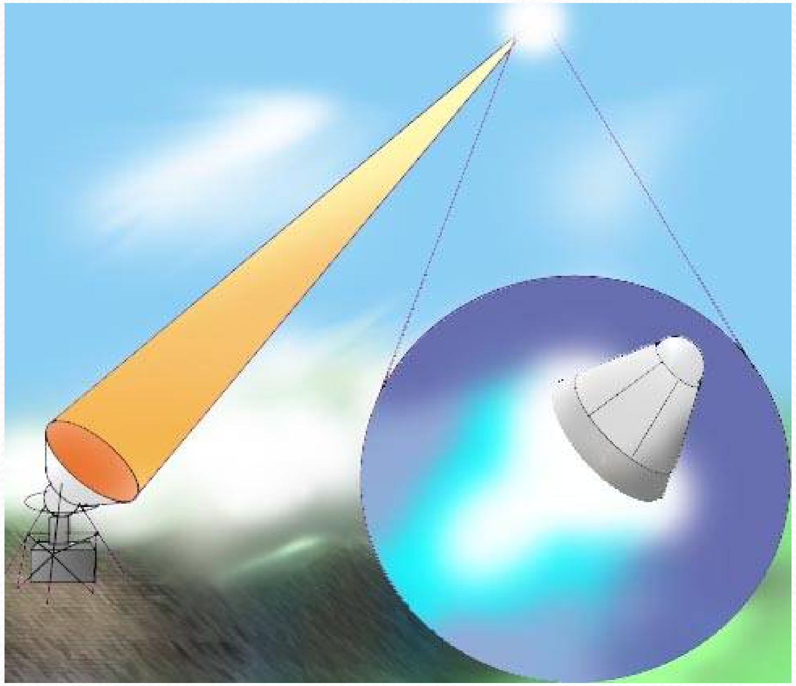
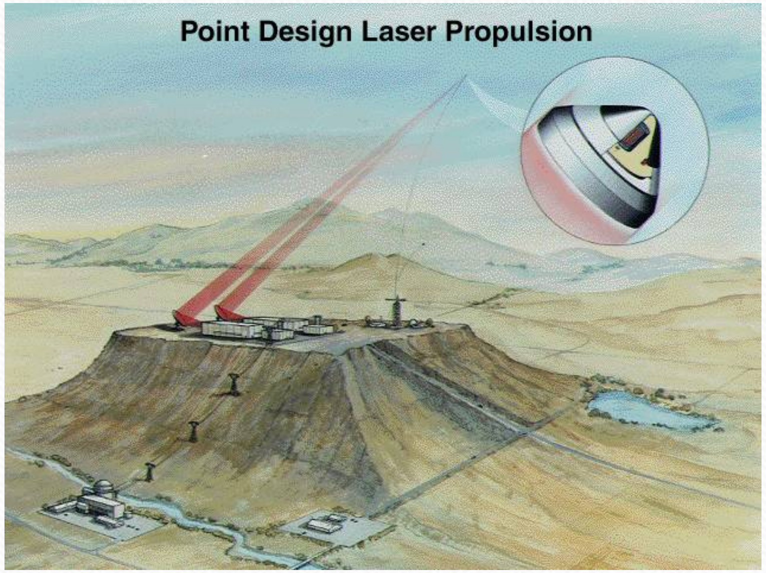
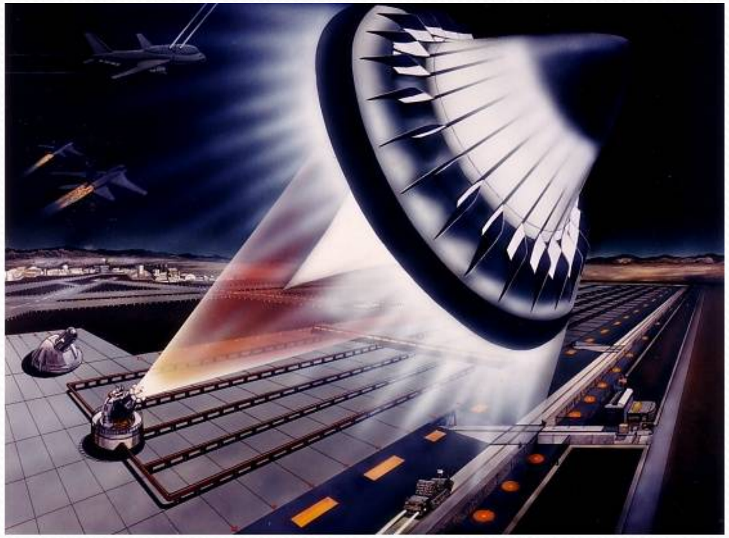
Beamed Energy Propulsion Overview



Beamed Energy Propulsion

“Distinguished by its use of a collimated laser or microwave beam”





Concept of laser propulsion system

Categorization

- Ⅰ. Powered by Ground /Space-based Lasers
  - 1. Ablative Thrusters
    - Solid and Liquid Ablative
      - Space-Debris Removal
    - Ablative Thermal/Aerodynamic
  - 2. Detonation Thrusters
    - Air-breathing laser thrusters
    - Microwave Rocket
  - 3. Continuous Wave Laser Thrusters
    - Laser Plasma Thruster
    - Heat Exchanger Thrusters
- Ⅱ. Powered by On-board Lasers
  - 1. Laser Micro-thrusters
    - Drag Reduction
  - 2. Laser-electric Hybrid thrusters
  - 3. Relativistic Acceleration Thrusters

As a launch system from the ground

1. First proposed by Kantrowitz in 1972.
2. Propulsion parameters are not limited by propellant chemistry.
3. Thrust is a function of available laser power, and *high acceleration* is achievable (greater than 10*g*.)
   - The craft need not to park in a low earth orbit and
   - can head directly for a geosynchronous or *super-geosynchronous orbit*.
4. No-fuel flight is realized in *air-breathing* flights in the atmosphere.
5. No pressure vessel nor turbo-pump system is required when gas is heated isometrically through laser *detonation* or *ablation*.
   - Simple, inexpensive, and disposable vehicle structures.
6. Laser facility, the most complex and expensive one, is maintainable and replaceable at any time on the ground.
   - *Redundancy* without vehicle-mass penalty.
   - *Reusable*
7. *low-cost*, *low-emission*, and *resource-saving*

As an in-space propulsion system

1. First proposed by Minovich in1972.
2. Using a remote power supply from space-based lasers, *unlimited specific power* (power per thruster system weight) would be available (greater than that of solar electric propulsion)
   - *Mission period shortened*.
3. Plasma is generated and sustained apart from chamber walls or electrodes, so that a *higher gas temperature > 10,000K* is expected at higher pressure than EP.
   - *low propellant consumption*
3. Laser micro-thrusters using on-board diode lasers for orienting or repositioning microsatellites with precise thrust control.

   The diode lasers will be driven directly by a solar array.
   - *very compact electric propulsions*

Non-propulsive applications

1. Wireless power beaming to aircraft, spacecraft, and satellites.
2. Space-debris removal by laser ablation
3. Drag reduction of supersonic vehicles using laser energy deposition

Summary

Beamed Energy Propulsion

1. Advantages against chemical rockets from the ground
   - High specific power, High gas temperature.
   - Air-breathing and no fuel flight.
2. Advantages against Electric propulsion in space
   - Direct drive by solar array
   - High temperature plasma sustained apart from electrodes.

References

- Laser Propulsion, in Encyclopedia of Aerospace Engineering, R. Blockley and W. Shyy (eds). John Wiley & Sons Ltd, Chichester, UK. pp. 1351-1360.

- Beamed Energy Propulsion, AIP Conference Proceedings 1230 (2009).

1. Ablative Thrusters

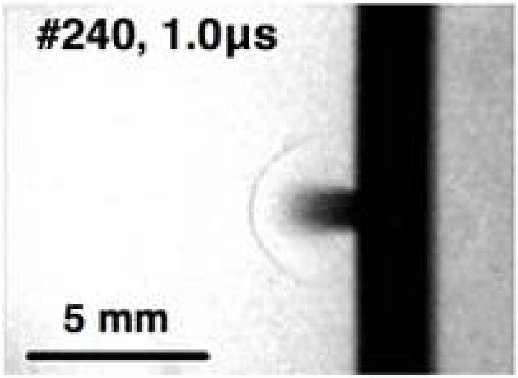
"Laser Ablation"

- Laser energy is absorbed through inverse bremsstrahlung, which requires the presence of initial free electrons.

