Laser Power Beaming Demonstration

Illuminating Photovoltaic Cells with Laser Light to Power an Aircraft

University of Alabama in Huntsville Center for Applied Optics Dryden Flight Research Center using MSFC facilities

OCTOBER 14TH 2004
Third International Symposium on Beamed Energy Propulsion 10-11-04
By Tim Blackwell UAH
And By DFRC and our VENDORS

A SUCCESSFUL TAPE AND BUBBLEGUM EXPERIMENT
WHAT IS POWER BEAMING?

• THE ABILITY TO PLACE POWER IN REMOTE LOCATIONS WITH THE GREATEST POSSIBLE EFFICIENCY.

• THE ABILITY TO TRANSMIT THE POWER TO THESE LOCATIONS WITH A MINIMUM OF LOSSES.

• THE ABILITY TO RECEIVE THE BEAMED POWER WITH THE GREATEST POSSIBLE EFFICIENCY.

• THE ABILITY TO UTILIZE THE RECEIVED POWER IN THE MOST COST EFFECTIVE MANNER

• A MEANS TO ACHIEVE THAT WHICH PROVIDES THE BEST SOLUTION TO A REQUIREMENT WITH THE BEST OVERALL EFFICIENCY
Brief History of Power Beaming

• RADAR beams first used to control smart bombs (WWII, signal).
• RADAR beams energy to RECTENNA (Rectifying Antenna) for aircraft engine power (1960’s).
• RADAR beams energy to ground and air receivers (1970’s).
• Microwaves proposed for beaming energy from space to earth (1970’s, 1980’s, 1990’s)
• LASERs evaluated for space power beaming (1980’s).
• Free Electron LASER proposed for space power beaming
Why is Power Beaming Important?

• Airborne platforms such as airplanes require substantial amounts of power to fly.

• Balloons must drift with the winds unless they carry a propulsion source.

• Satellites rely on solar energy collected by often massive photovoltaic arrays.

Power Beaming offers the opportunity to directly power remotely placed objects from external power sources, extending their useful flight time, increasing payload capability, and extending their working life.
What is Required to do Power Beaming?

Rich Technology Testbed History

Utilization of Existing Hardware

Enabling High Power Laser Systems

Earth Based Experiments

Space based Flight Experiment

Advanced System Concepts

Validation in Large Ground-Based Observatory/Beam Director systems

- Control Systems
- Wavefront Sensors
- Edge Sensors
- Actuators
- Software

- Electronics
- Flexures
- Backplane
- Mirrors
- Operations
Collaborators with academia & government

Collaboration:

- DFRC
- EAFB
- Other NASA facilities
- Other government facilities
- School facilities

Potential NASA sources:
1. Freebees (Give aways)
   - --ERAST
   - --Ames
   - --GRC
   - --GSFC
   - --LaRC
   - --DoD
2. Existing
   - --ERAST/Aerovironment
   - --GRC
   - --Air Force Academy
   - --Other NASA or government centers (sat. programs)
   - --Other industry/university
3. Purchase
   - --Identify vendors & cost estimates

Laser power beaming was seen as a way to augment the power collection capability of a solar aircraft with additional energy as needed
Continuous indoor Laser Beam Powered Flight  
September 17, 2003  
Hosted by the Marshall Space Flight Center,

Laser Beam Powered Rotorcraft Flight  
November 13, 2003  
with  
New Mexico State University,  
Studying rotorcraft configurations.  
&  
Marshall Space Flight Center facilities

Outdoor Laser Beam Powered Flight  
November 14, 2003  
Hosted by the US Army, Redstone Arsenal, Alabama

http://www.dfrc.nasa.gov/Gallery/Movie/Power-Beaming/HTML/EM-0066-02.html
Demonstration Purpose

• The primary interest in doing this demonstration was to increase public awareness to the viability of alternate sources of power; from harnessing solar power to utilizing the rapid growth of the laser and photovoltaic technologies for wireless transmission.

