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GAS-JET BASED IONIZATION PROFILE MONITOR FOR PROTON FLASH THERAPY

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Abstract

In proton FLASH therapy, the beam monitoring is crucial to ensure the targetted dose delivery to the tumor and effective Organ at Risk (OAR) sparing. A non- invasive real time beam monitoring gives more control over the beam as the dose is delivered in shorter time scales. To achieve this, the gas-jet based Ionization Profile Monitor (IPM) is currently being developed with potential capability towards real time beam monitoring. It detects ions produced by the interaction of primary beam using a thin (<1 mm) gas-curtain without perturbing the beam. This work presents the simulation of IPM to study the ion extraction under different design configurations to identify parameters affecting the reconstruction of the beam shape. The effect of the IPM electric field on ion trajectory and energy distribution inhomogeneity, which affects the beam profile, are studied. The study also investigates the effect of beam misalignment and the gas-curtain density distribution. Future work will address configuration required to accommodate broader range of beam relevant to clinical application.

INTRODUCTION

Proton therapy has emerged as a highly precise form of radiation therapy, offering superior tumour control and reduced dose to surrounding healthy tissues compared to conventional photon therapy [1]. The recent development of FLASH proton therapy, where ultra-high dose rates are delivered within milliseconds, has shown additional promise by further sparing surrounding normal tissues while maintaining the tumor control. However, the success of this technique strongly depends on accurate monitoring of the beam to ensure conformal dose delivery and to prevent unintended irradiation of critical OARs [2].

Conventional beam diagnostics face significant challenges when applied to high-intensity proton beams. These FLASH beams often require monitoring at very short timescales. Traditional interceptive diagnostics are not suitable for routine use in a clinical environment, as they can perturb the beam and limit treatment accuracy. Therefore, there is a requirement for non-invasive, real-time monitoring techniques capable of providing reliable beam profiles under FLASH therapy conditions [3].

Gas-jet based Ionization Profile Monitors (IPMs) represent a promising solution. This system introduces a thin curtain of gas into the beam path, the primary protons ionize the gas molecules, and the resulting ions can be extracted and detected without significantly disturbing the beam while keeping the projection of the beam same [4]. This technique, with appropriate optimization, can be adapted for medical accelerators and proton therapy facilities.

In this work, we present initial simulations of a gas-jet based IPM, focusing on ion extraction process and the inhomogeneity in the ion energy distribution at the Micro Channel Plate (MCP) due to the 45 degree tilt of the thin gas curtain and the electric field configuration. Particular attention is given to how these factors influence the reconstruction of the beam profile. The effects of beam position fluctuations and the gas-curtain density distribution, which is considered uniform, are investigated. The probability of generating different ionization states was negligible and therefore omitted from the simulation [5]. The study supports the development of compact gas-jet based IPMs optimized for FLASH proton therapy applications.

SIMULATION SETUP

The compact configuration of the IPM [6] was modeled in the CST studio suite, with respective bias potentials applied to each electrodes of the system, the schematic of the same is given in Fig. 1, in comparison with the older version of the system. The lateral and vertical sizes were reduced by about 40 %. The potentials were calculated by setting the voltage of MCP at -2 kV and of the interaction point as 0 V. The ionization cross sections are calculated by extrapolating the available experimental cross sections upto 100 MeV using Rudd model [7]. The particle distribution was created considering each incident Gaussian beam of different radii for a 100 MeV proton beam with 600 nA beam current. The density of the gas particles along the thickness of 1 mm of the curtain was assumed uniform, and this was also incorporated when defining the distribution, along with the tilt of 45 degree of the gas curtain. The obtained ion distribution for a beam radius of 2.5 mm, with σ_x and σ_y of 1.14 mm and 1.08 mm respectively, is shown in Figs. 2(a) and (b).

