Design of the PET-MR system for head imaging of the DREAM project

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Abstract

In this paper we describe the overall design of a PET-MR system for head imaging within the framework of the DREAM Project as well as the first detector module tests. The PET system design consists of 4 rings of 16 detector modules each and it is expected to be integrated in a head dedicated radio frequency coil of an MR scanner.

The PET modules are based on monolithic LYSO crystals coupled by means of optical devices to an array of 256 Silicon Photomultipliers. These types of crystals allow to preserve the scintillation light distribution and, thus, to recover the exact photon impact position with the proper characterization of such a distribution. Every module contains 4 Application Specific Integrated Circuits (ASICs) which return detailed information of several light statistical momenta. The preliminary tests carried out on this design and controlled by means of ASICs have shown promising results towards the suitability of hybrid PET-MR systems.

Keywords: Hybrid PET-MR, SiPM

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1. Introduction

It has been widely suggested the convenience of simultaneously obtain Positron Emission Tomography (PET) and Magnetic Resonance (MR) images[(1)]. Both sets of data, if they are furthermore obtained on a dynamically mode (time dependent), could provide unprecedented information on the studied disease. MR results provides images with higher contrast compared to the Computerized Tomography (CT) and at the same time the patient avoids radiation since MR is not based on x-ray sources[(2)]. There are many advantages of fusing PET and MR modalities, but the technological challenges are still challenging. Good substitutes for the conventionally used Photomultiplier Tube (PMT) technology, are the so-called Silicon Photomultipliers (SiPMs)[(3,4)]. SiPMs are fast, have high gain, they are hardly affected by magnetic fields[(5)] and are suitable for Time of Flight (TOF) measurements due to their working principle[(6)].

An architectural approach to combine the PET and MR techniques within the same gantry or structure, has already been suggested[(7)]. It is a very promising solution since it could allow to simultaneously acquire PET and MR data. An alternative approach would be the design of a PET insert, MR compatible (see Fig. 1). This is specially cost effective when the MR is mainly assigned to the neurology field. Note that for head explorations, the conventional whole-body PET scanner is not optimized and that a dedicated one could provide higher spatial resolution and sensitivity performances. A dedicated PET would also reduce the scanning time of brain studies which currently last about 30 minutes.

This work shows the preliminary design and tests of an MR compatible PET insert. This contribution is performed within the framework of the DREAM Project.

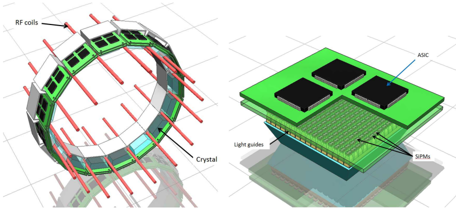

Figure 1: Drawings for the hybrid PET ring along with the brain RF coil and, the detail of one single detector module.

2. Material and methods

The PET system consists of 4 rings of 16 detector modules each and it is integrated in the head dedicated radio frequency (RF) coil of an MR system. The detector modules are designed to fit in the gaps between two wires of the RF coil (bird cage shape). In Fig. 1 a sketch of the configuration for one detector ring and one module is given. The blue blocks represent the crystals and, the black squares on top of green layers are the data control chips and their allocation boards, respectively. The RF coils can also be distinguished as red bars.

Based on tabulated data for human head dimensions obtained from *PeopleSize 1999*, it was found the convenience for a transaxial field of view (FOV) of the designed system to be of at least about 206 mm in diameter. From the PET module dimensions we plan to use, and the number of allowed coincidence detector pairs, we found that 16 modules could allow one to obtain images of about 240 mm FOV size without loosing significant sensitivity due to the existing gaps in between neighboring modules. In order to be able to visualize the entire brain including the hippocampus region, 4 detector rings have been suggested, covering nearing 200 mm axial FOV.

Each detector module has been designed with the aim to be controlled by means of a reduced number of Application Specific Integrated Circuits (ASICs). In particular, every detector contains 4 ASICs. The main components of the detector block are a continuous scintillator crystal, an array of solid state Silicon Photomultipliers (SiPM) detectors, and the ASICs.

The PET modules allocate a single continuous LYSO (Cerium doped lutetium based scintillation) crystal block with an entrance surface of 40×40 mm^2 and an exit face of 50×50 mm^2, coupled to an array of 256 SiPMs of 1×1 mm^2 area each, through a matrix of light guides(8). Several configurations for crystal surface treatment have been studied aiming at preserving the original scintillation light distribution. The most suitable solution is to black paint all crystal faces but the exit one in contact with the photosensor block, in order to absorb the undesired reflected light(9). The thickness of the crystal is still under study in order to keep a small edge effect, characteristic of continuous crystals without great penalty on PET sensitivity(10,11). A previous work(8) showed that this border effect can be diminished by using optical devices capable to reduce the acceptance angle (AA) of the scintillation light into the photosensor.

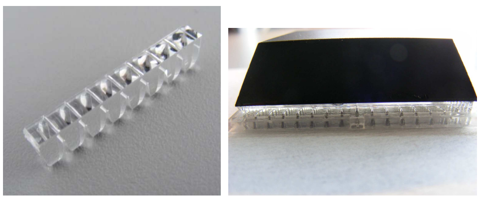

Figure 2: Photographs of the light guide array and its coupling with the scintillation crystal.

