Test of Compton camera components for prompt gamma imaging at the ELBE bremsstrahlung beam

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ABSTRACT: In the context of ion beam therapy, particle range verification is a major challenge for the quality assurance of the treatment. One approach is the measurement of the prompt gamma rays resulting from the tissue irradiation. A Compton camera based on several position sensitive gamma ray detectors, together with an imaging algorithm, is expected to reconstruct the prompt gamma ray emission density map, which is correlated with the dose distribution. At OncoRay and Helmholtz-Zentrum Dresden-Rossendorf (HZDR), a Compton camera setup is being developed consisting of two scatter planes: two CdZnTe (CZT) cross strip detectors, and an absorber consisting of one Lu₂SiO₅ (LSO) block detector. The data acquisition is based on VME electronics and handled by software developed on the ROOT framework. The setup has been tested at the linear electron accelerator ELBE at HZDR, which is used in this experiment to produce bunched bremsstrahlung photons with up to 12.5 MeV energy and a repetition rate of 13 MHz. Their spectrum has similarities with the shape expected from prompt gamma rays in the clinical environment, and the flux is also bunched with the accelerator frequency. The charge sharing effect of the CZT detector is studied qualitatively for different energy ranges. The LSO detector pixel discrimination resolution is analyzed and it shows a trend to improve for high energy depositions. The time correlation between the pulsed prompt photons and the measured detector signals, to be used for background suppression, exhibits a time resolution of 3 ns FWHM for the CZT detector and of 2 ns for the LSO detector. A time walk correction and pixel-wise calibration is applied for the LSO detector, whose resolution improves up to 630 ps. In conclusion, the detector setup is suitable for time-resolved background suppression in pulsed clinical particle accelerators. Ongoing tasks are the quantitative comparison with simulations and the test of imaging algorithms. Experiments at proton accelerators have also been performed and are currently under analysis.

KEYWORDS: Instrumentation for hadron therapy; Compton imaging

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1 Introduction

Ion beam therapy is a promising technique for cancer treatment because of the high relative biological effectiveness of certain ions as well as the dose profile and the well defined range of the accelerated ionizing particles [1]. In contrast to a photon, a proton or heavier ion travelling through matter is stopped completely at a certain depth: the particle range. In addition, the dose profile is characterized by a Bragg peak and a sharp fall-off at the distal edge, as the ionization density is maximal at the end of the particle’s path. This feature is crucial in cancer treatment for an accurate dose delivery to a target volume and for sparing the irradiation of tissue behind the distal edge (a lateral spread is still present [2]).

The position of the Bragg peak is dependent on the atomic number of the ion, its energy, and on the density and composition of the traversed tissue [3]. Minor changes in tissue dependent parameters may produce ion range deviations, which is critical for treatment plans where the ions are expected to stop in front of an organ-at-risk. Accordingly, particle range verification is a major challenge for the quality assurance of the treatment. Several research institutions across the world aim at developing a real-time technique that verifies the particle range and even the dose distribution in vivo [3, 4].
One approach is the measurement of the prompt gamma rays produced in nuclear reactions between the projectile ions and nuclei of the irradiated tissue. A Compton camera comprising several position sensitive gamma ray detectors measures the energy deposited by the prompt gamma rays in each detector pixel. Based on the Compton equation, an iterative imaging algorithm reconstructs the prompt gamma ray emission density map [5], which is correlated with the dose deposition distribution of the incident ions [6].

The ongoing development of a Compton imaging setup [7–9] is described. Detector components of this setup have been tested at the linear electron accelerator ELBE at HZDR.

2 Aim

The aims of this experiment are:

- To explore the behaviour of the detector in the energy range relevant for prompt gamma imaging, which is not accessible by means of common radioactive sources.
- To measure the effects of different photon energy ranges on the spatial resolution of the detectors.
- To test the timing properties of the detectors, which are important for the suppression of background, produced in the clinical environment by neutron reactions and material activation.
- To test the data acquisition and event selection of the Compton imaging setup.
- To provide data for testing imaging algorithms [10].

This paper focuses on the individual characterization of the detectors of the Compton camera setup while the angular resolution of the system and the image reconstruction are discussed in [5, 11]. The time and space resolution of the CZT and LSO detectors for different energy ranges and the suitability of the setup for time-resolved background suppression is analyzed.

