Detection of Cherenkov Photons from Compton Scattered Electrons for Medical Applications

Reimund Bayerlein
H. Bäcker, J. Bensberg, I. Fleck, T. Peterson

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Introduction

Gamma Ray Detection in Medical Physics: Compton Camera
Purpose and Goals

• **The Aim:**
  - Gamma ray detection for higher energy range (> 1MeV)
  - Improve efficiency of existing detection principle: The Compton Camera

• **Increasing Interest of Gamma Ray Detection in Medicine:**
  - Dose delivery verification in proton beam therapy
  - Radio-immunotherapy with alpha particles (e.g. $^{212}\text{Bi} \rightarrow ^{212}\text{Po}$)
  - Biological studies

![Proton Therapy: Safety margins for lung tumor treatment](image1)

![Spot Scanning Proton Arc Therapy (SPArc)](image2)

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Durante M and Flanz J Sem Oncol 2019

Li X et al. Oncol 2019
Compton Camera

• **Using the Compton Effect**
  - Incoming gamma scatters under certain angle
  - Releases high energetic electron

• **Two-layer detection system**
  - Scatter plane: Energy and position measurement of Compton-scattered electron
  - Absorption plane: Impact position of the scattered photon

Compton Camera Working Principle
From: Bruce Smith, *A New Compton Camera Imaging Model to Mitigate the Finite Spatial Resolution of Detectors and New Camera Designs for Implementation*, 2015

Coincident detection of electron and scattered gamma
→ Momentum reconstruction of initial gamma
The Principle

Electron Detection using Cherenkov Light
Electron Detection Using Cherenkov Light

- High-energetic Compton-scattered electron emits Cherenkov light
- Effect occurs for particles with $v > c/n$
- Emission only along the surface of a cone
- Cherenkov angle depends on
  - refractive index $n$
  - electron velocity $\beta = v/c$
- $\cos (\theta) = (1/(\beta n))$

http://large.stanford.edu/courses/2014/ph241/alaelian
Electron Detection Using Cherenkov Light

- Optically transparent radiator material
- Instantaneous emission of Cherenkov photons
- Opening angle dependent on refractive index $n$ and electron energy

Array of Silicon-Photomultiplier (SiPM)
- Coincident photon detection
- Measurement of the distribution of photons

Reconstruction of ellipse and Cherenkov cone
- Number of detected photons
  - Electron energy
- Size of the ellipse
  - Compton scattering vertex
- Eccentricity of ellipse
  - Momentum information on electron
Required Components

- **Radiator material:**
  - Optically transparent
  - High refractive index
  - Low density

- **Silicon-Photomultiplier-Arrays**
  - High spectral sensitivity (down to near UV range)
  - Fast signal rise-time

- **Fast read-out electronics**
  - Timing resolution on sub-nanosecond scale

- **Pattern recognition and cone reconstruction algorithm**
  - Ellipse fit algorithm
  - Hough-transform
Challenges

- **Cone diffusion due to**
  - Energy loss of electron along the track
  - Multiple scattering of electron

- **Scarcity of Cherenkov Photons**
  - High PDE needed
  - High radiator transparency

The Experiment

Description of Set-Up and Components
Set-Up

- Measurement of Cherenkov light from electrons from a $^{90}\text{Sr}$ source in UV-transparent PMMA

![Diagram of detector array and SiPM array]

- 8x8 SiPM array: Hamamatsu S13361-series
  - Rise Time < 1ns
  - High Gain: $> 5 \times 10^6$
  - Dark rate @ -6°C: 60kHz / channel

![Graph of detection efficiency and transparency vs. wavelength]

PC for data taking

Offline Coincidence search
Set-Up

- Measurement of Cherenkov light from electrons from a $^{90}$Sr source in UV-transparent PMMA

![Detector array diagram](image)

- TOFPET2-ASIC
  - (PETsys electronics, Lissabon)
  - Time Binning: 30 ps
  - Read-out of up to 64 channels per chip
  - Time-over-Threshold measurement
Set-Up

- Measurement of Cherenkov light from electrons from a $^{90}\text{Sr}$ source in UV-transparent PMMA

  - Coincident Event:
    - At least 5 out of 64 channels within the coincidence time window (5 ns)
Proof of Concept

Measurements, results and comparison to simulation data
Coincidence Time Resolution

- Coincidence Measurement on all 16 Channels (3 or more channels)
- Coincidence time window 800 ps
- Correction of inherent time differences for each channel

