ELECTRON BEAM DIAGNOSIS USING K-EDGE ABSORPTION OF LASER-COMPTON PHOTONS*

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Abstract

The mean energy, energy spread and divergence of the electron beam can be deduced from laser-Compton scattered X-rays filtered by a material whose K-edge is near the energy of the X-rays. This technique, combined with a spot size measurement of the beam, can be used to measure the emittance of electron bunches, and can be especially useful in LWFA experiments where conventional methods are unavailable. The effects of the electron beam parameters on X-ray absorption images are discussed, along with experimental demonstrations of the technique using the Compact Laser-Compton X-ray Source at LLNL.

INTRODUCTION

In addition to being used as a novel light source, X-rays and γ-rays from Compton scattering of laser by a relativistic electron beam has been used to measure almost every electron beam parameter, such as transverse beam size [1–4], divergence [4], energy spectrum [5–7], bunch length [4] and polarization [8, 9]. More recently, similar methods have been applied to laser wakefield-accelerated (LWFA) electron beams to determine the spectrum and emittance [10]. In the above schemes, X-ray spectrometers were used to measure the X-ray spectra and therefore the electron beam spectra. However, using the well-known energy-angle correlation of laser-Compton photons, it is possible to infer local X-ray spectra from just the intensity profile using K-edge filters [11–14] or diffraction from crystals [15, 16]. Therefore, it is possible to extract information about the electron beam's parameters by simulating the parameters that best match the K-edge filtered image. This technique can be used to determine the mean energy, energy spread and divergence of the beam. The last parameter can coupled with a transverse size measurement to infer the transverse emittance of the beam.

LOCAL X-RAY SPECTRUM

The energy of a photon Compton-scattered by a relativistic electron in a head-on collision can be approximated as

$$E = \frac{4\gamma^2}{1+\gamma^2\theta^2} E_L \tag{1}$$

for $\theta \ll 1$ and negligible Compton recoil and nonlinear effects, where θ is the angle between the scattered photon and the incident electron, γ is the electron Lorentz factor and E_L is the incident photon energy. Therefore, the twice Doppler-upshifted energy is correlated with the observation angle. When an electron is replaced by a bunch of electrons, the energy at any observation angle now has a finite bandwidth, since every electron has a slightly different energy and is moving at a different angle, causing θ to be different at a fixed location. The effect of beam energy spread σ_E and divergence σ_θ on the local spectra is shown in Figs. 1 and 2.

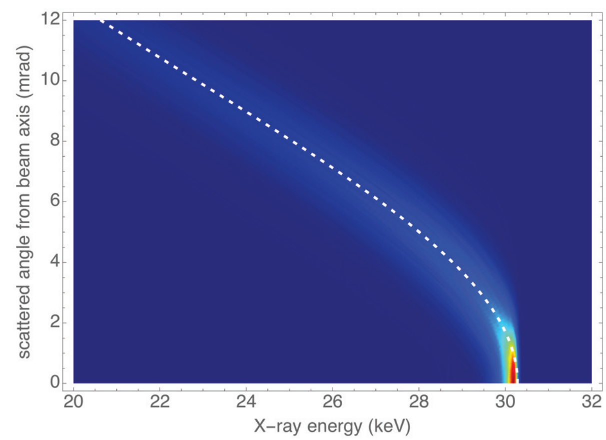

Figure 1: Energy-angle spectrum for a divergence-dominated beam ($\sigma_\theta = 1$ mrad, $\sigma_E = 0.06$ %). Dashed line corresponds to Eq. (1).

In these simulations, the laser is modeled as a 532 nm plane wave with a three-dimensional Gaussian envelope structure, and the electrons are 10,000 PARMELA particles modeled for the LLNL X-band linac, with scaled, shifted or convolved parameters for manipulation. Each particle's Compton contribution is summed incoherently. Mean energy $\bar{E}$ of the particles is 28.6 MeV.

K-EDGE ABSORPTION FILTERING OF X-RAYS

The spectral broadening effect of beam divergence and energy spread can be easily seen by imaging the X-rays with a material whose K-edge lies slightly below the on-axis energy with appropriate thickness so that photons above the K-edge are strongly attenuated compared to those below the K-edge. When filtered with the K-edge material, a Compton X-ray image from a single electron will exhibit a dark

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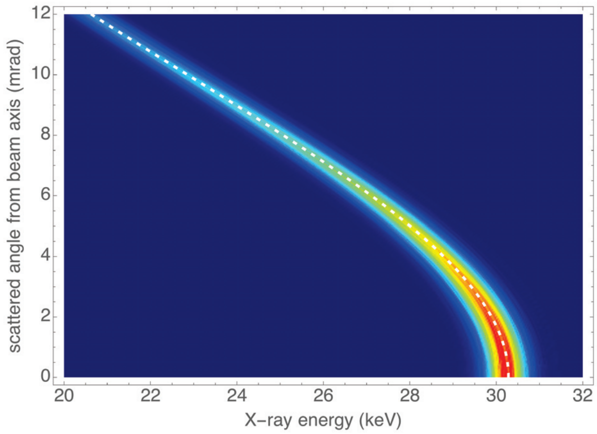

Figure 2: Energy-angle spectrum for an energy spread-dominated beam ($\sigma_\theta = 0.2$ mrad, $\sigma_E = 0.5$ %).