- A solid propellant usually possesses sufficient free electrons

- A fluid propellant, which is in a gaseous state by the time it is exposed to the laser irradiation, must first be ionized.

- If the light is focused near or on a solid surface, breakdown threshold is considerably reduced.

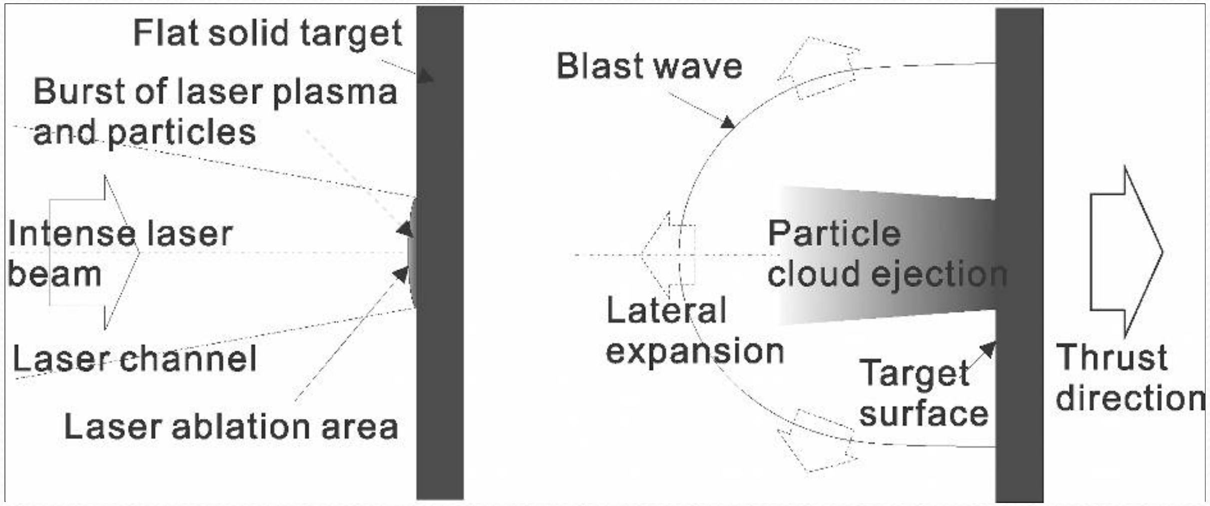


Laser Ablation Phenomena

Thrust generation by ablation

- When laser pulse energy is focused on a solid target, highly ionized matter is ejected at a supersonic speed from the target surface as ablation.

- Ablation imparts an impulse to the target in the direction opposite the jet and the target is propelled. Solid laser ablation can generate V_e of about 10km/s.



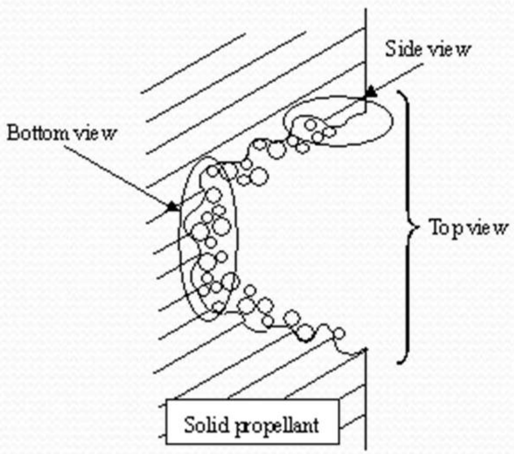
1. Reaction of gas ejection (Ablative thrust in vacuum)

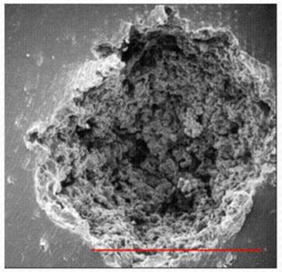
2. Pressure increase in a blast wave (Ablative thermal thrust in air)

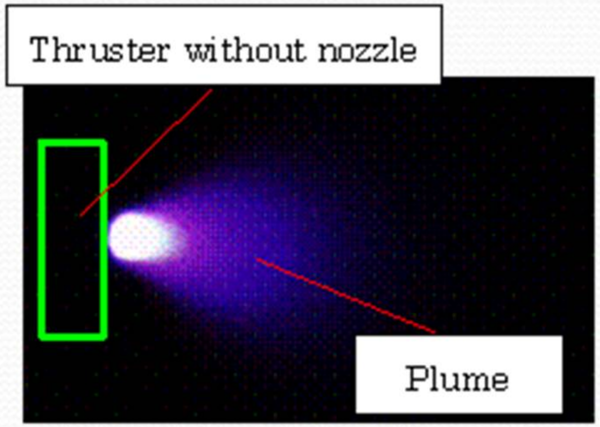
Ablative laser thruster

Solid Ablative thrusters

- Focus the laser beam on a solid ablation propellant.
- No propellant feed system, very simple structure. cf . Pulse plasma thruster (EP). Low thrust level.
- For attitude control of satellites, orbital transfer of microsatellites.







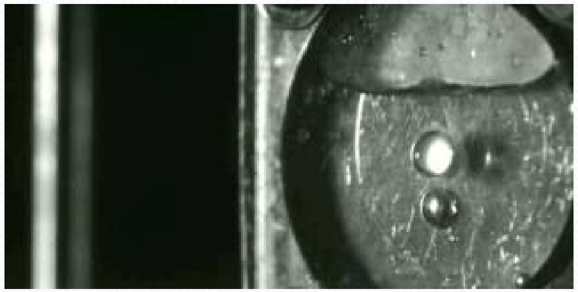
Solid ablation and ablation thruster.

Liquid Ablative thrusters (1)

A liquid ablative thruster can achieve high thrust (N/MW) at low V_e.

- Transparent substances are placed in contact with the water propellant.

-A laser pulse can ablate the water through the substance and give a large impulsive thrust in the direction opposite to the laser incidence.

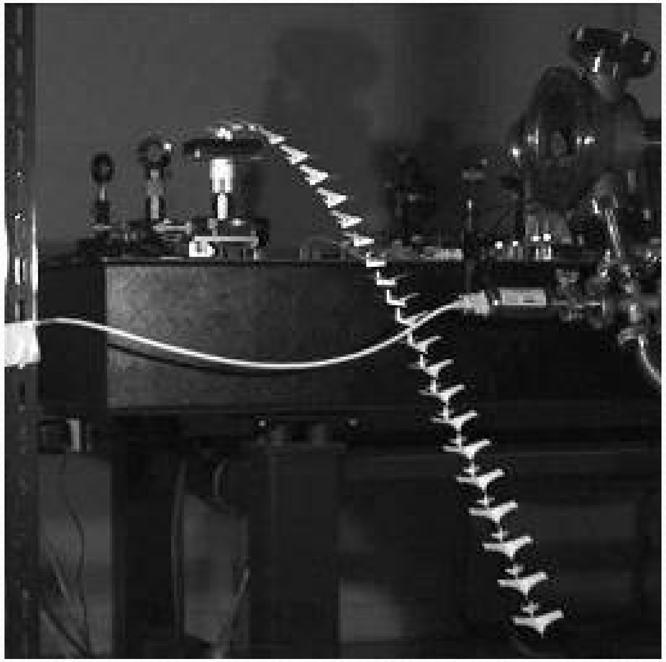


(a) Caliber: 2 mm

(b) Caliber: 1 mm

Liquid ablative thruster (Tokyo Institute of Technology)

Liquid Ablative thrusters (2)



- Thrust of more than 4000 N/MW was achieved at V_e of several m/sec.

- Reduction in the breakdown threshold is expected..

-Long-duration missions would be possible with a continuous water supply.

