Performance Evaluation of the Extraction System of Supersonic Gas Curtain Ionization Profile Monitor for FLASH Protons

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Introduction

- **Clinical Challenge:** FLASH radiotherapy delivers ultra-high dose rates (>40 Gy/s), by sparing healthy tissue while preserving tumour control [1].
- **Detector Limitations:** Conventional gas-filled ionization chambers saturate under ultra-high dose rates, while solid-state transmission detectors cause beam scattering and degradation [2].
- **SGC-IPM:** A Supersonic Gas Curtain-Based Ionization Profile Monitor (SGC-IPM) enables real-time, non-invasive beam monitoring [3,4,5].
- **Working Principle:** A thin, low-density supersonic gas curtain intersects the therapeutic proton beam, generating ions that are electrostatically extracted onto an MCP-phosphor-CMOS system to map transverse profile and position.
- **Study Objectives:** Evaluates extraction field geometry, validates CST Studio Suite simulations against experimental 28 MeV proton beam data, and proposes a compact extraction setup for clinical integration.

Methodology

1. SGC-IPM Geometry & CST Simulation

- **Extraction System Geometry:** Consists of a repeller plate, ring electrodes, electrostatic drift space, and a two-stage MCP–phosphor detector. This is housed inside the interaction chamber of SGC-IPM as shown in Fig. 1.
- **Tested Configurations:** Evaluated an ideal field setup (**Voltage 1**) across proton beam radii from 0.5 to 15 mm, alongside a custom voltage configuration matching experimental 28 MeV beam tests (**Voltage 2**) and is presented in Fig. 2.
- **Beam & Jet Modelling:** Simulated a 100 MeV, 600 nA clinical FLASH proton beam intersecting a 1 mm thick Argon gas curtain (3.9×10^{16} particles/m^3) tilted at $45°$with a supersonic velocity of 587 m/s (Y-direction).

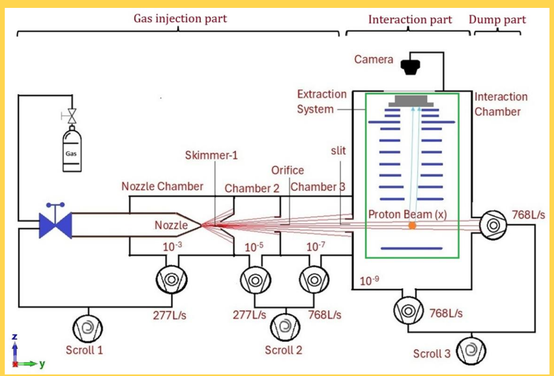

Figure 1. Schematic of the gas jet-based IPM with the highlighted part in the green box indicating the extraction system.

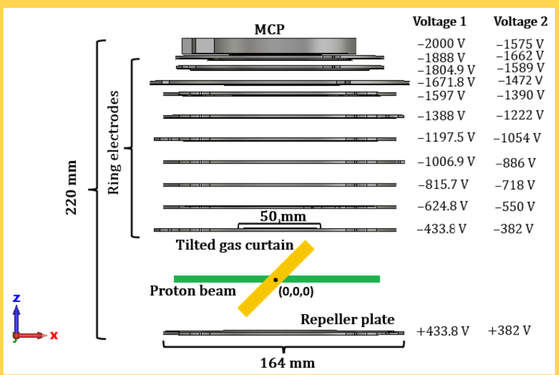

Figure 2. The potential configuration of each ring electrode, MCP, and repeller plate and the dimensions of the extraction system.

2. Ion Generation Physics & Tracking

- **Cross-Section Model:** Applied Rudd et al. [6] semi-empirical formulation to determine proton–argon impact ionization and extrapolated to 100 MeV proton and given in Fig. 3. (2.84×10^3 ions produced per beam pass)
- **Particle Tracking:** Solved 3D ion trajectories through the electrostatic extraction fields using CST Studio Suite.
- **Position Monitoring:** Applied beam displacement offsets (± 1 mm and ± 5 mm in Y / Z) to test transverse position-tracking capability.

