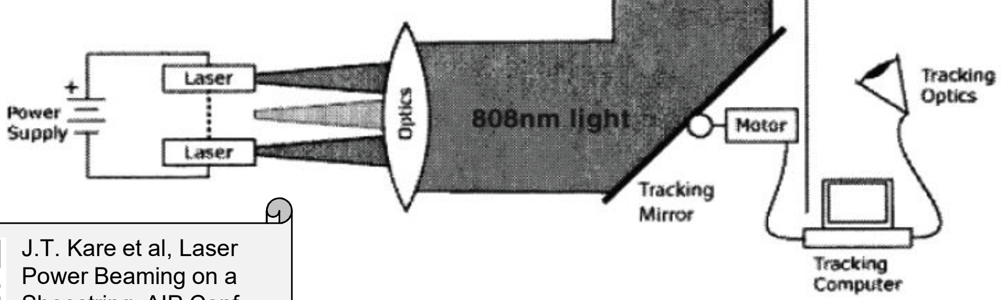
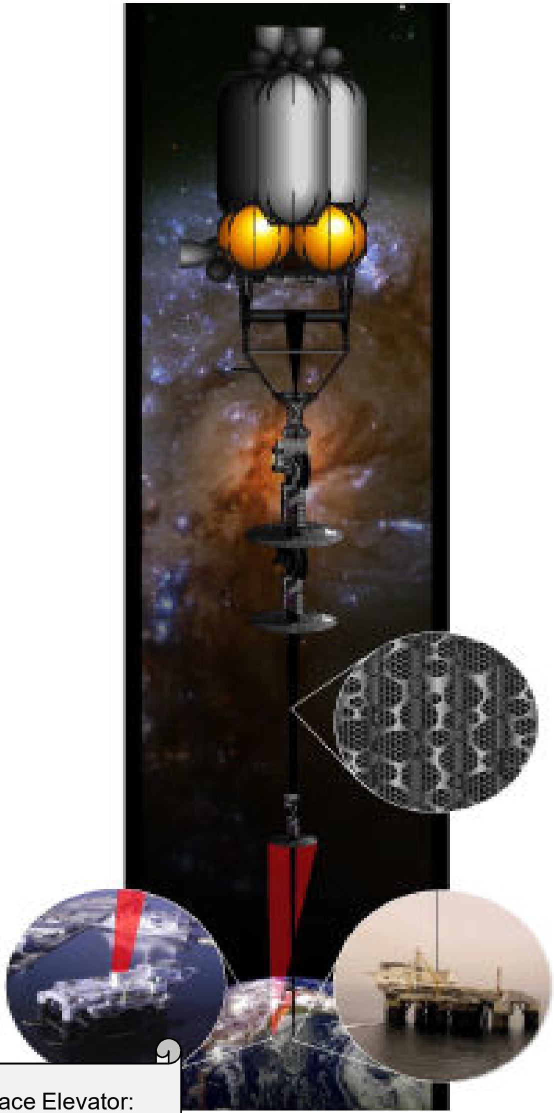
Laser-powered Space Elevator

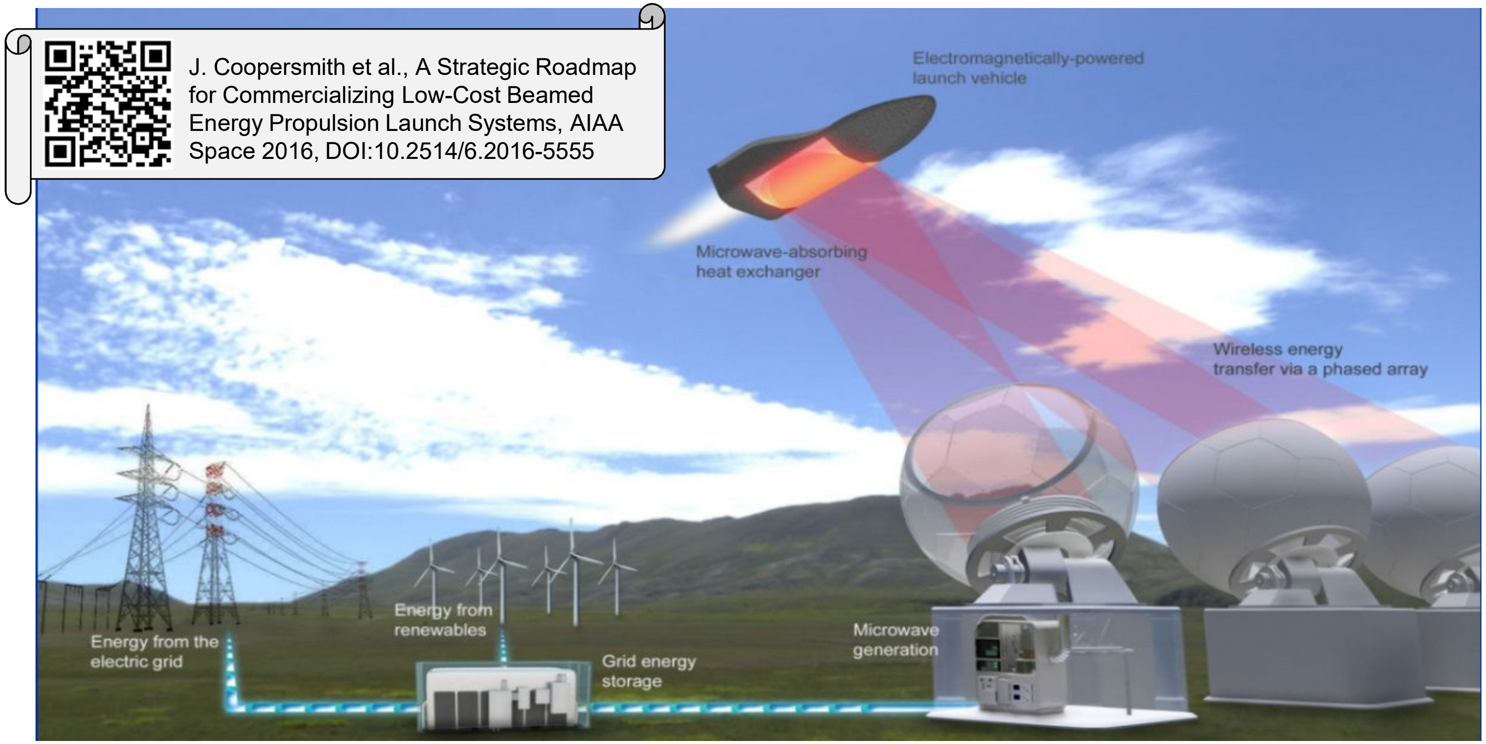


J.T. Kare et al, Laser Power Beaming on a Shoestring, AIP Conf. Proc. 997, 97-108 (2008), DOI: 10.1063/1.2931935



B.C. Edwards, The Space Elevator: an Ideal Application for the Free Electron Laser, Proc. SPIE 4632, 134 (2002), DOI: 10.1117/12.469764

Beamed Energy: Thermal Propulsion – General Remarks



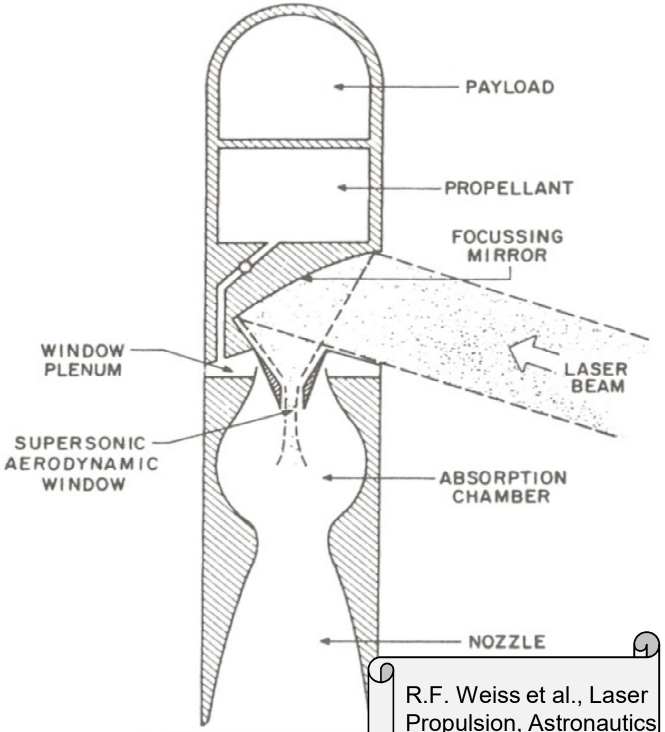
J. Coopersmith et al., A Strategic Roadmap for Commercializing Low-Cost Beamed Energy Propulsion Launch Systems, AIAA Space 2016, DOI:10.2514/6.2016-5555

Special laser-thermal propulsion concepts:

- Detonation and combustion → Laser Lightcraft (Part IV)
- Material ablation → Laser-ablative propulsion (Part V)
  → Space debris propulsion (Part VI)

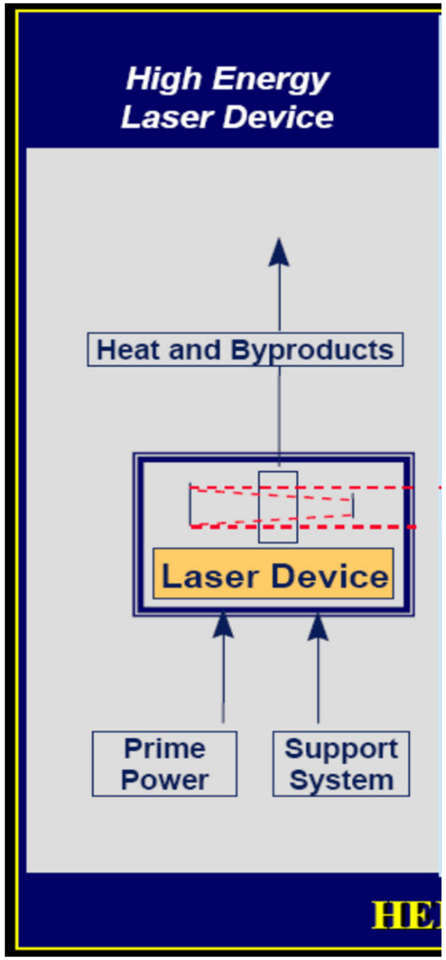
Propulsion principle:

- Remotely based high power laser (or microwave) source (cw or pulsed)
- Propellant heating by focused beam
- Jet expansion and thrust generation



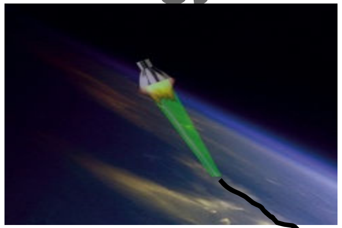
R.F. Weiss et al., Laser Propulsion, Astronautics and Aeronautics, March 1979: 50 – 58

Architecture for remotely-powered Laser Propulsion



J.R. Cook, Atmospheric Applications of High Energy Lasers, Proc. of the XV. International Symposium on GCL-HPL 2004, Prague

Energy Conversion Efficiencies in remotely-powered Laser Propulsion



$$E_{kin} = {}^{1}\!/_{2}\, m v^2 = \eta_{prop} \psi^{-1} \alpha\beta\gamma\delta \cdot E_{wall}$$

Spacecraft kinetic energy

Propulsion efficiency η_{prop}

Energy coupling to spacecraft

Mechanical efficiency ψ^{-1}

Jet kinetic energy

Expansion efficiency α

Propellant inner energy

if applicable:
Detonation
Combustion
mQ/E_L

Energy absorption efficiency β

Laser pulse energy incident at the propellant

Transmission efficiency γ

Initial laser pulse energy

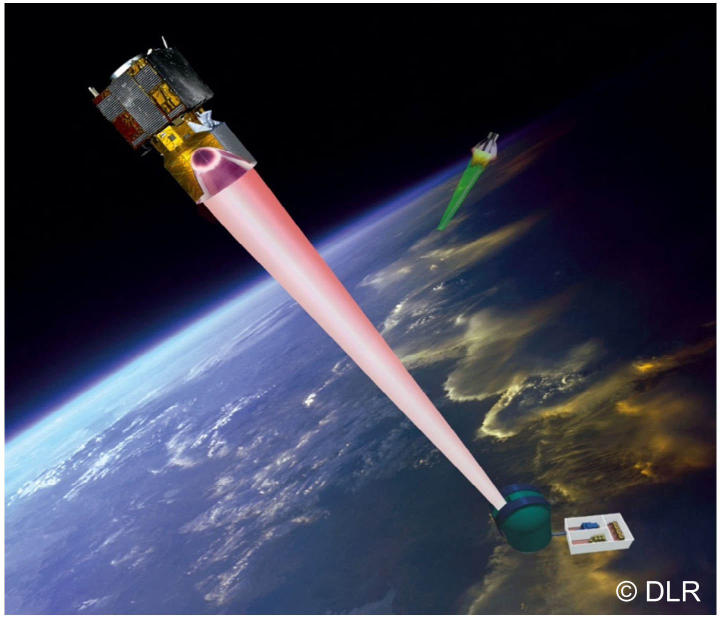
Electro-optical conversion efficiency δ

Electric energy

Laser Propulsion

Lectures on Unconventional Space Propulsion

Part IV: Laser Launchers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IRS Institute of Space Systems, University of Stuttgart
February 10, 2023

Dr. Stefan Scharring

Institute of Technical Physics,
German Aerospace Centre (DLR)

Outline

Part I. Introduction

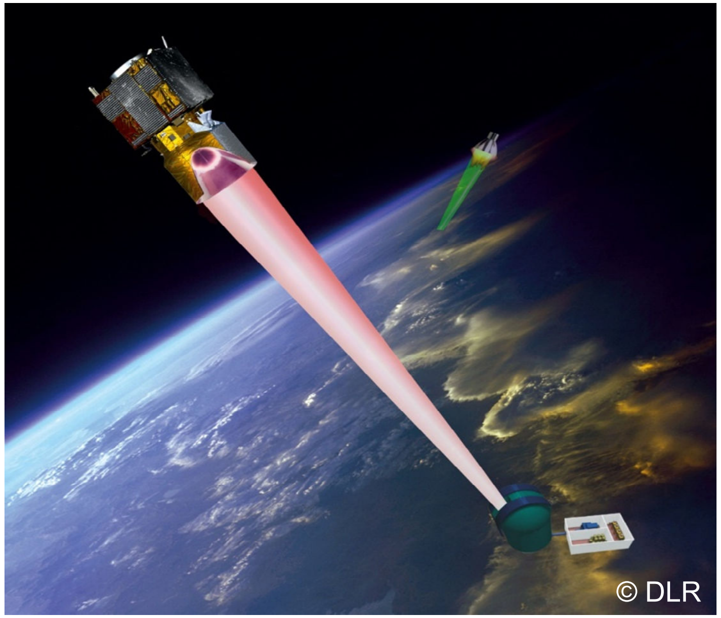
Part II. Lasers

Part III. Power beaming propulsion

Part IV: Laser launchers
- Lightcraft Technology Demonstrator
- Parabolic Lightcraft
- Russian Aerospace Laser Propulsion Engine

Part V: Laser-ablative propulsion

Part VI. Spacecrafts‘ debris propulsion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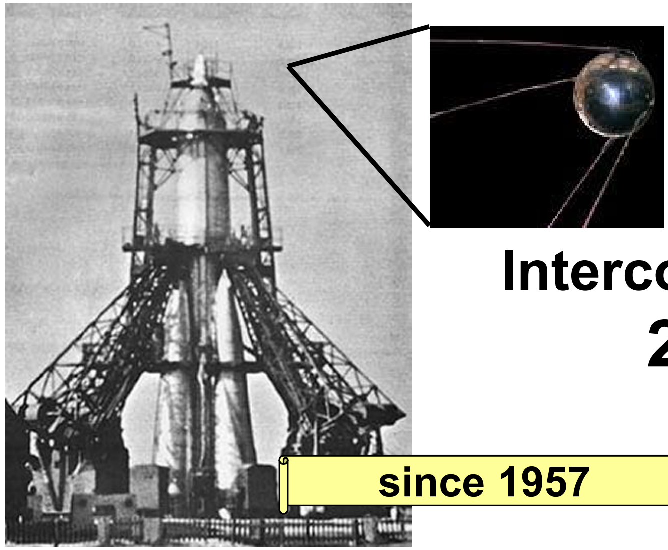
Laser Launchers

Carrying the energy carrier…

External energy source



Payload: Sputnik-I
83,6 kg, 58 cm

Intercontinental missile

280 t, 34 m

since 1957

75 years of R&D?

*** 2032 ?**

since 1804

75 years of R&D

*** 1879**

Laser-supported Absorption Waves

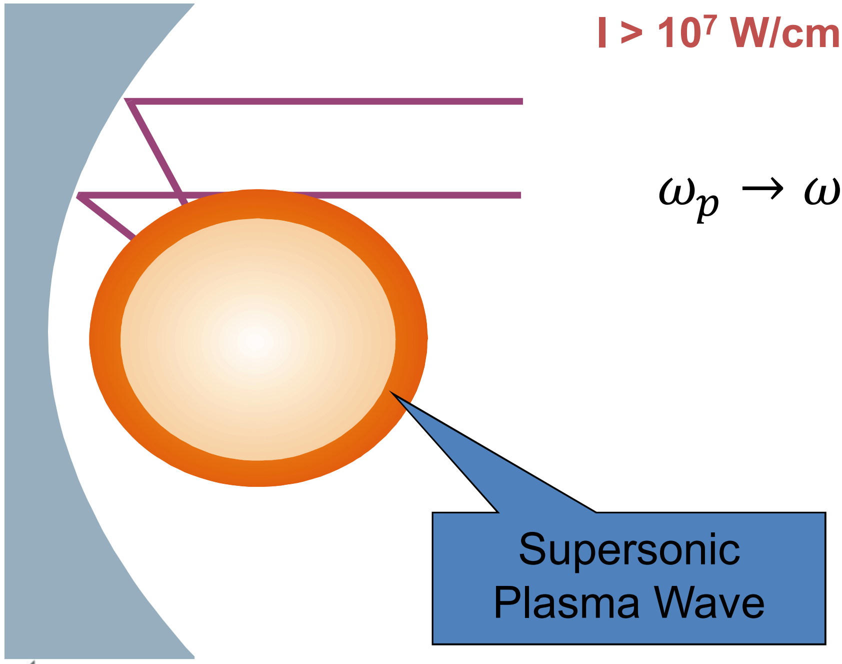
Plasma frequency:

$$\omega_p = \sqrt{4\,\pi\,e^2\,\boldsymbol{n_e}/m_e}$$

Laser (radian) frequency:

$$\omega_L = 2\pi\,c/\boldsymbol{\lambda}$$

Laser Supported Detonation Wave (LSDW)

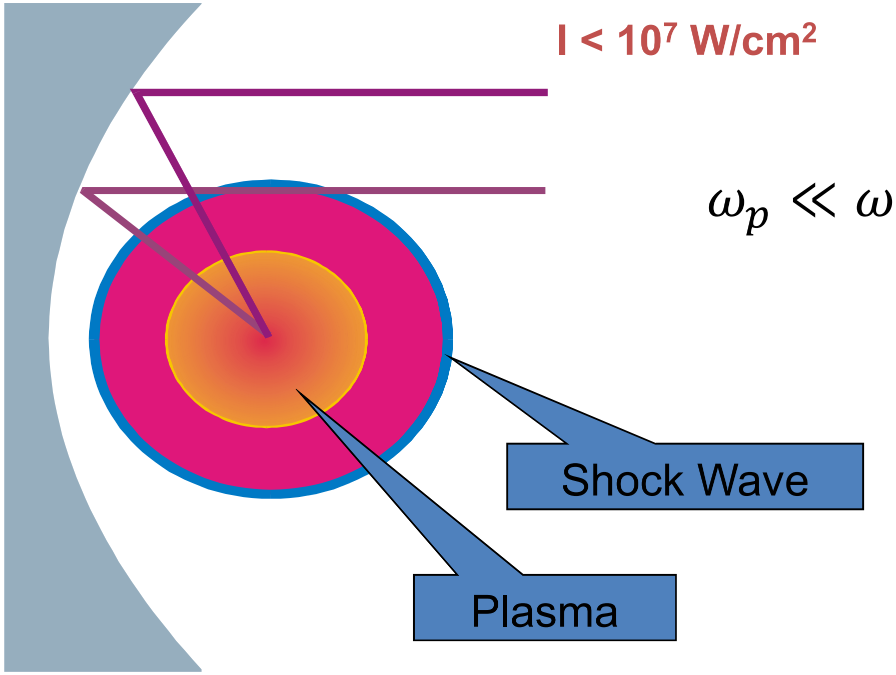


I > 10^7 W/cm²

$$\omega_p \rightarrow \omega_L$$

Supersonic Plasma Wave

Laser Supported Combustion Wave (LSCW)



I < 10^7 W/cm²

$$\omega_p \ll \omega_L$$

Shock Wave

Plasma

Propellant Detonation

Internal efficiency of pure ablation (cf. Part V): $\eta_{abl} = {}^1\!/_2\ c_m \cdot v_{jet} = \alpha\,\beta$

α Expansion efficiency
β Absorption efficiency

Internal efficiency of exothermal reactions: $\eta_{ex} = \alpha\,(\beta + m\,Q/E_L)$

Q Specific heat of reaction
E_L Laser pulse energy

with: $Q = Q_{det} + N_{db} Q_{db}$

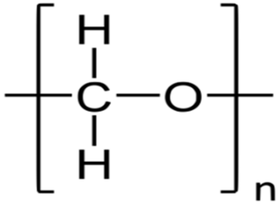
Q_{det} Specific detonation energy
N_{db} Fraction of delayed burning
Q_{db} Specific energy of combustion

Detonation and combustion of CHO polymers

$$C_a H_b O_c \rightarrow CO_2 + H_2O + \boxed{H_2 + \mathrm{C}} + Q_{det}$$

$$\boxed{\mathrm{C} + H_2} + O_2 \rightarrow CO_2 + H_2O + Q_{db}$$

Example: Polyoxymethylene (Delrin, POM)

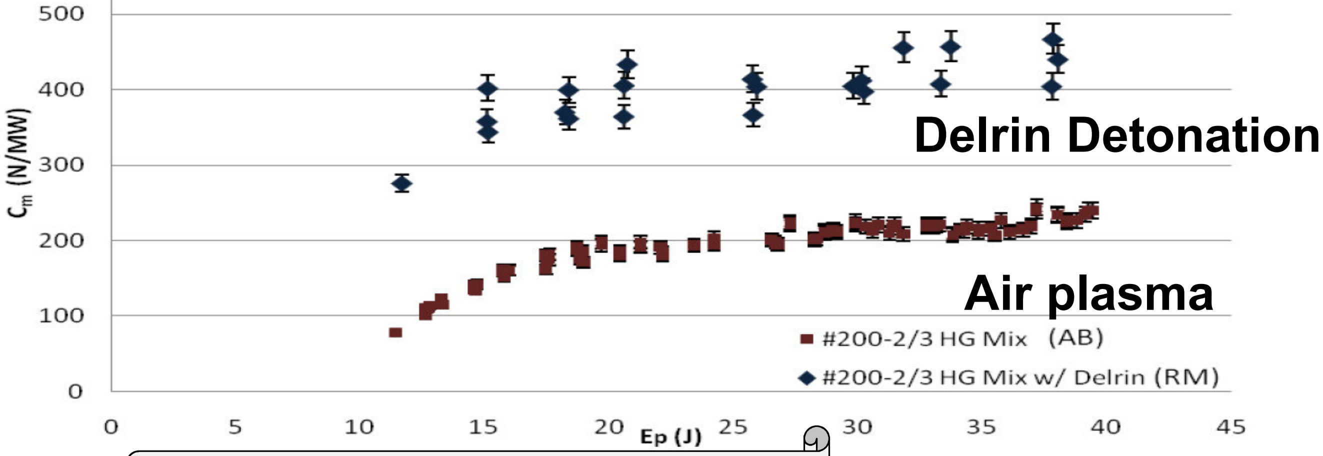


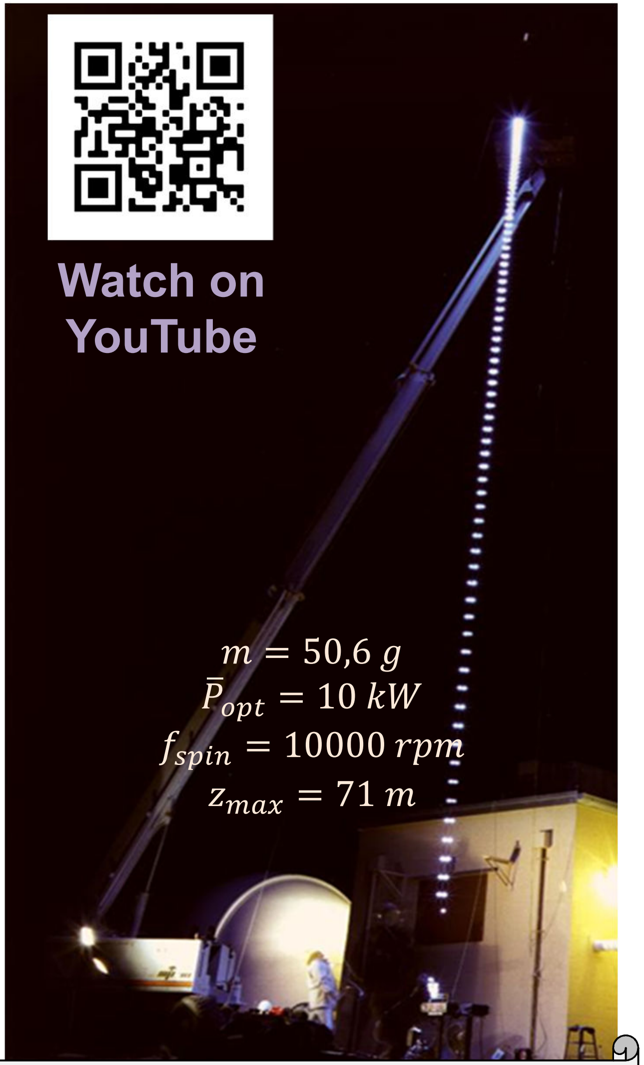
$$\left[-\mathrm{CH_2}-\mathrm{O}-\right]_n$$