Micro airplane powered by a RP laser (Tokyo Institute of Technology)

Ablative Thermal Thrusters

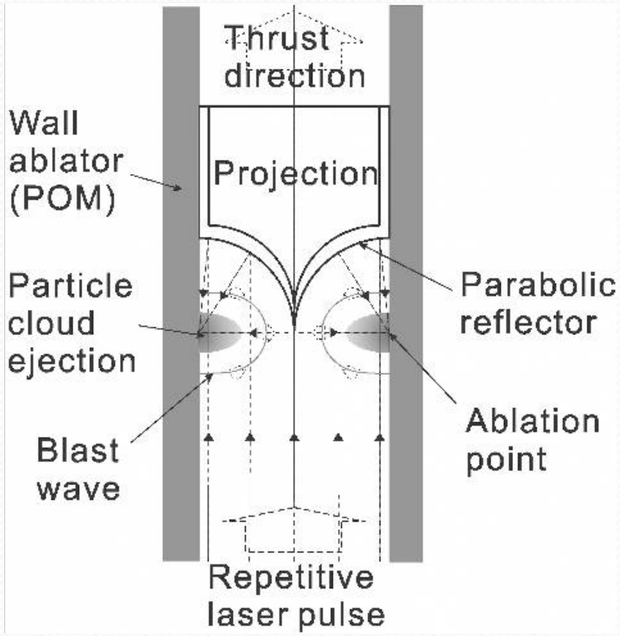
When pulse duration >> ablation time, Laser Supported Detonation is the major energy transfer mechanism.

In-Tube Accelerator with a wall ablator:

A projectile is held in a tube whose walls are made of ablator material, POM.(Polymer) Parabolic reflectors set on the bottom focus on the ablator surfaces.

When the POM wall is ablated, the ablated gas is ejected normal to the wall. The ablation plumes are reflected on the parabolas, and collimated downward.

Thrust was 160 N/MW in vacuum with the propellant off-board.



Laser In-tube Accelerator with a wall ablator. (Nagoya Univ.)

Space-Debris Removal by Laser Ablation

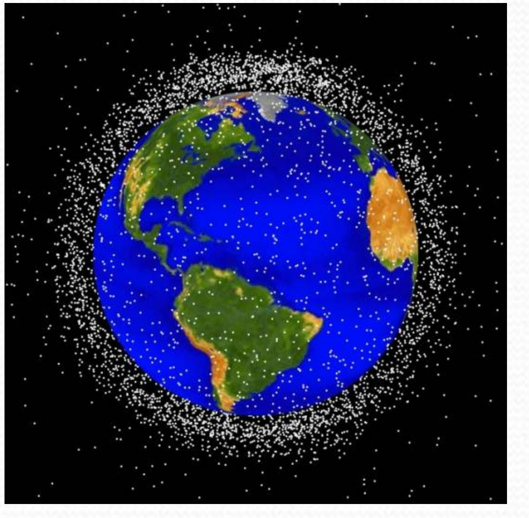
Clearing near-Earth space debris in the 1–10 cm size by pushing debris into an orbit intersects the atmosphere by laser ablation. Δv is approximately 100 m/s.

1) Using a ground-based pulsed laser (ORION Project)

   - clear near-Earth space in two years with modest laser power.
   - a sensitive optical detector is necessary to track objects as small as 1 cm at 1500 km range.

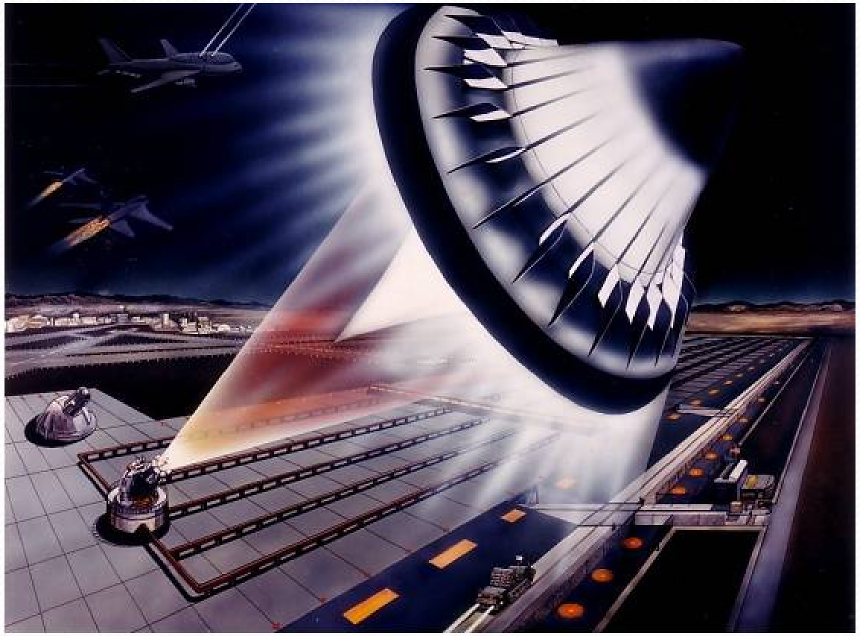
2) Using a space-based pulsed laser

   - detection is easier
   - with a much smaller aperture
   - more appropriate vector relation between the laser propagation and debris velocity.