3 Experimental setup

At OncoRay and Helmholtz-Zentrum Dresden-Rossendorf, a Compton imaging setup (figure 1) is being developed consisting of two scatter planes (named as CZT0 and CZT1) and an absorber plane (named as LSO). Each scatter plane consists of a single Cd$_0.9$Zn$_{0.1}$Te (CZT) cross strip detector with a size of $20\text{ mm} \times 20\text{ mm} \times 5\text{ mm}$ obtained from Baltic Scientific Instruments (Riga, Latvia). It comprises 16 cathode and 16 anode strips with a 1.05 mm pitch in a perpendicular cross-strip configuration, and a steering grid on the anode side [12] as well as a guard ring. The absorber plane is a Siemens/CTI Hi-Rez PET block detector (employed in commercial Biograph PET/CT scanners) with a size of $52\text{ mm} \times 52\text{ mm} \times 20\text{ mm}$, consisting of a pixellated block of $13 \times 13 \text{ Lu}_2\text{SiO}_5$ (LSO) crystals with a cross section of $4\text{ mm} \times 4\text{ mm}$ and coupled through a common light guide to $2 \times 2$ (quad) Photo Multiplier Tubes (PMT). The separation between CZT0-CZT1 crystal centers is $(46 \pm 2)\text{ mm}$, whereas the separation between CZT1-LSO detector centers is $(57 \pm 3)\text{ mm}$. 
The readout electronics (figure 2) is based on CAEN (Viareggio, Italy) VERSAModule Eurocard (VME) front-end modules. The data acquisition is handled by a custom software tool based on the ROOT framework (CERN) [13]. For the CZT detectors, the analog signals are split actively for each electrode with a discrete preamplifier with high-pass and pole zero cancellation. The heat generated by the preamplifiers around the detectors is dissipated with Peltier elements and fan units so that the semiconductor operating temperature is kept stable at 30°C.

In the case of the LSO detector, the PMT signals are split actively with a 4-fold transimpedance preamplifier common board.

One branch is fed to a constant fraction discriminator (CFD), model V812 (20% constant fraction), for trigger generation, whereas the other is delayed and fed to a charge to digital converter (QDC), model V965. A time to digital converter (TDC), model V1290A, monitors the trigger signal generated by the CFD as well as the accelerator bunch reference signal. A custom logic module based on a field programmable gate array (FPGA), model V1495, generates the event trigger (the gate) and a Universal Serial Bus (USB) controller, model V1718, handles the communication between a Linux computer and the VME bus.

The Compton imaging setup is tested at the linear electron accelerator ELBE, which in the present experiment is used to provide a continuous-wave electron beam of 13 MeV (total energy) with a repetition rate of $f_{\mu_p, ELBE} = 13$ MHz, corresponding to 77 ns bunch separation. A twofold buncher section (operating at $f_{\mu_b, ELBE} = 260$ MHz and $f_{RF, ELBE} = 1.3$ GHz, respectively) precedes the injection of the electrons into the superconducting linear accelerator. This consists of two consecutive modules of two standing wave radiofrequency (RF) cavities each, operated at the frequency $f_{RF, ELBE}$.

The electrons are focused to a diameter below 2 mm and shot onto a 2 $\mu$m thick Niobium foil. As a result of the deflection of the electrons in the electric field of the atomic nucleus, prompt bremsstrahlung photons are emitted predominantly in forward direction. The energy distribution exhibits a continuous spectrum up to 12.5 MeV (figure 3). A detailed description of the setup is given in [14].
Figure 2. Sketch of the front-end readout electronics and data acquisition system of the Compton imaging setup. CZT1 sketch is analogue to CZT0. Detector signals (A denotes the anode, C the cathode) are actively splitted. One branch is fed into a CFD, the other is delayed and fed into a QDC. A TDC monitors the CFD trigger output and the accelerator bunch reference. A logic module generates an integration gate for the QDC and a trigger for the TDC. Data are sent to the computer via a USB controller.