$Q_{det} = 2{,}69\ J/mg$
$Q_{db} = 16{,}1\ J/mg$

A.A. Ageichik et al, Detonation of CHO Working Substances in a Laser Jet Engine, Technical Physics **54**: 402 (2009), DOI: 10.1134/S1063784209030128

Lightcraft Technology Demonstrator





Watch on YouTube

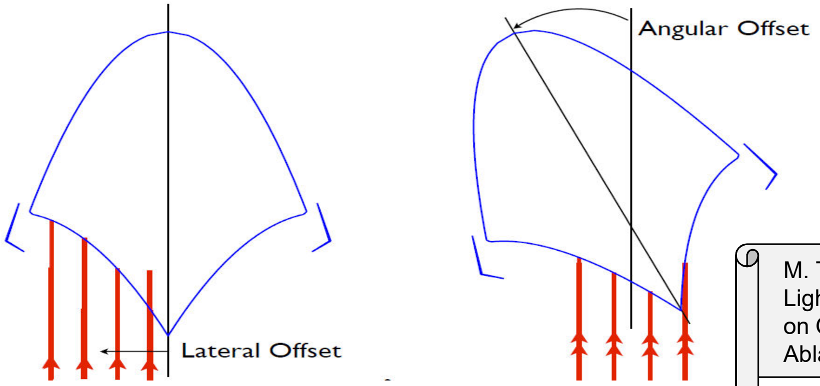
$$m = 50{,}6\ g$$
$$\bar{P}_{opt} = 10\ kW$$
$$f_{spin} = 10000\ rpm$$
$$z_{max} = 71\ m$$

D.A. Kenoyer et al, Axial Impulse Generation of Lightcraft Engines with ~ 1 µs Pulsed TEA CO_2 Laser, AIP Conf. Proc. **1402**: 82 – 92 (2011), DOI: 10.1063/1.3657018

Image Credits: Leik Myrabo

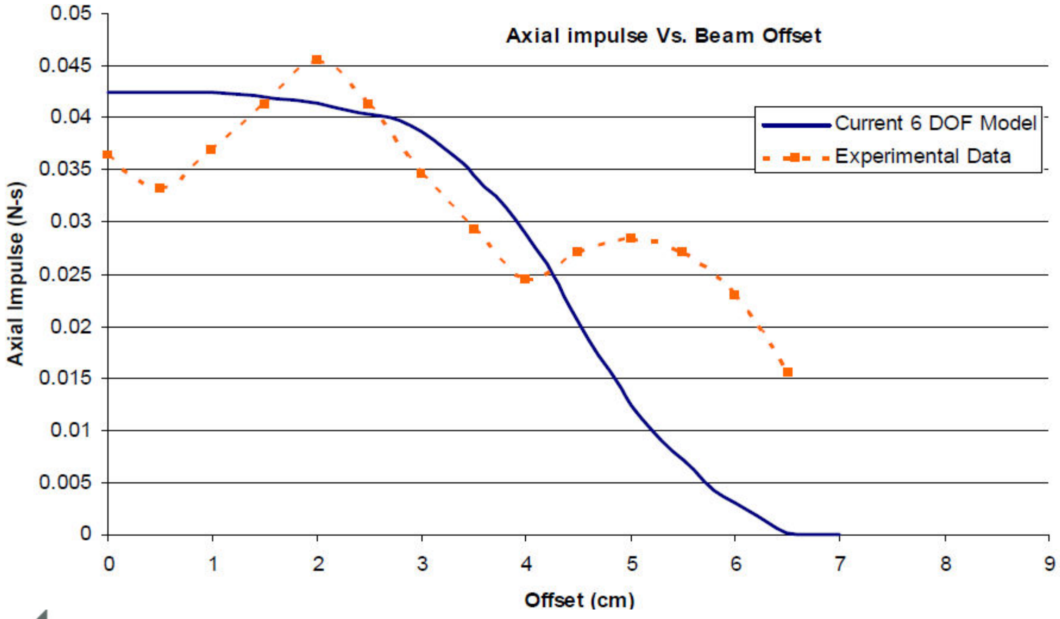
L.N. Myrabo, World Record Flights of Beam-Riding Rocket Lightcraft: Demonstration of „Disruptive Propusion Technology, AIAA Paper 2001-3798, DOI: 10.2514/6.2001-3798

Flight Trajectory Analysis

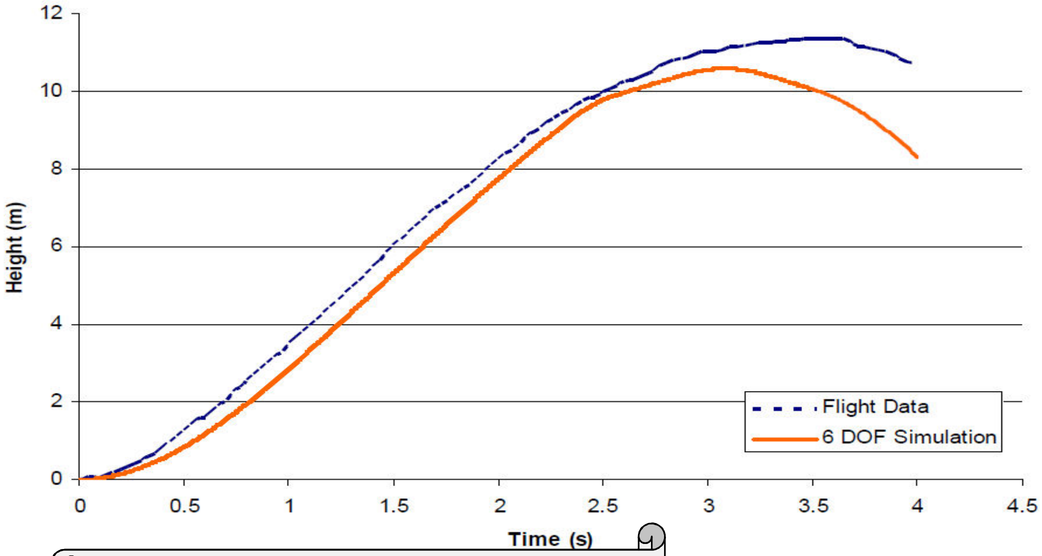


M. Takahashi and N. Ohnishi, Flight analysis of Lightcraft using Actively-Controlled Beam Based on Genetic Algorithm, High Power Laser Ablation / Beamed Energy Propulsion 2014

Axial momentum – pendulum experiment

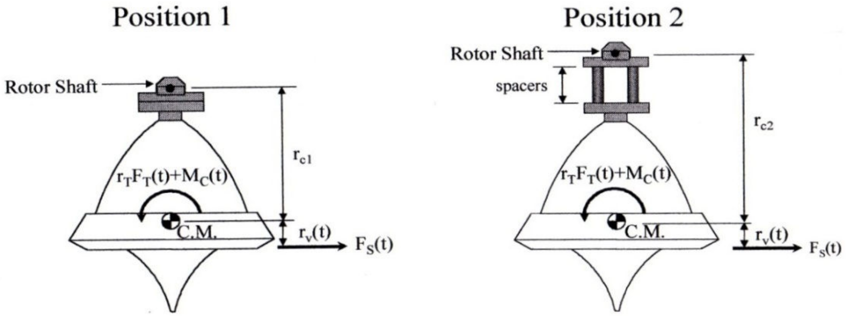


Aerodynamic simulation



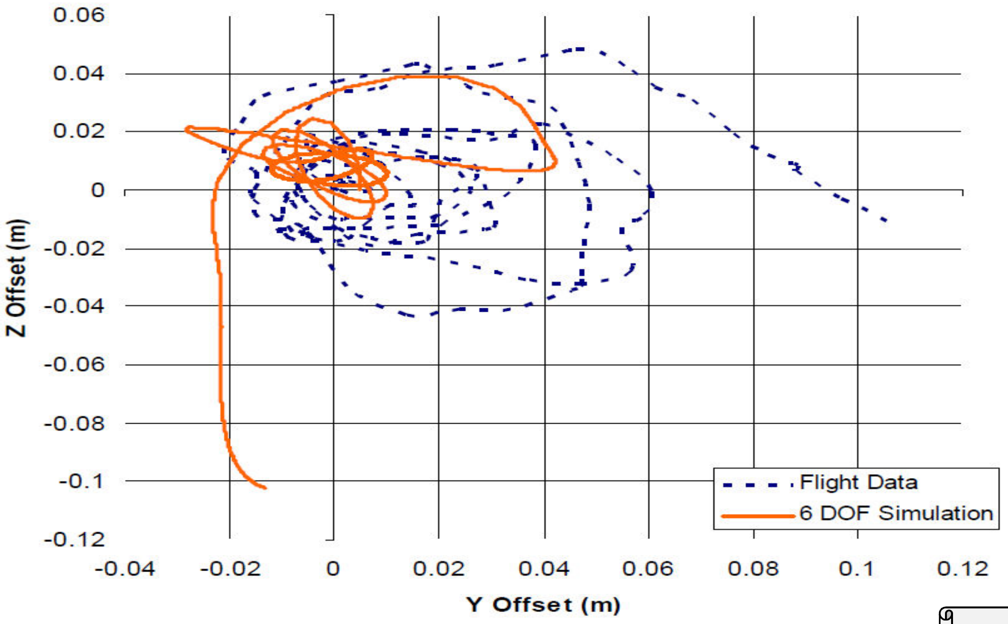
D.A. Kenoyer et al, Calibration and Validation of a 6-DOF Laser Propelled Lightcraft Flight Dynamics Model vs. Experimental Data,AIP Conf. Proc. **997**: 325 (2008), DOI: 10.1063/1.2931903

Lateral Motion

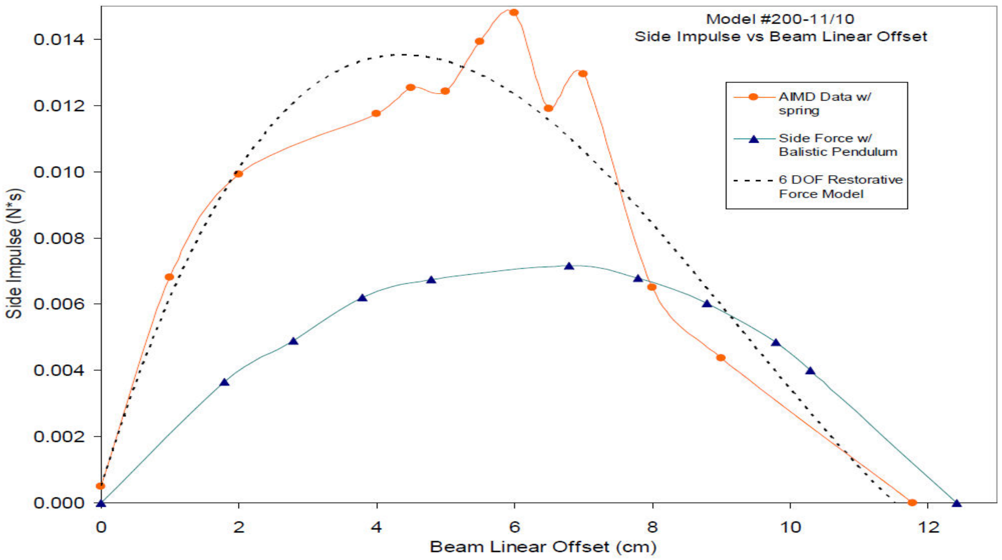


Angular Impulse Measurement Device

Ground trajectories



Lateral momentum



D.A. Kenoyer et al., AIP Conf. Proc. **997**: 325 (2008), DOI: 10.1063/1.2931903

Flight Stabilization Concept

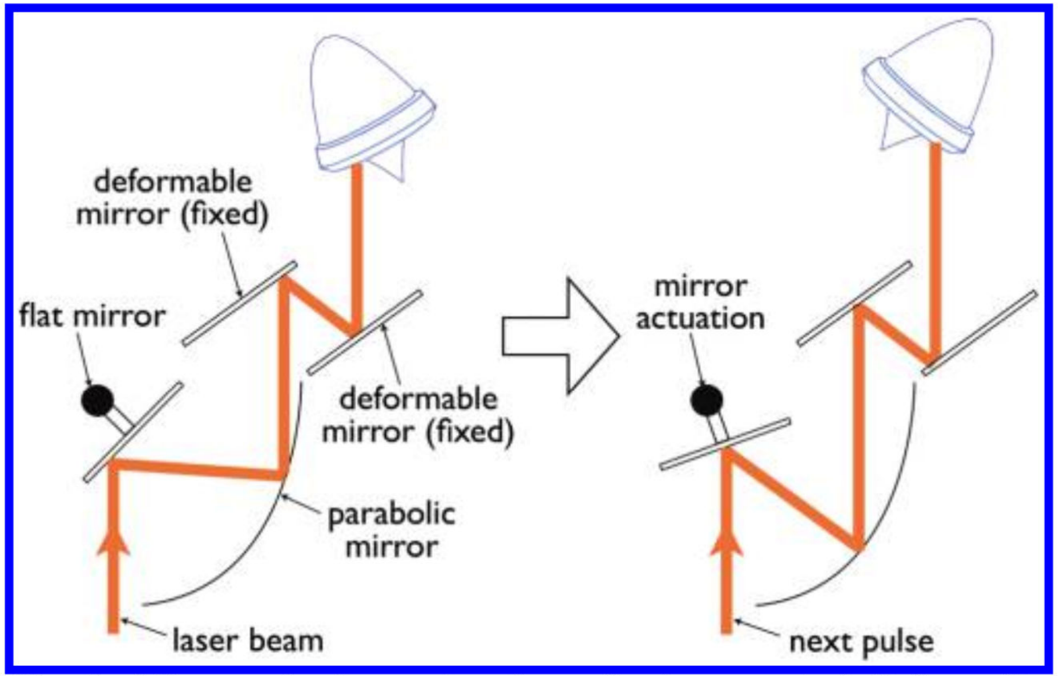
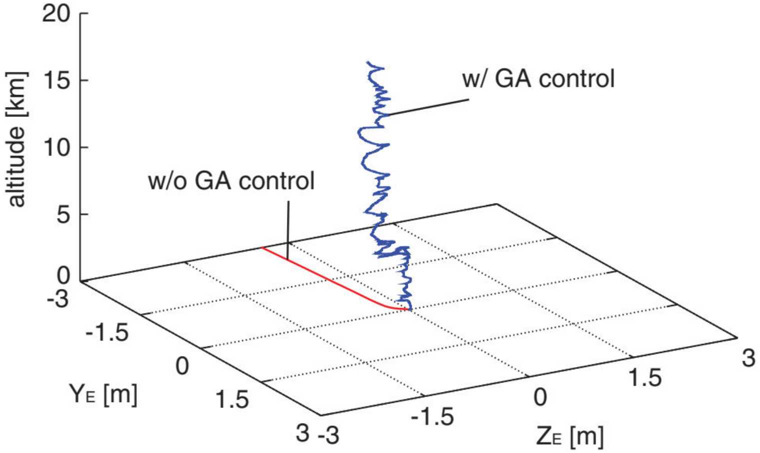
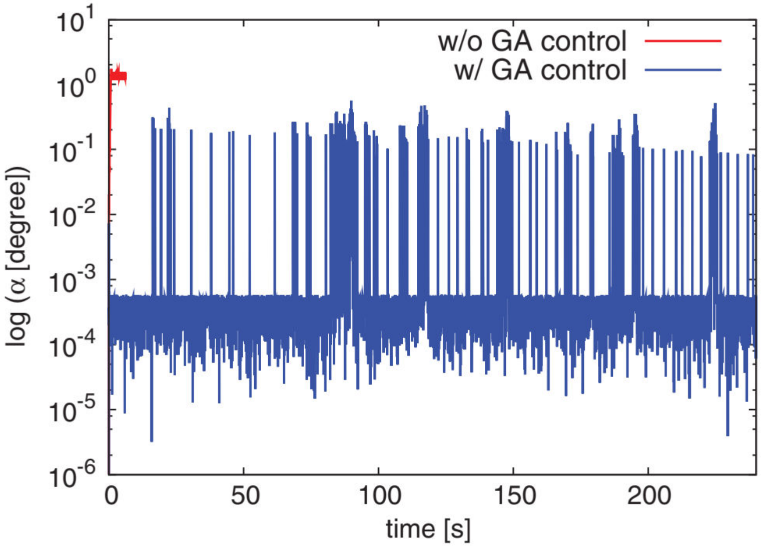


Fig. 5 Mirror-actuating system for active laser control. Deformable mirrors are used to compensate for the coma aberration and disturbance in the wave front of the laser beam.

M. Takahashi and N. Ohnishi, Beam-Riding Flight of a Laser Propulsion Vehicle Using Actively Controlled Pulse, Journal of Propulsion and Power **32**(1): 237 (2016), DOI: 10.2514/1.B35631

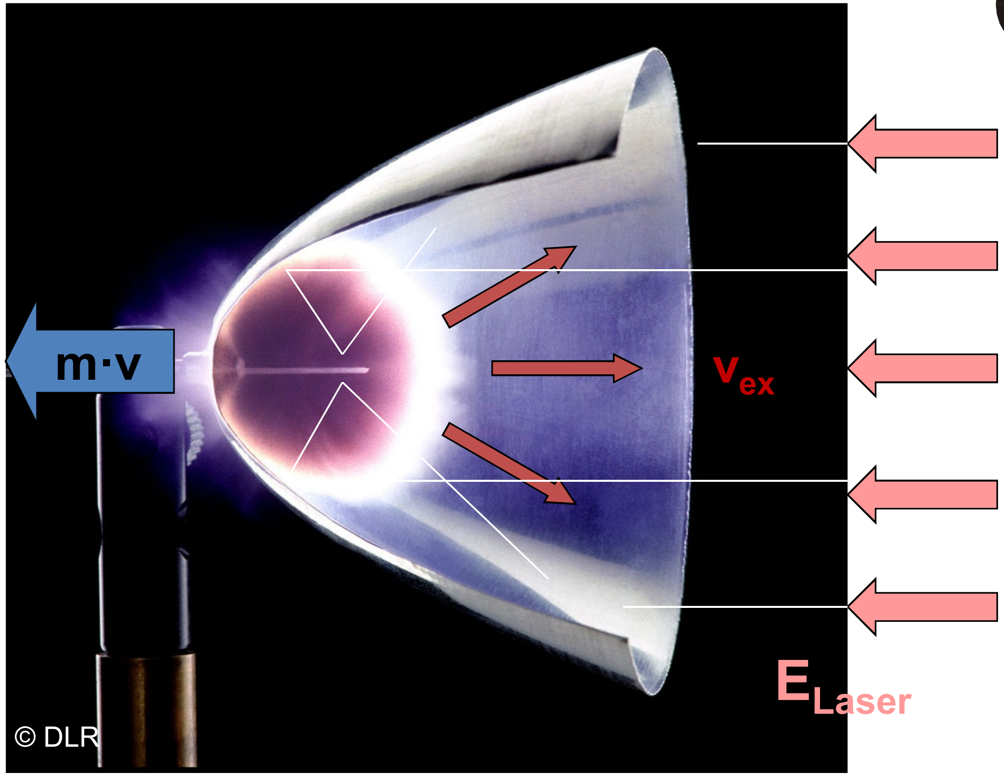


a) Flight trajectories with and without GA control

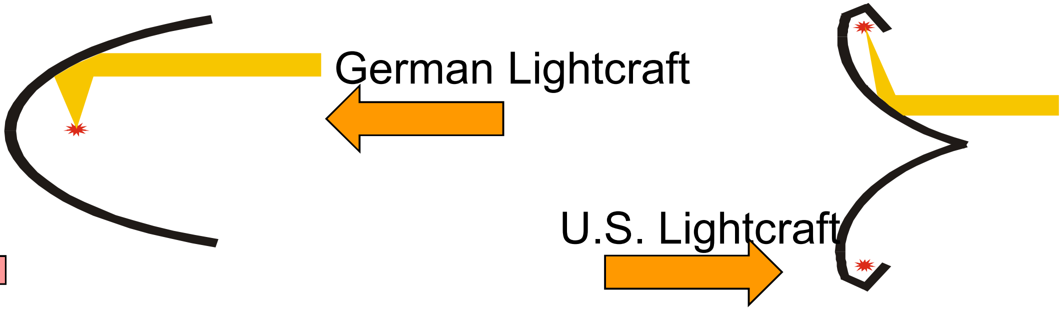


b) Angular offsets with and without GA control

Parabolic Lightcraft („Bohn Bell“)



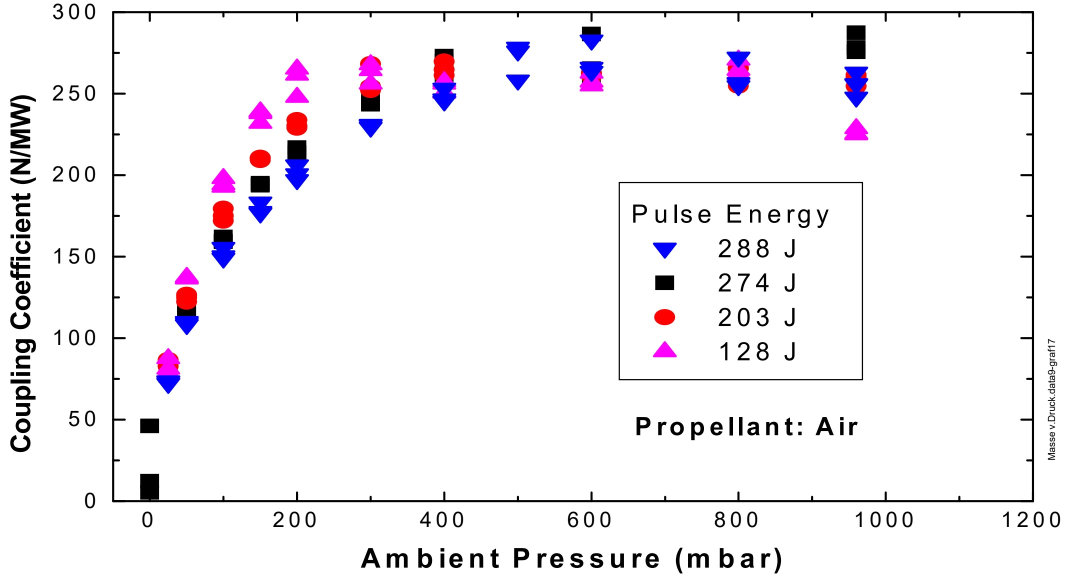
Air Plasma

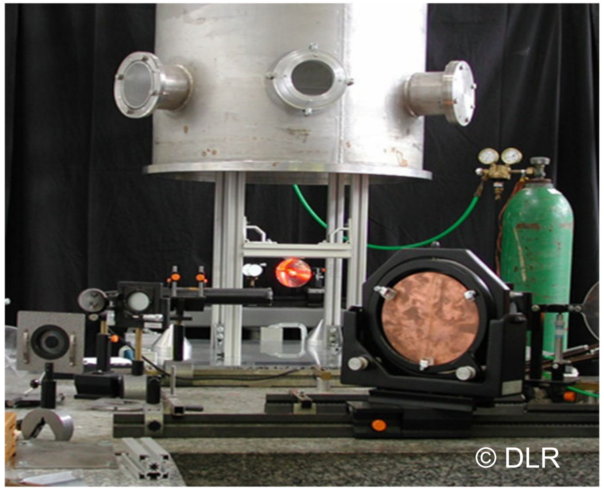


Laser pulse energy:	20 … 200 J
Pulse duration:	~ 8 …12 µs

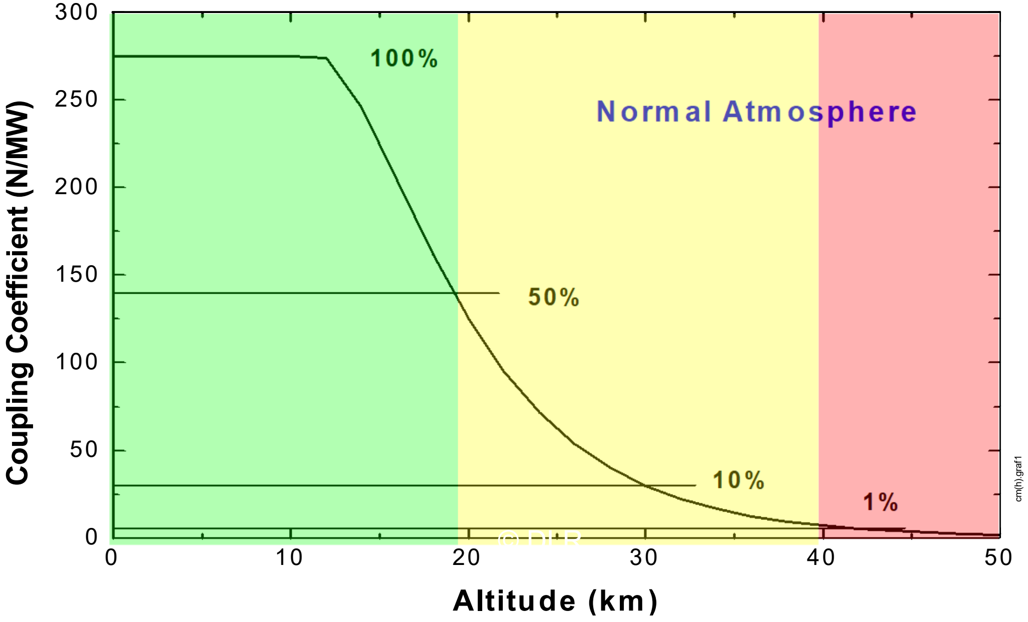
- ⇨ Focus intensity > 10^7 W/cm^2
- ⇨ Plasma ignition
- ⇨ Rapidly expanding plasma
- ⇨ Momentum transfer by increased pressure and gas exhaust (air/propellant)

