「先端宇宙推進工学」

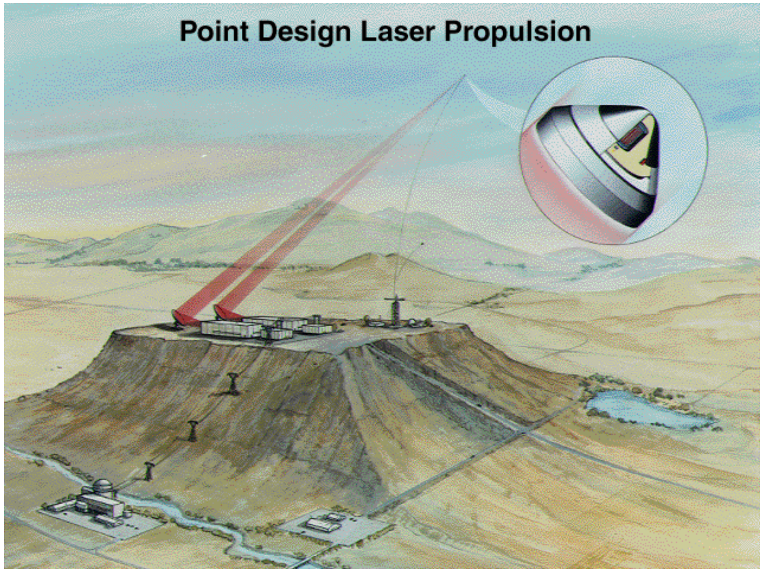
３限　ビームエネルギー推進

1. ビームエネルギー推進とは
2. デトネーション型レーザー推進/マイクロ波ロケット
3. ワイヤレスエネルギー伝送
4. 宇宙へ行くシナリオ
5. 想定される大量物資輸送ミッション

小紫公也

1．様々なビームエネルギー推進

"Distinguished by its use of a collimated laser or microwave beam"



Concept of laser propulsion system

ビームエネルギー推進の分類

- I. Powered by Ground /Space-based Lasers
  - 1. Ablative Thrusters
    - Solid and Liquid Ablative
    - 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
  - 2. Laser-electric Hybrid thrusters
  - 3. Relativistic Acceleration Thrusters

打ち上げ推進システムとしての利点

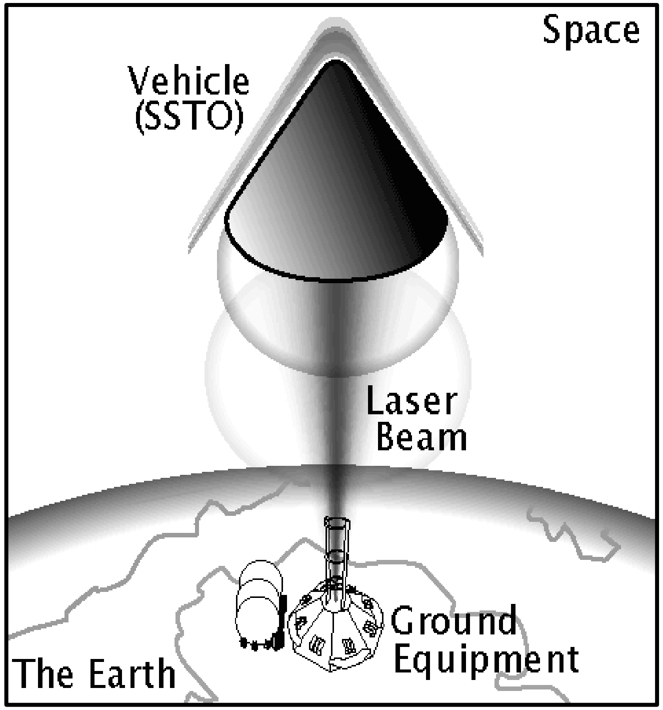
1. Propulsion parameters are not limited by propellant chemistry.
2. Thrust is a function of available laser power, and *high acceleration* is achievable (greater than 10*g*.)
   - ・The craft need not to park in a low earth orbit and
   - ・can head directly for a geosynchronous or *supersynchronous orbit*.
3. No-fuel flight is realized in *air-breathing* flights in the atmosphere.
4. 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.
5. Laser facility, the most complex and expensive one, is maintainable and replaceable at any time on the ground.
   - ・*Redundancy* without vehicle-mass penalty.
   - ・*Reusable*
6. *low-cost*, *low-emission*, and *resource-saving*

宇宙機の推進システムとしての利点

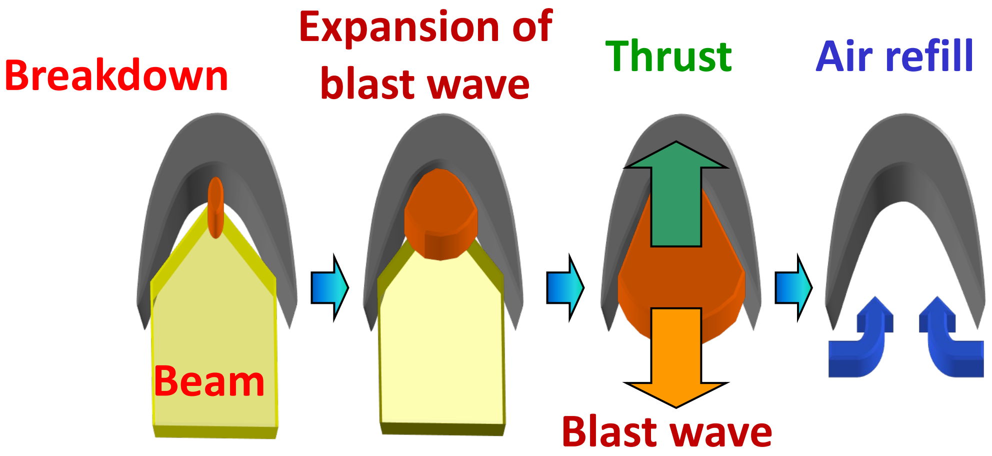
1. Using a remote power supply from space-based lasers, *unlimited specific power* (power per thruster system weight) would be available (greater than that of solar electric propulsion)
   ・*Mission period shortened*.
2. Plasma is generated and sustained apart from chamber walls or electrodes, so that a *higher gas temperature > 10,000K* is expected at higher pressure than EP.
   ・*low propellant consumption*
3. <u>Laser micro-thrusters</u> 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*

2. デトネーション型レーザー推進

地上から供給する電磁ビームで駆動
空気を吸いこんで推進剤とする



A laser launcher.



パルスデトネーションエンジンサイクル

デトネーション推進打ち上げ機の利点

Beam oscillators on the ground → Reusable, redundant → Amortizable constraction cost

Coupling with advanced aerospace technologies

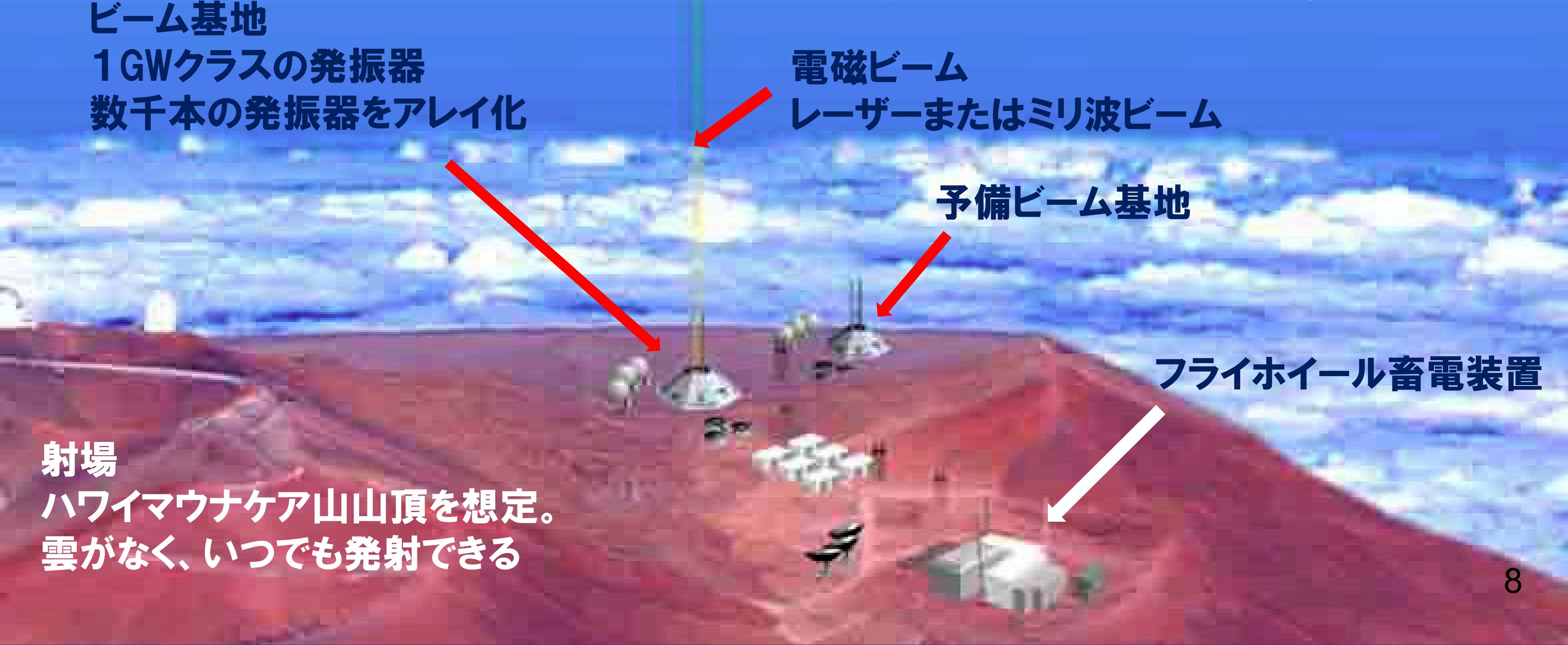
Air-breathing → No combustion, infinite I_{sp} → High payload ratio

Pulse detonation → No turbo-pumps → Low manufactureing cost

再使用性・冗長性

最も高価なビーム基地を再使用

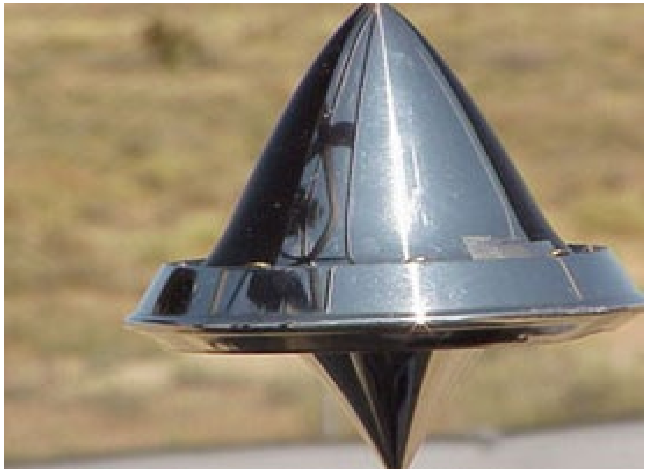
・レーザー寿命まで使い切る
・建設費償還が打ち上げ回数に反比例
・保守点検が容易
・冗長システムがペイロード比に影響しない



“光のハイウェイ”と“ビームライディング”

打ち上げ想像図

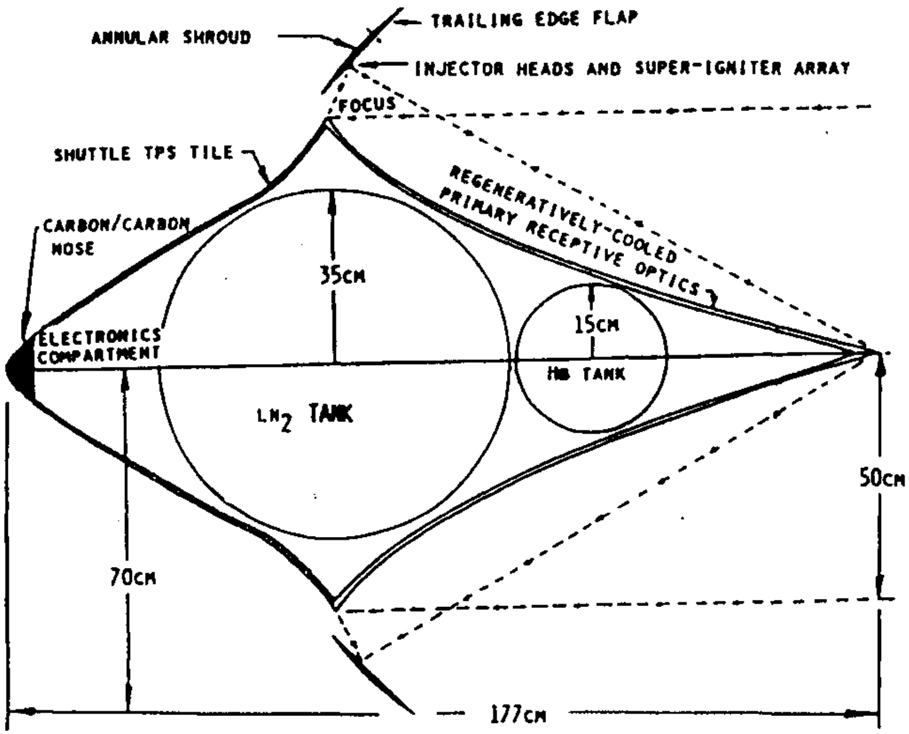
レーザーライトクラフト

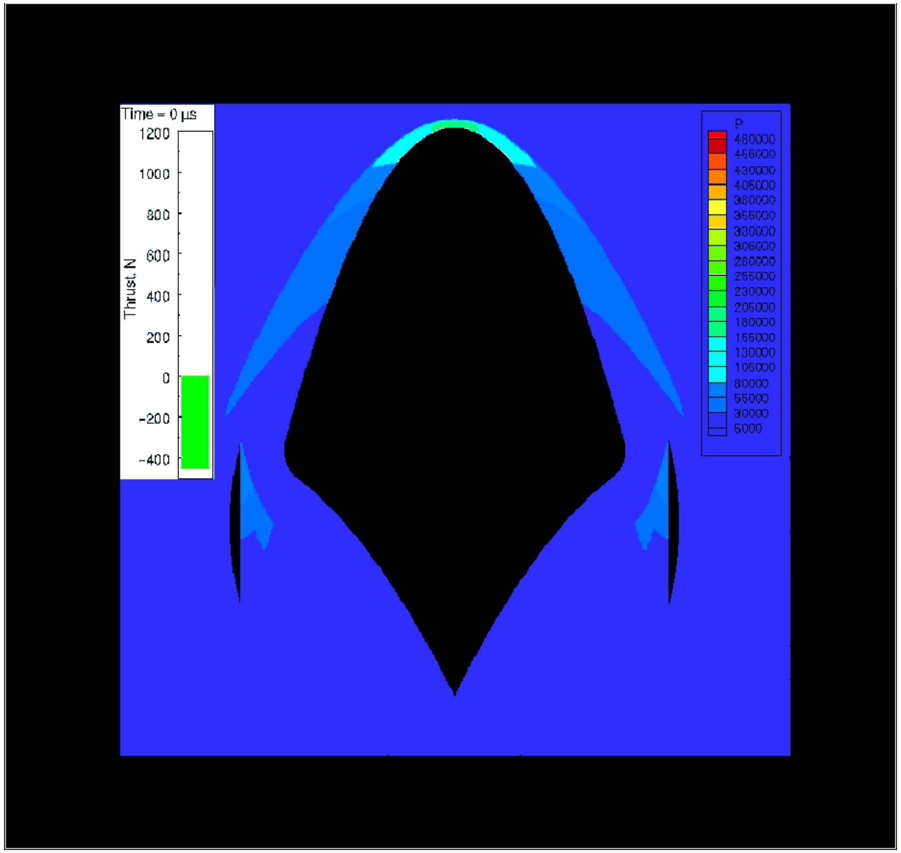


ライトクラフト 米空軍/NASA

打ち上げ高度世界記録達成(2000)

