AFRL-DE-PS-
TN-2005-1002

AFRL-DE-PS-
TN-2005-1002

Transitioning HELs to Commercial Viability

Dr. Laverne Schlie

February 2005

Technical Note

Approved for Public Release; distribution is unlimited.

AIR FORCE RESEARCH LABORATORY
Directed Energy Directorate
3550 Aberdeen Ave SE
AIR FORCE MATERIEL COMMAND
KIRTLAND AIR FORCE BASE, NM 87117-5776

This report has been approved for publication.

//signed//

LAVERNE SCHLIE, PhD
Project Manager

//signed//

KIRK M. KLOEPPEL, Lt Col, USAF
Chief, Tactical Systems Branch

//signed//

L. BRUCE SIMPSON, SES
Director, Directed Energy Directorate

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 15-February-2005	**2. REPORT TYPE** Technical Note	**3. DATES COVERED** *(From – To)* 1-October 03 – 30-September-2004
4. TITLE AND SUBTITLE Transitioning HELs to Commercial Viability		**5a. CONTRACT NUMBER** In-House **5b. GRANT NUMBER** **5c. PROGRAM ELEMENT NUMBER** 61102F
6. AUTHOR(S) Dr. Laverne Schlie		**5d. PROJECT NUMBER** 2305 **5e. TASK NUMBER** LY **5f. WORK UNIT NUMBER** 01
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AFRL/DELS 3550 Aberdeen Avenue SE Kirtland AFB, NM 87117-5776		**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory 3550 Aberdeen Avenue SE Kirtland AFB NM 87117-5776		**10. SPONSOR/MONITOR'S ACRONYM(S)** **11. SPONSOR/MONITOR'S REPORT NUMBER(S)** AFRL-DE-PS-TN-2005-1002

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The simultaneous dual use of HEL (High Energy Lasers) for both commercial and industrial uses is outlined covering various types of gas, liquid and solid-state lasers. Brief description of BCS (Beam Control Systems) are included. The basic laser elements for large systems illustrate the role of thermal management and the need for more compact system such as in solid-state lasers to reduce the size and the logistical support. Finally, the latest status on the attempt to make 25 kW solid-state lasers operate reliably are discussed.

15. SUBJECT TERMS:
Lasers, HEL, BCS, solid-state lasers

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Dr. Laverne Schlie
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified	SAR	42	**19b. TELEPHONE NUMBER** *(include area code)* (505) 853-3440

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

EXECUTIVE SUMMARY

This presentation reviews the technological status and prospects for transition to military and commercial applications for a variety of High Energy Laser (HEL) systems. Specific topics include available platforms, beam control systems (BCS's), local and target loop jitter, power and weight scaling issues, and laser architecture. The principle candidate laser systems discussed include the Chemical Oxygen Iodine Laser (COIL), and bulk solid state lasers. Finally, recently developed ceramic materials and advanced solid state laser concepts such as thin disks and high efficiency diode lasers are reviewed.

U.S. AIR FORCE

Chemical - EDL's - Solid State Laser

HIGH ENERGY LASERS

Transitioning HEL's To Commercial Viability

Applications - Uses
Future Thrusts

CLEARED
FOR PUBLIC RELEASE
AFRL/DEO-PA
4 NOV 02

Dr. Vern Schlie

Directed Energy Directorate (AFRL/DE), Kirtland AFB, NM

SSL-HEL-#-1/34

22-621

Introductory Vu-graph giving title and Author Names

Please Note:

This is very high level presentation and is tutorial in nature and does not provide any significant technical details. Nearly everything in this presentation has already been cleared in previously cited reports, books, or presentations. Although the subject title is High Power / HEL Lasers, most of the topics matters discussed / presented are commercial use and are part of open literature throughout the world in the laser field

AFRL/DE 22-621

U.S. AIR FORCE

What's Real HEL's Uses <u>and</u> Needs

- **Military uses**
  - **Imaging / remote sensing / "star wars" (ABL) homeland defense / theater missile defense (TMD)**

Requirements: **High Powers (> 10 Kw) *and* BQ**
High Brightness = B (watts/sr)

$$B = \frac{\pi}{4} \frac{P_S D^2}{\lambda^2} \frac{SR}{R^2}$$

Most Difficult ⇒ HEL, BCS & Effects

- **Commercial uses**
  - **Material cutting / welding / semiconductor mfg**

Needs: **Excellent Reliability, Low Cost, Efficiency**
Moderate-High Powers (1 – 25 KW), Eye Safe - ? (enclosed)

Desires: ***Affordable*, Low – Low Maintenance, No Large "Logistical Trails"**

SSL-HEL-#-2/34 Cleared - ???

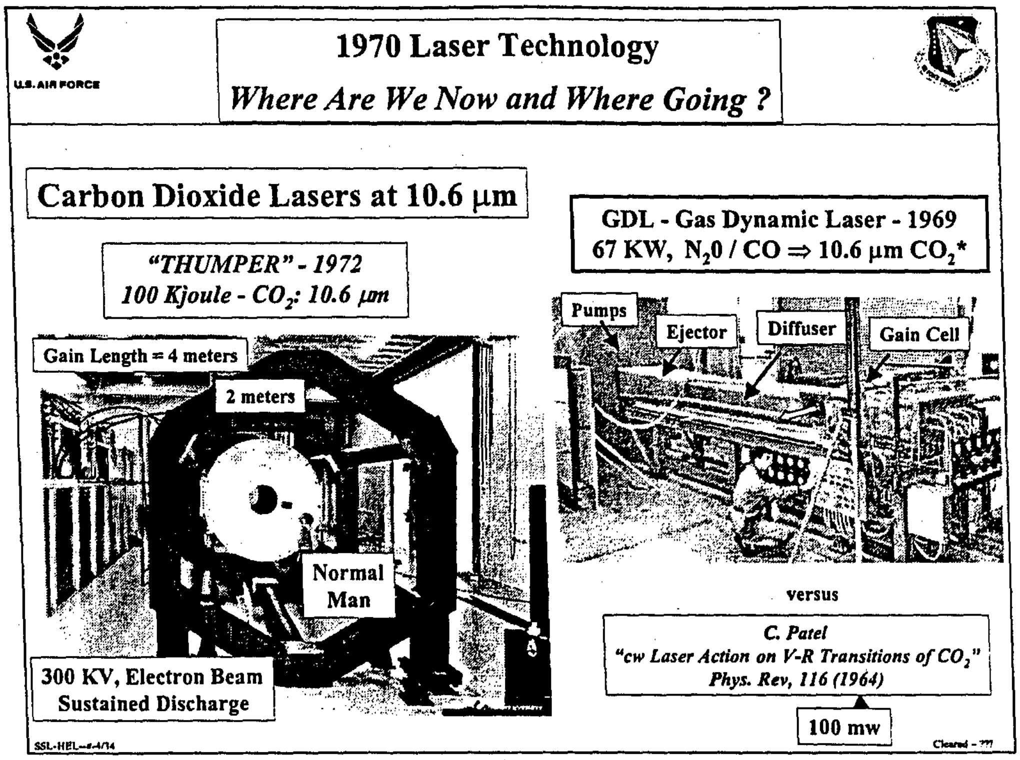
List of various applications of HEL. Cited applications have been reported in many books previously. Also, the subject matter has previosly been cleared

