LASER WIRE SCANNING FOR 2D ELECTRON BEAM SIZE MEASUREMENT IN SLANT-SCATTERING MODE AT SLEGS

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Abstract

The precise measurement of electron beam profiles is important for accelerator diagnostics. Laser wire scanning is a classical and practicable method for beam size measurement which is based on Laser Compton scattering (LCS). Conventional laser wire scanning methods require two separate scans: one for the horizontal and one for the vertical size. However, the slant-scattering geometry of Shanghai Laser Electron Gamma Source (SLEGS) beamline station enables the simultaneous projection of both dimensions onto a gamma-ray intensity profile, allowing both sizes to be extracted from a single scan. To enable this extraction, we developed a novel analysis approach. This approach involves numerical integral modeling of the slant-scattering process with a genetic algorithm to optimize the beam parameters. Using this method, we successfully measured the transverse electron beam size at the interaction point in the slant-scattering mode of SLEGS.

INTRODUCTION

Laser wire scanning is a non-destructive diagnostic technique for electron beam characterization, in which a focused laser is scanned across the electron beam. The transverse beam size can be inferred from the Compton photon yield as a function of the relative offset between the laser and electron beam centers. With the focusing laser, this technique has the potential to measure beam sizes at the micrometer or even sub-micrometer scale. SLEGS, a beamline station at the Shanghai Synchrotron Radiation Facility (SSRF), is based on LCS and supports both backscattering and slant-scattering modes [1]. In the backscattering mode, the laser-electron interaction angle is fixed at 180°, whereas in the slant-scattering mode it can be continuously varied from 20° to 160°. This capability makes it possible to tune the energy of the generated gamma rays by adjusting the interaction angle. More importantly, the slant-scattering mode provides the possibility of simultaneously measuring the horizontal and vertical electron beam sizes within a single scan.

EXPERIMENTAL SETUP

The experiments were performed in the slant-scattering mode at SLEGS. A schematic of the experimental setup is shown in Fig. 1, and the main components are described below.

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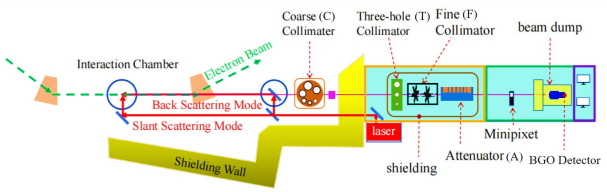

Figure 1: Schematic of the SLEGS experimental setup.

At SLEGS, gamma photons are generated via LCS between a 3.5 GeV electron beam from SSRF and a CO_2 laser with a wavelength of 10.64 µm. The theoretical transverse electron beam sizes are 312.5 µm in the horizontal direction and 10.23 µm in the vertical direction.

Laser Transportation System

In the slant-scattering mode at SLEGS, the generated gamma-ray energy can be continuously tuned by varying the laser-electron interaction angle using an optical rotation platform integrated into the interaction chamber [2]. Before entering the chamber, the laser beam is transported through a series of optical elements, including off-axis parabolic (OAP) mirrors ($f = 5$ m each), plano-convex lenses ($f = 350$ mm), plane mirrors, a beam combiner, and a beam splitter, which provide beam steering, expansion, and focusing. Although the interaction with the electron beam is driven by a CO_2 laser, the laser position offset in the laser wire scanning experiment is monitored using a coaxially aligned HeNe laser imaged by a camera. The CO_2 and HeNe lasers are pre-aligned such that they share the same propagation direction and transverse beam center. The CO_2 laser operates in continuous-wave (CW) mode and is modulated by a signal generator during the scan with a predefined duty cycle. A motorized steering mirror located upstream of the beam splitter serves as the scanning mirror. By controlling this mirror, the laser beam can be scanned in two dimensions, which is the key enabling simultaneous extraction of the horizontal and vertical electron beam sizes at SLEGS. After the beam splitter, the HeNe laser is sent to a camera for position monitoring, whereas the CO_2 laser continues along the transport line and is focused into the interaction region within the optical rotation platform. There it collides with the electron beam, producing a gamma ray with a finite opening angle.

Gamma Source System

The generated gamma ray passes through a three-stage collimation system consisting of a coarse collimator, a three-hole collimator, and a fine collimator, as shown in Fig. 1. In the scan experiment, the C20T2 collimator configuration is used, in which the coarse collimator and the three-hole collimator have aperture diameters of 20 mm and 2 mm, respectively. This configuration reduces the divergence of the gamma ray, thereby yielding a quasi-monochromatic energy spectrum. After the collimation system, the gamma ray passes through a copper attenuator. The attenuator serves two main purposes: it reduces the photon count rate entering the detector to avoid excessive detector dead time, and it suppresses the bremsstrahlung background originating from the storage-ring electron beam.

