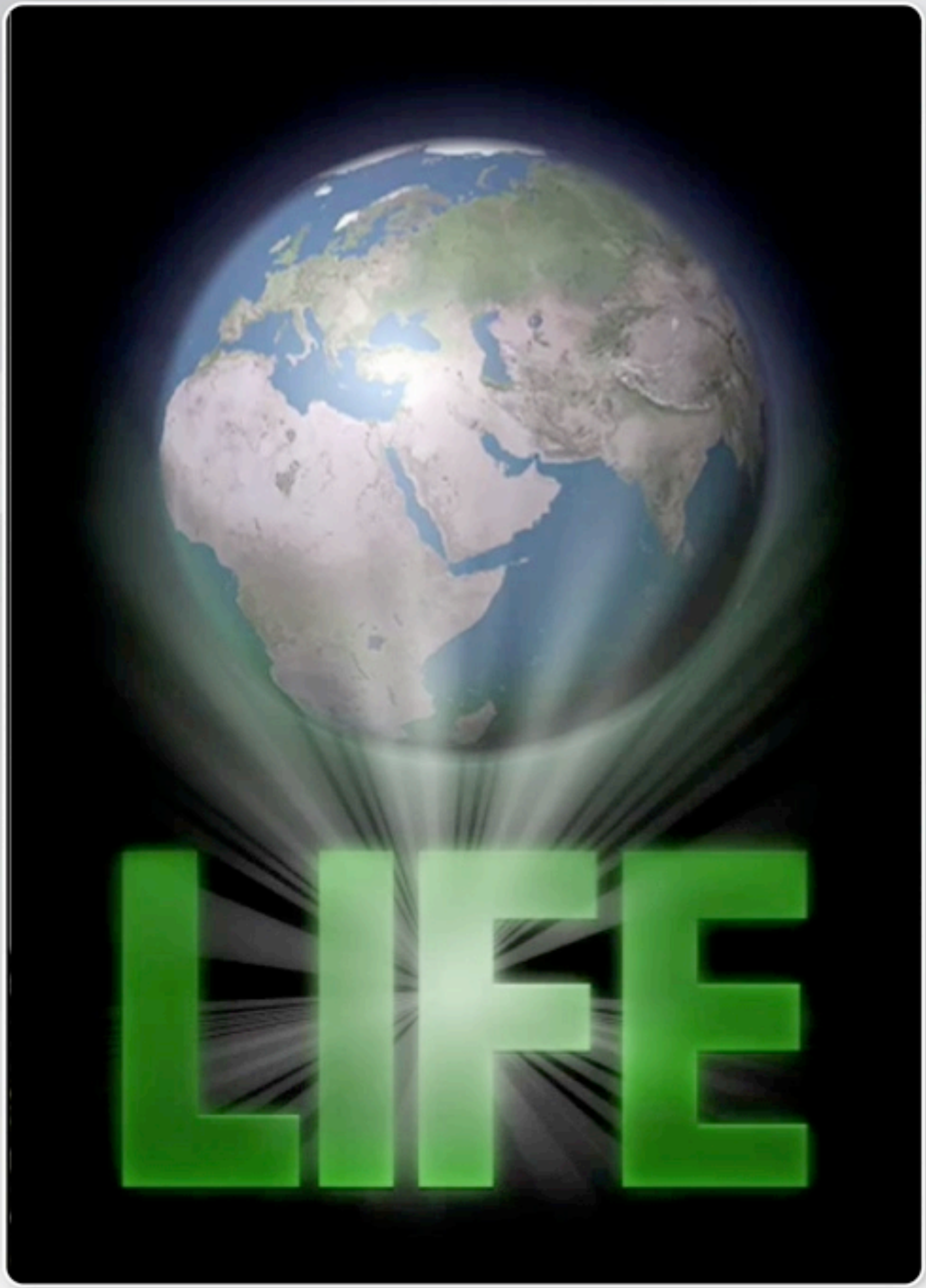


Lasers for LIFE

CPJ Barty
Program Director
Photon Science & Applications Program

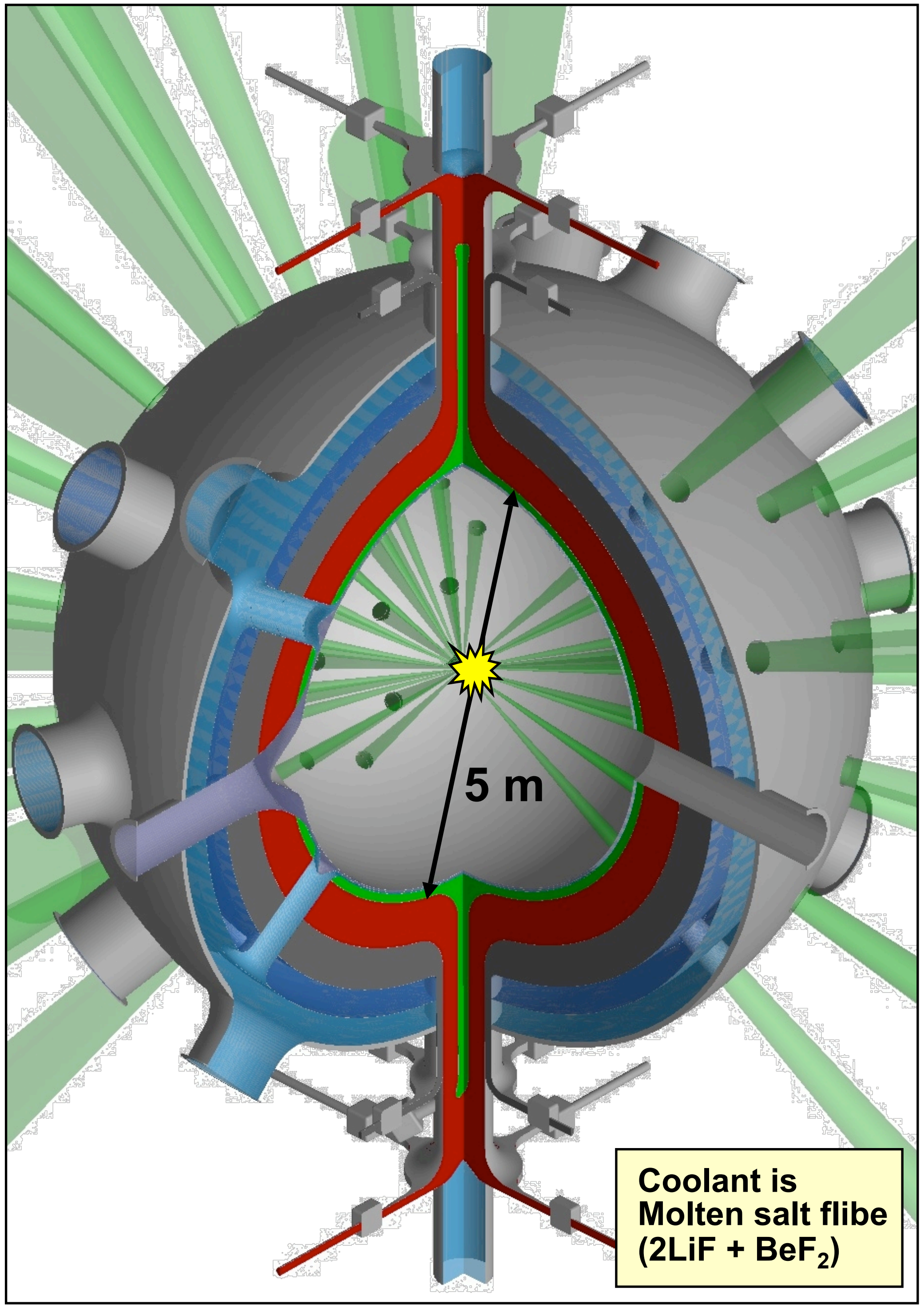
December 4, 2008

Fusion Power Associates Annual Meeting

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

LIFE uses inertial confinement fusion neutrons to fission a sub-critical fuel and produce power

- Compact target chamber (5-m-diameter)
- 500 MW_f fusion yield
- 40 tons of depleted uranium in solid or liquid fuel
- Fission blanket gains of 4-8 → 2000-4000 MW_{th}
- $P_{e,net}$ → 750-1500 MW_e



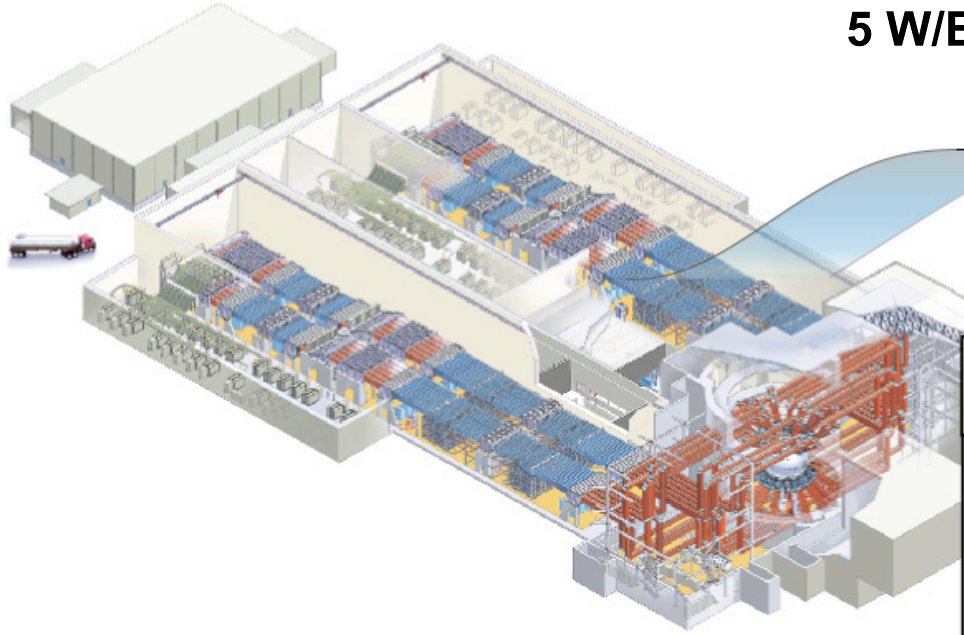
LIFE requires high-repetition, MJ-class laser technology to produce the seed neutrons

Coolant is Molten salt flibe ($2LiF + BeF_2$)

NIF is the origin of LIFE

NIF (2 MJ)

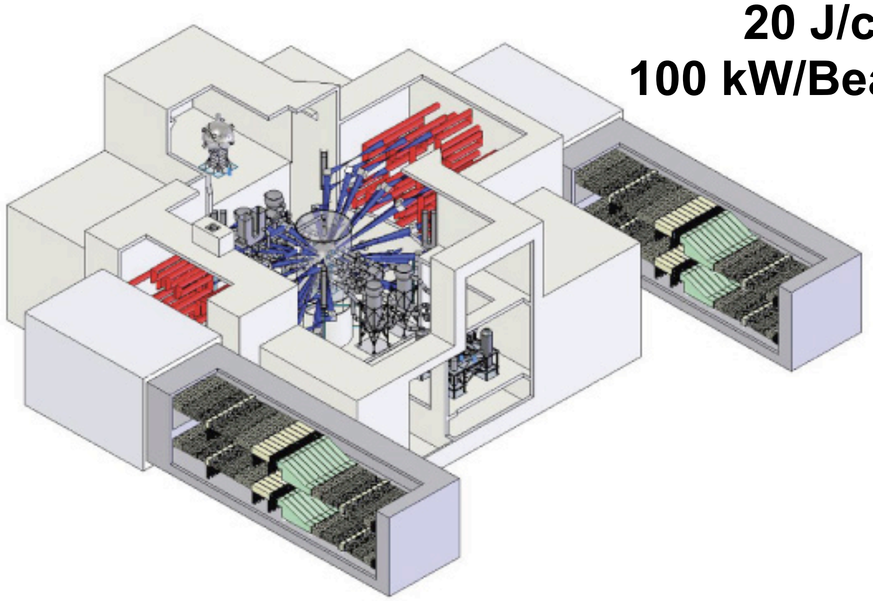
20 J/cm^2
5 W/Beam



Repetition frequency 10^{-4} Hz
Electrical efficiency 1%

LIFE (17 MW)

20 J/cm^2
100 kW/Beam



Repetition frequency 13 Hz
Electrical efficiency >10%

- Fluence is identical
- He cooling enables high average power
- Diode pumping enables high efficiency

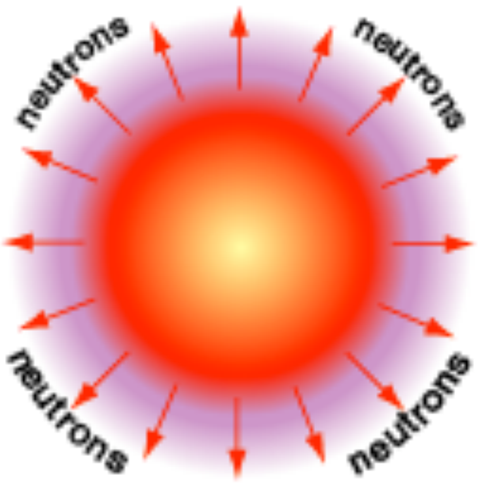
NIF architecture is well suited for a LIFE Laser fusion driver

- Key features
  - Compact and close to optimal uniform aperture size
  - Number of beams effectively uses solid angle of target chamber
  - Operating fluence is sub-damage AND well saturated

NIF architecture is well suited for a LIFE Laser fusion driver

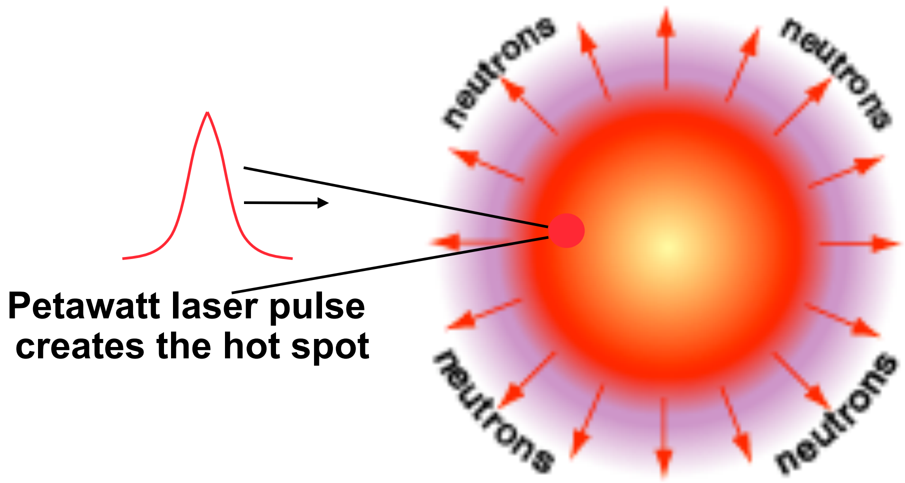
- **Key features**
  - **— Compact and close to optimal uniform aperture size**
  - **— Number of beams effectively uses solid angle of target chamber**
  - **— Operating fluence is sub-damage AND well saturated**
  - **— NIF high energy petawatt technology could also enable fast ignition**

Hot Spot Ignition



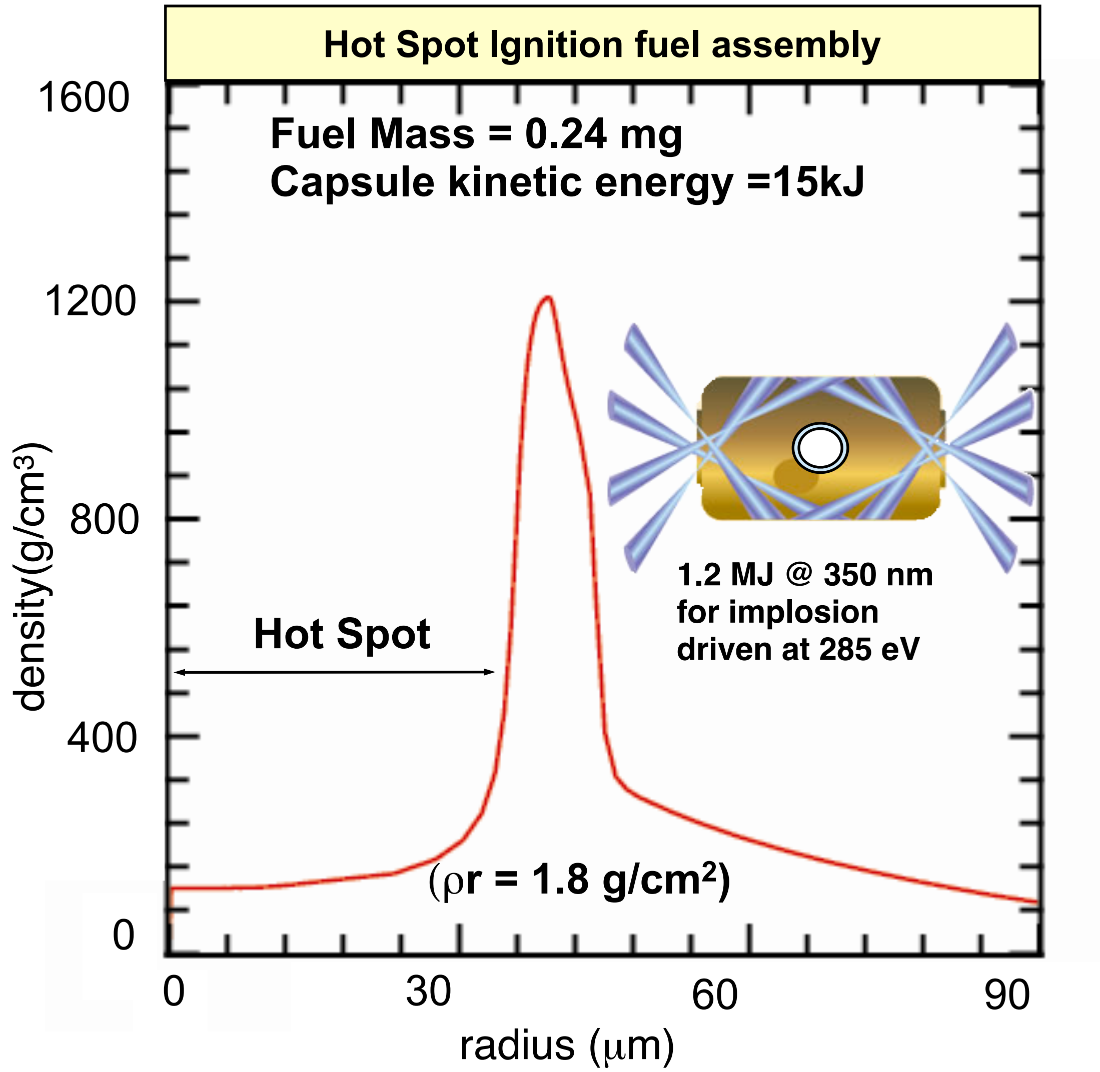
"diesel-like" ignition

Fast Ignition

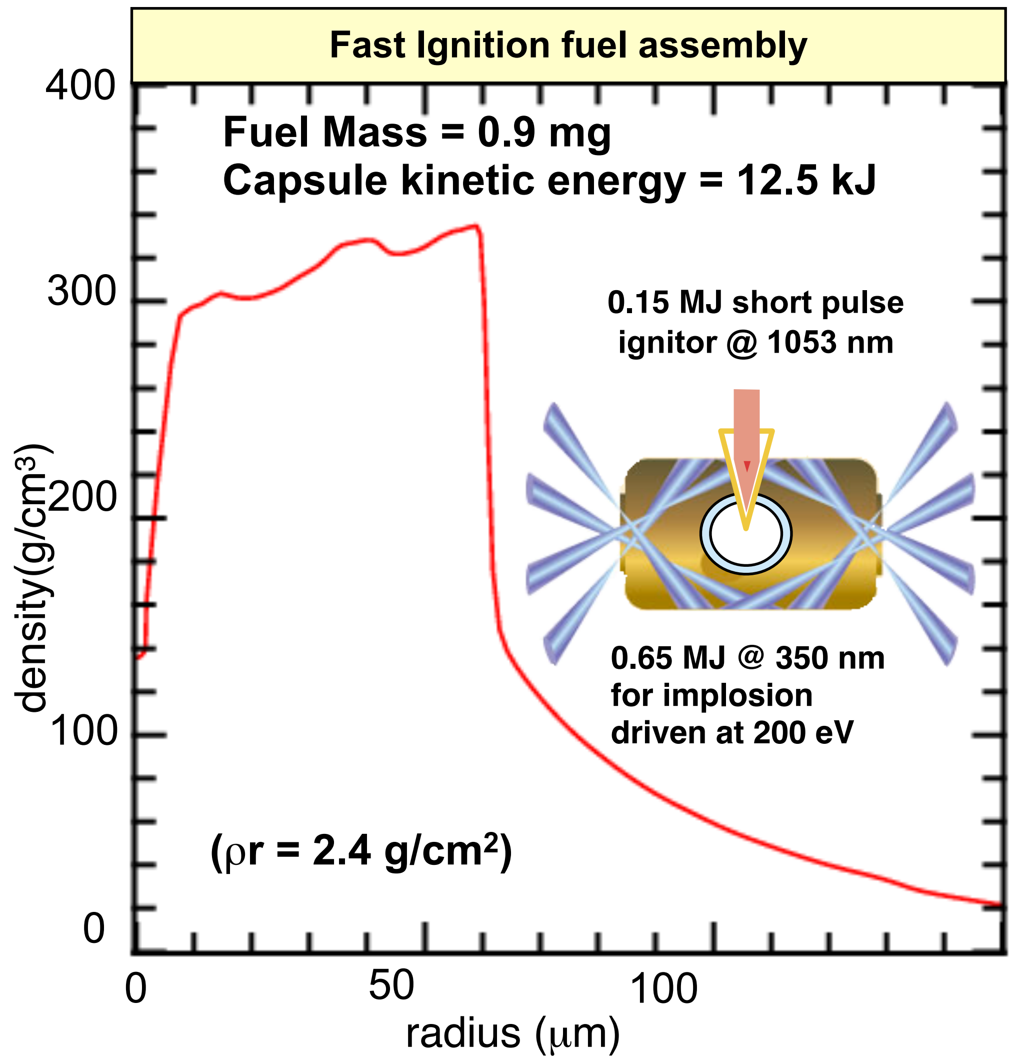


"spark plug" ignition

Fast ignition targets compress more fuel to ignition conditions with less laser energy

