Yehoshua Socol

High-Power Beams in Defense and Security

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Acknowledgements

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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

- **D**efense: Military tasks / Army
- **S**ecurity: 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

$\Delta t \sim 200\ ^oC$

Steel: $c \sim 0.5\ J / g\ ^oC$ $(3R \sim 25\ J/mol)$

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

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

thickness ~ 3 mm -> $m \sim 3\ g / cm^2$

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

A ~ 5x5 cm -> ***$Q \sim 10\ kJ$***

Laser Ablation

Shock destruction

Fe boiling: Impact ***$P \sim Q / v_z$***

Fe vapor – molecular velocity

v_z~500m/s

$mv_z^2 / 2 = kT / 2$

$T \sim 3000K \sim 0.25$ eV

$m \sim 60$ GeV $/c^2$

Q = 10 kJ

$P \sim 20$ N s

τ= 1 μs -> ***$F \sim 2$ 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

	Glass	Quartz	Al	PMMA	LiF
E (threshold) 2μs J/cm^2	1.4	3.6	2.2	9.0	8.0
E (threshold) 10μs J/cm^2	1.7	3.6	6.5	13.0	15.0

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

Typical laser (pulse)	E ~ 0.1 J
"Nautilus"	E ~ 100 kJ
Bullet (10g, 1000 m/s)	E ~ 5 kJ
Hand grenade (8g explosive)	E ~ 30 kJ

Lasers may be cost-effective

only

against extremely important targets

Anti-Missile Counter-Measures

High-Power Lasers

Solid State: heating ->
thermal lensing…

Therefore:

- Gas lasers ("Naultilus")
- Vacuum devices

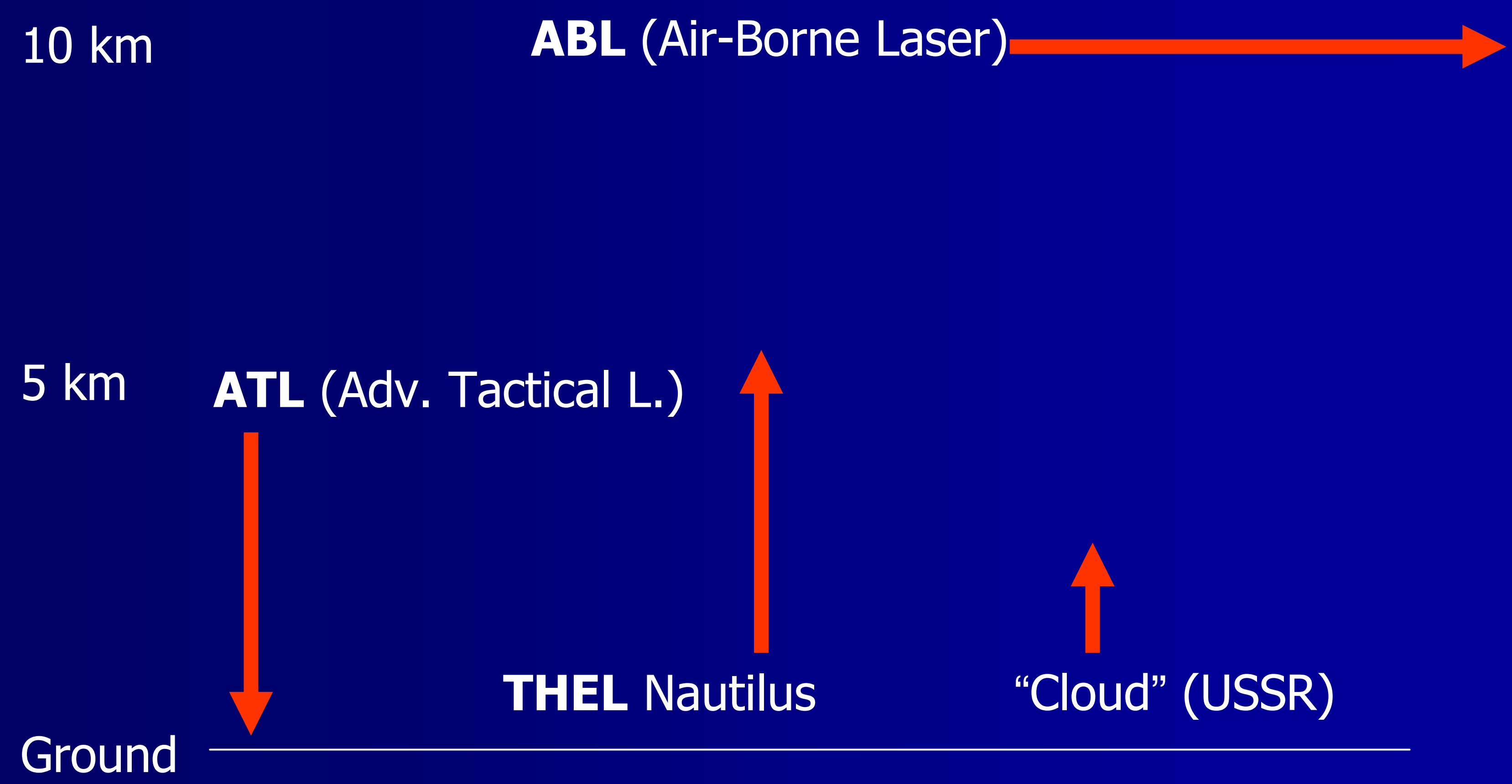
FEL / FEM – free electron laser/maser

CRM (Gyrotron) – cyclotron resonance maser (ADS)

High-Power Gas Lasers

	Wavelengh µm
COIL Chemical Oxygen Iodine Laser	1.315
DF Deuterium Fluoride	3.8
CO_2	10.6

HELWS projects
High-Energy Laser Weapon Systems



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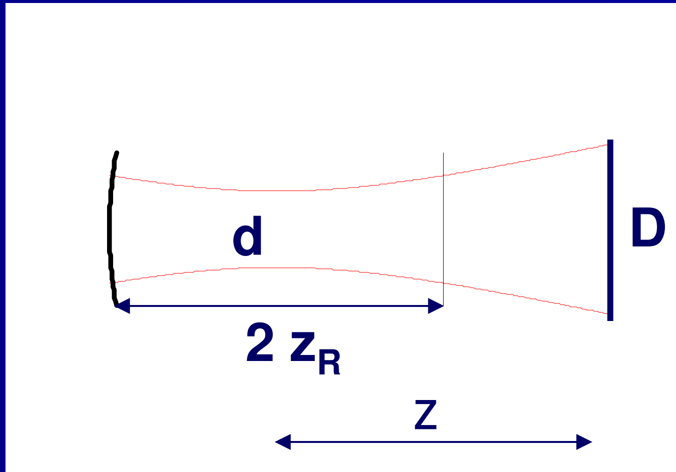
Beam propagation – factors

