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A POSITIONING METHOD OF THE HIGH-ENERGY PHOTON

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Abstract

A photon positioning method using Silicon Stripe Detectors (SSD) for the detection of the photo-produced electron-positron pairs was tested. A detector system with SSD and scintillation counters was used for the determination of positioning resolutions. An achieved resolution at the photon energy 0.85 GeV is 570μm, which is limited in this measurement by the stripe size of the SSDs. The method is applied to obtain an image of an object.

1 Introduction

The position information of the photon is important for the medical application such as nuclear medicine (SPECT and PET) in order to determine the size, the shape, and the flow of the photon emitter in the human body. Positioning of the photon is also important for fundamental studies such as nuclear physics and high-energy physics. In this photon positioning, the position resolution is very important.

There are a several established methods. (1) To use segmented calorimeter blocks and take the position of the block that gives the maximum output. (2) To determine an average of the positions of the blocks which are weighted by the output pulse height. (3) To place collimators in front of the calorimeter. (4) To convert the photon into an electromagnetic shower and measure the shower positions by position-sensitive detectors for charged particles.

When one uses the inorganic crystal scintillation counter of suitable size as the photon detector for the methods (1) and (2), position resolutions of a few mm can be reached. A dependence of the resolution on the hit position to the counter is unavoidable. The use of collimators in the method (3) deteriorates the detection efficiency. While, the method (4), where a use of a converter in front of the positioning device such as multi-wire proportional chambers with sub-mm resolutions, gives a flat response, and leads to a few-mm resolution due to the transverse spread of the shower. In this method, one suffers from event-by-event fluctuation.

In this study, we carry out the measurement to test a method of the photon positioning by using the Silicon Stripe Detector (SSD) for the detection of the photo-produced electron-positron pairs in a converter in front of the SSDs. The merit of this method is an expectation for the high-position resolution as well as high-time resolution that can be achieved by the use of high-speed detectors such as SSD and scintillation counters. These make possible good position measurements of high rate photons.

2 Experimental Methods

2.1 Principle of the positioning method

The photon hitting a matter produces a pair of electron and positron. The production probability, P, depends on the cross section, σ, and the matter thickness, t. When P is much smaller than one, it can be written as follows,

$$P = \frac{N_A \sigma \rho t}{A} \tag{1}$$

where N_A is Avogadro's number, A the atomic number, and ρ the matter density. σ is in proportional to the atomic number (Z) squared for low Z matter, and it increases slowly as a function of the photon energy, E. The Bethe-Heitler equation gives the following estimate at E ~1GeV.

$$\frac{\sigma}{Z^2} \cong 10[\mathrm{mb}] \tag{2}$$

The production angles of the electron and positron can be calculated by the Bethe-Heitler equation, where the peak of the angular distribution, θ_0 , is approximated by

$$\theta_0 \approx \frac{m}{E_0}, \tag{3}$$

and this is of the order of 1 mrad for the present experiment using the E ~1 GeV photon beam.

The photon hits a thin target, and produces a e^-e^+ pair. The pair is detected by a position sensitive detector, which is d [m] downstream from the target (Fig. 1). By taking an average of the two hits positions on the detector, one can determine the photon incident position as follows under the condition of small emission angles,

$$x = \frac{x_- + x_+}{2} = \frac{d(\theta_- + \theta_+)}{2} \tag{4}$$

where + and - refers to the e^- and e^+ respectively, and x is for the SSD hit positions and θ are emission angles. The calculated distributions of the e^- and e^+ are shown in Fig. 2. The curve predicts position resolutions much less than 1 mm in case of the sub-GeV photons.

For the estimation of the position resolution and the detection efficiency of the present method, we have carried out analytical calculations. We are expecting to use the capability of the EGS4 program for the estimation with more reliability.