推力発生メカニズム

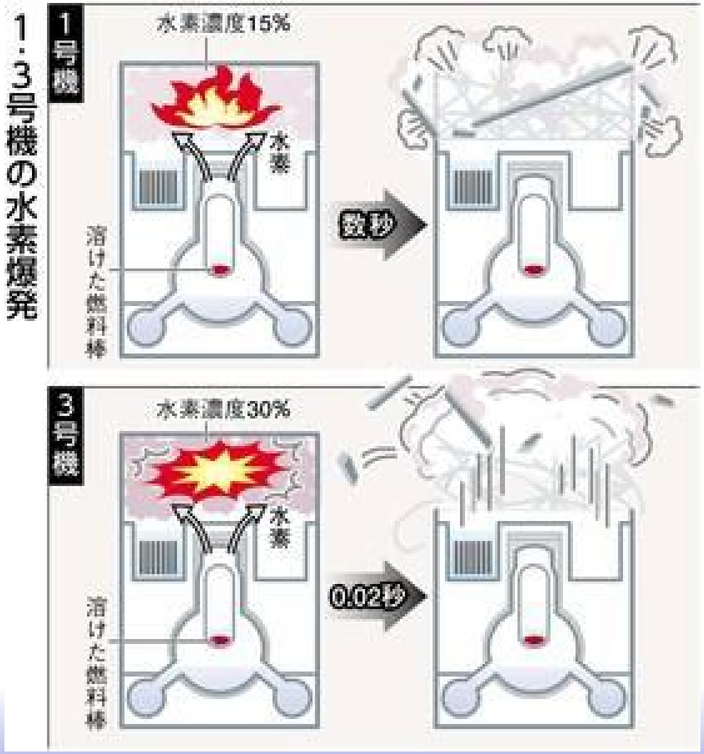




爆風によって推進機が押される様子

爆轟（デトネーション）

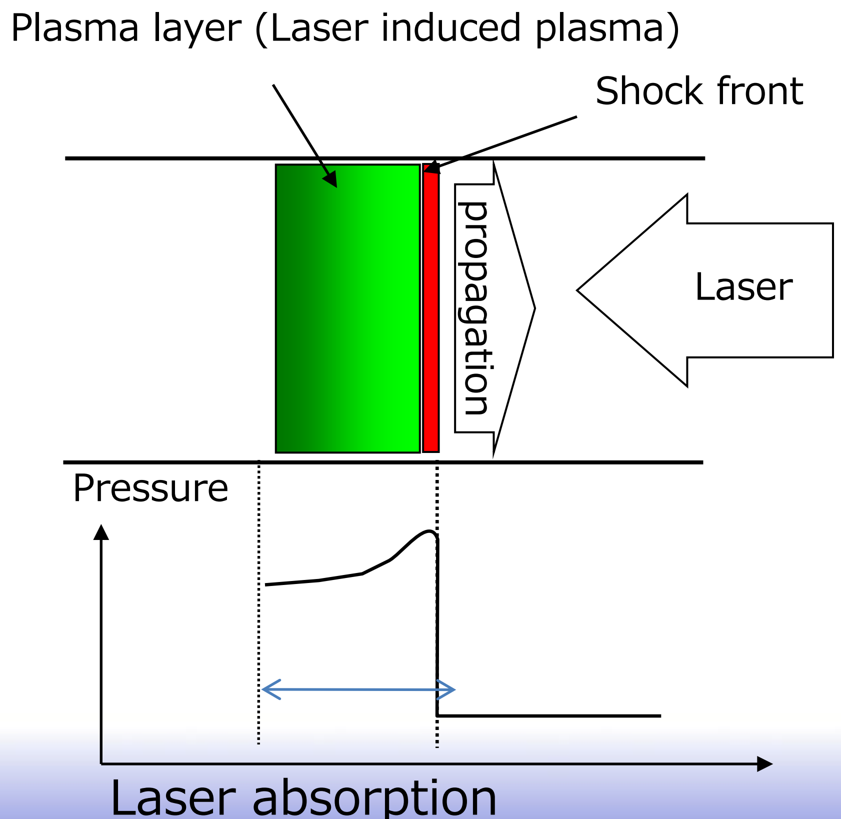
可燃気体と空気が混合した状態で着火した場合、火炎の伝播速度が音速を超え衝撃波を伴いながら燃焼する現象



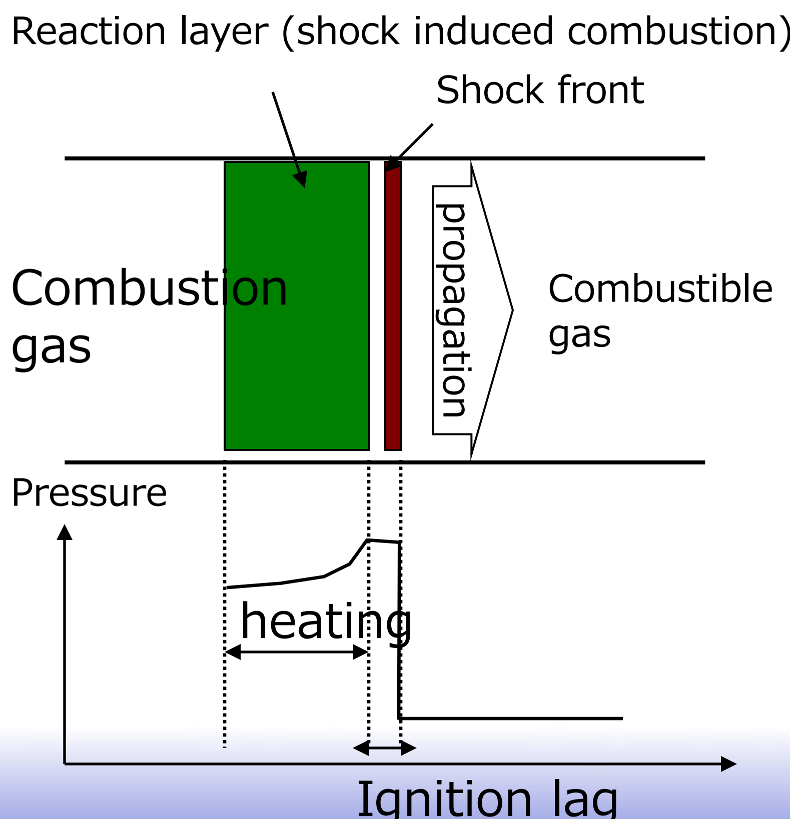
東京電力福島第一原発３号機で起きた水素爆発

レーザー爆轟と化学爆轟

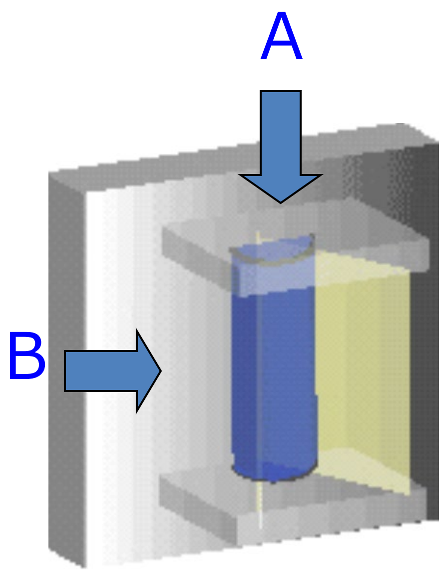
レーザー爆轟波

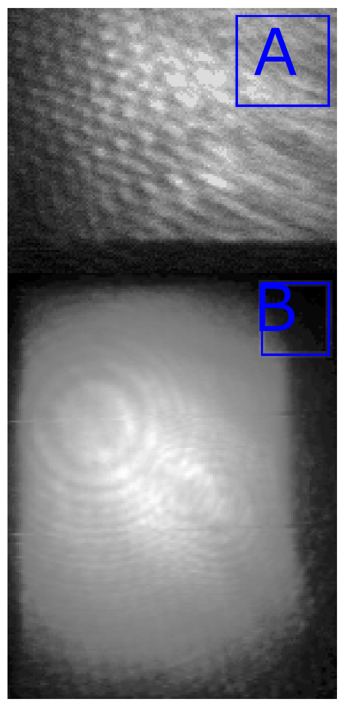


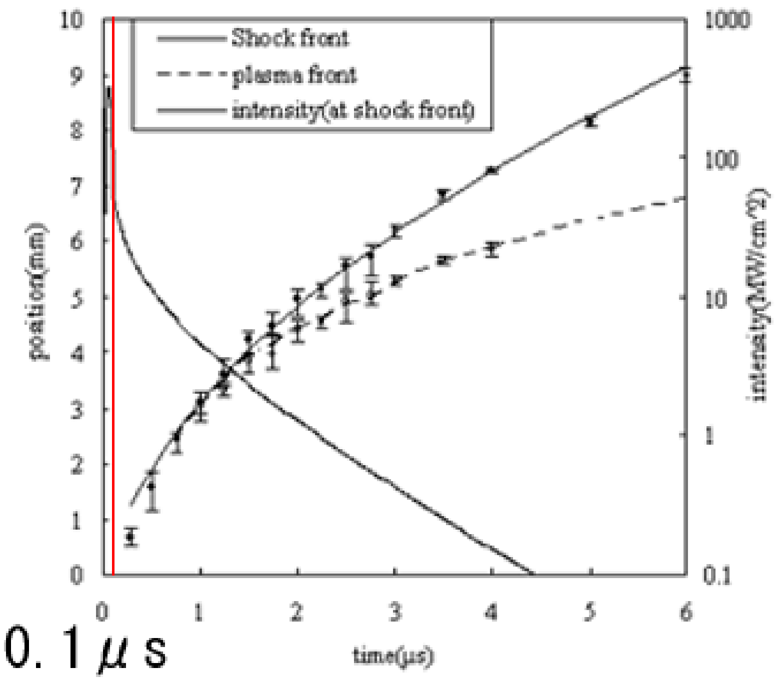
化学爆轟波



レーザー爆轟現象を可視化すると







Shadowgraph image

A shock front and ionization front displacements

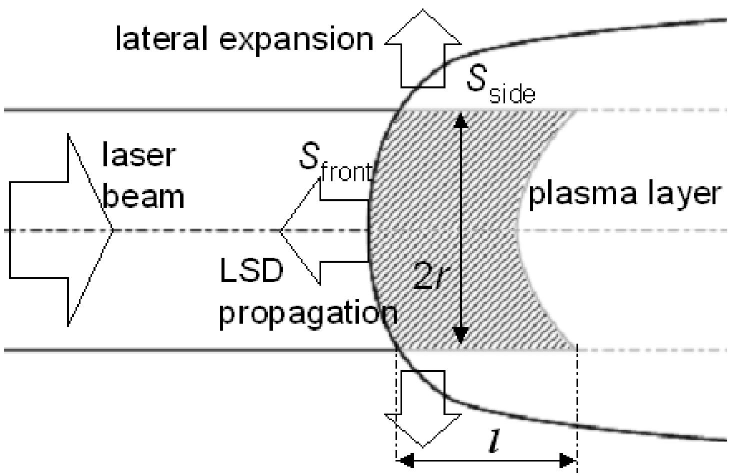
レーザー爆轟の維持条件

Raizer's empirical theory

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

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

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



r: LSD wave spot size

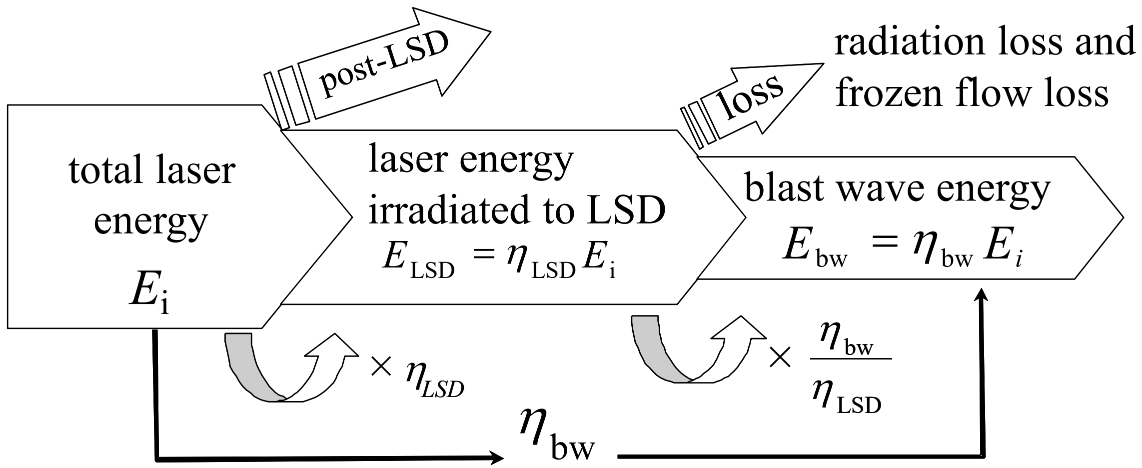
l: absorption layer thickness

- LSD Termination condition

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

Schematic of LSD enthalpy balance.

