Power Beaming Applications for High Efficiency Lasers

C.R. Phipps, Ph.D.

Photonic Associates LLC, 200A Ojo de la Vaca Road
Santa Fe, New Mexico USA 87508
Phone/fax: +1-505-466-3877, mobile: +1-215-358-4360
crphipps@aol.com

Christophe Bonnal and Frédéric Masson

CNES, Direction des Lanceurs, 52 rue Jacques Hilairet, 75612 Paris Cedex, France
christophe.bonnal@cnes.fr; frederic.masson@cnes.fr

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Laser space propulsion

Outline

- Introduction to authors
- Purpose
- What is laser ablation propulsion?
- Why is it useful compared to pure photon propulsion?
- Terminolgy and relationships
- For FEL ablation, limited data compared to that for pulsed lasers
- Shortest efficient wavelength is best in space
- Applications: pushing rocks, laser rockets but not space debris removal (SDR)
- Issues: thermal coupling, mechanical coupling
- Exciting prospects: what can be done with 0.1 – 1MW
- Conclusions

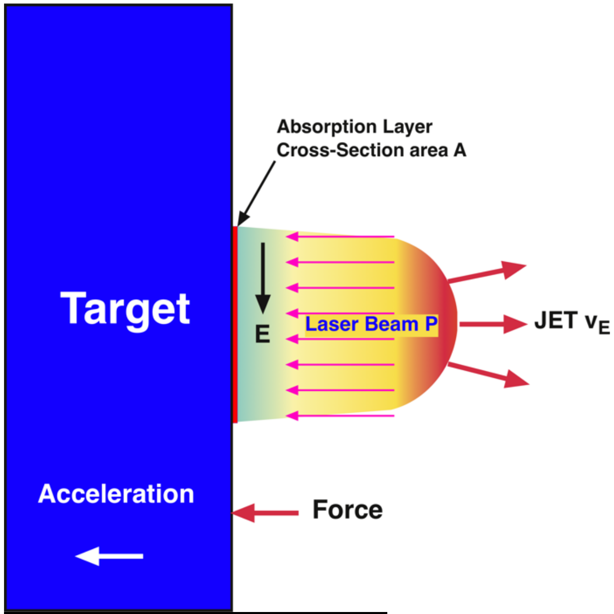
Authors

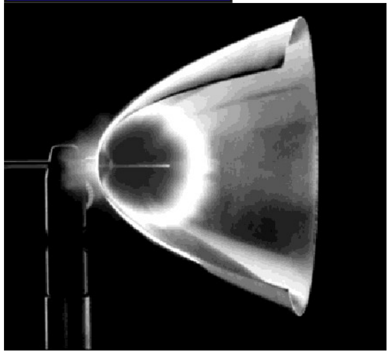
- C. Phipps: Ph.D. Stanford in 1972, specializing in plasma physics, laser-materials interactions
- Worked in laser programs at LLNL, LANL
- Formed PALLC in 1995: Santa Fe High Tech consulting company devoted to peaceful applications in space
- Invented space debris removal with groundbased pulsed lasers in 1995
- Now, working intensively on laser driven propulsion
- C. Bonnal is chief engineer of the launcher directorate at CNES in Paris
- F. Masson is in charge of advanced concepts for space transportation at CNES

Purpose of this talk

- At PALLC, most of our history working with pulsed laser ablation propulsion
  - Space debris reëntry, collision avoidance, laser rockets…
- We judged that CW (continuous) lasers could only produce splashing with low velocity “specific impulse,” $I_{sp}= v_E/g_o$, and low ablation efficiency $\eta_{AB}=C_m v_E$
  - This could still be true!
  - $C_m = p/I$ is the momentum coupling coefficient, units N/W of incident laser light
- Our applications require average power in the tens, hundreds of kW, or MW
- Largest available pulsed laser average power is 1kW; FEL’s could create MW
- Stimulated by Prof. Lubin’s work at UCSB asteroid deflection, curiosity at LANL about FEL’s, and the topic of this workshop, we took a second look
- Despite uncertainties, we will sketch some posible FEL applications in this talk

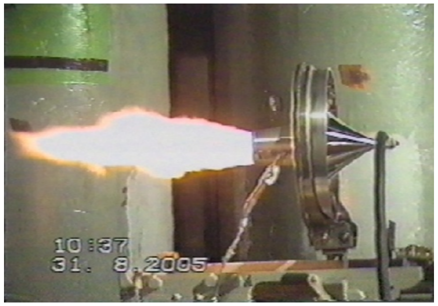
What is laser ablation propulsion?





"Bohn Bell" parabola4) (DLR)

- A form of electric propulsion that uses laser ablation of a surface to make a high speed jet1)
- Why is it useful?
  - ➢ Remote propulsion at speed of light
  - ➢ Flexibility. Gives v_E >> chemical jets
  - ➢ Tiny impulse bits with pulses
  - ➢ C_m is 10k times larger than that of pure photons
- Record: 2N thrust2), 72m altitude3)



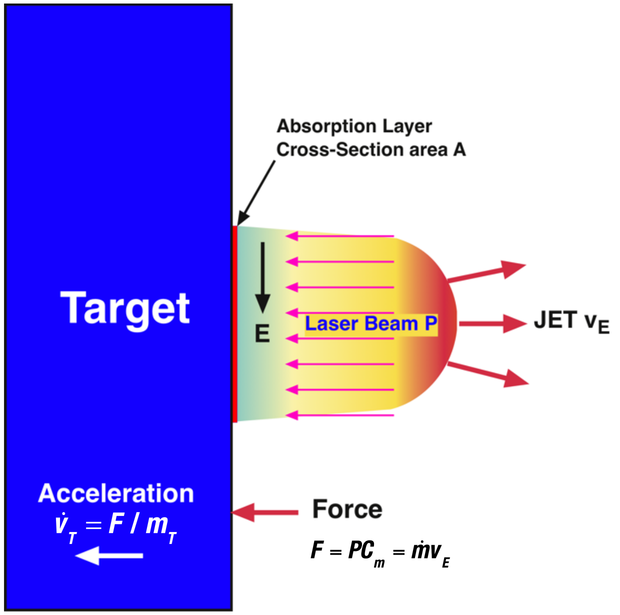
- Efficiency always better for pure electric propulsion (Ion, HET, FEEP)

1) A. Kantrowitz, "Propulsion to orbit by groundbased lasers," *Astro. and Aero.* **10**, No.5 (1972)
2) L. Myrabo, et al, "Ground and flight tests of a laser propelled vehicle," AIAA paper 98-1001, 36th AIAA Aerospace Science Meting and Exhibit, Reno, NV 12-15 Jan. 1998
3) Y. Rezunkov, et al., "Performance characteristics of laser propulsion engine operated both in CW and repetitively-pulsed modes," AIP Conference Proceedings **830** Ameerican Institute of Physics pp. 3-12 (2006)
4) W. Schall, et al., "Lightcraft impulse measurements under vacuum," EOARD Report FA8655-02-M4017 (2002)

Pulsed or CW laser relationships

• Pressure	$p = C_m I$
• Force	$F = PC_m = \dot{m} v_E$
• Ablation efficiency	$\eta_{AB} = (\dot{m} v_E^2 / (2P) = C_m I_{sp} g_o / 2$
• Fuel use rate	$\dot{m} = 2P\eta_{AB} / (g_o I_{sp})^2 = PC_m^2 / (2\eta_{AB})$
• Recession velocity	$v_r = \dot{m} / (A\rho_T) = IC_m^2 / (2\rho_T \eta_{AB})$
• Rocket equation: with Δv is total change of payload velocity, m/M is delivered mass fraction	$^*m / M = \exp(-C_{mo} \Delta v / 2)$

* Expression 5) shows that, if C_{mo} is sufficiently <u>small</u>, almost any space mission is possible with enough laser power P_o to overcome gravity



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5) C. Phipps, et al., "Transfers from Earth to LEO and LEO to Interplanetary Space using Lasers," https://doi.org/10.1016/j.actaastro.2018.02.018 (2018)

