Coincident Detection of Cherenkov Photons from Compton Scattered Electrons for Medical Applications

R. Bayerlein[1], A.B. Brill[3], I. Fleck[1], L.R. Furenlid[4], W. Khalid[1], T.E. Peterson[2,3], A.H. Walenta[1,2]

[1]Physics Department, University of Siegen, Germany

[2]Physics Department, Vanderbilt University, Nashville, TN, USA

[3]Radiology & Radiological Sciences, Vanderbilt University Medical Center, Nashville, TN, USA

[4]College of Optical Sciences, University of Arizona, Tucson, AZ, USA

INTRODUCTION

The Compton Camera is one possible concept to meet the increasing demand for a gamma ray detector in the higher energy range (>1 MeV) for medical imaging. The detection concept comprises a two layer system, where in the first one the incident photon scatters releasing a highly energetic Compton electron. In a second layer the scattered photon is then absorbed. Thus, position and energy sensitive detection of the electron in coincidence with the scattered photon allows to reconstruct the incident direction of the photon to lie on the surface of a cone [1].

The detection of Cherenkov photons from energetic Compton scattered electrons is one possible way to realize such a detection concept. Figure 1 shows the detection principle: An incoming gamma scatters inside the radiator releasing a higher-energetic Compton electron. Assuming an electron speed close to *c*, the opening angle of the Cherenkov emissions is mainly determined by the refractive index of the material. Reconstruction of that cone yields information on the interaction vertex of the Compton scattering and also on the momentum direction of the electron, while the number of detected photons contains information on the electron energy [2].

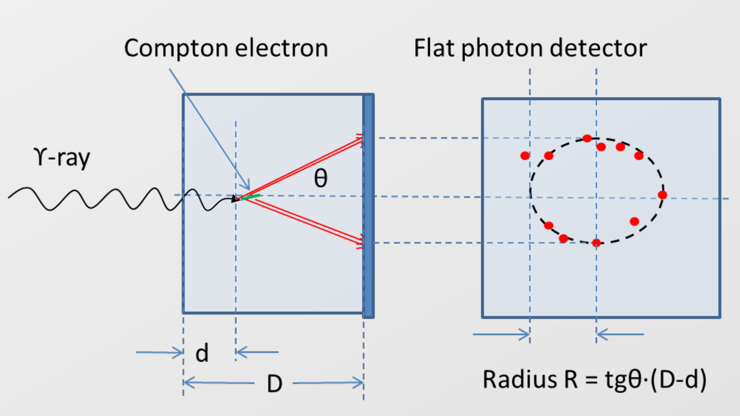


Fig. 1: Detection of Cherenkov light from Compton scattered electrons. The obtained ellipse on the read-out plane yields information on momentum direction and interaction vertex of the electron while the energy is obtained by the number of detected photons [3].

In order to provide a first proof of concept, this poster presents the results of the coincident detection of Cherenkov photons from electrons in poly-methyl-metacrylate (PMMA) using a 4x4 array of Silicon-Photomultipliers (SiPM). The influence of the thickness of the PMMA sample on the width of the distribution of Cherenkov photons as well as on the number of created photons is investigated.

EXPERIMENTAL SET-UP

- **Goal:**
  - Coincident detection of Cherenkov photons from electrons in PMMA
  - Counting the number of photons per channel
- **Required Components:**
  - Optically Transparent Radiator Material
  - High detection efficiency in the near UV
  - Pixelized detector for spatial resolution
  - High refractive index preferred
  - Fast signal rise time

