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Performance of a fast acquisition system for in-beam PET monitoring tested with clinical proton beams

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ABSTRACT

In this work we present the performance of a fast acquisition system for in-beam PET monitoring during the irradiation of a PMMA phantom with a clinical proton beam. The experimental set-up was based on 4 independent detection modules. Two detection modules were placed at one side of a PMMA phantom and the other two modules were placed at the opposite side of the phantom. One detection module was composed of a Silicon Photon Multiplier produced by AdvanSiD coupled to a single scintillating LYSO crystal. The read-out system was based on the TOFPET ASIC managed by a Xilinx ML605 FPGA Evaluation Board (Virtex 6). The irradiation of the PMMA phantom was performed at the CNAO hadrontherapy facility (Pavia, Italy) with a 95 MeV pulsed proton beam. The pulsed time structure of the proton beam was reconstructed by each detection module. The β^+ annihilation peak was successfully measured and the production of β^+ isotopes emitters was observed as increasing number of 511 keV events detected during irradiation. Finally, after the irradiation, the half lives of the ^{11}C and ^{15}O radioactive isotopes were estimated.

1. Introduction

1.1. Hadrontherapy monitoring

The aim of a radiotherapy treatment of a cancerous disease is to deliver a high radiation dose to the tumor volume while sparing the surrounding healthy tissue. In the case of radiotherapy treatments with external radiation beams this is more easily achieved if ion beams are used in place of photon beams. This is because of the characteristic Bragg curve which describes the energy deposition of charged particles within the matter. The Bragg curve is characterized by a pronounced peak (the so-called Bragg peak) at the end of the particle range which allows the delivery of a high radiation dose to the tumor volume while sparing the tissues around. The knowledge of the position of the Bragg peak within the patient is crucial for a successful hadrontherapy treatment.

Daily changes in the patient anatomy and uncertainties in the calibration of the CT Hounsfield Units to particle stopping powers used by the treatment planning system introduce uncertainties in the position of the Bragg peak which could accidentally be within a critical structure close to the tumor volume. Therefore the on-line monitoring of the hadrontherapy treatments is desirable. There are different approaches to the monitoring of hadrontherapy treatments [1]. One of the non-invasive methods includes the use of a PET scanner. During the irradiation, different β^+ emitter isotopes, like ^{15}O and ^{11}C, are created within the patient. A PET scanner allows the measurement of the 3D distribution of the activity of the β^+ emitters. The aim of a PET monitoring is therefore to compare the measured activity distribution with the one calculated during the treatment planning. There are three different ways of performing a PET monitoring of a hadrontherapy plan: off-line, in-room and in-beam. In the off-line approach, right after the radiotherapy treatment the patient is moved to another room where a standard clinical PET scanner is installed. This is the easiest way of performing a hadrontherapy monitoring, however only the β^+ activity of the isotopes with a long half life can be detected, as for example ^{11}C (20 min), while the activity of the isotopes with a short half life, as for example ^{15}O (2 min), is lost. Moreover the biological washout makes the comparison with the calculated β^+ activity more difficult. These issues are partially overcome in the in-room approach, where the PET scan of the patient is performed with a PET scanner installed in the treatment room. However, the time spent to execute the PET scan slows down the clinical workflow. Moreover it is not possible to monitor

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the outcome of each beam of the treatment plan. In the in-beam approach a PET scanner is integrated with the treatment unit. The PET data acquisition is performed during the irradiation of the patient therefore it has the lowest impact on the clinical workflow. Moreover, it allows the imaging of the activity distribution for each beam composing the treatment plan and it is the least influenced by the biological processes. Therefore the comparison with the simulated activity distribution is easier [2]. However the integration of a PET scanner with the treatment unit is a challenging task because of geometrical constraints which require an opening for the radiation beam portal and for the flexibility on the patient positioning. There are two hadrontherapy centres with a PET scanner integrated with the treatment unit: the Proton Radiotherapy Department of the National Cancer Center, Kashiwa, Japan, and the GSI heavy ion center, Darmstadt, Germany, which is now dismissed from the clinical usage. They have been especially used for the monitoring of the head and neck treatments. They are both dual-head PET scanners because it is the geometrical configuration which allows more freedom in the patient positioning [3,4].

The use of the prompt gamma radiation has been lately proposed as an alternative approach to the PET monitoring. The correlation between the prompt radiation and the position of the Bragg peak has been demonstrated by different research groups [5–7]. However at the moment there are no acquisition systems of prompt radiation installed in a clinical setting.

1.2. The INSIDE project

The INSIDE project, which is under the Italian national research program PRIN MIUR 2010–2011 2010P98A75, aims to the development of a hadrontherapy monitoring system based on the detection of both the prompt radiation and the back-to-back annihilation photons created during the irradiation of the patient.

