Yehoshua Socol

High-Power Beams in Defense and Security

06. 2007
## Acknowledgements

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y. Pinhasi</td>
<td></td>
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<tr>
<td>M. Einat</td>
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<td>B. Kapilevich</td>
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<td>A. Yahalom</td>
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<tr>
<td>D. Hardon</td>
<td>(CJS)</td>
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<tr>
<td>A. Gover</td>
<td>(TAU)</td>
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<tr>
<td>Y. Krasik</td>
<td>(Technion)</td>
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<td>G. Falkovich</td>
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<td>V. Fisher</td>
<td>(Weizmann Inst)</td>
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<td>I. Shoshan</td>
<td>(ELOP)</td>
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<td>Z. Schneider</td>
<td>(ELTA)</td>
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<td>Y. Danziger</td>
<td>(RAFAEL)</td>
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<td>G. Avital</td>
<td>(Elbit)</td>
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<td>A. Shor</td>
<td>(Soreq)</td>
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<td>V. Bratman</td>
<td>(IAP)</td>
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<td>N. Vinokurov</td>
<td>(BINP)</td>
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<tr>
<td>A. Narodetskiy</td>
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<tr>
<td>R. Rovinskiy</td>
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</table>

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**Note:** The above list includes the names and institutions of individuals acknowledged for their contributions. The abbreviations refer to specific institutions or projects, such as CJS, TAU, Technion, ELOP, ELTA, RAFAEL, Soreq, BINP, Elbit, IAP, and BINP. This list acknowledges the collaborative efforts in the respective domains.
Contents

- Lasers as Weapons
- Beam Propagation
- Airborne Lasers – ABL, ATL
- Ground-based: “Cloud”, “Nautilus”
- Current trend: Solid-State, FEL
- Electronic Warfare:
  - DIRCM, gyrotrons and e-bombs
- Conclusions
Defense vs. Security

- **Defense**: Military tasks / Army
- **Security**: Law enforcement tasks / Police
- **LIC** – Low Intensity Conflict
  Army / police tasks -> 😞
Laser Beam – hit factors

- Heat and detonate (deflagrate)
  “Rapid cook-off”

- Kick and destroy
  laser ablation <- thermo-nuclear fusion
Laser Heating
Detonation/Deflagration

$\Delta t \sim 200 \, ^\circ C$

Steel: $c \sim 0.5 \, J / g \, ^\circ C \quad (3R \sim 25 \, J/mol)$

$c \Delta t \sim 100 \, J / g$

$\rho = 7.8 \, g / cm^3$

thickness $\sim 3 \, mm \quad \Rightarrow \quad m \sim 3 \, g / cm^2$

$c \Delta t \, m \sim 300 \, J / cm^2$

$A \sim 5 \times 5 \, cm \quad \Rightarrow \quad Q \sim 10 \, kJ$
Laser Ablation
Shock destruction

Fe boiling: Impact \( P \sim Q / v_z \)
Fe vapor – molecular velocity
\( v_z \sim 500 \text{m/s} \)
\( m v_z^2 / 2 = kT / 2 \)
\( T \sim 3000 \text{K} \sim 0.25 \text{eV} \)
\( m \sim 60 \text{ GeV/c}^2 \)

\( Q = 10 \text{kJ} \)

\( P \sim 20 \text{N s} \)

\( \tau = 1 \mu\text{s} \rightarrow F \sim 2 \text{Kton} \)
## Plasma Formation

- USSR NPO “Astrophysics” 1969-1985
- Initial idea: anti-ICBM (SDI analog)
  - laser ablation -> kick and destroy

### Plasma formation threshold, CO$_2$ laser irradiation

<table>
<thead>
<tr>
<th></th>
<th>Glass</th>
<th>Quartz</th>
<th>Al</th>
<th>PMMA</th>
<th>LiF</th>
</tr>
</thead>
<tbody>
<tr>
<td>E (threshold) J/cm$^2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2µs</td>
<td>1.4</td>
<td>3.6</td>
<td>2.2</td>
<td>9.0</td>
<td>8.0</td>
</tr>
<tr>
<td>10µs</td>
<td>1.7</td>
<td>3.6</td>
<td>6.5</td>
<td>13.0</td>
<td>15.0</td>
</tr>
</tbody>
</table>

