High performance 3D CZT spectro-imager for BNCT-SPECT: preliminary characterization

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***Abstract*—The National Institute of Nuclear Physics (INFN) is supporting the 3CaTS project with the aim of developing a new Single Photon Emission Computed Tomography (SPECT) system for real time ^{10}B therapeutic dose monitoring in the binary experimental hadron therapy called Boron Neutron Capture Therapy (BNCT). BNCT is a highly selective tumour treatment based on the neutron capture reaction ^{10}B(n,α)^{7}Li. The secondary particles have a high LET with ranges in tissues of the order of 10 μm (thus less than the mean cell diameter of few tens μm). Targeting the ^{10}B delivery towards cancer, the released energy lethally damages only the malignant cells sparing the normal tissues, thus enabling a cell-level selective treatment. To properly exploit this selectivity it is mandatory to know the ^{10}B spatial distribution inside patients body during neutron irradiation. This can be achieved by detecting the 478 keV γ ray emitted in the 94% of ^{10}B capture reactions by a SPECT system. A 3D CZT drift strip detector with a sensitive volume of 20x20x5 mm^{3} was developed, able to perform high-resolution X-ray and γ ray spectroscopic imaging (10-1000 keV). The detector signals are analysed by a custom digital multi-channel electronics, based on two pipelined fast and slow analysis, able to perform multi-parameter analysis and fine temporal coincidences ($<$ 20 ns). Energy resolution of 3.3% (4 keV) and 2% (13 keV) FWHM was measured, with uncollimated sources and no corrections, at 122 keV and 662 keV, respectively.**

I. INTRODUCTION

The INFN 3CaTS project (High performance 3D Cadmium-Zinc-Telluride spectro-imager for X and γ ray applications) is presently carried out at Pavia University and Pavia INFN Unit in collaboration with Palermo University, the Bologna Unit of the Italian National Institute of Astrophysics (INAF), the Institute of Materials for Electronics and Magnetism (IMEM) of the Italian Research National Council (CNR) and the start-up due2lab s.r.l. in Parma, Italy.

The aim of the project is to develop an innovative highly segmented prototype of a CdZnTe (CZT) room temperature solid state photon detector and to evaluate its performance as spectrometer with 3D spatial resolution capabilities suitable for different spectroscopic and imaging applications in the range from few tens of keV up to 1 MeV, mainly in astrophysics and Boron Neutron Capture Therapy (BNCT).

BNCT is a binary radiotherapy based on the high cross-section of the capture reaction $^{10}B(n,\alpha)^{7}Li$ induced by thermal neutrons [1] [2]. A tumour targeting drug is used to concentrate the ^{10}B in the tumour tissue. The high LET (Linear Energy Transfer) particles produced in the capture reaction have a range small enough to be comparable to the mean cell diameter, thus they deposit all their energy inside the single cell. In this way BNCT is a highly selective therapy able to destroy the tumoural cells while sparing the normal tissue. To properly exploit the efficacy of BNCT it is needed to correctly estimate the boron concentration in the cells and the dose given to the patient during the clinical treatment.

To date there are no real-time means to evaluate this concentration in the patients treated by BNCT. Dose calculations are based on ^{10}B content in blood, tumour and normal tissues obtained performing pharmaco kinetic studies beforehand. In clinical cases, ^{10}B distribution varies from patient to patient and large uncertainties exist in the tumor-to-blood concentration ratio. Alternatively the ratio is extrapolated from PET studies using boronated drugs marked with ^{18}F [3]. Since the protocol of administration of the PET-probe is different from that of the drug used in BCNT, estimated doses from PET imaging are poorly reliable and several clinical trials reported different outcomes even after application of the same BNCT protocol [4].

In this scenario, the strategy investigated by the 3CaTS project is based on the detection of the 478 keV photon emitted in 94% of ^{10}B capture reactions. This photon can be used to acquire data for a Single Photon Emission Computed Tomography (SPECT) that can be performed during the therapy. SPECT can give both qualitative information through ^{10}B distribution imaging and quantitative in-patient dosimetry based on Eq. 1Introductionequation.1.1.

$$D \propto \int n_B \sigma \phi dV \tag{1}$$

where n_B is ^{10}B nuclei concentration measured in ppm, σ is the capture cross section at 25 meV of thermal neutron energy, ϕ is the thermal neutron flux irradiating the volume dV. Indeed, the counting of the 478 keV γ rays allows a direct

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estimation of the delivered therapeutic dose, thus opening the route for a real-time and in vivo BNCT dose monitoring and not merely the quantification of ^{10}B concentration in the irradiated tissues.