レーザーエネルギーから圧力への変換効率



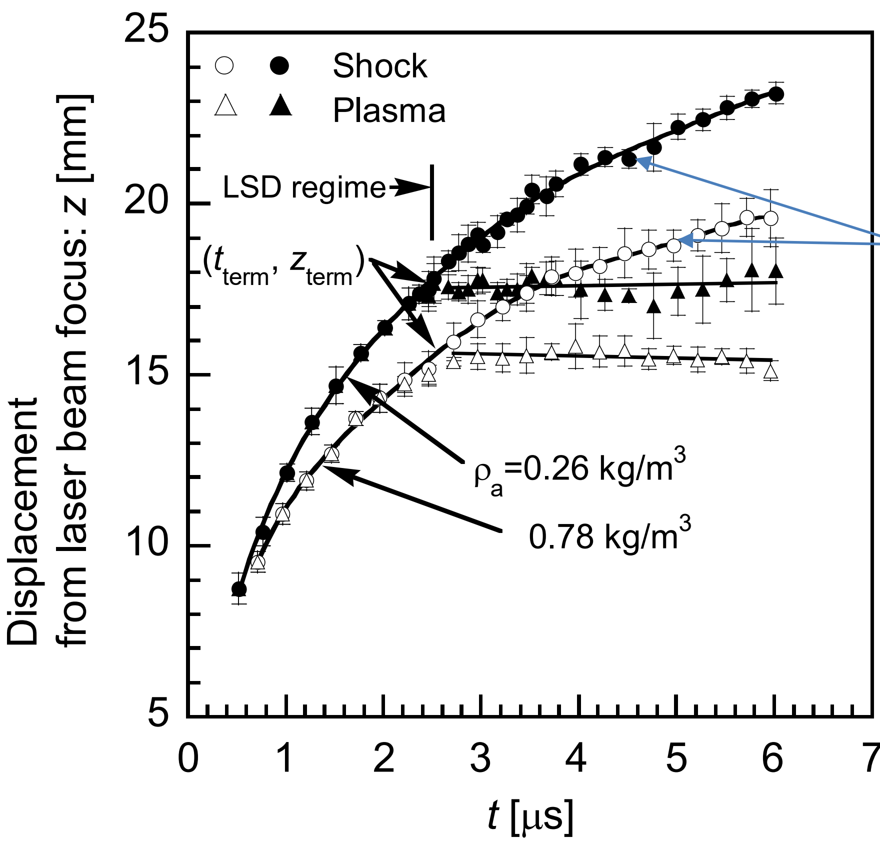
LSD energy efficiency

$$\eta_{LSD} = E_{LSD} / E_i \qquad (3)$$

Blast wave energy efficiency

$$\eta_{bw} = E_{bw} / E_i \qquad (4)$$

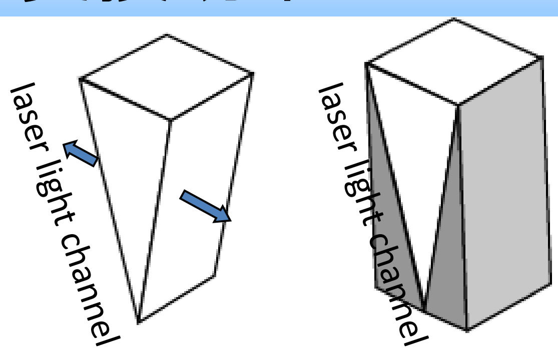
爆風波エネルギーの求め方



Adiabatic expansion range is fitted to the self-similar solution

Displacements of a shock front and plasma front

測定された変換効率



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.

デトネーション型レーザー推進まとめ

1. Laser energy is directly converted to pressure through 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 low-weight vehicles and efficient supersonic flights.
4. Environmental acceptability is another aspect of this system.

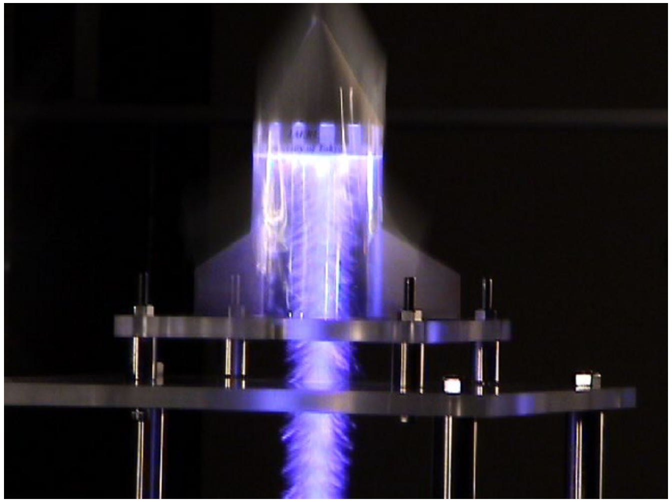
References

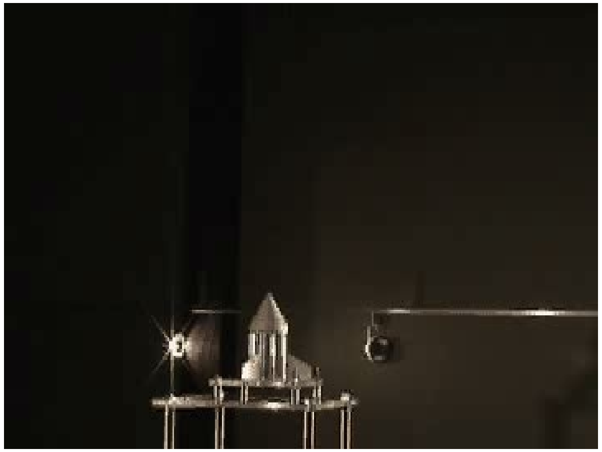
- Y. P. Raizer, *Laser-Induced Discharge Phenomena*. New York, NY, USA: Springer-Verlag, 1978.

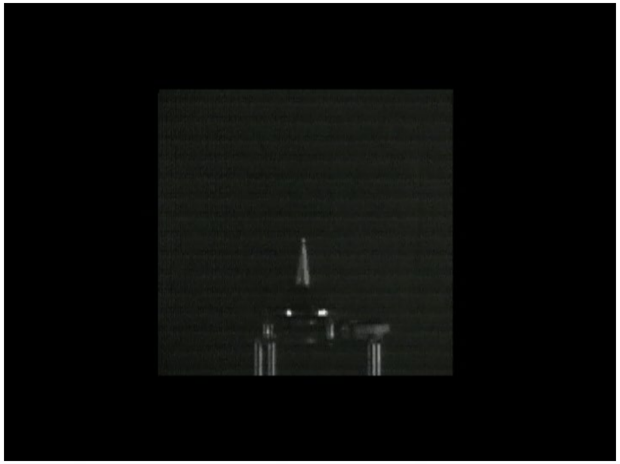
- Myrabo, L. N. (2001).World Record Flights of Beam-Riding Rocket Lightcraft, AIAA Paper 2001-3798.

３．　マイクロ波ロケット

Not Laser, but Microwave!

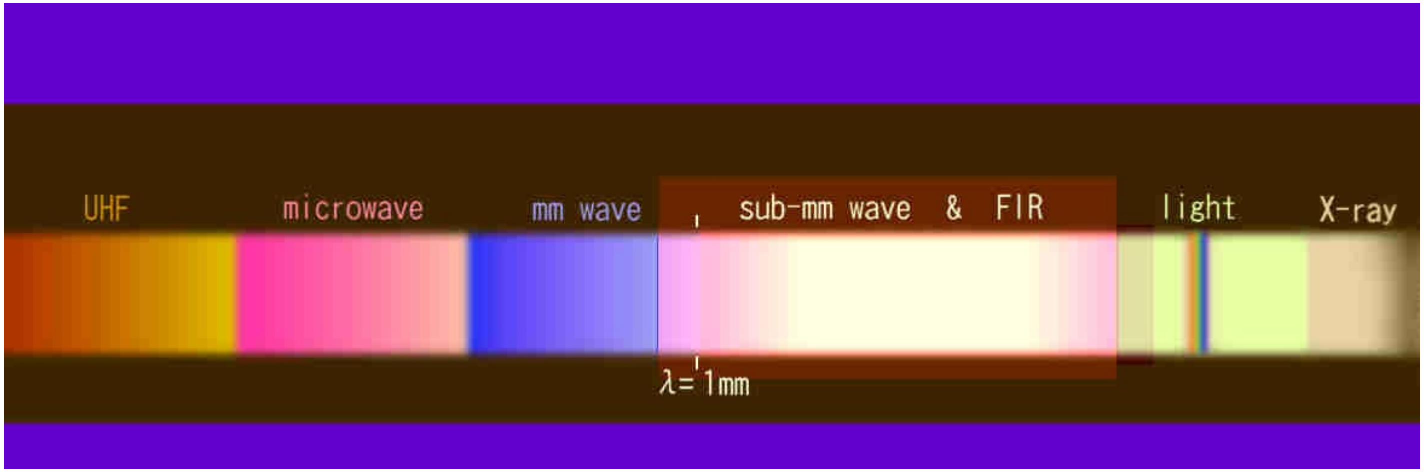






Vertical Launch experiment in 2003.
A 9.5-g model was lifted up to 2 m altitude.

ミリ波/テラヘルツ波: 新技術分野



ミリ波，　サブミリ波、テラヘルツ波

Millimeter-waves are in use for

- ✓ Weather radars, Defense radars
- ✓ Collision avoidance radars for automobiles,
- ✓ Body scanners
- ✓ Inter-satellite communications

ミリ波利用の利点

1. Availability of a GW-class beam station.

- Microwave sources are technically easier than laser sources. eg. Magnetron, Gyrotron, etc.

- Economically affordable. 0.1 \$/W will be achieved. cf. laser source 10 \$/W (diode laser).

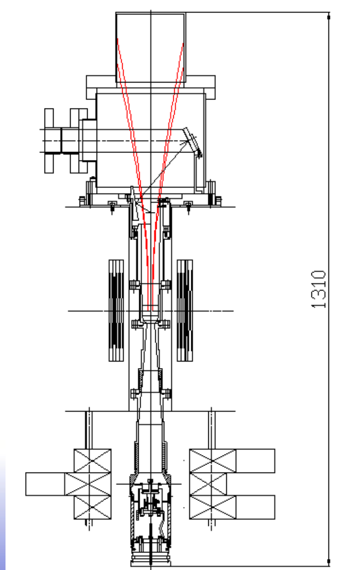
2. High DC-RF conversion efficiency.

- Magnetron 90%, Gyrotron 60%. cf. Diode laser 50%, Solid laser 20%.

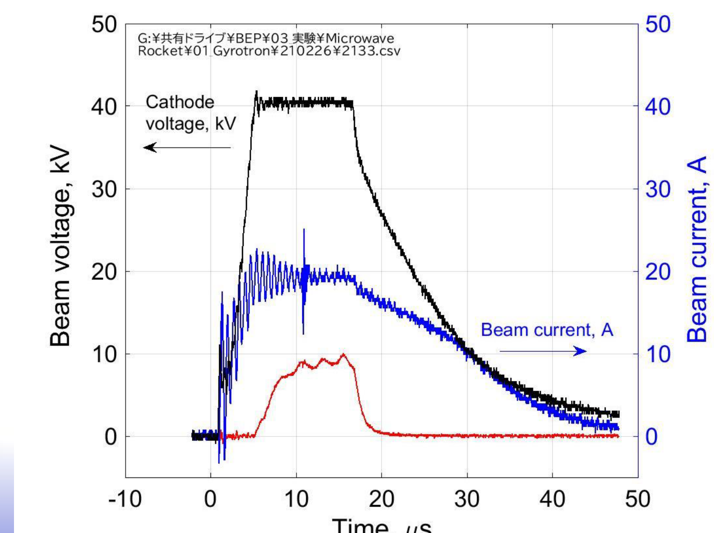
- Cooling capability is the key issue.

高出力ミリ波発信源 ジャイロトロン

	Gyrotron facilities available for atmospheric discharge research					
	MIT	QST	Inst. Applied Physics, RAS	Tsukuba Univ. Plasma R.C.	Fukui Univ. R.C. for Far-Infrared Region	Univ. of Tokyo
Frequency	110 GHz	137, 170, 203 GHz	263, 670 GHz	28 GHz	303 GHz	94 GHz
Beam power	1.5 MW	< 1 MW	< 250 kW	< 500 kW	104 kW	600 kW
Pulse duration	3 μs	10 ms	100 μs	10 ms	< 65 μs	100 μs

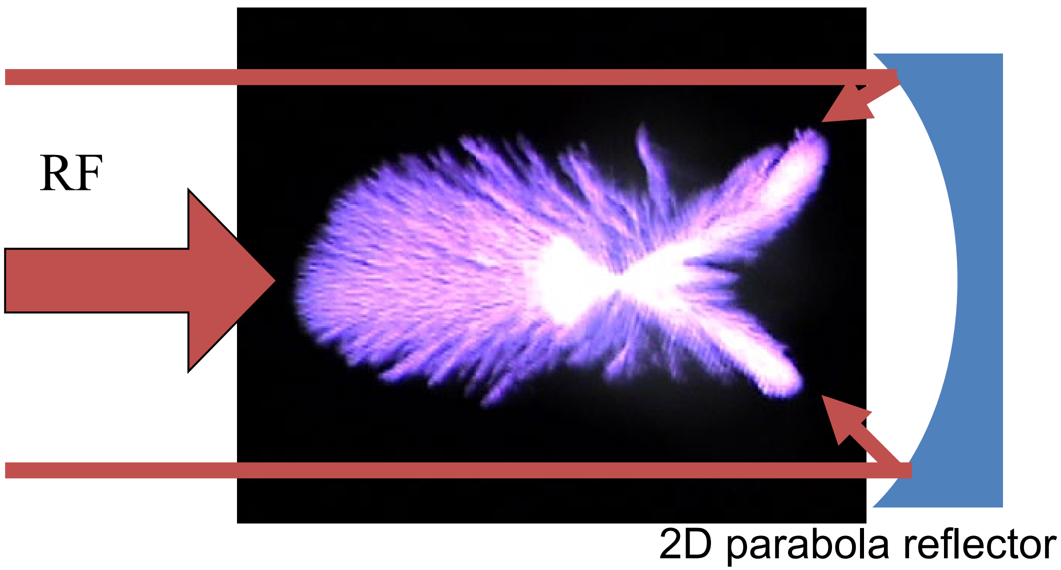


UTokyo 94 GHz gyrotron



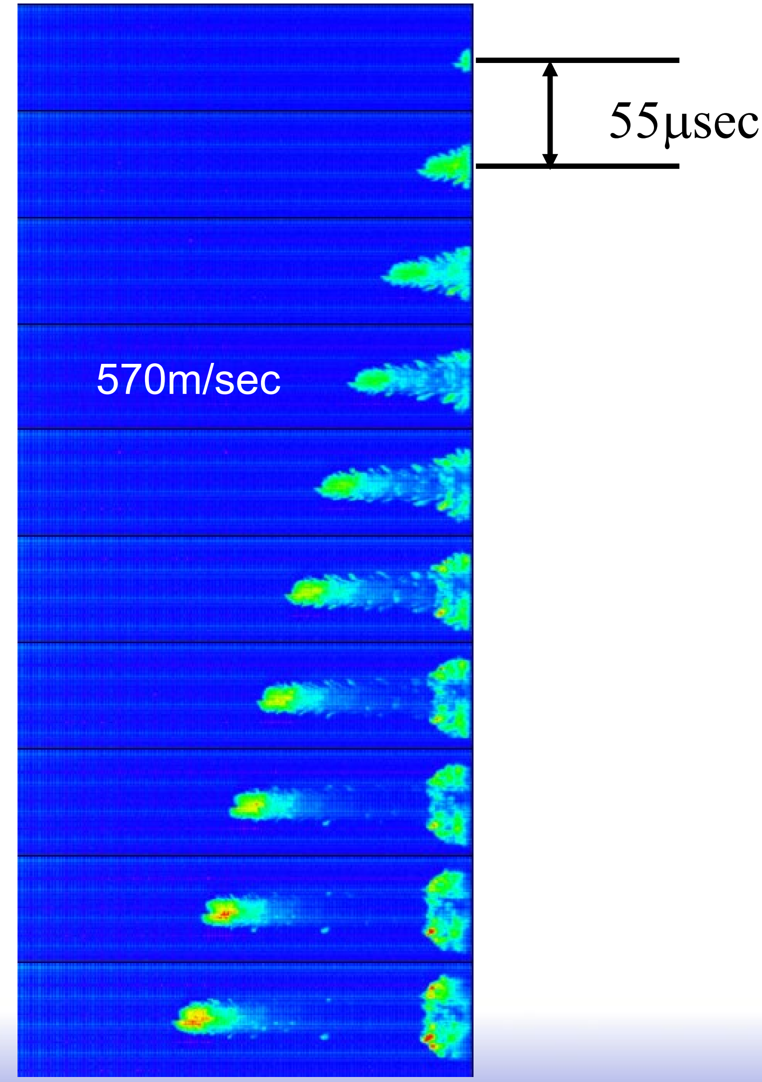
Typical output pulse

ミリ波による絶縁破壊と放電面の超音速伝播

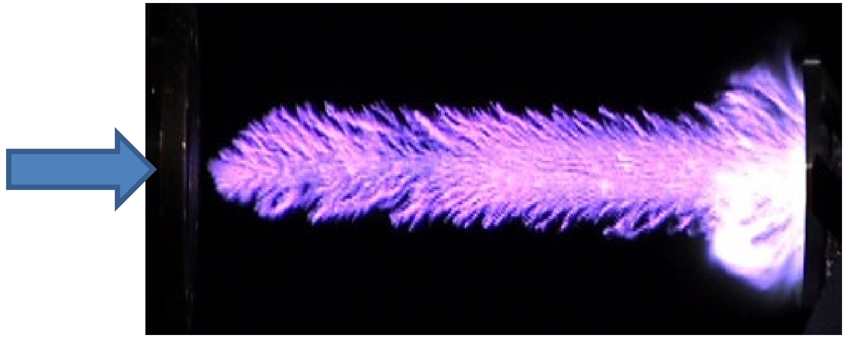


RF Power 930kW, Pulse duration 0.2 msec.

