Direct Conversion for Space Solar Power

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Direct Conversion Concept

- **Given broad/narrow band EM radiation source**
  - Sun
  - Man made EM transmission
  - Other bodies: Jupiter, albedo from the Moon
- **Absorb radiation and convert directly to lower narrowband frequency for re-emission**
- **Benefits:**
  - **Increased efficiency**
  - **Lower mass**
  - **Increased simplicity**

Project Goals

- Study a number of options that might lead to direct conversion
- Analyze technology that would warrant further exploration:
  - -Aerospace systems applications?
  - -Possible mass per unit power?
- Provide a justifiable estimate of mass per unit power of future direct conversion systems
- Identify possible future applications that would benefit from direct conversion technology.

Current Technological Road Blocks to Space Solar Power Systems (1)

- Photovoltaic Technology
  - Old technology w/ low efficiency
  - Band gap
  - Direct current only – must re-oscillate
  - Relatively low specific power

Solar Cell Performance	Thick Film	Thin Film
Efficiency	25-40%	10-20%
Specific Power (kW/kg)	.05-.25	.05-.25
Power Density (kW/m^2)	.1-.4	.1-.4

Solar Cell Performance [1,2,3,4,5]. Note: high estimate taken, usually not that good and decays w/ time.

Current Technological Road Blocks to Space Solar Power Systems (2)

- **High Launch Costs**
  - **Importance of specific power**

Booster	2004 Cost ($ millions)	Payload to LEO (kg)	Payload Cost ($/kg)
Atlas 5 551	125.1	20,050	6239.4
Delta 4 Heavy	193.4	25,800	7496.12
Space Shuttle	284	24,400	11639.3
Titan 4B	491.6	21,680	22675.3

Robel, M. [6]

Initial Direct Conversion Options

- Shocked Photonic Crystals [Joannopoulos 7,8,9]
- Signal Processing Solutions
- Optical Resonators [Iltchenko 10]
- Rapidly Ionizing Plasma [Ren 11]
- Solar Pumped Lasers and Masers [12,13]
- Optical Rectennae [14,15]
- Nanofabricated Antennae

Discounted Options (1)

- Signal Processing Solutions
  - Inefficient and some require a significant additional power source
  - Tube, Cyclotron, Gyrotron type devices
    - Mechanical tolerances
    - Scaling problems
    - More difficult at higher frequencies
    - Low efficiency that degrades over time
    - Heavy
    - Impedance mismatching
    - Breakdown fields
    - Have not found any efficiencies over 60% and few near it

Discounted Options (2)

- Optical Resonator
  - Converts to amplified narrowband but does so inefficiently by rejecting non-resonant wavelengths
- Rapidly Ionizing Plasma [Ren 11] and Nanofabricated Antenna
  - Difficulty further developing viable concept

Discounted Options (3)

- **Optical Rectenna [1,2]**
  - **Based of previous work of ITN Energy Systems and W.C. Brown**
  - **Still very applicable technology, however it is surpassed by the possibility of focusing broadband radiation directly onto a medium**
    - **Estimated Efficiency = 85-100%:**
    - **Power Density = 1.165 kW/m^2 [W.C. Brown Microwave Rectenna Weight = .25 kg/m^2** [3]
    - **Specific Power = 4.658 kW/kg**
    - **1763% Increase in Specific Power over photovoltaics**

