ULTRACOMPACT ACCELERATOR TECHNOLOGY FOR A NEXT-GENERATION GAMMA-RAY SOURCE *

R.A. Marsh†, F. Albert, S.G. Anderson, D.J. Gibson, S.S. Wu, F.V. Hartemann, C.P.J. Barty
Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

Abstract

This presentation reported on the technology choices and progress manufacturing and testing the injector and accelerator of the 250 MeV ultra-compact Compton Scattering gamma-ray Source under development at LLNL for homeland security applications. This paper summarizes the status of various facets of current accelerator activities at LLNL.

INTRODUCTION

Extremely bright, narrow bandwidth gamma-ray sources are expanding the application of accelerator technology and light sources in new directions. Mono-energetic gamma-rays enable new features in nuclear applications by tapping into the very narrow unique nuclear resonances of various isotopes [1]. Advancements in nuclear material detection, fuel rod assay, and waste management only begin to hint at the possibilities made possible by this transformational technology.

The nascent field of nuclear photonics is enabled by the recent maturation of new technologies, including high-gradient X-band electron acceleration, robust fiber laser systems, and hyper-dispersion CPA [2]. Recent work has been performed at LLNL to demonstrate isotope-specific detection of shielded materials via NRF using a tunable, quasi-monochromatic Compton scattering gamma-ray source operating between 0.2 MeV and 0.9 MeV photon energy. This technique is called Fluorescence Imaging in the Nuclear Domain with Energetic Radiation (or FINDER). This work has, among other things, demonstrated the detection of ^{7}Li shielded by Pb, utilizing gamma-rays generated by a linac-driven, laser-based Compton scattering gamma-ray source developed at LLNL [3, 4, 5]. Within this context, a new facility is currently under construction at LLNL, with the goal of generating tunable gamma-rays in the 0.5-2.5 MeV photon energy range, at a repetition rate of 120 Hz, and with a peak brightness in the 10^{20} photons/(s $\times$ mm$^2\times$ mrad$^2\times$ 0.1% bw) range.

This paper will briefly summarize the status of current activities at LLNL. Other relevant work is presented independently in these proceedings, and is summarized separately, including: multibunch laser development [6], multibunch modeling activities [7], magnet measurement and qualification [8], and gamma-ray modeling [9].

Compton Scattering

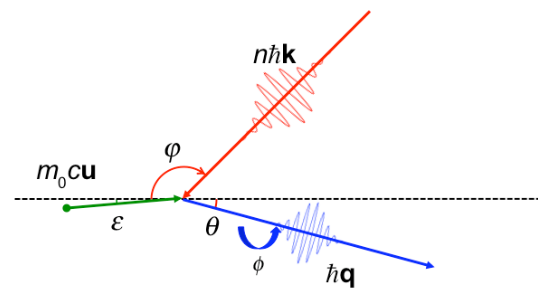

Figure 1: Compton interaction geometry.

This section is a brief summary of the main properties of Compton scattering. The incident electron and photon 4-momenta are given by $u_\mu = (\gamma, \mathbf{u})$ and $k_\mu = (k, \mathbf{u})$; the scattered photon 4-wavenumber is $q_\mu = (q, \mathbf{q})$, and the electron 4-velocity after the interaction satisfies energy-momentum conservation: $v_\mu = u_\mu + \lambda' (nk_\mu - q_\mu)$, where λ' is the reduced Compton wavelength and n is the harmonic (multi-photon) number. From these parameters, the incident and scattered light-cone variables can be computed, along with the Compton formula:

$$\frac{q}{k} = \frac{\gamma - u\cos(\epsilon+\phi)}{\gamma - u\cos\epsilon + (1-\cos\phi)\left(\frac{\langle -A_\mu A^\mu\rangle}{2(\gamma - u\cos(\epsilon+\phi))} + n\lambda' k\right)} \tag{1}$$

Here, ϵ is the angle between the electron initial velocity and the mean electron beam axis; ϕ is the angle of incidence of the laser photon(s); $-A_\mu A^\mu$ corresponds to radiation pressure; finally, the result is given for on-axis radiation ($\theta = 0$). The relativistic Doppler upshift, radiation pressure, and recoil are the main contributions to the scattered photon energy. This equation also shows that the frequency is very sensitive to both the electron beam and laser pulse phase spaces. Additional information can be derived from the Klein-Nishina differential scattering cross-section, 3D effects, and nonlinearities.

