Ion-Acoustics Journal Paper

Abstract

The SmartPhantom is a novel detector developed for real-time three-dimensional dosimetry in particle therapy using pulsed proton and light-ion beams. The system integrates the detection of ion-induced acoustic signals with optical readout using a liquid scintillator. A detailed simulation pipeline using BDSIM, Geant4, k-Wave and Ansys Zemax OpticStudio have been performed alongside experimental validation at the MC40 cyclotron at the University of Birmingham and the Laser-driven Ion Acceleration (LION) beamline at the Centre for Advanced Laser Applications (CALA). The SmartPhantom's performance is evaluated in terms of energy resolution, beam characterization, response linearity, and spatial reconstruction accuracy, demonstrating its potential as a powerful tool for advanced ion beam dosimetry.

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1.1 Particle Therapy and the Bragg Peak

Conventional radiotherapy uses x-rays (photons) to target and destroy the tumour region. While photons effectively damage cancerous cells, their energy is not confined to the tumor; instead, they deposit dose along their entire path through the body. This exposes healthy tissue before and beyond the tumor, potentially causing unwanted side effects [2].

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resulting in a charge separation field. This field further ionizes atoms, which originate mainly from water vapor, hydrocarbons, and oxide contaminants on the target surface [16]. The ions are then accelerated to high speeds, exiting the foil normal to its surface, driven by the direction of the charge-separation field. This process is known as Target Normal Sheath Acceleration (TNSA).

1.5.2 Collimation and Downstream Propagation

The LION beamline features a quadrupole doublet composed of two orthogonally arranged permanent magnet quadrupoles. The first quadrupole has a length of 40 mm and a measured magnetic field gradient of 332±13 T/m, while the second measures 20 mm and has a measured magnetic field gradient of 334±13 T/m. Both have a 10 mm bore and a total outer diameter of 50 mm [17]. The drift lengths between the quadrupoles are optimized and adjusted using a motorized stage to magnetically focus specific beam energies downstream. The total length from the target to the exit window is 1.845 m and operates in vacuum. A schematic diagram of the LION beamline is shown in Figure 2.

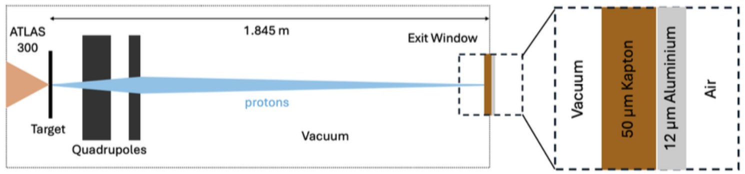

Figure 2: Schematic diagram of the LION beamline featuring the permanent quadrupole doublet focusing mechanism and beamline element configuration.

After the exit window, the particles travel through air towards the detector. The LION beamline exit window consists of a 50 μm Kapton® (polyimide) foil and a 12 μm aluminium foil; a combination that effectively stops protons up to 2.1 MeV. In addition, the quadrupoles' limited aperture blocks some source-generated particles, and those reaching the magnet bore can cause severe damage. To prevent this, an elliptical aluminum shielding plate is placed in the front.

Table 1 summarizes the drift lengths required to focus protons with modal energies between 10 and 20 MeV. Here, Drift 1 is the distance from the source to the first quadrupole, Drift 2 is between the two quadrupoles, and Drift 3 spans from the second quadrupole to the exit window.

Table 1: Ideal drift lengths to focus different beam energies at the LION beamline.

