Prompt gamma imaging of a clinical proton beam using Cd Zn Te Compton cameras with a maximum likelihood expectation maximization technique

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PGI CAPE TOWN

UCT PROTON THERAPY INITIATIVE

Cancer – A treatable problem

Globally

2020

A leading cause of death with 10 million deaths 1 in 6 deaths

Africa

2022:

1,185,216 cancer cases with 763,843 deaths

100,000 new childhood cancer cases are being diagnosed annually in Africa.

Treatment

Surgery

Immunotherapy

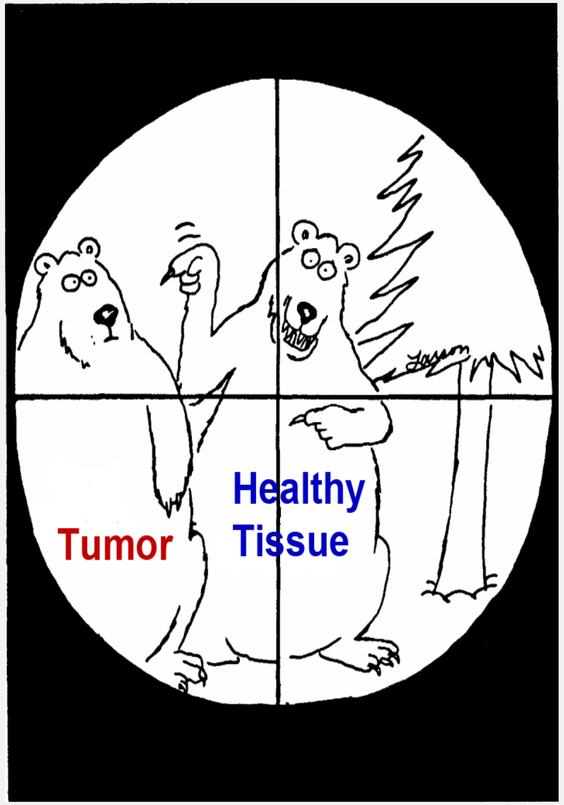
Chemotherapy

Radiation Treatment

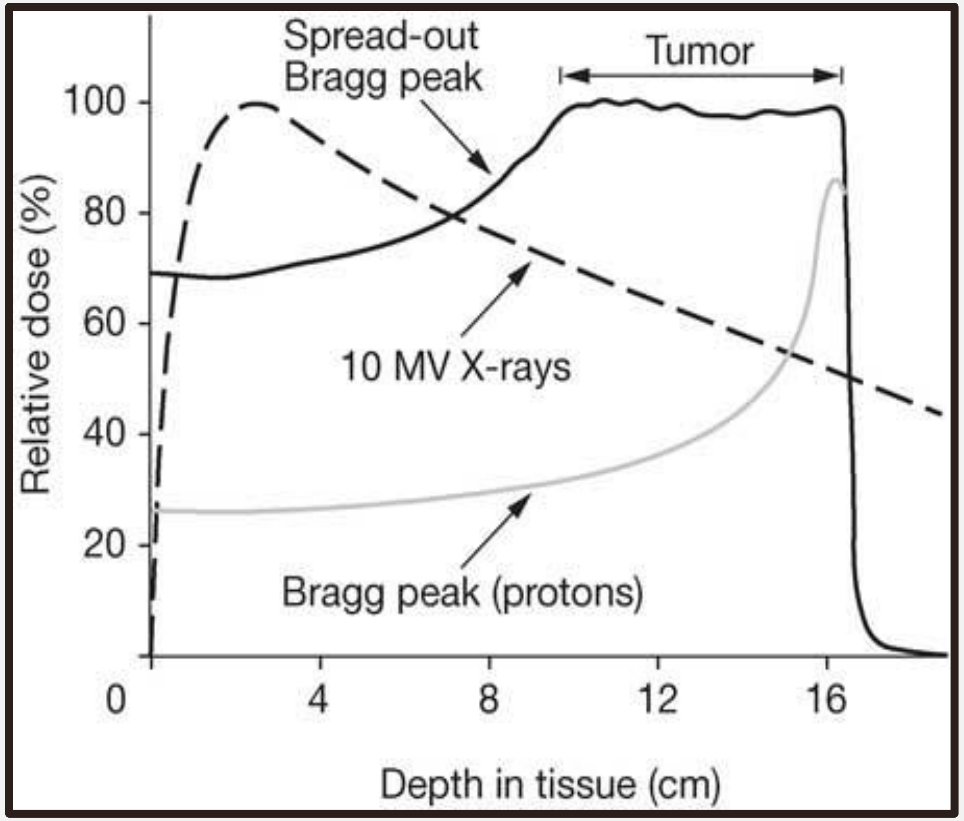
Radiation treatment: Proton therapy

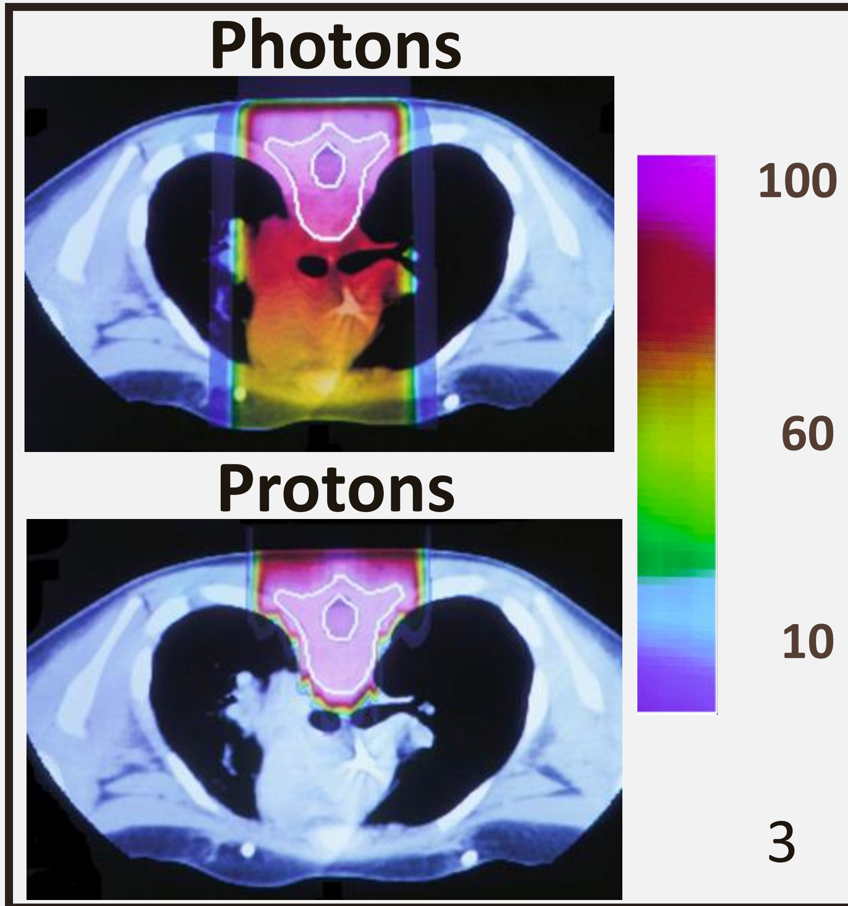
Goal: **To deliver a therapeutic dose to the tumor while minimizing radiation exposure to surrounding healthy tissues**

How: **Precise treatment planning and accurate dose delivery.**



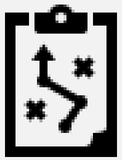
The Far Side – Gary Larson





Radiation treatment: Proton therapy

Goal: To deliver a therapeutic dose to the tumor while minimizing radiation exposure to surrounding healthy tissues



How: Precise treatment planning and accurate dose delivery.

Benefits

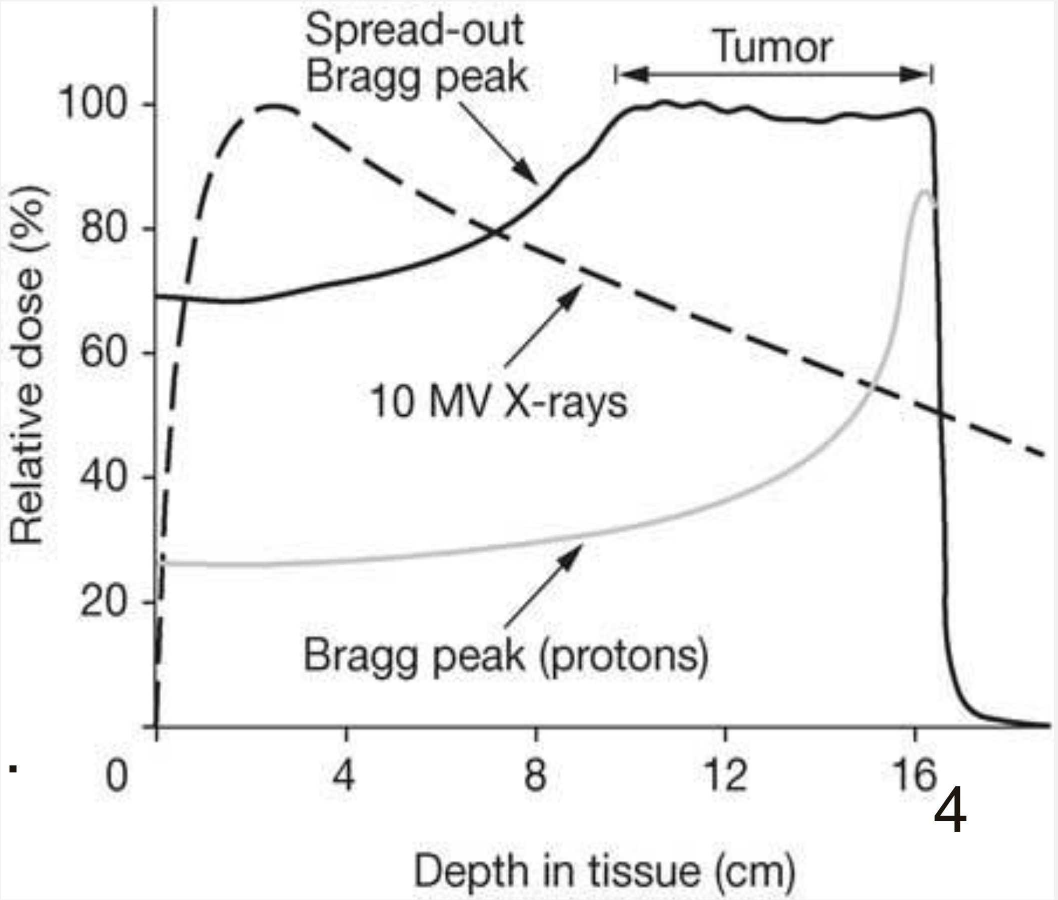
The low entry point and sharp distal fall-off i.e., protons stop (Finite range)

The low-dose plateau with low energy transfer after the Bragg peak

Limitations

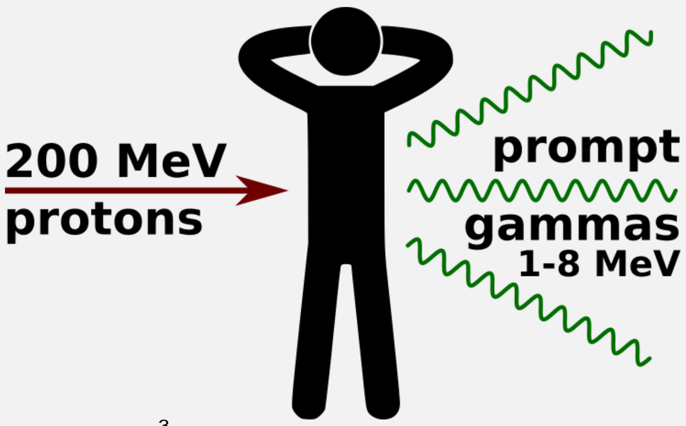
Beam range uncertainty: tissue density fluctuation, range straggling , large penumbra ….

