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.

1 Introduction

Cancer is the second leading cause of death globally, with radiotherapy treating about 50% of cancer patients [1]. Conventional radiotherapy uses photons (x-rays), however it often irradiates healthy cells surrounding the cancerous region. New cancer treatment facilities use protons and light ions for their ability to deposit maximum dose in a small tissue volume at the end of their range [2].

To enable next-generation therapy, the *Laser-hybrid Accelerator for Radiobiological Applications (LhARA)* has been proposed [3]. LhARA aims to advance radiobiological research by exploring the therapeutic benefits and biological responses of different particle beam characteristics [3]. Using pulsed proton and light-ion beams, LhARA will deliver a variety of different ions, beam widths, pulse durations and repetition rates, flexibly and precisely. To minimize uncertainties in dose delivery, accurate real-time monitoring is essential; however, current techniques such as PET and prompt gamma imaging lack the spatial and temporal resolution required for this purpose [4, 5].

This work presents the *SmartPhantom*, a novel detector designed to monitor the three-dimensional dose accumulation from pulsed ion beams on the nanosecond timescale, such as those to be produced by LhARA and other laser-driven accelerators. The proposed instrumentation introduces novel capabilities, such as providing calibrated feedback, unlike other monitoring devices that provide a relative, not an absolute, determination of the dose delivered. The SmartPhantom achieves that by enabling simultaneous ionoacoustic and optical measurement of the energy deposition distribution within a liquid scintillator.

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.
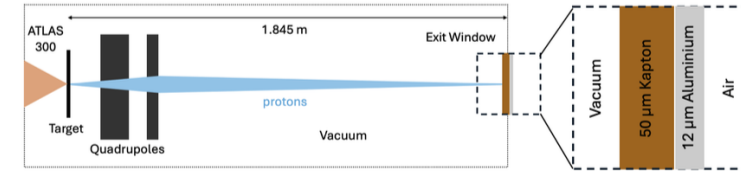