- 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
- λ – wavelength, z – distance to target
- $\pm\ w_0 = \pm\ 2\sigma$ (Energy)



$$d \sim 4\ z\ \lambda\ /\ \pi\ D$$

$w(z) \sim z\ \lambda\ /\ \pi\ w_0$

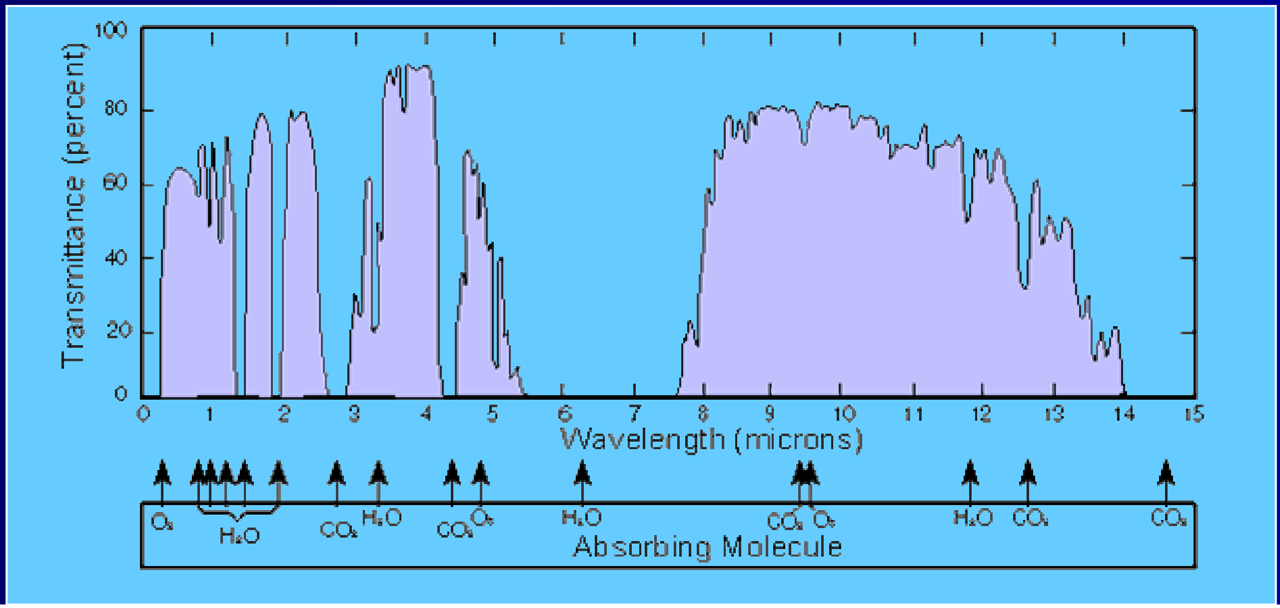
if $D > 4 \sqrt{z\ \lambda\ /\ \pi}$

$z > 2\ z_R\ ,\ z_R = \pi\ w_0^{\ 2} / \ \lambda$

$z = 5$ km, $\lambda = 3.8\ \mu$m, $D=50$ cm -> **$d \sim 5$ cm**

Beam propagation

	λ, μm	Attenuation (atmosphere)
Nd:YAG	1.06	30%
COIL Chemical Oxygen Iodine Laser	1.315	50%
HF Hydrogen Fluoride	2.7-2.9	100%
DF Deuterium Fluoride	3.8	10%
CO_2	10.6	20%

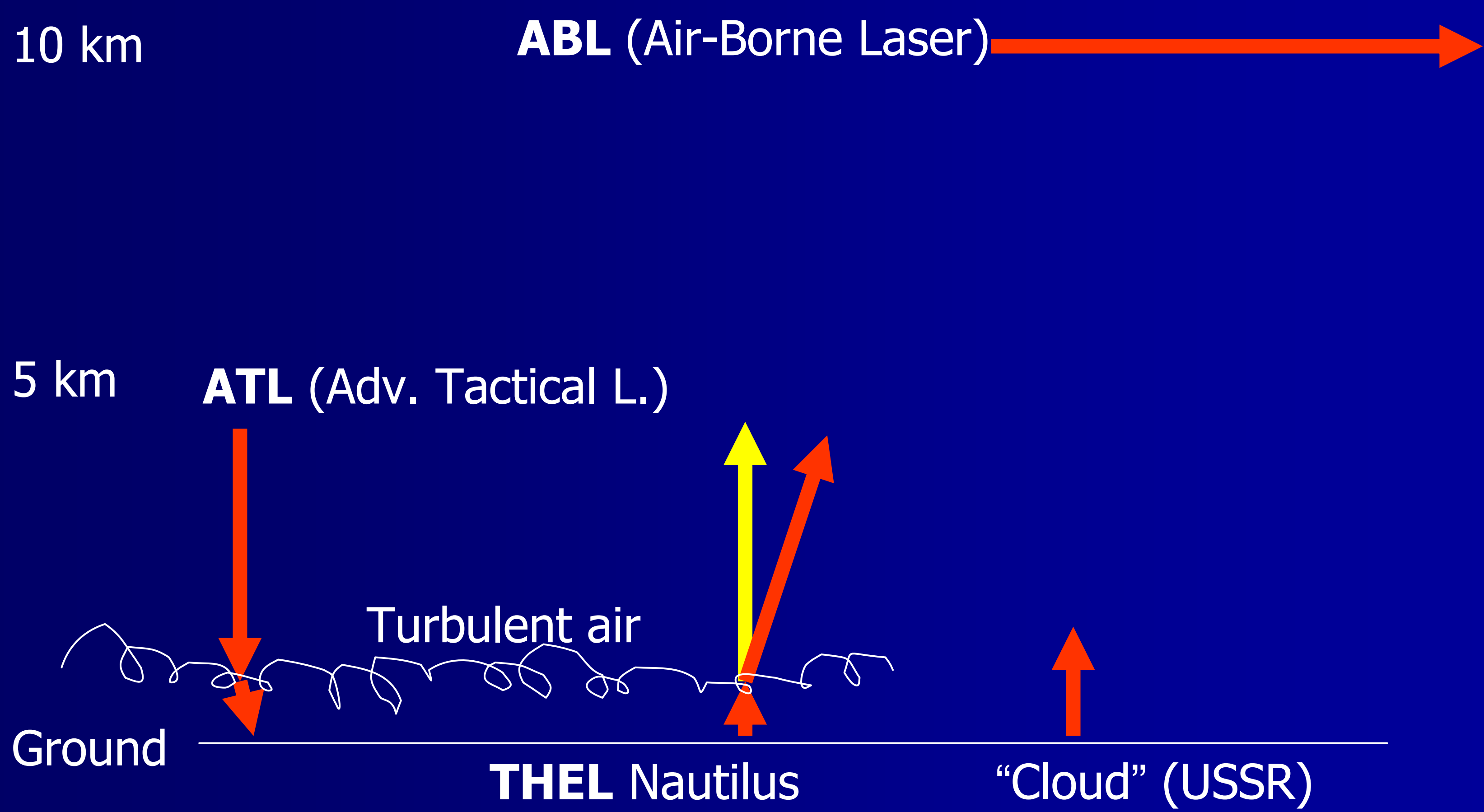


Beam propagation

Scattering

- Scattering $\sigma \sim \omega^4 \sim 1 / \lambda^4$
- σ(Nd:YAG) ~ 2 σ(COIL) ~ 150 σ(DF)
  1.06 μm 1.315 μm 3.8 μm

