Ultracompact Accelerator Technology for a Next-Generation Gamma-ray Source

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- Tor Raubenheimer
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- Faya Wang
- Juwen Wang
- Arnold Vlieks
- Feng Zhou
• Introduction

• X-band Test Station

• Ongoing Exploratory Research
Scattering optical photons off electron beam generates a keV-MeV photon beam.

\[ E_{\gamma-ray} \quad \frac{4\gamma^2}{1 + \gamma^2 \theta^2 + 4\gamma k_0 \lambda_C} \quad E_{laser} \]

Energy-angle correlation
Doppler upshift
Compton recoil

Electron beam
Laser beam
Electron and γ-ray beam

Bremstrahlung
MEGa-rays

Photon Frequency
Amplitude
The optimized scattering of laser pulses off of relativistic electrons can create beams of ultra-bright, Mono-Energetic Gamma-rays (MEGa-rays)

Scattered radiation is Doppler upshifted by more than 1,000,000x and is forwardly-directed in a narrow, polarized, tunable, laser-like beam
The peak brilliance & bandwidth of an optimized MEGa-ray source is revolutionary & transformative.
Gamma-ray absorption & radiation by the nucleus is an “isotope-specific” nuclear signature.

Nuclear Resonance Fluorescence (NRF) is analogous to atomic resonance fluorescence but depends upon the number of protons AND the number of neutrons in the nucleus.
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NRF $\sim 10^{-5} - 10^{-6}$ $\Delta E/E$
MEGa-ray Enabled Isotope-Specific Nuclear Photonics

HEU Grand Challenge
- detection of shielded material

Nuclear Fuel Assay
- 100 parts per million per isotope

Waste Imaging & Assay
- non-invasive content certification

Stockpile Surveillance
- micron-scale & isotope specific

Medical Imaging
- low density & isotope specific

HED Science
- isotope mass, position & velocity

US patent #7,564,241
MEGa-ray Enabled Isotope-Specific Nuclear Photonics

- **Spectral Flux:** photons/s/eV
- **Bandwidth**
- **Real world architecture**

**HEU Grand Challenge**
detection of shielded material

**Waste Imaging & Assay**
non-invasive content certification

**Stockpile Surveillance**
micron-scale & isotope specific

**Medical Imaging**
low density & isotope specific

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isotope mass, position & velocity

US patent #7,564,241
The T-REX (Thomson-Radiated Extreme X-ray) project created LLNL’s first MEGA-ray source.
To achieve precision gamma-rays we need a robust laser and linac platform

Linac
- Up to 250 MeV
- <1 mm.mrad
- 0.25 nC

Lasers
- PDL
- ILS

Control room

Experiments

Interaction point

Modulators And Klystrons
• Energy: 246 MeV
• Energy Spread: 0.2%
• Charge: 250 pC
• Emittance: < 1 mm mrad
• Focal Spot Size: 20 µm \textit{rms}
• Duration: 2.5 ps
Current status of Nuclear Photonics laser systems

Rod Fluorescence showing gain uniformity
High Bay Decontamination and Demolition
X-Band Test Station in B194

- High voltage modulator, XL4 Klyston
- High power RF distribution
- Photocathode Drive Laser
- RF gun, T53, Diagnostics
- Controls
X-band Test Station

- Charge: 250 pC
- Bunch Duration: 2 ps
- Bunch Rise/Fall: <250 fs
- Normalized Emittance: <1 mm mrad
- Gun Energy: 7 MeV
- Cathode Field: 200 MV/m
- Coupling $\beta$: 1.7
- Section Gradient: ~70 MV/m
- Final Energy: 30–50 MeV
Solid-state modulator has been installed and tested into low average power load at LLNL
LLNL XL4 fabricated, commissioned and tested at SLAC, and has now been delivered to LLNL

Klystron installation begins this week: lift, dress, move, install

<table>
<thead>
<tr>
<th>Frequency</th>
<th>11.424 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam voltage</td>
<td>427 kV</td>
</tr>
<tr>
<td>Perveance</td>
<td>1.09 μA/V^{3/2}</td>
</tr>
<tr>
<td>Max RF pulslength</td>
<td>1.5 μs</td>
</tr>
<tr>
<td>Saturated power</td>
<td>50 MW</td>
</tr>
<tr>
<td>RF drive</td>
<td>700 W</td>
</tr>
<tr>
<td>Gain</td>
<td>49 dB</td>
</tr>
<tr>
<td>Efficiency</td>
<td>41%</td>
</tr>
<tr>
<td>-3dB bandwidth</td>
<td>50 MHz</td>
</tr>
<tr>
<td>Cathode heater current</td>
<td>22 A</td>
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<tr>
<td>Vacuum level</td>
<td>10^{-9} Torr</td>
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Flexible RF Distribution will use a single RF source to power both the RF gun and T53 linac

All major parts designed, fabricated, and awaiting installation
T53 Accelerator section had coupler redesign for lower emittance operation, and is completed.

