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First Beam Test of Nanometer Spot Size Monitor Using Laser Interferometry

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Abstract

The nanometer spot size monitor based on the laser interferometry (Laser-Compton Spot Size Monitor) has been tested in FFTB beam line at SLAC. A low emittance beam of 46 GeV electrons, provided by the two-mile linear accelerator, was focused into nanometer spot in the FFTB line, and its transverse dimensions were precisely measured by the spot size monitor.

Introduction

In order to demonstrate feasibility of TeV-scale electron-positron linear colliders, the Final Focus Test Beam (FFTB) line has been constructed at SLAC under the international collaborations[4]. This specially designed focusing system aims to focus a low-emittance electron beam to a tiny flat beam of 1 μm in horizontal and 60 nm in vertical sizes. To measure these small spot dimensions, a new method was devised by the author[1,2]. This method utilizes a laser interference fringe as a direct scale of the spot size measurement.

The spot size monitor system based on this method has been installed[3,5] in the focal point of FFTB line in summer 1993. In the recent dedicated beam run for FFTB during April and May 1994, we started to use the monitor for machine tuning.

Experimental Setup

Figure 1 shows the schematic diagram of the spot size monitor. The Nd: YAG-laser emits the pulsed laser light at 1064 nm of infrared wavelength, pulse energy of 200 mJ and repetition rate at 10 pps. The laser beam is split into two beams, then focused and meet at the focal point. Overlapping two laser beams interference fringe pattern is generated at the interaction point as shown in the figure. The high energy electron beam is injected from the perpendicular direction to the laser beams, and generates γ-rays by the Compton scattering. The flux of γ-rays are measured by monitoring the Cherenkov radiation in a gas behind a lead-shower-conveter after the bending magnet.

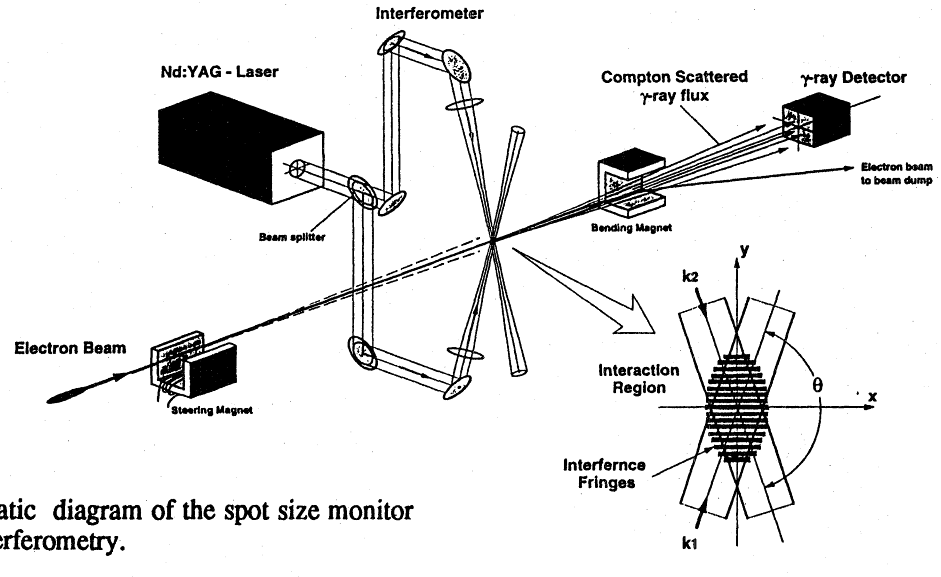


Fig.1. Schematic diagram of the spot size monitor using laser interferometry.

In the actual system, the laser beam is split into six beam lines. By selecting different combination of beam lines, three types of fringe pattern of different fringe pitch can be generated to measure different spot-size range. These technical details are described in ref. 5.

Noise Background Subtraction

Since the spot size is determined by the modulation depth in the Compton scattered γ-ray data, i.e., the ratio of AC to DC components, for accurate measurements it is very important to eliminate the effect of the noise background. To do this, a synchronous detection technique is used. When the electron beam runs at 30 Hz, the laser is fired at 10 Hz. That is, for each electron beam pulse the laser beam is fired alternatively: ON_OFF_OFF_ON_OFF_OFF... The laser-ON γ-ray data is averaged for six pulses, and the noise-background (laser-OFF) γ-ray data is averaged for twelve pulses, then the noise-background data is subtracted from the laser-ON data.