HELWS projects
High-Energy Laser Weapon Systems



Beam propagation

Non-linear effects

- DC break-down (avalanche)

  $E_{b\text{-}d}$ 30 kV/cm

  P 2.5 MW/cm^2

  Holds up to ~10 GHz (microwaves)

- Optical break-down

  $E_{b\text{-}d}$ 1000-10,000 kV/cm

  P 2.5-250 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 ***Hiroshima: 15 Kton***

destruction range ~1 km ***LD_{50} 0.5 km***

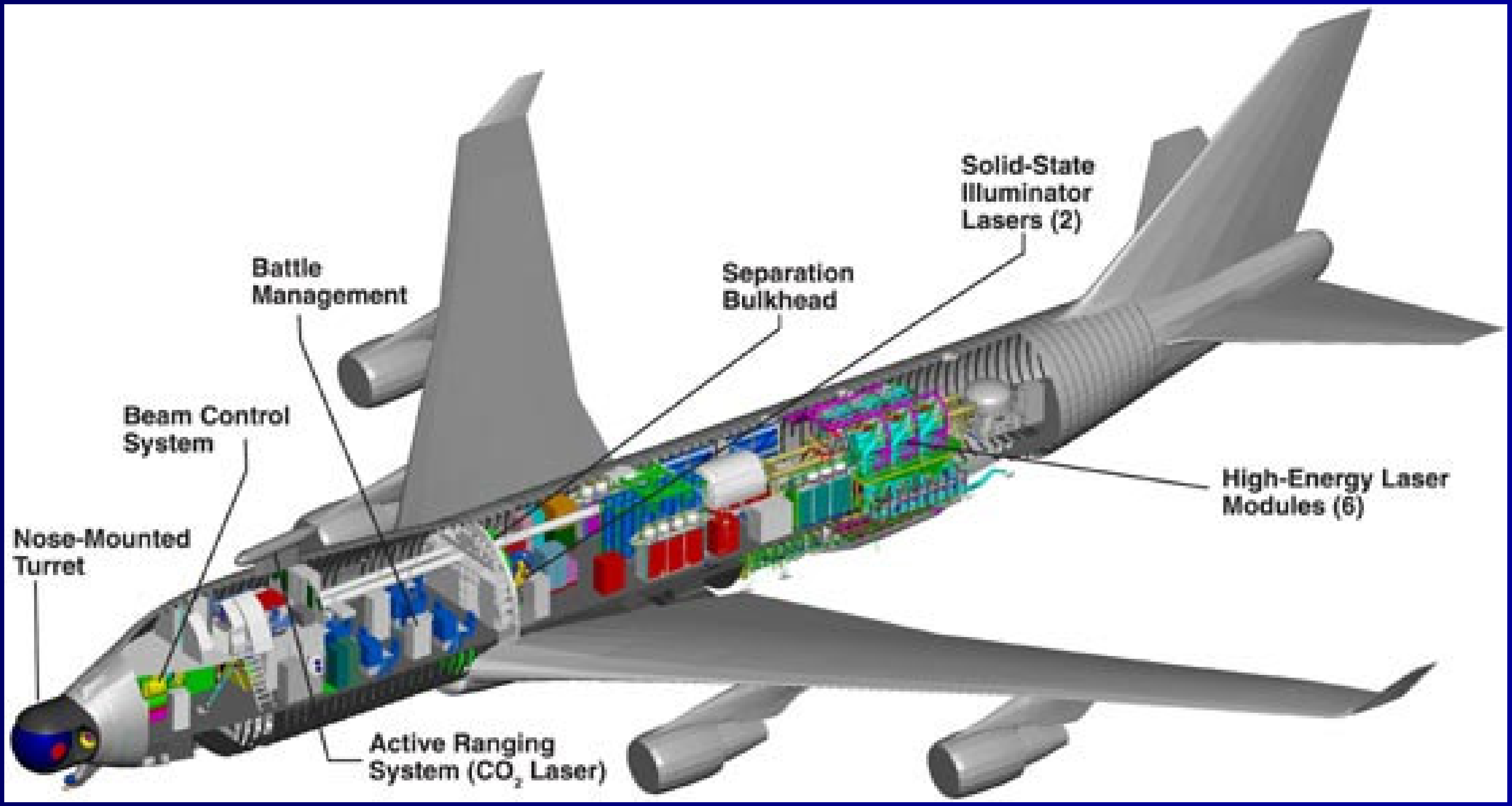
"Hydrogen" 100-1000 Kton

(thermo-nuclear)

destruction range ~3-4 km ***$P \sim 1/r^3$***

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

ATL – Advanced Tactical Laser

Target	Urban warfare, …
Range	20 km
Laser	COIL 1.315 µm
Power	~ 1 MW
Pumping	Chemical
Lay-out	C-130H Hercules

Test program: 2007 - 2009

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USSR

NPO “Astrophysics” 1969-1985

	"Stilet“ (Dirk)	"Oblako" (Cloud)
Laser type	Nd-Glass	CO_2
Wavelength	1.06µm	10.6µm
Pumping	Flash lamp	300kV e-beam
Pulse energy	3kJ	30kJ
Pulse length	10µs	2µs
Action	Glass destruction (thermal shock)	Plasma formation Jamming imagers
Lay-out	Armored vehicle	Two 30-ton platforms

Nautilus –> THEL

LIC

Tactical High-Energy Laser 1996-2006

Photo: Northrop Grumman

Target:	Rocket MRL	Cannon 122-155mm
Range, km	20-30	12-15
Velocity, m/s	250-300	600-1200
Accuracy, m at 2/3 range	~150	~25
Warhead, kg	20-25	5-10
Fire rate per 20s	40	~1

Nautilus – THEL **LIC**

Range	5 miles	
Principle	Heating	
Laser type	Deuterium Fluoride	
Power	100 kW	
Pumping	Chemical	
Cost per shot	$ 3000	**Fuel only!!!!!**
Beam diameter	~ inches	
Successful hits	***28***	1996-2004
Project cost	***> $ 300M***	1996-2004
Main contractor	Northrop Grumman, USA	
Sub-contractors	ELTA, RAFAEL, …	