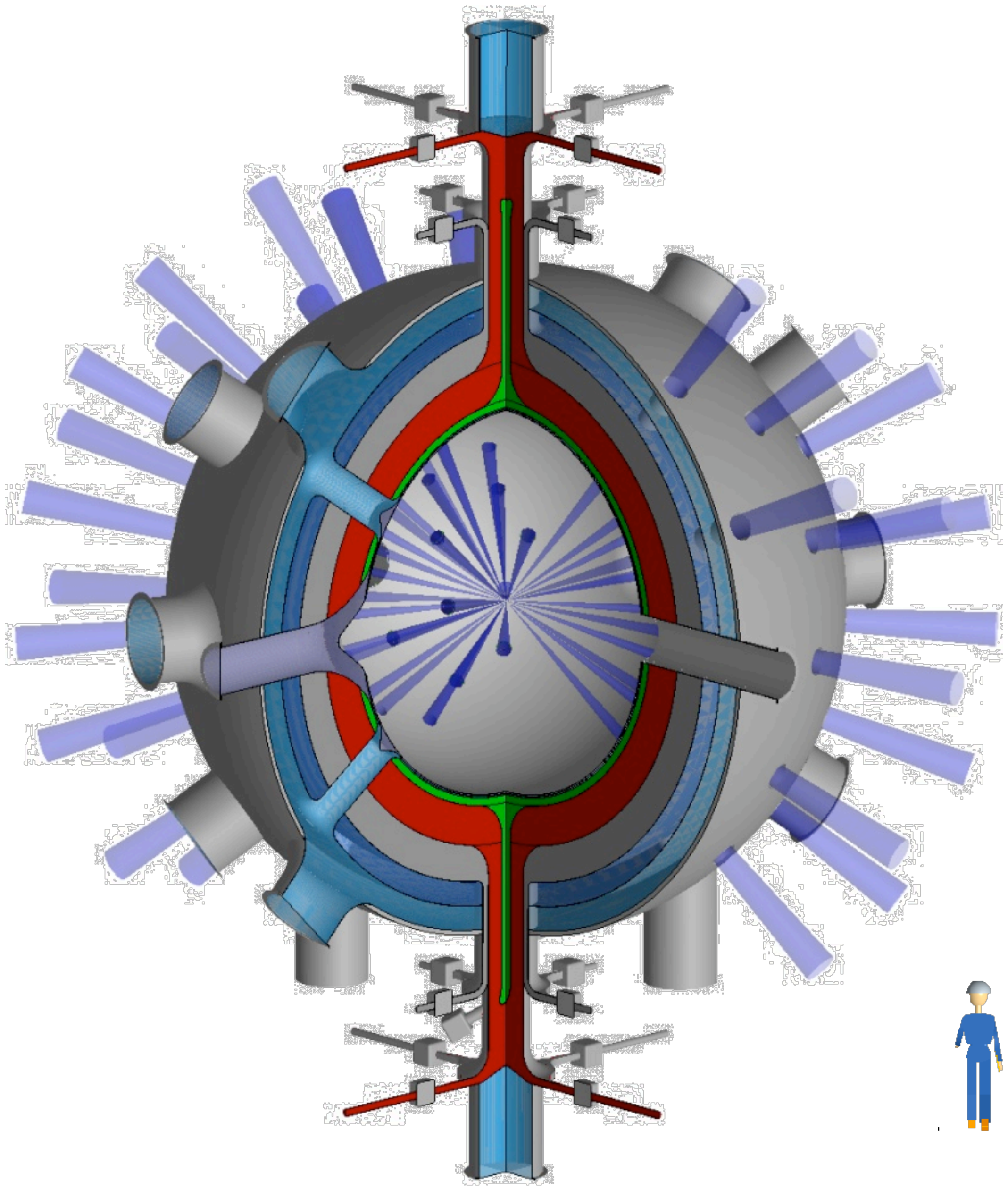


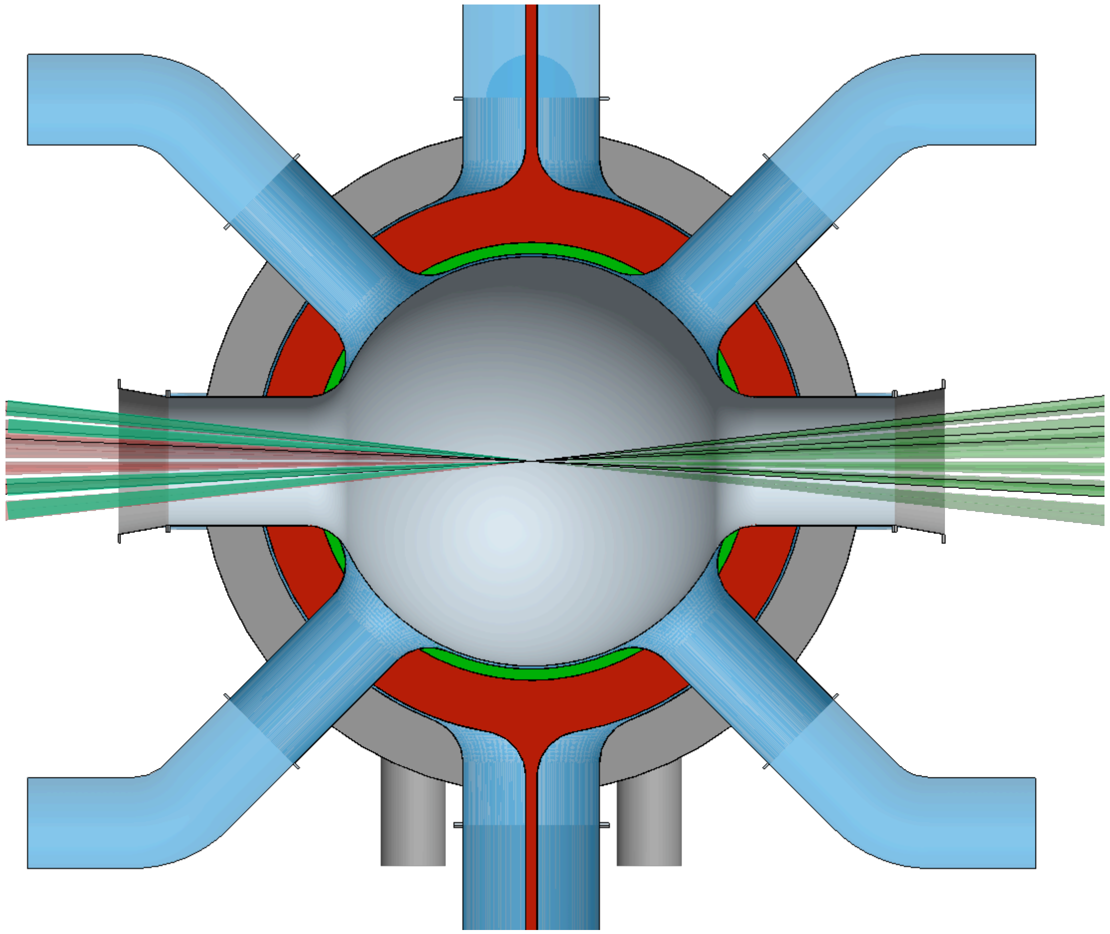
20 MJ of fusion yield for a Gain of 17

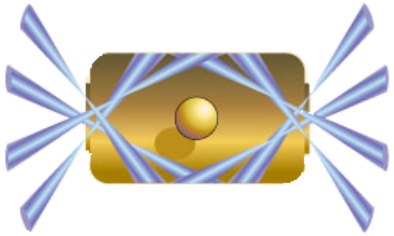


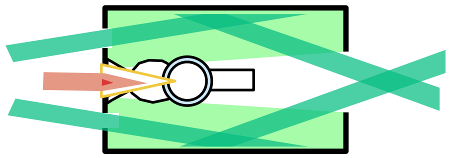
90 MJ of fusion yield for a Gain of 112

Fast ignition also offers the possibility of low incidence angle chambers

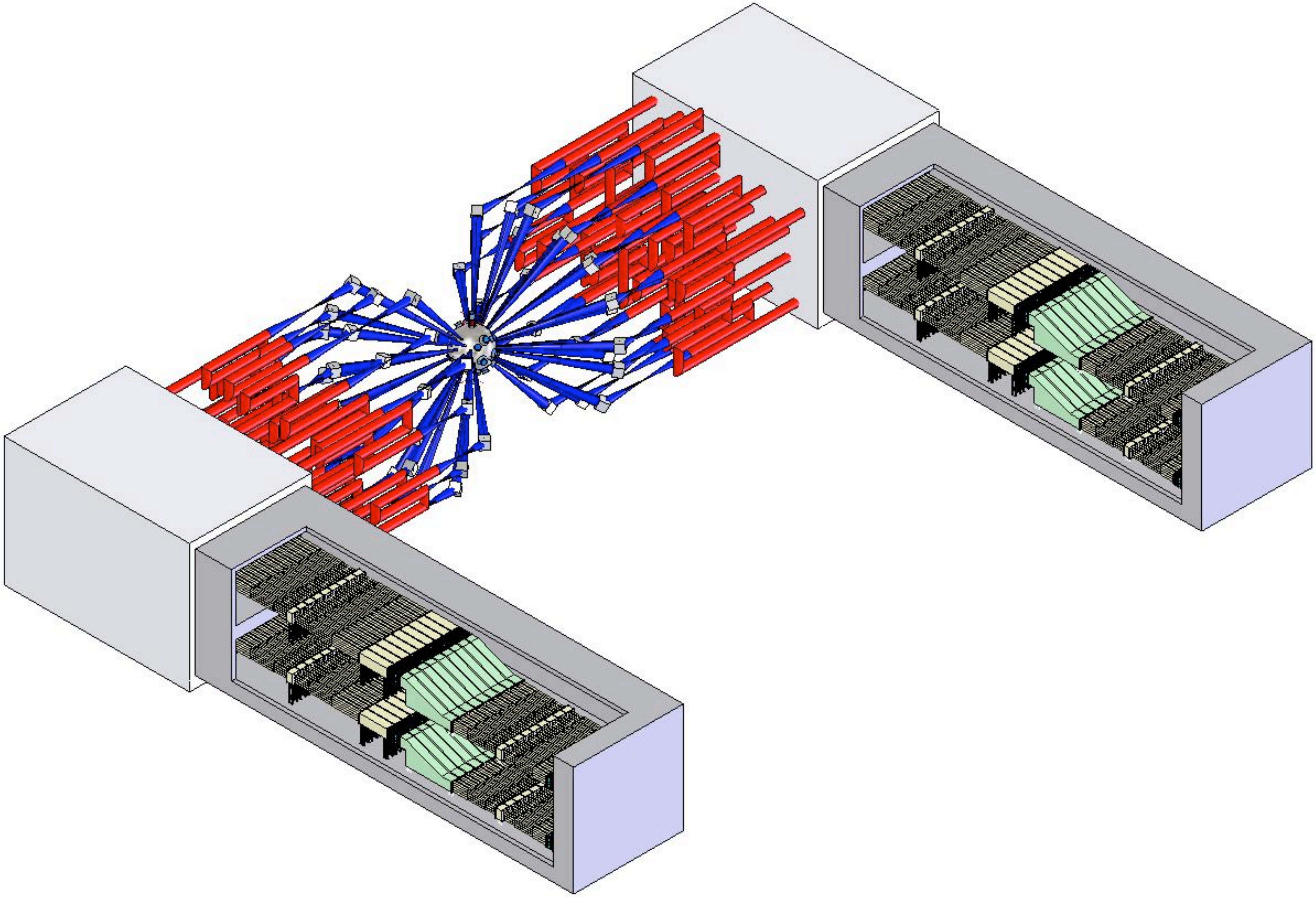






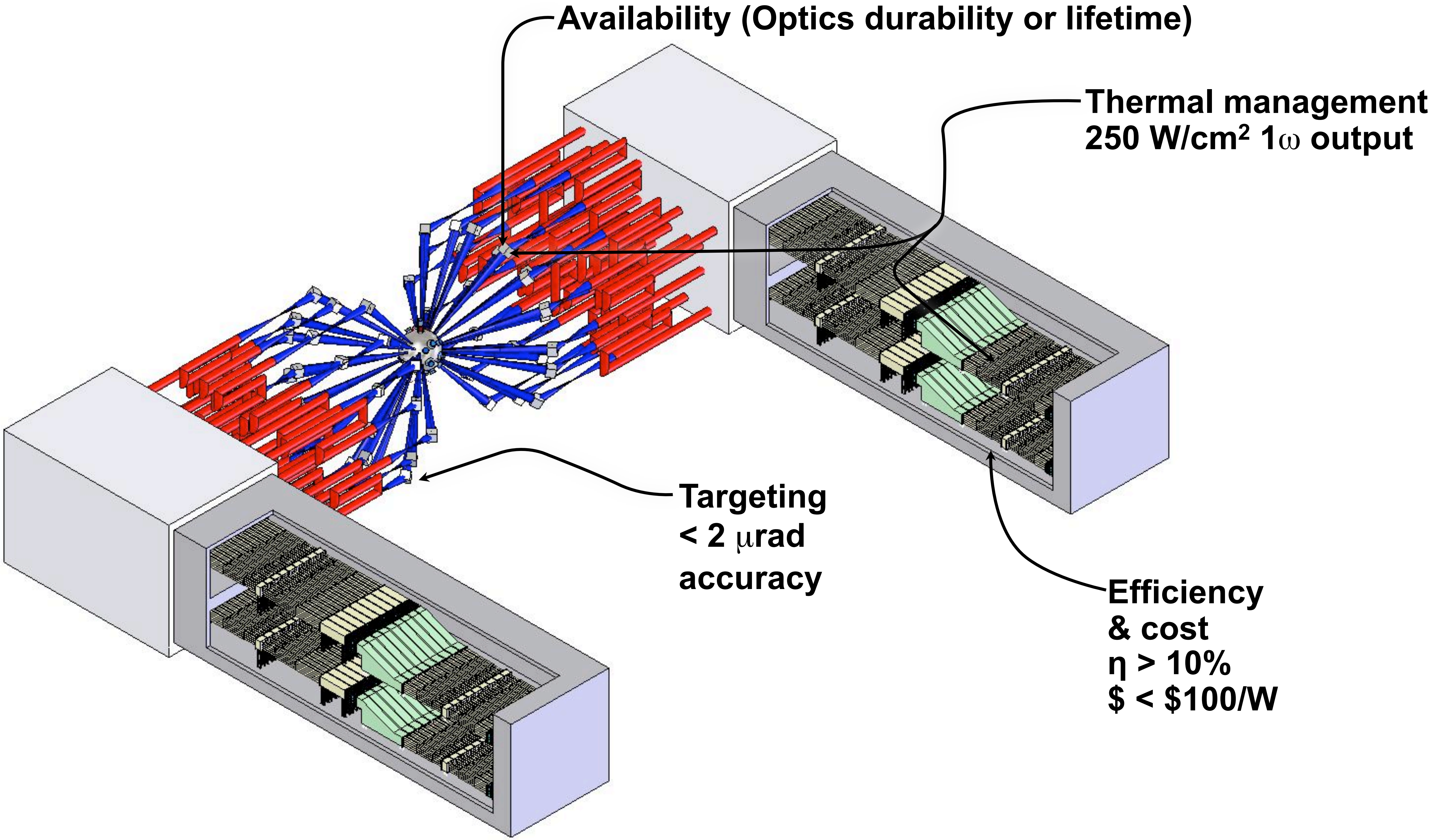


LIFE laser system baseline HSI with blue light

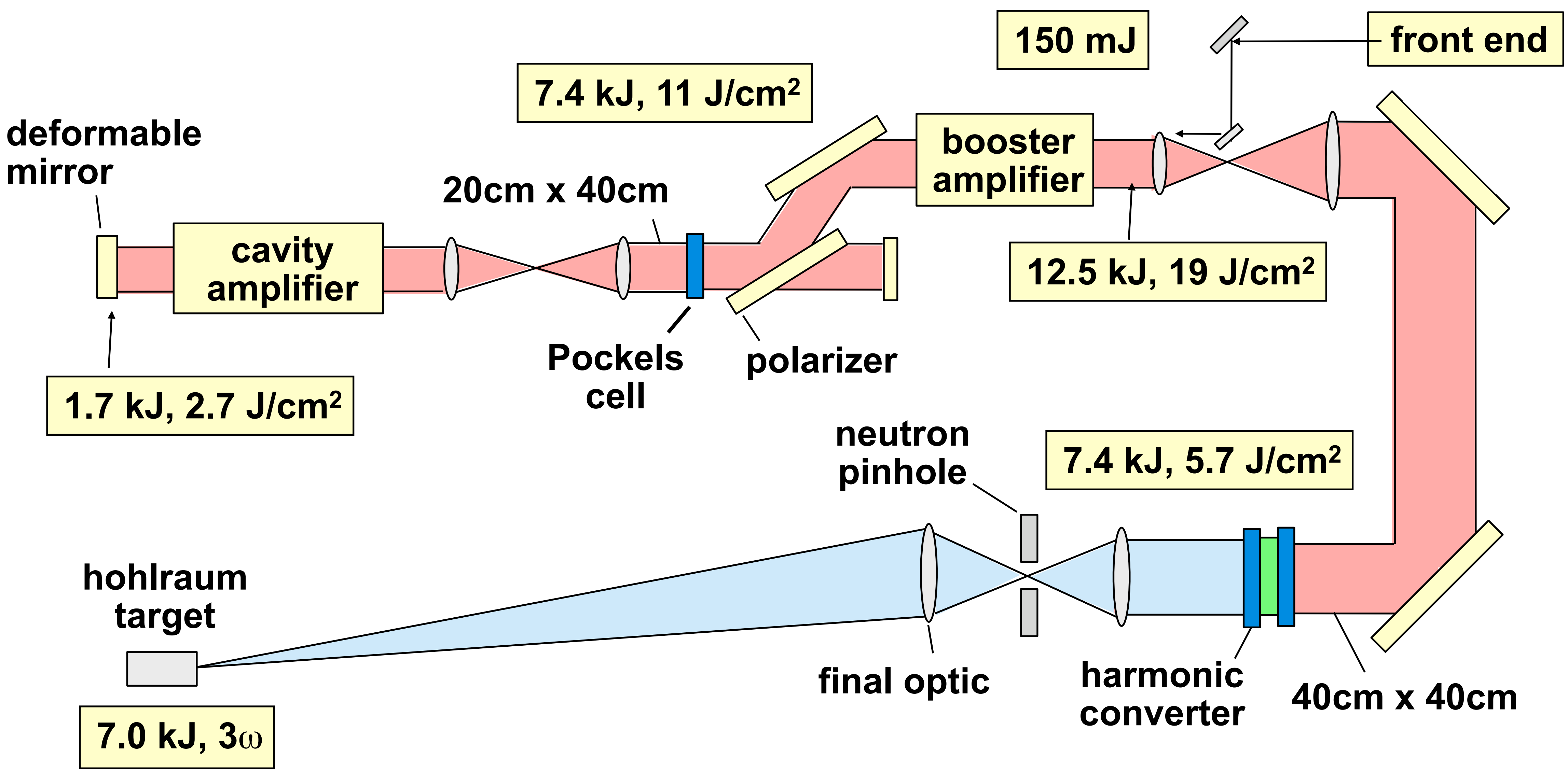


- 17 MW
- 1.3 MJ
- 13.3 Hz
- η > 10%

LIFE laser system optical challenges