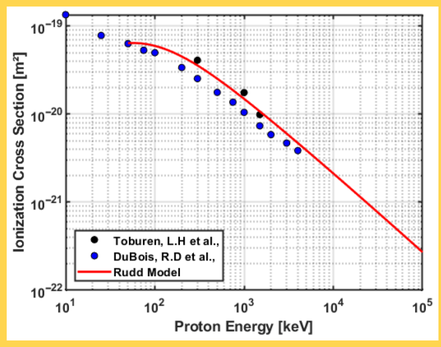

Figure 3, Extrapolated argon-proton cross sections up to 100 MeV using Rudd's model [6] and the experimental data reported in the literature [7,8].

3. Profile Reconstruction & Signal Processing

- **MCP Efficiency:** Weighted projected 2D spatial maps (X, Y) by the energy-dependent MCP detection efficiency, $Q(E)$.
- **Discretization:** Bound ion positions to $25\,\mu$m channel boundaries and extracted horizontal/vertical beam profiles using Gaussian fits.

4. Experimental Benchmarking (28 MeV Proton Beam)

- **Beam Parameters:** 28 MeV energy, 70 nA average beam current.
- **Detector Bias:** Operational MCP voltage at -1.575 kV(accounting for series resistance drop) and phosphor screen at $+3$ kV, imaged via CMOS camera (gain: 240).
- **Validation:** Isolated beam signal via background subtraction ("Gas On" minus "Gas Off") and benchmarked supersonic drift-induced spatial offsets against CST simulations to validate extraction field performance.

Results and Conclusion

- Electric field distribution along the extraction region (Fig. 4) remains within 11.87\% of the mean value along the extraction axis (X = 0).
- This uniform field ensures minimal impact and distortion on ion trajectories traversing the extraction zone.

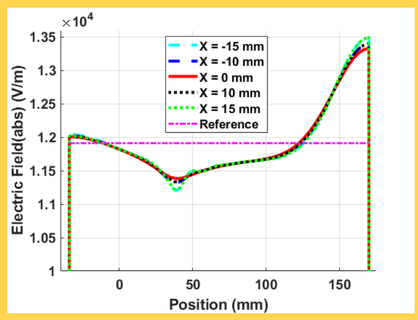

Figure 4. The Z-component of the electric field along the axis of the extraction system

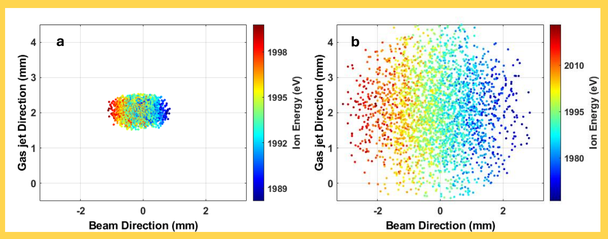

Figure 5. The simulated spatial distribution of ions at MCP for incident beam radii of a) 0.5 and b) 2.5 mm

- Two-dimensional spatial energy maps of generated ions for incident proton beam radii of 0.5 mm (FWHMy = 0.485 ± 0.013 mm, FWHMz = 0.483 ± 0.012 mm) and 2.5 mm (FWHMy = 2.420 ± 0.009 mm, FWHMz = 2.412 ± 0.009 mm) are shown in Fig. 5.
- Extracted vertical and horizontal profiles were fitted with Gaussian distributions to quantify beam widths for 0.5 mm (Fig. 6) and 2.5mm (Fig. 7) .