Figure 2: Schematic diagram of the LION beamline featuring the permanent quadrupole doublet focusing mechanism and beamline element configuration.
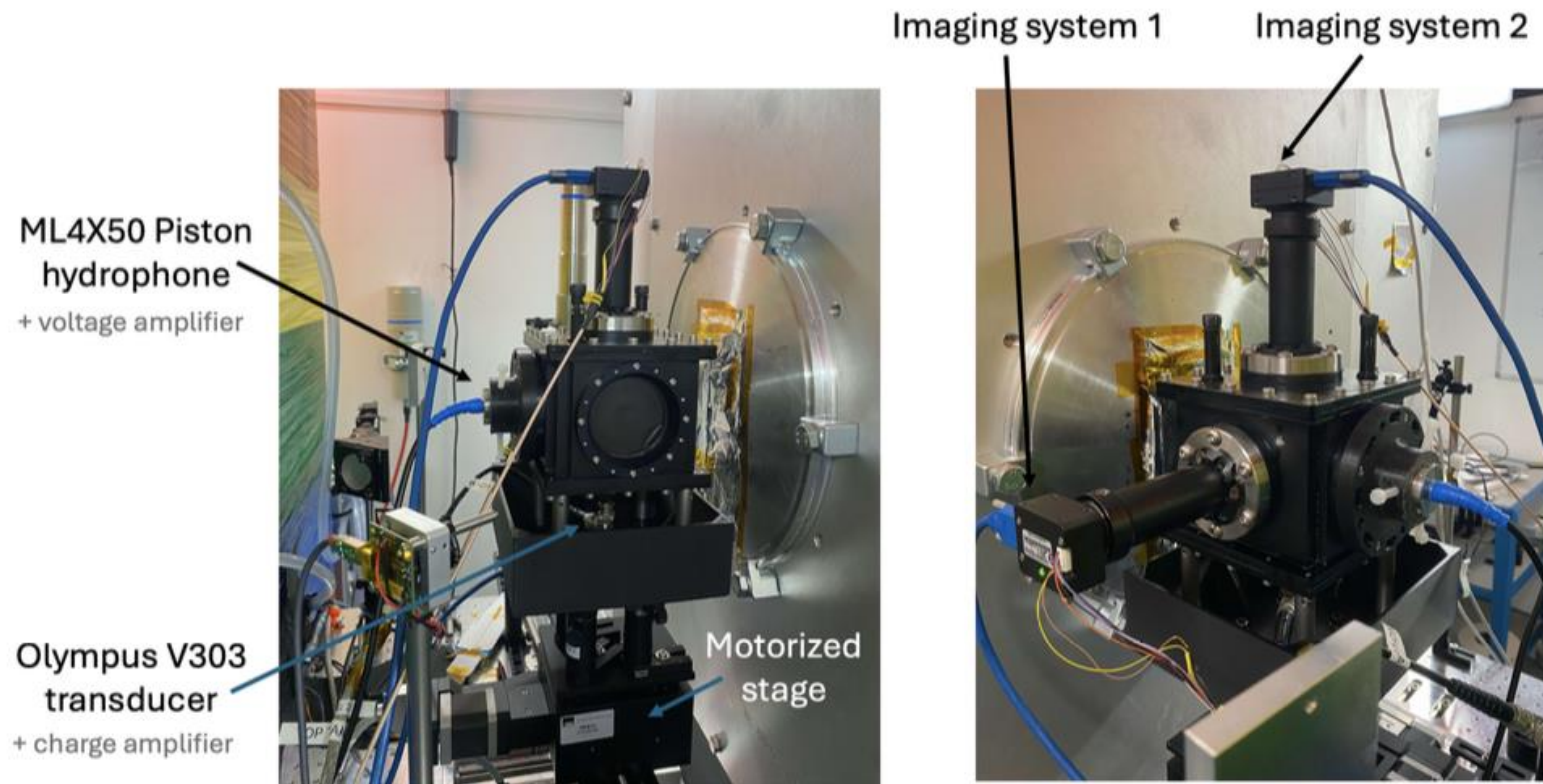
After the exit window, the particles travel through air towards the detector. The LION beamline exit window consists of a 50 μm Kapton® (polyimide) foil and a 12 μm aluminium foil; a combination that effectively stops protons up to 2.1 MeV. In addition, the quadrupoles' limited aperture blocks some source-generated 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.
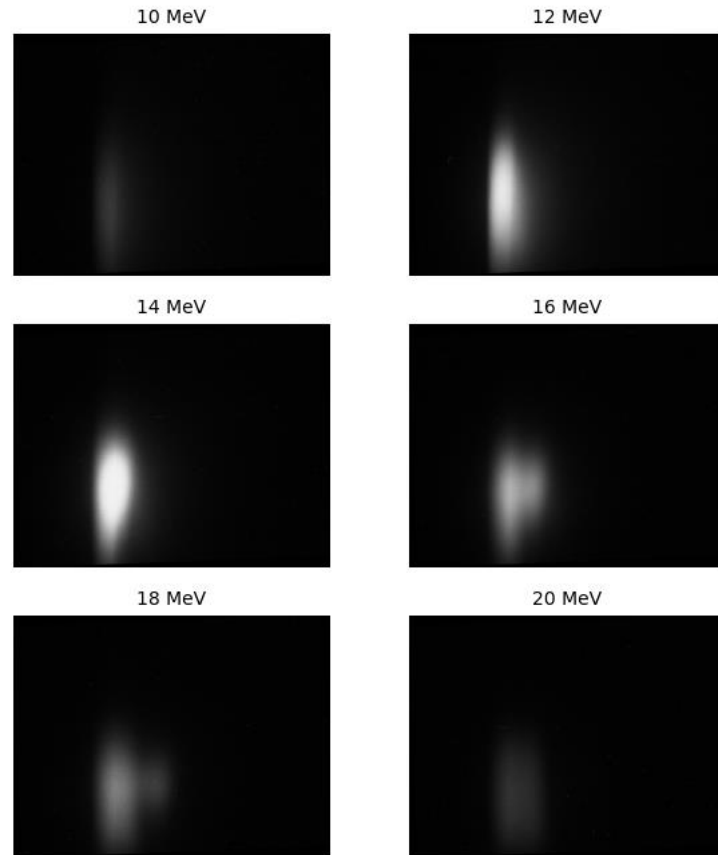
Table 1: Ideal drift lengths to focus different beam energies at the LION beamline.