Outline

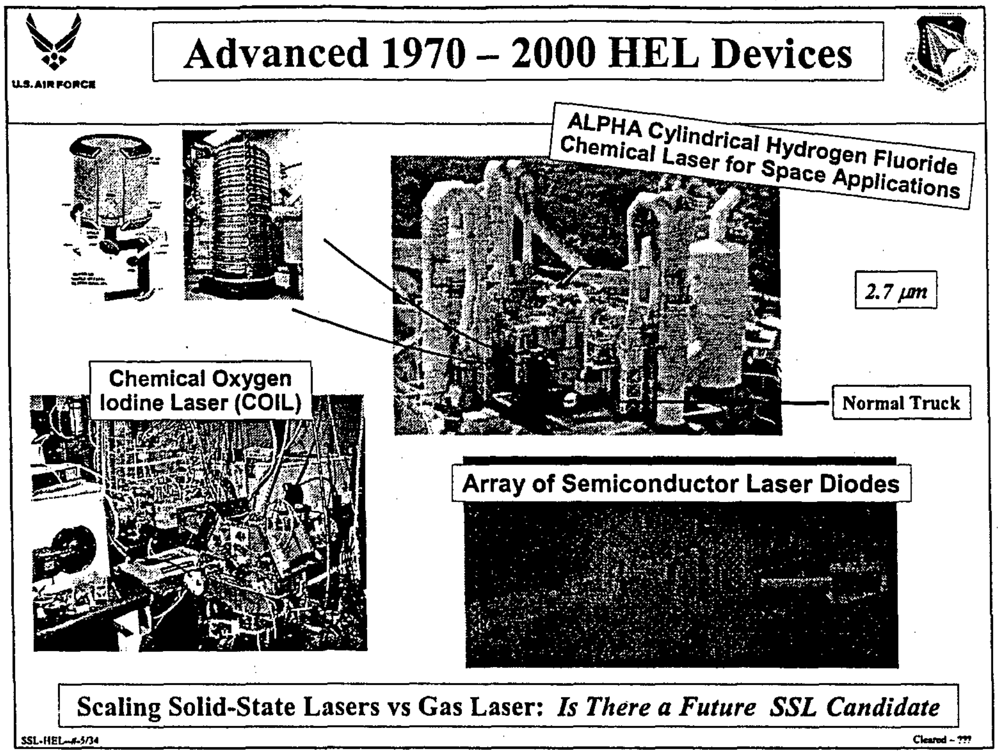
- *What Are HEL's – High Energy Lasers: Examples*
- **BCS – Beam Control Systems: Energy on Distant Targets**
  - **Why So Important for Military / Homeland Defense**
- **Basic Laser Elements for Laser Systems**
- **Comparison of HEL Technologies**
  - **Gas Phase vs Solid-State vs Liquids vs Vacuum Lasers**
- **What 's Needed to Scale Solid-State Lasers to HEL**
- **Specific Commercial HEL Applications: SSL at 25 KW ??**
- **Summary / Recommendations**

SSL-HEL-#-3/34 Cleared - ???

Outline of talks - merely gives list of topics being discussed. There is nothing classified on this vg



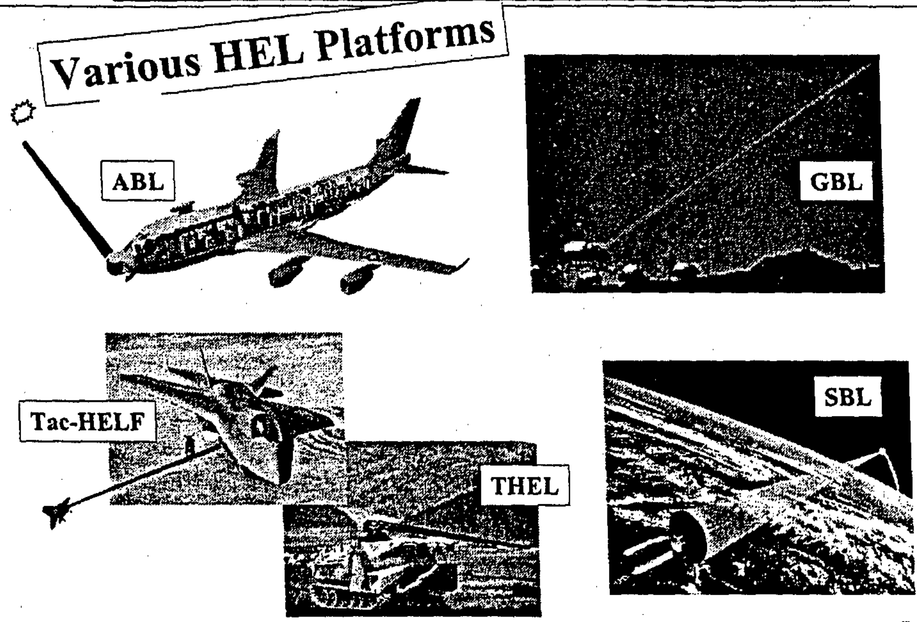
Photographs of carbon dioxide laser developed in 1972. Also, a GDL - Gas Dynamics Laser - developed in the late 1970. None of this is classified and has been reported / illustrated in book back in the 1970's. DoD does not work on such laser since the mid - 1970's.



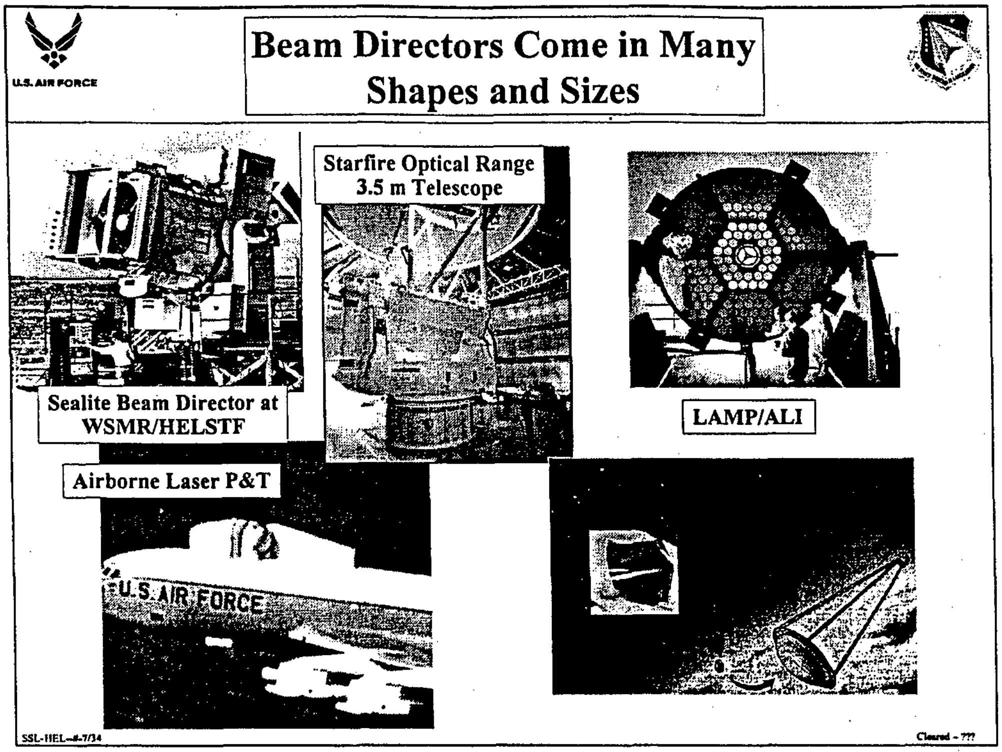
This vg is very similar to the previous vg and has been cleared in previous cleared presentations. Photographs of HF ALPHA chemical laser produced during the 1970's and closed down officially last year. Other photos ar of COIL laser and is picture previously cleared. The last right hand corner photo is photograph of low power (< 10 watts) of semiconductor diode array. None of this is classified and has been reported / illustrated in books back in the 1970's and 1980's

Beam Control Requirements - System Configurations

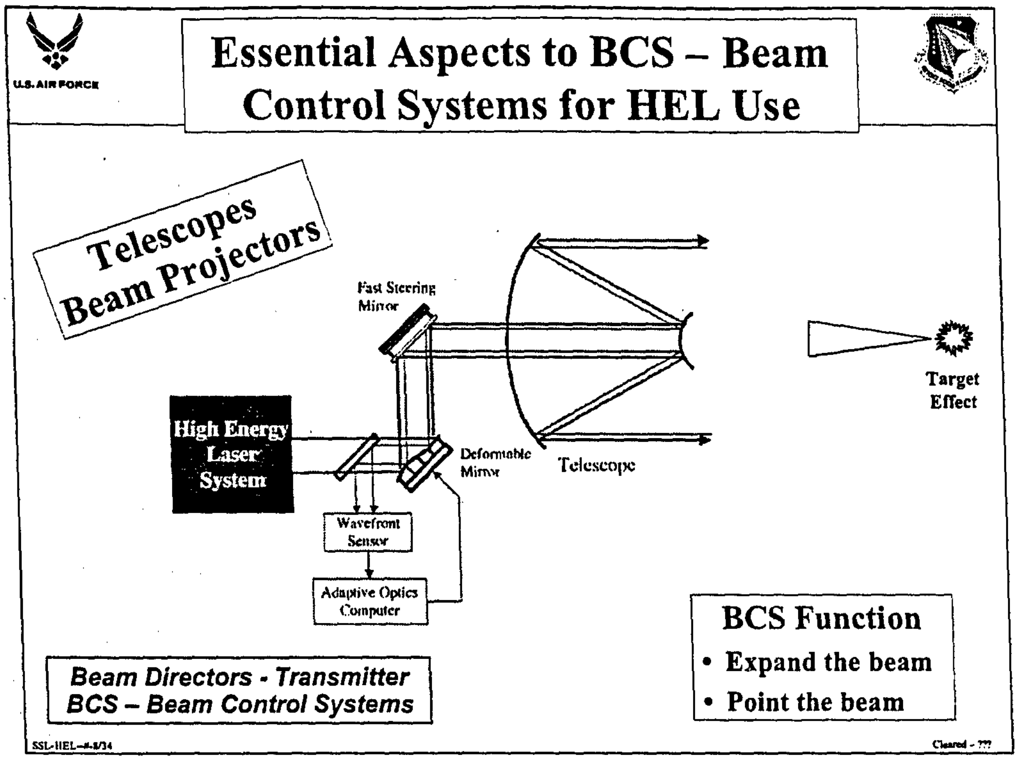
Drastically Different for Implementations and Applications