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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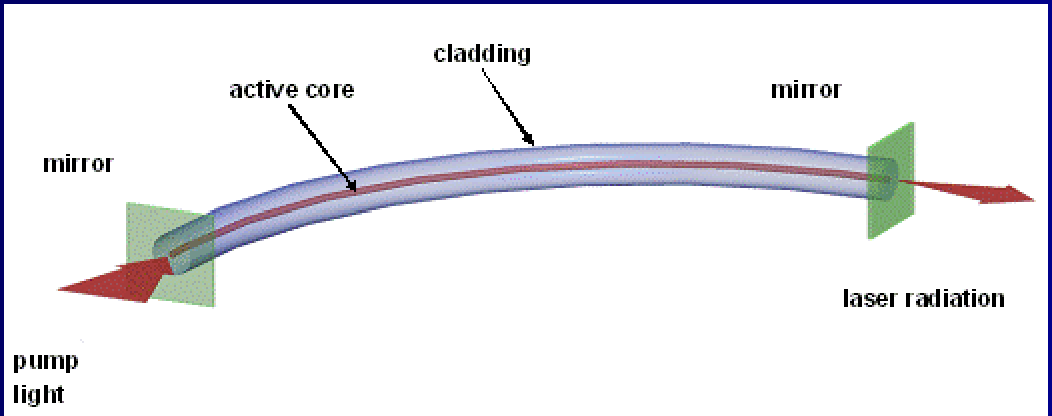
High-Power Solid-State

- Present trends:

  fiber, disk, …



IPG Photonics: 10 kW (CW), 1.06 µm

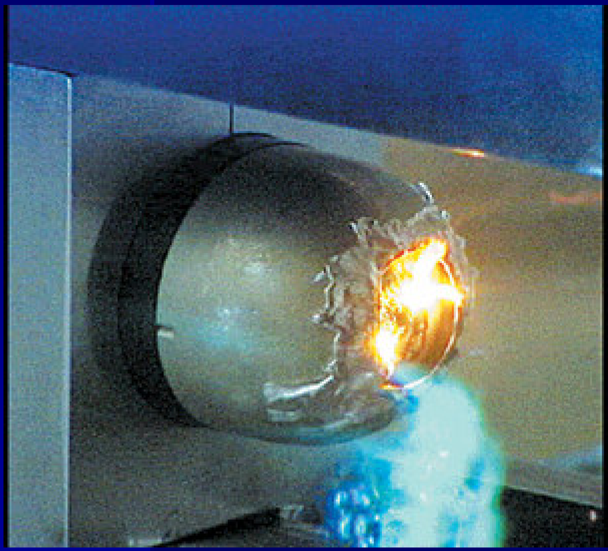
1000 kg, 25% eff. (wall-plug)

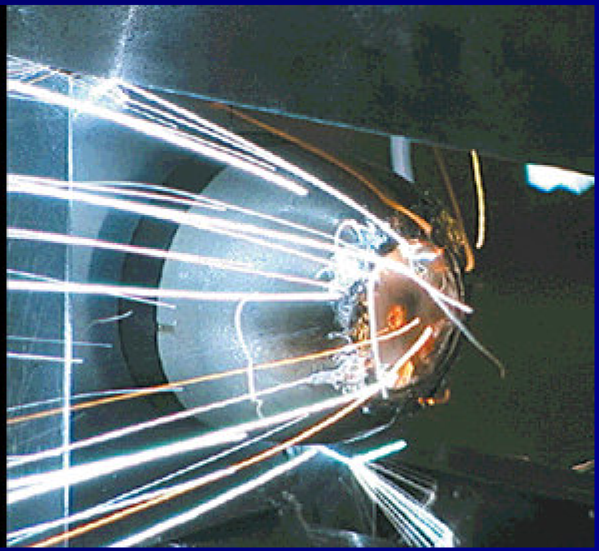
Incoherent adding!

High-Power Solid-State

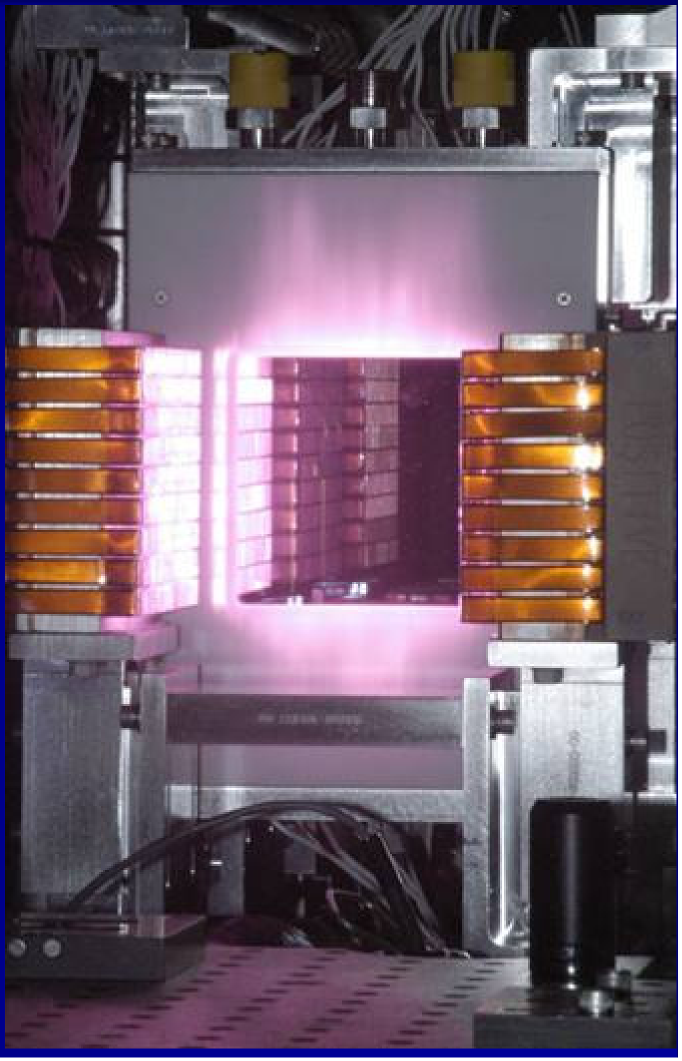
- Present trends:

