Photon tagging at the DESY II test beam facility

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Abstract

In this summer student report, I discuss the implementation of a tagged photon beam in the DESY II test beam facility. A simulation of test beam area 21 which is equipped with a dipole magnet was developed. The simulation studies provided the guidelines for test beam measurements over a week in August 2018. A 3 mm thick copper target was installed before the dipole magnet to facilitate the production of bremstrahlung photons. A measurement of the incident electrons before and after photon production provided an indirect measurement of the photon energies. A lead-glass Cherenkov detector was used to measure the energies of the photons directly. The rate of production of different photon energies is also reported.

Contents

1 Introduction

1.1 DESY II Test Beam

DESY II is an electron-synchrotron that serves mainly as a pre-accelerator for electrons injected into PETRA III, a radiation source at DESY[1]. The synchrotron also provides a source of electrons for three independent test beam lines. The test beams are used by research groups for prototyping, validation, and calibration of detection devices. The test beams are generated from a carbon fiber target in the DESY II ring. At this carbon fiber, bremsstrahlung photons are generated which travel to a converter plate that creates electron positron pairs with momenta in the range of 1–6 GeV/c. These particles pass through a variable magnetic field and finally a lead collimator that allows particles of a specific momentum through to the test beam area.

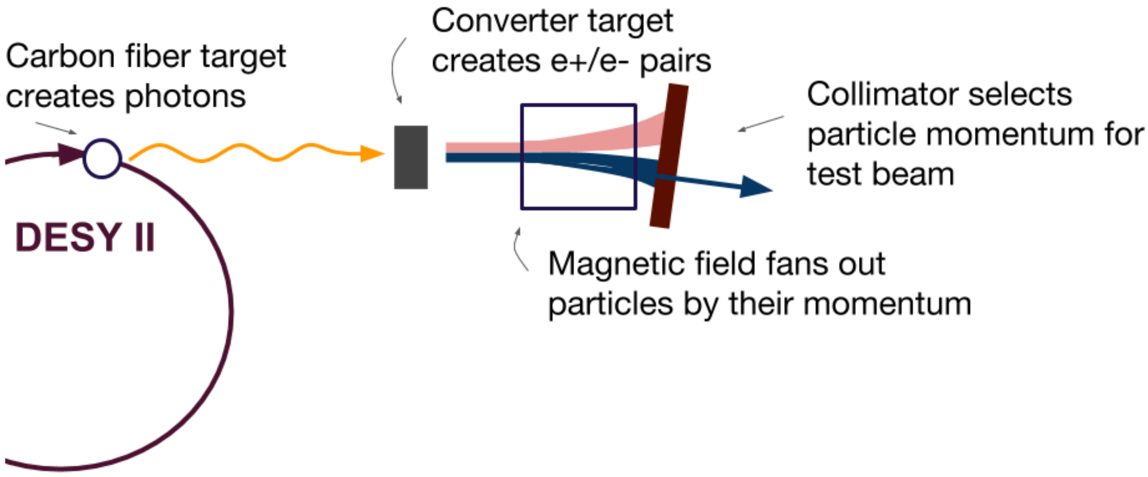

Figure 1: DESY II test beam generation

1.2 Photon Tagging

In the photon tagging system, electrons collide with a converter target of some material. Photons are created in the bremsstrahlung process. After the interaction, the photons and electrons continue together in the same direction down the beamline. A magnetic field is placed within the path of the particles. The deflection angle of the electron can be calculated, and is discussed in section 2.2. The photon will not be deflected, and will continue in the path of the beamline. Determining the energy of the photon directly would be a destructive process. Instead, a measurement of the energy of the electron before and after the photon is generated allows us to calculate indirectly the energy of the photon. This provides a method for test beam users to select a desired photon energy based on a well defined electron energy.