• Although many research engineers show convincing calculations that power beaming is scientifically viable, there are always the unknowns that can only be addressed with a technology demonstration.
Laser Powered Flight Demonstration

Initial Challenges

- Necessary Laser and Photovoltaic Technology
- Optimum Efficiency of Source and Receiver
- Acquisition and Tracking
- Aircraft design, cell placement
- Eye Safety
- Sufficient funding
- Test locations
Parameter Dependence

- Controls, Servo, receiver
- Weight
- Motor
- Power capability
- Propeller RPM
- Airframe
- Wing area
- Cell area, efficiency, Power production
- Light Source power
- Performance; Climb, flight time
Choosing the cells
Terrestrial Cell Efficiencies Over Time – from DOE’s Strategic Program Review March 2002
<table>
<thead>
<tr>
<th>Material</th>
<th>efficiency</th>
<th>waveband</th>
<th>status</th>
<th>comments</th>
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<tbody>
<tr>
<td>Multicrystalline silicon</td>
<td>22.7%</td>
<td>500-900nm</td>
<td>research</td>
<td></td>
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<tr>
<td>Pearl Si</td>
<td>23.1%</td>
<td>500-900nm</td>
<td>research</td>
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<tr>
<td>GaInP2/GaAs/Ge</td>
<td>30% AM1.5D</td>
<td>600-1400nm</td>
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<tr>
<td>Cu(In,Ga)Se2</td>
<td>12.8%</td>
<td>TBD</td>
<td>product</td>
<td>polymer sheet</td>
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<td>TBD</td>
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<td>1997</td>
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<td>10.1</td>
<td>500-900nm</td>
<td>research</td>
<td>2001</td>
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<tr>
<td>QW cell</td>
<td>42.5%</td>
<td>TBD</td>
<td>research</td>
<td>sydney</td>
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<tr>
<td>GaAs/Ge</td>
<td>25-35%</td>
<td>600-1400nm</td>
<td>used in space</td>
<td>mars lander</td>
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<tr>
<td>ZnO/CdS/Cu(In,Ga)Se2</td>
<td>35%</td>
<td>600-2000nm</td>
<td>NASA</td>
<td>Glen and Lewis</td>
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<tr>
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<td>TBD</td>
<td>research</td>
<td>Berkley</td>
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<tr>
<td>A-Si</td>
<td>10%</td>
<td>500-900</td>
<td>product</td>
<td>PVMAL inc</td>
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<td>Photosynthesis</td>
<td>72%</td>
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<td>research</td>
<td>DOE</td>
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<tr>
<td>InGaP,GaAs,Ge</td>
<td>29%</td>
<td>Unknown</td>
<td>research</td>
<td>GRC/NASA</td>
</tr>
</tbody>
</table>
Xenotech
L.A., CA Sept 10, 2001
ITF Cell performance with search light

Current over distance

Voltage over distance

Tilt losses

Intensity over distance

Beam intensity profile

Dryden lamp spectrum
PURCHASED PHOTOVOLTAIC CELLS

24 - K6700 Si SOLAR CELLS

~12.5 inch Diameter

Mounted on Kapton Film (2 mil thick)

17.7% @940nm

SPECTROLAB
PURCHASED PHOTOVOLTAIC CELLS

20 GaInP CELLS

SPECTROLAB

~ 5 inch Diameter

11.95% @ 532nm

Measured efficiency

Purchased Photovoltaic Cells

~ 5 inch Diameter
Choosing the aircraft
RC motorized gliders were acquired and studied to determine performance capabilities and expectations.

Engineers developed and prototyped various concepts for aircraft based on margin objectives and operational concepts.

Full access to DFRC and EAFB Aircraft design experience

Examples from Gossamer Penguin

Other NASA lightweight designs

The New Mexico State University Constrained Helicopter

First Test Model
Aircraft Final Design

Two models built:

Aircraft #1: 10 oz.
Aircraft #2: 9 oz.