Different types of SiPM devices have been evaluated. In order to facilitate their assembly, surface mounted device (SMD) packaging is preferable among others along with a relative small active area in order to reduce the dark counts

(DC) contribution which squarely increases with the detection surface. Note that instead of recording all SiPMs output signals (256), we will read them out with ASICs in order to obtain a few parameters containing the information of the light distribution, the so-called momenta. Thus, it is required to reduce the DC to avoid errors in the characterization of the light distribution that could cause a lost of precision in the determination of the photon impact position. Other effects like temperature, SiPM breakdown voltage or its photon detection efficiency also play an important role when characterizing a system that is composed of SiPMs[12,13]. However, our set-up is not susceptible yet to accurately study these contributions and, therefore, they are not further commented in this work.

Following the idea of reducing the AA at the time to focus the scintillation light into the small area of the SiPM, some optical coupling devices, here called light guides, were studied. The optical design of these guides has been optimized using the ZEMAX simulation program that is based on light propagation within the crystal and guides. An optimal configuration using parabolic surfaces was found to represent a balance between light detection efficiency and cros–talk between channels. The system works under the total internal reflection principle. Although metallic coatings such as Gold and Silver, were tested, they translated into transmission losses. These guides make it possible to reduce the AA to about 16°, compared to 55° characteristic when the scintillation crystal is coupled to a Position Sensitive Photomultiplier (PSPMT) through optical grease (n_{LYSO}=1.82, $n_{PSPMT,\, borosilicate}$=1.49, n_{grease} ≈1.56).

The selected optical configuration has already been implemented by developing a special cast for an array of 8 light guides using polymethyl methacrylate (PMMA) as material. Figure 2 shows a real photograph of this array on the left hand side. We decided to manufacture it with this configuration (1$\times$8) to avoid stratification problems due to cooling of the PMMA when injecting it into a mold. A final matrix of 256 light guides was built by gluing 32 of those arrays. During the simulation stage it was observed the convenience to avoid the adhesion of any material in optical contact with the light guide walls in order to minimize light transmission losses. The picture on Fig. 2 (right) shows the scintillation crystal coupled to the array of 256 light guides.

2.1. Module Readout

The SiPM matrix is readout through 4 identical ASIC chips called AMIC[(14)], (see sketch in Fig. 1). Each AMIC reads 64 SiPM inputs and outputs up to 8 signals each. The AMIC chip is fully scalable: 4 AMICS are coupled together to read 256 SiPMs in parallel but work as a single unit with only up to 8 output signals. Each AMIC first makes up to 8 copies of the input signal from each SiPM, which are then multiplied by a different constant depending on the copy and SiPM position. Finally, all the input signals multiplied by the corresponding constants are added, therefore forming up to 8 linear combinations of the 256 input signals.

Selecting the set of constants properly it allows for example the construction of the different momenta of the light distribution in Cartesian coordinates, although other bases of functions may be used. In such a way, the AMIC mainly serves as a data reduction device that compresses the information from 256 input channels into up to 8 parameters describing the light distribution. Note that higher orders than the second moment are hardly to be analogically implemented[(15)] and, therefore, the proposed approach could provide very valuable results.

3. Results

Some measurements were performed in order to test the feasibility of using the ASIC to read out the array of SiPMs. Here, only 64 SiPMs were used and, thus, only one ASIC was required to return the light distribution information. For these first tests, the SiPM array without the coupling light guides was mounted. The scintillator crystal had dimensions of 50×50 mm^2 and 40×40 mm^2 for the entrance and exit faces, respectively. The crystal thickness was 10 mm and all faces black painted but the one in contact with the SiPM array which was polished. The system was programmed to deliver the zero momentum (Energy) and, $< x >$ and $< y >$ impact positions. All SiPMs were powered at -71.1 V, which was the lowest manufacture suggested voltage among the 64 detectors. The system was run at ambient temperature.

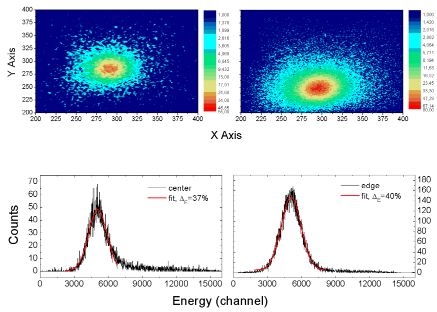

Figure 3: Top, countour plots for the acquisition of a point-like source located at the detector center and border. Bottom, energy spectra of the two acquisitions.

A ^{22}Na point-like source with about 1 μCi of activity and 1×1 mm^2 size was used in these tests. It was moved across the crystal to validate the X and Y impact photon coordinates. The source was collimated through a Tungsten pinhole of 1 mm in diameter and 30 mm thickness placed just on the incoming detector surface.

Figure 3 depicts the acquisition of the source located at the detector center and also close to the photosensor array border.

Since the light guides were not used, the photosensor area only covered about 4.9% of the total exit scintillator surface. Therefore, the determined energy resolution was as poor as about 37% and 40% for the center and edge regions of the detector block, as it can be estimated in Fig. 3 (bottom).

4. Conclusions

We have developed a detector module for PET-MR systems specially dedicated to brain imaging. The module is based on a continuous scintillating crystal coupled through light guides to 256 SiPMs which are read by data reduction ASIC chips. The use of the light guides, due to the AA reduction, would help to increase the crystal thickness without significantly worsening the image compression due to border effects and, therefore, increasing the sensitivity of the PET system.

Preliminary results without the light guides showed the possibility of merging SiPMs with ASIC devices to return valuable coincidence gamma ray (511 keV) images. These results show that, even without the proper light collection, the use of an ASIC allows to compute the impact coordinates. Undergoing tests have delivered a depth of interaction of 3 mm resolution enabling to distinguish among several virtual crystal layers and, thus, allowing to partially correct for the parallax error.

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