GENERAL ATOMICS
PHOTONICS DIVISION

The next step in high average power laser technology for EUV light sources

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Laser driver requirements for LPP have been a significant challenge in laser design.

Parameter	EUV driver specs	GA proposed specs	Comment
Output power	> 7 kW	> 7 - 15 kW (scalable)	Requirement likely to increase
Focused irradiance	~ 10^{11} W/cm^2		
Pulse energy		> 300 – 1000 mJ	Optimized for target coupling
Pulse length		5 – 15 ns	Adjustable as required to achieve irradiance
Beam quality		$M^2 < 2$	Increased focusability, better standoff
Pulse rep. frequency	> 10 kHz	10 kHz (5-25 kHz)	Adapted to achieve average power
Wavelength	Design dependent	1064 nm	
Amplitude stability	< 10%	< 5% RMS	

- **Any laser system concept must be capable of scaling to higher average powers since power requirements are likely to increase and flexibility to optimize the laser-plasma interactions (maximum in band EUV output, minimize debris)**

Solid State Lasers have many attractive features for an EUV laser driver

- **High efficiency**
  - **Wall-plug efficiencies > 10% possible with laser diode pump**
    - Improves consumable costs, power costs
  - **High energy storage give compactness**
- **Damage resistant optical materials**
  - **Optics for λ = 1064 nm are well-developed and robust.**
  - ***No corrosive or active chemicals***
- **Extensive and growing supplier base**
  - **motivated by DOD interest and commercial applications**
    - Cost reduction and performance enhancements (i.e. laser diode efficiency, lifetime)
- **Extensive (multi-decade)experience and data on laser plasma interactions**
  - **Conversion to 13.5 nm radiation (in ~2% band) >2% for Sn containing plasmas**

DoD is committed to significantly fund the development of high average power solid state laser (SSL) systems

- **Joint High Power Solid State laser (JHPSSL) Program (10-20 kW demonstrated, 100 kW goal)**
  - ~20 kW (CW) in high quality beam
- **DARPA program to demonstrate 150 kW SSL at ~5kg/kW**
  - (> 5 kW) demonstrated
- **Missile Defense Agency (MDA) programs to develop hardened 5 kW, 10 ns, 5 kHz laser system**
- **DARPA funding in high brightness, high efficiency diodes (SHEDS)**
  - CW operation is the same for high prf (>10 kHz) requirements for EUV

DOD focus on cost, compactness (kg/kW), stability, operability in extreme environments will drive SSL improvements beneficial for EUV applications

Diode improvements results in cost-effective LPP source

DoD HEL Programs → **Diode lifetime & efficiency for on/off cycling, extreme environments**

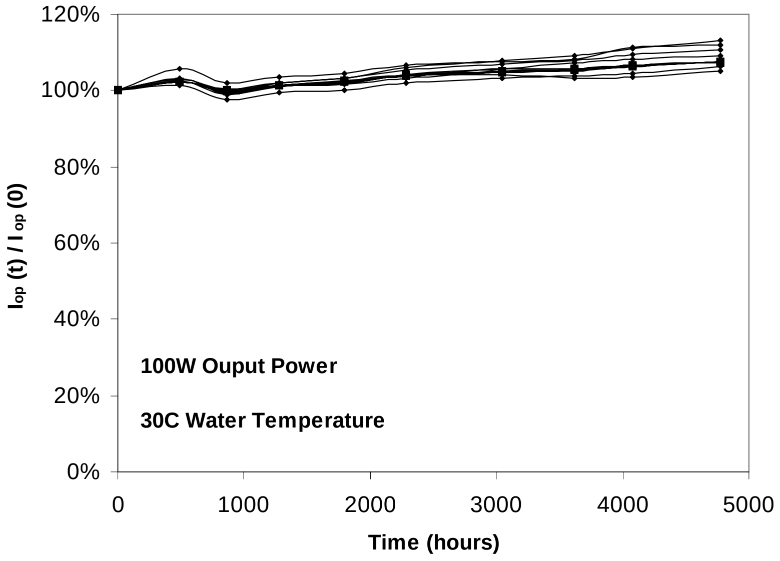
- EUV environment is constant on, temperature controlled (most benign environment possible for diode reliability and lifetime)
  - Several vendors have demonstrated > 10,000 hours lifetime at rated powers. All expect > 20,000 hours within 2 years. Appropriate design will extend this significantly
  - DoD program driving efficiency up (bar efficiency demonstrated to be > 60% wall plug)