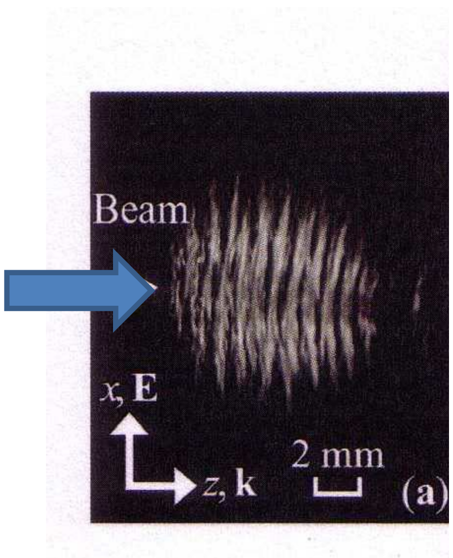
- Plasma is easily ignited



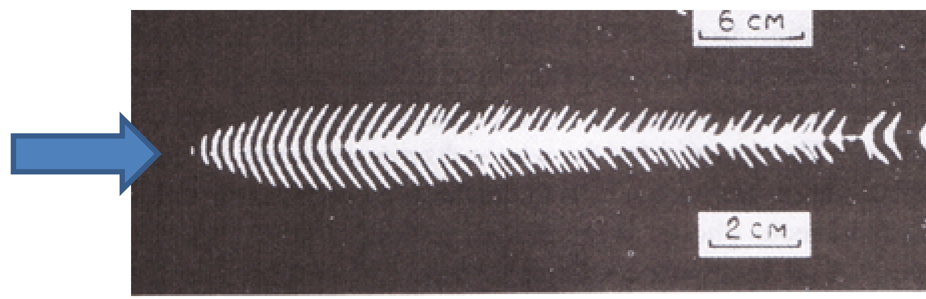
ミリ波放電におけるフィラメント構造



Atmospheric discharge (170 GHz, 0.1 MW/cm^2)
Oda, Y. et al. J. Appl. Phys. 2006.



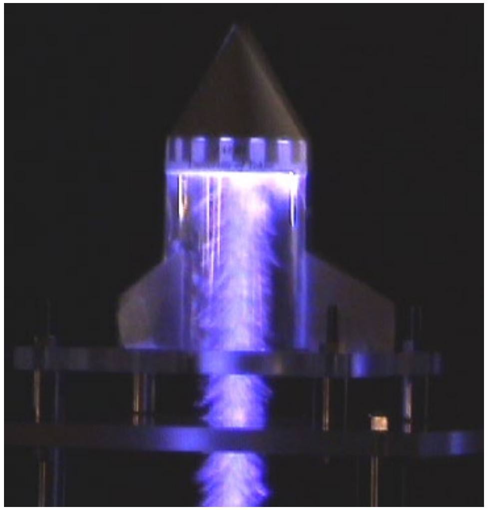
Discharge at focus (110 GHz, 3 MW/cm^2)
Hidaka et al. Phys. Rev. Lett. 2008.



Discharge in He (35 GHz)
Vikharev et al., *Sov. Phys, JETP*, 1988.

マイクロ波ロケット vs レーザーライトクラフト

マイクロ波ロケット



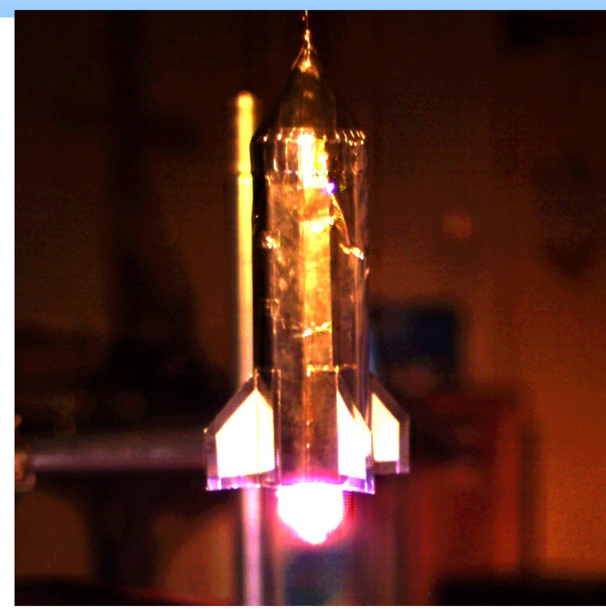
- Pulse width of a few ms
- Cylindrical detonation tube structure, similar to Pulse Detonation Engine (PDE).
- Thrust generated by stagnation pressure on the nose cone.

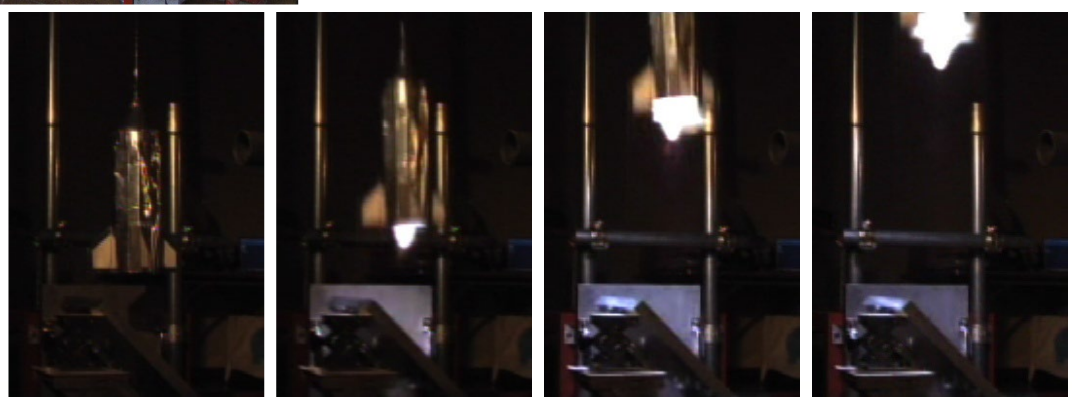
レーザーライトクラフト

Myrabo (1995)

- Pulse width of sub-ms
- High repetitive frequency of KHz
- Thrust generated by a blast wave reflection.

マイクロ波ロケット開発

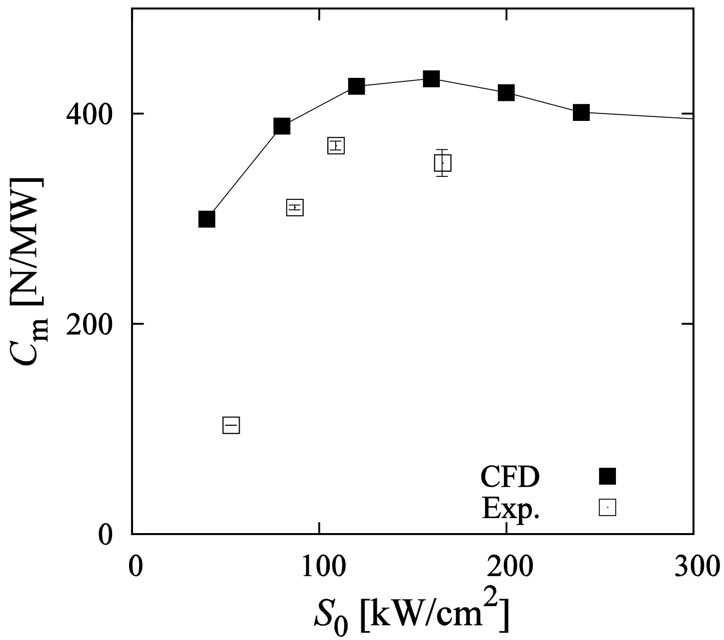




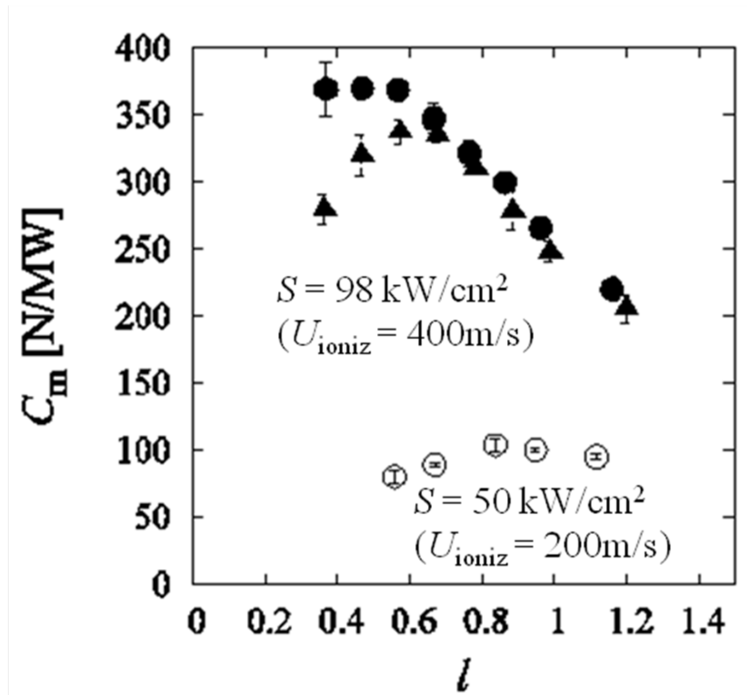
Φ100、L300、
109g（Al製）

Continuous thrust generation for 1.2 altitude was demonstrated.
Power: 600kW, PR frequency:100Hz,:1.25msec, Average power 75kW

単パルス照射時の推力電力比



C_m vs. S_0

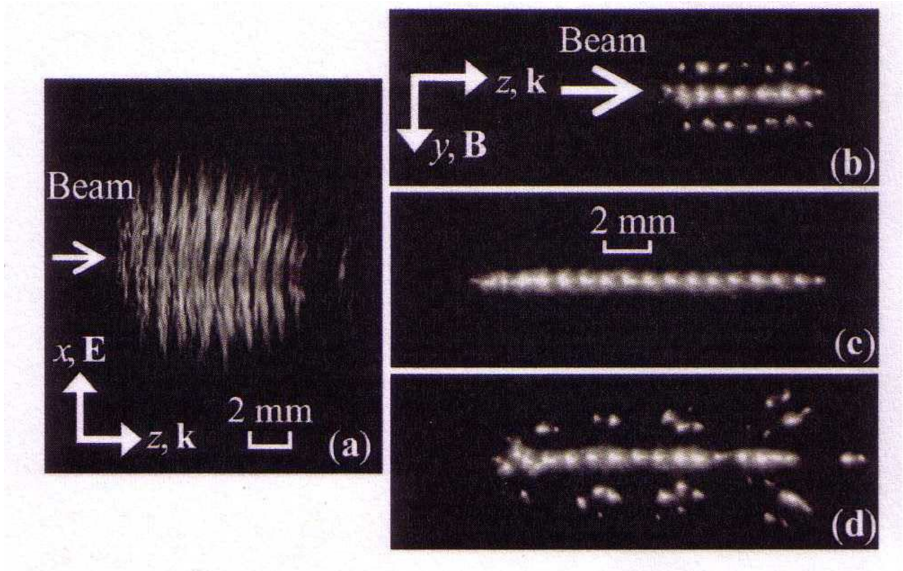


C_m vs. $l=L_{plasma}/L_{thruster}$.

Momentum coupling coefficient.