2.2 Beams and yield

As for the selection of the photon energy, we have taken into account two facts: (1) the angular distribution of the pairs requires higher energies, and (2) the reduction of angular deflection due to the multiple Coulomb scattering of the particles in the matter also prefers higher energies. Accordingly the highest energy available at the 1.3-GeV Electron Synchrotron, KEK Tanashi, was used. A 1-GeV electron beam from the accelerator hits a thin target to produce a bremsstrahlung photon beam. The high-energy photon beam was tagged to determine the energy of each photon by the Photon Tagging System [1].

The maximum photon flux was 1.0×10^6 photons/s. Angular spread of the photon was 1 msr. The beam spot size was typically 1mmϕ, and it could be extended to 5×5 cm^2 by defocusing the

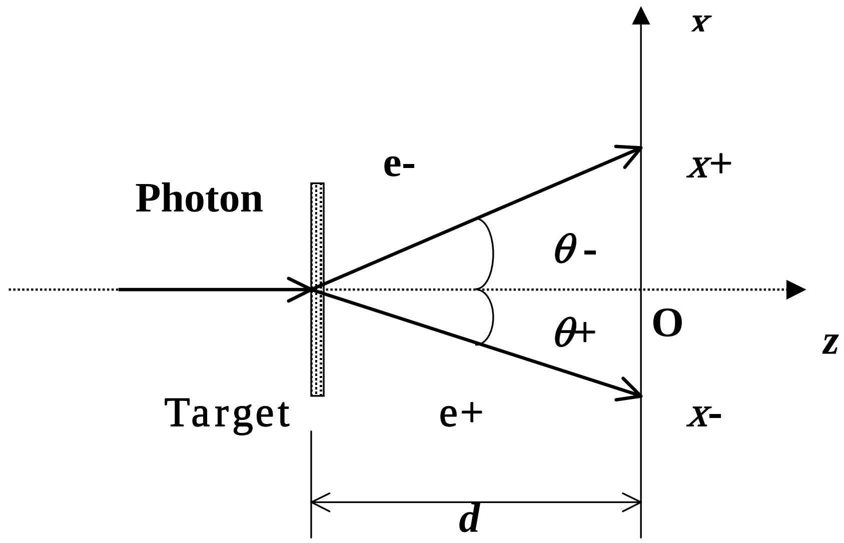

Figure 1: The photon hits a target at $z = -d$ to produce an electron-positron pair. The electron and positron in the forward to a positioning detector placed on the axis at z=0. See text.

quadrupole magnets in the electron transportation, where the photon-beam fluence rate is 4.0×10^4 photons/ cm^{2}s. This number and the cross section formula 2 give yield estimation as follows,

$$Y[\text{Pairs/mm}^2\text{s}] = 1.2Zt[\text{g/cm}^2] \tag{5}$$

As an example, one can obtain 10 pairs per mm^{2}s for 1 g/cm^2 thick target of Z=8.

2.3 Detector layout

The layout of the experimental detectors is shown in Fig. 3. A Lead collimator of 20 cm thick removed associated halo from the photon beam (electron beam) from the synchrotron. A set of two plastic scintillation counters of PMT readout (1 mm thick for upstream and 5 mm thick for downstream) on the beam line identified the event, and triggered the data acquisition.

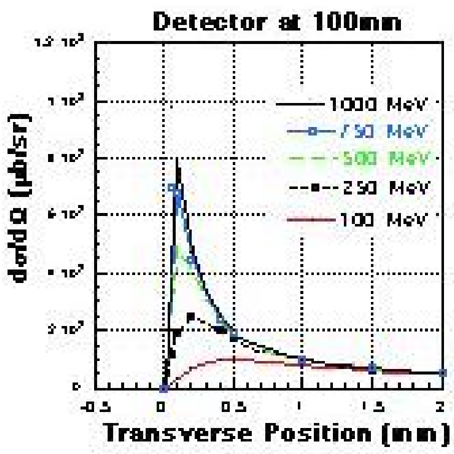

Figure 2: Transverse position distribution of the produced electrons and positrons at various photon energies. The peaks and the widths are much less than 1mm

In between the counters, a target and two single-sided SSDs (S2461, Hamamatsu Photonics) were placed. Upper stream one was for horizontal (X) position measurement and the other for vertical (Y) position measurement. The beam was caught by a lead-glass calorimeter of 11.6 X_0 thick (SF5, Ohara Optical Co.) to measure the total energy of the beam particle.

