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► **To cite this version:**

J. Livingstone, A. Etxebeste, S. Curtoni, D. Dauvergne, M. Fontana, et al.. Ultra fast prompt-gamma imaging for the online monitoring of the ion range in hadron therapy. IEEE MIC 2019, Oct 2019, Manchester, United Kingdom. hal-02309773

HAL Id: hal-02309773

<https://hal.science/hal-02309773v1>

Submitted on 20 Mar 2020

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Ultra fast prompt-gamma imaging for the online monitoring of the ion range in hadron therapy

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Abstract—Uncertainties in the ion range mean that the ideal ballistic properties of ions are not fully exploited in hadron therapy. Prompt γ imaging using a Compton camera has been proposed as a method of online monitoring and range verification for proton therapy. Monte Carlo studies of the CLaRyS Compton camera prototype demonstrated a 2 mm precision in the measured proton range for 10^8 particle histories using an iterative method, whilst the line cone reconstruction method was faster but yielded a precision ~ 3 times worse. The effect of temporal resolution on the precision on the line cone reconstruction was investigated and a method to improve its precision based on time of flight has been proposed.

Index Terms—Compton camera, Monte Carlo simulation, GATE, Prompt gamma, Hadron therapy

I. INTRODUCTION

UNCERTAINTIES in the ion range in a patient undergoing hadrontherapy, which may result from patient mispositioning or changes in tumour morphology or patient anatomy [1], [2], often result in conservative dose prescription and treatment planning. A better knowledge of the ion range *in vivo* via online monitoring will lead to improved dose conformation. As the ion beam is stopped inside the patient, many of the proposed online monitoring techniques are based on the detection of secondary particles, such as prompt γ rays, emitted as a result of nuclear reactions in the patient. The spatial distribution of prompt γ is highly correlated with the proton range [1] and their fast emission allows discrimination from other, slower secondary particles such as neutrons.

A Compton camera uses Compton kinematics to construct conical surfaces on which prompt γ emission vertices lie and the spatial distribution of prompt γ -rays is reconstructed via an iterative algorithm. The use of a beam tagging hodoscope speeds up the reconstruction by reducing the possible solutions to the two solutions given by the intersection of a line (proton beam trajectory) and the Compton cone, in addition to providing a time reference for measuring the time of flight (TOF). The French CLaRyS collaboration (LPSC, IPNL, CPPM, CREATIS) has constructed a Compton camera prototype consisting of semiconductor and scintillating detectors as described by Krimmer *et al.* 2015 [3]. In a Monte Carlo study of this camera, Fontana *et al.* 2019 [4] reported a precision of

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2 mm in the identification of the proton range via an iterative reconstruction, based on 10^8 primary particle histories. The precision of the line cone reconstruction reported in the same study is ~ 3 times worse than that of the iterative method, due to the inability to discriminate between the two solutions of the intersection. The precision may be improved by using the TOF to distinguish between the two solutions, but a temporal resolution of the order of several hundreds of ps or better is required.

The aim of this study is to investigate the effect of the temporal resolution on the precision of the ion range identification based on the line cone reconstruction method using Monte Carlo simulations and thus to propose a method of solution discrimination based on the TOF.

II. MATERIALS AND METHODS

All simulations were performed using GATE version 7 which had been compiled with Geant4 version 10.03.p03. Simulations were performed in two steps. In the first step, a 5 mm diameter proton beam (10^9 particles) of 160 MeV was generated towards a cylindrical polymethyl methacrylate (PMMA) phantom of 75 mm radius and 200 mm height as illustrated in Figure 1.

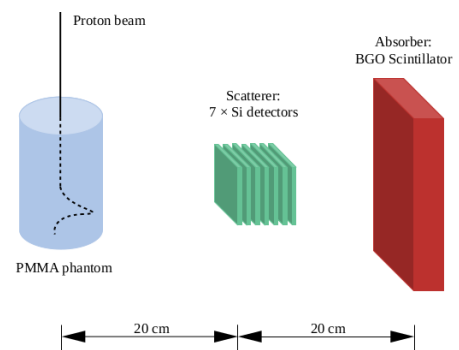


Fig. 1. Illustration of the detector and phantom geometry used in the GATE simulations.

A phase space plane, PSF_{hodo} , positioned 5 mm above the phantom stored the phase space information (momentum, position, time) of the proton beam just before entering the phantom. A second phase space plane, PSF_{source} was positioned next to the phantom, in the plane perpendicular to the first, to score the particles exiting the phantom and travelling towards the Compton camera. The hadronic physics list QGSP_BIC_HP with the Livermore electromagnetic physics option was used. In the second step of the simulation, the PSF_{source} was used to generate particles towards the Compton camera, which was placed at a distance of 20 cm from the

phantom. The Compton camera consists of a semiconductor based scatterer and a scintillating absorber. The scatterer is comprised of 7 plane silicon detectors with dimensions of $9 \times 9 \times 0.2 \text{ cm}^3$ spaced 1 cm apart and the absorber is comprised of a $35 \times 35 \times 3 \text{ cm}^3$ block of BGO scintillator. Coincidences within a window of 40 ns were recorded using the GatePulseAdder. For each event in a coincidence, the time, energy deposition and 3D position of the interaction were also recorded. Coincidences containing events in multiple scatterer detectors were not considered in the analysis.