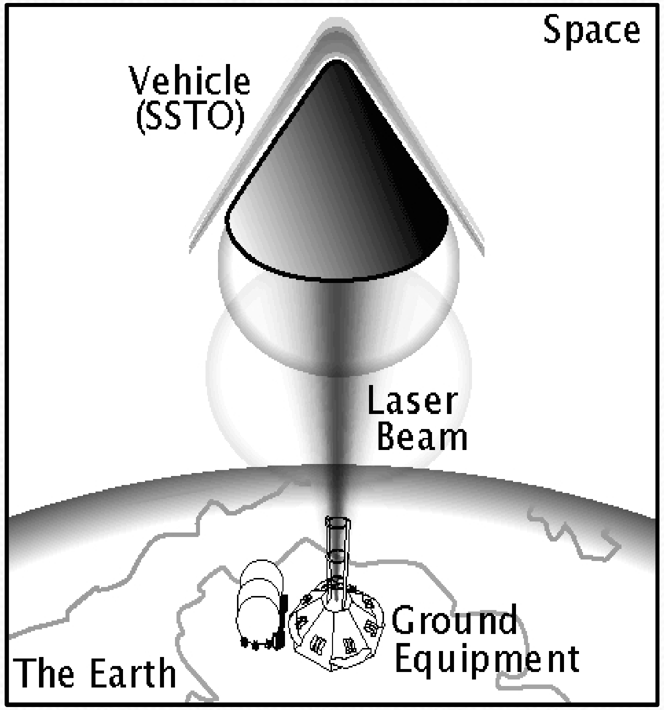


Debris in the earth orbit

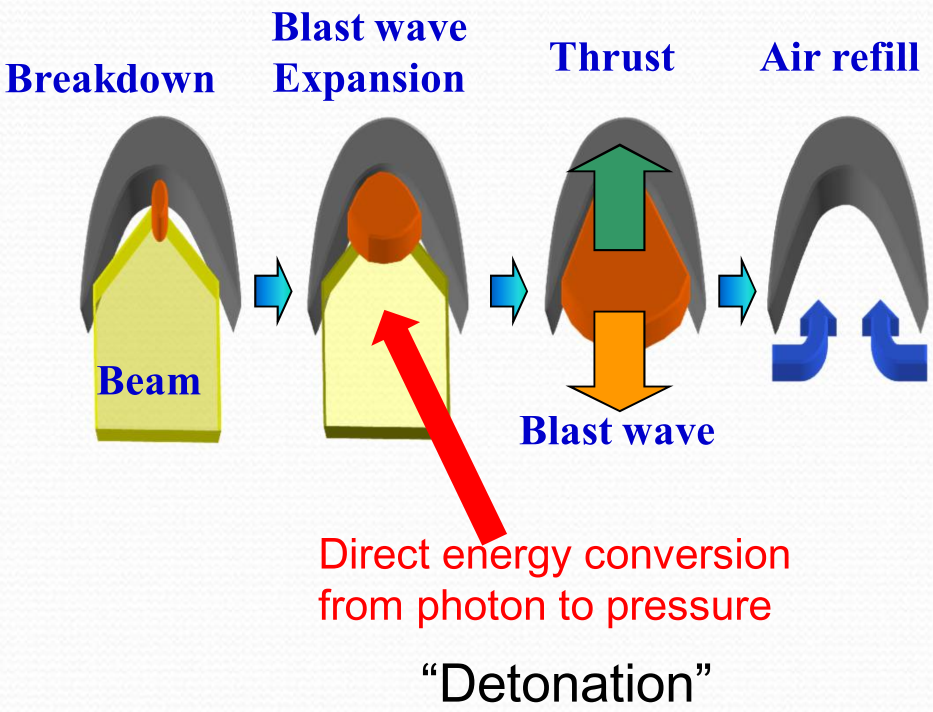
2. Detonation Thrusters



Operational principle of detonation thrusters



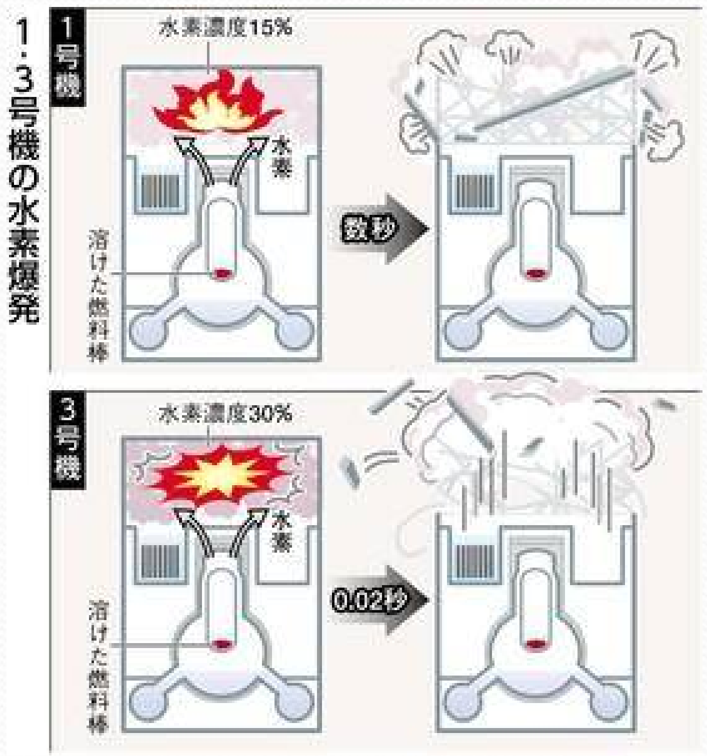
A laser launcher.



Engine cycle.

What is Detonation

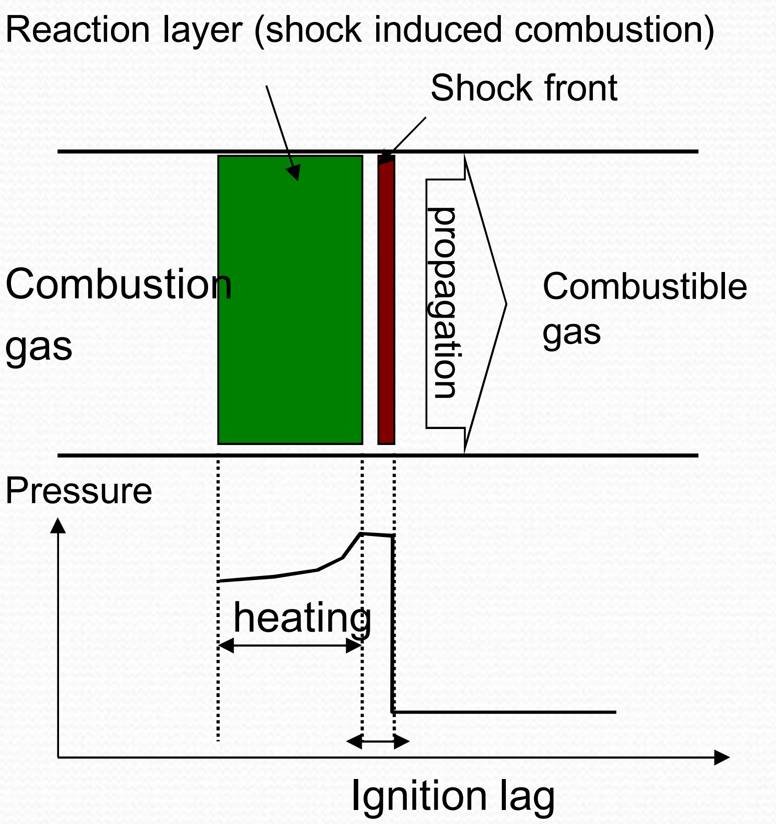
In a gaseous mixture of fuel and oxidant, a supersonic exothermic (combustion) front is accelerated through the gas driving a shock wave in front of it.



Explosions in H_2-air in Fukushima Nuclear Plant

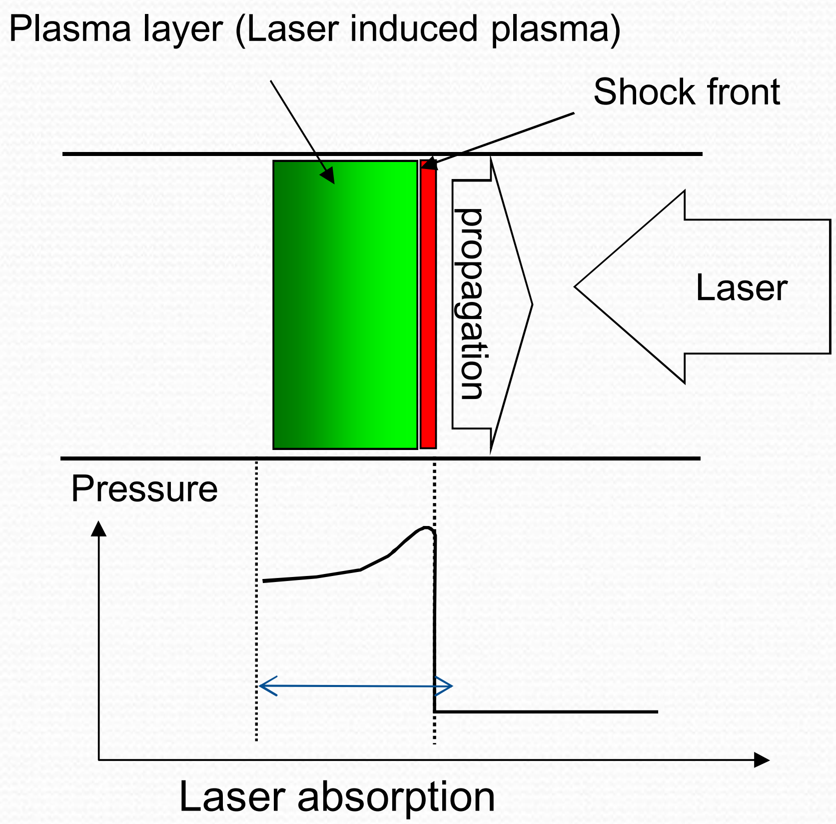
Detonation wave structures

Chemical detonation



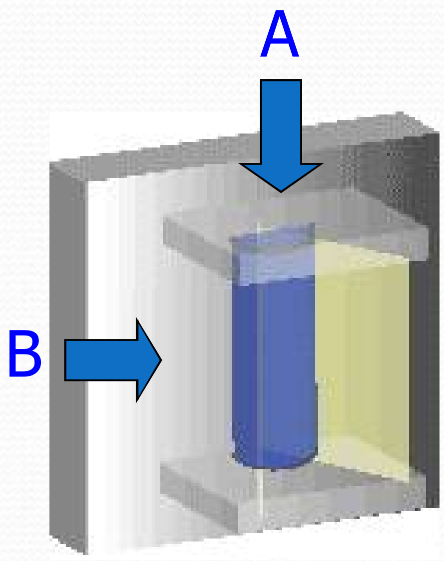
Zel'dovich-Neumann-Doring (ZND) structure