The particle distribution, simulated using Matlab, was loaded into the CST and the particle trajectory and profile information were obtained. Each ion in the distribution were assigned a constant velocity of 580 m/s, which is due to the supersonic nature of the Argon gas jet. This velocity was calculated considering room temperature of gas jet at 20 °C. These ions are allowed to drift through the electric field created by the electrodes and their distribution on the MCP is recorded to get the beam profile and energy distribution of these ions. A position shift of 1 mm applied in both left/right and up/down directions and again the beam profiles

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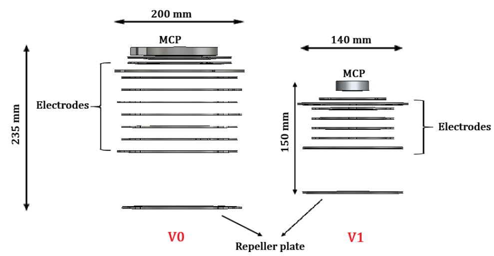
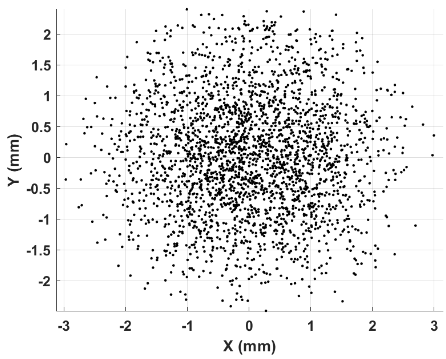
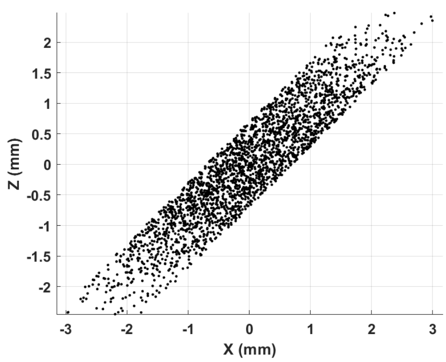


Figure 1: Schematic of the old design and new design configurations of the IPM.



(a) Distribution in the XY plane.



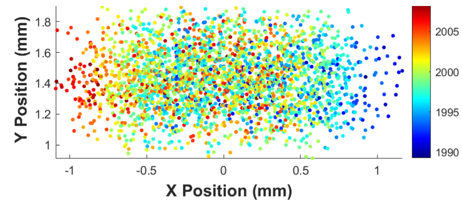
(b) Distribution in the XZ plane.

Figure 2: Ion distribution at the interaction point for 2.5 mm proton beam radius. The X axis represents the beam direction, Y axis represents the gas-jet direction and Z represents the direction of extraction.

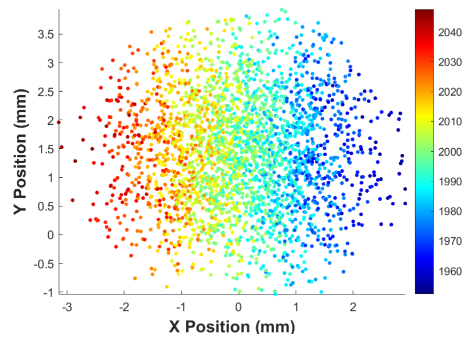
are obtained at the MCP and is analyzed to quantify the shift based on the spatial distribution of ions at the MCP.

RESULTS AND DISCUSSIONS

The spatial distribution of ions at the MCP was simulated for different beam sizes. An energy inhomogeneity along the beam direction was observed, arising from the 45° tilt of the gas curtain. Due to this tilt, ions travel different distances from the interaction region to the MCP, leading to an energy variation along the x direction. This observation was more significant for larger beam sizes. The energy variations for beam radii of 0.5 mm and 2.5 mm are shown in Figs. 3(a) and (b), with the color map representing the particle energy



(a) 0.5 mm proton beam radius.

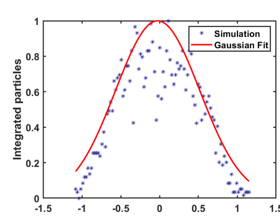


(b) 2.5 mm proton beam radius.

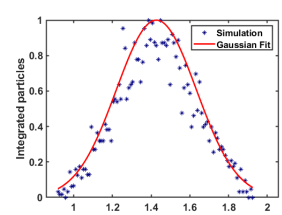
Figure 3: Spatial energy distribution of ions at the MCP.

at MCP. For smaller beam radii below this non-uniformity is negligible, but it increases as the beam size grows. To correct for this effect, the integrated energy, which reflects the number of particles, along the Y direction is taken for each X value, effectively using the central line of the distribution parallel to the Y-axis as a reference.

