*The 8th Symp. on Accelerator Science and Technology, 1991, Saitama, Japan*

# Nano-meter Beam Size Monitor by Laser-Compton Scattering

## ( Laser-Compton Beam Size Monitor )

Tsumoru SHINTAKE

*KEK: National Laboratory for High Energy Physics*
*Oho 1-1, Tsukuba-shi, Ibaraki 305 Japan*

### Abstract

A spot size measurement system at nano-meter range using Compton scattering of laser beam has been proposed for a reliable diagnostic instrument of electron beam at interaction point in $e^+e^-$ linear colliders. The high energy electron beam is injected into a standing wave of laser light, and generates high energy $\gamma$-rays by Compton scattering. We measure spatial modulation of $\gamma$-ray flux by scanning the electron beam trajectory along laser axis. From the modulation depth, the transverse electron beam size is determined. A system based on this scheme using Nd:YAG-laser of 1064 *nm* wavelength is under construction, and will be installed in FFTB beam line in SLAC, and tested with a fine beam of 1 $\mu m$ by 60 *nm* in transverse dimensions.

### Introduction

In future $e^+e^-$ linear colliders of TeV region (JLC, VLEPP, NLC, CLIC, ..), the electron and positron beams are focused into ultra-small spot size at the interaction point. A typical spot size of a few 100 *nm* horizontal by a few *nm* vertical, flat beam is necessary to get a luminosity near $1 \times 10^{34}\ cm^{-2}s^{-1}$. This spot size is much smaller than that in any conventional colliding machines, therefor it is one of the most important tasks to develop new technologies of beam diagnostics, especially a reliable spot size measurement system.

In the previous paper(1), a new method was proposed, which utilizes the Compoton scattering in a standing wave of laser beam. The transverse dimension of the electron beam is determined from the modulation depth in the measured $\gamma$-ray flux.

We are now developing a beam size monitor system based on this scheme using Nd:YAG-laser at 1064 *nm* wavelength, which will be installed in FFTB(2) beam line in SLAC, and used to measure a beam of 1 $\mu m$ by 60 *nm* in transverse dimensions. The same system will be installed also in FFT facility(3) in KEK, and used to measure 3.9 $\mu m$ by 30 *nm* beam.

In this paper, firstly the basic principle of measurement will be explained briefly. Then, we will explain the laser optics design of our system, and discuss some practical problems.

### Basic Principle of Measurement

Figure 1 shows a schematic illustration of the Laser-Compton Beam Size Monitor. The intense laser beam is focused into the interaction point by a lense in order to define the interaction area in a so small spot as to measure the electron beam size precisely at the interaction point, and also to increase the light power density. The laser beam is reflected back by the second mirror, and focused into the interaction point. These two laser beams interfere and form a standing wave at the interaction point. The high energy electron beam is injected into this standing wave, and collide with the photons of laser light and generate high energy $\gamma$-rays by the Compton scattering. We measure the flux of these high energy $\gamma$-rays. After the interaction, the electron beam is swept out by a bending magnet.

The number of $\gamma$-rays radiated per bunch is proportional to the square of the electric field intensity of the laser.

$$N_\gamma \sim E^2 \sim \sin^2(y/2\pi\lambda_0) \qquad (1)$$

$E^2$ has peaks and nodes in each $\lambda_0/4$ spatial period. If an electron goes through at the node position, the electron does not radiate any $\gamma$-rays. When it goes through at the peak position, the electron will radiate the maximum number of $\gamma$-rays. Now, we inject a bunch of electrons, and slowly scan the trajectory along laser axis. If the transverse size of electron beam is much larger than the spatial period of standing wave, the radiated $\gamma$-ray flux will show small modulation as shown in Fig. 2(a). When the electron beam is focused, it will show medium depth modulation. For well focused beam, the modulation depth approaches 100 % as Fig. 2(c). From the modulation depth, we can determine the electron beam size. Assuming the Gaussian distribution, the beam size is given by

$$\sigma_y = \frac{\lambda_0}{4\pi} \cdot \sqrt{2 \cdot \log M^{-1}} \qquad (2)$$

where $M$ is the modulation depth defined by $\Delta N/N_0$, and $\lambda_0$ is the wavelength of laser light.