Altitude Simulation (no propellant)

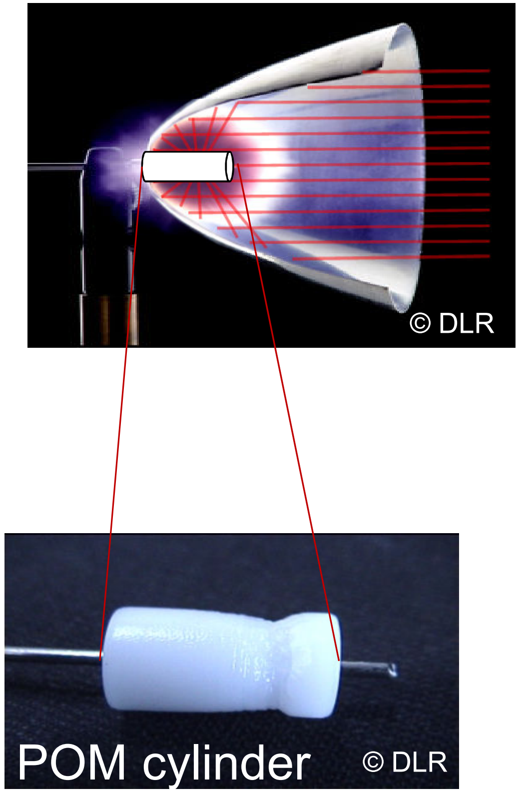


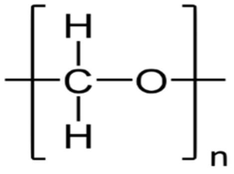


Ballistic pendulum
in vacuum chamber

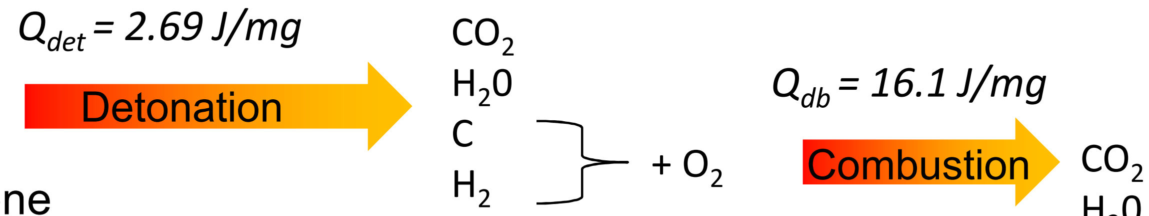


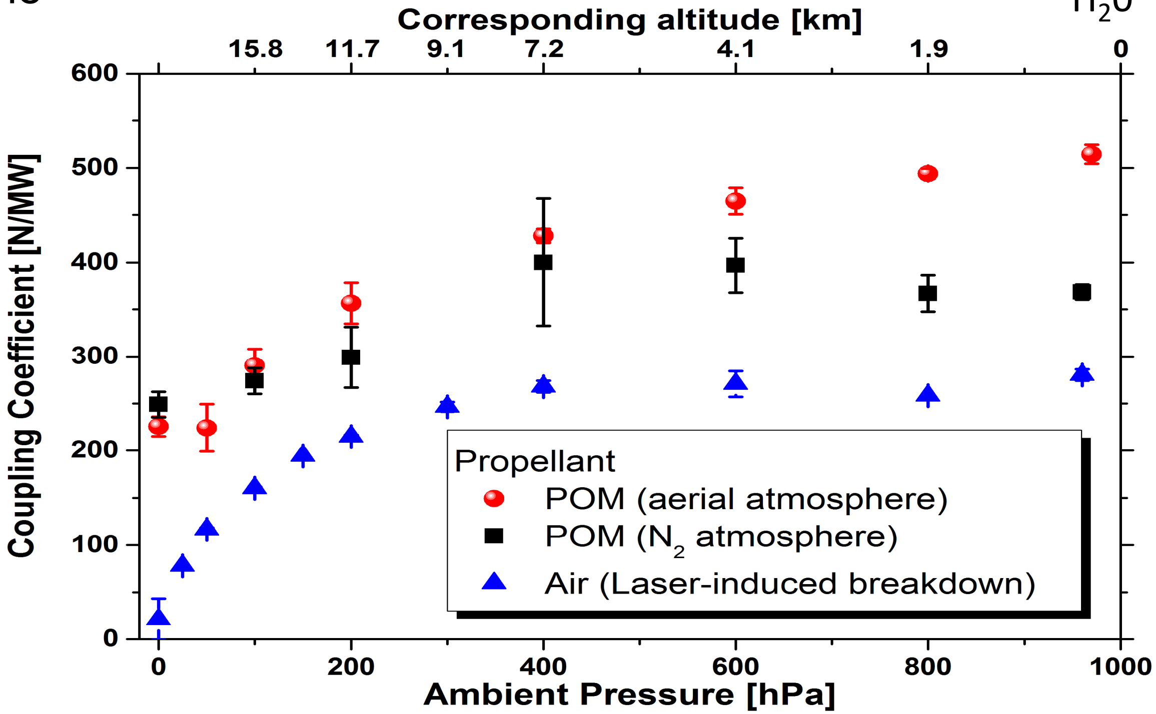
Altitude Simulation (with Propellant)





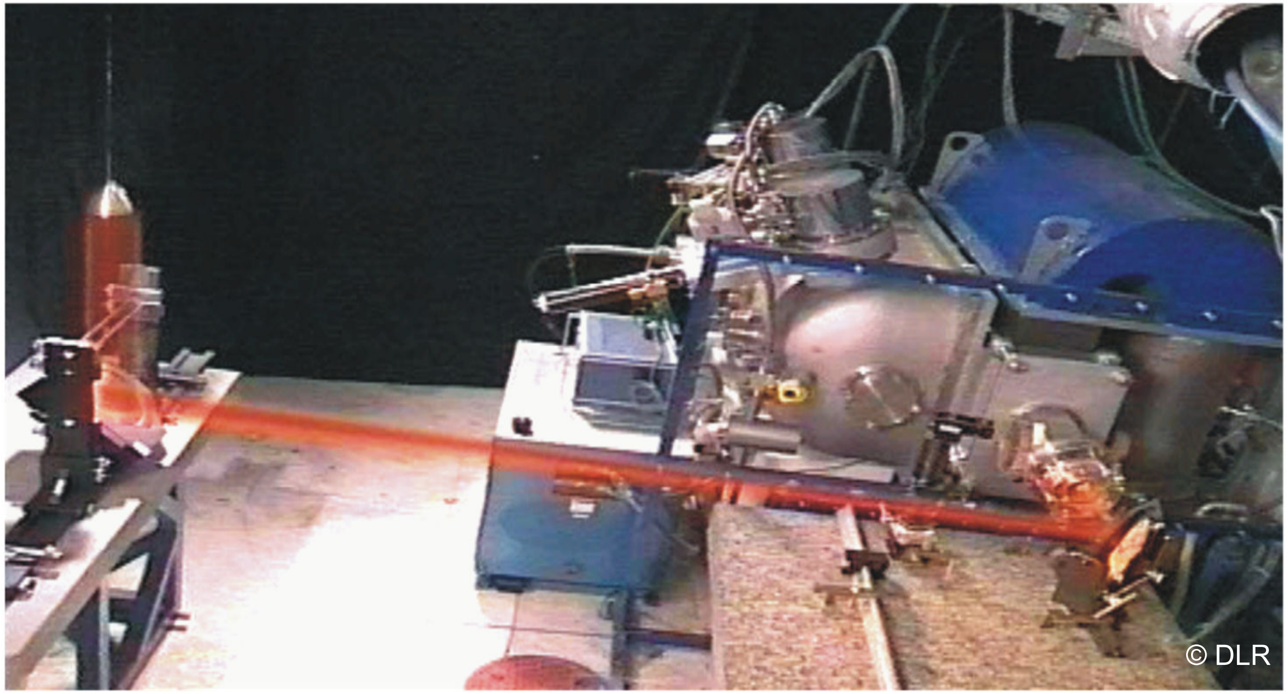
Polyoxymethylene (POM, Delrin)





Wire-guided Flight Experiments

Lightcraft mass	22…55 g
No propellant	
8 Laser pulses	
Pulse energy:	80 J
Pulse repetition rate:	15 Hz



© DLR

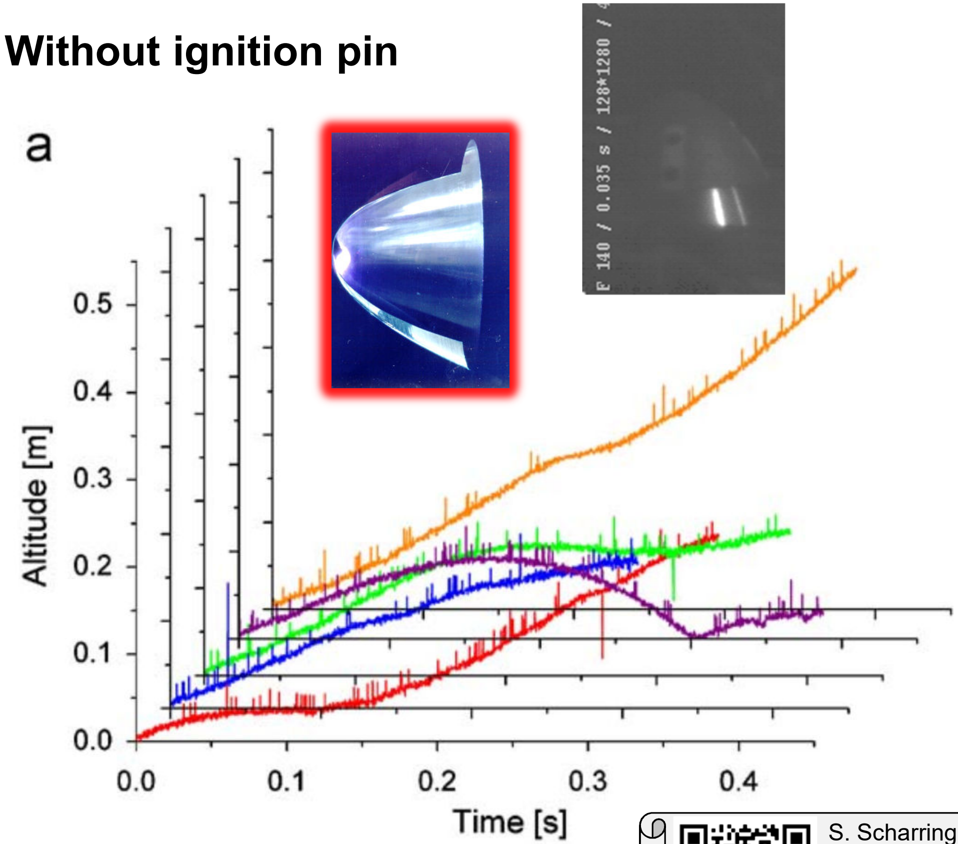
Acceleration:	~ 1g
Thrust:	1.05 N
Flight altitude:	6 m

Free-flight Experiments (no Spin)

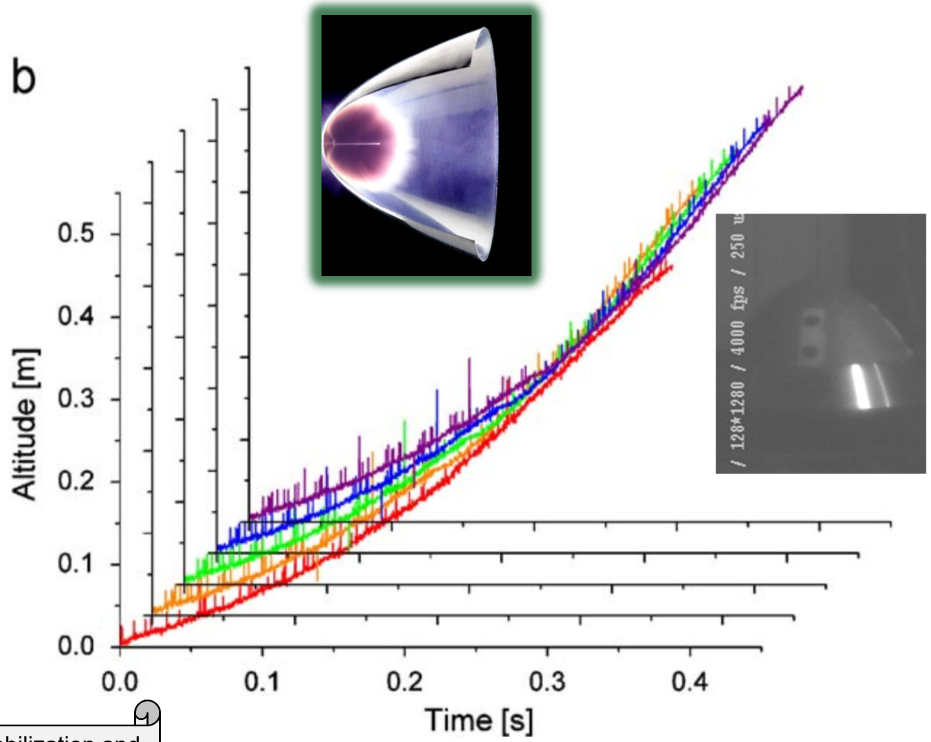
Fig. 5. Time–altitude curves of five flights each of a parabolic lightcraft during a laser burst of 10 pulses, $P_L = 2.9\,\text{kW}$ averaged, (a) without ignition pin, $m_{LC} = 45.6\,\text{g}$, and (b) with ignition pin, $m_{LC} = 49.3\,\text{g}$.

200 N/MW – 600 mN – 2 m/s²

Without ignition pin

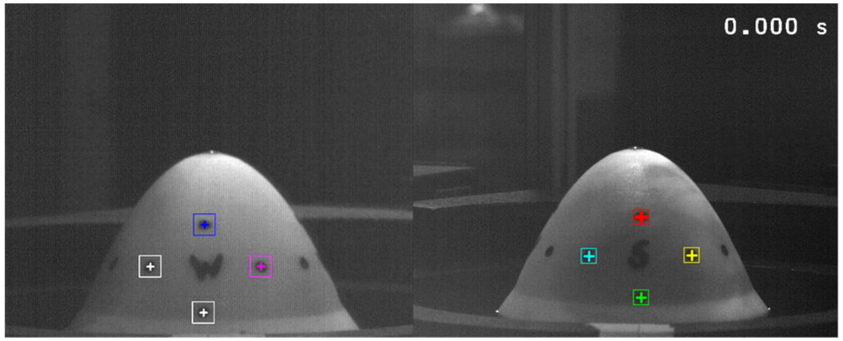


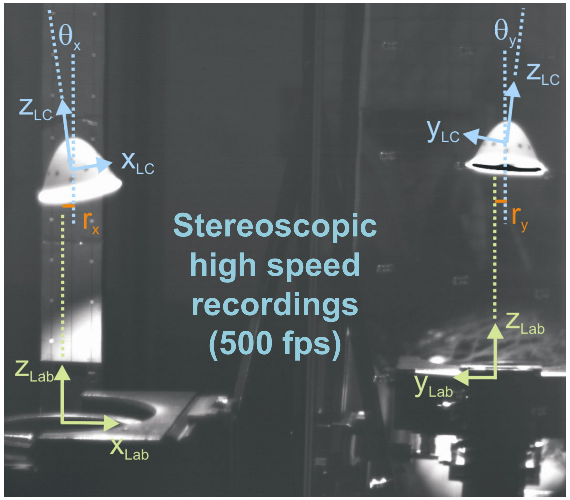
With ignition pin

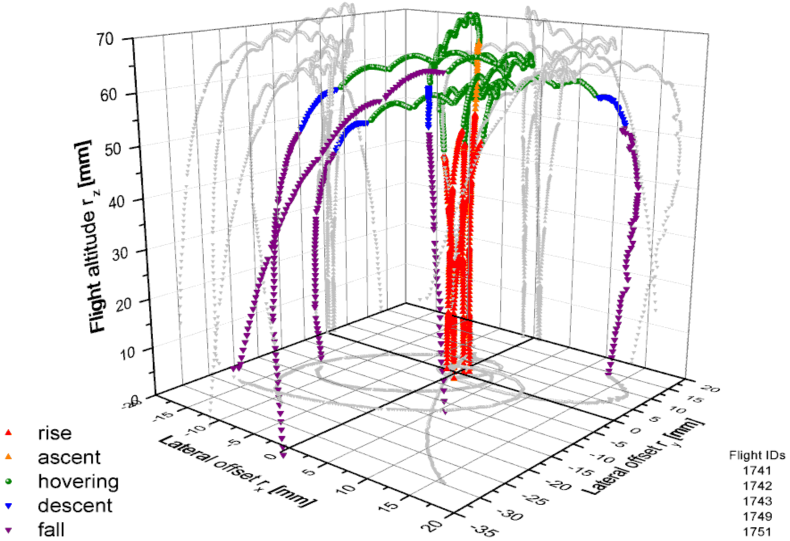


S. Scharring et al, Stabilization and steering of a parabolic laser thermal thruster with an ignition device, Acta Astronaut. **65(11-12)**: 1599 (2009), DOI:10.1016/j.actaastro.2009.04.007

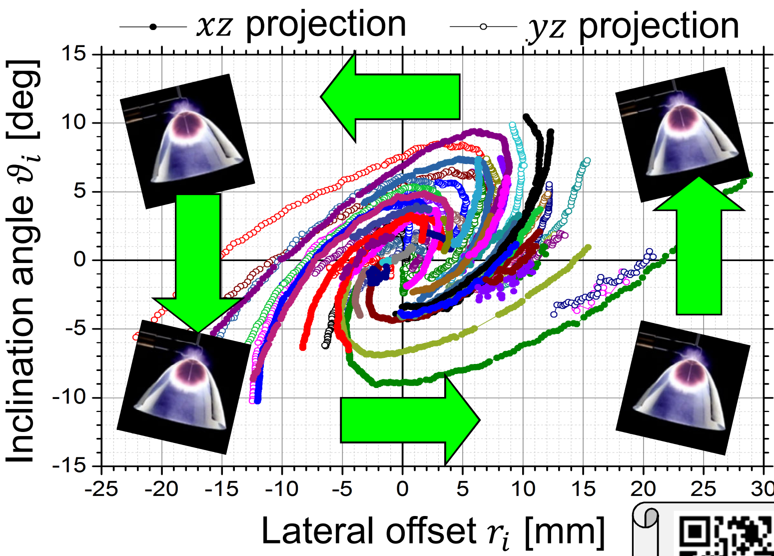
Hovering Experiments







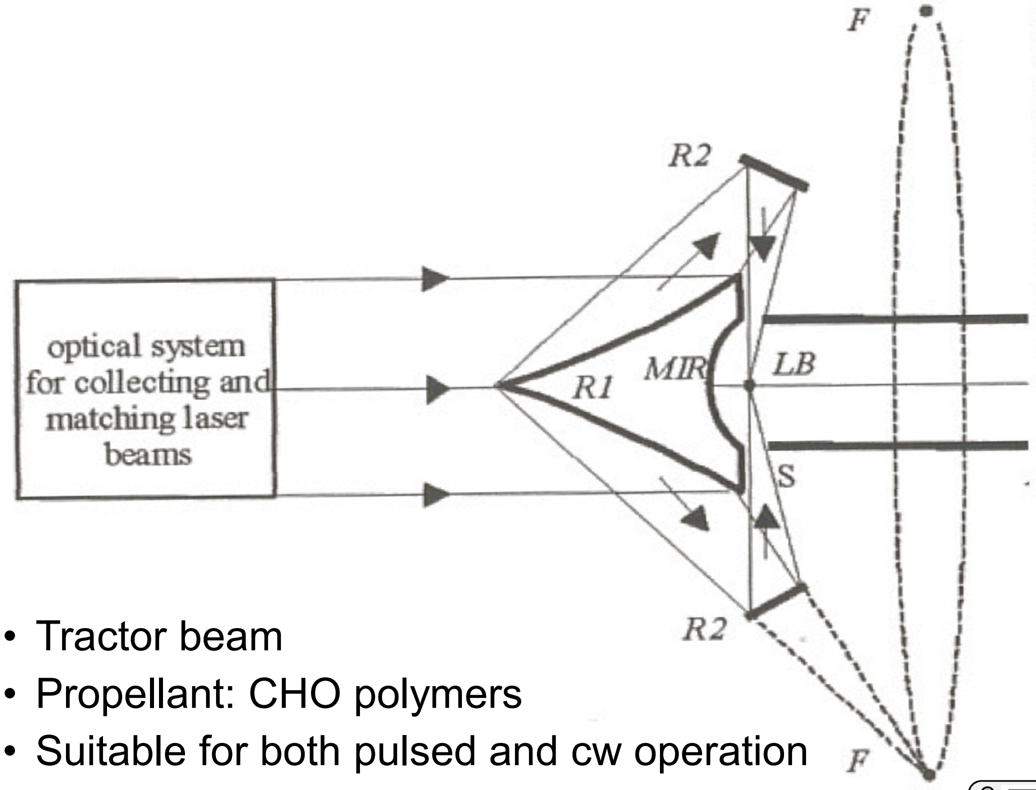
Trajectory



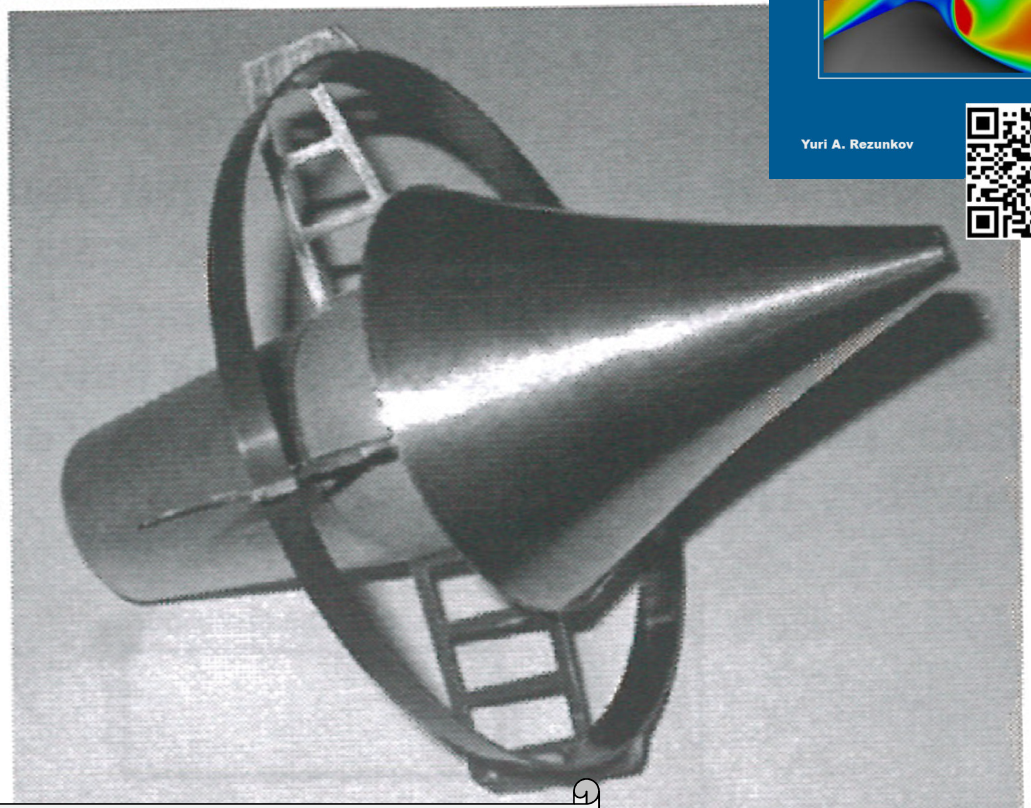
Beam-riding limitations

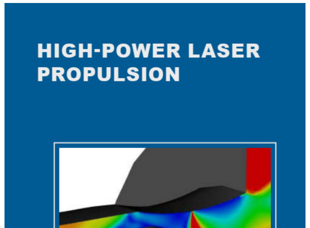
S. Scharring et al, Beam-Riding Analysis of a Parabolic Laser-thermal Thruster, AIP Conf. Proc. **1402**, 115 – 131 (2011), DOI: 10.1063/1.3657021