Patient and organ movement

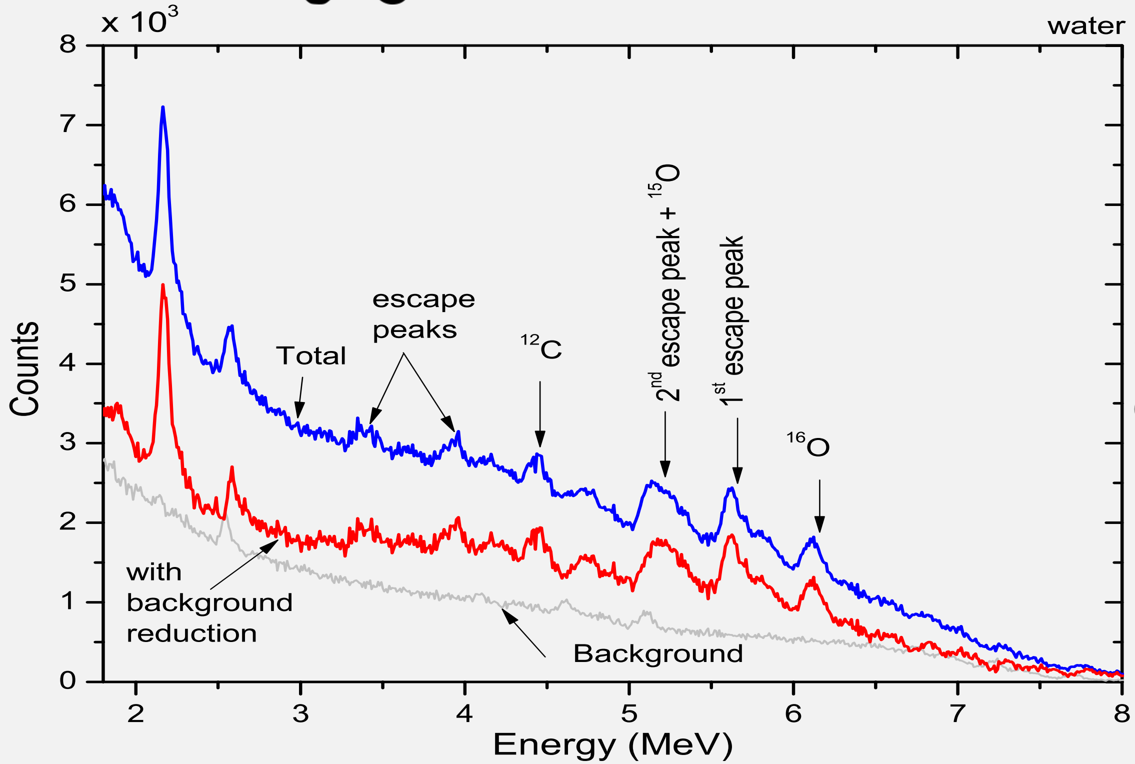


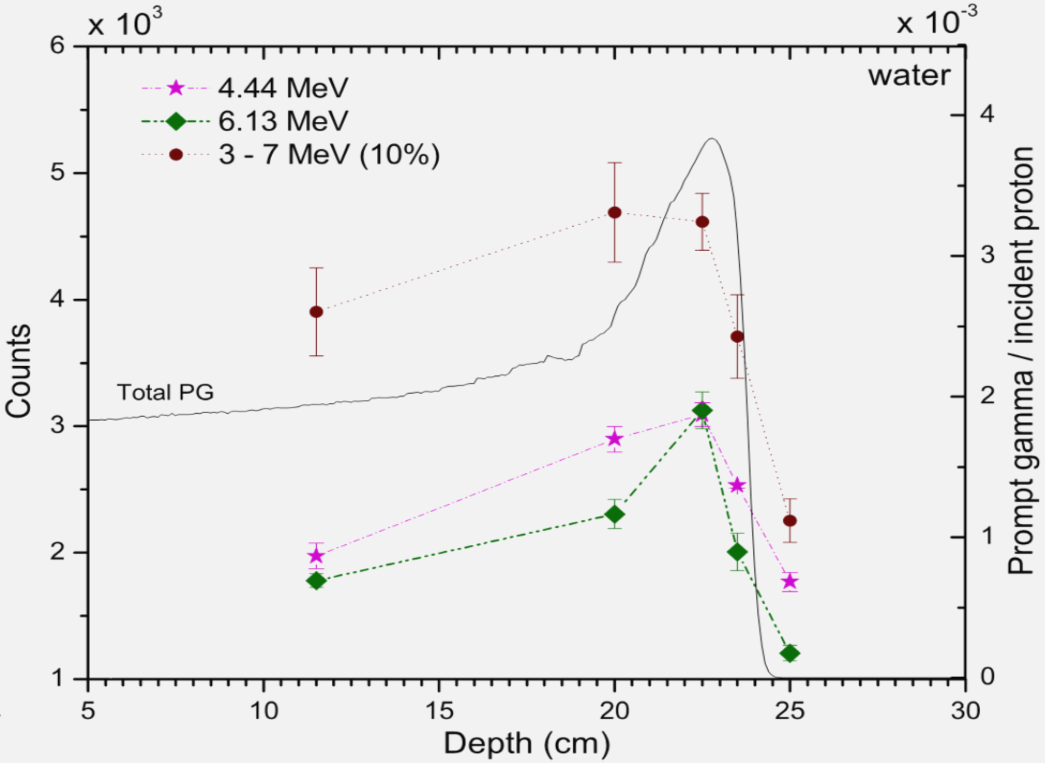
Prompt Gamma Imaging (PGI)

A solution to proton range verification



During proton therapy, accelerated protons excite atomic nuclei, which promptly de-excite and emit prompt gamma rays.



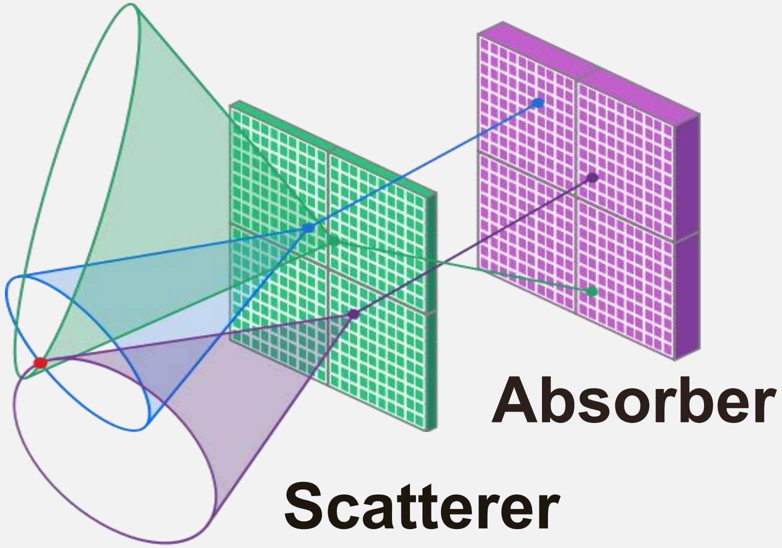


200 MeV protons on water target

J Jeyasugiththan et al 2021 BioMed Express, **7**, 025013

Prompt Gamma Imaging (PGI)

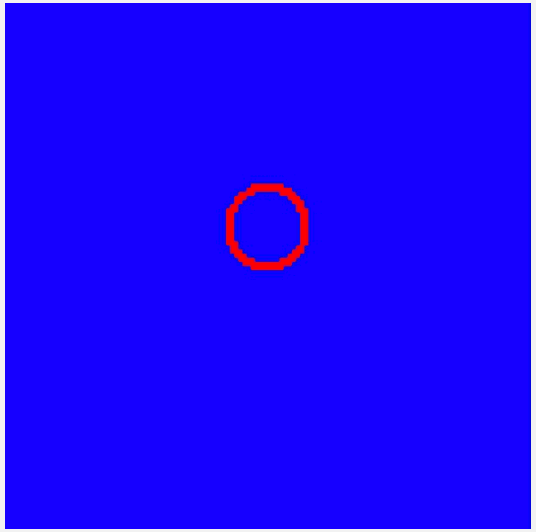
Compton Cameras

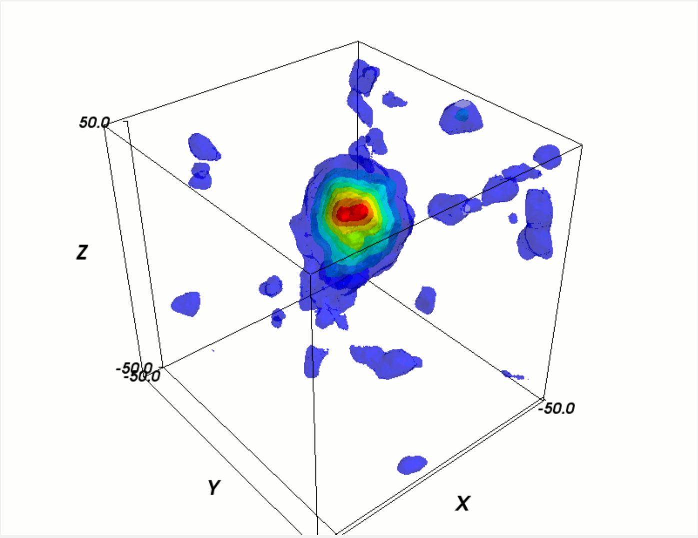


Each event in the Compton camera produces a cone-of-origin.

$$\cos\theta_1 = 1\, m_e c^2 \left(\frac{1}{E_0} - \frac{1}{E_0 - E_1}\right)$$

The cones are overlapped to produce an image of the source location.

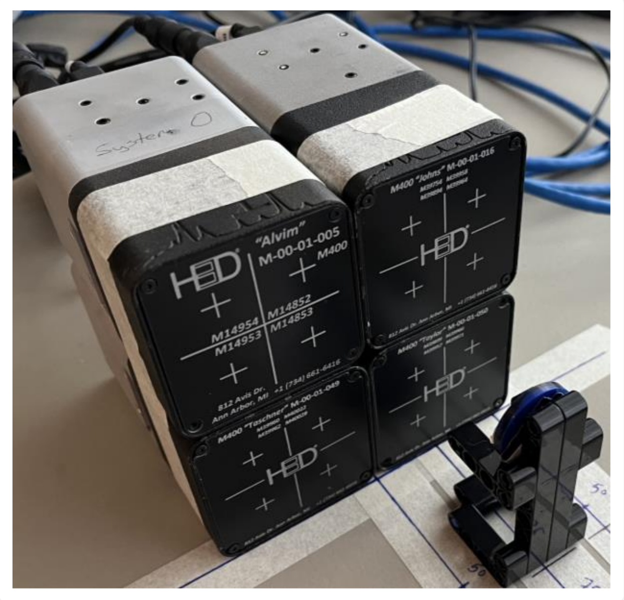


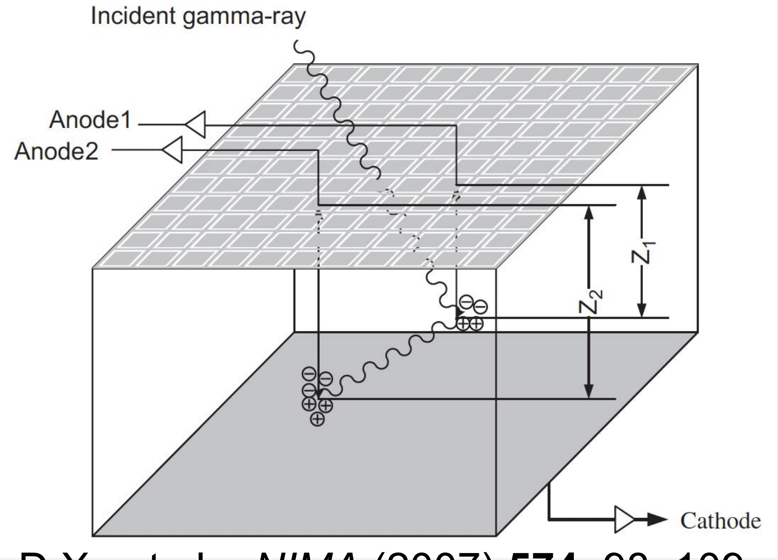


^{137}Cs point source using CORE algorithm from the UCT Polaris detector system

CdZnTe CC Detector Systems

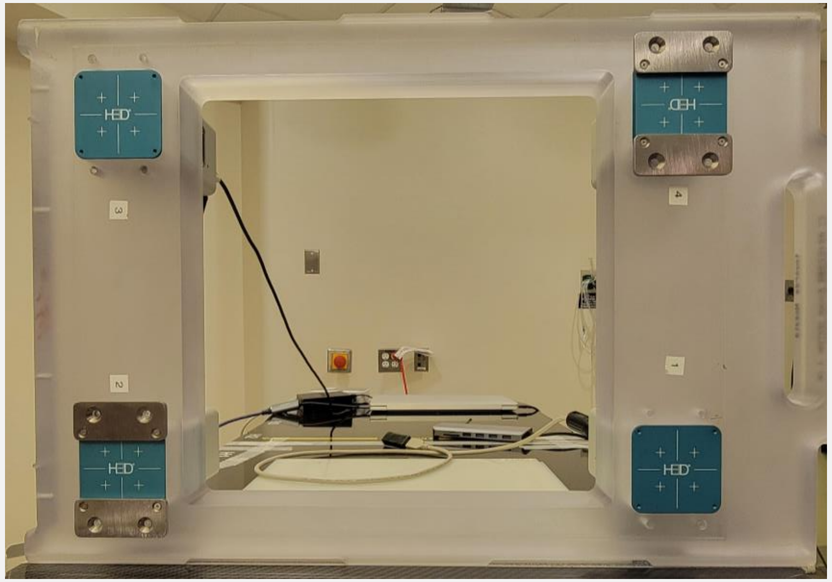
UCT





D Xu et al – *NIMA* (2007) **574**, 98–109

UMMC Nozzle-mounted



- Four 20×20×10 mm^3 cadmium zinc telluride crystals

- Each crystal arranged in a 2×2 array, pixelated in a 11×11 *x*- and *y*- direction and a *z*- direction depth of interaction

