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PREPRINT

# Diode-Pumped Solid State Lasers (DPSSLs) for Inertial Fusion Energy (IFE)

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## DISCLAIMER

# Diode-Pumped Solid State Lasers (DPSSLs) for Inertial Fusion Energy (IFE)

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## ABSTRACT

The status of diode-pumped, transverse-gas-flow cooled, Yb-S-FAP slab lasers is reviewed. Recently acquired experimental performance data are combined with a cost/performance IFE driver design code to define a cost-effective development path for IFE DPSSL drivers. Specific design parameters are described for the Mercury 100J/10 Hz, 1 kW system (first in the development scenario).

Key Words: diode-pumped solid state laser; Yb:S-FAP; inertial fusion energy (IFE), turbulent gas cooling; regenerative amplifier; fusion power reactor.

## 2. INTRODUCTION

The development of efficient (>50%) room-temperature semiconductor laser diode arrays as power-scalable (>>kW) pump sources for solid state lasers has significantly improved the prospects for developing a solid state laser system with characteristics suitable for driving an IFE central electric power plant [1-4]: efficiency >10% and average output power >10 MW. In order to exploit diode pump arrays for this application, it is also necessary to: 1) identify and develop advanced crystalline laser gain media with energy storage lifetimes that are long compared to the typical 0.3 msec lifetime of Nd-doped laser materials, and that have favorable bulk mechanical, optical, and thermal properties; 2) develop an efficient laser gain disk cooling architecture that permits adequate surface cooling (~ 1 watt/cm$^2$) while maintaining adequately high beam quality (<few x diffraction limit) and an acceptable B-integral (<~2.5); and 3) develop a concept for protecting the last optic in the laser beam delivery system against the anticipated neutron flux.

In response to these needs, we have: 1) identified, developed, and characterized the novel gain material, ytterbium doped strontium fluorapatite (Yb:S-FAP), as an attractive candidate gain crystal that possesses the combination of optical, physical, thermal, and spectroscopic characteristics required for an IFE laser driver [5-9]; 2) developed and characterized the gas-flow-cooled, disk-face-pumped architecture [1,10-12]; and 3) conceived of and progressively assessed the heated, refractive quartz last-optic concept to withstand the neutron flux within an $GW_e$ IFE power plant [13,14]. All of these advances have been incorporated into a system design code that describes the cost and performance of a gas-cooled, diode-pumped Yb:S-FAP driver for an IFE power plant [4,15-17 ].

This paper reviews the point design of a Yb:S-FAP DPSSL IFE driver system and summarizes experimental data obtained on the first integrated test of a helium-gas-flow-cooled diode-pumped Yb:S-FAP slab laser [12], designed and built to validate the gas cooling approach to IFE driver lasers. Based on this work, we discuss a scenario for the cost-effective and timely development of a diode-pumped Yb:S-FAP IFE driver.

## 3. GAS-FLOW COOLED Yb:SA-FAP SLAB LASER EXPERIMENT

C. D. Marshall, et. al. [9] have developed and reported on a laboratory experiment designedto explore the performance of transverse, turbulent helium-gas-flow-cooling of a Yb:S-FAP diode-pumped slab laser. Figure 1 shows a schematic view of the experimental set-up and Figure 2 shows a photo of the 5 x 19 x 19 mm Yb:S-FAP slab gain element mounted in the fixture design to allow for the flow of helium over both slab faces at a 0.07 Mach number. Figure 3 summarizes the achieved performance. In the free-funning long-pulse mode of operation, the maximum output energy of 2 joules was obtained with a power slope efficiency of 51% and an electrical energy efficiency of ~9%. The pulse repetition rate was increased up 25 Hz, producing an average power output of 50 watts, before thermal fracture of the slab occurred. The helium cooling gas removed heat from each surface at a flux up to >3 watts/cm$^2$ before slab fracture occurred. This result was quite satisfactory, since IFE driver design analyses [4, 16] indicate that the amplifier slabs in an optimized Yb:S-FAP IFE driver will require only about 0.75 watts/cm$^2$ of heat flux removal per slab surface. Interferometric imaging of the thermally loaded Yb:S-FAP slab indicated that less than an optical wave of distortion was thermally induced in the slab, even at the highest loading imposed. These experiments clearly validate the concept of turbulent gas-flow-cooling of face-pumped, face-cooled slabs for high average power (>>10 kW) applications, such as the IFE driver.

## 4. A IFE DRIVER DEVELOPMENT SCENARIO

The worldwide development and construction of flashlamp-pumped Nd-glass laser systems needed to successfully carry out single-shot inertial fusion research to date has taken more than two decades. Figure 4 shows the series of Nd:glass lasers developed and constructed at LLNL, culminating with the National Ignition Facility expexted to operate just past the turn of the century. In light of the long development and construstion timelines for major programmatic facilities, it seems prudent to soon depart along the development path for high repetition rate, post-NIF laser drivers. In doing so, it will be important to define demonstration systems lying along the path that logically and progressively reduce residual technical risks (in the various major subsystems and in system integration), and provide progressively more useful experimental capabilities, while minimizing the aggregate development cost. Because the diode-pumped solid state IFE driver is highly modular in scaling to high average power, the IFE DPSSL driver development path can be constructed with this investment characterisatic.

Figure 4 shows a sequence of diode-pumped Yb:S-FAP laser driver systems (here named Mercury, Venus, Terra, and Helios) with increasing output energy and average power that might logically developed during the next several decades. Table 1 summaries some of the key distinguishing characteristics of these demonstration systems, including the areal size of the Yb:S-FAP gain slab utilized, the number of beamlets pumped, the total pump arrays peak and average powers, and the system output energy and average power. All of the systems are designed to operate at a pulse repetition rate of nominally 10 Hz.

The Mercury system produces an output of 100J/1kW at the fundamental 1047 nm wavelength (Using an expected ~80% conversion efficiency, the output at 349 nm is ~80J/0.8 kW). Mercury uses 22 gain slabs of 3 x 5 $cm^2$ transverse dimensions (a 4x area scale-up from presently available slabs) and demonstrates the full functionality of the proposed IFE driver (analogous to the NIF Beamlet) architecture. The transverse slab dimensions are sufficiently large so as to reasonably minimize edge thermal distortion effects on the output beam, while restraining the required pump array power (and cost). This laser requires a pump array peak and average power of 900 and 4.5 kW (fundamental), respectively.

The Venus system produces an output of nominally 5.4kJ/54kW at 1047 nm (4.3 kJ/43 kW at 349 nm). Venus uses gain slabs of 10 x 16.6 $cm^2$ transverse dimension, the largest slab size needed for all following systems. Three full-dimension beamlet apertures are pumped in the Venus laser to evaluate the issue thermal beam cross-talk between contiguous beamlets positioned along the gas-flow-cooling direction. The required pump array peak and average power increase to 11.4 and 0.135 MW, respectively.

The Terra system produces an output of nominally 27kJ/267kW at 1047 nm (21 kJ/214 kW at 349 nm). Like the Venus system, Terra uses full aperture 10 x 166.6 $cm^2$ gain slabs (slab development risk resolved on the Venus system). Terra incorporates 15 beamlets, corresponding to a full beamline. Terra requires a pump array peak and average power of 56 MW and 670 kW, respectively.

The Helios system is essentially a full IFE driver, suitable to drive a 1 $GW_e$ IFE power plant. It produces an output of nominally 4.6 MJ/51 MW at 1047 nm (3.7 MJ/41 MW at 349 nm).

## 5. THE NEAR FUTURE AND MERCURY DEVELOPMENT

Beginning with the 1997 fiscal year (October 1996), LLNL will commense the design and constution of the Mercury laser. Envisioned as a three year effort, the next year will focus on risk reduction of the major subsystem technologies: 1) Yb:S-FAP slab growth to the 3 x 5 $cm^2$ size, 2) development of an ASE slab edge cladding, and 3) optimized design and development of the InGaAs pump array unit cell. We will also conduct as CDR to produce a Mercury system point design to guide subsystem risk reduction efforts toward optimum component specifications. The second year will center on engineering design of the system, fabrication of major system pump array and laser gain elements, and procurement of long-lead system utilities. The thrid year will complete activities of the swecond year, and carry out integration of the functional Mercury system.

This paper is based on the team work of a great many LLNL colleagues, notably Chris Marshall and Steve Payne, as well as Kathleen Schaffers, Mark Emanuel, Jay Skidmore, Barry Freitas, Larry Smith, Laura DeLoach, Charles Orth, Steve Sutton, Howard Powell, and Mike Campbell. I am also pleased to acknowledge the contributions to Yb:S-FAP crystal growth by Bruce Chai of the University of Florida at Orlando.

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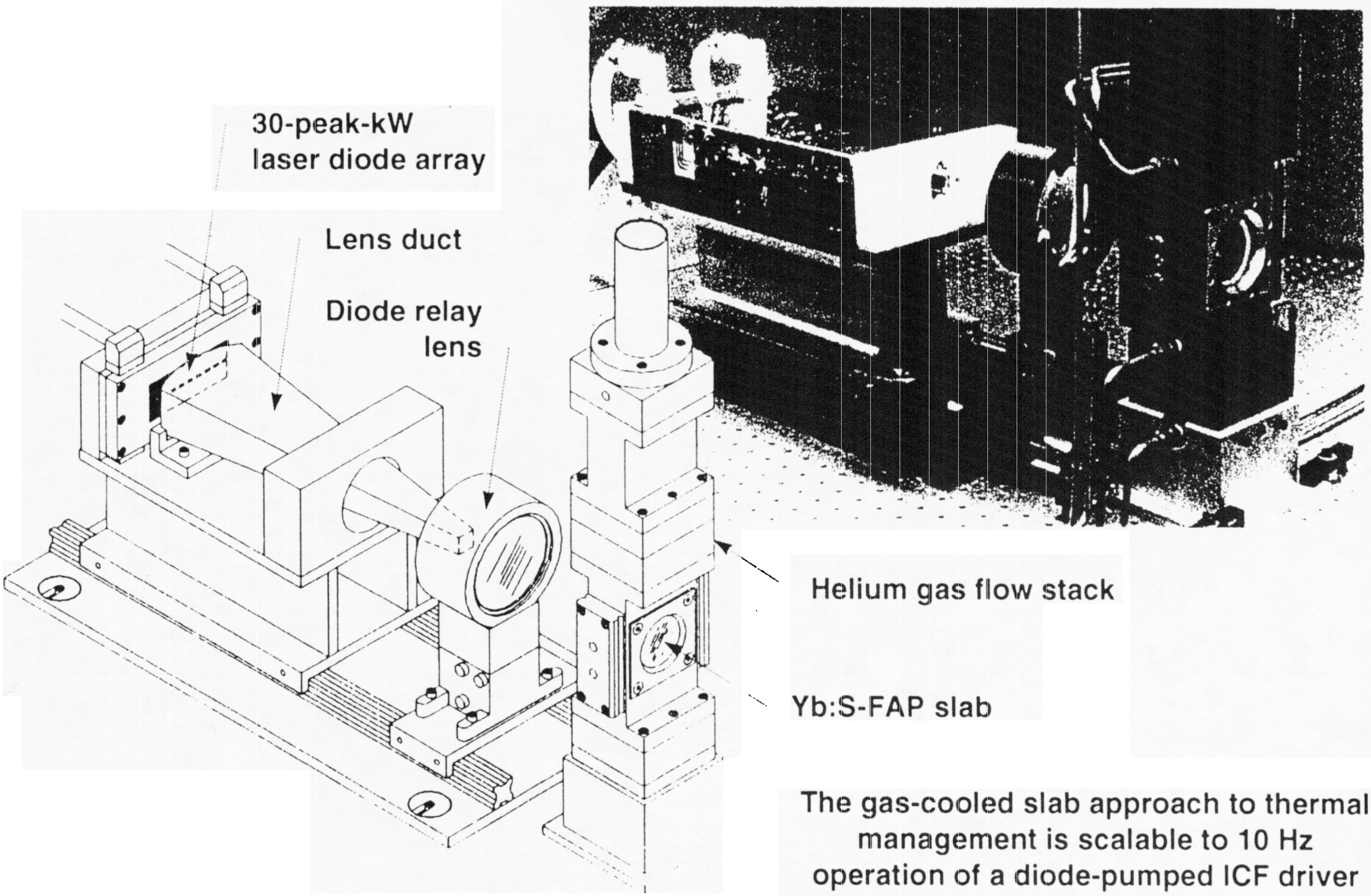
Fig 1