Russian Aerospace Laser Propulsion Engine

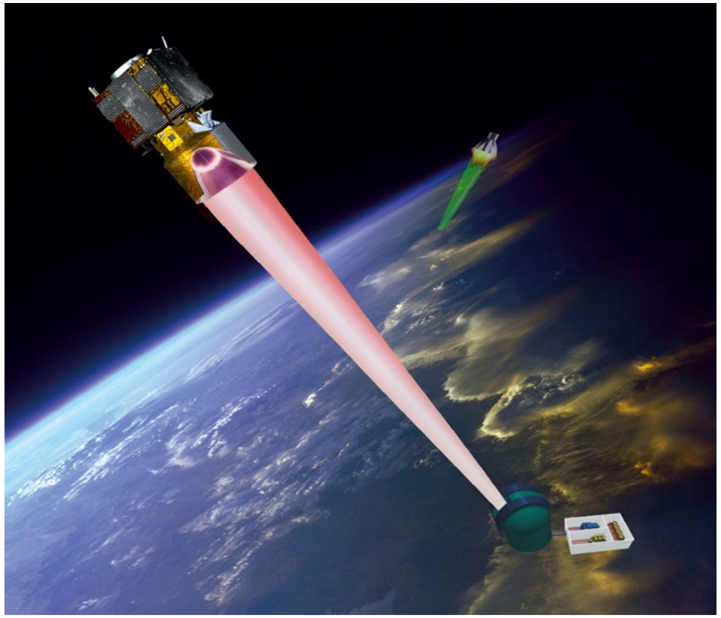


- Tractor beam
- Propellant: CHO polymers
- Suitable for both pulsed and cw operation





Yu. A. Rezunkov et al, Performance Characteristics of Laser Propulsion Engine Operating both in CW and in Repetitively-Pulsed Modes, AIP Conf. Proc. 830: 3 – 13 (2006), DOI: 10.1063/1.2203241



Laser Propulsion

Lectures on unconventional propulsion

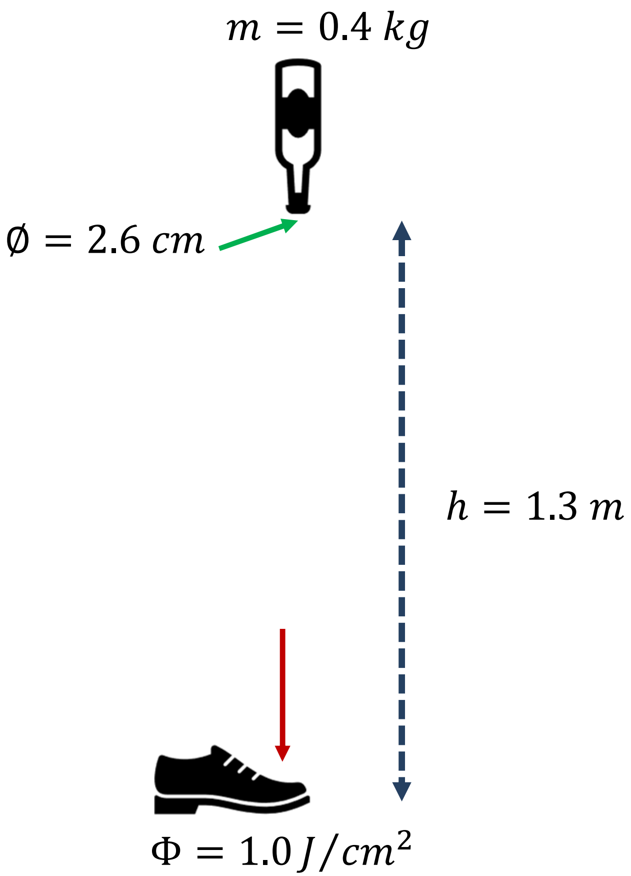
Part V: Laser-ablative Propulsion

IRS Institute of Space Systems, University of Stuttgart
February 10, 2023

Dr. Stefan Scharring

Institute of Technical Physics,
German Aerospace Centre (DLR)

A Thought Experiment



$m = 0.4\ kg$

$\emptyset = 2.6\ cm$

$h = 1.3\ m$

$\Phi = 1.0\, J/cm^2$

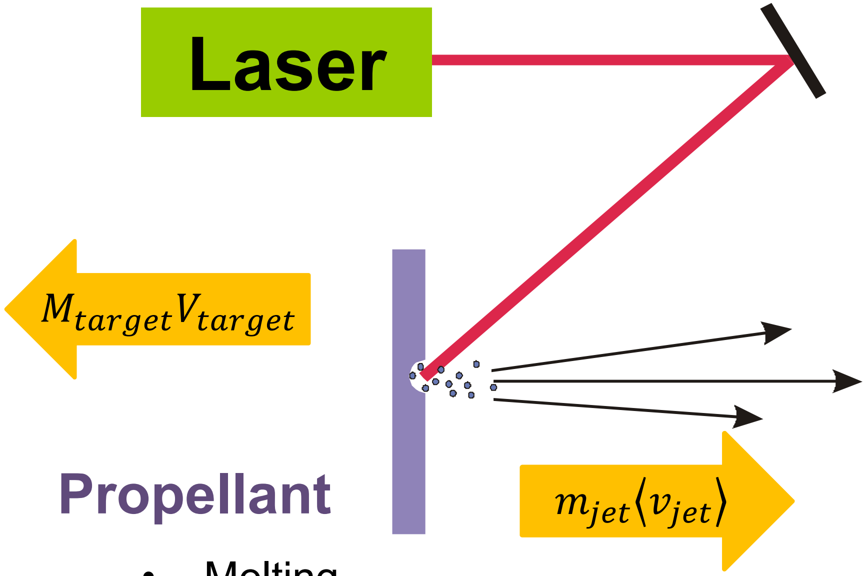
Interaction time

- $\Delta t = 1\, ms \rightarrow I = 1\ \ kW/cm^2$
- $\Delta t = 1\, \mu s \rightarrow I = 1\ \ MW/cm^2$
- $\ldots$
- $\Delta t = 1\, ps \rightarrow I = 1\ \ TW/cm^2$

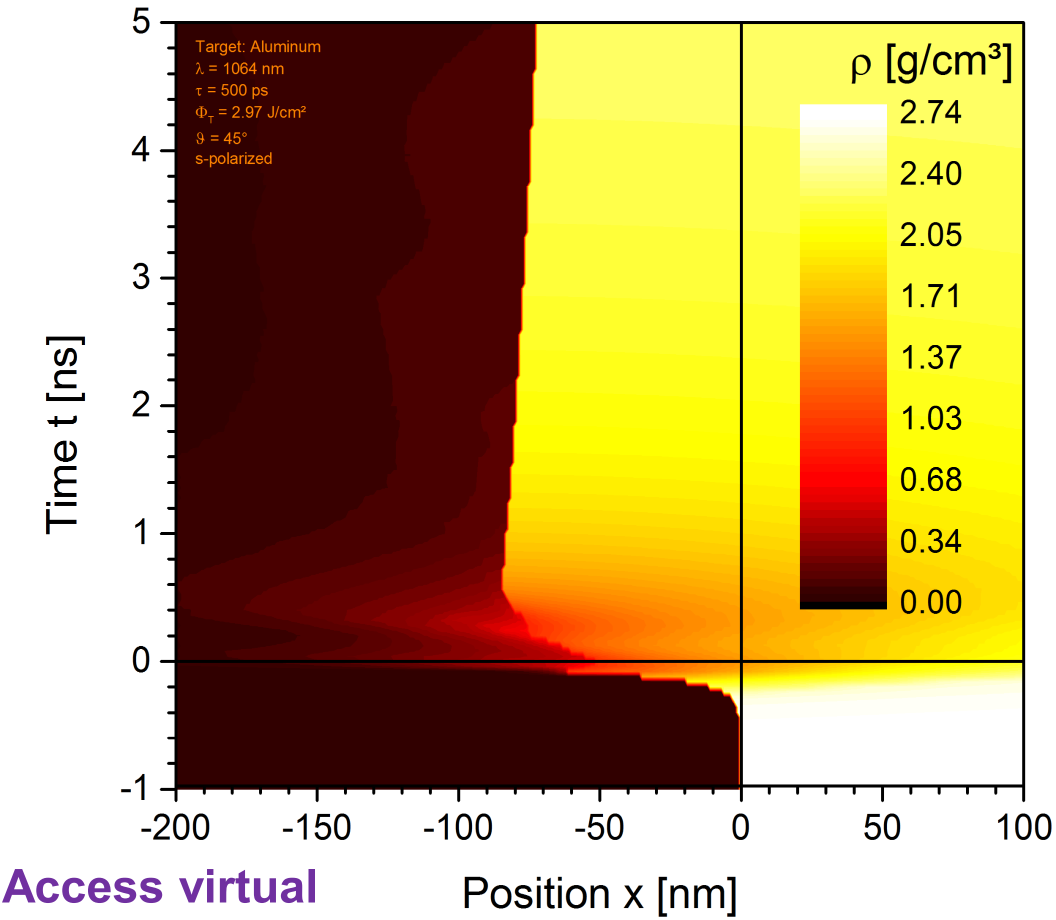
Solar constant: 137 mW / cm²

Laser-induced Ablation Process

$$c_m = \frac{\Delta p}{E_L} = \frac{M_{target} V_{target}}{E_L} = \frac{m_{jet} \langle v_{jet} \rangle}{E_L}$$



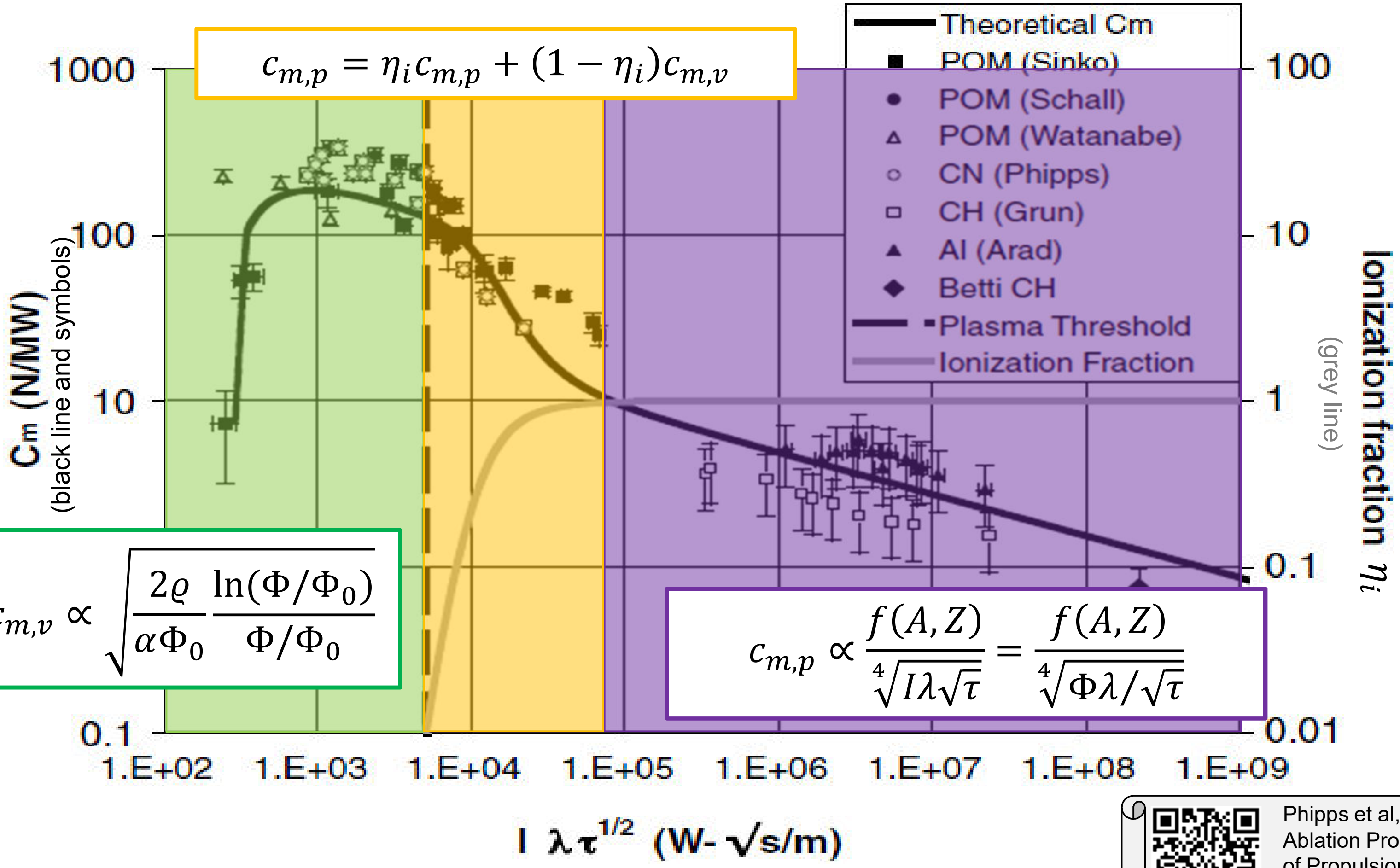
- Melting
- Vaporization
- Spallation (at ultra-short laser pulses)
- Plasma formation (at higher laser fluence)
- Thermal expansion
- Momentum transfer



Results from hydrodynamic simulations with Polly-2T from the Joint Institute of High Temperatures, Russian Academy of Sciences, Moscow

Access virtual laser lab

Regimes of Interaction in Laser Ablation



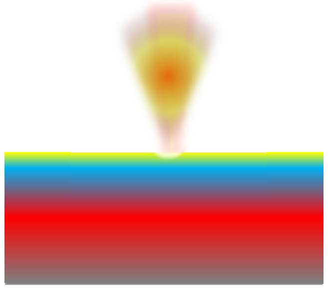
$$c_{m,p} = \eta_i c_{m,p} + (1-\eta_i) c_{m,v}$$

$$c_{m,v} \propto \sqrt{\frac{2\varrho}{\alpha\Phi_0} \frac{\ln(\Phi/\Phi_0)}{\Phi/\Phi_0}}$$

$$c_{m,p} \propto \frac{f(A,Z)}{\sqrt[4]{I\lambda\sqrt{\tau}}} = \frac{f(A,Z)}{\sqrt[4]{\Phi\lambda/\sqrt{\tau}}}$$

Phipps et al, Review: Laser-Ablation Propulsion, Journal of Propulsion and Power **26**(4): 609-637 (2010), DOI: 10.2514/1.43733

Laser Ablation Process



Heat conduction

$$c_i(T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left[\kappa_i \frac{\partial T}{\partial z}\right] + S(\vec{r},t)$$

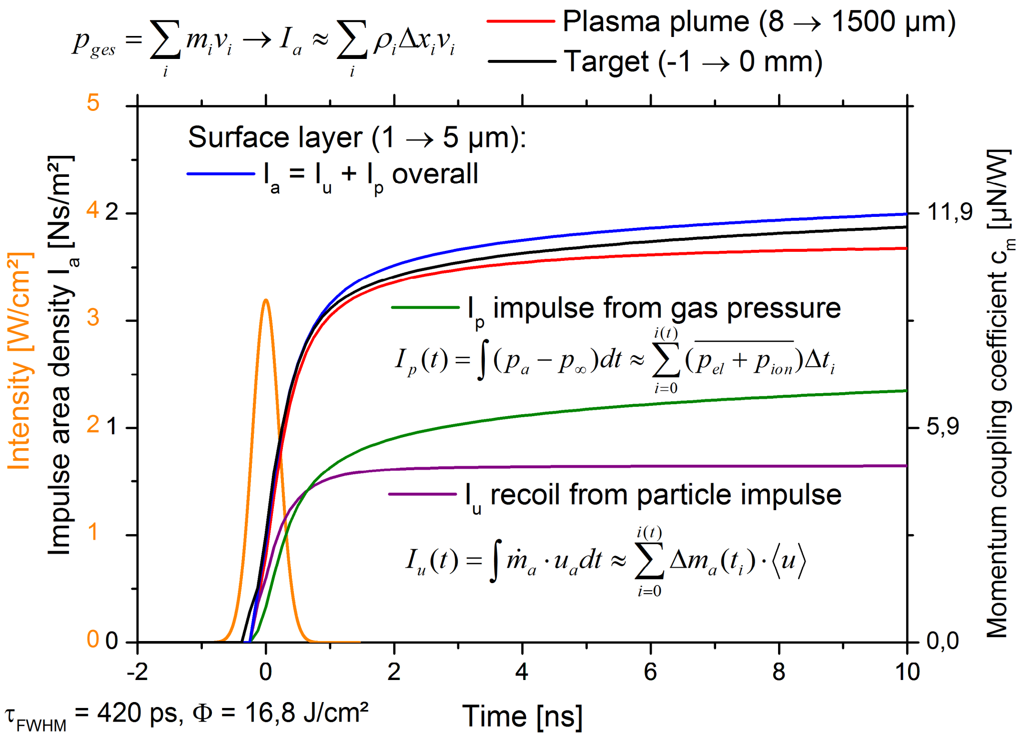
Material heating

Laser irradiation

Heat conduction equation

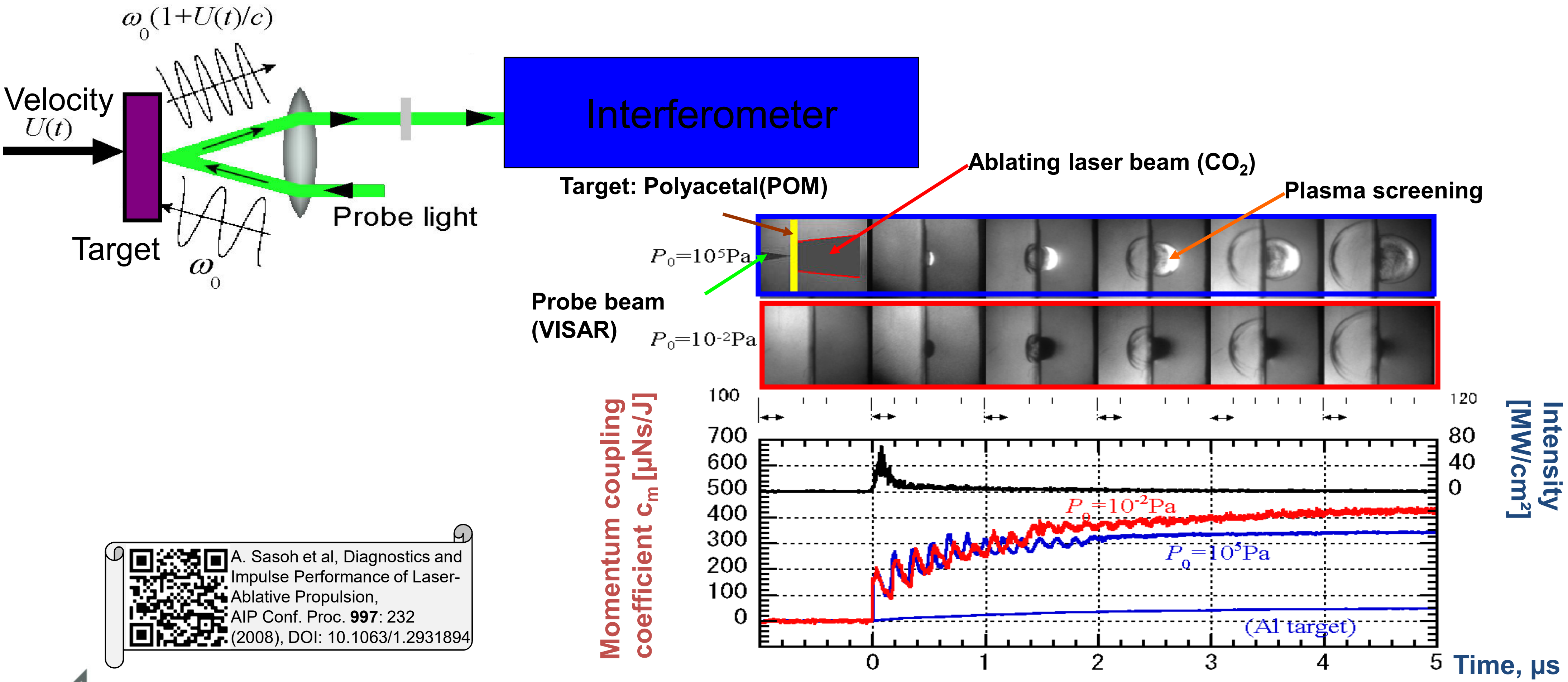
B.N. Chichkov et al., *Appl. Phys*. A, **63: 109-115**, 1996.

c_i: specific heat capacity
T: lattice temperature
κ_i: heat conductivity
S: laser energy density



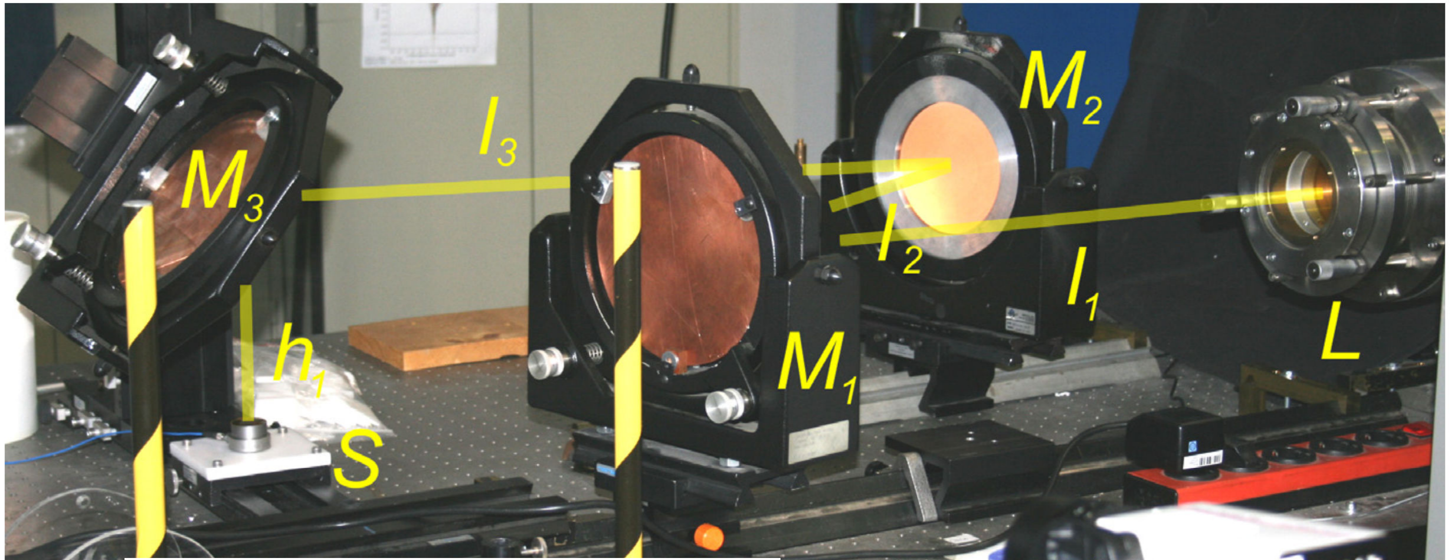
τ_{FWHM} = 420 ps, Φ = 16,8 J/cm²

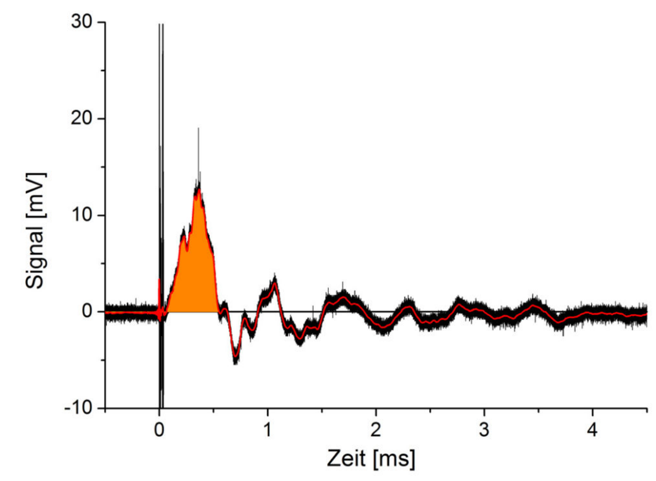
Measurement of momentum: Interferometry



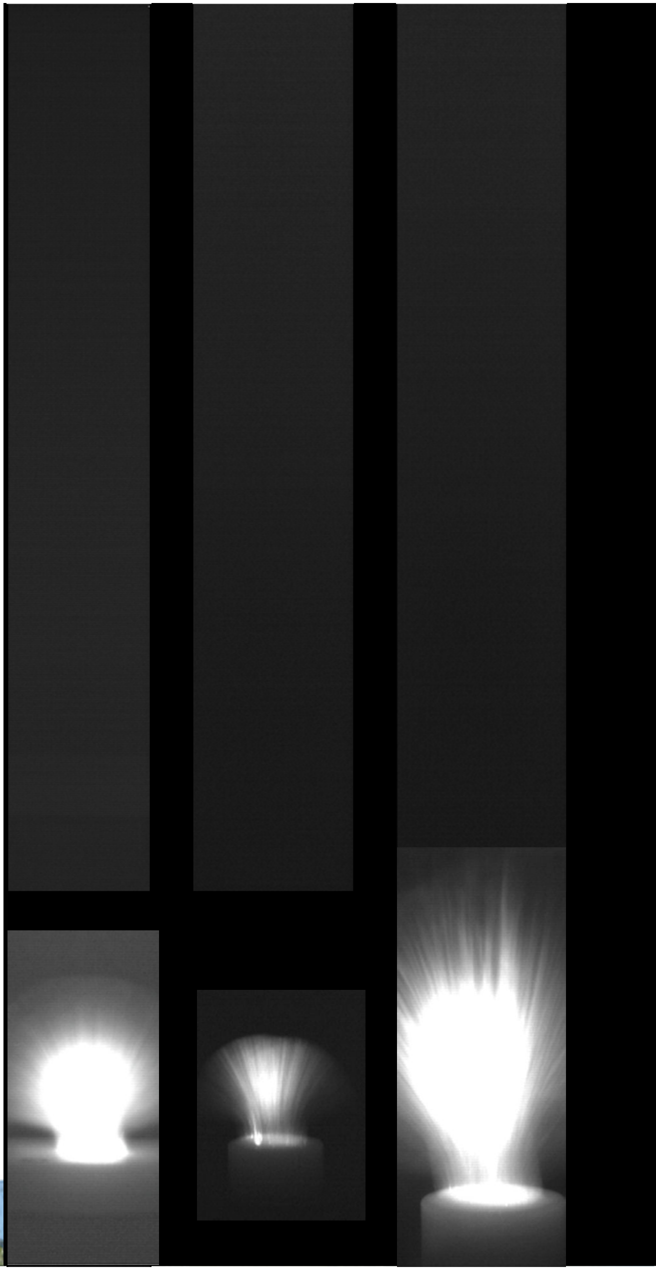
A. Sasoh et al, Diagnostics and Impulse Performance of Laser-Ablative Propulsion, AIP Conf. Proc. **997**: 232 (2008), DOI: 10.1063/1.2931894

