HEXITEC Detector Response to Complex Radiation Fields Applied to Proton Beam Therapy

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***Abstract*—The purpose of this study is to analyse the response of a single HEXITEC detector system when it is exposed to complex radiation fields such as proton beam therapy and evaluate its feasibility to tackle the uncertainty in the proton range via secondary particle detection. For the present research, experimental data is taken in a clinical proton beam therapy room at different nominal proton energies, where a water phantom is irradiated and a HEXITEC detector is placed on one side. The results of the detector output are compared with simulations performed on Geant4, which include additional information about the particles entering the detector such as particle type, kinetic energy and parent ID. The resulting comparison shows that the computational model can simulate the experimental data with a high level of accuracy. In terms of particle flux, there is a consistent agreement between simulation and experimental data. In addition, a relationship between experimental and modelled acquisition frames is achieved. Particle discrimination can be done by performing a cluster size analysis for each particle type.**

I. Introduction

IONISING adiation semiconductor detectors are currently considered in the X-ray imaging world, due to their ability to convert the energy of incoming photons directly into electric pulses that can, in some detectors, lead to spectroscopic information. The HEXITEC (High-Energy X-ray Imaging Technology) detector provides this last feature, and has the potential to perform high-Energy X-ray spectroscopic images [1]. Although the detector was originally developed for material science and X-ray imaging, its sensitivity to detect other particles give HEXITEC the potential to be used in other scenarios with more complex fields like nuclear security or proton beam therapy, provided that an adequate method is used to extract the useful information from the raw output data. In practice, the aim in these cases is to be able to detect the secondary particles that are produced inside a sample and retrace their production origin. In nuclear security, prompt gammas and neutrons are the particles of interest as they are common decay products.

The HEXITEC detector has already been tested for neutron detection and source localisation from radioactive sources inside a water phantom [2]. However, for proton beam therapy applications, this is the first HEXITEC response study, since the availability of clinical proton beams tends to be limited. The importance of this particular study lies in the fact that although a growing number of cancer patients are treated with proton therapy rather than conventional radiotherapy, there is a concern about the uncertainty in the proton range inside the body, which may limit the ability of proton therapy to spare organs at risk to their maximum potential. Opportunely, the nuclear interactions between the protons and the target produce particles such as prompt gammas and neutrons. As there is a clear relationship between the secondary particle creation origin and the proton Bragg peak, the secondary particle information can lead to in vivo proton range verification [3], [4]. Thus, the present study aims to analyse the response of a single HEXITEC detector system when it is exposed to a proton beam therapy secondary field and evaluate how feasible it is to tackle uncertainty in proton beam therapy.

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II. Methods

This study is subdivided in two experiments which are then compared. The first one is an experimental set up in the University College London Hospital (UCLH) Proton Beam Centre, where a proton beam is incident on a 50x50x50 cm^3 water phantom at different energies. At 90 cm from the phantom and at 90 degrees from the beam axis, a 2 mm thick, 80x80, 250μm pitch, Cadmium Zinc Telluride (CZT) HEXITEC detector is placed. A more detailed depiction of the set up is shown in Fig. 1. For the measurements, a frame rate of 1.6 kHz was used, and the detector was set to low gain in order to record energies up to 700 keV without data overflow.

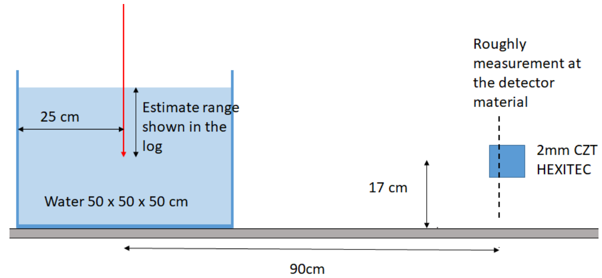

Fig. 1. Diagram with the experimental set up in the Proton Beam Centre. The Geant4 model was designed based on this geometry. The red arrow indicates proton beam axis and direction.

The second experiment was performed to fully understand the physical processes behind the HEXITEC data, and it consists of a Geant4 [5] model that accurately resembles the experimental set up. The added value of using G4 includes a more detailed information on the particles that enter the detector, namely, its kinetic energy just before crossing the detector boundary, its type, its parent ID and the primary proton number, also known as event ID. In addition, a pencil beam proton source (with 10^9 primary protons) of various nominal beam energies is included in the model, and the physics list used is the QGSP_BIC_HP_EMZ for maximum physical accuracy. The relationship between the number of primary protons and the equivalent number of frames can be obtained by using the detector frame rate and the cyclotron currents for each proton energy. Let q_p the proton charge, I the cyclotron current and α a correction factor that accounts for the actual particle flux that comes out of the beam nozzle. The time to produce a single proton is given by $q_p/\alpha I$. Hence, the number of protons produced during a single detector frame (ppf) can be given by

$$ppf = \frac{q_p}{(\alpha I)t_p}. \tag{1}$$

The final outcome is a much more complete understanding at what to expect from the detector and, in the future, optimise the system to retrace the origin position, ideally with a Compton camera based on HEXITEC detectors.