Construction: Mylar, balsa wood, Graphite fiber, aluminum

Photovoltaic Panels Mounted on Side of Aircraft

- 2 meter wing span
- Electric powered*
- 10 oz weight
- 7 to 15 mph
- 2 watt cruise power

Characteristics
Wing span ~ 2 meters
Electric motor direct wired to PV
PV mounted below airframe on CG facing right side,
Flight controls operated on separate battery for safety

Aircraft 1

Aircraft 2
Determining the flight path
FLIGHT PATH OPTIONS

- Create a flight path specifically for the Laser Power beaming demonstration
- Assumptions:
  - RC class aircraft
  - Slow speed
  - Flight indoors
  - limited range
  - Manual tracking
  - 1kw laser system
Circular Path Operational Considerations

Position of Aircraft Relative to Light Source

- **Horizontal**
  - Light source
  - Light beam
  - Airplane

- **Elevated**
  - Light source
  - Light beam
  - Airplane

- **Above**
  - Airplane
  - Light beam

- **Below**
  - Light source
  - Light beam
  - Airplane
Flight Paths for Demonstrating Laser Power Beaming to an Aircraft Inside a Building

Linear Track
- Glider like airplane with photovoltaic cells facing light source and charging motor
- Light beam
- Flight path
- Track carriage
- Camera Track (used in movie productions)

A light source mounted on a camera track moves along in parallel with the airplane beaming energy to the plane to sustain level flight.

Circular Track
- Airplane with fixed rudder
- Flight path
- Light beam
- Light source on stand
- Light source rotates on stand

The airplane would have a fixed rudder that would cause it to fly in a circle of a given diameter. The light source would be mounted on a stand in the middle and rotate around to track the airplane as it flies around the circle.

Circular path selected
Tracking
Tracking Issues

Power Transfer Pointing System

Ground Vehicle System

Stabilized Platform

- Stabilization system
- Sensor input
- Algorithms
- Drive motors
- Tracker mount
- Laser
- Optics

- Power supply
- Cooling system
- Ground Control Station (on vehicle)
  - Command link
  - Data link
  - Pilot station
  - Payload station

Aircraft System

- Sensor input
- Airframe
- Flight surfaces
- Command link
- PV mount
- Actuators
- Algorithms
- Motor
- Propeller
- Photovoltaic
- Power regulation
- Payload
- Data link

"$ $$ "$
The Tracking Decision

MANUAL TRACKING CHOSEN
Built by SPARTA of Huntsville

A. Tracking Illuminator
B. Retro-reflected Tracking Beam
C. Tracking Camera
D. Power transfer laser
E. Human in the loop tracking
Inside Launch Test Plan

Dual Beam
- Hand launch
- First tracker
- Handoff
- Second tracker
- Handoff
- etc...

Single Beam
- Hand launch
- circular tracking
- etc...
• Zero zenith
• Optical path to space
• Dry atmosphere
• No volcanic ash
• .01 cm-1 resolution

Transmission:
Adiabatic processes
Clouds
High altitude ice crystals
The set of wireless power transmission flight tests actually performed

- single searchlight
- dual searchlight
- indoor laser flight
- outdoor laser flight
- indoor helicopter flight
Early tests
Objective of Searchlight Demonstration
DFRC discretionary fund ~ 60K

• Achieve level flight
• Validate aircraft design
• Identify operational quirks
• Investigate flight patterns

Flown indoors due to safety
Searchlight instead of laser
COTS PV
Manual tracking

Web site at DFRC:
http://www.dfrc.nasa.gov/Gallery/Movie/Power-Beaming/Small/EM-0066-01.mov
Searchlight Flight Operation

Small Dryden Hanger
July 31, 2002

Single beam tracking $R < 100$ feet

- Track speed
- Aircraft location in beam
- Handoff requirements
- Climb vs. level flight

Longest flight: 10 min.

Big Dryden Hanger
October 2, 2002

Discretionary project teamed with NASA
And UAH

Dual beam track

http://www.dfrc.nasa.gov/Gallery/Movie/Power-Beaming/Small/EM-0066-01.mov
Searchlight Operations Team

Dryden Hanger
July 31, 2002

Xenotech L.A.
Sept 10, 2001
Indoor laser flight preparations
Two Days of Indoor Testing

Logged 185 minutes
Total Flight Time

Continuous Flight Time <25 min
DATA FROM LASER POWER TRANSFER TESTS TO THE MOTH UAV

LASER:

1.5 kw Rofin Sinar 940nm laser array pumped to a fiber, beam expanded, and collimated.