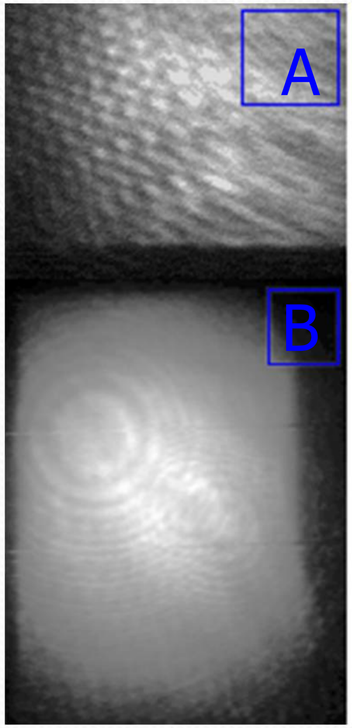
Laser Supported Detonation（LSD）

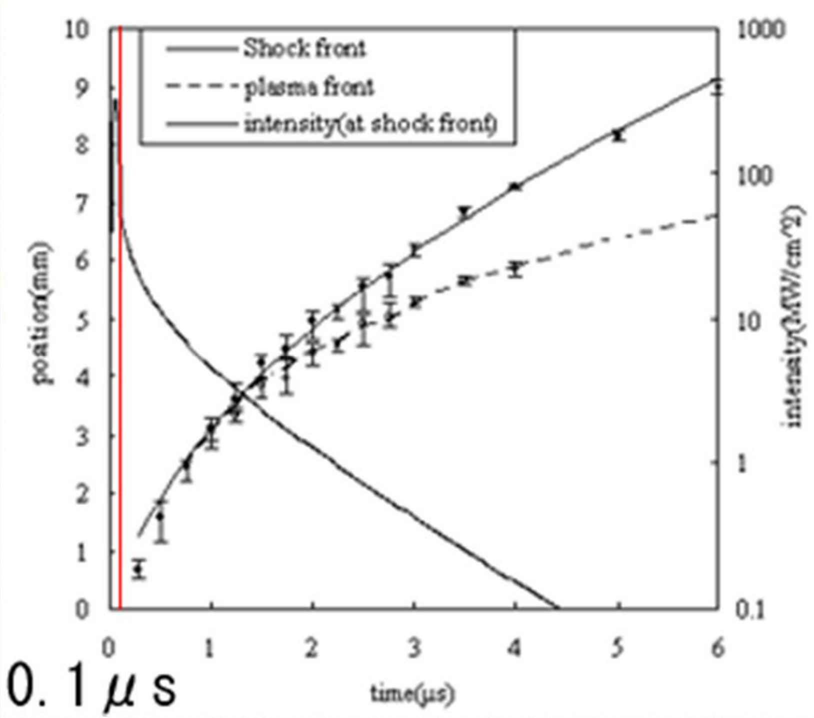


LSD structure

Transition from Laser Supported Detonation (LSD) to Laser Supported Combustion (LSC)



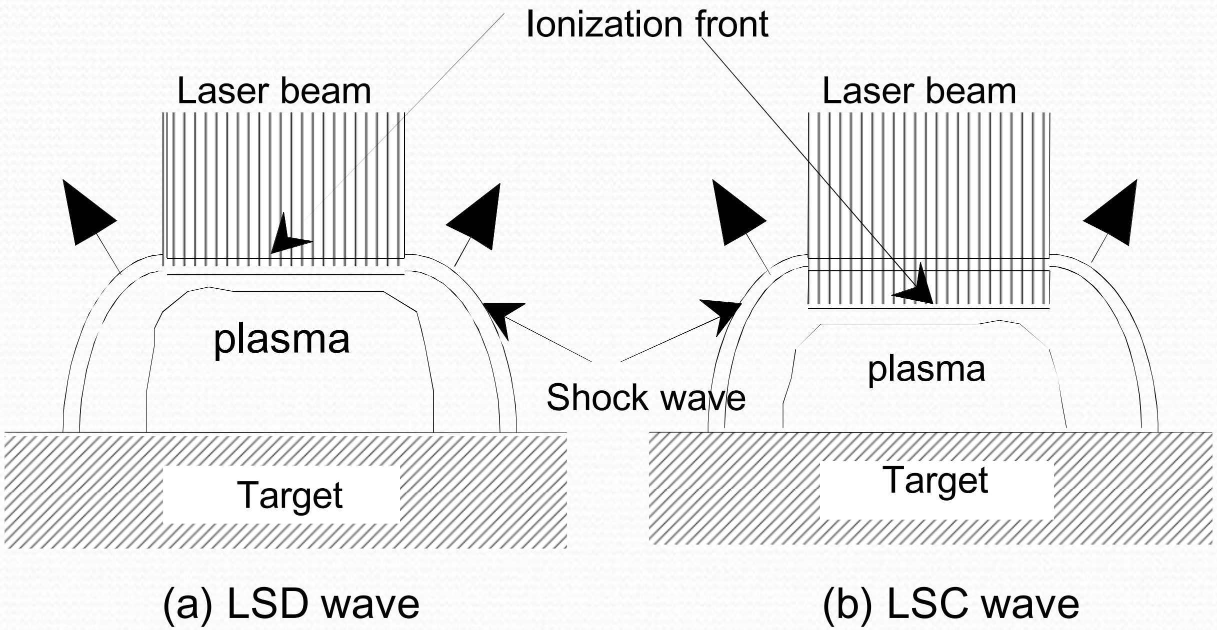




Shadowgraph image

A shock front and ionization front displacements.

LSC and LSD



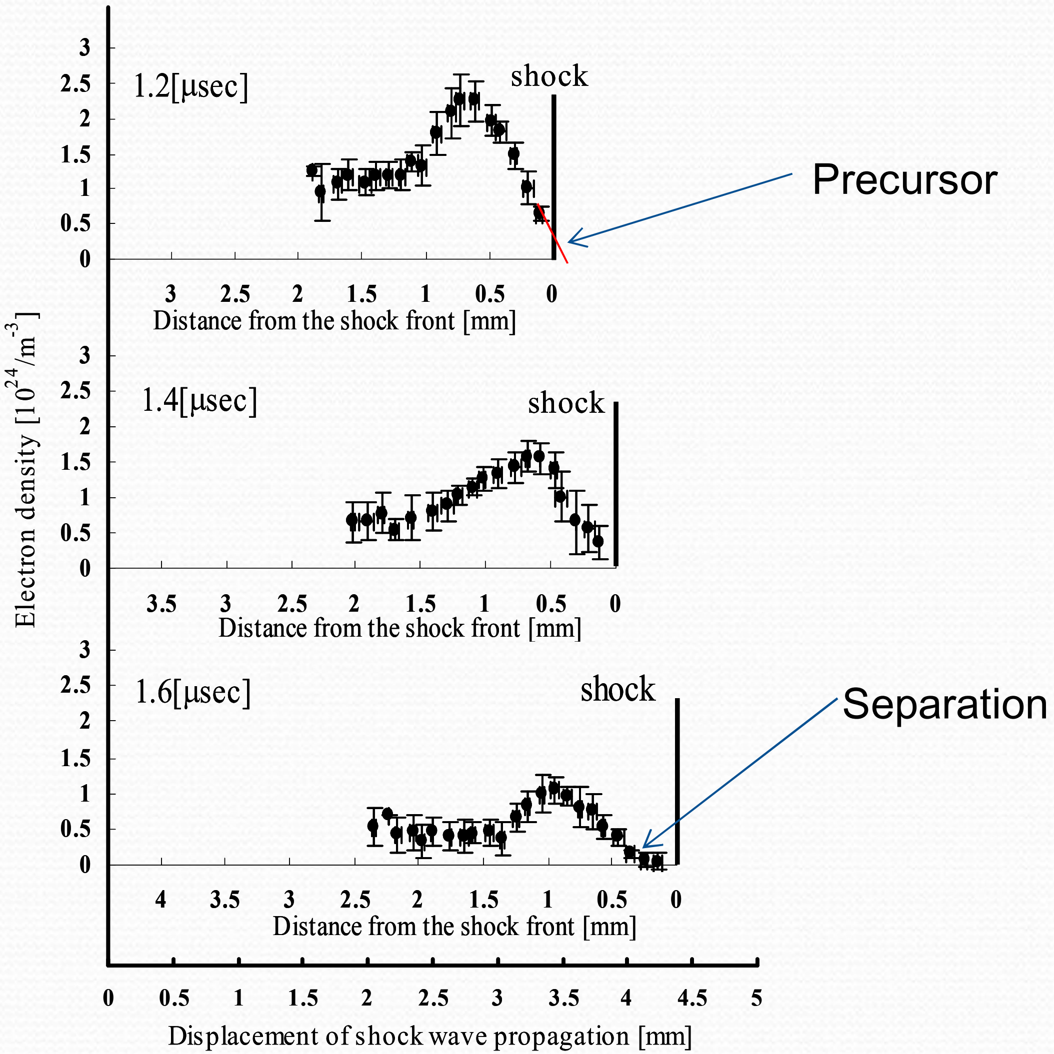
Schematics of laser supported detonation (LSD) wave and laser supported combustion (LSC) wave.