In this experiment, the indirect energy of a photon is confirmed by absorbing the photon completely using a lead-glass Cherenkov detector and triggering on electrons that are deflected to a know position given a magnetic field. The discussion of the determination of the deflection position by simulation is discussed in section 3.1. The experimental setup in the test beam area is discussed in sections 3.2 and 3.3

1.3 Motivation

A photon tagged beam is useful for the characterization of electromagnetic calorimeters. For instance, the sensitivity of physics searches at the LHC for decay modes involving photons are greatly affected by the energy resolution of the measurement. DESY Test Beam users have requested the addition of a photon tagged beam. This would facilitate the calibration of detectors, the validation of simulations describing electromagnetic interactions and particle shower characteristics, and the shower separation characteristics of future calorimeters[7][8].

2 Theory

2.1 Bremsstrahlung

In the Bremsstrahlung process, an electron interacts with a nucleus of the atoms making up a material. The electron is decelerated, and a photon is created in the exchange. The electron continues through the material, generating bremsstrahlung photons until it exits the material. Photons created from incident electrons in the GeV range will continue to travel in the the same direction of the electrons, the angular distribution of the photons being less than 1 mr from the beam direction [9].
The bremsstrahlung spectrum has an energy dependence of 1/E, with the majority of photons created being on the low energy end of the spectrum[2]. An approximation of the number of photons created within an energy range of k_{min} and k_{max} given a thin target is

$$N_\gamma = \frac{d}{X_0}\left[\frac{4}{3}\ln\left(\frac{k_{max}}{k_{min}}\right) - \frac{4\left(k_{max}-k_{min}\right)}{3E} + \frac{k_{max}^2-k_{min}^2}{2E^2}\right] \tag{1}$$

Section 4.1 presents the results of the Bremsstrahlung spectrum measured in the experiment.

2.2 Magnetic Force on an Electric Charge

Charged particles traveling in a perpendicular path through a homogeneous magnetic field will undergo circular motion. The Lorentz force given by the magnetic field is

$$F = qv \times B \tag{2}$$

The magnitude of the Lorentz force is equal to the centripetal force experienced by the particle

$$qvB = \frac{mv^2}{R} \tag{3}$$

The radius of curvature of the path of the particle can then be found by

$$R = \frac{mv}{qB} \tag{4}$$

$$R = \frac{p}{qB} \tag{5}$$

Figure 2 depicts the path of the particle. R is the radius of curvature of the circular path which is proportional to the momentum of the particle. The deflection distance, d, depends on the distance from the magnetic field at which it is measured, and the angle at which the particle exits the magnetic field.

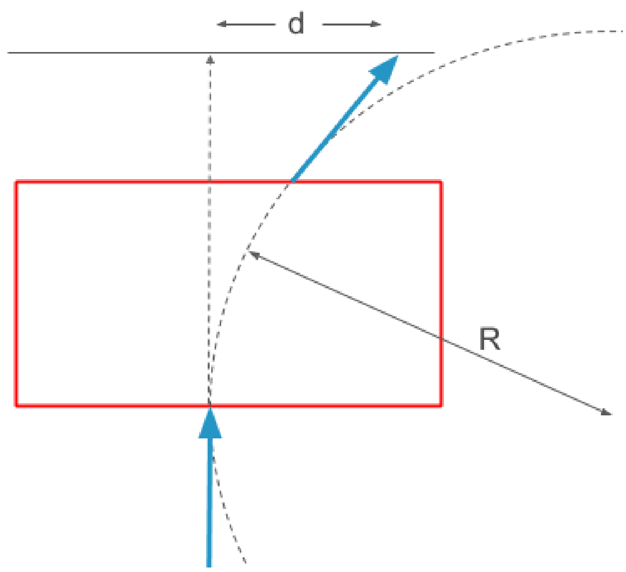

Figure 2: Motion of a charged particle in a homogeneous magnetic field

3 Method

For this experiment, a simulation of the test beam conditions was first performed. The information from the simulation guided the set up of the test beam 21 at DESY, as the area is equipped with a dipole magnet. The following sections discuss the experimental set up, calibration, and measurements taken.

