LLNL-PRES-601872

Laser for CLIC-based gamma-gamma collider

Presented by: Andy Bayramian

Lawrence Livermore National Laboratory

Accelerators for a Higgs Factory: Linear vs. Circular (HF2012)

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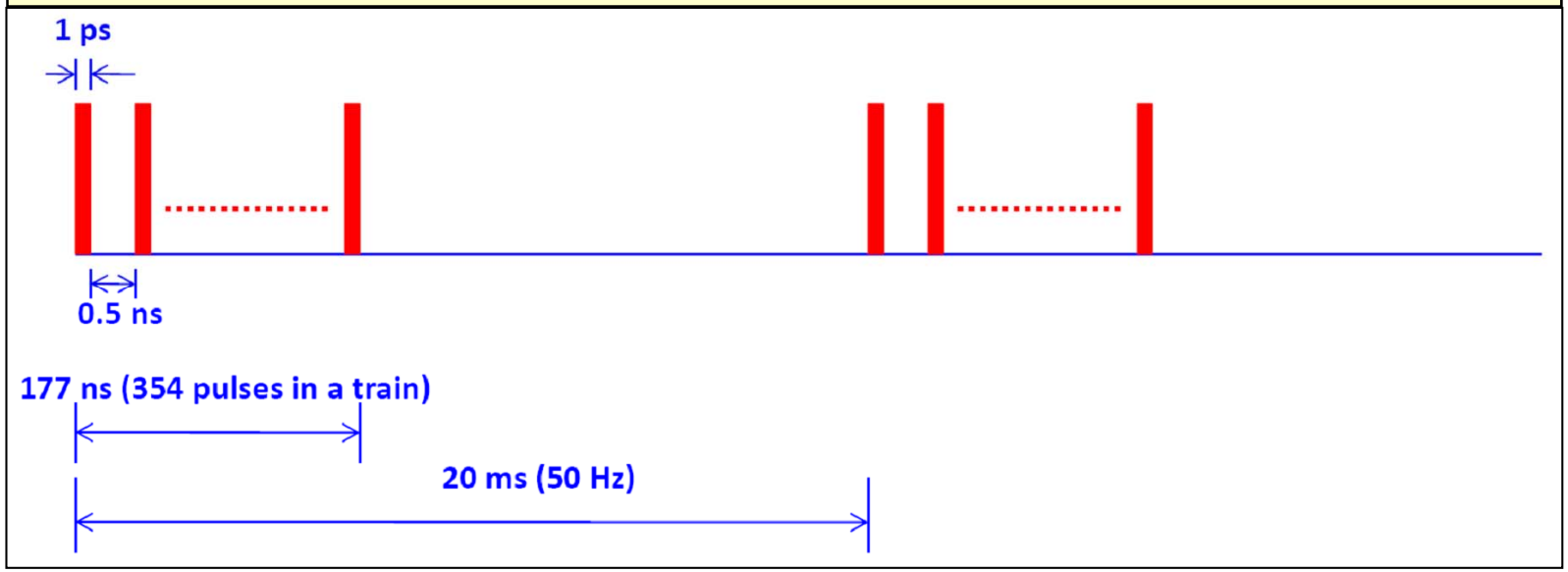
The CLIC based γ–γ collider has energy and power requirements synergistic with LIFE laser designs

Electron Beam Parameters	ILC	CLIC	LPA $n_e=10^{17}$/cc	LPA $n_e=10^{18}$/cc
Energy per electron beam (GeV)	100	100	75	100
Max energy of photons (GeV)	60 (75)	60	60	60
$\gamma\gamma$ luminosity at the high energy peak (10^{34} cm^{-2}s^{-1})	0.13	0.19	0.3	0.3
Electrons per bunch ($\times 10^{10}$)	2	0.68	0.4	0.13
Number of bunches in a train (n_b)	2640	354	1	1
Distance between bunches (t_b, ns)	370	0.5	n/a	n/a
Length of the train (n_b*t_b , ms)	980	0.177	n/a	n/a
Repetition frequency ($f_{rep,}$ Hz)	5	50	4	40
Electron bunch length σ_z (mm)	300	44	1	0.3
Normalized emittance $\varepsilon_{x/y}$ (mm-mrad)	10/0.035	1.4/0.050	0.1	0.1
Beta-function at IP $\beta_{x/y}$ (mm)	4/0.3	2/0.02	0.15	0.2
Beam size $\sigma_{x/y}$ (nm)	450/7.3	120/2.3	10	10
Distance between conversion point and IP (mm)	~1.5	~0.5	<75	<350
Crossing angle (mrad)	25	25	<50	<50
Laser Parameters				
Wavelength (μm)	1 (0.5)	1	0.3	1
Rayleigh range (mm), f#	~0.5, 20	~0.4,18	0.3	1
Laser pulse energy (J)	~10/Q	5	2	6
Pulse length (r.m.s., ps)	~1.5	~1	2	7
Peak power (TW)	~2.5/Q	2	1	1
Average power (kW)	150/Q	90	8	240
Laser power in a train (MW)	25/Q	10000	n/a	n/a
Cavity enhancement factor	Q~300	1	1	1

The LIFE laser is specified to produce 130 kW average power which could be modified for CLIC pulsetrains