- Scintillator (mean = 492.4 ps)
- PMMA (mean = 240.0 ps) \(^{(1)}\)

PVT scintillator
(1.2 ns decay time constant)

\(^{(1)}\) R. Bayerlein et al., 2018, https://doi.org/10.1016/j.nima.2019.03.049
Counting coincident Cherenkov photons

- Time-over-Threshold (=signal width) increases with number of detected photons
- ToT spectrum of coincidence Cherenkov photons
  - Find peak positions → calibration for each detector channel

\[\text{ToT}(n) = \tau \cdot \ln \left( n \cdot \frac{A_1}{h_{Tr}} \right)\]

- \(\tau\): signal decay constant
- \(A_1\): 1-pe level
- \(h_{Tr}\): trigger level
Number of detected Cherenkov photons

- **Comparison: Measurement (using the $^{90}$Sr source)**

- **Decreasing number with increasing thickness:**
  - Absorption in the medium
  - Geometric boundaries of the SiPM array
  - Multiple scattering of the electron

**Geant4 Simulation**

Distribution of Cherenkov light:

Electron tracks in PMMA:
Distribution of photons

- Measurement with various thicknesses of PMMA
  - Distribution increases with thickness
  - Position sensitive measurement
  - Maximum Cherenkov angle in PMMA: 47.8°
  - Influenced by multiple scattering

![Graphs showing distribution of photons with various thicknesses of PMMA]
Reconstruction of the electron

- Measurement of the distribution of photons for various angles
- Fitting an ellipse to the distribution:
  - Cone tip (= vertex position)
  - Momentum direction of the electron
- Limited resolution due to
  - Low granularity (64 channels)
  - Multiple scattering of the electron
  - Changing Cherenkov angle with decreasing kinetic energy of the electron

- Center of gravity of the distribution on the array
- Projection of the cone tip onto the detector surface
Gamma Source

Detecting Cherenkov Photons from Compton and Photo electrons
Detection of 511 keV Photons

- PET-like set-up with a $^{22}$Na positron source
- Inside the detectors creation of
  - Compton electrons
  - Photo electrons

![PET-like set-up diagram](image-url)
Detection of 511 keV Photons

- PET-like set-up with a $^{22}$Na positron source
- Inside the detectors creation of
  - Compton electrons
  - Photo electrons
- Scintillator: reference detector

Energy spectrum of the $^{22}$Na source represented by the Time-over-Threshold signal from the scintillator
Detection of 511 keV Photons

- PET-like set-up with a $^{22}\text{Na}$ positron source
- Inside the detectors creation of
  - Compton electrons
  - Photo electrons
- Scintillator: reference detector
- Cherenkov photons for electron detection

Coincident hits of Cherenkov photons in PMMA from Compton electrons and photo electrons

Measurement time: 200 min
Number of coincidences: 8367
Detection of 511 keV Photons

- PET-like set-up with a $^{22}\text{Na}$ positron source
- Inside the detectors creation of
  - Compton electrons
  - Photo electrons
- Scintillator: reference detector
- Cherenkov photons for electron detection

Histogram:
Number of detected photons per coincidence for at least 5 channels per event

Calculation:
Expected number of detected Cherenkov photons for a 511 keV photo electron: 18.3

Main Influence:
Minimum number of channels per coincident event changes detected number of photons.
Number of Detected Cherenkov Photons

![Graph showing the number of detected photons vs the required number of channels for Cherenkov scattering events.](image)

- **Linear Extrapolation Fit**: Background corrected data.
- **Mean value at 1 channel level**: 7.03 ± 0.84 photons/event.

![Diagram illustrating Compton scattering](image)

- **Compton Scattered γ**
- **Incoming γ**
- **SiPM array**
- **θ**

![Graph showing the angular distribution of photon scattering](image)

- **Gamma Energies**: 5 MeV, 3 MeV, 0.5 MeV, 0.1 MeV
- **Thomson Scattering**
Summary

Achievements and Outlook
Summary and Outlook

- **Previous successes and achievements:**
  - Coincidence measurement of Cherenkov photons in sub-nanosecond time resolution
  - Implemented counting of Cherenkov Photons on 1pe level
  - Good agreement with Geant4 simulation
  - Detection of Compton scattered electrons using Cherenkov light

- **Current Focus of Research**
  - Determination of the electron energy
  - Reconstruction of electron momentum direction and scattering vertex
  - Improvement of the coincidence time resolution

- **Detection of electrons using Cherenkov light is next step towards an application in a Compton camera**