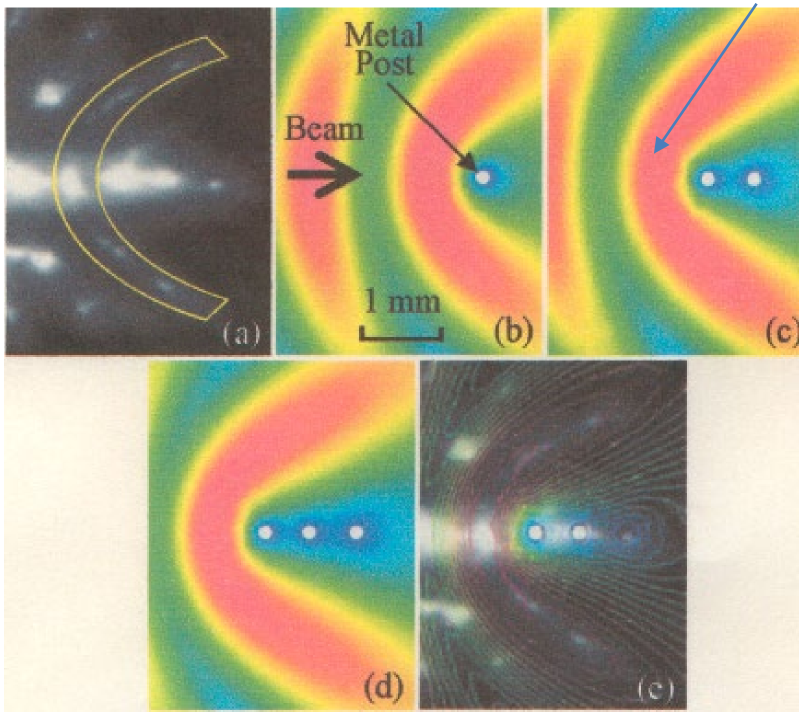
	C_m, N/MW
Microwave Rocket	350
Bell nozzle laser thruster	250
Lightcraft (repetitive)	150

λ/4 プラズマ構造の物理モデル



Measured λ/4 filamentary structures. (a) E plane, (b)-(d) H plane. Temkin *et al.*

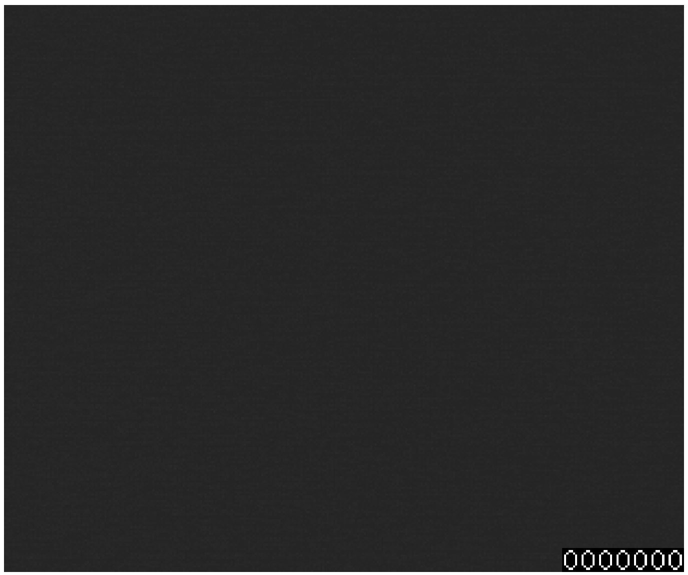
Standing wave



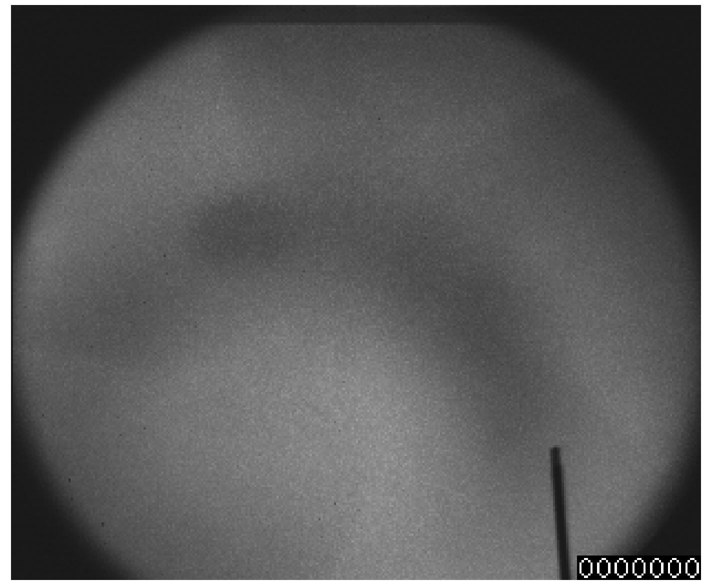
Computed filamentary structures in *H-z* plane.

Y. Hidaka et al., *Phys. Rev. Lett.*, 100, 035003 (2008)

マイクロ波支持デトネーションの発達の様子

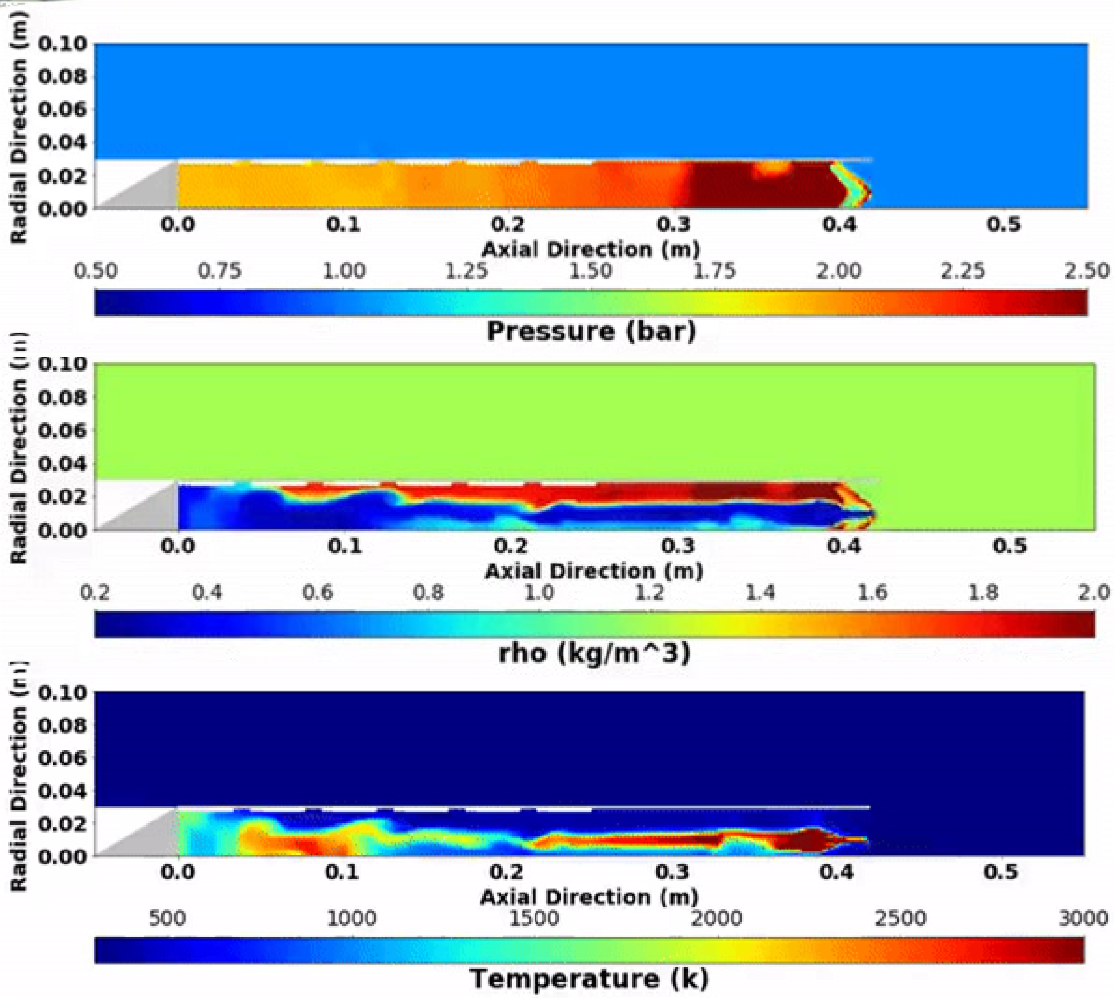


Self-emission images

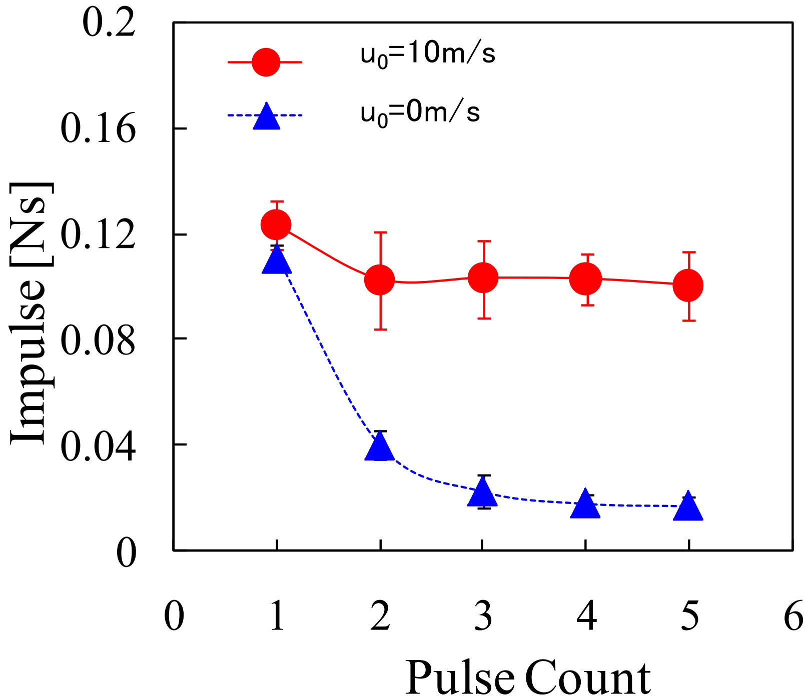


Schlieren images

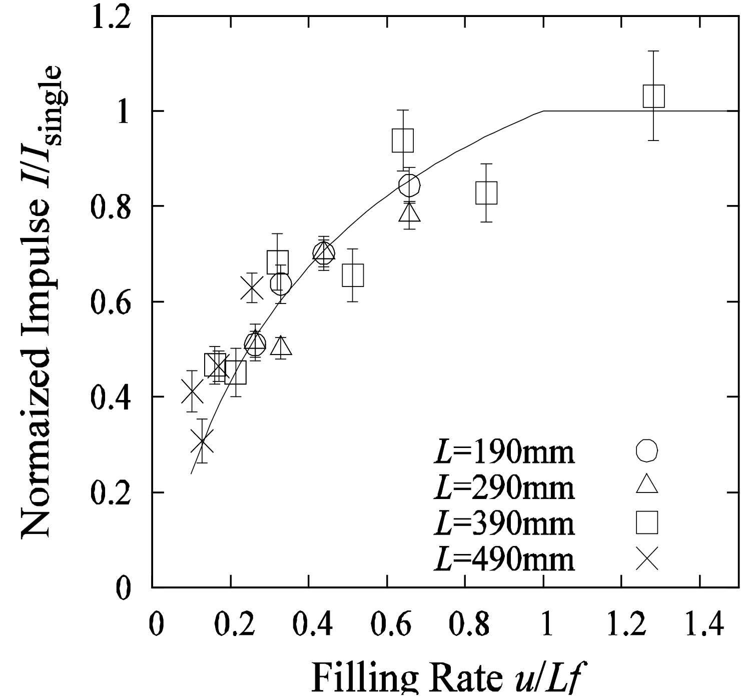
リードバルブを用いた吸気ステージ



繰り返しパルス照射時の性能(空気吸い込み有)



Measured impulse with and without forced breathing

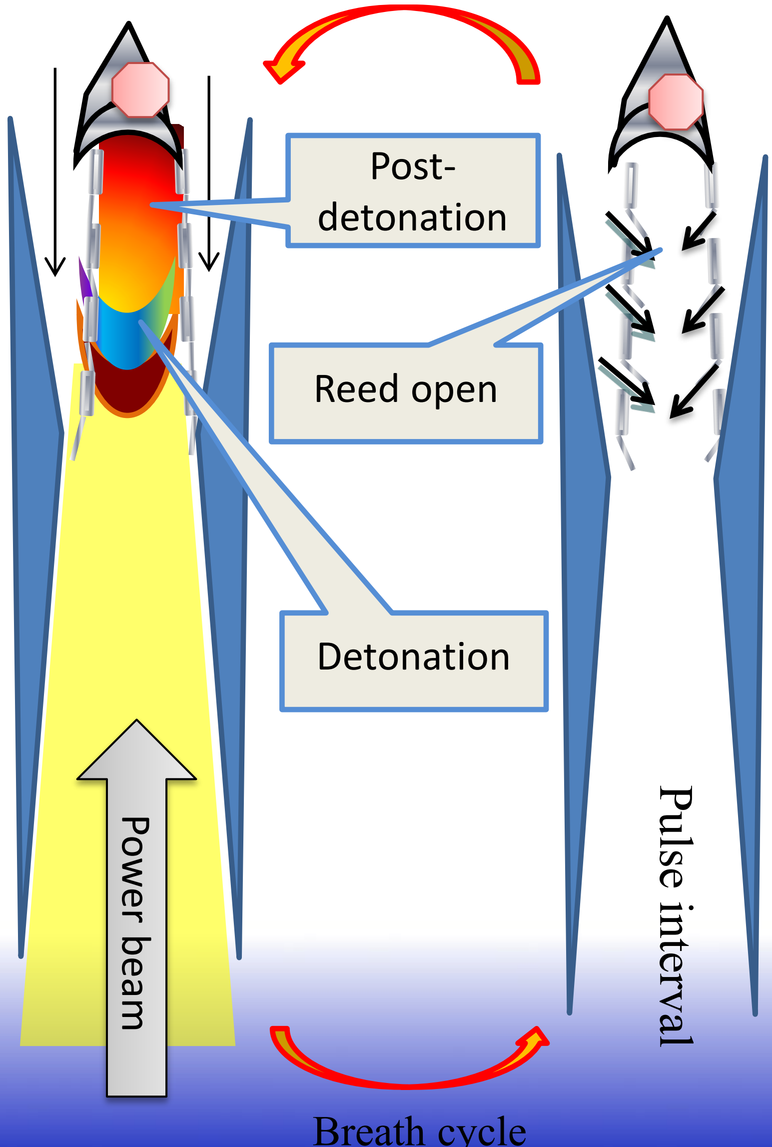


Performance dependence on the partial filling rate.

