Prompt Gamma Monitoring in Particle Therapy using silicon detectors and a Coded Mask

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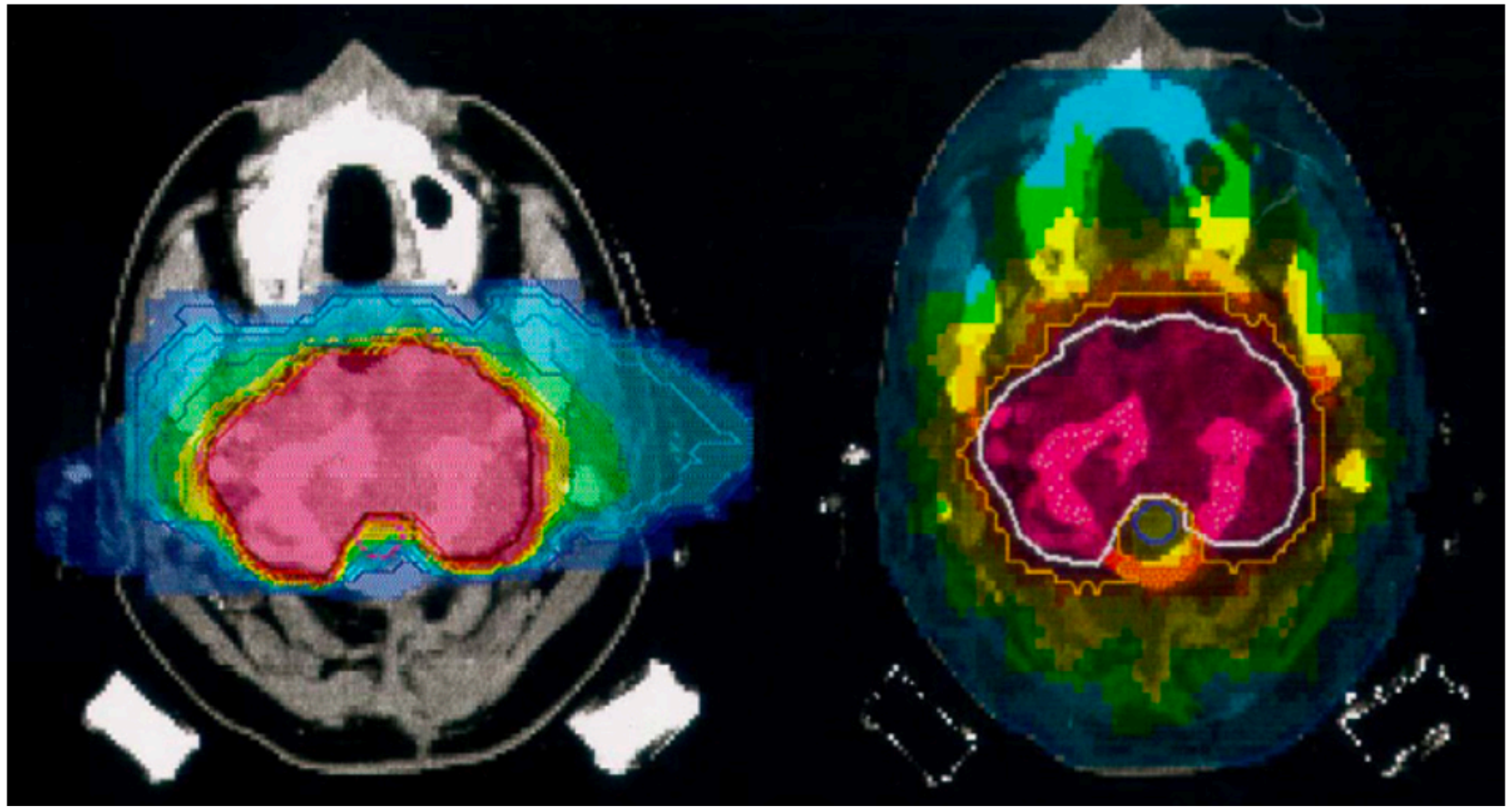
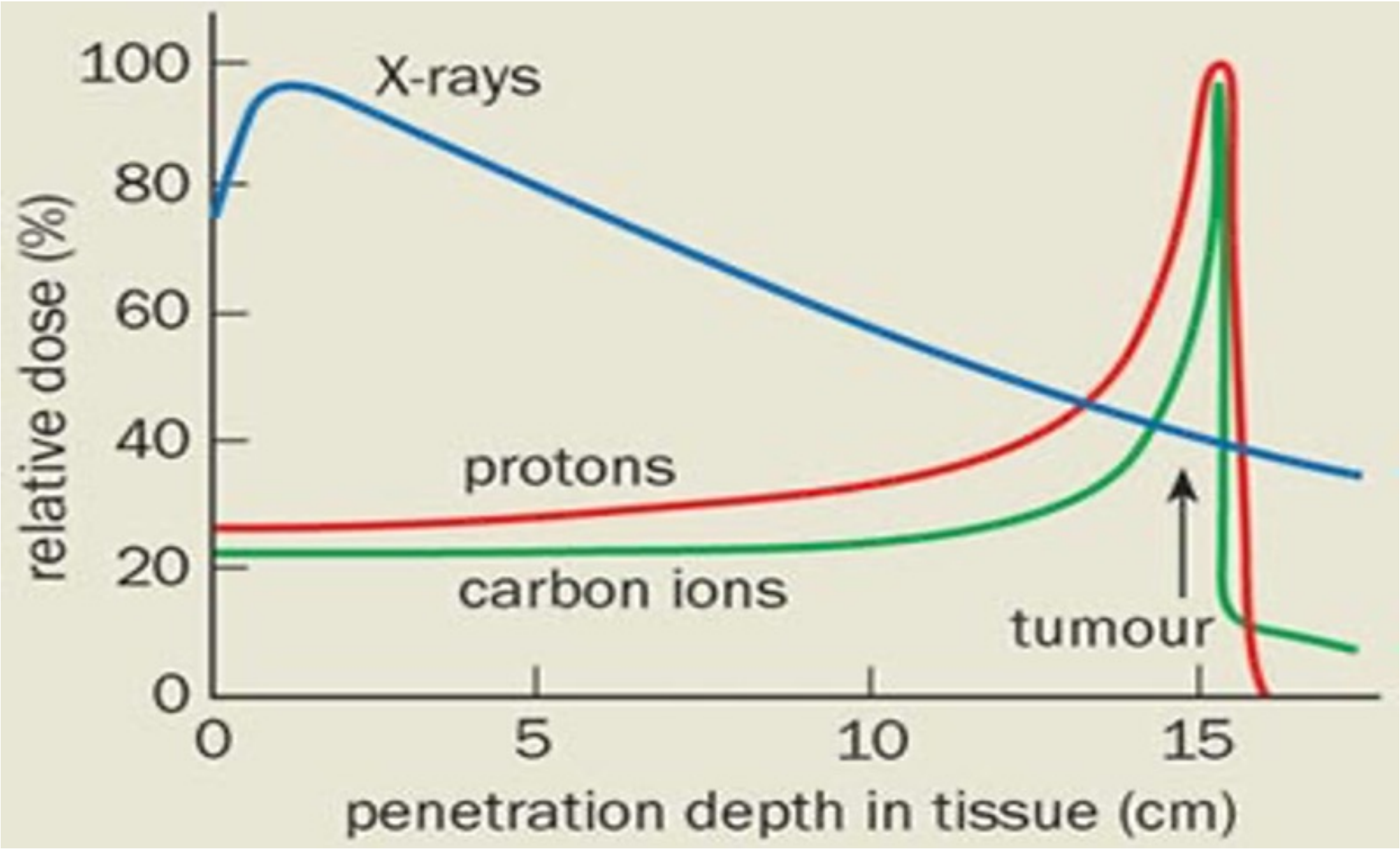
Introduction to Particle Therapy:



Carbon ion therapy provides more confined and precise dose delivery compared to conventional X-ray therapy.



The dose from photon, proton, and carbon ion beams as a function of depth of penetration

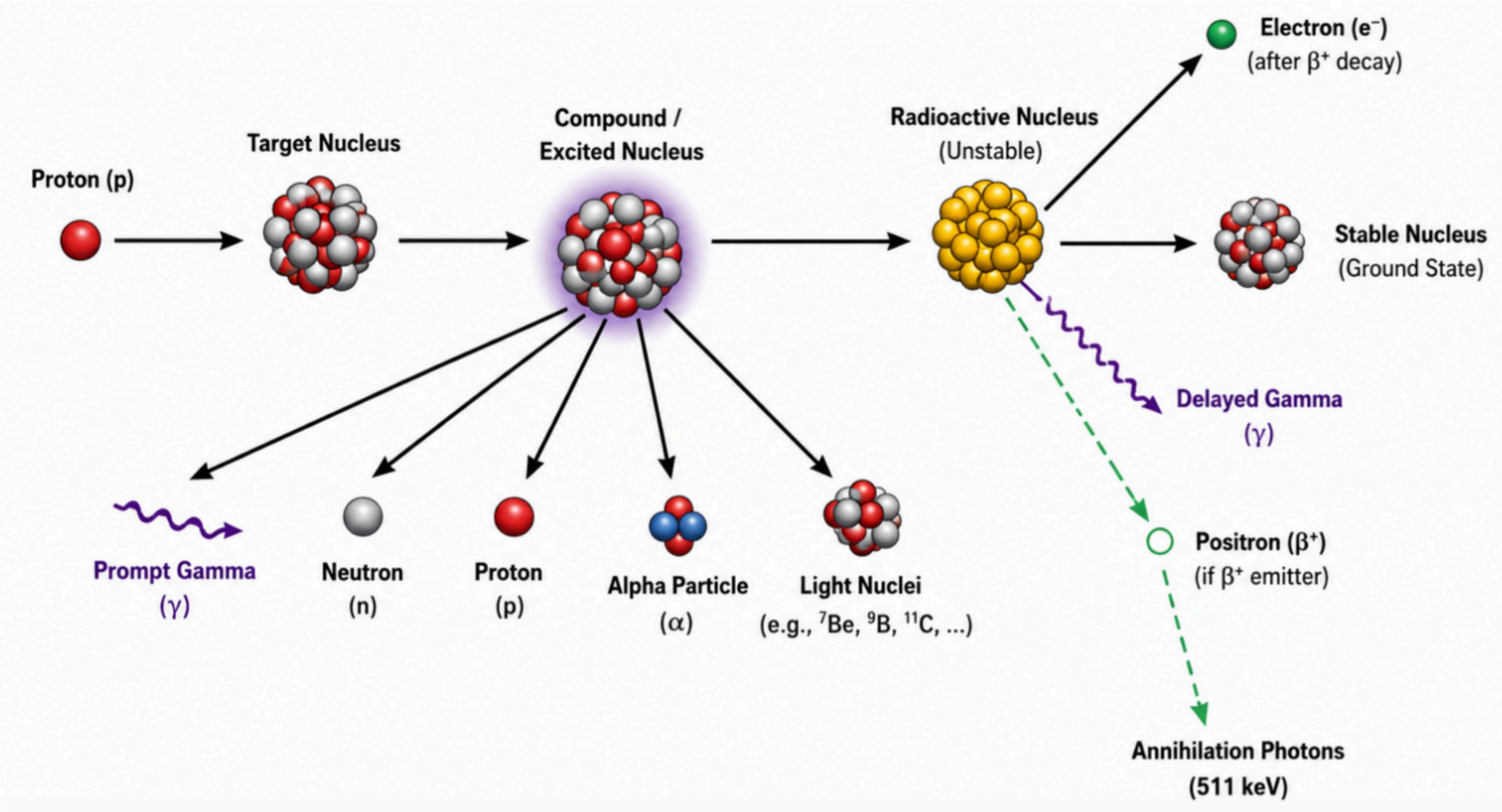
Accurate range verification remains a major challenge in particle therapy. Prompt gamma monitoring is one of the promising techniques for range monitoring in particle therapy.

