LASER POWER TRANSMISSION

- Laser is the only feasible system for long range (>1,000 km) power transmission in space.
- Laser beam acts as "super conductor" to deliver high grade power—near zero entropy.
- Multi-mission support possible—economical.
- Lightweight systems identified—direct solar pumped lasers and laser diode arrays.

TRANSMITTER/RECEIVER SIZES vs RANGE

[Graph showing transmitter/receiver sizes vs range with various wavelengths and system types for different ranges.]
LASERS AVAILABLE FOR LASER POWER TRANSMISSION

0 REQUIREMENTS

LASER POWER
> 10 MW ORBITAL MANEUVERING
> 1 GW EARTH-TO-ORBIT LAUNCHING (> 1 TON)
~ 1 MW OTHER MISSIONS

PHOTON FLUX
< 2 x 10^5 W/cm^2 CW
< 2 x 10^7 W/cm^2 PULSED (LSD PROP.)

WAVELENGTH
> 10 μm THROUGH ATMOSPHERE
~ 1 μm DEPENDS ON THE POWER RECEIVERS IN FREE SPACE

PULSE WIDTH
50 ns - 1 μs PLASMA GEN. AND HEATING

EFFICIENCY
HIGH TRANSMITTER AND RECEIVER

0 GROUND BASED WITH SPACE RELAY
FREE ELECTRON LASER (PULSED), CO_2 LASER (CW)
STATE-OF-THE-ARTS: MULTI-KILOWATT (CW), 500 kJ (PULSED)
SCALING-UP: POSSIBLE TO MULTI-MW LEVEL.

0 TECHNICAL ISSUES:
MANY ORDERS OF MAGNITUDE UP-SCALING NEEDED
ATMOSPHERIC INTERFERENCE

SPACEBORNE LASER OPTION SHOULD BE CONSIDERED

SPACE-BORNE LASERS FOR POWER TRANSMISSION

0 SOLAR POWERED LASERS

DIRECT SOLAR PUMPED LASERS
IODINE PHOTODISSOCIATION LASER, IBr PHOTODISSOCIATION LASER
SOLID STATE LASERS (Nd:5⁺), LIQUID Nd:5⁺ LASERS, DYE LASERS

INDIRECT SOLAR PUMPED LASERS
N₂-CO₂ BLACKBODY PUMPED LASER, CO BLACKBODY PUMPED LASER

SOLAR PHOTOMIXED LASERS
ELECTRIC DISCHARGE LASERS (EXCIMER, COPPER, CO₂)
DIODE LASER ARRAYS/DIODE LASER PUMPED LASERS.

0 NUCLEAR POWERED LASERS

DIRECT NUCLEAR-PUMPED LASERS
HIGH EFFICIENCY ELECTRIC DISCHARGE LASERS OR DIODE LASERS
### SOLAR PHOTOVOLTAIC ELECTRICALLY PUMPED ONE MW LASER SYSTEMS

<table>
<thead>
<tr>
<th></th>
<th>Krf ExCimer</th>
<th>Copper vapor</th>
<th>Diode array</th>
<th>CO₂</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Wavelength</td>
<td>µm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.248</td>
<td>0.510</td>
<td>0.570</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intrinsic Efficiency</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electric Efficiency</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>1.4</td>
<td>30</td>
<td></td>
<td></td>
<td>WALL-PLUG EFF.</td>
</tr>
<tr>
<td>Solar to Laser</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.40</td>
<td>0.24</td>
<td>6.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar Power Collected</td>
<td>MW</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>412</td>
<td>16.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electric Power from PV Array</td>
<td>MWₑ</td>
<td>50</td>
<td>82</td>
<td>3.3</td>
<td>22.7</td>
</tr>
<tr>
<td>Solar Panel Area</td>
<td>m²</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>185,185</td>
<td>305,185</td>
<td>12,318</td>
<td></td>
<td>84,444</td>
<td>1.55 kW/m² AMO</td>
</tr>
<tr>
<td>Thermal Radiated Power</td>
<td>MW</td>
<td>49</td>
<td>81</td>
<td>2.5</td>
<td>21.7</td>
</tr>
<tr>
<td>Radiator Temp./Area</td>
<td>K/1000m²</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300/21.8</td>
<td>300/107</td>
<td>250/10.4</td>
<td>300/9.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>375/27.3</td>
<td>1770/0.057</td>
<td></td>
<td>409/10.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>326/19.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>63.2</td>
<td>107.057</td>
<td>10.4</td>
<td>20.6</td>
<td></td>
</tr>
</tbody>
</table>