  fiber, ***disk***, …

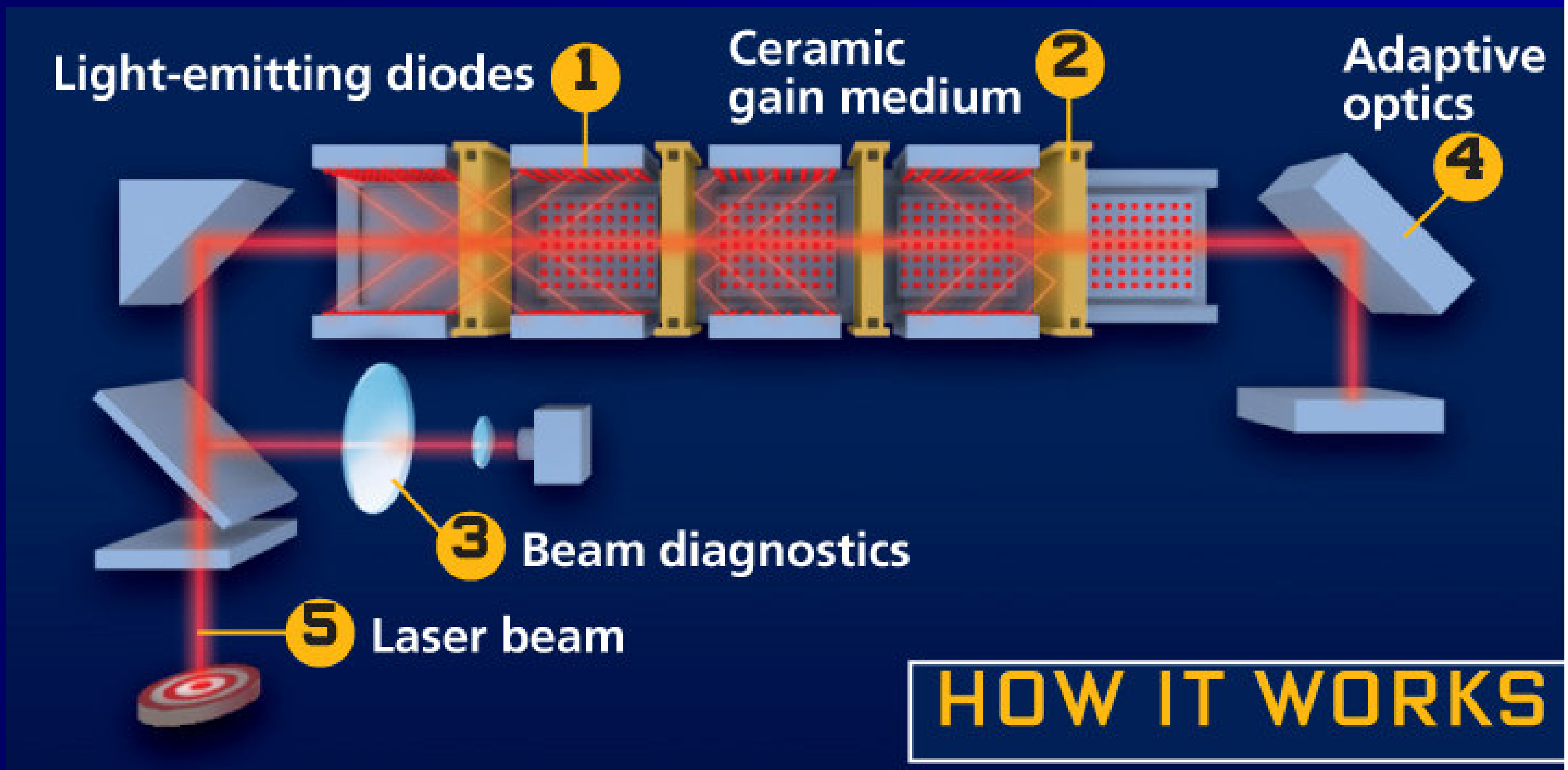




Lawrence Livermore National Laboratory
Nd:YAG 45kW (CW)



High-Power Solid-State



Lawrence Livermore National Laboratory

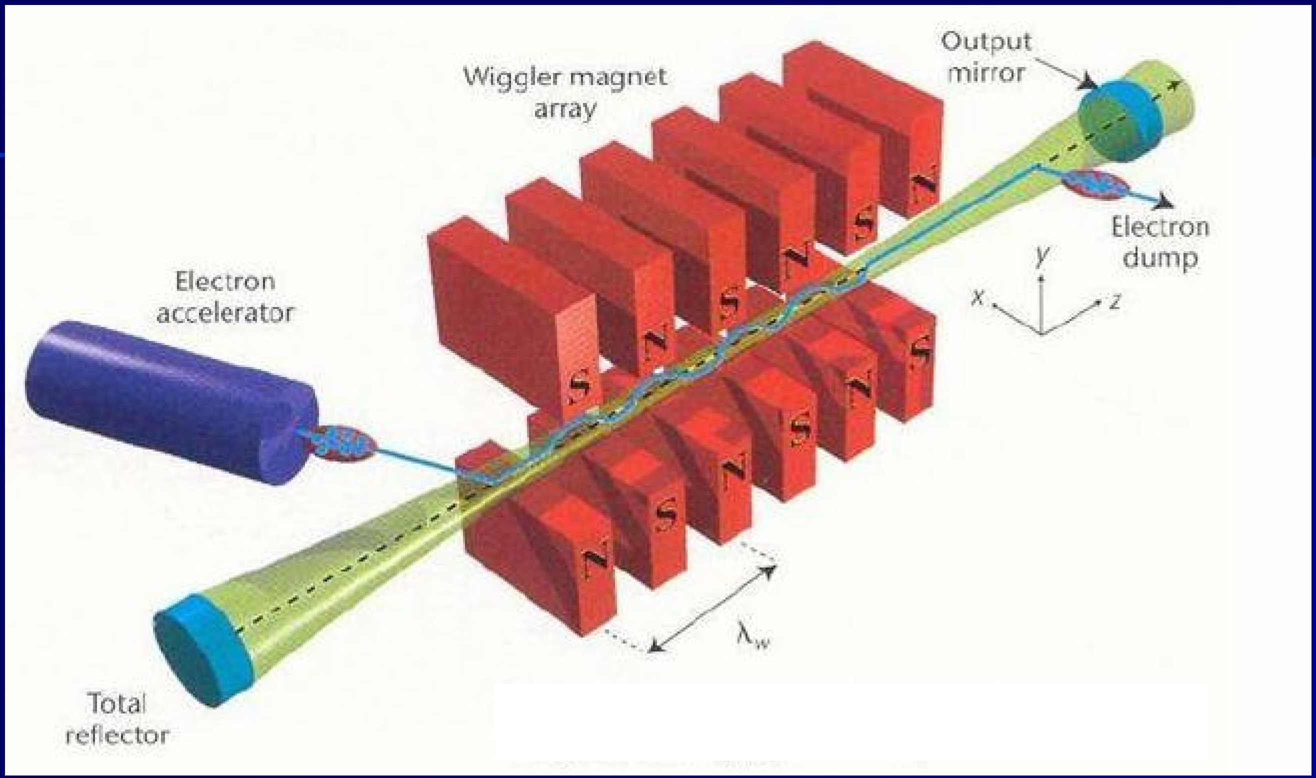
Nd:YAG 45kW

High-Power Solid-State

Current projects	Power, kW (CW)
~ 1.06 µm	
▪ Northrop Grumman	15
▪ Raytheon (Phase Conj. Mirror Loop)	3
▪ Textron	15
▪ LLNL (5 slabs)	67

