First in-beam tests on simultaneous PET and Compton imaging aimed at quasi-real-time range verification in hadron therapy

Javier Balibrea-Correa[1]*, *Jorge* Lerendegui-Marco[1], *Victor* Babiano-Suarez[1], *César* Domingo-Pardo[1], *Ion* Ladarescu[1], *Carlos* Guerrero[2,3], *Teresa* Rodríguez-González[2,3], *Maria del Carmen* Jiménez-Ramos[2,3], and *Begoña* Fernández-Martínez[2,3]

[1]Instituto de Física Corpuscular, CSIC-University of Valencia, Valencia, Spain
[2]University of Seville, Seville, 41012 Spain
[3]Centro Nacional de Aceleradores (U. Sevilla, CSIC, Junta de Andalucía), Sevilla, 41092 Spain.

Abstract. Hadron therapy with protons has advantages with respect to conventional radiotherapy because of the maximization of the dose at the Bragg peak. As a drawback, and because of different systematic uncertainty sources, a quasi-real time monitoring for the proton range verification is required to reduce safety margins. In this respect, two gamma-ray imaging techniques are pursued: prompt gamma-ray monitoring and positron-annihilation tomography (PET). The promising prompt gamma-ray monitoring requires detection systems with large detection efficiency, high time resolution, compactness, fast response, low sensitivity to neutron-induced backgrounds and powerful image reconstruction capabilities. On the other hand, in-beam PET surveys require additionally good γ-ray position reconstruction resolution. In this contribution we show that, to a large extent, both approaches can be simultaneously accomplished by using an array of Compton cameras conveniently arranged around the target volume. Here we demonstrate experimentally the suitability of such an array, named i-TED, for PG monitoring in ion-range monitoring during Hadron Therapy, in-beam PET survey and β^+ production yield measurements capability. Furthermore, with the use of GPUs, a quasi-real time PG monitoring and in-beam PET can be achieved.

1 Introduction

Over the last decades Hadron Therapy (HT) has gained popularity for treatment of certain type of cancers. This increasing trend is reflected on the more than 220000 patients treated using protons by 2019 worldwide, the 111 HT centers currently in operation and the more than 50 under construction or at planning stages [1, 2].

The benefits from HT are larger compared to the conventional radiotherapy, targeting precisely the tumor area and minimizing the damage into neighbouring tissues.

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*Corresponding author: javier.balibrea@ific.uv.es

As a consequence, these treatments decrease the probability of secondary cancers and other related issues derived from conventional radiotherapy [3]. However, as a drawback, different sources of systematic uncertainties arise in HT affecting to the treatment plans, thus increasing the safety margins and reducing the potential aforementioned benefits. The most critical uncertainties sources are anatomical changes, patient setup errors and uncertainty of proton stopping powers in different materials [4].

Ion range verification, and if possible on-line, is one of the keys to reduce those safety margins using imaging techniques and secondary particle produced in nuclear reactions during the proton irradiations. Two main imaging techniques can be used either alone or combined: Prompt Gamma-ray (PG) monitoring [5] and In-vivo PET survey [3]. PG monitoring takes advantage of the high spatial correlation from the quasi-instantaneous secondary γ-ray particles emitted just after the nuclear reactions occur during the irradiation, such as $^{16}O(p,x\gamma)^{12}C$, $^{12}C(p,p')^{12}C$, $^{16}O(p,x\gamma)^{15}N$. The monitoring is made by means of collimated γ-ray detection systems and/or Compton cameras during the patient irradiation. However, the harsh background conditions and large counting rates registered by the detection systems during the proton irradiations introduces large measurement complications. In the other hand, in-vivo PET monitoring benefits from the relative long-lived isotopes produced during the irradiation that decays by β^+ emission (^{11}C, ^{13}N, ^{15}O...). After the proton irradiations, the patients are moved to a commercial PET machine. Compared to the PG monitoring, the detection systems suffers from less counting rate and background problems. However, the biological wash-out deteriorate the accuracy of the image, and therefore the precision of the dose assessment.