Operated at two levels:

1) 300 Watt at the dial
2) 500 Watt at the dial

The dial setting does not include losses from the optical system or any losses due to the optical fiber. Also, 500Watt on the dial is about 400Watts at the fiber end.

Laser beam size at 15.2 meters range is 85-95 cm diameter.

OPTICS:

The collimating lens is uncoated SCHOTT F1 glass, a condenser lens.

The scanning mirror is an 8-inch diameter dielectric over-coated aluminum flat

The fiber is 1.5mm diameter with a numerical aperture of 0.35.
DATA FROM LASER POWER TRANSFER TESTS TO THE MOTH UAV

Si PHOTOVOLTAICS:

Array area: 706 cm²

MEASUREMENT AT 15.24 METERS:

Laser dial power: 300 Watts
Meter power: 0.66 Watts
Irradiance: 0.0336 Watts/cm²

Laser dial power: 500 Watts
Meter power: 1.1 Watts
Irradiance: 0.0560 Watts/cm²
### DATA FROM LASER POWER TRANSFER TESTS TO THE MOTH UAV

**AIRCRAFT PERFORMANCE DATA AT 15.24 METERS:**

<table>
<thead>
<tr>
<th>Test</th>
<th>Dial power</th>
<th>Prop speed</th>
<th>Power to motor</th>
<th>Voltage at motor</th>
<th>Current at motor</th>
<th>Irradiance at cells</th>
<th>Efficiency of loaded cells</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Test 1)</strong></td>
<td>300 Watts</td>
<td>2040 RPM</td>
<td>2.57 Watts</td>
<td>8.57 Vdc</td>
<td>0.30 A</td>
<td>23.72 Watts</td>
<td>10.8%</td>
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<tr>
<td><strong>Test 2)</strong></td>
<td>500 Watts</td>
<td>2580 RPM</td>
<td>7.0 Watts</td>
<td>11.5 Vdc</td>
<td>0.61 A</td>
<td>39.56 Watts</td>
<td>17.70%</td>
</tr>
</tbody>
</table>
INDOOR LASER POWERED FLIGHT OPERATIONS TEAM

MSFC hanger
Sept. 17 2003

Home Movie
The helicopter tests
DFRC-MSFC-UAH-UNM
Tall test stand at Redstone Arsenal

Leg @ 120 degrees
Leg length = 18 inches
Rotor diameter = 10 inches
Power Req. = 18W @ 8.3 vdc
With 85 gram sling load

Helicopter Power Beaming Demonstrator

Home movie
Crafts developed by Dryden Flight Research Center and New Mexico State University

- Performed laser power beaming tests on several rotorcraft configurations held between guide wires
- Allowed for controlled measurements of heat load on PVs at various power settings
- Prop wash is significant factor

H > 250 feet

Home movie
The outdoor laser flight tests
Laser Range Test

- Tests conducted at the Redstone Arsenal laser range.
- Flight test with 1.5kW Rofin Sinar Laser diode array.
- Achieved brief outdoor flight of aircraft in twin motor configuration
- Excessive wind gusts
- Range > 250 feet
Project Highlights for FY03

DFRC and MSFC: funding participants
SPARTA of Huntsville: provided laser and optics
UAHuntsville: primary system, flight tests, principal design contractor
New Mexico State University:
   Helicopter Guide wire demonstrator
Summer Faculty Support from Inter American University
    Dr. Eduardo Lay
    Four Summer students involved

Boeing Phantom Works expressed interest in funding high altitude
laser beaming flight demonstration upon successful completion of primary
objectives
The beam propagation questions
circular vs square aperture output

Normalized far field distance x $\frac{\pi d_{\text{aperture}}}{\lambda z}$

normalized intensity

- red: circular aperture
- blue: square aperture
- ↓: circular zero
- ↓: square zero

d_{\text{aperture}}
Far field: $z \gg \frac{2\pi}{\lambda} \frac{d^2}{2}$
12 meter aperture for NASA

Wide Apparent Aperture to maintain a reasonable spot size at the receiver.