The number of stripes of each SSD is 48, and each stripe has 900μm width and 100 μm gap. The wafer thickness is 250 μm. Stripe capacitance is 40 pF at the biasing voltage of 60 V. Forty-eight outputs from the SSD were amplified by the preamplifier and the linear amplifiers constructed for the SSD [2].

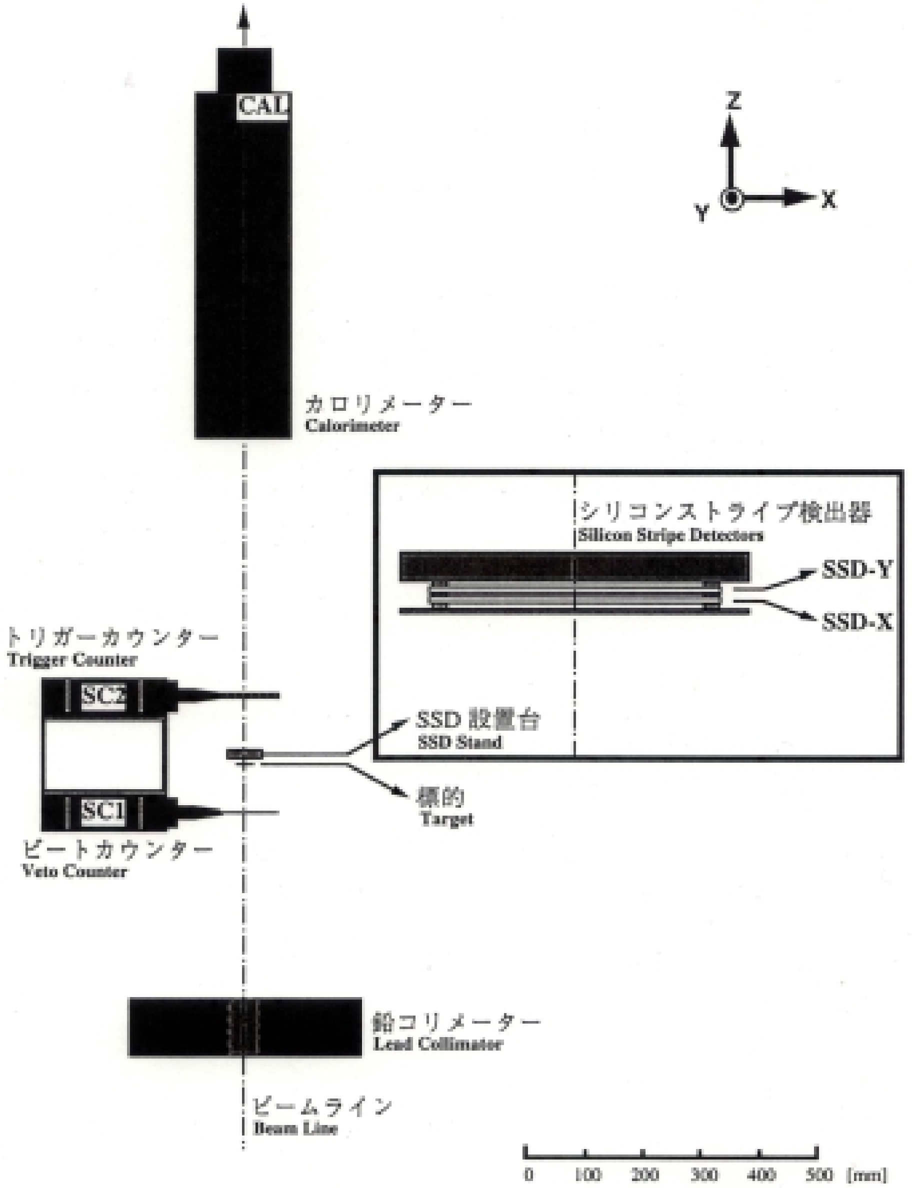

Figure 3: Layout of the detector. The electron beam and the photon beam from the accelerator are incident on the target through the collimator. SC1 and SC2 are for the scintilltion counters, CAL for the lead-glass calorimeter, and SSD for position measurements (see text).

The 48 outputs from the SSD and the three PMT outputs were sent to electronics hut for pulse height measurements with Analogue-to-Digital Converter (ADC, Lecroy 2249A and 2249W). Timing measurements were also made with TDCs. All the ADC and TDC data were sent to a PC (MICRON Millenia XKU) through the CAMAC data acquisition electronics. The OS used on the PC was Linux. The data were analyzed event by event basis for monitoring and for event reconstruction analysis. Analyzed data were stored on the discs for further analyses.

3 Experiments

3.1 Detector Tuning