Figure 3. Emission energy spectra of the bremsstrahlung photons ($\gamma_{\text{ELBE}}$ — blue) in the experimental setup at the ELBE accelerator (GEANT4 simulation), of the expected prompt gamma rays ($\gamma_{\text{prompt}}$ — red) arising from 200 MeV proton irradiation of a water target (GEANT4 simulation) [8], compared to the CZT1 detector response spectrum to a $^{22}$Na source measured in the laboratory ($\gamma_{\text{lab}}$ — black).
Figure 4. Experimental setup at the ELBE accelerator. Electrons with 13 MeV total energy in 13 MHz bunches — corresponding to 77 ns bunch separation — collide with atoms of a Niobium foil. As a result of the deflection of the electrons in the electric field of the nucleus, bremsstrahlung photons are radiated promptly (continuous spectrum up to 12.5 MeV) and measured by the Compton camera. A $^{22}$Na source is placed between the scatter planes for monitoring purposes.

Figure 1 shows a photograph, figure 4 a schematic sketch of the experimental setup. The wide energy distribution of prompt bremsstrahlung photons, which are bunched with the $f_{\mu \text{ELBE}}$, are measured by the Compton camera. The correlation between the detector signals and the accelerator bunch frequency is analysed. A $^{22}$Na source is placed between the scatter planes for energy calibration purpose and for testing the time-resolved event discrimination, as its photons will contribute to the background without time correlation with the accelerator.

The ELBE accelerator is a very good platform for the camera setup tests prior to the clinical scenario due to the following reasons:

- In a clinical proton cyclotron, the emitted prompt gamma rays are correlated with the accelerator frequency as well, e.g. 106 MHz (corresponding to 9.4 ns bunch distance) for the Cyclone® 230 of IBA (Louvain-la-Neuve, Belgium) [15].

- The energy range of the bremsstrahlung photons (several MeV) is comparable to the one expected for prompt gamma rays in a clinical proton beam (evidence in figure 3) and allows testing detectors in an energy range not obtainable using common radioactive sources.

- The electron bunch width [14] is about 5 ps, in contrast to around 1.5 ns proton bunch spread [16] in the Cyclone® 230 at 160 MeV, thus allowing an intrinsic detector time resolution measurement.

- The prompt gamma rays are produced in a 2 $\mu$m thin foil and 2 mm diameter spot, in contrast to a several cm thick target in the clinical case, which allows testing a Compton camera setup with an almost point-like prompt gamma ray source.

4 Methods

4.1 Measurement regime

In this experiment, we measure in a trigger regime that accounts for the three detectors used. Each CZT detector has an independent CFD board with 16 channels for the cathode signals. Each channel has an individual threshold of 10 mV and a logic trigger output with a width of 20 ns. The logic OR output of each CFD defines the CZT detector trigger. In the case of the LSO detector, the analog sum of the 4 PMT outputs is fed into a separate CFD, with a threshold of 3 mV, and its logic output (20 ns wide) defines the LSO detector trigger. No trigger on individual PMT channels is performed.
In the Compton camera, we aim at measuring events with simultaneous trigger in both detectors. Therefore, the FPGA based logic module generates the event trigger (master gate) when at least two of the three detectors are triggered simultaneously. The events are only registered in the VME modules if the master gate is present, and individual CFD channels do not trigger the data acquisition (figure 2). The master gate (900 ns long) is used as integration gate for the QDCs (the same length for all modules or detectors) and simultaneously as trigger for the TDC, whose own configurable search window width is set to 200 ns (longer than the separation between electron beam bunches). The CFDs are blocked during the QDCs ~ 6 µs long dead time (QDC BUSY output fed into CFD VETO input).

Every 30 gates, an interrupt signal is generated by the QDC (almost full buffer signal). Subsequently, the computer reads out the TDC and QDC data via the VME bus. Afterwards, their buffers are cleared and the module event counter is reset for synchronizing all the modules. During data readout, the logic module is blocked and no additional gate signals are generated.

In this paper, the study is focused on detectors CZT1 and LSO. We analyse them individually, but all the events stem from this trigger regime and are therefore coincident events (not single events). The FPGA based logic only monitors the overlapping of the trigger outputs (20 ns wide) for defining the coincidence. This condition is the one used for the individual detector analysis in terms of spatial and time resolution. Only for the final analysis of Compton scattering events (figure 16), a finer selection of simultaneous events is performed offline based on the TDC time measurements in order to reject background events and focus only on the prompt bremsstrahlung photons.

