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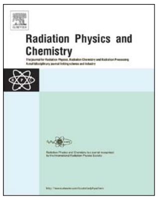

Development of a Compton camera for prompt-gamma medical imaging

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ABSTRACT

A Compton camera-based detector system for photon detection from nuclear reactions induced by proton (or heavier ion) beams is under development at LMU Munich, targeting the online range verification of the particle beam in hadron therapy via prompt-gamma imaging. The detector is designed to be capable to reconstruct the photon source origin not only from the Compton scattering kinematics of the primary photon, but also to allow for tracking of the secondary Compton-scattered electrons, thus enabling a γ-source reconstruction also from incompletely absorbed photon events. The Compton camera consists of a monolithic $LaBr_3$:Ce scintillation crystal, read out by a multi-anode PMT acting as absorber, preceded by a stacked array of 6 double-sided silicon strip detectors as scatterers. The detector components have been characterized both under offline and online conditions. The $LaBr_3$:Ce crystal exhibits an excellent time and energy resolution. Using intense collimated ^{137}Cs and ^{60}Co sources, the monolithic scintillator was scanned on a fine 2D grid to generate a reference library of light amplitude distributions that allows for reconstructing the photon interaction position using a k-Nearest Neighbour (k-NN) algorithm. Systematic studies were performed to investigate the performance of the reconstruction algorithm, revealing an improvement of the spatial resolution with increasing photon energy to an optimum value of 3.7(1)mm at 1.33 MeV, achieved with the Categorical Average Pattern (CAP) modification of the k-NN algorithm.

1. Introduction

The clinical application of tumor therapy via proton or heavy-ion beams has largely expanded over the last two decades. It exploits the favorable dose delivery properties of charged hadrons compared to conventional photon radiotherapy and major advancements in the fields of accelerator technology as well as treatment planning and diagnostic capabilities. The well-localized Bragg peak of charged particles in matter allows for a highly conformal dose deposition in the tumor, especially effective for the treatment of tumors in the vicinity of critical organs at risk. Moreover, sparing healthy tissue from unnecessary dose deposition is another benefit of particle therapy. However, while the number of clinical particle therapy facilities is still rapidly increasing (COG16article), exploiting the full benefits of the well-localized Bragg peak without applying large safety margins to account for methodological range uncertainties necessitates a reliable monitoring and in-vivo verification of the ion-beam stopping range (Knopf and Lomax, 2013). Several experimental signatures are being investigated in view of their potential to provide precise in-vivo information on the Bragg peak position: prompt photons or delayed photons (exploiting their energy and timing properties) (Min, 2006; Golnik, 2014), secondary ions (Gwosch, 2013) or ion-induced ultrasonic shock waves (Assmann, 2015). The direct detection of promptly (< ns) emitted γ radiation from nuclear reactions induced by the therapeutic proton or ion beam within the patient constitutes a promising option, since the distribution of prompt photons will not be blurred by physiological effects and no “wash-out” processes will occur, unlike in PET monitoring. The perspectives of “prompt-γ”-based medical imaging have been intensively studied in recent years, starting with feasibility studies to determine the correlation between the prompt γ radiation and the dose profile for mono-energetic proton beams (Min, 2006) and carbon beams (Testa, 2010). Several groups

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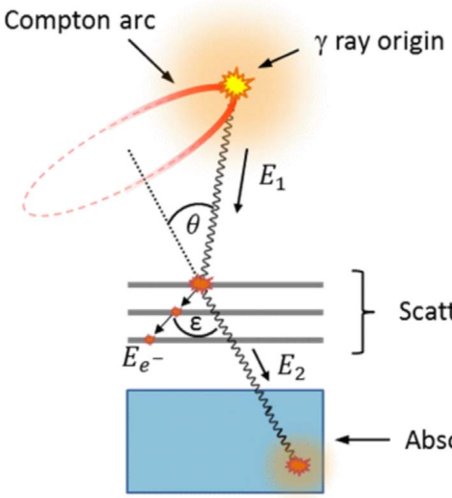

Fig. 1. Scheme of the principle of Compton camera operation in electron tracking mode.

investigate the possibilities for a range verification and in-vivo dosimetry via prompt γ radiation from nuclear reactions, either employing passively collimated imaging devices (Min et al., 2012; Roellinghoff, 2014; Perali, 2014) or electronically collimated systems based on the Compton-camera principle (Kormoll, 2011; Richard, 2011; Llosa, 2013; Polf, 2015; Thirolf, 2016).

