Mono-energetic photon sources

Photon source
Cameron G.R. Geddes, cgrgeddes@lbl.gov

Hai-En Tsai, Sven Steinke, Jeroen van Tilborg, Carlo Benedetti, Eric Esarey, Hann-Shin Mao, Kei Nakamura, Tobias Ostermayr, Carl B. Schroeder, Csaba Toth, Jean-Luc Vay, Remi Lehe, Brian J. Quiter, Paul Barton, Kai Vetter, Wim Leemans
Lawrence Berkeley National Laboratory

David Grote, Alex Friedman
Lawrence Livermore National Laboratory

Bernhard Ludewigt, John Valentine, Brian J. Quiter
Lawrence Berkeley National Laboratory

Marie-Anne Descalle
Lawrence Livermore National Laboratory

Glen Warren
Pacific Northwest National Laboratory

David Chichester
Idaho National Laboratory

Cameron Miller
U. Michigan, Ann Arbor

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Improved container, rail, air cargo and vehicle scanning enabled by mono-energetic photon sources

- **Application space:** Screening of container, rail, and air cargo as well as vehicles

- **Problem:** Xray and CT material identification, resolution, and penetration currently limited
  - bremsstrahlung dose, energy & angle spread

- **Solution:** Photon source producing mono-energetic, narrow angle, pulsed beam

- **Results:** Mono-energetic source reduces dose 10-100x, improves discrimination ~10x
  - Present project: demonstrate path to compact system using plasma based accelerators
  - Path to applications: development of robust, kHz laser drivers and systems

- **TRL:** 3

- **Contact:** cgrgeddes@lbl.gov, 510-495-2923
Laser-driven systems are shrinking rapidly
Already at trailer scale, smaller systems in development

- Lab experiments set needs:
  - COTS 10 TW, 10 Hz, trailer
  - 2 MeV concept fits 20’ van
    - Smaller systems anticipated
    - kHz laser needed for applications

LPA drive laser
COTS: Amplitude TT-Mobile
10 Hz, 10 TW

Scattering laser: similar to pump of drive laser, plus compressor to ~3 ps

Rotate for rastering

Fits 20’ truck

Layout with current laser

MeV Photons

Shield

5.1 m

2.4 m

30m²

1: Amplitude Technologies
One to two orders of magnitude improved dose and signal accessible with mono-energetic photon sources

Energy selection: enhance signal

- **Radiography**: maximize transmission and material contrast, reduce dose
  - Removes beam hardening

- **NRF**: enable specific detection based on atomic ratios with greatly reduced dose

- **Photofission**: lower dose for Rad/Nuc

Enables precision measurements: Cargo, single sided detection cases simulated

- Dose reduced 10x-100x with energy control + narrow divergence
- Material discrimination improved 10x
- Spatial resolution improved
- NRF material identification and backscatter 3D enabled/improved

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Related:
- Joe Harms, PhD Dissertation Georgia Tech, 2018 (Erickson group).

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mrad divergence: mitigate scatter, target dose

Also: EZ3D type methods

Pulsed beam: 3D
- Enable backscatter timing, 3D without tomography (INL)
- Micron emission spot:
- Potential micron-scale resolution
Monoenergetic, narrow-angle, pulsed & small spot size photon sources offer new capabilities if compact

- Applications use bremsstrahlung due to size

- Thomson scattering a laser from an e-beam produces high performance photon sources
  - Low energy spread: enhanced signal, low dose
  - Tunable energy: material discrimination
  - mrad divergence: high contrast, low dose
  - Small spot, short duration: resolution & 3D
  - Adjustable per-shot: flux, energy, polarization

- Proven on large fixed science facilities
  - Size limits deployment: 0.5 GeV class accel.

- Laser plasma acceleration (LPA): GeV in cm (vs 10’s of m): path to a compact system¹

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Demonstration addresses key enabling techniques for a compact MPS in integrated experiment

**Requirement & conventional limit**

- **High-energy, high quality e-beam at 0.2-0.6 GeV for MeV photons**
  - Conventionally, long accelerator

- **High flux photon production from low scattering cross-section**
  - Conventionally, requires very large accelerator current or laser

- **Shielding increases with energy and current, limits source size**
  - Conventionally, larger than accel.

**Project: integrate solutions**

- **High quality cm-scale LPA**
  - Meets photon source need

- **Techniques to increase photon yield, reduce current/laser size**
  - Diffraction: Guide scatter laser
  - Nonlinearity: shaped pulse

- **Deceleration of electrons by LPA: reduce beam dump size**
  - Demonstrated in staged exp.