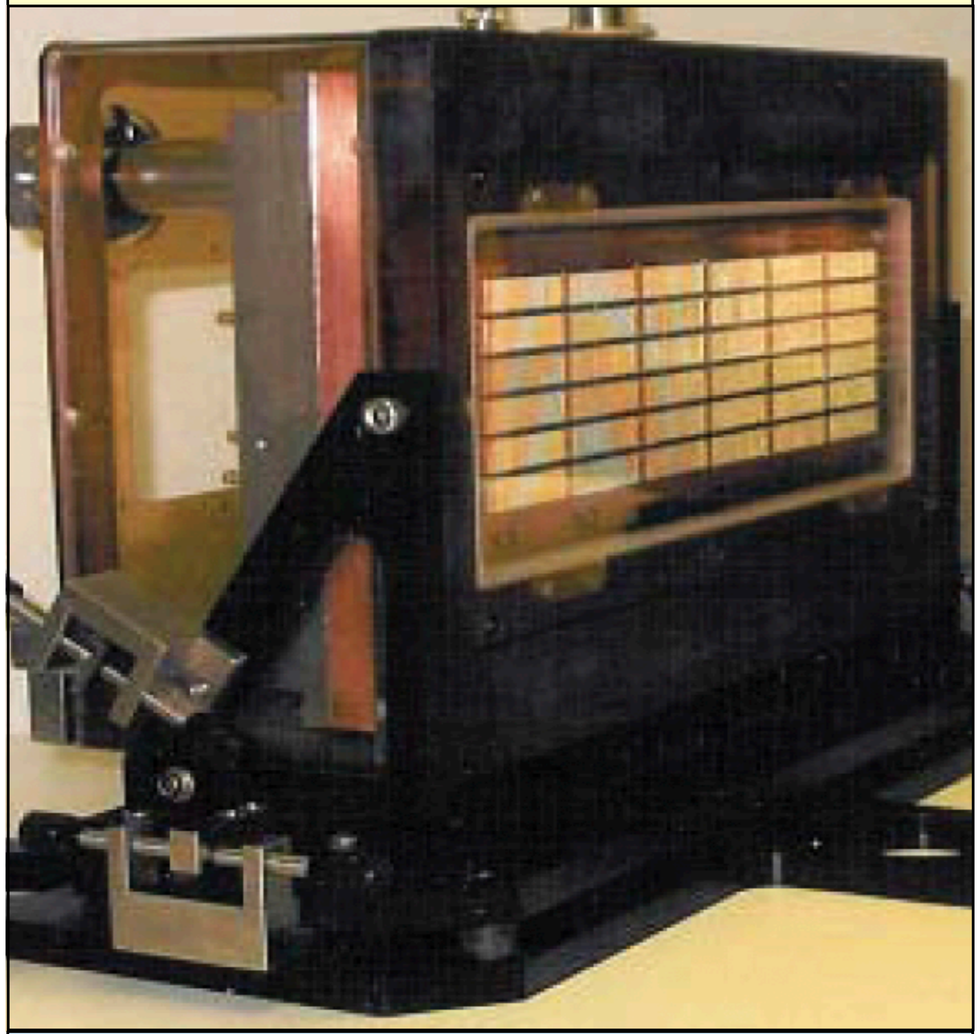
The current baseline design produces 3ω pulses using a NIF-like multipass architecture



- Amplifier aperture is 20-cm x 40-cm
- Magnification factors are adjusted to give desired fluence at final optics

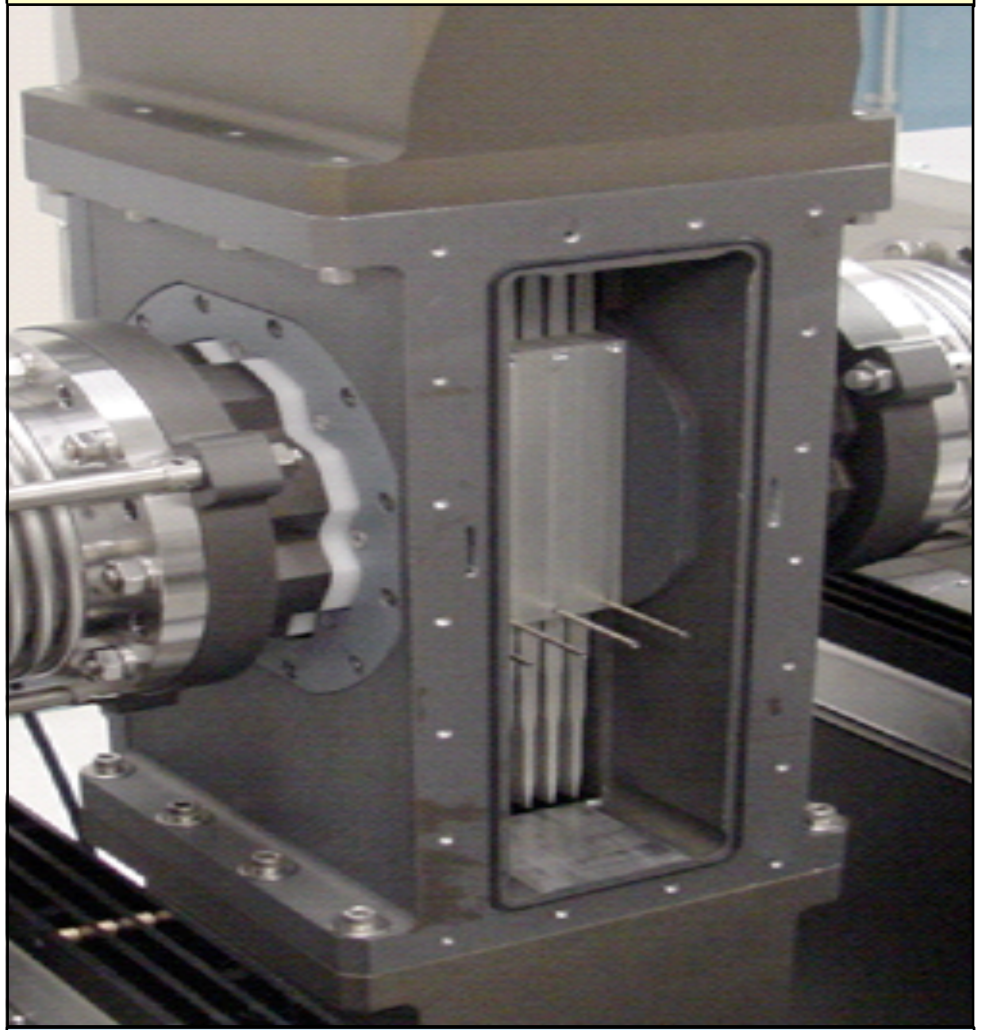
Laser diodes and helium gas cooling enable a NIF-like architecture to meet LIFE driver requirements

High Power Diode Arrays



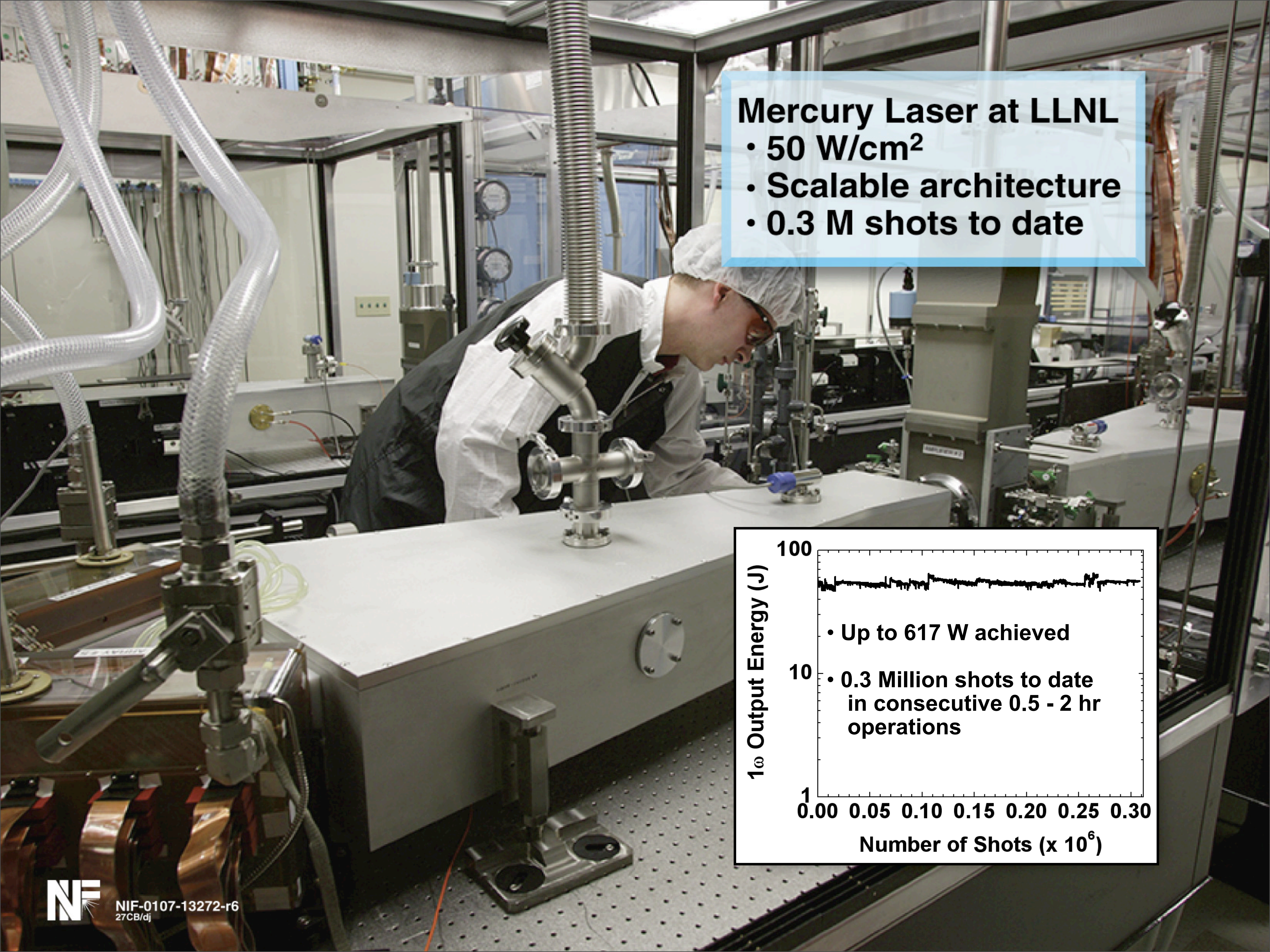
100 kW peak power

High Speed Gas Cooling

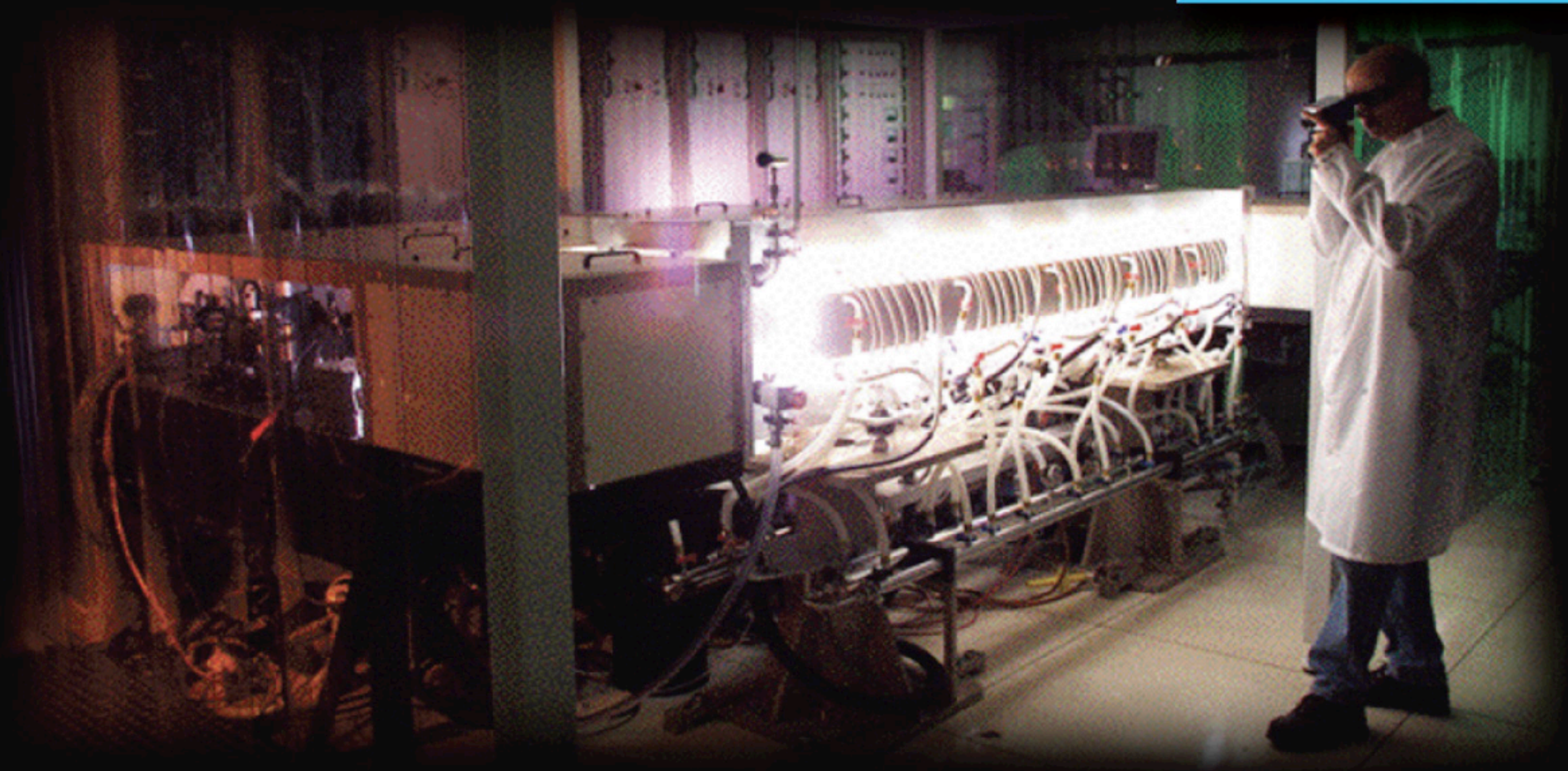


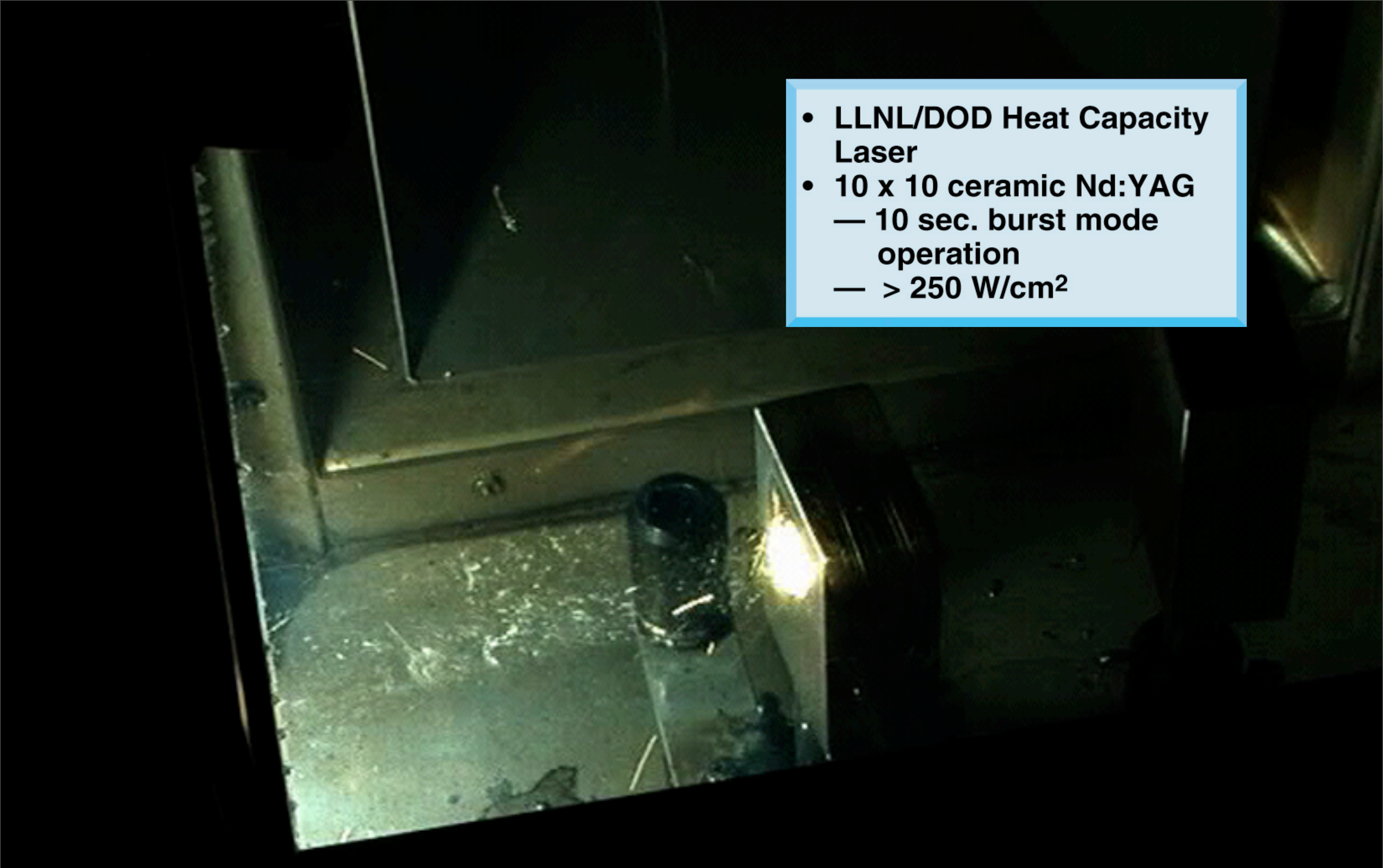
3 W/cm^2 cooling (average)