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

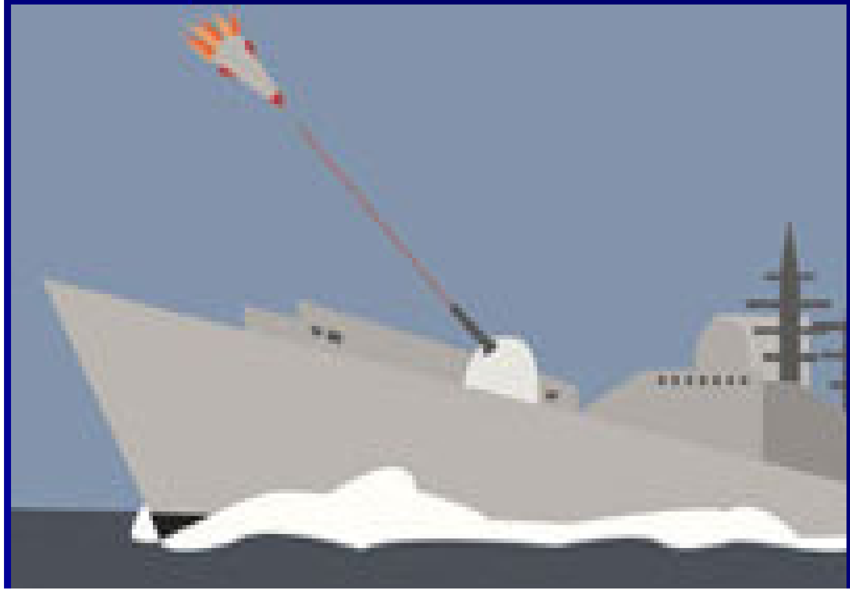
Disadvantages

- 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



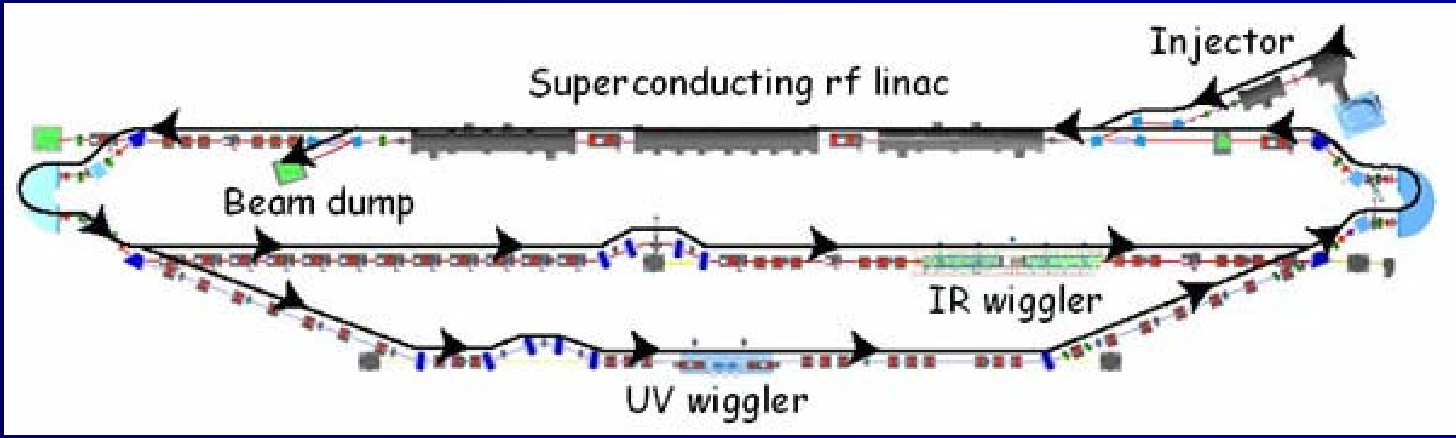
Target power: 100 kW

Jefferson Lab FEL

Funding: US Navy

Project funding

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



Contents

Shoulder-fired missiles

Manpads (man-portable air defense system)

anti-tank

Range	3-6 km
Speed	250-600m/s
Accuracy	<1 m
Warhead	~1 kg

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 **S-D**

DIRCM Directed Infrared Counter-Measures

Northrop Grumman (SkyGuard)

Lay-out	External pod
Weight	220 kg (500 lb)
Unit cost	$ 2.1M

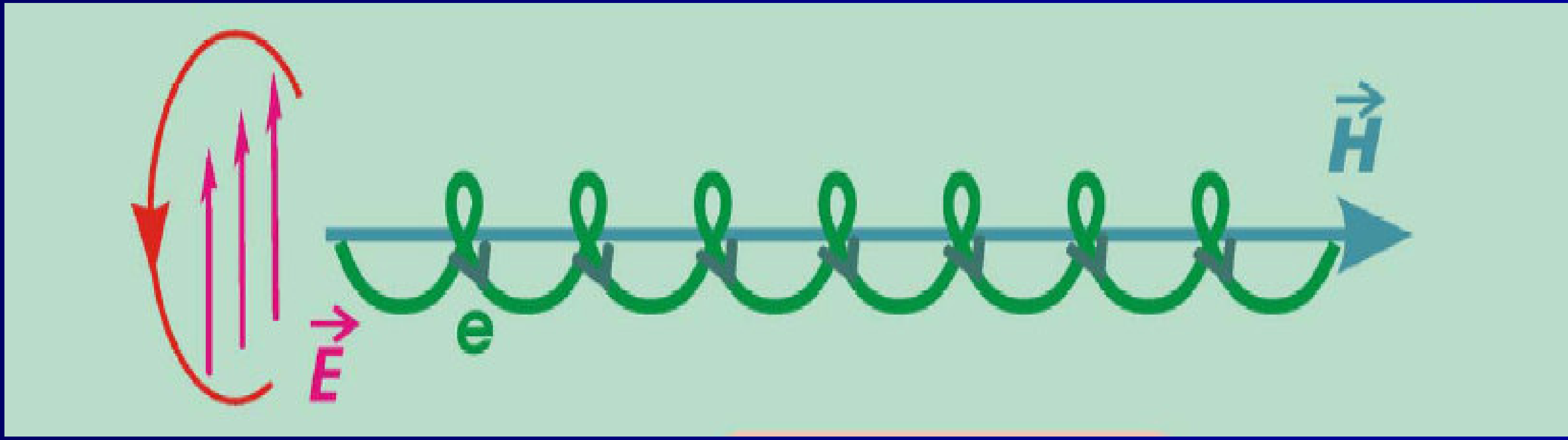
US fleet protection cost

■ Capital investment	$ 11,000M
■ Per flight	$ 365

(including extra ~1% fuel)