**Current Project: Integrated prototype to demonstrate key per-shot elements**

- Newly constructed laboratory based 50 TW laser at 5Hz repetition rate
- Provides test-bed for evaluations of application utility, signatures
Photon source integrates past individual results
New facility enables combined test

Controllable LPA at Photon-Source Energies
Up to 1 GeV in few-cm plasmas (for 20 MeV photons)

Electron Deceleration

Controlled Thomson Scatter Photon to produce 10% ΔE, mrad

0.1 μm photon emission spot size
fs-class short pulse

Plateau et al., PRL 2012.
van Tilborg et al., PRL 2006.
kHz laser drivers are being developed to enable application-motivated scan rates

High peak power, low average power

Near term: kBELLA kHz, 3 Joule demonstrate photon source driver

High average and peak power

1 Hz, PW BELLA laser

High average power, low peak power

Long term: Coherent combining of fiber lasers offers efficient path to 10's of kHz

100 kW average power, industrial lasers, 35% wall plug efficiency
Conclusion and future work

- Compact near-monoenergetic photon sources provide strong benefit
  - Moderate (10-30%) energy spread improves radiography and material discrimination, scalable to narrow (<1%) to enable/improve NRF
  - mrad angular spreads – mitigate scattering, improving contrast & dose
  - ≤μm emission spot – very high spatial resolution
  - fs-class short pulse – facilitates backscatter 3D methods

- Improved signal > 10x in many cases, with > 10x reduction in dose
  - Cargo, vehicle, pallet and other scanning and detection applications

- Compact source demonstration commissioned, in progress: control energy & energy spread, photon production, e- deceleration
  - Test applications/benefit: test cases & collaboration welcome

- Laser drivers are being developed to deliver ≥ kHz repetition rates motivated by applications
Primary references, available at [http://geddes.lbl.gov](http://geddes.lbl.gov)

**Survey of applications impact:**

**Plans for development of the source:**
Backup slides – Photon Source
Thomson/Compton photon sources require precise control of accelerator electron beam and scattering laser.

Narrow $\Delta E_\gamma$ requires high quality e-beam.

- $\Delta E_{ph} \sim 10\% \Rightarrow \Delta E_e \sim 5\%, \leq \text{mrad}$
- $\Delta E_{ph} \sim 2\% \Rightarrow \Delta E_e \sim 1\%, \leq 0.1 \text{ mrad}$

Energy $\Rightarrow$ Angle $\Rightarrow$

Focal depth $\sim$ Pulse length

Low scattering cross section: quality & flux trade off

1 ph/e- in 10% $\Delta E_{ph}$: 40J at $a_0=0.3$

LPA based Thomson photon sources
Intensively developed worldwide

Selected highlights

**United States**
- U. Nebraska – multi-MeV energies, energy control
- U.T. Austin – back reflection, 0.2 MeV
- U. Michigan – high brightness nonlinear at MeV
- LLNL – high energy density physics applications
- LBNL – facility for MeV + guiding and deceleration

**Europe**
- Jena – LPA demonstration, theory
- LMU and MPI Garching – keV energy spread control
- Helmholtz-Zentrum Dresden - Rossendorf
- LOA – foil back-reflection at 50 keV, control
- ELI Beamlines – upcoming experiments

**Asia**
- SIOM-CAS – MeV energy spread measurement
- KAERI, Korea – experiment in progress
- AIST and U. Tokyo, Japan – source control
Photon source is part of BELLA Center, driving LPA technology for high energy physics and applications.

Existing and planned laser facilities in Building 71 at LBNL.

Current BELLA
MeV photons

k-BELLA (initiative)
BELLA-i beamline (Initiative)
Medical
FEL
Plasma wave driven by radiation pressure of TW, fs laser GeV/cm gradients: compact accelerator for Thomson sources.

Recent GeV-class LPA development demonstrates high quality beams needed for 1-9 MeV photon sources

Electrons to 250 MeV using 0.5J/10TW + laser phase front control

$\Delta E_e < 1.4\%$ FWHM from Colliding pulse injection control

$\varepsilon \sim 0.1\mu m$ via Betatron emission

Tunable 0.5 GeV - modulated density 1.5-2 J/50 TW class

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Matlis et al., Proc. AAC 2012
Geddes et al., Proc. AAC 2014; NIM-B 2015
Gonsalves et al., Nat. Physics 2011

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Plateau et al., PRL 2012

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Gonsalves et al., Nat. Physics 2011
Integrated experiment to demonstrate, laser-plasma driven, compact photon system concept

• Build and test concept for a compact source & system
  - Electron beam produced by compact cm-scale laser plasma accelerator (LPA)
  - Produce 1-9 MeV photons
  - Increase photon production: control scattering laser length & focusing
  - Reduce shielding: decelerate electrons after scattering
LPA experiment running to prepare for laser-plasma driven, compact photon source work

