Abstract

Fast-timing radiation detectors are leading to numerous innovations in the fields of high energy physics (HEP) and medical physics. One of the possible applications in the field of medical physics is positron emission tomography (PET). PET is a functional imaging technique able to provide 3D information on the metabolic activity in a living organism. To achieve this, a β^+-emitting isotope embedded in a drug that follows a specific metabolic pathway is injected into the patient. As a result of the β^+ decay, the positron annihilates with an electron, and two back-to-back gamma photons of 511 keV energy are produced. The gammas are detected in coincidence using detector blocks placed around the patient and organized in rings, made of scintillators, photodetectors, and readout electronics. They allow for the reconstruction of the line along which the annihilation process took place, called line of response (LOR). After the accumulation of many LORs, the reconstruction of a 3D image is possible.

The localization of the electron-positron annihilation along a LOR can be obtained by measuring the time difference between the detection of the two photons, known as time of flight (TOF), whose accuracy is defined by the coincidence time resolution (CTR). In TOF-PET this information allows to improve the signal-to-noise ratio (SNR) and therefore the quality of the reconstructed image. This resolution is affected by all components in the detector chain and, hence, to improve its performance, a careful optimization of all detector elements is needed.

The current state-of-the-art CTRs for commercially available PET scanners were set by the Siemens Biograph Vision PET/CT scanner, with a time resolution of 214 ps full-width-at-half-maximum (FWHM), and the Biograph Vision.X PET/CT system, with a even better time resolution of 178 ps FWHM thanks to the use of artificial intelligence. Such a good time resolution already leads to a 3 cm spatial resolution along the LOR. Nonetheless, a number of medical challenges call for a further improvement in TOF precision of TOF-PET scanners. Achieving a CTR of 100 ps FWHM translates to a shorter examination time or a lower radioactive dosage administered to the patient. The ultimate goal is to reach 10 ps FWHM, which translates to 1.5 mm spatial resolution and also corresponds to the range of the positron. This level of precision would provide the true space points of positron annihilation, enabling reconstruction-less imaging.

Scintillating inorganic crystals like lutetium–yttrium oxyorthosilicate (LYSO) represent the best scintillator for TOF-PET scanners, owing to their high light yield and fast scintillation kinetics. With new advancements in silicon photomultiplier (SiPM) technologies and electronics readouts, the timing performance of this scintillator is pushed

to its limit. As a consequence, the depth of interaction (DOI) of a gamma inside the scintillator and its contribution to the CTR are no longer negligible. This is particularly important in preclinical and organ-dedicated human PET scanners, which require high spatial resolution and sensitivity to achieve detailed imaging and high SNR.

This thesis investigates a detector block made of a set of crystals with depolished lateral surfaces together with a light guide placed on top of it to enable light sharing between neighboring crystals, and thus allow for the extraction of DOI information of gamma rays. This approach is applied to a matrix of 15 mm long LYSO:Ce scintillators and the most advanced SiPMs available, using both custom-made and commercially available electronic readout systems. The custom-made readout is based on the NINO 32-chip used for time extraction and on an analog amplifier for energy extraction. The readout processes each SiPM output signal of the array, which is later digitized with a sampling rate of 5 GS/s. With this setup and using the new Metal-in-Trench SiPM technology, a CTR of 170 $\pm$ 5 ps FWHM is achieved after DOI correction, along with a DOI resolution of 2.5 $\pm$ 0.2 mm FWHM. On the other hand, using the PETsys TOF-PET2 ASIC, a commercially available electronic readout, a CTR of 216 $\pm$ 6 ps FWHM and a DOI resolution of 2.6 $\pm$ 0.2 mm FWHM are obtained. The PETsys TOFPET2 ASIC readout is chosen for comparison to assess the detector's performance and applicability to future scalable systems of several thousands of channels.

In addition, a custom-made and sixteen-channel low-noise, low-power, high-frequency (LNLPHF) board is tested to further enhance the time resolution by making use of a lower leading-edge threshold that allows the detection of the earliest photons produced, such as Cherenkov photons. Using 20 mm long crystals, commonly used in commercial PET scanners, the DOI-capable detector block achieves a new benchmark CTR of 133 $\pm$ 2 ps FWHM after DOI correction. For comparison, the CTR of the standard (non-DOI) module of the same length is 130 $\pm$ 2 ps FWHM. Thus, the DOI-capable concept not only achieves similar performance as the standard configuration but also has the benefit of retrieving the DOI information, which can later be used to correct parallax errors in scanners.

The merits of the LNLPHF board become particularly visible in crystals with slow scintillation profiles where, however, few Cherenkov photons are produced owing to these crystals' high refractive index, such as in bismuth germanate (BGO) or in scintillators with high photon density, such as in plastic. In fact, the timing resolution of these materials crucially depends on the threshold applied to extract the time information. If 250 μm thick layers of BGO and plastic scintillators are alternately stacked, in the so-called heterostructure concept, the fast scintillation production of the plastic and the high stopping power of BGO can be combined in one "crystal", and the light attenuation due to the stratification of the layers be used to retrieve the DOI information by means of a light sharing mechanism. Selecting events where part of the energy is shared between the two materials and using the DOI information for time correction, a CTR of 182 $\pm$ 6 ps FWHM is achieved with a matrix of 20 mm long heterostructured scintillators. This approach offers a cost-effective compromise between adequate time resolution and high sensitivity.

Finally, the DOI-capable detector block is used to explore a new statistical method designed to identify the first crystal-of-interaction in the stack in the case of inter-crystal scatter (ICS) events. These events, in which gamma rays interact with multiple crystals, degrade spatial resolution if not properly addressed. Removing the ambiguity in the determination of the crystal of the first interaction could improve LOR delineation and therefore spatial resolution. If the expected charge distribution across all photodetectors, as a function of DOI and energy deposition, is known from prior calibration procedures, the information can be used to estimate the most probable gamma-ray interaction points across multiple crystals and accurately identify the first crystal of interaction. The statistical method is tested using Geant4 Monte-Carlo simulations and proves to be accurate to better than 85% and predicts a DOI resolution of 4.5 mm FWHM. This approach offers a novel strategy to enhance the spatial resolution of ICS events used for image reconstruction.