# GENERATION AND APPLICATION OF LASER-COMPTON SCATTERING (LCS) FROM RELATIVISTIC ELECTRON BEAMS

K. Chouffani[1,*], F. Harmon[1], D. Wells[1], S. Naeem[2]
[1,*]Idaho Accelerator Center, 1500 Alvin Riken Drive, Pocatello, Idaho 83209, USA
[2]Physics Department, Idaho State University, 921 South 8th Avenue, Pocatello, Idaho 83209, USA

*Abstract*

Laser Compton scattering experiments were carried out at the Idaho Accelerator Center (IAC) using the 5-44 MeV linear accelerator (LINAC). LCS X-rays were generated using a 50 ps electron beam colliding with a 4 GW, 250 ps, phase locked Nd:YAG laser. 60 Hz x-rays bursts resulting from the approximate head-on collision of relativistic electrons with the high peak power laser second (532 nm) and fourth harmonic (266 nm) lines were generated respectively.

LCS x-rays were used for x-ray fluorescence (XRF) experiments and x-ray transmission/absorption measurements in several foils of different atomic numbers and thicknesses including neodymium (Nd), lead (Pb) and bismuth (Bi). One of the purposes of this work is to use LCS x-rays as a non-invasive means for material identification and quantification. Results from our experiments showed that because of its relatively low spectral bandwidth, energy tunability and low bremsstrahlung background, LCS could be a useful x-ray source for hybrid k-edge densitometry.

## INTRODUCTION

Hybrid k-edge densitometry (HKED) is a technique that exploits both K-edge absorption (K-edge densitometry or KED) and X-ray fluorescence. HKED allows simultaneously greater elemental specificity and lower detection limits [1,2]. With conventional x-ray sources, if a sample contains a few grams per liter of a given actinide, an absorption edge is observed corresponding to the K-edge energy. This abrupt change of the transmitted x-ray intensity at the absorption edge is a measure of the actinide concentration in the sample. In addition, KED can also be used for x-ray fluorescence, where incoming x-rays with energies above the k-absorption edge can excite the atoms of the actinide element resulting in emission of characteristic x-rays. In HKED, XRF determines various ratios of concentrations such as uranium/thorium, uranium/plutonium, plutonium/americium and plutonium/neptunium [2]. The measured ratios allow the determination of each minor element relative to the major elements and therefore after appropriate calibration allow the determination of absolute concentration of a minor element of interest. However in the case of KED, the transmission spectrum is measured in narrow energy windows located slightly above and below the absorption edge. X-rays with energies outside the narrow windows contribute solely to the background recorded by the detector and provide no information on the actinide samples to be tested. The narrowing of the incoming x-ray beam spectral width can be achieved by further filtration of the x-ray beam and by reducing the x-ray tube voltage at the expense of the x-ray yield.

The addition of a highly collimated, bright, tunable, quasi-monochromatic and virtually bremsstrahlung free x-ray source such as LCS to the K-edge/XRF technique should reduce detection limits considerably because signal-to-noise (S/N) ratios associated with background radiation are greatly improved.

*e-mail: khalid@physics.isu.edu

## EXPERIMENTAL SETUP AND EXPERIMENT

### *Brief description of LCS*

Laser-Compton Scattering is the exchange of energy between a relativistic electron beam and a laser beam. Laser photons interact with high-energy moving electrons (in the MeV region or higher) and the electrons scatter these low energy photons to a higher energy at the expense of the electrons' kinetic energy. This interaction results in the emission of highly directed (peaked in the direction of the incident electron beam), quasi-monochromatic, highly polarized and tunable x-ray beams [3-6]. LCS was originally proposed an intense gamma source, it is similar to channeling or undulator radiation. Experimental observations of bright photons generated by backscattered laser photons from relativistic electron have been reported in literature, and conferences [3-6].

The scattered photon energy is given by:

$$E_\gamma \approx E_L 2\gamma^2 (1-\cos\alpha)/(1+\gamma^2\theta^2) \qquad (1)$$

where $E_\gamma$ and $E_L$ are the photon and laser photon energy respectively, $\gamma$ is the electron beam energy ($E/mc^2$), and $\alpha$ and $\theta$ are the crossing angle between the laser and electron beam and emission angle respectively.