STATUS

The X-band linear accelerator design for the next generation gamma-ray source at LLNL has been named *VELOCIRAPTOR* and is described in detail in [10]. This 250 MeV linac is comprised of a 5.59 cell X-band RF gun [11], and 6 T53 accelerator sections operating at 70 MV/m gradient.

* This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

† marsh19@llnl.gov

Using an intrinsic emittance of 0.9 μm per mm of laser spot size on the cathode, a 250 pC bunch achieves a normalized rms emittance of 0.35 mm mrad with an energy spread of 0.2%. A quadrupole magnet triplet forms a final focus for the Compton laser interaction region, and a chicane prior to the final focus is used to block on-axis Bremsstrahlung radiation. A final set of dipole bends is used to separate the electron beam from the gamma-ray beam. We have chosen to reuse the target bay of the decommissioned NOVA inertial confinement fusion laser, as it already has sufficient shielding. Preparation for construction requires demolition of the massive existing infrastructure that supported the target chamber and its associated optics and diagnostics. Work is underway and making significant progress in demolishing and decontaminating the area for beneficial occupancy as seen in Fig. 3.

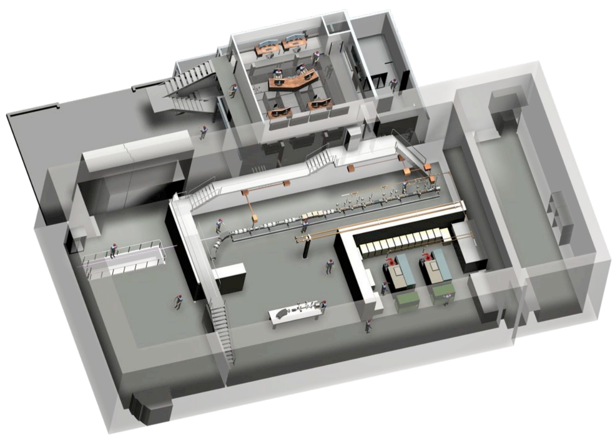

Figure 2: CAD rendering of the Nuclear Photonics Facility at LLNL.

Figure 3: Target bay demolition in preparation for construction.

Until the full facility is built in the target bay, the test station will be established in the shielded caves of LLNL's S-band accelerator facility in Building 194 (B194) [12]. Early establishment of the test station will enable operational experience, and allow multi-bunch experiments to begin in advance of the full target bay facility being available for occupancy. The parameters for the test station are shown in Table 1. The test station layout is shown in Fig. 4. The test station will consist of a control room with equipment racks, a high power solid-state modulator and XL-4 klystron, RF distribution, the Mark 1 RF gun and a single T53 traveling wave accelerator section with beamline transport magnets and diagnostics. The system is discussed in more detail in other work including: the beam dynamics [13], laser systems [14], and RF distribution [15]. A similar system is being built at SLAC for testing X-band RF guns, as discussed in [16]. At LLNL, the test station components are being assembled and components such as the modulator are being tested prior to integration and full system commissioning. A discussion of the status of various major components of the test station follows.

Table 1: Test Station Parameters

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 β	1.7
Section Gradient	$\sim$70 MV/m
Final Energy	30–50 MeV

Modulator

The high voltage pulse required by the klystron is provided by a state-of-the-art, solid-state high voltage modulator. The solid-state modulator (K2-3X) built by ScandiNova was chosen for its pulse-to-pulse stability and solid-state modular design. This modulator has been installed with its support hardware and chiller in B194 as seen in Fig. 5, and has been pulsed into a low average power high voltage load as typified by Fig. 6.

Klystron

The high power RF source is a X-band klystron (XL-4), which was developed by SLAC in the mid 90s for the high power testing of the X-band structures. The XL-4 is a solenoid focused klystron which requires a 0.5 Tesla solenoid. Commissioning and final testing of the LLNL XL-4 klystron are complete, and the tube has been delivered to LLNL. Installation of the klystron into the modulator will be completed soon. The final klystron parameters are detailed in Table 2. The tube meets all required specifications.