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

LION Experiment: Cross-correlation between acoustic signals and luminescence

ML4X50 Piston hydrophone
+ voltage amplifier

Olympus V303 transducer
+ charge amplifier

Motorized stage

Imaging system 1

Imaging system 2

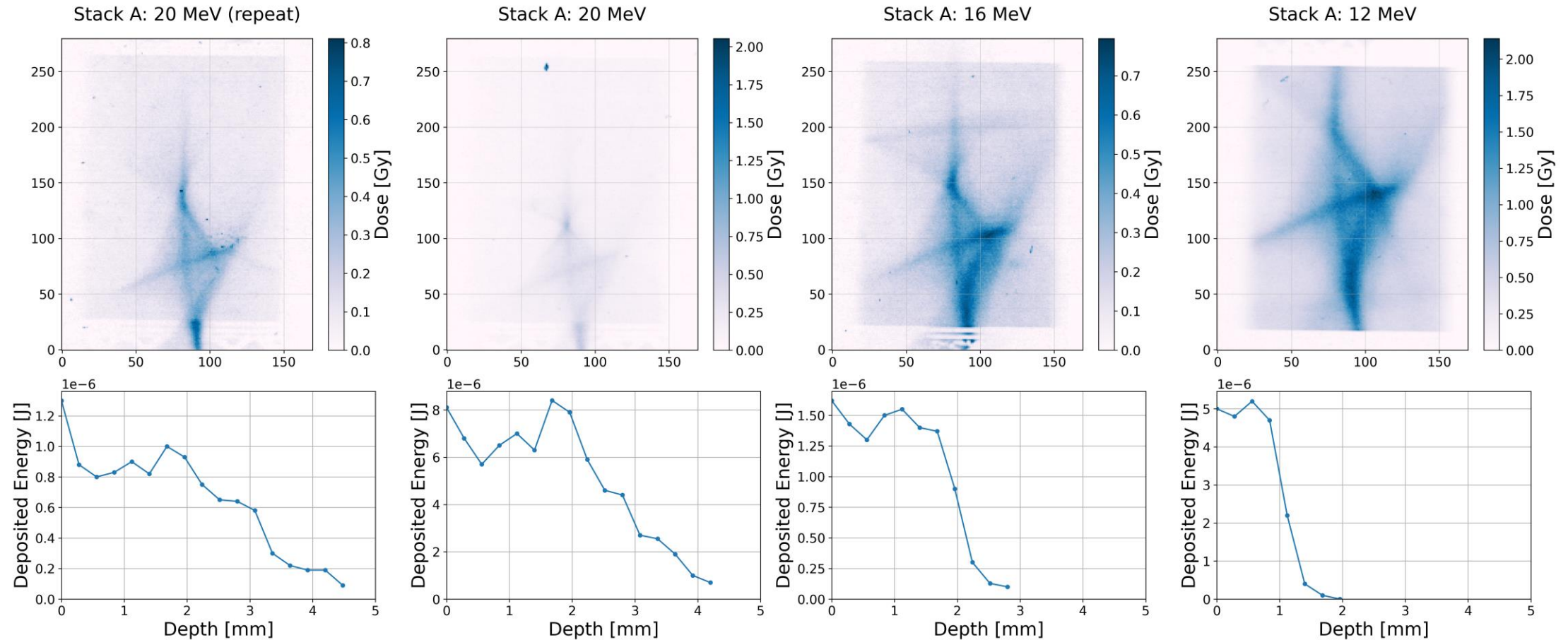# LION Experiment: Cross-correlation between acoustic signals and luminescence