We can normalize to unit η_{AB}

- If ablation efficiency is not known, we can still study propulsion possibilities
- Take

$$P = P_o / \eta_{AB}$$

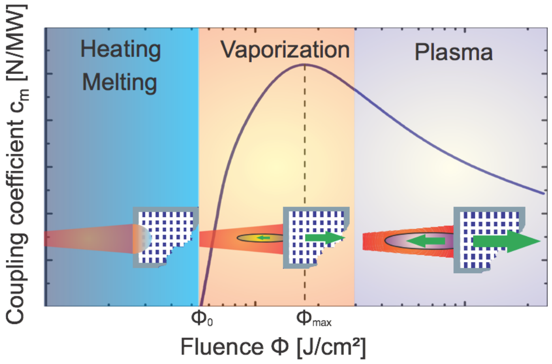
$$C_m = C_{mo} \eta_{AB}$$

$$F = C_{mo} P_o$$

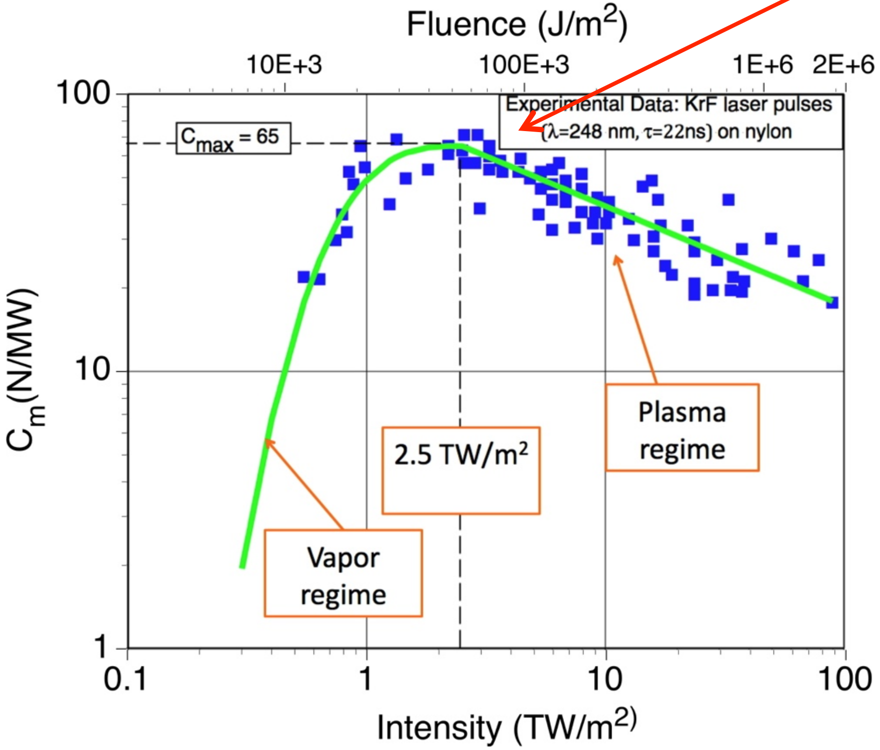
- Then fuel usage is constant $\dot{m} = P_o C_{mo}^2 / 2$
- As is fuel lifetime
  (Large at low C_{mo}) $M / \dot{m} = 2M / (P_o C_{mo}^2)$

Optima: maximum C_m

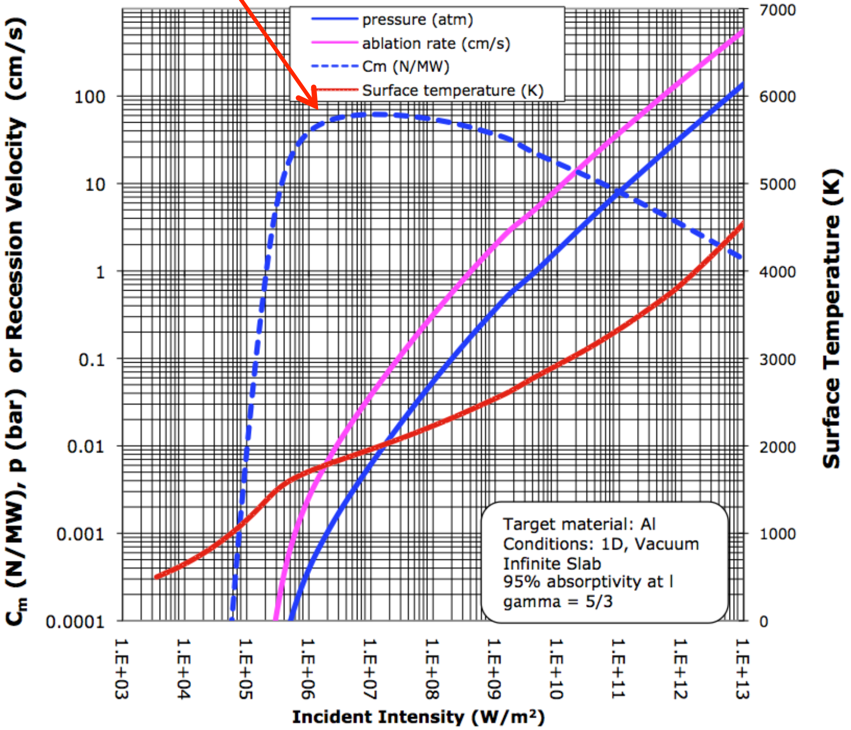
Same behavior for pulsed or CW: plasma onset6) limits max C_m



Pulsed (nylon)6)



CW (Al)7)



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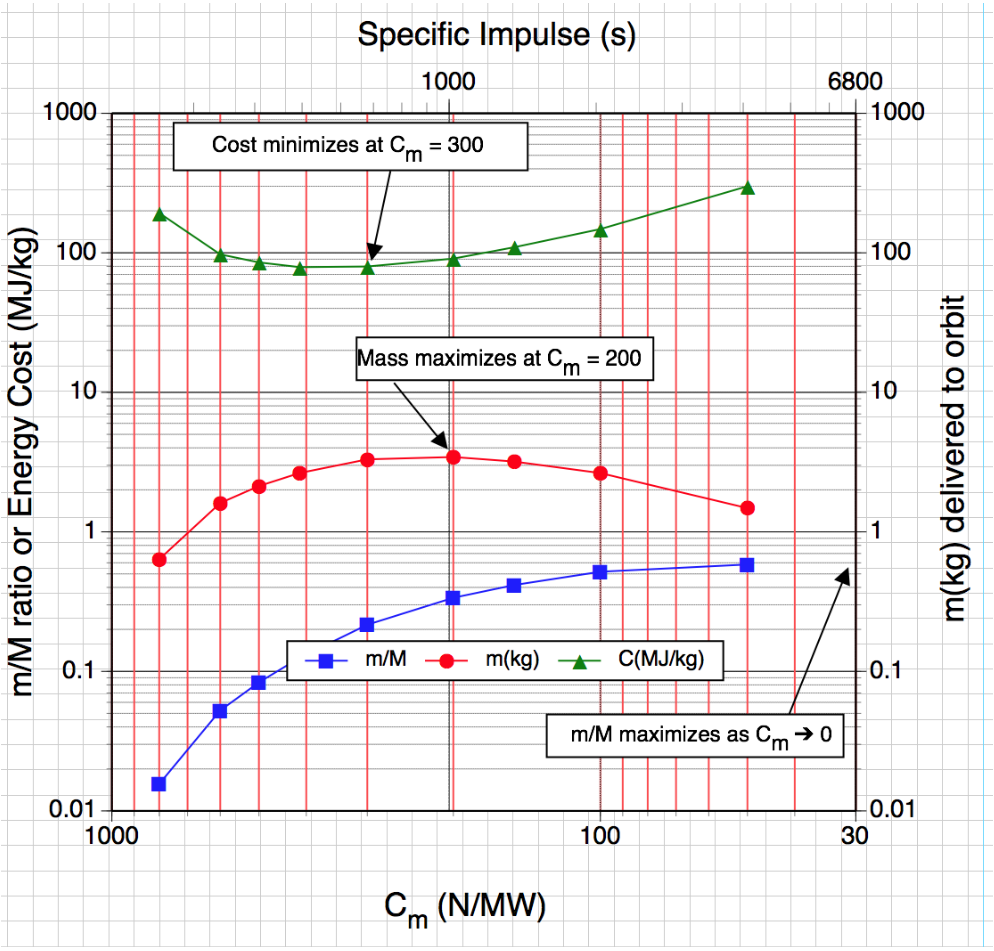
6) C. Phipps, et al., "Laser impulse coupling measurements at 400fs and 80ps using the LULI facility at 1057nm wavelength," *J. Appl. Phys.*, **122**, 193103 (2017)

7) C. Phipps, calculations with CLAUSIUS code show C_m=15N/MW with 10MW/m² on Al (2018)

Other optima: maximum m/M

- Simulations show[8)] that mass, mass ratio and cost from ground to LEO optimize at different values of the coupling coefficient C_m.
- Maximum m/M ratio at $C_m \rightarrow 0$, $I_{sp} \rightarrow \infty$, $P \rightarrow \infty$


Cost minimizes at C_m = 300

Mass maximizes at C_m = 200

m/M maximizes as $C_m \rightarrow 0$

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8) C. Phipps, et al., “Optimum Parameters for Laser-launching Objects into Low Earth Orbit,” J. Laser and Particle Beams, **18** (4), 661-695 (2000)

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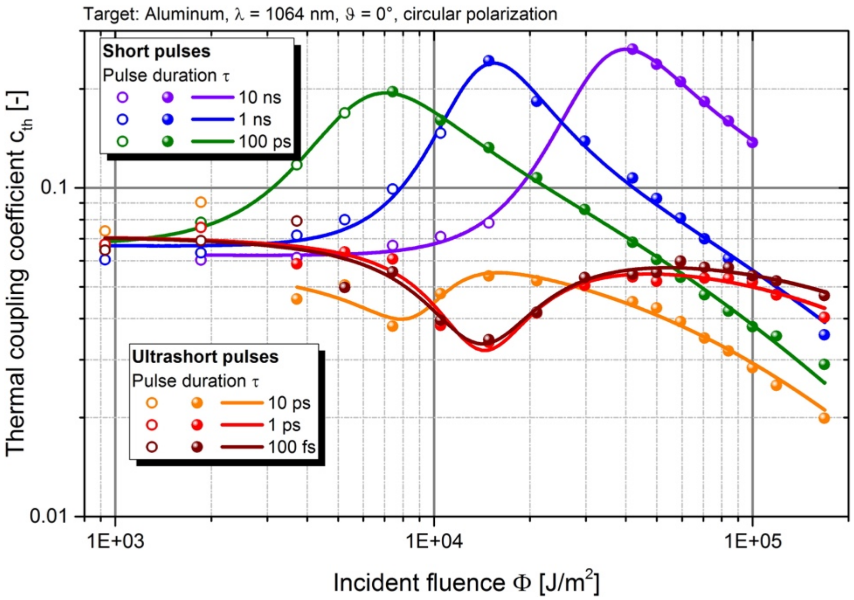
Laser space propulsion

