Optically controlled laser-plasma electron accelerators for compact $\gamma$-ray sources

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3rd European Advanced Accelerator Concepts Workshop, La Biodola, Isola d’Elba, Italy
WG 6, 26 September, 2017
Controlling transverse effects:
Match the pulse spot size to
\[ R_m = \frac{2^{3/2}}{k_p^{-1}} \left( \frac{P}{P_{cr}} \right)^{1/6} \gg k_p^{-1} \]
⇒ Stable self-guiding & Full electron cavitation

Longitudinal effects
– red-shift of the pulse leading edge & self-compression due to negative GVD of radiation in plasma –
remain uncontrolled
⇒ Reduced phase velocity of the bubble
⇒ Early electron dephasing, limited energy gain
⇒ Massive continuous self-injection

Matching strategy leads to unfavorable energy scaling

Match pulse length and spot size to make electrons dephase as the pulse depletes:

\[ \tau_L = \frac{2R_m}{3c} \]

Energy gain at dephasing/depletion:

\[ \Delta E \ [\text{GeV}] = 0.125 \ (P[\text{PW}])^{1/3} \ (n_{20} \ \lambda_{\mu m}^2)^{-2/3} \]

Robust self-guiding & self-injection:

\[ \frac{P}{P_{cr}} > 10 \ \Rightarrow \ n_{20} \ \lambda_{\mu m}^2 > 1.8 \times 10^{-3} \ (P[\text{PW}])^{-1} \]

Stringent scaling of the energy gain:

\[ \Delta E \ (\text{GeV}) < 8.6 \ P[\text{PW}] \]

\[ \Delta E \approx 1 \ \text{GeV} \ \Rightarrow \ P \approx 120 \ \text{TW} \]

\[ \tau_L \approx 32 \ \text{fs} \]

\[ L_{\text{dephasing}} \approx 0.7 \ \text{cm} \]

Regime is accessible, but

the repetition rate is <<<< 10 Hz
Inverse Compton (Thomson) scattering and its requirements for e-beams

From: C. P. J. Barty, LLNL Proposal for the ELI-NP $\gamma$-Source, ELI-NP Gamma Source Meeting, 04/18/2011

- Photon flux $> 10^6$/shot/full bandwidth
  
  E-beam 5-D brightness $>10^{16}$ A/m$^2$ [A. Cianchi et al., NIM A 829, 343 (2016)]

  Sub-% energy spread in the e-beam

- Photon energy 10-20 MeV – challenge

  GeV e-beams needed – scaling suggests using PW-/kJ-scale pulses

- Repetition rate in kHz to raise the dosage – major challenge

  MW-class average-power laser amplifiers are not going to be available soon
Raising the repetition rate:
GeV LPA with sub-Joule (10-TW-scale) pulses

Moderate average power:

1. Enables **high repetition rate** needed by applications that require high dosage (medicine, nuclear fluorescence studies *etc.*)

   1J @1 kHz = 1 kW — a hard, yet manageable laser engineering problem.

2. Helps **reduce the size and cost of facilities**.

3. **Lifts the barriers for first-principle modeling.**

4. Enables **real-time control** of the laser pulse phase (using genetic algorithms) for optimization of the acceleration process

**Transform-limited, 10-TW-class pulse rapidly destroys itself and e-beam 😞**

1. Self-guiding needs a dense, highly dispersive plasma (\( \sim 10^{19} \text{ cm}^{-3} \))

2. Self-compression of the pulse

   (a) keeps the energy gain below half-GeV

   (b) forces expansion of the bubble, hence massive dark current

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**CALDER-Circ code:**

**VORPAL-PD code:**

<table>
<thead>
<tr>
<th>Power / energy / length</th>
<th>70 TW / 2.1 J /30 fs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma density, ( n_0 )</td>
<td>( 6.5 \times 10^{18} \text{ cm}^{-3} )</td>
</tr>
</tbody>
</table>

\( P/P_{cr} \approx 16 \)


E \( \approx 420 \text{ MeV} + \text{huge tail} \)
Large bandwidth \((\Delta \lambda \sim \lambda_0)\) and negative chirp solve the problem 😊

These features:

- mitigate the frequency red-shift
- slow down pulse self-compression in dense plasmas \((\sim 10^{19} \text{ cm}^{-3})\)
- extend the dephasing length, boosting the energy gain to GeV level
- strongly reduce the energy tail.