Achieved over 90 MV/m gradient with very low breakdown rates.
LLNL/SLAC developed single bunch high brightness RF photoinjector

X-band RF gun has been fabricated, tuned, vacuum baked and delivered to LLNL
LLNL’s asymmetrical laser-electron Compton scattering configuration further reduces the bandwidth & increases flux of MEGa-ray sources

“Asymmetric” scattering
Laser duration $>>$ electron duration
$\sim 25$ pC per bunch, $10^7$ per laser pulse
$10^7$ Compton photons per pulse
effective repetition $\sim 100$kHz
LLNL’s asymmetrical laser-electron Compton scattering configuration further reduces the bandwidth & increases flux of MEGa-ray sources

LLNL patent pending
LLNL’s asymmetrical laser-electron Compton scattering configuration further reduces the bandwidth & increases flux of MEGa-ray sources.
## Photocathode Drive Laser Specifications

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<th>Parameter</th>
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<th>Mg cathode (high efficiency)</th>
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<tr>
<td>Micro-pulses per macro-pulse</td>
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<td>Energy @ 260 nm</td>
<td>5 µJ</td>
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<td><strong>Macro-pulse specifications</strong></td>
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*really hard*

*demonstrated at 1MHz*
11.424 GHz Photocathode Drive Laser concept: generate bandwidth using self phase modulation
GHz laser demonstration status

- Current specs: 1.7 nJ in 2 ps at 10 GHz, 100 ns macropulses at 20 kHz.
- Currently finishing comparison of ps pulses and verifying SPM models.
- Next step: add more amplification to increase both the energy and bandwidth at the system output.
LLNL/SLAC developed a single bunch high brightness RF photoinjector for X-band test station

The next step is to test this RF gun and design a removable photocathode version so that we can change the cathode material.

2 µm of Mg is sputtered in a 1 cm diameter spot on the Cu back plane of the photoinjector.
Dropping the per-bunch charge from 250 pC to 25 pC will lower the emittance and energy spread.

PARMELA modeling of full 250 MeV linac with reduced charge show promising scaling.
ACE3P Results using both: times domain (T3P), and Particle-in-cell (PIC3P) codes
X-Band Test Station for multibunch operation

- Install new laser designed for multi-GHz pulse production
- Replace gun with revised, demountable-cathode version
- Existing RF power provides 50 MW, 1.6 µs pulses
- Existing distribution hardware will be sufficient for testing
- Existing accelerator section and beamline will be used for multi-GHz diagnostics
- Demonstrate a high-quality multi-GHz electron bunch train
PARMELA: low charge electron bunches yield lower normalized emittance and energy spread

\[ \frac{\theta}{\sum_n} = \text{constant} \]

\[ \frac{\theta}{\sum_n^2} = \text{constant} \]

\[ \frac{\sigma_x}{\sigma_y} = 0.16\% \]
\[ \sum_n = 0.35 \text{ mm.mrad} \]

\[ \frac{\sigma_x}{\sigma_y} = 0.03\% \]
\[ \sum_n = 0.1 \text{ mm.mrad} \]
Electron bunches with lower charge reduce the bandwidth.
Dual Isotope Notch Observation (DINO) eliminates the need for high resolution spectroscopy.
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LLNL patent pending
• F. Albert: MOPPP011, “Narrow Band Optimization of a Compton Scattering Gamma-ray Source Produced from an X-band Linac”

• D.J. Gibson: WEPPD060, “A Drive Laser for Multi-bunch Photoinjector Operation”


• A.E. Vlieks: WEPPB007, “Initial Testing of the Mark-0 X-band RF Gun at SLAC”
SLAC NLCTA X-band Test Area

T105 Accelerator
Slice Emittance Diagnostic
Cavity BPMs
Ancillary systems: controls, diagnostics, and magnets have been designed and delivered

Magnet measurement of quadrupole focusing triplets for alignment
Comparison with results from T-REX at 478 keV

- We expect to do faster detection than T-REX (mins vs. hours)
- Source optimized depending on applications
- The source can be optimized for a given energy
Outline

• Introduction
  — Compton Scattering Overview
  — Nuclear resonance fluorescence
  — Nuclear Photonics Facility and VELOCIRAPTOR

• X-band Test Station
  — Mod
  — Klystron
  — Components
  — T53
  — Gun

• Ongoing Research: Exploratory Research
  — GHz
  — Narrowband
  — DINO

• Conclusion