LCS can occur at any crossing angle between the electron and laser beam. The x-ray energy of interest can be selected by choosing the proper energy, laser wavelength and collision angle. There are two basic configurations used in LCS: a head-on collision where the laser photon acquires the highest gain in energy (most energy efficient geometry) and a 90$^o$ geometry where the electron beam and laser beam are orthogonal to each other. In the 180$^o$ geometry, the x-ray pulse duration is determined primarily by the electron bunch length. The typical microbunch length in linear accelerators is about 2-10 ps and can be further compressed to a few hundred femto-seconds. In the 90$^o$ geometry, the X-ray pulse length is defined by the crossing time, and shorter interaction times can be achieved by further focusing the electron beam at the interaction spot. Femto-second X-rays were successfully generated and used for electron beam diagnostics by Leemans et al. using the $90^o$ geometry [5,6].

LCS can also provide information on the electron beam direction, beam energy, and beam energy dispersion [5,6]. Equation (1) shows a direct relationship between the emitted X-rays and electron beam energies. LCS maximum X-ray energy is achieved when the emission angle is $\theta = 0$ relative to the electron beam direction. Narrow X-ray lines with a $\Delta E_\gamma/E_\gamma = 1.5\%$ were recorded at the IAC [1].

The number of x-rays per collision emitted into a cone of half opening angle $\theta_c$ for the head-on interaction geometry, when the electron and laser beams have identical longitudinal and transverse sizes, is given by:

$$N_\gamma = L\sigma_c. \qquad (2)$$

$L$ is the single collision luminosity and $\sigma_c$ is the Thomson scattering cross section for photons scattered into a cone of half opening angle $\theta_c$. When the laser pulse length is much shorter than Rayleigh range and the electron beam envelope function greater than electron beam pulse length the transverse rms widths can be considered as independent of the longitudinal coordinate and $L = N_e N_L/4\pi\sigma^2$ where $N_e$ and $N_L$ are the total number of electrons and laser photons in each bunch respectively, and $\sigma$ is the transverse rms width. For optimum X-ray yield the interaction region should be made as small as possible by focusing the electron beam to confine it within the laser beam over the interaction region (i.e. spatial coincidence of beam-waists). There is however, for a given electron beam emittance, an optimum yield for a certain size of the interaction area. As the electron and laser spot sizes are reduced further the electron beam divergence increases and causing the Thomson cross section to decrease leading to a decrease in the x-ray yield.

At the $90^o$ collision geometry, Eq. 2 becomes

$$N_\gamma = N_e N_L\, \sigma_c / 4\pi\sigma\sqrt{\sigma^2+\sigma_z^2}\,, \qquad (3)$$

where $\sigma_z$ is the longitudinal rms width.

## *Experimental setup*

Figure 1 shows the IAC LINAC layout, after acceleration the electron beam is bent by 2 $45^o$ bending magnets toward the $90^o$ B-line and injected into the interaction region. Bending the electron beam by $90^o$ allows us to carry out LCS experiments away from the LINAC axis where the Bremsstrahlung background is relatively large. A slit located between the $45^o$ bending magnets is used to change the energy distribution, spot size and current of the electron beam. This geometry enables us cleaning and energy monochromatization of the electron beam before interaction with the laser pulse. In order to improve the spectral bandwidth, high flux of LCS and optimum spatial and temporal overlap, knowledge of the position of the laser-electron beam interaction is mandatory for proper electron beam tuning and laser focusing. Since the quality of LCS X-rays is closely related to properties of the electron beam such as electron beam divergence, spot size, energy spread and direction, electron beam diagnostics are critical.