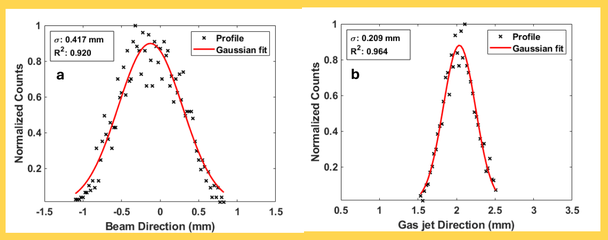

Figure 6. The (**a**) horizontal and (**b**) vertical beam profile for 0.5 mm proton beam

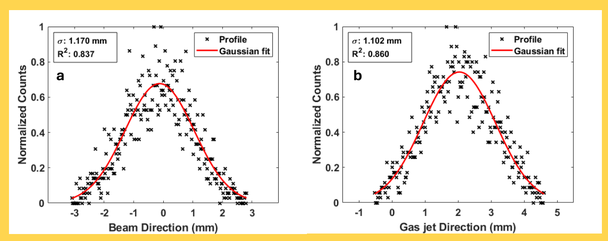

Figure 7. The (**a**) horizontal and (**b**) vertical beam profile for 2.5 mm proton beam

- Energy inhomogeneity for varying beam sizes, quantified as deviation from average energy, is shown in Fig. 8.
- Inhomogeneity values were ±0.29% (1 mm), ±1.42% (5 mm), ±2.90% (10 mm), ±5.45% (20 mm), and ±8.48% (30 mm).

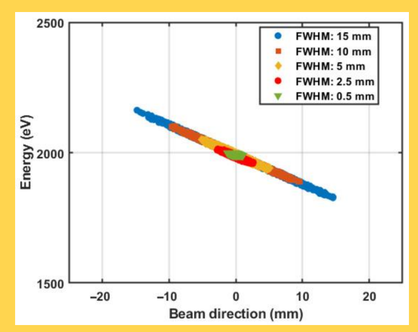

Figure 8. The energy distribution for different incident beam radii.

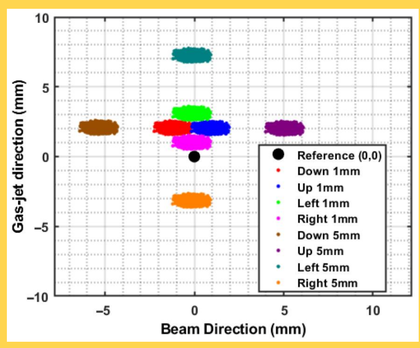

Figure 9. Displacement of the beam profile centroid at the MCP in X and Y directions

- Agreement between quantified shifts in simulation and measurement (Fig. 10) validates the accuracy of the model in capturing profiles from beam–gas interactions.
- Simulations verified beam position monitoring by introducing 1 mm and 5 mm proton beam shifts, which were proportionally reflected in beam profile measurements at the MCP (Fig. 9).

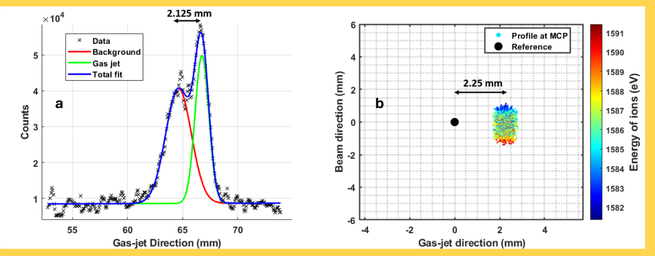

Figure 10. Comparison of beam profile shift caused by the supersonic gas jet for a 28 MeV an 70 nA proton beam: (**a**) experimental, and (**b**) simulation.

- **Accurate Transverse Profiling:** Successfully reconstructed transverse beam profiles for small beam sizes, confirming SGC-IPM feasibility for clinical FLASH proton beams.
- **Linear Position Tracking:** Reconstructed centroid shifts showed a highly linear response to intentional beam offsets (± 1 to ± 5 mm), validating robust beam-position monitoring within structural constraints of extraction system and gas curtain.
- **Experimental Benchmarking:** Good agreement between simulated and measured supersonic jet drift-induced offsets confirmed the accuracy of the CST ion interface model.
- **Design Insight:** Identified potential profile distortion for large beam sizes caused by the $45°$curtain tilt, guiding future extraction field optimization.
- **Next Steps:** Development of a **compact SGC-IPM** is underway to enable seamless integration into space-constrained clinical setups, such as laser-driven proton accelerators.

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