In general, a Compton camera consists of a scatterer and an absorber component. While in the conventional design of a Compton camera exclusively the photon interaction is registered, an advanced approach, pursued in the LMU Compton camera design, targets the tracking of the Compton electrons as well. Fig. 1 displays this 'electron-tracking' mode of operation, which is characterized by a stack of position-sensitive scatter detectors forming a tracking array (instead of a monolithic scatter detector), where the thickness of the individual detectors has to be chosen thin enough to allow the Compton scattered electrons to penetrate at least 2–3 layers without too much deflection by Moliére scattering, thus enabling their trajectory reconstruction. The primary γ ray with energy E_1 interacts with one of the scatter detectors, depositing a fraction of its initial energy, while being deflected by the Compton scattering angle θ. If the remaining photon energy E_2 is low enough, the scattered photon is fully absorbed by the second component of the Compton camera. The Compton scattering angle θ can be inferred by detecting the deposited energies and the interaction positions of the primary and the Compton-scattered photon in the two detector components, exploiting the Compton scattering kinematics based on energy and momentum conservation. Thus the primary photon origin can be constrained to the surface of the *Compton cone*, spanned by θ with its apex given by the primary interaction position in the scatter detector. From the intersection of different Compton cones, inferred from subsequent photon interactions originating from the same source, the γ-ray source position can be determined.

In addition to this conventional source reconstruction scheme, the kinematical information carried by the Compton electron trajectory can be exploited to derive independent spatial information, which restricts the Compton cone to an arc segment (as indicated in Fig. 1). This mode of operation provides an increased reconstruction efficiency, since it allows to reconstruct the photon source position also from incompletely absorbed events, i.e. events, where part of the scattered photon energy escapes the absorption in the second component of the Compton camera, e.g. by Compton scattering or pair creation with subsequent single- or double escape of the 511 keV annihilation photons.

1.1. The Compton camera prototype

The geometrical layout of the LMU Compton camera prototype is schematically shown in Fig. 2. The scatter component is formed by a stacked array of six double sided silicon strip detectors (DSSSD), each of them with a thickness of 500 µm and an active area of 50×50 mm^2. Each detector layer is segmented into 128 strips on the *n* and *p* sides, respectively, with a pitch size of 390 µm. The 256 silicon strips per detector are read out via 64-pin connectors at each of the four detector sides. Signals are transferred via AC coupling boards to the subsequent compact front-end signal processing boards, based on the GASSIPLEX (Santiard, 1994) ASIC chips. The signals processed in the six front-end boards of one detector side are then collected in a bus card and guided to a VME-based readout controller. Thus finally all 1536 DSSSD signals are fed into the combined event data stream together with the data from the absorber detector.

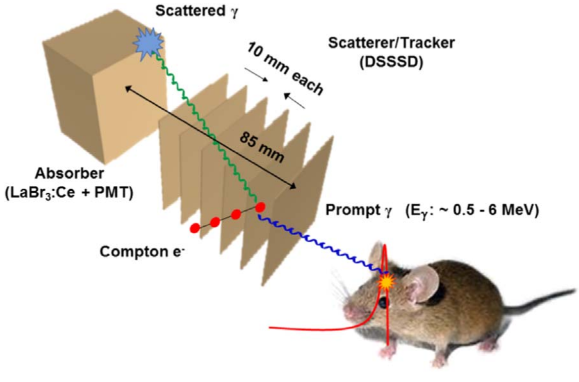

Fig. 2. Sketch of the layout of the LMU Compton camera prototype.

The absorber component of the Compton camera is a monolithic 50×50×30 mm^3 LaBr$_3$:Ce^{3+} scintillator crystal (Gobain). This scintillator material offers favorable properties in all relevant quantities for γ-ray detection. LaBr$_3$:Ce^{3+} outperforms other commonly used scintillation materials in terms of timing and energy resolution. It exhibits a very fast decay time τ=17 ns, very high light yield (63,000 photons/MeV), good energy resolution and reasonably high mass density (ρ=5.07 g/cm^3). Similar to all lanthanum halide crystals, also LaBr$_3$:Ce features an unavoidable amount of internal radioactivity, due to contaminations from ^{227}Ac and its daughter products, as well as the presence of a small amount of the radioactive isotope ^{138}La. In case of our absorber crystal, an internal activity of 2 Bq/cm^3 (in total 150 Bq) was measured.

The scintillation crystal is read out by a multi-anode photomultiplier tube (PMT) with 16×16 segments (each 3×3 mm^2, Hamamatsu H9500). In addition to the 256 individual channels of the PMT, a sum signal can be extracted via the 'sum dynode' output. The 257 signals are fed into 16-channel amplifier and Constant Fraction modules (mesytec MCFD-16), generating both amplified charge signals and amplitude-independent timing gates. Subsequently, the charge signals are fed into VME-based Charge-to-Digital (QDC) converter modules (mesytec MQDC-32), while time-of-flight measurements (relative to an external trigger) are enabled by sending the gate signals to Time-to-Digital (TDC) modules (mesytec MTDC-32). Finally, data acquisition of the combined data stream from the two Compton camera detector components is achieved through a frontend CPU (Power-PC RIO-3, operated with the LynxOS real-time operating system) and the MBS- and ROOT-based acquisition and analysis system MARABOU (Lutter, 2000).

The scintillation detector was characterized in the laboratory with calibration sources, revealing a position independent relative energy resolution of ΔE/E =3.5(2)% and an excellent time resolution of 273(6) ps (FWHM) (Thirolf, 2014; Marinšek, 2015).

2. Determination of the photon interaction position in a monolithic scintillator

The determination of the interaction position of Compton-scattered multi-MeV photons in the absorbing scintillator of the Compton