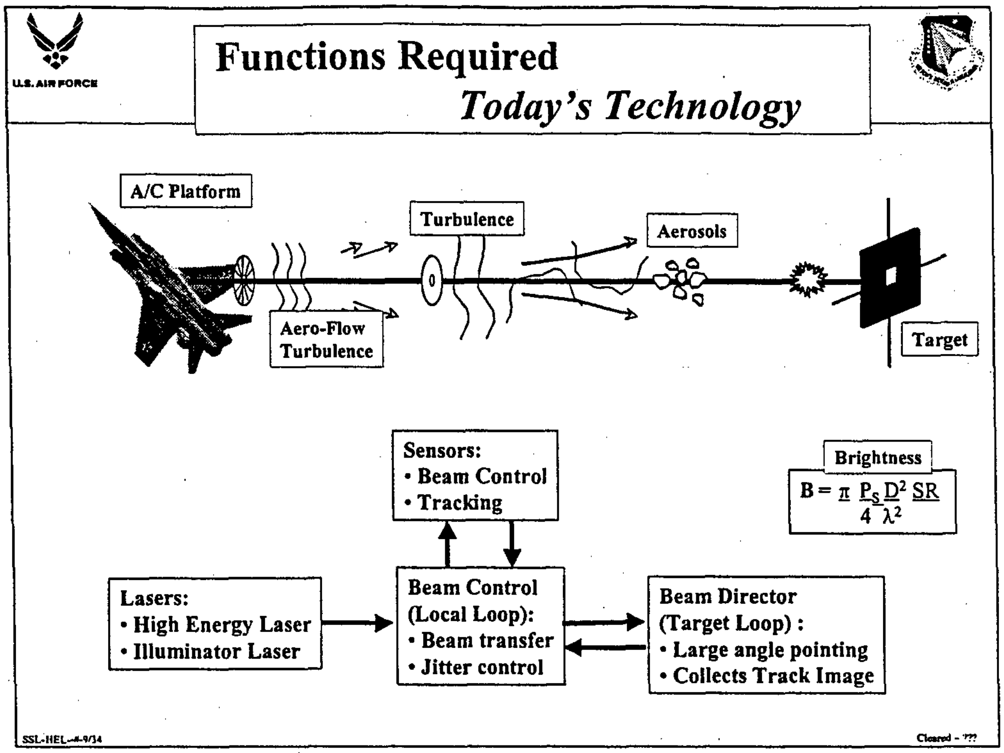
Illustrates conceptually how laser beam would be transmitted out of various platforms. Several of these pictures appear or have appeared on the AFRL/DE web page.



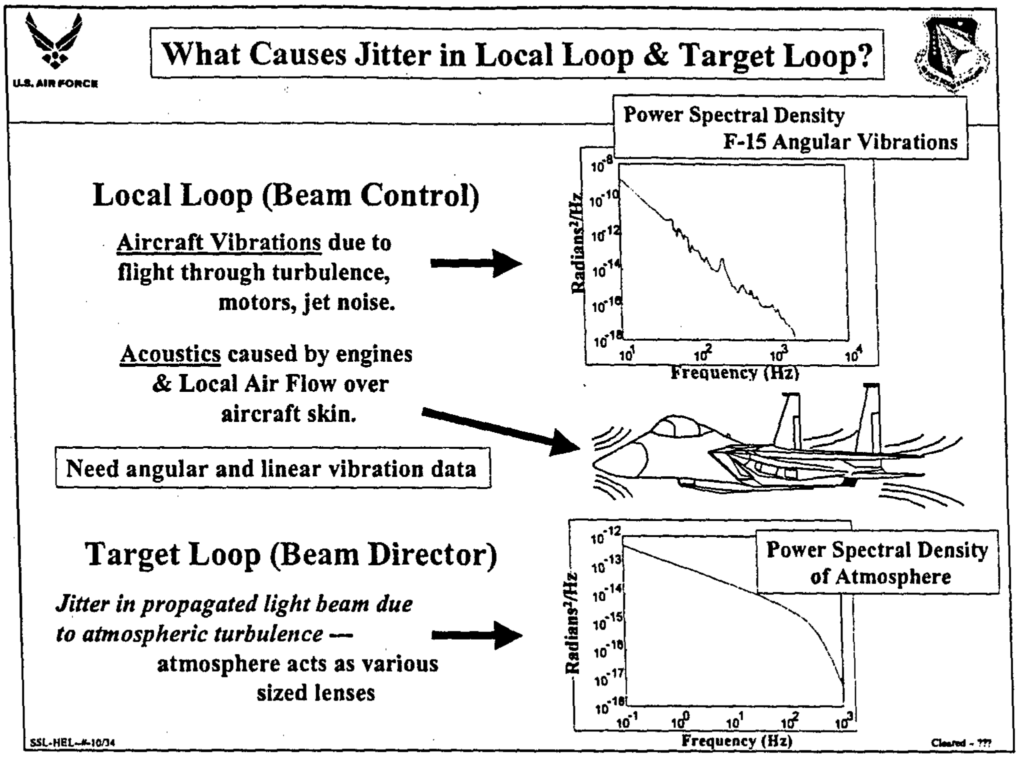
Shows pictures of former high energy lasers. Shown previously in many articles such as Aviation Week and also on AFRL/DE web page.



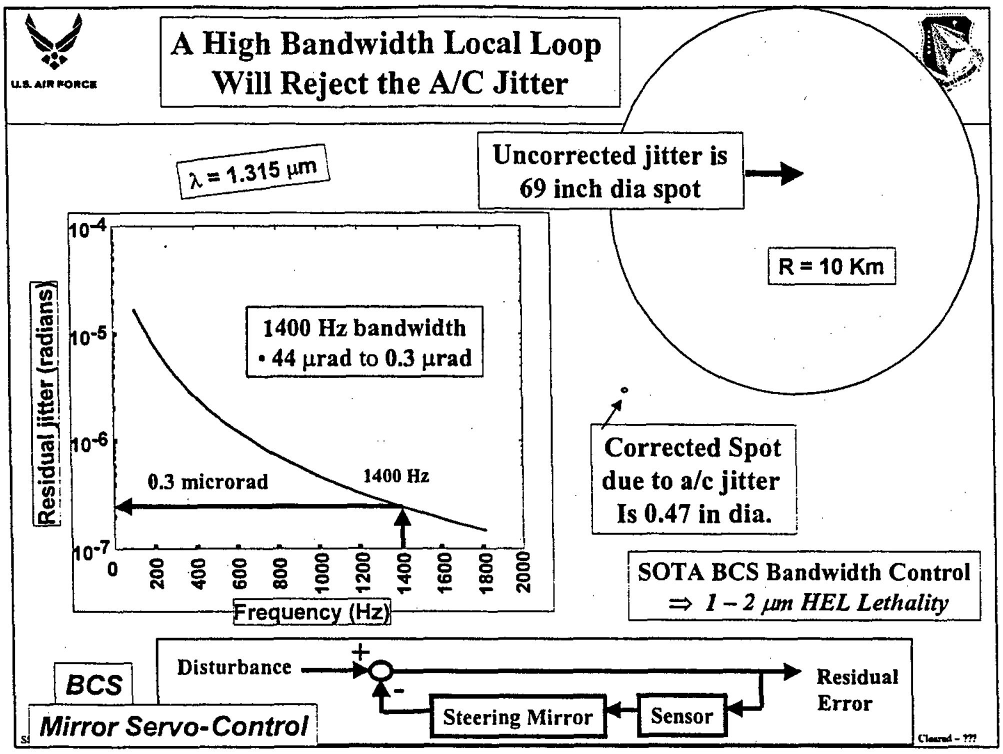
Illustrates a BCS – Beam Control System and the parts used. Commonly show in technical journals.