RF Components

The RF distribution transports high power RF to both the RF gun, which requires $\sim$20 MW, and the T53 accelerator

ISBN 978-3-95450-115-1

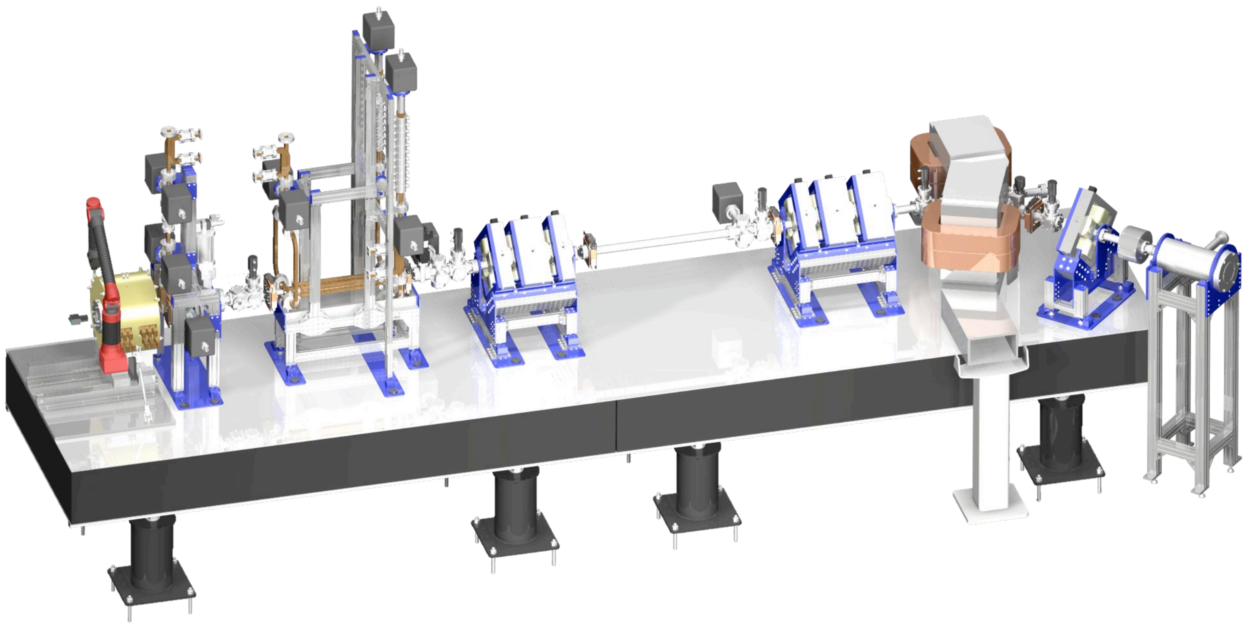

Figure 4: CAD rendering of the X-band test station.

Figure 5: ScandiNova solid-state modulator installed at LLNL.

section, which will receive the remainder. The RF distribution takes advantage of two 3dB couplers mounted back-to-back with phase shifters between them. This arrangement allows power to be distributed to either the RF gun, or the T53 accelerator structure [15]. An additional phase shifter allows the relative phase of the RF to be adjusted. All components have been fabricated and await installation, with the exception of final WR90 transport lengths that have yet to be determined based on the final location of components relative to one another.

Photoinjector

The RF gun is based on an earlier high gradient 7 MeV, 5.5-cell X-band RF gun. *PARMELA* simulations revealed that a longer first half- cell, as simulated with *SUPERFISH* resulted in a lower final emittance for the setup planned at

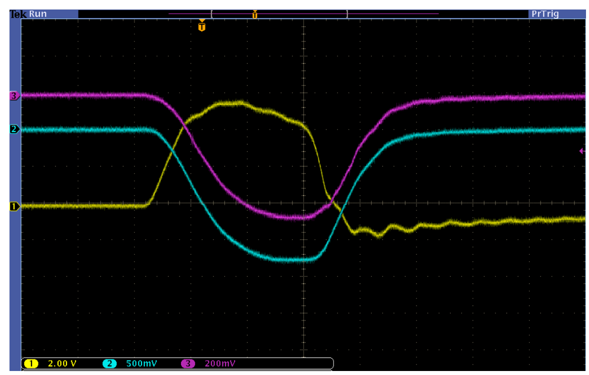

Figure 6: Typical 1 μs 100 kV high voltage trace of modulator pulsing into low power resistive load. Yellow is a current transformer on the low voltage side of the transformer secondary that has saturated, Red is an accurate current transformer that has been installed on the high voltage end of the secondary, and Blue is an uncalibrated capacitive voltage divider.

LLNL. As a result a full redesign of the RF gun has been performed, using a longer first half-cell, lengthened from a 0.49 cell to a 0.59 cell. This new RF gun also boasts an improved mode separation of >20 MHz, which decreases mode beating of the electric field on the cathode. The new RF gun also employs a racetrack coupler to reduce the RF quadrupole field experienced by the electron beam, and elliptically contoured irises to decrease the maximum surface electric field. The RF gun properties required to complete final tuning are: field balanced across all cells, mode frequency of 11.424 GHz, and a coupling β of $\sim$1.7. The RF gun has been fabricated, with final tuning showing very

Figure 7: XL-4 klystron completed at SLAC and dressed for shipping.