**HIGH EXPECTATIONS**: Background-“free” near-GeV acceleration with 1.4J laser energy

20–30 fs pulse

\(n_0 = 6.5 \times 10^{18} \text{ cm}^{-3}\)

![Graph showing energy distribution with and without chirp effects]
Temporally advanced blue-shifted "head" protects the optical driver from nonlinear erosion

Head: 20 fs, 0.7 J, $\lambda_{\text{tail}} = 0.8 \mu m$
Tail: 20 fs, 0.7 J, $\lambda_{\text{head}} \approx 0.53 \mu m$

orthogonally polarized (incoherent mixing)

- Frequency shift in Raman cells with subsequent conventional CPA
  [F. B. Grigsby et al., JOSA B 25, 346 (2008)]
- Energy-efficient methods of 2nd harmonic pulse generation.
Acceleration with a single TLP: Electron beam ruined

Pulse at dephasing:
Compressed to a single cycle and 60%-depleted

“Photon phase-space rotation”: mid-IR photons slide into the bubble

QME bunch:
\[ \langle E \rangle = 427 \text{ MeV} \]
\[ \sigma_E / \langle E \rangle = 6\% \]
\[ \varepsilon_{\text{norm, } \perp} = 0.7 \text{ mm mrad} \]
Charge \[ 0.495 \text{ nC} \]
RMS current \[ 90 \text{ kA} \]
RMS divergence \[ 2.9 \text{ mrad} \]

5-D brightness:
\[ 2\langle I \rangle (\pi \varepsilon_{\text{norm, } \perp})^{-2} = 3.8 \times 10^{16} \text{ A/m}^2 \]

Simulation codes: WAKE and CALDER-Circ (energy spectra)
Bi-color stack: Doubling electron energy

QME e-beam at dephasing ($L_{\text{dephasing}} \times 1.8$):

- $\langle E \rangle$: 882 MeV ($\times 2$ of reference)
- $\sigma_E/\langle E \rangle$: 3.2%
- $\varepsilon_{\text{norm, } \perp}$: 0.4 mm mrad ($\times 1/2$ of reference)

Charge: 73 nC
RMS current: 88 kA (same as reference)
RMS divergence: 1.35 mrad

5-D brightness: $1.1 \times 10^{17}$ A/m$^2$ ($\times 3$ of reference)

Tail at dephasing:
Reduction by a factor 6 in charge, by a factor 20 in average flux
Improvement in Thomson scattering signal

E-beam phase space and flux (in $10^7$ MeV$^{-1}$) at dephasing

Photon flux (in $10^{12}$ MeV$^{-1}$ sr$^{-1}$) in the e-beam propagation direction
- head-on collision
- on-axis observation

- Photon energy boost by a factor 4.2 (to 16 MeV)
- Increase in the signal to background ratio, from 2:1 to 4:1

**Thomson back-scattering (almost linear regime, quasi-planar-wave interaction):**
Interaction laser pulse: Linearly polarized, $r_0 = 16.8 \, \mu m$; $a_0 = 0.1$; $\lambda = 0.8 \, \mu m$; FWHM 250 fs
**Time delay in the stack controls $\gamma$-photon flux and energy**

Electron energy spectra at dephasing

$\gamma$-ray flux in the direction of e-beam propagation

<table>
<thead>
<tr>
<th>QME $\gamma$-ray signals</th>
<th>Reference</th>
<th>Stack wit full overlap ($T = 0$)</th>
<th>Stack with $T = 15$ fs</th>
<th>$z = 1.47$ mm</th>
<th>Dephasing (3.07 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\langle E_\gamma \rangle$ (MeV)</td>
<td>3.85</td>
<td>5.67</td>
<td>4.35</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>$\sigma_E / \langle E_\gamma \rangle$, %</td>
<td>18.7</td>
<td>17.1</td>
<td>21.3</td>
<td>15.5</td>
<td></td>
</tr>
<tr>
<td>$N_\gamma$ per $\Omega_d$</td>
<td>$8.95 \times 10^6$</td>
<td>$5.08 \times 10^6$</td>
<td>$1.52 \times 10^6$</td>
<td>$1.58 \times 10^6$</td>
<td></td>
</tr>
<tr>
<td>Energy ($\mu$J)/power in $\Omega_d$</td>
<td>5.5 (1 GW)</td>
<td>4.6 (1.2 GW)</td>
<td>1.1 (1.3 GW)</td>
<td>4 (4.7 GW)</td>
<td></td>
</tr>
</tbody>
</table>
Few-% energy spread of e-beam imparts 15–20% bandwidth into the Thomson signal

Full phase space of e-beam:

\[ \langle p_z \rangle = 1726 \, m_e c, \quad \sigma_{p_z} = 56 \, m_e c \quad (3.25\% \text{ energy spread}) \]
\[ \langle p_r \rangle = 0, \quad \sigma_{p_r} = 2.3 \, m_e c \quad (1.35 \text{ mrad divergence}) \]