The detector system was tuned by injecting a momentum analyzed electron beam. SC1 and SC2 were adjusted in gain and in timing by the minimum ionizing electrons. CAL was also tuned in gain and in timing by the beam. For the SSD, the pulse height spectra of 96 stripes were recorded in a signal-in run and a pedestal run to determine discrimination channels of the ADC data. An example of the SSD data from one stripe is shown in Fig. 4.

3.2 Scintillation counters

For the electron beam runs, a coincidence signal between SC1 and SC2 was used for event triggering. For the photon beam run, SC1 played the role of veto to reject charged particle contamination in the beam, and SC2 triggered data acquisition.

Figure 5 shows the ADC spectrum of the SC2 in a photon beam run. One observes three peaking: the first is for the tail of the counter noise, the second for passage of one minimum-ionizing particle. Therefore, the third is for the passage of two minimum-ionizing particles, i.e. one electron and one positron. Event selection criteria for the pair production are to pick up the events in the third peaking area.

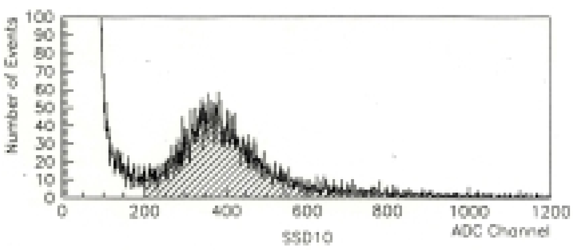

Figure 4: ADC distyributions of SSD.

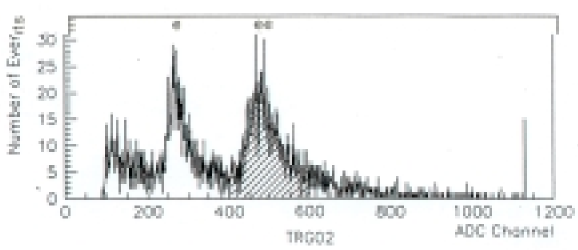

Figure 5: ADC distyributions of SC2.

4 Calorimeter

ADC data of the calorimeter was analyzed to confirm the event due to the beam. Figure 6 is ADC spectrum for the tagged-photon beam run, where tagged-photon signal, $E = 0.84\pm$ 0.08 GeV was required to trigger the event acquisition.