3.1 Simulation

The test beam conditions were first simulated using SLIC (Simulation for the International Linear Collider) [3], a software framework based on Geant4. The beam is defined using a General Particle Source (GPS) defined to be 2 cm x 2 cm with a momentum spread of 6.173 MeV. The deflection positions are simulated by placing a dipole with constant magnetic field of 0.18 T inside of a box of 100 cm x 200 cm x 110 cm. To simulate the bremsstrahlung process, a 3 mm thick copper target is defined and placed 45 cm from the particle source, 10 cm from the beginning of the magnetic field and 65 cm from the center of the dipole. The magnetic field extends forwards and backwards 55 cm from the center of the dipole. The simulation geometry matches the later test beam measurements and is based on a simulation of the DESY II test beam facility[5]. The properties of the magnetic field match measurements of the test beam dipole magnet made previously [4]

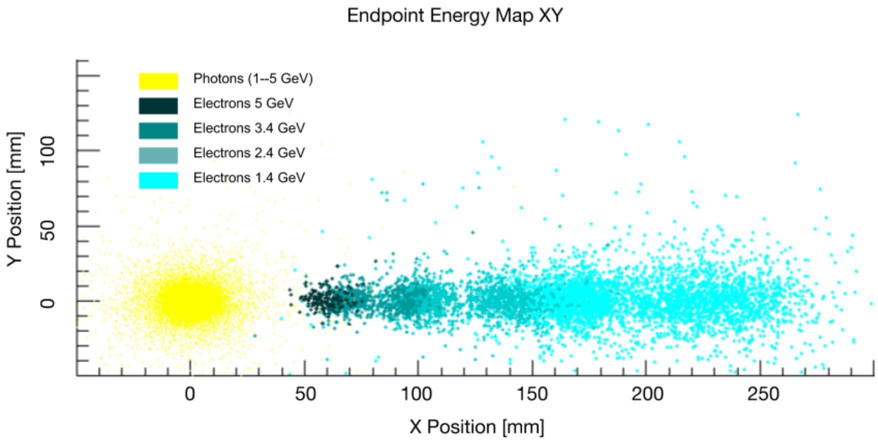

Figure 3: Endpoints of particles based on type and momentum from simulation

Figure 3 depicts the simulated bremsstrahlung process, with generated photons distributed around the '0' position–the beamline. The deflected electrons are shown deflected to the right of the photons. The different colors correspond to the electron momentum at the end of the bremsstrahlung process

3.2 Electron Calibration

The calibration measurements with electrons were done without the converter target. For pulse height calibration, a chosen momentum electron beam travels straight to the pair of scintillators and the lead-glass detector without a magnetic field.

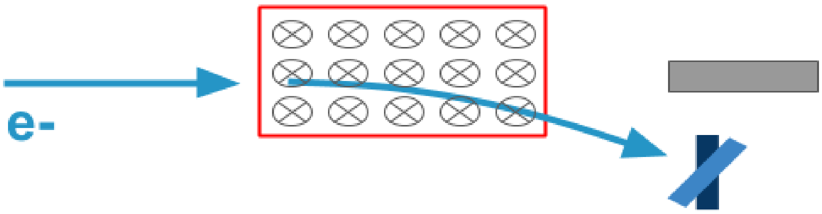

Figure 4: Schematic of measurement setup for deflection position. Electrons travel directly through a magnetic field and to a pair of scintillators.

The measurement of deflection position is done with a magnetic field applied. The scintillator pair is moved to a given position and a set of count rate measurements are performed at each position. The schematic for deflection position is in Figure 4.

Figure 5: Screenshot from Techtronix MSO500 oscilloscope. The yellow pulse is the signal from the lead-glass detector. The vertical histogram records the pulse minimum value over a period of time

3.2.1 Pulse Height

The measurement devices were calibrated first using an electron beam with a known momentum. The calibration of the lead-glass detector provided a correlation between pulse height and incident particle momentum. The signal from the lead-glass detector is sent directly to a Tektronix MSO0500 oscilloscope. For each momentum measurement, the minimum voltage measured is recorded for 2000–4000 events. The oscilloscope automatically creates a histogram of these values. An example histogram can be seen in Figure 5.