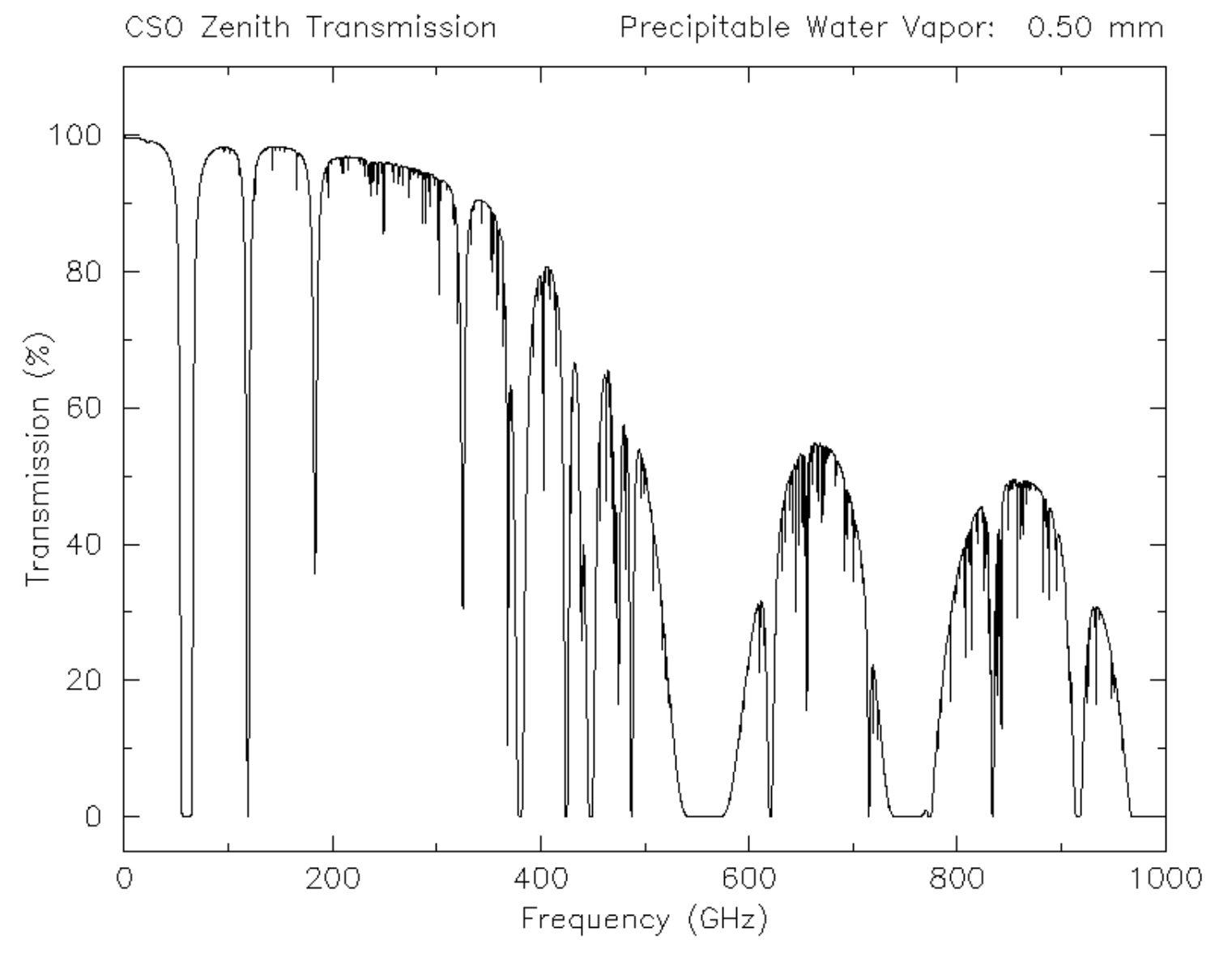
Refined System Concepts

- Near Term Concept
  - Solar Pumped Maser
- Long Term Concept
  - Shocked Photonic Crystals

MASERs

- MASER=**M**icrowave **A**mplification by **S**timulated **E**mission of **R**adiation
- Naturally Occurring
  - Detection of 183 GHz water vapor maser emission from interstellar and circumstellar sources [16]
    - Rotational transition of H2O
  - 145 GHz Methanol maser
    - Collision excited [17]

Earth Atmosphere Absorption



http://www.islandone.org/LEOBiblio/microwave_transm.gif

MASER/LASER Examples

- Saiki, T. “Development of Solar-Pumped Lasers for Space Solar Power Station” [18]
  - Solar pumped Nd/Cr:YAG ceramic laser
  - Demonstrated 38% efficiency
- Kiss, Z. J. “Sun Pumped Continuous Optical Maser” [19]
  - 1963
  - Shows same principle of solar pumped lasers can be applied to lower more convenient frequencies