A $20 \times 20\ cm^2$ dose profiler will be used to reconstruct the Bragg Peak position from the prompt gamma radiation and the emitted charged particles, in the case of irradiation with the ^{12}C ion beam. The dose profiler will be made of a particle tracker, an absorber and a calorimeter. The tracker will be made up of 6 XY planes of BCF-12 plastic scintillating fibers coupled to $1 \times 1\ mm^2$ Hamamatsu SiPM. The BASIC32 ASIC [8] will be used for the SiPMs read-out. 24 mm of EJ-200 plastic scintillator will be placed behind the tracker as absorber to measure the energy of the Compton electrons. At the back of the absorber there will be the calorimeter made of 4×4 matrices of pixellated LYSO crystals read by a multi-anode H8500 PMT. A schematic picture of the dose profiler is shown in Fig. 1. The expected resolution in the reconstruction of the emission point of the charged particles is 1–2 mm.

The PET monitoring will be performed by a dual-head scanner. Each head will be made of 2×5 modules, with a total area of 10 cm (transaxially) $\times 25$ cm (axially). Each module of the head will be composed of a $5 \times 5\ cm^2$ pixellated LSF (Lutetium Fine Silicate) crystal with 16×16 pixels. The LSF crystal will be coupled one to one to a matrix of 16×16 Multi-Pixel Photon Counters (MPPC) arrays from Hamamatsu. Each MPPC array will be read by 4 TOFPET ASICs [9].

In this work we present the performance of a first prototype of the PET detection system proposed above during the irradiation of a PMMA phantom with a 95 MeV proton beam. The prototype under test was based on single Silicon Photon Multipliers coupled one-to-one to LYSO scintillating crystals and connected to a dedicated read-out electronics. The tests were carried out at the CNAO (Pavia, Italy) hadrontherapy facility.

2. Methods and materials

2.1. Detection system and read-out

The first prototype of the PET detection system was composed of 4 independent detection modules. Each detection module was composed of a single Silicon Photon Multiplier (SiPMs) produced by AdvanSiD [10], with an active area of $3 \times 3\ mm^2$ and 50 μm cell size, and a $3 \times 3 \times 10\ mm^3$ LYSO scintillating crystal, white wrapped. The SiPMs were all biased at 33 V by means of a Keithley 2410 voltage source. The read-out system was based on the 64-channels ASIC TOF PET. Each read-out channel of the ASIC is composed of an analog block which amplifies the SiPM input signal and delivers two digital signals to the Time to Digital Converter (TDC). The TDC output contains information on the trigger time and on the Time-over-Threshold (ToT) of the input signal. The ToT information is related to the energy deposited in each crystal pixel. The acquisition board where the ASIC was bonded and the acquisition software were adapted from the ones developed within the INFN 4DMPET project [11].

2.2. Experimental set up

The performance of the PET system prototype was tested during the irradiation of a $5 \times 5 \times 7\ cm^3$ PMMA phantom. The 4 detection modules were placed at two opposite sides of a PMMA phantom, at 5 cm from the surface therefore the distance between two opposite detection modules was 15 cm. A schematic picture (not to scale) of the experimental set up is shown in Fig. 2. The experimental measurements were carried out at the CNAO hadrontherapy facility. The CNAO hadronterapy facility is based on a synchrotron particle accelerator therefore the radiation beam is not continuous with time but it has a pulsed structure. The time interval when the proton radiation is effectively present is called

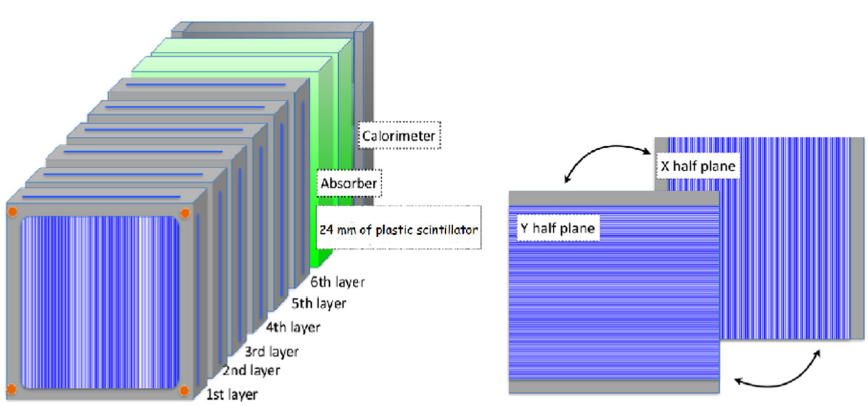

Fig. 1. Schematic picture of the dose profiler (left) and schematic picture of one of the tracker layers (right).