Energy [MeV]	Drift 1 [mm]	Q1 Tilt [°]	Drift 2 [mm]	Q2 Tilt [°]	Drift 3 [mm]
10	42.28	0	27.20	0	1715.52
12	46.94	0	32.31	0	1705.75
14	51.24	0	37.09	0	1696.67
16	55.24	0	41.62	0	1688.14
18	59.00	0	45.94	0	1680.06
20	62.56	0	50.08	0	1672.36

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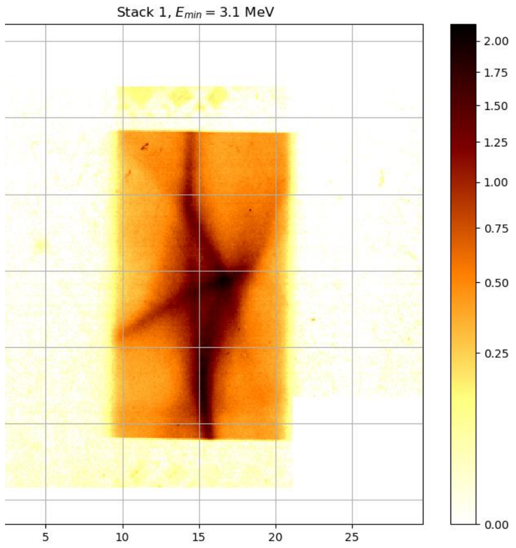
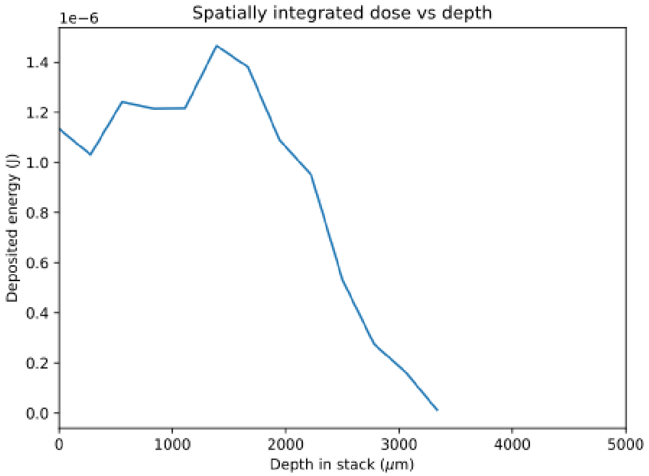
1. Understand the shape of the beam

Calvin set up LO & Geant4 simulations





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2. Quadrupole settings for obtaining beam deposition patterns in the experiment

Ideal configuration:

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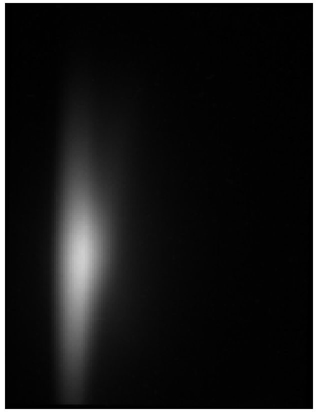
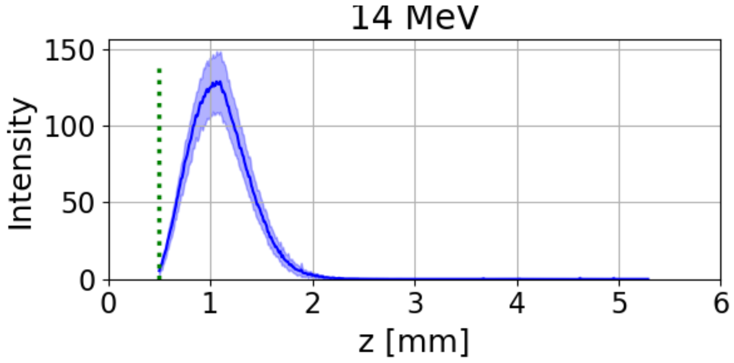
14 MeV





