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IONIZATION PROFILE MONITOR FOR IN-VIVO DOSIMETRY IN MEDICAL ACCELERATORS

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Abstract

In-vivo dosimetry is essential to deliver a precise dose to patients in ion beam therapy. Real-time dose monitoring without disturbing the beam improves patient safety and treatment efficiency by increasing the precision of the dose delivery. It is especially critical for emerging treatment modalities like FLASH therapy due to narrow dose tolerance. Existing real-time dosimetry devices are invasive to the beam, necessitating the development of a non-invasive dosimetry solution. The gas-jet based beam profile monitor developed at the Cockcroft Institute (CI), is being studied for application in medical accelerator facilities. Recent measurements at the Dalton Cumbrian Facility, UK yielded promising results for beam monitoring at energies equivalent to that of medical beams. These studies have indicated the need to improve the gas-jet based Ionization Profile Monitor (IPM) to monitor dose in real time. A new IPM detector system is under development at CI to reduce the monitor size and complexity, and increase its sensitivity, resulting in fast acquisition, paving the way for real-time in-vivo dose monitoring. This contribution presents the design of the optimized IPM detector, and its working principle based on electrostatic field and particle trajectory simulations.

INTRODUCTION

The use of a neutral gas beam, shaped into a sheet/curtain offers a non-invasive method to profile charged particle beams. In this, the gas is injected perpendicular to the beam forming a curtain with plane inclined at an angle of 45-degree to the beam's cross-section. The interaction between them leads to the ionization and/or excitation of the gas atoms. In one approach, the radiative de-excitation within the interaction region is imaged with an intensified camera looking perpendicular to both beam and curtain axes [1]. In this, the projection of the interaction region forms the image of the beam profile. Alternatively, ionized gas atoms can be extracted using an electric field and deflected onto a spatially resolved detector, such as a microchannel plate (MPC). This enables beam-profile reconstruction [2]. While the former is simpler, the latter yields a stronger signal due to the higher ionization cross-section and full solid angle collection. The reconstruction requires maintaining the relative spatial positions of the ions constant as they are extracted on to the MCP. This requires a uniform electric field distribution along the extraction path necessitating a careful design of the extraction system. This paper discusses the design of such a system here termed as an the Ionization Profile Monitor (IPM detector).

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DESIGN CONSIDERATION

The present study builds upon the existing detector [3], shown in Fig. 1. It uses a series of metal plates biased extending from the interaction region towards the MCP detector. Plates are negatively biased progressively, to generate a uniform electric field for ion extraction. At a typical gas density of 10^{16} m^{-3} for a nA beam current, the ionization per second is of the order 1000 [4]. Hence, capturing all the ions is necessary to maximize the signal.

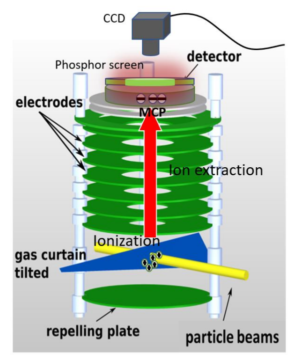

Figure 1: Operational schematics of the ionization profile monitor.

Recent experiments at DCF [5] for 4-24 MeV Proton and Carbon beams highlight the need to increase sensitivity and decrease detection time below the current threshold of a few seconds to achieve real-time monitoring. This requires to increasing the detector gain substantially. Naturally, this amplifies undesired signals from stray charges generated by ion-detector collisions, potentially degrading the signal-to-noise ratio. Additionally, ions acquire random recoil energy upon interaction, along with their inherent free-stream velocity, leading to an initial energy spread and inducing drift during extraction. This distorts the reconstructed profile and increases the probability of collision with plates, generating more stray ions and contributing to noise. The current IPM detector is originally conceived for research accelerators and needs refinement to suit smaller medical accelerators, requiring compactness without sacrificing functionality. Achieving this poses additional challenges such as ensuring tight tolerances for ion trajectory separation relative to the extractor plates, maintaining uniform field distribution while avoiding local concentration due to vessel walls, and preventing strong fields that could disrupt particle beam trajectories.

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Given these, an iterative design approach coupled with the field distribution and particle trajectory simulation using commercial tool CST studio is considered. The simulated field distribution and beam profile is benchmarked against the earlier simulations [4] and also the experimental data [5], followed by optimization of detector size while ensuring field uniformity and validating through particle trajectory analysis. The IPM detector is planned accommodate a beam of 3 cm in diameter or an equivalent scanning region for pencil beam. This aligns with the requirements of the LhARA collaboration [6], where it is envisioned as a potential beam monitoring device while also covering typical beam sizes of medical accelerator. The design is conceived for proton beam therapy machines, as their relatively large size makes it more practical and also because hadron beam therapy holds promise for future radiotherapy applications. In the treatment modalities like FLASH proton beam therapy, online non-invasive monitoring becomes crucial, especially where detectors like ionization chambers fail to provide accurate results. Hence, the use of IPM detector, which in principal is suited for intense beams can be justified.