Post-shock plasma density profiles

LSD

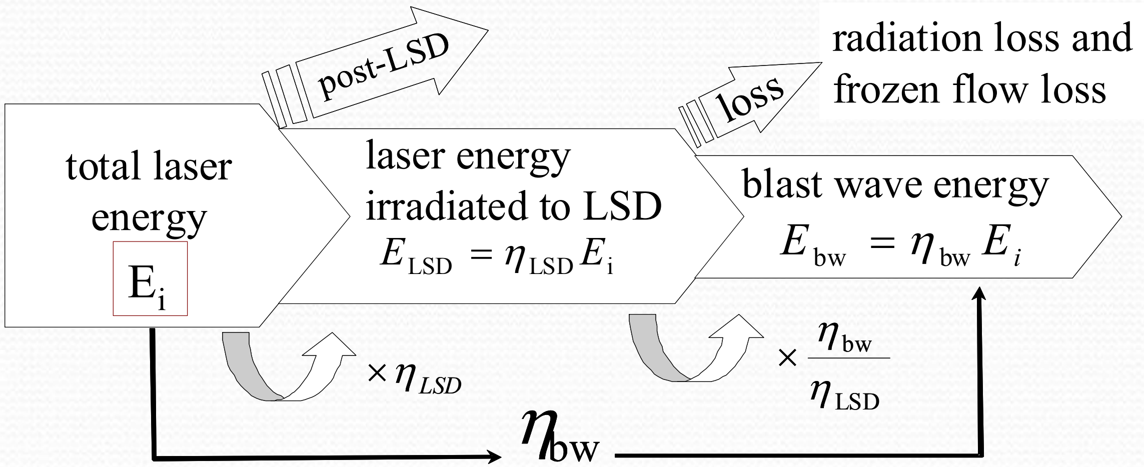
LSD → LSC

LSC



Measured plasma density profiles.

How to define energy efficiencies



LSD energy efficiency

$$\eta_{LSD} = E_{LSD} / E_i \tag{5}$$

Blast wave energy efficiency

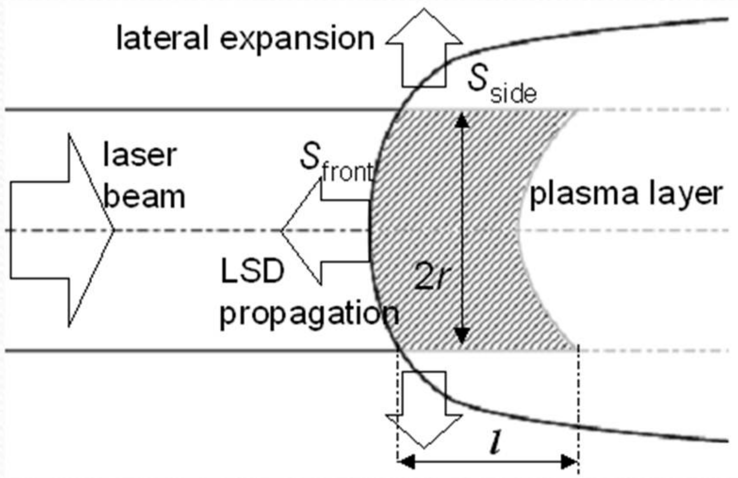
$$\eta_{bw} = E_{bw} / E_i \tag{6}$$

Raizer's LSD termination theory

- LSD speed at choking condition (minimum to maintain detonation)

$$D = \left[2\left(\gamma^2 - 1\right) I_0 / \rho_a\right]^{\frac{1}{3}} \qquad (1)$$

D is approximately 100 km/s when a 10 MW beam is focused on a circle of 0.1 mm diameter in the atmosphere (ρ_0 = 1 kg/m^3).



r: LSD wave spot size

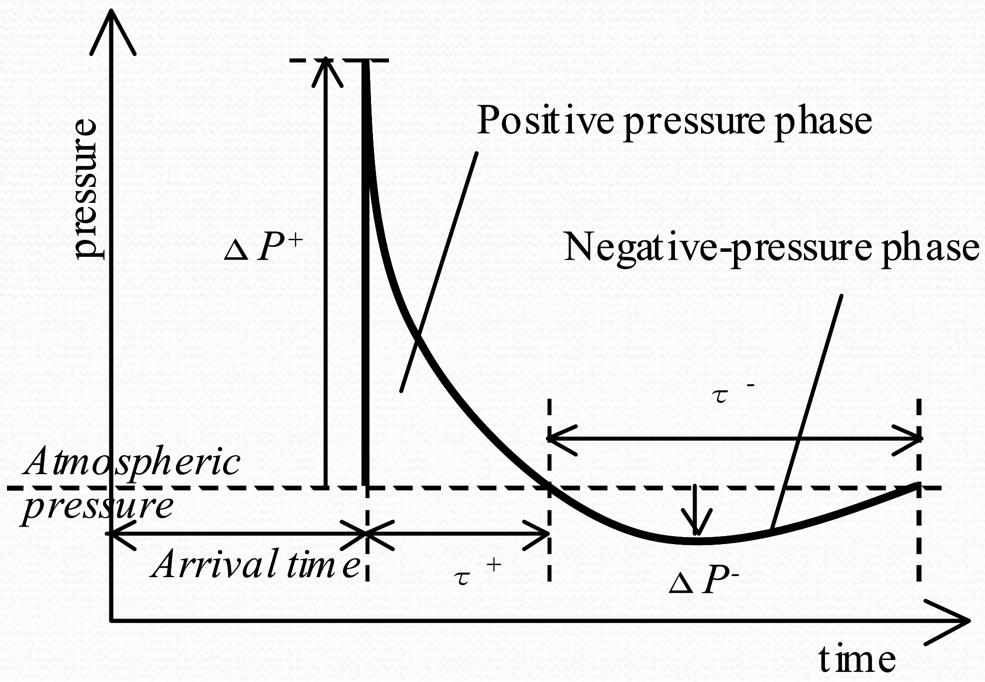
l: absorption layer thickness

Schematic of LSD enthalpy balance.

- LSD Termination condition

$$\left(\frac{2\pi r l}{\pi r^2} = \right) \frac{S_{\text{side}}}{S_{\text{front}}} \approx 8 \qquad (2)$$

Self-similar structure of a blast wave



Pressure history measured on a gauge set at a certain distance from the explosion source.

Definition of the blast wave energy E_{bw}

Explosion Source Model

Adiabatic expansion of the blast wave can be expressed using Sedov-Taylor self-similar solution.

$$16\pi\xi_0^{5}/75\gamma V_{bw}(t)M(t)^2 = E_{bw}/p_a = R^{*3} \tag{3}$$

E_{bw} : source energy necessary to drive an equivalent blast wave in a calorically perfect gas.

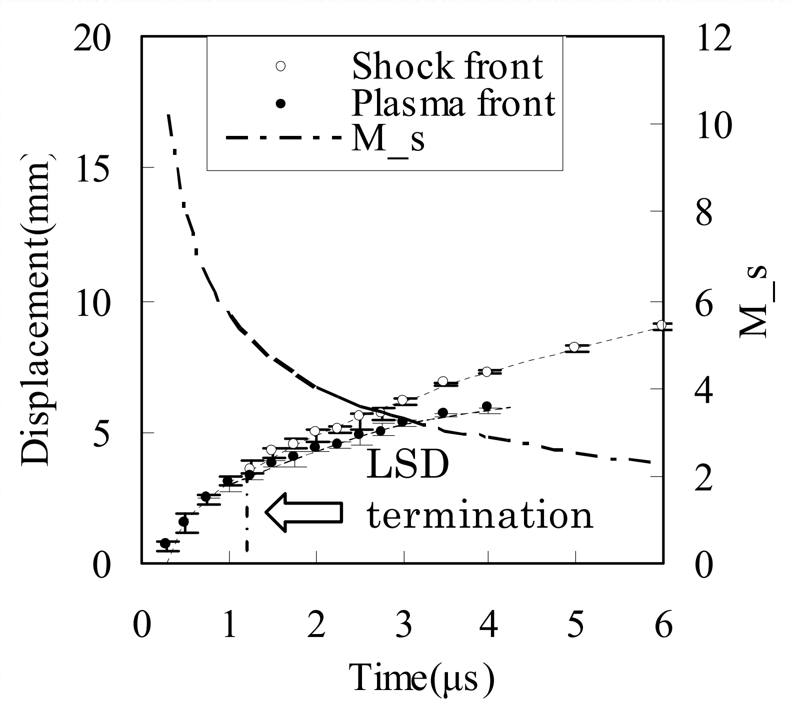
R^* : Characteristic radius of a blast wave

Let the source radius r_0 to be 0.15 R^*. M is a function of the distance r from the source as,