Table 2: XL-4 klystron parameters.

Frequency	11.424 GHz
Beam voltage	427 kV
Perveance	1.09 μA/V$^{3/2}$
Max RF pulselength	1.5 μs
Saturated power	50 MW
RF drive	700 W
Gain	49 dB
Efficiency	41%
-3dB bandwidth	50 MHz
Cathode heater current	22 A
Vacuum level	10^{-9} Torr

close agreement with the design.

The X-band test station will include a single T53 accelerator section to increase the beam energy to 20–30 MeV, so that the emittance can be measured using a quad scan technique. The T53VG3 travelling wave structure has been extensively tested and has operated at high gradient with low breakdown rates. The T-series structures are essentially the low group velocity (downstream) portion of the original NLC 1.8 m structures. This structure can be operated with acceptable breakdown rate at gradients up to 90 MV/m. The T53 has been fabricated and is awaiting installation on the test station.

Miscellaneous

The emittance compensation solenoid for the photoinjector, in addition to focussing quadrupoles, steering magnets, and a dump dipole (which doubles as a spectrometer magnet) have been procured and measured [8], and await installation on the test station. Vacuum hardware is in the final stages of procurement, though the bulk of hardware is in hand. Controls for various signal digitization and communication has been partially implemented, and will continue when more hardware is in place.

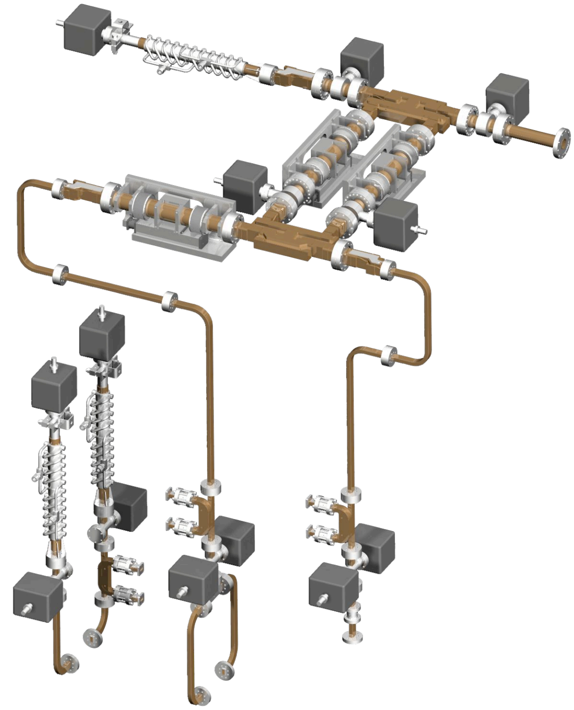

Figure 8: CAD rendering of test station RF distribution. Majority of components have been fabricated, delivered, and await installation.

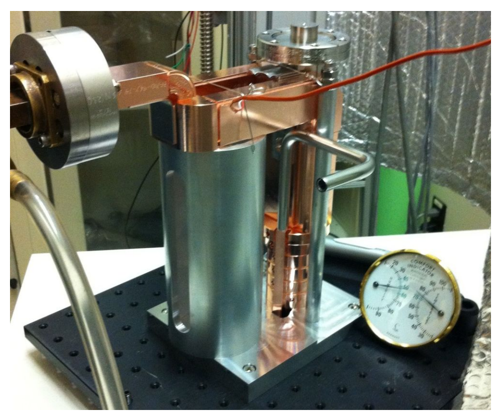

Figure 9: Cold test setup at SLAC for beadpull measurement and final tuning. RF gun currently under final bake.

ONGOING RESEARCH

Multibunch Photoinjector

One area of active current research is to design, model, assemble, and demonstrate a high-brightness electron-beam source that is capable of generating electron bunches

ISBN 978-3-95450-115-1

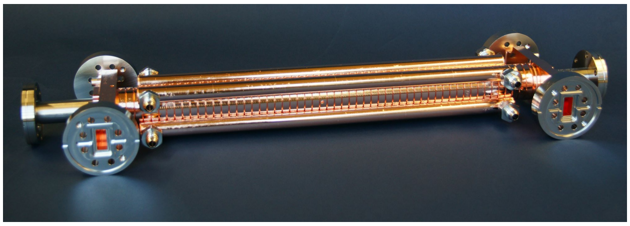

Figure 10: Completed T53 accelerator section.

in each accelerating bucket of the drive RF [6, 7]. This research objective will be accomplished by building a new multiple gigahertz-compatible photoinjector and a gigahertz-compatible cathode illumination laser, which will be integrated with existing radio-frequency power and electron accelerator hardware to make beam measurements.