- Initial idea: anti-ICBM (SDI analog)
  - laser ablation -> kick and destroy

### Table

<table>
<thead>
<tr>
<th></th>
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<th>Quartz</th>
<th>Al</th>
<th>PMMA</th>
<th>LiF</th>
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<td>6.5</td>
<td>13.0</td>
<td>15.0</td>
</tr>
</tbody>
</table>
Lasers vs. Kinetic

1 Horse Power (hp) = 736 W

Typical laser  100 W  average
High-Power  10 kW  average

- 100 kW = 135 hp  ~ light truck
- 1 MW = 1350 hp  ~ 4 trucks, <“Merkava”
## Lasers vs. Kinetic

<table>
<thead>
<tr>
<th>Type</th>
<th>Energy (E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical laser (pulse)</td>
<td>E ( \sim 0.1 ) J</td>
</tr>
<tr>
<td>“Nautilus”</td>
<td>E ( \sim 100 ) kJ</td>
</tr>
<tr>
<td>Bullet (10g, 1000 m/s)</td>
<td>E ( \sim 5 ) kJ</td>
</tr>
<tr>
<td>Hand grenade (8g explosive)</td>
<td>E ( \sim 30 ) kJ</td>
</tr>
</tbody>
</table>
Lasers may be cost-effective only against extremely important targets.
High-Power Lasers

Solid State: heating ->
thermal lensing...

Therefore:

- Gas lasers ("Naultilus")
- Vacuum devices
- FEL / FEM – free electron laser/maser
- CRM (Gyrotron) – cyclotron resonance maser (ADS)
# High-Power Gas Lasers

<table>
<thead>
<tr>
<th></th>
<th>Wavelength $\mu$m</th>
</tr>
</thead>
<tbody>
<tr>
<td>COIL</td>
<td>1.315</td>
</tr>
<tr>
<td>Chemical Oxygen Iodine Laser</td>
<td>1.315</td>
</tr>
<tr>
<td>DF</td>
<td>3.8</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>10.6</td>
</tr>
</tbody>
</table>
HELWS projects
High-Energy Laser Weapon Systems

10 km

ABL (Air-Borne Laser)

5 km

ATL (Adv. Tactical L.)

THEL Nautilus

Ground

“Cloud” (USSR)
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Beam propagation – factors

- Diffraction-limited divergence
- Normal attenuation in air
- Atmospheric turbulence (scattering)
- Self-focusing and break-down
- Plasma formation (target)
Beam propagation - focusing

Gaussian beam - diffraction-limited spot

- \( d = 2 w_0 \) – waist (focus) diameter
- \( D = 2 w(z) \) – focusing mirror diameter
- \( \lambda \) – wavelength, \( z \) – distance to target
- \( \pm w_0 = \pm 2\sigma \) (Energy)

\[
d \sim 4 \frac{z \lambda}{\pi D}
\]

If \( D > 4 \sqrt{\frac{z \lambda}{\pi}} \)

\[
w(z) \sim \frac{z \lambda}{\pi w_0}
\]

\[
z > 2 z_R, z_R = \frac{\pi w_0^2}{\lambda}
\]

\( z = 5 \text{ km}, \lambda = 3.8 \mu\text{m}, D=50 \text{ cm} \) \( \rightarrow d \sim 5 \text{ cm} \)
# Beam propagation