# 50-W diode-pumped Yb:S-FAP gas-cooled slab aser tes' bed demonstrates potential of advanced ICF aser drivers




The gas-cooled slab approach to thermal management is scalable to 10 Hz operation of a diode-pumped ICF driver

Fig. 2

# Modular Yb:S-FAP slab gas-cooling manifold allows for flexible slab configurations

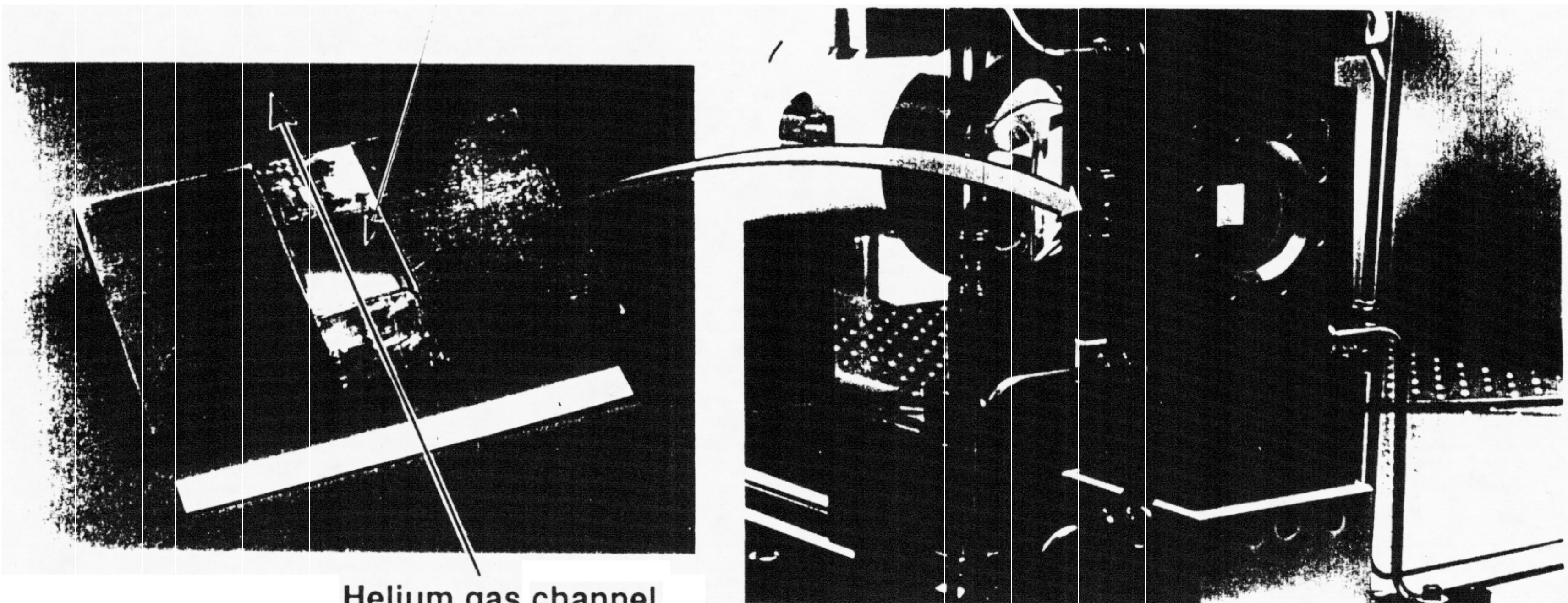
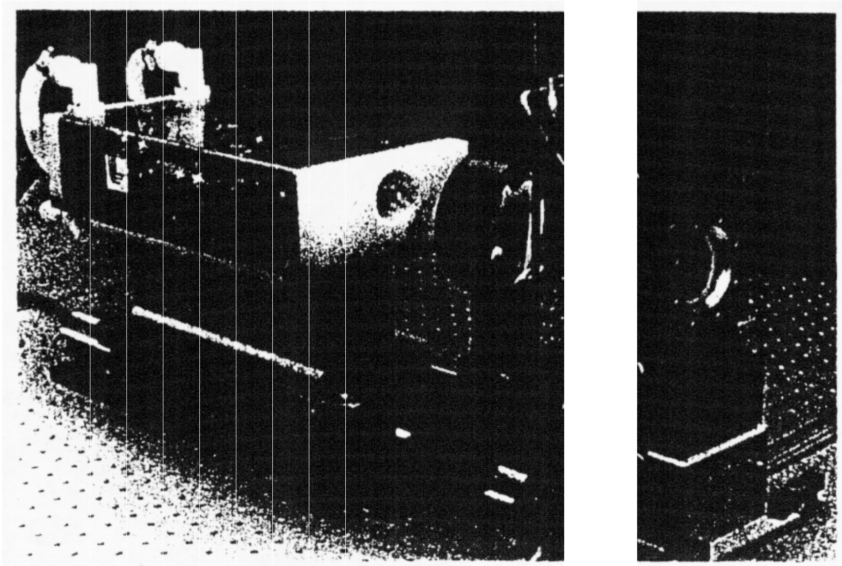
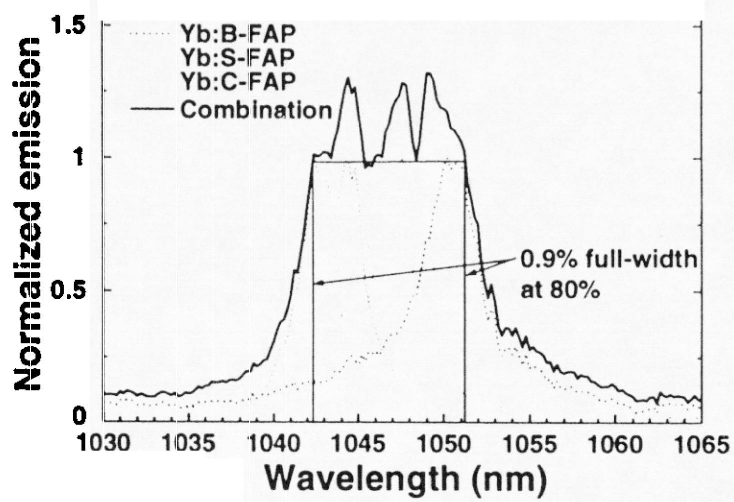


Fig 3

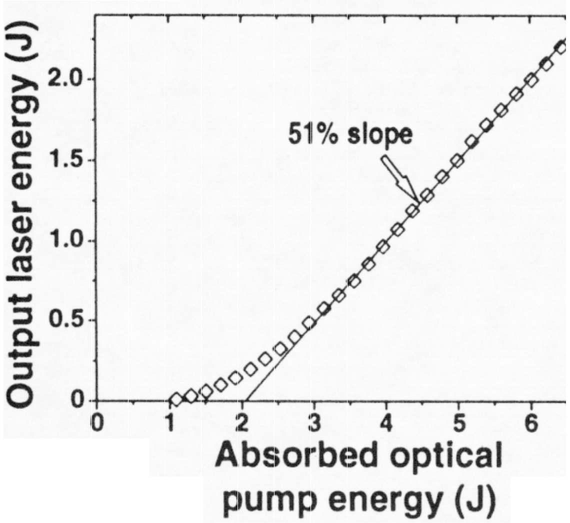
# Gas-cooled, diode-pu ped, solid-state lasers are being developed for IFE an high-average-power applications



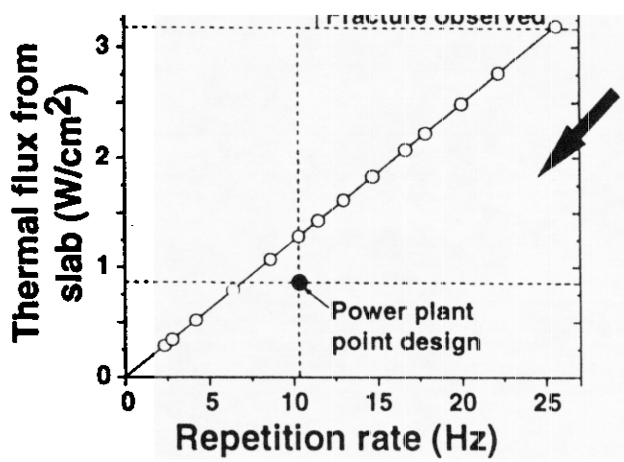
## Large bandwidths of ~1% are also possible in future systems




## Laser efficiencies



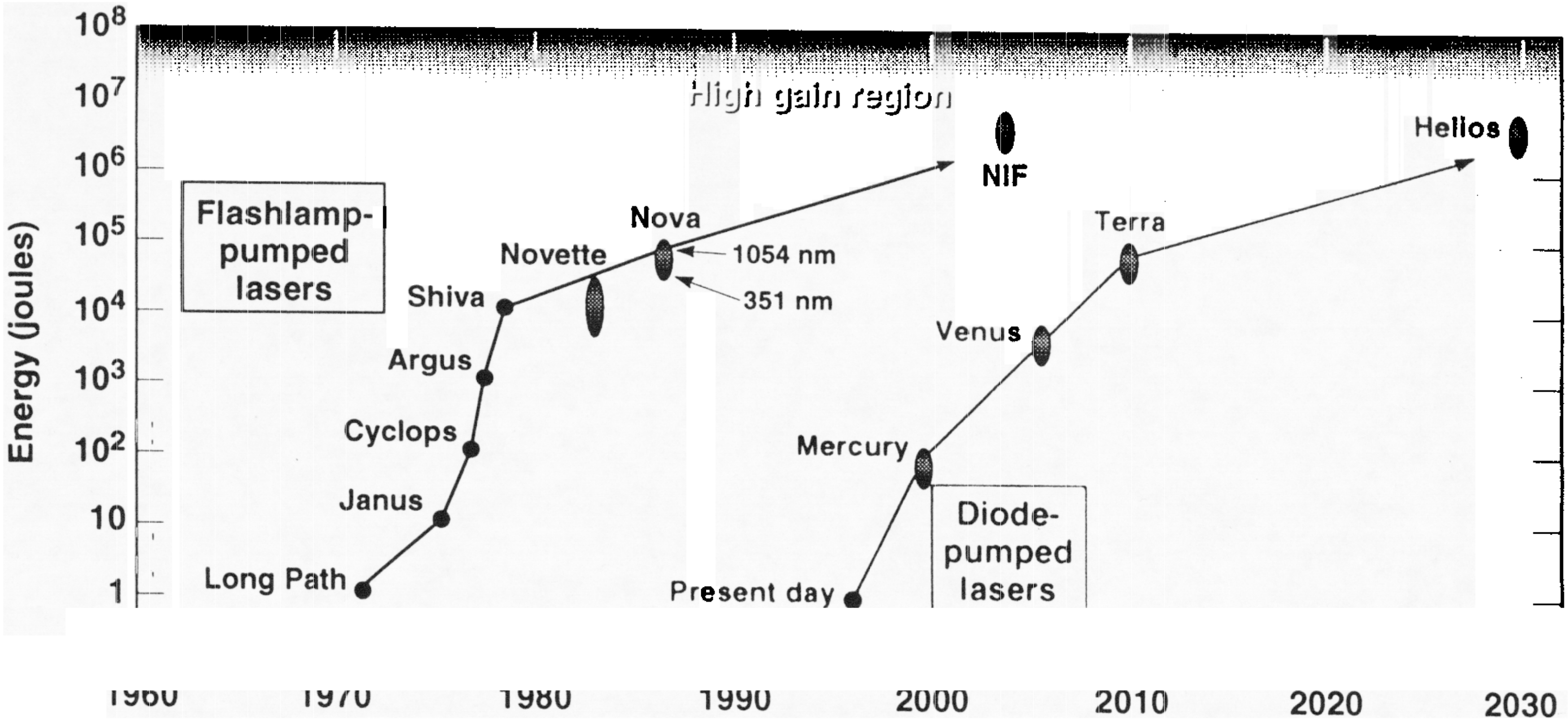

## Thermal loading




Shaded exceeds thermal requirements

Fig 4

# Multiple decade long development cycles are required to carry new ICF laser architectures to maturity




- Terra laser can serve concurrently with NIF as a Nova-class rep-rated system

Diode-pumped solid-state lasers (DPSSL) offer the option of higher rep-rate, better beam quality, and more compactness for advanced ICF drivers and other applications