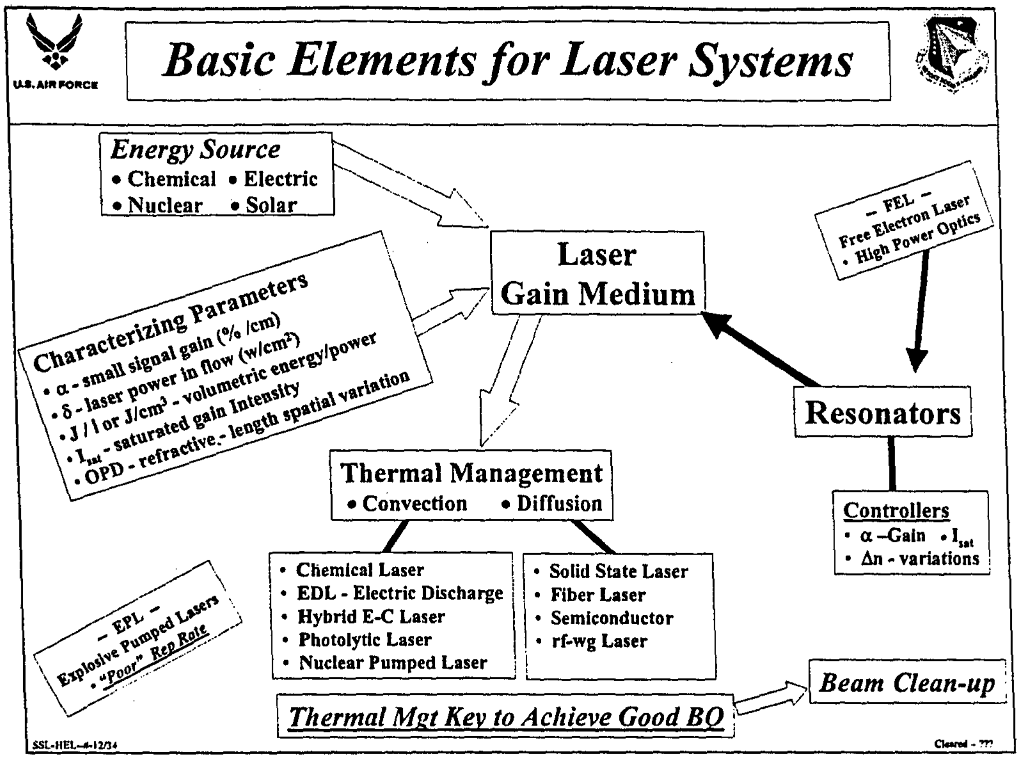
VG shows schematic diagram of various parts of beam control systems. This vg has previously been cleared plus has been shown / described in many technical proceedings – especially the SPIE – Society for Professional and Industrial Engineers



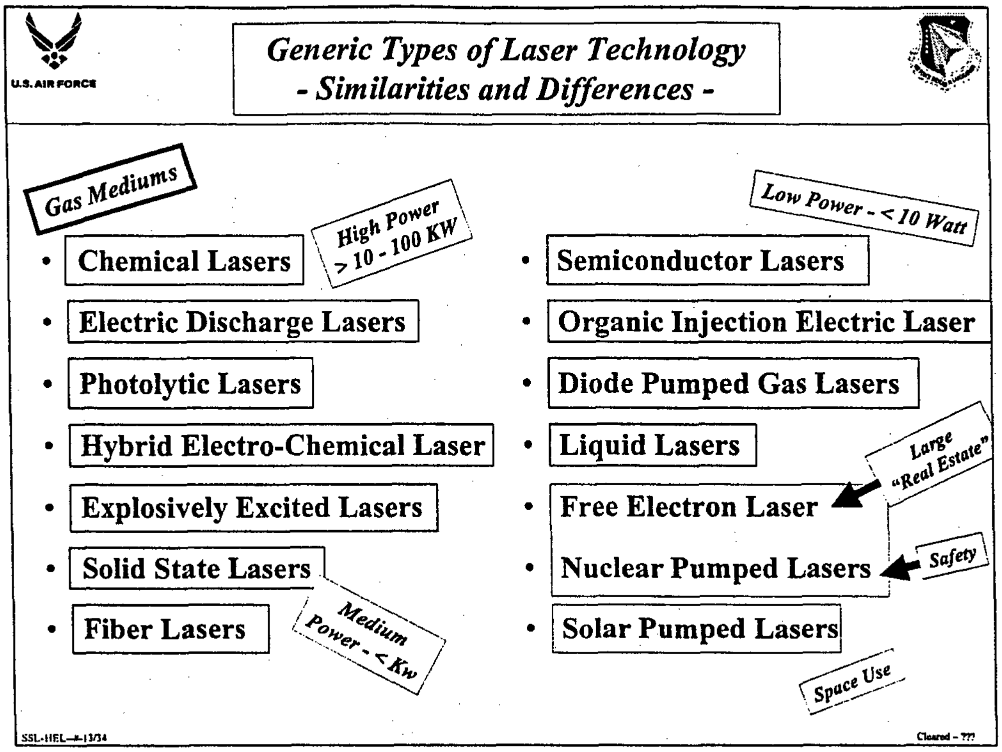
Again this vg is based on information which has been cleared previously. It is meant to shown that the PSD (Power Spectral Density) of vibrations on fighters plus commercial aircraft have behaviors shown above on right hand side of the vg. This information can be obtained from various government reports on unclassified information about fighter aircrafts. Its main purpose is to show how aircraft components vibrate while they fly through the air.



VG shows how using a servo-mechanism often described in college textbooks can be used to compensate for the vibrations induced into a standard beam control system (BCS). It just shows the a sport size can become small when a servo-mechanism system is sued having a bandwidth of 1400 Hz. Such information can be obtained from open publications like SSPIE –Society of Professional Engineers.



Lists all basic elements for lasers - provides audience for talk overall view of all aspects of laser devices. This is reported in many textbooks.



Lists all types of laser technologies used for various power regimes - all this information is recorded in standard textbooks on lasers

U.S. AIR FORCE

High Brightness HEL's

- **Chemical HEL Devices**
  - **HF / DF Supersonic Laser - 2.7 / 3.7 μm**
  - **COIL - Chemical Oxygen Iodine Laser - 1.315 μm**
- **EDL - Electric Discharge Lasers**
  - **CO_2 / CO – 10.6 / 5.0 μm** ← *rf waveguide Lasers*
  - **Excimers - KrF / XeF - 0.248 / 0.351 μm**
- **Photolytic HEL Devices**
  - **PIL - Photolytic Iodine Laser - 1.315 μm**

Gas-Phase Lasers

SSL - Solid State Laser / FL - Fiber Lasers

- **Nd:YAG - 1.06 μm – Heat Capacity Devices (Nd: GGG)**
- **Yb: YAG – 1.03 μm – Slab Lasers**
- **Er^+ doped fibers - 1.55 μm – High Intensity Diode Pumped**

SSL-HEL-#-14/14 Cleared - ???

List of all types of laser technology and specific examples. Commonly shown in laser textbooks.