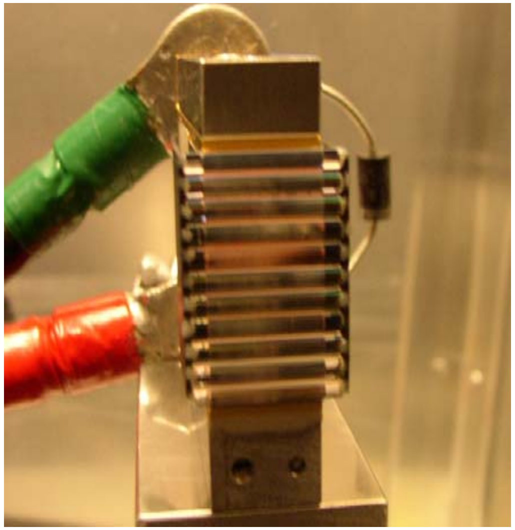
High efficiency laser design
Long life, high brightness arrays → **Low capital and operating costs for diodes**

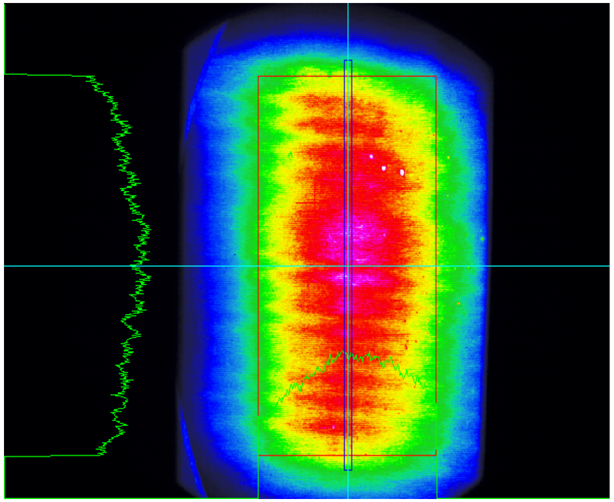
- Best design uses arrays of lensed bars
  - Lensed bar arrays cost today is $15/W in small quantity
  - All vendor project quantity pricing in 2 years to be $8/W
  - High power, fiber-coupled diodes and fiber lasers are ~$100/W—financially less attractive

Diode operating cost for high efficiency system is ~ $100K/yr

Stackable, high brightness diode arrays are increasing in performance and reliability and decreasing in cost







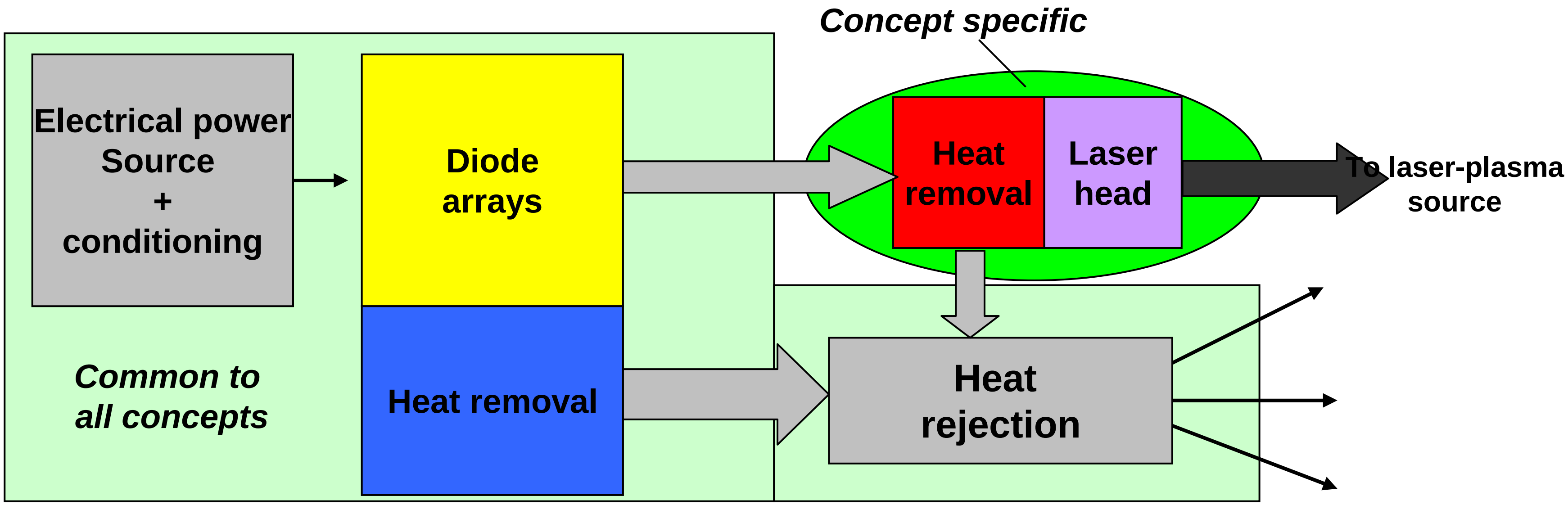
- **High average power government programs are provided sufficient market pull for high power density arrays**
  - Every diode array vendor estimates > 20,000 hr lifetimes within 2 yr
  - Efficiency increasing to > 60% wallplug