Partial filling rate

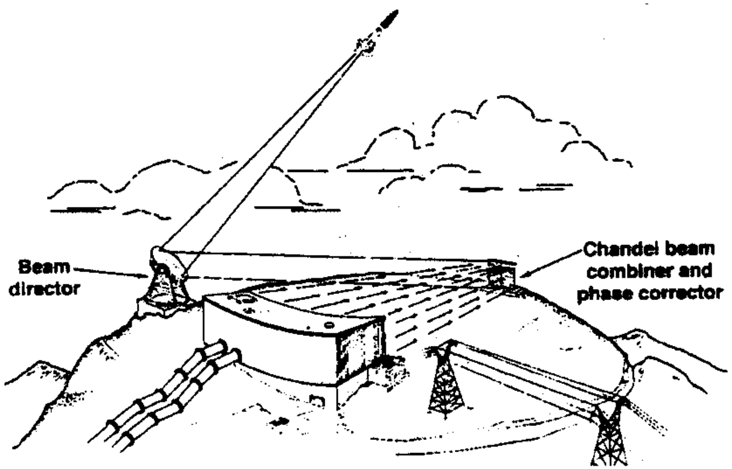
$$\frac{\text{Replaced air volume}}{\text{Cylinder volume}} = \frac{Au_0/f}{LA} = \frac{u_0}{Lf}$$

リードバルブ吸気機構とビーム集光器

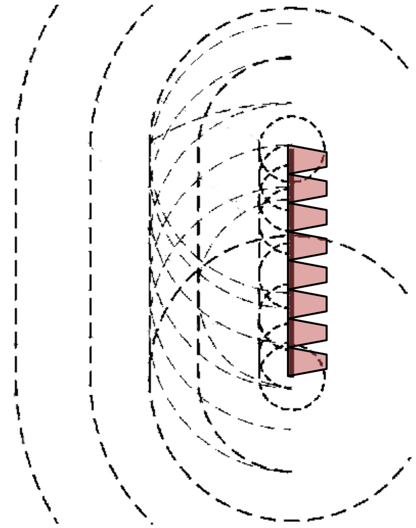


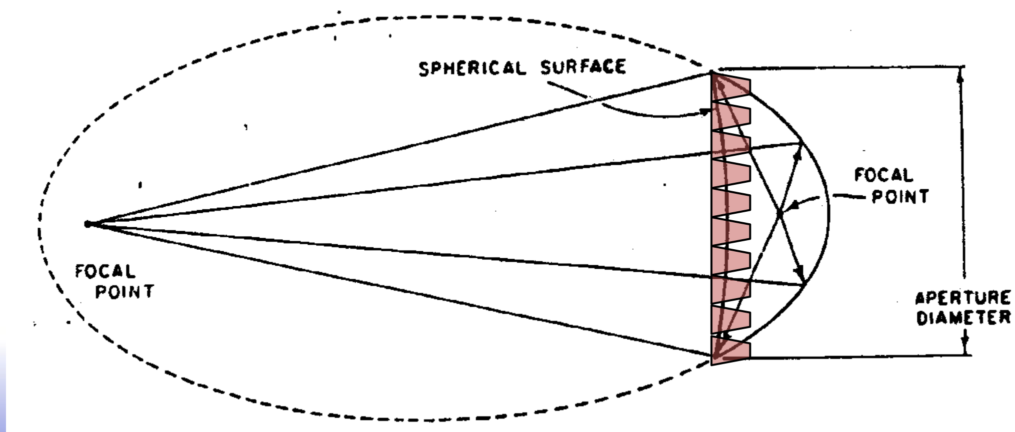
Animation

3. ワイヤレスエネルギー伝送技術



地上レーザー基地





電磁波方程式

Maxwell equations in vacuum (no charge, no current)

$$\nabla \times \boldsymbol{E} = -\frac{\partial(\mu \boldsymbol{H})}{\partial t} \quad (1)$$

$$\nabla \times \boldsymbol{H} = \frac{\partial(\varepsilon \boldsymbol{E})}{\partial t} \quad (2)$$

$$\nabla \cdot \boldsymbol{E} = 0 \quad (3)$$

Take a curl of Eq. (1)

$$\nabla(\nabla \cdot \boldsymbol{E}) - \nabla^2 \boldsymbol{E} = -\mu \frac{\partial(\nabla \times \boldsymbol{H})}{\partial t} \quad (4)$$

Using Eqs. (2) and (3), we have

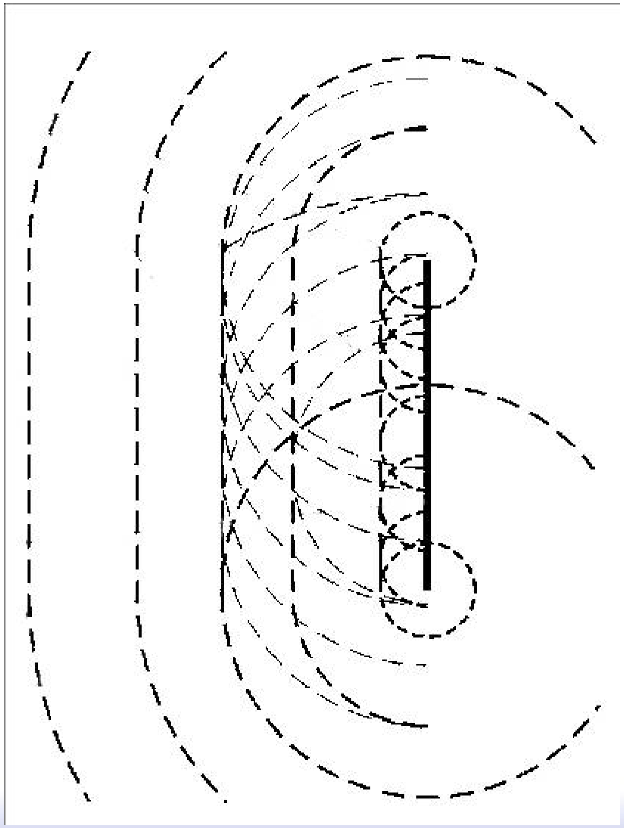
$$\nabla^2 \boldsymbol{E} - \varepsilon\mu \frac{\partial^2 \boldsymbol{E}}{\partial t^2} = 0 \quad (5)$$

Wave equation. Propagation speed *v* (=speed of light) is

$v = 1/\sqrt{\varepsilon\mu}$ =299,792,458 m/s in vacuum

Coherence and directivity

Superposition of coherent spherical waves→ a plane wave→ Directivity



Coherent wave superposition
（Huygens–Fresnel principle ）

An advancing wave is the sum of all the secondary waves arising from points in the medium already traversed.

Gaussian Beam (1)

Transverse distribution of intensity is given by 0-th order Gaussian. $E=\sqrt{\frac{2}{\pi}}\frac{1}{w}\exp\left(\frac{-r^2}{w^2}\right)$

E is described in a paraxial form along the *z* axis (近軸近似)

$$E(r,z)=\varphi(r,z)\exp(-jkz) \qquad r=\sqrt{x^2+y^2},k=2\pi/\lambda \tag{6}$$

Substituting Eq.(6) into Eq.(5),

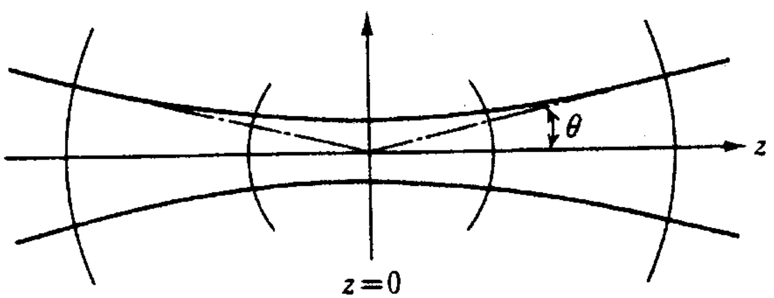
$$E=\sqrt{\frac{2}{\pi}}\frac{1}{w(z)}\exp\left[\frac{-r^2}{w^2(z)}\right]\exp\left[-jk\left(z+\frac{r^2}{2R(z)}\right)\right] \tag{7}$$

w(*z*) : Beam spot size (beam radius)

$$w(z)=w_0\sqrt{1+\left(\frac{\lambda z}{\pi w_0^2}\right)^2} \tag{8}$$

R(z): Radius of curvature

$$R(z)=z\left\{1+\left(\frac{\pi w_0^2}{\lambda z}\right)^2\right\}$$



Gaussian beam

Gaussian Beam (2)

$z \leq w_0,$

$$w(z) = w_0\sqrt{1+\left(\frac{\lambda z}{\pi w_0^2}\right)^2} \to w_0$$

Beam waist
(minimum beam spot size)

$$R(z) = z\left\{1+\left(\frac{\pi w_0^2}{\lambda z}\right)^2\right\} \to \infty$$

Plane wave

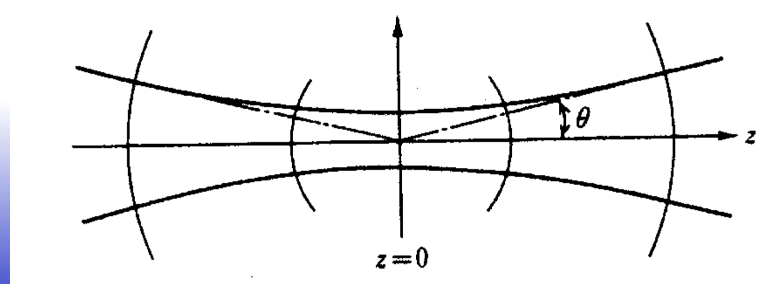
$z \gg w_0,$

$$w(z) = w_0\sqrt{1+\left(\frac{\lambda z}{\pi w_0^2}\right)^2} \to \frac{\lambda z}{\pi w_0}$$

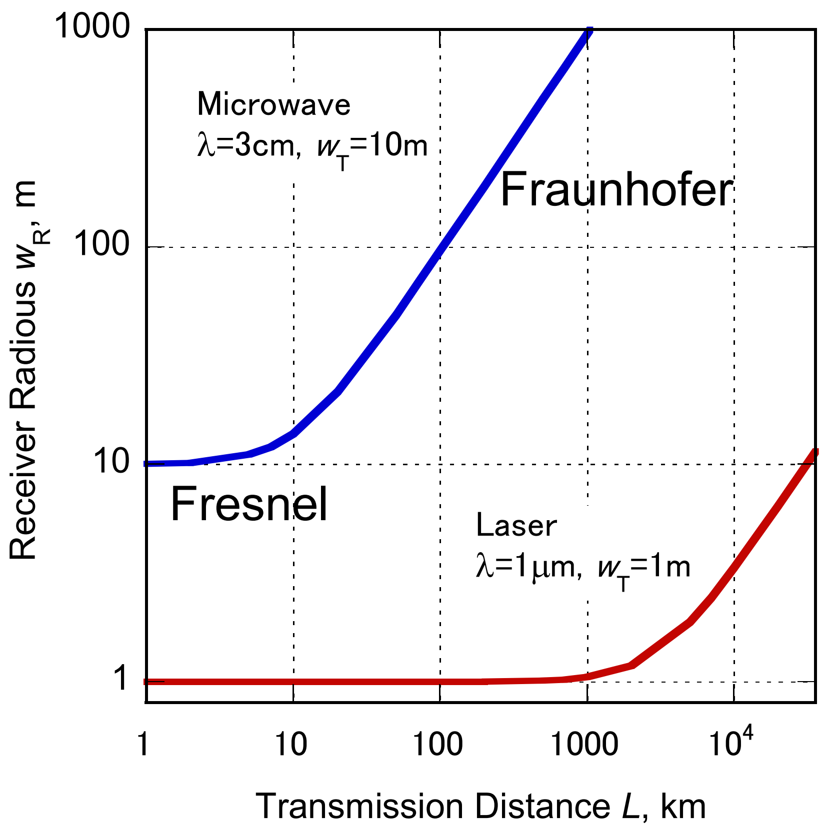
$$\theta = \tan^{-1}\left(\frac{\lambda}{\pi w_0}\right)$$ Divergence angle

$$R(z) = z\left\{1+\left(\frac{\pi w_0^2}{\lambda z}\right)^2\right\} \to z$$

$$E \propto \frac{1}{R}\exp(-jkR)$$ Spherical wave



伝送距離と受電面サイズ



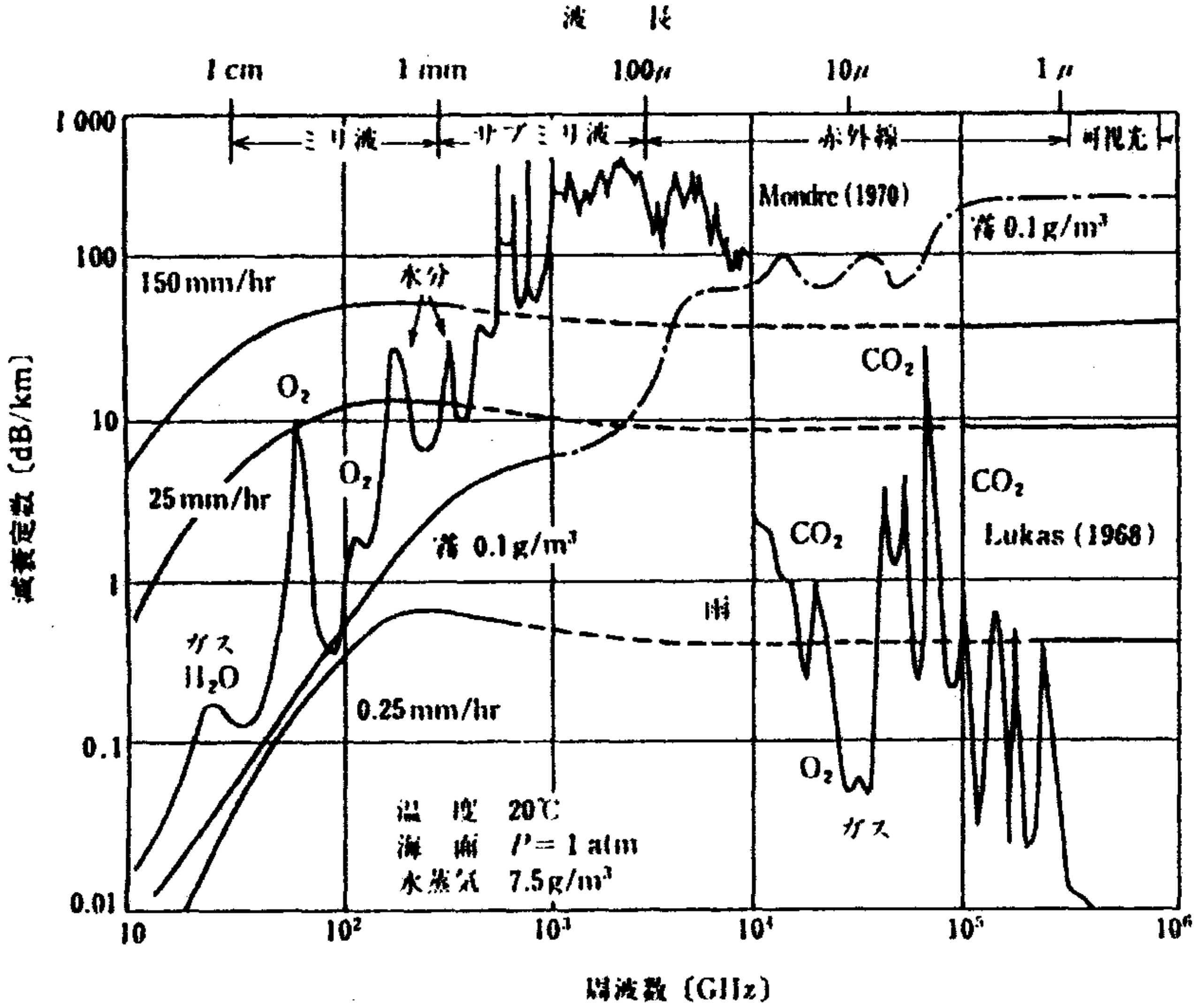
Fresnel - Fraunhofer boundary
Laser beam: 2,000 km
Microwave beam: 7 km

$$w_R = w_T \sqrt{1 + \left(\frac{\lambda z}{\pi w_T^2}\right)^2} \approx \frac{\lambda z}{\pi w_T} \quad (8)$$