![U.S. AIR FORCE]

Chemical HEL's -- Gas Phase High Energy Laser Systems

- **Chemical HEL Devices**
  - **HF / DF Supersonic Laser - 2.7/ 3.7 µm -- $H_2(D2)$ / F2 ⇒ HF (DF)**
  - **COIL - Chemical Oxygen Iodine Laser - 1.315 µm -- H_2O_2 / Cl_2 / I_2 ⇒ O_2* - I**

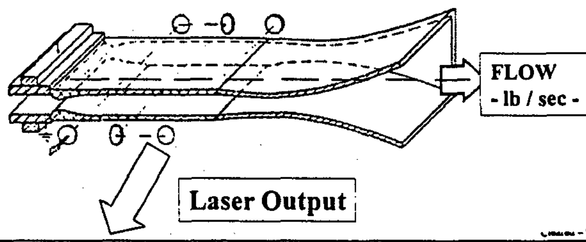
All Employ *Convective* Supersonic Flow for Thermal Mgt

Lasing Species

COIL

σ = 296 KJ / KG

δ = 100 - 200 watts /cm²

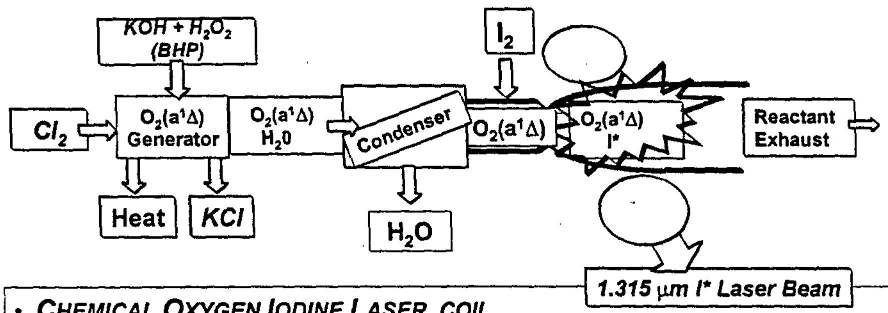


SSL-HEL-#-15/34

Schematic diagram (generic) of use of supersonic flow to produce high power lasers - technology used in all types of chemical lasers. Technology developed in 1970 and early 1980s. Reported in literature and textbooks.

Chemical Oxygen Iodine Laser COIL Laser

U.S. AIR FORCE



- *CHEMICAL OXYGEN IODINE LASER, COIL*
  - Based on *CHEMICAL PRODUCTION* of $O_2(a^1\Delta)$ metastables
  - $O_2(a^1\Delta)$ produced from heterogeneous $KOH/H_2O_2/Cl_2$ mixtures:

$$Cl_2 + H_2O_2 + OH^- \longrightarrow O_2(a^1\Delta) + H_2O + Cl^-$$

  - Energy Transfer and Laser:

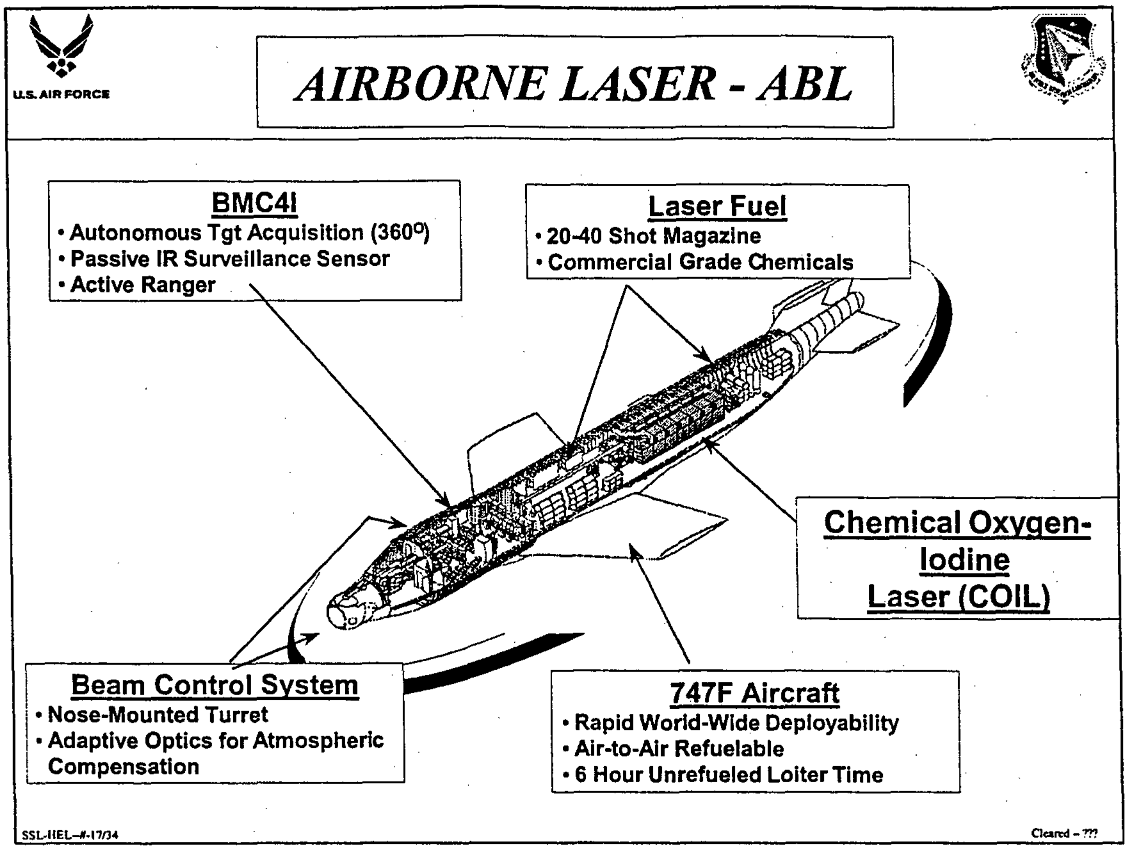
$$O_2(a^1\Delta) + I(^2P_{3/2}) \longrightarrow I^*(^2P_{1/2}) + O_2(X^3\Sigma), \ \Delta E = 279\text{cm}^{-1}$$

$$I^*(^2P_{1/2}) + h\nu \longrightarrow I(^2P_{3/2}) + nh\nu \ \text{(laser 1.315 μm)}$$

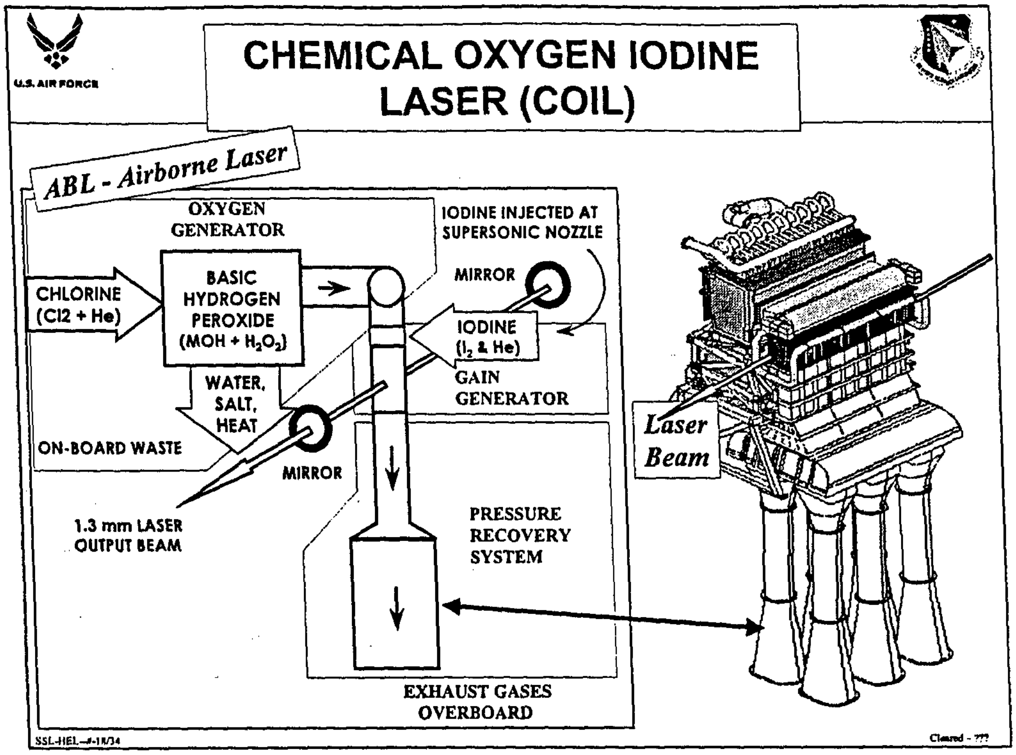
SSL-HEL-#-16/34

Cleared - ???