The lead-glass pulse is depicted in yellow. The blue signal is the coincidence signal between the lead glass and both of the scintillators. A distribution of these pulse minimums corresponding to the incident momentum can be seen in Figure 6.

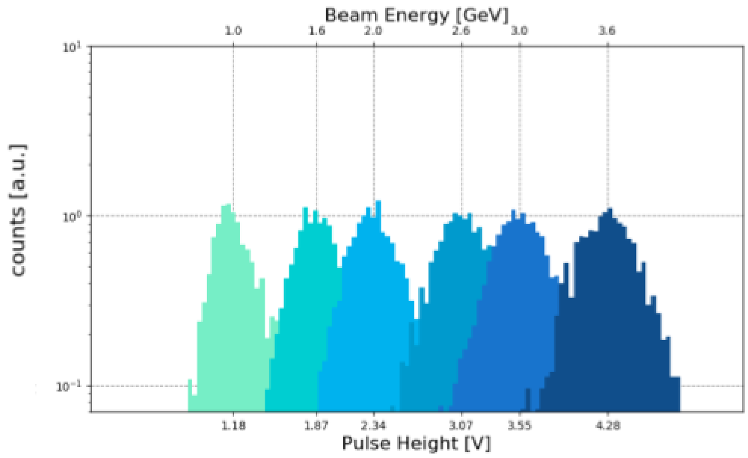

Figure 6: Distribution in Volts of pulse height measured with lead-glass detector.

3.2.2 Deflection Position

The horizontal deflection positions for electrons traveling through the magnetic field were measured with different momentum beams and a fixed magnetic field of 0.18 T. Several measurements were taken in 3 mm steps around the position predicted by the simulation software. At each of these positions, a count of the number of coincidence signals between the horizontal and vertical scintillators in a duration of 10 seconds was taken. An average of each of the measurements is taken, and the position with the highest count rate is taken to be the central deflection position. A plot of the beam momentum versus deflection position is seen in Figure 7.