### SOLAR PHOTOVOLTAIC PUMPED ONE MW LASER SYSTEMS

<table>
<thead>
<tr>
<th></th>
<th>Krf ExCimer</th>
<th>Copper vapor</th>
<th>Diode array</th>
<th>CO₂</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric Efficiency</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>1.4</td>
<td>30</td>
<td></td>
<td></td>
<td>AFTER POWER</td>
</tr>
<tr>
<td>Electric Power</td>
<td>MWₑ</td>
<td>50</td>
<td>82</td>
<td>3.3</td>
<td>22.7</td>
</tr>
<tr>
<td>Solar Panel Area, Mass</td>
<td>m²/ Kg</td>
<td>185,185</td>
<td>305,185</td>
<td>12,318</td>
<td>84,444</td>
</tr>
<tr>
<td></td>
<td></td>
<td>166,666</td>
<td>273,333</td>
<td>11,000</td>
<td>76,000</td>
</tr>
<tr>
<td>Power Conditioner</td>
<td>Kg</td>
<td>88,000</td>
<td>144,320</td>
<td>5,808</td>
<td>40,120</td>
</tr>
<tr>
<td>Thermal Power</td>
<td>MW</td>
<td>49</td>
<td>81</td>
<td>2.3</td>
<td>21.7</td>
</tr>
<tr>
<td>Radiated</td>
<td>m²/ Kg</td>
<td>63,200</td>
<td>107,057</td>
<td>10,400</td>
<td>20,600</td>
</tr>
<tr>
<td>Radiator Area, Mass</td>
<td>Kg</td>
<td>170,640</td>
<td>289,054</td>
<td>28,080</td>
<td>55,620</td>
</tr>
<tr>
<td>Total Mass</td>
<td>Kg</td>
<td>425,306</td>
<td>706,707</td>
<td>44,888</td>
<td>171,740</td>
</tr>
</tbody>
</table>

**Remarks:**
LASER DIODE ARRAY TECHNICAL ISSUES

ADVANTAGES:
- High system efficiency (6%)
- Small and potentially least massive system
- No laserant flow required
- Reasonable laser wavelength
- Laser diode array has good power coupling to solar array
- Low weight/size waste heat radiator

DISADVANTAGES:
- Low temperature laser operation requires low T radiator and heat removal subsystem
- Very temperature sensitive
- Effects of space radiation may be severe

TECHNICAL ISSUES:
- Phase matching entire laser array not demonstrated
- Scaling present 1-Watt single diodes to 1MW diode array
- Array cooling with heat pipes
- Electrical diode laser network

WEIGHT ESTIMATE OF DIODE PUMPED Nd YAG LASER SYSTEM

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diode laser efficiency</td>
<td>30%</td>
</tr>
<tr>
<td>Pumping efficiency</td>
<td>Nd:YAG laser output/diode laser input</td>
</tr>
<tr>
<td></td>
<td>35% (Ref.)</td>
</tr>
<tr>
<td>Electric efficiency</td>
<td>10.5%</td>
</tr>
<tr>
<td>Solar diode laser efficiency</td>
<td>6%</td>
</tr>
<tr>
<td>Overall system efficiency</td>
<td>.06 x .35 = .021 or 2.1%</td>
</tr>
<tr>
<td>Solar power collected</td>
<td>1-MW/.021 = 48 MW</td>
</tr>
<tr>
<td>Electric power</td>
<td>48 MW x .20 = 9.6 MWe</td>
</tr>
<tr>
<td></td>
<td>6.72 (thermal) + 2.88 MW (laser)</td>
</tr>
<tr>
<td>Solar panel area</td>
<td>35,477 m²</td>
</tr>
<tr>
<td>Weight</td>
<td>32,000 kg</td>
</tr>
<tr>
<td>Power conditioning</td>
<td>16,896 kg</td>
</tr>
<tr>
<td>Cooling power</td>
<td>8.6 MW</td>
</tr>
<tr>
<td>Radiator temperature</td>
<td>300 K/350 K</td>
</tr>
<tr>
<td>Area</td>
<td>18,770 m²</td>
</tr>
<tr>
<td>Weight</td>
<td>50,680 kg</td>
</tr>
<tr>
<td>Total weight</td>
<td>99,576 kg</td>
</tr>
</tbody>
</table>