Measurement Procedure

Since the electron beam has 0.1 mm of vertical beta-function at the focal point, for accurate measurements the laser beam cross-section must be smaller than the beta-function. We designed the laser beam waist size w_0 = 100 μm. To make the fringe contrast better than 98%, which corresponds to accuracy ± 3 nm at 60 nm spot size, we have to align the laser beams at the common focal point with accuracy better than ±20 μm.

z-axis alignment

For z-axis alignment of the laser beams, we prepared a slit scanner. We insert the slit at the focal point, and scan the z-position of laser beam by the mirror mover. We measure the transmitted laser power through the slit using a photo-detector at opposite side as shown in Fig. 2. In this example, we set the z-position of the mirror to the center position at -0.59 mm. We repeat this process for all laser beam lines.

xy-axis alignment

For xy-axis alignment, we use γ-ray signal from the electron beam. By scanning the electron beam trajectory along x or y axis, we look for a γ-ray peak of the laser beam as shown in Fig. 3. By adjusting x or y axis of mirror, we can align each laser beam to the center(electron beam axis).

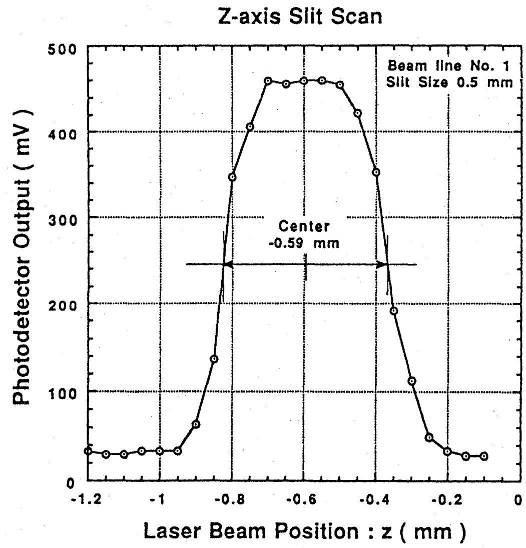
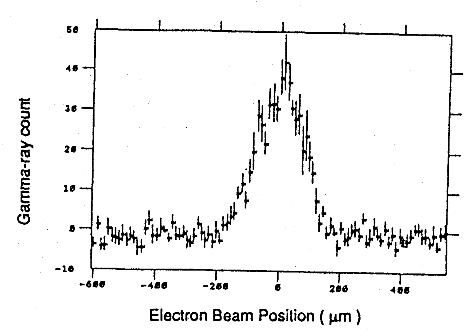
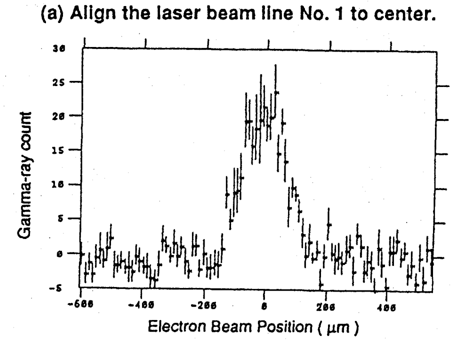


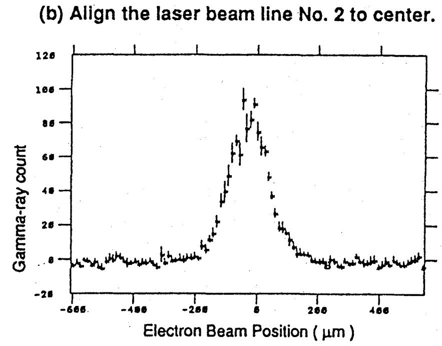
Fig. 2. Z-axis slit scan. The slit center is found at -0.59 mm. We move the z-axis of the mirror No. 1 to this center.



(a) Align the laser beam line No. 1 to center.