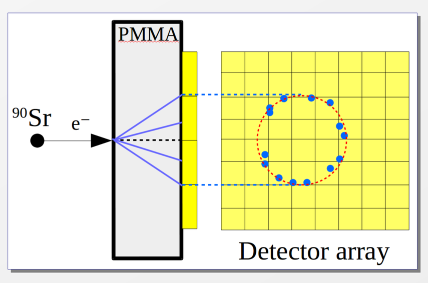
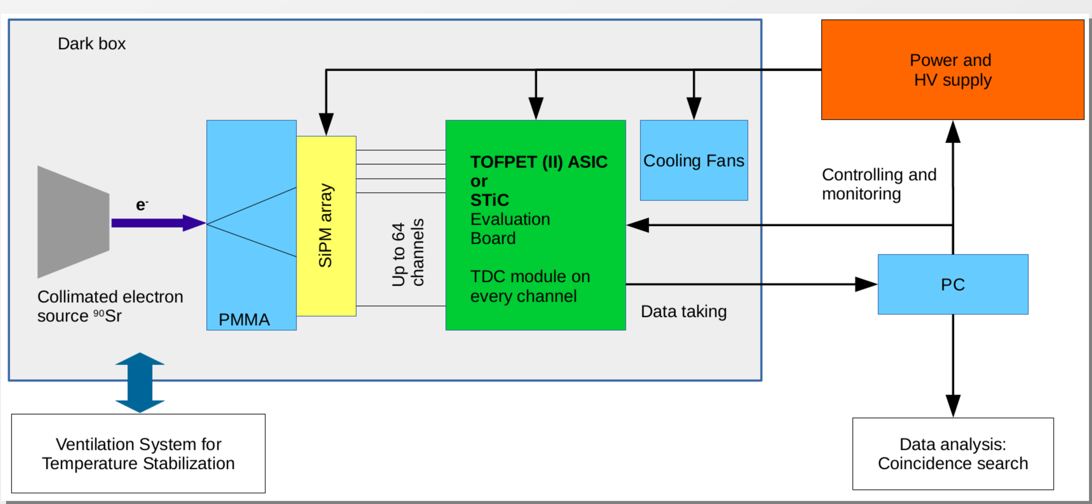


Fig. 2 (top, right): Schematic principle for the detection of Cherenkov light from electrons in PMMA using SiPM arrays. Strontium (^{90}Sr) is used as electron source.

Fig. 3 (bottom): Sketch of the Measurement Set-Up using a SiPM timing Chip (STiC) or the TOFPET-II ASIC with 64 channels. The PMMA samples are optically coupled to a SiPM array. The set up is placed inside a temperature stabilized dark box.



Signal Read-Out using two different ASICs:

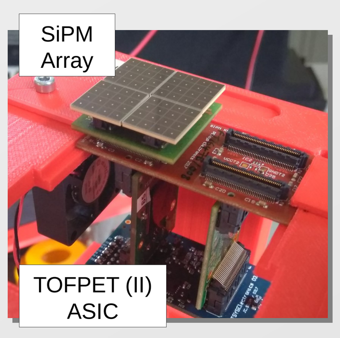


Fig. 4 (left): Front-End-Module of the TOFPET-ASIC (II) with TDC modules for every channel with a time binning of 30ps. FPGA-based data read-out is applied. On top of that is the 8x8 array of SiPMs (Hamamatsu, S13360 series) with a 75µm pixel pitch, a channel size of 3x3 mm² and a rise time of 1ns. The array is optically coupled to PMMA samples of various types and thicknesses.

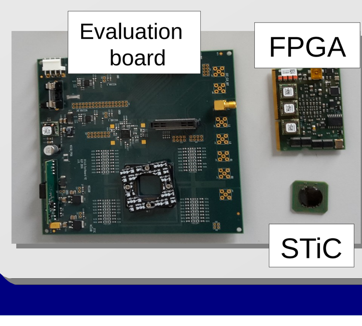


Fig. 5: SiPM Timing Chip (STiC) with a time binning of 50.2ps [4] was used to determine the coincidence timing resolution for the detection of Cherenkov light using SiPMs. A 4x4 array was read out in this case.