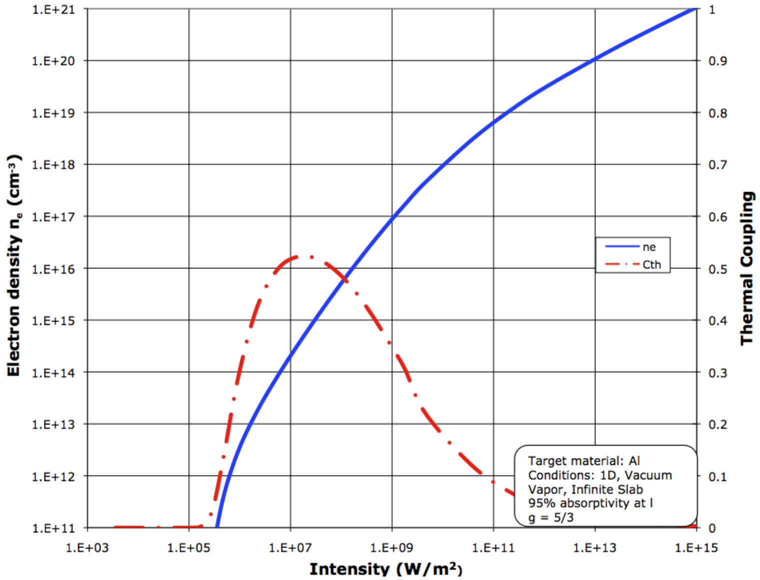
Thermal coupling a critical factor

- C_{th} not measured
  - ➢ Simulations predict pulsed C_{th} as small as 2% at 100ps[9)]
  - ➢ Must be this small to avoid melting target after 100k pulses in our applications!
  - ➢ Similar considerations apply for CW

Pulsed[9)]



CW[7)]



7) C. Phipps, et al., calculations (2018)

9) S. Scharring, et al., “Numerical simulations on laser-ablative micropropulsion with short and ultrashort laser pulses,” *Trans. Jpn. Soc. Aeronaut. Space Sci.* **14**, pp. Pb_69–Pb_75 (2016).

Pulsed vacuum data

- Pulsed ablation efficiency:
  - Tons of data exist for ns-ms pulses
  - Example: with 4ns pulses, we measured η_{AB} = 100% on gold[10)]
  - Need 80ps to minimize C_{th} (shorter is difficult)
    - » η_{AB} not measured at 80ps
  - Practical requirements
    - » Need 100J/pulse to create plasma at 1000km with a 3m dia. mirror and fs-ps pulses
    - » Need 10-1000kW time average power for useful work
  - fs-pulse lasers not powerful: 30J/pulse, 300W (ELI)
- Pulsed coupling coefficient:
  - $C_m \le$ 770N/MW with 80ps pulses on polyoxymethylene[6)] (POM) [Table 4]
  - C_m = 30N/MW on Al

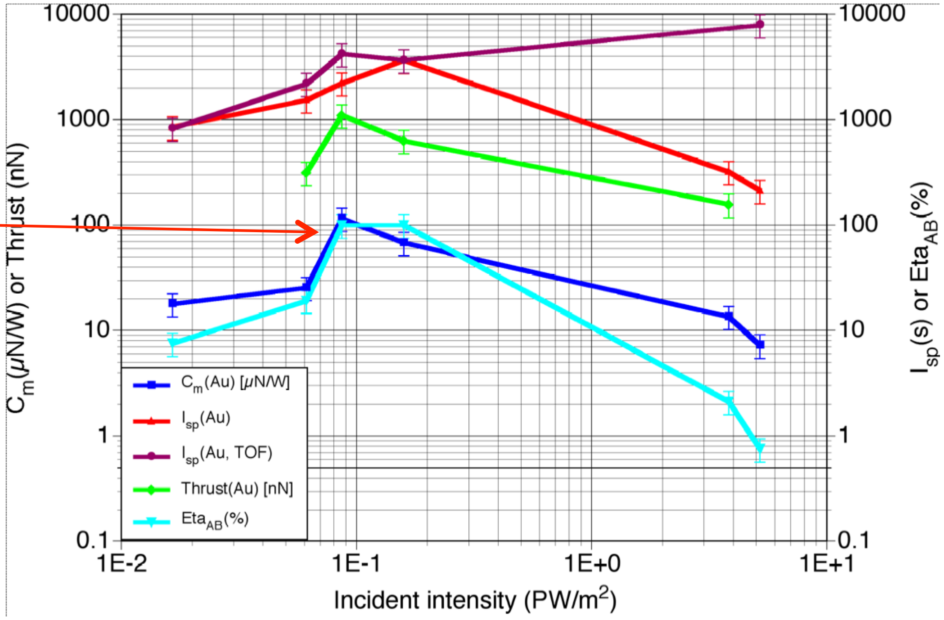


TABLE IV. Optimum coupling results for Al and POM at 1057 nm.

Material→	Al		POM	
Pulsewidth	C_m(N/MW)	Φ(kJ/m²)	C_m(N/MW)	Φ(kJ/m²)
400 fs	30±5	50±10	125±12	32±6
80 ps	28±5	30±6	773±70	40±8

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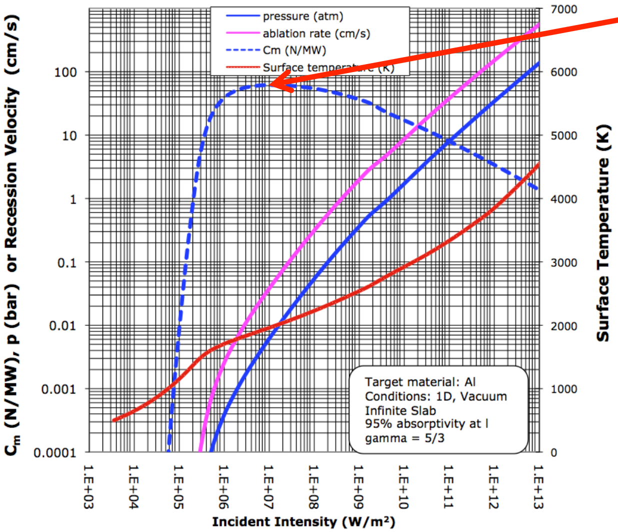
6) C. Phipps, et al., "Laser impulse coupling measurements .." (2017)

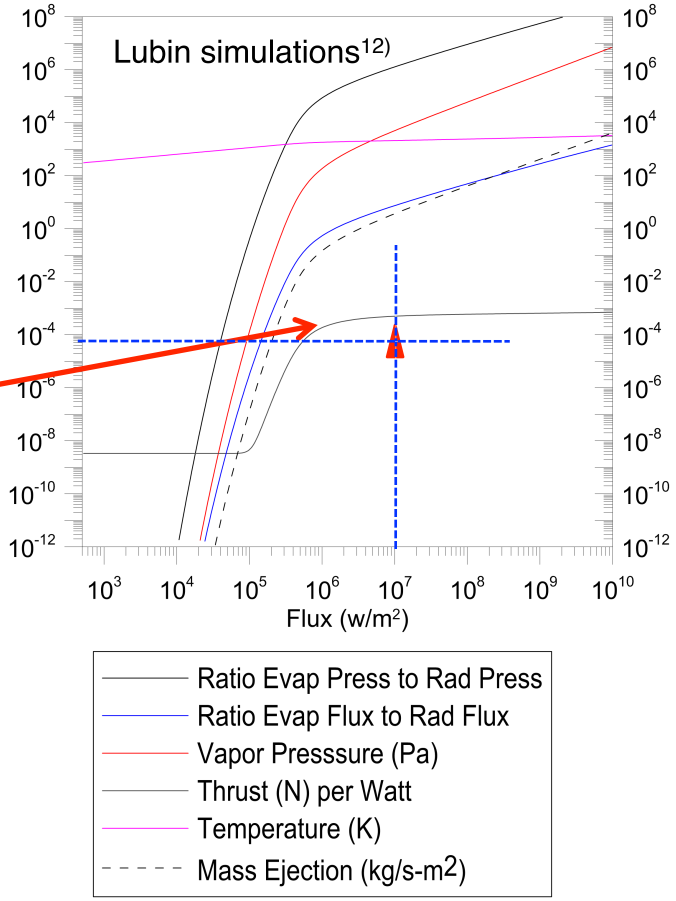
10) C. Phipps, et al., "3ks specific impulse with a ns-pulse laser microthruster," paper IEPC 319, 29th International Electric Propulsion Conference, Princeton (2005)

CW ablation data

- No published vacuum C_m data to my knowledge except Lubin's[11-12)]
  - ➢ In the "DE-STAR" concept, Lubin's simulations for refractories (SiO_2) give C_m=600N/MW at 70MW/m².
  - ➢ But simulation doesn't look right: plasma formation doesn't permit a plateau in C_m vs. intensity.
  - ➢ Recall this plot from page 8? Plasma saps momentum!
  - ➢ Our calcs give 70-100N/MW
  - ➢ That's not so bad!
  - ➢ Still: what are I_{sp} and η_{AB}?