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Table 1

## IFE driver modularity enables a rational cost-effective development path

| Scaling characteristic | Demonstration System | | | |
|---|---|---|---|---|
| Demonstration System Name | Mercury | Venus | Terra | Helios |
| Modularity level | sub-beamlet | 3-beamlets | beamline | 345 beamlines |
| Yb:S-FAP gain slab dimensions ($cm^2$) | 3 x 5 | 10 x 16.6 | 10 x 16.6 | 10 x 16.6 |
| No. of beamlets pumped | 1 | 3 | 15 | 345 |
| Total pump array peak power | 900 kW | 11.4 MW | 56 MW | 20 GW |
| Total pump array average power | 4.5 kW | 135 kW | 670 kW | 230 MW |
| System output energy @ 1047 nm | 100 J | 5.4 kJ | 27 kJ | 4.6 MJ |
| System output av. power @ 1047 nm | 1 kW | 54 kW | 267 kW | 51 MW |
| Risk reduced: | 1/10 area slab<br>regen amp. functionality | *full slab*<br>beamlet cross-talk | validate beamline | validate system |

# Diode Pumped Solid State Lasers for IFE


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**Second Annual International Conference**
**on**

**Solid State Lasers for Application to Inertial Confinement Fusion (ICF)**

**October 22-25, 1996**
**Paris, France**

## Contributors

**Laser/System**

- Chris Marshall
- Steve Payne
- Ray Beach
- Larry Smith
- Steve Sutton
- Charles Orth
- Howard Powell

**Diode Pump Arrays**

- Mark Emanual
- Jay Skidmore
- Barry Freitas

**Yb-S-FAP Material**

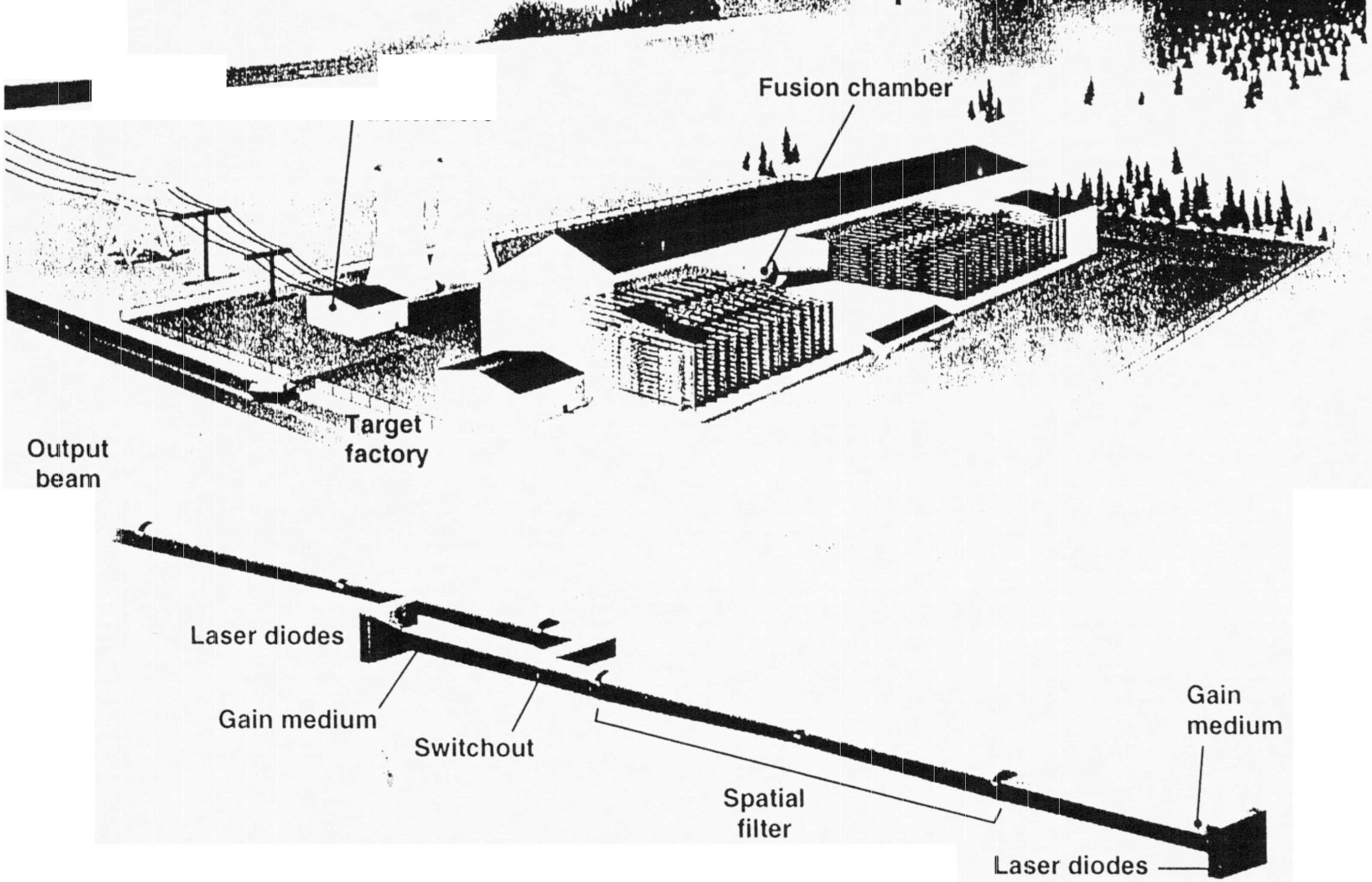
- Kathleen Schaffers
- Laura DeLoach
- Bruce Chai (U of Florida)

# Presentation Topics

- Background
- IFE Diode-Pumped Solid State Laser (DPSSL) Driver Concept
- Enabling Technology Advances
- Status of IFE DPSSL Specific Technologies
- A System Development Strategy
- Future Plans

# DPSSLs provide a pathway for solid-state lasers that reaches beyond the NIF to IFE

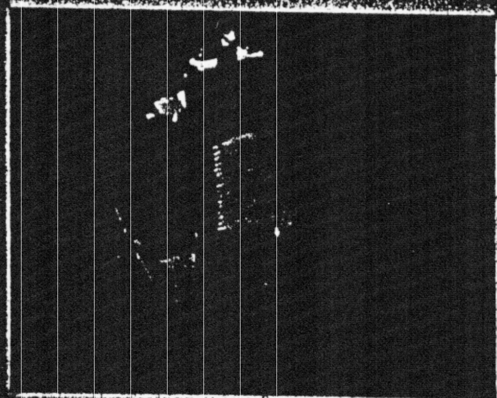
An artists rendition of a DPS[illegible]riven IFE powe[illegible]




- DPSSLs offer high rep-rates, efficiency, reliability, and long operating lifetime
- DPSSLs are grounded in well-known physics and design principles previously established with large Nd:glass fusion laser facilities

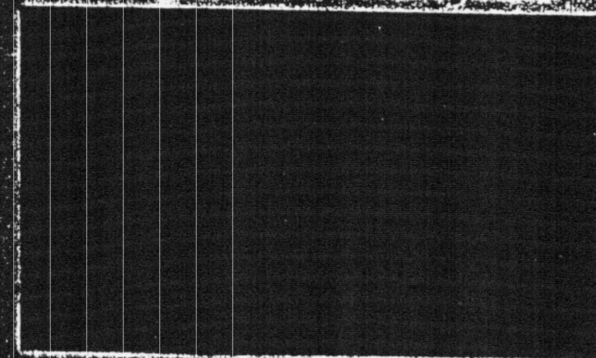
# Gas-cooled diode-pumped solid-state laser architectures will allow for significantly increased shot rate and improved beam quality

**Issue:** Flashlamps do not offer adequate lifetime or pumping efficiency
**Solution:** Flashlamps ⟶ Laser diodes



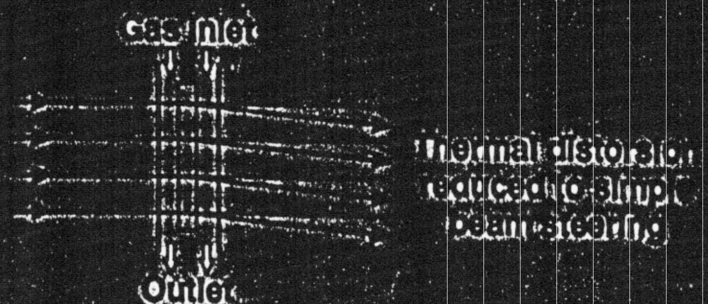
Diodes provide:
- High efficiency
- Long lifetime
- Less thermal loading

**Issue:** Nd:glass storage time is too short to take full advantage of diodes
**Solution:** Nd:glass ⟶ Yb:crystals



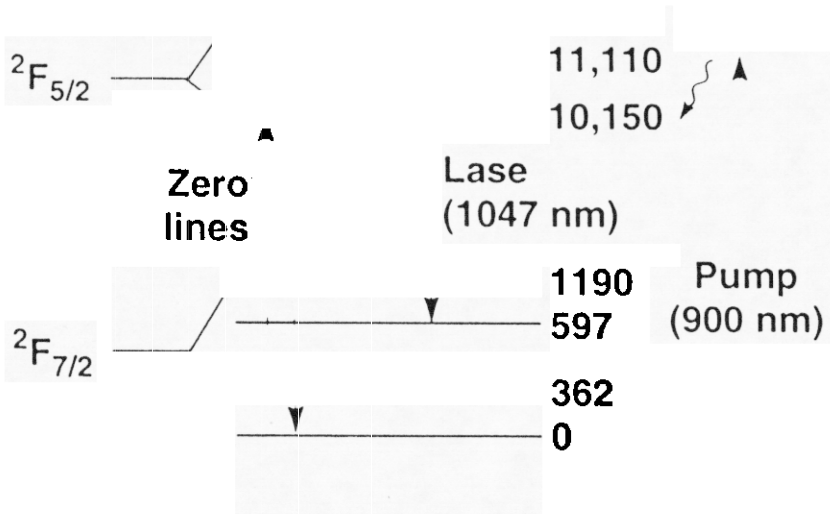
Yb:S-FAP offers 4X longer energy storage times than Nd:glass with lower diode cost and higher efficiency

**Issue:** Heat from the gain medium must be managed in a scalable manner
**Solution:** Passive cooling ⟶ forced gas-cooling