III. Results and Discussion

To perform a comparison between Geant4 and the experimental data, 6 different proton energies within the clinical range are used, and the main parameter to compare is the mean number of clusters (groups of adjacent pixels being lit up) in each acquisition frame. From Figure 2, it can be evidenced that the model behaves like the experiment in terms of particle flux, whereas Figures 3 (G4 simulation) and 4 (UCLH Proton Centre data), which are images of a single frame for a 160 MeV proton beam, show similar behaviour, where particle hits can be seen with more than one pixel being lit up, generating clusters that represent the passage of a particle.

Both single-frame images show, with high resemblance and a similar scale in energy deposition, that the HEXITEC detector is able to detect particles with a different energy deposition behaviour, where clusters can be: 1) composed of single pixels, 2) composed of a few pixels concentrated in a small area, or 3) in a track-like arrangement. By looking at the cluster size distribution along all frames in both experiments, it was found that the majority of clusters have a size of 1 pixel. Since there is no information on the particle type for the UCLH experiment, a solution was to look at the cluster size distribution per particle type for the Geant4 data, and with this information, start to discriminate the incoming particles depending on their cluster sizes and shapes. The results are shown in Figure 5, which shows that prompt gammas are the most common particles reaching the detector and interacting with it, producing mainly one-pixel clusters, whereas electrons and positrons tend to produce track-like clusters that light up more pixels, meaning that a potential discrimination could be done with the entries based on the cluster size. As in the future there will be a need to explore the exclusive detection

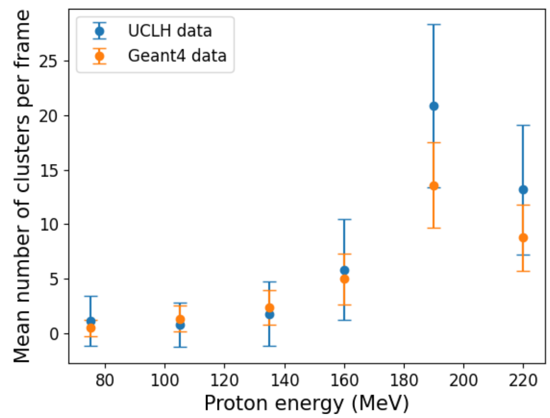

Fig. 2. Comparison plot showing the mean number of clusters found in each frame for both scenarios.

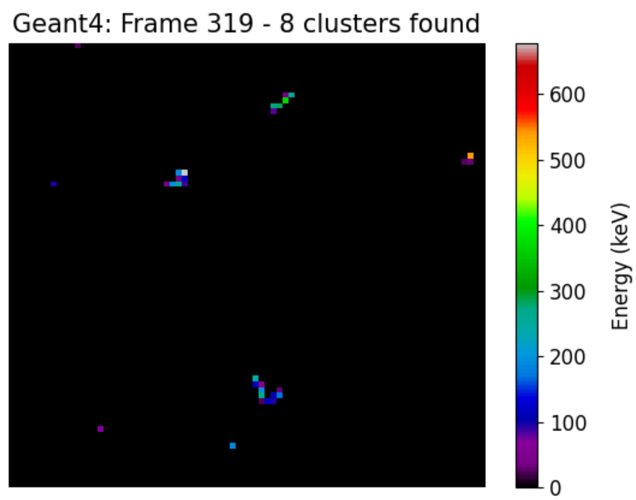

Fig. 3. Example of single frame output in G4.

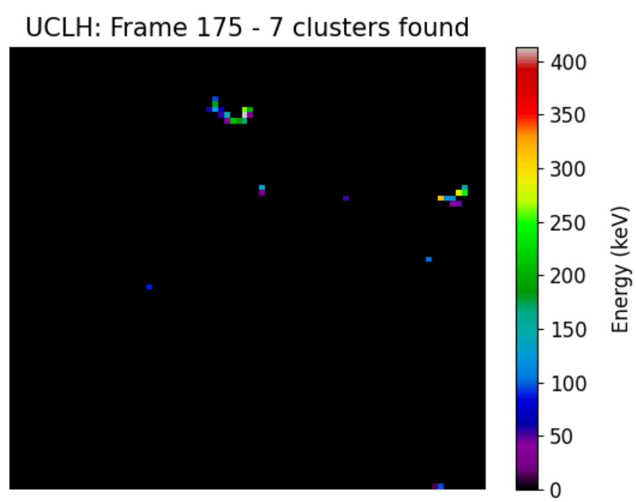

Fig. 4. Example of single frame experimental output.

of prompt gammas, further filtering must be done for neutrons and scattered protons.