Technology limitations have restricted the scaling of DPSSLs

- **Thermally induced distortions in optical media**
  - Limits achievable gain
  - Increases system complexity
  - Designs are aimed at reducing thermo-optic distortions, not increasing efficiency
- **Optical switching**
  - Electro-optic limited in aperture and average power handling (< 100-200 W)
  - Acousto-optic limited in aperture and switching rate (pulse lengths > 10s ns) and average power < ~1 kW
- **System reliability and performance**
  - Increases with designs which are not stressing technology state-of-art
  - Diodes
- **Beam control**
  - Related to thermally induced distortions

All diode-pumped lasers have the same basic components and issues:

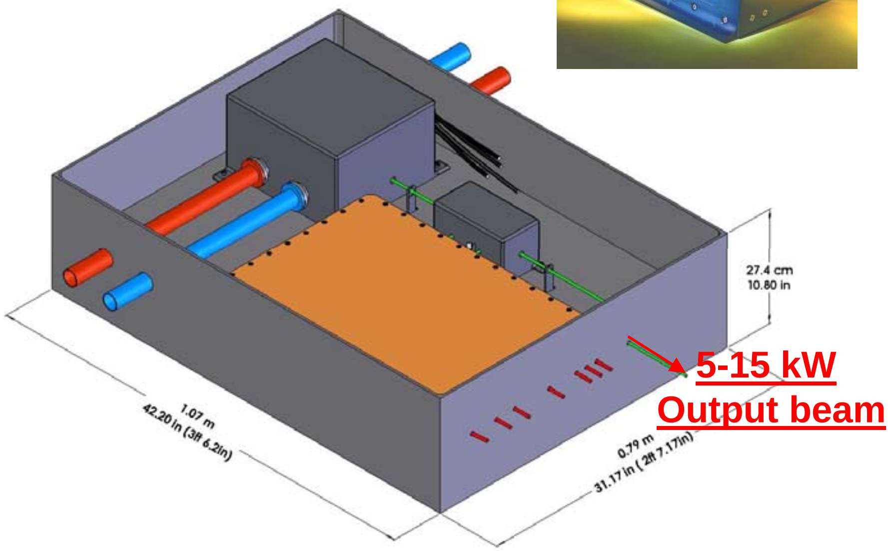
Efficiency, power supply, thermal management and beam quality



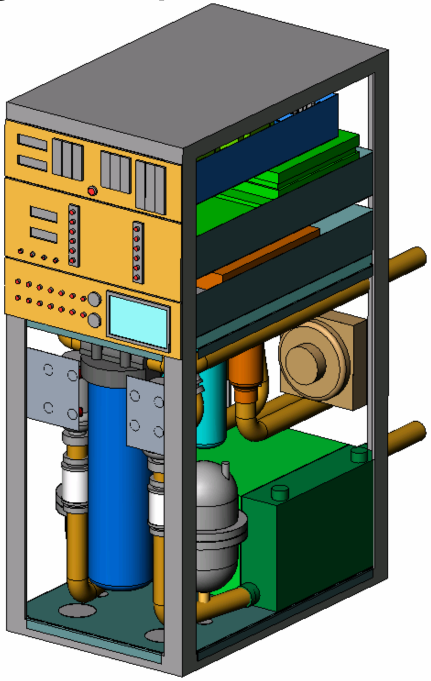
The "balance of plant" must be addressed in order to have any significant effect on system cost