Schematic of basic COIL laseer showing all basic parts. Lower half shows basic kinetics of system for COIL laser All of this information has been cleared previously



• Schematic of COIL laser copied from ACC previously cleared presentation



Schematic of COIL laser copied from ACC previously cleared presentation
Every aspects of this technology has been cleared and may have been shown on CNN

Why Is COIL Such Great Laser

U.S. AIR FORCE

Low Pressure < 10 Torr ⇒ Small Refractive Effect

ϕ_{input} | Laser Gain Medium | ϕ_{output}

⇒ Excellent BQ < 1.1 x Diffraction Limited

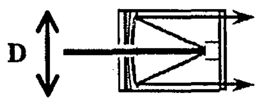
$$\phi(\omega) = \frac{\omega\, n(\omega)\, L}{c}$$

$n(\omega) \Rightarrow$ pressure

1987 - 35 KW "Roto-COIL"

Beam Control System

D - Primary Mirror



$$I = \frac{\pi}{4}\,\frac{P_S\, D^2\, SR}{\lambda^2 R^2}$$

$\theta = 1.22 * \lambda / D$

COIL at $\lambda = 1.315\ \mu m$ ⇒ High Brightness
plus Excellent Atmospheric Transmission
and *Single Wavelength*

SSL-HEL-#-19/34

Cleared Public Release
8 Jan 2002

Description of why COIL system is very good. All information has been described in open literature previously

U.S. AIR FORCE

High Brightness HEL's

- **Chemical HEL Devices**
  - **HF / DF Supersonic Laser - 2.7 / 3.7 µm**
  - **COIL - Chemical Oxygen Iodine Laser - 1.315 µm**
- **EDL - Electric Discharge Lasers**
  - **CO_2 / CO – 10.6 / 5.0 µm**
  - **Excimers - KrF / XeF - 0.248 / 0.351 µm**
- **Photolytic HEL Devices**
  - **PIL - Photolytic Iodine Laser - 1.315 µm**

Gas-Phase Lasers

☆ **SSL - Solid State Laser / FL - Fiber Lasers**
- **Nd:YAG - 1.06 µm – Heat Capacity Devices (Nd: GGG)**
- **Yb: YAG – 1.03 µm – Slab Lasers**
- **Er^+ doped fibers - 1.55 µm – High Intensity Diode Pumped**

Diode Pumping

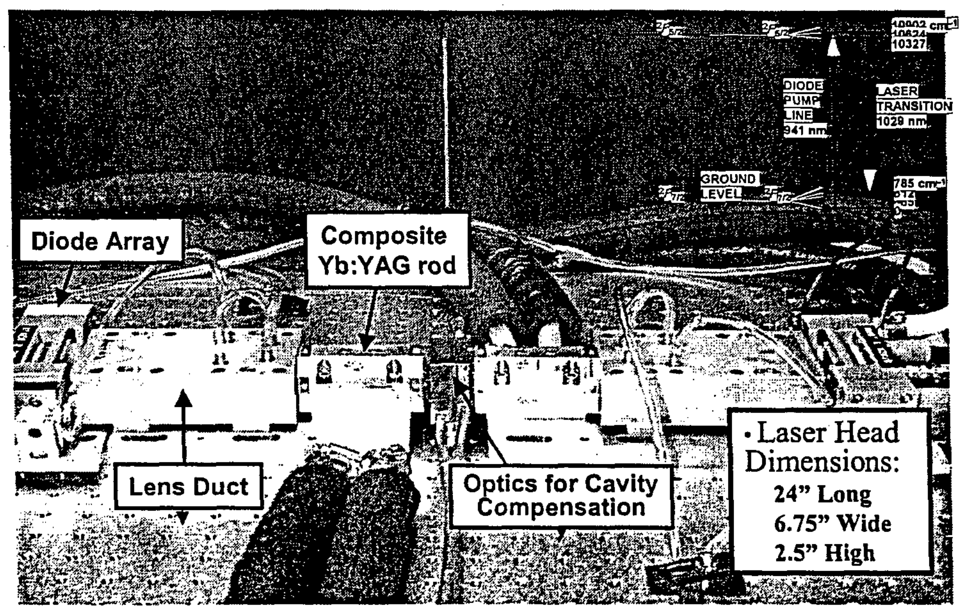
SSL-HEL--#-20/34 Cleared - ???

List of all types of laser technology and specific examples. Commonly shown in laser textbooks.

1 KW Yb: YAG Laser: 1.03 microns
Solid-State Slab Lasers

U.S. AIR FORCE

Yb:YAG



SSL-HEL-#-21/34

Cleared - ???

This photograph of typical slab solid-state laser system using Yb:YAG as the laser gain medium. Identified parts are various parts of the laser system. All of this information has been shown in technical articles published by various universities and companies plus work in Germany, France and Japan.

U.S. AIR FORCE

Status of Laser Technology

Options for Laser Users

To date the only viable HEL option has been a Chemical Laser

- **–Chemical Lasers: *<u>COIL</u>*, HF, DF, (CO_2)**
- **–Platforms: ABL, THEL, SBL, ATL**

Why have Electric Lasers not been a viable option?

Needs ⇨ ***Capable Scalable Modules*** ⇨

- ***•Low-cost - Future***
- ***•Reliable***
- ***•High Efficiency***
- ***•Compact Package***

Laser	Diffraction Limited Watts per lb	Diffraction Limited $ per Watt	Status and Lessons Learned
COIL	50 *"fits in space available?"*	50 *"affordable?"*	DEW by combining modules, BUT Run time depends on fuel available.
Bulk Solid-State	1 *"Bulky, non-integrated!"*	2000 *"expensive!"* *"not modular?"*	KW near diffraction limited, BUT Bulky, complex and expensive Unreliable operation

Pumping Diode Expense

SSL-HEL-#-22/34

Cleared - ???

VG shows various cost for diffraction limited COIL laser versus that of bulk solid-state lasers. In addition, it also lists the weight of COIL and solid-state laser per watt of laser power. Such information has previously been reported in SPIE publications plus scientific conferences.

U.S. AIR FORCE

Thermal Management for Scaled SSL

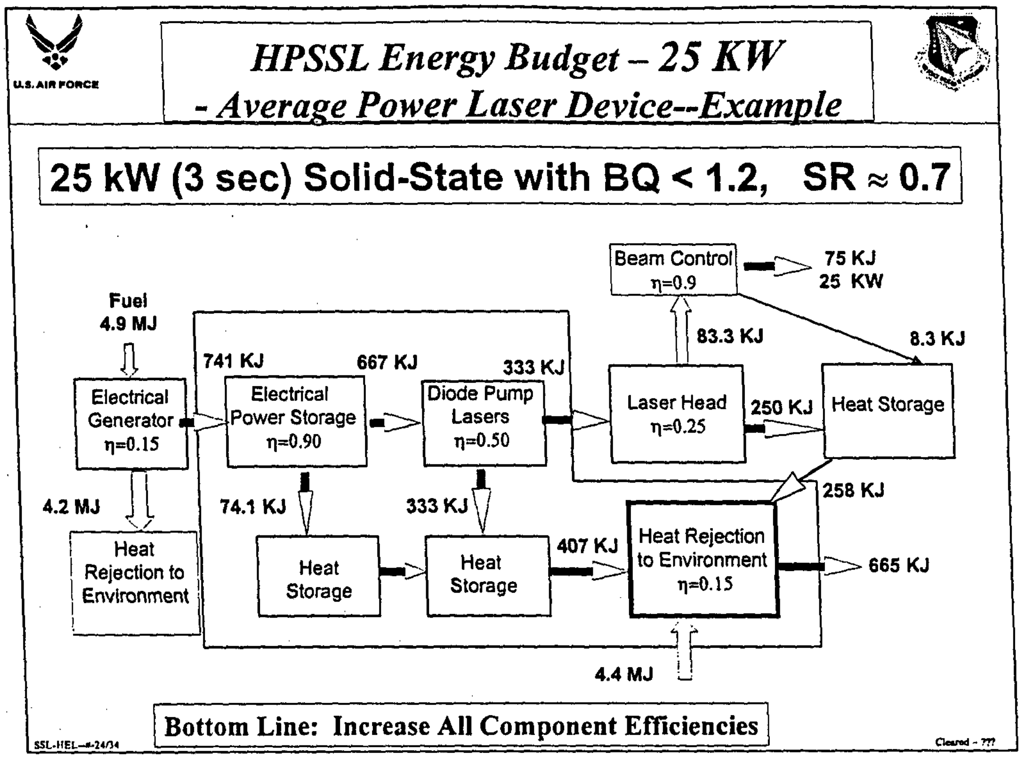
- Diffusion Rates – Thermal Conductivity
- Minimize Aberrations – Stress

Critical Enabling Technology:

- Advanced SSL Materials with High Thermal Conductivity
- Clever Methods to Remove Heat – e.g., "Micro-Heat Pipes"

SSL-HEL—#-23/34 Cleared - ???

