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Monte Carlo characterisation of the Dose Magnifying Glass for proton therapy quality assurance

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Monte Carlo characterisation of the Dose Magnifying Glass for proton therapy quality assurance

Abstract

A Geant4 Monte Carlo simulation study was carried out to characterise a novel silicon strip detector, the Dose Magnifying Glass (DMG), for use in proton therapy Quality Assurance. We investigated the possibility to use DMG to determine the energy of the incident proton beam. The advantages of DMG are quick response, easy operation and high spatial resolution. In this work we theoretically proved that DMG can be used for QA in the determination of the energy of the incident proton beam, for ocular and prostate cancer therapy. The study was performed by means of Monte Carlo simulations Experimental measurements are currently on their way to confirm the results of this simulation study.

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Monte Carlo characterisation of the Dose Magnifying Glass for proton therapy quality assurance

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Abstract. A Geant4 Monte Carlo simulation study was carried out to characterise a novel silicon strip detector, the Dose Magnifying Glass (DMG), for use in proton therapy Quality Assurance. We investigated the possibility to use DMG to determine the energy of the incident proton beam. The advantages of DMG are quick response, easy operation and high spatial resolution. In this work we theoretically proved that DMG can be used for QA in the determination of the energy of the incident proton beam, for ocular and prostate cancer therapy. The study was performed by means of Monte Carlo simulations Experimental measurements are currently on their way to confirm the results of this simulation study.

1. Introduction

While proton radiotherapy has experienced a growth in the number of operational facilities and an increase in capabilities of beam delivery technology, there has been a substantial lack of development in commercial detectors for related Quality Assurance (QA). In particular, fast verification of the beam energy, range in water and position of the characteristic pristine or spread out Bragg Peak in both a pre-treatment and real time setting is necessary to prevent radiation accidents and deliver treatment to the patient safely, minimising the damage to healthy tissues and critical structures. Ideally detectors used in proton therapy QA should provide sub-millimetre spatial resolution determination of proton range over a wide energy range to resolve the steep energy gradient of the Bragg Peak and be able to provide this information at a sub-second temporal resolution.

Currently, the generation of available detectors implemented for proton therapy QA include ionization chambers, as recommended by the ICRU Report 78 and IAEA TRS-398 [1, 2], single diodes and films to derive the Bragg Peak position in water phantoms [3].

The Dose Magnifying Glass (DMG) is a silicon strip detector developed by the Centre of Medical Radiation Physics (CMRP) at the University of Wollongong. It is a miniature detector for use in proton therapy QA, with applications into X-ray stereotactic radiosurgery (SRT) and intensity modulated radiotherapy (IMRT) investigated previously demonstrating the DMG capability to provide sub-millimetre spatial resolution at a sub-second temporal resolution over a large (10^3) dynamic range [4]. Its advantages over existing commercial QA detectors include the simple device operation and high spatial resolution over a wide dynamic energy range, required to resolve the Bragg Peak accurately.

This paper presents the Monte Carlo characterisation of the DMG as device to determine the energy of the incident proton beam for ocular and prostate cancer proton therapy treatment. At this stage, the principle of operation is proved for mono-energetic proton beams only.



2. Dose Magnifying Glass

The DMG is a 128 channel p-silicon strip detector, with each strip consisting of a sensitive implanted n+ area of 20x2000 μm , separated by a pitch of 200 μm . This detector, in singular configuration, is mounted upon a thin Kapton carrier, as presented in figure 1, which provides a convenient connection of the 128 channels to a FPGA based multichannel electrometer, resulting in a total size of 4x28x0.25 mm. In serial configuration an additional detector, providing a further 128 channels, is positioned 4 mm behind the first, rotated 180° and translated such that the sensitive volumes remain aligned in both detectors. In this configuration the detectors are mounted upon a PCB board with the entire ensemble placed in a housing consisting of a 75x95x5 mm PMMA lower half and a RMI457 Solid Water top half with a wax recess for the detectors.

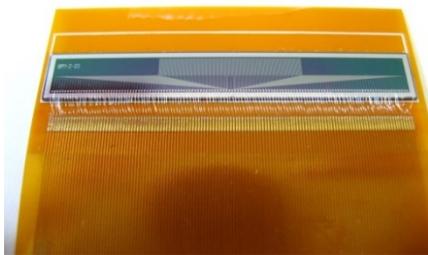


Figure 1. Singular configuration of the DMG mounted on a Kapton Carrier.

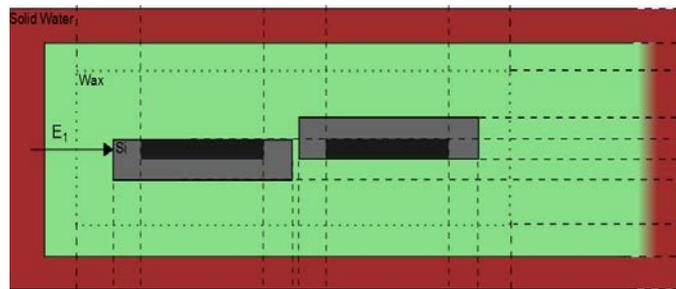


Figure 2. Serial configuration of the DMG mounted on a PCB board with wax recess and solid water housing shown.