4.2 LSO detector

The LSO detector is operated at +850 V. For this block detector, an extended calibration procedure is mandatory to obtain a good energy, spatial and time resolution. The main steps are enumerated below and are detailed in the corresponding subsections.

- The 4 PMT output channels are recorded by the QDC and energy-calibrated independently.
- The hit position map, also known as flood map, is generated.
- The pixel centers are identified in the flood map.
- Energy spectra for each pixel are recalibrated.
- Time spectra for each pixel are corrected for time delay between pixels.
- Global time spectrum is corrected for energy dependent time walk in the LSO.

4.2.1 Energy calibration

A $^{22}$Na radioactive source is used for the calibration of the LSO block detector. Each PMT channel is calibrated separately. The calculated energy is used for reconstructing the hit position (see subsection 4.2.2). After the spatial calibration is performed, separate energy spectra are drawn for each pixel and individually recalibrated with an automatic procedure.
In the case of the ELBE experiment, the absence of characteristic photopeaks in the energy spectrum prevents us from calculating the detector energy resolution for high energies. However, the energy information is still relevant for analysing the spatial and timing resolution for different energy ranges of interest:

- Low range: 0–1 MeV.
- Middle range: 1–2 MeV.
- High range: 2–13 MeV.

As the LSO detector is deployed in the Compton camera as absorber (high energy deposit), the middle and high range are of special interest.

### 4.2.2 Spatial calibration

The flood map can be obtained from the relative intensities (energies) measured at the four light-sharing PMTs (figure 5): the Anger logic. The following center of gravity equation \[17\] is used for the relative crystal coordinates \(X_{LSO} \in [0, 1], Y_{LSO} \in [0, 1]\):

\[
X_{LSO} = 0.5 + 0.5 \times \frac{E_2 + E_3 - E_0 - E_1}{\sum_{i=0}^{3} E_i}
\]

\[
Y_{LSO} = 0.5 + 0.5 \times \frac{E_2 + E_0 - E_3 - E_1}{\sum_{i=0}^{3} E_i}
\]

where \(E_i\) is the energy measured at the channel (PMT) \(i\).

The interaction position map is drawn and the pixel centers are identified manually. The map is then divided into crystal regions: each hit in the map is then assigned to the crystal with the nearest pixel center.

Energy and time histograms are then drawn for each of the regions separately for a refined pixel-wise calibration.
4.2.3 Time calibration

The rise time of the LSO scintillator (coupled with PMTs and a transimpedance preamplifier) is $\sim 5$ ns and the CFD internal delay line is set to 4 ns. The correction of transition time effects and time walk can not be done for each PMT separately as we trigger on the analog sum. Alternatively, we perform a pixel-wise delay correction based on the flood map and a single time walk correction for the whole detector.

**Pixel delay calibration.** For each crystal, the time difference between trigger signal and accelerator time stamp is analysed with an energy threshold of 2 MeV. The peak centroid is fitted with an automated procedure. The pixel with the smallest value of the peak centroid is chosen as the reference. The time values of the rest of the pixels is then shifted in order to match its centroid with the reference one.

**Slewing correction.** A time walk correction (also known as slewing correction) is applied. For the CFD V812, the internal zero crossing discriminator can not be adjusted to the input signal shape. In addition, for signals below 10 mV, the leading edge principle is applied instead of the constant fraction. The time stamp of the CFD signal is then expected to comprise a time shift (walk) dependent on the energy: low energy (small pulse height) leads to delayed LSO detector timestamp.

One can draw an energy over time scatter plot, make a projection for each energy bin and identify the relationship between mean time $t_m$ (peak centroid) and energy bin center $E$. The resulting profile can be described empirically with a square root exponential model:

$$t_m = t_s e^{-\sqrt{E/E_0}} + t_0$$

(4.3)

where $E_0$, $t_s$ and $t_0$ are free parameters.

With the fitted parameters, a corrected time $t_c$ for any given pair $(E, t)$ is defined:

$$t_c = t - t_s e^{-\sqrt{E/E_0}}$$

(4.4)

4.3 CZT detector

Each CZT cross-strip detector is operated at a bias voltage of -500 V, and -100 V are applied to the steering grid.