GA has developed a new solid state laser technology that enables a high efficiency solution for EUV laser driver requirements

- **Uses existing GA product as pulse seed**
  - < 5 nsec
  - 10-30 kHz
  - M^2 ~1.2



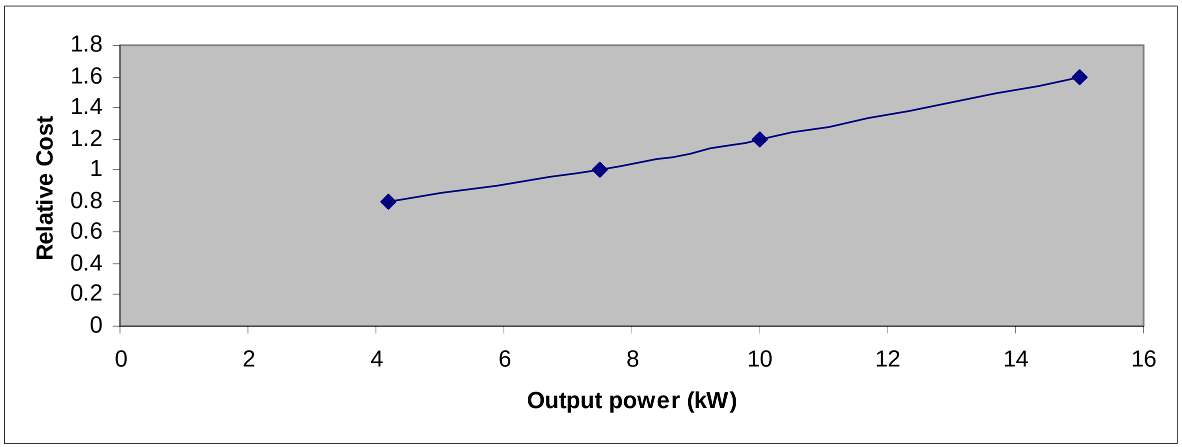
- **Facilities rack provides control electronics, power supplies and heat exchangers for operation**



- **New technology makes small laser possible with small component count**
  - 1.1 x 0.8 m footprint for 5 kW output
  - Based on novel GA technology as well as proven GA products
- **Delivers high beam quality and short pulses required for high irradiances necessary for EUV generation**
- **Concept shown is capable of producing**
  - 5-8 kW, 7-20 kHz, 5 ns pulses, BQ < 2, optical efficiency > 10%

This architecture can meet a wide range of requirements without significant modifications.

Power Amplifier	10 kHz	10 kHz	10 kHz	15 kHz	15 kHz
Diode power	17 kW	27 kW	35 kW	36 kW	57 kW
Required input power	170 W	250 W	300 W	300 W	300 W
Predicted output power	**4.4 kW**	**7.5 kW**	**10 kW**	**10 kW**	**15 kW**
Predicted output energy	440 mJ	750 mJ	1.0 J	670 mJ	1 J



- **Other design points from 2.5 – 10 kHz have been analyzed for MDA**
- **Higher PRFs (~30kHz) can simply be achieved by polarization-multiplexing two modules**
  - **Does not significantly increase cost/W**
  - **Still only a single beam line to plasma source**
  - **Passive components only**
- ***Laser will adapt to design point which optimizes total EUV source.***

GA has analyzed production and support costs for new laser design. Projections are consistent with cost requirements for EUV source.