(Amaldi and Kraft (2005)

Author, N. (2003). Accessed: 14 May(2026)

Prompt Gamma in Particle Therapy

Prompt gamma rays are high-energy photons emitted almost instantaneously following proton-nucleus interactions inside the irradiated material within less than 1 nanosecond.



- Excited nuclei rapidly de-excite by emitting prompt gamma radiation.
- Characteristic energy peaks, such as 4.44 MeV (^{12}C) and 6.13 MeV (^{16}O), help distinguish PG rays from background radiation.
- Their spatial distribution correlates with proton range, making them useful for Bragg Peak verification.
- PG energies typically range from hundreds of keV up to several 10 MeV.

Cheon, B.-W. and Min, C.H. (2024)

Prompt Gamma Imaging:

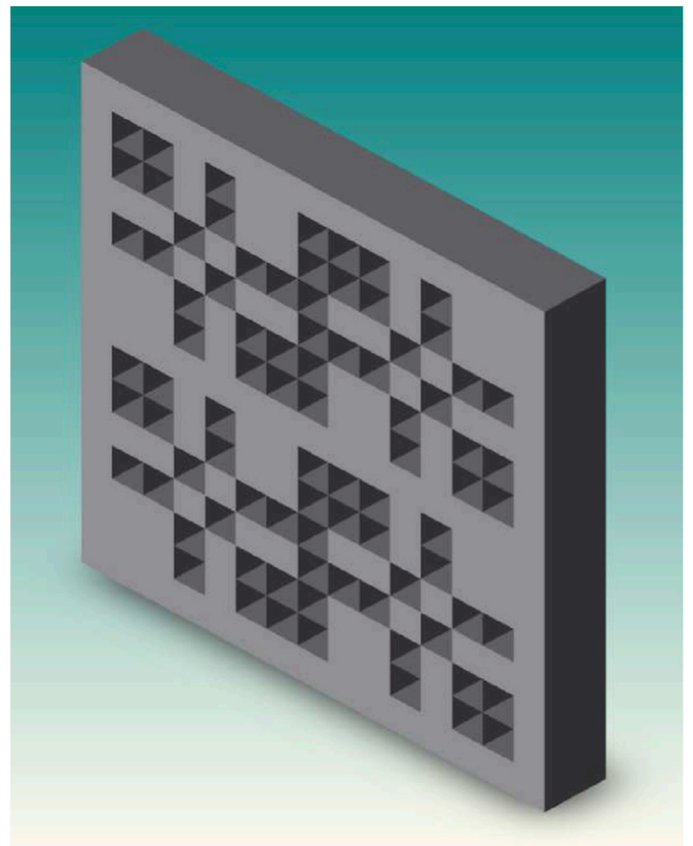
For prompt gamma monitoring and particle range verification, conventional lenses and mirrors are not suitable for high-energy gamma-ray imaging.

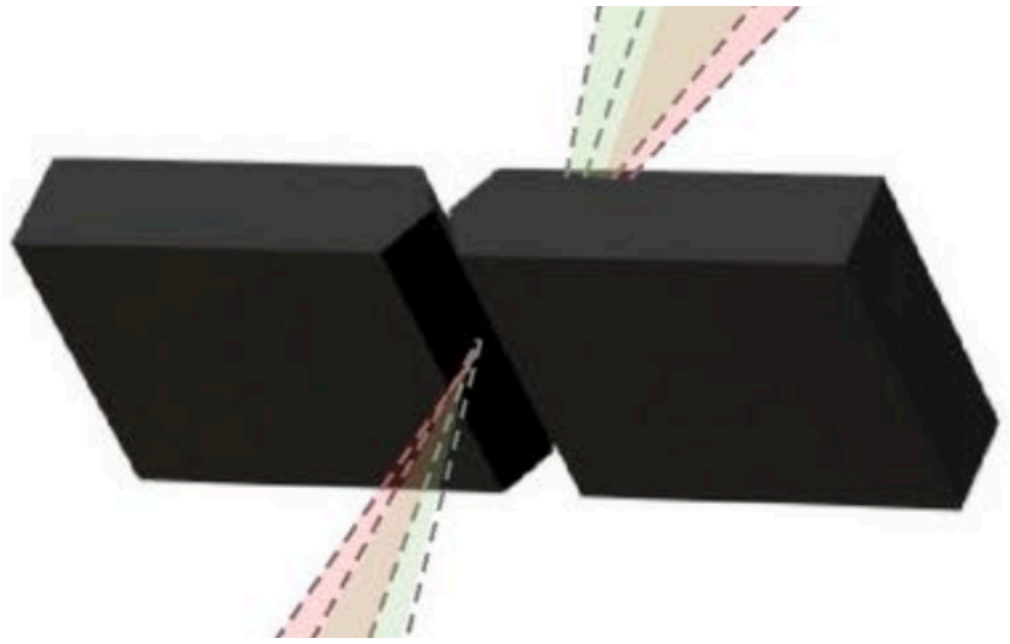
Prompt Gamma Imaging Modalities

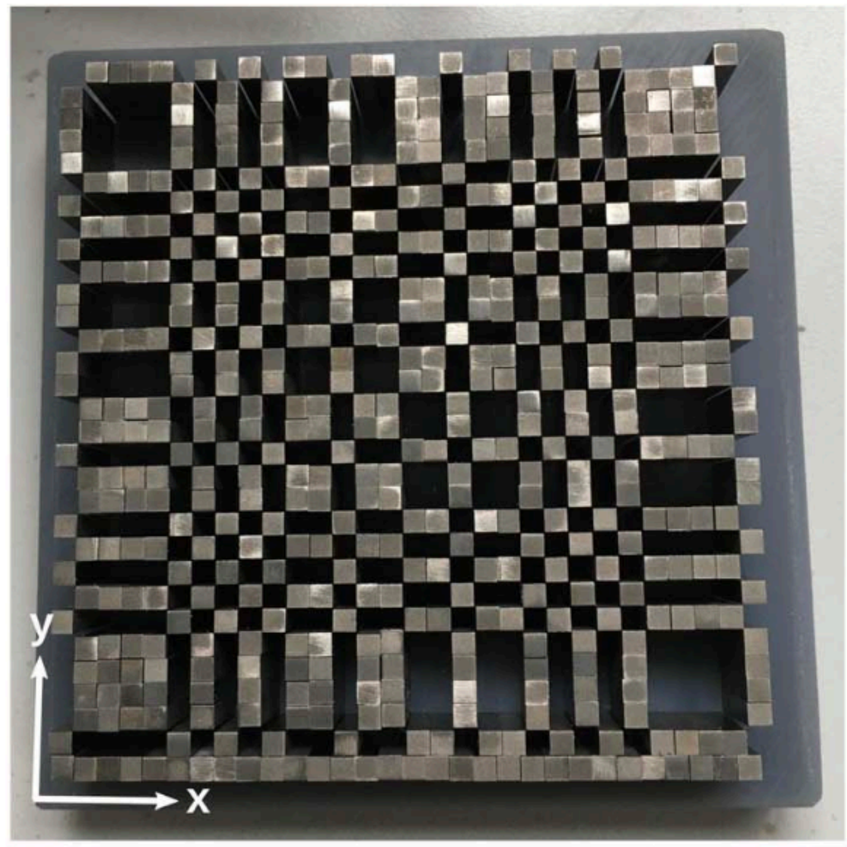
- Compton imaging.
- Knife-edge slit camera.
- Collimator-based imaging.
- Multi-Slit Collimators.
- **Coded Mask** /Aperture imaging.

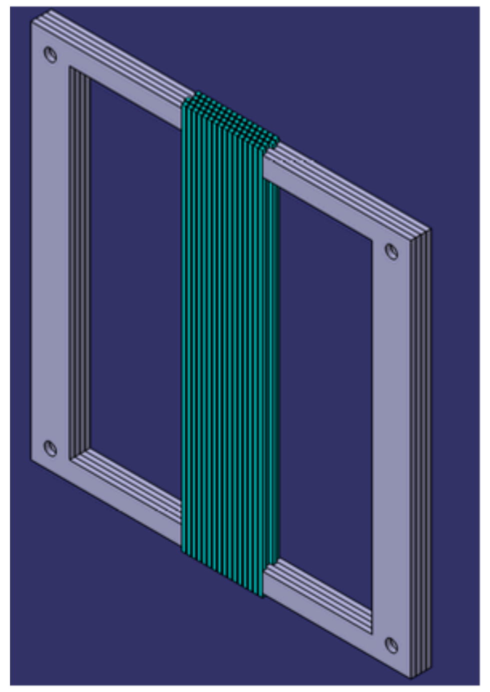
Coded Mask Principle:

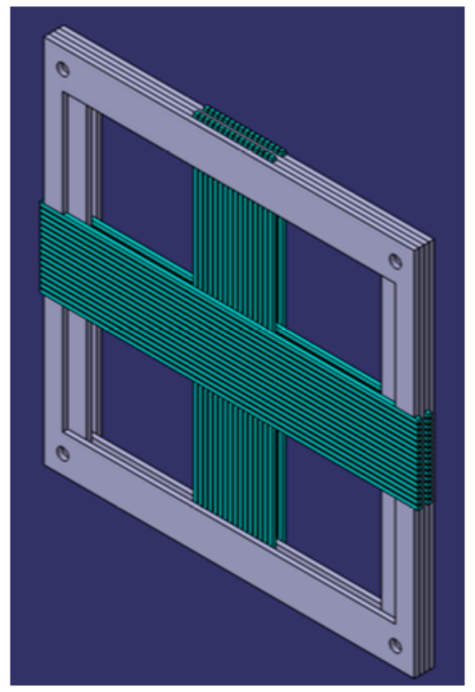
A coded mask is such as ,density material-simply a barrier made of a high tungsten or lead. Gamma rays pass through the holes and make a shadow pattern on the detector. Because there are many holes, more gamma rays are collected than with a single pinhole, and the pattern is decoded later to reconstruct the image.

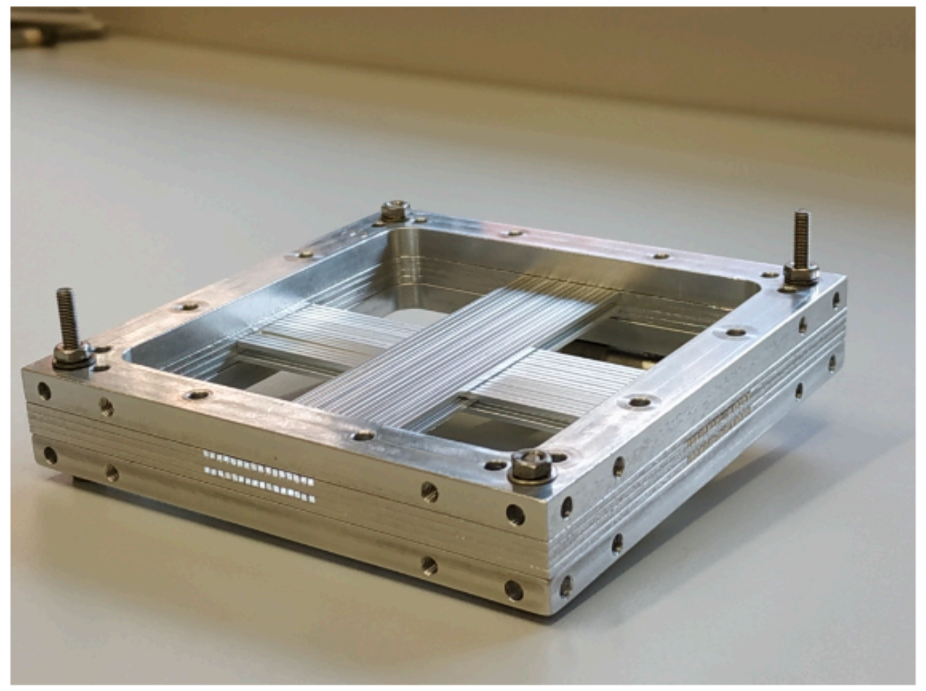












Wrońska, A. (2020)
Hetzel, R. et al. (2023) ʼ
Susaiev, Y., Schoepff, V. and Limousin, O. (2023)
Idrissi, A.B. et al. (2024)
Cieślak, M.J., Gamage, K.A.A. and Glover, R. (2016)