Luminescence
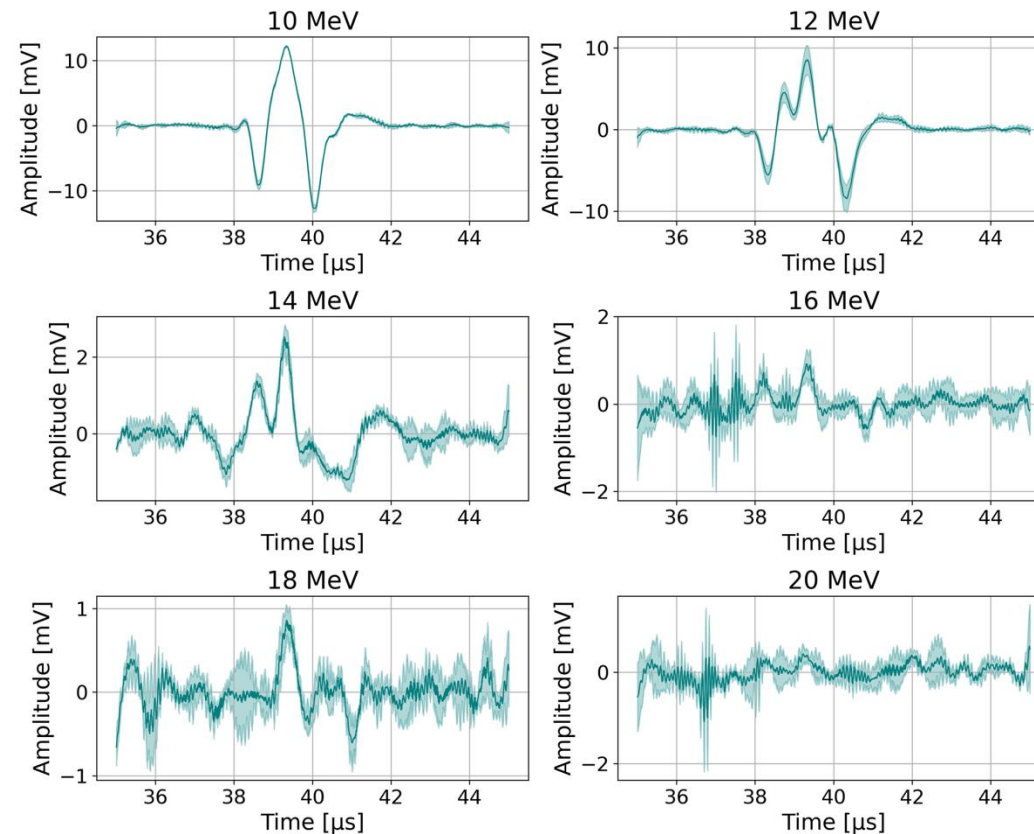
Acoustic signals

Understanding the beam shape
RadioChromic Films

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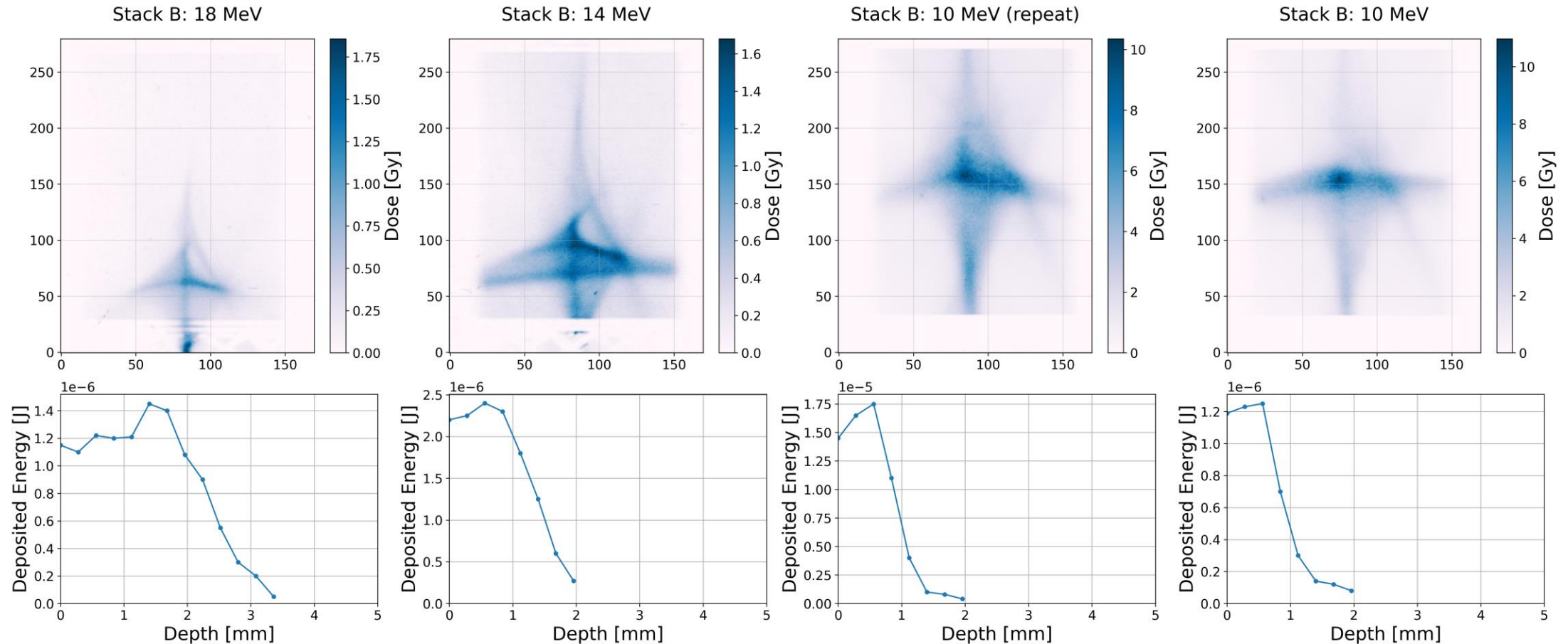
Ideal Quadrupole Settings
Verified using BDSIM