These technologies have been developed as part of the Mercury HAPL Project


Mercury Laser at LLNL
• 50 W/cm²
• Scalable architecture
• 0.3 M shots to date
100
10
1
1ω Output Energy (J)
0.00 0.05 0.10 0.15 0.20 0.25 0.30
Number of Shots (x 10^6)
• Up to 617 W achieved
• 0.3 Million shots to date in consecutive 0.5 - 2 hr operations

- **LLNL/DOD Heat Capacity Laser**
- **10 x 10 ceramic Nd:YAG**
  - **— 10 sec. burst mode operation**
  - **— > 250 W/cm^2**

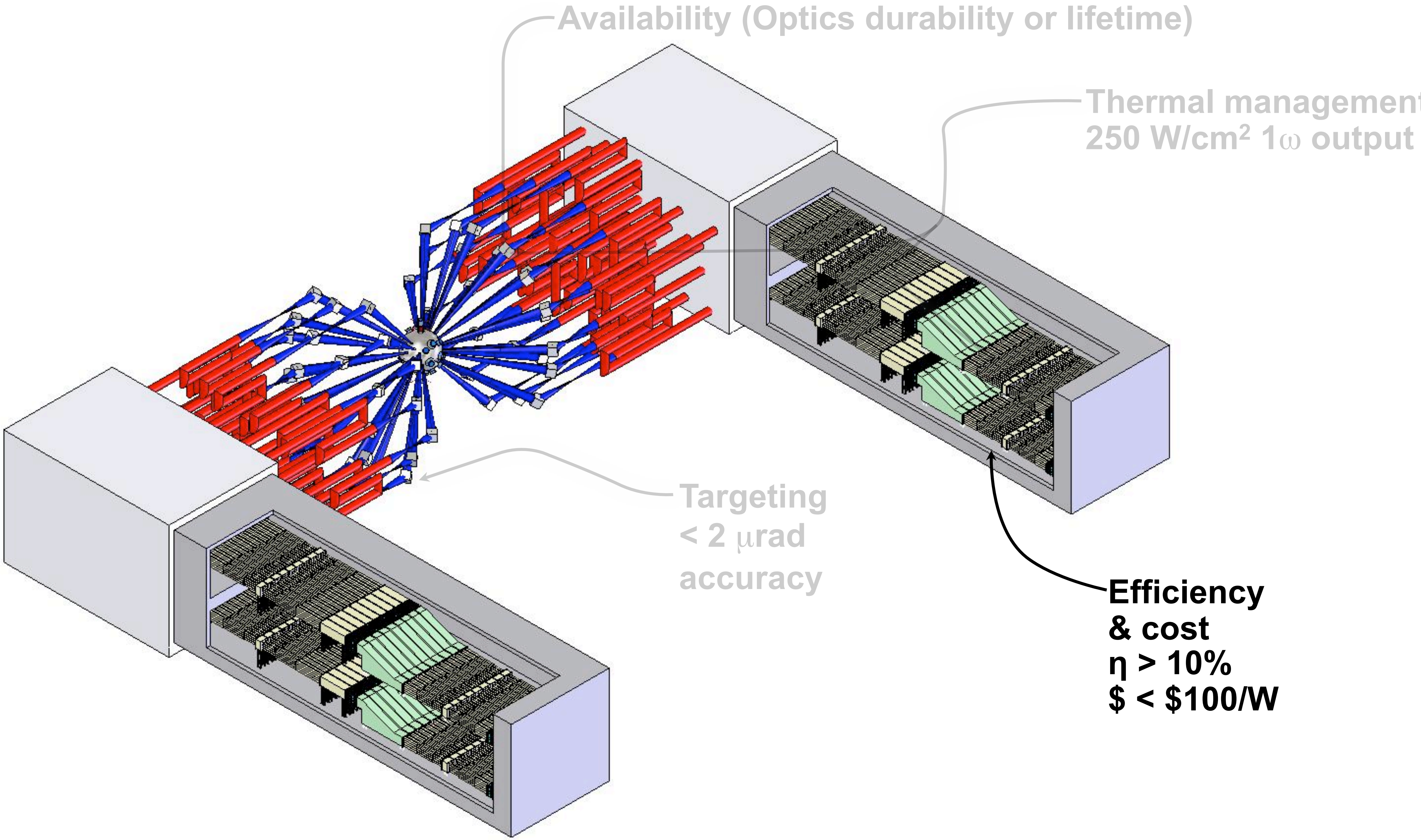




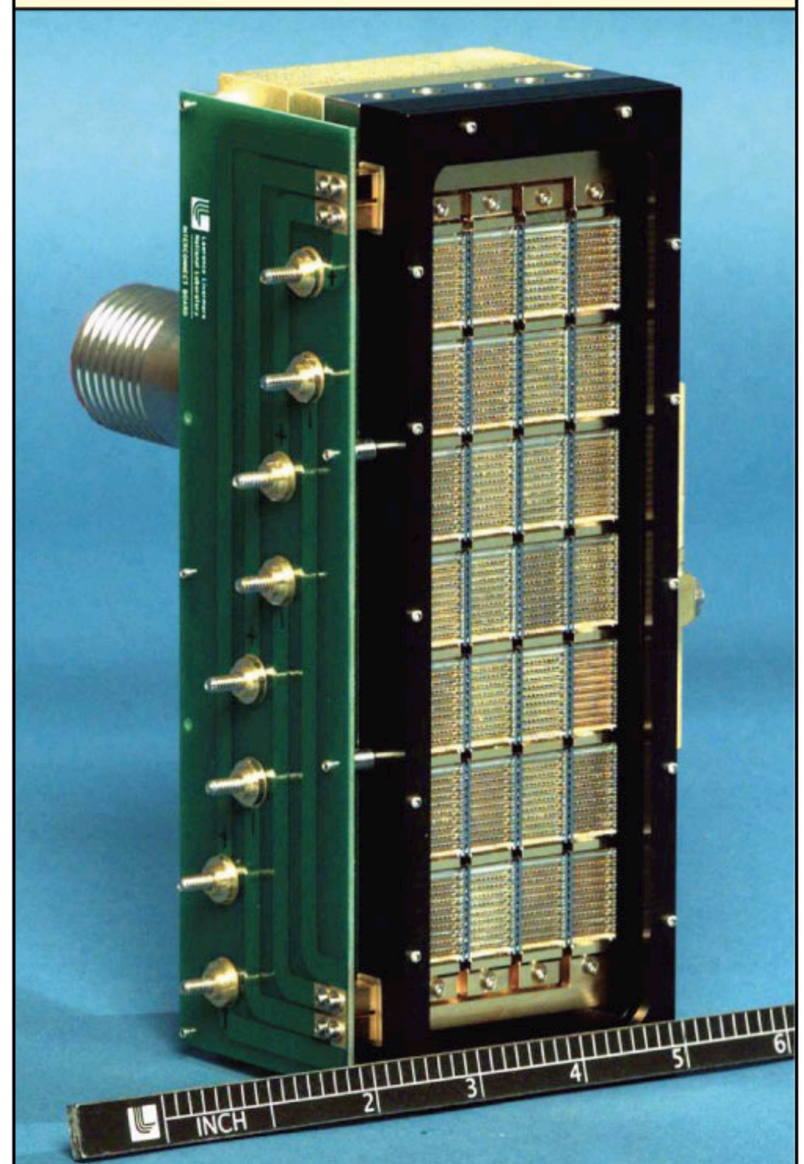
LLNL DoD diode-pumped, solid-state laser vs. 1” steel block

25 kW, 2.5 x 2.5 cm spot, real time

LIFE laser system optical challenges

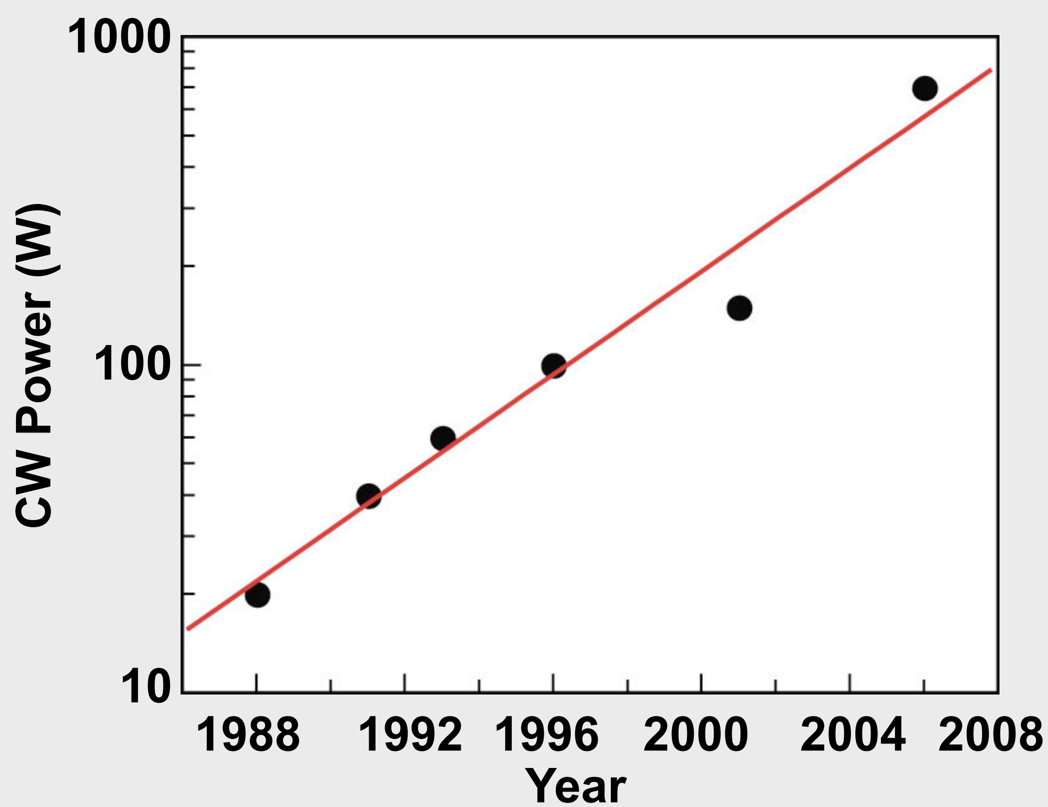


Diodes are high efficiency, compact and robust converters of electricity into pump radiation

Flashlamps	Diodes
	
400 W average power η = 6% in band	30 kW average power η = 50% in band

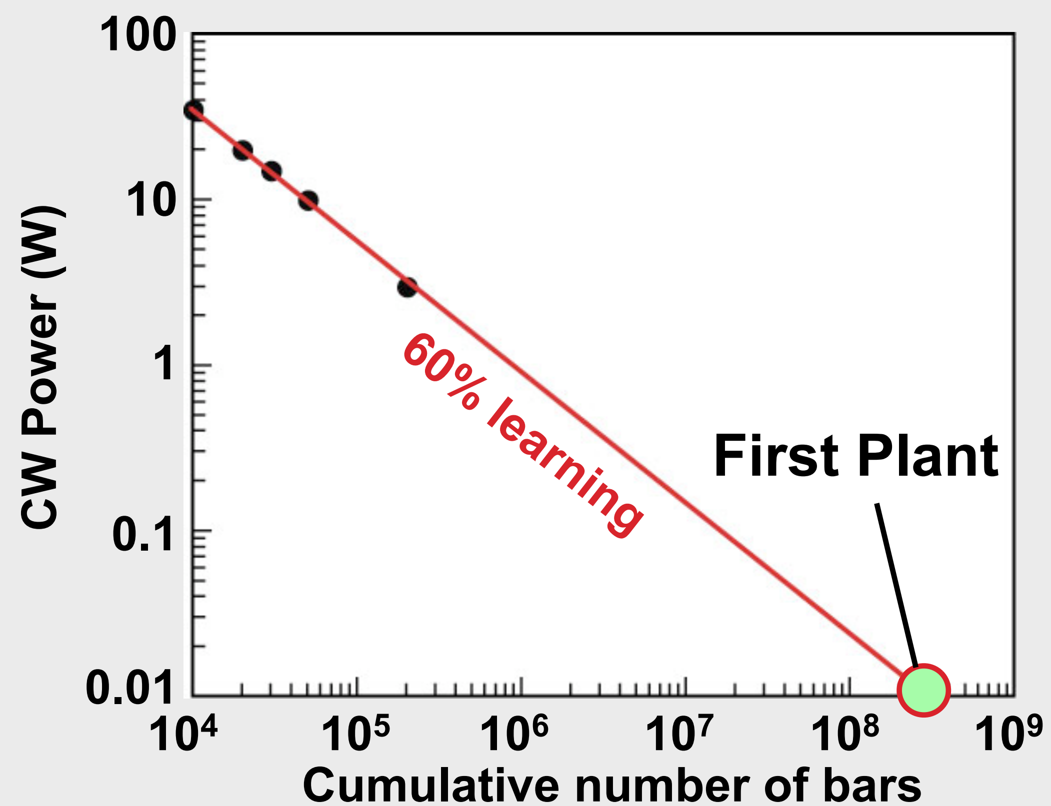
Diodes are experiencing aggressive learning

Continuous wave diode bar performance has increased by 35x since 1988



1 cm bar CW power developed

Diode bar prices are dropping with growing market



1 cm bar learning curve

Baseline LIFE plant requires — 40 GW pump

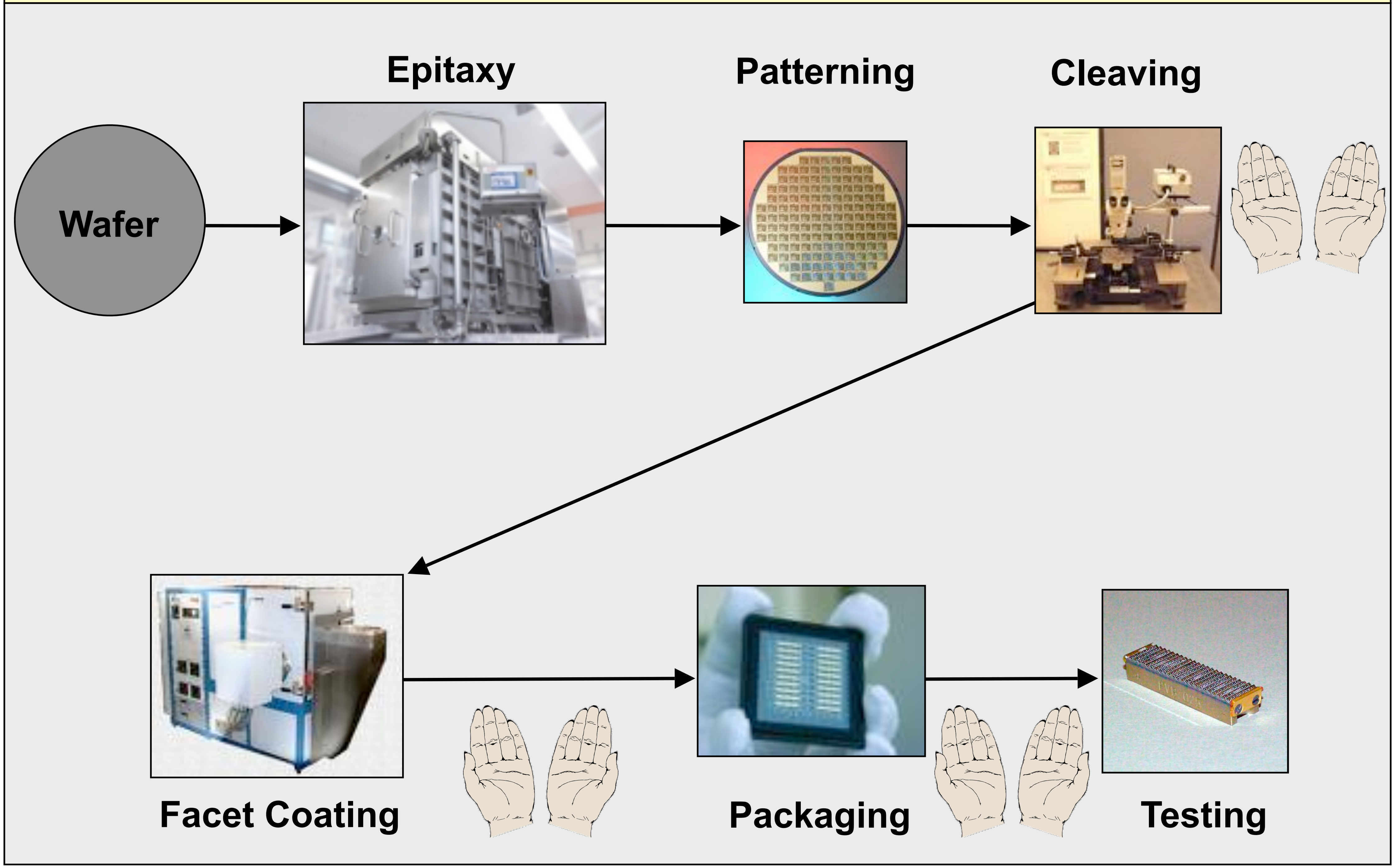
Learning happens

5 MB hard drive 1956

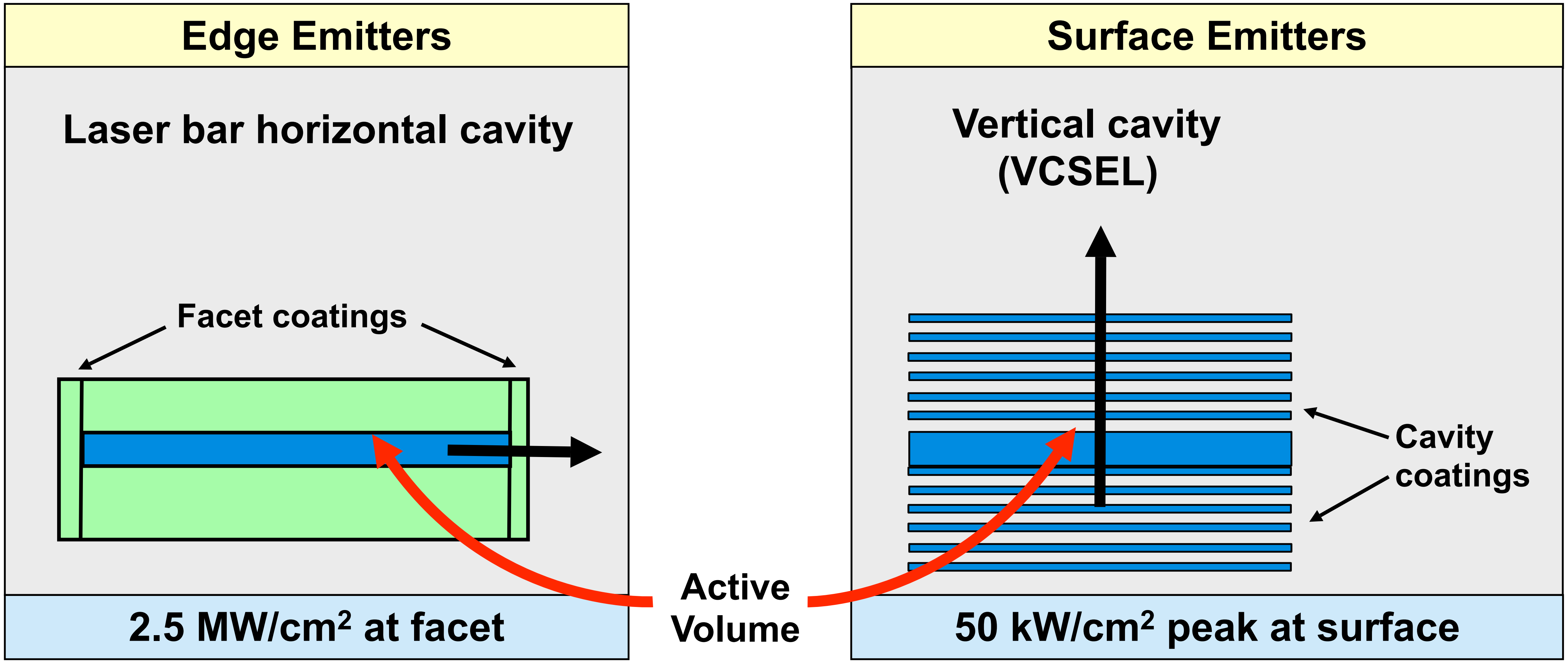
32 GB USB flash-drive 2008

The diode bar package production flow loop for edge emitters involves human hands