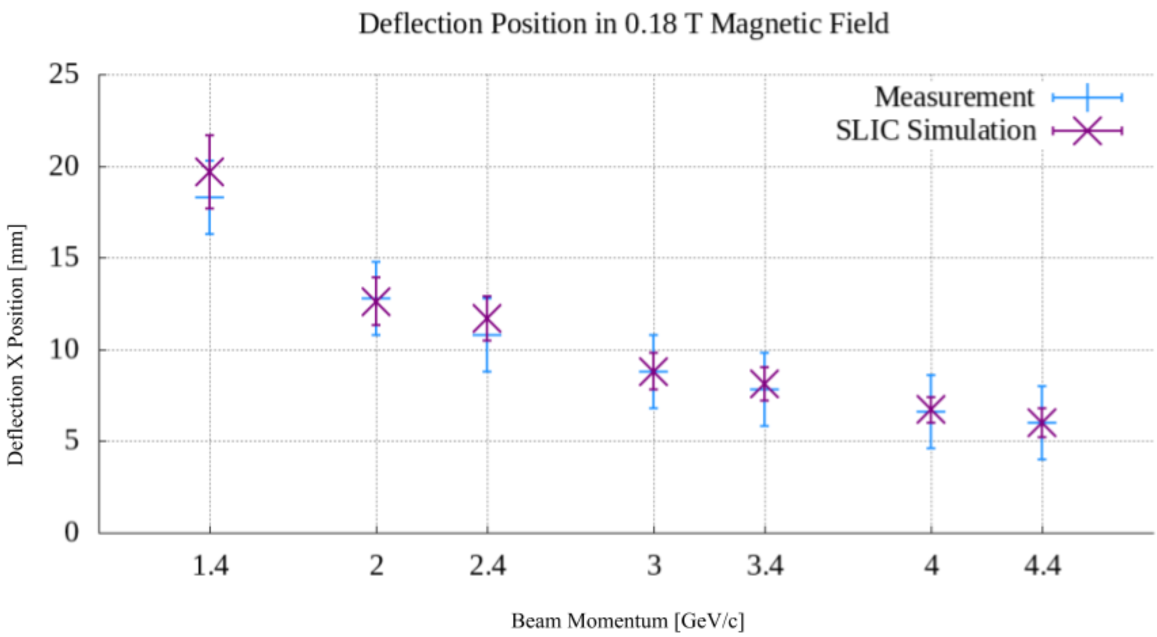

Figure 7: Deflection in horizontal plane of electrons of varying momenta

The deflection positions are used to trigger a photon momentum measurement, based on the momentum of the deflected electron. A table of the electron momentum, triggering position, and corresponding photon momentum is found in Table 1.

Trigger Position [mm]	Electron Momentum [GeV/c]	Photon Momentum [GeV/c]
18.3 ± 0.1	1.4	3.6
12.8 ± 0.3	2.0	3.0
10.8 ± 0.1	2.4	2.6
8.8 ± 0.2	3.0	2.0
7.8 ± 0.1	3.4	1.6
6.6 ± 0.2	4.0	1.0
6.0 ± 0.1	4.4	0.6

Table 1: Table of the triggering position corresponding to an electron momentum and photon momentum.

3.3 Photon Measurements

The photon measurements were done with the converter target installed in the test beam area. The 3 mm thick copper target was placed 30 cm from the test beam collimator and 65 cm from the center of the dipole magnet. The copper target can be seen in Figure 8.

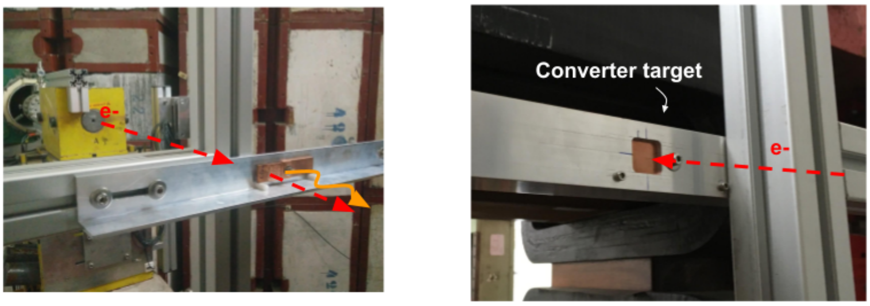

Figure 8: 3 mm copper target installed before the magnet. On the left is view towards lead collimator. On the right is view towards magnet

3.3.1 Photon Energies

Photon pulse heights were recorded first by triggering on all incident particles in the lead-glass detector. This provides the spectrum of all photons created in the bremsstrahlung process. The measurement schematic is shown in Figure 9.

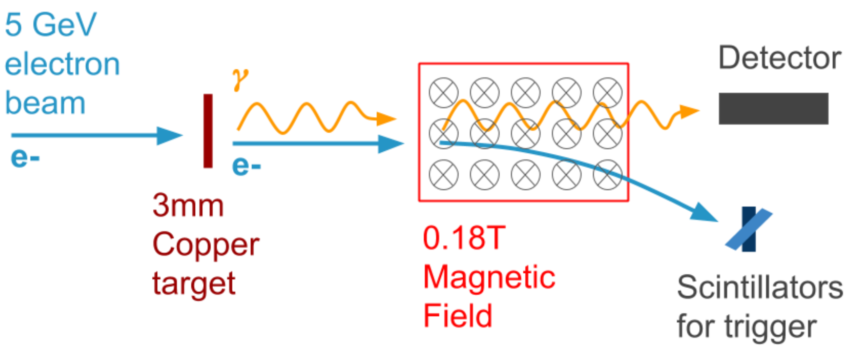

Figure 9: Schematic of measurement setup for photon energy measurements. The measurement in the lead-glass detector is triggered upon a coincidence with the 2 scintillators

The distribution of photon pulse heights were then measured by triggering a lead-glass measurement on a coincidence between the two scintillators placed at the corresponding deflection position.