Measurement of momentum: Piezo-electric sensors





S. Scharring, Impulse Analysis of Air-breathing Pulsed Laser-thermal Propulsion with a Parabolic Reflecting Nozzle for Space Applications, PhD thesis, University of Stuttgart (2012)



Laser Ablation of Metals

Electron gas

$$c_e(T_e)\frac{\partial T_e}{\partial t} = \nabla[\kappa_e(T_e)\nabla T_e] \; -\gamma_{ei}(T_e - T_i) \quad + \quad S(\vec{r}, t)$$

Surface layer heating

Heat conduction

τ_i

Laser irradiation

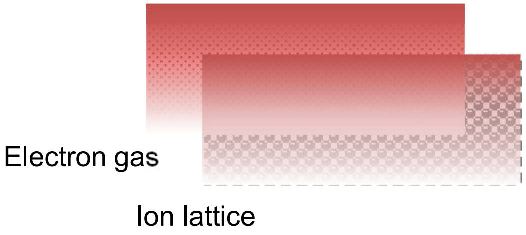
Electron-phonon coupling

Ion lattice

$$c_i(T_i)\frac{\partial T_i}{\partial t} = \nabla[\kappa_i(T_i)\nabla T_i] + \gamma_{ei}(T_e - T_i)$$

Anisimov, S. I. et al., *JETP Lett.*, **39** (2), 1974.

c_e, c_i: specific heat capacities
T_e, T_i: electron and lattice temperature, resp.
κ_e, κ_i: heat conductivity
γ_{ei}: heat exchange coefficient
τ_e, τ_i: thermalization times
S: laser energy density



Laser Ablation of Metals

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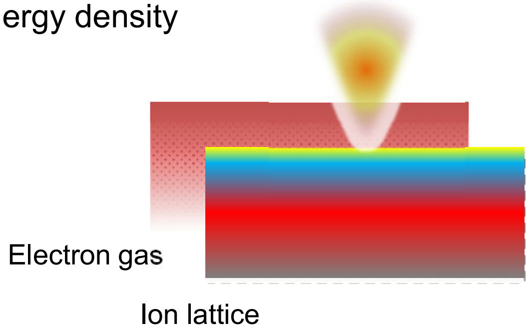


Efficiencies in Laser Ablation

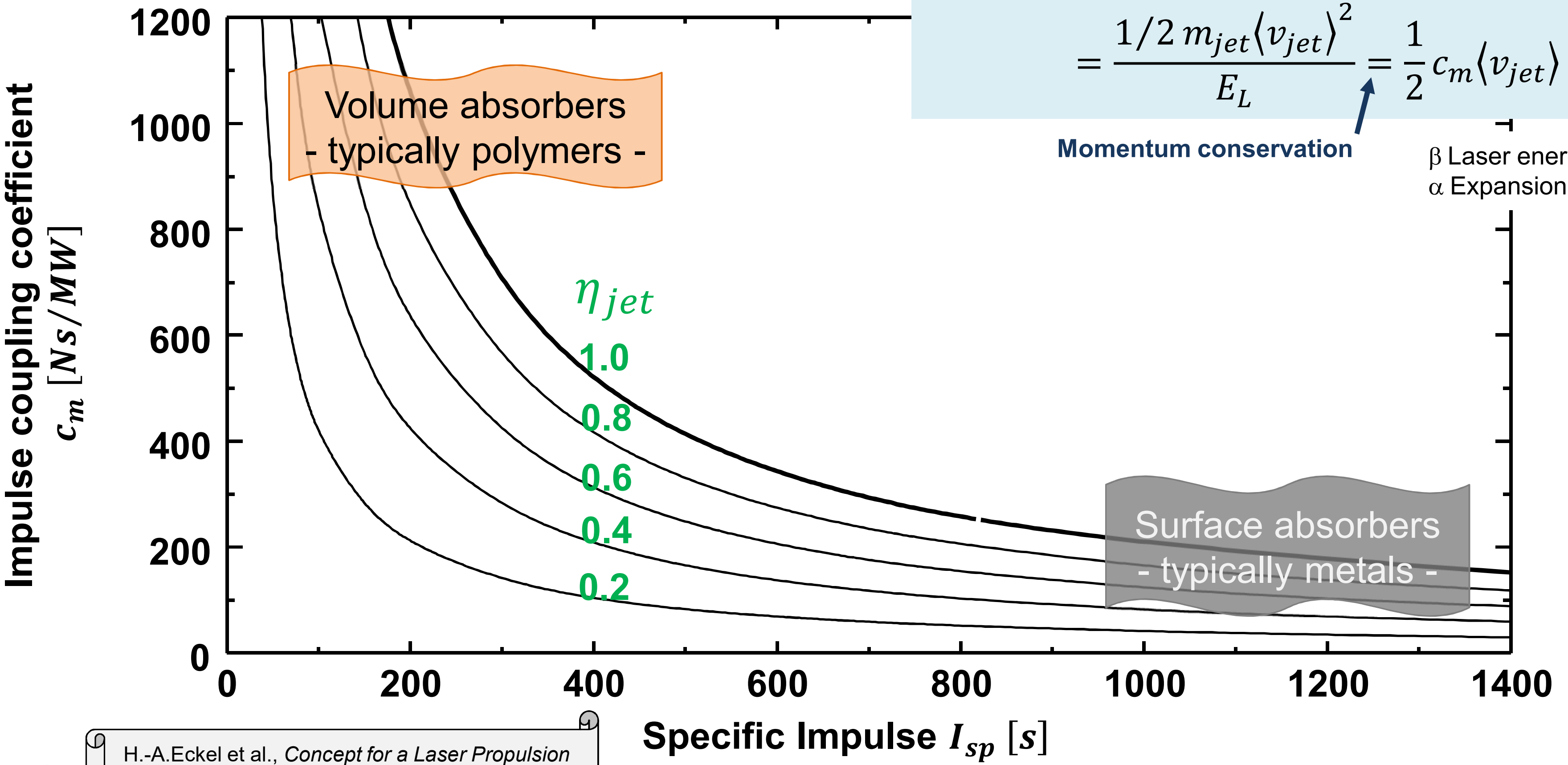
Jet efficiency (Internal propulsion efficiency)

$$\eta_{jet} = \eta_{int} = \frac{\text{Reference jet kinetic energy}}{\text{Incident laser pulse energy}} = \frac{E_{jet,0}}{E_L}$$

$$= \frac{1/2\, m_{jet}\langle v_{jet}\rangle^2}{E_L} = \frac{1}{2} c_m \langle v_{jet}\rangle = \frac{g}{2} c_m I_{sp} = \alpha\beta$$

Momentum conservation

β Laser energy absorption efficiency
α Expansion efficiency



H.-A.Eckel et al., *Concept for a Laser Propulsion Based Nanosat Launch System*, AIP Conf. Proc. **702**, 263 – 273 (2004), DOI: 10.1063/1.1721006

Efficiencies in Laser Ablation

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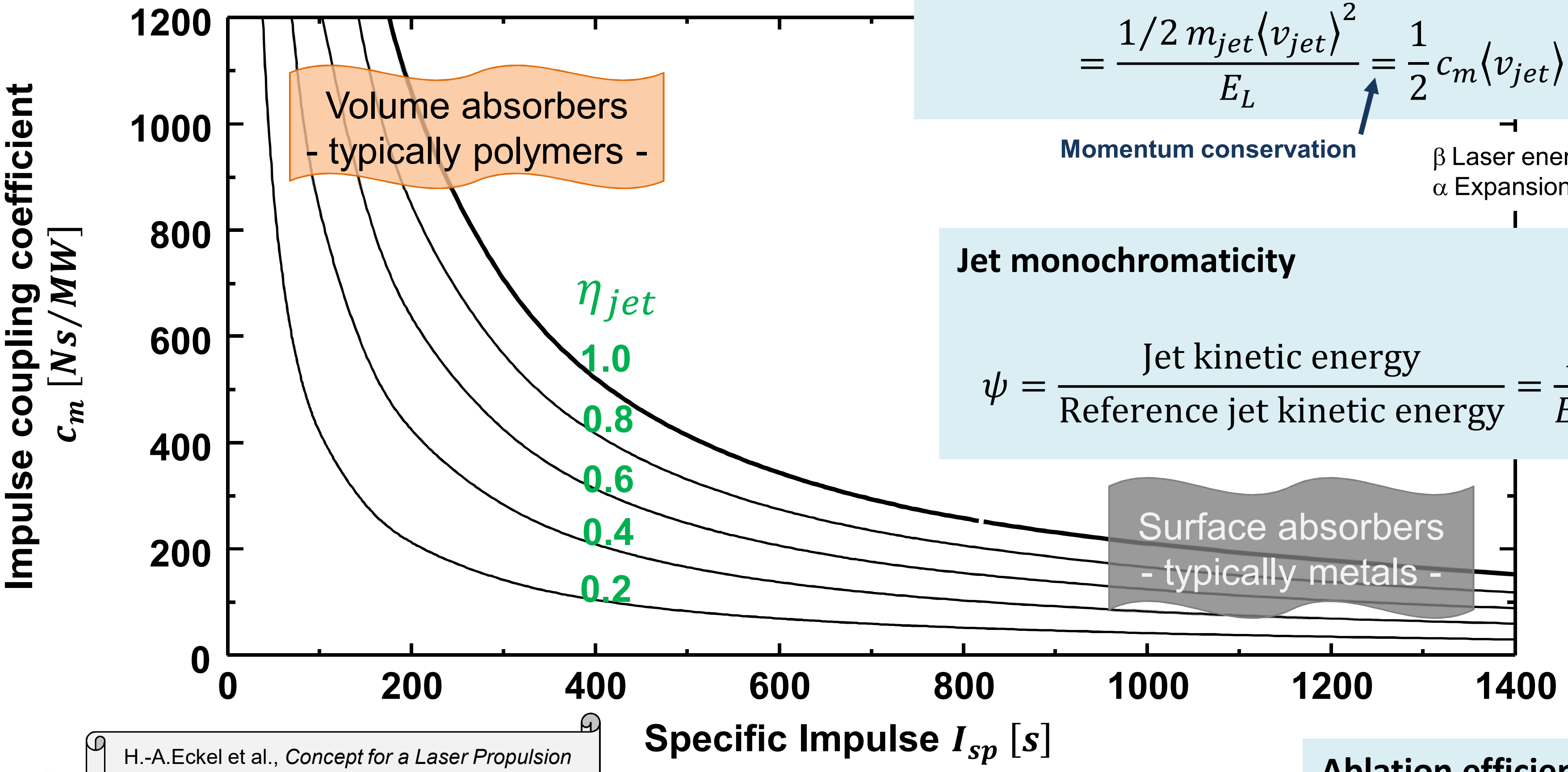
Momentum conservation

β Laser energy absorption efficiency
α Expansion efficiency

Jet monochromaticity

$$\psi = \frac{\text{Jet kinetic energy}}{\text{Reference jet kinetic energy}} = \frac{E_{jet}}{E_{jet,0}} = \frac{\sum_j [v_{jet,j}^2]}{\langle v_{jet} \rangle^2}$$



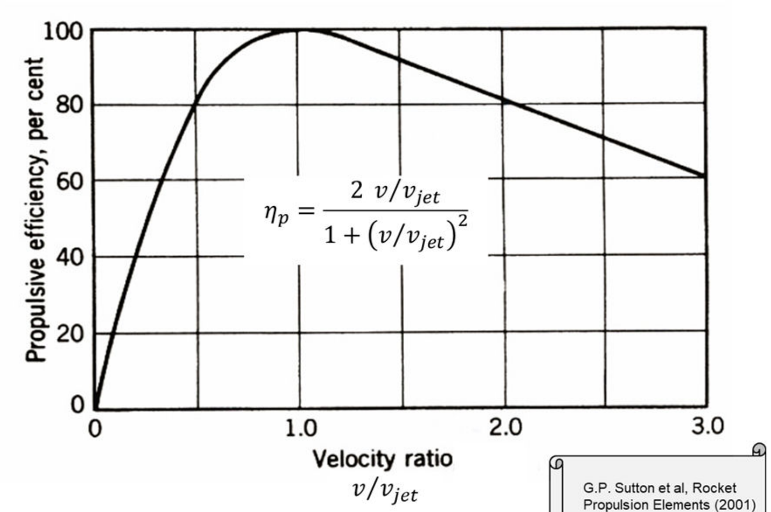
H.-A.Eckel et al., *Concept for a Laser Propulsion Based Nanosat Launch System*, AIP Conf. Proc. **702**, 263 – 273 (2004), DOI: 10.1063/1.1721006

Ablation efficiency

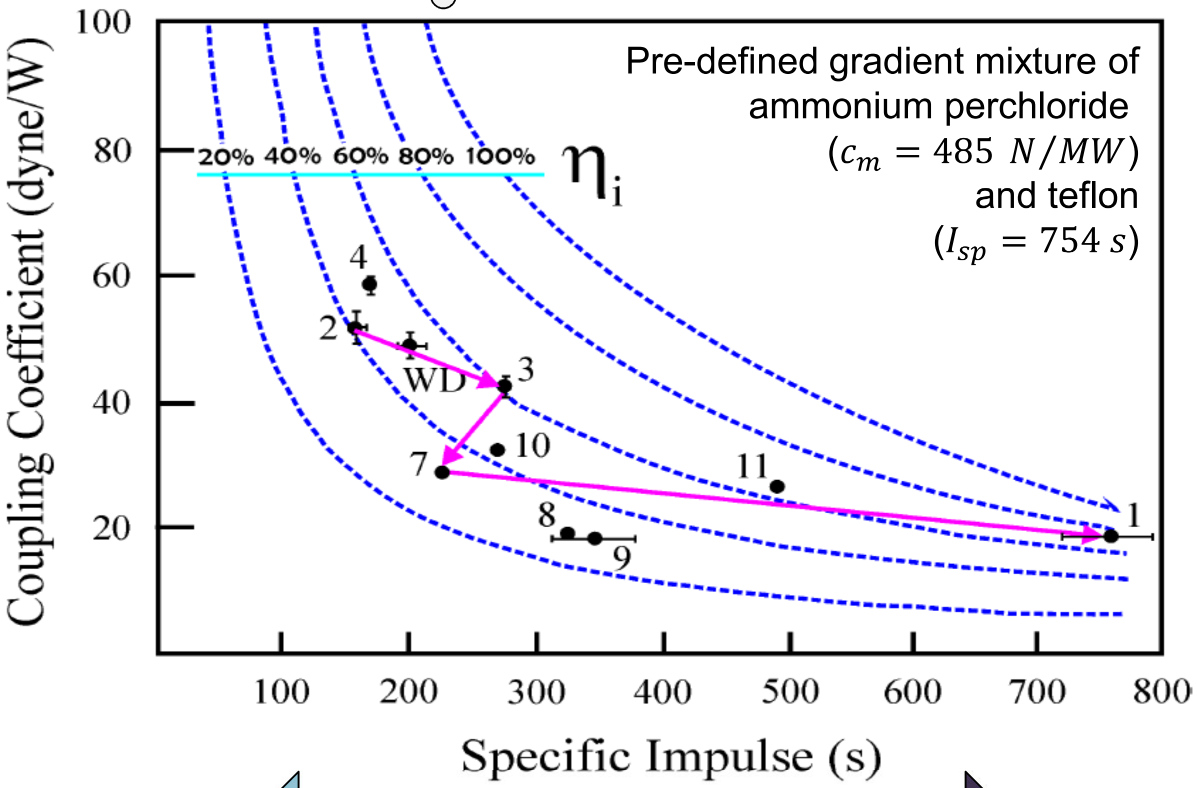
$$\eta_{abl} = E_{jet}/E_L = \eta_{jet} \cdot \psi$$

Constant Momentum Mission for Launch

Pakhomov, A.V., Mahaffy, K.E., Binary Solid Propellants for Constant Momentum Missions, AIP Conf. Proc. 997, 266 – 279 (2008), DOI: 10.1063/1.2931897



G.P. Sutton et al, Rocket Propulsion Elements (2001)



Pre-defined gradient mixture of ammonium perchloride ($c_m = 485\ N/MW$) and teflon ($I_{sp} = 754\ s$)

Ground

Low Earth Orbit

Optimization of propulsive efficiency

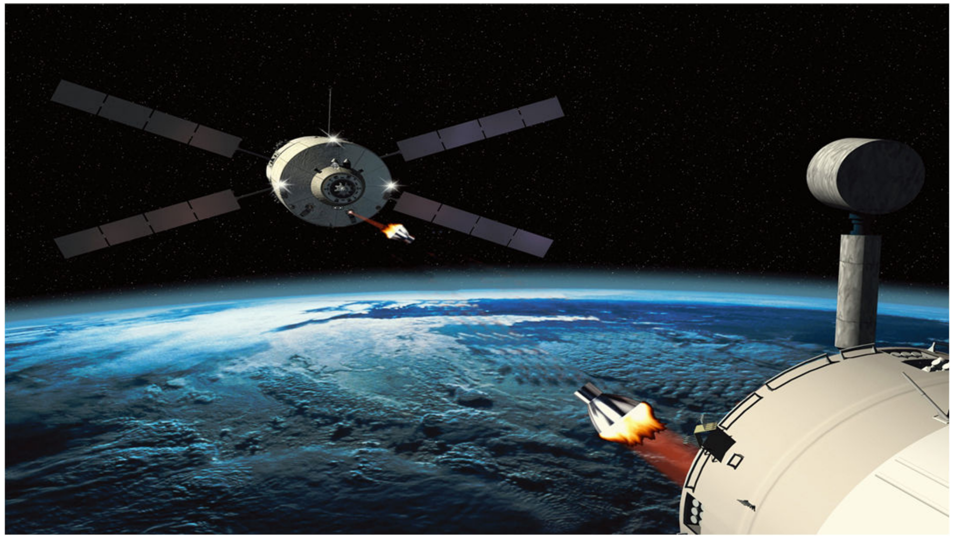
Dynamic adaptation of $\langle v_{jet} \rangle = g \cdot I_{sp}$

$$\langle v_{jet} \rangle(t) = v_{s/c}(t)$$

instead of $\langle v_{jet} \rangle = const.$

In-orbit Applications

Logistics



Sample Return

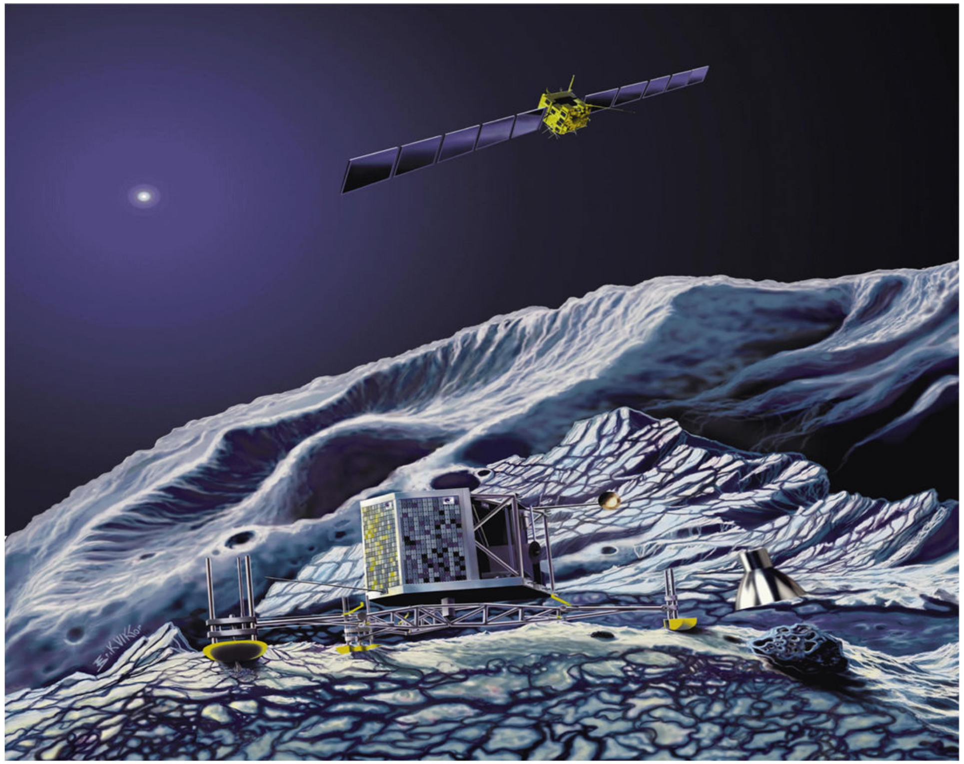
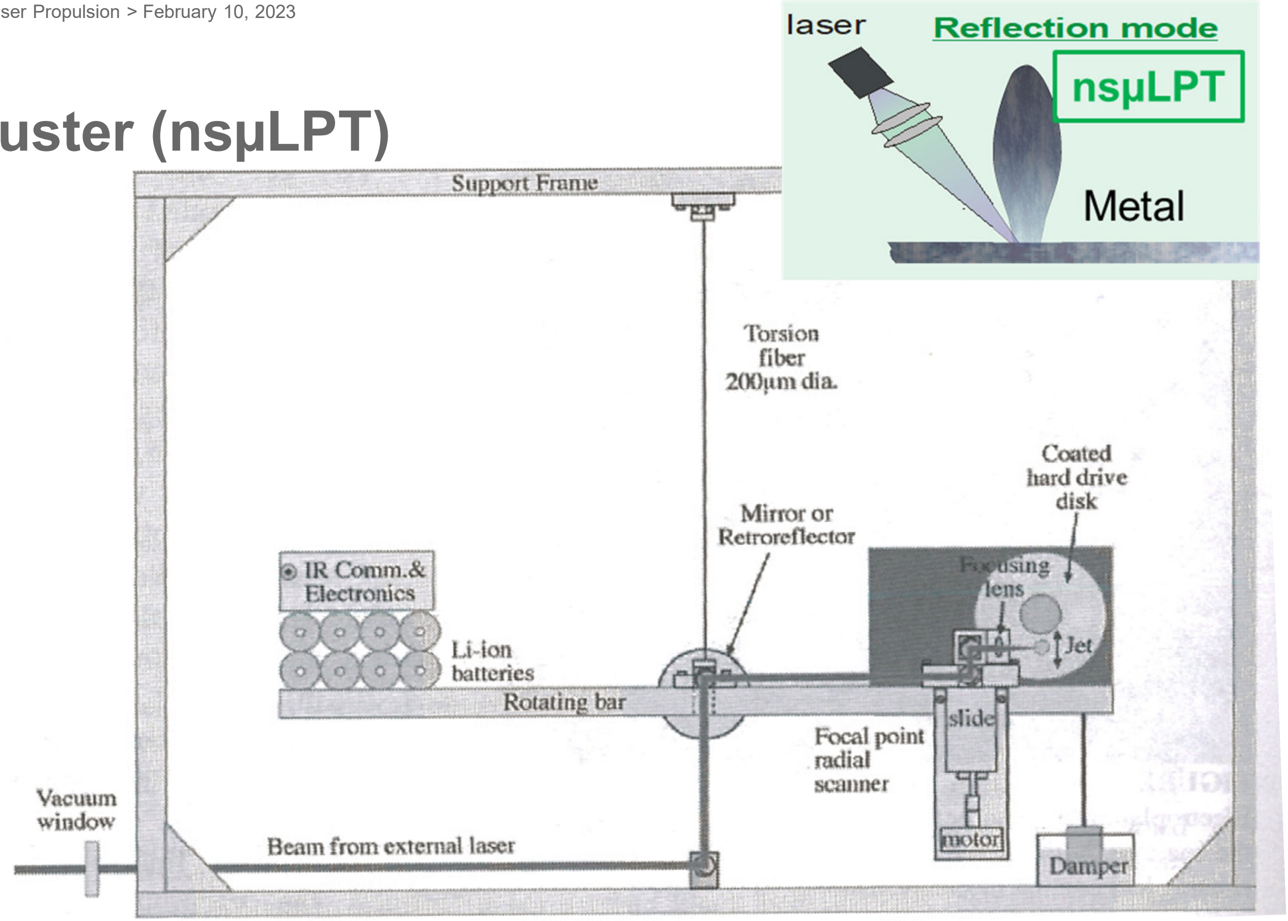