Construction of existing arrays have seven steps

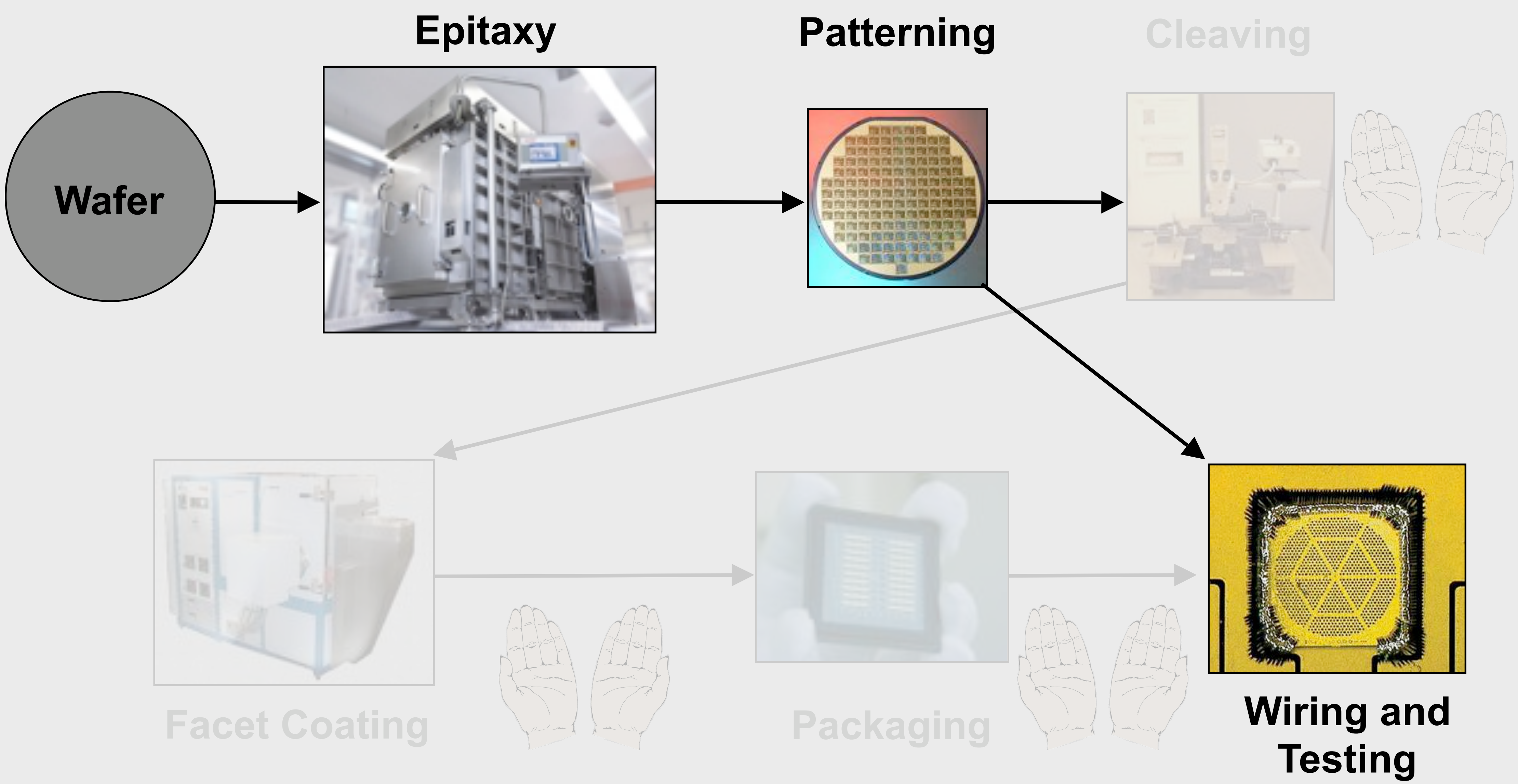


Surface emitting diode lasers are another route to creating efficient, high power, pump light



Output facet irradiance is reduced 50x for VCSELs

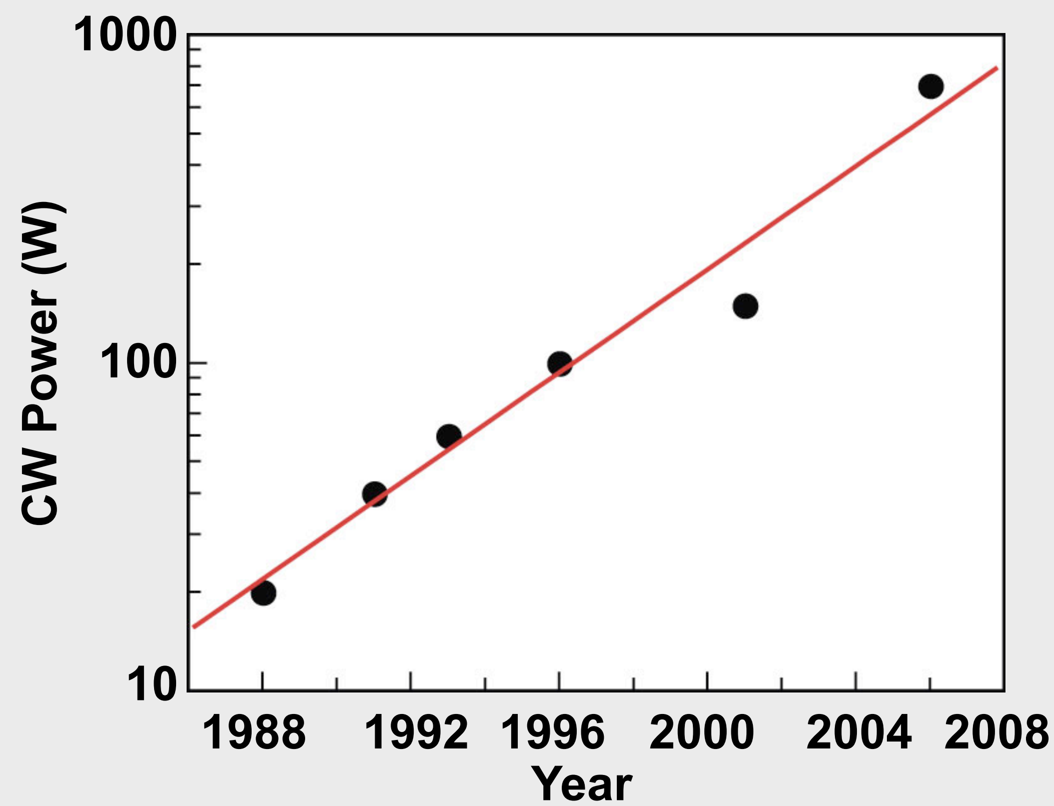
Vertical Cavity Surface Emitting Laser (VCSEL) production takes human hands out of the loop



VCSELs leverage GaAs cell phone chip technology

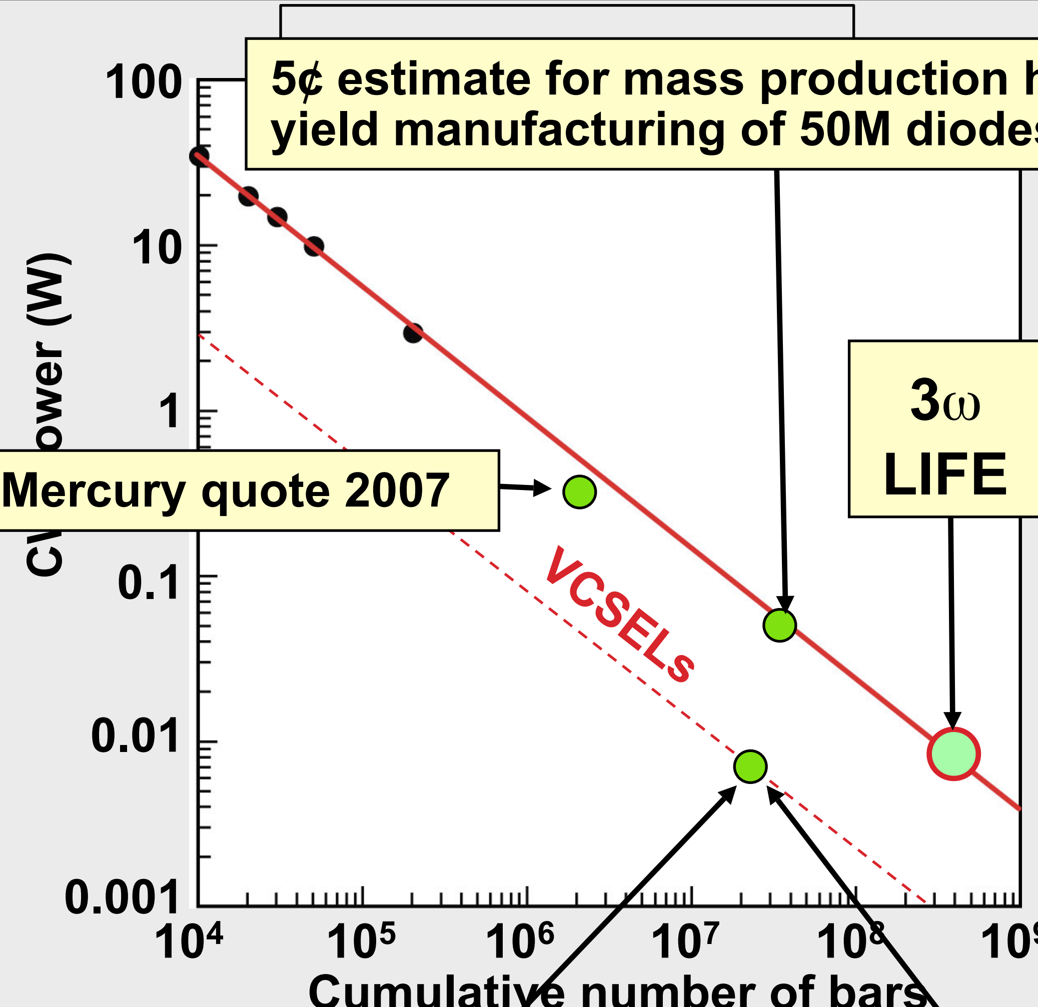
Diodes are experiencing aggressive learning

Continuous wave diode bar performance has increased by 35x since 1988



1 cm bar CW power developed

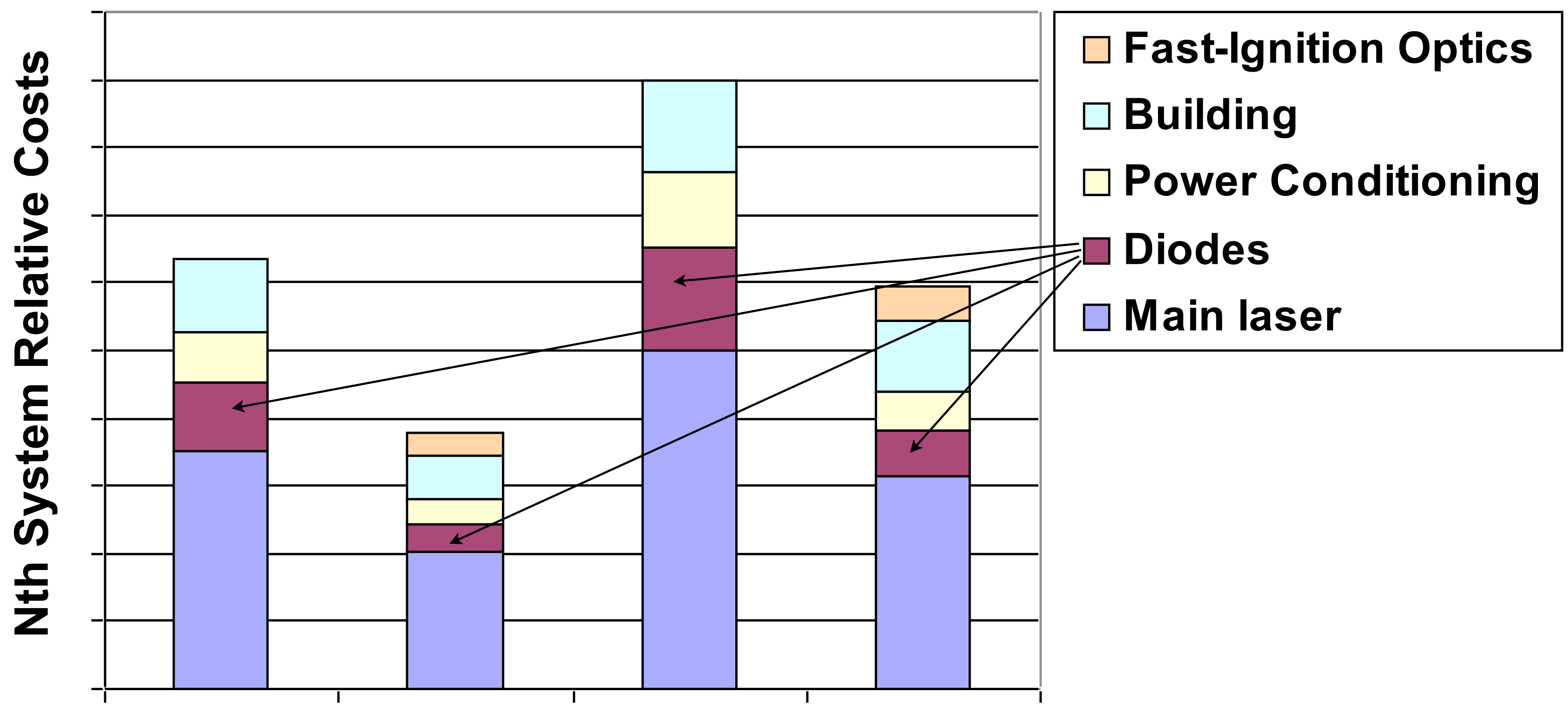
Diode bar prices are dropping with growing market



1 cm bar 60% learning curve

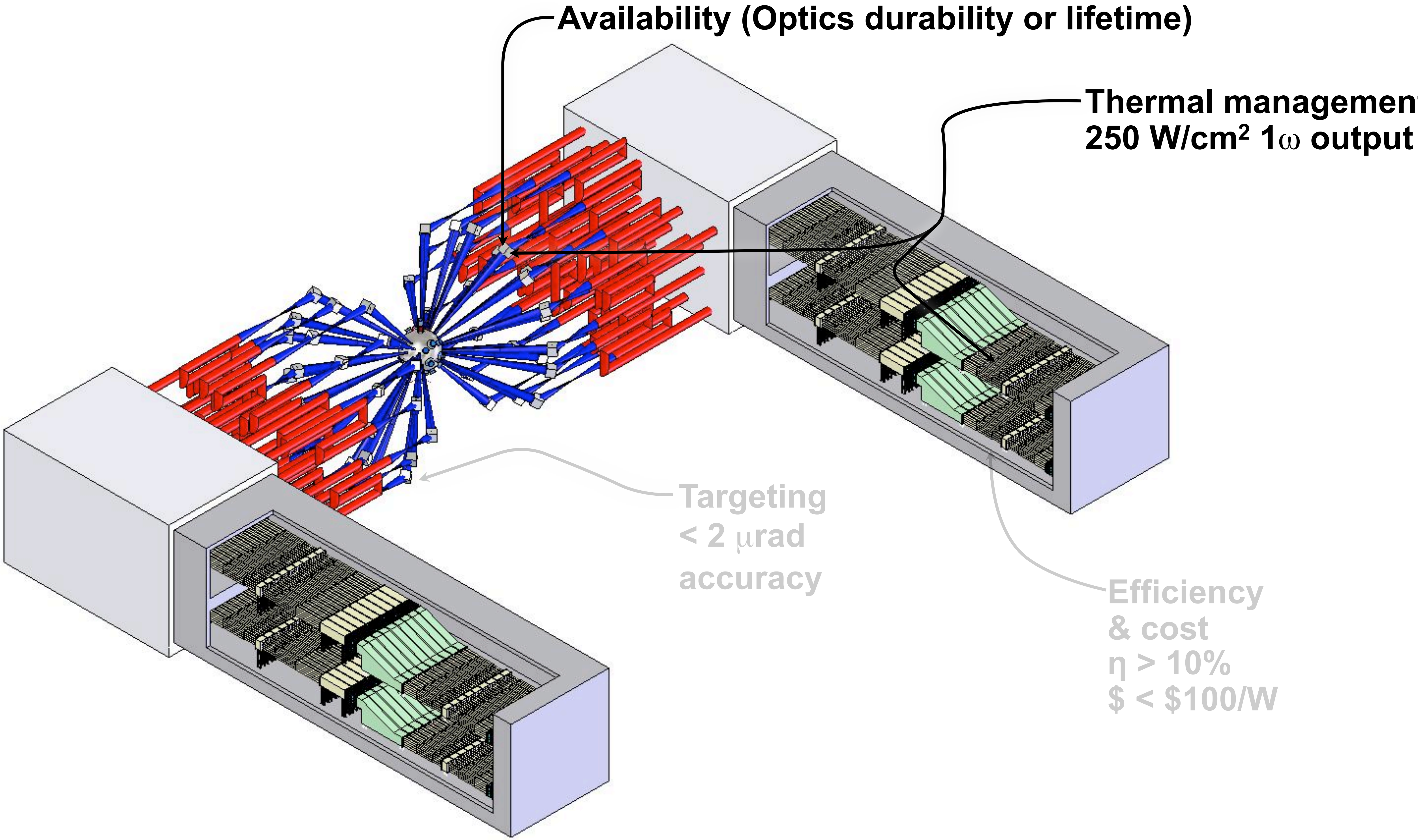
0.72¢ estimate for VCSEL for mass production high yield manufacturing of equivalent of 28M Bars

At $0.01/Watt diodes are a small fraction of cost



Ignition Type	HSI	FI	HSI	FI
Laser Energy	1.3 MJ	0.5 MJ	1.9 MJ	0.8 MJ
Fusion Yield	37.5 MJ	37.5 MJ	75 MJ	75 MJ