The required laser power to get 1000 $\gamma$-rays per pulse by a bunch of $1\times10^{10}$ electrons is about 10 MW. This amount of laser power is easily available by commercially provided pulsed Nd:YAG-laser system. The detailed discussions on principle of measurement are given in ref. 1.

**Laser-Compton Beam Size Monitor**

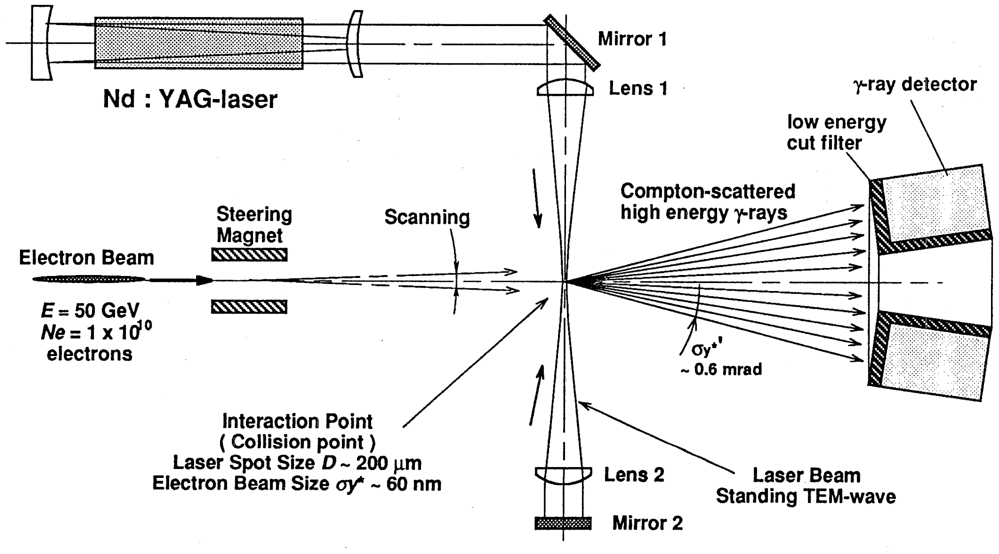
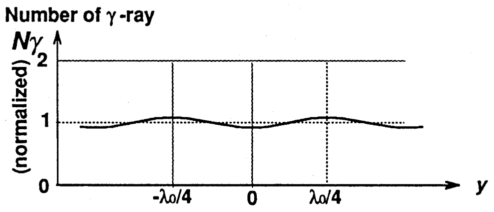
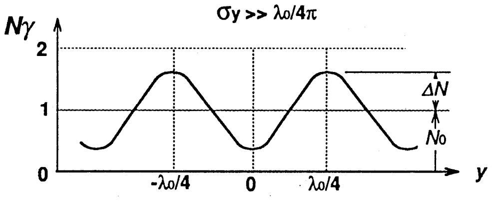


Fig. 1 Conceptual drawing of Laser-Compton Beam Size Monitor system.



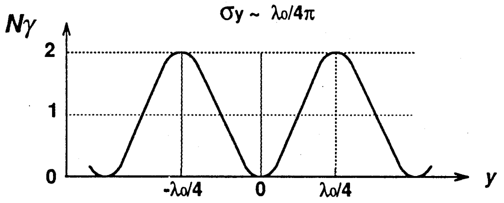
( a ) Non focused beam

$\sigma_y >> \lambda_0/4\pi$



( b ) Focused beam

$\sigma_y \sim \lambda_0/4\pi$



( c ) Well focused beam

$\sigma_y << \lambda_0/4\pi$

Fig. 2 Variation of the $\gamma$-ray flux by scanning the electron beam trajectory in vertical direction. The electron beam size is known by measuring the modulation depth: $\Delta N/N_0$.

## Laser Optics Design

Here we will explain the laser optics design of our system, and discuss some practical problems.