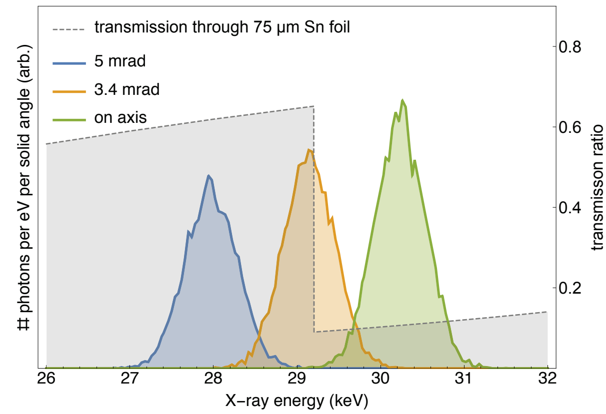

Figure 4: Local X-ray spectra at various observing angles and transmission through 75 μm thick Sn foil.

'hole' centered on the electron beam's direction with a sharp contrast edge where the energy corresponds to the K-edge, as shown in Fig. 3(a). The oblong shape of the intensity is due to linear polarization of the laser (horizontal in the image), suppressing the radiation in that direction. The sharp edge is blurred by the finite X-ray bandwidth for an electron beam with divergence and energy spread; beam divergence causes holes to be created at different positions while energy spread creates holes of varying sizes. Figure 4 shows the local X-ray spectra at various angles for a beam with 0.5 % energy spread overlayed with the transmission ratio of a 75 μm thick Sn foil. The K-edge filter image from the same beam demonstrating the blurred edge effect is shown in Fig. 3(b).

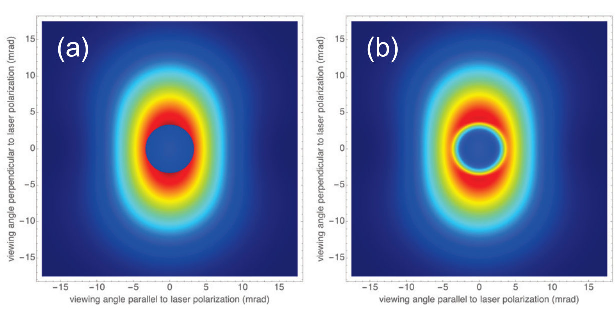

Figure 3: Sn-filtered laser-Compton X-ray intensity distribution from a single electron(a) and an energy spread-dominated beam(b).

ELECTRON BEAM DIAGNOSIS THROUGH FITTING THE DATA

The shape and size of the blurred edge in the K-edge filtered image is very sensitive to the electron beam's energy, energy spread and divergence. Therefore, one can create simulated images with varying parameters to find the best match with experimental data. This technique has been applied to laser-Compton X-rays produced at the LLNL Compact Laser-Compton X-ray Source [17]. The image shown in Fig. 5 was acquired with a Fujifilm BAS-MS imaging plate placed 2.6 m away from the interaction region and exposed for 30 minutes. a 75 μm thick Sn foil was used to filter the beam. Because of the head-on geometry of the machine, the outgoing X-ray beam has to pass through a fused silica mirror for the interaction laser; a 10 mm-radius portion of the mirror has been back-thinned to 2 mm, creating the football-shaped aperture when viewed at 45°.

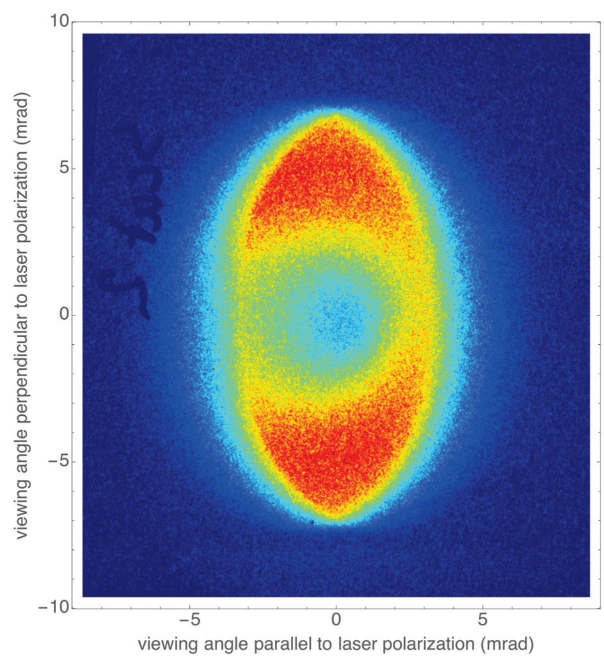

Figure 5: 30-minute integration image of Sn-filtered laser-Compton X-rays.