Spot Diameter (meters)

Distance From Earth (km)

1000

35 GHz Microwaves 94 GHz

100

Near Infrared

Spot Size \( D = \frac{L}{D} \) (urad)

\( L \) = wavelength

\( D \) = beam diameter (12 meters)

\( R \) = range

Lunar

10 um

GEO

3.8 um

LEO

1.6 um

0.84 um

1.06 um

12 meter aperture for NASA

Wide Apparent Aperture to maintain a reasonable spot size at the receiver.

Spot Size \( D = \frac{L}{D} \) (urad) \( \cdot R \)

\( L \) = wavelength

\( D \) = beam diameter (12 meters)

\( R \) = range
Future prospects
Meressene Beam Expander

- Small FOV
- No central obscuration
- Adaptive wavefront
- Autonomous capability
Testing of Optical Beam Expander

Thermal Properties

Soak Temperature

- **Athermal Design:**
  - Telescope mirrors and support structure are all made of the same material
  - The thermal expansion of the support structure are perfectly balanced by the changes in radius of curvature and thickness of the mirrors to maintain the system alignment

Temperature Gradients

- Telescope tolerates up to 2°C of steady state temperature gradients
- Thermal response time is of order of 2 minutes (from 8°C gradient to 2°C gradient)

Operational Temperature Range:

- 0°C to 25°C

Survivability Temperature Range:

- -40°C to 60°C

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>ASD Level (G²/Hz)</th>
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<tbody>
<tr>
<td>20</td>
<td>0.025</td>
</tr>
<tr>
<td>20-50</td>
<td>+6 dB/oct</td>
</tr>
<tr>
<td>50-600</td>
<td>0.15</td>
</tr>
<tr>
<td>600-2000</td>
<td>-4.5 dB/oct</td>
</tr>
<tr>
<td>2000</td>
<td>0.025</td>
</tr>
<tr>
<td>Overall</td>
<td>12.9 G rms</td>
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Vibration Test

Acceleration Spectral Density Qualification Levels

Temperature Cycles

<table>
<thead>
<tr>
<th>Operational Temperature Cycles</th>
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<tbody>
<tr>
<td>8.5°C/min.</td>
</tr>
<tr>
<td>7 cycles: -50°C to +70°C</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Operational Temperature Cycles</th>
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</thead>
<tbody>
<tr>
<td>Measurements 15 min.</td>
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<tr>
<td>1 hour</td>
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<tr>
<td>5 cycles: -5°C to +30°C</td>
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</table>

<table>
<thead>
<tr>
<th>Survival Temperature Cycles</th>
</tr>
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<tbody>
<tr>
<td>-60°C to +70°C</td>
</tr>
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</table>

Survivability Temperature Range:

<table>
<thead>
<tr>
<th>Operational Temperature Range:</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°C to 25°C</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Survival Temperature Range:</th>
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<tbody>
<tr>
<td>-40°C to 60°C</td>
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<table>
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<tr>
<th>Operational Temperature Range:</th>
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<tr>
<td>-5°C to +30°C</td>
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<table>
<thead>
<tr>
<th>TUBE STRUCTURE TEMPERATURE GRADIENTS (8 deg. C)</th>
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<tbody>
<tr>
<td>TEMP (deg. C)</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
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<table>
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<tr>
<th>POSITION</th>
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<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
</tbody>
</table>
Future Ultra Lightweight Telescope

- Metal structure and optics - Athermal
- Material Properties:
  - High stiffness
  - Minimal self-weight deflection
  - Low coefficient of thermal expansion
  - High thermal conductivity
  - High thermal capacitance to dampen out transient thermal effects
  - Good hardness suitable to diamond turn and polish
- Fabrication and manufacture by conventional tools and machines
High Efficiency Photocells
Figure 1. Terrestrial Photovoltaic Cavity Converter (PVCC) Prototype for Ultimate Solar-to-Electricity Conversion Efficiency

UNITED INOVATIONS INC.
PV cell sub-arrays, interconnected in series and in parallel to generate the required system voltage and current for the nominal power output. Anti-reflective coating.

Single-junction PV cell with optimized doping and grid design for high intensity monochromatic laser light.