Narrowband Gamma-rays

Another area of active current research is to optimize LLNL's Compton-scattering gamma-ray source technology for a potential 100,000-fold bandwidth reduction [9]. This bandwidth reduction will enable direct nuclear resonance fluorescence isotope-specific detection, assay, and imaging of special nuclear materials and other materials of interest. This research involves detailed computer models of gamma-ray production, tracking, and interaction with gamma-ray optics, along with optimization algorithms, as well as experimental characterization of gamma-ray optics.

Detector Technologies

Conventional detectors, such as high-purity Germanium, are ill-equipped to handle very high gamma-ray flux. Detector research at LLNL is investigating techniques compatible with the gamma-ray sources under development [17].

CONCLUSION

The major components for the X-band test station have been designed, fabricated, and await installation. The XL-4 klystron has been delivered, and will shortly be dressed and installed in the ScandiNova modulator. High power testing of the klystron into RF loads will follow, including adjustment of the modulator for the klystron load as necessary. Assembly of RF transport, test station supports, and accelerator components will follow.

Commissioning will focus on processing the RF gun to full operating power, which corresponds to 200 MV/m peak electric field on the cathode surface. Single bunch benchmarking of the Mark 1 design will provide confidence that this first structure operates as designed, and will serve as a solid starting point for subsequent changes, such as a removable photocathode, and the use of various cathode materials for enhanced quantum efficiency. Charge scaling experiments will follow, partly to confirm predictions, as well as to identify important causes of emittance growth, and their scaling with charge. Multi-bunch operation will conclude testing of the Mark 1 RF gun, and allow verification of code predictions, direct measurement of bunch-to-bunch effects, and initial implementation compensation mechanisms. Modeling will continue and focus on supporting the commissioning and experimental program, as well as seeking to improve all facets of linac produced Compton gamma-rays [7, 9].

REFERENCES

[1] C.P.J. Barty, and F.V. Hartemann, "T-REX: Thomson-Radiated Extreme X-rays Moving X-ray Science into the"Nuclear" Applications Space with Thomson Scattered Photons", **UCRL-TR-206825** (2004).

[2] M.Y. Shverdin, et al., Opt. Lett. **35**, 14 (2010).

[3] F. Albert, et al., Opt. Lett. **35**, 354 (2010).

[4] D.J. Gibson, et al., Phys. Rev. STAB **13**, 070703 (2010).

[5] F. Albert, et al., Phys. Rev. STAB **13**, 070704 (2010).

[6] D.J. Gibson, et al., "A Drive Laser for Multi-bunch Photoinjector Operation", WEPPD060, IPAC 2012.

[7] R.A. Marsh, et al., "Modeling Multi-bunch X-band Photoinjector Challenges", MOPPP042, IPAC 2012.

[8] R.A. Marsh, et al., "Precision Magnet Measurements for X-band Accelerator Quadrupole Triplets", THPPD018, IPAC 2012.

[9] F. Albert, et al., "Narrow Band Optimization of a Compton Scattering Gamma-ray Source Produced from an X-band Linac", MOPPP011, IPAC 2012.

[10] S.G. Anderson, et al., Nucl. Instrum. Methods Phys. Res., Sect. A, **657** 1, pp. 140–149 (2011).

[11] R.A. Marsh, et al., Phys. Rev. ST Accel. Beams, submitted (2012).

[12] R.A. Marsh, et al., "X-band Test Station at LLNL", MOPC067, IPAC 2011.

[13] S.G. Anderson, et al., "Optimized X-band Photoinjector Design for the LLNL MEGa-Ray Project" MOP128, PAC 2011.

[14] D.J. Gibson, et al., "Laser Systems for Livermore's Mono-energtic Gamma-Ray Source" THP223, PAC 2011.

[15] R.A. Marsh, et al., "50 MW X-Band RF System for a Photoinjector Test Station at LLNL" TUP132, PAC 2011.

[16] C. Limborg-Deprey, et al., "An X-band Gun Test Area at SLAC" **MOP015**, PAC 2011.

[17] C.P.J. Barty, "Dual Isotope Notch Observer for Isotope Identification, Assay and Imaging with Mono-Energetic Gamma-ray Sources", WIPO Patent Application **WO/2011/071563**