### Laser System

We will use pulsed Nd:YAG-laser, model GCR-3 produced by Spectra Physics Inc., which generates 400 *mJ* pulse energy at 1064 *nm*, at 10 *pps* pulse rate, with pulse length of 7 ~ 9 *nsec.*

### Laser Spot Size

Because the vertical beta-function $\beta_y$* of electron beam at the final focus point in FFTB is only 100 $\mu m$. In order to measure the minimum spot size precisely, we must focus the laser beam into a small spot whose diameter is less than a few times of beta-function. We chose the laser beam spot 200 $\mu m$ in diameter.

### Damage Threshold

In order to prevent the optical instruments from high power damage, we use long focus lense of *f* 500 *mm*. The laser beam sizes on every optical components stay 3 ~ 7 *mm* in diameter, and power density 0.1 ~ 0.5 $GW/cm^2$, which is well below the damage threshold of 5 $GW/cm^2$.

### Coherency Requirement

In the conceptual drawing of Fig. 1, we used intra-cavity scheme to explain the basic measurement principle, where the laser light is reflected back into the interaction point by the second mirror. Two lights form a standing wave by ovelaping each other. However, the two laser lights have path difference about 1 *m*. The natural spectral line with of Nd:YAG-laser light is about 1 $cm^{-1}$. It is apparent that the coherent length of this laser is much shorter than the path difference, and we do not observe any interference pattern (standing wave pattern) at the interaction point. The required line width to get enough interference effect (visibility > 95%) is 0.0013 $cm^{-1}$, this is not achievable by any kind of pulsed high power lasers, even with the injection seeding laser system. Hence, instead of the intra-cavity scheme, we employed interferometer scheme in the practical design. In this scheme, we can let the path difference almost zero, and coherency requirement is extensively relaxed.

### Two-dimensional Measurement

The FFTB beam has a flat cross-section: 1 $\mu m$ by 60 nm. If we wishes to measure the horizontal beam size of 1 $\mu m$ by the same method, from eq. (2) it is known that we must add another laser system of longer wavelength (10 ~ 20 $\mu m$), and the total system will become more complicated and expensive. Instead of using such long wavelength laser, we can equivalently establish long period modulation as shown in Fig. 3. In the Young's configuration, light beam emerged from the first slit splits in two beams, and path through two slits, then overlap each other and finally illuminate the screen. Due to the interference, we observe periodic spatial modulation on the screen. The period of this pattern is much longer than the light wavelength. The period is given by $\lambda/\theta$, where $\theta$ is opening angle between two lights. Using laser beam, we can establish the same field pattern by splitting a laser beam by a half mirror in two beams and injecting into the interaction point with opening angle $\theta$. In our beam size monitor system, we chose the angle 6.0 deg., and inject four beams as shown in Fig.4. At the interaction point, we have a two dimensional standing wave pattern, with horizontal and vertical periodicities of 20.3 μm by 1.06 $\mu m$. By scanning the electron trajectory in horizontal and vertical directions, we can measure the horizontal and vertical beam sizes, respectively ( named Mode-1). The sensitive range is $\sigma_x$ = 0.8 ~ 3.4 $\mu m$ and $\sigma_y$ = 40 ~ 180 *nm*. In the same way, to measure the vertical beam size at the larger dimensions, we inject two beams with opening angle 30 *deg.* as shown Fig. 5 (named Mode-2). In this mode the modulation pattern becomes horizontal comb with 4.1 $\mu m$ period, and the sensitive range is $\sigma_y$ = 160 ~ 720 *nm*. The sensitivities for two modes are summarized in Fig. 6.

Figure 7 shows overview of the laser system. Every optical components are mounted on a optical table of 1.6 *m* by 1.6 *m*, which is mounted on a dynamically stabilized table specially designed to support the final Q-magnets. The laser beams are injected into vacuum interaction chamber through flat windows, and focused at the interaction point. The electron beam is focused by the final Q-magnet, and injected into the interaction chamber. The generated $\gamma$-rays are detected by a calorimeter located down stream of the beam line. This system will be installed in FFTB$^{(2)}$ beam line in SLAC.