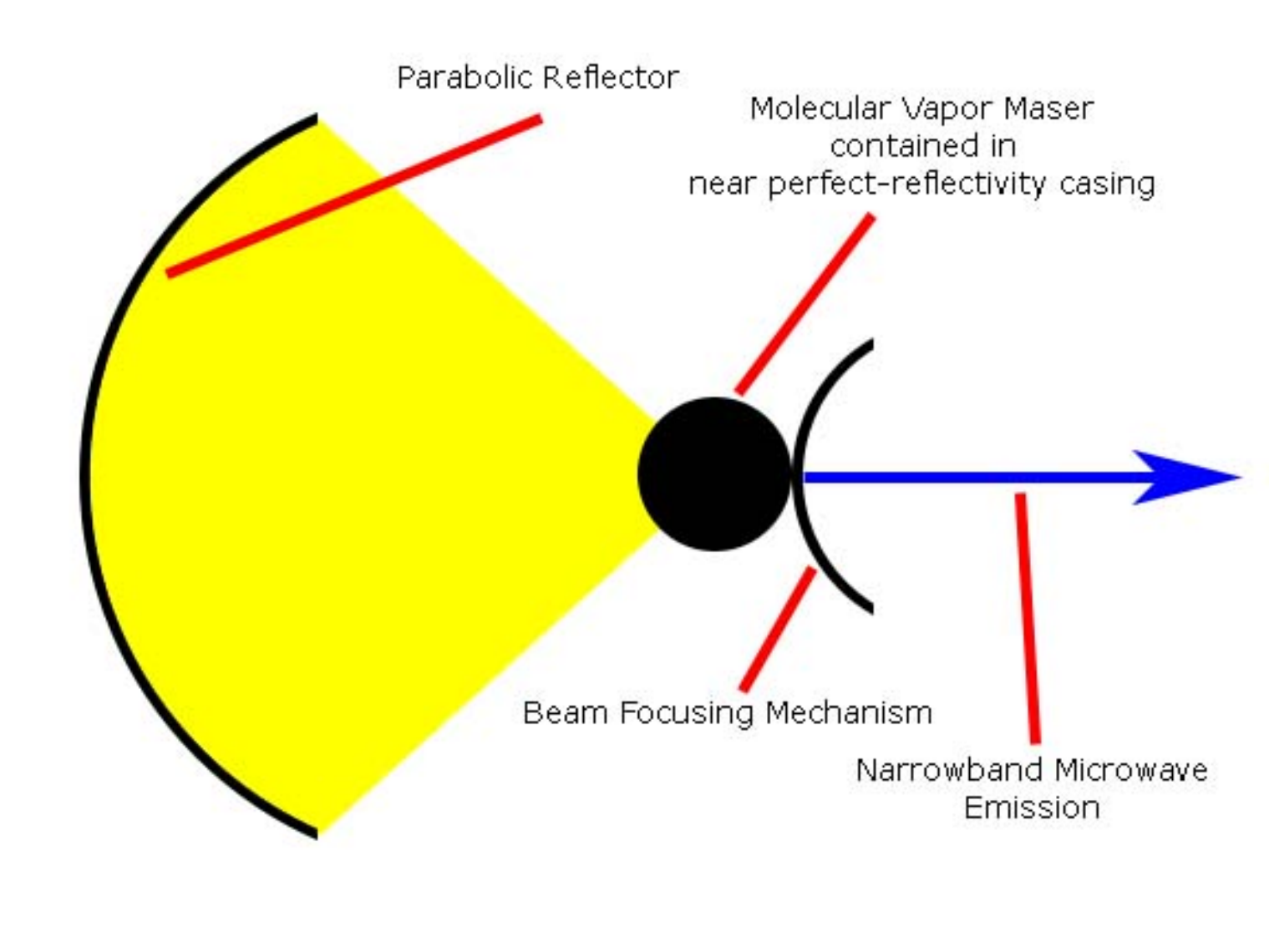
Argument for Efficiency

- Use low density molecular vapor as in naturally occurring masers
  - Analogous to lasers
- Maser uses rotation-vibration transitions on the molecular level
  - Laser uses optical-electronic transitions on the subatomic level
  - 38% with a laser already proven – should be able to do better.
  - DARPA aiming for 50% with 1W CW laser
- Longer wavelengths – everything scaled up and easier to control

Parabolic Reflector

- Solar sail type material for reflector
  - 1-10 g/m^2 [20]
  - May be heavier to prevent scatter – but will still be significantly lighter than traditional options

MASER System



Problems/Considerations

$$\eta_{\text{Total}} = \eta_{\text{Reflector}} * \eta_{\text{Maser absorption}} * \eta_{\text{Heat \& Scattering}} * \eta_{\text{Broadband Losses}} * \eta_{\text{Emission}}$$

- Gas would have to be kept at uniform temperature for maximum efficiency
  - Balance between heating of radiation and cooling to the vacuum
  - Solar weather
- Unpredictability due to low density and possible high temperature
- Possible band gap – ie: portions of band perhaps ineffective towards transition
- Scattering/surface losses

MASER Calculations (1)

Maximum Power from Radiation into the Volume (as definined by desired Temperature)

$$= \alpha = \left[\frac{\text{kW}}{\text{m}^3}\right]$$

Maximum Power Flux through the Surface of the Maser
(as defined by Temperature at the interface and maintained uniformity)

$$= \beta = \left[\frac{\text{kW}}{\text{m}^2}\right]$$

Reflector Specific Mass

$$= \pi = \left[\frac{\text{kg}}{\text{m}^2}\right]$$

Maximum Focusing Ratio of Parabolic Reflector $\left(\text{Geometric Property, } \frac{A_{\text{Parabolic Reflector}}}{A_{\text{Maser Inlet}}}\right)$

$$= \phi = [\text{Unitless}]$$

P = Desired Power of the system

MASER Calculations (2)