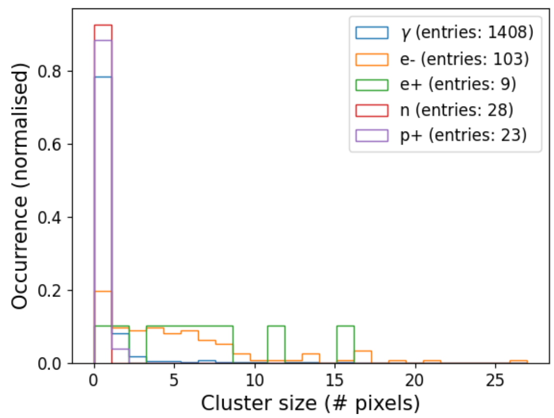

Fig. 5. Cluster size distribution classified by particle type.

To evaluate the efficiency of the detection system under study, Figure 6 shows the energy spectrum for particles that go through the detector compared with the ones that not only go through it but also interact with it and end up depositing energy. As prompt gammas have discrete peak energies due to nuclear interactions with the atoms of the water target, it is expected that we see discrete Oxygen peaks. It is shown that physical processes are well considered, as those peaks are evidenced for incoming particles. However, the present system shows not to be optimised for the detection of these characteristic gammas, as those peaks fade away for the interacting particle energy spectrum. This leads us to think that the detector system should involve a higher thickness to increase its efficiency, but already shows potential and a solid ground to work on.

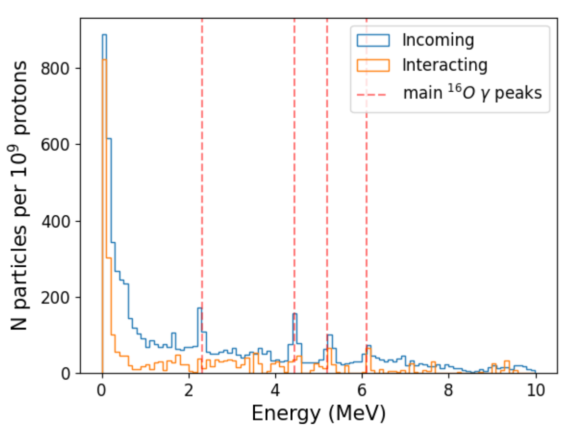

Fig. 6. Kinetic energy spectrum (zoomed in for energies below 10 MeV) for particles that go through the detector (labelled as incoming) and deposit energy (labelled as interacting). Prompt gamma peaks for O_2 are shown for reference. Results from a 160 MeV proton beam simulation.

IV. Conclusions

This study successfully shows the first results obtained by a HEXITEC detector immersed into a complex radiation field created by a proton beam therapy scenario. By comparing the experimental output with the Geant4 model output, it can be concluded that the latter has the potential to accurately simulate the outcome of an experimental set up in a proton beam therapy environment, which is promising in the sense that future set ups can be tested and optimised without depending on the limited availability of the proton source and the limitations on the geometry of existing HEXITEC detectors. New challenges arise from this first study, including more complex filtering to obtain prompt gamma information exclusively for a Compton camera detection system, with an enhanced setup for this purpose.

References

[1] M.C. Veale, P. Seller, M. Wilson, and E. Liotti. "HEXITEC: A high-energy X-ray spectroscopic imaging detector for synchrotron applications". Synchrotron Radiation News, vol. 31, no. 6, pp. 28-32. 2018.

[2] J.C. Khong. "Nuclear Security Workshop: Neutron sensitivity of HEXITEC and capability in localisation of neutron radiation source". 2019. Retrieved from URL https://indico.cern.ch/event/731980/contributions/3313735/attachments/1829498/2995909/NuSec_JC.pdf.

[3] K. Parodi and J.C. Polf. "In vivo range verification in particle therapy". Medical physics, vol. 45, no. 11, p. e1036-e1050, 2018.

[4] R. Panthi, P. Maggi, S. Peterson, D. Mackin, J. Polf and S. Beddar. "Secondary particle interactions in a Compton camera designed for in vivo range verification of proton therapy". IEEE Transactions on Radiation and Plasma Medical Sciences, vol. 5, no. 3, pp. 383-391, 2020.

[5] S. Agostinelli et al. "GEANT4—a simulation toolkit". Nuclear instruments and methods in physics research section A, vol. 506, no. 3, pp. 250-303. 2003.