Experimental data point[11)]: Basalt, 880nm, C_m=70N/MW at 10MW/m²





11) T. Brashears, et al., "Directed Energy Laboratory Measurements," *SPIE Optics & Photonics*, San Diego (2015)

12) P. Lubin, et al, "Toward directed energy planetary defense," *Opt. Eng.* ***53***(2), 025103 (2014)

Multiple considerations in system design

- Diffraction controls spot size on target

$$d_s = a_d M^2 \lambda z / D_{eff}$$

[z is range, λ is wavelength, T_{eff} is system transmission, M^2 is beam quality (2 for a good laser), I is intensity on target, a_d is 2.44 for a hard aperture and $4/\pi$ for a gaussian beam shape]

- This leads to a constraint on power P and mirror size D_{eff}.

$$PD_{eff}^2 = \frac{\pi M^4 a_d^2 \lambda^2 z^2 I}{4T_{eff}}$$

  - If we need $I = 10\text{MW/m}^2$, and have D_{eff}=3m, λ=1µm and z=1000km, P=5MW. This is why we need FEL's!
  - Note λ^2 factor!
- Thermal coupling and splashing are terrible for metal targets. This is why we have ruled out SDR with CW lasers.
- What about refractory targets? Brashears says: "There is bubbling, mass ejecta, sparks and plume clouds." 11)
- What is the minimum mass of an FEL? Five tons or less? Then it might be useful in space.

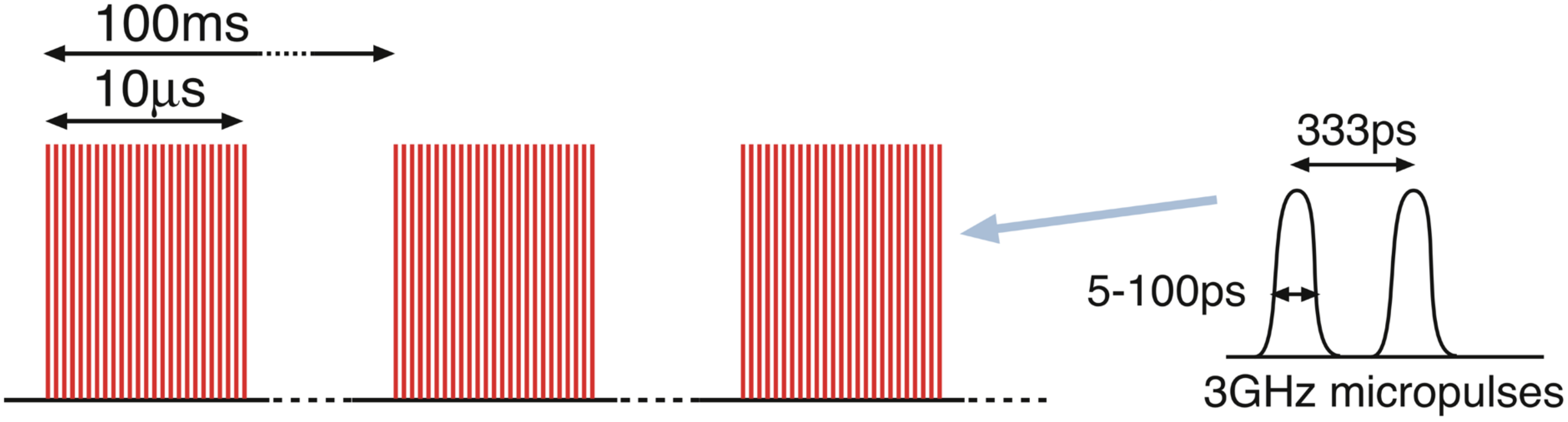
Considerations, cont'd

- If C_m on refractories is close to estimates, FEL lasers are useful for laser propulsion!
  - This is because FEL's are the only way to get high beam quality, MW-level power in the near term. Largest average pulsed power today is 1kW$^{13)}$.
- Beam quality is very good, $1.25<M^2<1.5$ $^{15)}$
- Thermal coupling could be good, or disastrous, although simple heat conduction model says it should be OK on refractories.
- What about fracturing, splashing and flaking? Not known, may be ok

13) HiLASE Project, Czechia, "Advanced DPSSL laser, DiPOLE 100, delivers 1kW performance," http://www.hilase.cz/en/advanced-dpssl-laser-dipole-100-delivers-1kw-performance/ (2016)

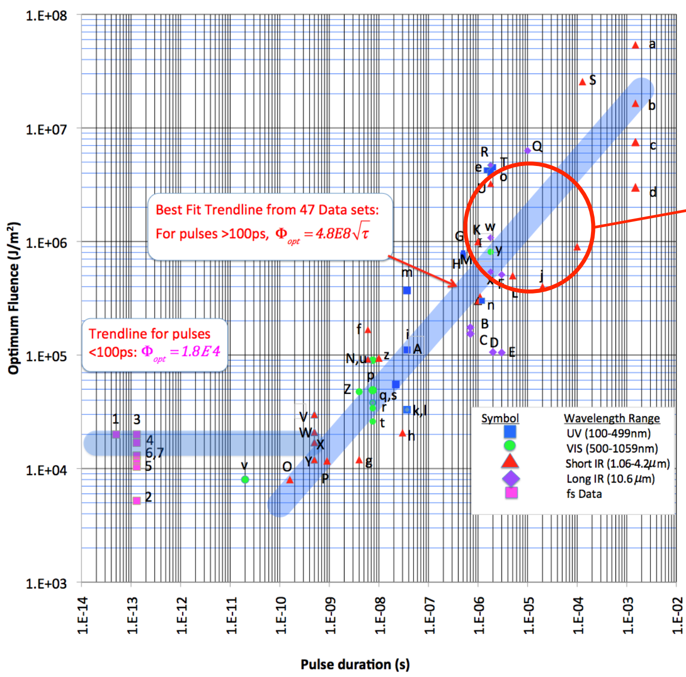
14) Dr. Bruce Carlsten, LANL, private communication (2018)

XFEL beam temporal profile



XFEL in Germany: at 1MW, essentially 10Hz, 10µs, 100kJ pulses

We have data in pulsed regime⁶⁾! This chart shows fluence (J/m²) needed to get optimum C_m vs pulse duration



Need 1MJ/m² in a 10µs pulse for optimum coupling, 10MW/m² avg. intensity at 10Hz. Spot size is 11cm for 1MW laser.

On many materials, 10µs pulses give C_m=20-50N/MW¹⁵⁾

6) C. Phipps, et al., "Laser impulse coupling measurements .." (2017)

15) C. Phipps, et al., "An alternate treatment of the vapor-plasma transition," *Int. J. Aero. Innovations* **3**, 45-50 (2011)

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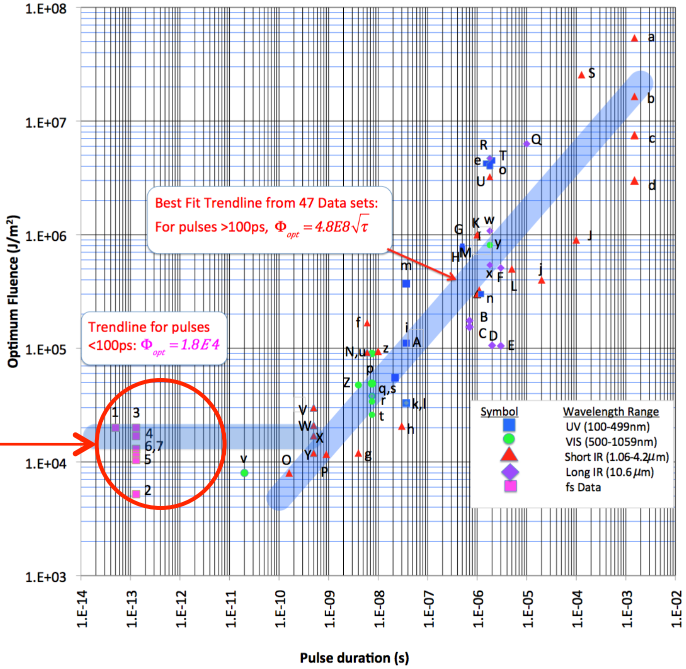
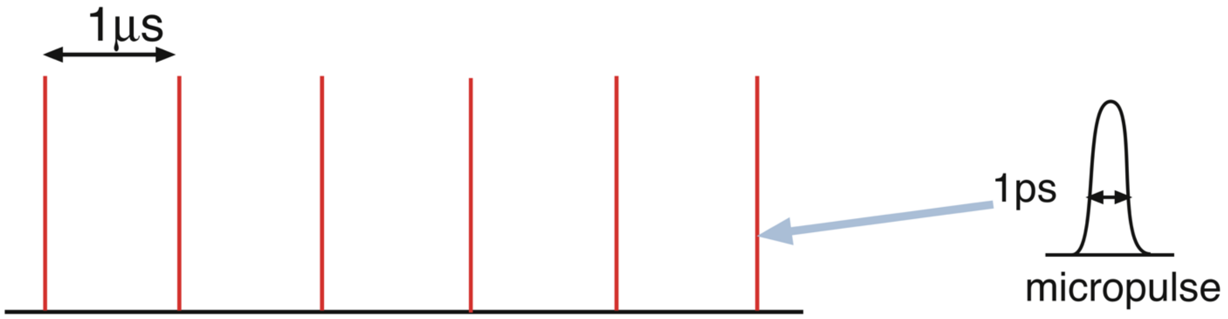
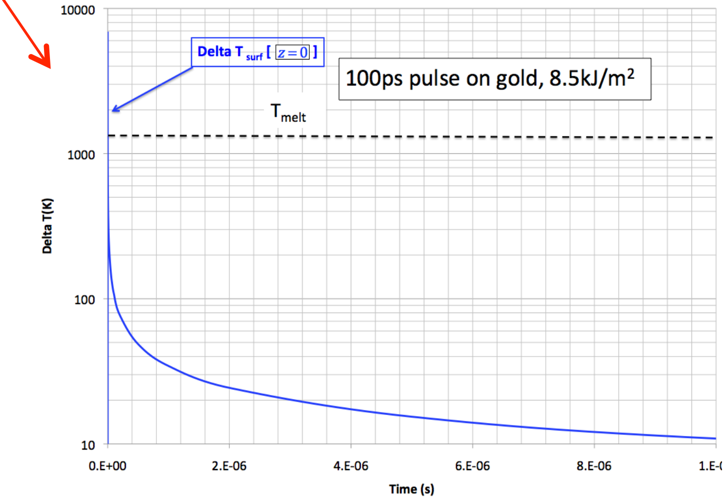
Laser space propulsion