$$\text{Specific Power} = \frac{\left(1.37\left[\frac{\text{kW}}{\text{m}^2}\right]\text{Solar Radiation}\right) * \eta_{\text{Total}} * (\text{A}_{\text{Parabolic Reflector}})}{(\text{m}_{\text{Structure}} + \text{m}_{\text{Vapor}} + \text{m}_{\text{Parabolic Reflector}})}$$

$$\text{m}_{\text{Structure}} \propto \text{m}_{\text{Vapor}}$$

$$\text{m}_{\text{Vapor}} = \frac{\rho_{\text{Vapor}} * \text{P}}{\alpha}$$

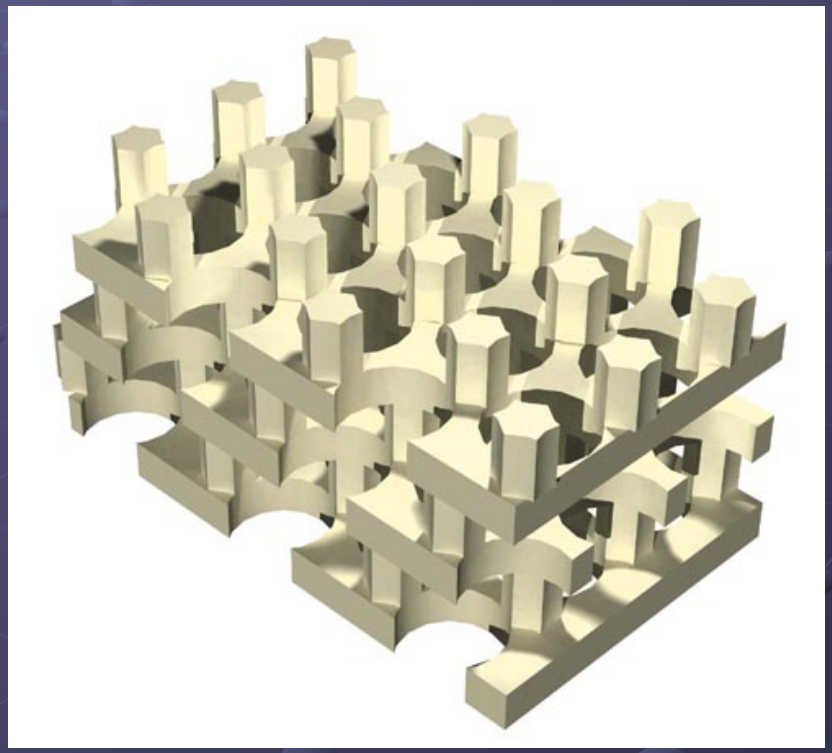
$$\text{m}_{\text{Parabolic Reflector}} = \text{A}_{\text{Parabolic Reflector}} * \pi$$