(b) Align the laser beam line No. 2 to center.



(c) Overlap two beams at center.

Fig. 3. xy-axis alignment.

Measurement Example

If we scan the electron beam trajectory with fine step, we observe a periodic intensity modulation in the γ-ray data as shown in Fig. 4. The solid curve is least-mean-square fit of analytical function :

$$Y = A + B \sin\left(\frac{2\pi}{d}y + C\right) \qquad (1)$$

where d is period of fringe pattern(dark-to-dark distance). We use theoretical value of $d = \lambda_0/2\sin(\theta/2)$, where λ_0 is wavelength of laser, θ is crossing angle of laser beams, in this case, λ_0 = 1064 nm, θ = 174 deg., and d = 533 nm. A, B and C are unknown free parameters, which will be determined by the data fitting. In this case A = 106.7, B = 72.6, and the modulation depth is B/A = 0.68.

Assuming a Gaussian beam, the modulation depth is related to the spot size:

$$M = B/A = |\cos\theta| \cdot C_p \cdot \frac{1}{\sqrt{1+(k_y\sigma_y{*}w_0/\beta{*})^2}} \cdot \exp(-2k_y^2\sigma_y{*}^2), \qquad (2)$$

where

$|\cos\theta|$: correction factor for traveling wave component.
θ = 174 deg., $|\cos\theta|$ = 0.9945

C_p : correction factor for power imbalance of two laser beams.

$$P_2/P_1 = 1.26, \qquad C_p = \frac{2\sqrt{P_2/P_1}}{1 + P_2/P_1} = 0.993$$

Since the laser beam has a finite waist size at the focal point, the spot size monitor provides an average value of the electron beam size within the laser beam cross-section, which becomes bigger than the actual spot size at the waist. The third term corrects this effect. At 60 nm spot size, and the laser waist size w_0 = 100 μm, this term becomes 0.944. The last term is the ideal spot size response. Solving eq. (2), we have $\sigma_y{*}$ = 66 nm.

We estimated measurement error by incorporating the statistical error in the data fitting, the electron beam position jitter, the laser beam position jitter, the laser beam misalignment, and error in the background subtraction. Finally we conclude the spot size is

$$\sigma_y{*} = 66^{+3}_{-11} \text{ nm}.$$

Summary

Nanometer beam was produced in FFTB and whose transverse dimensions were successfully measured by the spot size monitor based on the laser interferometry. This success is a big milestone in the electron-positron linear collider R&D project. In an actual linear collider, we use a short wavelength laser such as 5th harmonic radiation of Nd: YAG-laser at 213 nm. Fully utilizing the synchronous-noise-background-subtraction technique and using a stable laser oscillator, it will be possible to utilize the modulation amplitude up to 95% or more. Therefore the design spot size of 3~4 nm at interaction point can be measured with enough accuracy based on this method.

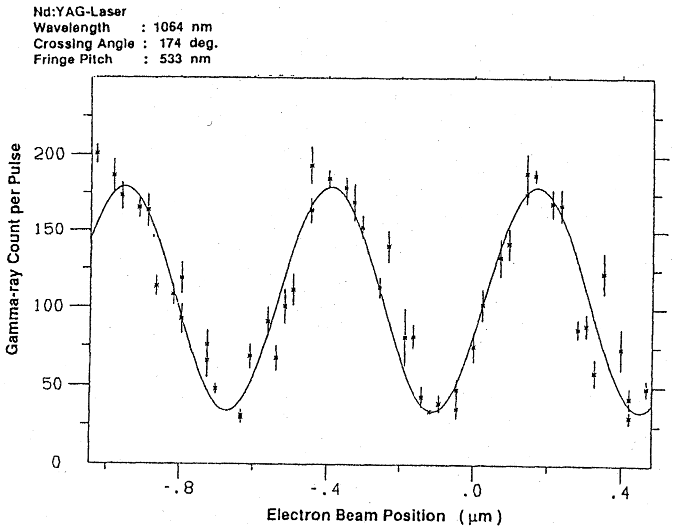


Fig. 4. Measured fringe pattern in the Compton scattered γ-ray. Solid curve is the least-square-fit of sin-function.

Acknowledgments

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