Laser operating at 0.6J/42fs; 3J amp ready

LPA running, photon experiment ready

Mode out at 1J
42 fs pulse

High quality focal mode

First electron beams produced
Simulations show that narrow energy spread photon sources are enabled by high performance LPAs

\( \Delta E_{\text{ph}} \) limited by electron quality: \( \text{div}_e, \Delta E_e \)

Demonstrated LPAs allow \( \Delta E_{\text{ph}} \approx 10\% \)
- \( E_{\text{ph}} \) of 1-10 MeV
- Electron emittance dominates \( \Delta E_{\text{ph}} \)
- Divergence still dominant for scatter in plasma

Scattering laser control separate from LPA laser required for high photon yield/low \( \Delta E_{\text{ph}} \)
- Low amplitude to avoid nonlinearity
- \( \sim 1\text{-}10 \text{ ps} \gg \text{LPA driver duration for } \sim 1 \text{ photon/e-} \)

Demonstrated 1\% \( \Delta E_e \) allows \( \Delta E_{\text{ph}} \approx 2 \% \)
- Experiments indicate potential for <1\%
- e-beam refocusing or emittance reduction required to reduce divergence

10-20\% \( \Delta E_{\text{ph}} \) simulated from direct in-plasma scattering
0.2 GeV LPA
0.5 GeV LPA

Percent-level \( \Delta E_{\text{ph}} \) with divergence control

Related A.G.R. Thomas et al PRST-AB 2010 (U. Michigan); Ghebregziabher PRSTAB 2013 (UNL)
Simulations show high photon yield with realistic scattering laser & e-current by controlling scattering laser

Issue: large laser spot, high energy typically required for ps scatter laser
- Wastes energy, requires larger laser

• Reduce scatter laser energy: guiding\(^1,2\)
  - Mitigates diffraction, lengthens scattering

• \(10^8\) ph/shot possible w/ scatter energy
  ~LPA driver, in range of applications

Requirement: separately controlled scattering laser pulse, \(E_{\text{scatter}}\sim\) Joule

Further improvement: Laser shaping\(^3\)
- Mitigates nonlinearity, intense scattering

Guiding increases focused propagation length: \(> 10 Z_R\) routine\(^2\)

![Graph showing minimal broadening with laser shaping](image)

40J Unguided
1J Guided \(w=6\mu m\)

\(5\) ph/e- at \(a_0=0.15\)

Simulations indicate minimal broadening

Backup slides – Mono-energetic photon applications
Monoenergetic photon sources could enhance radiography, fission signatures, NRF

- **Radiography:**
  - Energy selection for maximizing transmission and Z-contrast, minimizing dose

- **Photofission:**
  - Energy selection to maximize fission signatures

- **Nuclear Resonance Fluorescence:** narrow line → low energy spread / high spectral density greatly improve signal to noise
Quasi-monoenergetic photons at ~10\% \Delta E improve radiography and material discrimination

- Application survey\(^1\) shows high potential impact, including:
  - Screening & Inspection (Cargo)
  - Resolution of different materials
  - Penetration of thick targets
  - High resolution radiography of fine features

- Controlling photon energy improves signal
  - Mitigate contrast degradation by scattering/hardening
  - Remove low energy photons: reduce dose 3x-4x
  - Multiple energies: improve material discrimination

Bremsstrahlung sources - limited resolution
CAARS radiography/Z: U sphere in Pb & Lexan

MPS dual energy ratio increases contrast
Energy spread at 20\% level\(^1\)

1: Final report of project “Impact of Monoenergetic Photon Sources on Nonproliferation Applications,” Cameron Geddes, Bernhard Ludewigt, John Valentine, Brian Quiter, Marie-Anne Descalle, Glen Warren, Matt Kinlaw, Scott Thompson, David Chichester, Cameron Miller, Sara Pozzi (2017)
Narrow-angle beams further improve mono-energetic photon applications

- milliradian (mrad) divergence ‘pencil beam’ isolates scattering-induced degradation
  - Improves contrast, resolution
  - Allows dose targeting
  - Dose reduced 1-2 orders
  - Clear signal through thick objects

- dual-E ratio for distinguishing materials improved >10x

- Requires high pulse rate and scanning of beam
  - Example: container scan at 80cm/sec, 1cm res. =20kHz
  - 20-40cm steel: $10^6$-$10^8$ ph/pulse in mrad cone