Figure 2. Principles of PowerSphere Concept with a Dielectric Laser Beam Injector
Photovoltaics at the University of Toledo

Faculty investigators:
Physics:  Al Compaan, Xunming Deng, Victor Karpov, Randy Bohn
Chemistry:  Dean Giolando

Polycrystalline thin-film CdTe-based cells
- on glass superstrates and foil substrates
- magnetron sputtering (low temperature)
- collaborations with First Solar, LLC

Amorphous-silicon-based thin-film cells
- triple-junction on light-weight SS foil
- glow-discharge and hot-wire deposition
- collaborations with ECD, United Solar

Progress in UT fabricated a-Si solar cells

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PV at UT for CEECAP discussion 4/30/02
examples of UT’s flexible solar cells

cadmium telluride on molybdenum sheet

amorphous silicon on stainless steel sheet

on Kapton

on SS foil
Thin Disk Laser Technology

• Adolf GIESEN,
• Inventor of thin disk architecture
• Licensed technology to UAHuntsville
• Friend of CAO

University of Bonn
1969 – 1975

Diploma thesis
"Glory oscillations in total scatter cross sections of rare gas atoms
Ne-Kr, Ne-Ar, Ar-Kr) in atomic beam experiments"

Ph.D. (doctorate) at University of Bonn 1982
"Frequency doubled single frequency dye laser in the wavelength range 282 nm for determination of rotational inelastic cross sections for the system H₂ – OH in a molecular beam experiment.


Since 1984: Head of the department "Quantum Optics"

Since 1996: University of Stuttgart, Institut fuer Strahlwerkzeuge, Head of department : "Laser Development and Laser Optics"
The principal of power scaling for the thin disk laser
THIN DISK LASER CHARACTERISTICS

- DIODE PUMPED SOLID STATE LASER
- USES LARGE AREA SMALL VOLUME GAIN MATERIAL
- MANY WAVELENGTHS AVAILABLE FOR NASA MISSION SUPPORT
- SMALL BUT COMPACT AND RUGGED
- OUTPUT POWERS UP TO 100W FOR MINITURIZED SYSTEM
- LARGER SYSTEMS UP TO 4 KW
- MULTIPASS PUMP CAVITY DESIGN
- HIGH EFFICIENCY, AS MUCH AS 50% CONVERSION TO LASER LIGHT
- THERMALLY STABLE USING PASSIVE OR ACTIVE COOLING
- STABLE FREQUENCY OUTPUT
Performance: Output power and beam quality

- **Output power in W** vs. **Pump power in W**
- **L = 95 mm, R = 0.75 m**
- **L = 90 mm, R = 1.5 m**
- **L = 90 mm, R = 2.0 m**
- **L = 415 mm, R = 2.0 m**

- **M²** vs. **Output power in W**
- **rOC = 0.5 m**
- **l = 9 cm**
- **rOC = 2 m**
- **l = 75 cm**
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output power</td>
<td>&gt; 10 kW / disk</td>
</tr>
<tr>
<td>Electro-optical efficiency</td>
<td>&gt; 30 %</td>
</tr>
<tr>
<td>Beam propagation ratio</td>
<td>$M^2 &lt; 1.5$ for 1 kW</td>
</tr>
<tr>
<td>Pulse energy</td>
<td>&gt; 1 J / disk</td>
</tr>
</tbody>
</table>
FUTURE ASPECTS of WPT

• Pending NASA proposal for long duration UAV demonstration—goal one month continuous flight
• Communication relay/Observation

• Investigating Flight corridor from Edwards to Byamon Campus
• Studying high altitude airship beaming operations
• Reviewing extra terrestrial transmission of power
• Continuation of cell progress
• Continuation of laser progress
Power Beaming Summary

HISTORY
9/10/01 Characterizing cells and sources
7/31/02 First power beaming, single searchlight
  9/9/02 First power beaming, multiple searchlights
  7/25/03 Tested cells with laser
  9/18/03 First power beaming flight with Laser

FUTURE
Test multi Kw laser
  Demo flight to 1Km altitude
Where Else?

THANK YOU FOR YOUR TIME...

LONG ENDURANCE AIRSHIP