3D Gamma detection

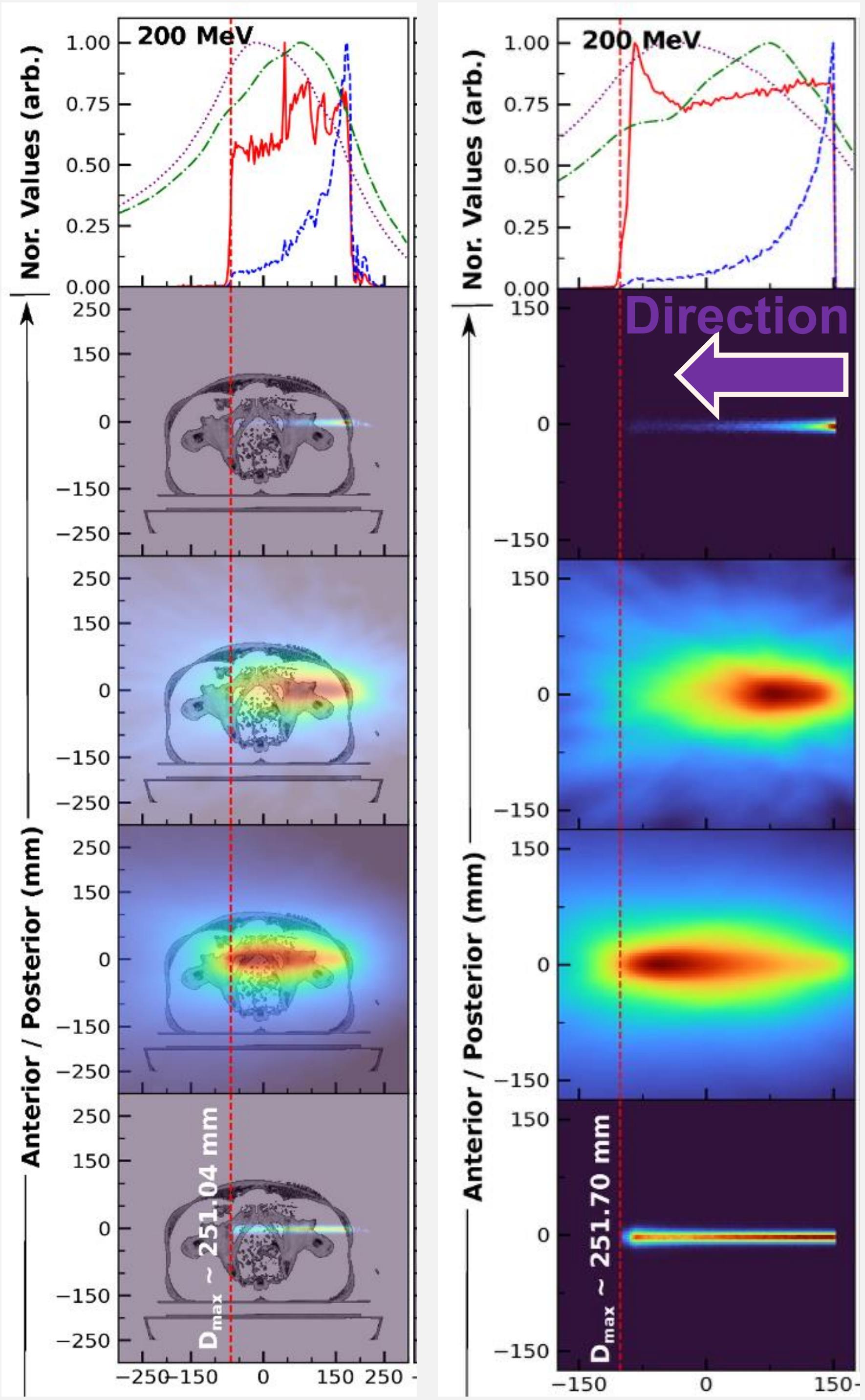
Room Temperature

Good Energy Resolution (0.8% FWHM at 662 keV)

Compact

Gamma Attenuation

In a nozzle-mounted detector system, reconstruction along the direction of the beam is challenging due to attenuation of the gammas as they travel through the patient.

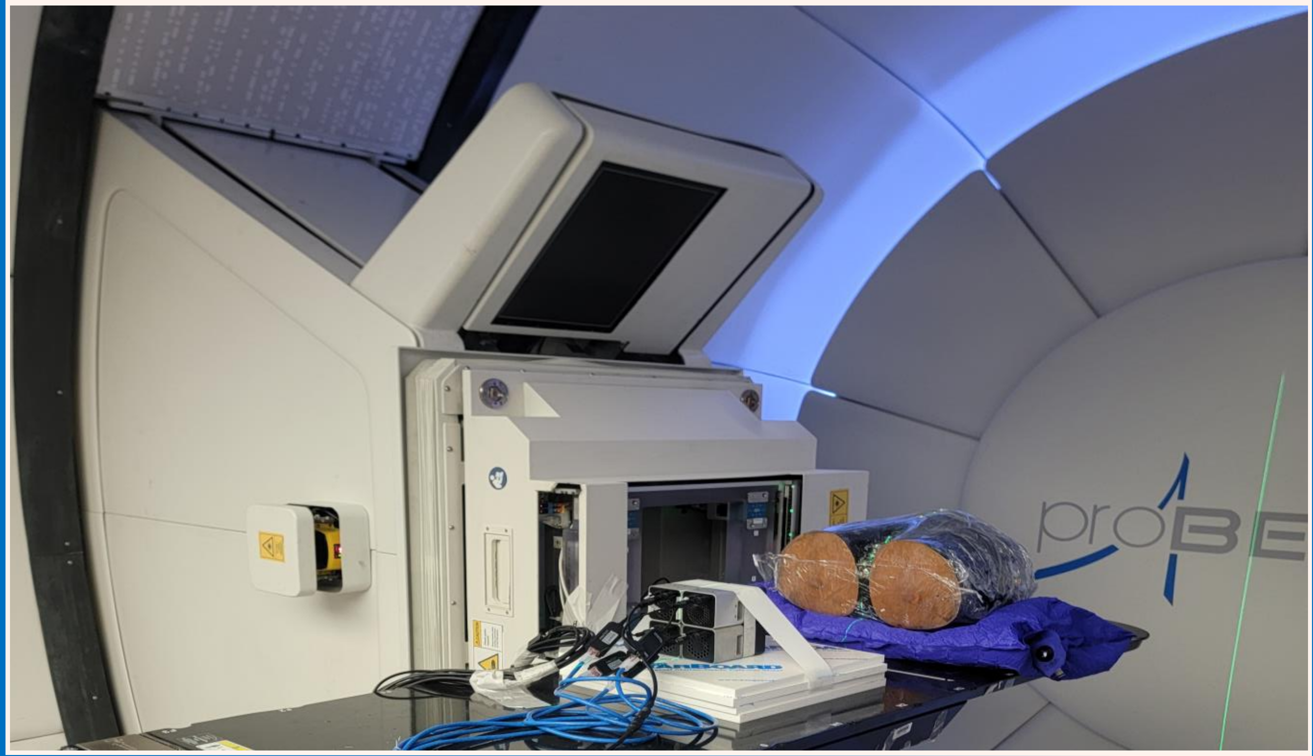


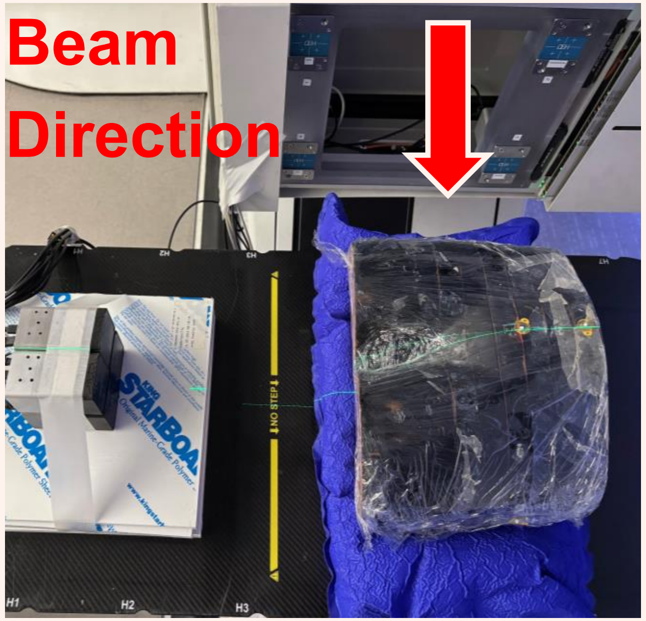
Raw Reconstruction

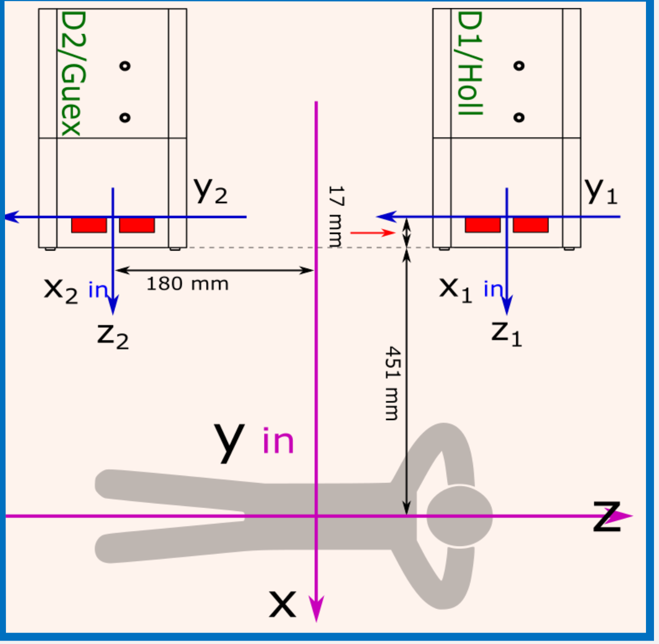
Corrected Reconstruction

Monte Carlo Simulations of 200 MeV protons incident on water target of the Maryland Clinical System

V Sharma et al 2025 IEEE Trans. Rad. Plas. Med. Sci., currently under review







Maryland Proton Treatment Centre in Baltimore

1. **Feasibility — Can the detector system reconstruct proton depth deposition?**
2. **Investigate gamma-ray attenuation and range shift.**
3. **Using the UCT detector system to support the UMMC detector system**

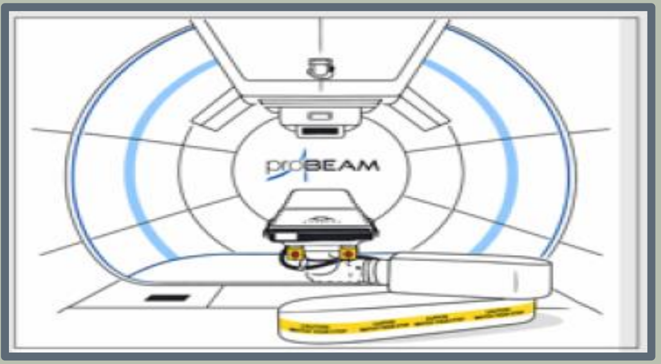
150 MeV single-spot beam
Gantry 270°
80 nA · 60 kMU

Image Recon. Pipeline

Data Acquisition

Quad CC System

UCT M400s



Data Preprocessing

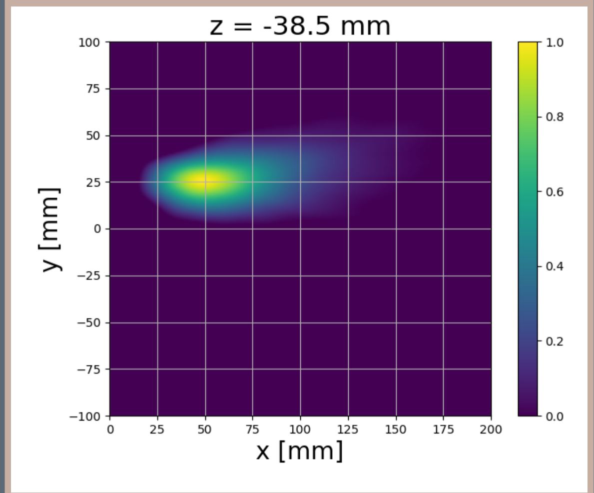
- Binary Format Conversion
- Coordinate transformation
- Filtration
- Merging data

- Double events

CORE Algorithm

Image Analysis

- Region of Interest Extracted
- Generate 2D Slices & 1D Profiles
- Gaussian Fitting
- Estimate Source Position & Peak Intensity