Image credits: ESA, montage:DLR

R-Mode Micro Laser Plasma Thruster (nsµLPT)



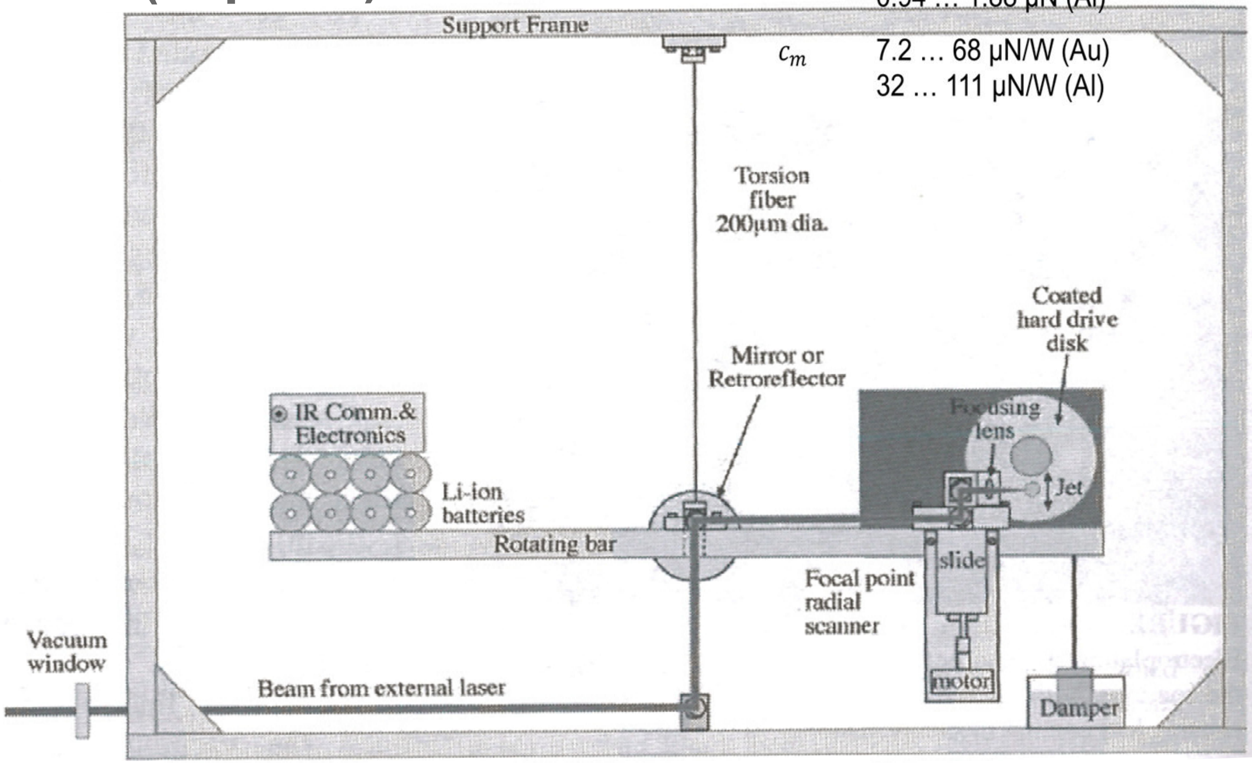
Phipps et al, A ns-Pulse Laser Microthruster, AIP Conf. Proc. **830**, 235-246 (2006), DOI: 10.1063/1.2203266

R-Mode Micro Laser Plasma Thruster (nsμLPT)

Propellants:	
	Aluminium, Gold
T	0.47 … 0.63 μN (Au) 0.94 … 1.88 μN (Al)
c_m	7.2 … 68 μN/W (Au) 32 … 111 μN/W (Al)
I_{sp}	3664 … 7905 s (Au) 822 … 6610 s (Al)

Laser:	Nd:YAG-Laser
τ	5 ns
λ	1064 nm
f_{rep}	10 Hz
E_L	1 … 20 mJ

Propellants:
Aluminium, Gold
T 0.47 … 0.63 μN (Au)
0.94 … 1.88 μN (Al)
c_m 7.2 … 68 μN/W (Au)
32 … 111 μN/W (Al)



Minimum impulse bit: $\Delta p = 0.04\ nNs$

Phipps et al, A ns-Pulse Laser Microthruster, AIP Conf. Proc. **830**, 235-246 (2006), DOI: 10.1063/1.2203266

For comparison:
FEEP $\Delta p = 1\ \mu Ns$
μPPT $\Delta p = 2\ \mu Ns$

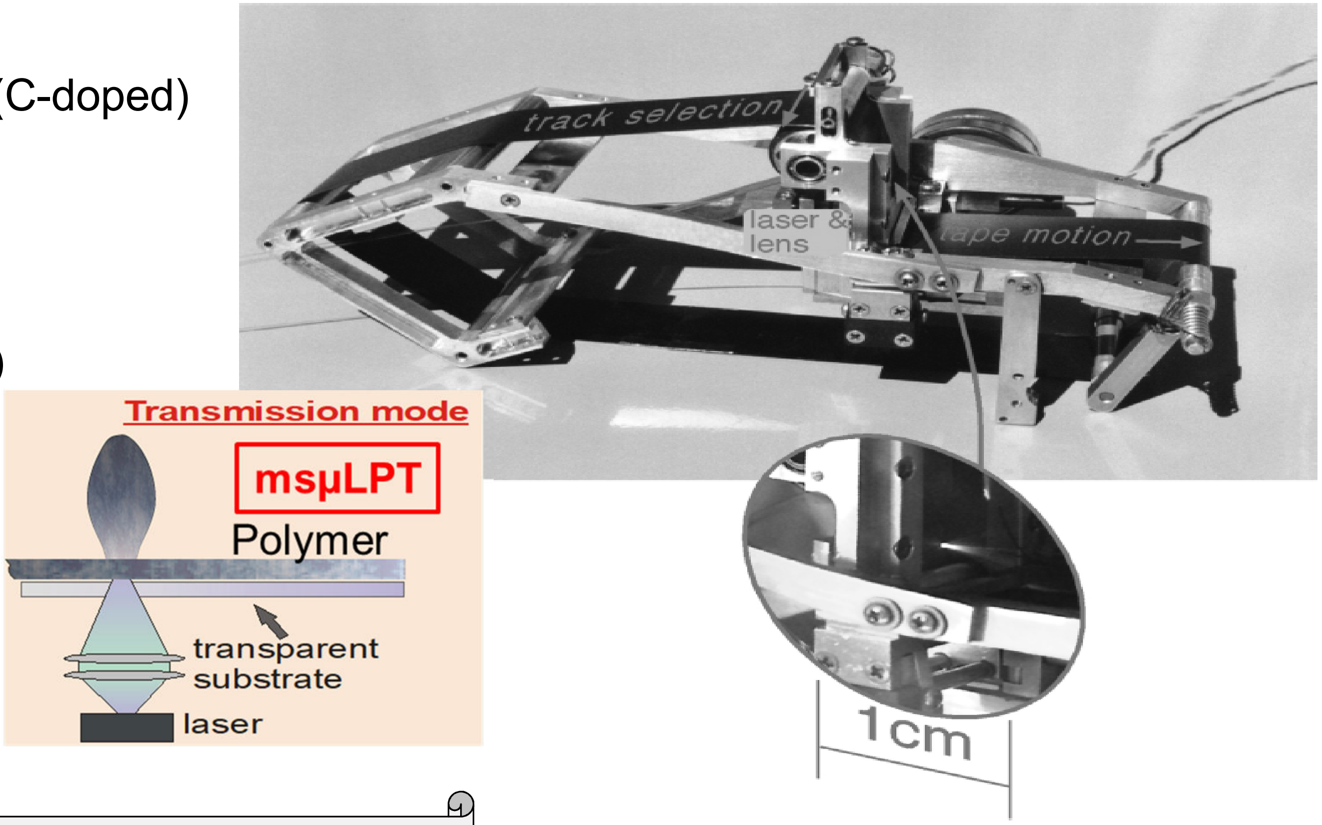
T-Mode Micro Laser Plasma Thruster (msμLPT)

Propellants:

PVC, exothermal polymer (C-doped)

T	0.14 … 0.29 mN (PVC:C) 2.8 … 7.2 mN (EP:C I)
c_m	60 … 120 μN/W (PVC:C) 1170 … 3000 μN/W (EP:C)
I_{sp}	650 … 750 s (PVC:C) 160 … 540 s (EP:C)

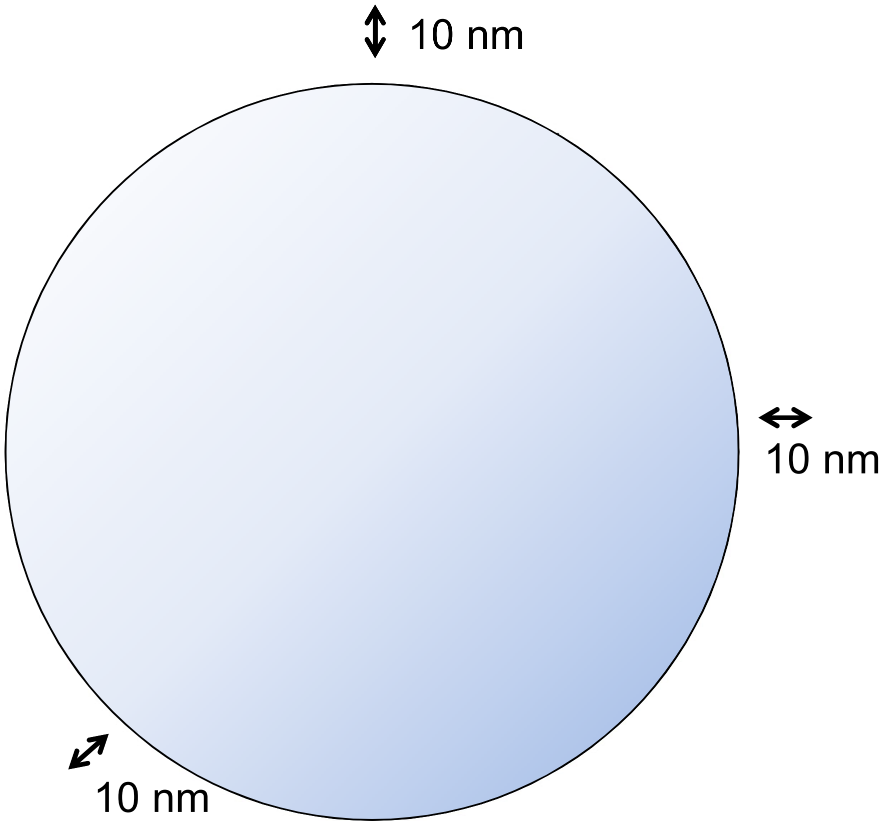
Laser:	Diode laser
τ	2 ms
λ	920 nm
f_{rep}	80 Hz
E_L	30 mJ



Phipps et al, Micropropulsion using a Laser Ablation Jet, J. Prop. Pow. 20(6), 1000-1011 (2004), DOI: 10.2514/1.2710

Minimum impulse bit: $\Delta p = 0.05\ \mu Ns$

Ultimate Demands for Attitude and Orbit Control Systems (AOCS)



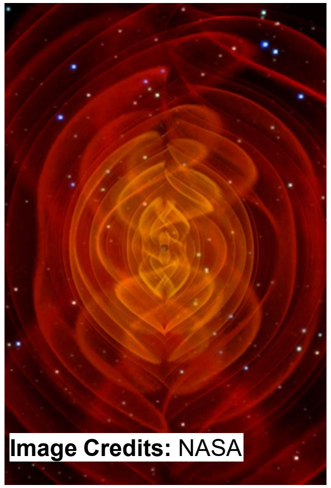


Image Credits: NASA

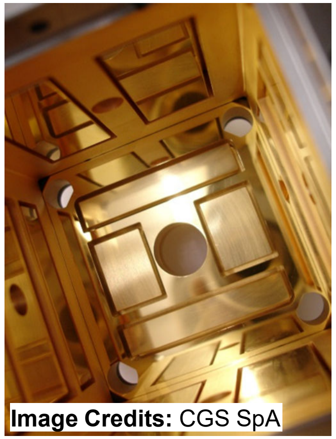


Image Credits: CGS SpA

sub-µN to mN range

Scientific missions (drag free / free fall)

Earth observation formation flights

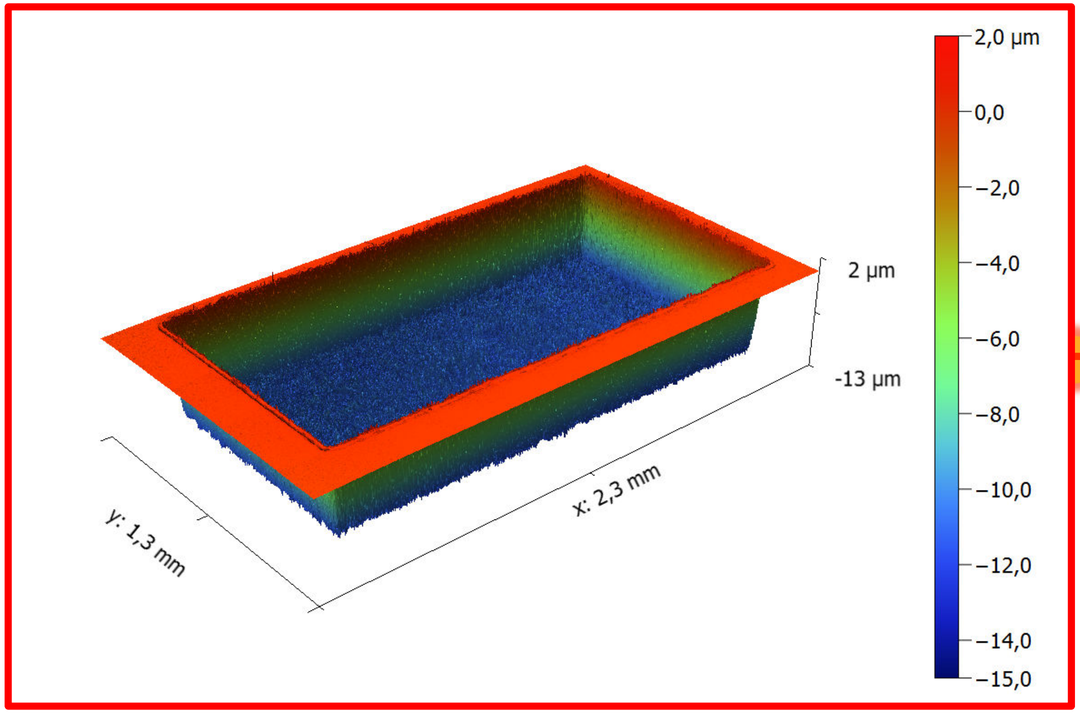
Long-term operation

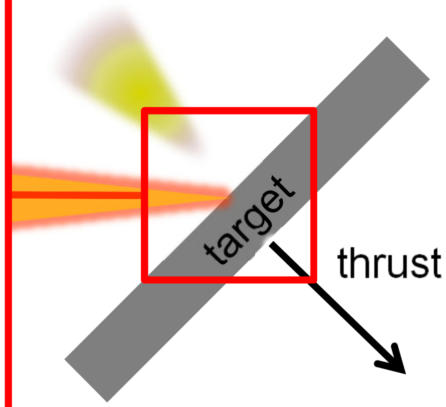
Zero moving parts

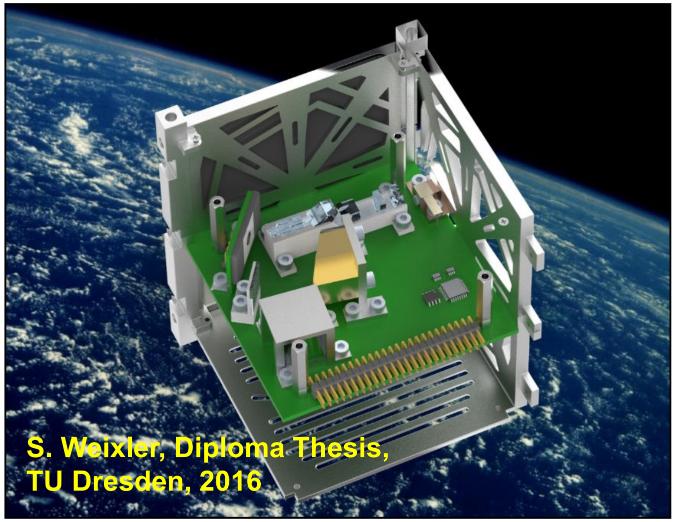
Residual acceleration $< 10^{-14}\ \mathrm{m \cdot s^{-2} \cdot Hz^{-1/2}}$

Low-Noise Microthruster Concept

(MICROLAS, DLR)







S. Weixler, Diploma Thesis, TU Dresden, 2016

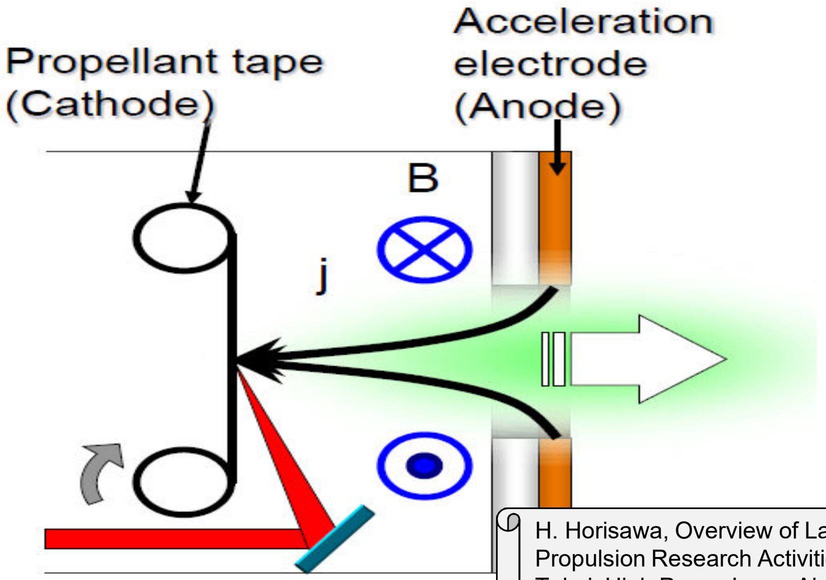
DLR microthruster demonstrator

Advanced Concepts

Hybrid ablative/electrostatic thruster

optional:

- + *electrical discharge (electro-thermal)*
- + *high currents → self-induction*



H. Horisawa, Overview of Laser Propulsion Research Activities at Tokai, High Power Laser Ablation / Beamed Energy Propulsion 2014

Advanced Concepts

Hybrid ablative/electrostatic thruster

optional:

- *+ electrical discharge (electro-thermal)*
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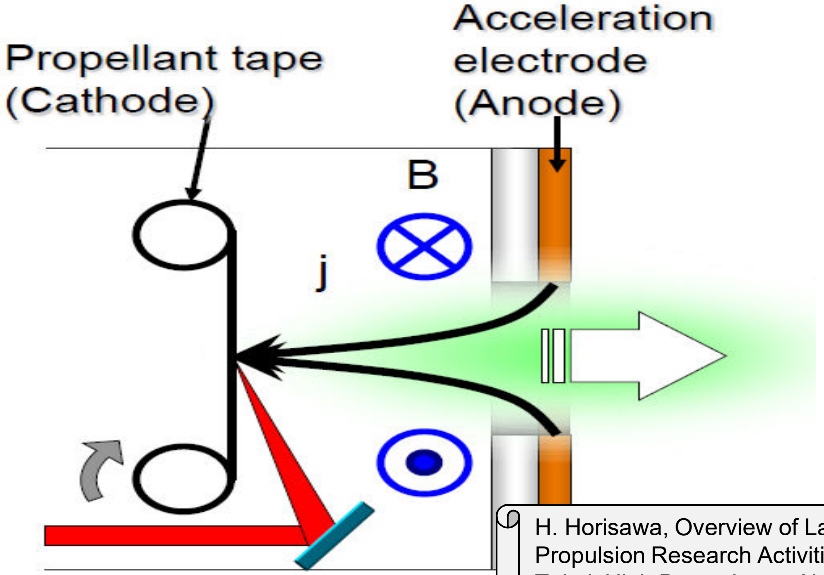
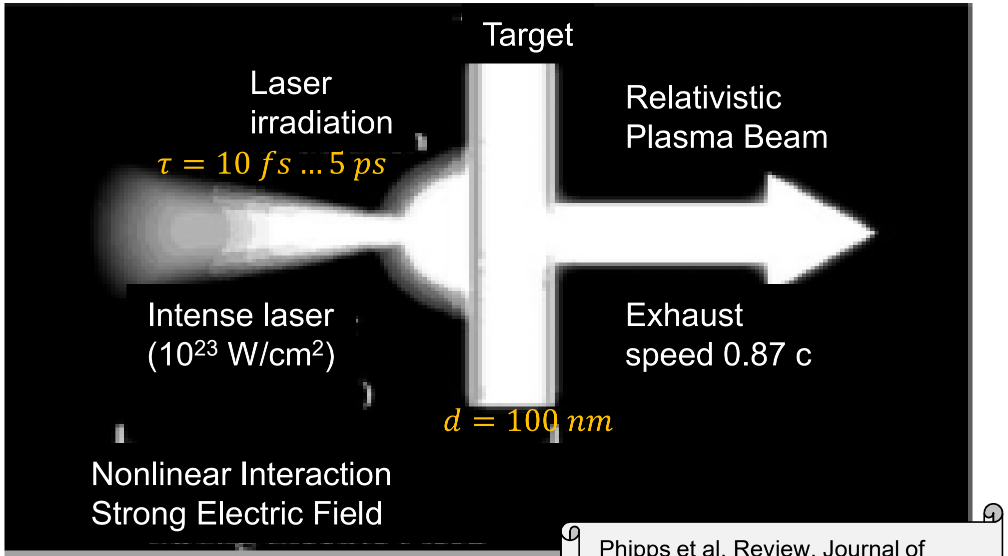


H. Horisawa, Overview of Laser Propulsion Research Activities at Tokai, High Power Laser Ablation / Beamed Energy Propulsion 2014

Relativistic thruster

Coulomb explosion

- Generation of high energetic electrons
- Strong electric field
- Ion gas expansion



Phipps et al, Review, Journal of Propulsion and Power **26**(4): 609-637 (2010), DOI: 10.2514/1.43733

Laser Propulsion

Lectures on Unconventional Space Propulsion

Part 6: Spacecrafts’ Debris Propulsion

IRS Institute of Space Systems, University of Stuttgart
February 10, 2023

Dr. Stefan Scharring

Institute of Technical Physics,
German Aerospace Centre (DLR)