Data Acquisition

A BGO detector (76.2 mm × 200 mm) was used with an appropriate threshold to reject low-amplitude signals [3]. The scanning mirror was used to steer the laser beam to each scan point, where an energy spectrum was acquired over 60 s. After background subtraction and integration of the spectrum, the gamma count at that point was obtained, and the corresponding camera position was recorded. Repeating this procedure for multiple scan points yielded a dataset containing the gamma counts and corresponding camera positions for each point.

DATA ANALYSIS

In the conventional 90° laser wire scanning, the Compton photons as a function of offset can, under certain conditions, be approximated by a Gaussian distribution with standard deviation σ_m. Using the quadratic-sum relation in Eq(1), the electron beam size along the scan direction, σ_{se}, can then be determined from the known laser beam size along the scan direction, σ_{sl0}.

$$\sigma_m = \sqrt{\sigma_{sl0}^2 + \sigma_{se}^2}. \tag{1}$$

For slant-scattering angles other than 90°, the gamma photons depend on the relative laser-electron displacement in the plane perpendicular to the laser propagation direction. Unlike the 90° configuration, in which the scan is performed along orthogonal transverse directions and the beam size is extracted directly along the corresponding scan axis, the slant-scattering geometry produces an oblique scan trajectory in the collision plane. Consequently, the measured signal is coupled to the longitudinal density distribution of the electron beam. However, owing to the high repetition rate of the electron beam, the longitudinal density information cannot be effectively resolved. The electron beam can thus be approximated as a cylinder with an elliptical transverse cross-section. Consequently, the slant-scattering mode enables the extraction of electron beam transverse size. As noted above, the beam splitter acts differently on the two lasers: it reflects the HeNe laser to the CCD for position monitoring, while transmitting the CO_2 laser. The transmitted CO_2 laser then passes through a set of optical elements and is finally guided into the interaction region, where it collides with the electron beam. The optical path relevant to the laser wire scanning experiment is schematically shown in Fig. 2.

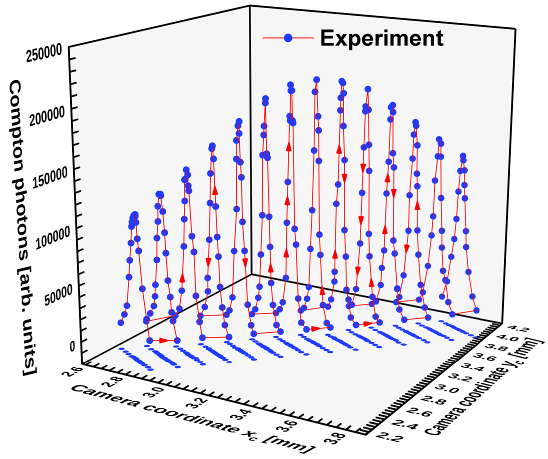

Figure 2: Schematic of the optical path relevant to the laser-wire scanning experiment.

In the coordinate system of Fig. 2, the electron beam propagates along the z-axis, and θ_i denotes the laser incident angle. Owing to the slant-scattering geometry, the laser motion measured on the CCD is related to, but not identical to, the actual laser motion in the interaction region. Therefore, the CCD-measured position (x_c, y_c) must be transformed into the true laser position (x_i, y_i) in the interaction region according to

$$x_i = x_c \cos\theta_s + y_c \sin\theta_s, \tag{2}$$

and

$$y_i = y_c \cos\theta_s - x_c \sin\theta_s. \tag{3}$$

Here, $\theta_s < 0$ ($\theta_s > 0$) denotes a clockwise (counterclockwise) rotation, with

$$\theta_s = \theta_i - \frac{\pi}{2}. \tag{4}$$

The laser spot profile undergoes the same rotational transformation. After applying this mapping, the CCD measured laser position can be used to represent the actual spot offset relative to the electron beam center in the interaction region.

Based on the expression for the photon yield in LCS [4], the Compton photons N_t in the SLEGS slant-scattering mode can be written for arbitrary relative spatial offsets as

$$N_t = N_e N_l \sigma_c \int \rho_e(x, y, z, t)\, \rho_l(x, y, z, t, x_c, y_c)\, \mathrm{d}V\, \mathrm{d}t. \tag{5}$$

Here, the spatial density distributions of the electron beam, ρ_e, and the laser, ρ_l, are both assumed to be three-dimensional Gaussian profiles. N_e and N_l denote the total numbers of electrons and laser photons in the corresponding pulses, respectively. σ_c is the total Compton scattering cross section averaged over the momentum distributions of the incident electrons and photons. All three quantities are assumed to remain constant throughout the scanning process. As shown in Fig. 2, when $y_i = 0$, the centers of the electron beam and the laser coincide in the y direction, so that the laser, steered by the scanning mirror, scans within the collision plane. In contrast, when $y_i \neq 0$, the two centers are no longer aligned, and a relative offset is introduced in the y direction. Since the position monitored by the camera is related to the actual position in the interaction region via a coordinate transformation, the most efficient scanning method is to define a set of trajectories along which the laser performs a raster scan in the plane perpendicular to its propagation direction within the interaction region. In this plane, the scan pattern is an orthogonal raster grid. By repeatedly performing the scanning procedure described above, namely moving the laser and recording the Compton photons together with the corresponding camera-monitored position, a three-dimensional scatter plot of the Compton photons as a function of the camera-monitored coordinates can be obtained, as shown in Fig. 3. Because the camera-measured position is related to the actual position in the interaction region through a coordinate transformation, the scan trajectories are most conveniently defined in the plane perpendicular to the laser propagation direction within the interaction region. In this plane, the laser follows an orthogonal raster pattern. By repeating the scan while recording both the Compton photon signal and the corresponding camera coordinates, a three-dimensional scatter plot can be constructed, as shown in Fig. 3, with the two camera coordinates and the Compton photon counts as the three axes.