List parameters which determine the thermal management in solid-state lasers. Also lists critical enabling technologies needed to scale solid-state lasers. This information is commonly listed in Solid-State Laser Engineering like the textbook by Dr. Koechner which was published more than 10 years ago



VG shows hypothetical example of energy budgeting for 25 KW average power solid-state laser. All of the numbers are made up to show how one would analyze such a system The approach is similar to that shown in thermodynamic textbooks accounting for all of the energy consumed in a total system. The analysis described / shown is made up and is not associated when any solid-state laser that anyone in the world has. Everything is unclassified in this hypothetical vg.

U.S. AIR FORCE

Major Aspects to High Avg Power (HAP) Solid-State Lasers

- **Materials – Bulk Gain Medium & Optics**
  - **Thermal Conductivity (eg, Japan's ceramics & GE thin disks)**
  - **Higher Dopings**
  - **Isolators (Faraday rotators)**
  - **Growing large crystals**
- **Architectures**
  - **Thermal Mgt Approaches**
  - **Bonding Techniques – Gain Matl – Cooling Structures**
- **Resonators – Efficient Energy Extraction**
  - **Supergaussian, Unstable Resonators**
  - **Saturate Gain Medium, Uniform Intensity**
- **Infrastructures**
  - **Power Supplies & Heat Exchangers**

Reliable Diodes

Need Detailed M&S

SSL-HEL-#-25/34

Cleared - ???

VG lists all of aspects for a solid-state laser system including information commonly show in textbooks like Koercher's Solid-State Laser Engineering. All of the information give various options which are commonly taught in university laser courses.

U.S. AIR FORCE

Features - Advantages of Ceramic Lasers

- **Scaling to large apertures active elements**
  large and thin (1m x 1m) : effectively no limit
- **Low cost, mass production**
- **Easy to fabricate**
- **Gain uniformity and profile control**
- **Can combine activators**
- **Wave guide and gain profile control**
- **Multi-functional elements (ex. gain + sat. ab.)**
- **Higher Nd concentration than single crystal (provides thinner samples for same gain giving better heat extraction)**
- **Fabricated** Nd^{3+}:YAG, $Nd^{3+}:Y_2O_3$, $Yb^{3+}:Y_2O_3$, Cr^{4+}:YAG

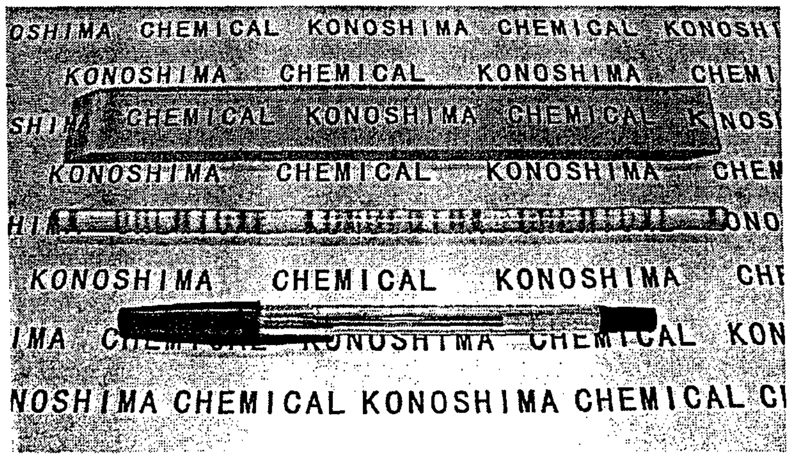
SSL-HEL-#-26/34 Cleared - ???

VG lists various features of solid-state laser systems described by Prof Ueda from the Japan University in Tokyo, Japan. He has presented this information at various CLEO conferences plus published the results in technical journals.

U.S. AIR FORCE

Ceramic Slabs and Rod

Prof. Ueda, Japan
ILS/UEC



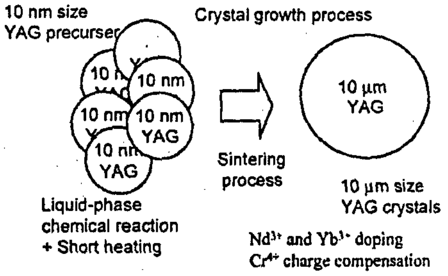
Slab: polished, Rod: unpolished

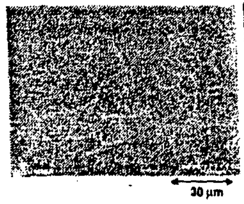
SSL-HEL-#-27/34 Cleared - ???

Like the previous vg, this VG's information comes from various information and features of solid-state laser systems described by Prof Ueda from the Japan University in Tokyo, Japan. He has presented this information at various CLEO conferences plus published the results in technical journals. These are merely photographs of the ceramic lasers that they have made in Japan during the last 2-3 years.

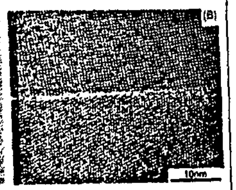
U.S. AIR FORCE

Ceramics Preparation & Results





SEM image of ceramic YAG grain structure



TEM image of ceramic YAG grain boundary

- **Sintering yields large grains, thin clean grain boundaries and very few voids.**
- **Result: low scattering (competitive with single crystals)**

Source: Prof. K. Ueda, CLEO 2002

U. S. Does Not Yet Have Capability

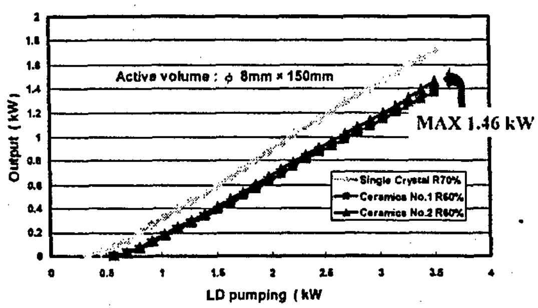
SSL-HEL-#-28/34 Cleared - ???

This vg like the last two vg is based on the information provided by Prof Ueda from the Japan University in Tokyo, Japan. VG shown synthesis process and lists various features of solid-state laser systems described by Prof Ueda from the Japan University in Tokyo, Japan. He has presented this information at various CLEO conferences plus published the results in technical journals.

U.S. AIR FORCE

Fostering domestic laser ceramics development for HEL programs

• *Nd:YAG - ceramics vs single crystal*



measured by Toshiba

Recent kW-level laser results

•Ceramic Nd:YAG becoming competitive with single crystal

Source: Prof. K. Ueda, CLEO 2002

Material properties comparisons

•Light scattering in ceramic low, but still not as low as in single crystal

•Thermal conductivity reported to be as good as in single crystal

Over-all pattern

•Ceramic not yet equal to single crystal, but encouragingly close

•Further development and close comparison warranted

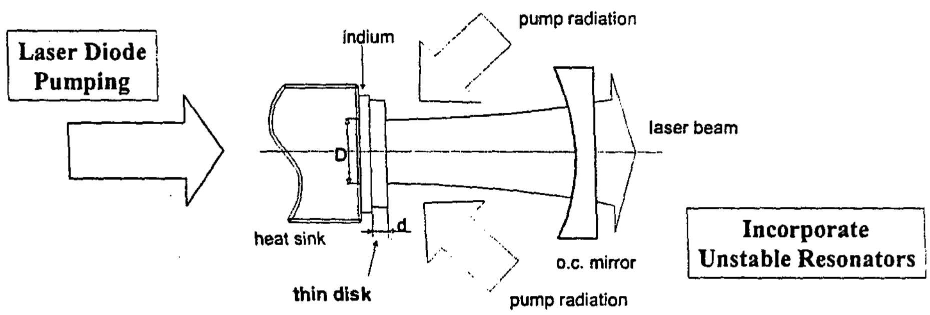
U. S. Does Not Yet Have Capability

SSL-HEL-#-29/34

Cleared - ???