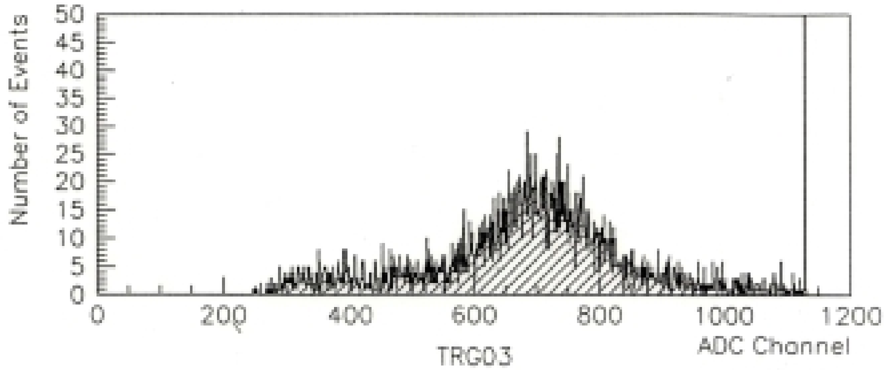

Figure 6: ADC distribution of CAL.

4.1 Beam profile runs

In order to confirm the detector system in operational, an electron beam was injected to the detector system. Observed SSD hit distribution, a profile of the electron beam, is shown in Fig. 7. By changing the triggering condition for the photon as stated above, a photon beam run was recorded as shown in Fig. 8. The electron beam profile of 3×6 mm^2 cross section is in accordance with other beam profile measurement equipped in the beam channel such as the wire scanner, multi-wire ion chamber, and film. The obtained photon profile of 10mmϕ is also consistent with the result of beam scanning method.

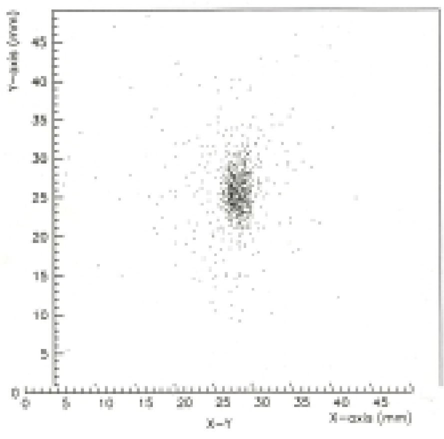

Figure 7: A profile of the electron beams.

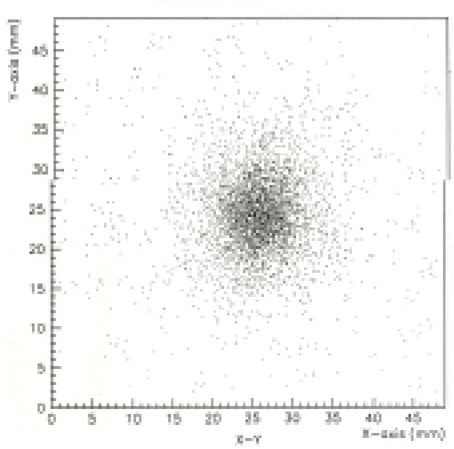

Figure 8: A profile of the photon beams.

4.2 Wire target runs

The photon positioning resolution was measured by placing a copper wire of 1.3 mm in diameter at the position of 20 mm upstream of the SSD. The wire was extended in horizontal and vertical directions for the measurements in X and Y, respectively. Event selection criteria are to satisfy the pair production, i.e. to require the passage of two minimum-ionizing particle in SC2, proper energy deposit in CAL, and single or double hits in SSD. When two hits in SSD were more than one stripe away, the event was not used.

Figure 9 shows the result in horizontal direction, where horizontal axis is for the SSD channel determined to be an average of two hits or the channel of single hit. A shape peak is seen above widely spread background events. A fitting to the data by a sum of constant and a gaussian successfully reproduces the data. The rms width of the gaussian is 865 μm. A similar result is obtained in Y direction. Background events are pair production in the materials except the target.