BENCHMARK STUDIES

Simplified model extracted from the design files of the existing IPM detector is simulated using the AC/DC module of COMSOL and also CST. The plates are modeled perfect electric conductors (PEC) and surrounding area as a perfect vacuum. Electric potentials are applied to individual plates and the resulting field is compared to Opera simulations form an earlier work [4] which reveals a similar trend, as shown in Figure 2.

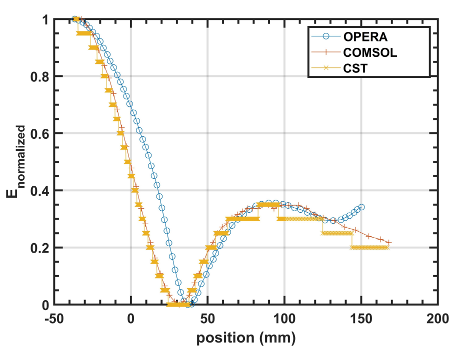

Figure 2: Comparison of the E-field distribution on the IPM detector axis as simulated by COMSOL, CST with historical data of Opera simulation.

The interaction region is modeled as an ion source, an elliptical surface formed by projecting a 3 cm beam onto the gas curtain plane. Taking the curtain to be of Argon, simulated trajectories of argon ions yield realistic results without considering individual ion effects on the field. The resulting distribution of the ions on the detector plane is shown in Fig. 3. Note that color bar is scaled to the absolute coordinate position and represents the offset of beam from the center position. The center position of the simulated beam (panel B) closely matches with the historical (panel A) and experimental (panel C) data. Offset of the beam center along the x-axis is due to the jet velocity, while the offset in y-axis offset is due to recoil velocity. Distinguishing recoil velocity in experiments is not possible, hence the corresponding offset is zero.

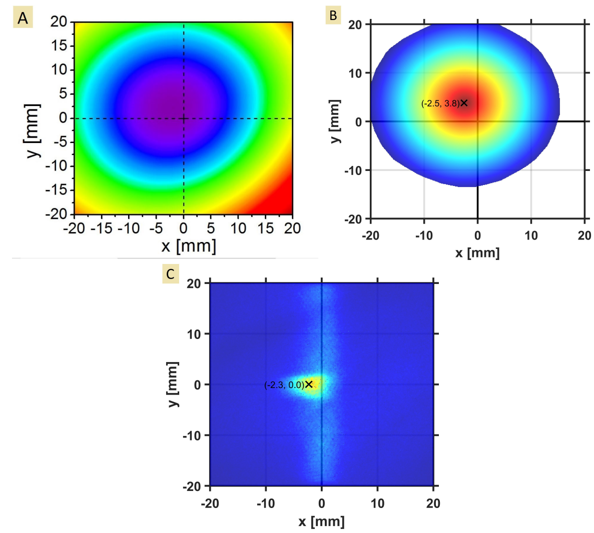

Figure 3: Beam center position on the MCP plane; (a) historical [4], (b) COMSOL, (c) experimental. Color scale (linear) represents position of ions.

PARAMETRIC OPTIMIZATION

In parametric optimization, a systematic sweep of plate dimensions and applied potential is conducted iteratively to determine the smallest feasible size while ensuring field uniformity and minimizing profile deviation. The axial field distribution for key iterations is depicted in Figure 4, illustrating the axial electric field scales with the applied potential (V) and the dimensional parameters defined by length (L), outer diameter (D), repeller diameter (D_{rep}), and internal diameter (d). Particle trajectories for original and optimized versions reveal non-uniform ion energies across the profile, which can impact detector gain thus the accuracy of intensity distribution. A study by S. Hosokawa et al. [7] demonstrates this gain saturates for ion energies exceeding 1.5 keV for Argon. Therefore, applied potentials are recalculated to ensure the ion energy remains above the saturation threshold to ensure the uniform gain. The resulting field strength is represented by the yellow curve in Fig. 4.