The electron beam is focused by a set of quadrupoles into the interaction chamber and collides at about $180^o$ with a 250 pico-second, 4 GW peak power pulsed Nd:YAG laser. After interaction, the electron beam is refocused by a quadrupole doublet and bent at $45^o$ with respect to the forward direction and dumped into air. The laser and focusing optics are located is two separate rooms respectively and are well shielded from any radiation from the LINAC. The laser beam is first collimated with a set of lenses and sent into the optics room where it is reduced (to accommodate 1’’ in diameter optics such as waveplates and polarizing beam splitters) and then focused by a set of lenses at the interaction point. A slightly off axis mirror located in a vacuum chamber located above the optics table deflected the laser beam toward the interaction point located inside the first chamber (closest to the quadrupoles). After interaction, the laser beam is blocked by a water-cooled laser-beam stop.

Electron beam diagnostics include a gold-coated Kapton optical transition radiation foil placed inside the

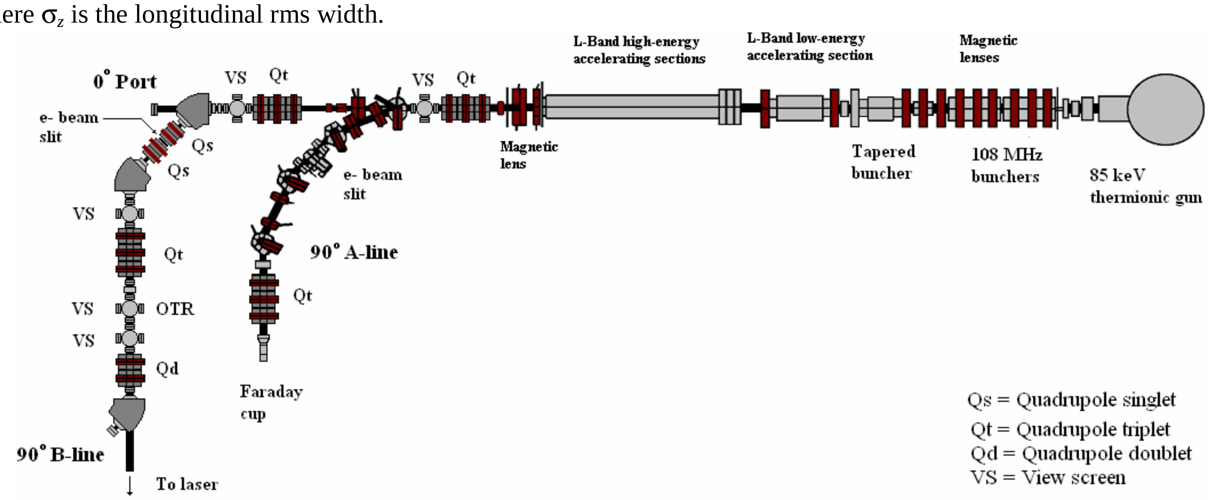



Figure 1: IAC LINAC layout. The B-line is a dedicated to LCS experiments.

upstream interaction chamber; two fluorescent screens placed inside each chamber and 3 stripline position monitors. Both fluorescent screens contain a pin-size hole at their center and are used for laser alignment purposes. Both sides of the OTR foil are coated and were used for electron and laser beam timing purposes. The OTR foil was also used for electron spot size measurements for various slit opening and electron bunch charge. The stripline position monitors allowed us to monitor the position of the electron beam with respect to the beam line axis, the beam current as well as the jitter between the electron beam and laser pulses. The delay between the electron and laser beams was monitored with the signals from a stripline position monitor and fast photodiode located in the optics room.

A scintillator detector placed in the vicinity of the x-ray detector was used to monitor the bremsstrahlung background during electron beam tuning. LCS x-rays traveled in vacuum and through a 12.7 µm thick stainless steel window before they were recorded by a high-resolution nitrogen cooled germanium detector. To prevent saturation of the x-ray detector, the laser pulse energy was either lowered or lead collimators of various diameters were used.