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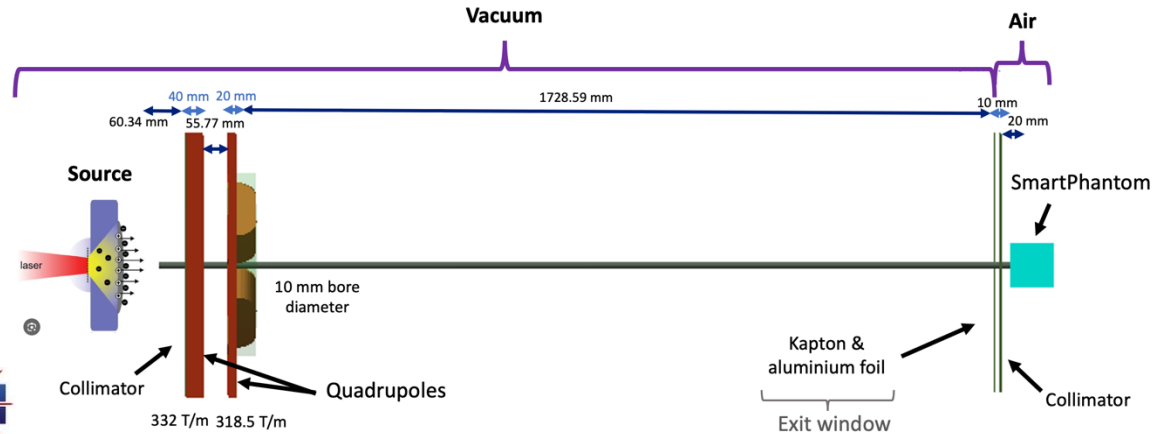14 MeV example
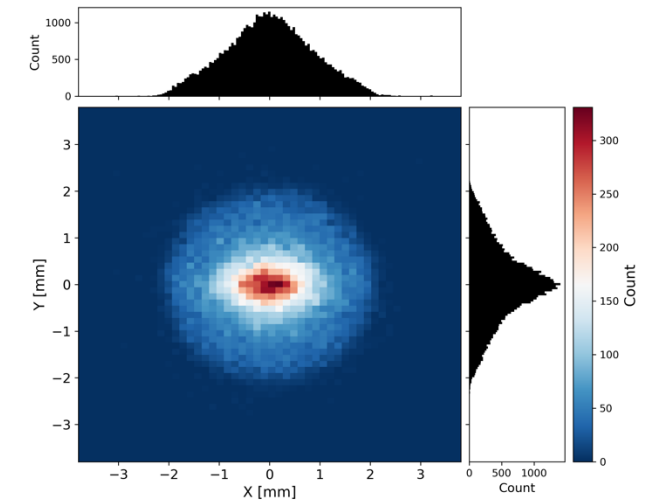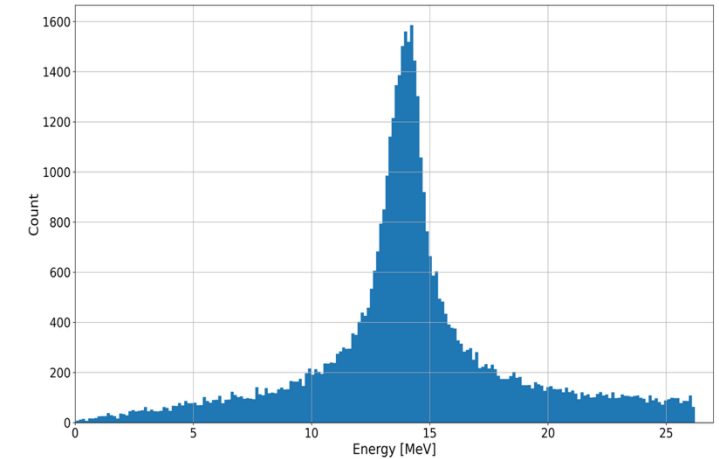
Ideal Quadrupole Settings