To be able to build a performing BNCT-SPECT imaging system it is important to have a detector with high energy resolution, high efficiency and compact dimensions. CZT semiconductor detector was chosen for this task thanks to the highly ideal characteristics of this compound for the detection of X and γ rays in the energy range 10-1000 keV and preliminary positive results for BNCT applications have been already reported [5] [6]. CZT has indeed a high atomic number which assures high detection efficiencies even within small volumes. In addition the wide energy band-gap allows room temperature operation thus making possible the construction of a compact and highly portable imaging system capable of improving detection sensitivity as well as patient comfort during image acquisition. The direct conversion of the incident photon into an electric signal leads to a very good energy resolution and finally the possibility to realise pixels/stripes electrodes by standard photolithography guarantees high spatial resolution imaging detectors. In the last years, and thanks to these characteristics, CdTe and CZT photon detectors have gained increasing attention from the scientific community in specific fields of nuclear medicine and cancer diagnosis, as well represented by the small Field Of View cardiac SPECTs [7] and the application in Breast Molecular Imaging (BMI) [8].

II. Materials and Methods

A CZT drift strip detector was fabricated at IMEM-CNR (Parma, Italy; http://www.imem.cnr.it) and by due2lab (Reggio Emilia, Italy; http://www.due2lab.com). Recently, high-resolution CZT detectors have been successfully developed at IMEMCNR [9] - [16]. The detector is based on a CZT crystal (20 x 20 x 5 mm^3), grown with the traveling heater method (THM). The 3D electrode geometry is based on strip electrodes with 0.4 mm pitch (0.15 mm width and 0.25 mm gap) on one side and 10 cathode strips with 2 mm pitch (1.9 mm width and 0.1 mm gap) on the other side (Fig. 1The 5x5x20 mm^3 CZT detector employed in the measurements, designed and delivered by due2lab s.r.l. and Parma CNR-IMEM for BNCT applications. (left) Overview of the anode side; (right) overview of the cathode sidefigure.1). The detector was configured with several drift cells, each comprising one collecting anode strip with four drift strips, two on the left and two on the right side of the anode strip. The complete drift cell dimensions are 1.6 mm 5 mm 20 mm. The drift strips are biased such that the electrons are focused and collected by the anode strips [17] [18]. The detector is AC coupled to fast and low noise preamplifiers developed at University of Palermo (ENC $<$ 100 e).

The output waveforms from the detector-preamplifier are digitized and on-line processed by a custom digital electronics, recently developed at DiFC of University of Palermo (Italy) [19] - [23]. The digital electronics is able to perform a real-time pulse shape and height analysis (event arrival time, pulse height, pulse time width, peaking time) of the CSP waveforms even at high rates and at different throughput and energy resolution conditions. The digital system consists of four digitizers (DT5724, 16 bit, 100 MS/s, CAEN S.p.A., Italy; website: http://www.caen.it) and a PC, through which the user can control all digitizer functions, the acquisition and the analysis. The digitizers are connected and synchronized to realize a digitizing system with 16 channels.

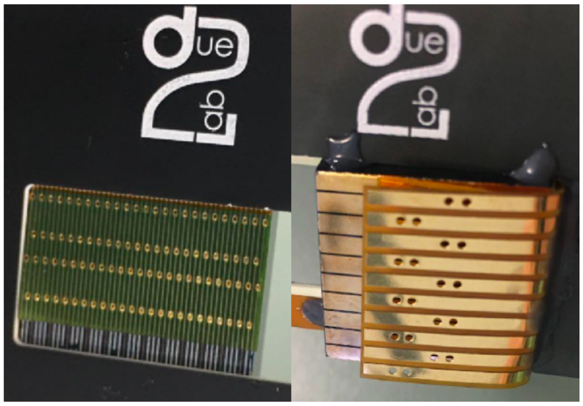

Fig. 1. The 5x5x20 mm^3 CZT detector employed in the measurements, designed and delivered by due2lab s.r.l. and Parma CNR-IMEM for BNCT applications. (left) Overview of the anode side; (right) overview of the cathode side.