THEORY AND CALCULATIONS

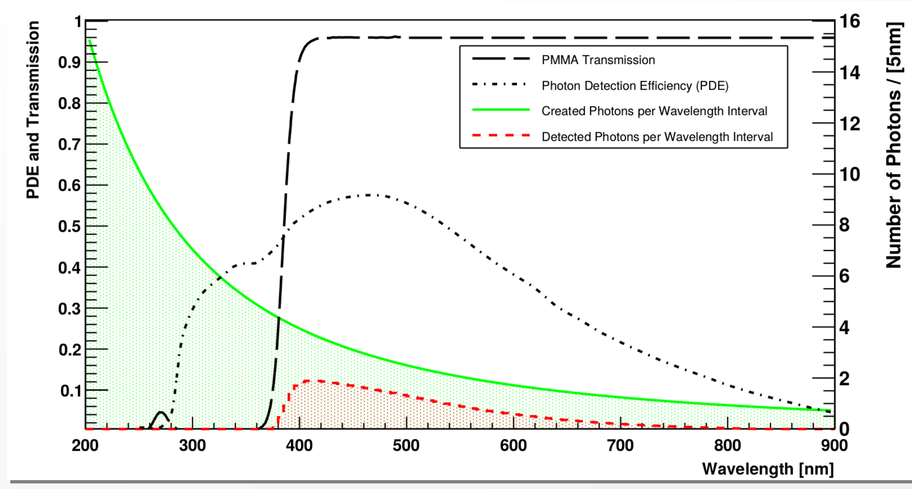
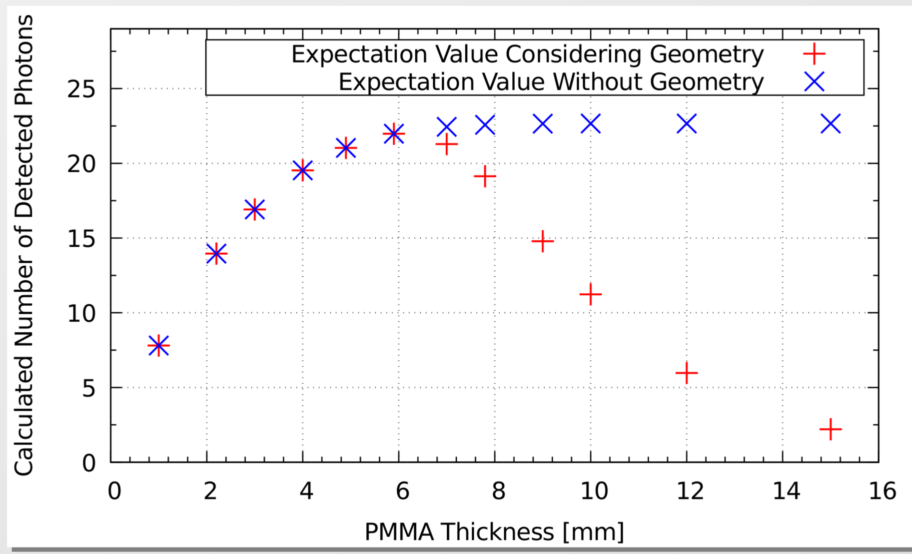


Fig. 6 (top): Calculated number of emitted (green) and detected Cherenkov photons (red) for an electron energy of 1.5 MeV in the wavelength range of 200-900nm. The calculation is based on stopping power values from the NIST data base [5] and takes wavelength-dependent PMMA transmission and SiPM detection efficiency into account. At this energy the number of generated photons is 504, while 73 photons are still detected.

Fig. 7 (bottom): Expected number of detected Cherenkov photons versus PMMA thickness with (red) and without (blue) considering the SiPM geometry. These values take the continuous nature of the ^{90}Sr electron source into account. The lower numbers of photons for smaller thicknesses represent limited electron range of higher energetic electrons that subsequently do not have the full light yield. At higher thicknesses the Cherenkov cone exceeds the boundaries of the array.