Gyrotron – CRM

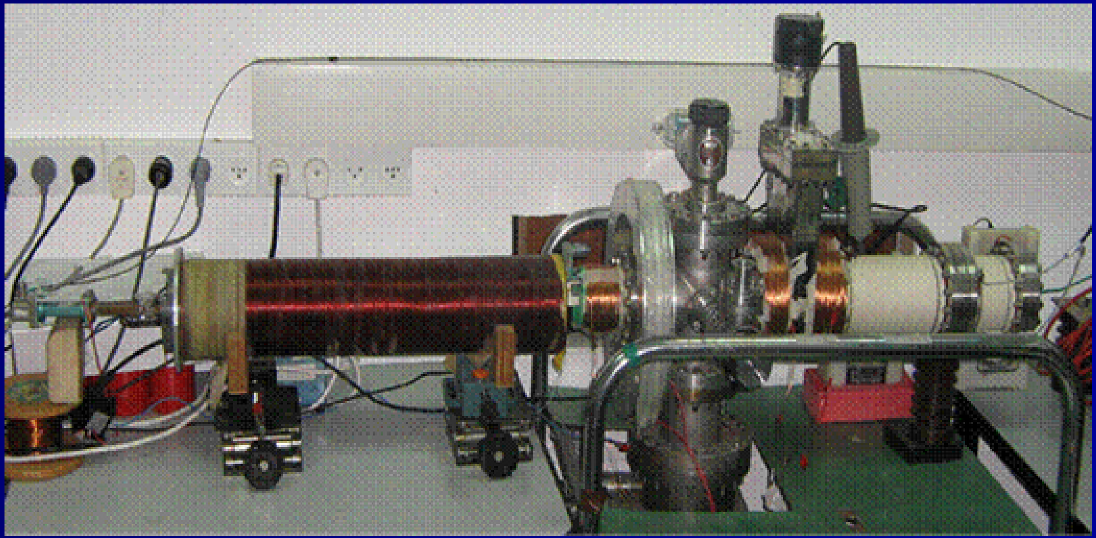
Cyclotron Resonance Maser



YOSH Gyrotron

Frequency 6.7 GHz

Power 1 kW



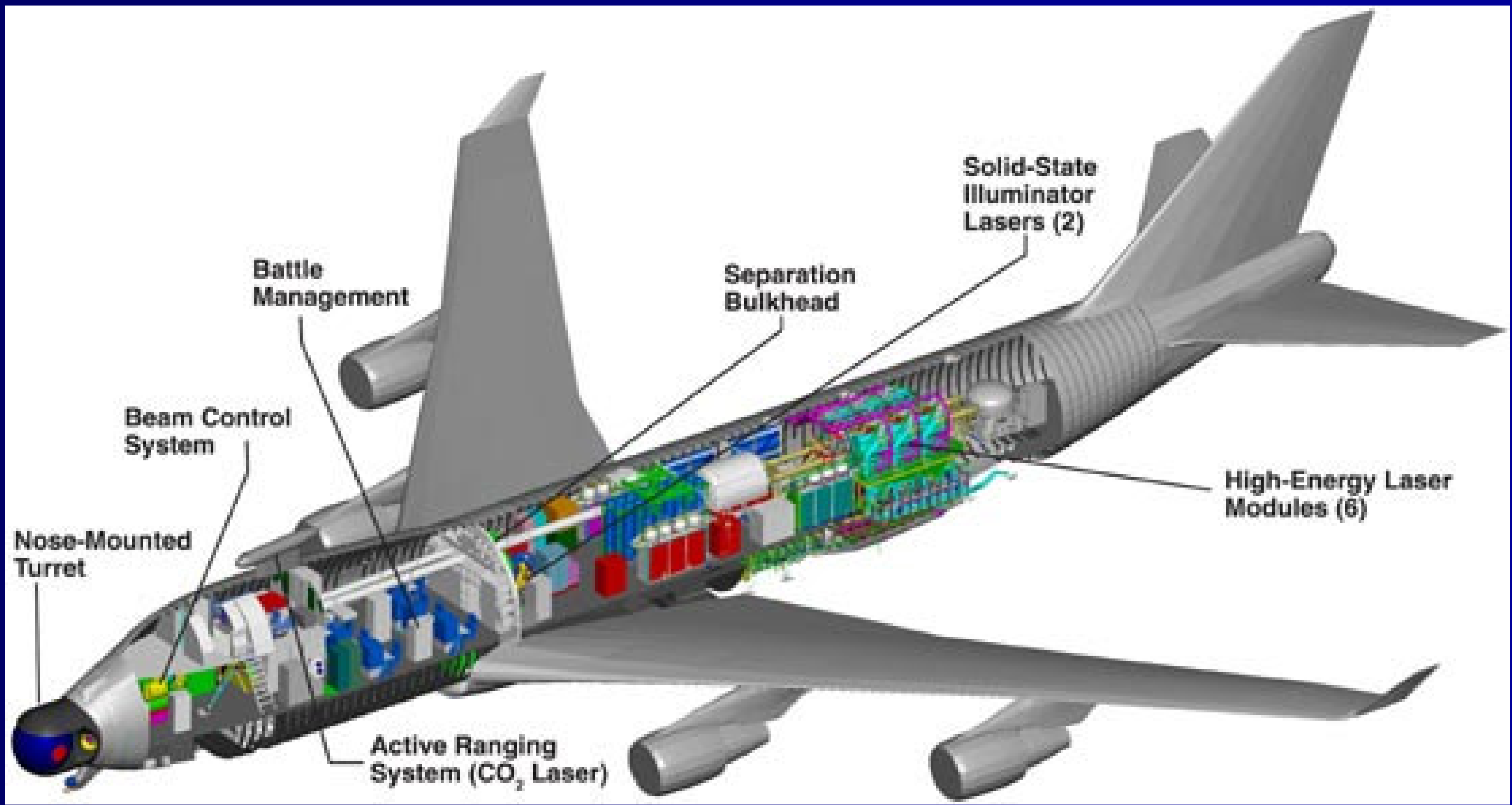
Gyrotrons – the state of the art

TOSHIBA GYCOM THALES CPI

- Frequency <800 GHz
- Power (CW) 1 MW
  at 170 GHz

- Pulse duration 20 s
- Efficiency 45 %

GYCOM 1MW Gyrotron



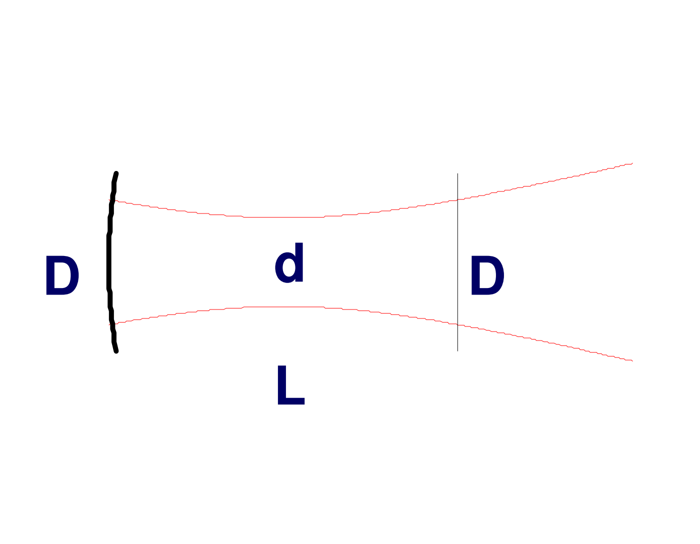
1 MW COIL laser

Gyrotron

S-D

Electronic Warfare; non-lethal weapon

$$w_0 = \sqrt{L\,\lambda / 2\,\pi}$$



$$D\ (\text{antenna}) = 2\sqrt{2}\, w_0$$

$$L = \pi\, D^2 / 4\,\lambda$$

$\lambda = 3$ mm