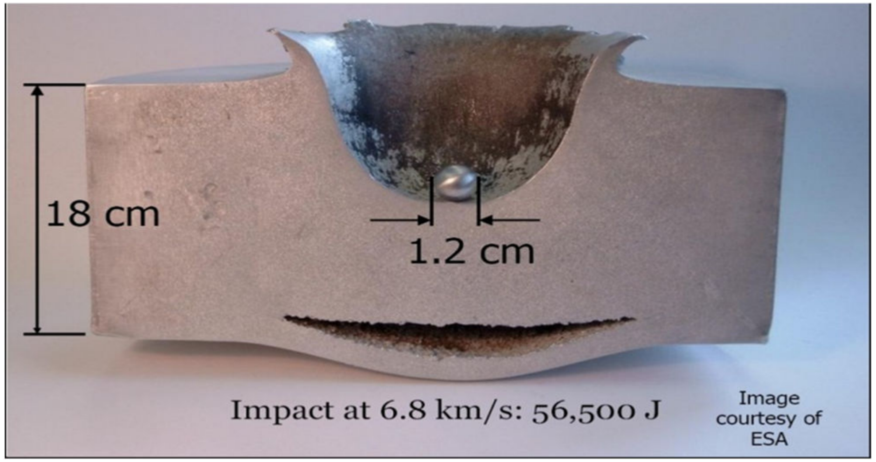
The Space Debris Threat

Objects > 10 cm

- Fragments, Rocket bodies, Defective satellites
- s/c destruction (→ Kessler syndrome)
- Monitoring & obstacle avoidance possible
- 34,000 objects;
  - Public catalogue: 18,800 objects

Objects between 1 cm and 10 cm

- s/c wall penetration (→ loss of functionality)
- Difficult to detect
- 900,000 objects (estimated)



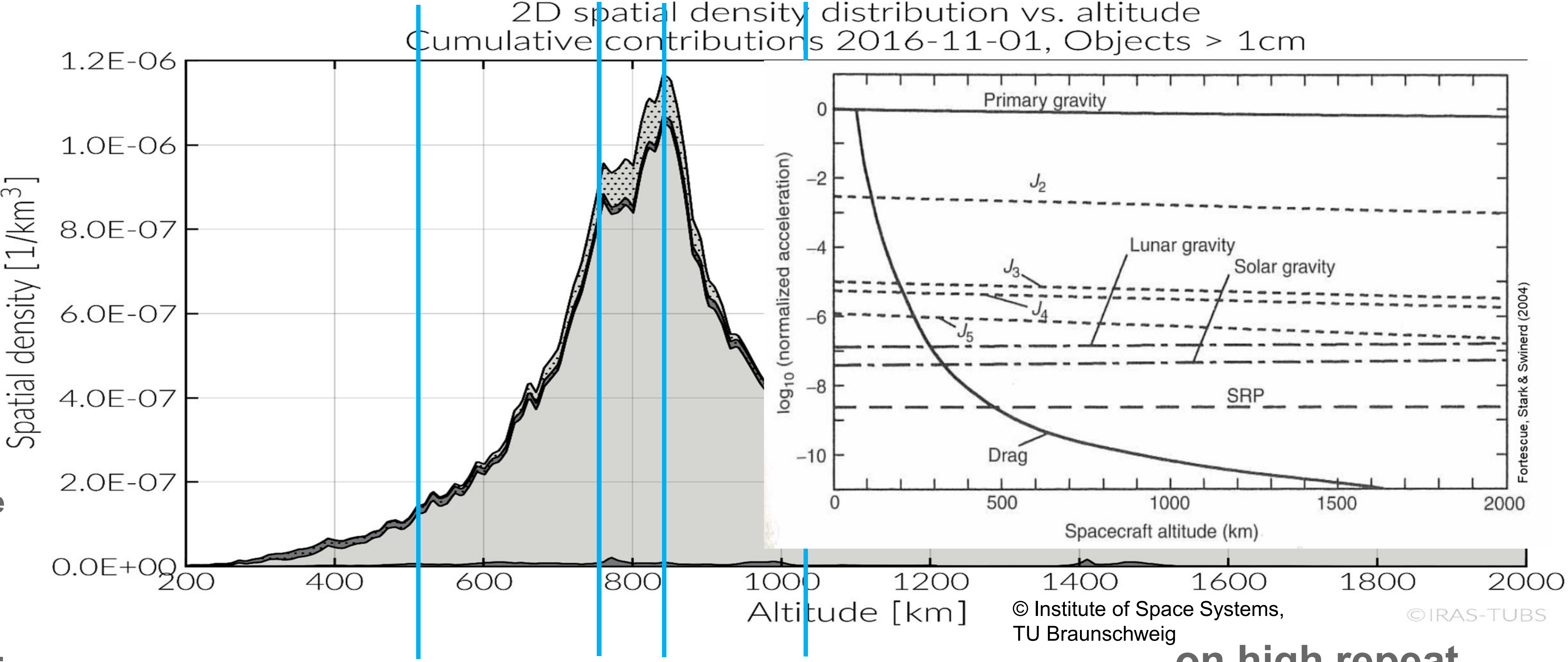
Impact of aluminum sphere in aluminum block @ 6.8 km/s

Objects between 1 mm and 1 cm

- 128,000,000 objects
- s/c damage (→ loss of performance)
- No detection possibilities

In the Low Earth Orbit, everything is for a long time …

Orbital residence time, **years**: 1 25 100 1000



© Institute of Space Systems,
TU Braunschweig

Orbit period, **minutes**: 94 99 101 106

… and there is less space than it may seem.

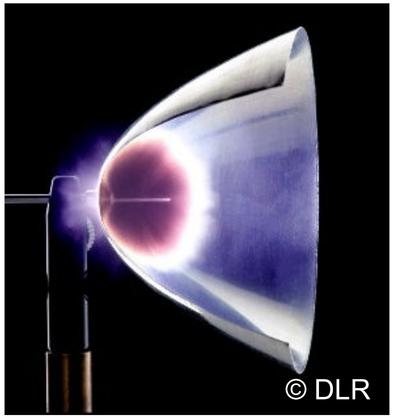
… on high repeat …

Extending Propulsion …

… from „cooperative“ targets …

- Intensity (focused): 3.3 MW / cm^2
- Mechanism: Laser-supported detonation and combustion


© DLR


© DLR

Laser parameters in both cases:

- Average optical power: 7.5 kW
- Pulse duration: ~ 10 µs
- Pulse energy: 150 J
- Pulse repetition rate: 50 Hz
- Beam diameter: 8 cm

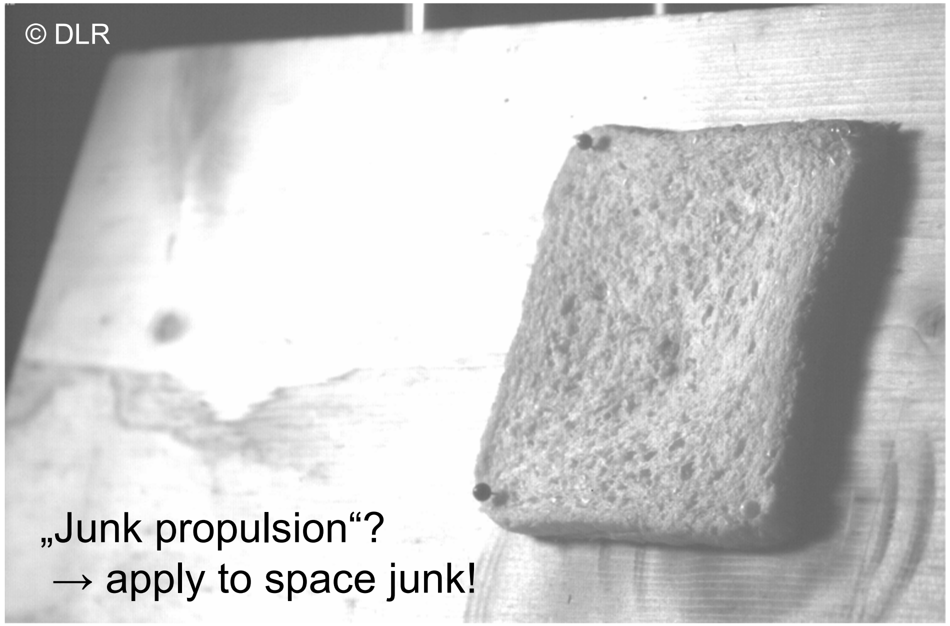
Solar constant: 137 mW / cm^2

… to „uncooperative“ targets

- Intensity (unfocused): 290 kW / cm^2

  Fluence: 3 J/cm^2

  Mechanism: Laser ablation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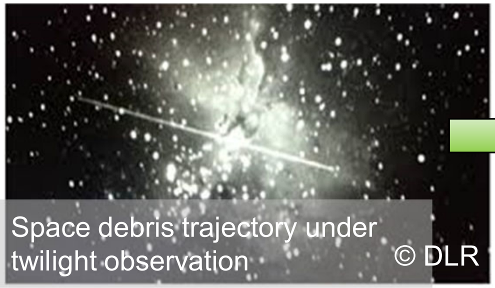
„Junk propulsion“?
→ apply to space junk!

Debris Mitigation Step 1: Collision Avoidance

(Step 0: Avoid Generation of New Debris)

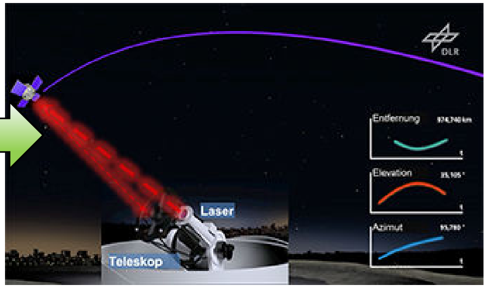
Passive-optical Detection



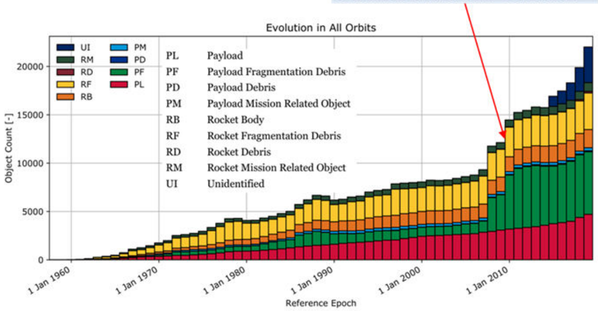
Space debris trajectory under twilight observation

© DLR

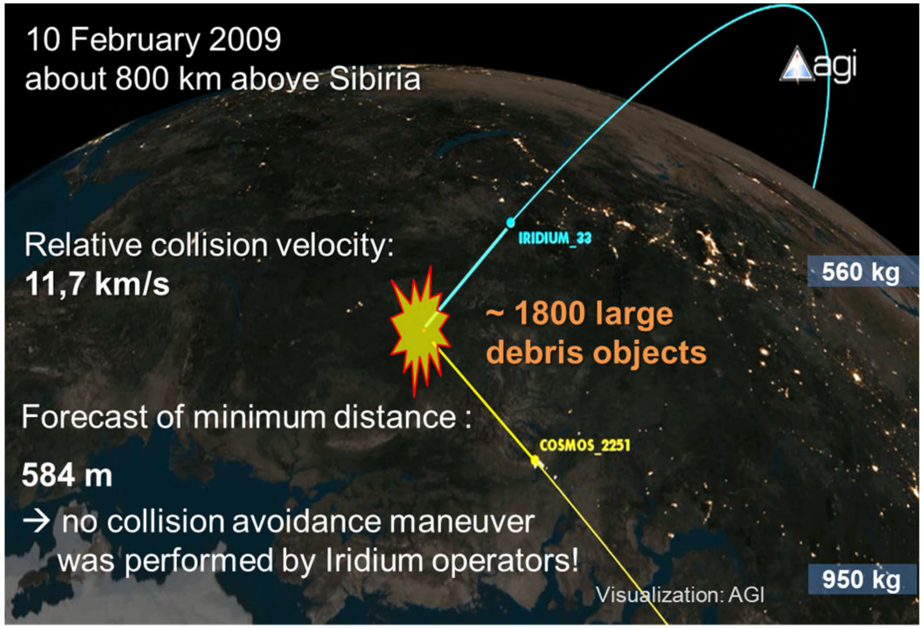
Laser Tracking



Cosmos./.Iridium collision



ESA's Annual Space Environment Report
Issue Date 17 July 2019 Ref GEN-DB-LOG-00271-OPS-SD
ESA Space Debris Office, European Space Operations Centre (ESOC), Darmstadt



10 February 2009
about 800 km above Sibiria

Relative collision velocity:
11,7 km/s

~ 1800 large debris objects

Forecast of minimum distance :
584 m

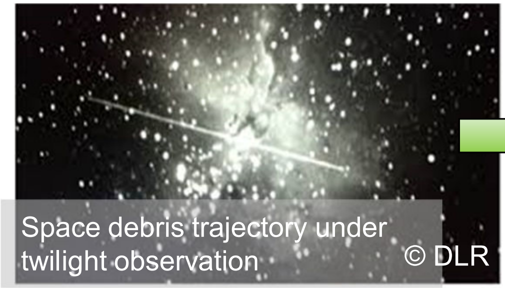
→ no collision avoidance maneuver was performed by Iridium operators!

Visualization: AGI

Debris Mitigation Step 1: Collision Avoidance

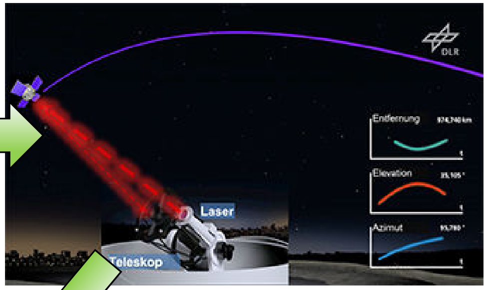
(Step 0: Avoid Generation of New Debris)

Passive-optical Detection

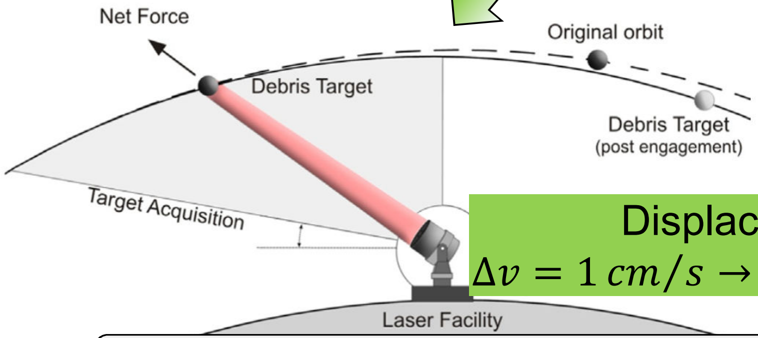


Space debris trajectory under twilight observation © DLR

Laser Tracking



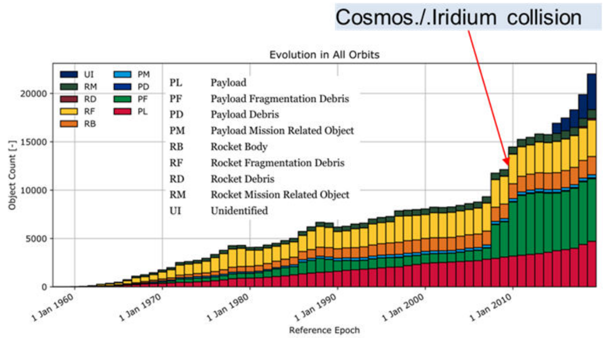
Laser Debris Nudging



Displacement:

$$\Delta v = 1\, cm/s \rightarrow \Delta x = 2.5\ km/d$$

Yang et al., LightForce photon-pressure collision avoidance: Efficiency analysis in the current debris environment and long-term simulation perspective, *Acta Astronautica* **126**: 411 (2016), DOI: 10.1016/j.actaastro.2016.04.032



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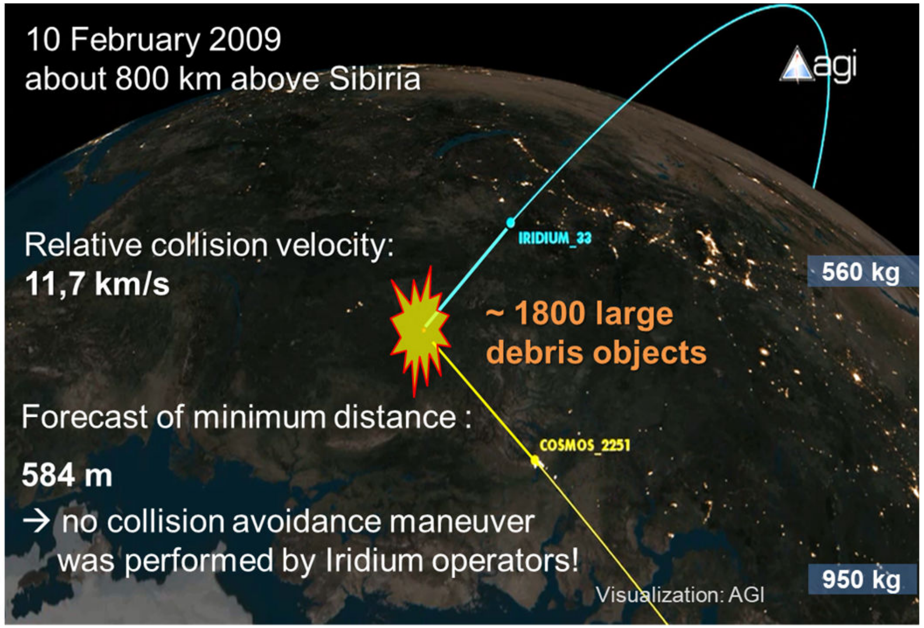

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Relative collision velocity:
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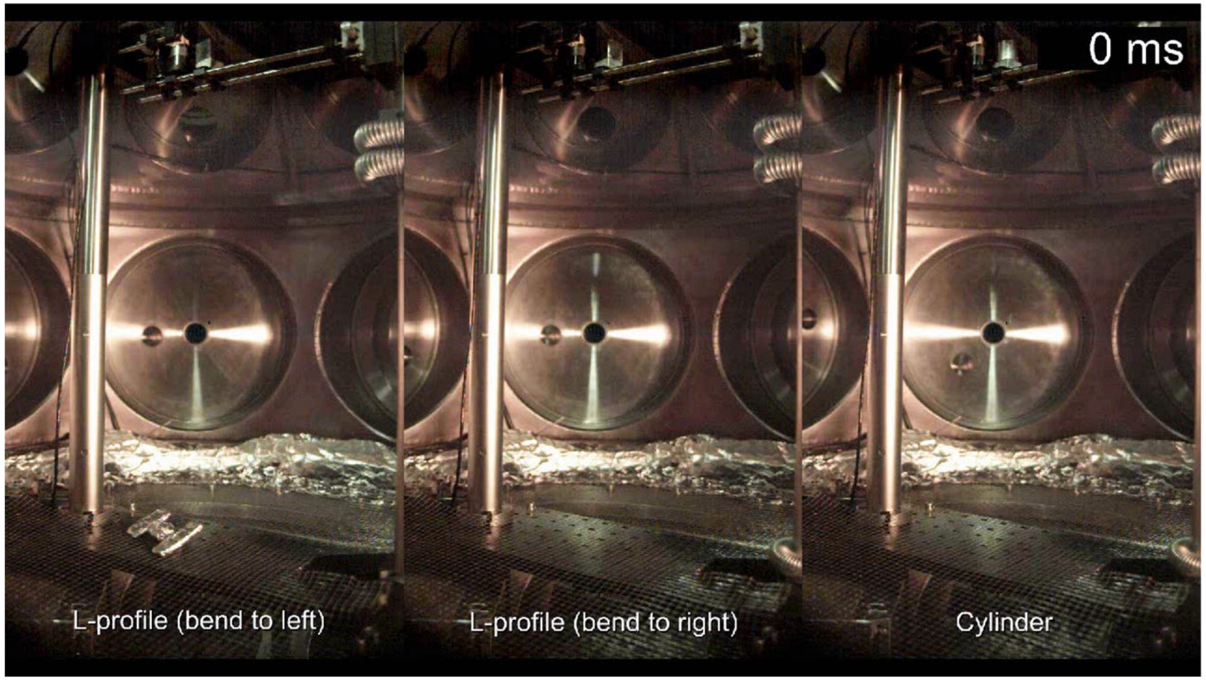
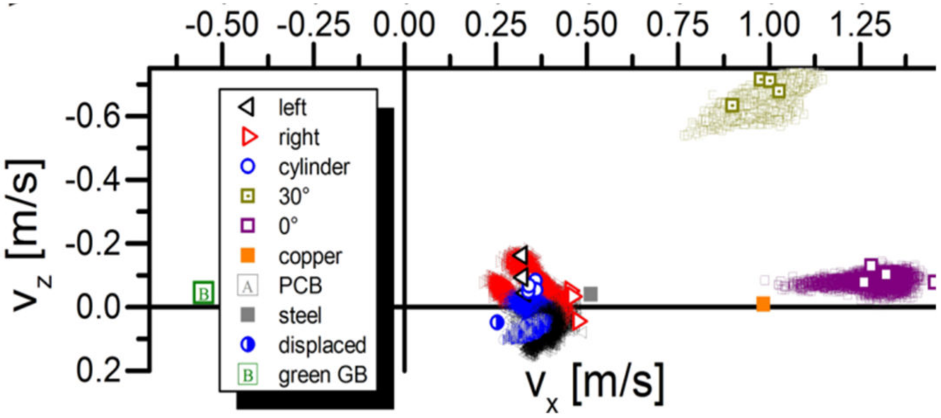
Visualization: AGI

Collision Avoidance by Laser Ablation

Single pulse laser

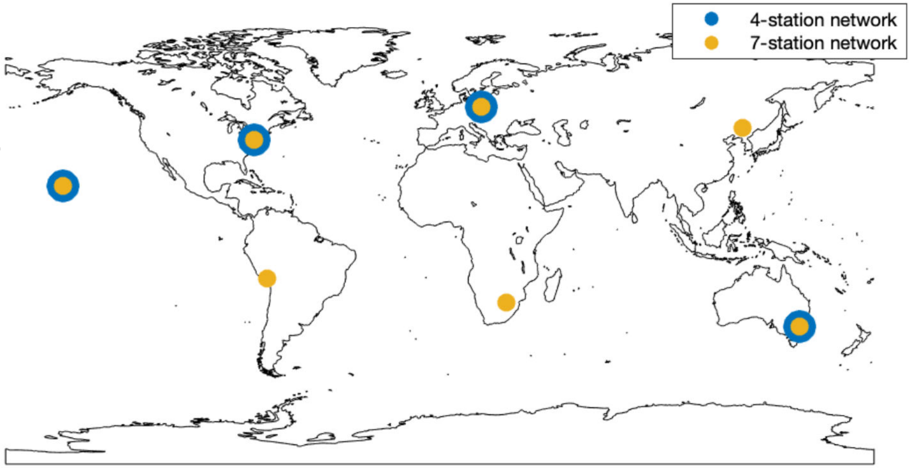




R. Lorbeer et al., Experimental verification of high energy laser-generated impulse for remote laser control of space debris, *Scientific Reports* **8**: 8453 (2018) (open access)
DOI: 10.1038/s41598-018-26336-1

Collision Avoidance by Laser Photon Pressure

Laser Station Network



Single station transit

Irradiation time $\Delta t = 5\ \mathrm{min}$,

Full power absorption

Momentum direction discarded

$$\rightarrow \Delta v = \frac{3.3\ \mu N/kW \cdot P_L[kW] \cdot 300\ s}{m}$$

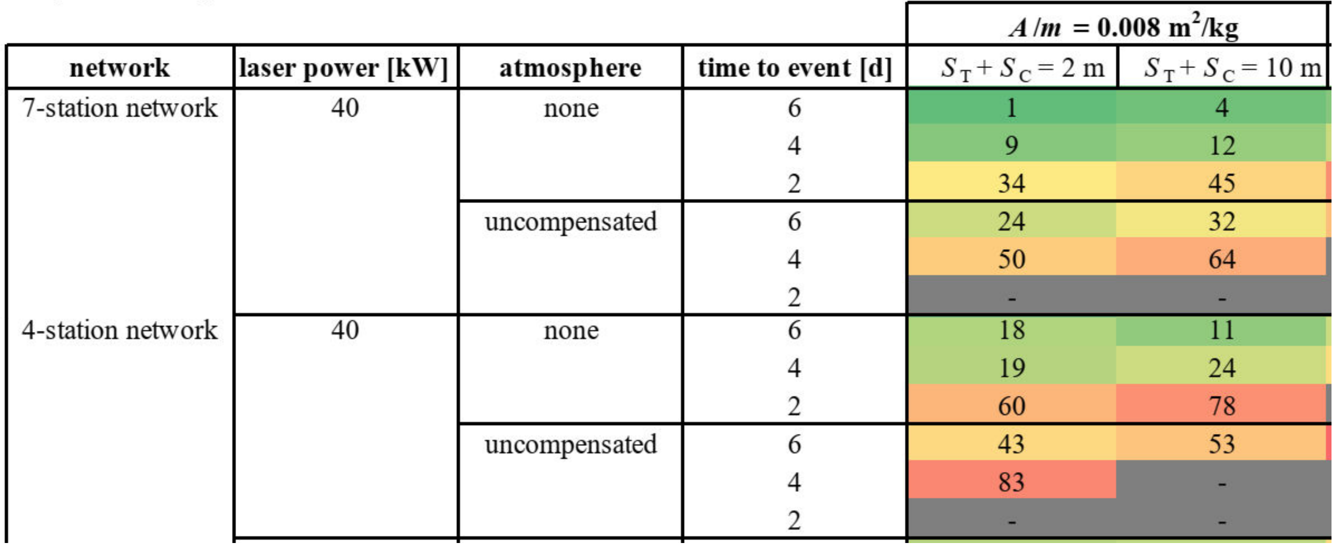
$$= 1\ mm/s \cdot \frac{P_L[kW]}{m[kg]}$$