Compare: 44,888 kg for diode laser array and 30,270 kg for solar iodine laser
VARIOUS SOLAR PUMPED GAS LASERS

SOLAR PUMPED LASERS

ONLY PART OF SOLAR SPECTRUM UTILIZED

WHOLE SOLAR SPECTRUM UTILIZED TO HEAT A CAVITY

DISSOCIATIVE

NON-DISSOCIATIVE ELECTRONIC EXCITATION e.g. Na₂

DIRECT BLACK-BODY PUMPED LASERS (CO₂)

GAS-DYNAMIC LASERS, WITH COOLING OF MEDIA BY EXPANSION

SEPARATE ABSORBER HANDS OVER ENERGY TO LASANT Br₂-CO₂-He

ONE MATERIAL ABSORBS AND LASES

ONE MATERIAL ABSORBS AND HANDS OVER ENERGY TO LASANT

ONE MATERIAL ABSORBS AND LASES CO₂ (?)

X₂

XY (IBr)

RX

C₃F₇I

PREMIXED N₂-CO₂

POST MIXED N₂-CO₂

X = halogen, Y = different halogen atom
R = complex radical
CHARACTERISTICS OF IDEAL SOLAR PUMPED LASER

Good Solar Utilization

High Quantum/Kinetic Efficiency

Closed Cycle Operation of Lasant Fluid

Low Pumping Threshold

- 20k Solar constants max. con.
- 2.7 kw/cm²

IODINE LASER KINETICS

PUMP $\lambda^* \sim 25 \sim 29 \mu m$
LASER $\lambda = 1.315 \mu m$, $\eta = 21\%$
ABSORPTION CROSS SECTIONS OF PERFLUOROALKYL IODIDES

SOLAR-PUMPED LASER EXPERIMENT
SOLAR SIMULATOR PUMPED IODINE LASER EXPERIMENT

PROGRESS IN SOLAR LASER POWER

YEAR

LASER POWER, WATT

(LESS THAN SEC)
STATUS OF SOLAR-PUMPED IODINE LASER

0 KINETICS:
- LASER MEDIUM: C_{2}F_{7}I, C_{2}F_{9}I
- 99 PERCENT RECYCLABLE
- PUMP BAND: 250-290 nm NUV
- INTRINSIC EFFICIENCY: 21 PERCENT
- EXCITATION MODE: PHOTODISSOCIATION TO I^*
- SOLAR-TO-LASER EFFICIENCY: 0.2 TO 0.6 PERCENT

0 SCALABILITY:
- PULSED POWER > 2 TW/2 KJ ACHIEVED (MARX-PLANCK INT.)
- CW > 15 W ACHIEVED (WITH SOLAR SIMULATOR)
- SCALING: NO THEORETICAL LIMIT, 1 GW LEVEL POSSIBLE
- 1MW SYSTEM STUDY COMPLETED

0 SOLAR-SIMULATOR PUMPED LASER EXPERIMENT:
- 15 W CW, > 250 W PULSED (Q-SWITCHED)
- FLOW, SUBSONIC
- REP. PULSED MOPA UNDER DEVELOPMENT

0 R & D ISSUES:
- LARGE SOLAR UV COLLECTOR
- CHEMICAL REVERSIBILITY
- BEAM PROFILE CONTROL
- FLIGHT EXPERIMENT FOR THERMAL MANAGEMENT/BEAM TRANSMISSION

ONE MEGAWATT IODINE SOLAR PUMPED LASER POWER STATION

Lasant supply tanks — Solar collector

Laser

Transmission optics

Radiator 4 MW —

Compressor turbine

157 MW — 1 MW

162 MW
### ONE MW SOLAR IODINE LASER SYSTEM MASS

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collector</td>
<td>14,800</td>
</tr>
<tr>
<td>Radiator</td>
<td>15,470</td>
</tr>
<tr>
<td>Total</td>
<td>30,270</td>
</tr>
</tbody>
</table>