Coded Mask informations:

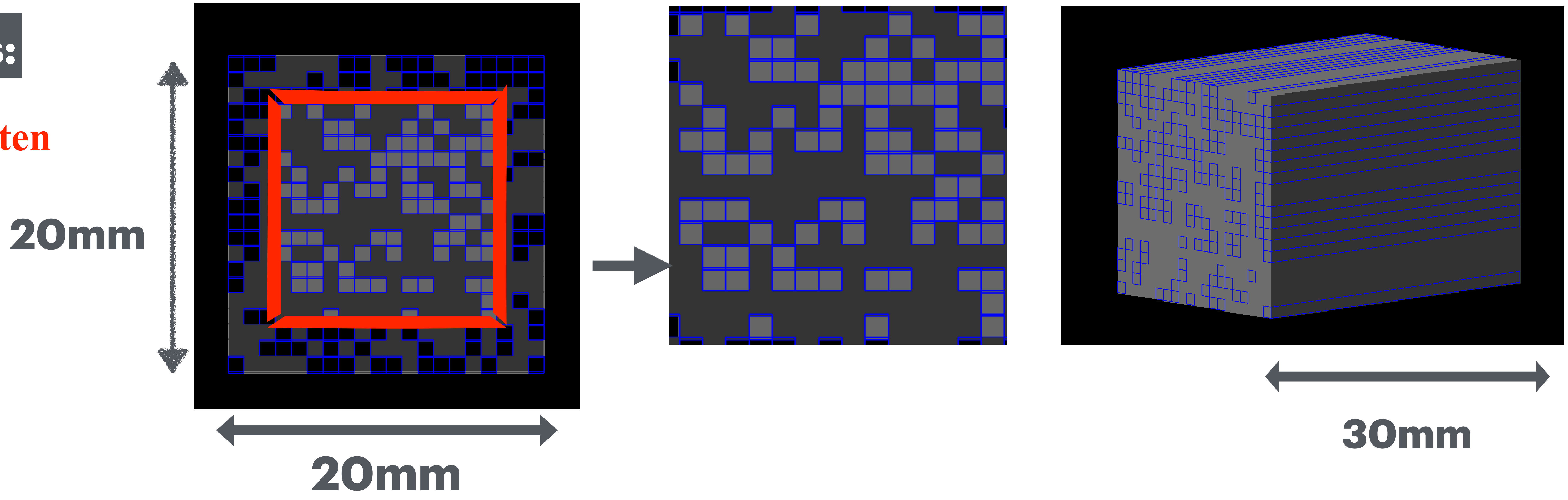
The mask material used is **Tungsten**

thickness=30 mm

Cell size = 1 mm

Mask cells are 20x20= 400 cells

The density 19.3 g/cm3



The Shielding information:

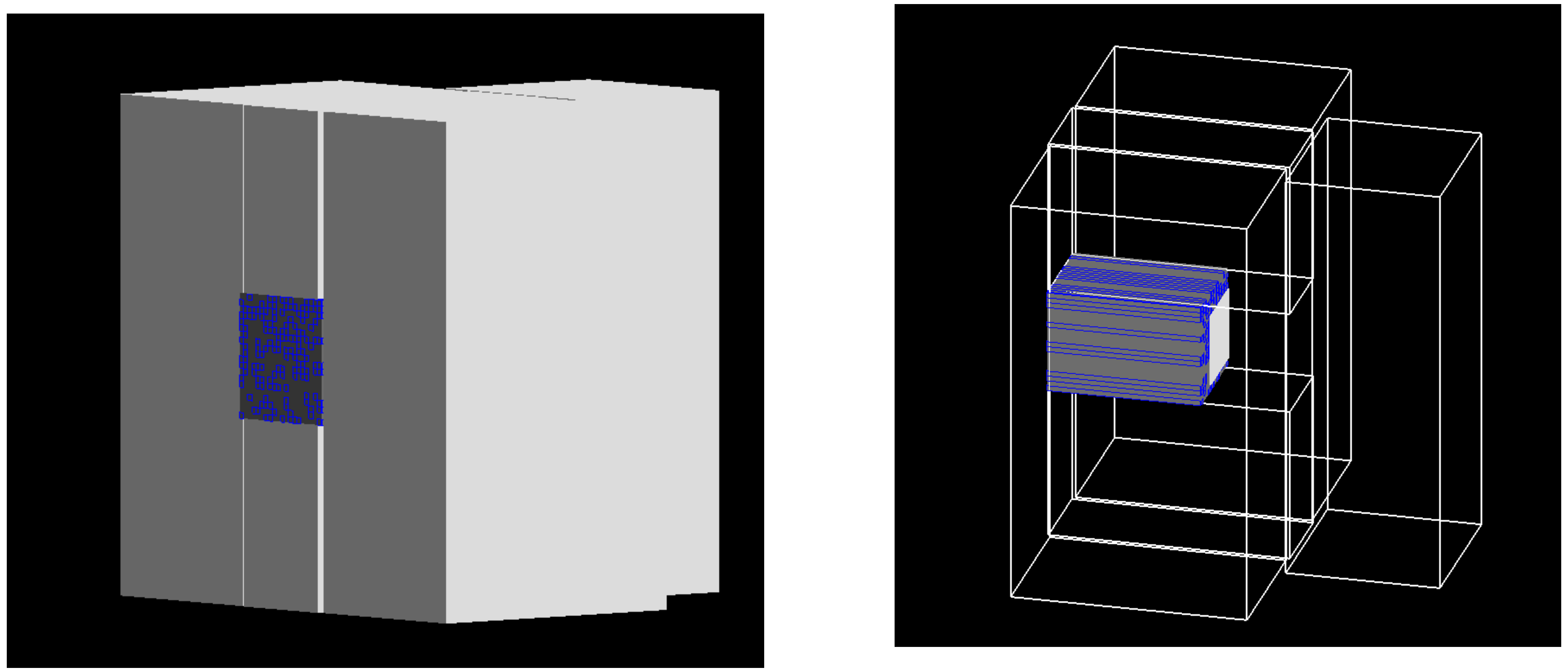
The material used is **Tungsten**

thickness

Above and below = 18 mm

Right and left = 30 mm

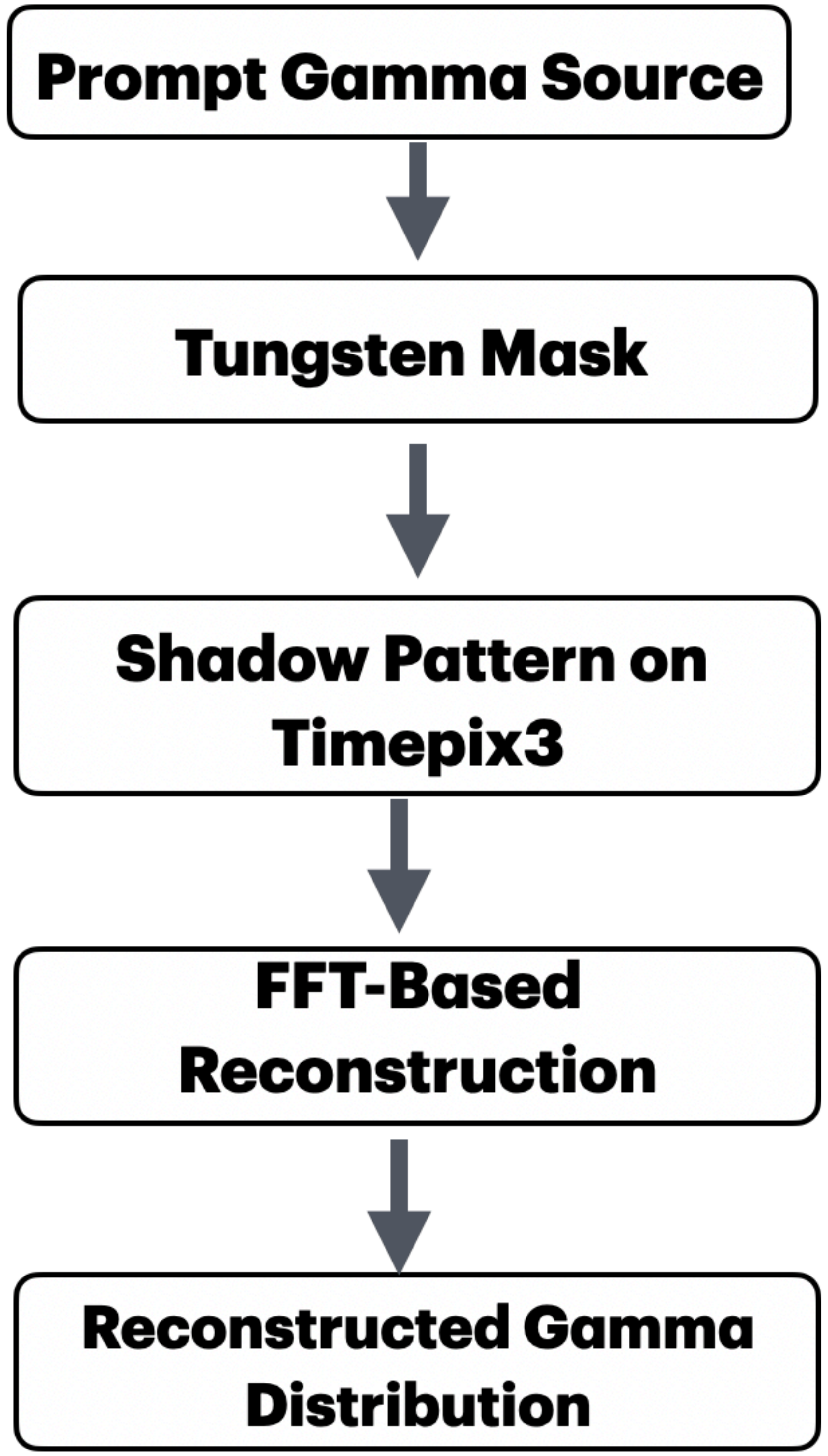
Behind the mask =32 mm



The mask dimensions were selected to fully cover the silicon detector area, while a tungsten thickness of 3 cm was chosen to effectively block and modulate high-energy prompt gamma photons.

Prompt Gamma Reconstruction Method:

- The tungsten mask modulates incoming prompt gamma rays.
- The silicon detector records a shadow pattern.
- FFT-based correlation is applied to decode the shadow image.
- The reconstructed image estimates the prompt gamma source distribution.