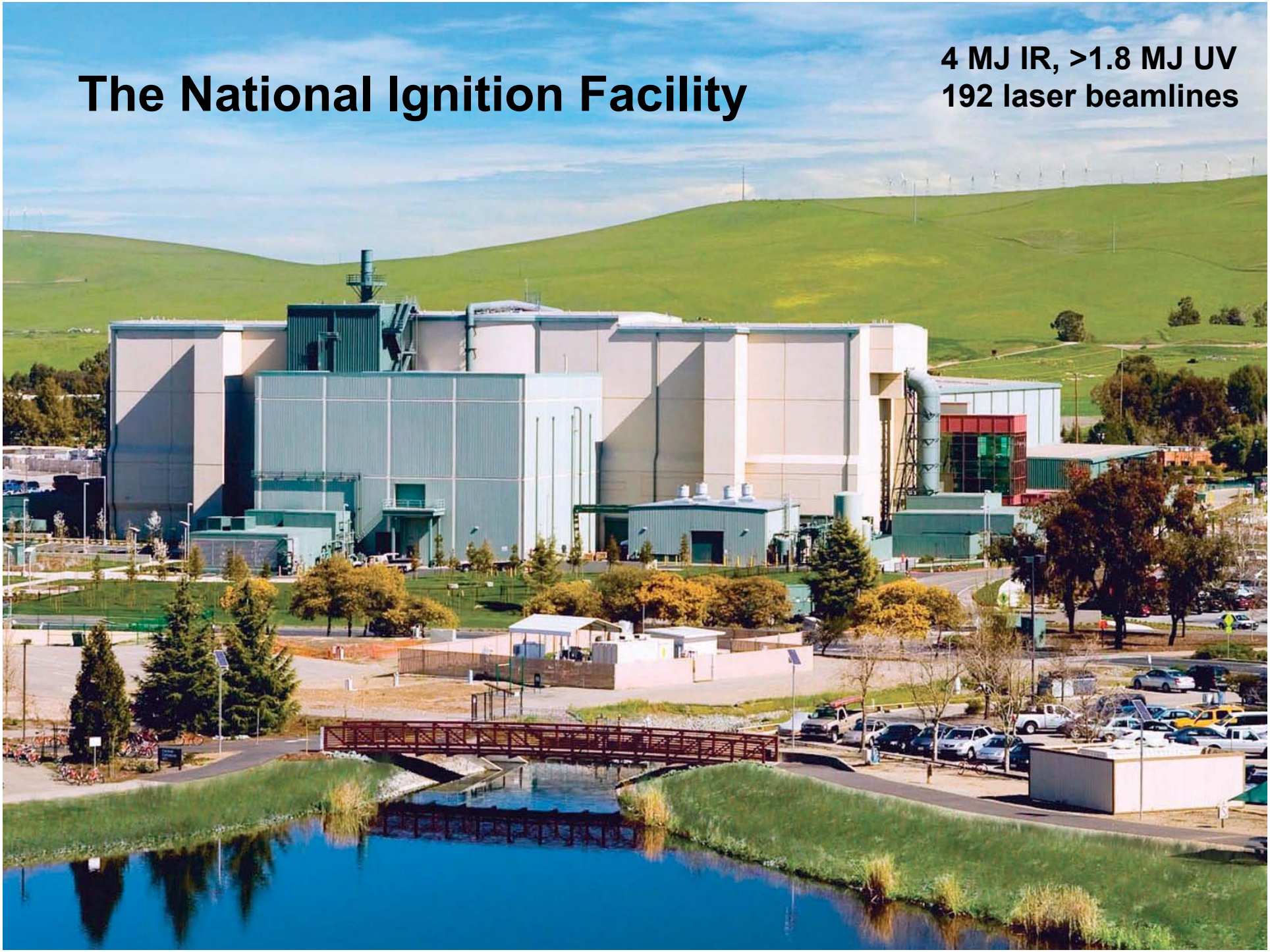
Beam structure of a CLIC-based γγ collider



- The laser pulse train is a burst of 354, 5-J, 1-ps pulses separated by 0.5 ns for a total of 1770 J/burst.
- These bursts occur at 50 Hz, yielding 88.5 kW of 1-micron light.
- The LIFE laser on the other hand is designed to produce over 130 kW of average power with pulse energies of 8.1 kJ at 16 Hz.
  - CLIC is 3X LIFE repetition rate, but 4.6X lower energy