This vg like the previous 4 vg's is based on the work of Prof Ueda from the Japanese University in Tokyo, Japan. VG shows ceramic laser performance compared to more conventional glass substrate solid state laser system commonly available for more than 20 years and cited in textbooks. The information and various features of solid-state laser systems described by Prof Ueda from the Japan University in Tokyo, Japan. He has presented this information at various CLEO conferences plus published the results in technical journals.

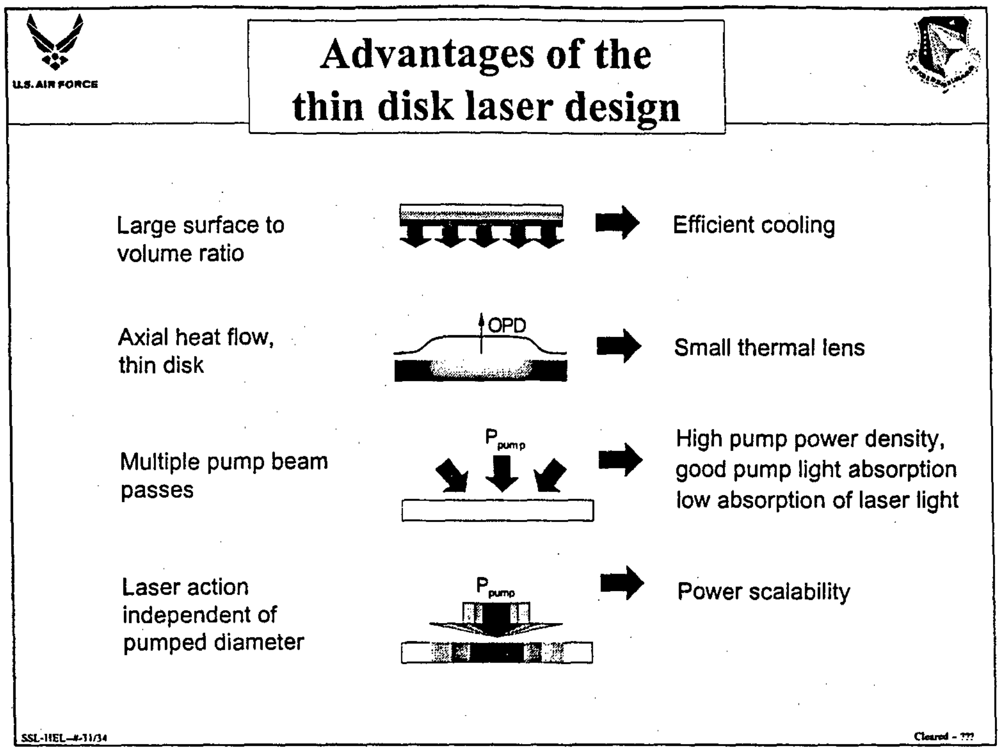
Thin disk laser principle



- decoupling of pump absorption and reabsorption of laser radiation
- weak thermal lens
- high efficiency and good beam quality simultaneously

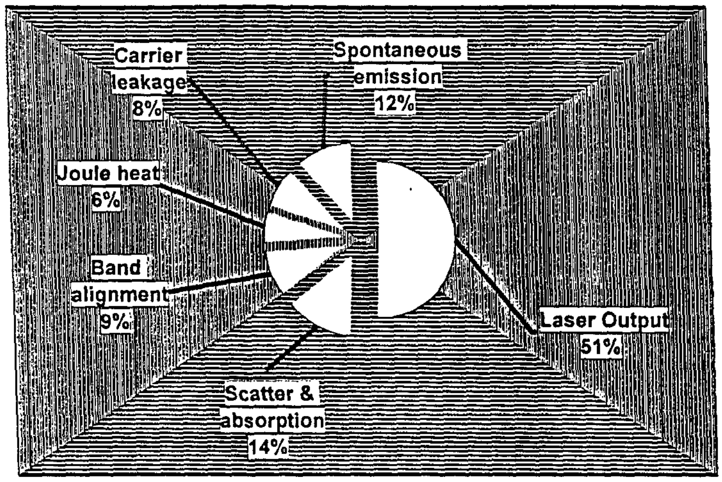
*** Based on the work of Dr. Adolf Giesen, University of Stuttgart**

This vg shows the thin disk concept originally developed and demonstrated by Prof Adolf Giesen from the Stuttgart, GE university. All of this information has previously been reported by Prof Giesen in various technical journals and conferences like CLEO



This vg like previous one is from the published work of Prof Giesen at Stuttgart University in Stuttgart Germany. This vg shows the thin disk concept describing the features of the thin disk solid-state lasers originally developed and demonstrated by Prof Adolf Giesen from the Stuttgart, GE university. All of this information has previously been reported by Prof Giesen in various technical journals and conferences like CLEO

High power diode laser pump arrays represent **primary enabling technology** for *any* high average power, excellent beam quality, solid-state laser

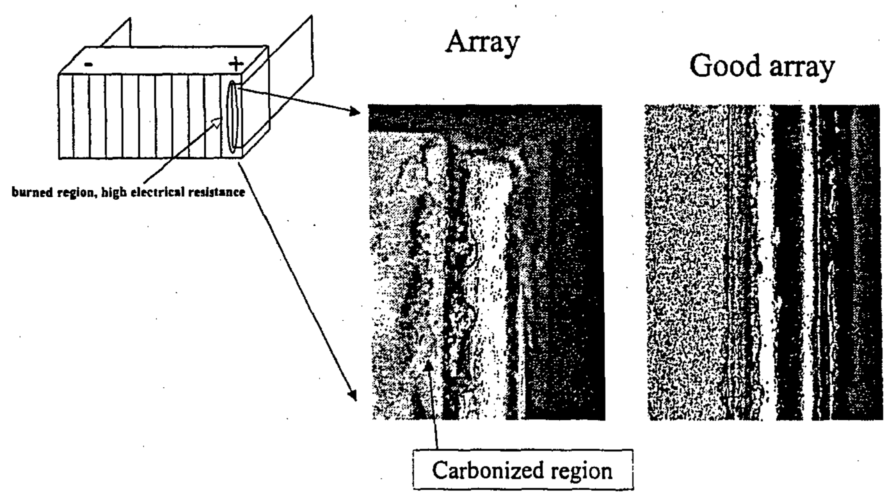


Power Consumption of Nominal 100 W Output of 980 nm Bar

This vg shows the various energy losses associated with laser diodes and is commonly described in various solid-state laser textbooks plus laser diode books and technical journal publications. It mainly shows the distribution of enabling technology of fabrication costs for low-cost laser diodes

U.S. AIR FORCE

Electrical Contact on Array Failed after 500 Hours



SSL-HEL—#-33/34 Cleared - ???

VG shows the failure of electrical wire contacts to laser diodes. Has been reported in laser conferences and now be prepared for university textbooks.

U.S. AIR FORCE

Summary - Recommendations

- Gas Phase Chemical & EDL (Electric Discharge Lasers) Operate at HEL Today
- Solid-State Laser for HEL Have Very Significant Technical Challenges but Very Essential for Commercial Product
- US Significantly Behind Germany and Japan in All High Average Power (HAP) Solid-State Laser Technology
- Key factors Improving SSL & Commercial Acceptance
  - Improve Laser Diode Efficiency: 60-80 %)
  - Drastically Reduce Cost of Laser Diode or Perfect New Concepts - "Out-of-Box Thinking" : $10 / watt Today
  - Strongly Pursue Thin Disk and Ceramic SSL Approaches
  - Think SSL Laser Total Scientific – Engineered System
  - Establish Automated Packaging of Diode Bars for SSL

SSL-HEL-#-14/34 Cleared

Summary of talk giving main highlights. All of the cited information has either been previously cleared on published in technical journals or reported at technical conferences like CLEO

DISTRIBUTION LIST

DTIC/OCP 8725 John J. Kingman Rd, Suite 0944 Ft. Belvoir, VA 22060-6218	1 cy
AFRL/VSIL Kirtland AFB, NM 87117-5776	2 cys
AFRL/VSIH Kirtland AFB, NM 87117-5776	1 cy
Official Record Copy AFRL/DELS/Vern Schlie	3 cys