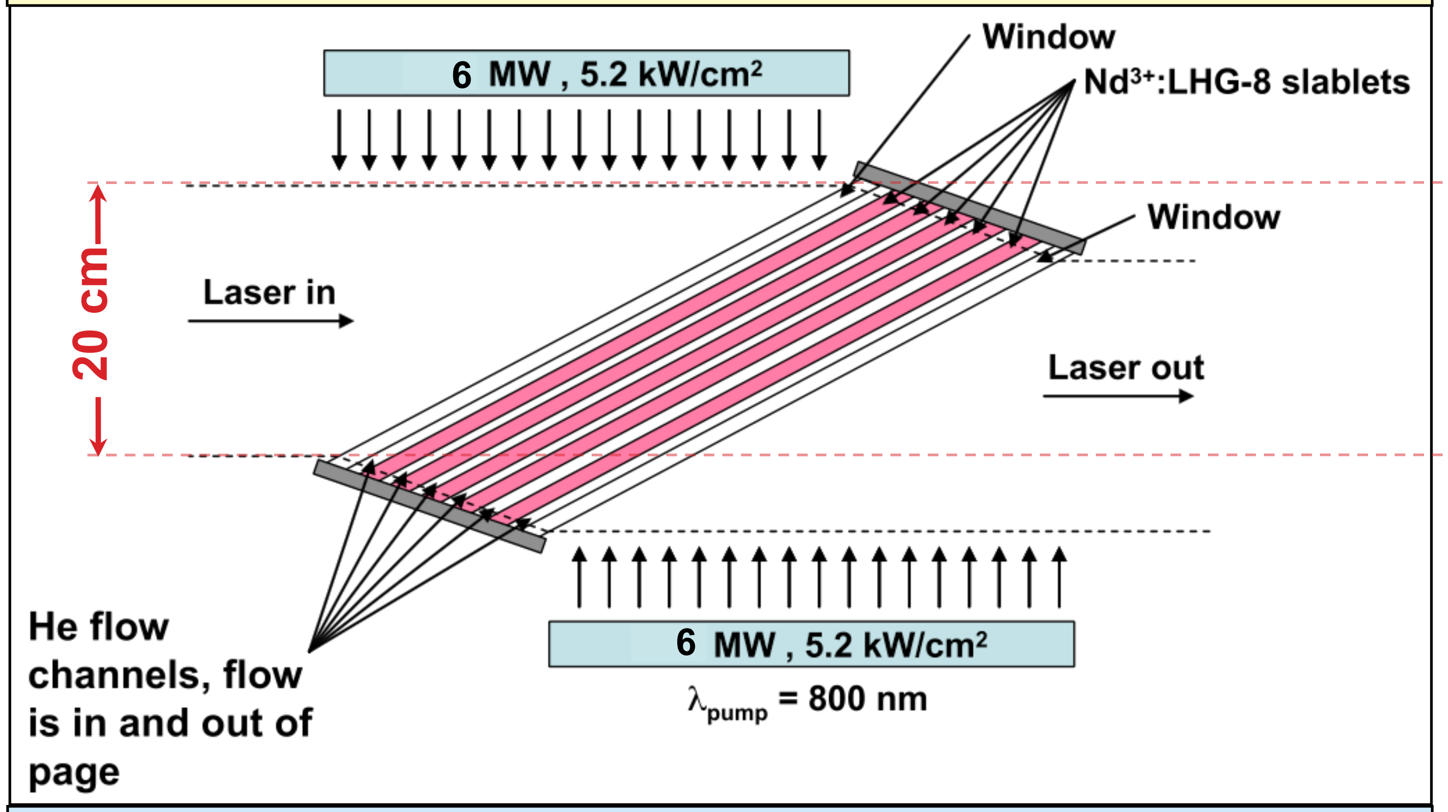
LIFE laser system optical challenges



Thermal management of LIFE laser components is facilitated by flowing He gas cooling

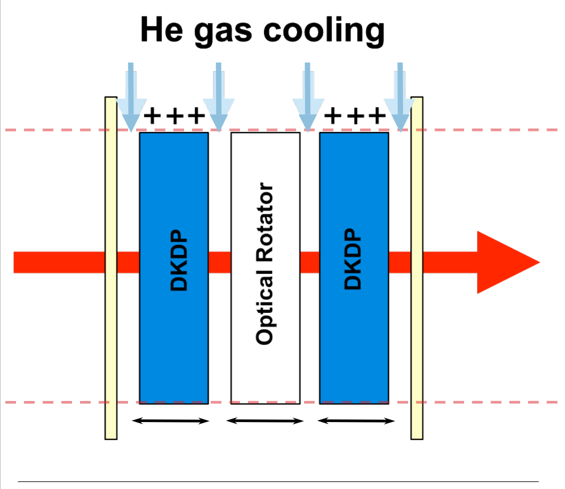
The National Ignition Facility

Laser Amplifier



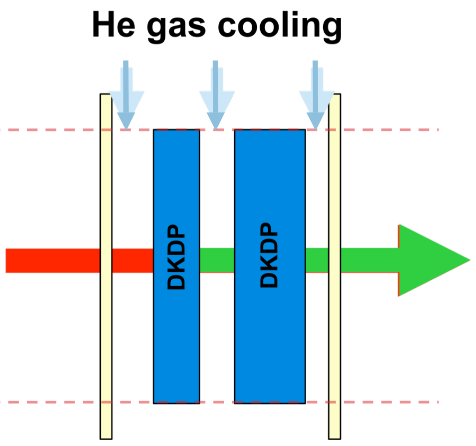
Laser thin slab glass LRUs

Optical Switch



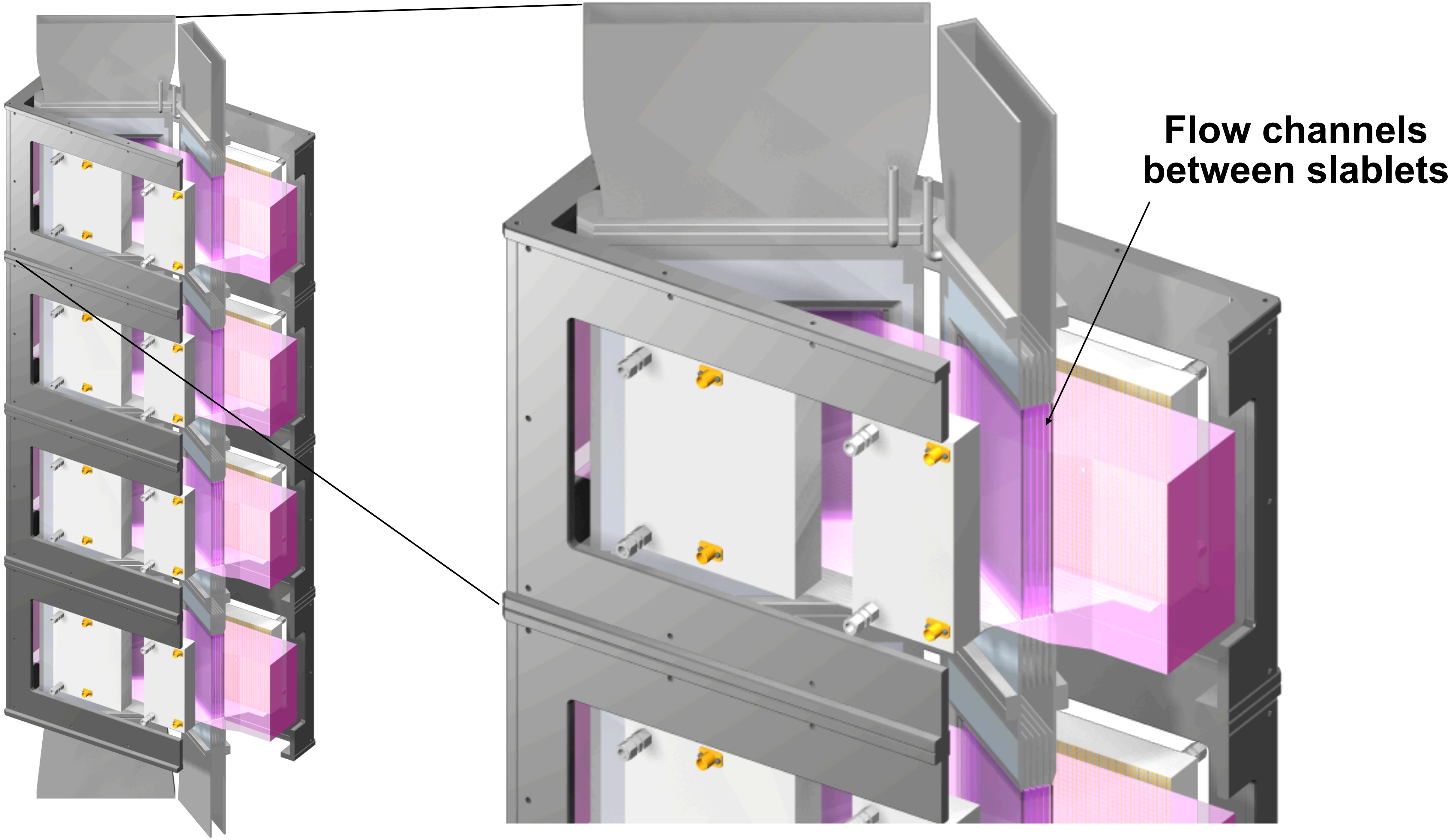
Transverse Electrode Pockels Cell

Frequency Conv.



NIF Frequency Conversion Analog

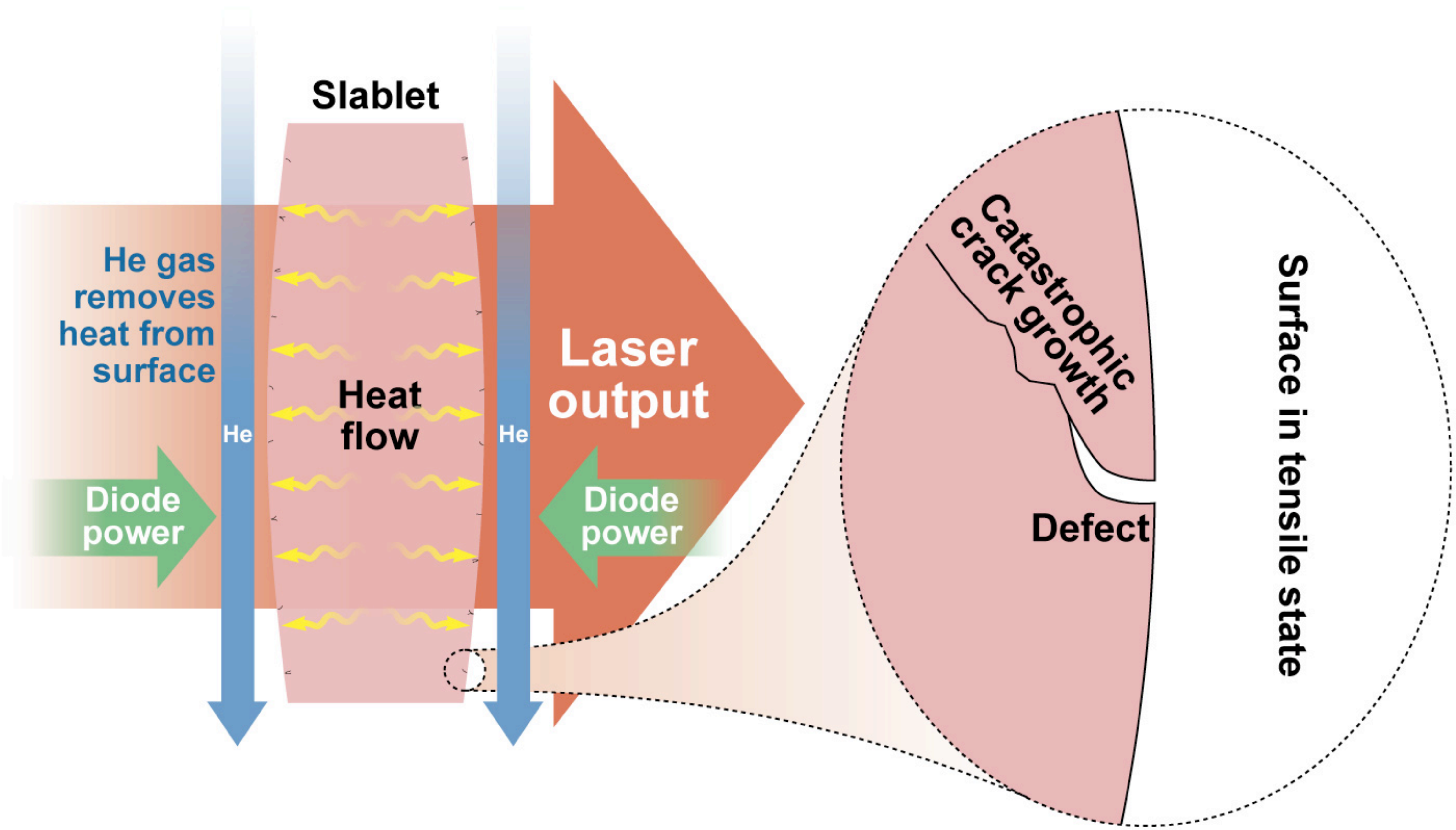
Amplifier Line Replaceable Unit (LRU) concept has been developed



4 Stack

Cutaway view of individual amplifier

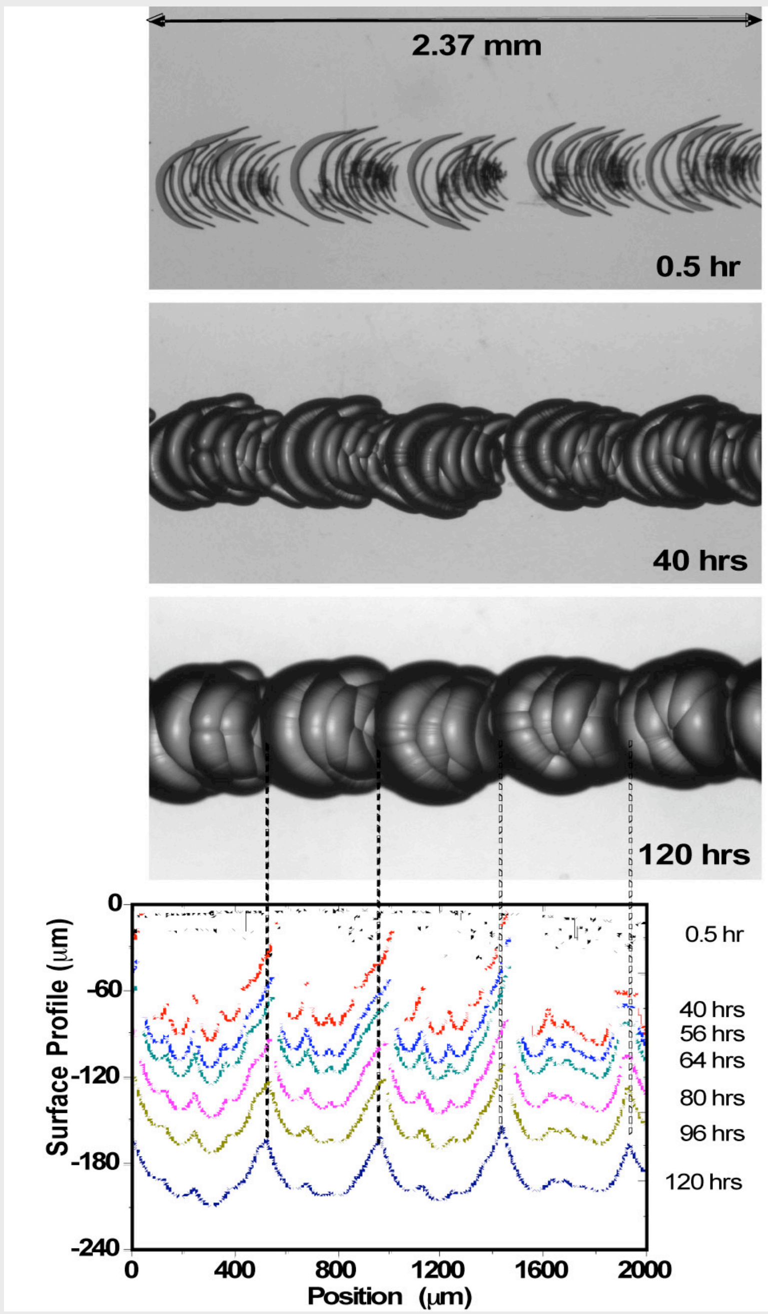
Optical finishing defects are seed locations for "high average power" crack growth



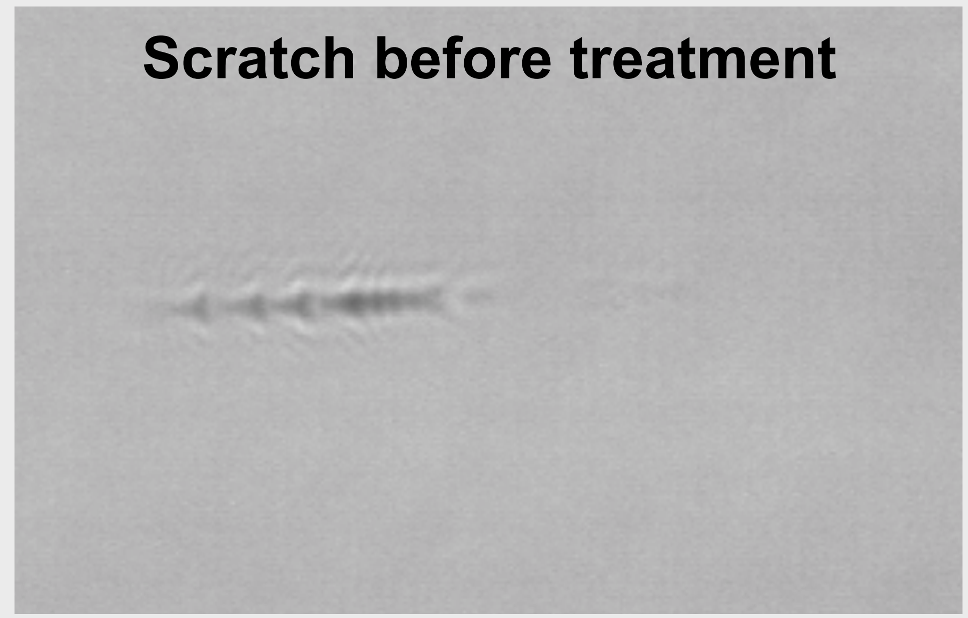
New glass compositions or finishing methods will enable fewer slablets

Chemical etching & CO2 laser mitigation are two routes for increasing laser glass strength