Capital Costs

- $1.9M (reducing to $1.5M in full production) for laser source (in 2007 prices)
  - 8 kW
  - PRF up to 35 kHz
  - 5 ns pulses
  - High beam quality ($M^2 < 2$)
- Cost projection is price to source vendor
  - Includes parts, labor, overhead, profit

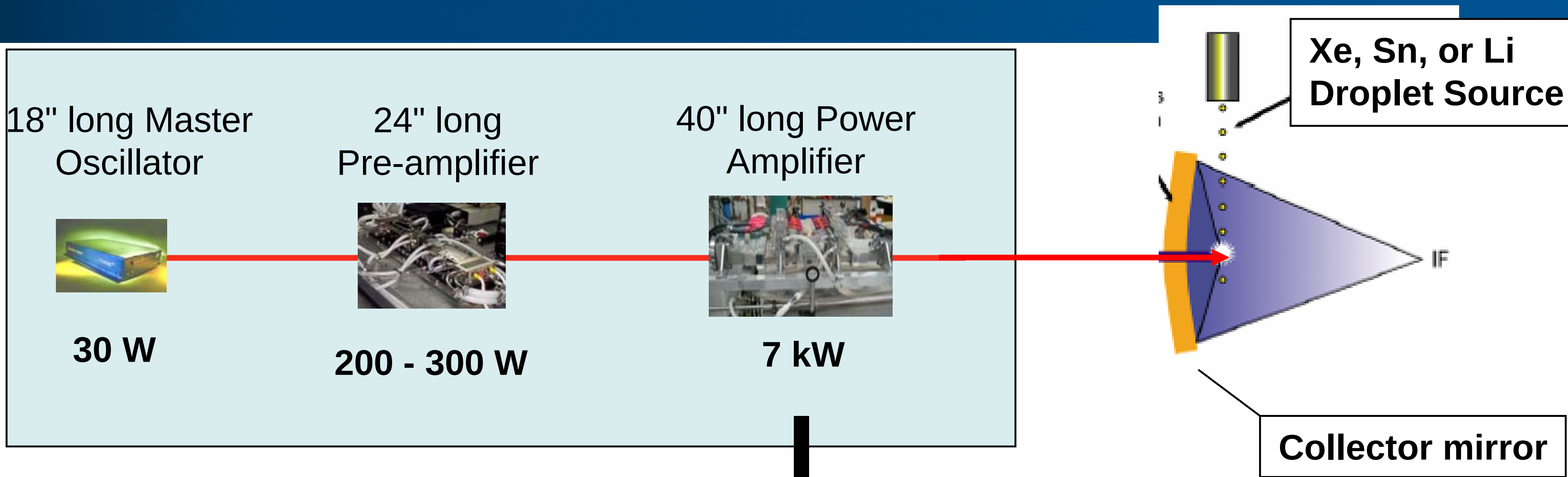
Operating costs

- Yearly cost-of-ownership anticipated to be < $200K
- Diodes will last > 3 years (based on 7000 hrs/yr operation)
- GA design has no other significant consumable
  - Only normal, scheduled replacement of filters, coolant

Diode performance and cost

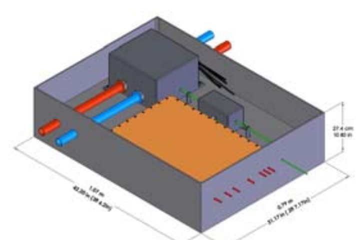
- Diode packaging advancement and efficient system design have made diode cost a much lower value for both operating and capital costs
  - Lifetime for EUV environment will exceed 20,000 hours
  - 99% uptime requirement is reasonable expectation (always on will improve diode lifetime

GA Photonics path to a price-effective HVM Source



72" scale

Power Supply 19" Rack Mount



7 kW DG Laser 50" x 30" x 10"

Li droplet generator and Collector Assembly (12" diameter)

Summary

- EUV community has unique opportunity to leverage DOD investment in High Power SSL
  - Diodes
  - Concept and system development and demonstration
- GA SSL concept meets EUV laser source needs and is SCALABLE
  - Single aperture compact MOPA design
    - Passive components
    - Single aperture (~cm)
    - Compact (~0.25 m^3)
  - η >10%
  - M^2 ~2 (I >10^{11} Watts/cm^2 at distance (>1 m)
  - PRF's ~10-30 kHz
  - Pulse width < 5 nsec
  - Production sales price ~$1.5M (~$200/watt)
  - Annual O&M <$200k (~$25/watt)
- $4M to demonstrate multi-kilowatt laser system that can be coupled to a laser-plasma source (Heavily leverage DoD Program)