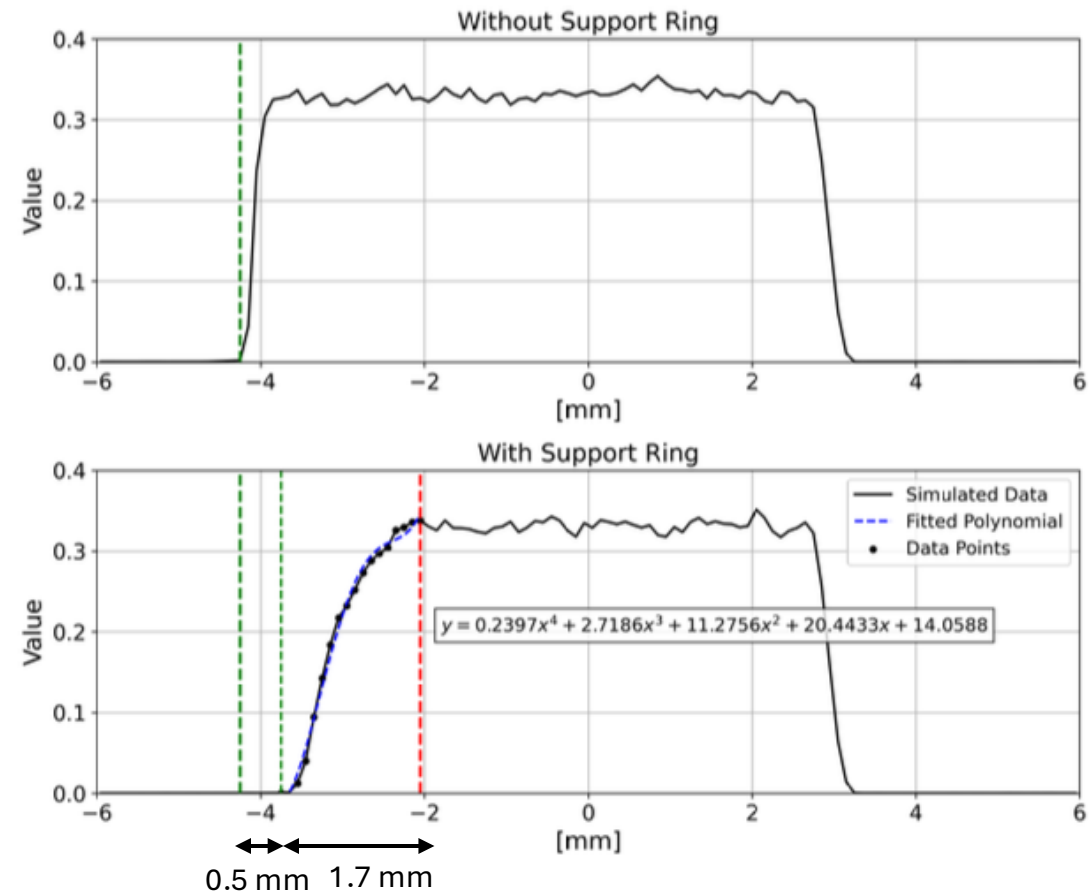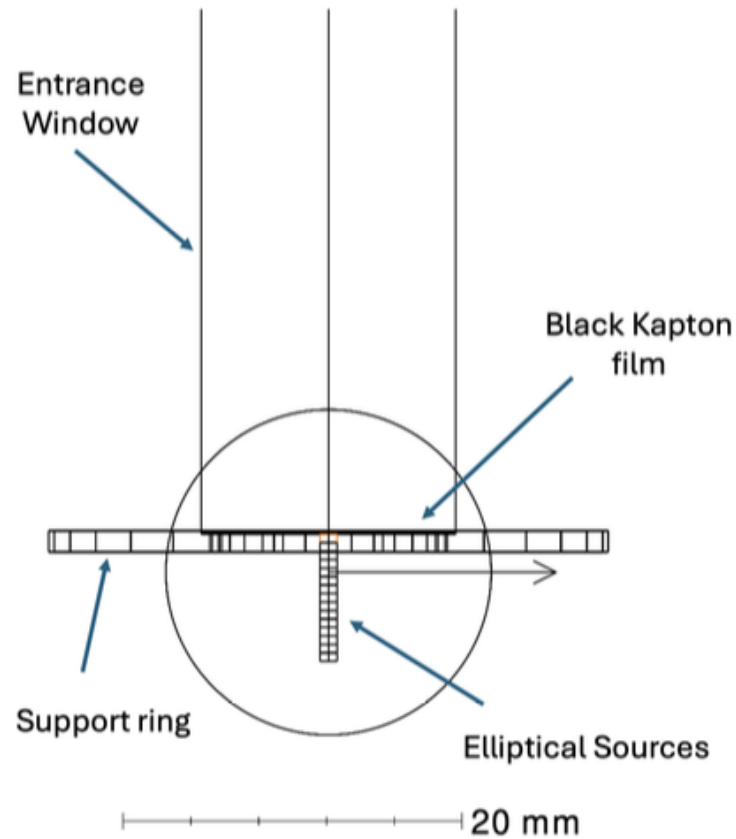## Simulation: from particle source to detection
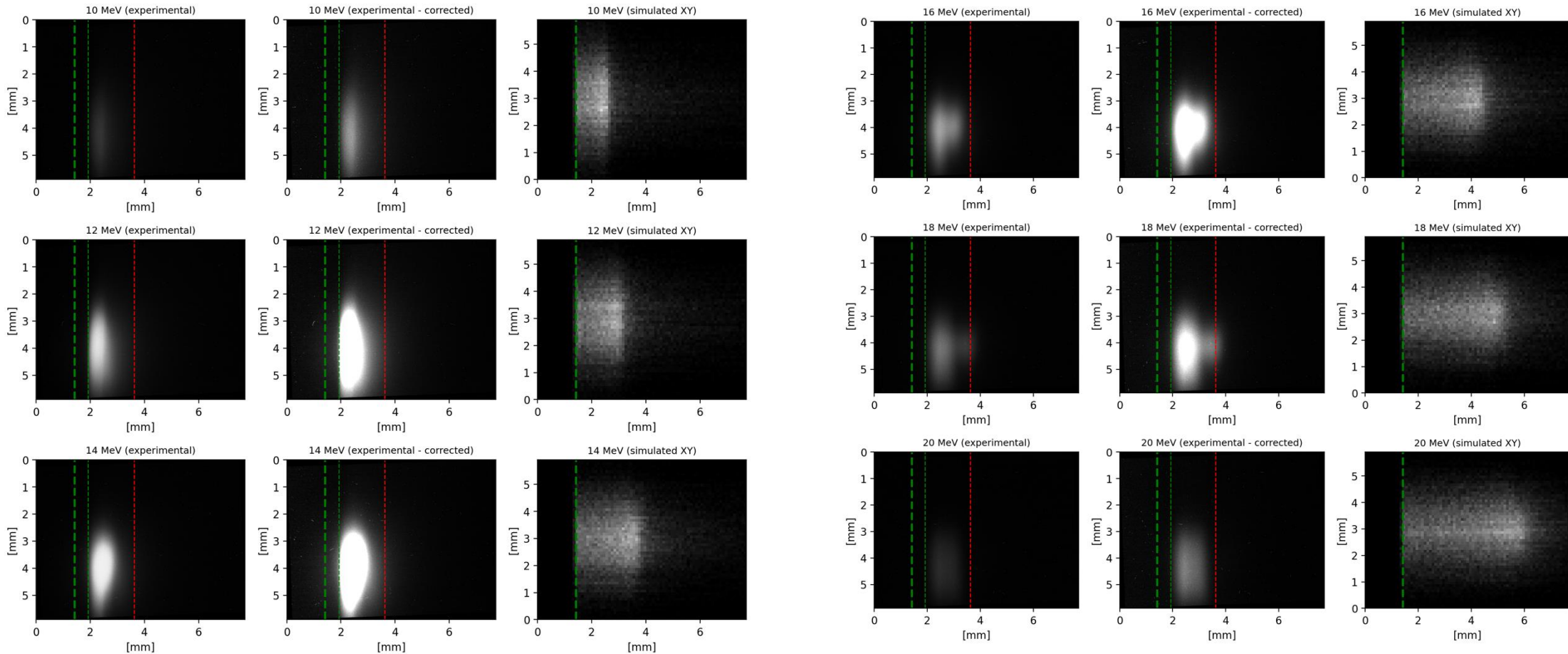
Acoustic Signal
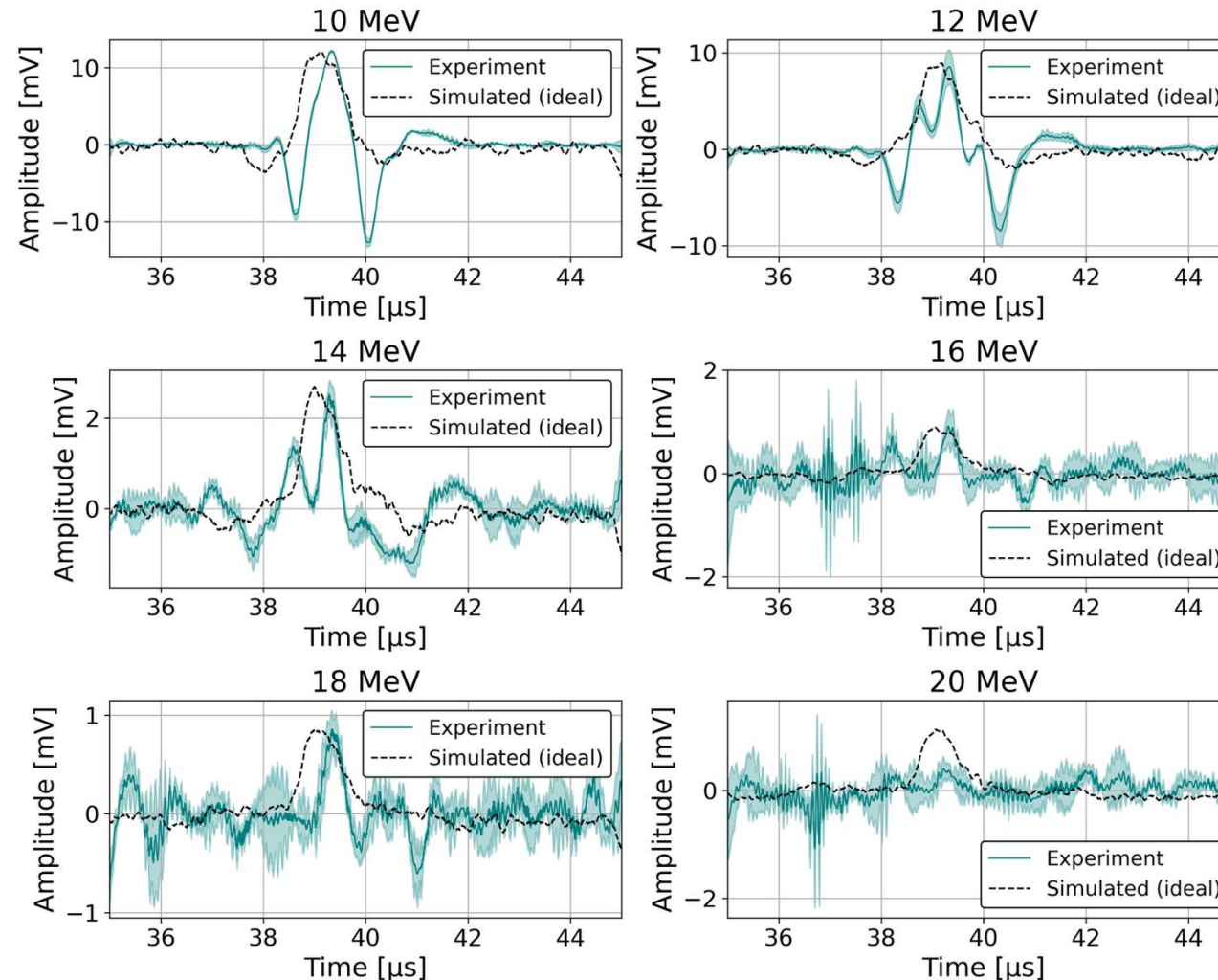
Particle Source