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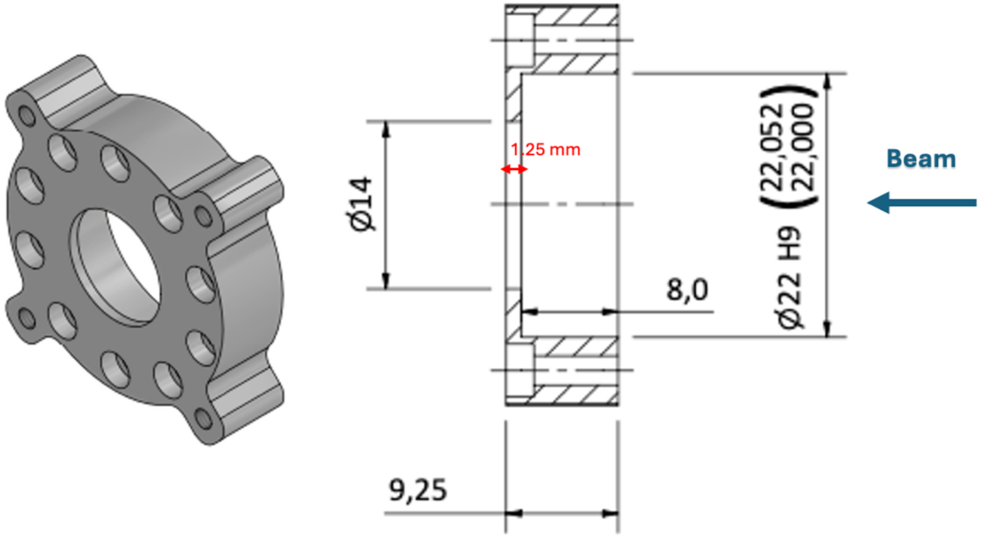
3. Characterize the occlusion caused by the entrance window flange



An experiment is being designed by Peter Hobson

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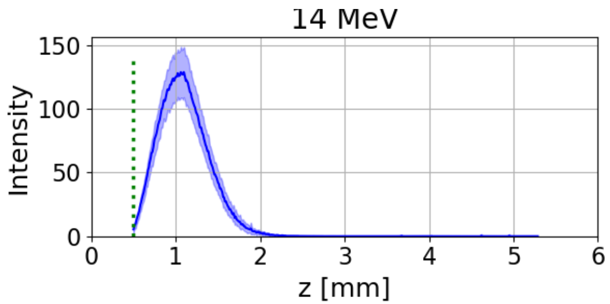
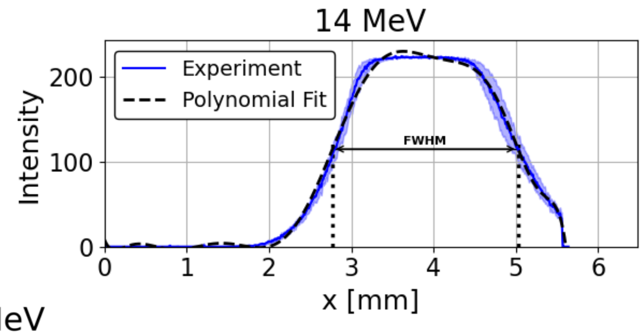
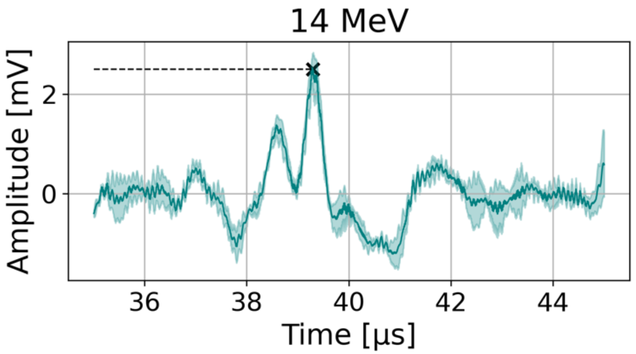
4. Compare experimental results with simulations

- Optical data: energy deposition patterns
- Acoustic data: signal waveforms







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5. Correlate the optical images and acoustic signals

6. Calibrate the acoustic response