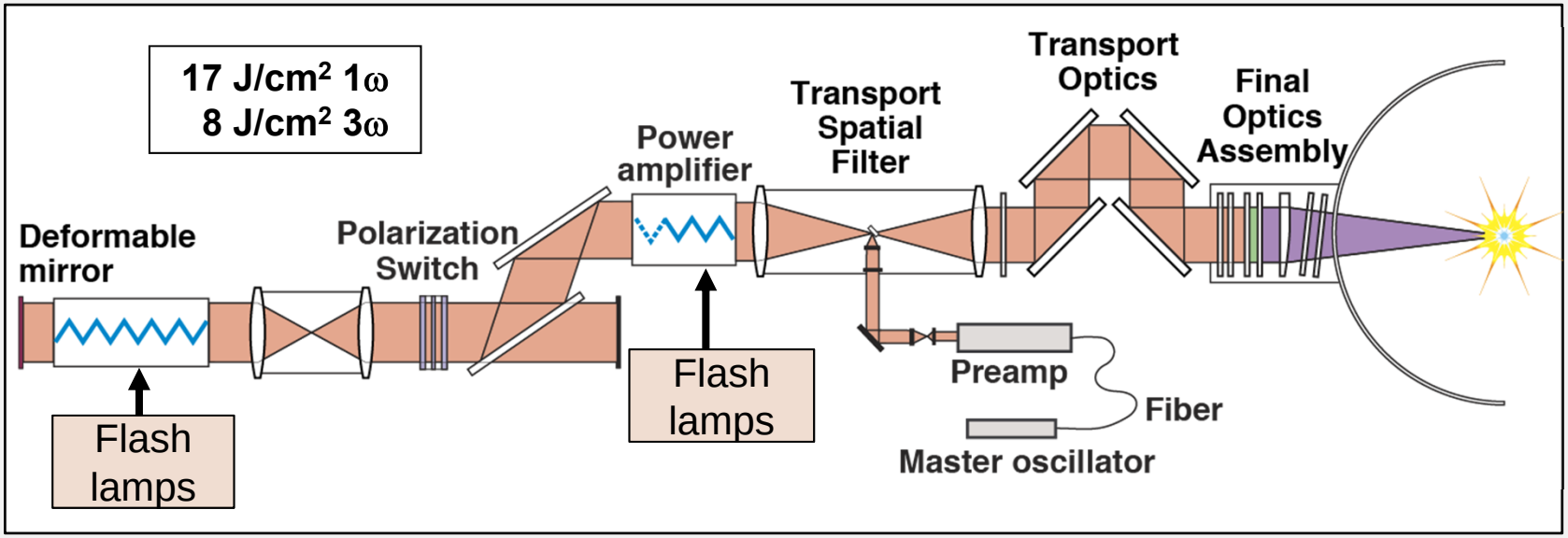
The National Ignition Facility

4 MJ IR, >1.8 MJ UV
192 laser beamlines



The NIF laser provides the single-shot baseline

NIF Beamline



Master oscillator / Preamplifier / Multi-pass architecture

Passive optical system performance

Line Replaceable Unit (LRU) methodology

Whole-system design, construction, commissioning and operation

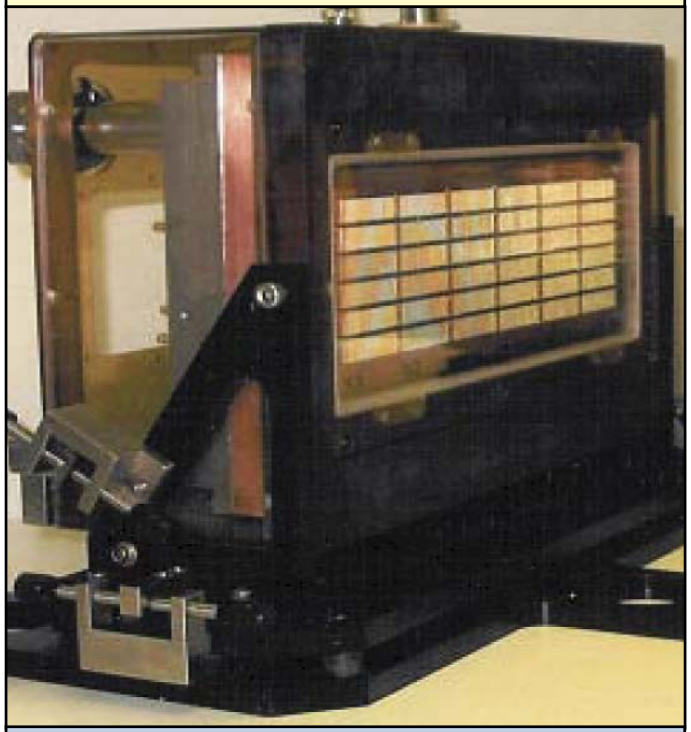
Optics production and performance experience base

Coupling demonstration to full-scale IFE target


Laser Bay
00ABC/abc • NIF-0508-14729s2

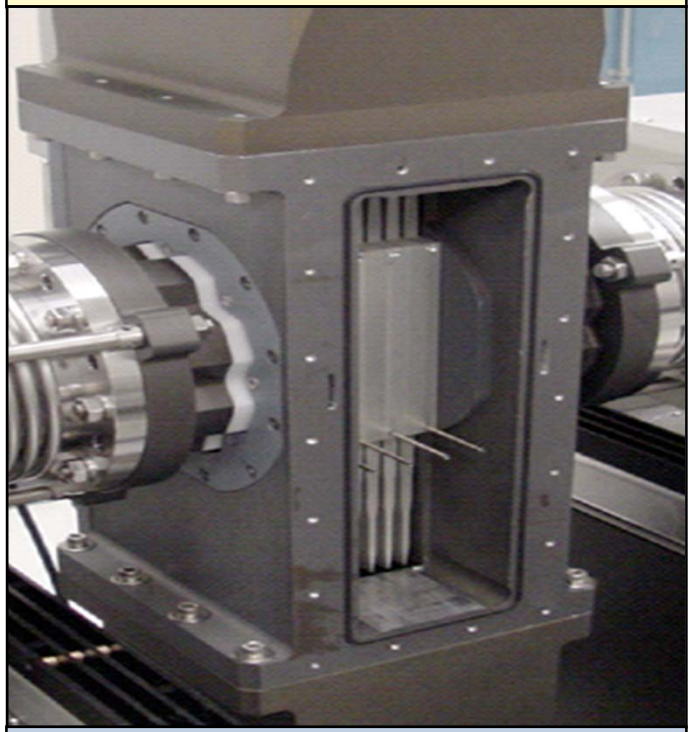
Laser diodes and helium gas cooling enable a NIF-like architecture to meet LIFE driver requirements

High Power Diode Arrays



100 kW peak power

High Speed Gas Cooling

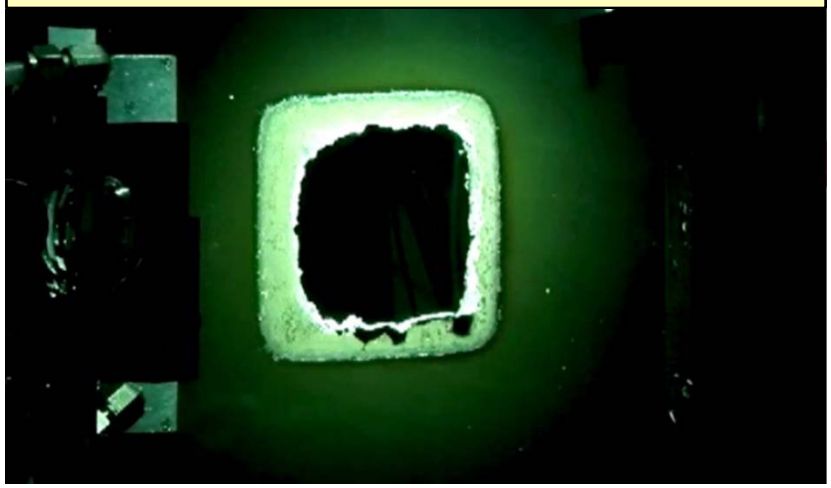


3 W/cm^2 cooling (average)

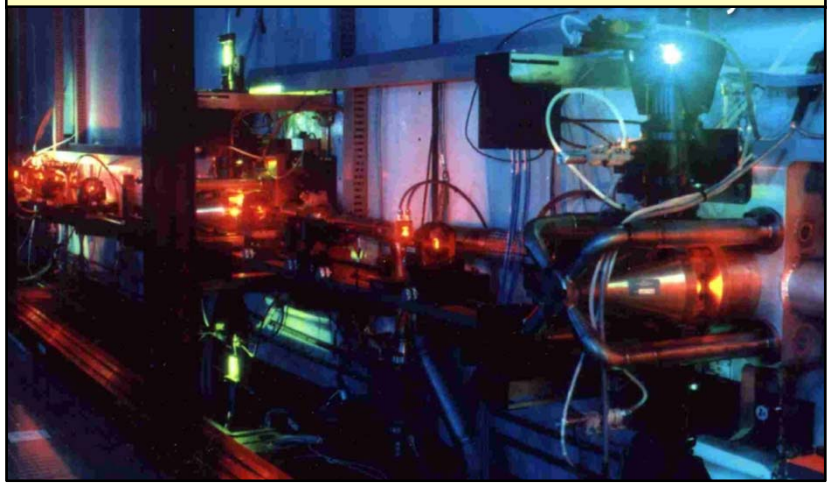
These technologies were developed as part of the Mercury HAPL Project