4.3.1 Energy calibration

A $^{22}$Na radioactive source is used for the calibration of the CZT detectors. Each anode and cathode channel is calibrated separately. The calibrated energy is used for reconstructing the hit position (see subsection 4.3.2).

As described in subsection 4.2.1, the detector performance will be analyzed for the low, middle and high energy ranges. As the CZT detector is employed in the Compton camera as scatterer (low energy deposit), the low and middle energy ranges are of special interest.
4.3.2 Spatial calibration

The hit position map is obtained from the relative intensities (energies) measured at the strips (figure 6). The following center of gravity equation is used for the relative crystal coordinates $X_{CZT} \in [0, 1], Y_{CZT} \in [0, 1]$:

$$X_{CZT} = \frac{\sum_{i=0}^{15} (i + 0.5) \times E_{A,i}}{\sum_{i=0}^{15} E_{A,i}}$$  

(4.5)

$$Y_{CZT} = \frac{\sum_{i=0}^{15} (i + 0.5) \times E_{C,i}}{\sum_{i=0}^{15} E_{C,i}}$$  

(4.6)

where $E_{A,i}$ is the energy measured at the anode strip $i$ and $E_{C,i}$ is the energy at the cathode strip $i$.

4.3.3 Time calibration

The rise time of the preamplified CZT cathode signals is of 25 ns and the CFD internal delay line is set to 20 ns. A similar procedure as for the LSO detector is applied regarding pixel-wise delay correction and slewing correction (see description in subsection 4.2.3).

4.4 Background suppression figure of merit

We define a figure of merit $FoM$ that quantifies the percentage of background a detector is able to reduce with timing information in a bunched accelerator:

$$FoM = 1 - \frac{\Phi^2_{r,\text{det}} + \Phi^2_{r,\text{bunch}}}{\Delta t_{\text{bunch}}}$$

(4.7)

where $\Phi_{r,\text{det}}$ is the detector time resolution (FWHM), $\Phi_{r,\text{bunch}}$ the accelerator bunch width (FWHM) and $\Delta t_{\text{bunch}} = f_{\text{bunch}}^{-1}$ the time separation between consecutive accelerator bunches. This figure of merit is useful for estimating whether the detector timing resolution is sufficient for a clinically realistic radiation environment.
Figure 7. Hit position map of the CZT1 detector for the low energy range (left, 0.1–1 MeV), for the middle range (center, 1–2 MeV) and for the high range (right, 2–13 MeV). The $X_{\text{CZT1}}$ coordinate corresponds to the anode, the $Y_{\text{CZT1}}$ coordinate to the cathode strips.

5 Results and Discussion

The incident photon flux was $\sim 200$ kcps and the individual count rates on CZT1 and LSO detectors was estimated to be $\sim 6$ kcps and $\sim 90$ kcps respectively.

The trigger count rate (two of three detectors of the setup in coincidence) was approximately 600 cps at a beam current of 1 $\mu$A.

Around 1 million events were registered by the Compton camera during half an hour acquisition time. The dead time induced by the data transfer through the VME bus to the computer is around 5 ms per readout. As the readout is performed every 30 gates, the effect of the readout time on the overall count rate is minor for this concrete measurement: the dynamic system dead time is about 10%.

The hit position map of the CZT1 (figure 7) reveals the strip structure of the detector (cathodes horizontally, anodes vertically). Some dead channels (anode as well as cathode strips) can also be identified in all scatter plots. For high energies, charge sharing effects appear and the strip structure washes out. This effect is reduced for the anode coordinate ($X_{\text{CZT1}}$) thanks to the surrounding steering grid focusing the charge cloud into the anode strip.

In any case, this washout does not imply a degradation of the spatial resolution, as the center of gravity of the interaction is reconstructed taking into account all the fired strips (see eqs. (4.5) and (4.6)). In fact, charge sharing between strips might allow a sub-pitch detector spatial resolution, but can also lead to charge loss in the steering grid around the anode strips. However, a direct quantitative measurement of the spatial resolution of the CZT1 detector on the $X_{\text{CZT}}$ and $Y_{\text{CZT}}$ coordinates is neither feasible nor intended within this experiment, as the bremsstrahlung beam spot covers the whole detector area and a collimator for photon energies up to 12.5 MeV is not available.