Scaling of beamed radiation transmission

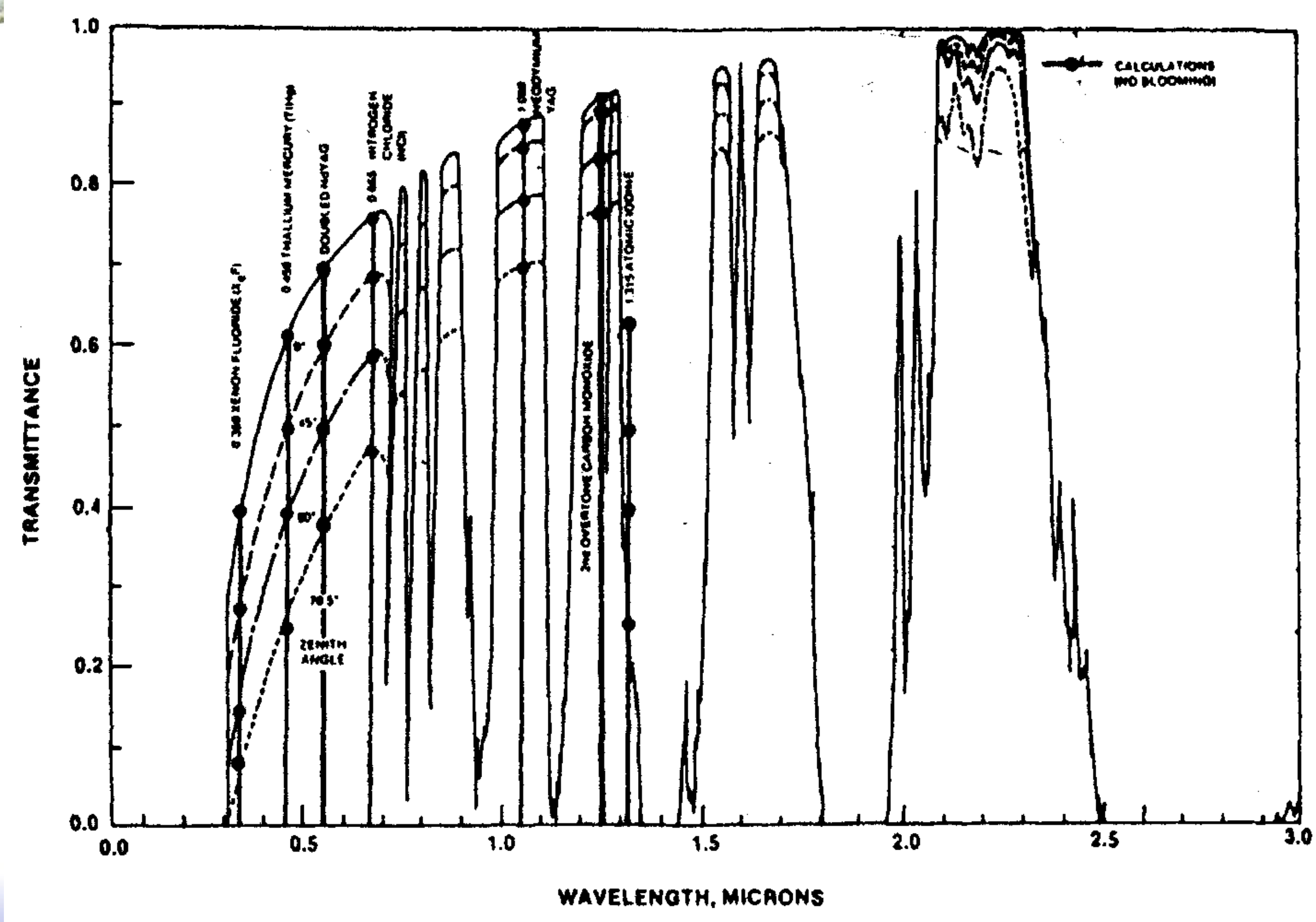
$$L_B : w_T : \lambda$$
$$= 200 : 10 : 1$$
$$= 20000 : 100 : 1$$
$$= \cdots$$

大気による減衰



Attenuation due to rains and fogs

レーザーに対する大気の窓



Transmittance of laser beam

ワイヤレスエネルギー伝送技術まとめ

✓ Power is transmittable in long distance by a diffraction-limit (Gaussian) beam.

✓Transmittable distance, L_B is in proportion to the square of beam aperture.

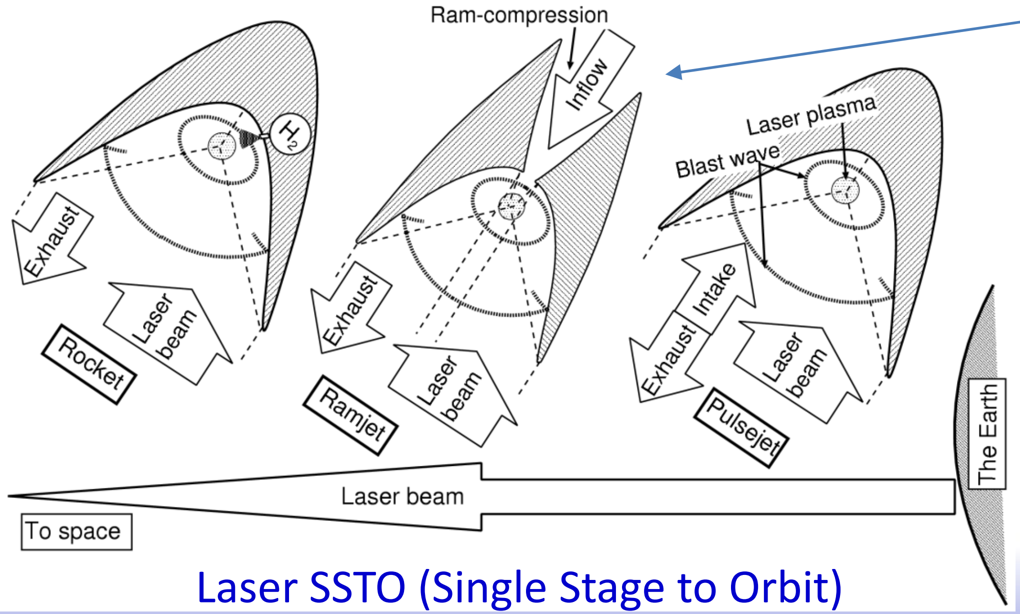
✓Atmospheric attenuation and Scintillation should be cared.

5．宇宙へのシナリオと将来の大量物資輸送

シナリオ１　Laser SSTOで静止軌道へ

Flight modes

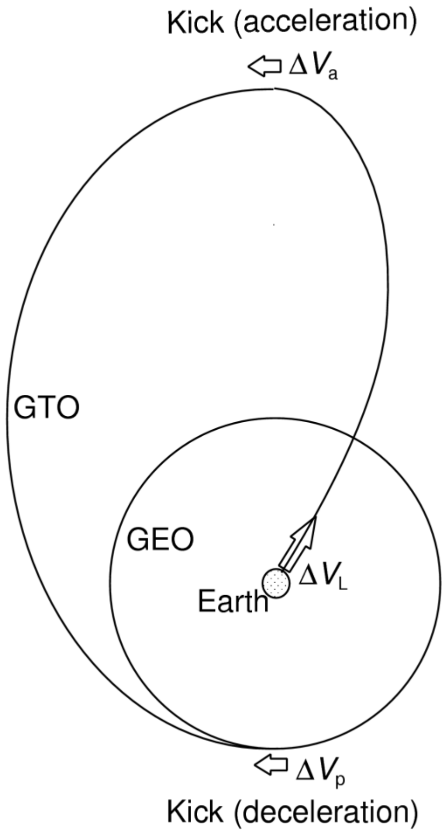
Flight modes	**Flight *M***	Altitudes
Pulsejet	～5	～10km
Ramjet	～12	～40km
Rocket	12～	40km～



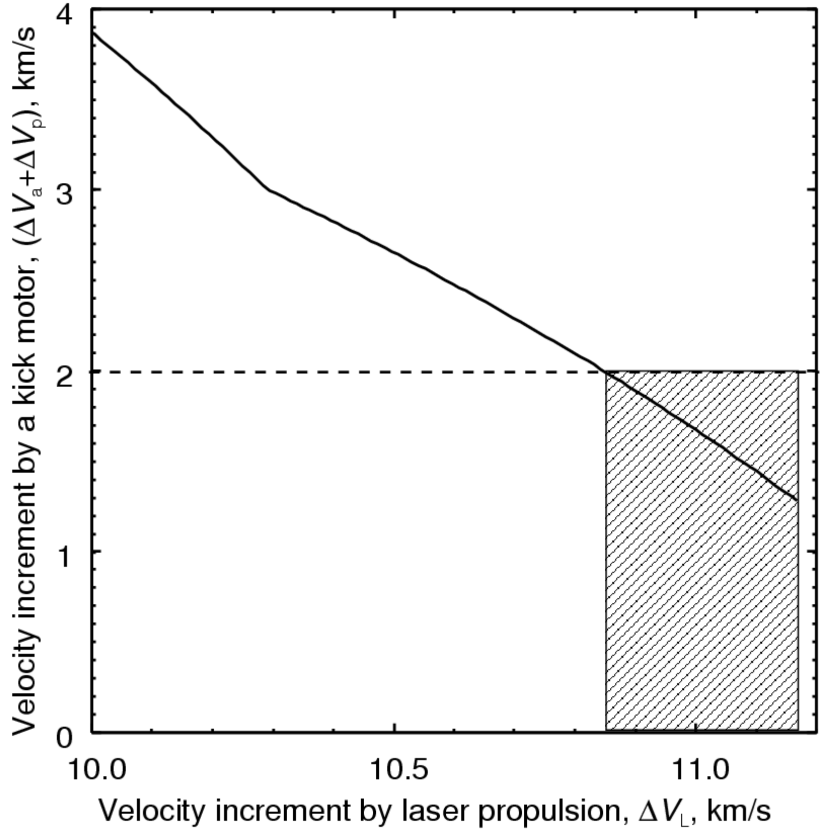
Laser SSTO (Single Stage to Orbit)

Laser-Ramjet is most efficient and attractive mode.

静止軌道(GEO)への直接投入軌道

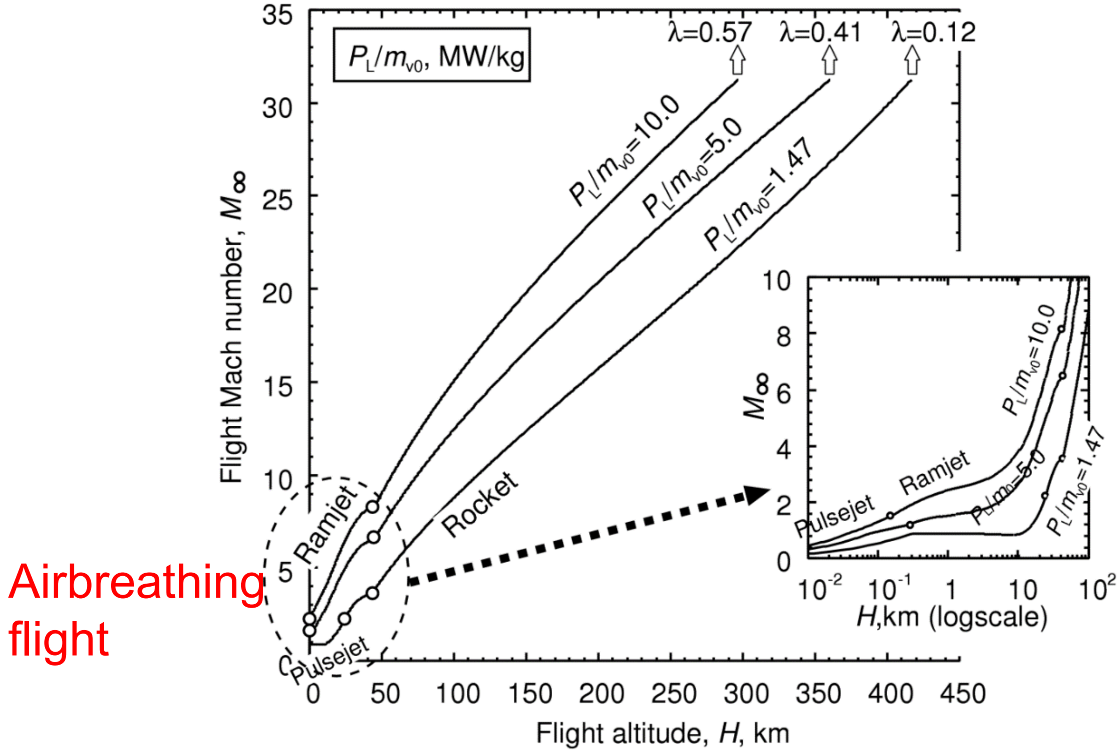


Supersynchronous orbit.



Vertical acceleration completes by 100 – 400 km altitude.

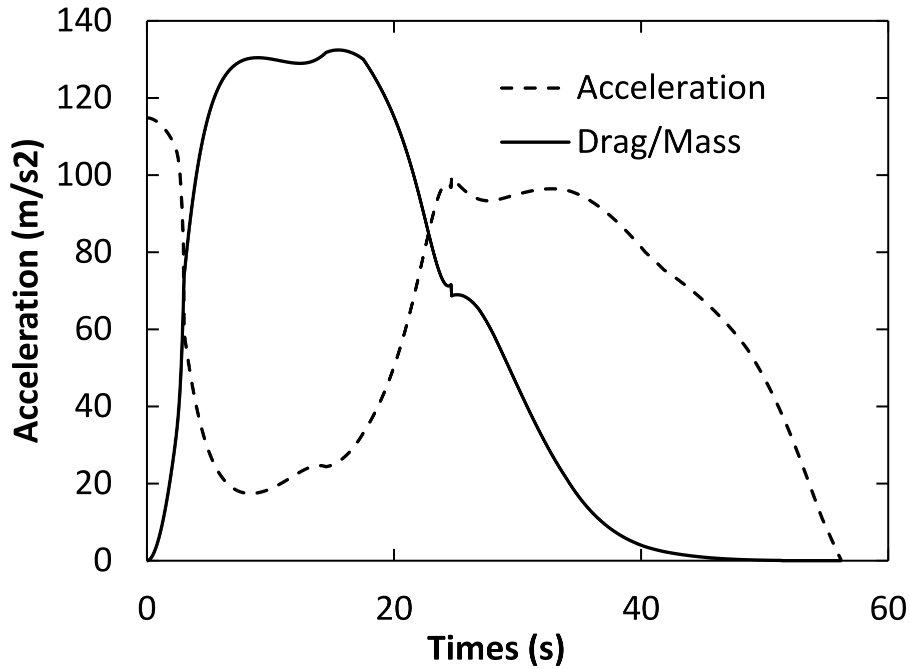
飛行解析結果



飛行経路（飛行マッハ数*M* と飛行高度 *H*)

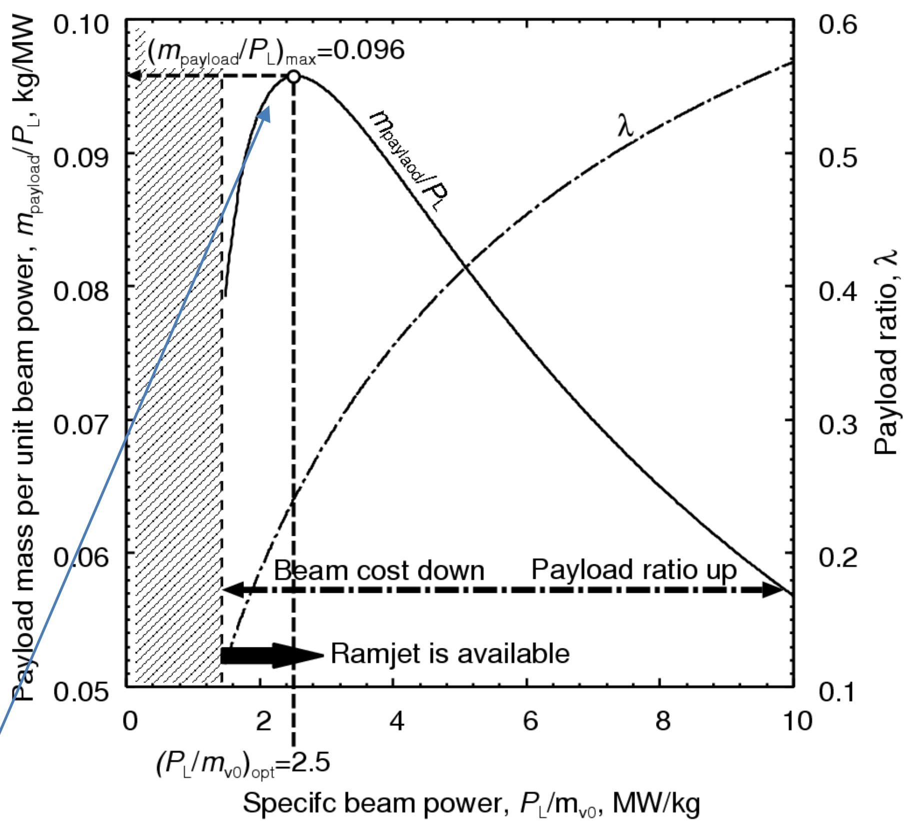
- C_m (=thrust/power) is assumed constant in Pulsejet mode.
- Diffuser efficiency and thermal choke are assumed in Ramjet mode.
- Initial vehicle mass: 100 kg, the vehicle diameter: 1 m.