LLNL average power lasers have been proving grounds for several key LIFE technologies

25 kW high average power laser



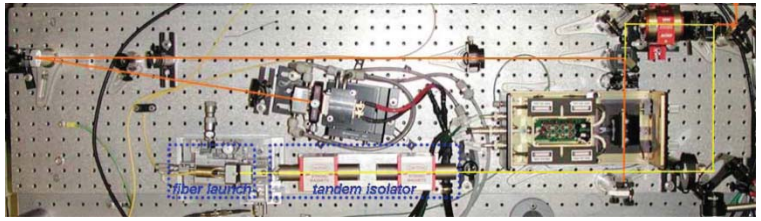
AVLIS 24/7 operational laser

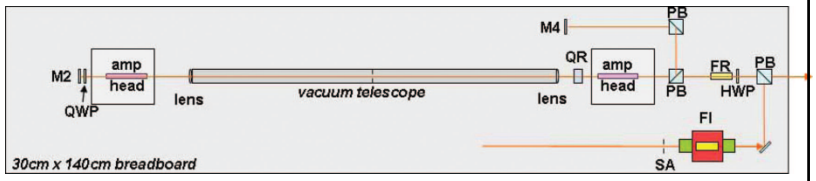


600W, 10 Hz Mercury Laser

A.J. Bayramian et. al, *Fusion Sci. Tech.* 52, 383 (2007)

300 Hz, 38 W Pulse Amplifier





J. Honig, et. al, *Appl. Opt.* 46, 3269 (2007)

NIF capability in a very small box: LIFE high average power laser architecture attributes

Provides efficiency (~18%) at high repetition rate (16 Hz)

- High brightness efficiency diode pump arrays
- Helium gas-cooled amplifiers
- High efficiency harmonic conversion using pulse splitting

Will be built with existing materials

- Glass slabs: thermal birefringence compensated by architecture
- DKDP Pockels cell: polarization switching minimizes heat load

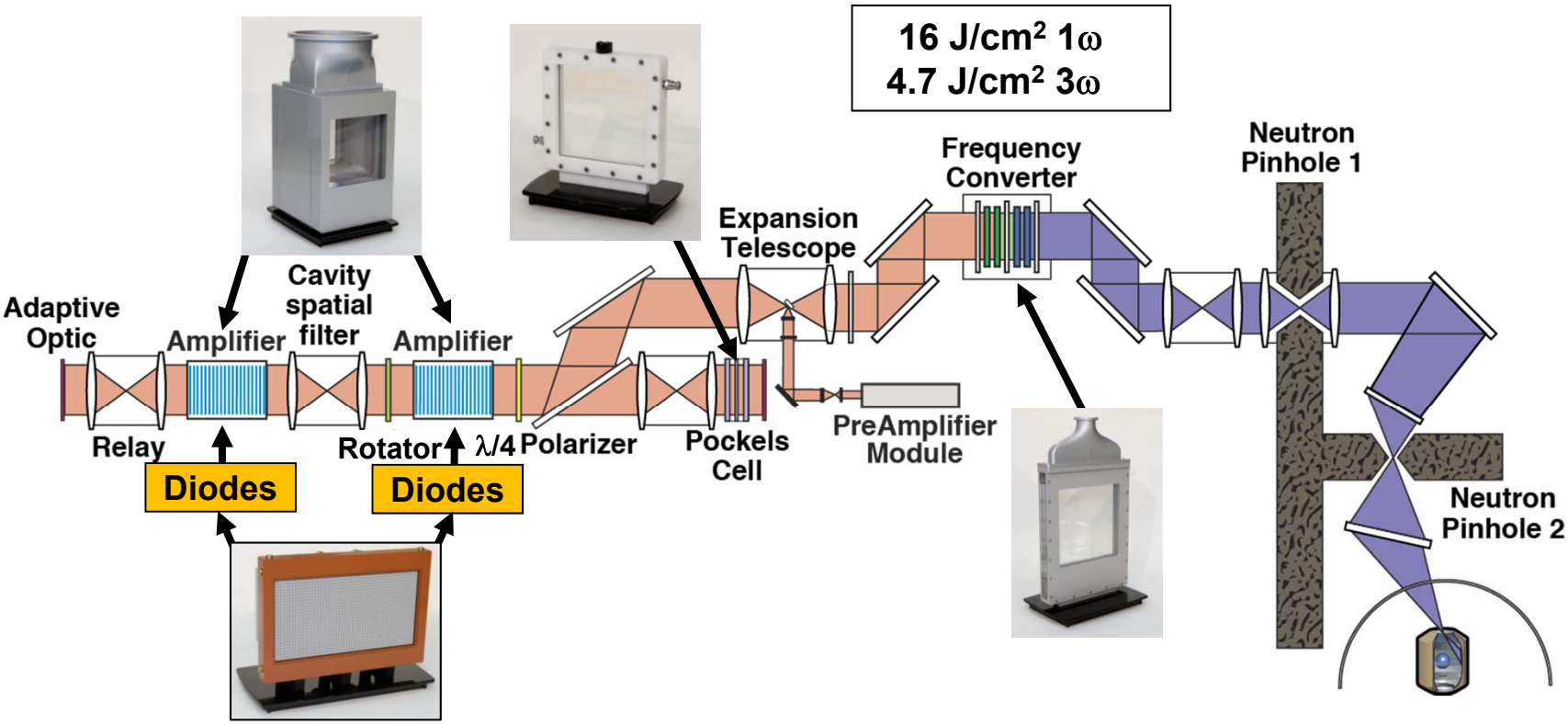
Designed for high availability operation

- Robustness: Low 3ω fluence operation
- Headroom in beamline power to meet operational availability
- Optics preparation to mitigate damage