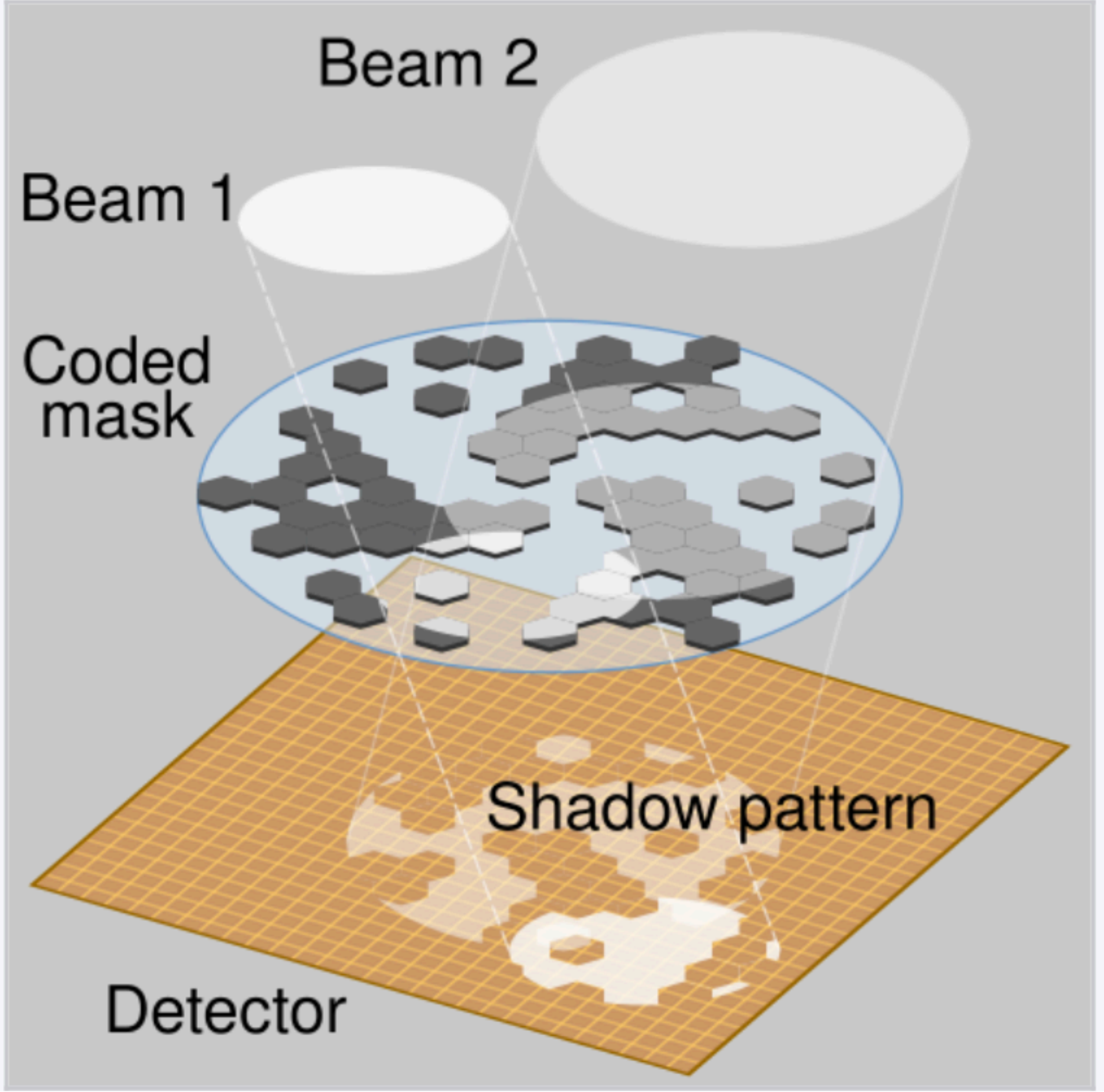


FFT-Based Image Reconstruction:

$$R = \mathcal{F}^{-1}\left[\mathcal{F}(D) \cdot \mathcal{F}(M)^*\right]$$

Where,

- D : Detector shadow image.
- M: Mask pattern.
- R: Reconstructed image.
- F: Fourier transform.

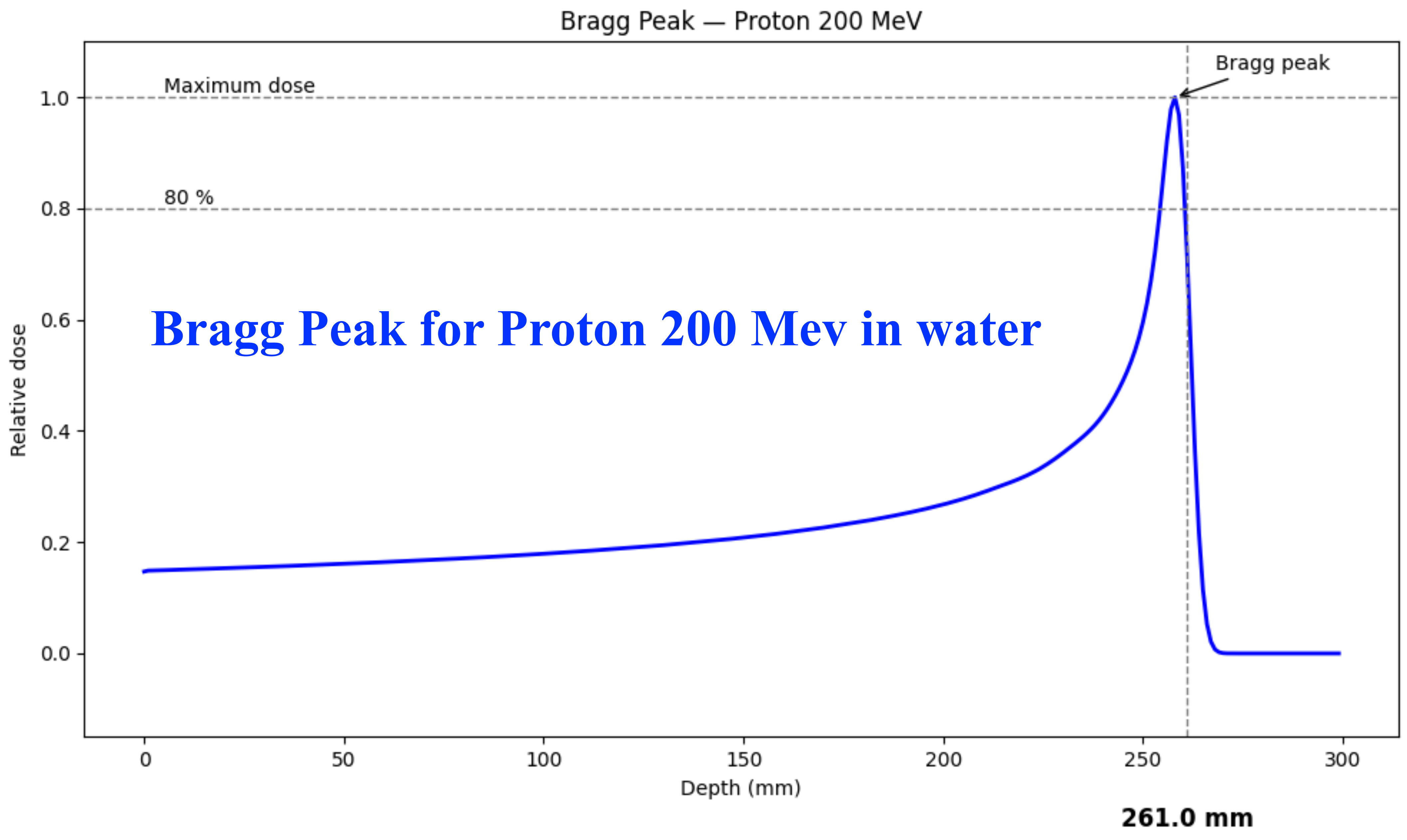


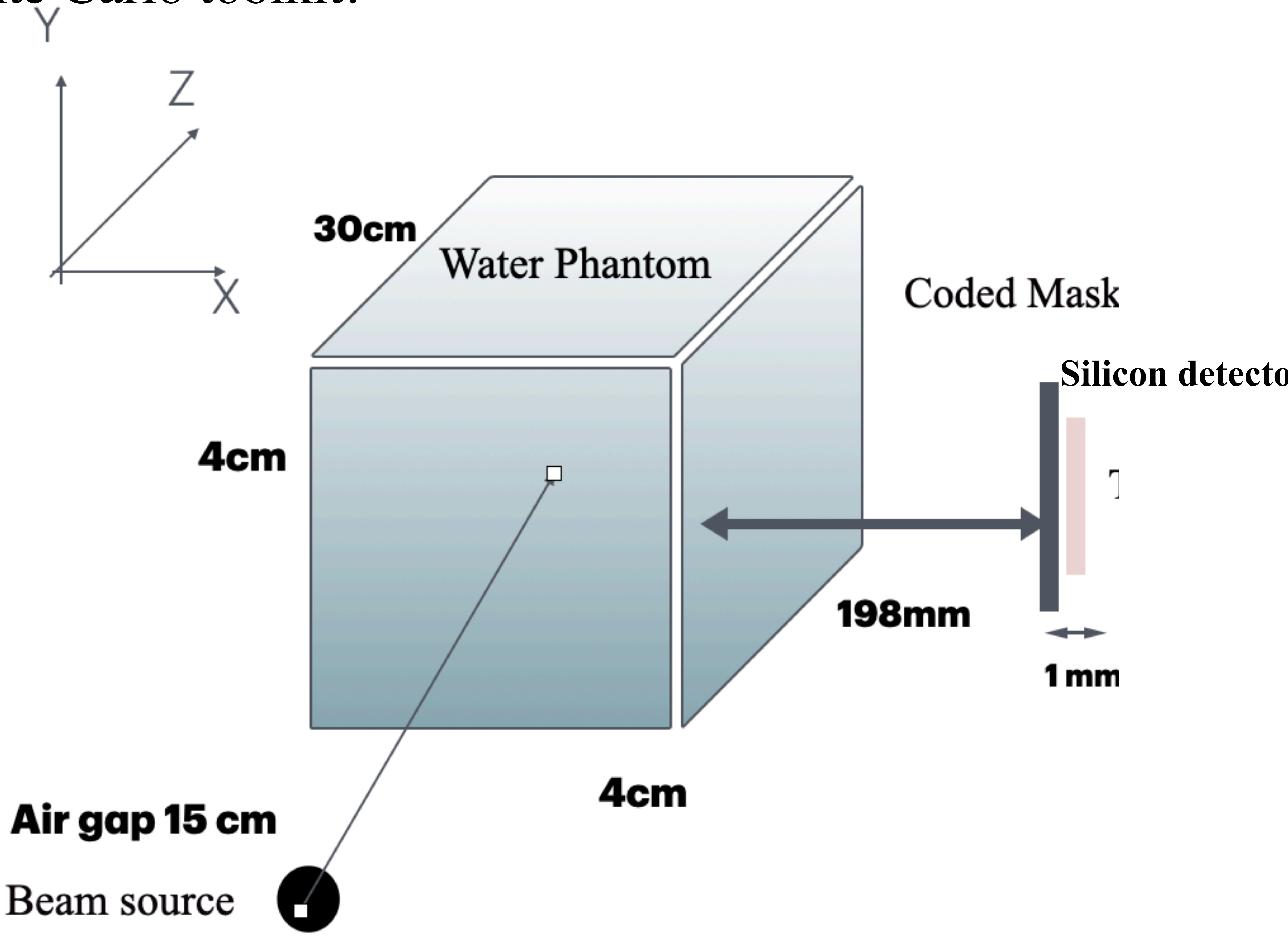
Fenimore, E.E. and Cannon, T.M. (1978)

Wikipedia

Prompt Gamma Detection Setup:

The PG detection setup was simulated using the TOPAS Monte Carlo toolkit.