加速度と空気抵抗



Acceleration and Drag on rocket mass as function of time. Results obtained for: m = 500 kg, L = 12 m, D = 1.5 m, L_{th} = 6.3 m, D_{th} = 1 m; P/m = 1.57 MW/kg

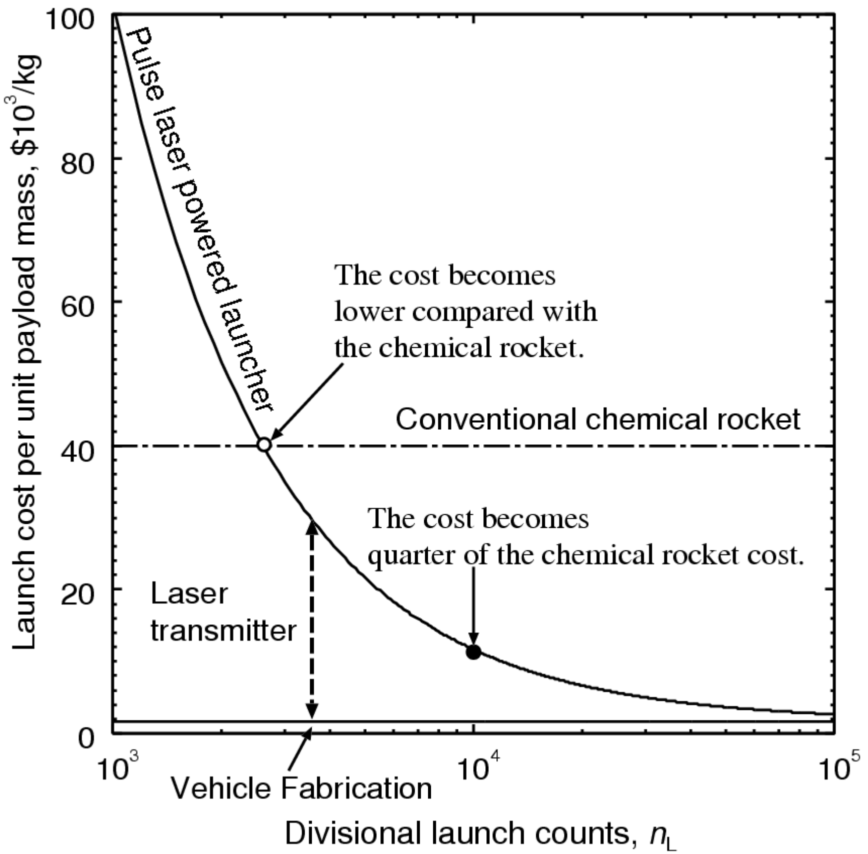
最適レーザーパワー



Payload mass vs. required power.

Optimum condition which minimizes required beam power

打ち上げコスト推算



Launch cost based on the flight trajectory analysis

Laser base construction cost will be redeemed by repeated use of 2,000 times.

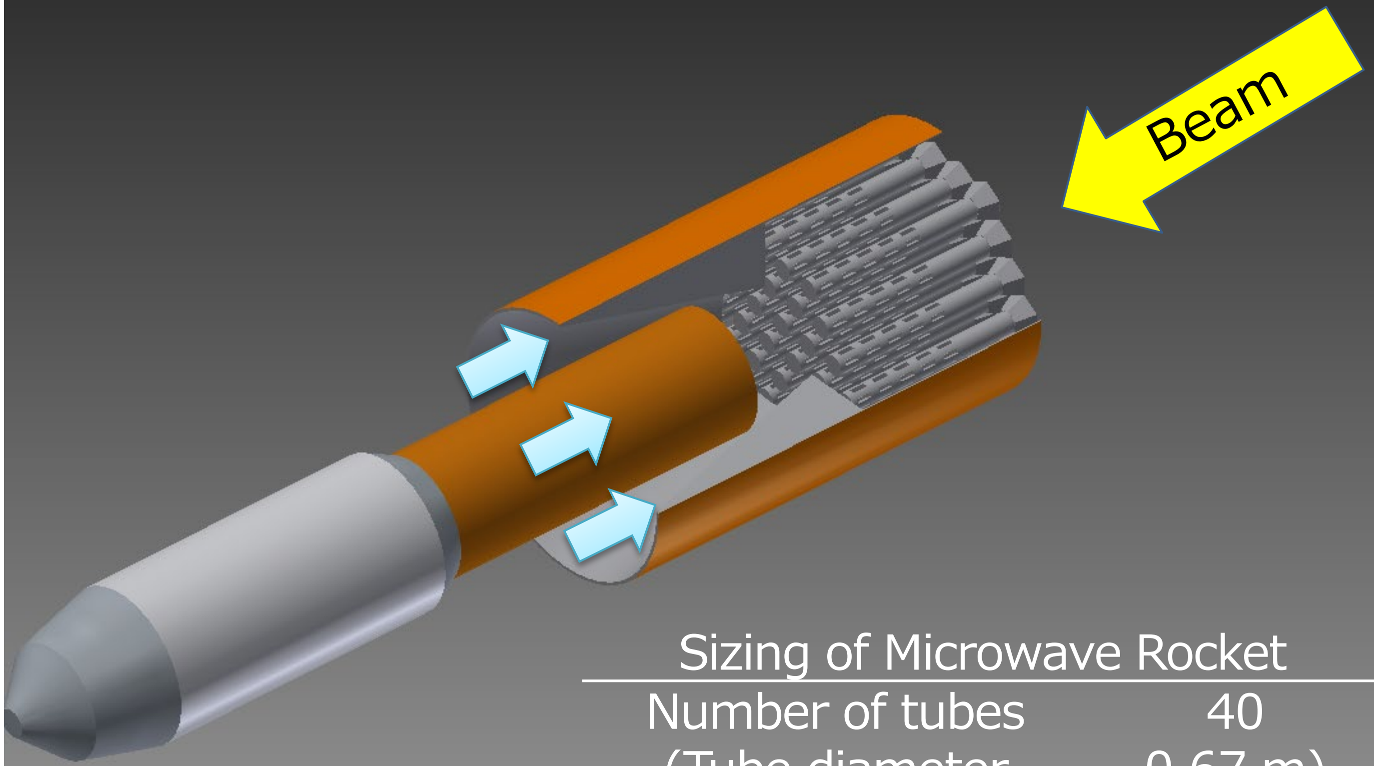
Laser SSTOのまとめ

- 無線電力伝送、空気吸いこみ、デトネーションエンジン、などの先進的な技術を導入することで、興味深い軌道提案ができる。
- ビーム発信基地の建設コストが、ビーム推進打ち上げ機の優位性を議論する上で重要である。
- ビーム発信装置を“使い切る”為には、大量輸送への応用が適している。



シナリオ２
H2-B １段目をマイクロ波ロケットに置き換えたら

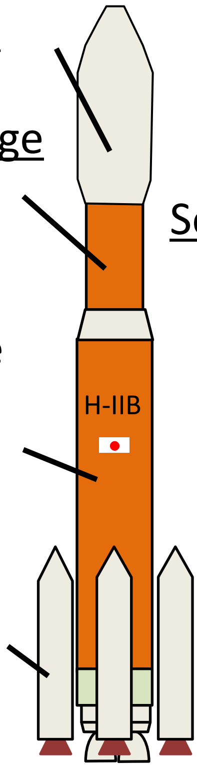
マイクロ波ロケットによるH-IIB１段目の置き換え



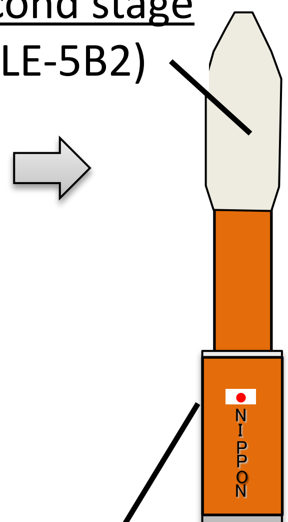
Sizing of Microwave Rocket

Number of tubes	40
(Tube diameter	0.67 m)
(Tube length	6 m)
Total diameter	8.5 m

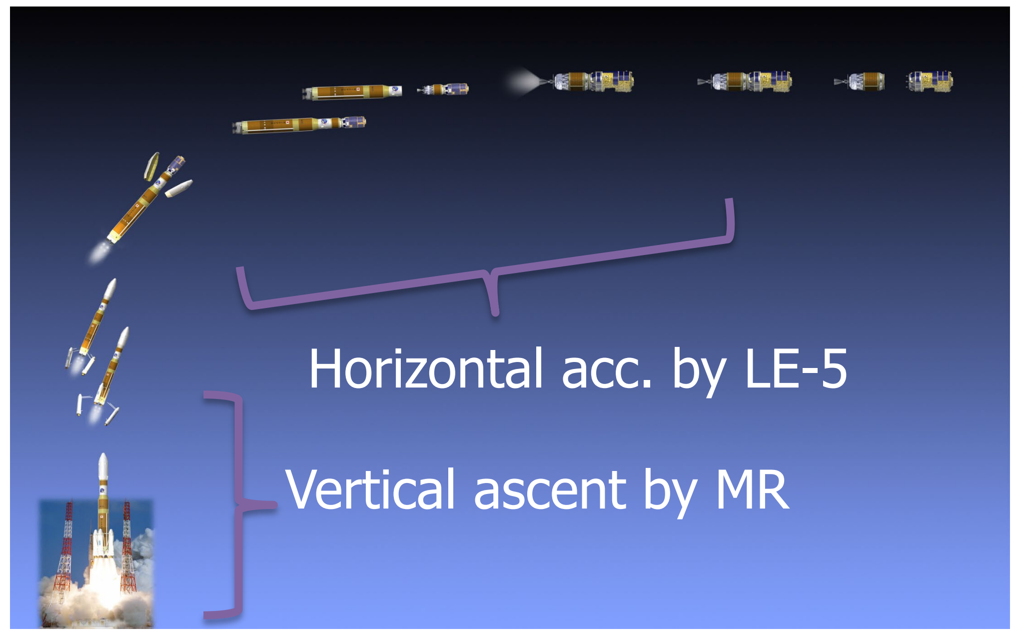
H-IIB 1段目の置き換えシナリオ



H-IIB



Hybrid



Trajectory

H-IIB 1段目の置き換えシナリオ

Cutoff velocity of MR
is set at 2 km/s.

ΔV by a 2nd stage engine
is 5.8 km/s

✓ No need of 1st stage engine and SRBs.

Launcher mass breakdown (ton).

	1st stage		2nd stage		Payload to LEO	Liftoff	Payload Ratio,%
	LE-7	SRBs	LE-5	Fairing			
H-IIB heavy	202	306	20	3.2	19	550.2	3.45
MR Hybrid	3		97			**122.2**	**15.5**

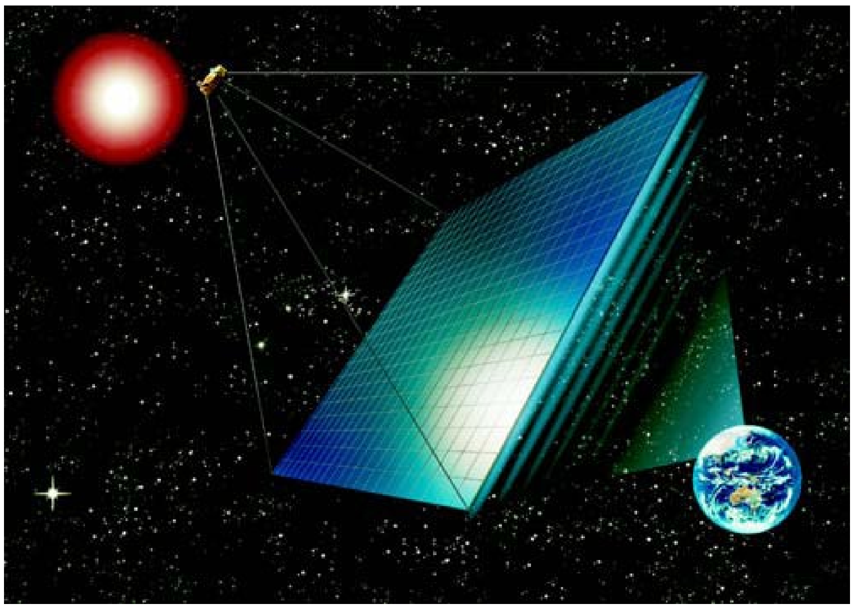
✓ Liftoff mass reduction saves launch power.

☞ **80% cost-cut is expected.**

マイクロ波ロケットによるハイブリッド飛行まとめ

1. 化学ロケットとの併用で、水平飛行へのマヌーバーを行わなくて良い。
2. 垂直加速部だけの推進であれば、空気吸い込みの利点を最大限に利用できる。
3. 約５倍のペイロード比の増加が見込める

想定される大量物資輸送ミッション



2万トンの太陽発電衛星建設
(JAXA)

- 太陽電池パネル2 km × 1.9 km
- 軌道：静止軌道
- 総質量: 20,000 tons
- 想定されるコスト
  建設機器費　１兆円
  宇宙輸送費　１兆円
- 現在の技術では
  建設機器費　100兆円
  宇宙輸送費　100兆円

打ち上げ費用を現在の１００分の１に！！