Suitable for remote (off-site) manufacturing

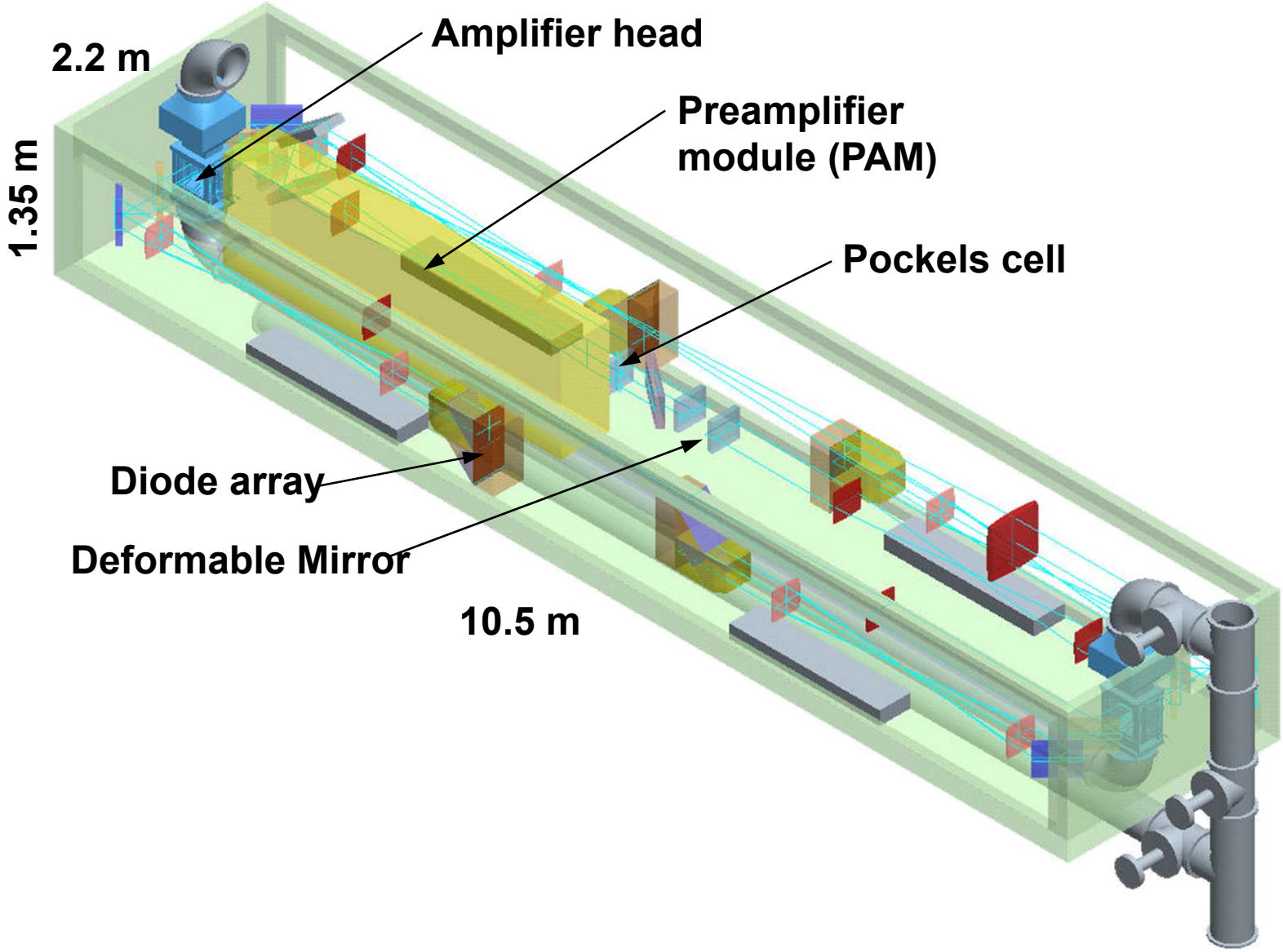
- Modular beamlines permit hot-swapping
- Separation of laser manufacturing & power generation operations

LIFE combines the NIF architecture with high efficiency, high average power technology



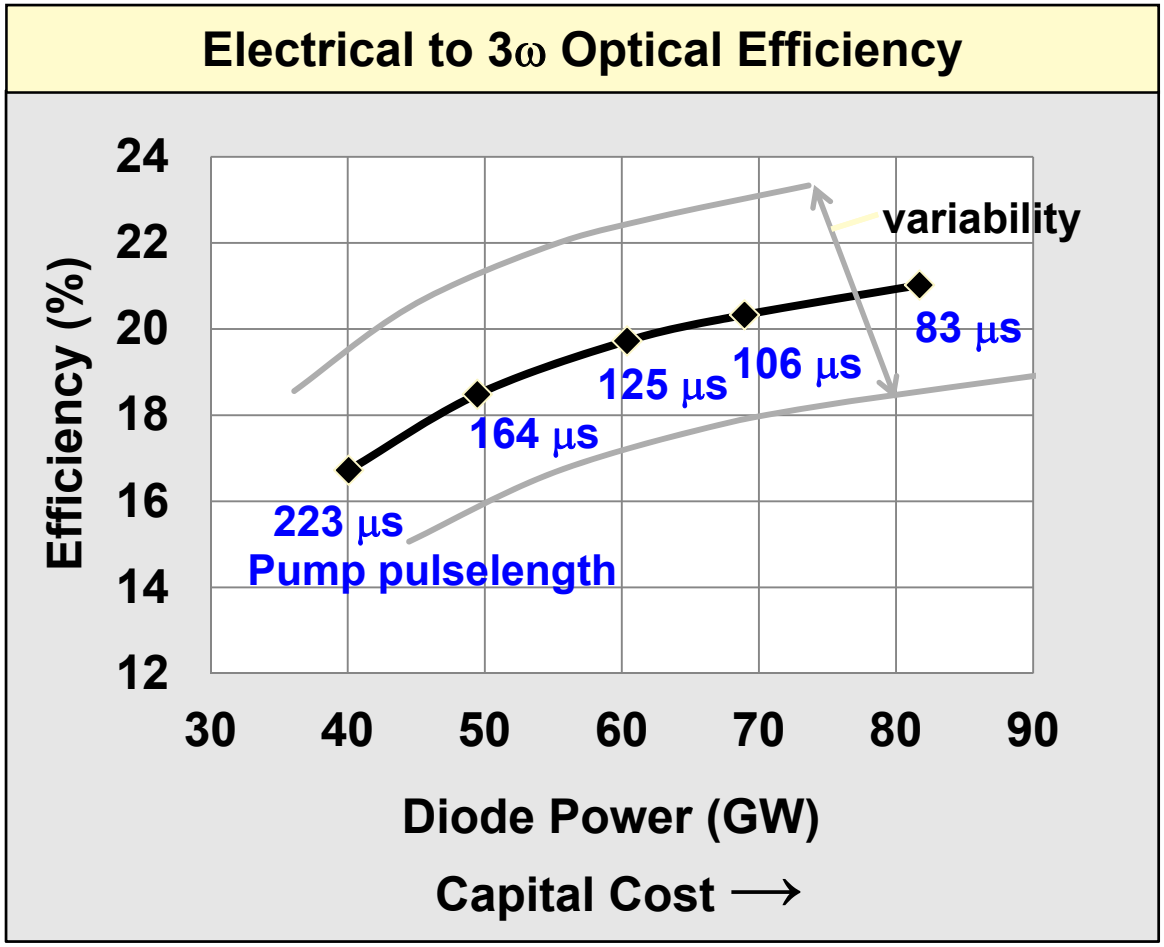
Diode pumps	→	high efficiency (18%)
Helium cooled amps	→	high repetition rate (16 Hz) with low stress
Normal amp slabs	→	compensated thermal birefringence, compact amp
Passive switching	→	performs at repetition rate
Lower output fluence	→	less susceptible to optical damage