### OTHER SUBSYSTEMS:
- **LASER CAVITY**
  - Quartz Tube, kg: 1,860
  - Laser Cavity Optics, kg: 1,000
  - Laser Transmission Optics and Structure (27.6 m Diam.), kg: 24,000

- **GAS FLOW SYSTEM**
  - Compressor (2 Stage), kg: 12,700
  - Turbine, kg: 12,200
  - Ducts, kg: 3,000
  - r-C₄F₉ STORAGE TANKS (4 Empty Tanks), kg: 270

- **ATTITUDE CONTROL SYSTEM (CMG AND FUEL)**
  - CMG, kg: 2,000
  - 150 kg FUEL/yr, kg: 4,500

### FLOW AND THERMAL CYCLES OF ONE MW IODINE LASER

![Flow and thermal cycles diagram](image-url)
OPERATION OF SOLAR PUMPED LASER POWER STATION

6378 km

Solar laser power station

Remote power user

Shuttle to LEO

Launch

Lasant resupply

Lasant manufacturing

300 km

Shuttle return
### LASER POWER CONVERSION SYSTEMS

<table>
<thead>
<tr>
<th>System</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>RECEIVER/PHOTOVOLTAIC/BATTERIES</td>
<td>34.0 %</td>
</tr>
<tr>
<td>RECEIVER/HEAT/BRAYTON/GENERATOR</td>
<td>34.2 %</td>
</tr>
<tr>
<td>RECEIVER/MHD GENERATOR</td>
<td>55.0 %</td>
</tr>
<tr>
<td>RECEIVER/PROPULSION (100 % THEORETICAL)</td>
<td>50.0 %</td>
</tr>
</tbody>
</table>

### LASER POWER TRANSMISSION APPLICATIONS

- VERY LOW EARTH ORBIT SATELLITE -- DRAG REDUCTION
- OTV (LEO TO GEO) -- WEIGHT REDUCTION
- MARS -- SCIENTIFIC PROBES
- DEEP SPACE SATELLITE -- PRIME POWER SUPPLY
- SPACE PROCESSING/MANUFACTURING
MILESTONES

0 BEAM TRANSMISSION CHARACTERIZATION 5/88
0 TEST OF MOPA SYSTEM 12/88
0 OTHER GAS LASER ALTERNATIVES Na₂, HoBr 12/88
0 Nd³⁺ LIQUID LASER EVALUATION 6/88
0 SOLID STATE LASER EVALUATION Nd³⁺: YAG, Nd³⁺: GSGG, Nd³⁺: YLF 3/88
0 PREFLIGHT EXPERIMENT GROUND TESTING 3/89
0 FLIGHT EXPERIMENT -- PLAN/DESIGN ?

SUMMARY AND CONCLUSION

0 SPACE-BORNE SOLAR-PUMPED LASER SYSTEMS ARE VIABLE OPTIONS FOR LASERS FOR FREE SPACE POWER TRANSMISSION. PRIME POWER SOURCE, SUN, IS FREE AND THE SYSTEM WITH 1.3-μM WAVELENGTH IS SUITABLE FOR TRANSMISSION OVER 1000 KM (LEO-GEO DISTANCE).

0 SOLAR-PUMPED IODINE LASER SYSTEM HAS SCALABILITY AND LIGHT WEIGHT (30 TONS/MW) SUITABLE FOR SPACE-BASED OPERATION.

0 DIODE LASER ARRAYS DRIVEN BY SOLAR PANELS OR SOLAR DYNAMIC GENERATORS COULD BE ANOTHER CANDIDATE FOR THE SPACE-BASED LASER SYSTEM IF BEAM PROFILE CONTROL FOR THE LONG DISTANCE TRANSMISSION IS POSSIBLE.

0 IODINE LASER PROGRAM PROGRESSSED STEADILY SINCE 1980 AND FLIGHT EXPERIMENT PROPOSED FOR 1990’S.