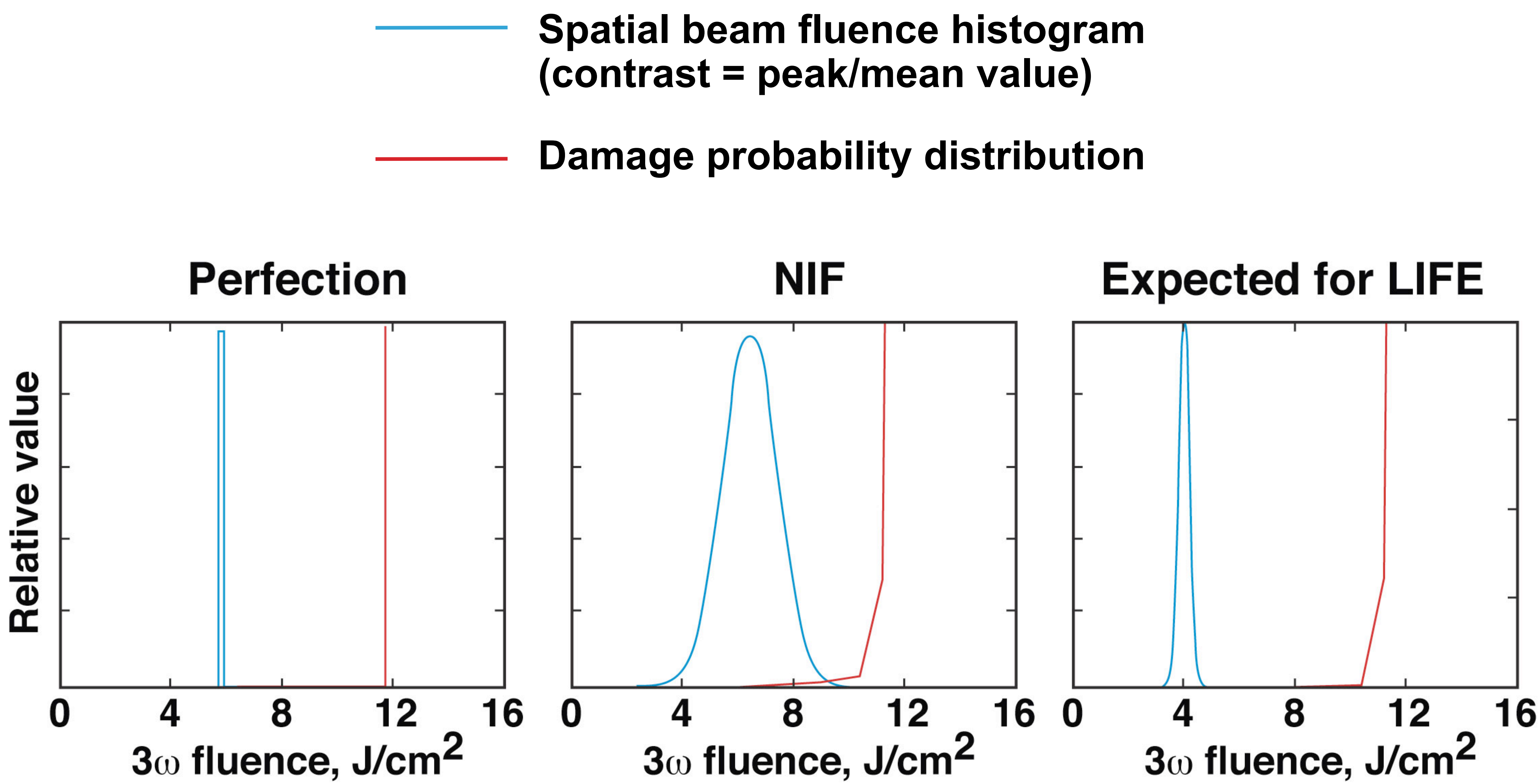
Acid etching of a scratch



CO_2 laser treatment of a scratch

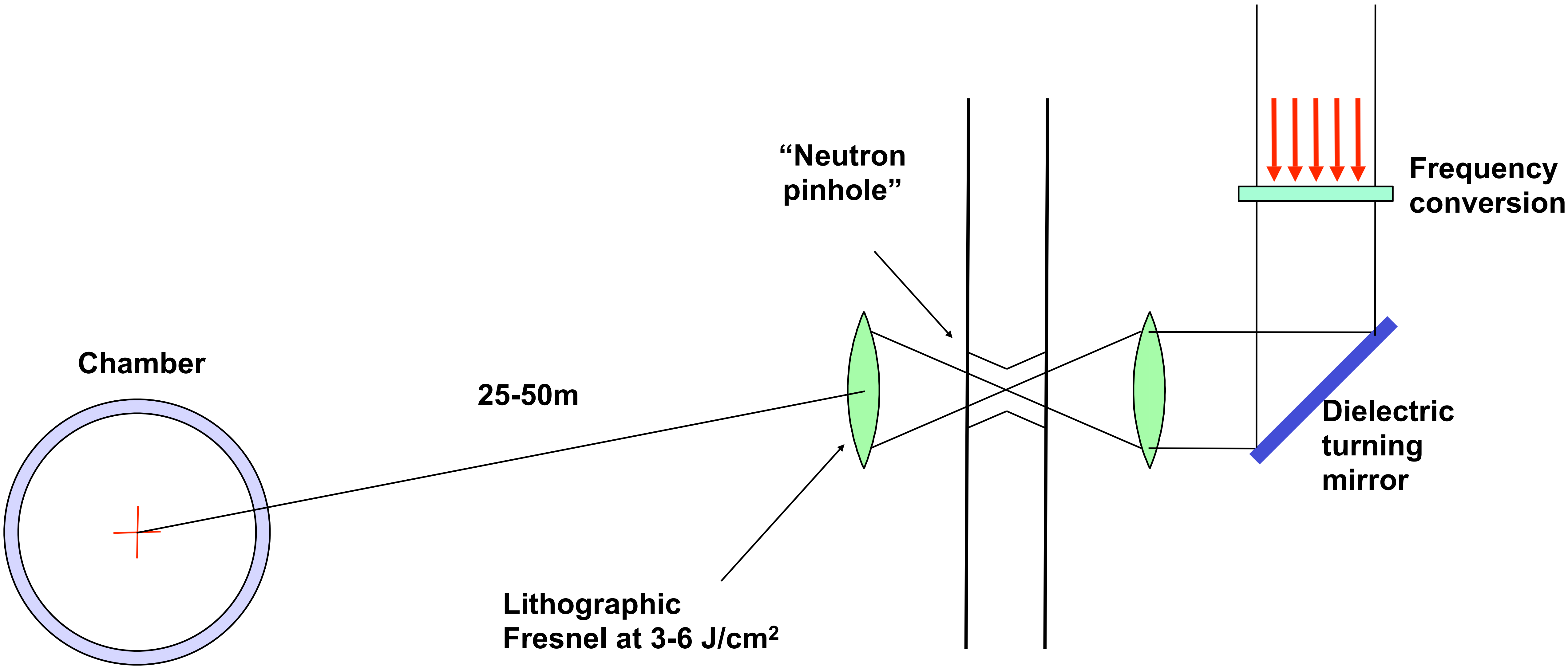


Optical lifetime predictions are based on NIF experience



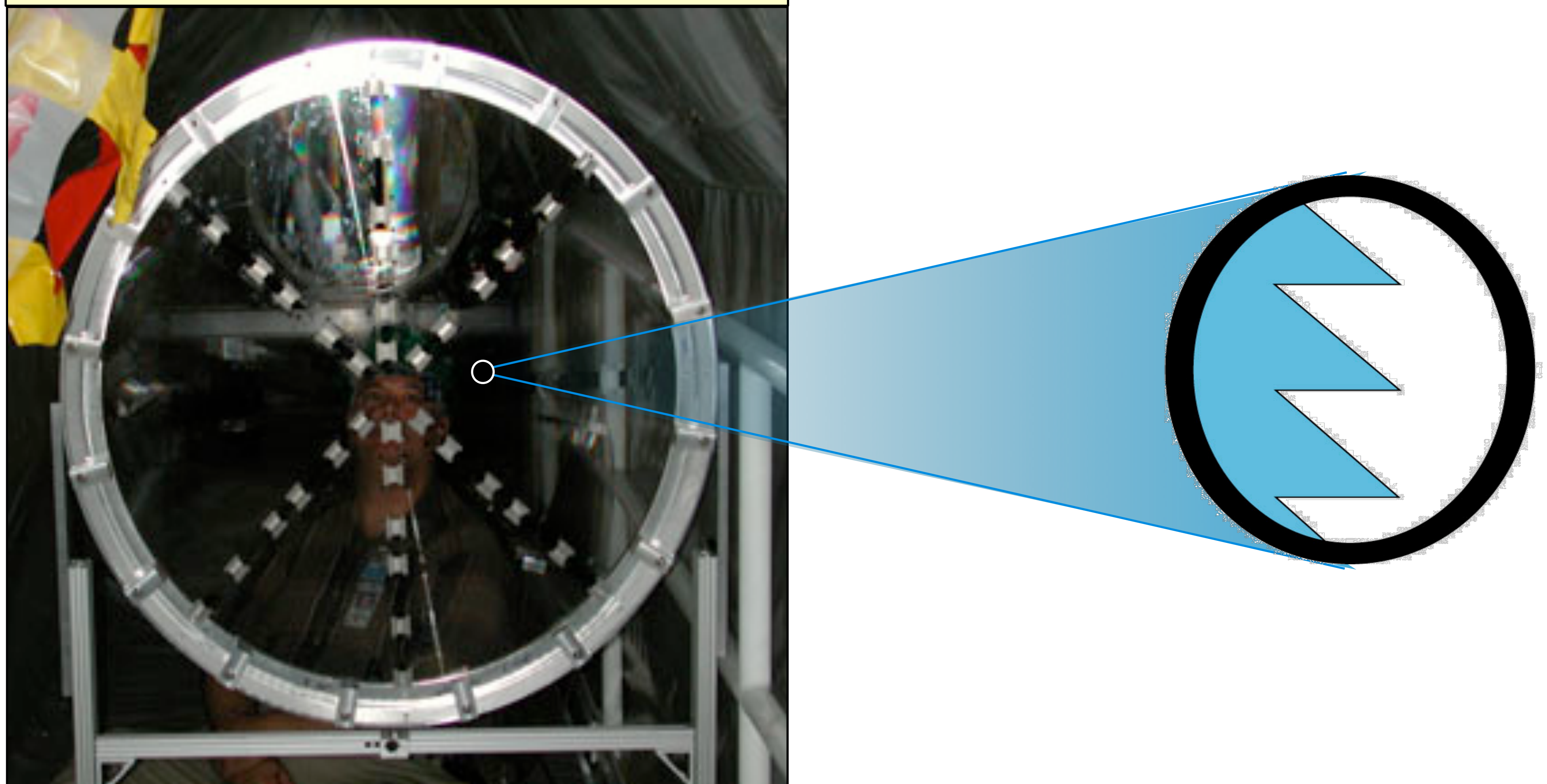
LIFE optics durability will be enhanced by reducing beam contrast and improving optical finishing

Schematic for the LIFE final optical path



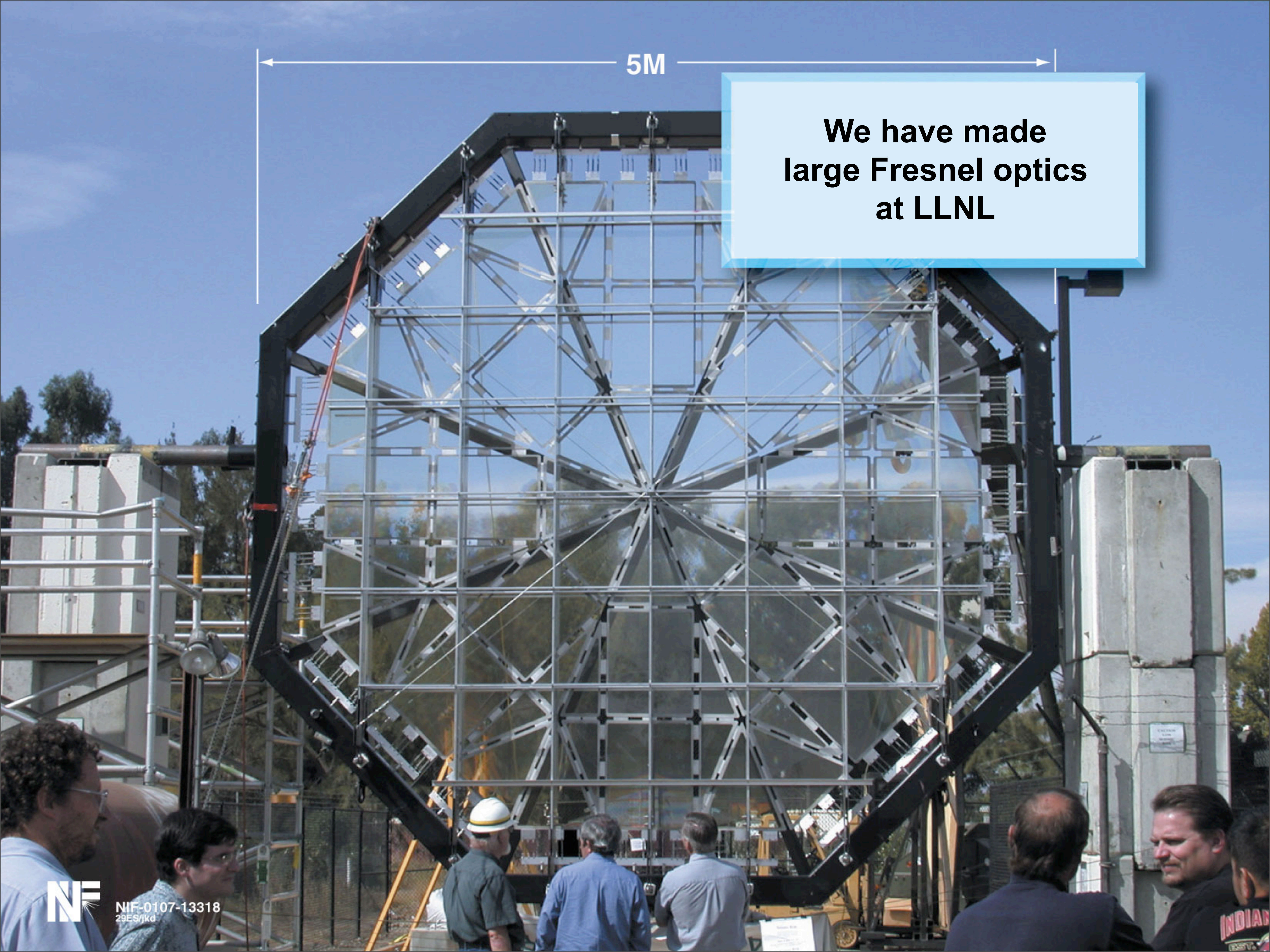
A hot, thin (0.5 mm) Fresnel lens (diffractive optic) is our choice for the LIFE focusing optic

25-m Focal Length Fresnel Lens



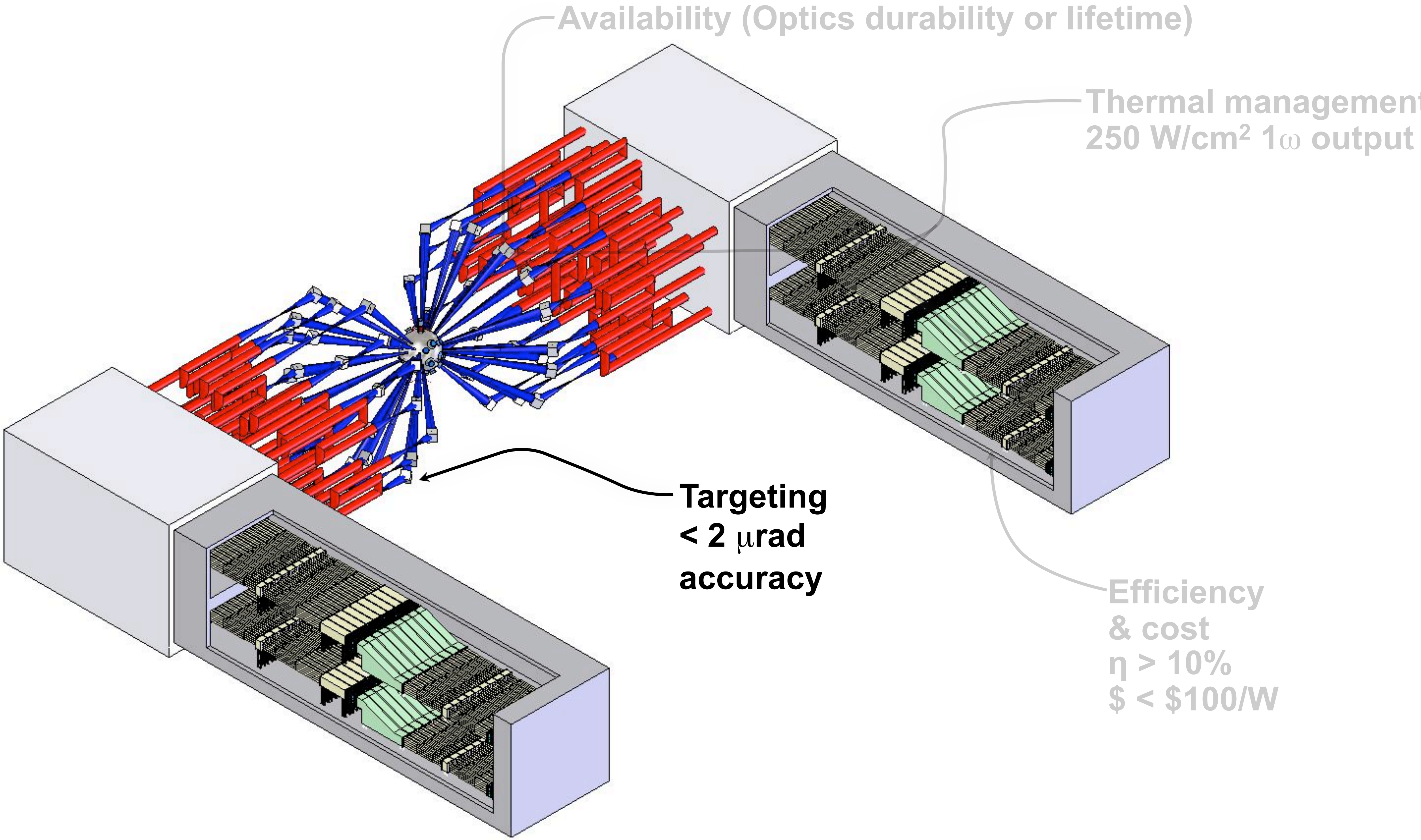
1 mm thick, 80 cm diameter

Static loss due to neutrons saturates quickly and drops when heated
Laser operations will replace optic as loss becomes excessive