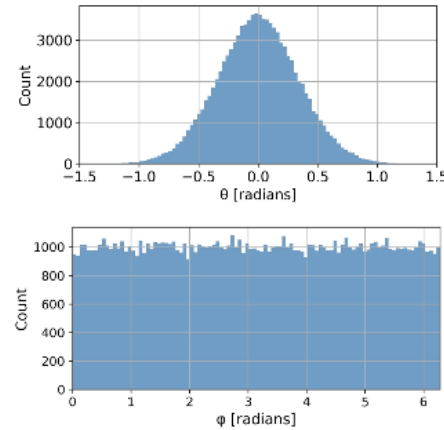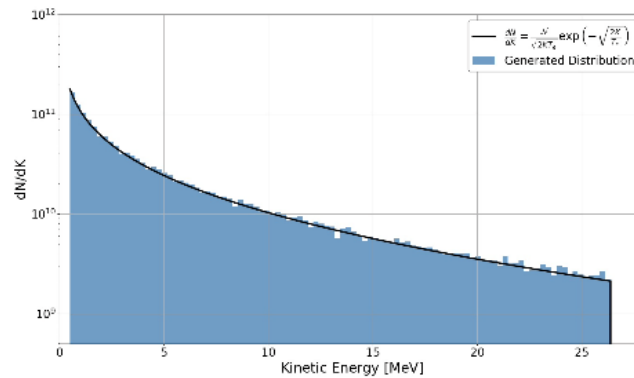
Beamline & particle tracking
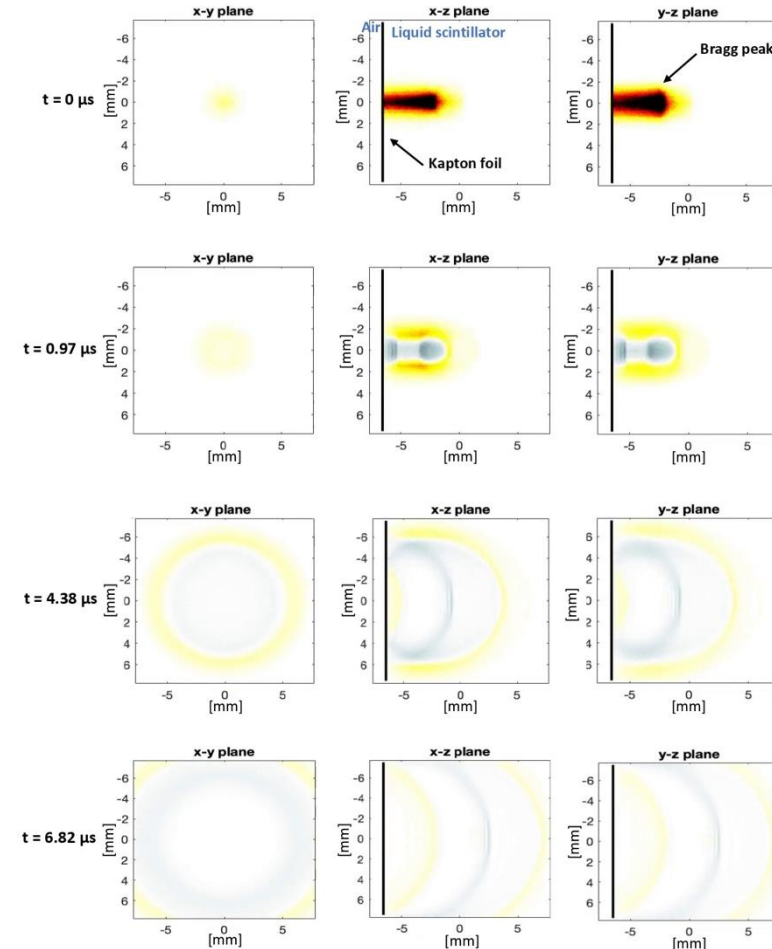
Entrance port occlusion

Comparison between experimental result and simulated data of 'ideal' beam

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Future Work

- Optimize quadrupole setting to recreate the beam we got in the experiment at LION

- Compare simulated beam shapes with RCF films

- Correlate acoustic signal and luminescence

- Paper's conclusion