UCLA's LCLS2 beam profile

- To first order, an LCLS2 FEL beam might behave like CW[16]. Note that Ref. (16) measured specific ablation energy (Q = J/kg ablated), not C_m.
- Yet, with one μs to recover between illumination spikes, the physics is complex![17] At 1MW, essentially 1MHz, 1ps,1J pulses
- As mentioned earlier, there is no significant vacuum data on C_m for a CW beam, certainly not for this one!
- For pulses: fluence (J/m²), for CW: average not peak intensity is important to heat target to plasma threshold, achieve C_{mopt}







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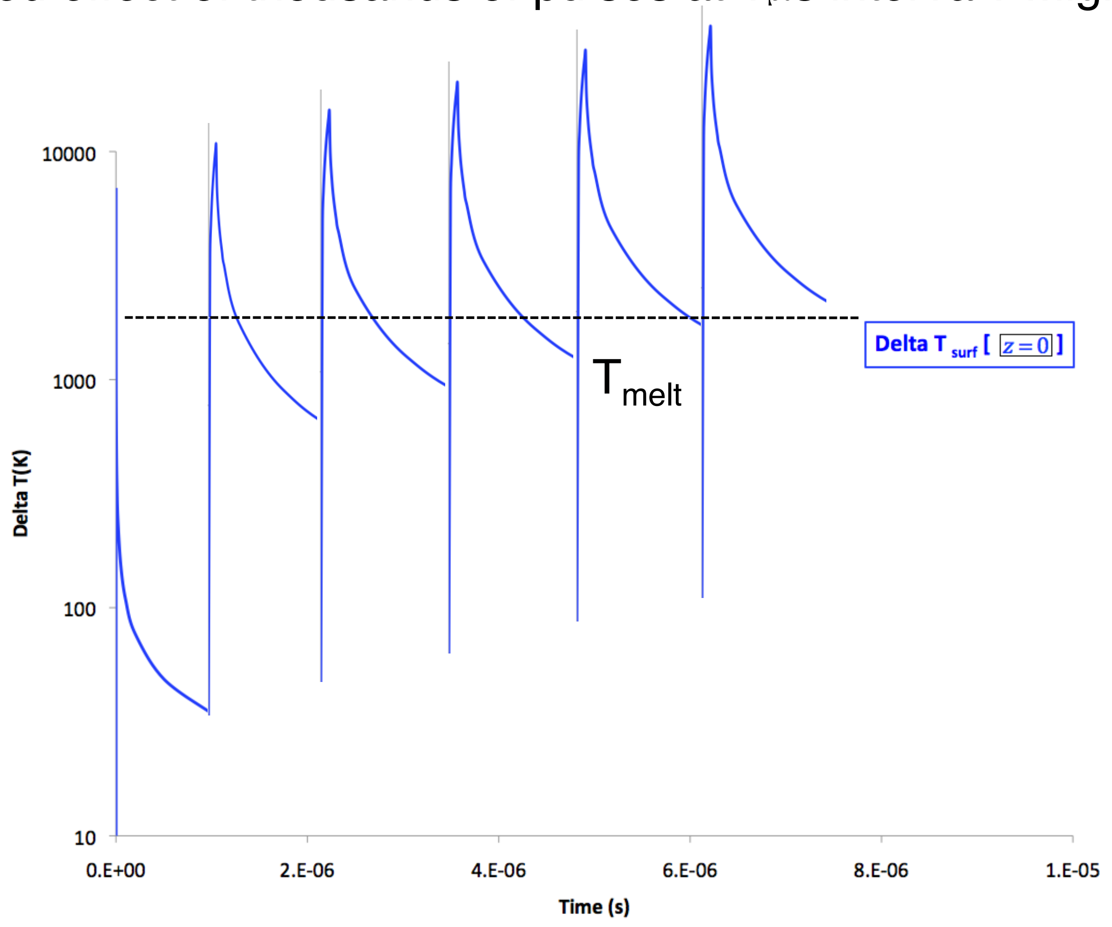
16) "As for the interaction of a high PRF (10's of MHz) FEL beam with matter, the Q's I measured were in line with those measured with CW lasers. This changes when the irradiance gets higher than 10^{10} W/cm² (the interaction looks like that typical of ultrafast lasers), but that would not be expected to occur in your application." Dr. Michelle Shinn, Jefferson Lab, March 27, 2014 [private communication]

17) C. Phipps, "Concerns for phased fiber laser arrays in space," 4th workshop on space debris modeling and remediation, CNES-HQ (2016)

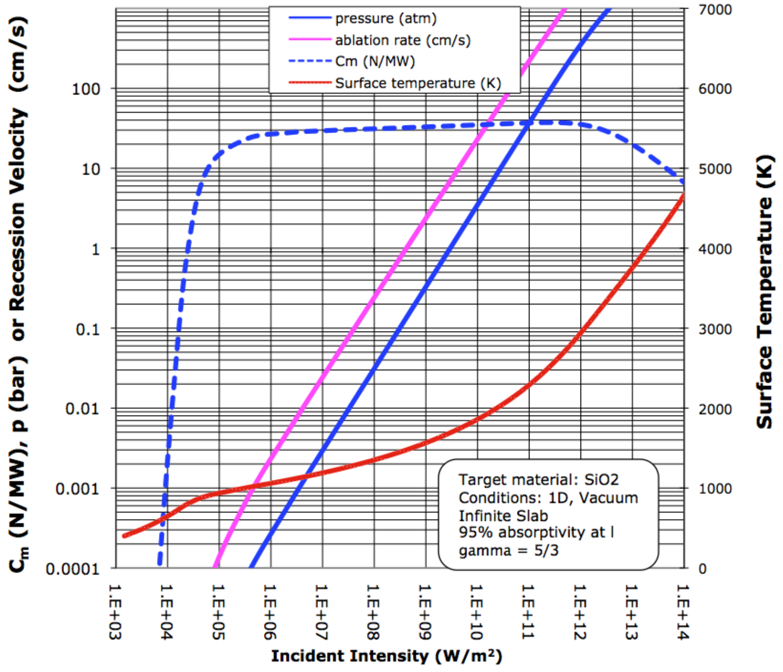
LCLS2 cont'd

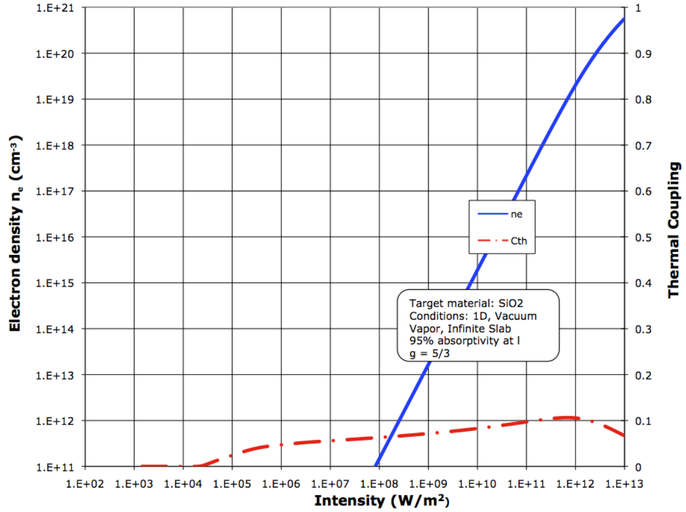
- Unrealistic spot size to achieve C_{mopt} at target with a single micropulse in 1MW beam (8mm).
- Guess: 10MW/m^2 avg. (11cm) still gives C_m=70N/MW
- Combined effect of thousands of pulses at 1μs interval? Might be pulse-like!