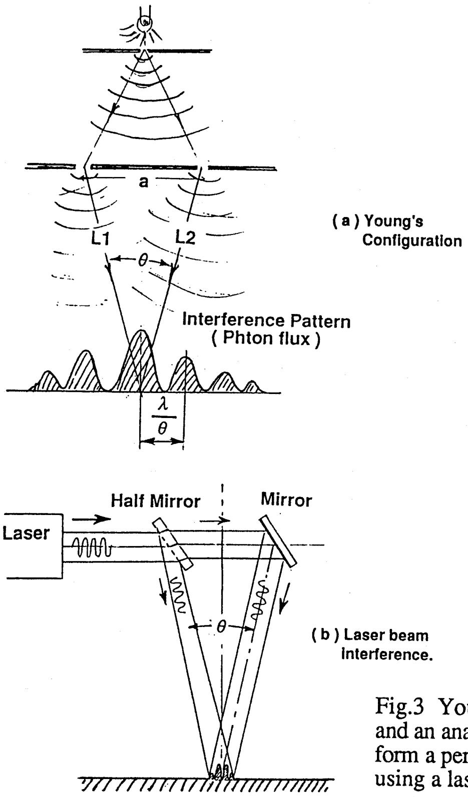


Fig.3 Young's configuration and an analogical method to form a periodic modulation using a laser beam.

## Summary

A reliable beam diagnostic system using Compton scattering of laser beam has been proposed for a spot size measurement of nanometer range at interaction point in $e^+e^-$ linear colliders. A system based on this scheme using Nd:YAG-laser at 1064 *nm* wavelength is under construction, and will be installed in FFTB beam line in SLAC, and used to measure a fine beam of 1 *µm* by 60 *nm* in transverse dimensions. The same system will be installed also in FFT facility in KEK, and used to measure the 3.9 *µm* by 30 *nm* beam. In the future, using the fourth harmonic radiation of Nd:YAG-laser at 266 *nm* wavelength, it is possible to measure 10 *nm* beam with enough accuracy, and by some excimer laser it will be possible to measure 5 *nm* beam.

## Acknowledgements

The author wishes to thank Prof. Yoshitaka Kimura, Prof. Koji Takata, Dr. Seishi Takeda ( KEK, Tsukuba) and Dr. David L. Burke (SLAC) for their encouragements on this work. The author also thanks to many colleagues in KEK and SLAC for their useful discussions.

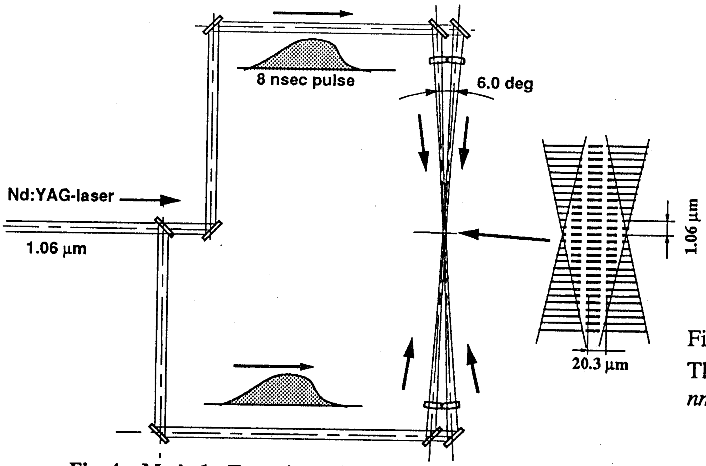


**Fig. 4** **Mode 1 : Two-dimensional Measurement**
**Range : $\sigma_y = 40 \sim 180$ nm**
**$\sigma_x = 0.76 \sim 3.4$ µm (10~90%modulation)**