Reduced phase space I:

\[ \langle p_z \rangle = 1726 \, m_e c, \quad \sigma_{p_z} = 0 \quad (\approx 0\% \text{ energy spread}) \]
\[ \langle p_r \rangle = 0, \quad \sigma_{p_r} = 2.3 \, m_e c \quad (1.35 \text{ mrad divergence}) \]

Reduced phase space II:

\[ \langle p_z \rangle = 1726 \, m_e c, \quad \sigma_{p_z} = 56 \, m_e c \quad (3.25\% \text{ energy spread}) \]
\[ \langle p_r \rangle = 0, \quad \sigma_{p_r} = 0 \quad (\text{zero divergence}) \]

\[ \langle E_\gamma \rangle = 16 \, \text{MeV} \]
\[ \sigma_E = 2.5 \, \text{MeV} \quad (15.5\% \text{ spread}) \]

\[ E_\gamma \approx 4E_{\text{int}} \langle \gamma_e \rangle^2 \approx 18.35 \, \text{MeV} \]

\[ E_{\text{int}} = 1.55 \, \text{eV} \]
Electrons from stack-driven LPA for quasi-monochromatic Thomson sources

- High-power (1–5 GW), fs-length $\gamma$-ray pulses contain $> 10^6$ photons in the sub-μsr observation solid angle

- This flux corresponds to the full bandwidth (1–2.5 MeV) imparted by a few-% energy spread in the e-beam

- Mean photon energy is tunable between 4 and 16 MeV without losing photons in the μsr observation solid angle $\Omega_d = (\pi/2)\langle\gamma_e\rangle^{-2}$

- Signal to background ratio is better than 4:1

- Changing time delay in the stack permits accurate tuning $e/\gamma$ energy and flux, with the same laser energy and frequency ratio in the stack

- Sub-Joule energy in stack components affords kHz repetition rate at the affordable average power

- Expectation of $10^{10}$ ph/s flux (good for NRF applications).
Trains of multi-color X/γ-ray pulses: What are they good for?

Comb-like X/γ - ray beam: Train of wave packets with an adjustable frequencies and time delays

Source: a comb-like e-beam – a train of bunches with adjustable energies and time delays

A bi-color X-ray beam @ SPARC-LAB

Generation mechanism: bi-color FEL or inverse Compton (Thomson) scattering

Images:

V. Petrillo et al., Dual-color X-rays from Thomson or Compton sources, Proc. SPIE 9512, 95121E (2015)

Applications:

- **Ultrafast** (on a fs- to ps-scale) pump-probe experiments in AMO or HEDP
- Time-domain spectroscopy [J. F. Cahoon et al., Science 319, 1820 (2008)]
Generating comb-like e-beams in stack-driven LPA

Stack (with $T = 15$ fs) permits focusing head and tail differently.

Weak focusing of the tail ($R_{\text{tail}} \geq R_{\text{head}}$) destabilizes the bubble. Periodic injection generates a polychromatic train of bunches.

\[ R_{\text{tail}} = R_{\text{head}} = 13.6 \, \mu\text{m} \]

\[ R_{\text{tail}} = (3/2)^{1/2} R_{\text{head}} \]

\[ R_{\text{tail}} = 2^{1/2} R_{\text{head}} \]

\[ R_{\text{tail}} = 3^{1/2} R_{\text{head}} \]

— too weak focusing makes injection ineffective

Brightness ($10^{17} \, \text{A/m}^2$): 

(1) 0.44  

(2) 0.96

\[ \sigma_{E}/\langle E \rangle: \]

(1) 3.2\%  

(2) 2.4\%
Generating X/$\gamma$-ray pulse trains using comb-like e-beams from stack-driven LPA

Characteristics of $\gamma$-ray energy bands (QME pulses):

$\sigma_E/\langle E_\gamma \rangle$: 14.7 to 19.5%

$N_\gamma$ per $\Omega_d$: 0.4 to $1.6 \times 10^6$

Total energy per band, in detector solid angle, $\Omega_d = (\pi/2)\langle \gamma_e \rangle^{-2}$: 0.17 to 4 $\mu$J

<table>
<thead>
<tr>
<th>Case 3</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\langle E_\gamma \rangle$ (MeV)</td>
<td>2.8</td>
<td>7.25</td>
<td>15.8</td>
</tr>
<tr>
<td>$\sigma_E/\langle E_\gamma \rangle$, %</td>
<td>19.4</td>
<td>14.7</td>
<td>15.7</td>
</tr>
<tr>
<td>$N_\gamma$ per $\Omega_d$</td>
<td>$0.91 \times 10^6$</td>
<td>$0.62 \times 10^6$</td>
<td>$1.25 \times 10^6$</td>
</tr>
<tr>
<td>Energy/power per $\Omega_d$ (\textmu J)</td>
<td>0.4 (0.17 GW)</td>
<td>0.72 (0.75 GW)</td>
<td>3.16 (4.27 GW)</td>
</tr>
</tbody>
</table>
Propagating the stack in a channel (a) adds more control, (b) further boosts electron energy.