The vertical lineout profile through the center of the hole was used for comparing against simulations. Since this image is a 30-minute integration, the energy spread and divergence values are not those of a single bunch but include all drifts and jitters. Therefore, the energy and transverse momenta of the PARMELA particles representing a single bunch were convolved with a Gaussian distribution of varying width. The best fit parameters were found to be $\bar{E} = 28.52$ MeV, $\sigma_E < 0.3$ %, $\sigma_\theta = 1.8$ mrad. The simulated lineouts with different parameters are shown in Figs. 6, 7 and 8 for energy, energy spread and divergence, respectively.

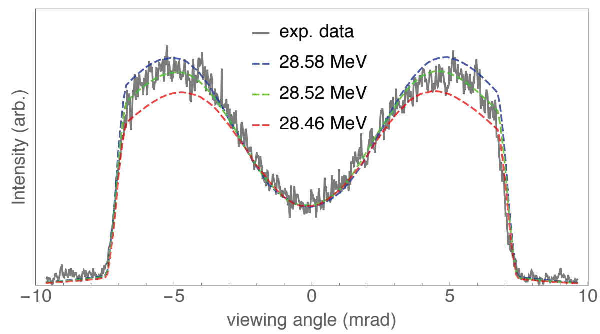

Figure 6: Effect of mean energy on lineout profile ($\sigma_E = 0.07$ %, $\sigma_\theta = 1.8$ mrad).

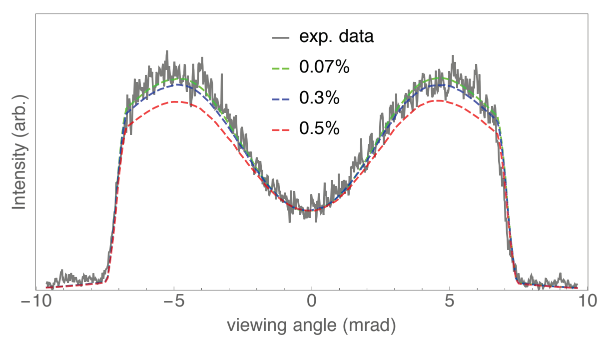

Figure 7: Effect of energy spread on lineout profile ($\bar{E} = 28.52$ MeV, $\sigma_\theta = 1.8$ mrad).

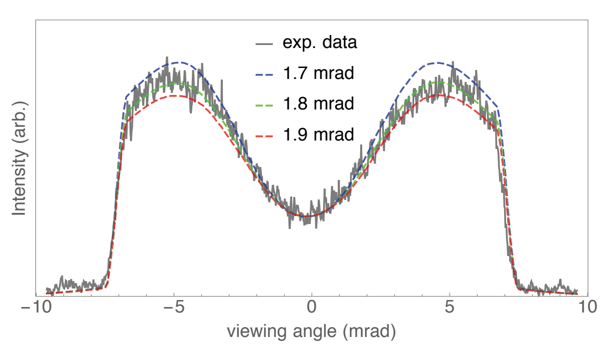

Figure 8: Effect of beam divergence on lineout profile ($\bar{E} = 28.52$ MeV, $\sigma_E = 0.07$ %).

While changing the mean energy by only tenths of a percent produces a distinct change in the shape, energy spread and divergence are complimentary to a degree and therefore when one parameter is dominant over the other, the minor parameter's margin of error can be big, as can be clearly seen here. Since the spectrum is blurred mostly by divergence, the additional blurring by energy spread is insignificant until it reaches a very high value of 0.3 %. The best fit value of 0.07 % was used based on independent dipole spectrometer measurements. Since the divergence can be determined to better than 5 %, it can provide a good estimate for the transverse emittance of the beam if an independent transverse size measurement is made.

CONCLUSION

A new technique of determining electron beam parameters using K-edge filtering of laser-Compton X-rays has been developed and tested. Preliminary results show that high accuracy in energy and beam divergence can be achieved for a divergence-dominated beam. Beam emittance can be inferred with additional measurement of beam spot size.

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