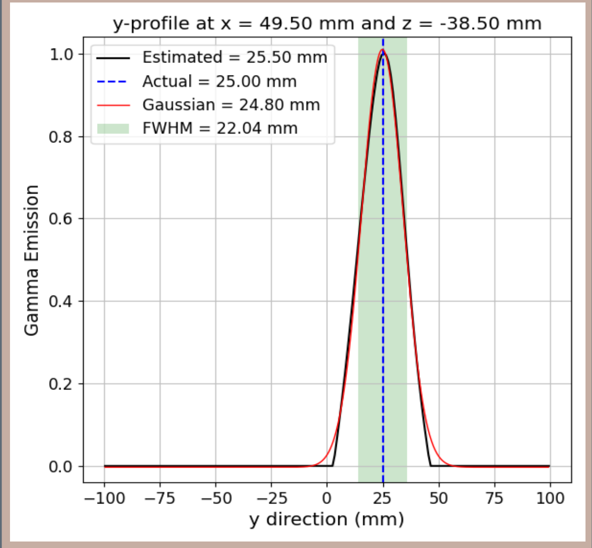


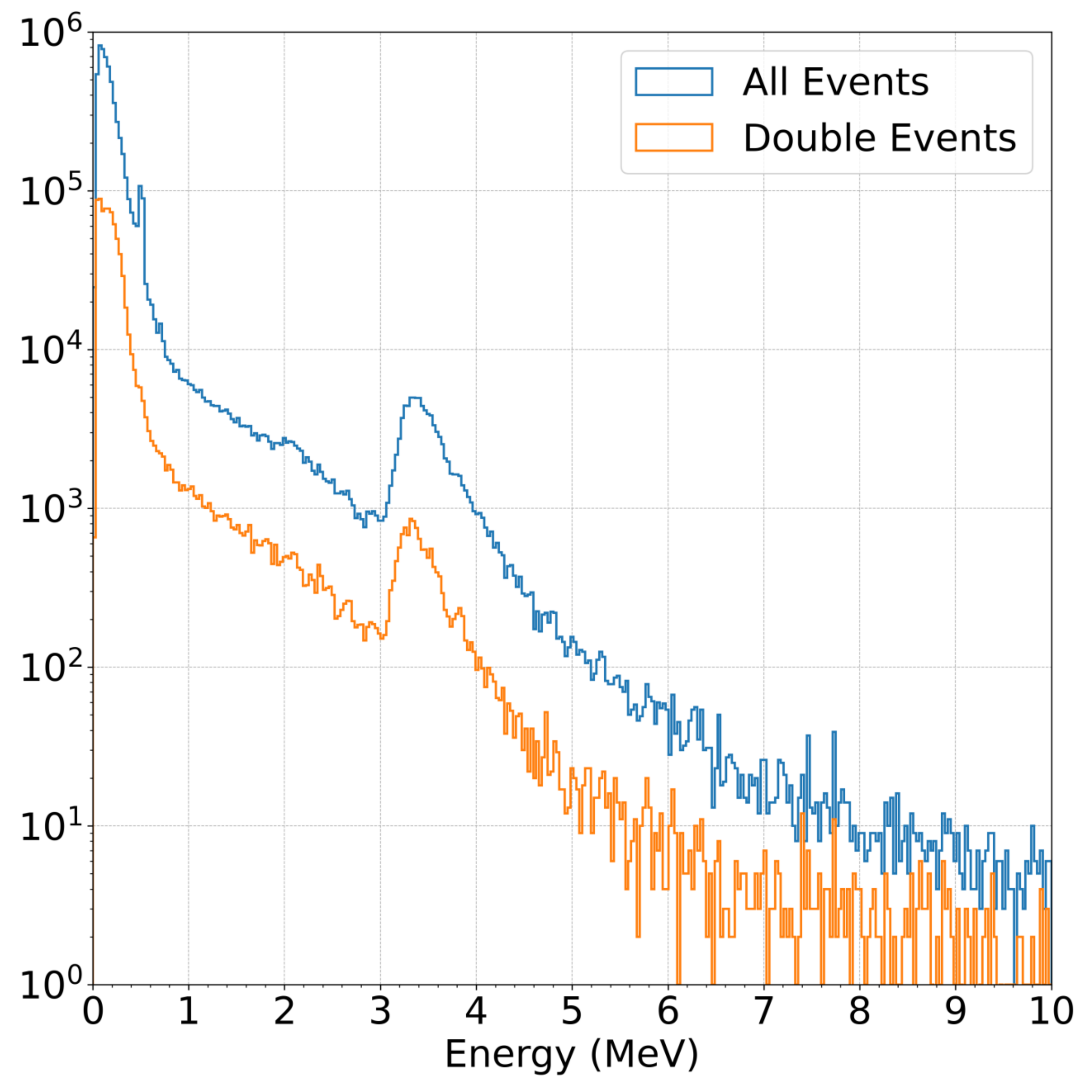
Image Algorithm

- SBP, SOE, Octane EM, KWPB
- 3D image source location

Filtration

- Scattering distance, angle
- Energy windowing
- Energy lost etc.

UCT Detector Results

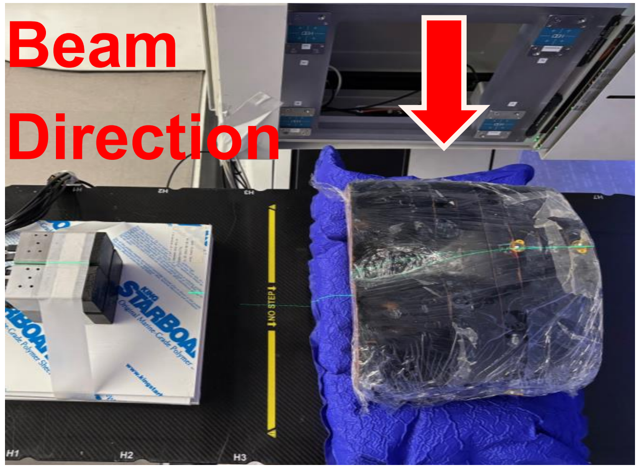


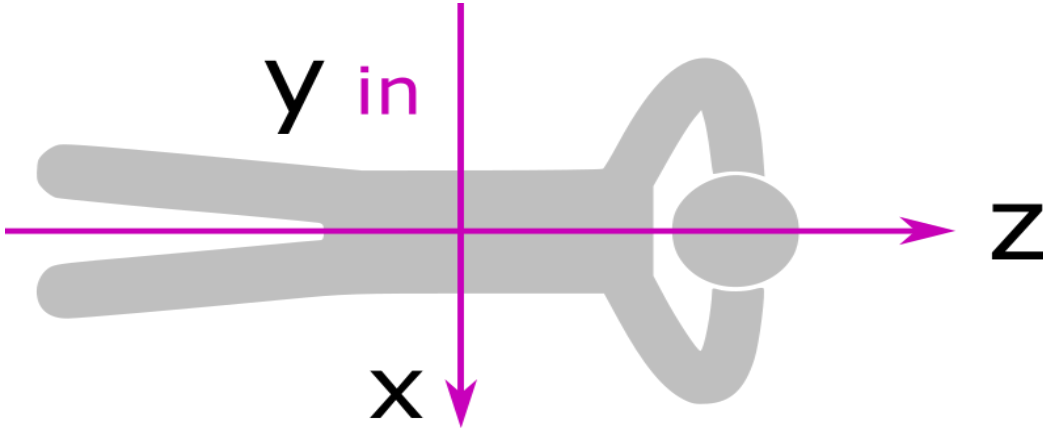
Total Events	4.99×10^6
Preprocessing	3.79×10^5
CORE Filtering	2.84×10^5
Used	2.84×10^5

Parameter	**Phantom**	**CORE**
Dims. (mm)	1280^3	800^3
Grid	64^3	100^3
Voxel (mm)	20^3	8^3