$$\text{A}_{\text{Parabolic Reflector}} = \text{A}_{\text{Maser Inlet}} * \phi$$

$$\text{A}_{\text{Maser Inlet}} = \frac{\text{P}}{\beta}$$

Photonic Crystals

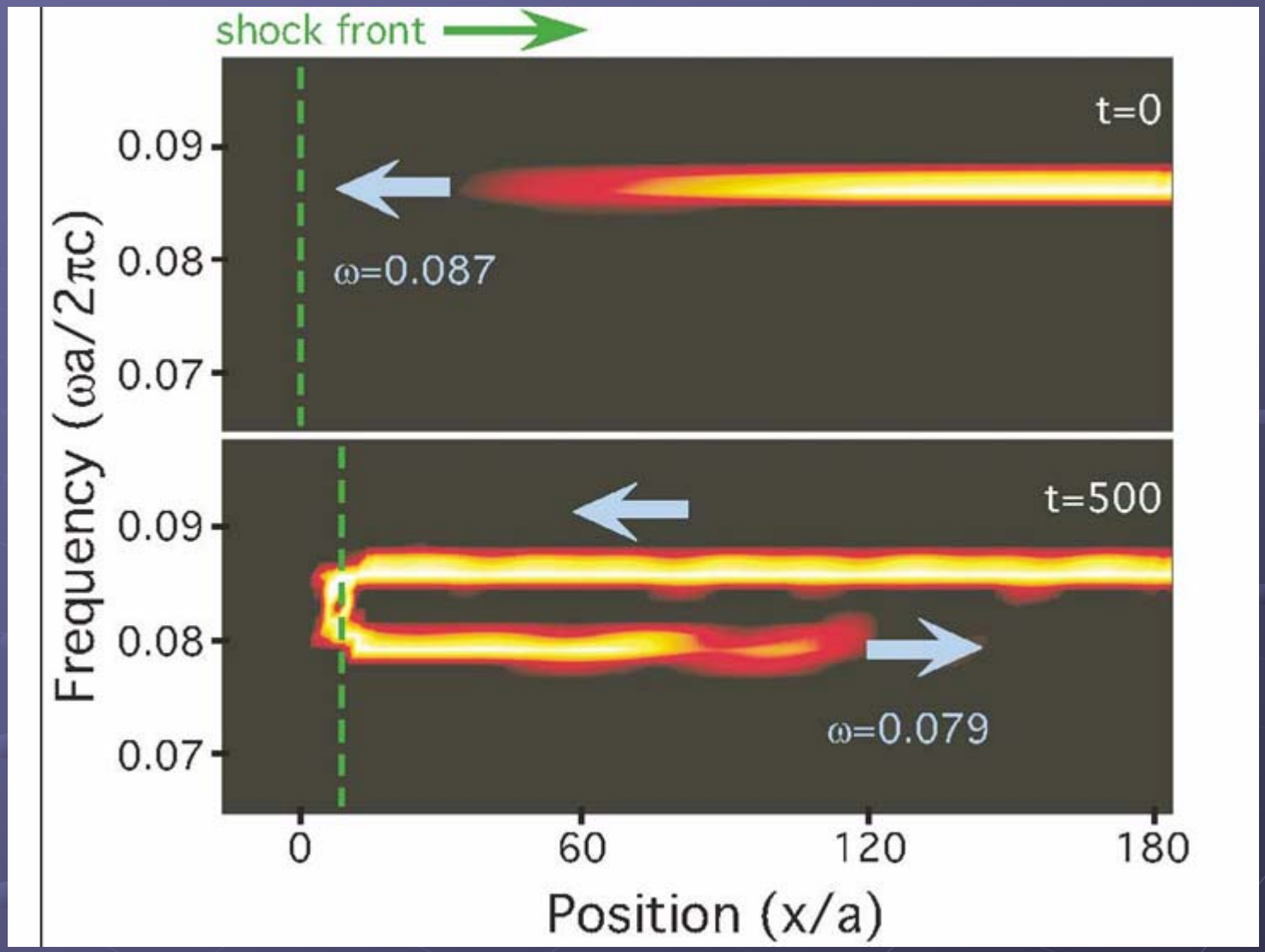
- Through artificial geometry can create perfect waveguides and resonant cavities
- High to perfect theoretical efficiencies



[Joannopoulos 7,8,9]

Shocked Photonic Crystals (2)

- **Doppler Shift and Photonic Crystals**
  - 2003 MIT
  - Discovered that a non-relativistic reversed Doppler Shift in light occurs when light is reflected from a moving shock wave propagating through a photonic crystal
  - Near 100% efficiency
  - Proposed that a similar system be used in micro-electrical-mechanical devices. [7,8]