The charge sharing effect has been simulated in [18] with GEANT4 for photoelectric interactions in CdZnTe detectors, where the electron cloud diameter exceeds the diameter of 1 mm (i.e. the strip pitch of our CZT detectors) for energy depositions over 2 MeV. The anode and cathode multiplicity over the measured energy is shown in figure 8 and is qualitatively in agreement with the mentioned simulations. Note that, at a given energy deposition, the number of fired anodes is on average lower than the number of cathodes due to the focusing steering grid on the anode side.
Figure 8. Left: number of fired cathode strips over an individual energy threshold of 100 keV as a function of the total measured cathode energy. Right: number of fired anode strips over an individual energy threshold of 100 keV as a function of the total measured anode energy.

Figure 9. Flood map of the LSO detector for the low energy range (left, 0.1–1 MeV), for the middle range (center, 1–2 MeV) and for the high range (right, 2–13 MeV).

The flood map of the LSO detector (figure 9) allows discriminating the 169 pixels for the full energy range. The crystal peak-to-valley decoding ratio improves with increasing gamma ray energy deposit. The reason is that high energy deposition leads to a larger number of scintillation photons, which are collected by the PMT. The uncertainty in the collection process is governed by Poisson statistics and, consequently, the signal to (statistical) noise ratio of the signal measured in the PMT is reduced for brighter events.

For prompt gamma imaging purposes, the Compton camera detector setup (CZT as scatterer, LSO as absorber) is convenient, as most of the Compton scattered coincidences are associated with a high energy deposit in the absorber. Consequently, the LSO detector will operate at its higher spatial performance.

The time study of the CZT1 (figure 10) shows a strict correlation between the signal detection and the accelerator bunch frequency: the histogram of the difference between the two timestamps is characterized by a sharp peak with a resolution of 2.8 ns FWHM for CZT1 at an energy threshold of 100 keV.

The achieved time resolution is significantly below the values reported by recent publications [19], around 5.8 ns/√2 ≃ 4 ns with thinner CZT detectors operated at lower temperatures and
Figure 10. Time difference between the CZT1 detector cathode signal $t_{\text{CZT1}}$ and the accelerator bunch reference signal $t_{\text{ELBE}}$. An energy threshold of 100 keV is set.

with more complex techniques to optimize the time resolution. The main reason for this discrepancy is that the trigger is on the cathode signal instead of on the anode signal. A trigger on the anode degrades the time resolution due to the drift time effect and varying pulse rise time depending on the depth of the interaction in the semiconductor detectors, until the carriers are collected by the strips.

On the other hand, when triggering on the cathode, the drift time plays a relatively negligible role, but only photon interactions close enough to the cathode generate a signal on the cathode strip over the trigger threshold of the constant fraction discriminator. As a consequence, the effective active thickness of the detector is much lower when triggering on the cathode and only around 10% of all interactions take place in the active volume. The drop in the efficiency is the significant drawback for boosting the time resolution.

As the CZT1 time resolution is significantly smaller than the separation between accelerator bunches (13 MHz corresponds to 77 ns bunch distance), one can discriminate background events (time uncorrelated) with a time filter around the peak identified in figure 10.

For the CZT1 detector, neither strip-wise time delay nor time walk is found to be significant. When analysing the time distribution separately for each strip, only a subset of neighbour strips showed the bump present on figure 10 at $-7$ ns. Thus, this effect may be related with CZT1 crystal inhomogeneities.

For the LSO detector, we apply the time pixel calibration (figure 11-left) with an offline 2 MeV energy threshold, and afterwards the slewing correction (figure 12).

The delay is significant (up to 5 ns) for the pixels aligned with the bottom left PMT and might be related with a transition-time effect in this PMT, e.g. due to a lower gain of the tube. The progressive increase in the delay as we approach the edge pixel $(0, 0)$ of the PMT is associated with the trigger configuration together with the light sharing effect. The CFD triggers on the analog sum of the 4 PMT. As the light is focused on a single PMT for edge pixels, its effect on the timestamp of the analogue sum is more significant.