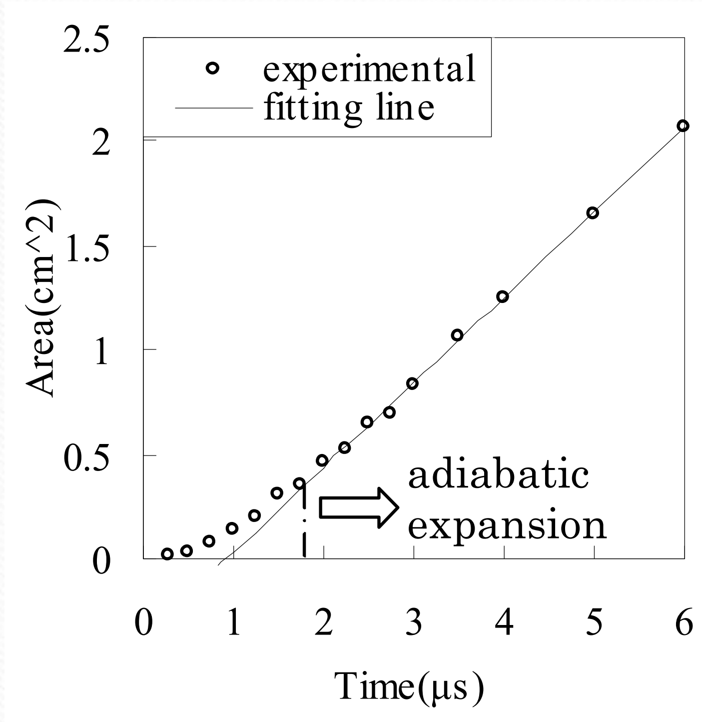
$$M = \left\{\left(M_0^{\ 2} - 1\right)\left(r_0/r\right)^{2K} + 1\right\}^{1/2} \tag{4}$$

E_{bw} or M_0 is deduced from measured shock expansion speed with fitting to the self-similar solution.

Fitting to the self-similar solution

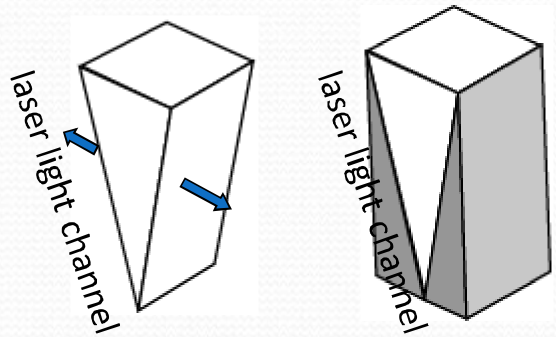


Displacements of a shock front and plasma front



History of S_{bw} (area surrounded by a blast wave).

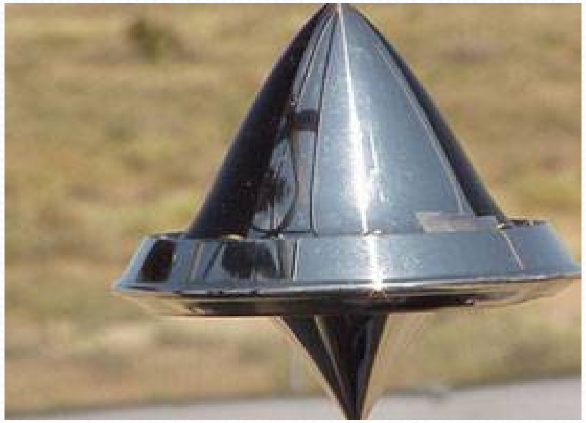
Measured efficiencies

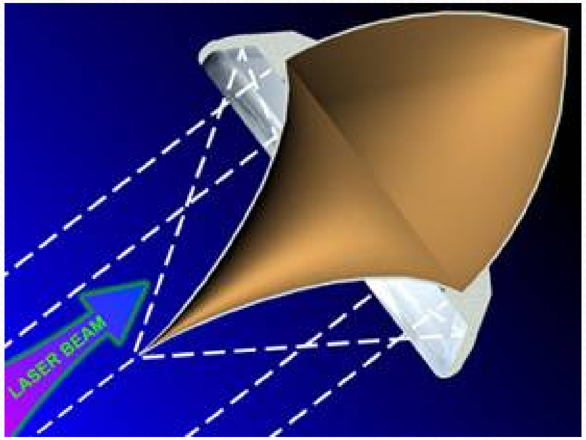


Dimension of phenomena	2-D	quasi 1-D
focal length / beam diam.	1.5	2.0
η_{bw}[%]	33	37
t_{LSD}[ms]	1.2	1.8
S_{LSD}[MW/cm^2]	3.4	1.7
M_{LSD}	5.3	6.3
η_{LSD}[%]	68	81
η_{bw}/η_{LSD}	49	47

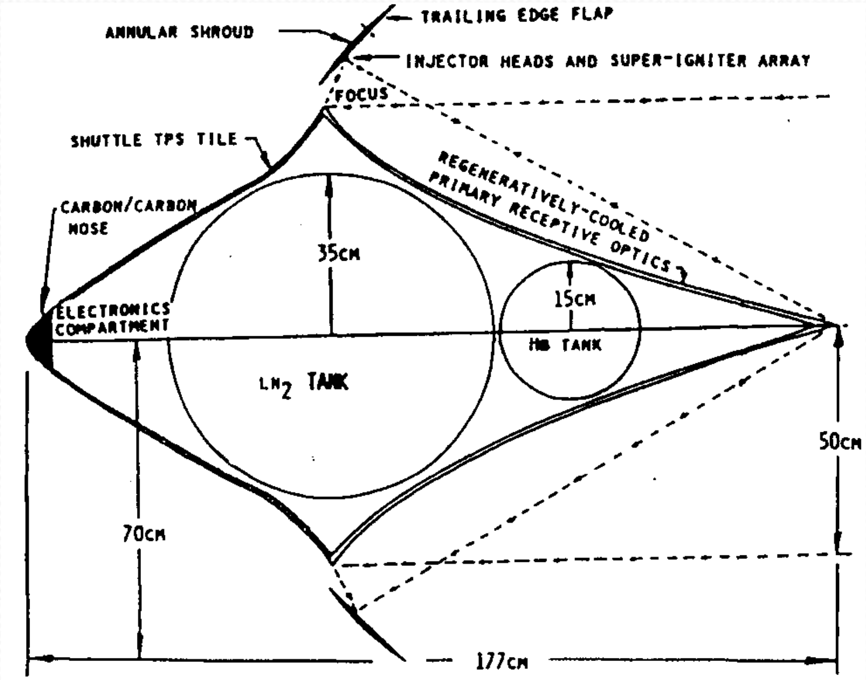
- Enthalpy confinement is effective for LSD sustention.

Laser Lightcraft (Dr. Leik Myrabo)