While the imaging is a well known methodology, the amount of secondary particles and therefore of the dose assessment strongly rely on the quality of nuclear data, particularly on the nuclear reactions cross-section data and β^+ yields in the proton energy range of interest for HT, usually tuned with Monte Carlo simulation codes to match the experimental data [6]. Thus, this is a strong indication that new nuclear data is needed to improve the dose and ion verification accuracy.

In this work we have tested the viability of a dual Compton imager and in-beam PET detection system for PG monitoring during the proton irradiations. This study was conducted in parallel to a survey for β^+ cross-section measurements as a function of the proton energy [7].

2 Experimental setup

The experimental apparatus used for this first in-beam test was a part of the so called iTED detection system [8], an advanced array of two-planes Compton cameras specifically designed for (n,γ) cross-section measurements using the Time-Of-Flight technique. In such experiments, the γ-ray yield from the radiative capture reactions of interest is rather low, when compared to the neutron-induced background levels in the experimental area. Additionally, the γ-ray energies from those reactions covers from a few keV up to 5-6 MeV, matching well with the γ-ray lines produced during HT treatments. Each i-TED module was therefore designed aiming at largest possible detection efficiency, while minimizing its sensitivity to neutron-induced γ-ray backgrounds. With that objective in mind we implemented large LaCl$_3$(Ce) monolithic scintillation crystals optically coupled to position sensitive Silicon Photomultipliers. For further details of the i-TED modules the reader is referred to [8– 12].

Given the similarities in experimental conditions between neutron capture cross-section experiments and proton therapy treatments, it becomes of interest to investigate the suitability

of the developed i-TED array also for ion-range verification studies. Thus, a first in-beam test experiment was carried out at the Cyclotron facility of the Centro Nacional de Aceleradores situated in Seville [13]. The accelerator delivers a 18 MeV proton beam to the dedicated radiobiological experimental bunker with currents up to ~80 μA [14, 15]. The experimental setup placed in the bunker was made of two i-TED modules (i-TED.A and i-TED.B), front
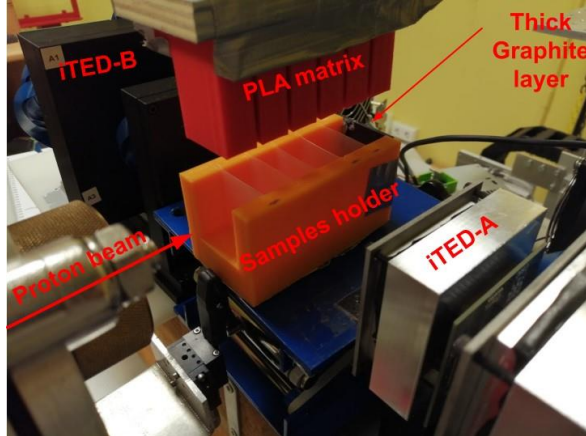
Figure. 1. Picture of the experimental setup. The different parts such as detectors, samples holder and others are labelled for a comprehensive understanding of the experimental arrangement.

to front and covering a 100×100 mm^2 PET Field of View (FoV), as it is displayed in the picture of Fig. 1. A sample holder was placed between both i-TED modules and fully aligned with entrance of the proton beam. Five thin samples or targets (41.2×41.2×0.8 mm^3) were situated in the slots of sample holder with a regular gap of 1.6 cm. At the end of the holder a thick graphite layer (2 mm thick) was placed in order to fully stop the beam and read the delivered proton current. A remotely movable PLA matrix, acting as β^+ converter, completed the experimental setup of this first test experiment. The sample holder together with the movable part and the thin samples makes a $5.2 \times 5.5 \times 10.3$ cm^3 solid piece.

Three different configurations were used during the experiment aiming to cover different material yiels and proton energies. In the first configuration the thin targets consisted of Nylon material. In the second one, in addition to the Nylon foils, a proton energy degrader was placed upstream in order to decrease the incoming proton energy. Finally, in the last configuration, the Nylon targets was replaced by PMMA material.