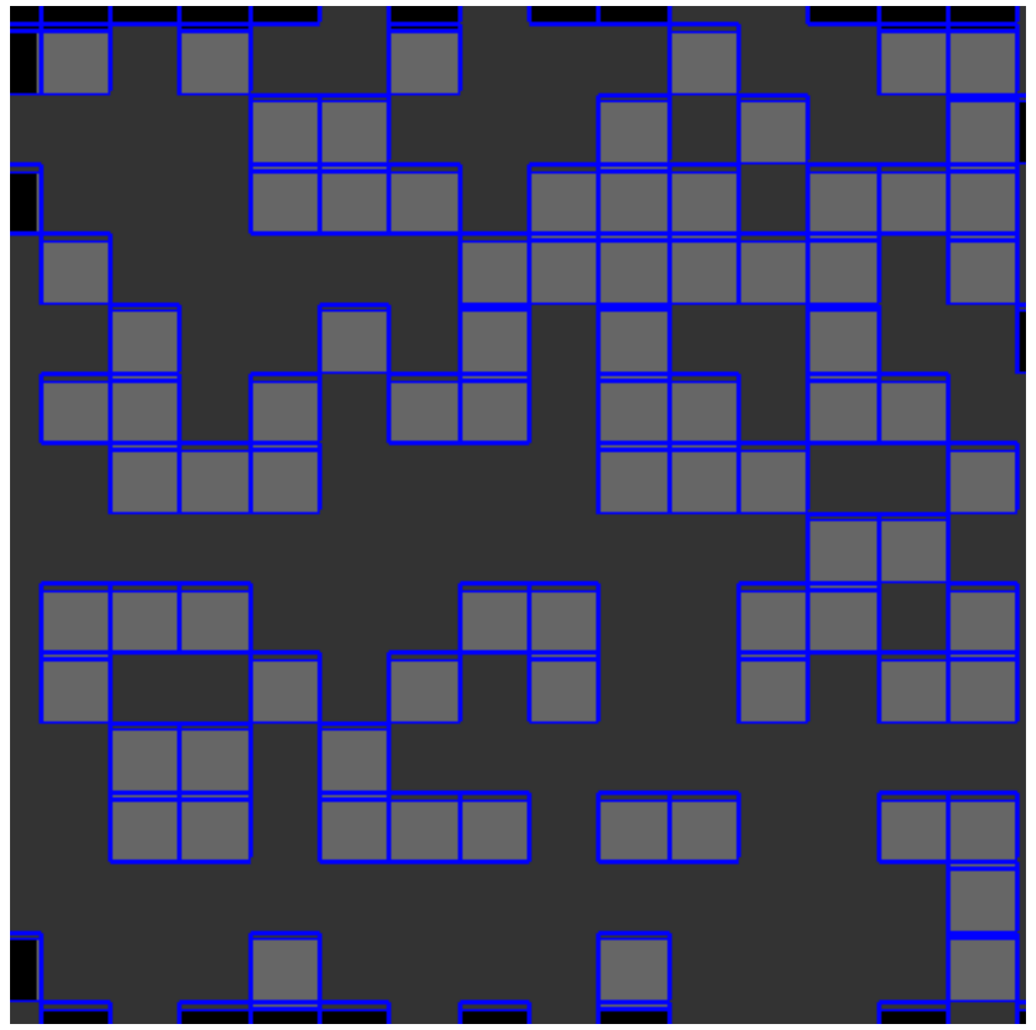


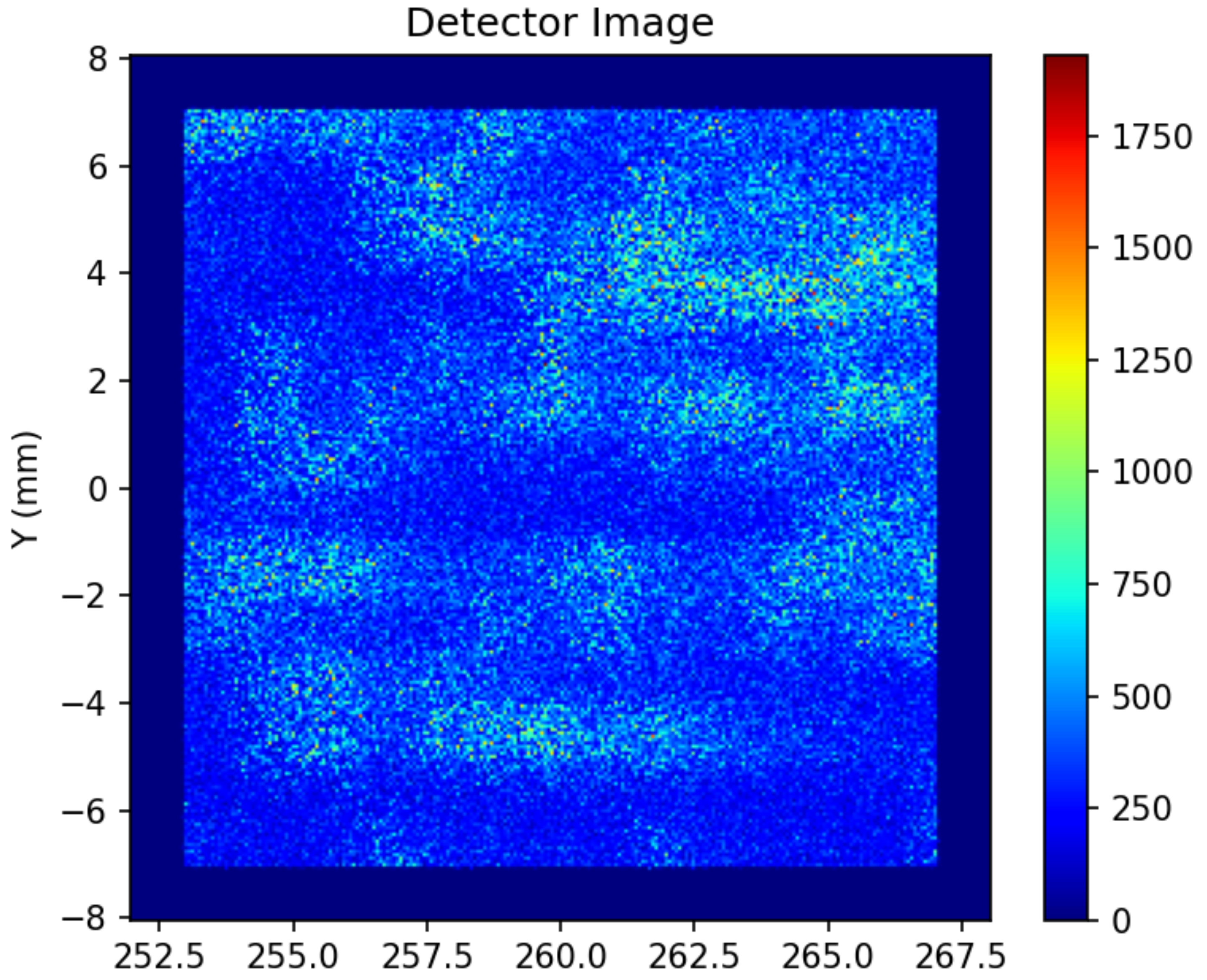
- Water phantom.
- 10^10 protons
- Silicon detector: **300µm thick.**
- Particle source: **Proton 200 MeV**.
- Distribution: **BiGaussian. (SigmaX=1.3 mm and SigmaY= 1.3 mm)**
- Physics List: **4 “g4em-standard_opt4" "g4h-phy_QGSP_BIC_HP" "g4ion-binarycascade" “g4decay"**

A two-step Monte Carlo approach was used to improve simulation statistics:

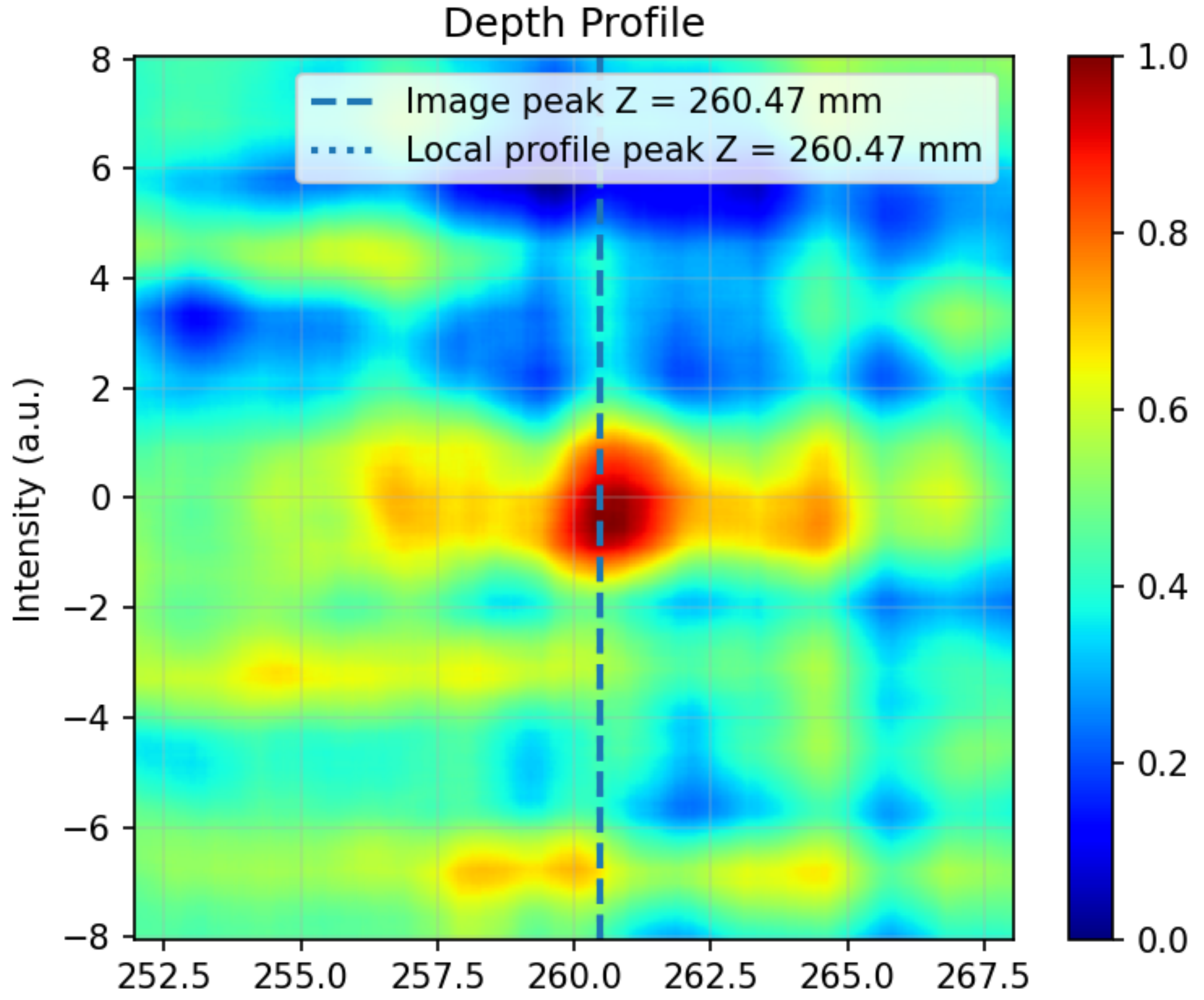
Primary Proton Simulation → **Phase Space output file** → **Secondary Simulation** → **Prompt gamma detection**

Preliminary Results:





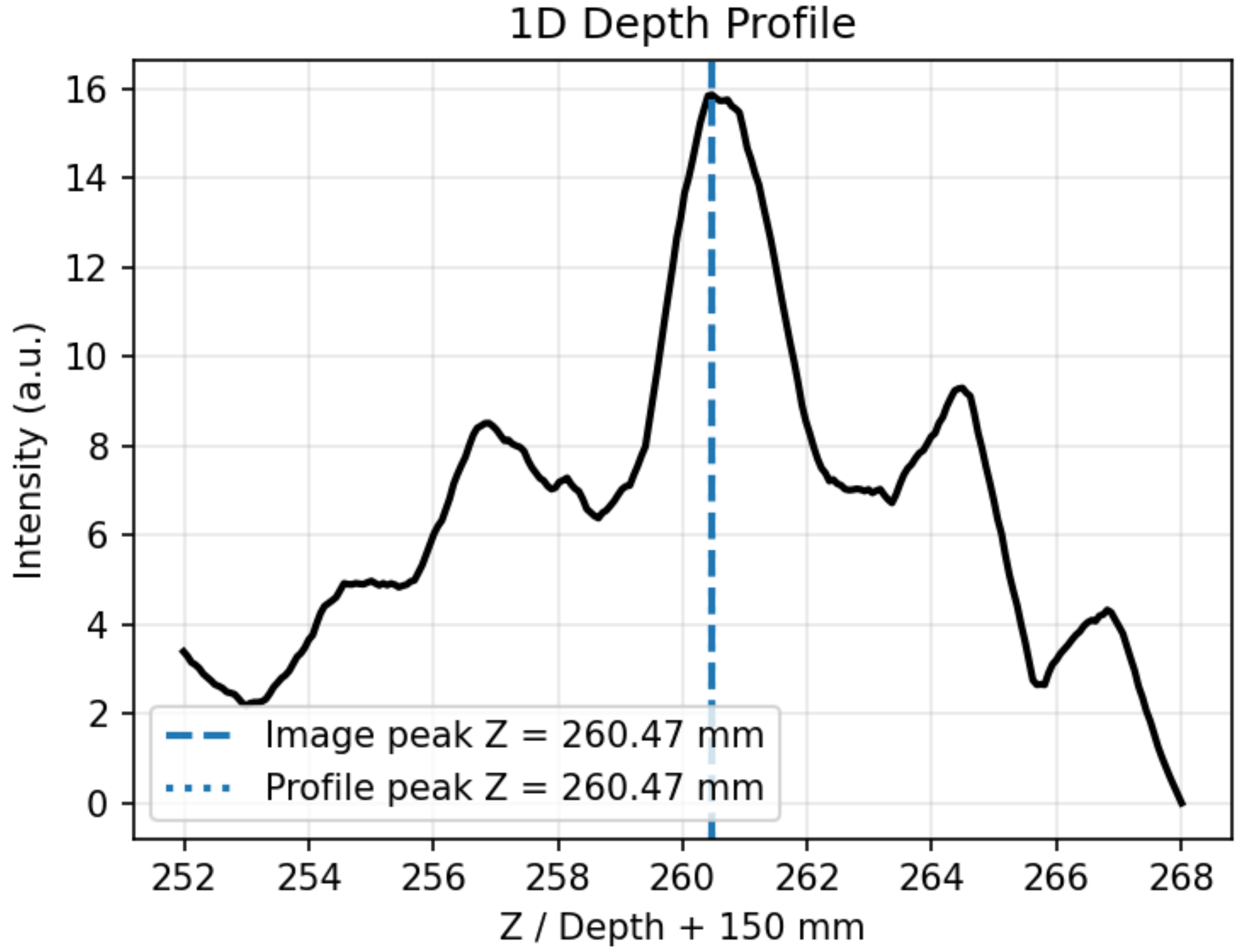
shadow image

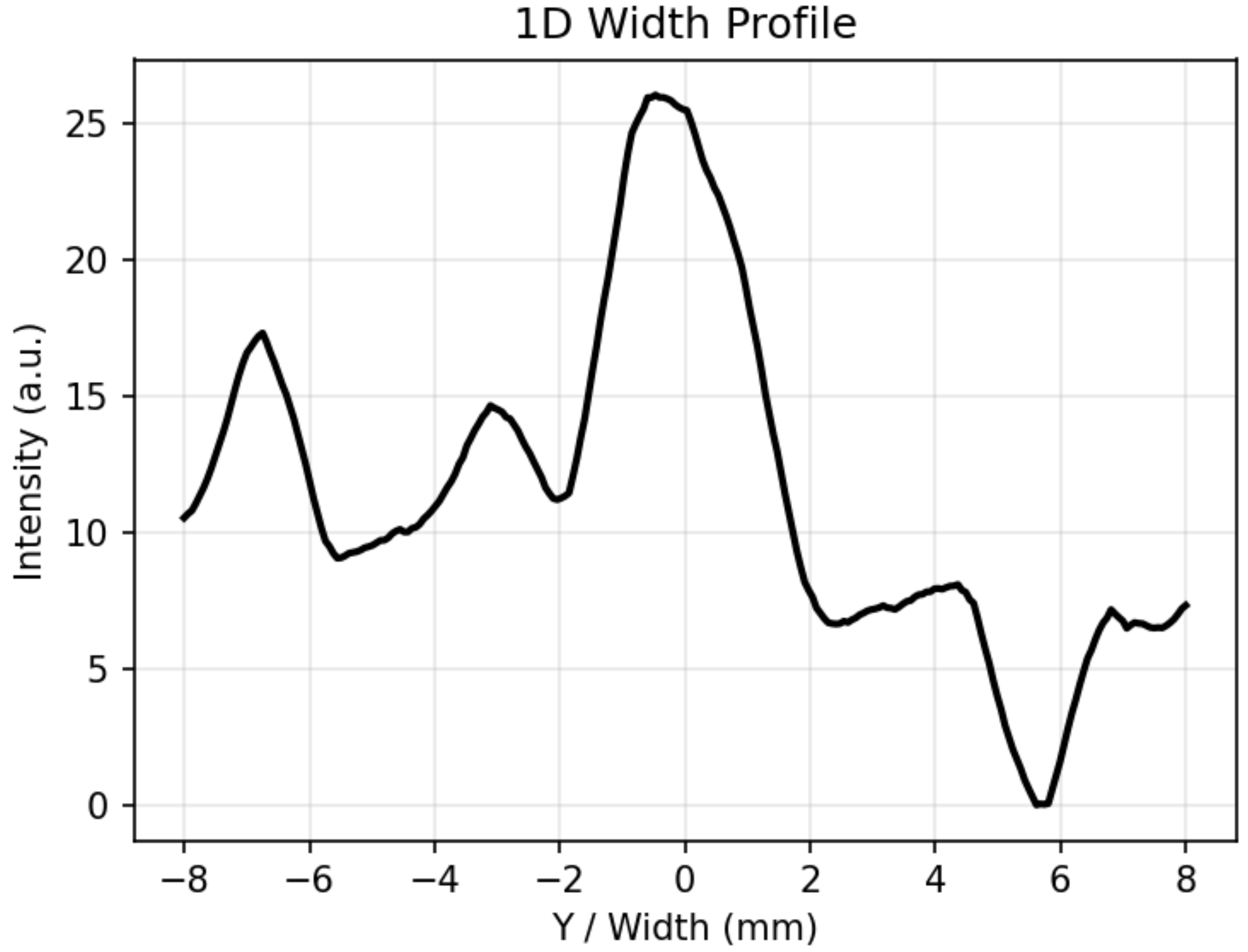


reconstructed image

10,000,000,000 events of proton,

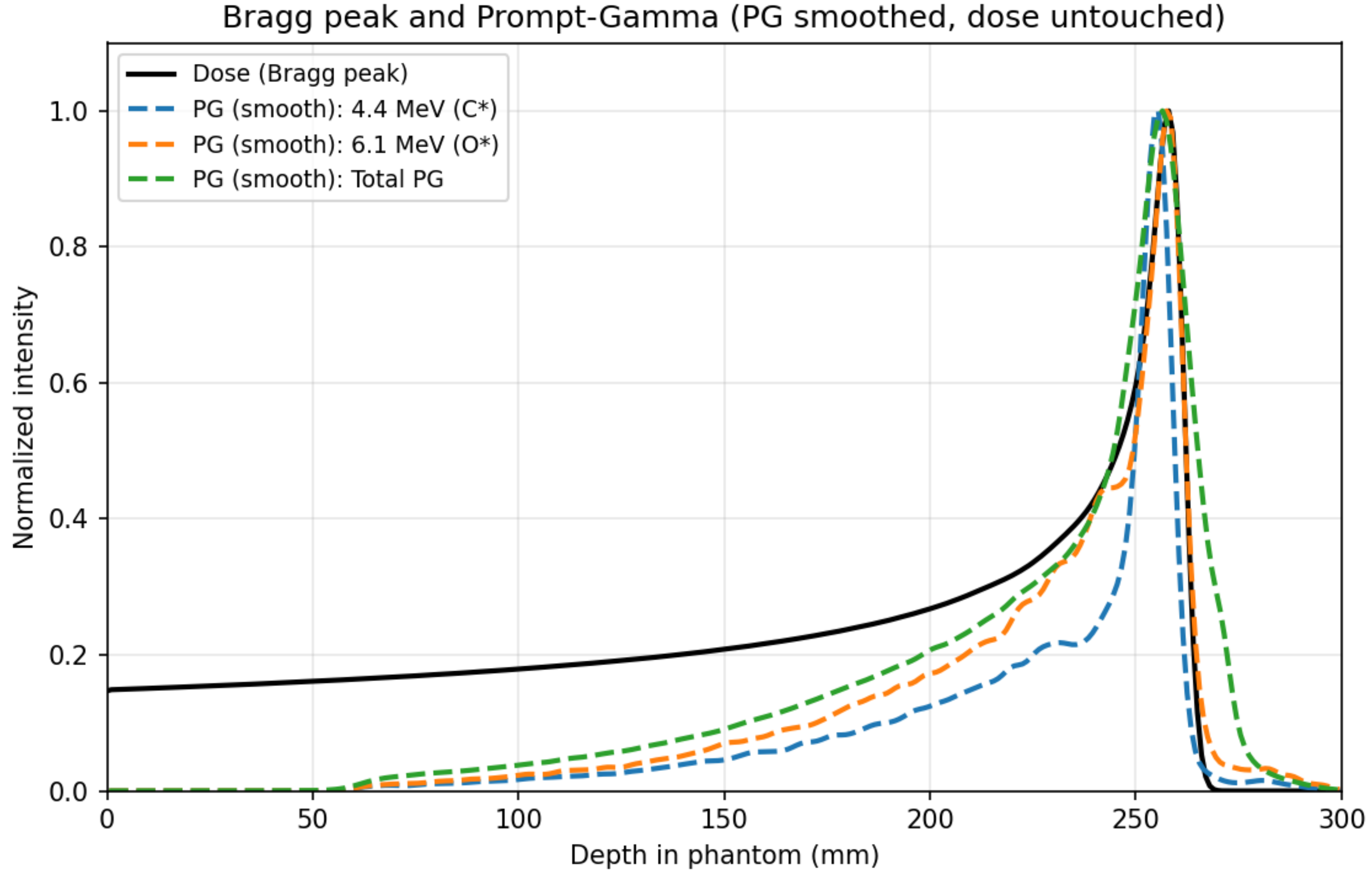
about 6,754,988 gamma



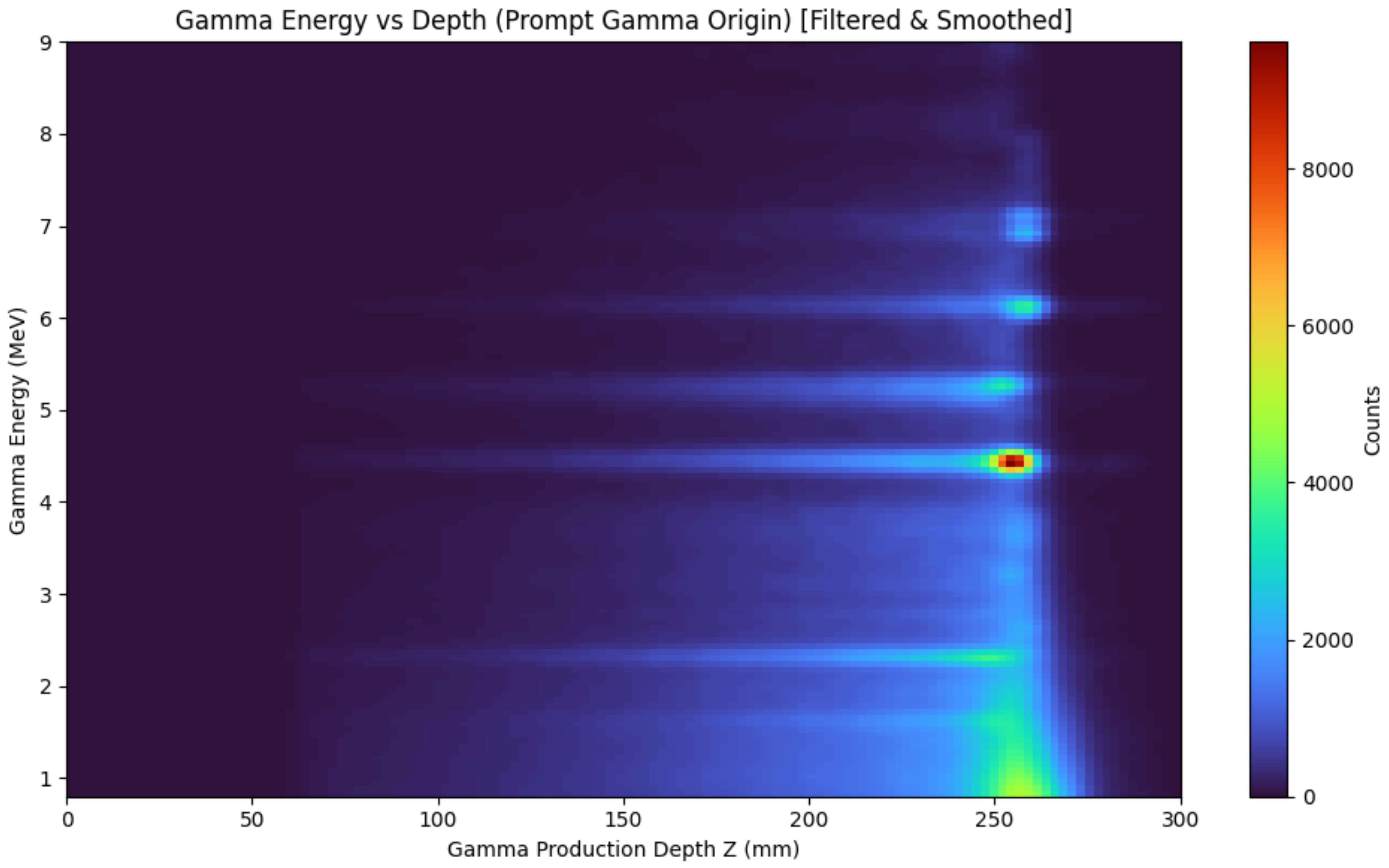


The reconstructed prompt gamma peak was located at 260.4 mm, showing close agreement with the expected Bragg Peak position at 261 mm.

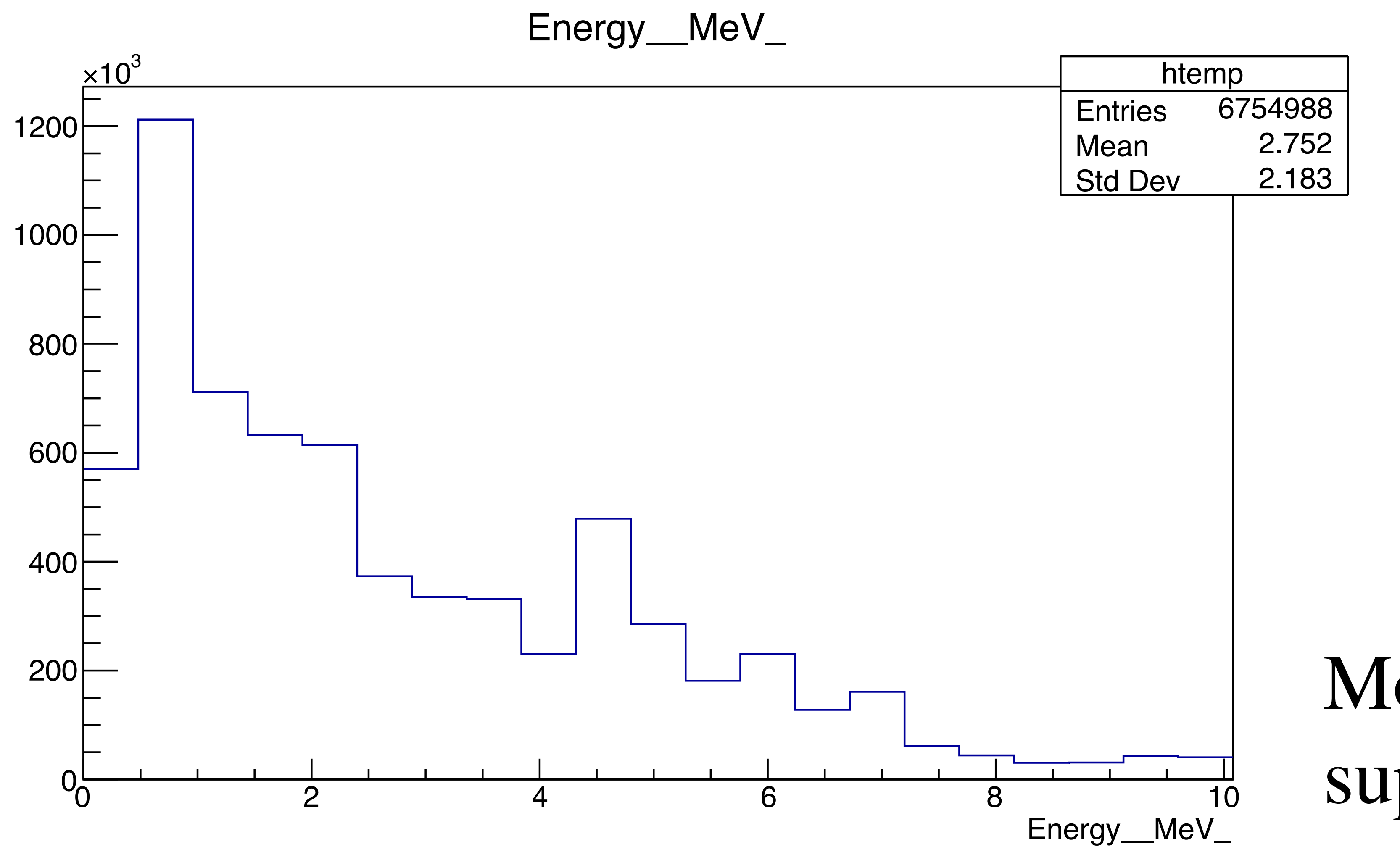
The reconstructed Bragg Peak position was estimated using the maximum bin intensity of the one-dimensional profile.



The relationship between prompt gamma emissions and the depth-dose curve of a 200 MeV proton beam



Variation of gamma-ray energy with emission depth in a water phantom