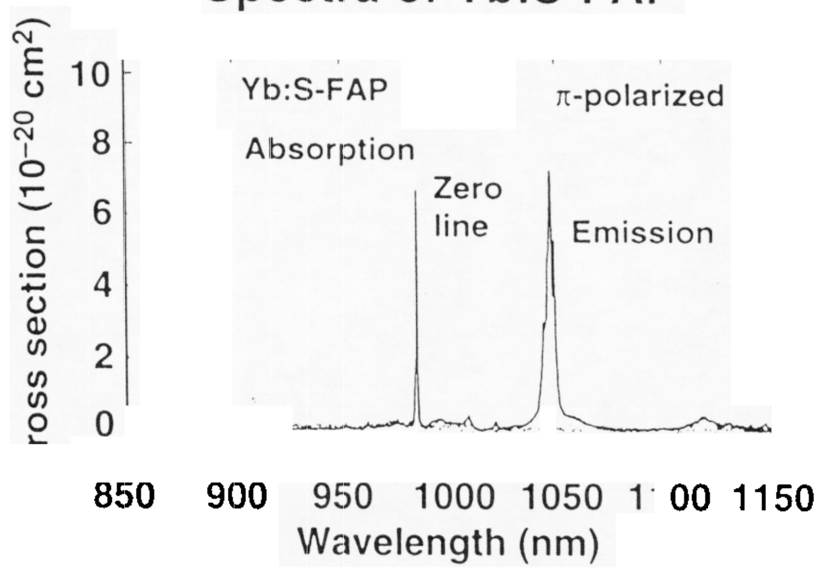


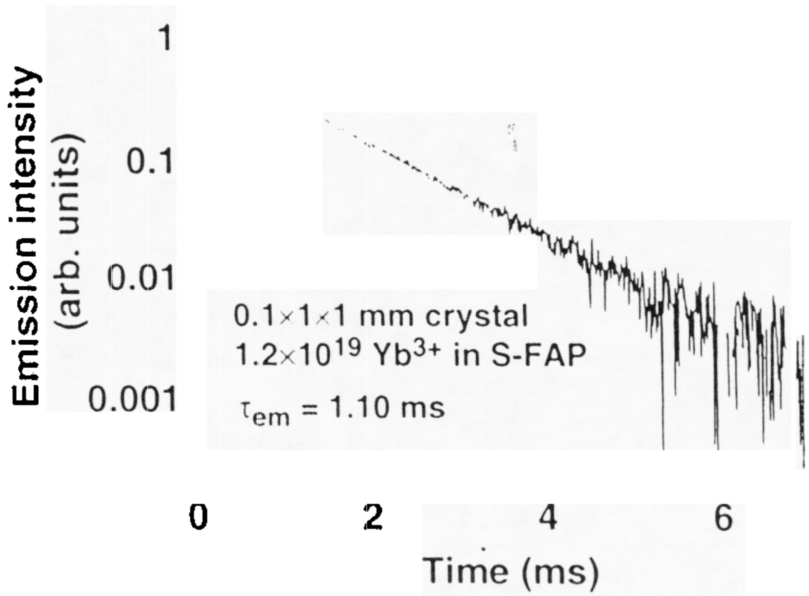
# The spectroscopic properties of Yb:S-FAP have been previously measured and reported*

## Energy levels of $Yb^{3+}$

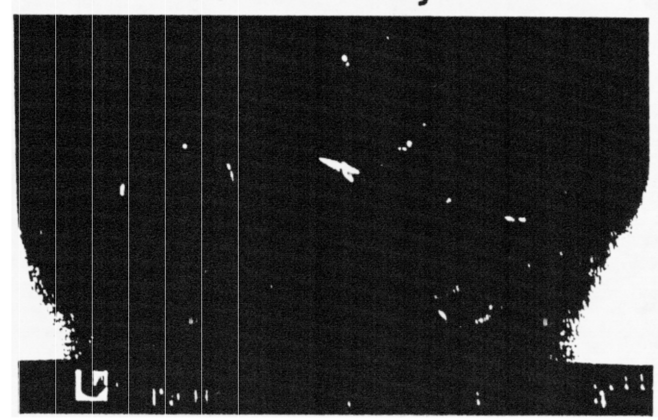



## Spectra of Yb:S-FAP




## Yb:S-FAP crystals



* L. D. DeLoach et al. "Laser and Spectroscopic Properties of $Sr_5(PO_4)_3F$:Yb," J. Opt. Soc. Am. B, vol. II 1994 and C. D. Marshall et al. "1.047-μm Yb:$Sr_5(PO_4)_3F$ Energy Storage Optical Amplifier," IEEE J. Quan. Electron., vol. 1 1995.

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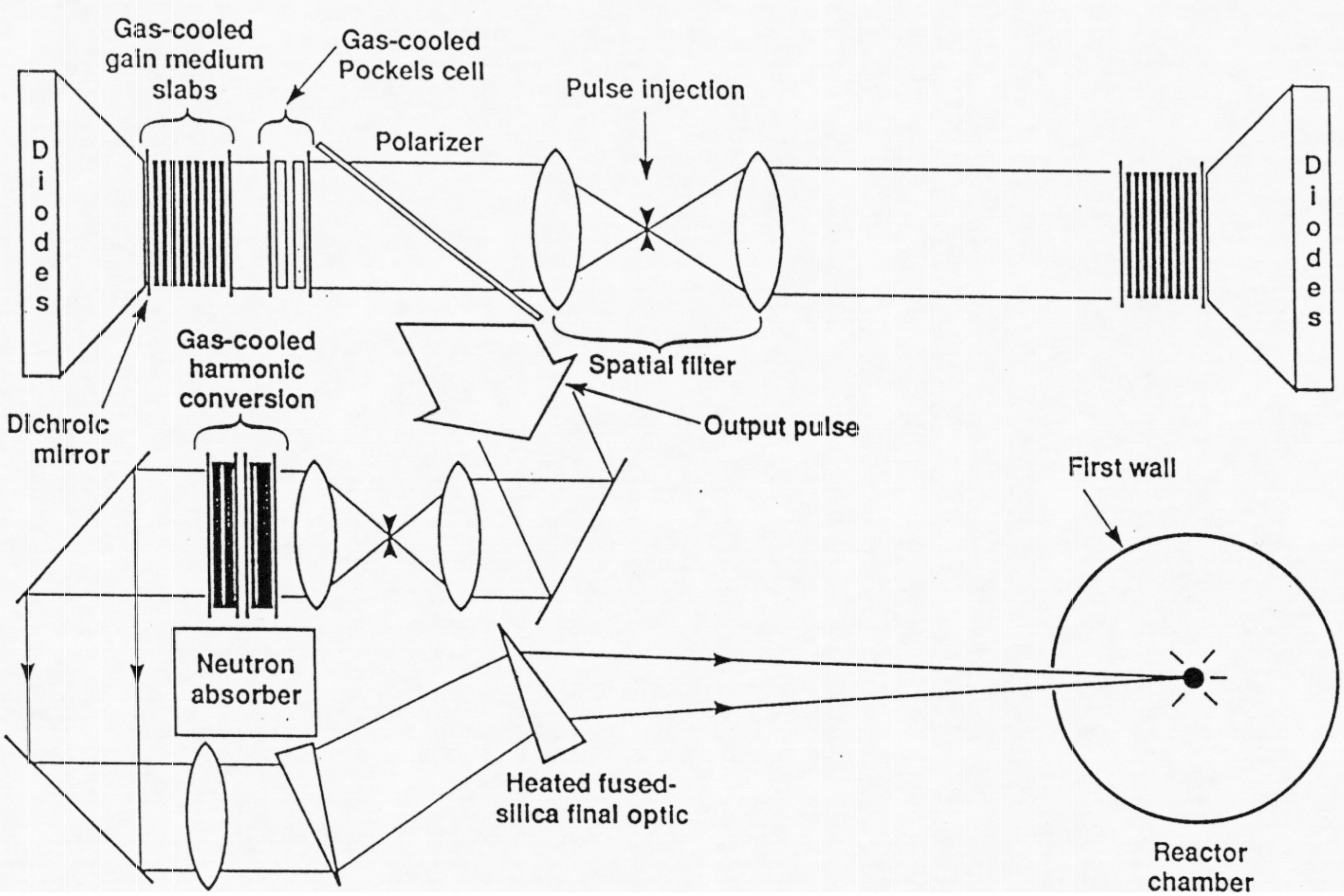
# The Yb:S-FAP IFE driver utilizes the NIF Beamlet system architecture*

[illegible]

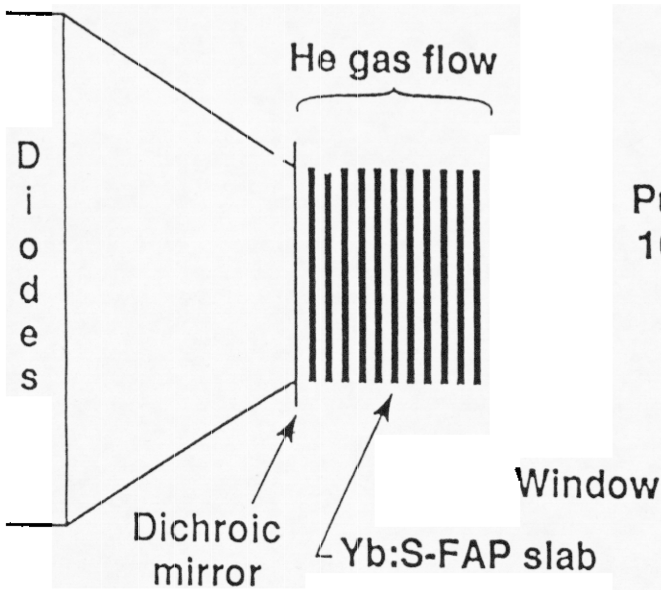


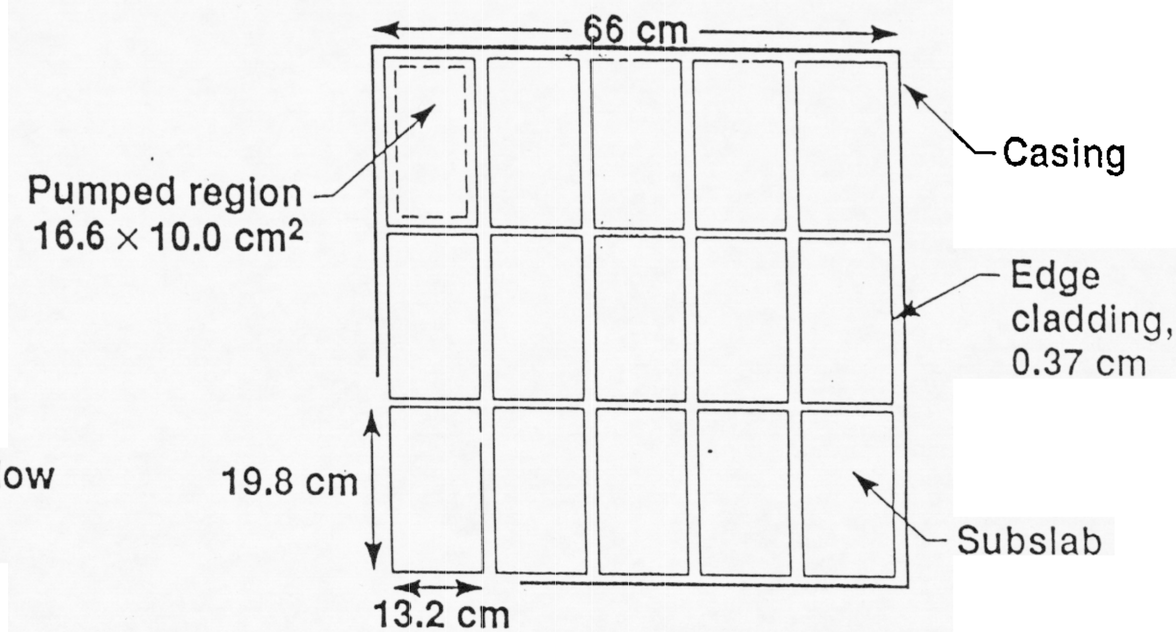

Driver system pulse energy and average power = 3.7MJ and 42 MW

Driver system has 345 beamlines (producing 10.7 kJ and 120 kW)

# Yb:S-FAP IFE driver beamline/amplifier characteristics *

* C. Orth, et. al., Nuclear Fusion, 36, 75 (1996)