3. DMG Principle of operation in pre-treatment QA to determine incident proton beam energy

When the device is positioned appropriately in the treatment target region in a water phantom, protons directly incident on the DMG produce a first Bragg Peak in the device. Other protons, instead, scatter in the phantom and in the detector packaging before entering in the DMG, producing a second Bragg Peak at a further depth. The distance between the two Bragg Peaks can be measured and uniquely related to the kinetic energy of the proton beam when incident on the device, using the CSDA range difference, shown in figure 3.

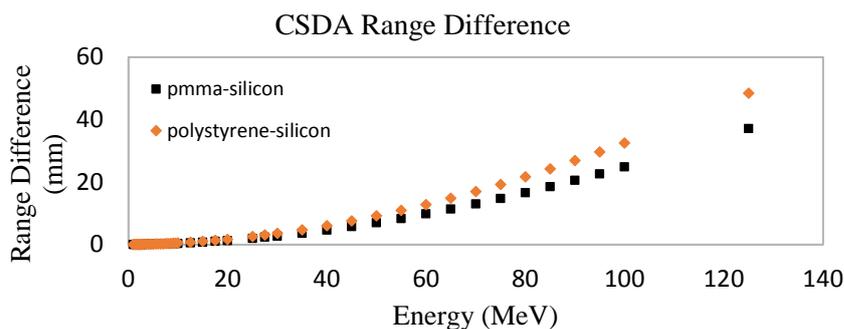


Figure 3. CSDA range difference of protons traversing silicon and PMMA/Polystyrene.

Once the energy E_{DMG} of the proton beam at the entrance of DMG is determined, the energy of the incident beam, $E_{incident}$ at the entrance of the phantom can be calculated by considering the associated CSDA range of protons, R_{CSDA} . By applying formula 1, $E_{incident}$ can be derived:

$$R_{CSDA}(E_{incident}) = R_{CSDA}(E_{DMG}) + x\rho, \quad (1)$$

where x is the path length and ρ the density of the phantom, traversed by the incident proton beam before entering the DMG. If different materials are traversed before entering in DMG, formula 1 has to be applied to obtain the energy of the proton beam $E_{incident}$ at the entrance of each specific material.

4. Methodology

Geant4 based simulations [5] were developed to prove the principle of operation of DMG for QA in ocular and prostate proton therapy. The DMG was modelled accurately in terms of geometry and materials. A proton beam of 62 MeV and 129.46 MeV was adopted for ocular and prostate cancer treatment, respectively. In both cases the proton beam is incident along the major axis of the DMG. To describe particle interactions in the simulation toolkit, the Livermore Data Libraries were adopted to model the electromagnetic interactions, while the QGSP_BIC_HP Physics list was adopted to describe hadronic interactions. The threshold of production of secondary particles was fixed to 0.01 mm. The energy deposition produced by the incident proton beam and its secondary particles was recorded in the silicon strip detectors.

4.1. Simulation application for Ocular Cancer Therapy QA

In the case of pre-treatment QA in proton therapy for ocular melanoma, a 62 MeV proton beam was simulated with particles generated at -20 mm in air. A beam radius varying between 1 and 15 mm was adopted to study its effect on the response of the detector. The detector was positioned within a PMMA spherical phantom with radius equal to 18 mm, modelling a simplified anatomy of the eye while remaining large enough to house the detector as shown in figure 4.

4.2. Simulation Application for Prostate Cancer Therapy QA

A 129.46 MeV proton beam was selected to model the beam energy of the first experimental measurements with DMG, performed by the CMRP and collaborators at the Massachusetts General Hospital, Boston. In this simulation, a polystyrene target of varying thickness (70.9 mm, 81.1 mm and 91.3 mm) was positioned in front of the DMG with polystyrene scattering blocks placed above and below the DMG, as shown in figure 5.

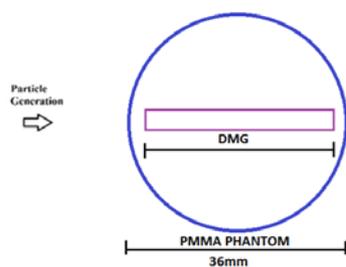


Figure 4. Simplified schematic of the simulation application setup for ocular cancer therapy QA.

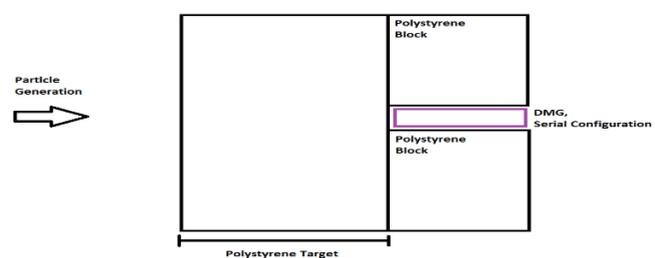


Figure 5. Simplified schematic of the simulation application setup for prostate cancer therapy QA.