C. Bamann et al., Analysis of collision avoidance via ground-based laser momentum transfer, *Journal of Space Safety Engineering* **7**(3): 312-317 (2020). DOI: 10.1016/j.jsse.2020.07.023

Required MT success rate [%] for 80 % COLA success

Chaser altitude $h = 850$ km, inclination $i = 65°$, conjunction angle $\psi = 45°$

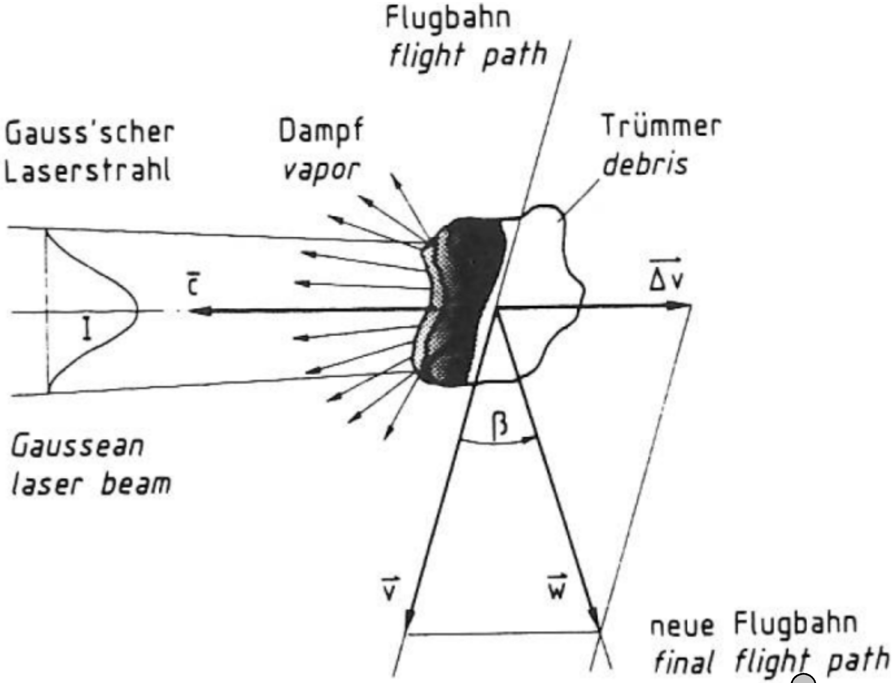
Only chaser nudged via MT



				A/m = 0.008 m^2/kg	
network	**laser power [kW]**	**atmosphere**	**time to event [d]**	$S_T + S_C = 2$ m	$S_T + S_C = 10$ m
7-station network	40	none	6	1	4
			4	9	12
			2	34	45
		uncompensated	6	24	32
			4	50	64
			2	-	-
4-station network	40	none	6	18	11
			4	19	24
			2	60	78
		uncompensated	6	43	53
			4	83	-
			2	-	-

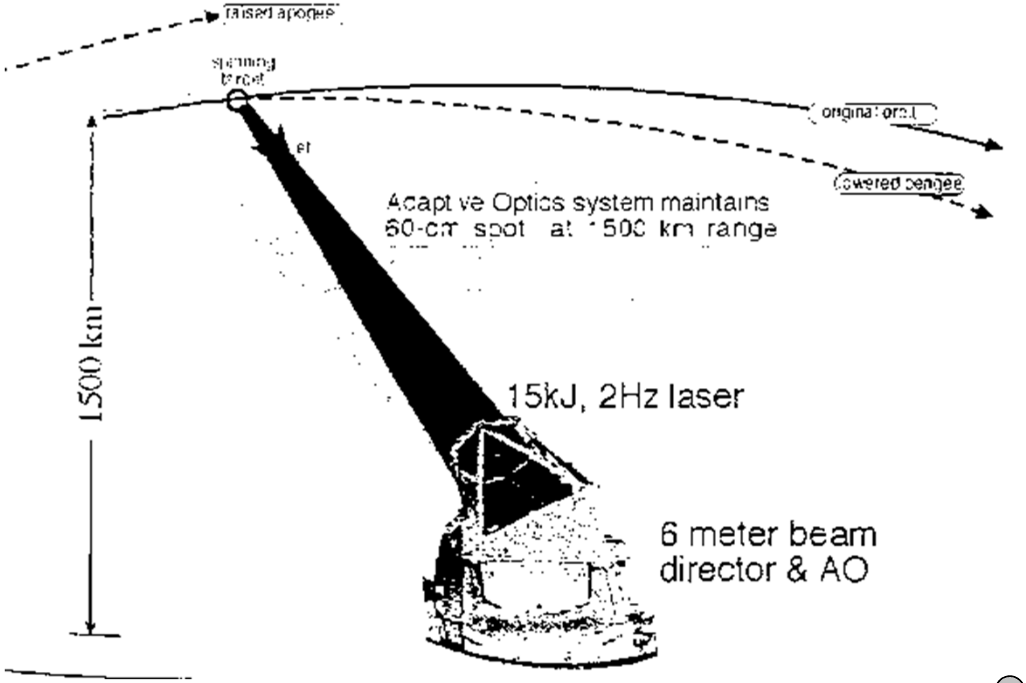
The Early Concepts of Laser-based Space Debris Removal (LDR)

Space-based LDR (Wolfgang Schall, 1991)



W. Schall, "Orbital debris removal by laser radiation," *Acta Astronautica* **24**: 343–351 (1991). doi:10.1016/0094-5765(91)90184-7

Earth-based LDR (Claude R. Phipps, 1996)

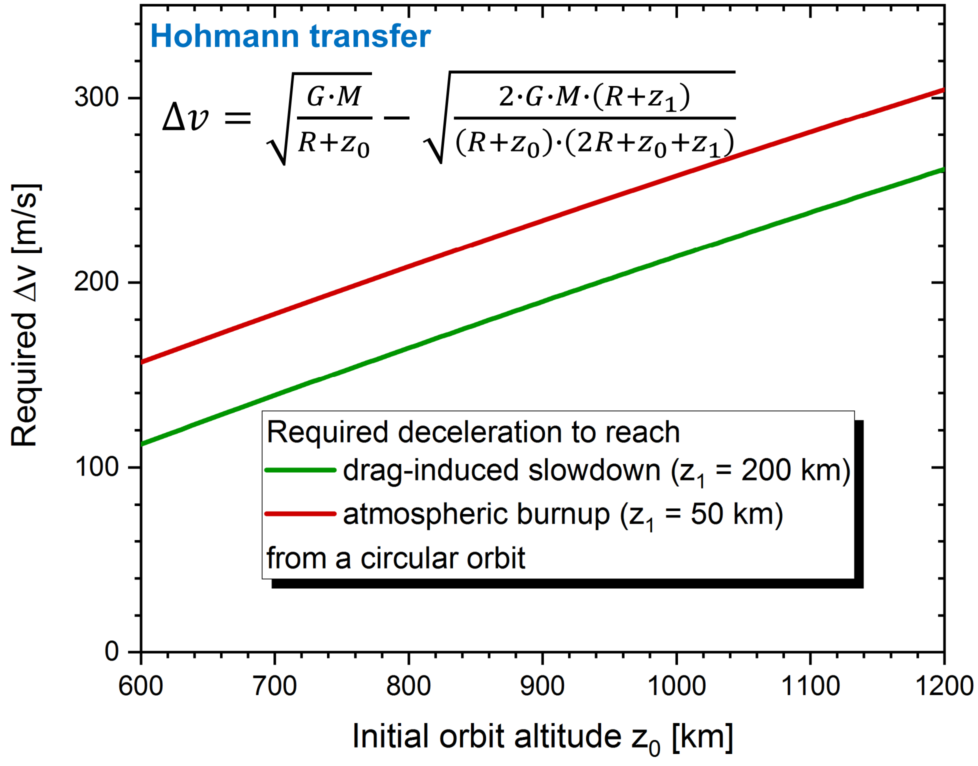


C.R. Phipps et al., „Orion: Clearing Near-Earth Space Debris Using a 20 kW, 530 nm, Earth-Based, Repetitively Pulsed Laser," *Laser and Particle Beams* **14**(1): 1-44 (1996)

Astrodynamical Options for Space Debris Orbit Modification

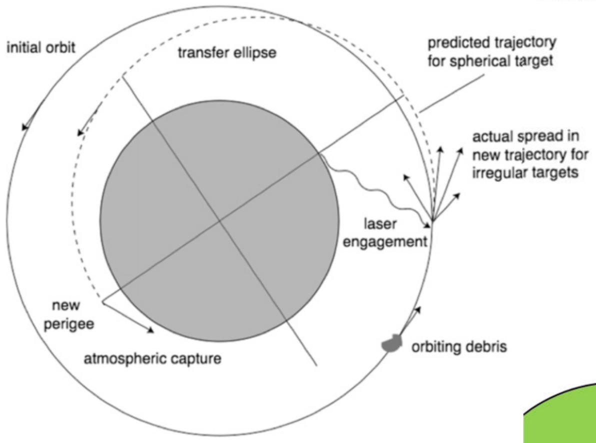
Target deceleration for atmospheric burn-up

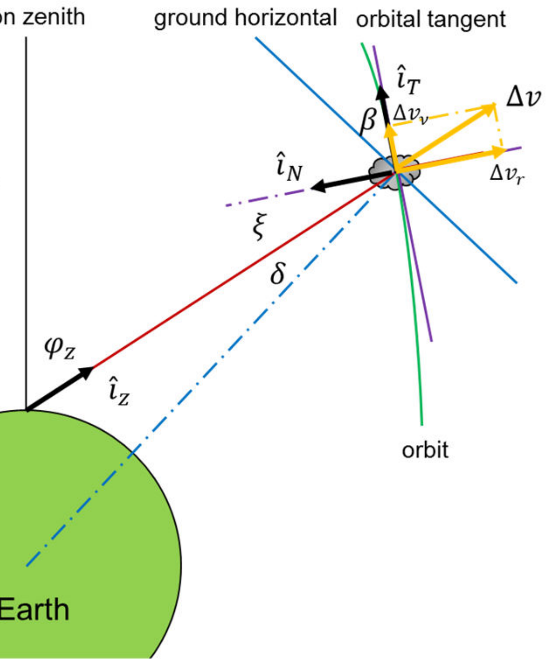
Perigee lowering



In-track / radial momentum transfer

Apogee lift + perigee lowering





$$H = \frac{v_v^2 + v_r^2}{2} - \frac{G \cdot M}{r}$$

$$\Delta a = \frac{G \cdot M}{2H^2} \Delta H$$

$$\Delta r_p = (1 - \varepsilon)\Delta a - a\Delta\varepsilon$$

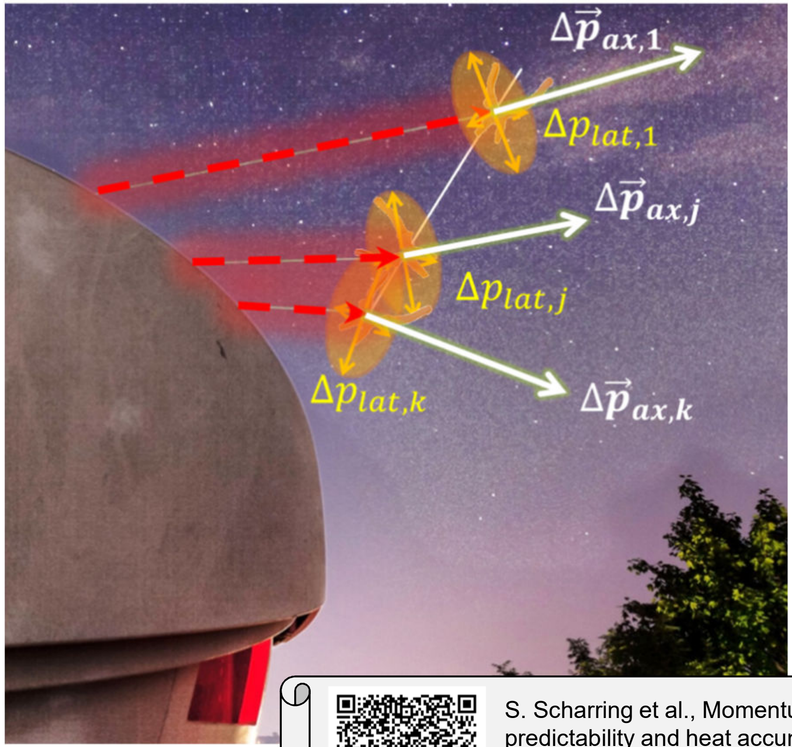
$$\Delta r_a = (1 + \varepsilon)\Delta a + a\Delta\varepsilon$$

adapted from:

C.R. Phipps et al., Removing orbital debris with lasers, Advances in Space Research **49**: 1283 (2012)
doi:10.1016/j.asr.2012.02.003

Debris Removal: Constraints of Laser-Matter Interaction

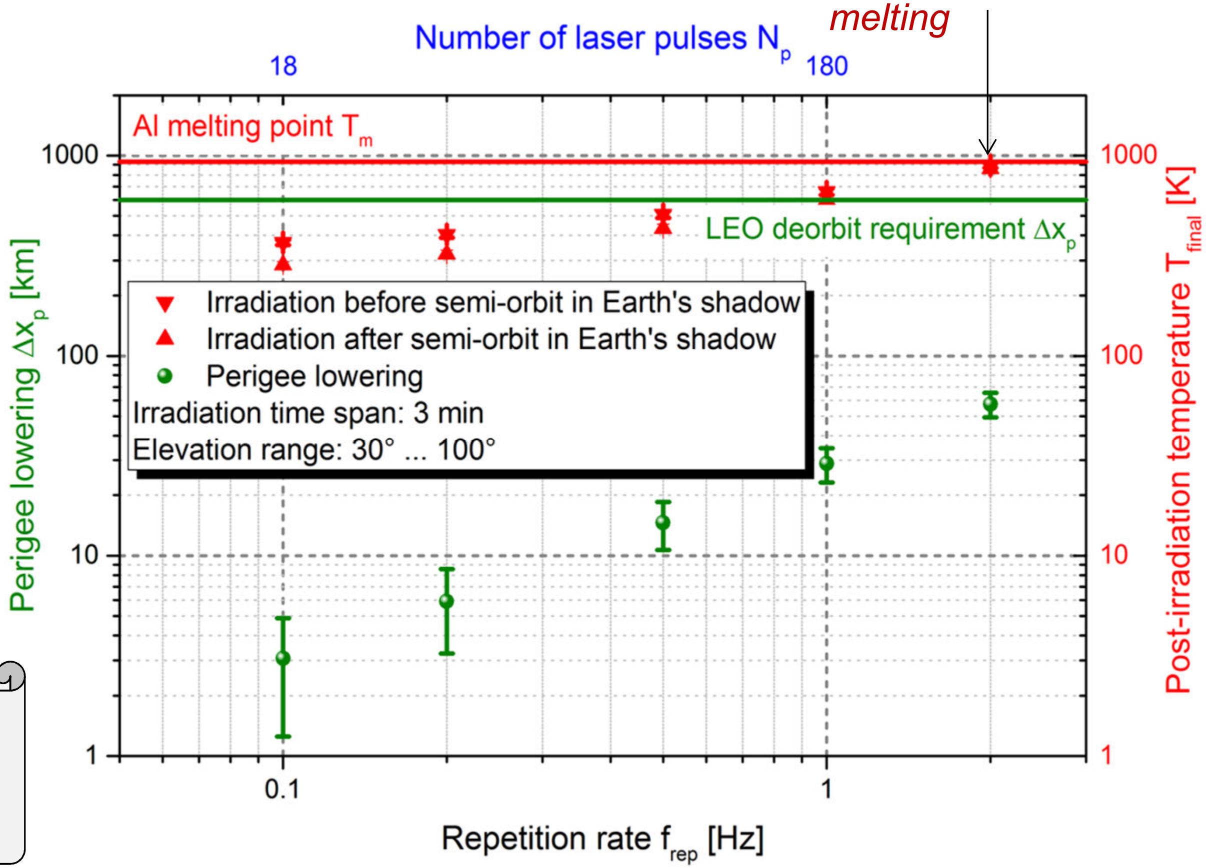
Momentum uncertainty



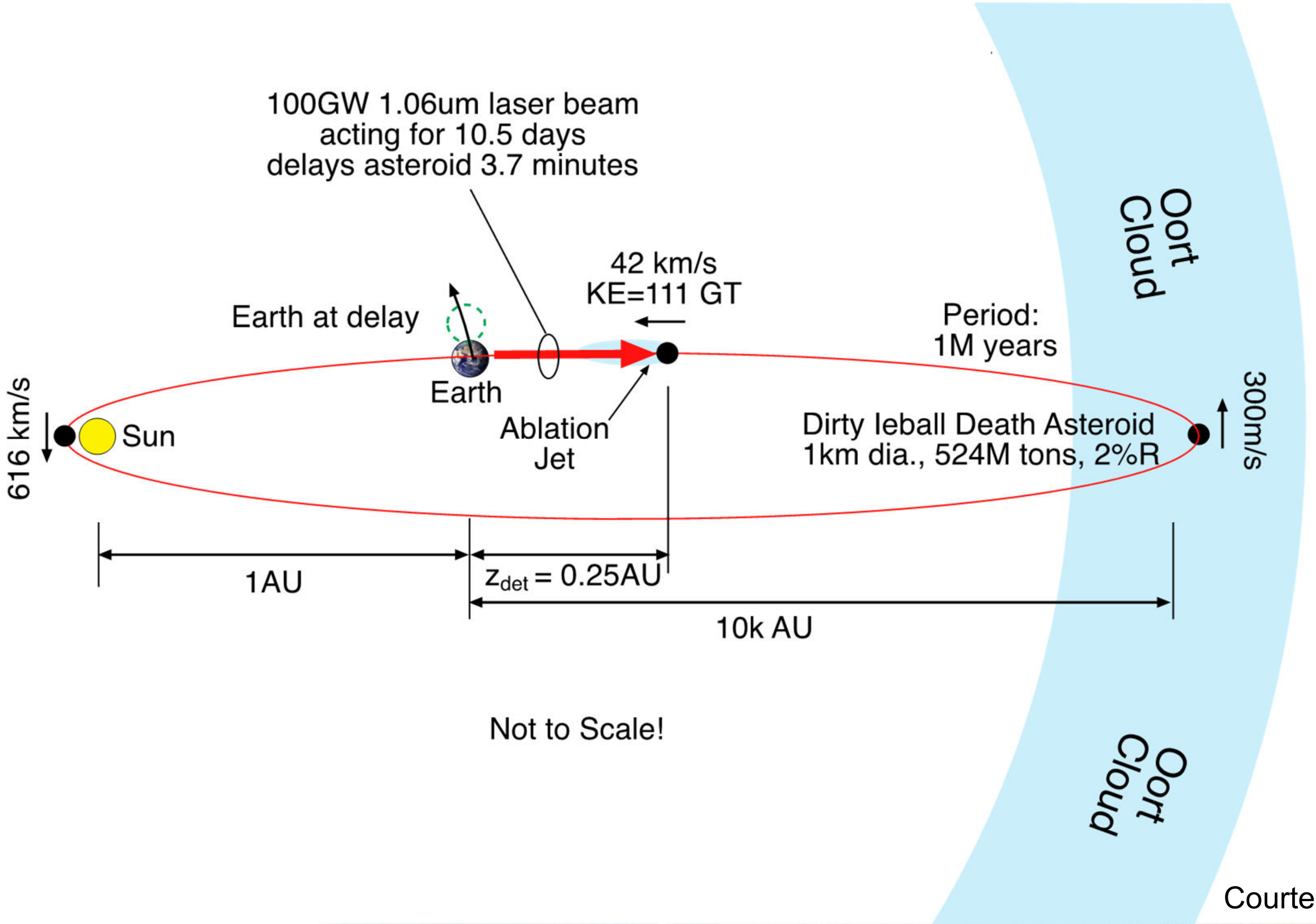
S. Scharring et al., Momentum predictability and heat accumulation in laser-based space debris removal, Opt. Eng. 58(1): 011004 (2018), 10.1117/1.OE.58.1.011004

Heating

Multi-pass irradiation required to prevent melting



Debris Propulsion Outlook: Deflection of Near-Earth Objects (NEO)



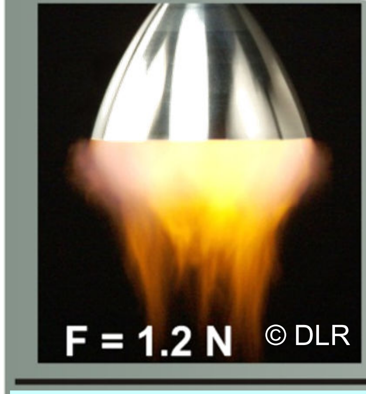
Not to Scale!

Courtesy of Dr. Claude Phipps

Summary: Laser Power Scaling vs. Applications

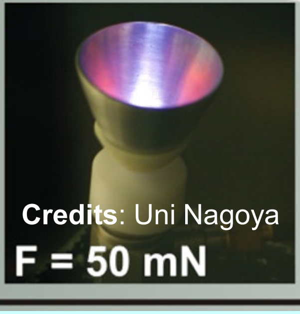
→ **What can be achieved in our lifetime?**

$$c_m = \frac{\text{thrust}}{\text{laser power}} =$$



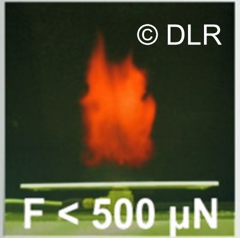
Long-term potential
MW level

=



Mid-term application
kW level

=

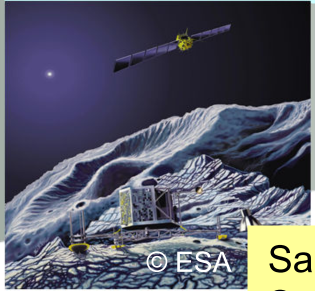


Short-term options
W level

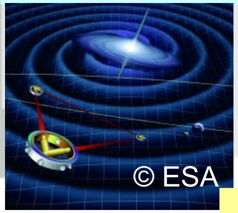
Very-long-term vision
GW level

Photon propulsion
NEO deflection

Lightcraft
Debris removal



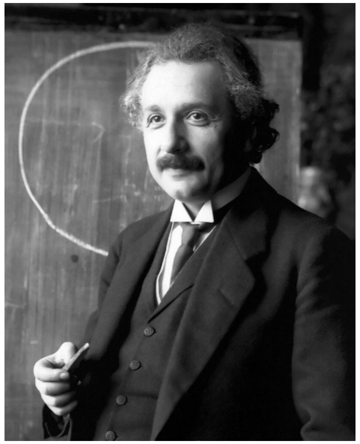
Sample return
Space logistics
Debris nudging



Micropropulsion
Laser photovoltaics

… What has been achieved in *their* lifetime?

Albert Einstein (1879 – 1955)



- 1916: Stimulated emission of light postulated
- Minor technological relevance (first MASER emission, 1954)
- Albert Einstein dies 1955.
- The success story of lasers: not anticipated
  - First Ruby laser: 1960
  - ….
  - ….

Stephen Hawking (1942 – 2018)

- 1963: ALS disease diagnosed; predicted lifetime: + 2 years
- 1966: PhD at Cambridge University
- Theory of singularities, quantum gravitation
- 1988: A Brief History of Time
- Stephen Hawking dies 2018.

Unconventional ideas foster unconventional propulsion

- *Breaking the rules is the first step to innovation*
- *How does a caterpillar evolve to a butterfly?*
  Lesson 1: Don‘t step upon.
- *Practise First Aid for ideas: Don‘t critize, improve.*
- *„Doesn‘t work!“ often just means „Didn‘t understand“*
- *Leaving the known always requires exceptional power.*
- *Prior to success there is not only readiness for failure,*
  but in fact failure itself.
- *Old ideas always stand in the way of new ideas.*
- *Everyone has got a prejudice about everything.*
- *Have you already calculated the costs of not risking anything?*

Martin Gaedt, Rock your idea, Murmann Publishing (2016)

Watch this lecture and more at:

Lasers and Space

Thank you for your kind attention

„Technology Vision Checkboxes“

✓ **Feasible?**

✓ **Reasonable?**

✓ **Desirable?**

→ **Already realized – in the future**

→ **Be part of its development – now**