<table>
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<tr>
<th>Type &amp; Energies</th>
<th>Ratio</th>
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<tr>
<td>Brems: Fe 9MeV/6MeV</td>
<td>1.57</td>
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<tr>
<td>Brems: Fe+Pb 9MeV/6MeV</td>
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<tr>
<td>MPS: Fe 9MeV/3MeV</td>
<td>2.87</td>
<td>41%</td>
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<td>MPS: Fe+Pb 9MeV/3MeV</td>
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mrad divergence: improved contrast & lower dose by mitigating scatter

log (photons/cm$^2$)

Scanned pencil beam concept

Radiography Detector

Simulation: Cameron Miller (U. Michigan)
Screening and interdiction alarm resolution: Reduced photofission dose, NRF enabled

- Pencil beam of $\leq 3$ mrad important to isolate dose to area of interest

- Photofission:
  - MPS dose per fission $\sim 50x$ lower than bremsstrahlung dose near 10 MeV
  - Detection of 2 kg HEU shielded by 20-30 cm thick steel box in seconds
    - KHZ MPS of a few $10^{11}$ ph/second in few mrad divergence at $\Delta E_{ph} \sim 20\%$

- NRF: isotope specific, SNM and non-SNM
  - Enabled at $\Delta E_{ph}$ at or below 2% range
    - Examples for HEU detection (6-$\sigma$) with backscatter in <100 seconds:
      - 0.65 kg HEU sphere centered in filled container (0.6 g/cc)
      - $\sim$2 kg HEU in Fe box with 10 cm thick walls
      - MPS: $3\times10^7$ photons/pulse, 20 kHz or $\sim 1.7\times10^7$ ph/eV/s at 1.733 MeV

- Improved signal vs. active and passive backgrounds
- Address a key CBP priority on contraband and explosives
- NRF: High explosive measurement via atomic ratios of C, O, N
  - MPS advantage increases at high energies (O: 7 MeV)
  - Presently simulating Treaty/Dismantlement only
  - Cargo scenarios require consideration of larger volumes and shielding thickness
- Photoneutron spectroscopy
  - Monoenergetic photons produce neutrons at isotope specific energies via $(\gamma,n)$ reactions ($^{14}$N$(\gamma,n)^{13}$N)
  - Percent-level photon energy spread
  - High resolution, high rate detector required
- Use radiograph/$Z_{\text{eff}}$ information to localize volume for interrogation

NRF spectra for a simulant explosive, melamine and water; 8.3 MeV bremsstrahlung.
Reproduced from Bertozzi et al. 261: 1-2, 331-336 NIMB 2007

*J.E. McFee et al., Nuclear Instruments and Methods in Physics Research A704 (2013) 131–139.
Narrow energy spread, small emission spots, further extend capability

- Emission spot size drives spatial resolution improvement
- Nuclear Resonance Fluorescence\(^1\): enable high-specificity identification of explosives, contraband and other materials
  - Lines 2 \(-10\) MeV
  - \(\Delta E_{\text{photon}} \leq 2\%\) enables signal; strong benefit if lower
  - Dose reduced orders of magnitude
  - Very low \(\Delta E_{\text{photon}}\) may enable isotopic/enrichment image

\(\leq\) micron emission spot: resolution

\[\text{Resolution} \leq \text{micron emission spot}\]

\[\text{Relative Intensity} \begin{array}{c}1.00 \\ 0.98 \\ 0.96 \\ 0.94 \end{array} \begin{array}{c}MPS \\ Brems \end{array} \]

\[\text{Distance [\(\mu\)m]} \begin{array}{c}0 \\ 1 \\ 2 \\ 3 \end{array}\]

Simulation: Glen Warren (PNNL)

NRF: Reduce time to detect \(~80\times\)
Cargo relevant objects in minutes

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<th>#8</th>
<th>#10</th>
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<td>(^{239}\text{Pu})</td>
<td>(^{12}\text{C})</td>
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<tr>
<td>Time-to-Detection [min]</td>
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<tr>
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<td>MPS-transmission</td>
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<tr>
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<td>Brems-scattering</td>
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<tr>
<td></td>
<td>Brems-transmission</td>
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<td>530</td>
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</table>

Simulation: Glen Warren, PNNL
Pulsed, polarized beams enable novel signatures  
Access to 3D information, isotopics, and more

- Pulsed, narrow-angle ‘pencil’ beam enables 3D resolution
  - Backscatter to date limited by brems. pulse structure & broad energy spread
  - Thomson scattering: pulsed pencil beam would enable high resolution  
    enhance other 3D methods such as EZ3D (Passport)

J. Callerame, AS&E, Advances in X-ray Analysis, Volume 49, 2006
M. Kinlaw et al, INL

- Polarized photon beam: photo-fission signal in and out of plane reveals isotope ratios