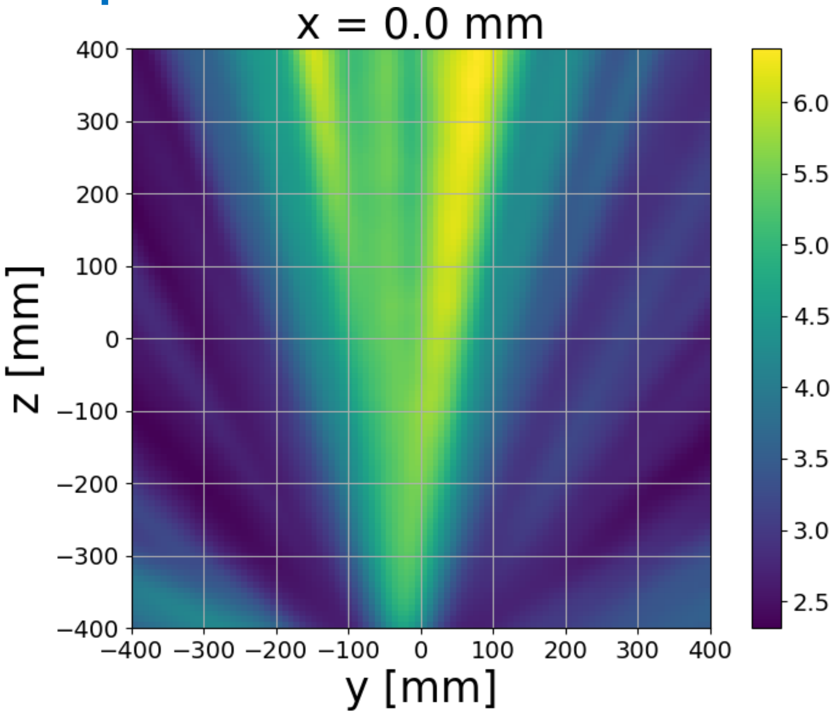
UCT Detector Results

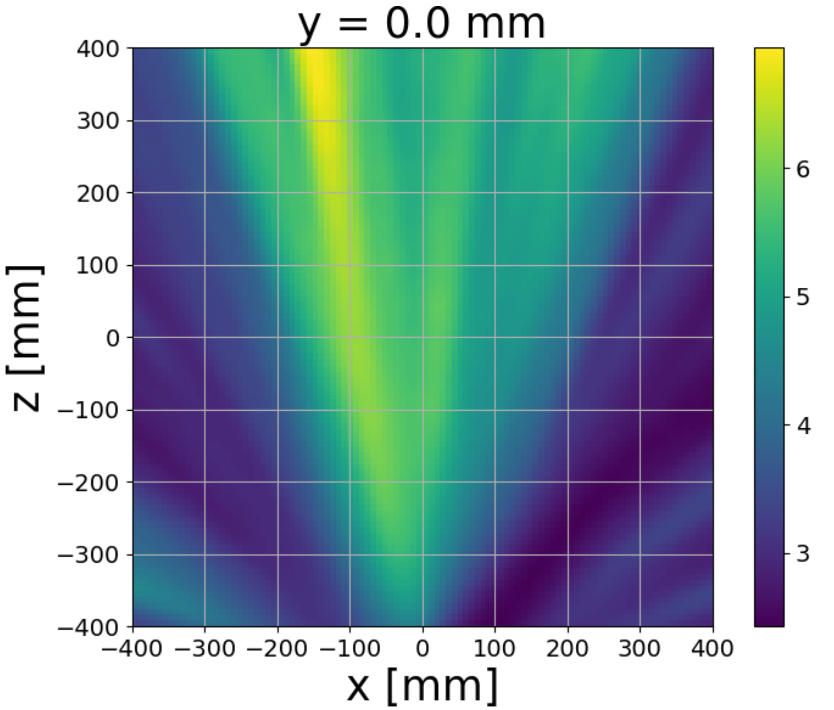
Experimental Setup

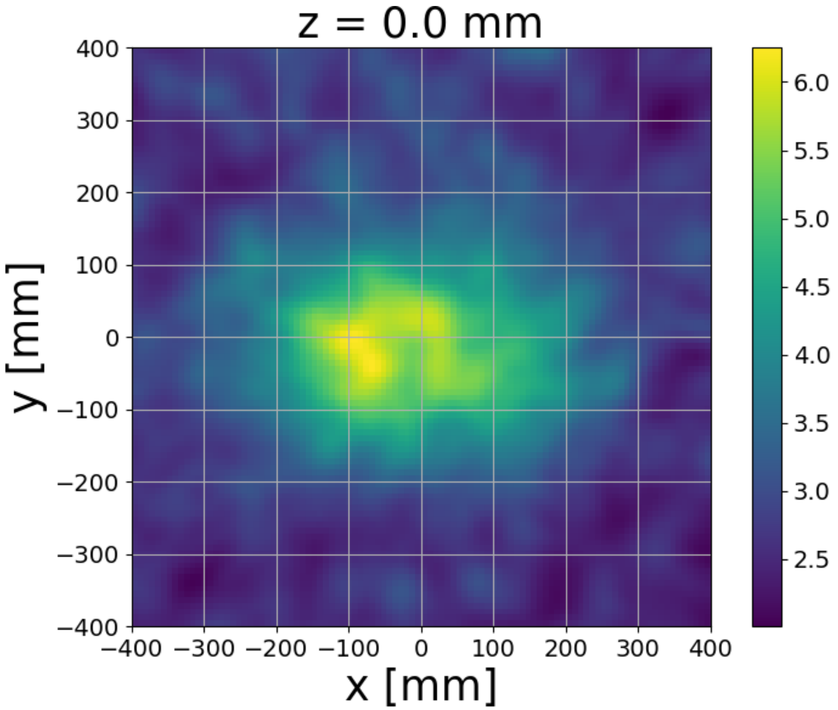




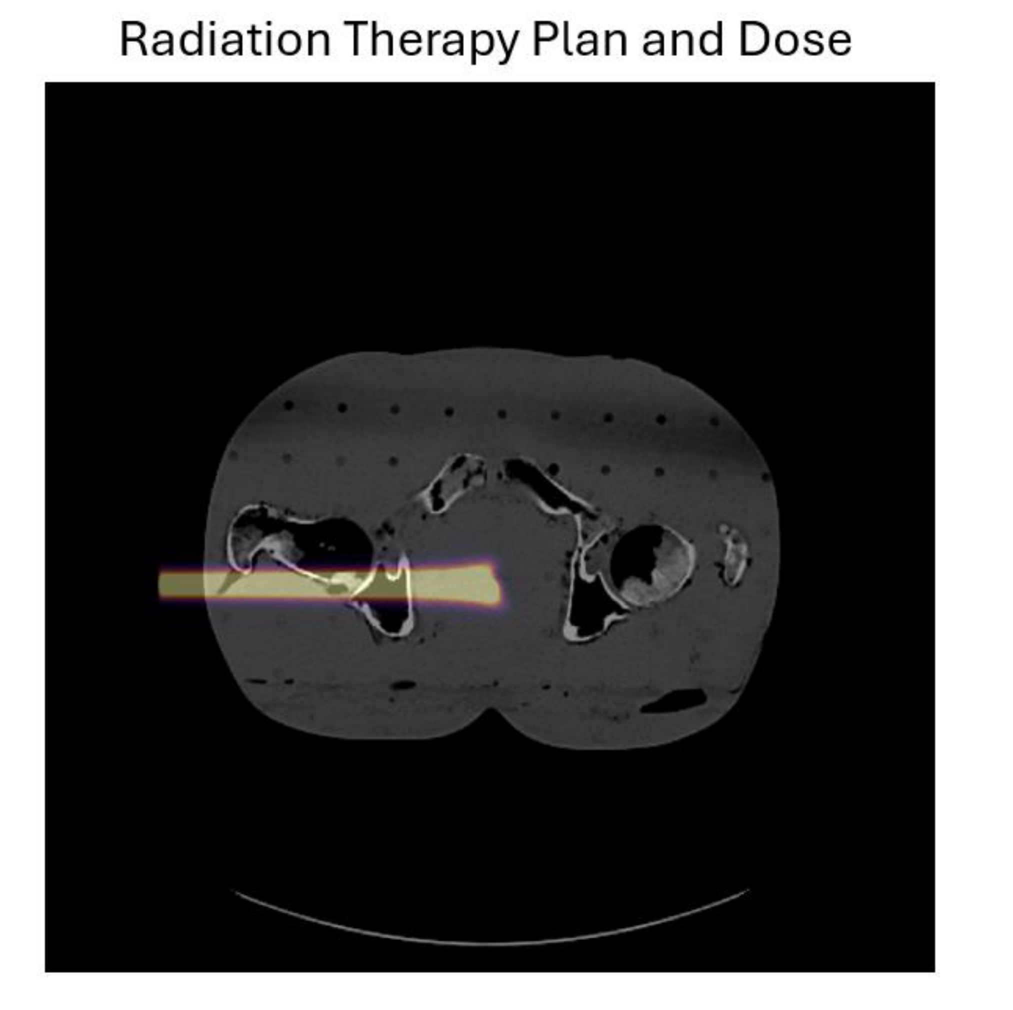
Expected Location



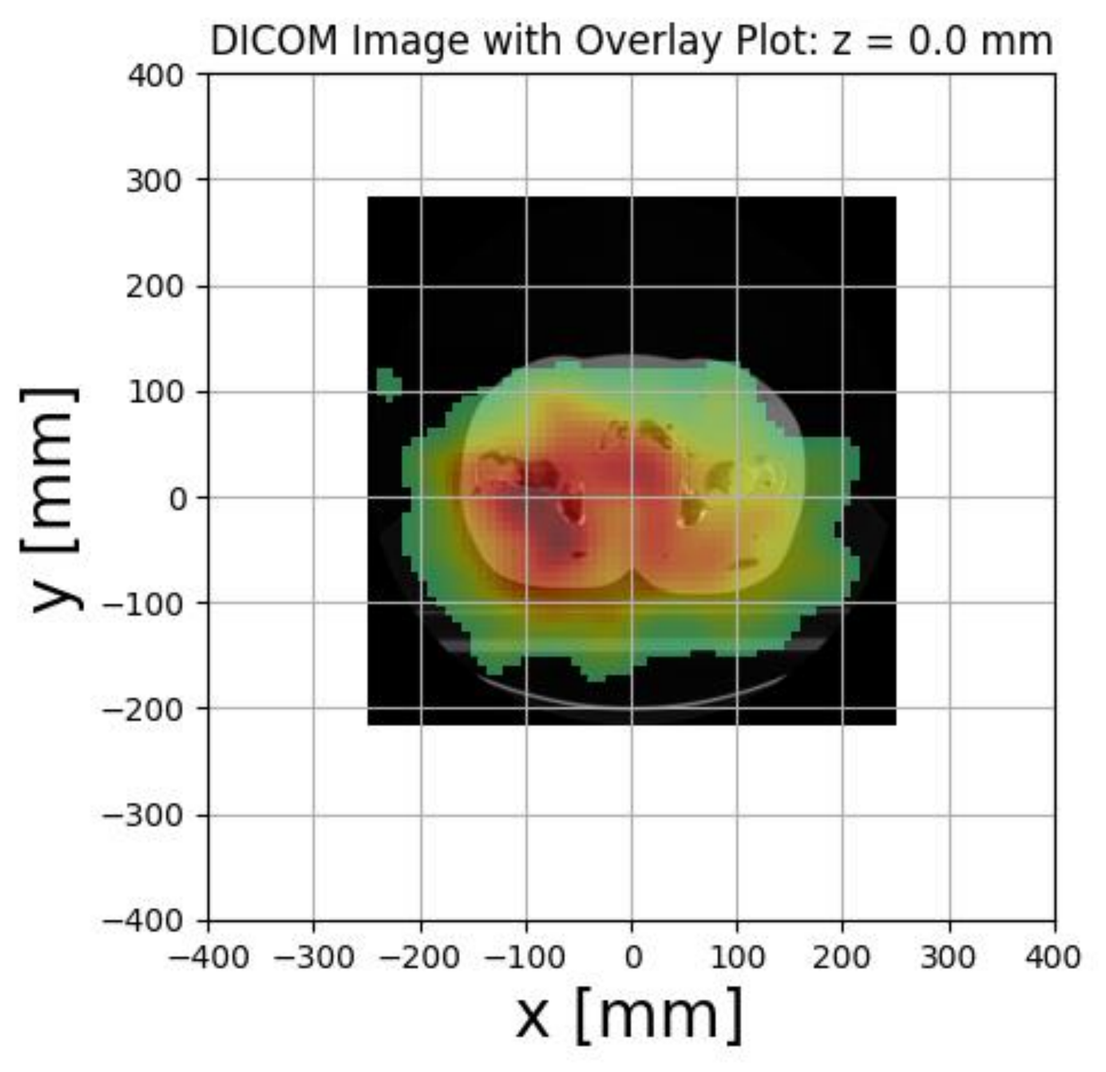




UCT Detector Results

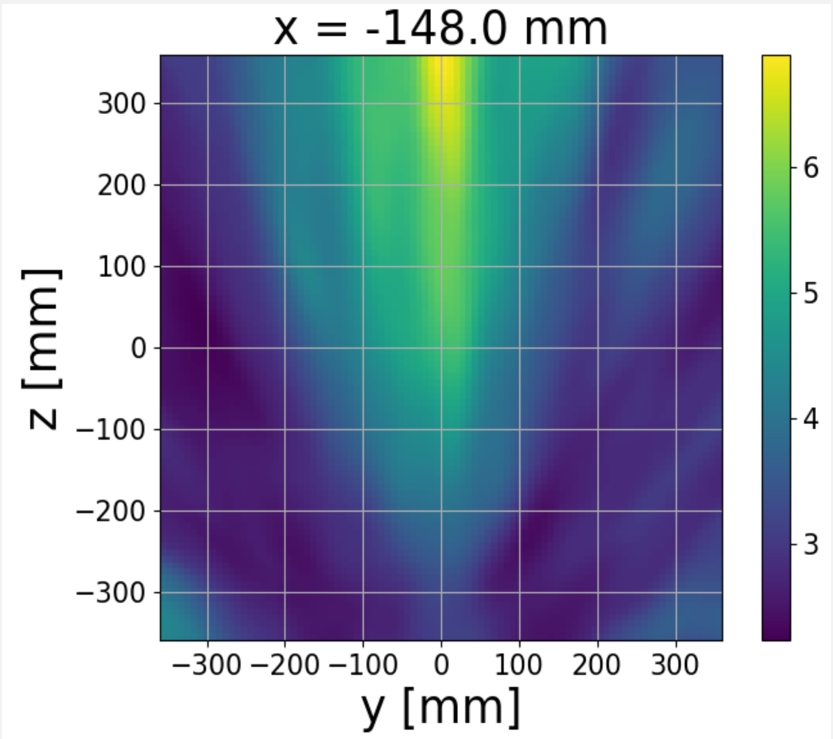


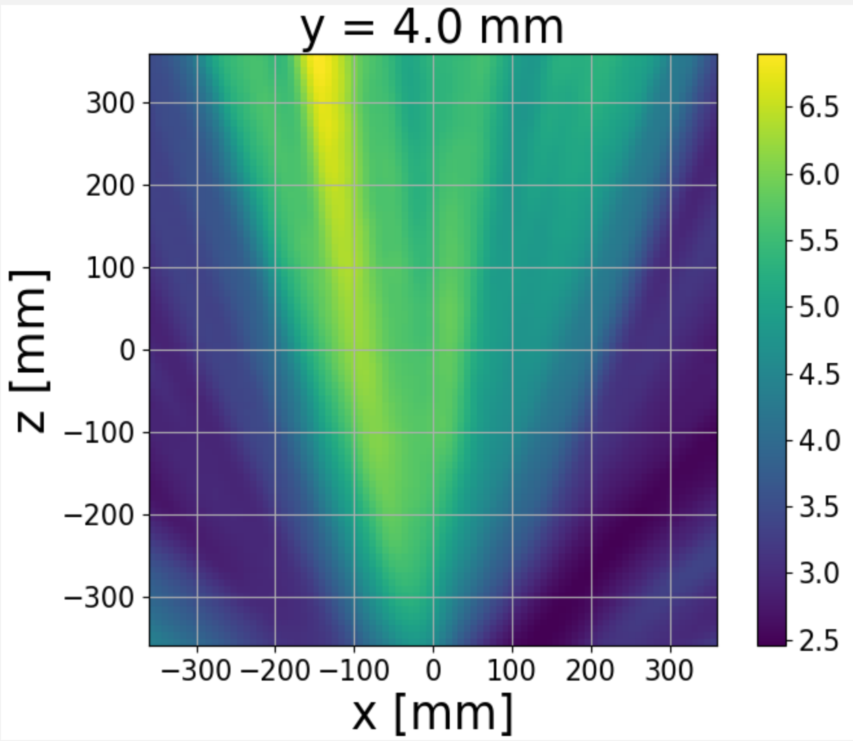
CT

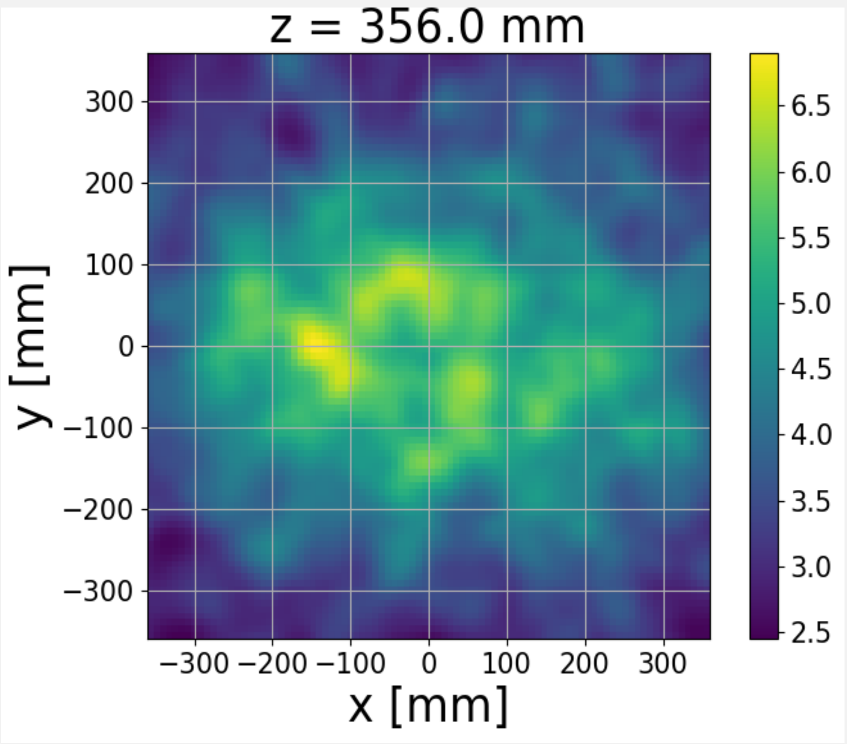