MEASUREMENTS

Trigger Method and Analysis

With both TOFPET and STiC the signal of any channel was recorded when being above the trigger threshold for this channel. Offline coincidence search was performed as follows: Starting with the earliest signal all channels within a coincidence time window of 3 ns (800 ps in case of STiC) were combined into one coincident event if there were at least 6 channels (3 in case of STiC) in this time window. The spatial distribution of coincident hits on the SiPM array was investigated (see occupancy of hits in figure 9). As the Cherenkov cone spreads out farther with increasing PMMA thickness, the width of the distribution of coincident hits increases too. The obtained pattern shifts with respect to the electron source location, demonstrating spatial sensitivity for accumulated events.

Timing Measurements with STiC:

The Coincidence time resolution (CTR) for the detection of Cherenkov Light with SiPMs was determined using the mean value of the time after first trigger. Cherenkov light shows a CTR of 242 ps while 492 ps CTR was obtained using scintillation light. The time after first trigger is shown in the histogram in figure 8.

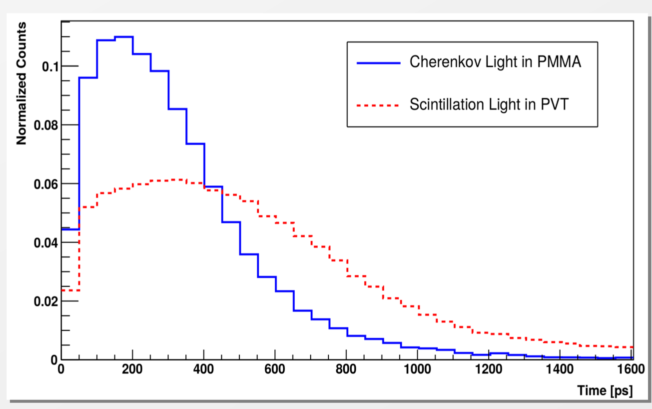
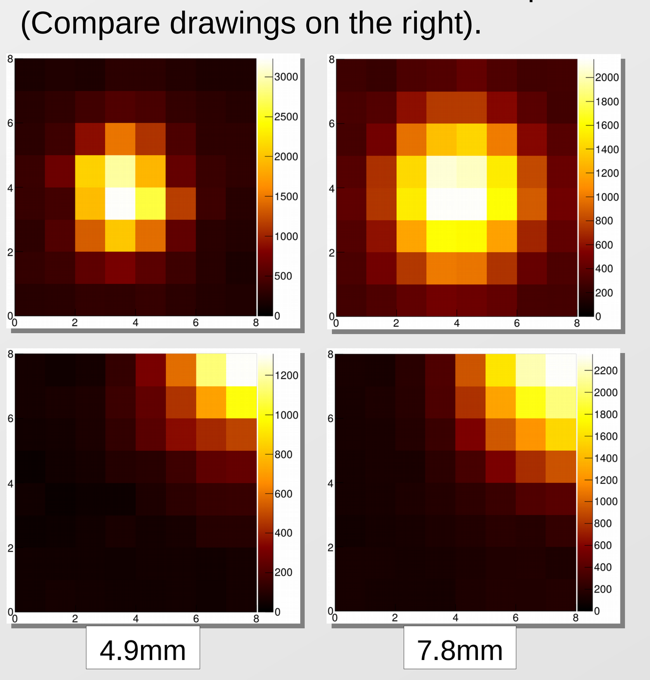


Fig. 8 (left): Coincidence time resolution (CTR) for the detection of Cherenkov light detection in PMMA and scintillation light in PVT.

Fig. 9 (below): Distribution of coincident hits on the 8x8 SiPM array for two thicknesses. The photons are created by electrons in PMMA for two different source positions (Compare drawings on the right).