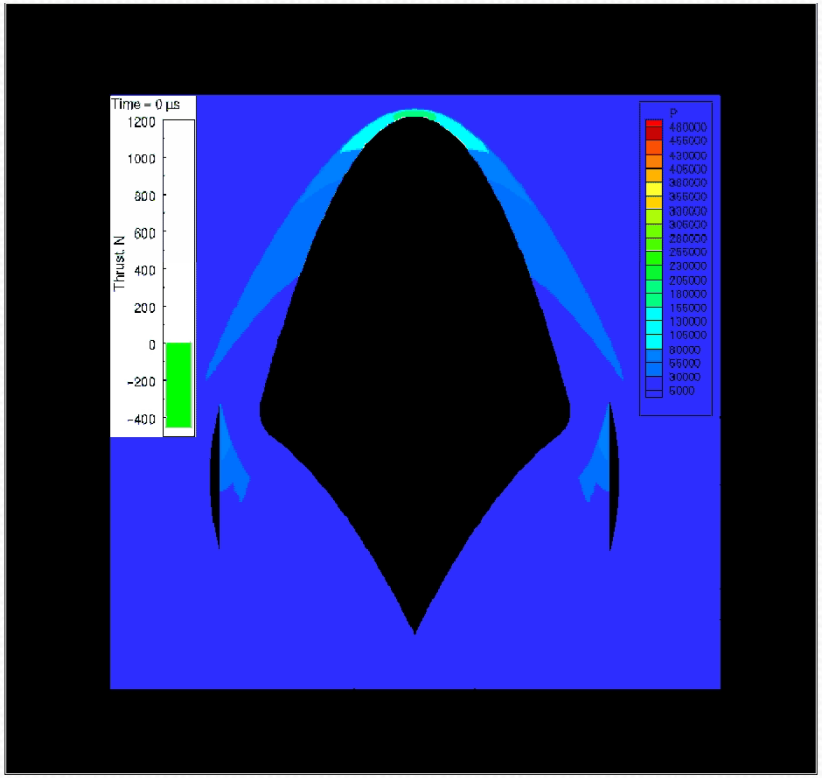




Thrusting Mechanism

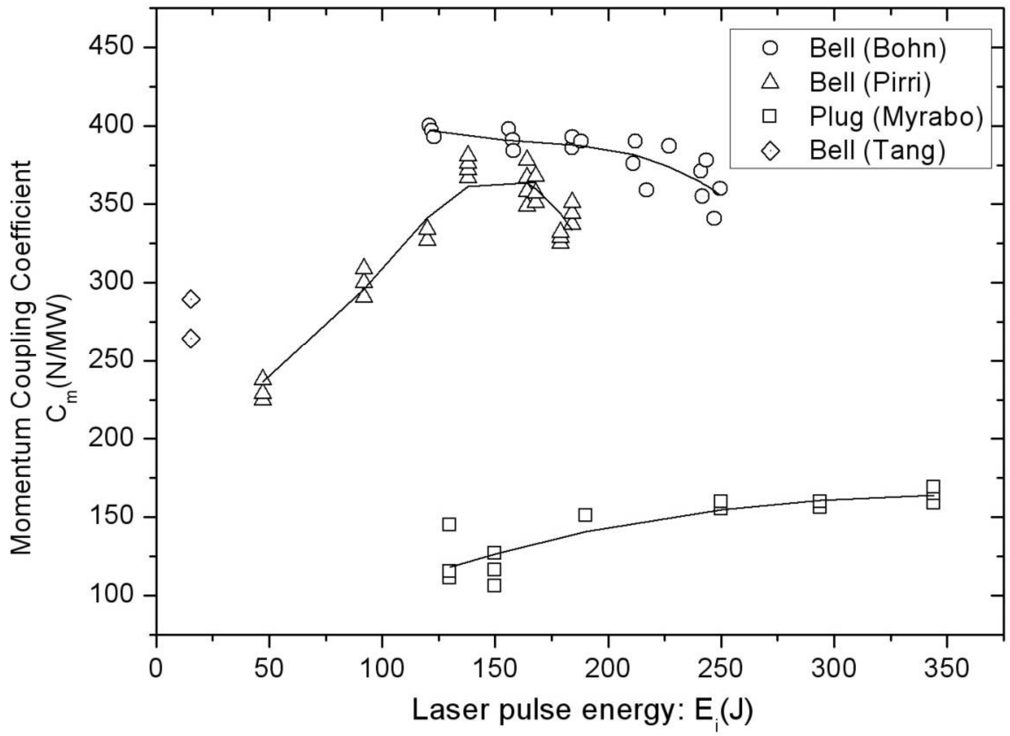


Cross section view of the Lightcraft.



Computed pressure contours in Lightcraft during the supersonic flight (M=10).

Momentum Coupling Coefficient



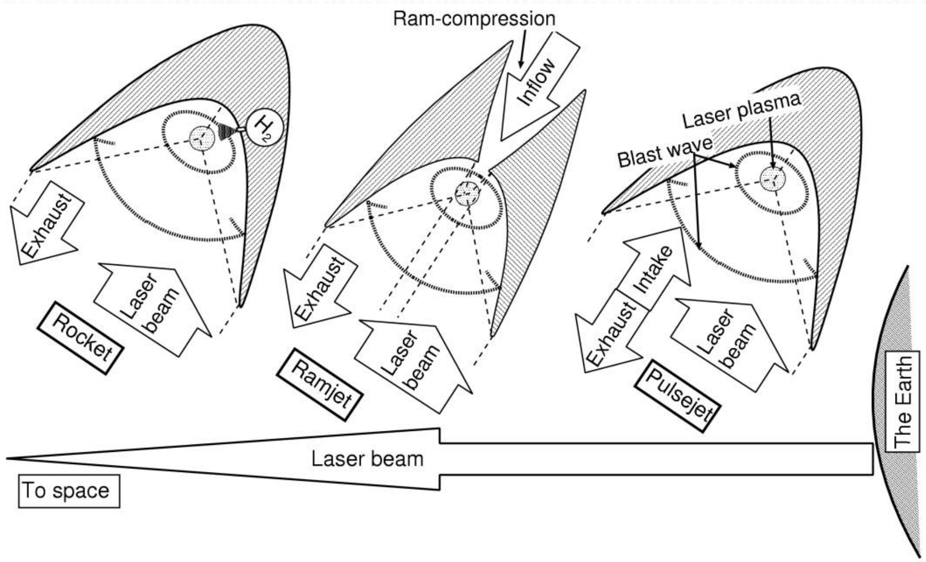
$$C_m = \frac{F\Delta t}{P\Delta t} = \frac{I[\mathrm{N}\cdot\mathrm{s}]}{W[\mathrm{J}]} = [\mathrm{N/W}]$$

Momentum coupling coefficient

Flight modes

Flight modes

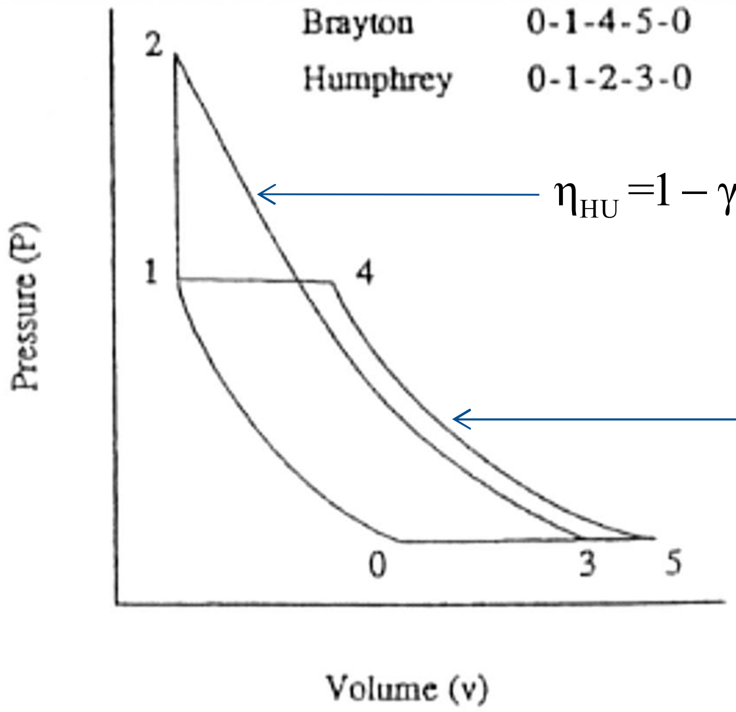
Flight modes	**Flight *M***	Altitudes
Pulsejet	～5	～10km
Ramjet	～12	～40km
Rocket	12～	40km～



Laser SSTO (Single Stage to Orbit)

Laser-Ramjet engine cycle

- Utilize atmosphere as a propellant
- Intake resembles to SCRAMjet one.
- No difficulties in fuel/air mixing .
- No air pollution



$$\eta_{HU} = 1 - \gamma T_0 / T_1 \left\{ \frac{(T_2/T_1)^{1/\gamma} - 1}{T_2/T_1 - 1} \right\}$$

$$\eta_{BR} = 1 - T_0 / T_1$$

$$\eta_{HU} > \eta_{BR}$$

P-*V* diagram of the engine cycles

Rocket exhaust and environment compliance

Atmosphere pollution caused by highly frequent launches of chemical rockets is of great concern especially for equipping space infrastructures; ex. future space station, Solar Power Satellite etc.

Troposphere (-15km): NOx and carbon exhaust.

Stratosphere (15-50km altitude): Ozone halls by H_2O etc.

⇒ Important technology for environment compliance

Summary

Detonation Thrusters

1. Laser energy is directly converted to pressure via Laser Supported Detonation.
2. Energy conversion efficiency from laser to pressure of about 40% has been achieved.
3. Air-breathing/Pulse Detonation Engine(PDE) will realize efficient engine cycle for supersonic flight.
4. Environment compliance is another advantage of this system.

References

- Y. P. Raizer, *Laser-Induced Discharge Phenomena*. New York, NY, USA: Springer-Verlag, 1978.

- Myrabo, L. N. (2001).World Record Flights of Beam-Riding Rocket Lightcraft, AIAA Paper 2001-3798.