The entire 1ω beamline can be packaged into a box which is 31 m^3 while providing 130 kW average power



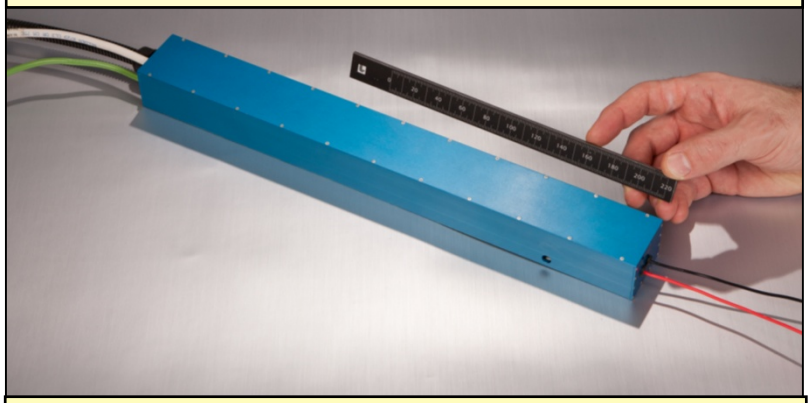
LIFE Box in NIF Laser Bay

The LIFE laser will achieve high efficiency, optimized at ~18% to balance economic and performance terms



Diode power conditioning has been made practical for the footprint and efficiency needed for Beam-in-a-Box