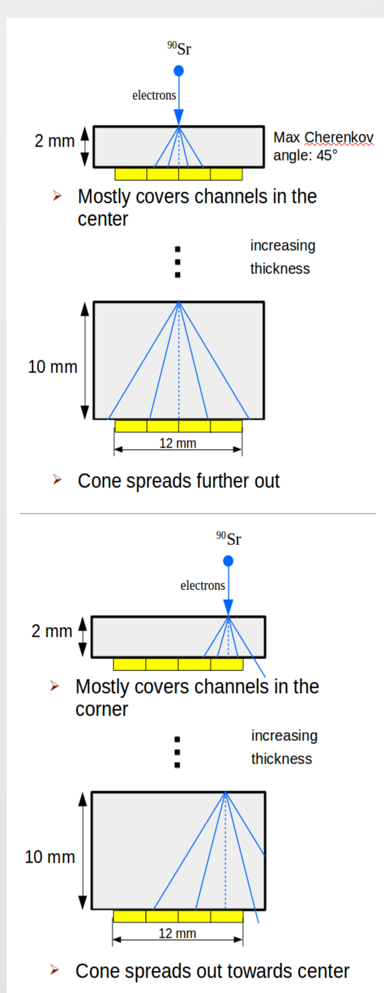
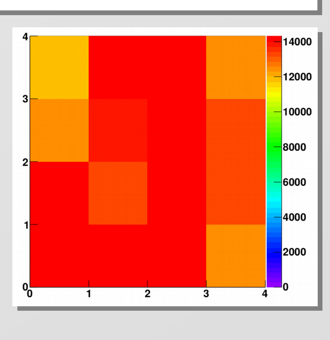


Fig. 10 (right): Occupancy of coincident hits on the 4x4 SiPM array using scintillation light from electrons in Poly-Vinyl-Tuelene (PVT). The mostly uniform distribution of coincident hits represents the isotropic nature of scintillation light and makes a clear distinction compared to Cherenkov light.



RESULTS

The measurements demonstrate the conic structure of the emitted Cherenkov light: While for smaller PMMA up to a thicknesses of 4.0mm the Cherenkov cone covers only a fraction of the array, the distribution spreads out farther with increasing sample thickness above a calculated thickness of 5.7mm. Measurements show good conformity with theoretical predictions (compare figure 7 and 11).

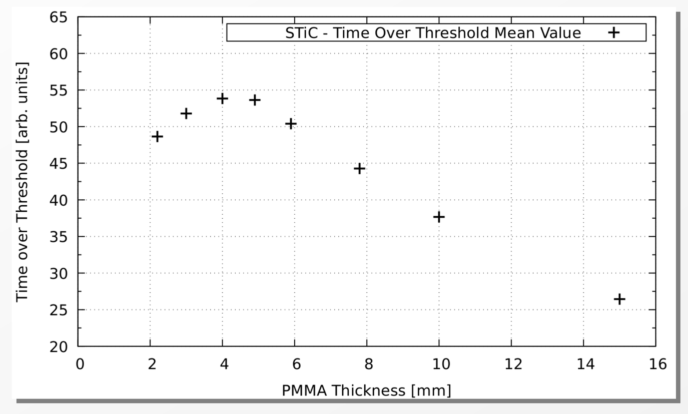


Fig. 11: Measured light level given as time over threshold (ToT) versus thickness. The ToT increases with number of detected photons.

Counting Coincident Cherenkov Photons

Using the Time-over-Threshold values, a calibration of each channel of the 8x8 SiPM array was performed, using a logarithmic dependency of the ToT vales on the number of detected photons. The trigger level was set to a level of two photons (2pe level).