### *LCS Experiments*

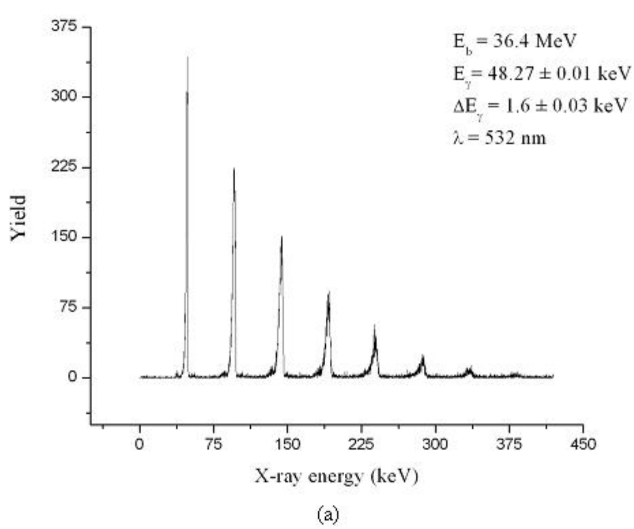
In these LCS experiments carried out at the IAC, the RF LINAC produced a 50 ps, 5-44 MeV electron beam that was brought to close to a head-on collision with a 250 ps long, phase locked, 4 GW peak power Nd:YAG laser. During these experiments only the laser second and fourth harmonics laser lines were used. The fourth harmonic was used in order to reach higher x-ray energies with the ultimate goal of generating x-ray energies higher than the absorption edge of uranium (115.6 keV) and plutonium (121.8 keV).

Figure 2a shows an LCS spectrum using the 532 nm laser line. The spectrum shows clear, sharp and distinct quasi-monochromatic X-ray peaks on top of a low bremsstrahlung background. The additional peaks at higher energy are due to pile-up from the major line located at 48.3 keV (the detector registered more than one LCS X-ray during each collision). These pile-up peaks can be removed by either closing the $90^o$ bending magnets slit or simply by decreasing the laser pulse energy or reducing detector solid angle. In this experiment the laser and the LINAC run at 60 Hz, the electron beam energy was equal to 36.4 MeV and the charge per pulse was about 0.35 nC. The laser pulse energy was equal 0.05 J (measured in the optics room) and the crossing angle was equal to 2.5 mrad. The electron and laser transverse dimensions (rms spot sizes) at the collision point were of the order of 1 and 0.1 mm respectively. During this experiment the laser pulse energy at 532 nm was one order of magnitude lower than the maximum pulse energy at the exit of the laser at the second harmonic. The solid angle subtended by the Germanium detector was equal to 0.26 µsr. Assuming that LCS x-ray and background emission processes follow Poisson statistics, the average number of LCS x-rays $N_{LCS}$ striking the detector in each collision was determined from a fit to the registered count rate in each LCS peak using the following expression (figure 2b):

$$r_{LCS}(m) = N_{LCS}^{m}(f - r_T)/m!, \tag{4}$$

where $r_{LCS}(m)$ is the count rate in peak number *m*, *f* is the collision frequency and $r_T$ is the total count rate.

Figure 3a and 3b show x-ray transmission and x-ray fluorescence measurement using the 266 nm laser line. The experiments were carried out using bismuth foils of various thicknesses. The electron beam energy was chosen such that the LCS peak energy was above the



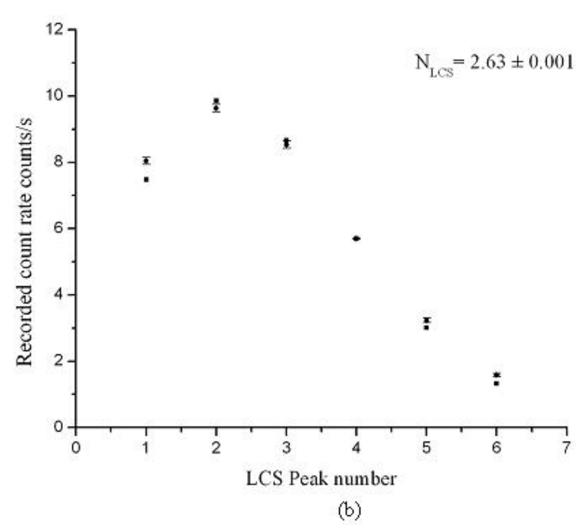




Figure 2: (a) LCS spectrum resulting from the interaction of a 36.4 MeV electron beam with 532 nm laser photons. (b) Average number of LCS photons per collision reaching the germanium detector. The x-ray yield was found to be equal to 0.005 photons/e-Sr. The square points correspond the count rates in each LCS peak for $N_{LCS}$ = 2.63.