The experiment was carried out in two separated stages consisting of beam-on and beam-off phases. During the first stage, the β^+ converter is removed from the proton beam path, thus irradiating with protons all the thin layers under study. During the beam-off phase the PLA converter was inserted into the samples holder, thereby filling up the gap between thin layers and reducing the mean free path of the e$^+$ particles from the nuclear decays.

3 Experimental procurement and results

The individual detectors were calibrated in energy using a ^{152}Eu standard calibration source together with the γ-ray lines observed during the proton irradiation. This approach ensured a reliable calibration for the individual detectors up to at least 4.5 MeV. Details about the γ-ray

reconstruction and the implemented Machine Learning algorithms are explained in [11]. The experimental PG images were reconstructed for each i-TED Compton module individually (see Fig. 1.). To this aim an analytical inversion formula of the Compton law was used, following the prescription given in Ref. [16] and using the 4.4 MeV γ-ray line produced mainly in $^{12}C(p,p')$ reactions. For PET imaging an analytical algorithm was used, which was based on the geometrical intersection with the image plane of 511 keV γ-ray pairs emitted in
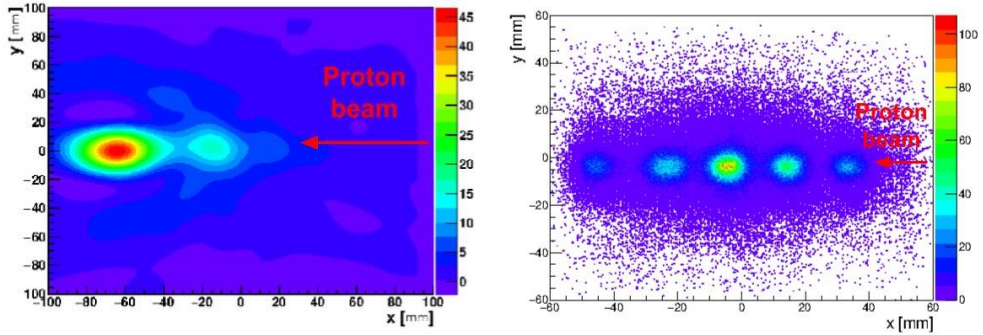
Figure. 2. Left panel: PG monitoring using Compton imaging for i-TED-B during the beam-on phase of the Nylon proton irradiation. Right Panel: PET imaging obtained during the Beam-off period of the same configuration.

back-to-back directions as reconstructed with the two i-TED modules operated face-to-face and in time-coincidence (see Fig. 1.).

It is worth mentioning that in order to accomplish a quasi-real-time monitoring, all the γ-ray position reconstruction in the individual detectors and the Compton imaging reconstruction algorithms were implemented in GPUs using CUDA [17], taking advantage of a speed-up factor of ∼300 compared to the same single-thread reconstruction code version.

Owing to space limitations, only the experimental results for the first configuration are presented here. The left panel of Fig 2. shows the PG monitoring of i-TED.B during the beam-on phase. As expected, the reconstructed Compton image is dominated by the thick graphite layer due to the large amount of Carbon material placed there. Additionally, a second peak is observed in the center of the image, where the maximum Compton detection efficiency of the setup is located, corresponding with the position of the central Nylon layer.

The right panel of Fig. 2. displays the PET reconstructed image during the beam-off phase. The five Nylon foils are reconstructed with high spatial resolution, covering almost 100% of the PET field of view in the transversal direction.

4 Summary and outlook

In this first pilot experiment we have demonstrated the suitability of two high-efficiency Compton cameras (i-TED modules) for simultaneous proton-range verification and in-beam PET imaging. The data obtained from this work will be used in another study [7] to extract valuable β^+ production cross-sections at low proton energies. The use of algorithms implemented in GPUs guarantee an almost quasi-real-time monitoring thanks to the ∼300 speed-up factor. An article is in preparation [18], which describes in detail the experimental setup, methodology, data reduction and results for all the different configurations.

Future experiments using a similar experimental setup are planned at the Heidelberg Ion Beam Therapy Center (HIT) for covering the proton energy of interest in HT with protons.

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