D (antenna)=4m L = 4000m

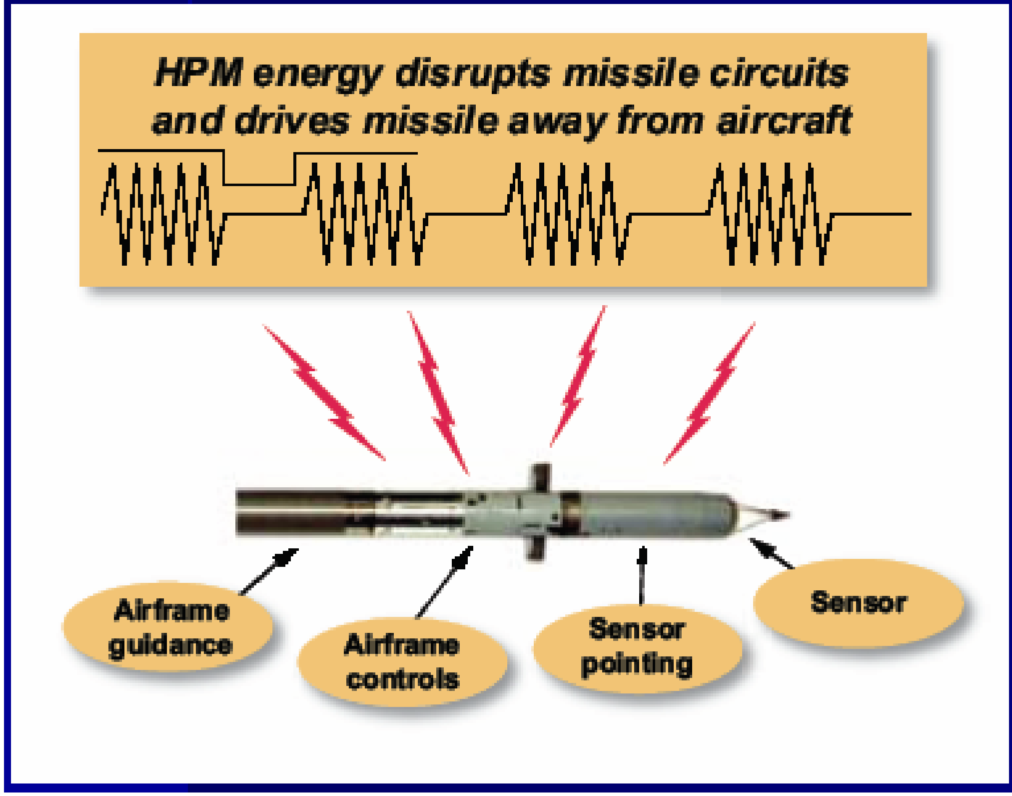
D (antenna)=2m L = 1000m

D (antenna)=1m L = 250m

Gyrotron s

Vigilant Eagle Airport Protection System

Raytheon



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

Gyrotron

S,LIC

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 re-usable 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

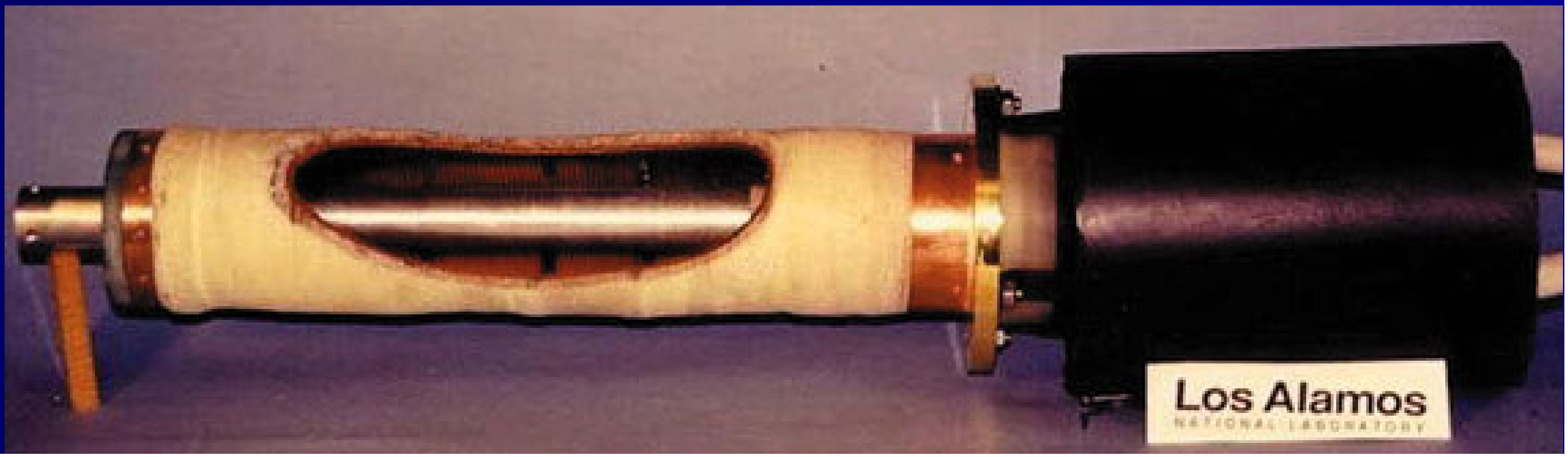
To be deployed:
08.2005

E-bomb

- Explosively-Pumped
  Flux Compression Generator

Pulse energy ~ 10^7 J

Pulse duration ~ 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