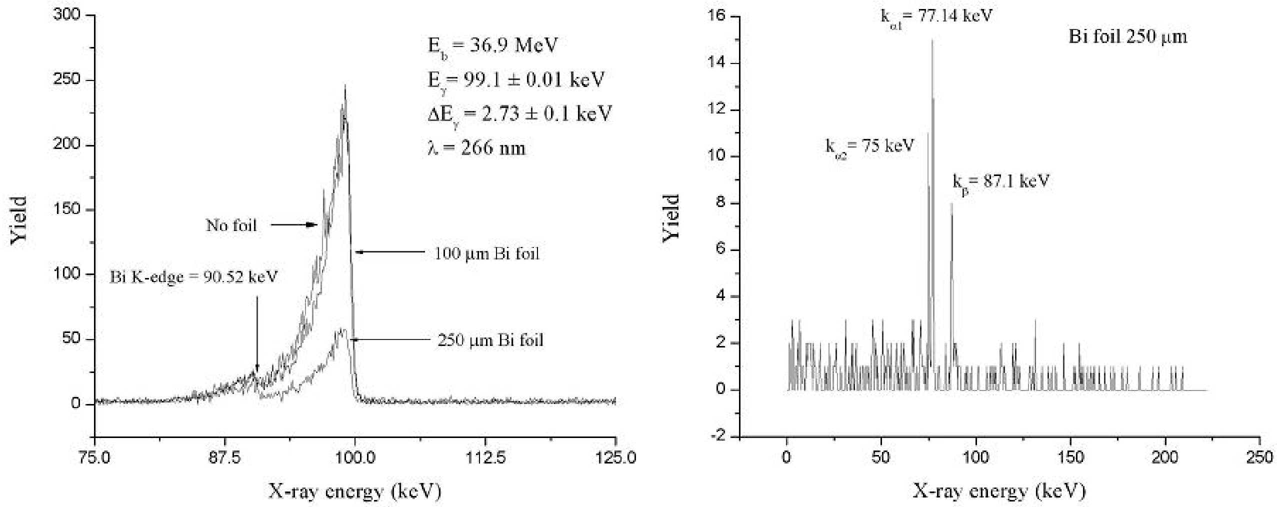



Figure 3: (a) Transmitted LCS spectra through Bi foils of different thicknesses. The pile up peaks (not shown) vanish when a 250 μm thick foil is used. (b) LCS-induced x-ray fluorescence from a 250 μm thick Bi foil, the brightest line is the $k_{\alpha 1}$ and is located at 77.14 keV. In these experiments lead was present in the shielding.

absorption edge of Bi located at 90.52 keV. The absorption and fluorescence measurements were carried out simultenously using two nitrogen cooled germanium x-ray detectors. One detector, placed behind the Bi sample and positioned at $0^o$ with respect to the incoming LCS beam, records the transmitted x-ray beam. A second detector placed at $90^o$ with respect to the x-ray beam direction records the LCS induced Bi characteristic x-rays. A lead collimator was placed in front of the $0^o$ detector in order to reduce the incoherent scattering seen by the x-ray detector. The electron beam energy was equal to 39.6 MeV and the UV line laser pulse energy measured at the exit of the laser was about 27.8 mJ. K-edges absorption of Bi can be seen in the “dip” in the transmitted spectra. As expected, the depth of the dip increases with increasing foil thickness.

Radiation-based NDA (non-destructive analysis) techniques can provide some vital information about nuclear materials much more quickly, cheaply and safely than chemical or radio chemical analysis. HKED is currently the most accurate nondestructive inspection technique that provides sensitive quantification of heavy metal contamination. The use of an LCS x-ray source has the ability to greatly simplify the analysis of KED and XRF spectra, and greatly enhance detection limits due to the near-elimination of background counts.

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