UCT Detector Results

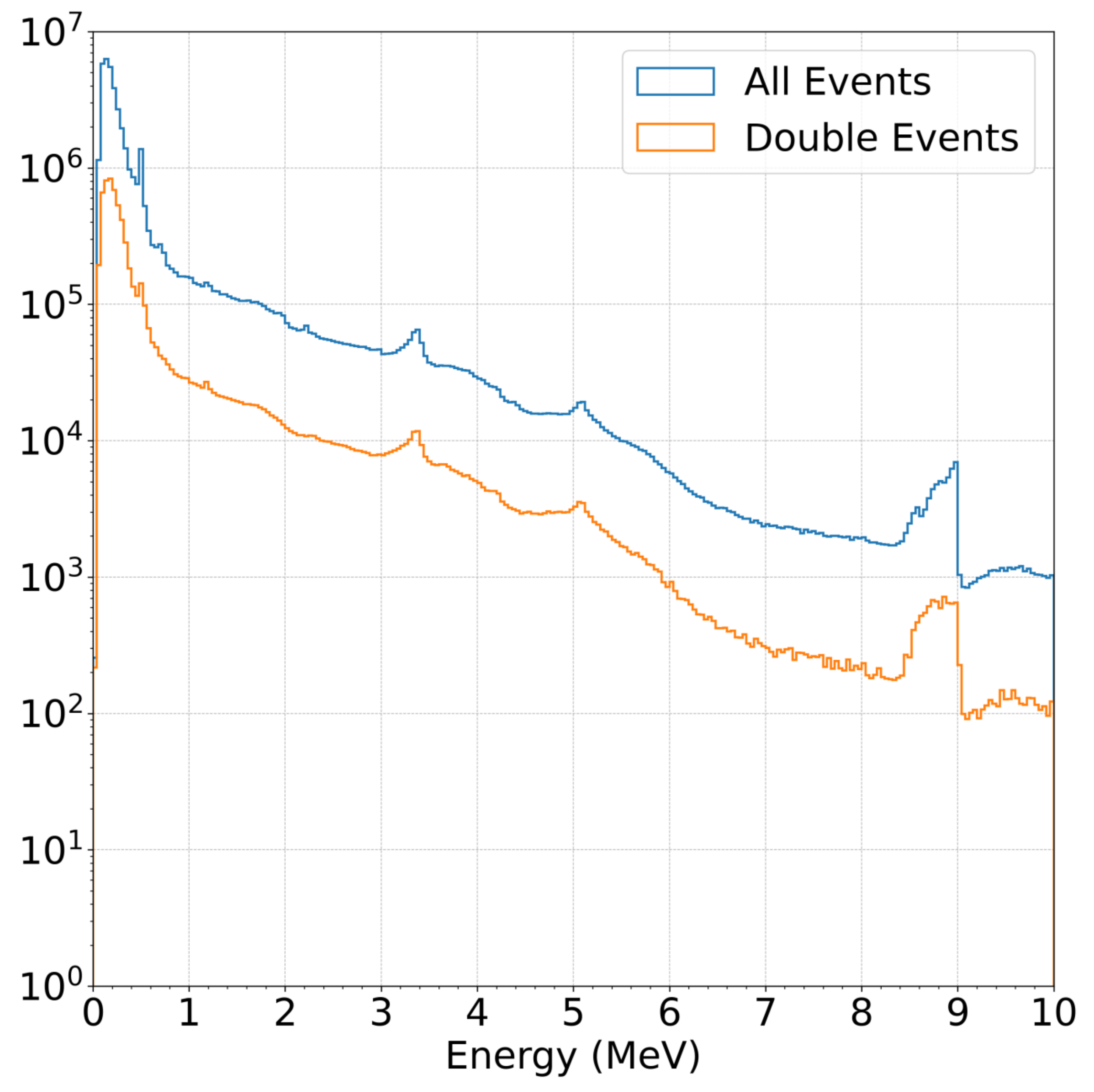
Expected Location : (-148.0, 4.0, 356.0) mm







UMMC Nozzle-mounted Results

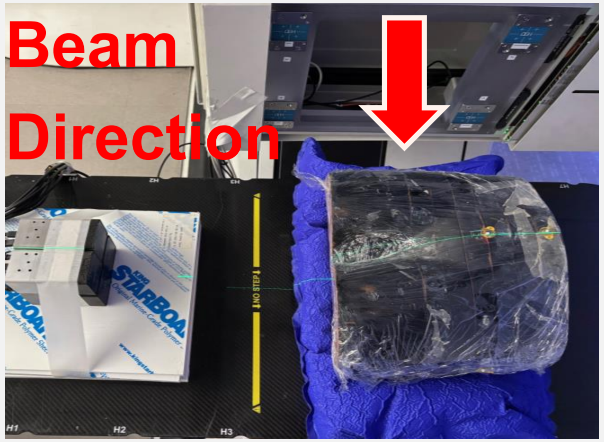


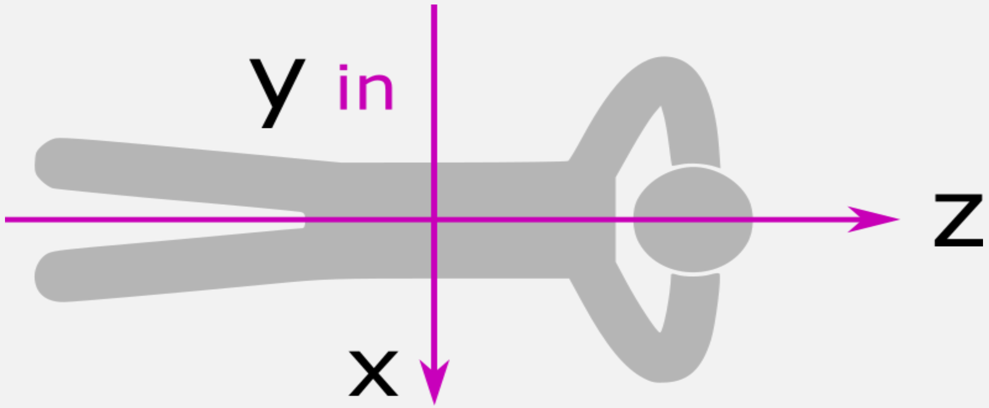
Total Events	3.79×10^7
Preprocessing	3.26×10^6
CORE Filtering	3.22×10^6
Used	2.00×10^6

Parameter	Phantom	CORE
Dims. (mm)	1280^3	1200^3
Grid	64^3	150^3
Voxel (mm)	20^3	8^3