In addition, a higher FWHM value is identified in figure 11-right also for this PMT compared to the other three, which might be related with a worse coupling of the PMT with its corresponding pixel.
Figure 11. Left: delay of the peak centroid in the time resolution spectrum of each pixel of the LSO detector with respect to the reference pixel (in white). Right: time resolution (FWHM) for each pixel of the LSO detector. Both: the detector front view is the same as in figure 5 and an energy threshold of 2 MeV is applied.

Figure 12. Time walk in the LSO detector fitted with eq. (4.3). Note that $t_m \equiv (t_{\text{LSO}} - t_{\text{µP,ELBE}})_m$ and $E \equiv E_{\text{LSO}}$.

The slewing correction and pixel calibration improves the time resolution from 2 ns to 630 ps as well as the symmetry of the peak, as shown in figure 13. The analysis is performed with an energy threshold of 100 keV.

In recent experiments, we improve the overall time resolution by triggering on each PMT channel separately, which also allows us to apply a PMT-wise correction instead of a pixel by pixel calibration on the sum signal. According to preliminary results, the LSO detector exhibits a time resolution of 500 ps FWHM.

The LSO detector has a better time resolution than the CZT1 detector (630 ps compared to 2.8 ns) because of several factors:

- short rise and decay times of the LSO scintillator (faster physical response);
- pulse shape much less dependent on the localization of the interaction for the LSO detector (no charge collection time as in the case of CZT detectors).
Figure 13. Time resolution of the LSO detector without corrections (in black), with slewing correction (in red) and with additional time pixel calibration (in blue). An energy threshold of 100 keV is set.

Figure 14. Distribution of the relative time between the LSO and CZT trigger signals. Slewing and time pixel calibration is applied for the LSO detector. An energy threshold of 100 keV is set for each detector.

In the clinical scenario, e.g. the Cyclone® 230 of IBA, $\Delta t_{\text{bunch}} = 9.4\, \text{ns}$, $\Phi_{t_bunch} \simeq 1.5\, \text{ns}$. The resulting background suppression figures of merit are $\text{FoM}_{\text{CZT1}} \approx 66\%$ and $\text{FoM}_{\text{LSO}} \approx 83\%$. Accordingly, LSO is more effective than CZT1 for background reduction, although the difference is moderated by the significant contribution of the bunch width to the $\text{FoM}$.

Thus, the LSO detector timing should be used for background reduction, whereas the CZT1 time resolution is primarily useful for rejecting coincidences LSO-CZT1 between prompt gamma rays that stem from different accelerator bunches.

The spectrum of the relative time between CZT1 and LSO detector signals (figure 14) exhibits a coincidence time resolution of 3.2 ns FWHM. Note that the dominant contribution to the FWHM and asymmetry of the distribution stems from the CZT1 detector. The non-Gaussian tail of the distribution is the consequence of fortuitous coincidences according to the measurement regime (a gate is generated when the 20 ns wide trigger signals overlap).
Figure 15. Energy deposited in the detector (CZT1-left, LSO-right) over the difference between detector signal and accelerator bunch timestamps. The LSO detector pixel-wise calibration and time walk correction are applied. Vertical lines are associated with events correlated with the accelerator (prompt bremsstrahlung photons), whereas the low energy horizontal line is associated with time uncorrelated background.

The energy over time scatter plot for the CZT1 and LSO detector (figure 15) shows that the prompt bremsstrahlung photons (with an energy up to 12.5 MeV) are concentrated in vertical peaks (time correlated with the accelerator bunches), whereas the 511 keV annihilation background (due to the sodium source as well as pair production and activation) is homogeneously distributed across the time axis (uncorrelated).

Note that the 3.8 ns periodic structure arising in figure 15 (right) stems from accelerator’s dark current electrons, which are bunched in the sub-harmonic buncher ($f_{hb,ELBE} = 260 \text{ MHz} \approx 1/3.8 \text{ ns}$) and accelerated as well up to 13 MeV. The resulting bremsstrahlung energy spectrum is similar to the one produced by electrons bunched with 13 MHz. The fraction of photons bunched with 260 MHz compared to 13 MHz depends on several settings of the accelerator and particular parameters of the experiment. In this case, the dark current photon fraction is found to be around 5%.

Applying a time filter around the vertical peaks in figure 15 ([-18 ns,-11.5 ns] for the CZT1 detector; [-16.5 ns,-14.5 ns] for the LSO detector), we can suppress most of the background, focus on the prompt bremsstrahlung photons and analyse events where detector CZT1 and LSO detectors have triggered simultaneously.