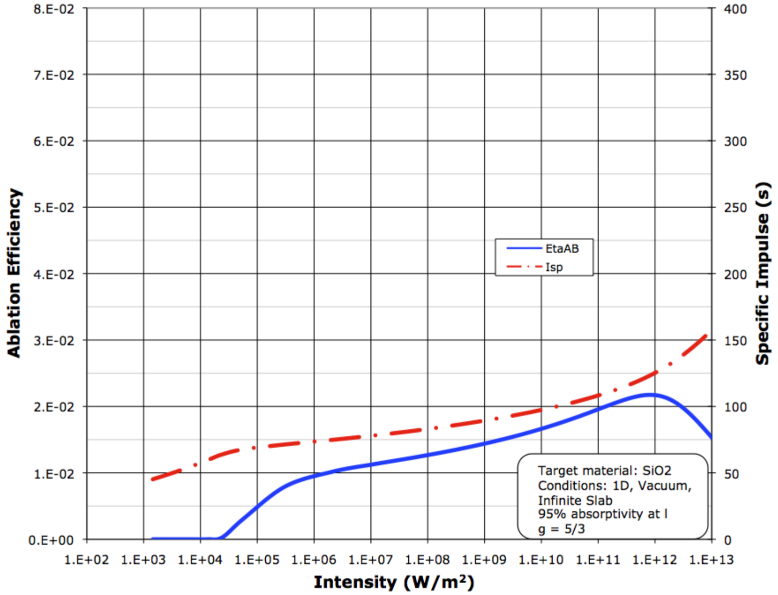


Latest calculations

- Our CW calcuations7) say η_{AB} is only ~ 3% on metals, still <u>unmeasured</u>
- What about nonmetals?
- Calculations for a CW 1µm laser on SiO_2 say:
  - ➢ C_m is as good as we get for pulses on metals
  - ➢ C_{th} is good, but
  - ➢ η_{AB} is disappointing for reasonable intensities
  - ➢ All of this needs further work!



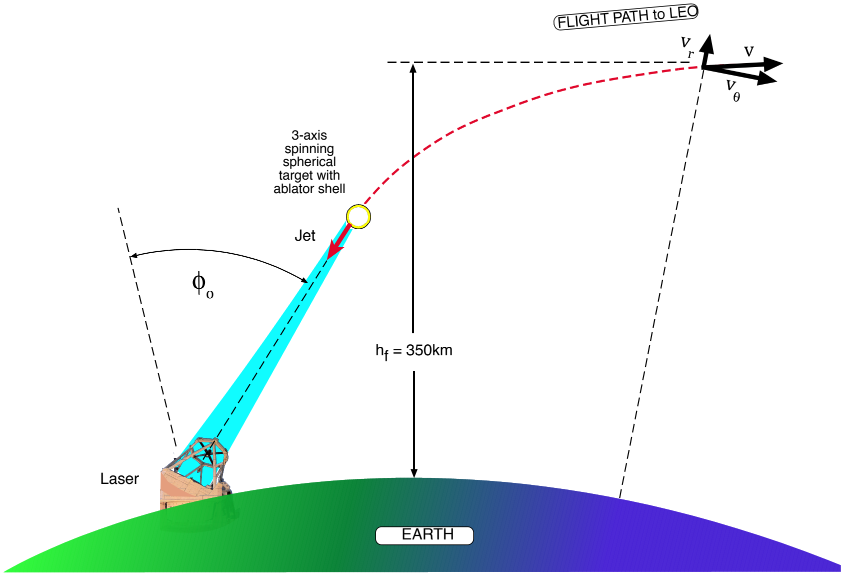


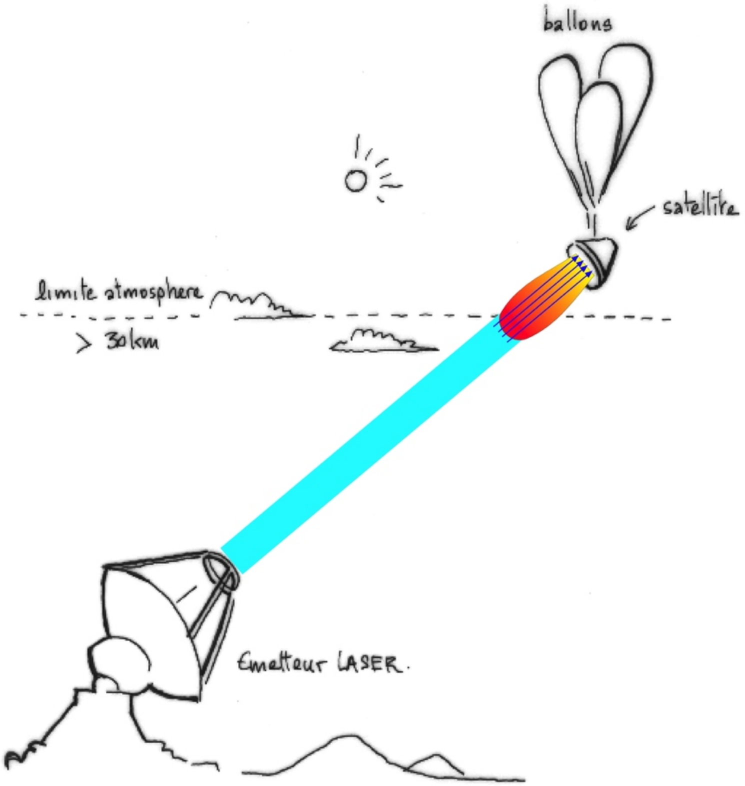


7) C. Phipps, et al., calculations (2018)

Applications: Laser launch

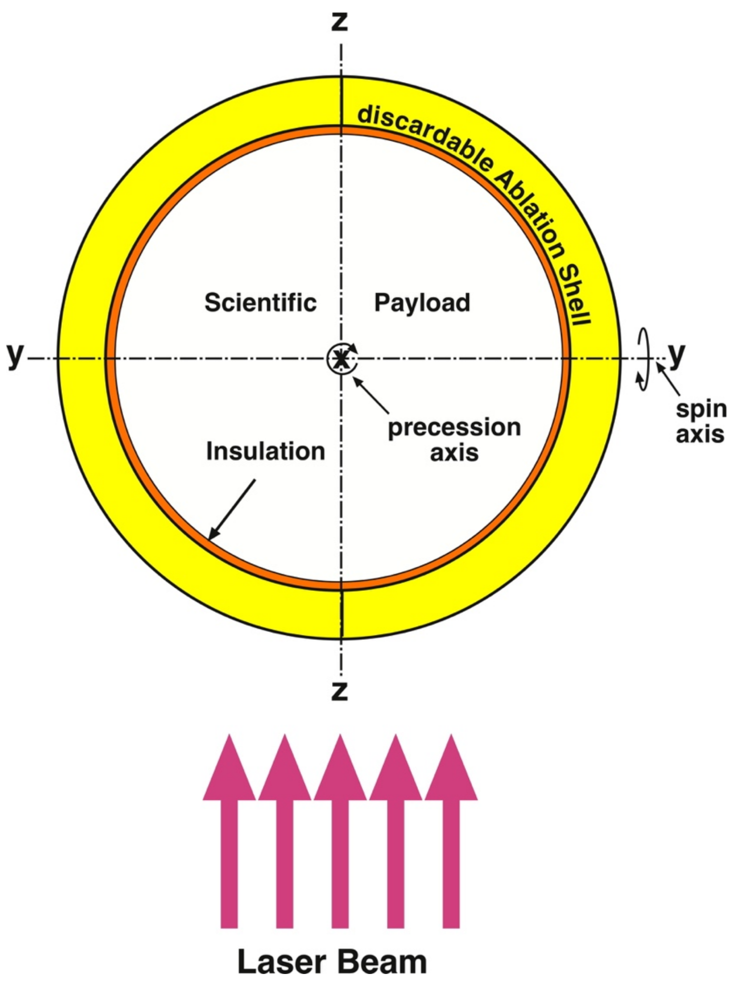
- Here’s the idea
- We may use balloons to get the target to a good launch altitude
- Groundbased or spacebased applications
- Could reduce launch cost to $300/kg5)



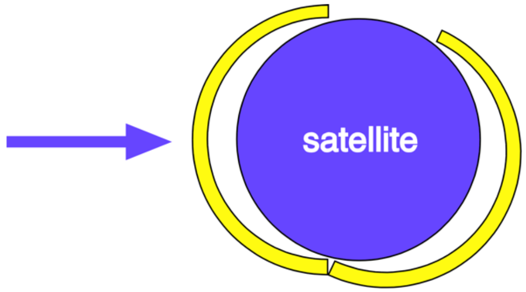


5) C. Phipps, et al. https://doi.org/10.1016/j.actaastro.2018.02.018 (2018) (2005)

Applications: Flights to LEO or the planets



- Our flyer is 50-80cm diameter, with a discardable ablation fuel layer outside a scientific payload
- Launched spinning about axis y-y and driven by gas jets to slowly precess about axis x-x, all surface elements eventually have equal beam exposure
- The entire object weighs 25kg at launch to LEO
- Optimized for 355nm pulses, the ablator has an Al/POM mixture, with C_m=70-150N/MW, using 80ps pulses at 35kJ/m^2 and 1.25MW average power5), 6)
- A spacebased application. Are FEL's light enough?