**For each of two amplifiers per beamline**

11 slab gain elements in axial direction
8.2 centimeter optical gain length
335 kW average power pump array
28.3 MW peak power pump array
30 kJ pulse energy pump array
10 $kW/cm^2$ pump flux at gain element
0.76 $watt/cm^2$ surface heat removal flux
0.07 Mach number of helium cooling gas

| Beamline characteristics (two amplifiers) |
|---|
| 10.7 kJ output energy @349 nm |

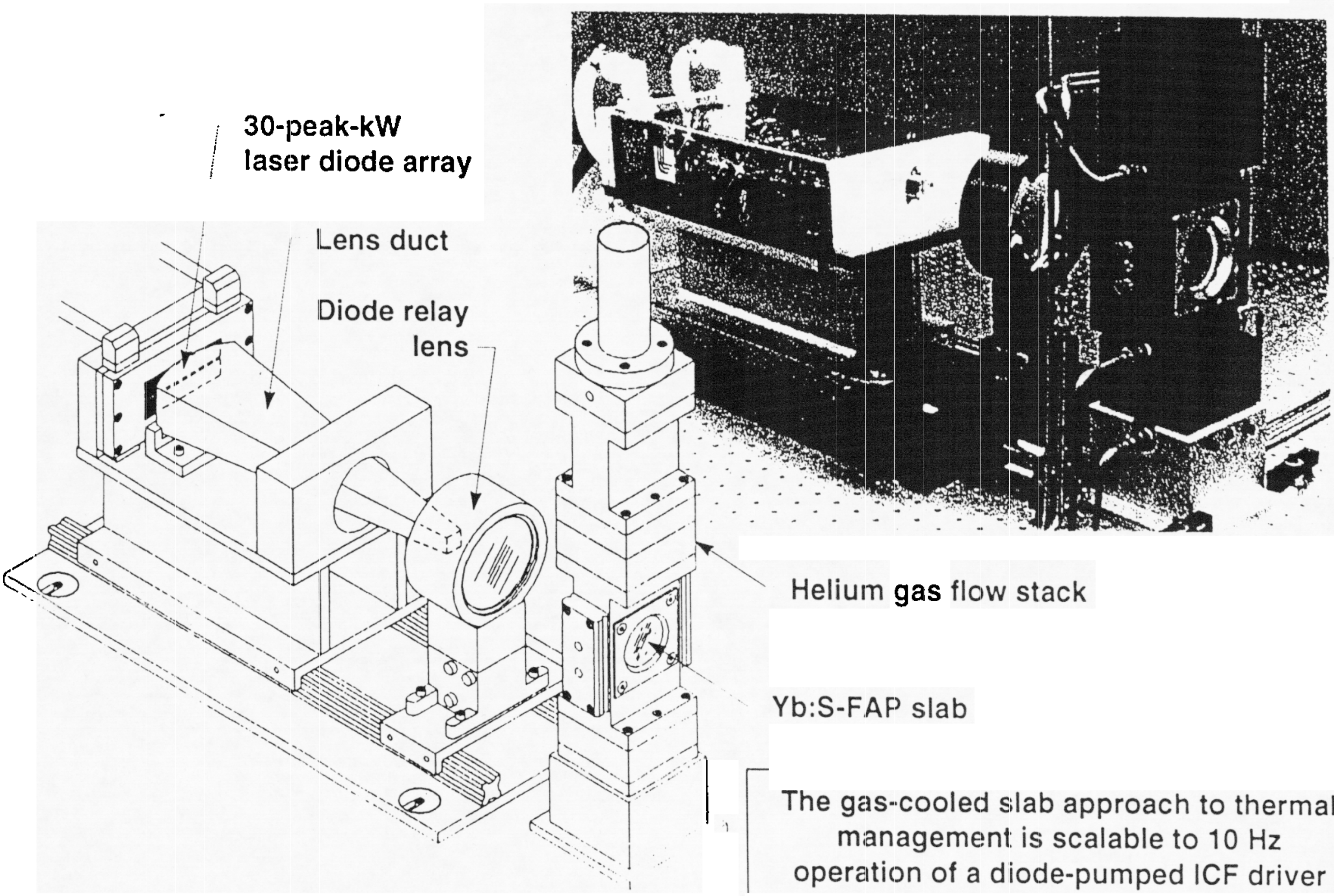
| Beamlet characteristics (15 per beamline) |
|---|
| 715 J output energy @ 349 nm |

# First demonstration of transverse, turbulent gas-flow-cooling of a diode-pumped slab Yb:S-FAP average power laser

Chris Marshall, Larry Smith, Mark Emanuel,
Kathleen Schaffers, Steve Mills, Steve Payne, and Bill Krupke

Advanced Solid State Lasers Meeting
San Francisco, CA
January 1996

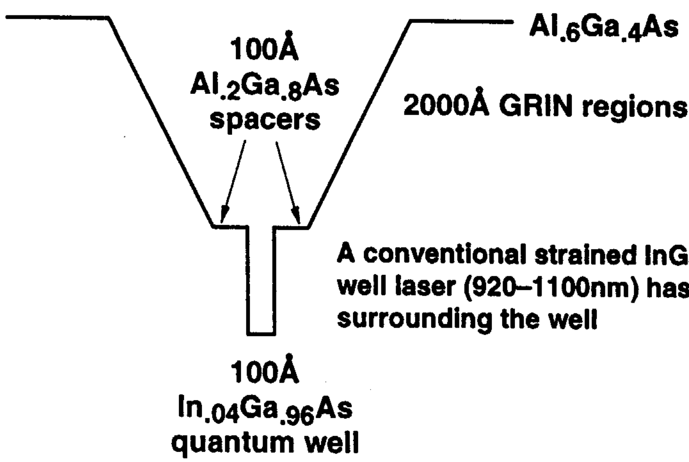
# 50-W diode-pumped Yb:S-FAP gas-cooled slab laser testbed demonstrates potential of advanced ICF laser drivers




The gas-cooled slab approach to thermal management is scalable to 10 Hz operation of a diode-pumped ICF driver

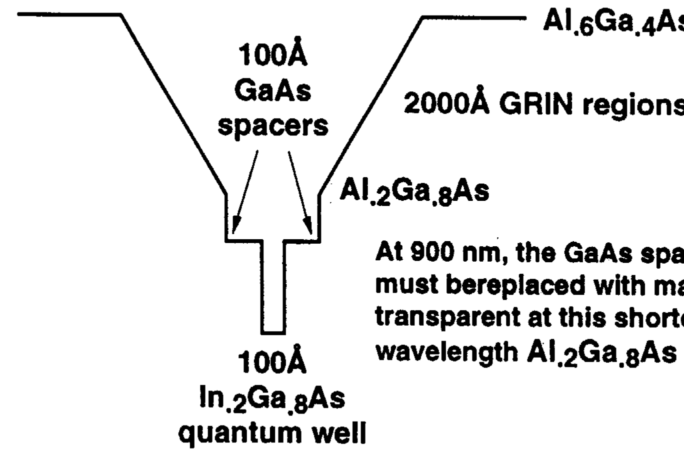
# Conventional strained InGaAs quantum structures have been altered to produce 900 nm diodes

## Conventional InGaAs diode structure



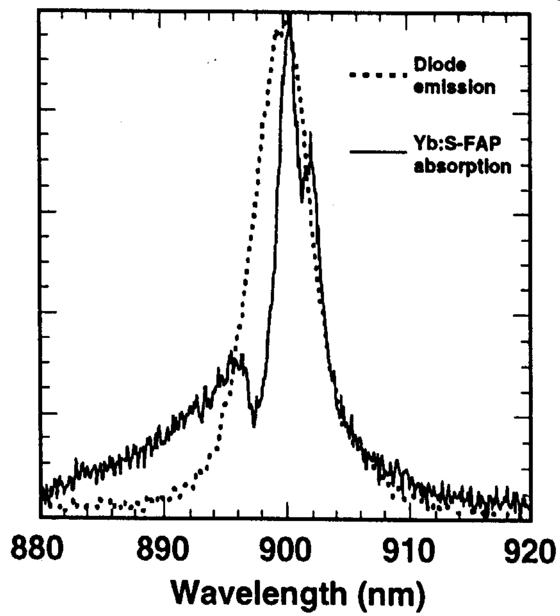

A conventional strained InGaAs quantum well laser (920–1100nm) has GaAs layers surrounding the well

## 900 nm diode structure




At 900 nm, the GaAs spacers must bereplaced with material transparent at this shorter wavelength $Al_{.2}Ga_{.8}As$

## Diode emission and Yb:S-FAP absorption overlap

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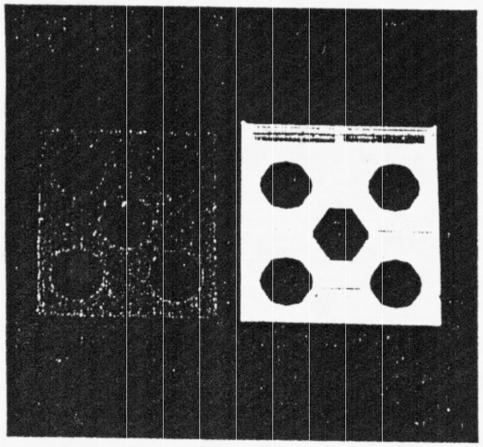
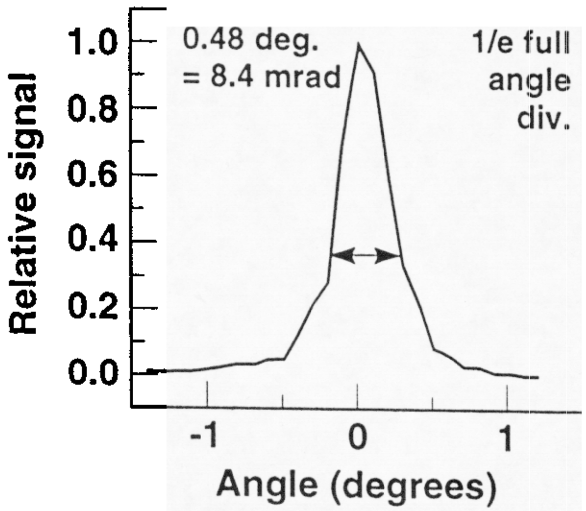
24CMB6/sse