The energy deposition scatter plot (figure 16) reveals a 511 keV gamma line in the LSO detector. This gamma line can be still identified after subtracting the background generated by random coincidences (mainly from the $^{22}\text{Na}$ source). Therefore, the main process leading to these 511 keV prompt coincidences is pair production in the CZT1 detector. The bremsstrahlung photon transfers completely its energy to the electron-positron pair inside the CZT1 crystal (no scattered gamma). The positron then annihilates and two 511 keV gamma rays are emitted back to back. At least one gamma ray escapes the CZT1 detector and is absorbed in the LSO, thus generating a coincidence.

This annihilation gamma line is prominent due to the significant pair production cross section for several MeV photons. Correspondingly, a gamma line is also observed in the CZT1 detector (pair production in the LSO detector), but with lower intensity, even though the cross section for pair production is higher for the LSO than for CZT1 detector. Qualitatively, the reasons for this
Figure 16. Energy deposited by prompt bremsstrahlung photons in the LSO detector (absorber) over the energy deposited in the CZT1 detector (scatterer), with an energy threshold of 100 keV for each one. Prompt bremsstrahlung coincident events are selected thanks to a time correlation filter around the vertical peaks of figure 15: $[-18 \text{ ns}, -11.5 \text{ ns}]$ for the CZT1 detector; $[-16.5 \text{ ns}, -14.5 \text{ ns}]$ for the LSO detector.

Asymmetry are:

- a much smaller escape probability of the annihilation gamma ray when the pair is produced in the LSO detector;
- a much smaller solid angle covered by the CZT1 detector than in the mirrored scenario due to different size of absorber and scatterer;
- a much smaller absorption probability in the CZT1 detector of the escaping annihilation gamma rays;
- these effects are not compensated by a higher pair production rate in the LSO detector.

If we focus on the range above 511 keV for the LSO detector (figure 16), the triangular shape of the plot with an energy sum border near the 12.5 MeV maximum bremsstrahlung photon energy suggests that most of the coincidences are indeed Compton scattered coincidences.

6 Conclusions

The Compton imaging setup developed at OncoRay and HZDR is tested at the linear electron accelerator ELBE, a good platform prior to the clinical scenario measurements. The prompt bremsstrahlung photons have a bunched time structure as in a clinical proton cyclotron and cover the energy range relevant for prompt gamma imaging, thus allowing the study of the detector behaviour in conditions that are not accessible by means of common radioactive sources. This paper focuses on the spatial and time resolution of the CZT1 and LSO detectors.
For the CZT1 detector, the charge sharing effect is qualitatively analyzed as a function of the energy for the anode and cathode strips separately. Concerning the LSO detector, the pixel discrimination resolution improves for high energies due to light collection statistics.

The measured time resolution is of 2.8 ns FWHM for the CZT1 detector and of 2 ns FWHM for the LSO detector, values which are significantly smaller than the 77 ns separation between accelerator bunches. Time walk correction and pixel delay calibration for the LSO detector improves its time resolution up to 630 ps.

The resulting background suppression figures of merit for the Cyclone® 230 of IBA, with 9.4 ns bunch separation and 1.5 ns bunch spread at 160 MeV, are $\text{FoM}_{\text{CZT1}} = 66\%$ and $\text{FoM}_{\text{LSO}} = 83\%$. Thus, the LSO detector timing should be used for background reduction, whereas the CZT1 time resolution is primarily useful for rejecting coincidences between prompt gamma rays of different accelerator bunches.

In conclusion, the detector setup is suitable for time-resolved background discrimination in realistic radiation environments corresponding to pulsed clinical particle accelerators.

Ongoing tasks are the quantitative comparison of the measured energy with simulations and the test of imaging algorithms. Further experiments have been performed (and others are upcoming) at proton accelerators [11] to test the system under clinical beam conditions, and the data analysis is ongoing.

Acknowledgments

This work is supported by the German Federal Ministry of Education and Research (BMBF-03Z1NN12) and the European Commission (FP7 Grant Agreement N. 241851 and N. 264552). The authors like to thank the ELBE accelerator crew for stable operations.

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