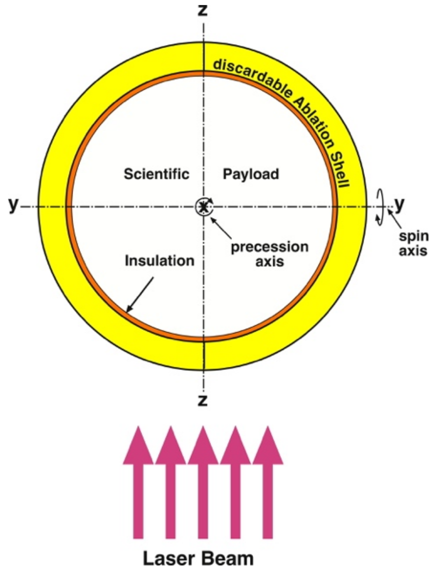
Disposing of the unburned fuel shells

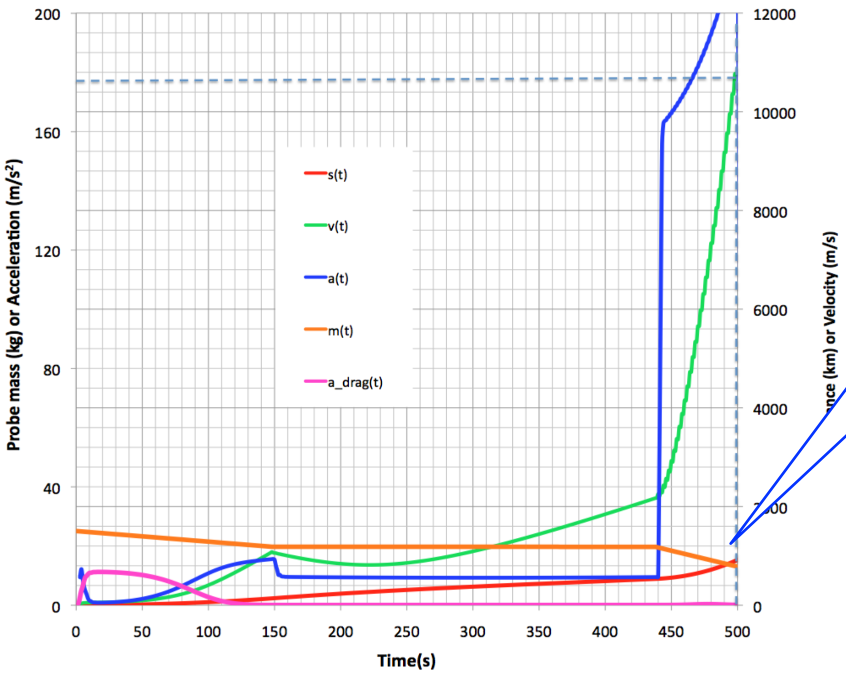
5) C. Phipps, et al., "Transfers…" (2018)

6) C. Phipps, et al., "Laser impulse coupling measurements… " (2017)

Why FELs <u>might</u> work very well for us

- Assume C_m=130N/MW for this flyer. Not an extreme assumption. If we trust simulations, I = 1MW/m^2 is adequate. Lubin obtained similar results for MgO and Al_2O_3. Then P=5.1MW at z=1000km.
- FEL's could offer this power. Our flyer is 85 cm dia.
- We can use 0.5µm wavelength and make it 50cm.
- Assume a refractory coating for the flyer and C_m=130N/MW.





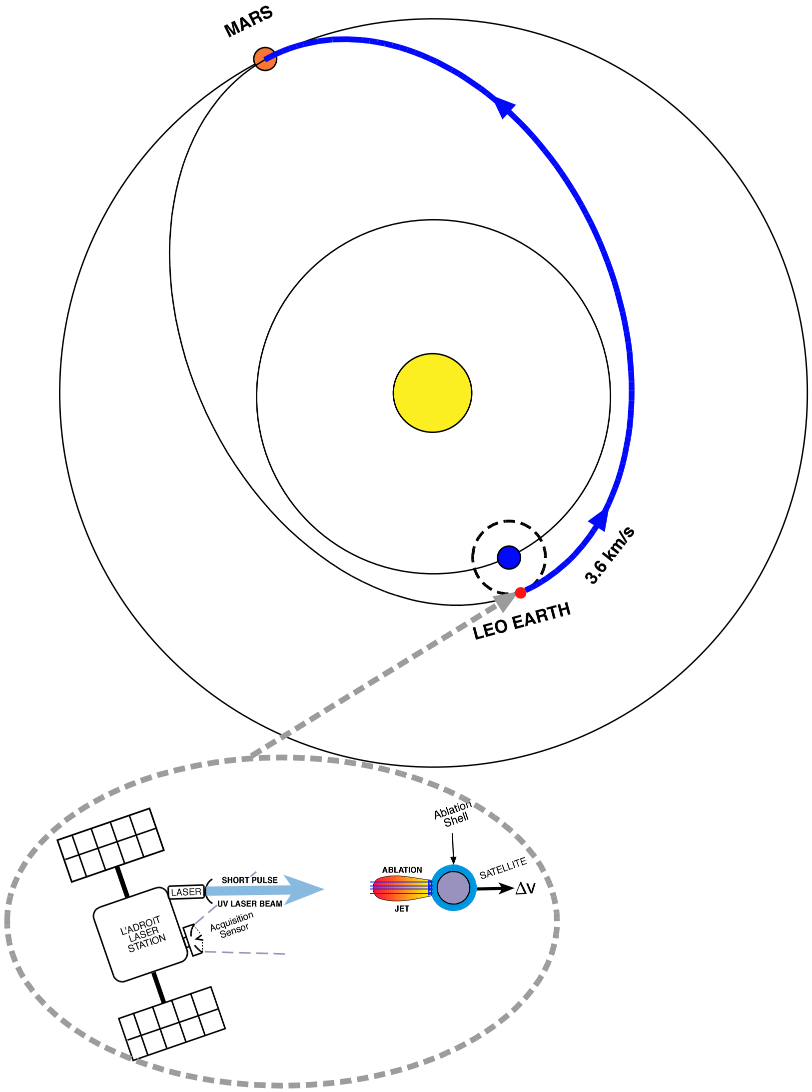
54% of launch mass survives

Result for launching 25kg to LEO using this C_m value and a 3-meter dia. mirror from ref. 5) with a 0.5µm, 5MW pulsed laser. Can FEL's do the same?

Applications: Laser-powered rocket to Mars5)

- Also a spacebased application
- Problem: provide Δv=3.6km/s impulsively in LEO to get to a cis-Mars orbit
- The laser is in space, can use 355nm for best focus, 3-m mirror
- No worries about perigee
- Batteries recharge in 3days at 25kW solar array input
- Equation of motion (no drag):

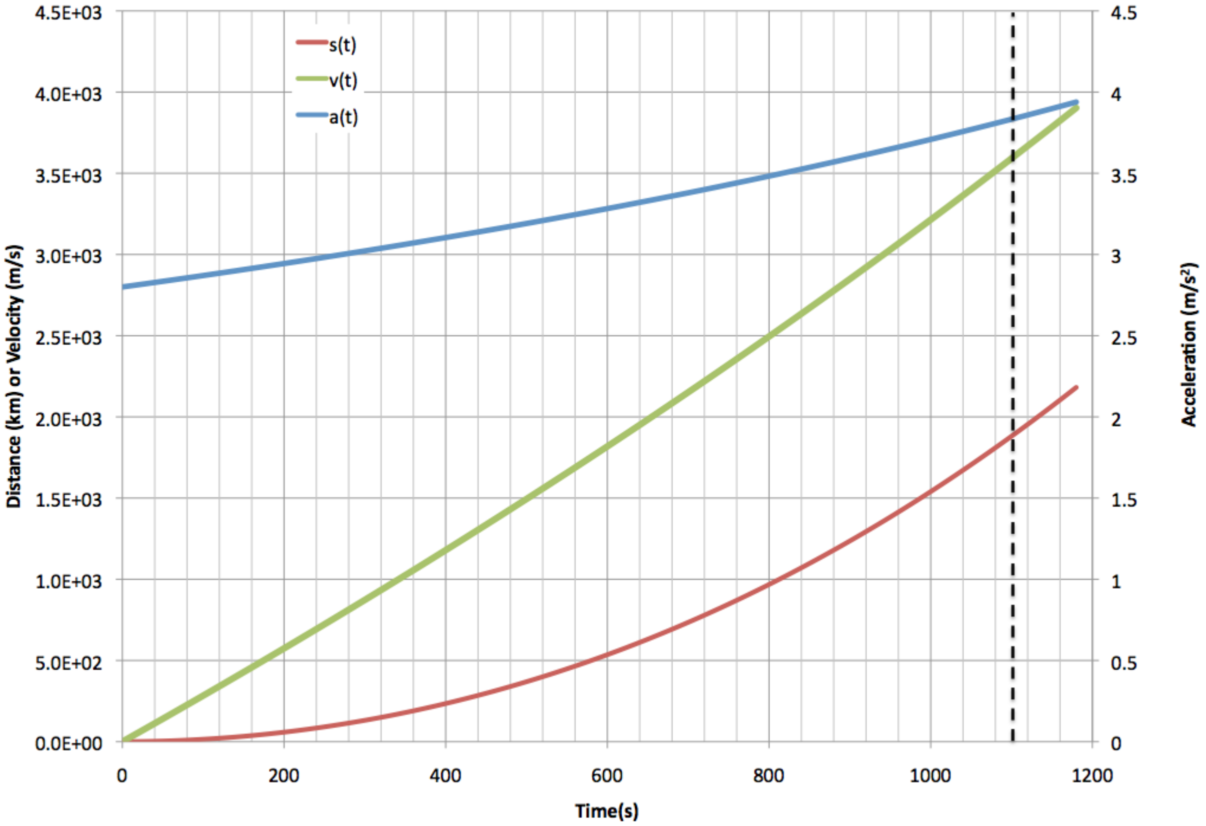
$$\ddot{s} = \frac{PC_m \eta_c}{m}$$



5) C. Phipps, et al., “Transfers…” (2018)