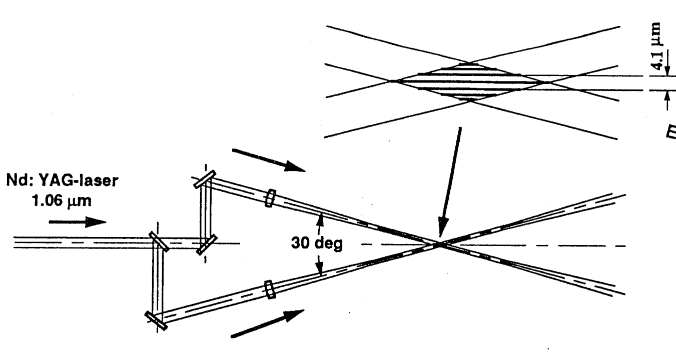


**Fig. 5** **Mode-2 : Vertical Beam Size Measurement (upper range)**
**Range : $\sigma_y = 160 \sim 720$ nm**

## References

1) Tsumoru SHINTAKE, "Proposal of Nano-meter Beam Size Monitor for $e^+e^-$ Linear Colliders", KEK Preprint 90–173, January 1991 A, to be published on Nucl. Instrum. Meth.

Tsumoru SHINTAKE, Divisione Acceleratori–Memorandum Interno, Laboratori Nazionali di Frascati Dell'INFN, SC–141, 13 December 1990.

2) "Final Focus Test Beam Project Design Report", SLAC-Report-376, March 1991

Katsunobu OIDE, "Design of optics for the Final Focus Test Beam at SLAC", SLAC-PUB-4953, May 1989 (A)

3) Katsunobu OIDE, "Final Focus Test at KEK", proceedings of the first workshop on Japan Linear Collider (JLC), KEK Report 90-2, April 1990 A/H.

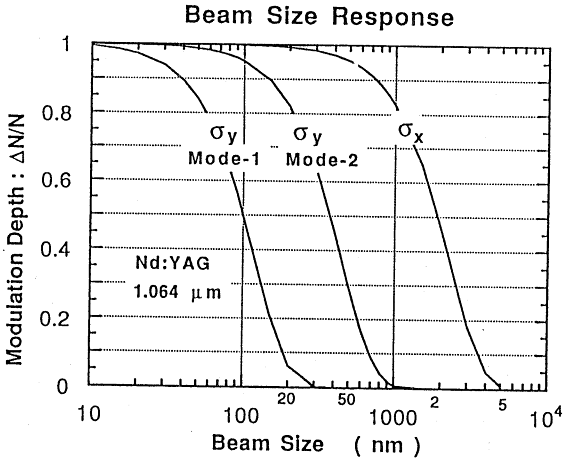


Fig. 6 Sensitivity of the Laser-Compton Beam Size Monitor System. The system covers wide range of vertical beam size : $\sigma_y = 40 \sim 720$ *nm* (10 to 90 % modulation) by means of two operation modes.

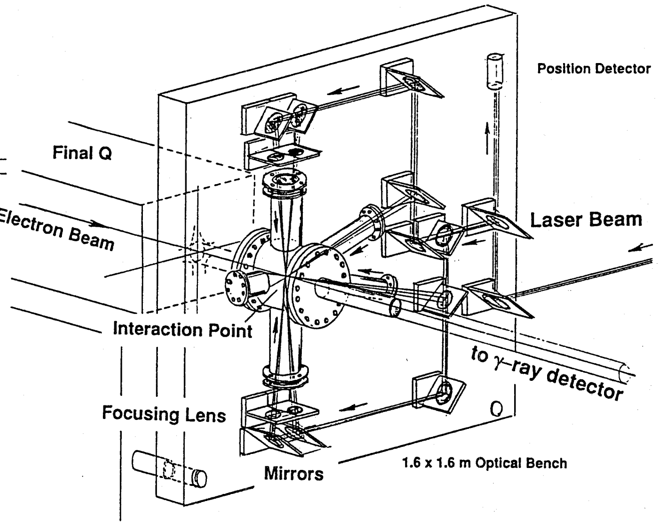


Fig. 7 Overview of optical system of the Laser-Compton Beam Size Monitor. This system will be installed in FFTB beam line in SLAC.