For each coincidence a line cone reconstruction was performed using the method described by Richard 2012 [5]. For both of the solutions given by the line cone reconstruction a time of flight, TOF_{est} , was estimated for the corresponding track (proton + γ) based on the distribution of time of creation of γ rays stored in the PSF_{source} . The TOF_{CC} (time of interaction in absorber - time of corresponding proton in PSF_{hodo}) for each reconstruction was then compared to TOF_{est} for the track corresponding to each solution. It is possible to select the solution with the smallest ΔTOF ($\text{TOF}_{CC} - \text{TOF}_{est}$), however this is not sufficient as there are cases where neither of the solutions are accurate, for example, partial energy deposition events in the absorber or photon scattering in the phantom. The magnitude of the ΔTOF can give an indication of where this occurs. Upper thresholds of 100 and 200 ps on the ΔTOF were applied to the reconstruction. All solutions not meeting this criteria were rejected, and in the case where both solutions met the criteria, the one with the smallest ΔTOF was accepted.

III. RESULTS AND DISCUSSION

The distribution of the time of emission of γ rays by proton interactions in the PMMA phantom as a function of the distance of the interaction from the position of the proton recorded in PSF_{hodo} is shown in Figure 2. The time is relative to the time of the proton in PSF_{hodo} . Only photons with an energy greater than 1 MeV and which have not interacted in the phantom are considered. A polynomial fit to the distribution was used to calculate the TOF_{est} for each set of line cone intersection solutions.

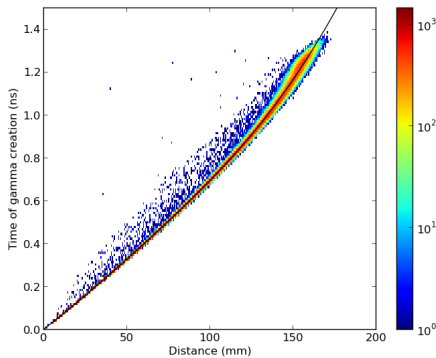


Fig. 2. Time of gamma creation (relative to time of proton in PSF_{hodo}) in phantom as a function of distance of emission vertex from the PSF_{hodo} . A sixth order polynomial has been fitted to the distribution.

Solution discrimination based on the ΔTOF as described in Section II was applied to the line cone reconstruction

and resulting γ emission vertex distributions are shown in Figure 3. Reconstructed emission profiles using the smallest ΔTOF , $\Delta\text{TOF} \leq 200 \text{ ps}$ and $\Delta\text{TOF} \leq 100 \text{ ps}$ are compared to the profile without solution discrimination and the real γ emission vertex distribution. The method is efficient at rejecting solutions beyond the distal fall-off of the real emission vertex peak, but at the expense of a reduction in statistics (~ 2 for $\Delta\text{TOF} \leq 100 \text{ ps}$ compared to the smallest ΔTOF). Reconstructed events upstream of the phantom entrance are partly due to the fact that the reconstruction algorithm does not take into account partial energy absorption in the detector system or photon scattering in the phantom.

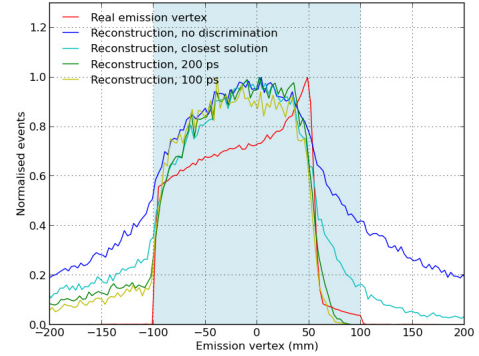


Fig. 3. The real γ emission vertex along the proton beam axis compared to reconstructions using various methods of solution discrimination: no solution discrimination, smallest ΔTOF , $\Delta\text{TOF} \leq 200 \text{ ps}$ and $\Delta\text{TOF} \leq 100 \text{ ps}$. The shaded area represents the phantom.

In practice, ultra-fast timing with a Compton camera may be envisaged with an upgrade to the CLaRyS prototype, using a very fast scintillator such as CeBr_3 coupled with SiPM matrices with 3D localisation capability.

IV. CONCLUSION

The effect of temporal resolution on ion range measurement based on the line cone reconstruction method was investigated via Monte Carlo simulation and a method to increase its precision via solution discrimination based on time of flight has been proposed. An ultra-fast temporal resolution is required and an upgrade to the CLaRyS Compton camera prototype using fast scintillators is envisaged.

ACKNOWLEDGMENT

The authors would like to thank ITMO-Cancer (CLaRyS-UFT project). This work is performed in the frame of Labex PRIMES (ANR-11-LABX-0063).

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