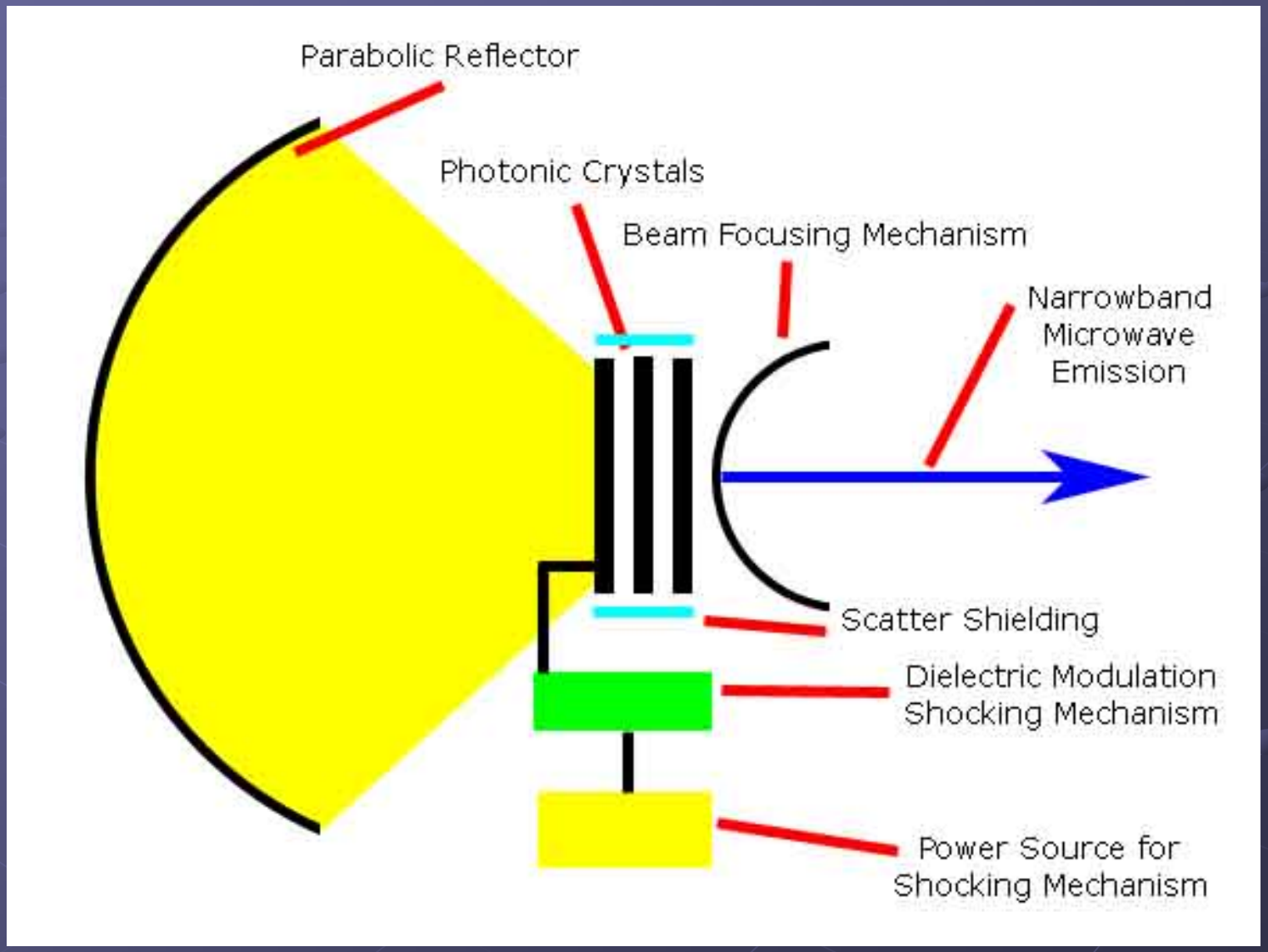


Simulation of frequency shift in photonic crystals from Joannopoulos J. [8]

Shocked Photonic Crystal System

- Solar sail type parabolic reflector
- “Shock like” modulation of the dielectric with separate power source
- Serially placed photonic crystals or single crystal with gradient geometry
  - Possible mismatch to geometry with large frequency shift over the course of the crystal
- Resulting pulsed transmission

Shocked Photonic Crystal System



Problems/Considerations

$$\eta_{Total} = \eta_{Reflector} * \eta_{Maser\ absorption} * \eta_{Heat\ \&\ Scattering} * \eta_{Broadband\ Losses} * \eta_{Emission} * \eta_{Efficiency\ Lost\ due\ to\ Generation\ of\ Dielectric\ Shock}$$

- Creating a shock
  - Physical shock too much energy
  - “Shock like” modulation of the dielectric – still energy loss, but perhaps smaller
    - Need more information
- Has not been physically tested – only simulations
  - Initial efficiency probably low
  - Depends greatly on nanotechnology
  - Would have to limit unexpected internal scattering
- Surface interface reflection and scattering still a problem
- Heat over time

Shocked Photonic Crystal Calculations (1)

$$\eta_{\text{Total without Dielectric Shock}} = \eta_{\text{Reflector}} * \eta_{\text{Maser absorption}} * \eta_{\text{Heat \& Scattering}} * \eta_{\text{Broadband Losses}} * \eta_{\text{Emission}}$$

Maximum Power from Radiation into the Volume (as definined by desired Temperature)

$$= \alpha = \left[\frac{\text{kW}}{\text{m}^3}\right]$$

Maximum Power Flux through the Surface of the Crystal
(as defined by Temperature at the interface and maintained uniformity)

$$= \beta = \left[\frac{\text{kW}}{\text{m}^2}\right]$$

Reflector Specific Mass

$$= \pi = \left[\frac{\text{kg}}{\text{m}^2}\right]$$

Maximum Focusing Ratio of Parabolic Reflector $\left(\text{Geometric Property, } \frac{A_{\text{Parabolic Reflector}}}{A_{\text{Crystal Inlet}}}\right)$

$$= \phi = [\text{Unitless}]$$

P = Desired Power of the system

Shocked Photonic Crystal Calculations (2)