Most detected gamma events are within the prompt time window, supporting their association with prompt gamma emission.

Future Work:

- Lateral displacement of the coded mask, detector, and shielding system will be performed in 10 mm steps to investigate Bragg Peak localization accuracy further.

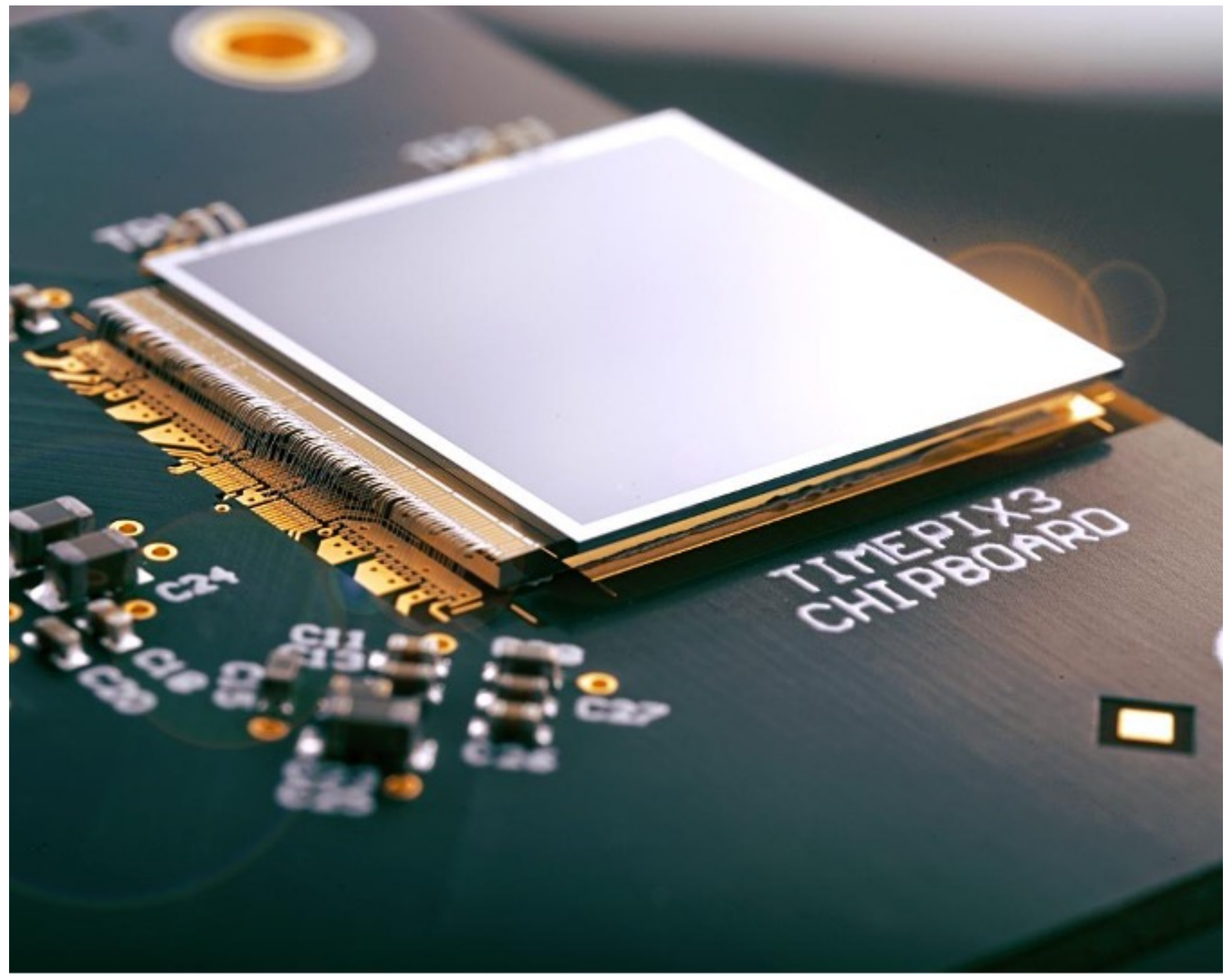
- The proposed prompt gamma imaging system will be extended to carbon ion therapy.

- Experimental measurements using radioactive sources, such as Na-22, will be conducted to evaluate detector response, validate the reconstruction method, and compare experimental and simulated results. These measurements are expected to provide controlled prompt gamma-ray data for testing detector sensitivity, spatial response, and reconstruction accuracy.