# Our pump source consisted of a 22 bar stack of microchannel cooled, microlensed InGaAs diodes

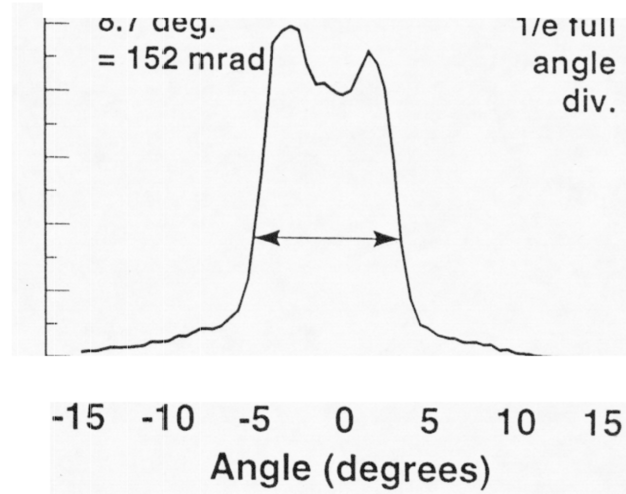
Single bar picture



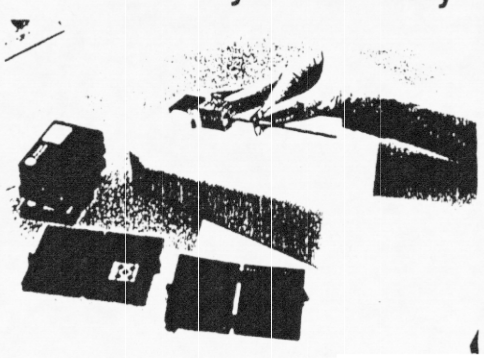
Fast axis (microlensed) data



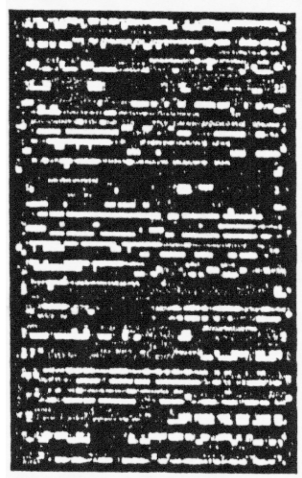

Slow axis data



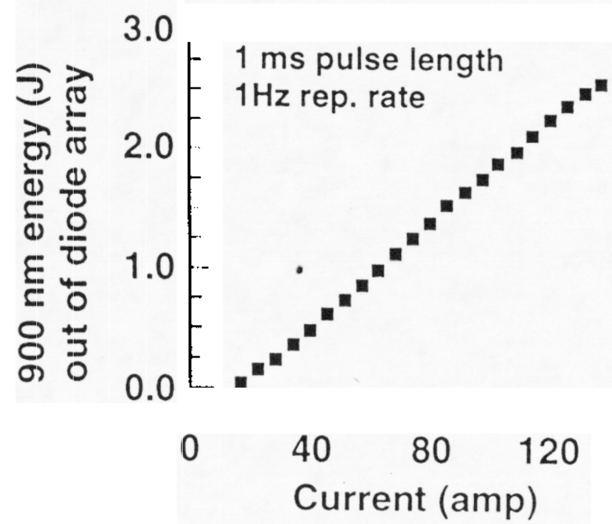

Diode array assembly



Diode array

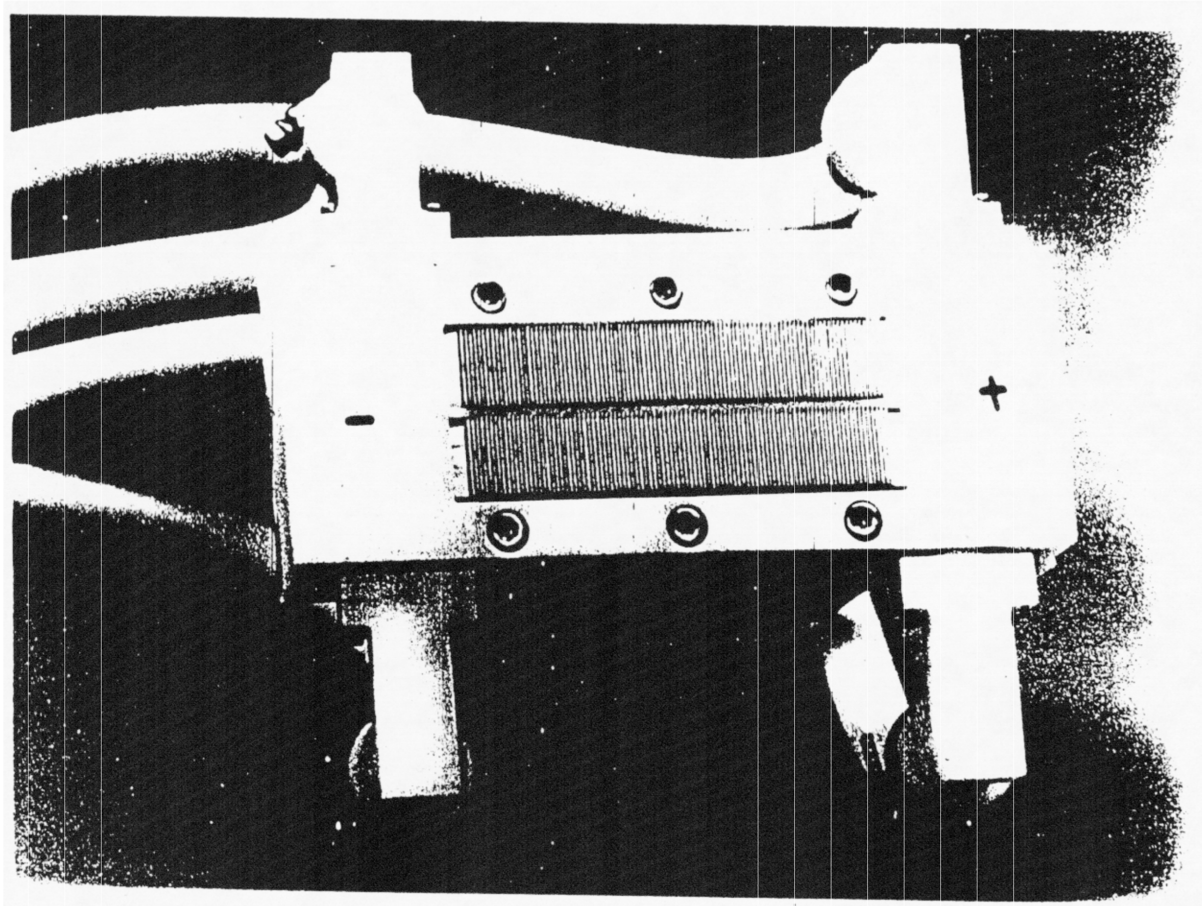


Output energy v.s. current data




70-17-0196-0172

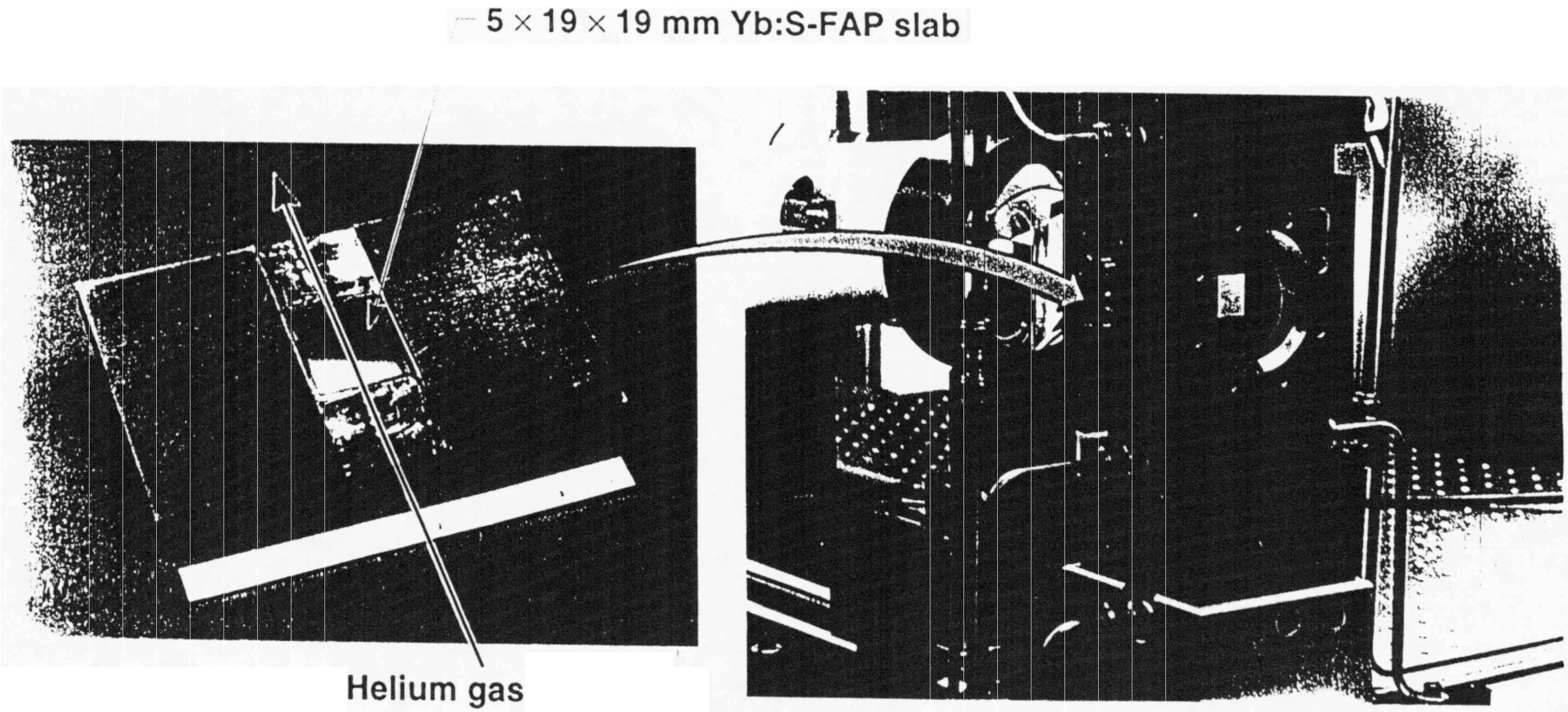
# 23-kW peak power InGaAs laser diode array




Microchannel coolers allow for a 20% duty factor at full peak power for 4.6-kW average power operation

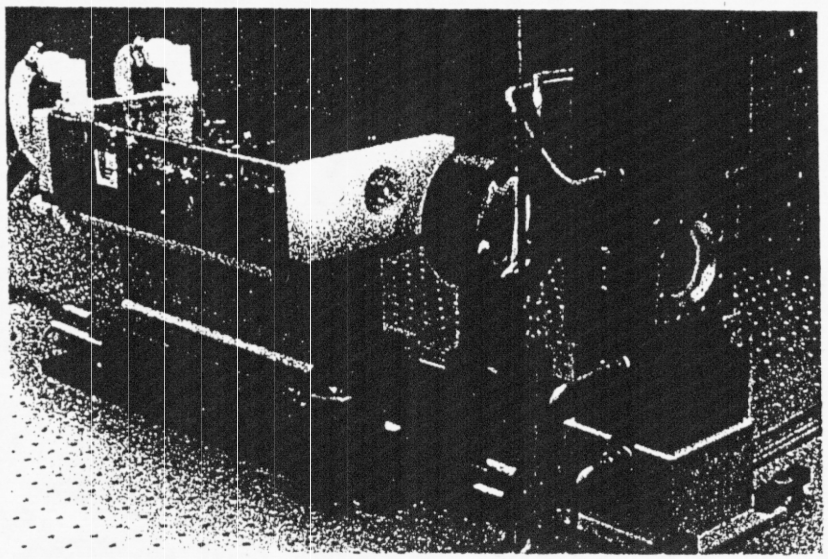
70-17-1195-2472A
7CDM

# Modular Yb:S-FAP slab gas-cooling manifold allows for flexible slab configurations

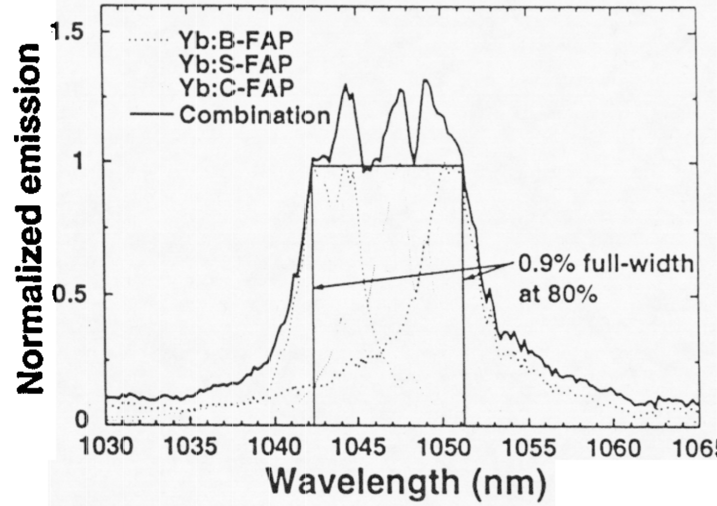



70-00-0795-1744C
12CDM/mcm

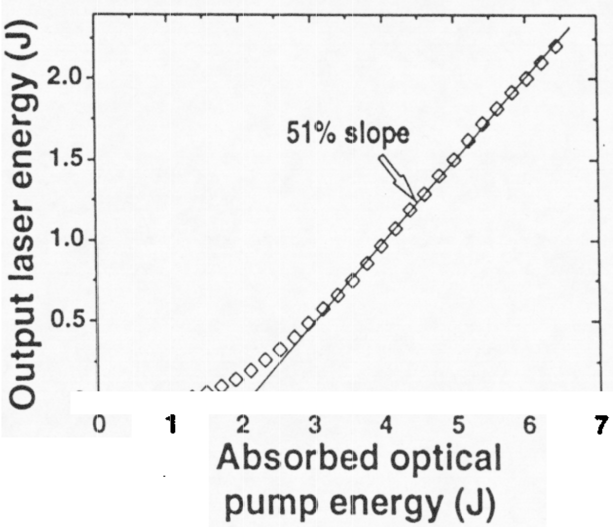
# Gas-cooled, diode-pumped, solid-state lasers are being developed for IFE and high-average-power applications