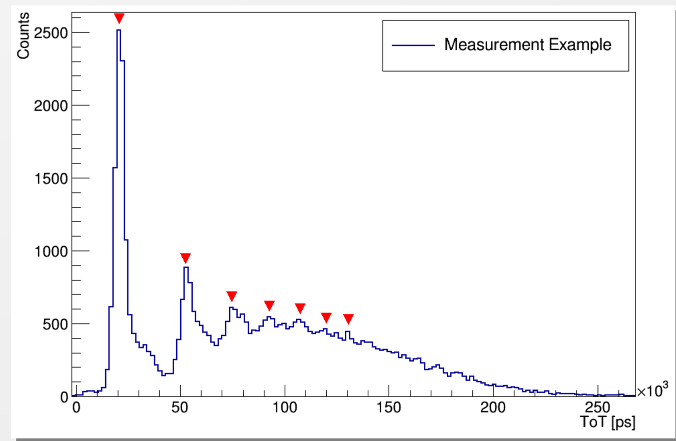
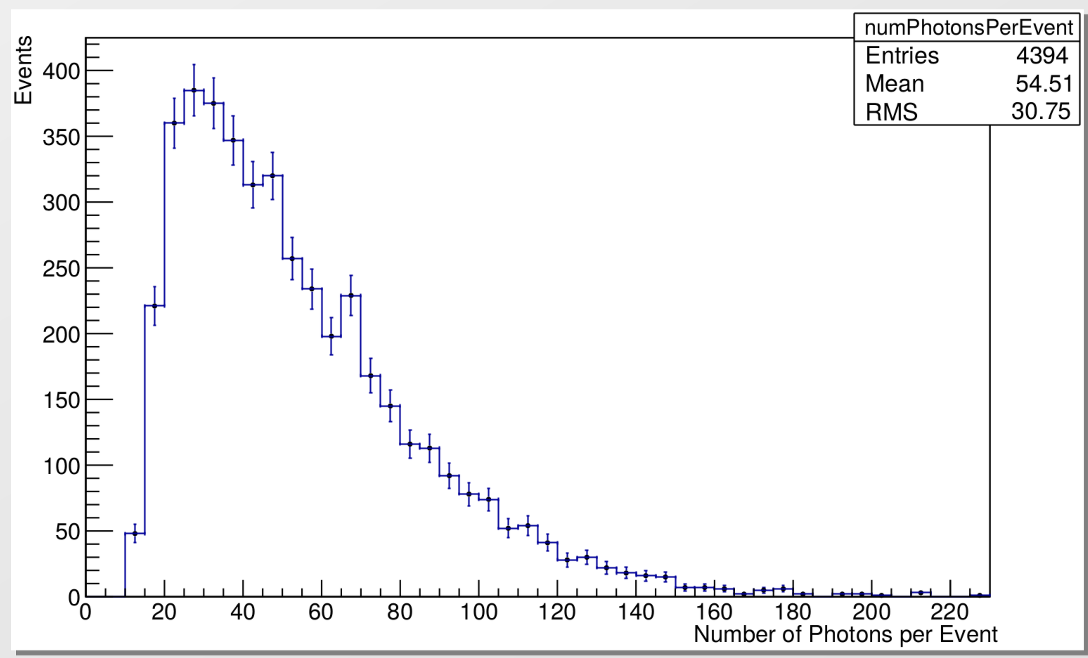


Fig. 12 (left): Example of a ToT spectrum of one channel for a 180s measurement. Each peak corresponds to a certain photon number starting at the 2pe level.

Fig. 13 (bottom): Histogram for the number of detected photons in each event.



The number of detected photons yields information on the electron energy, while the distribution of photons on the array can be used to determine its momentum. Thus, the next step will be the electron reconstruction from single coincident events.

CONCLUSION

In this poster the coincident detection of Cherenkov photons from energetic electrons in PMMA was demonstrated using SiPM arrays. The timing resolution of 242 ps promises good applicability for medical imaging techniques like a Compton Camera. Spatial sensitivity for a change in the source location could be demonstrated as well as the implementation of counting the number of detected photons per channel on 2 pe level. In the next steps imaging of single coincident events will be performed on 64 channels in order to reconstruct the Cherenkov cone projected on the array. Also, reducing the dark count rate of SiPMs by an order of magnitude through cooling is envisaged. This would enable to lower the detection threshold, improve the sensitivity for the number of photons being detected and therefore also the energy resolution. This can subsequently be used to reconstruct the momentum direction of single electrons in PMMA. In case of a Compton camera application, the electron would be created by a high-energy gamma scattering in the PMMA sample. The electron carries a large part of the momentum information of the incident gamma. This would be the next step towards a working Compton Camera prototype

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