Specific Power

$$= \frac{\left(1.37\left[\frac{kW}{m^2}\right]\text{Solar Radiation}\right) * \eta_{\text{Total-without Dielectric Shock}} * \left(A_{\text{Parabolic Reflector}} - A_{\text{Shock Power Source}}\right)}{\left(m_{\text{Structure}} + m_{\text{Crystal}} + m_{\text{Parabolic Reflector}} + m_{\text{Shocking Mechanism}} + m_{\text{Shock Power Source}}\right)}$$

$$m_{\text{Structure}} \propto m_{\text{Crystal}}$$

$$m_{\text{Vapor}} = \frac{\rho_{\text{Crystal}} * P}{\alpha}$$

$$m_{\text{Parabolic Reflector}} = A_{\text{Parabolic Reflector}} * \pi$$

$$A_{\text{Parabolic Reflector}} = A_{\text{Crystal Inlet}} * \phi$$

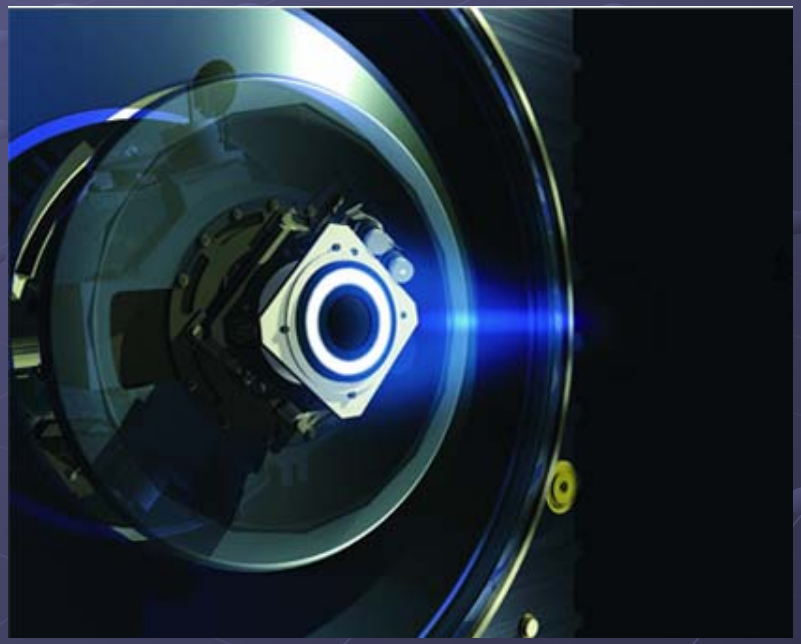
$$A_{\text{Maser Inlet}} = \frac{P}{\beta}$$

Applications (1)

- **Space Solar Power Grid**
- **Improved Efficiency:** Based on calculations by Kulcinski [21], assuming a change of conversion efficiency from 15.7%, and 76.6% efficiency loss due to DC to RF conversion (don't know where he got that number – should be lower)
  - **Overall system efficiency from 7.81% to 64.9%**
- **Distribution System:** no DC conversion between satellites

Applications (2)

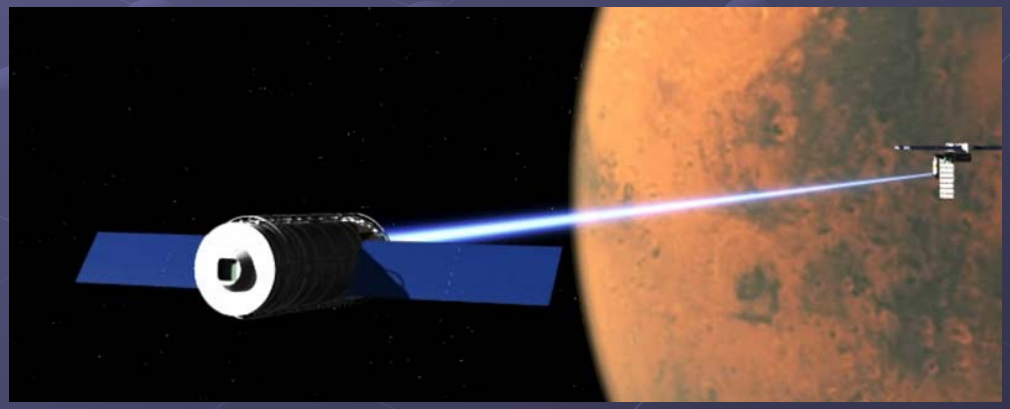
- **Electric Propulsion:**
- **Problems:** High mass per unit thrust, due to the power source and transmission system.
- **Potential Systems:**
  - **Ion Engines:** Ionize propellant particles such as xenon gas by EM radiation and accelerate them through an electric field.