The parametric sweep informs the minimum plate dimension and separation to maintain field uniformity in the volume enveloping particle path. The inner diameter of the plates is chosen to accommodate ion trajectories while ensuring that difference between inner and outer diameters remains greater than the interplate separation. This design approach approximates a parallel plate configuration to maintain field uniformity. The same principle guides the design of extractor and repeller plates, necessitating larger dimensions to accommodate the entire beam and curtain while providing clearance. Internal plates are then removed progressively while re-adjusting the separation between the

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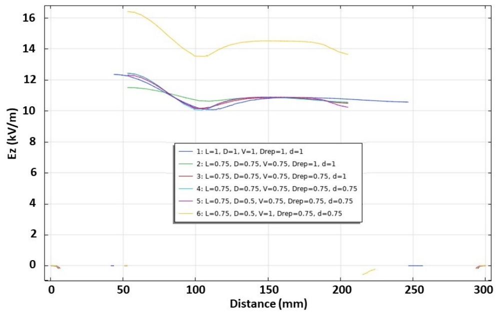

Figure 4: Graph shows electric field strength along the IPM detector axis during parametric sweep.

remaining plates to keep the field uniform until a new design with less number of plates is identified. Additionally, a flange-mounted MCP is selected for further simplicity and compactness. Complete 2D map of electric field and space potential on axial slice plane, considering distortion around plates due to vessel body is simulated as shown in Fig. 5.

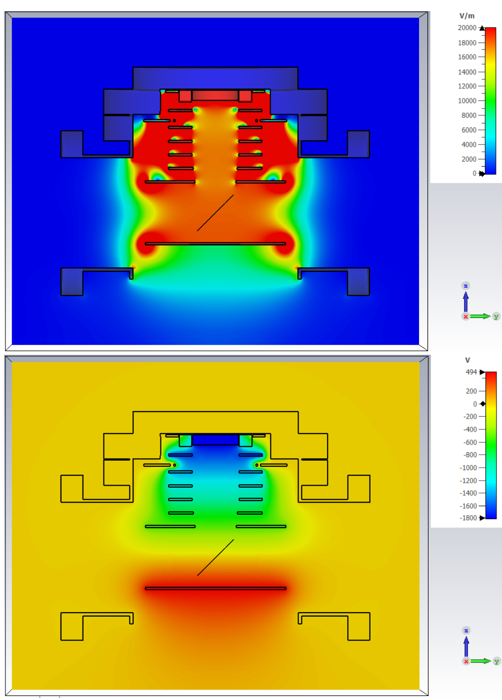

Figure 5: Electric field (top) and space potential (bottom) distribution around IPM detector.

The results demonstrate a uniform distribution of space potential except in close proximity to the MCP detector. This distortion is due to the proximity of ceramic mounting elements of a standard 150 CF flange-mounted MCP detector. Even though a larger detector covering the entire opening area of 44 mm diameter can mitigate this, attempts are made to incorporate smaller detector keep IPM detector size small. Nevertheless, this distortion is confined to the close proximity at the edge of the detector, affecting only ions at the end of their travel. As this forms only a small fraction of the total travel length, the resulting contribution has negligible effect on ion trajectory, as evident from particle trajectory simulations as discussed in the next section.

OPTIMIZED GEOMETRY

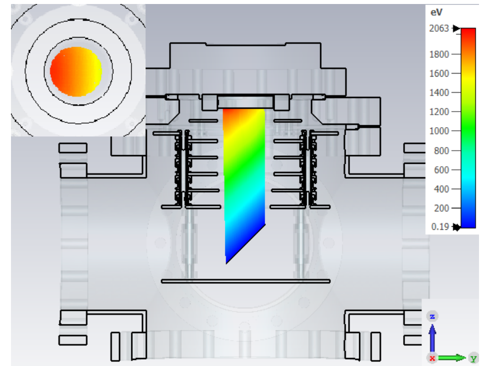

Figure 6: Particle trajectories and beam profile in the optimized IPM detector. Sub-panel shows beam profile at detector plane.

In the final step, mounting legs are modeled to hold the plates while providing electric isolation. A pair of four legs between the mount and extraction plate holds the intermediate plates, and another staggered pair holds the repeller plate. All legs are shielded with ceramic tubes for electrical isolation which are in turn covered by metallic shields, biased to the same potential as plates with which they are attached. This enlarges the region of space potential around them to maintain field uniformity. Metallic shield also covers the ceramic tube to prevent stray ions from hitting the tube and potentially sputtering additional electrons contributing to background noise. Shields are particularly crucial for the repeller and extractor plates, as they mask the region of the region of vessel in close proximity to interaction region, thus minimizing the distortion of the uniform field within them. The particles trajectories and beam profile for the optimized design is shown in Fig. 6.

CONCLUSION

In conclusion, a non-invasive beam ionization profile monitor (IPM) holds promise for real-time dose monitoring in ion beam therapy, particularly in emerging treatment modalities like FLASH therapy. This paper presents the design and optimization of an IPM detector through simulations and parameter optimization, key design considerations such as field uniformity and particle trajectories. The resulting system demonstrates reduction in the size and complexity, while also highlighting the challenges associated with field distortion at the edges. The future work will address these challenges and aims to manufacture and experimental testing.

ACKNOWLEDGEMENTS

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