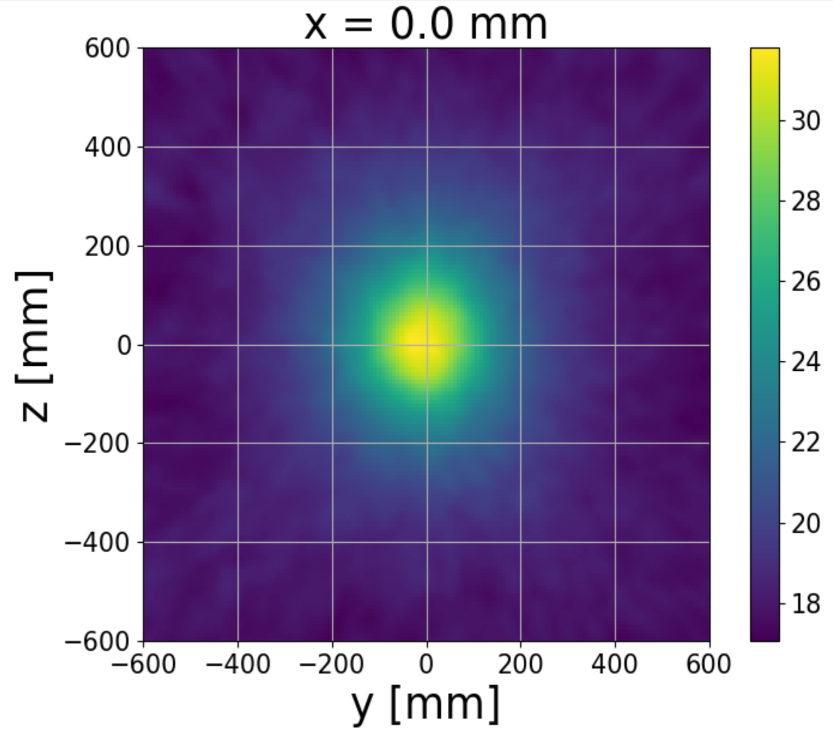
UMMC Nozzle-mounted Results

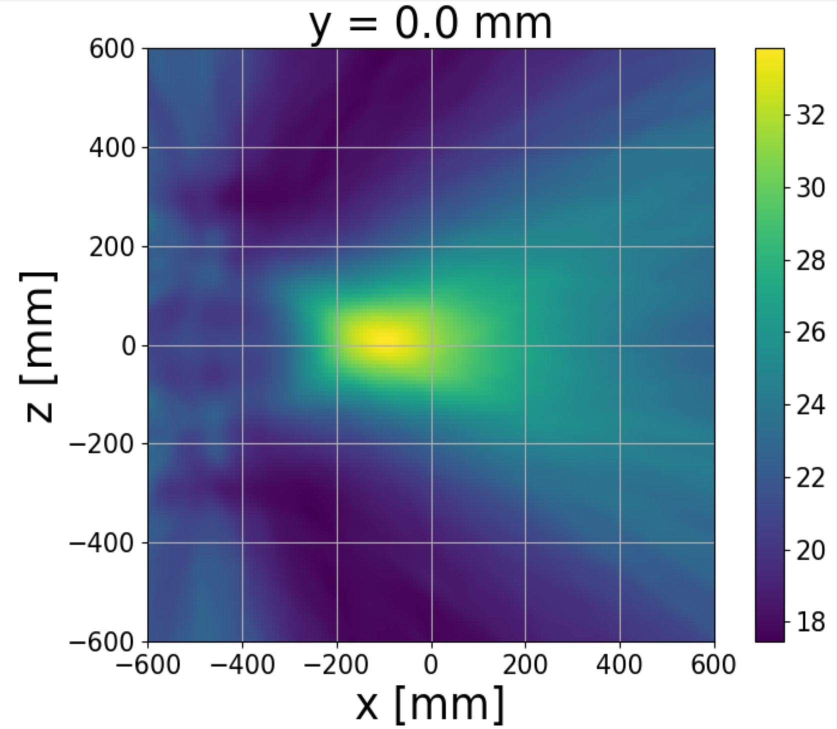
Experimental Setup

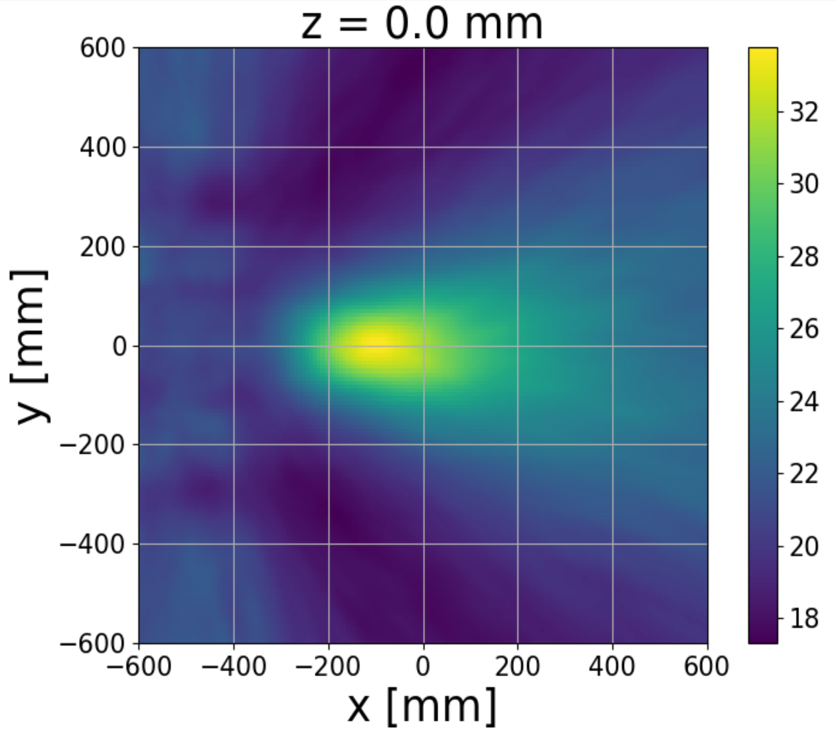




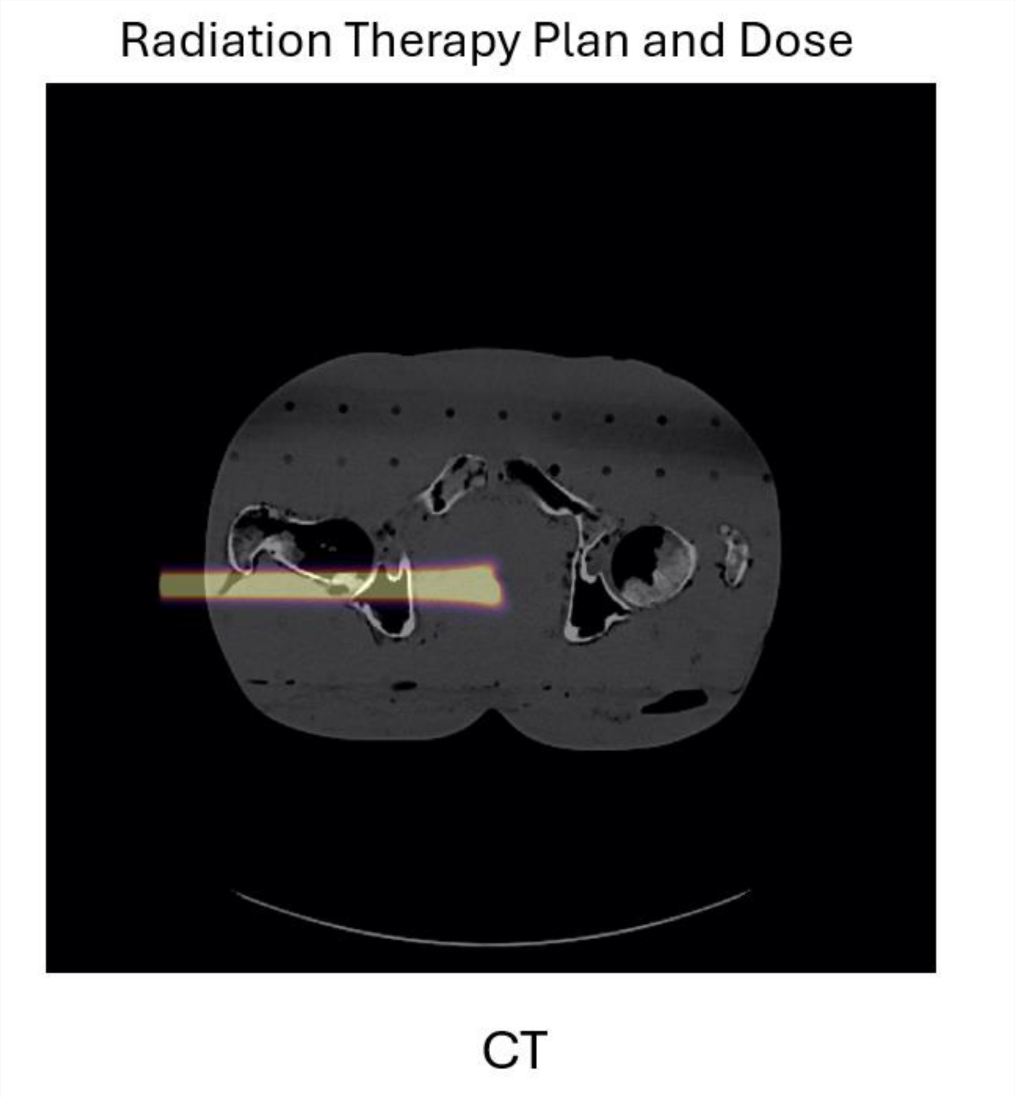
Expected Location

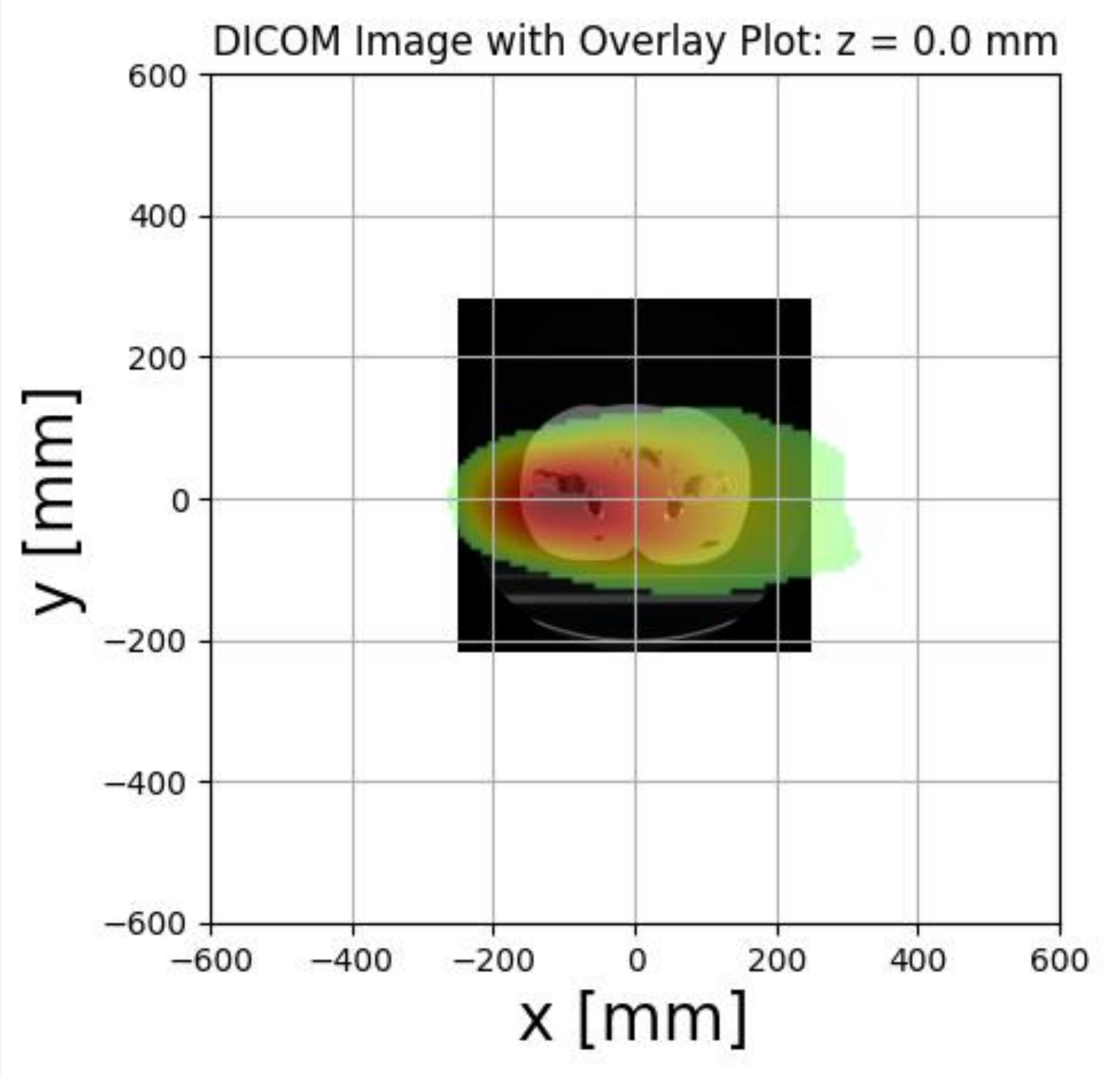






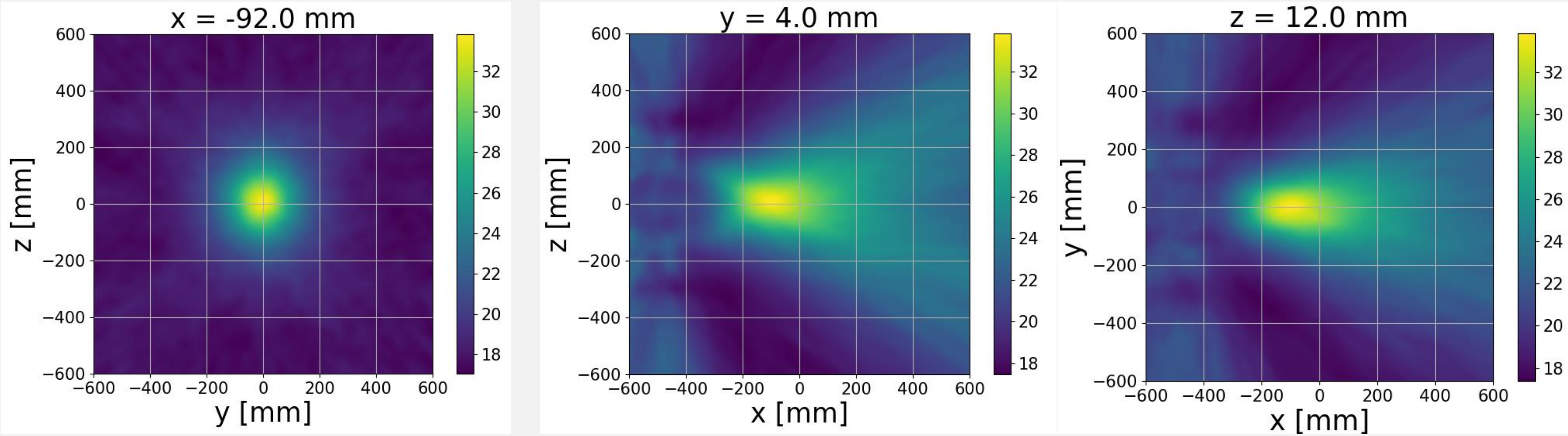
UMMC Nozzle-mounted Results



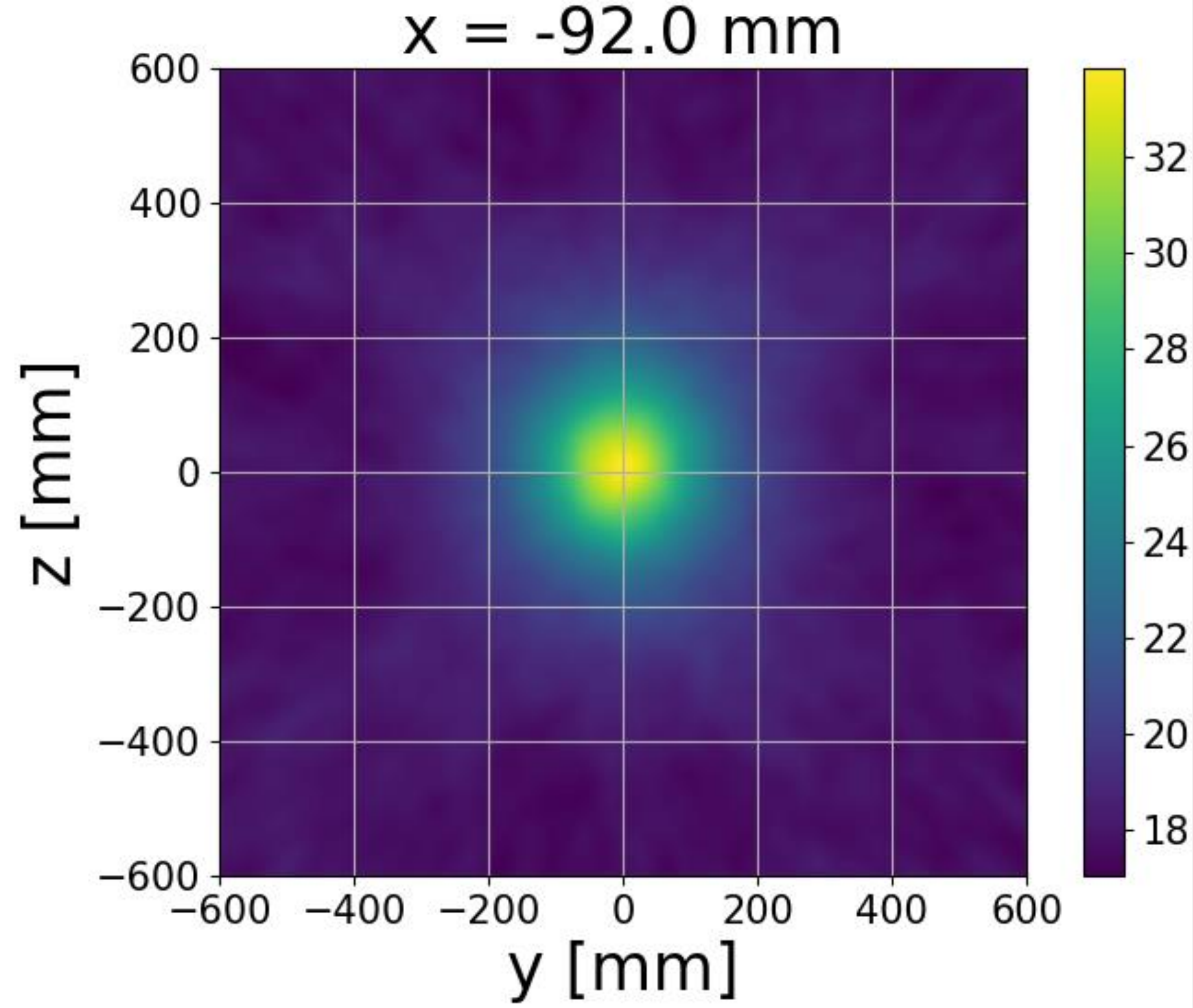


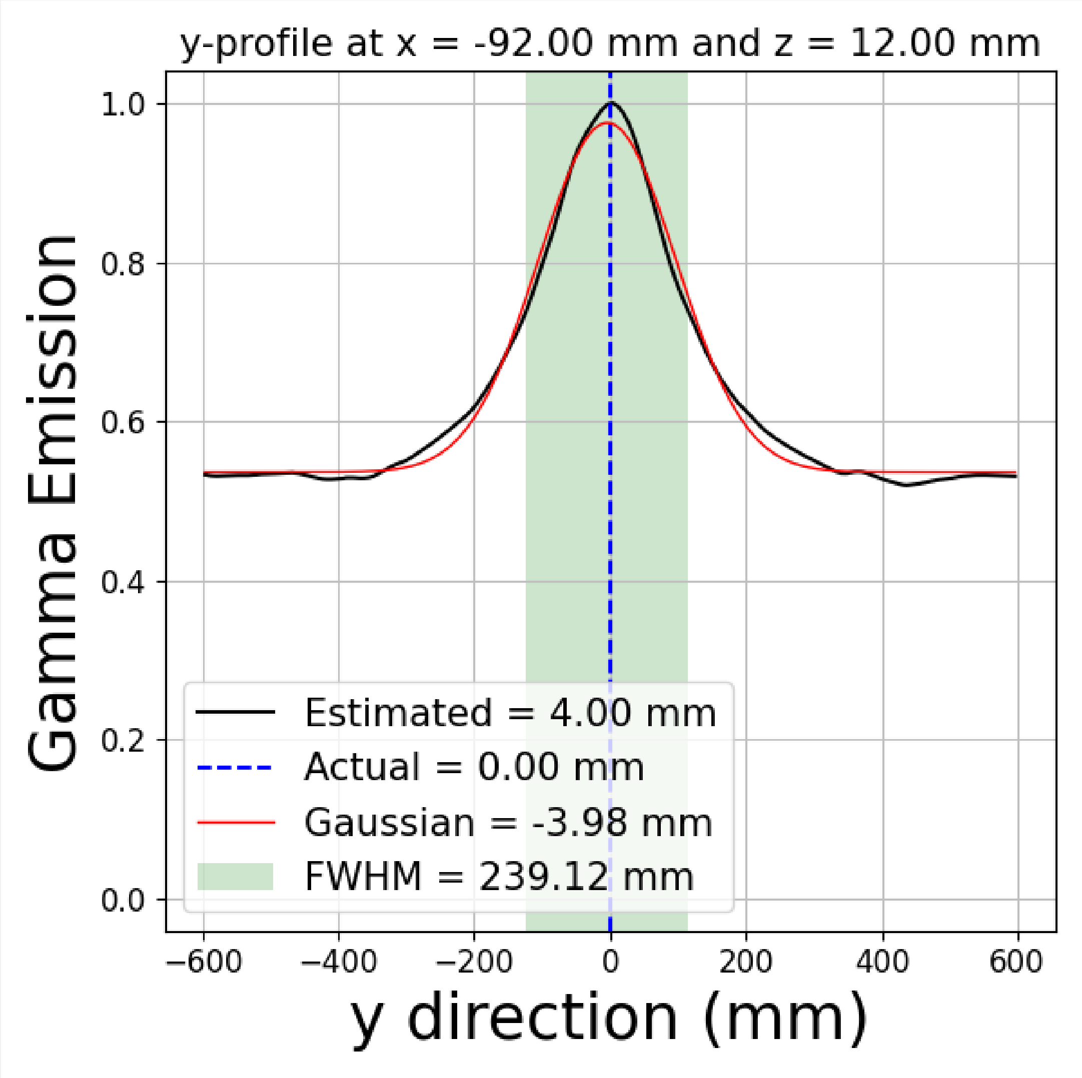
UMMC Nozzle-mounted Results

Expected Location : (-92.0, 4.0, 12.0) mm

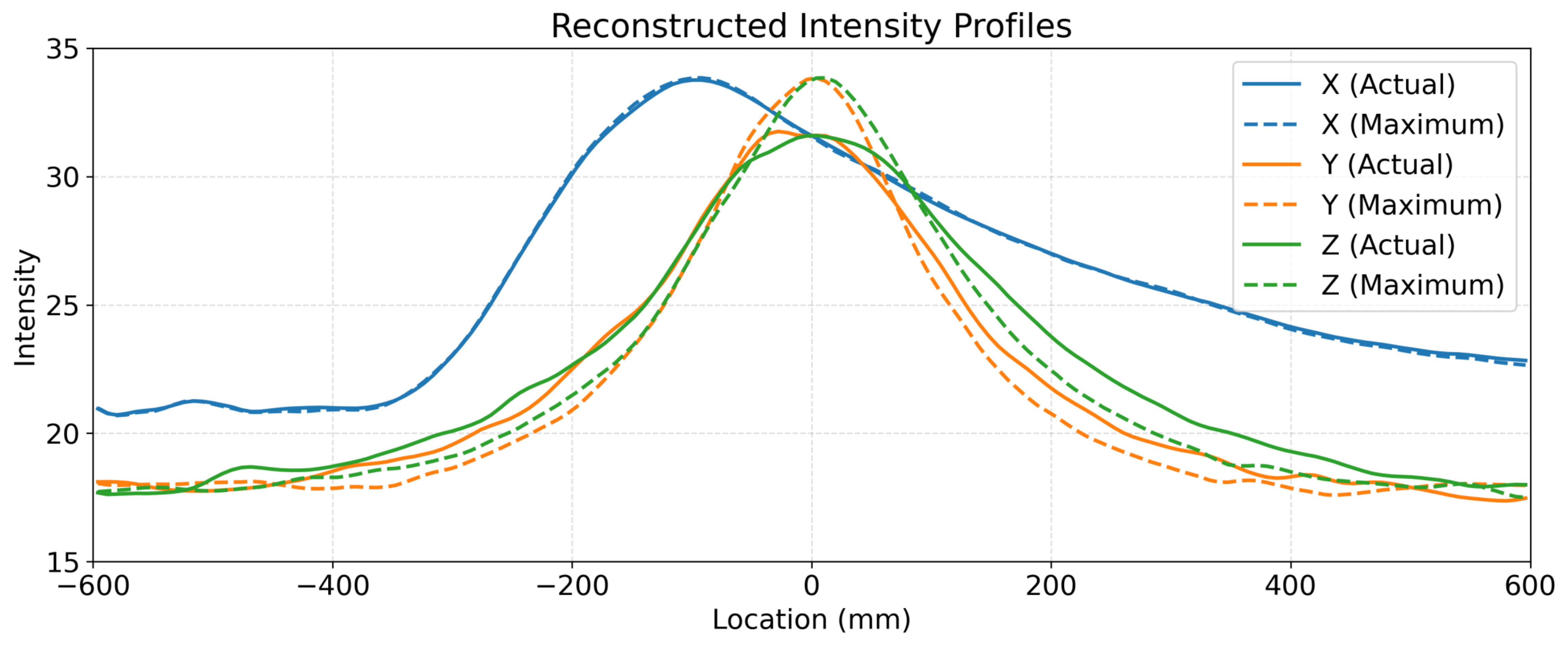


UMMC Nozzle-mounted Results





UMMC Nozzle-mounted Results



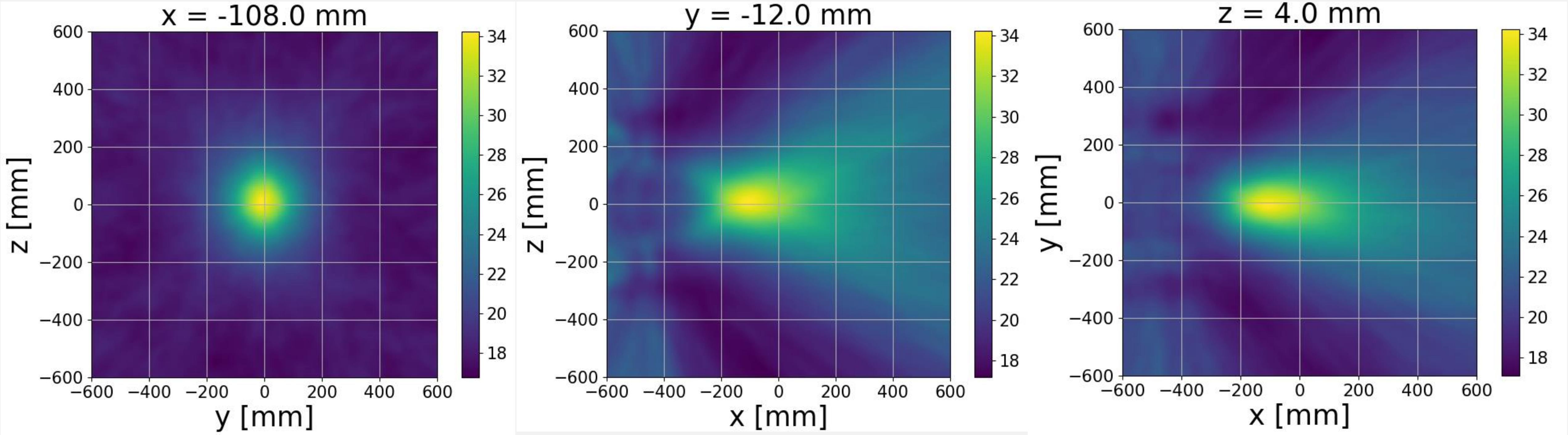
Axis	Max. (mm)	Fit (mm)	FWHM (mm)	σ (mm)
X	-92.00	–	–	–
Y	4.00	-3.98	239.12	101.54
Z	12.00	10.34	274.88	116.73

Distance (Estimated - Actual)

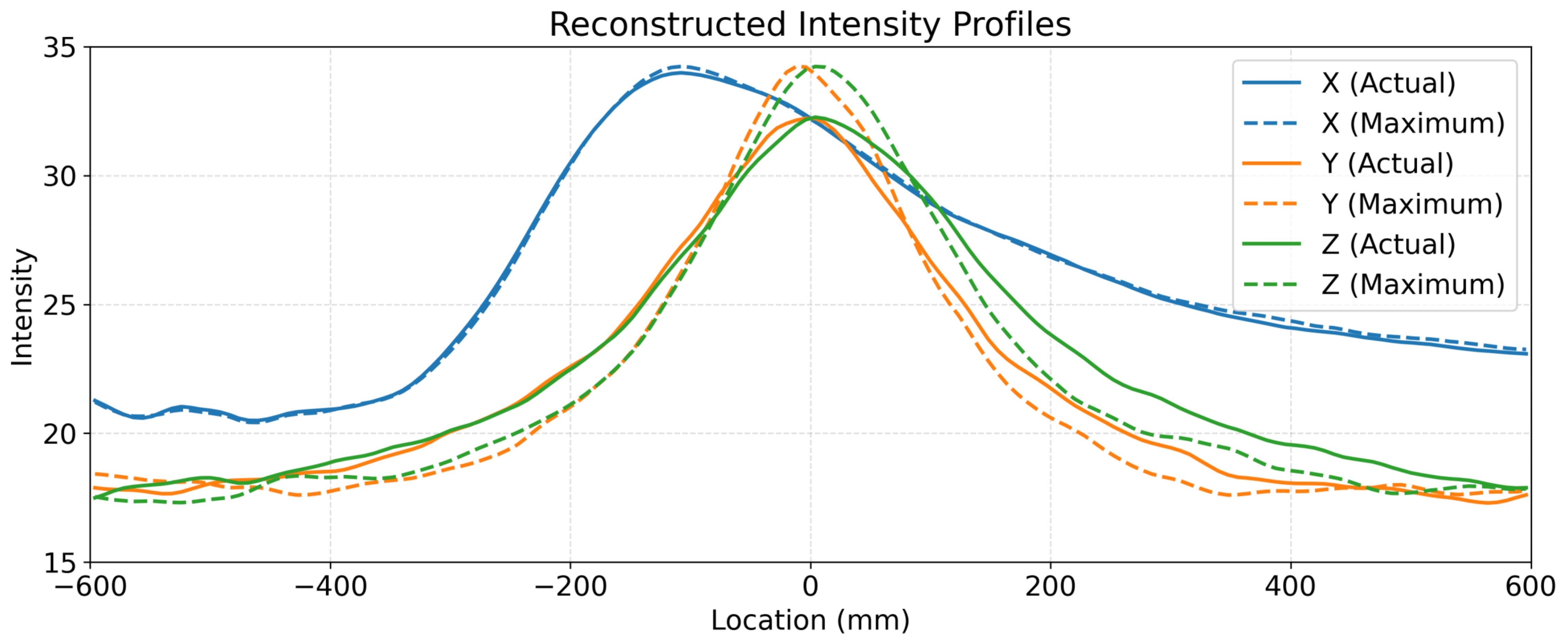
92.87 mm

UMMC 10 mm Range Shift Results

Expected Location : (-108.0, -12.0, 4.0) mm



UMMC 10 mm Range Shift Results

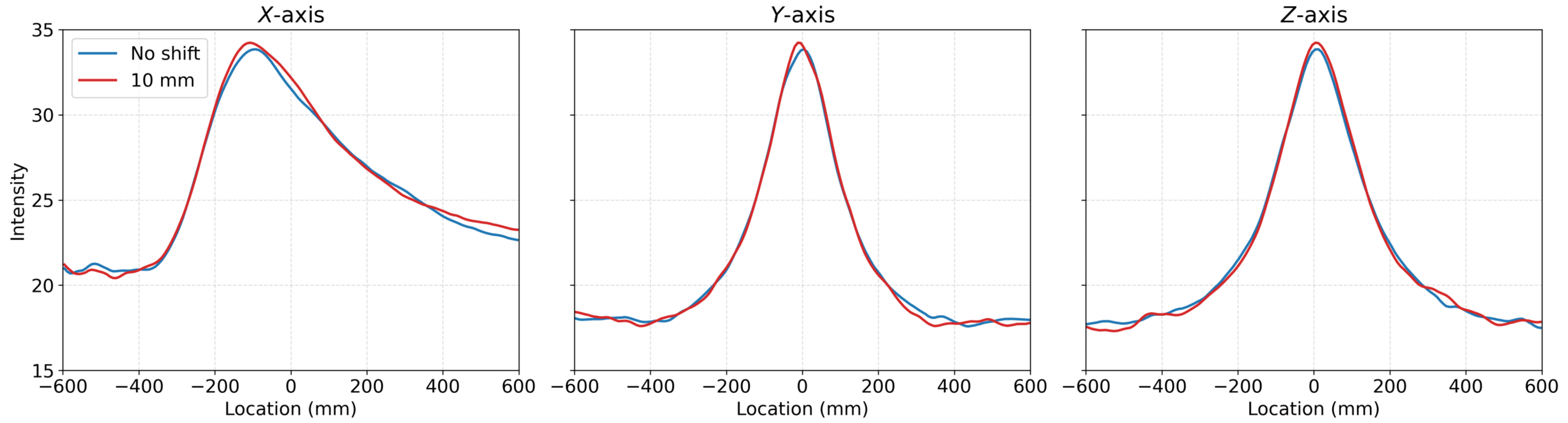


Axis	Max. (mm)	Fit (mm)	FWHM (mm)	σ (mm)
X	-108.00	–	–	–
Y	-12.00	-3.98	236.78	100.55
Z	4.00	11.94	263.63	111.95

Distance (Estimated - Actual)

108.74 mm

Range Shift Comparisons



Metric	No Shift	10 mm Range Shift	Change
Distance Error (mm)	92.87	108.74	+15.87 (+17.1%)
Y FWHM (mm)	239.12	236.78	-2.34 (-1.0%)
Z FWHM (mm)	274.88	263.63	-11.25 (-4.1%)

Conclusion

1. The Quad CdZnTe PGI detector system reconstructed proton depth distributions within a phantom.
2. Gamma attenuation in the nozzle-mounted detector geometry. Sensitivity to beam range changes through a10 mm proton range shift demonstrated
3. The UCT measurands may require further optimization before it can effectively support the UMMC measurements.

Future work

1. Optimize preprocessing, event filtering and image reconstruction algorithms.
2. Investigate CT-based attenuation correction to compensate for prompt gamma attenuation.
3. Investigate machine learning-based image reconstruction and attenuation correction.

Thank You !