Using this correction, the X and Y profiles were reconstructed from the spatial ion distribution and are presented in the Figs. 4(a) and (b) and 5(a) and (b) for the incident beam radii of 0.5 mm and 2.5 mm respectively. For the 0.5 mm beam, the sigma values of the X and Y profiles were found to be 0.54 m and 0.21 mm, respectively. For the 2.5 mm beam, the corresponding sigma values increased to 1.13 mm and 1.05 mm. The slight deviation in the σ_x for smaller beams is attributed to the 1 mm thickness of the gas curtain, which is comparable to the incident beam size. For larger beam sizes, this effect becomes negligible, and the reconstructed profiles more accurately reflect the true beam dimensions.



(a) X profile.



(b) Y profile.

Figure 4: Beam profiles for 0.5 mm proton beam radius.

The IPM's performance for beam position tracking was also evaluated through simulations. Deliberate position shifts for the incident beam were introduced in both the up/down(X-axis and Z axis) and left/right(Y axis) directions of the reference ion distribution. The resulting spatial ion

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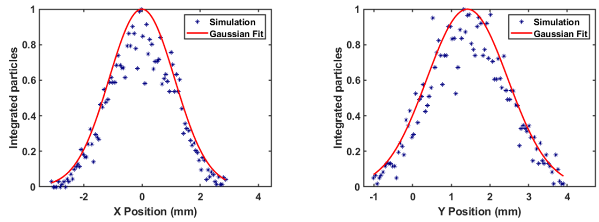
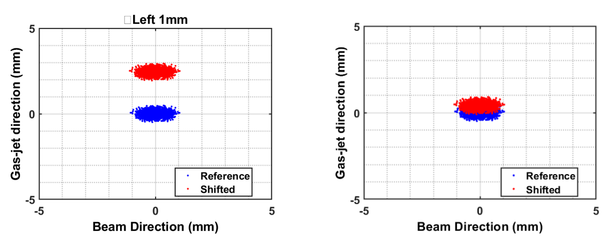


(a) X profile. (b) Y profile.

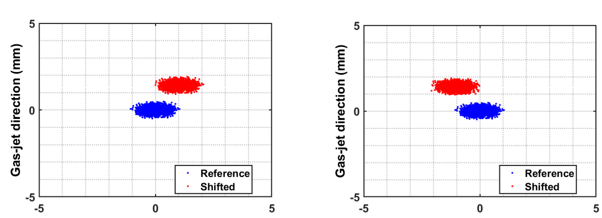
Figure 5: Beam profiles for 2.5 mm proton beam radius.

distributions at the MCP were analyzed. The distributions shifted in accordance with the applied displacements, and the centroids measured before and after the shifts closely matched the introduced values. This confirms the IPM's capability to accurately track beam position variations. As an example, a 1 mm shift was introduced in the up/ down and left/right directions of the reference ion distribution. In the Y-direction, there was already a shift observed which was due to the directional velocity of the gas particles. The introduced fluctuations in the left/right directions added to this existing shift and are estimated as 2.44 mm and 0.40 mm respectively, where 1.42 mm shift was introduced by the directional velocity of the gas jet. The observations are given in the Figs. 6 and 7 for the left/right and up/ down shifts of 1 mm respectively. For the up/down shift, a corresponding displacement of 1.01 mm and -1.04 mm were found.



(a) Left: 1 mm. (b) Right: 1 mm.

Figure 6: Beam position shift along the a) left and b) right direction of the reference ion distribution reflected in the ion distribution at the MCP.



(a) Up: 1 mm. (b) Down: 1 mm.

Figure 7: Beam position shift along the a) Up and b) Down direction of the interaction point reflected in the ion distribution at the MCP.

Additionally, the time required for the produced ions to reach the MCP (time of flight) is approximately 2.09 µs. The total signal collection time includes the ion generation time, the time of flight, and the time associated with signal processing by the MCP, phosphor screen, and camera. Overall, the total signal processing time will be within a few microseconds per bunch, which demonstrates the potential of the gas-jet–based IPM for real-time beam monitoring. If the number of ions generated per bunch within the gas jet is sufficiently high, the monitor could function as a real-time beam monitor for FLASH protons.

CONCLUSION

In this study, the initial simulation results of a compact design configuration of a gas-jet based IPM was discussed for the potential use in medical accelerators, especially for FLASH proton therapy application. The results showed the potential capability of this system for the reconstruction of beam profile and position monitoring for the clinically relevant energy and beam current, without perturbing the primary beam, which will enable simultaneous beam monitoring and patient treatment. The new compact design of the gas-jet-based IPM will facilitate its integration into medical accelerators.

ACKNOWLEDGEMENTS

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