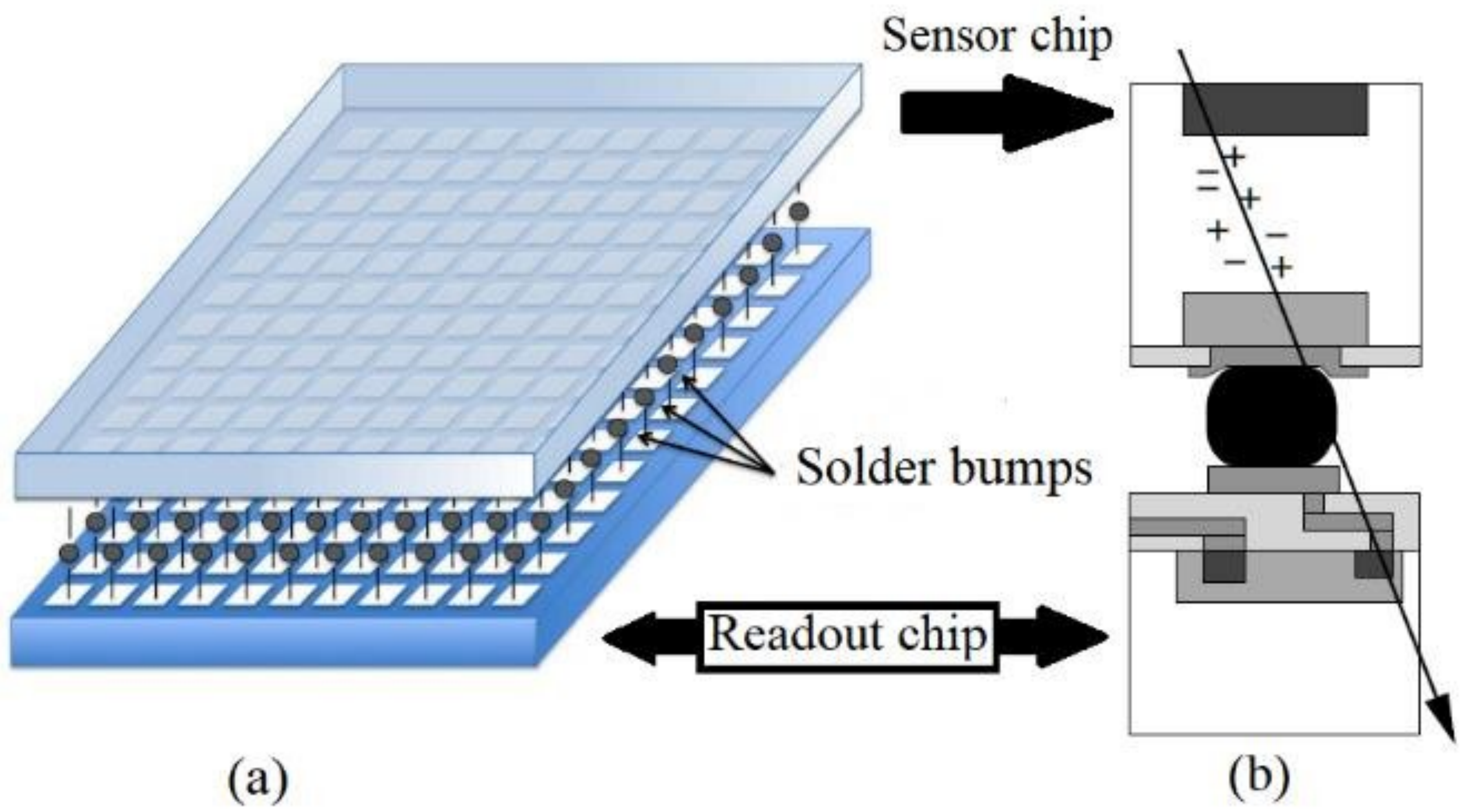
Thank you ….

Appendix:

Timepix3 detector:



- Timepix3 detector is a modern hybrid active pixel detector.
- Spatial and temporal resolution for the detection of ionizing particles.
- Each Timepix3 detector chip consists of **a 256 × 256 pixel** array with a pixel **pitch of 55 × 55 µm.**



Each pixel can function individually in one of the three modes:
1- **ToT mode** calculates the duration for which the input signal in each pixel exceeds a predetermined threshold.
2- **ToA mode** (the timer counts the seconds the particle is detected, acting as a timer.
3. **Medipix mode:** Each pixel serves as a basic digital counter, recording the frequency with which a particle or photon passes.

- Timepix3 — knowledge transfer (no date). Available at https://kt.cern/technologies/timepix3. (Accessed: 1 May 2025).

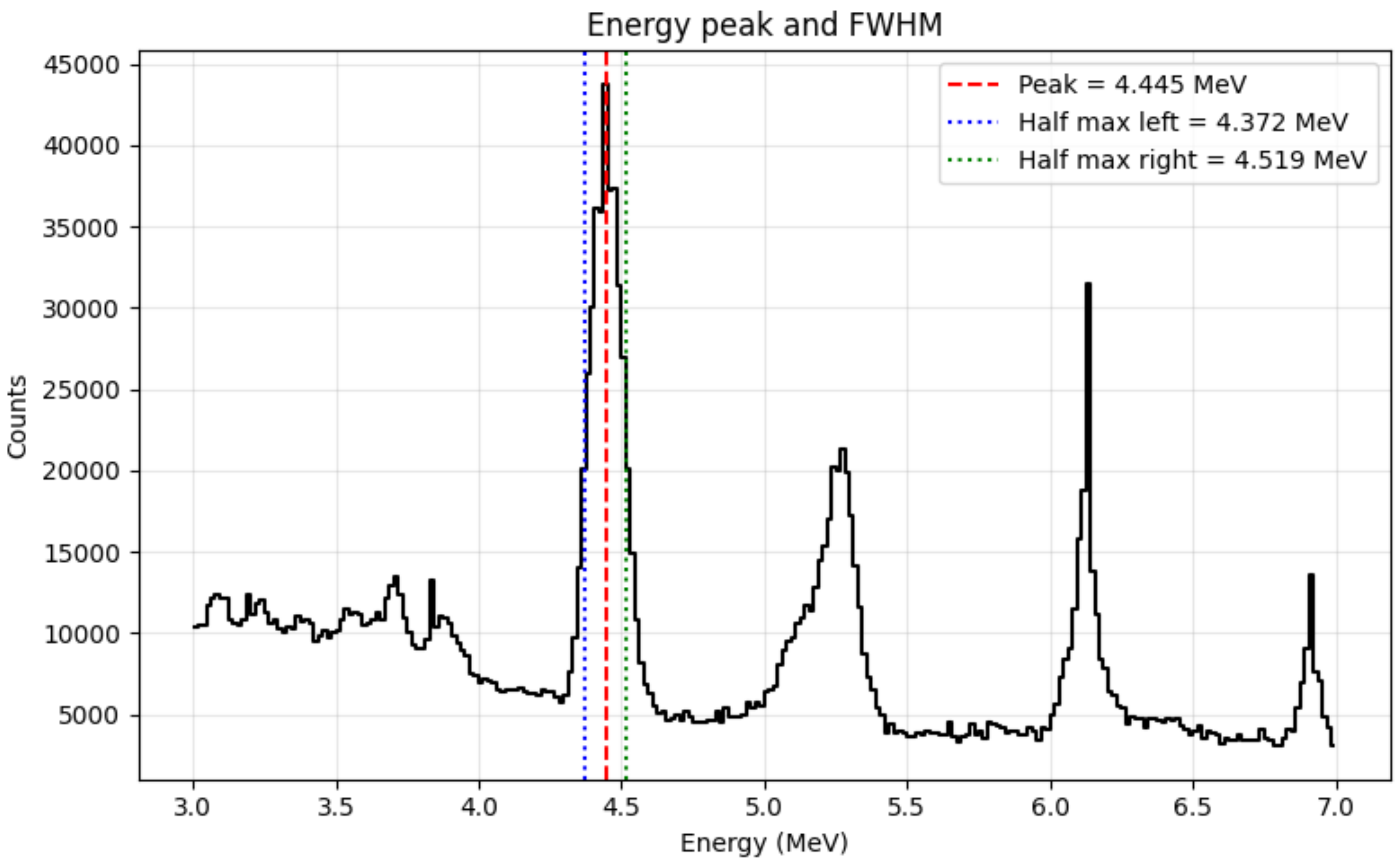
- Istaitia, O. et al. (2024) .Thermal and supply voltage analysis of optimized ring oscillator for pixel detector readout chip, An-Najah University Journal for Research - A (Natural Sciences), 38(1), pp. 1–7. Available at: https://doi.org/10.35552/anujr.a.38.1.2119.

Energy resolution for Silicon detector using **FWHM (Full Width at Half Maximum):**

For the simulated prompt gamma spectrum (1–8 MeV), we obtain a clear 4.44 MeV peak at 4.445 MeV with FWHM ≈ 0.141 MeV (141 KeV), ".corresponding to an energy resolution of ≈ 3.3%

Dynamic range / measurable energy per pixel

For Timepix3 with a 300 μm Si sensor, the per-pixel energy measurement is linear up to roughly 100–150 keV per pixel and tends to saturate around ~500 keV deposited per pixel, so prompt gamma interactions are fine as long as the energy is shared across a cluster and not dumped into a single pixel



The energy resolution is about 3.3% (147 keV FWHM at 4.445 MeV), and the per-pixel dynamic range is roughly ".up to a few hundred keV before saturation in Timepix3

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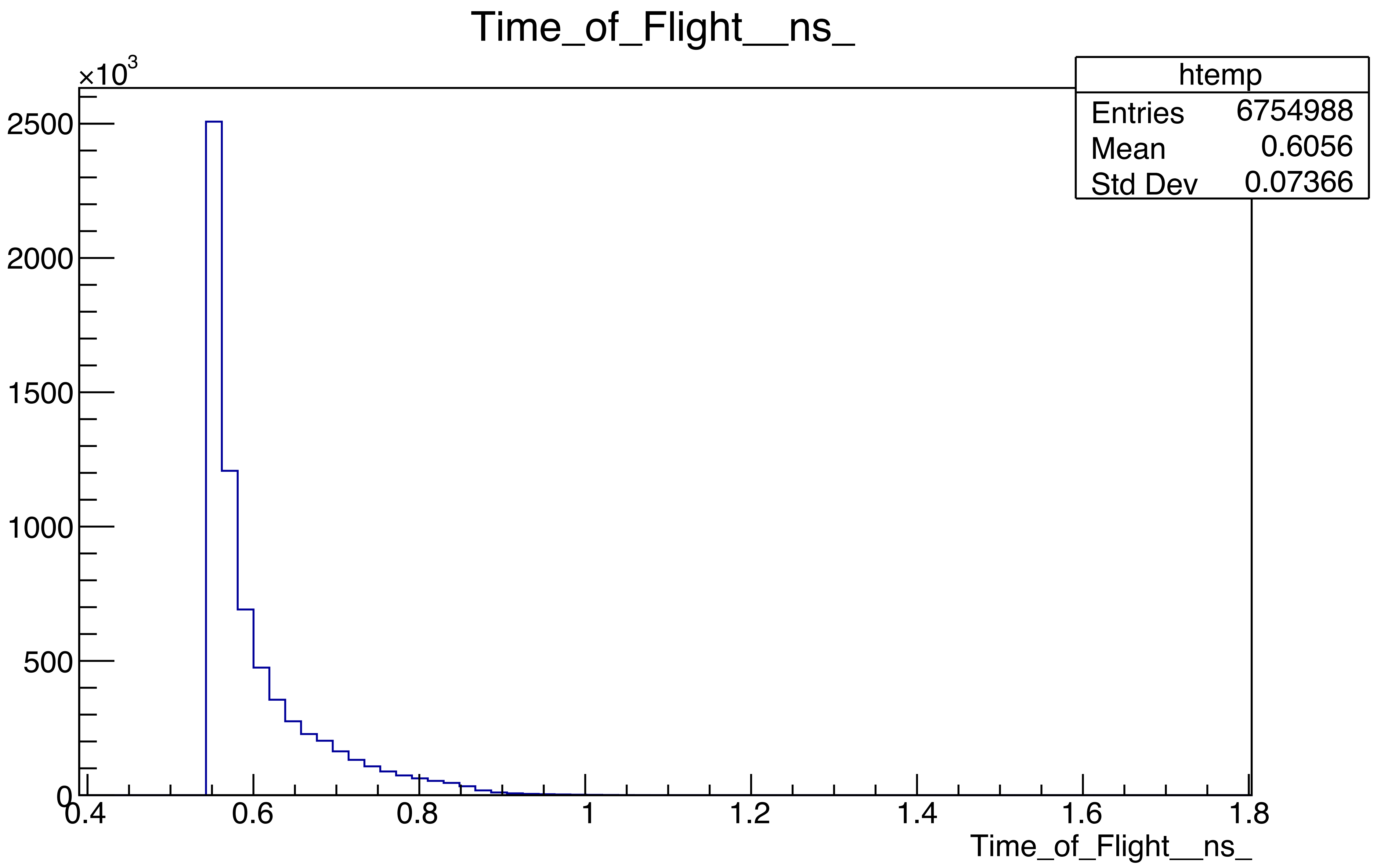
Bromberger, H. et al. (2024) 'Timepix3: single-pixel multi-hit energy-measurement behaviour', Journal of Instrumentation, 19(11), p. P11008. Available at: https://doi.org/10.1088/1748-0221/19/11/P11008.



The measured time-of-flight distribution was dominated by prompt gamma events (<1 ns) about (0.6 ns)