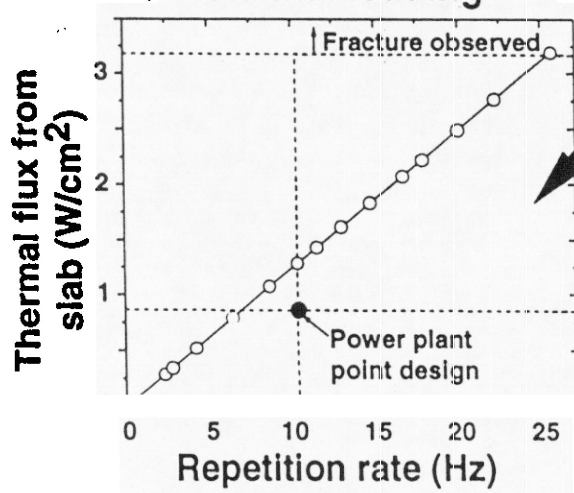
Large bandwidths of ~1% are also possible in future systems




Laser efficiencies



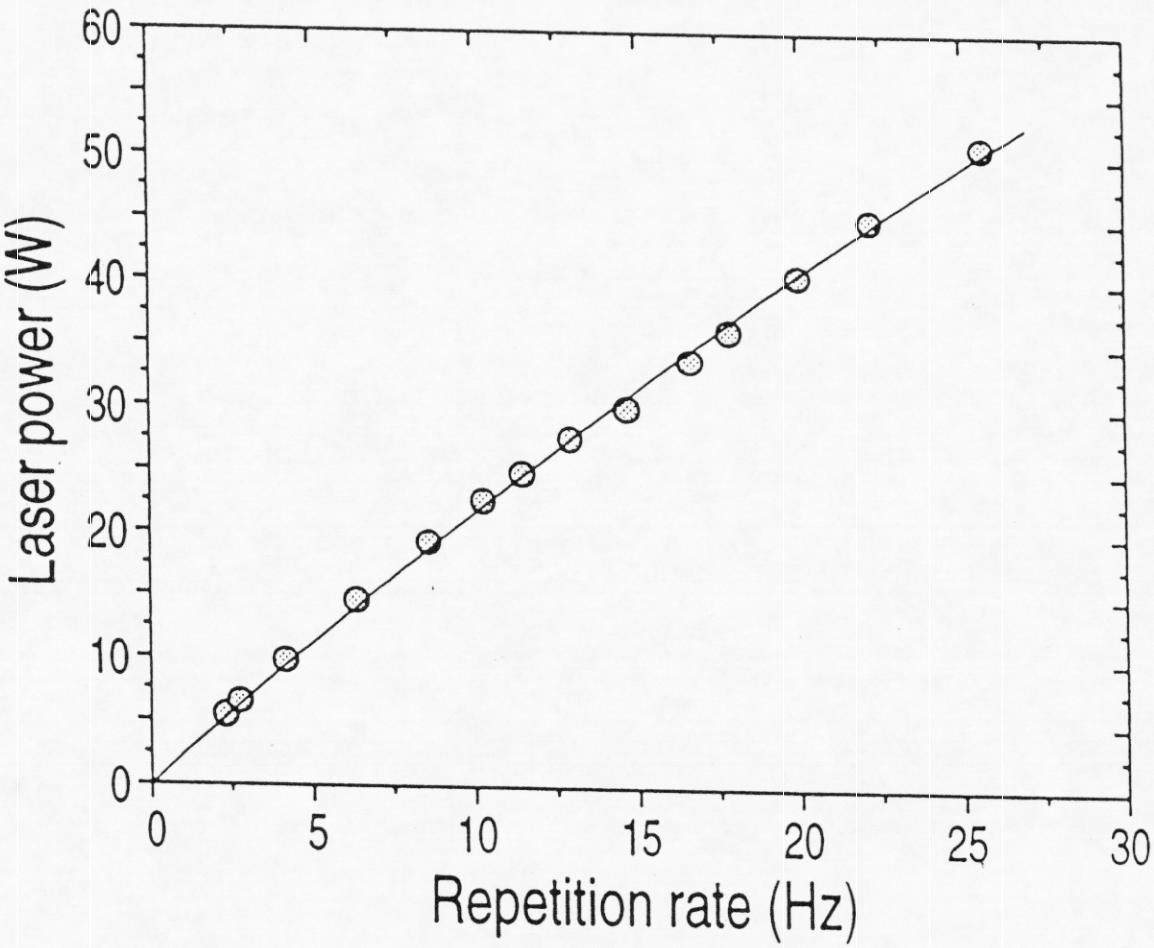

Thermal loading




Shaded **exceeds** thermal **requirements**

# The Yb:S-FAP GCS slab laser has produced 50 watt at 25 Hz*

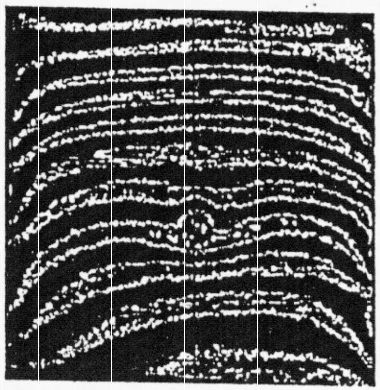
C. Marshall, et. al., Advanced Solid State Lasers, OSA Trends in Optics and Photonics, TOPS Vol. 1, 1996



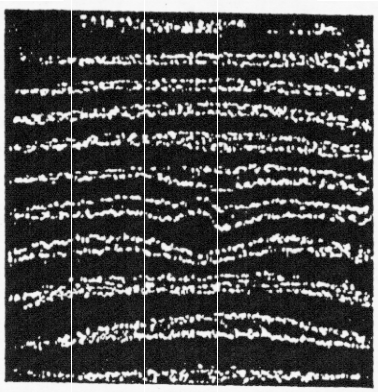

**Transverse, turbulent-gas-flow cooling of laser slabs is a viable method of thermal management in diode-pumped solid state drivers for IFE**

# Interferometer traces show that the central region of the crystal has <1 wave distortion due to thermal effects

Thermally loaded
with 3.5 W/cm$^2$

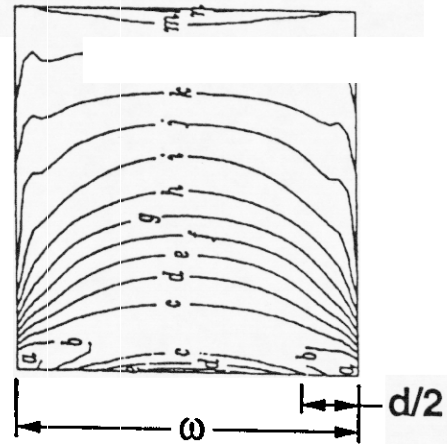


Unpumped
0 W/cm$^2$



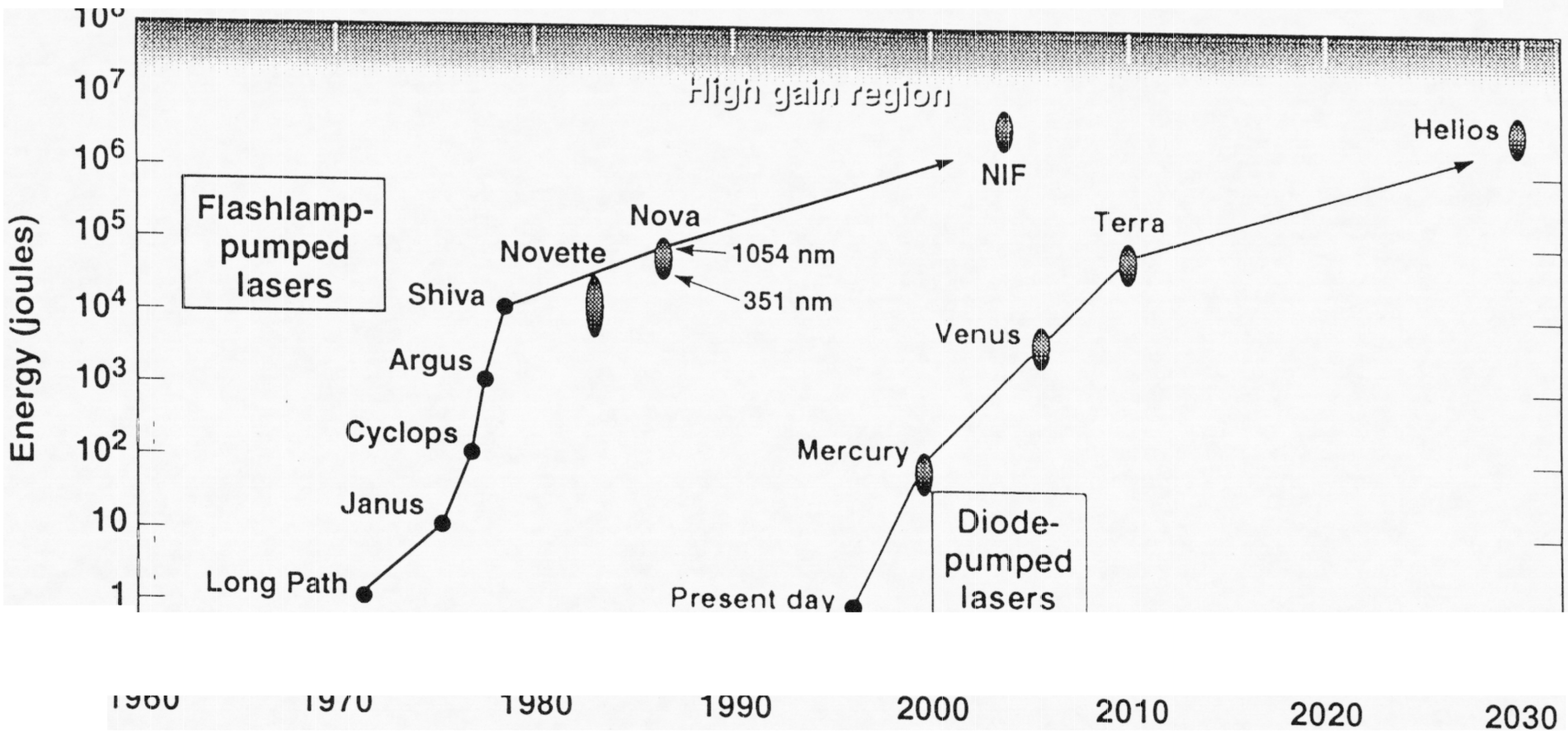
Gas
flow

Predicted wavefront
with ~2 W/cm$^2$




- Edge distortion is from thermal conduction out the sides and edge stress
- These edge regions will not grow larger when the crystal aperture is scaled up
- Distortion-free fraction scales as $\frac{(\omega - d)^2}{\omega^2}$ which approaches 1 for large $\omega$