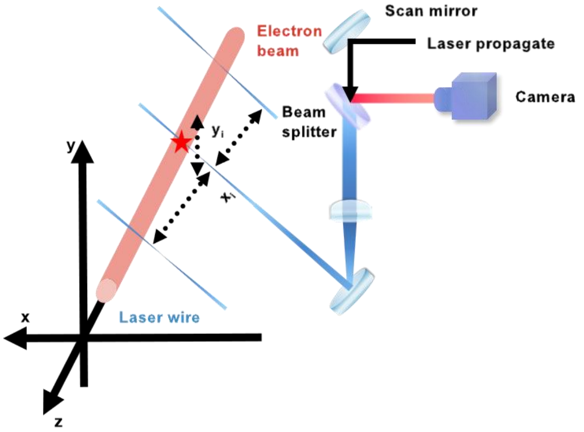

Figure 3: Three-dimensional scatter plot with the two camera coordinates and the Compton photon counts as the three axes. The projection onto the bottom plane shows the tilted raster scan pattern, with a tilt angle of θ_s.

When mapped into the camera coordinate system, the originally orthogonal scan trajectories appear tilted. The projection onto the coordinate plane therefore exhibits an inclined raster pattern with a tilt angle θ_s. By fitting the experimental data, which exhibit a peaked spatial distribution, the horizontal and vertical sizes of the electron beam can be determined simultaneously. Since the dependence of the Compton photon yield on the spatial offset is described by the integral in Eq.(5), an analytical expression for this function is difficult to obtain. Therefore, the measured distribution is fitted using numerical integration. The fit parameters include the horizontal and vertical electron beam sizes, the horizontal and vertical laser waist sizes, and the laser quality factor. For computational efficiency, the integration region is always centered on the electron beam, and the contribution from the region beyond three times the electron beam size is neglected. This approximation is reasonable because the electron beam is assumed to follow a Gaussian distribution, for which the beam density in that region is negligibly small; consequently, the corresponding Compton photon yield is also negligible. The fitting procedure is implemented using a genetic algorithm, with the goodness-of-fit metric serving as the fitness function. Assuming Poisson statistics for the photon counts, the fit quality is evaluated using the Poisson log-likelihood, following Ref. [5]:

$$LL(k) = \sum_i \left[y_i \log\left(\frac{f(x_i \mid k)}{y_i}\right) + y_i - f(x_i \mid k) \right], \quad (6)$$

where i denotes the index of the measured data point, x_i represents the scan position for the ith data point, y_i is the measured Compton photon count, and $f(x_i \mid k)$ is the corresponding fitted value. The vector k contains the fit parameters. By maximizing the Poisson log-likelihood in Eq(6), the electron beam and laser parameters that best reproduce the experimental data can be determined. The fitted results are summarized in Table 1.

Table 1: Fit Result

Parameter	**Value**
Electron beam horizontal size [μm]	309.35 ± 92.68
Electron beam vertical size [μm]	6.61 ± 0.85
Laser waist horizontal size [μm]	22.44 ± 2.80
Laser waist vertical size [μm]	22.97 ± 8.39
Laser horizontal quality factor	1.06 ± 0.28
Laser vertical quality factor	1.05 ± 0.77

As shown in Table 1, the fitted horizontal electron beam size is in good agreement with the theoretical value, whereas the fitted vertical size exhibits a deviation. This difference can be understood in terms of the relative sizes of the electron beam and the laser in the two transverse directions. In the vertical direction, the electron beam size is smaller than the laser size, so the scan is effectively carried out with a broader laser profile over a narrower electron beam, which limits the sensitivity to the vertical beam profile. By contrast, in the horizontal direction, the electron beam size is larger than the laser size, so the scan is more sensitive to the horizontal beam profile.

CONCLUSION

In summary, the laser wire scanning experiment performed in the slant-scattering mode at the SLEGS beamline station successfully demonstrated the simultaneous extraction of the horizontal and vertical electron beam sizes. These results confirm the feasibility of using this method for two-dimensional transverse beam size diagnostics. With a more tightly focused laser beam, the technique is expected to resolve even smaller beam sizes in the future, making it a promising tool for beam diagnostics in next-generation accelerator facilities with lower emittance and smaller transverse beam dimensions.

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