3.3.2 Photon Rates

The rate of photons detected by the lead-glass is measured by sending the lead-glass output to a discriminator with a threshold of 800 mV. The minimum momentum photon to be measured was 1 GeV, as lower momentum photons are created in a multitude of processes, for instance synchrotron radiation from electrons bending in the magnetic field. From the simulation, photons of momenta less than 1 GeV were distributed evenly

across a large horizontal and vertical space, while photons greater than 1 GeV were well contained within the lead-glass detector area.
From the electron calibration measurements, the pulse height for a 1 GeV particle corresponded to 1.18 ± 0.18V. The 800 mV threshold was chosen as 2-sigma away from this mean pulse height value. The scintillator signals were each discriminated with a threshold of 40 mV. The three discriminated signals were sent to a coincidence signal. The coincidence output was sent to a counter with a 10 second enabled gate. The 3-coincidence rate was measured several times for each expected photon momentum, and the average of the measurements was taken to be the rate. The standard deviation of the measurements is the given error.

4 Results

4.1 Photon Energies

The results of triggering only on the lead-glass detector can be seen in Figure 10. This corresponds to the bremsstrahlung spectrum. The spectrum has a 1/E dependence as expected from Equation 1 in section 2.1. More lower momentum photons are created, and there is a maximum to the spectrum as a consequence of the conservation of momentum as the created photon cannot have a larger momentum than the incident particle that created it.

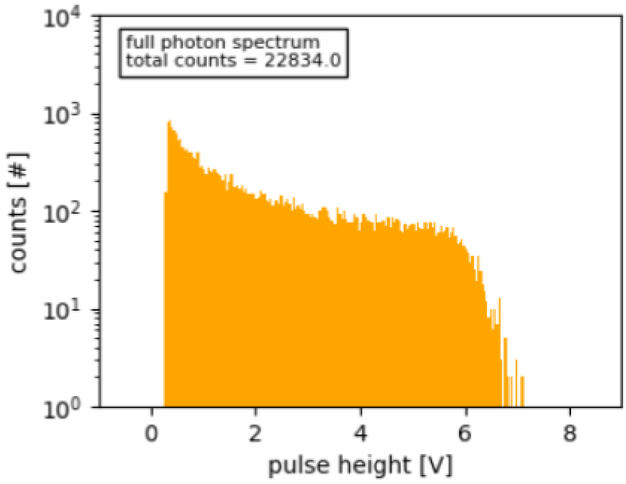

Figure 10: Bremsstrahlung spectrum measured from 5 GeV/c electron beam incident on a 3 mm copper target

Triggering on a specific momentum deflected electron provides a slice from this spectrum of the corresponding photon momentum. Figures 11,12 display the distributions of the photon measurements.