Single pulser unit of Diode Power Conditioning for LIFE

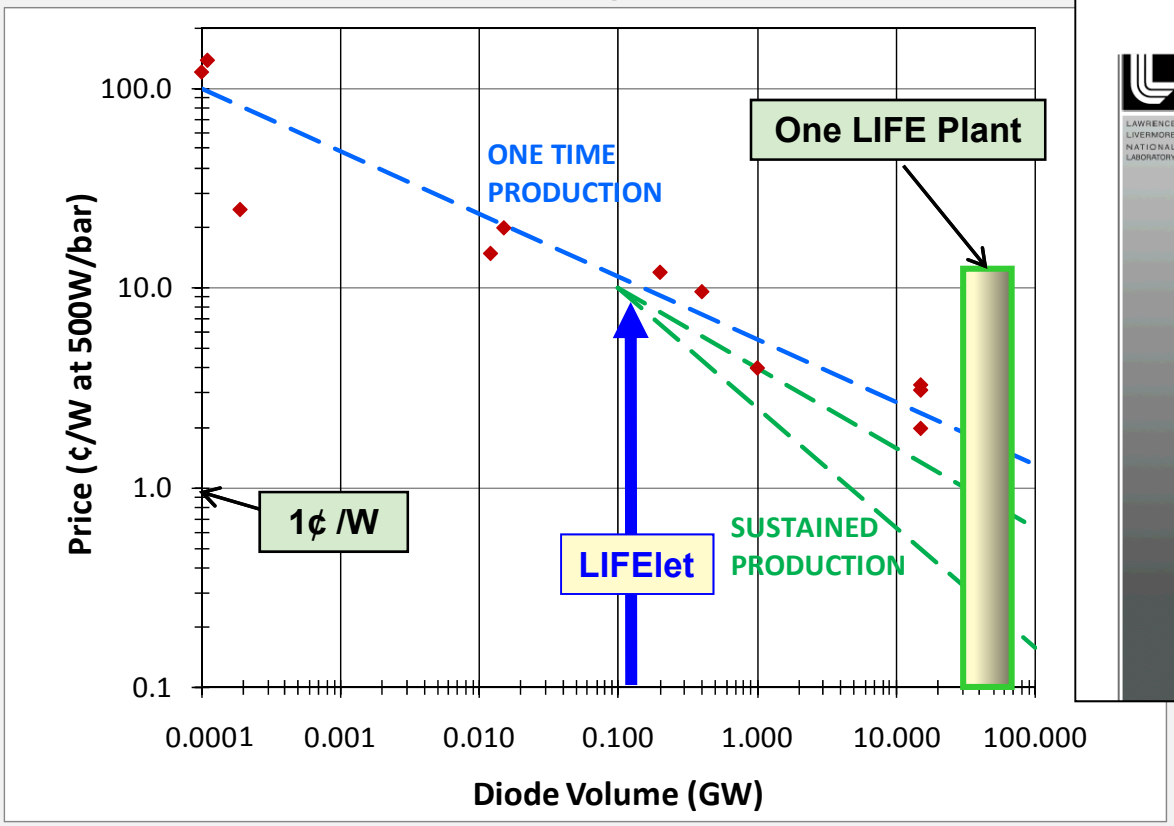


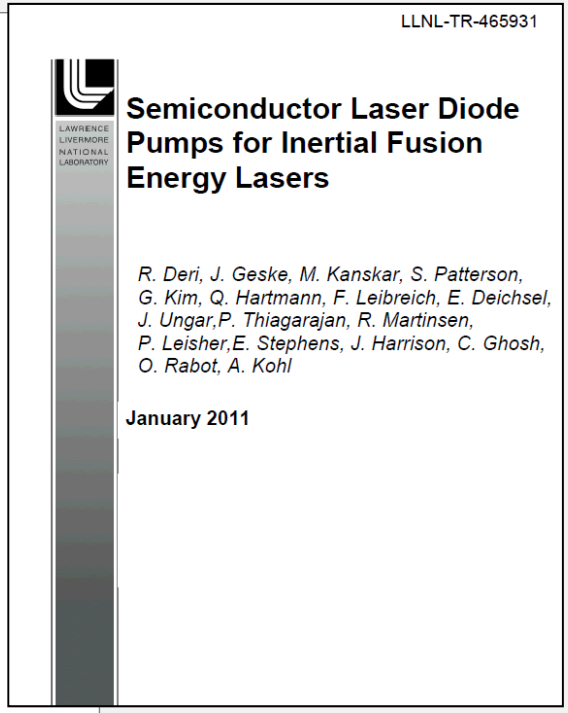
Size: 3.66 x 4.76 x 40.96 cm^3

- **Smart Pulser**
  - **"A more compact and efficient diode pulser"**
  - **High average power (12.5 kW)**
  - **High current (1000A)**
  - **High efficiency (90%) (95% efficiency possible with double size pulser**
  - **Low volume diode pulser (713 cm3)**
  - **Benefit: 10X average power, 10X decreased volume**
- **Licensing**
  - **This technology is currently being developed by a commercial company**

Diode technology will meet Beam-in-a-Box cost targets

- White paper co-authored by 14 key laser diode vendors
- 2009 Industry Consensus: 3¢/W @ 500 W/bar, with no new R&D




LLNL-TR-465931

Semiconductor Laser Diode Pumps for Inertial Fusion Energy Lasers

R. Deri, J. Geske, M. Kanskar, S. Patterson, G. Kim, Q. Hartmann, F. Leibreich, E. Deichsel, J. Ungar, P. Thiagarajan, R. Martinsen, P. Leisher, E. Stephens, J. Harrison, C. Ghosh, O. Rabot, A. Kohl

January 2011

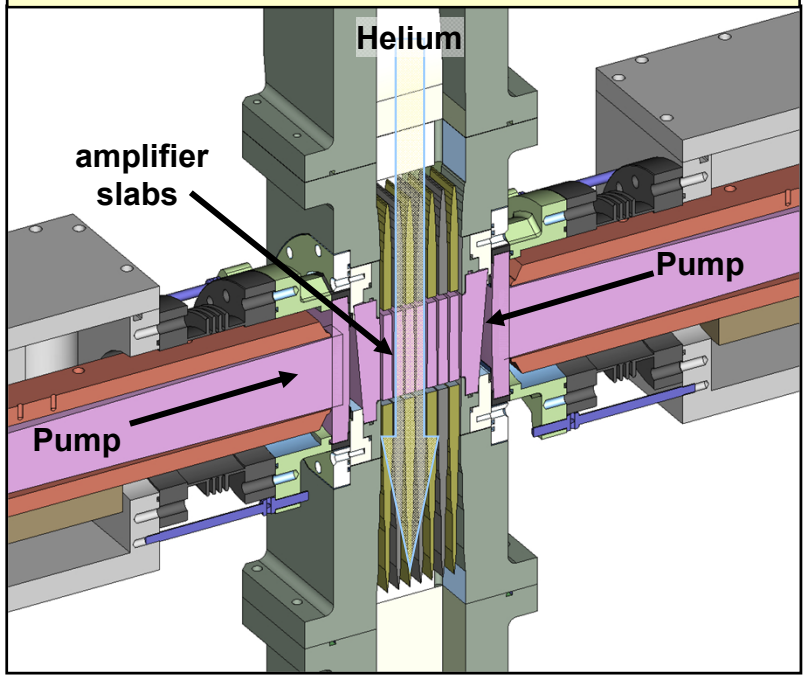
- Power scaling to 850 W/bar provides $0.0176/W (1st plant)
- Sustained production of LIFE plants reduces price to ~$0.007/W
- Diode costs for first plant: $880M
- Diode costs for sustained production: $350M

Diode costs for 1 beamline ~ $2.3M

LIFElet (1st beamline) $0.1/W
diodes for 1 beamline $13M

Amplifier heads employ gas-cooled glass slabs to remove heat longitudinally mitigating thermal lensing

Gas Cooled Amplifier Head



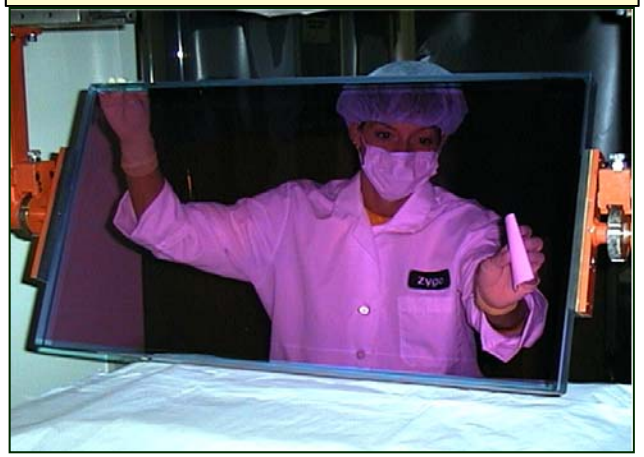
Details

- 20 glass slabs
- Aerodynamic vanes
- 5 atm Helium
- Flow rate Mach 0.1

This amplifier design was prototyped and thermal / gas cooling codes benchmarked on the Mercury laser system

The materials chosen for the LIFE laser are based on today's availability to meet near term build requirements