5M
We have made
large Fresnel optics
at LLNL
NIF-0107-13318
29ES/jkd


We have made high
damage threshold
large scale
diffractive optics

LIFE laser system optical challenges

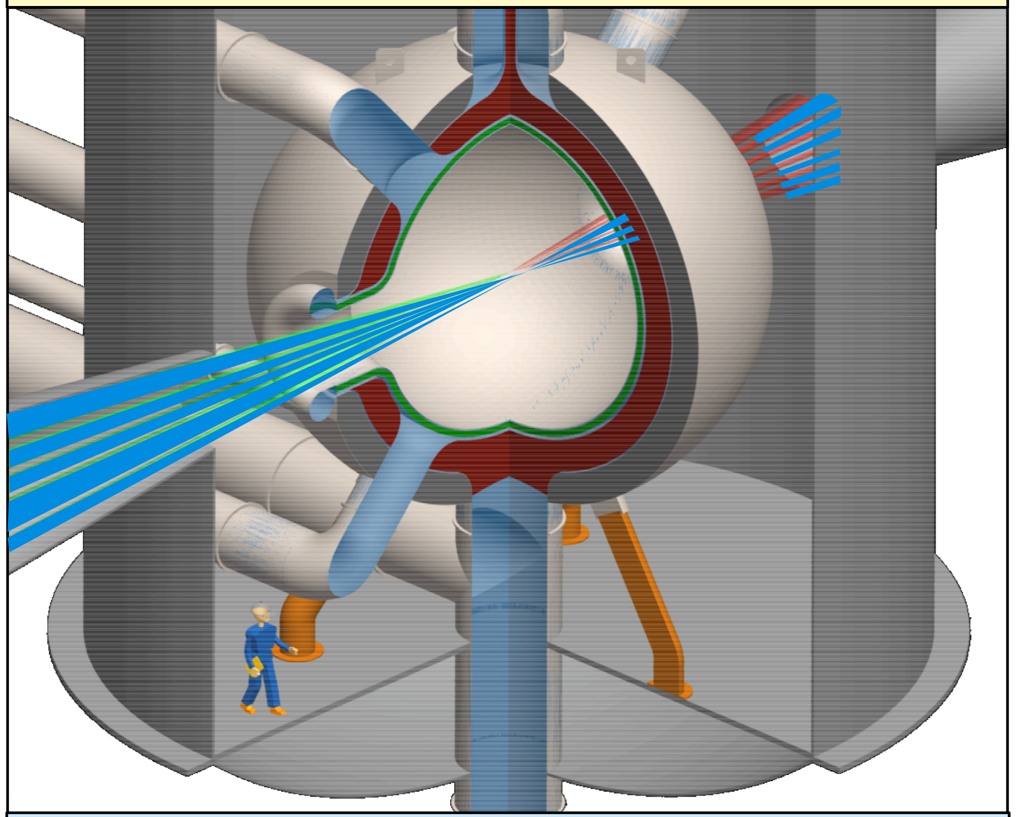


LIFE targeting requirement is similar to that of other demanding systems

Airborne Laser

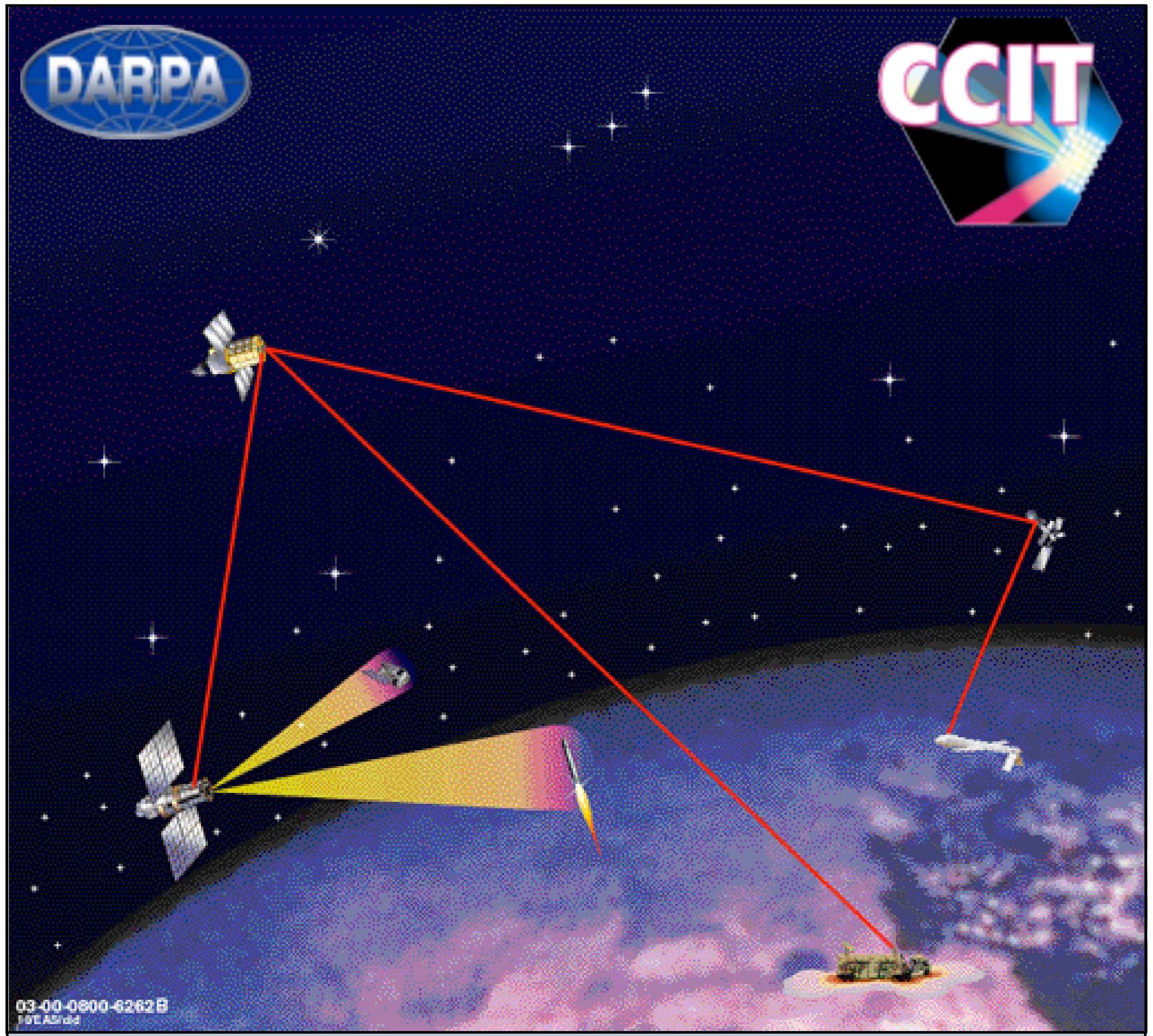
~1 μrad angular precision (~10 cm, 100's km)

LIFE

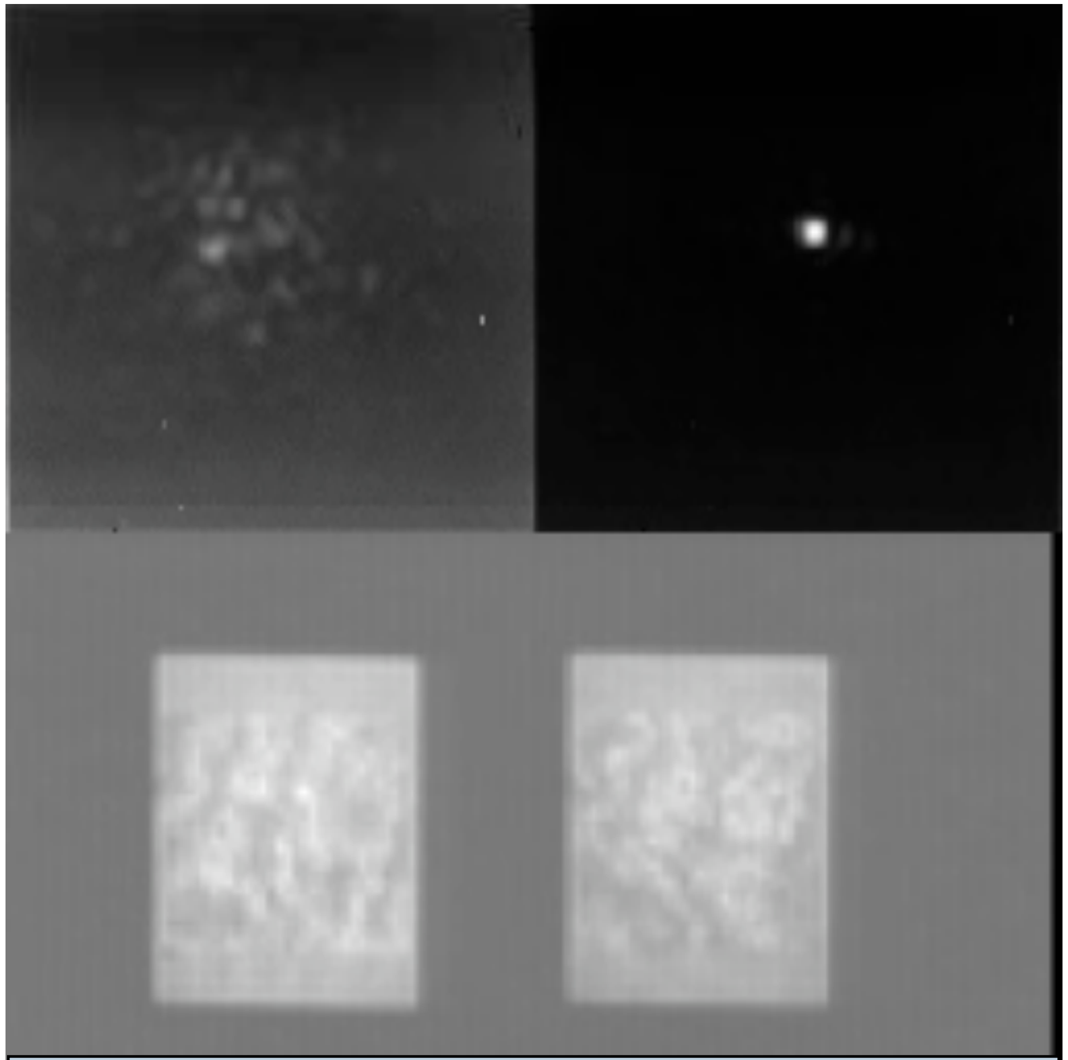


2 μrad precision (HS, 50 μm, f = 25 m)
0.4 μrad (FI, 10 μm, f = 25 m)

DARPA/LLNL Coherent Communications, Imaging, Targeting (CCIT) program enables LIFE targeting



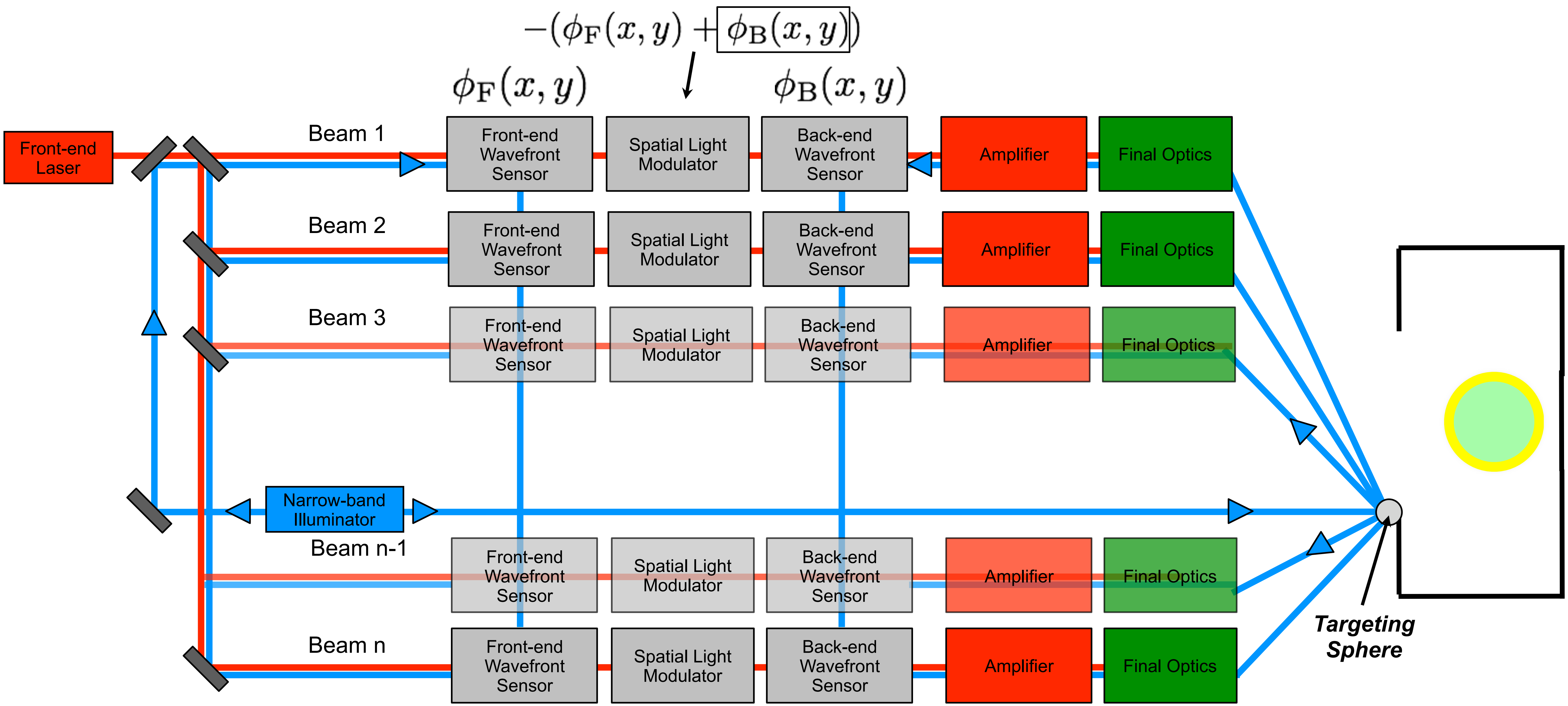
CCIT System Concept



Uncorrected and corrected far fields (top)
and holograms (bottom)
LLNL Site-300, 1.5 km path, 2003

The CCIT program aimed to create gigabit/sec free-space optical communication channels with quantum-limited coherent detection and novel high-speed micro-electro-mechanical (MEMS)-based adaptive optics

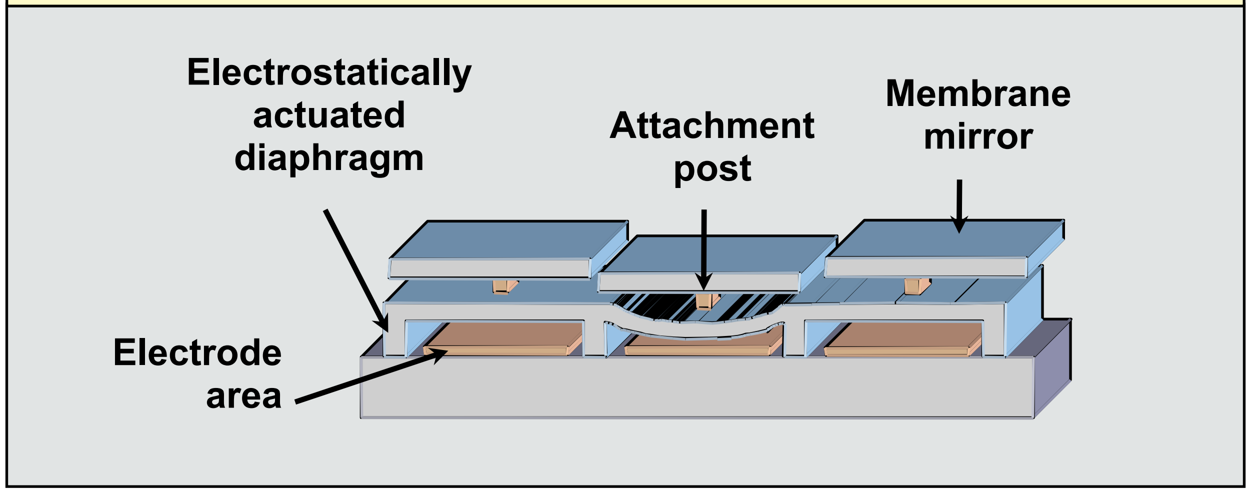
DARPA/LLNL CCIT program is the basis of LIFE pointing and tracking (and phasing scheme)



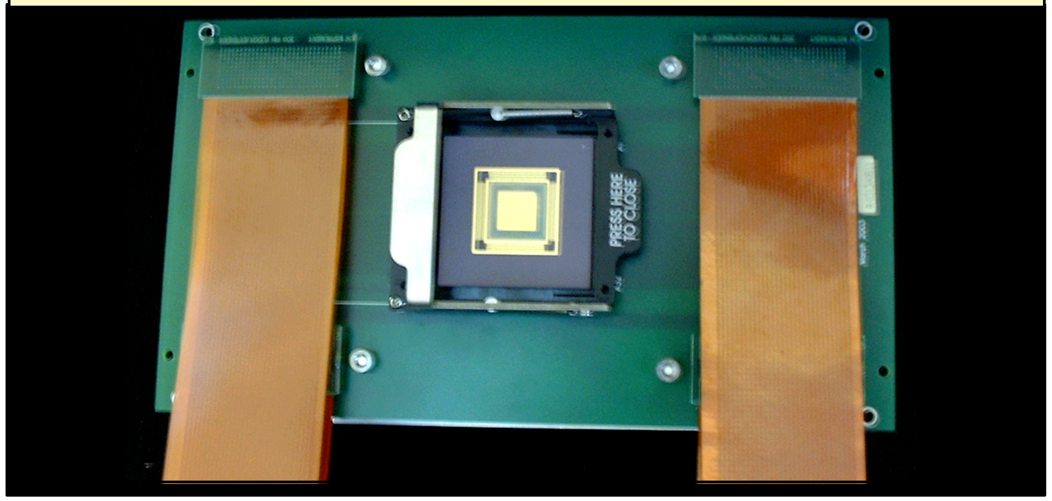
A single MEMS spatial light modulator both post-corrects front-end and pre-corrects back-end distortions, including pointing, wavefront, and inter-beam phasing

An enabling component for LIFE beam control is the CCIT MEMS Spatial Light Modulator

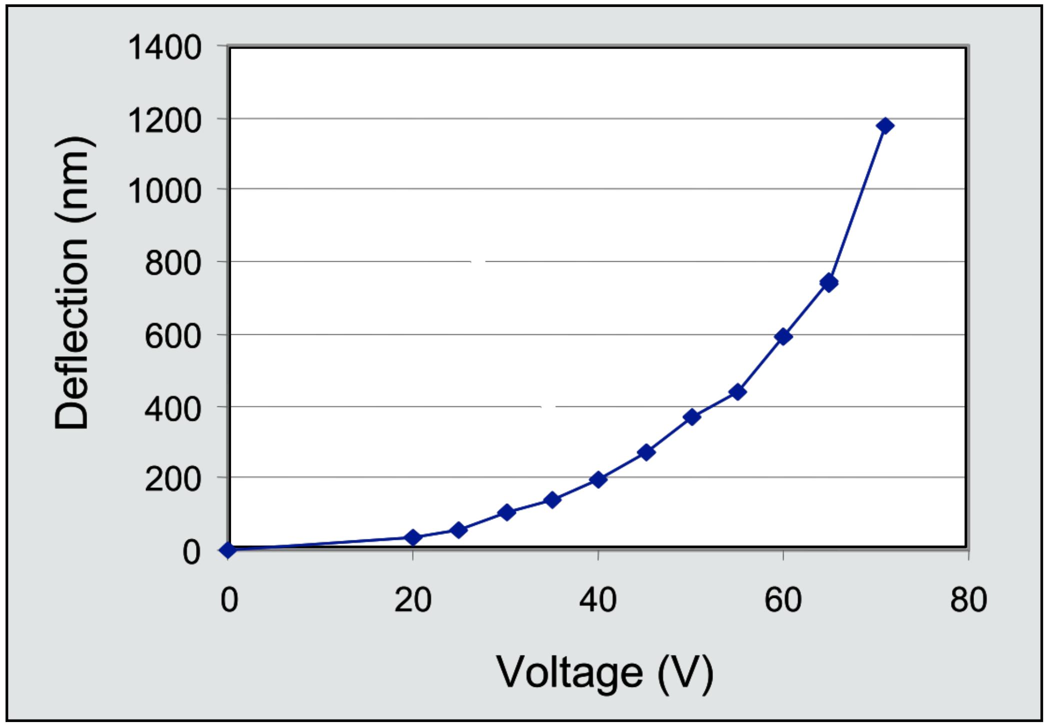
Cross-sectional schematic showing three pixels



32 x 32 SLM on Interface PCB with Cables to Lucent Driver**



Parameter	Goal	Achieved
Element Count	1024	1024
Flatness	λ/50 (31nm)	λ/100 (12nm)
Resolution	4nm	1.2nm
Response Time	10 μs (100kHz)	13 μs (75kHz)
Stroke	λ/2 (755nm)	λ/0.6 (1μm)
Fill Factor	98%	99%



The Boston Micromachines 32x32 MEMS SLM met all of DARPA's requirements

Conclusions

- NIF architecture with diode laser pumping and He-gas cooling is our baseline LIFE Laser design
- Optimization of the architecture will further improve system performance and economics
- Emerging but less proven technologies could also improve performance and economics
- We are developing a full sub-system R&D path outline

NIF is a prototype for LIFE laser performance

Acknowledgements

Team

Ryan Abbott
Peter Amendt
Andy Bayramian
Chris Barty
Ray Beach
Jerry Britten
John Caird
Diana Chen
Rick Cross
Chris Ebbers
Al Erlandson
Joe Farmer
Dain Holdener
Tony Ladran
Jeff Latkowski
Ken Manes
Joe Menapace
Bill Molander
Ed Moses
John Murray
Greg Rogowski
Kathleen Schaffers
Erik Storm
Tayyab Suratwala
Steve Sutton
Steve Telford
John Trenholme
Dave Van Lue

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Drew Felker, UC Davis
Schott Glass Technologies