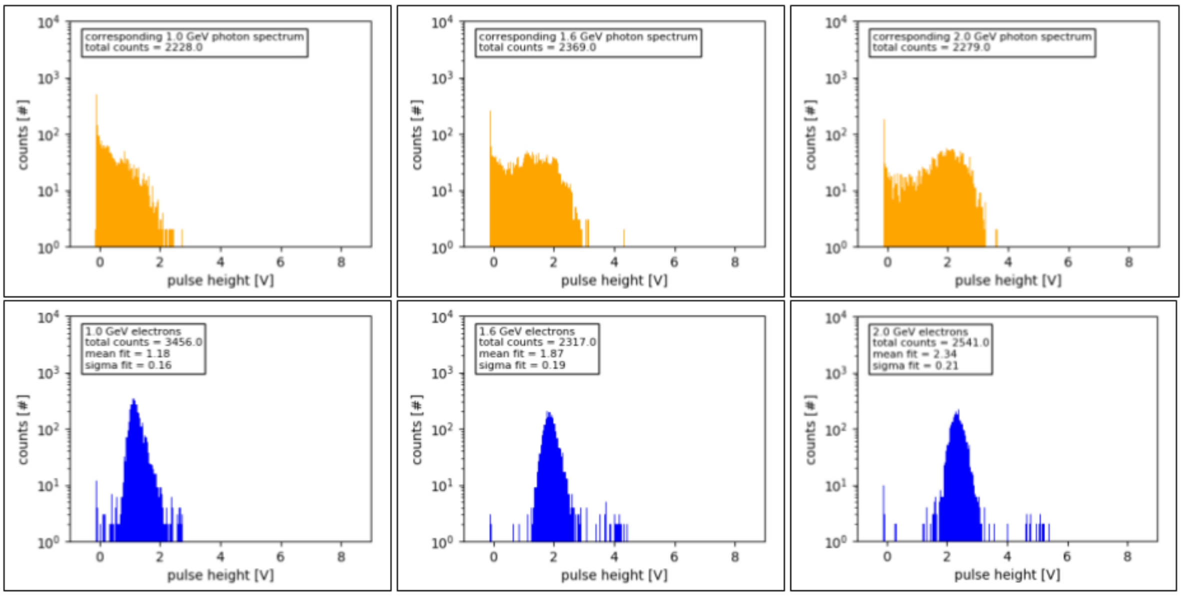

Figure 11: Pulse height distributions of photons in yellow, electron calibration in blue.

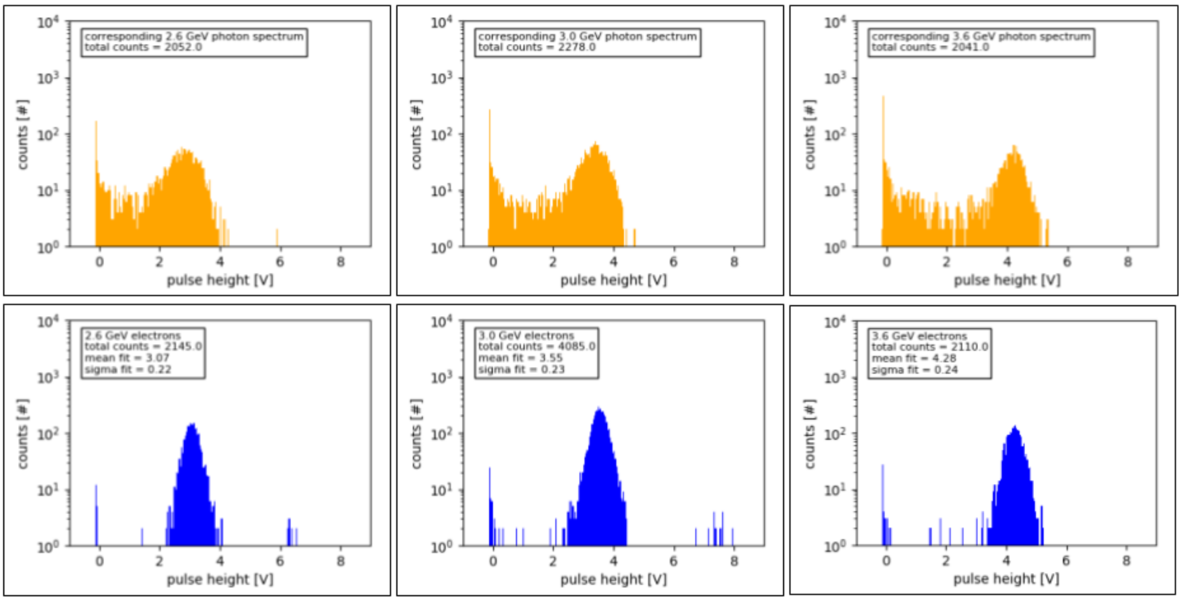

Figure 12: Pulse height distributions of photons in yellow, electron calibration in blue.