# Multiple decade long development cycles are required to carry new ICF laser architectures to maturity




- Terra laser can serve concurrently with NIF as a Nova-class rep-rated system

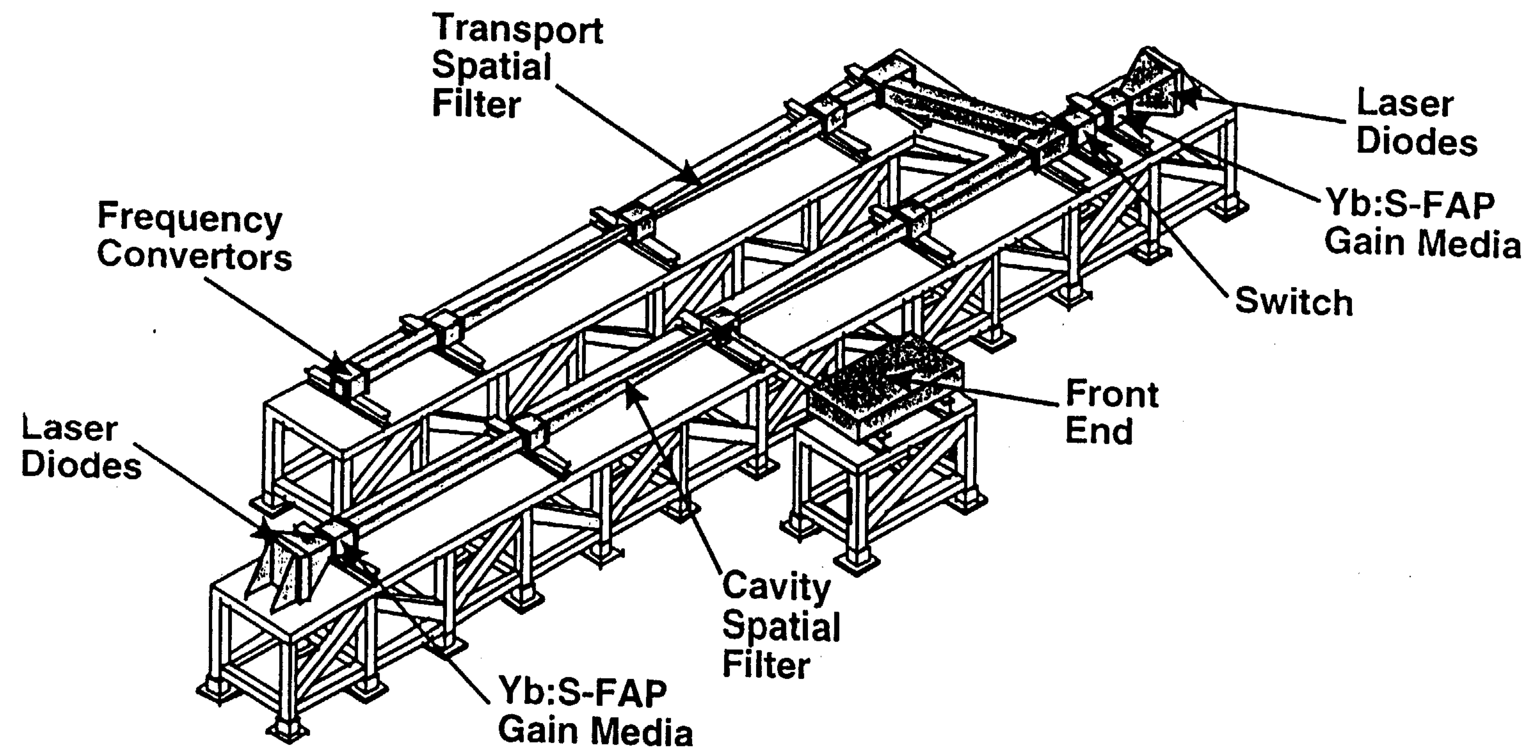
Diode-pumped solid-state lasers (DPSSL) offer the option of higher rep-rate, better beam quality, and more compactness for advanced ICF drivers and other applications

# IFE driver modularity enables a rational cost-effective development path

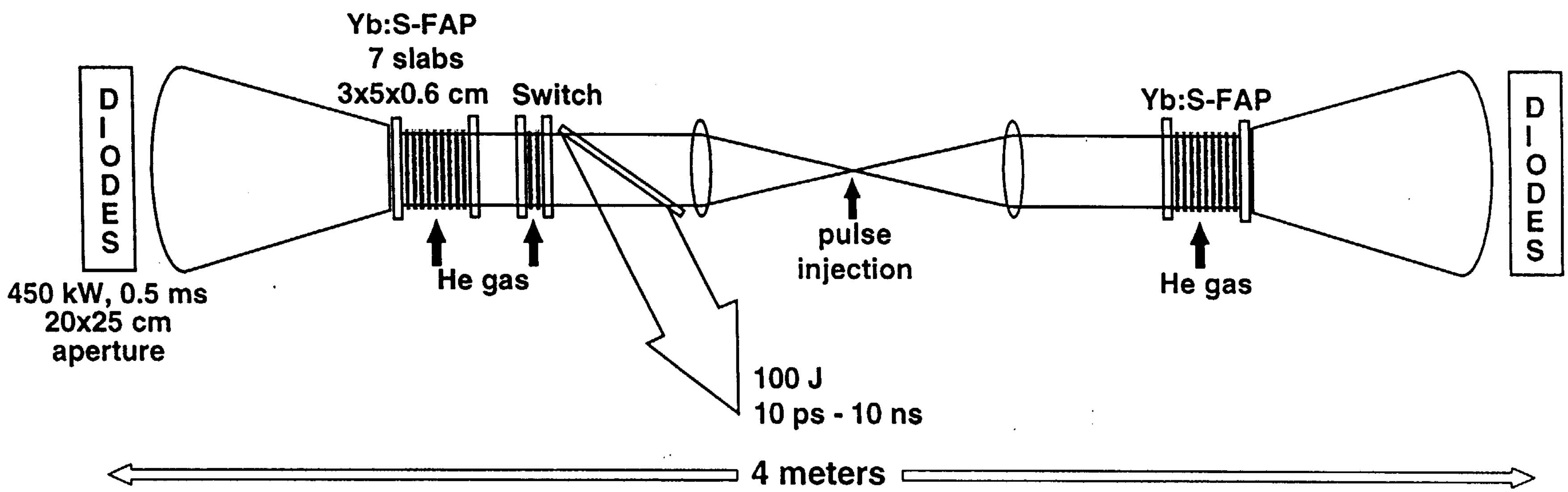
| Scaling characteristic | Demonstration System | | | |
| --- | --- | --- | --- | --- |
| Demonstration System Name | Mercury | Venus | Terra | Helios |
| Modularity level | sub-beamlet | 3-beamlets | beamline | 345 beamlines |
| Yb:S-FAP gain slab dimensions ($cm^2$) | 3 x 5 | 10 x 16.6 | 10 x 16.6 | 10 x 16.6 |
| No. of beamlets pumped | 1 | 3 | 15 | 345 |
| Total pump array peak power | 900 kW | 11.4 MW | 56 MW | 20 GW |
| Total pump array average power | 4.5 kW | 135 kW | 670 kW | 230 MW |
| System output energy @ 1047 nm | 100 J | 5.4 kJ | 27 kJ | 4.6 MJ |
| System output av. power @ 1047 nm | 1 kW | 54 kW | 267 kW | 51 MW |
| Risk reduced: | 1/10 area slab | full slab | | |
| | regen amp. functionality | beamlet cross-talk | validate beamline | validate system |

# The 100J Mercury laser system will demonstrate IFE driver functionality*

C. Marshall, LLNL, June 1996



# The Mercury laser architecture will extend our previously successful gas-cooled laser designs to 100X higher energy/power




- Mercury will be the first fusion laser facility to incorporate:
  - All laser-diode pumping
  - Turbulent-gas cooled laser-slabs
  - Advanced diode-compatible crystalline gain media
- Adopts succesfull Beamlet/NIF optical layout

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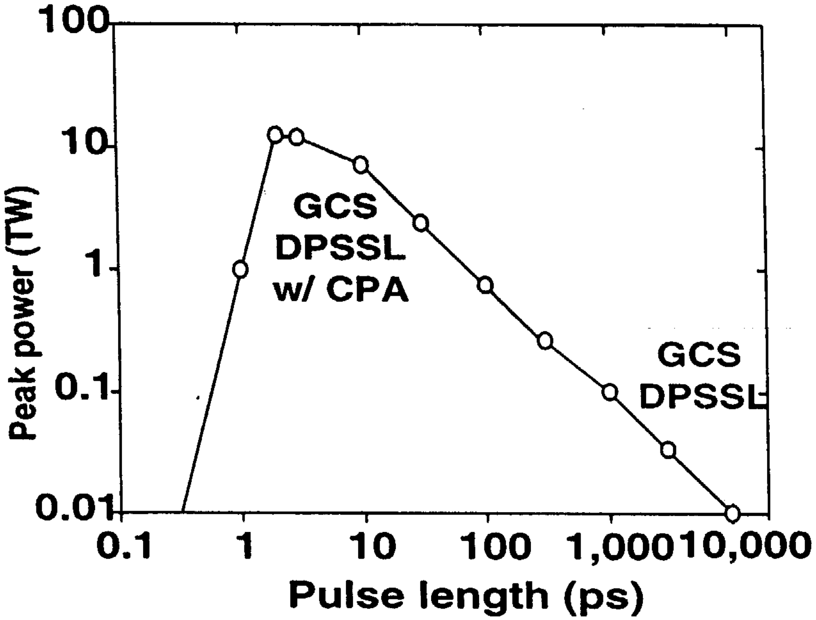
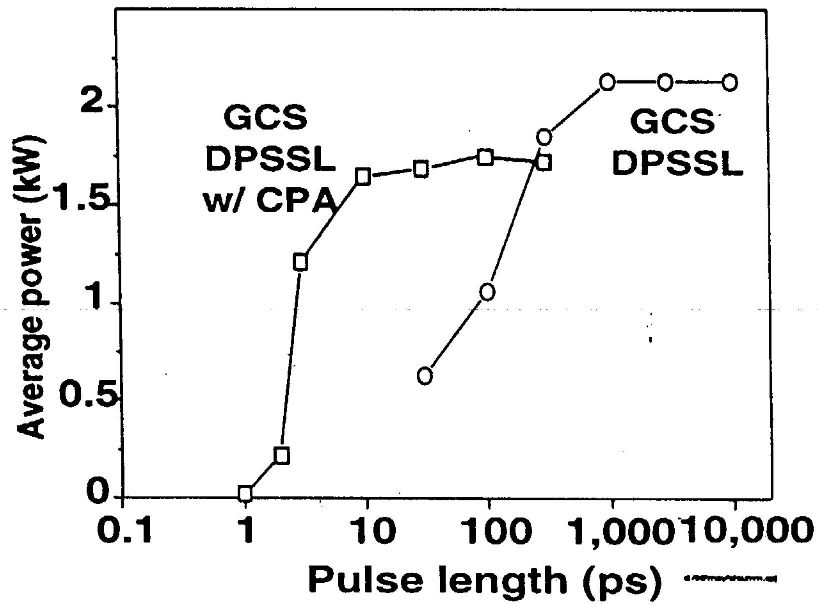
# Mercury will deliver high peak power (>TW) and high average power (>kW) for the first time

**Peak power performance**




- Chirped pulse amplification (CPA) below 300 ps

**Average power performance**




- 50 to 100 J/pulse
  9 J/cm$^2$ extraction fluence
  11% efficiency (@1 to 10 ns)
  B-integral < 2
  23 Hz

**The laser system will provide versatile shots-on-demand for high energy-density physics experiments**

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## Summary

- A system model of a Yb:S-FAP IFE DPSSL driver has been developed
- An IFE DPSSL driver producing 3.7MJ & 41 MW at ~9% eff. is projected
- InGaAs pump diode arrays and Yb:S-FAP gain crystal technologies have been advanced significantly in the past two years
- Transverse, turbulent gas flow cooling of a Yb:S-FAP laser slab has been demonstrated with excellent beam wavefront properties
- The 100 J / 1 kW Mercury laser system will demonstrate the functionality of a diode-pumped, gas cooled IFE DPSSL driver

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