Nd^{3+}: phosphate laser glass



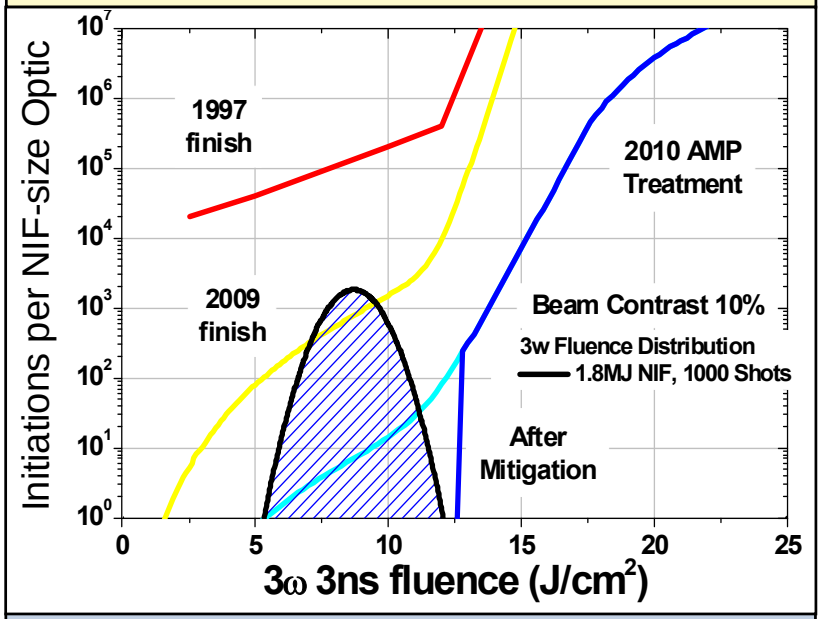
HEM Sapphire & EFG Sapphire waveplates

Quartz crystal rotators

KDP and DKDP frequency conversion crystals

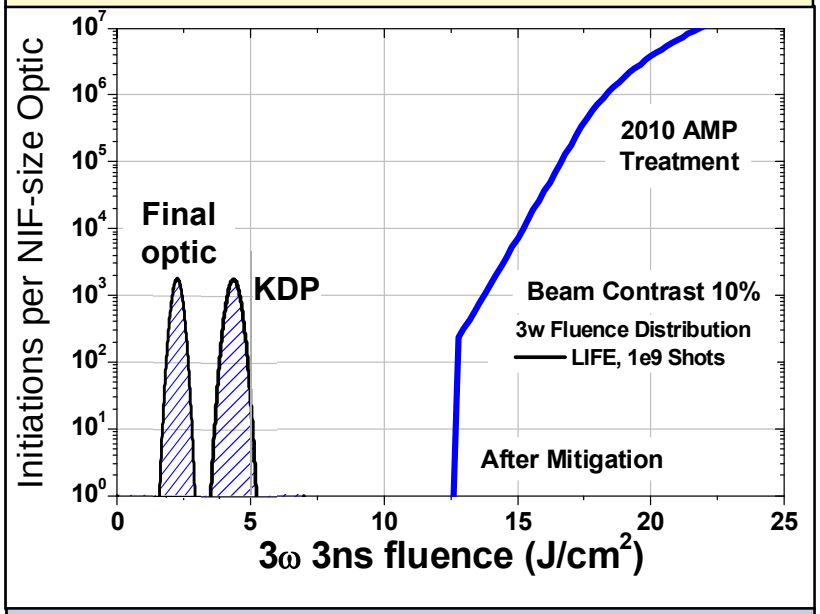
3ω optical damage (and 1ω damage) can be mitigated using existing NIF technologies and fluence scaling

Fused Silica Lenses



Tremendous progress has been made improving the damage resistance of optics for NIF

Fused Silica Lenses



LIFE: average fluence reduced by >2X to add margin against modulation for high average power

Notable differences either fall within specification or will need to be addressed in the future

- Lower average power relative to LIFE makes CLIC "easier" thermal management

- The higher repetition rate is commensurate with front end technologies, diodes, and the system Pockels cell.

- There will be some modification of the laser design to accommodate the lower extracted energy
  - LIFE diode arrays operated at lower power per pulse (this would enhance the lifetime of the diodes)
  - Smaller diode arrays with modified coolers operating at nominal LIFE power levels (lower initial capital cost)

- The front end source required to create and amplify the pulse train is completely different, but similar pulse trains have been generated for other systems

Other concerns: B-integral, beam quality, and power stability

- B-integral is less than a LIFE system (baseline 8.1 kJ, 5 ns pulse, 1.62 TW).
- Assuming a stretch factor of 10, the pulse train scales to 354, 10-ps, 5-J pulses
- Summed together, the single pulse equivalent = 3.54 ns pulse, 1770 J, 0.5 TW (significantly lower than LIFE design)
- Fluence on the gratings of an individual pulse = 9.2 mJ/cm^2, and for the overall pulsetrain = 3.26 J/cm^2

- Diffractive beamline modeling indicates we meet the LIFE specification of < 5X diffraction limit
- Underfill of the extraction aperture is possible at 1770 J which eliminates phase gradients at the edge of the thermal loaded amplifiers
- It is possible to invoke higher density adaptive optics (AO) than we might choose for LIFE due to cost / aperture issues.
- High density AO systems are used for exactly the purpose of converging on DL (they cost more, but small compared to beambox cost.)
- This is a steady state system, operated below design, so it should be very stable and long life including wavefront

- In steady state, we demonstrated < 0.6% on our front end in Mercury. Due to gain saturation, the amplifier produced ~0.3%.

Conclusion

- A baseline LIFE design and review is complete
  - Detailed designs and experimental benchmarking are underway
  - A subscale beamline is expected to be produced in the next few years
- Full scale beamlines (with associated cost reductions) are contingent on NIF ignition and the instantiation of the LIFE program
- LIFE laser 130 kW average power could be modified for CLIC based g-g pulsetrains
  - The LIFE pulsetrain is 8.1 kJ pulses at 16 Hz.
  - CLIC based pulsetrains are 3X LIFE repetition rate, but 4.6X lower energy
  - Minor modifications would be needed to accommodate the change of pulse format

LIFE

LIFE laser/laser materials team

Bob Deri
Andy Bayramian
Glenn Beer
Chuck Boley
Jeff Bude
Amber Bullington
Diana Chen
Al Erlandson
Steve Fulkerson
Glenn Huete
Travis Lange
Rod Lanning
Mark Henesian
Ken Manes
Naresh Mehta
Shahida Rana
Margareta Rehak
Sam Rodriguez
Kathleen Schaffers
Mary Spaeth
Chris Stolz
Tayyab Suratwala
John Trendholme
Steve Telford