4.2 Photon Rates

The rates measured for the given photon momenta can be seen in Figure 13. Higher momentum photons (3.6 GeV/c) have a production rate of less than 10 per second, while more lower momentum photons are created, with a rate of 330 per second for 1.4 GeV/c photons.

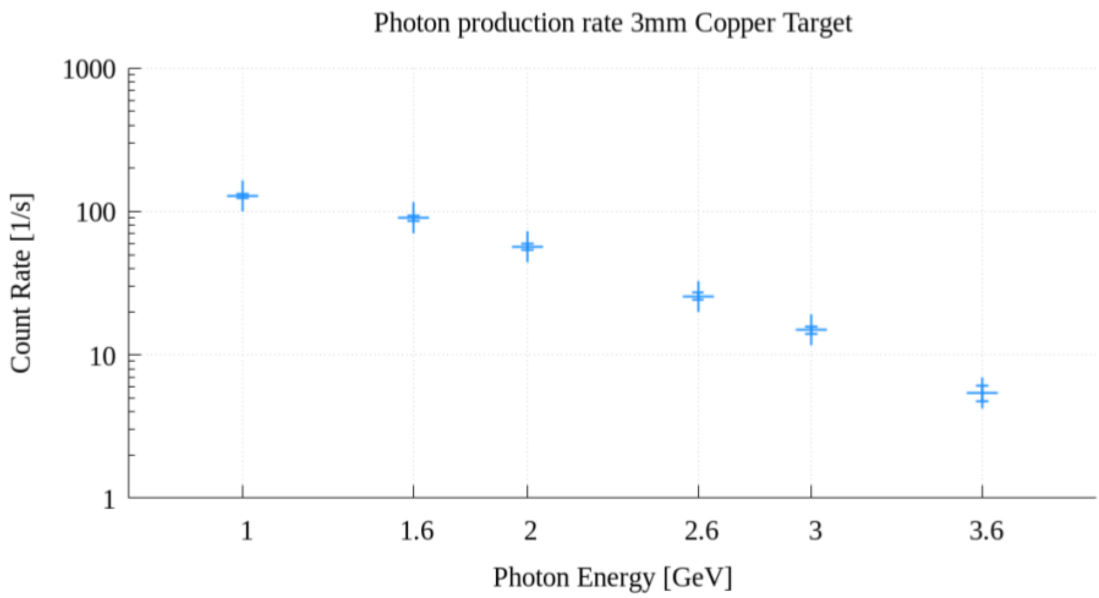

Figure 13: Production rates of photon momenta between 1.4 – 3.6 GeV/c

The scintillator area is 1 cm in the x plane and 2 cm in the y plane. Because of this, we are triggering on a subset of the electrons with a given momentum. The distribution in the x plane of low momentum electrons is very wide because of a more prominent effect from multiple scattering. This is widening effect can be seen in the plot of the simulation in Figure 3. The given production rate is then higher than that reported here. This explains in part the loss of rate for higher momentum particles seen in Figure 13. There also is a total maximum rate set by the rate of the incoming 5 GeV/c electron beam. The rates of the emission of photons at various momenta are then constituent parts of the total maximum rate.

5 Summary and Outlook

A photon tagging experiment has been performed at the DESY II test beam facility. The experiment has provided a proof of concept for resolving photon energies between 1–3.6 GeV using a lead-glass Cherenkov detector. The rates of the production of differing photon energies for this setup is on the order of 10–100 Hz.

From this information, test beam users will be able to produce a desired photon by installing a variable converter target, choosing a given distance z along the beamline, completing a calibration run with the corresponding deflection positions, and taking measurements with expected rates.

A further study should be done to investigate increasing the measured rates by triggering on electrons with wide horizontal distributions which escape the triggering window.

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