<table>
<thead>
<tr>
<th>Material</th>
<th>( \lambda ), ( \mu \text{m} )</th>
<th>Attenuation (atmosphere)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nd:YAG</td>
<td>1.06</td>
<td>30%</td>
</tr>
<tr>
<td>COIL Chemical Oxygen Iodine Laser</td>
<td>1.315</td>
<td>50%</td>
</tr>
<tr>
<td>HF Hydrogen Fluoride</td>
<td>2.7-2.9</td>
<td>100%</td>
</tr>
<tr>
<td>DF Deuterium Fluoride</td>
<td>3.8</td>
<td>10%</td>
</tr>
<tr>
<td>CO(_2)</td>
<td>10.6</td>
<td>20%</td>
</tr>
</tbody>
</table>

![Graph showing transmittance (%)](image)
Beam propagation

Scattering

- Scattering \( \sigma \sim \omega^4 \sim 1/\lambda^4 \)
- \( \sigma(\text{Nd:YAG}) \sim 2 \sigma(\text{COIL}) \sim 150 \sigma(\text{DF}) \)
- 1.06 \( \mu \text{m} \)  
- 1.315 \( \mu \text{m} \)  
- 3.8 \( \mu \text{m} \)
HELWS projects
High-Energy Laser Weapon System (THEL) Nautilus

10 km

ABL (Air-Borne Laser)

5 km

ATL (Adv. Tactical L.)

Turbulent air

Ground

THEL Nautilus

“Cloud” (USSR)
Beam propagation

Non-linear effects

- DC break-down (avalanche)
  \[ E_{b-d} = 30 \text{ kV/cm} \]
  \[ P = 2.5 \text{ MW/cm}^2 \]
  Holds up to \( \sim 10 \) GHz (microwaves)

- Optical break-down
  \[ E_{b-d} = 1000-10,000 \text{ kV/cm} \]
  \[ P = 2.5-250 \text{ GW/cm}^2 \]
  Self-focusing (collapse, filamentation)
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Target Missiles

- Range: 100 km -> non-limited
- Velocity: 2000-8000 m/s
- Accuracy: ~500m (50m for tactical)
- Warhead: 500kg -> Nuclear

Nuclear Warheads

- "Atomic": 1-20 Kton
  - Destruction range: ~1 km
- "Hydrogen": 100-1000 Kton
  - Destruction range: ~3-4 km

Hiroshima: 15 Kton
- LD$_{50}$: 0.5 km
- $P \sim \frac{1}{r^3}$
ABL – Airborne Laser

D, LIC

Courtesy: Boeing
ABL – Airborne Laser

- **Target**: Tactical ballistic missiles at boost stage
- **Range**: 500 km
- **Laser**: COIL 1.315 µm
- **Power**: ~ 1 MW
- **Pumping**: Chemical
- **Weight**: 300 ton
- **Lay-out**: Boeing 747-400F (320 ton)

Laser installation on board: 2007
<table>
<thead>
<tr>
<th>ATL – Advanced Tactical Laser</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Target</strong></td>
</tr>
<tr>
<td><strong>Range</strong></td>
</tr>
<tr>
<td><strong>Laser</strong></td>
</tr>
<tr>
<td><strong>Power</strong></td>
</tr>
<tr>
<td><strong>Pumping</strong></td>
</tr>
<tr>
<td><strong>Lay-out</strong></td>
</tr>
</tbody>
</table>

Test program: 2007 - 2009
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<table>
<thead>
<tr>
<th></th>
<th>&quot;Stilet“ (Dirk)</th>
<th>&quot;Oblako“ (Cloud)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser type</td>
<td>Nd-Glass</td>
<td>CO₂</td>
</tr>
<tr>
<td>Wavelength</td>
<td>1.06µm</td>
<td>10.6µm</td>
</tr>
<tr>
<td>Pumping</td>
<td>Flash lamp</td>
<td>300kV e-beam</td>
</tr>
<tr>
<td>Pulse energy</td>
<td>3kJ</td>
<td>30kJ</td>
</tr>
<tr>
<td>Pulse length</td>
<td>10µs</td>
<td>2µs</td>
</tr>
<tr>
<td>Action</td>
<td>Glass destruction (thermal shock)</td>
<td>Plasma formation Jamming imagers</td>
</tr>
<tr>
<td>Lay-out</td>
<td>Armored vehicle</td>
<td>Two 30-ton platforms</td>
</tr>
</tbody>
</table>
Nautilus -> THEL
Tactical High-Energy Laser
1996-2006