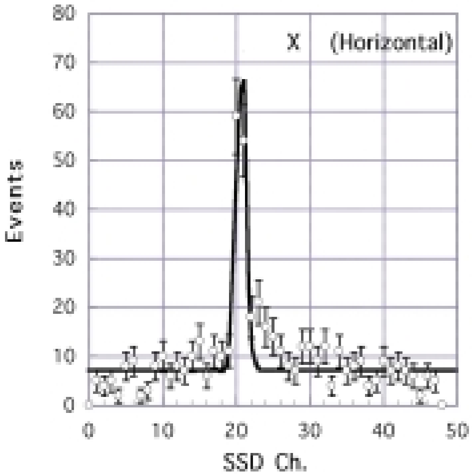

Figure 9: Distribution of the hits position of the pairs in X. Horizontal axis is for the 48 stripes of the SSD. Since each stripe is 1 mm wide, the peak extends in 2 mm.

5 Results and Discussion

5.1 Positioning of the photon

In the photon-beam runs, it was proved that our detector identified the pair production events. The peak in the wire distribution (Fig. 9) shows that the photon interaction is clearly seen. This means that an averaged SSD hit positions can be interpreted to be the photon incident position.

Positioning accuracy can be estimated from the interpretation of the width of the peak, σ. Three contributors to the width are the intrinsic position resolution, σ_0, the wire diameter, d, and the multiple Coulomb scattering of e^-e^+ pairs in the wire, δ. The following formula is used to estimate σ_0 from the measured resolution σ.

$$\sigma = \sqrt{\sigma_0^2 + \left(\frac{d}{2}\right)^2 + \delta^2} \qquad (6)$$

where d is calculated to be 150 μm. Obtained result is σ_0 =570 μm. The detection efficiency is estimated to be 0.68 using equation 2 for effective thickness 1.02 mm of the wire. One can conclude from this result that when we use a copper sheet of 1 mm thick as the photon converter, we are able to measure the photon incident position with the resolution σ by the present detector in a 50×50 mm^2 area. In order to obtain a better resolution in close to the intrinsic resolution σ_0, a thinner converter is necessary, although it leads to a smaller detection efficiency.

Since the stripe width is 1 mm (0.9 mm stripe + 0.1 mm gap), the intrinsic resolution σ_0 is found to be dominated by the width. A further improvement in the position resolution can be achieved by using higher resolution detectors.

5.2 Improvement and imaging with e- e+ pairs

The present photon positioning method works as theoretically predicted. When one needs a better resolution, a better positioning detector should be used. A theoretical limit comes from the multiple Coulomb scattering in the converter and production angle spread. Against these, multi-GeV photon beam available at KEK and Spring-8 are best selection.

A high-energy photon beam has high penetration capability due to the smaller cross sections for the Compton effect as well as the photoelectric effect. While, the pair production cross section increases slowly up to around 1 GeV. By utilizing this good feature of the photon and the positioning capability, we have tried to make an image of a thick matter by the photon beam [4]. The photons in the beam have to be in parallel.

6 Conclusions

A high-energy photon produces electron-positron pairs in matter. We have measured the positions of electron and positron in two directions by using two sets of the Silicon Stripe Detectors. The average of two positions represents photon interaction points. According to the facts that the production angles of the pairs are small and the distance between the points and SSD is short, the averaged positions can be interpreted to be the photon incident position. The measured rms position resolution with the present detector system is 570 μm at the photon energy 0.85 GeV. This figure is estimated to be dominated by the stripe width of the SSDs, therefore we expect an improvement of the figure by replacing the SSDs with narrower stripe size.

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References

1) K. Maruyama et al., *Nucl. Instrum. Methods Phys. Research* **A376**(1996)335-355.

2) K. Maeda et al., *Phys. Rev.* **C52**(1995)R1157-R1160.

3) K. Ito, Master Thesis, Department of Applied Physics, Tokyo University of Agriculture and Technology, Tokyo, 1999 [in Japanese].

4) K. Maruyama et al., to be submitted for for publication.