5. Results

5.1. DMG for Ocular Cancer Therapy QA

Figure 6 shows the DMG response with an incident beam of 62 MeV protons, with different beam radius. The energy deposition is calculated in the silicon strip detectors and then converted to depth in the DMG.

Two distinct Bragg Peaks are observed in the detector response. As the beam radius increases, a greater number of protons scatter into the silicon sensitive strips, following the interactions in the surrounding PMMA phantom. This translates in a higher second Bragg Peak in DMG.

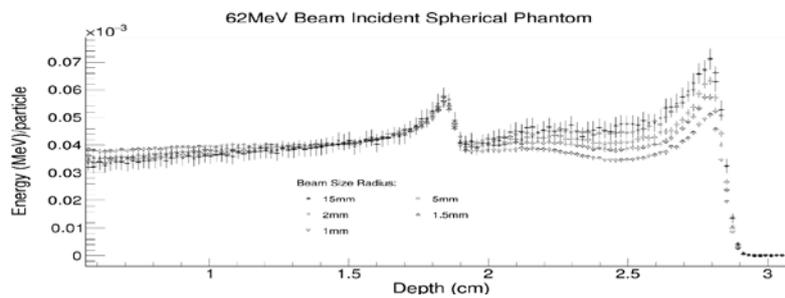


Figure 6. Response of the DMG to a mono-energetic 62MeV proton beam.

From the detector response, the distance between the two Bragg Peaks is determined to be 9.7 mm, corresponding to an energy of 60 MeV at the DMG entrance. Using the methodology outlined in section 3 the initial energy of the beam is determined to be approximately 62 MeV when entering in the phantom. This value agrees with the energy of the proton beam input to the simulation.

5.2. Application for Prostate Cancer Therapy QA

Response of the DMG in serial configuration to mono-energetic 129.46 MeV protons incident along the major axis of the detector is presented in figure 7 for the polystyrene thicknesses investigated. The range difference of Bragg Peaks is presented in Table 1 alongside with the calculated proton incident energy at the DMG entrance and the phantom entrance, derived using the method described in section 3. For polystyrene thickness of 70.9 mm, as the second peak occurs in the detector region of no response, analysis is unviable.

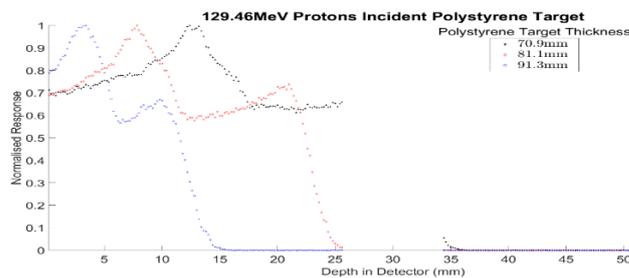


Figure 7. Response of the DMG in serial configuration to mono-energetic 129.46 MeV protons. In serial configuration a physical gap causes a region of no energy detection.

Table 1. Application for Prostate Cancer Therapy Results. E_{DMG} is the energy of the proton beam at the entrance of DMG. $E_{incident}$ is the energy of the proton beam at the entrance of the phantom.

Polystyrene Target Thickness (mm)	Peak Range Difference (mm)	E_{DMG} (MeV)	$E_{incident}$ (MeV)
81.1	13.2	61.25	131.6
91.3	6.4	41.25	128.9

6. Discussion and conclusions

The results of this work demonstrate the applicability of the DMG in pre-treatment QA to determine the energy of the incident proton beam.

The proof of principle has been demonstrated for ocular cancer therapy QA, with sharp, easily identifiable pristine Bragg Peaks observed in the detector response. This means that DMG in principle may be used to accurately resolve the initial beam energy, as demonstrated by the agreement in determined initial beam energy and injected particle energy.

When comparing the case of prostate cancer proton therapy against the treatment of ocular cancer, with a higher proton energy the position of the Bragg Peaks results to be less resolved as protons traverse a larger number of different materials surrounding the detector. This leads to a larger error in determining

the distance between the Bragg Peaks measured by the DMG. Despite these effects, our study shows that the energy of the incident beam can be resolved in principle with an error of ~ 1 MeV for a mono-energetic proton beam.

In conclusion this work proved the principle of operation of DMG for pre-treatment QA in proton therapy for the determination of the proton beam energy. CMRP is currently undertaking experimental measurements with collaborators at the Massachusetts General Hospital to prove this principle of operation.

In the near future, the simulation results shown in this paper will be compared to the experimental measurements. The simulations will be repeated with a Spread Out Bragg Peak to verify the principle of operation in this case as well.

7. Acknowledgments

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8. References

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