Photo: Northrop Grumman
<table>
<thead>
<tr>
<th>Target:</th>
<th>Rocket</th>
<th>Cannon</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MRL</td>
<td>122-155mm</td>
</tr>
<tr>
<td>Range, km</td>
<td>20-30</td>
<td>12-15</td>
</tr>
<tr>
<td>Velocity, m/s</td>
<td>250-300</td>
<td>600-1200</td>
</tr>
<tr>
<td>Accuracy, m</td>
<td>~150</td>
<td>~25</td>
</tr>
<tr>
<td>at 2/3 range</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warhead, kg</td>
<td>20-25</td>
<td>5-10</td>
</tr>
<tr>
<td>Fire rate</td>
<td>40</td>
<td>~1</td>
</tr>
<tr>
<td>per 20s</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Nautilus – THEL</strong></td>
<td>LIC</td>
<td></td>
</tr>
<tr>
<td>---------------------</td>
<td>-----</td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>5 miles</td>
<td></td>
</tr>
<tr>
<td>Principle</td>
<td>Heating</td>
<td></td>
</tr>
<tr>
<td>Laser type</td>
<td>Deuterium Fluoride</td>
<td></td>
</tr>
<tr>
<td>Power</td>
<td>100 kW</td>
<td></td>
</tr>
<tr>
<td>Pumping</td>
<td>Chemical</td>
<td></td>
</tr>
<tr>
<td>Cost per shot</td>
<td>$ 3000</td>
<td></td>
</tr>
<tr>
<td>Beam diameter</td>
<td>~ inches</td>
<td></td>
</tr>
<tr>
<td><strong>Successful hits</strong></td>
<td>28</td>
<td></td>
</tr>
<tr>
<td><strong>Project cost</strong></td>
<td>&gt; $ 300M</td>
<td></td>
</tr>
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<td>Main contractor</td>
<td>Northrop Grumman, USA</td>
<td></td>
</tr>
<tr>
<td>Sub-contractors</td>
<td>ELTA, RAFAEL, …</td>
<td></td>
</tr>
</tbody>
</table>

Fuel only!!!!!
## Anti-Nautilus

### Possible counter-measures

- Reflective coating
- Heat hardening
THEL -> MTHEL (Mobile)

Main contractor: Northrop Grumman, USA
Sub-contractors: ELTA, RAFAEL, …

Lay-out: Three 20-ton semi-trailers
 Estimated cost: $300-400M (?)

Project terminated: Jan 2006

SkyGuard (counter-Manpads): $1.9M
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High-Power Solid-State

Present trends:

_**fiber, disk, ...**_

IPG Photonics: 10 kW (CW), 1.06 µm
1000 kg, 25% eff. (wall-plug)

_Incoherent adding!_
High-Power Solid-State

- Present trends: fiber, *disk*, ...

Lawrence Livermore National Laboratory
Nd:YAG 45kW (CW)
High-Power Solid-State

Lawrence Livermore National Laboratory
Nd:YAG 45kW
## High-Power Solid-State

<table>
<thead>
<tr>
<th>Current projects</th>
<th>Power, kW (CW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>~1.06 μm</td>
<td></td>
</tr>
<tr>
<td>Northrop Grumman</td>
<td>15</td>
</tr>
<tr>
<td>Raytheon (Phase Conj. Mirror Loop)</td>
<td>3</td>
</tr>
<tr>
<td>Textron</td>
<td>15</td>
</tr>
<tr>
<td>LLNL (5 slabs)</td>
<td>67</td>
</tr>
</tbody>
</table>

*Scattering!*
Free Electron Laser (FEL)

- E-beam energy: 20-80 MeV
- Wavelength: 3-150 µm
- Power (average): 10-100 W
- Power (peak): MW +
FEL