III. Preliminary Results

We performed room temperature measurements with uncollimated radiation sources (^{57}Co and ^{137}Cs sources) by using the planar transverse field (PTF) irradiation. All strips are biased negatively: cathode HV = -170 V, central drift strips = -120 V and left-right drift strips = -40 V. Figs. 2The ^{57}Co energy spectrum (uncollimated source) measured with the 3D CZT detector. No corrections were performedfigure.2 and 3The ^{137}Cs energy spectrum (uncollimated source) measured with the 3D CZT detector. No corrections were performedfigure.3 show the spectroscopic performance of the detector.

For BNCT-SPECT application the energy resolution of the CZT detector is an aspect of particular importance due to the mixed (n+γ) radiation background in which the sensor must work. Apart from the unavoidable γ contamination of the primary neutron beam and the secondary photons produced by the neutron interactions with the patient, the irradiation set-up and the walls of the treatment room, the presence of a significant component of thermal neutrons affects specifically the CZT response due to ^{113}Cd isotope naturally present inside the crystal lattice. Indeed, ^{113}Cd isotope has a high cross section for thermal neutron capture and the subsequent activated radionuclide relaxes through the emission of high energy γ rays among which the most probable have energies of 558 and 661 keV, thus very close to the 478 keV signal of interest in BNCT. As a consequence, the CZT detector must show extremely good performances in terms of energy resolution to be able to clearly discriminate the ^{10}B signal

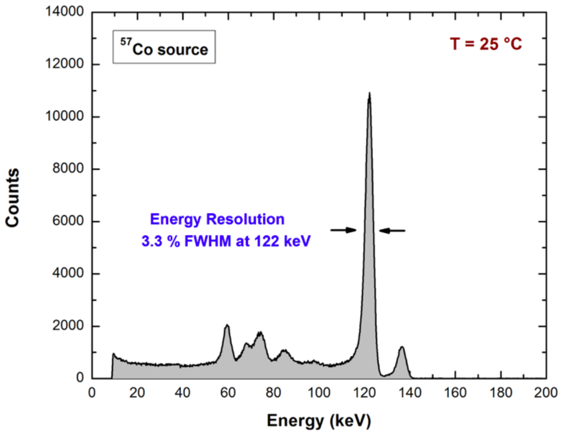

Fig. 2. The ^{57}Co energy spectrum (uncollimated source) measured with the 3D CZT detector. No corrections were performed.

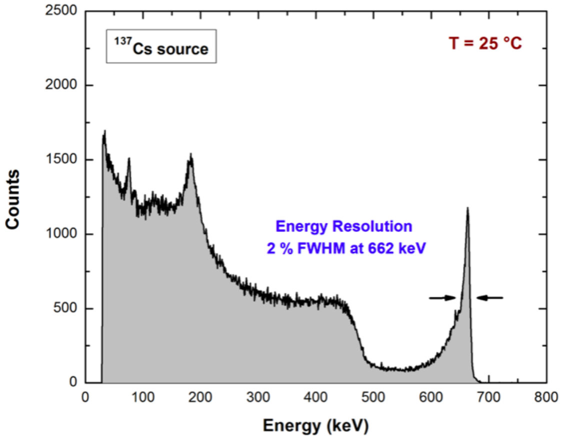

Fig. 3. The ^{137}Cs energy spectrum (uncollimated source) measured with the 3D CZT detector. No corrections were performed.

from the photons emitted by the sensor itself once employed in a BNCT-SPECT system.

IV. CONCLUSION

One of the aims of the 3CaTS project has been positively reached, i.e. the development of a 3D CZT photon detector for BNCT-SPECT. The prototype resulted to be compliant with the requirements for an effective application in BNCT, in particular in term of energy resolution considering the broad energy, mixed (n+γ) radiation field where the detector shall work. The reported energy resolutions support the expected result of less than 3% at 478 keV and confirm the suitability of the CZT technology for photon detection in BCNT.

Further studies on the 3D CZT detector are presently undergoing. In particular, the detector will be tested at the research nuclear reactor of Pavia University where a highly thermalised neutron beam has been recently implemented. This beam will be used as neutron source to generate the 478 keV photons inside ^{10}B-enriched tissue equivalent phantoms to evaluate the detection capability of the CZT sensor even when surrounded by a mixed (n+γ) radiation background resembling the one expected in a BNT clinical facility.

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