Laser for CLIC-based gamma-gamma collider

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### The CLIC based $\gamma$–$\gamma$ collider has energy and power requirements synergistic with LIFE laser designs

<table>
<thead>
<tr>
<th>Electron Beam Parameters</th>
<th>ILC</th>
<th>CLIC</th>
<th>LPA $n_e=10^{17}$/cc</th>
<th>LPA $n_e=10^{18}$/cc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy per electron beam (GeV)</td>
<td>100</td>
<td>100</td>
<td>75</td>
<td>100</td>
</tr>
<tr>
<td>Max energy of photons (GeV)</td>
<td>60 (75)</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>$\gamma\gamma$ luminosity at the high energy peak ($10^{34}$ cm$^{-2}$s$^{-1}$)</td>
<td>0.13</td>
<td>0.19</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Electrons per bunch ($\times 10^{10}$)</td>
<td>2</td>
<td>0.68</td>
<td>0.4</td>
<td>0.13</td>
</tr>
<tr>
<td>Number of bunches in a train ($n_b$)</td>
<td>2640</td>
<td>354</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Distance between bunches ($t_b$, ns)</td>
<td>370</td>
<td>0.5</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Length of the train ($n_b*t_b$, ms)</td>
<td>980</td>
<td>0.177</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Repetition frequency ($f_{rep}$, Hz)</td>
<td>5</td>
<td>50</td>
<td>4</td>
<td>40</td>
</tr>
<tr>
<td>Electron bunch length $\sigma_z$ (mm)</td>
<td>300</td>
<td>44</td>
<td>1</td>
<td>0.3</td>
</tr>
<tr>
<td>Normalized emittance $\varepsilon_{x/y}$ (mm-mrad)</td>
<td>10/0.035</td>
<td>1.4/0.050</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Beta-function at IP $\beta_{x/y}$ (mm)</td>
<td>4/0.3</td>
<td>2/0.02</td>
<td>0.15</td>
<td>0.2</td>
</tr>
<tr>
<td>Beam size $\sigma_{x/y}$ (nm)</td>
<td>450/7.3</td>
<td>120/2.3</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Distance between conversion point and IP (mm)</td>
<td>~1.5</td>
<td>~0.5</td>
<td>&lt;75</td>
<td>&lt;350</td>
</tr>
<tr>
<td>Crossing angle (mrad)</td>
<td>25</td>
<td>25</td>
<td>&lt;50</td>
<td>&lt;50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Laser Parameters</th>
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<tbody>
<tr>
<td>Wavelength ((\mu)m)</td>
<td>1 (0.5)</td>
</tr>
<tr>
<td>Rayleigh range (mm), f#</td>
<td>~0.5, 20</td>
</tr>
<tr>
<td>Laser pulse energy (J)</td>
<td>~10/Q</td>
</tr>
<tr>
<td>Pulse length (r.m.s., ps)</td>
<td>~1.5</td>
</tr>
<tr>
<td>Peak power (TW)</td>
<td>~2.5/Q</td>
</tr>
<tr>
<td>Average power (kW)</td>
<td>150/Q</td>
</tr>
<tr>
<td>Laser power in a train (MW)</td>
<td>25/Q</td>
</tr>
<tr>
<td>Cavity enhancement factor</td>
<td>Q~300</td>
</tr>
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</table>
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**

<table>
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<th>1 ps</th>
<th>0.5 ns</th>
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<tr>
<td>177 ns (354 pulses in a train)</td>
<td>20 ms (50 Hz)</td>
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- 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

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 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/cm² 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

300 Hz, 38 W Pulse Amplifier


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 $3\omega$ 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 $1\omega$ beamline can be packaged into a box which is $31 \text{ m}^3$ while providing $130 \text{ kW}$ average power.
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 cm³

• 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

- 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
$3\omega$ optical damage (and $1\omega$ 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.
- 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/cm², and for the overall pulsetrain = 3.26 J/cm²

- 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
<table>
<thead>
<tr>
<th>LIFE laser/laser materials team</th>
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<tbody>
<tr>
<td>Bob Deri</td>
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<td>Travis Lange</td>
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<td>Rod Lanning</td>
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