Advantages

- Vacuum device => High Power
- Tunability

Disadvantages

- High-energy (20-80MeV) electron beam
  - accelerator needed
  - ionizing radiation
- Size and weight
Jefferson Lab FEL

Funding: US Navy

- 2004 10 kW 6 µm
- 2006 14.2 kW 1.6µm

Target power: 100 kW
Jefferson Lab FEL

Funding: US Navy

Project funding

2006 $14M
2007 - 2014 $180M
in 8 years

Superconducting rf linac
Beam dump
IR wiggler
UV wiggler
Injector
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**Shoulder-fired missiles**

**Manpads** *(man-portable air defense system)*

**anti-tank**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>3-6 km</td>
</tr>
<tr>
<td>Speed</td>
<td>250-600m/s</td>
</tr>
<tr>
<td>Accuracy</td>
<td>&lt;1 m</td>
</tr>
<tr>
<td>Warhead</td>
<td>~1 kg</td>
</tr>
</tbody>
</table>
Laser Beam – hit factors

“Primitive”
- Heat and detonate
- Kick and destroy

“Advanced”
- Jam missile imager (self-guiding)
- Destroy imager (self-guiding)
## Counter-manpads

### S-D

**DIRCM** Directed Infrared Counter-Measures

- **2002** “Medusa” : 3 phases
- **2008** complete flight demonstrations
- **Phase I**
  - BAE Systems, Northrop Grumman, Lockheed Martin

- **Phase III** $109M
  - BAE Systems (JetEye)
  - Northrop Grumman (Guardian)
Counter-manpads

**DIRCM** Directed Infrared Counter-Measures

*Northrop Grumman (SkyGuard)*

- **Lay-out**
- **Weight**
- **Unit cost**

- **External pod**
- **220 kg (500 lb)**
- **$ 2.1M**

**US fleet protection cost**

- **Capital investment**
- **Per flight**

- **$ 11,000M**
- **$ 365**

(including extra ~1% fuel)
Gyrotron – CRM

Cyclotron Resonance Maser

YOSH Gyrotron
Frequency  6.7 GHz
Power  1 kW
### Gyrotrons – the state of the art

<table>
<thead>
<tr>
<th>TOSHIBA</th>
<th>GYCOM</th>
<th>THALES</th>
<th>CPI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>&lt;800 GHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power (CW)</td>
<td>1 MW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>at 170 GHz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulse duration</td>
<td>20 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Efficiency</td>
<td>45 %</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**GYCOM** 1MW Gyrotron
1 MW COIL laser
Gyrotron

Electronic Warfare; non-lethal weapon

\[ w_0 = \sqrt{\frac{L \lambda}{2 \pi}} \]

\[ D \text{ (antenna)} = 2 \sqrt{2} w_0 \]

\[ L = \pi D^2 / 4 \lambda \]

\[ \lambda = 3 \ mm \]

- \( D \text{ (antenna)} = 4m \quad L = 4000m \)
- \( D \text{ (antenna)} = 2m \quad L = 1000m \)
- \( D \text{ (antenna)} = 1m \quad L = 250m \)
Gyrotron

Vigilant Eagle Airport Protection System

Raytheon

18-month, $ 4.1M not testing HPM! (high-power microwave)
Gyrotron

ADS - non-lethal weapon

“Despite an enormous degree of hype, and considerable investment for more than a decade, the deployment of a tactical high-power microwave (HPM) weapon – a reusable mobile transmitter capable of damaging a range of targets – is some way off.”

Jane’s Defence Weekly
25.08.2006

World Tribune  03.02.05
ADS – Active Denial System

f = 95 GHz
L = 1 km

To be deployed: 08.2005
E-bomb

- Explosively-Pumped
  Flux Compression Generator

  Pulse energy \( \sim 10^7 \) J

  Pulse duration \( \sim 10-100 \) µs
Conclusions

- Considerable activity
- Expectations are still far ahead of the achievements
- High-cost targets should be considered
- Novel means of Electronic Warfare (gyrotron, e-bomb etc.) still await verification