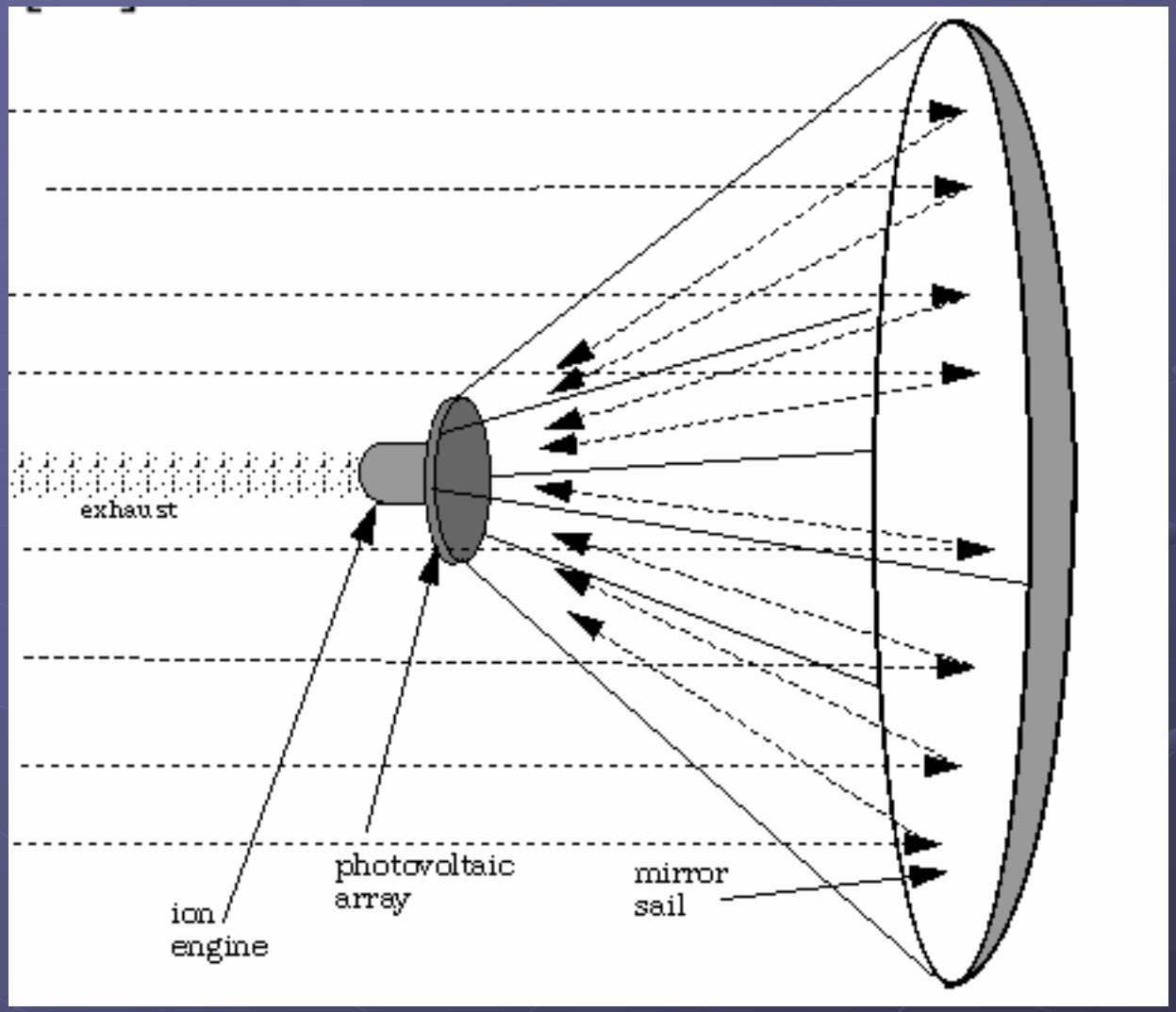
Ion Engine from ESA

Applications (3)

- **Magnetoplasma Engines and Mag Beam**: Heating neutral hydrogen gas into plasma using electric fields and contained by magnetic fields, the plasma then passes through an RF booster to further ionize the hydrogen plasma [22,23]
- **Solar Sail Hybrid Systems:** Solar sails are combined with electric propulsion systems to function as a both a solar sail and reflector to power the electric propulsion system [24].



Magbeam from Winglee, R. [23]



Hybrid system from Landis, G. [24]

Applications (4)

- **Benefits from Direct Conversion:**
- **More Available Energy**
  - **More energy can be gathered more efficiently**
  - Eliminate the need for an onboard power system
  - **Direct Conversion to Ionization Frequency**
  - **Ultra Thin Solar Sail Possibilities**
    - **Hybrid**

Future

- Refine Estimates
- Information Needed
  - Flux and Power capacities of molecular vapors and crystal systems
  - Temperature and density target for maser
  - How fast heat can transfer through the various mediums – determines geometry
  - Capacity of solar sail reflectors
  - Shock like modulation of the dielectric

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