Same stack as before, with a $T = 15$ fs delay. Stack head and tail have the same spot sizes, matched to the single-mode channel.

The e-comb absorbs 10% of laser energy.

The peak energy 1.2 GeV (vs $\sim 430$ MeV of the reference case).

Progress of comb-like e-beam through dephasing and generation of multi-color $\gamma$-ray beams

$z = 1.51$ mm

$z = 2.23$ mm

$z = 2.91$ mm

All four bunches have 5-D brightness above $1.4 \times 10^{17}$ A/m$^2$

<table>
<thead>
<tr>
<th>4-color $\gamma$-ray signal</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\langle E_\gamma \rangle$ (MeV)</td>
<td>24.1</td>
<td>12.6</td>
<td>4.67</td>
<td>2.27</td>
</tr>
<tr>
<td>$\sigma_E / \langle E_\gamma \rangle$, %</td>
<td>15</td>
<td>18.4</td>
<td>20</td>
<td>22.6</td>
</tr>
<tr>
<td>$N_\gamma$ per $\Omega_d$</td>
<td>$1.64 \times 10^6$</td>
<td>$0.66 \times 10^6$</td>
<td>$0.585 \times 10^6$</td>
<td>$0.595 \times 10^6$</td>
</tr>
<tr>
<td>Energy/power per $\Omega_d$ ($\mu$J)</td>
<td>6.5 (10.3 GW)</td>
<td>1.34 (1.8 GW)</td>
<td>0.46 (0.39 GW)</td>
<td>0.22 (0.34 GW)</td>
</tr>
</tbody>
</table>
Designing the LPA drive pulse as an incoherent stack of independent sub-Joule, transform-limited pulses with a large difference frequency ($\Delta \omega \sim \omega_0$) permits an unprecedented freedom in e-beam phase space control, suppressing the background and increasing 5-D brightness of individual bunches above $\sim 10^{17}$ A/m$^2$.

Stack-driven LPAs promise generation of fs-length, ultra-bright, near-GeV electron bunches at a kHz repetition rate, with affordable average power.

These bunches (or trains of bunches) promise to drive quasi-monochromatic (or comb-like) Thomson-scattering $\gamma$-ray sources, tunable into 10’s of MeVs, while keeping the $\gamma$-ray pulse length extremely short (100’s of as) and the number of photons high ($> 10^6$).

**ACKNOWLEDGEMENTS**

Inverse Thomson scattering simulations were completed by S.Y.K. utilizing the Holland Computing Center of the University of Nebraska.

SYK cordially thanks Natasha Pavlovikj of HCC for assistance.
Addenda
Simulation tools: fully relativistic PIC codes & particle tracker for radiation calculation

- Exploring optical pulse evolution in the plasma and beam loading effects: **WAKE**  
  (extended-paraxial, ponderomotive guiding center, quasi-static)  

- Accurate simulation of self-injection and acceleration: **CALDER-Circ**  
  (quasi-cylindrical, fully explicit; poloidal mode decomposition of fields and currents)  
  [A. F. Lifschitz et al., *J. Comp. Phys.* **228**, 1803 (2009)]

Also: numerical Cherenkov-free EM solver; 2\textsuperscript{nd} or 3\textsuperscript{rd} order macro-particles  
[R. Lehe, A. F. Lifschitz et al., PR-STAB Beams 16, 021301 (2013)]

- **Inverse Thomson scattering code**  

fully relativistic particle tracker; laser beam is paraxial; radiation calculation using classical formula

\[
\frac{d^2I}{d\omega d\Omega} = 2|A(\omega)|^2, \quad A(\omega) = \left(\frac{e^2}{8\pi^2c}\right)^{1/2} \int_{-\infty}^{\infty} \exp\left[\frac{n \times [(n - \beta) \times \hat{\beta}]}{(1 - \beta \cdot n)^3}\right]dt, \quad \frac{d^2I_\omega}{d\omega d\Omega} = \frac{1}{N_s} \sum_{i=1}^{N_s} \frac{d^2I_i}{d\omega d\Omega}.
\]
Stack vs. reference: Suppressing continuous injection

Due to much slower self-compression of the stack

- bubble expands slowly
- continuous injection insignificant (hence the weak energy tail)