Extreme levels of m/M for this application

Parameters for flight to Mars	
Wavelength (nm)	355
Average power (MW)	1.25
C_m(N/MW)	70
Fluence Φ (kJ/m^2)	35
Target diameter (cm)	50
Initial mass (kg)	25
Final mass (kg)	18.2 (73%)
Final velocity (km/s)	3.6
Acceleration time (min)	18.5
Mirror diameter (m)	3
Maximum range (km)	1900
Maximum acceleration (m/s^2)	3.84
Ablation efficiency	1.0



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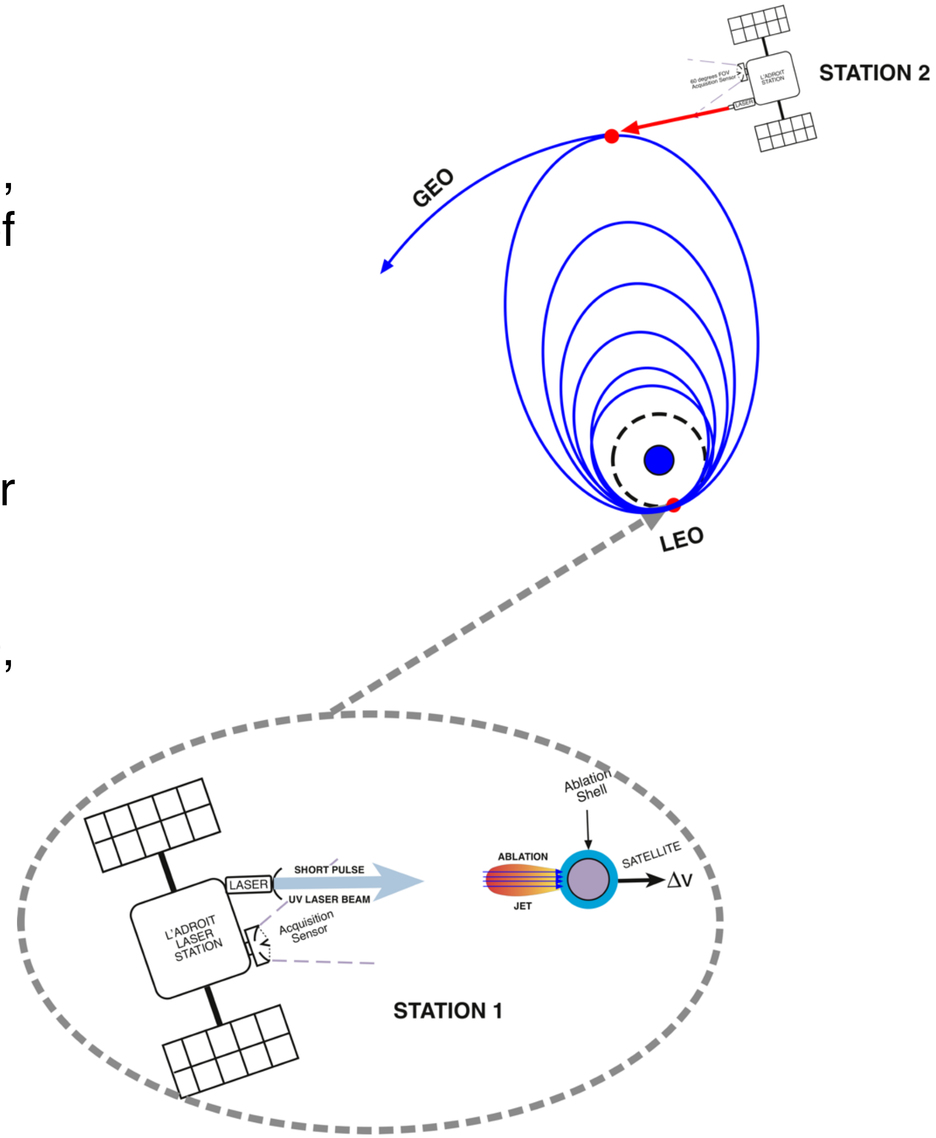
Laser space propulsion

Apps: Launching swarms of microsatellites

- Also spacebased
- Can we reduce power to the 100kW level, making it possible to launch swarms of microsatellites in the near term?
- We think so, but it's tedious!
- Increase velocity in 8 stages to limit laser power to 100kW
- Two "L'ADROIT" stations[18], one in LEO, one in GEO do the trick



19) C. Phipps, et al., "L'ADROIT – a spaceborne ultraviolet laser system for space debris clearing," *Acta Astron.* **104**, 243-255 (2014)

Swarms cont'd

- Multiple passes make L'ADROIT and satellite orbits resonant

Table: Eight stages to GEO or cis-Mars orbit

Parameters: W=5kJ, C_m=130N/MW, D_b=3m, λ=355nm

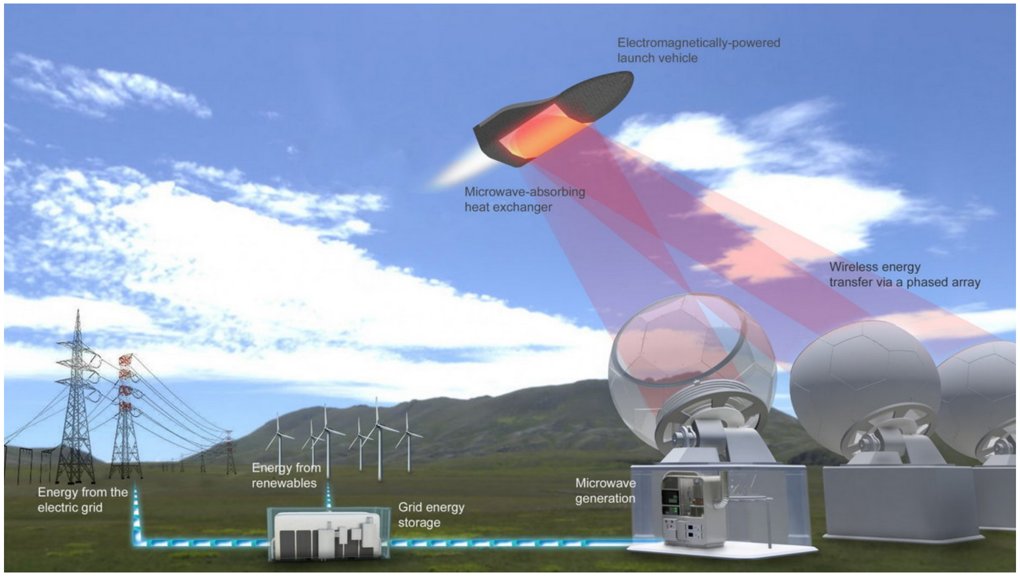
Phase	1	2	3	4	5	6	7	8A(GEO)	8B(Mars)
m_o(kg)	25	21.7	20.2	19.3	18.7	17.9	17.4	16.8	16.8
m_f(kg)	21.7	20.2	19.3	18.7	17.9	17.4	16.8	11.3	10.8
f(Hz)	17.3	13.9	10.9	8.97	14.4	9.74	14.8	23.2	50
P(kW)	86	70	54	45	42	49	74	116	250
Δv(m/s)	865	450	285	198	258	166	204	1470	2740
Δt(s)	2240	1300	1020	800	620	580	460	1820	1420
Passes	3	3	2	3	4	5	----	----	----
s(km)	951	293	147	80	81	50	49	1300	1820
e	0.24	0.37	0.46	0.52	0.60	0.66	0.73	0.998	----

Photonic Associates

Laser space propulsion

Applications: Kare/Parkin HX concept19)

- Task: ground launch to LEO
- Main example of laser-heated fluid propulsion (H_2)
- Clearly, a groundbased application
- Problems: 300-900MW electrical input, ~2B$ cost for ground station
- Problem: for microwaves, interference with radar, wireless and TV
- Benefit: At $3W, est $500/kg to LEO



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19) J. Kare and K. Parkin, “A comparison of laser and microwave approaches to beamed energy launch,” CP830, *Beamed Energy Propulsion, 4th International Symposium,* K. Komurasaki, ed. (2006)

Outstanding problems

- Determining interaction parameters for FEL beams on refractory materials
  - ➢ C_m
  - ➢ I_{sp}, η_{AB}
  - ➢ C_{th}
- Qualifying *any* large laser for these applications
- Are FEL's too massive to put in space?
  - ➢ If so, what can we do from the ground?
- Apologies to lawyers, but they may still stop us with liability considerations$^{18)}$

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18) S. Aoki, "Legal Aspects of Laser in Space Activities," Proc. Optics & Photonics International Congress, Yokohama, 17-20 May 2016

Conclusions

- Laser ablation propulsion is an effective method of propelling objects remotely
- High-payoff applications from LEO to GEO and beyond
- Still a lot of confusion on mechanical coupling and efficiency for CW beams
- Exciting developments may be near
- Some distance exists between requirements and actualities in “portable” high peak and high average power lasers
  - I hope you will help us close this distance!
- Thank you for your attention!
- Woops! 2 very recent slides follow showing ablation propulsion in action!

Laser propulsion demo

Here is what laser propulsion looks like.

In this video, created three days ago, a repetitive-pulse Nd laser (1.076um, 4ns) strikes a coated pingpong ball on a rail.

Total laser power is just 9W.

Drag force due to air is 14µN at maximum velocity of 13.6cm/s.