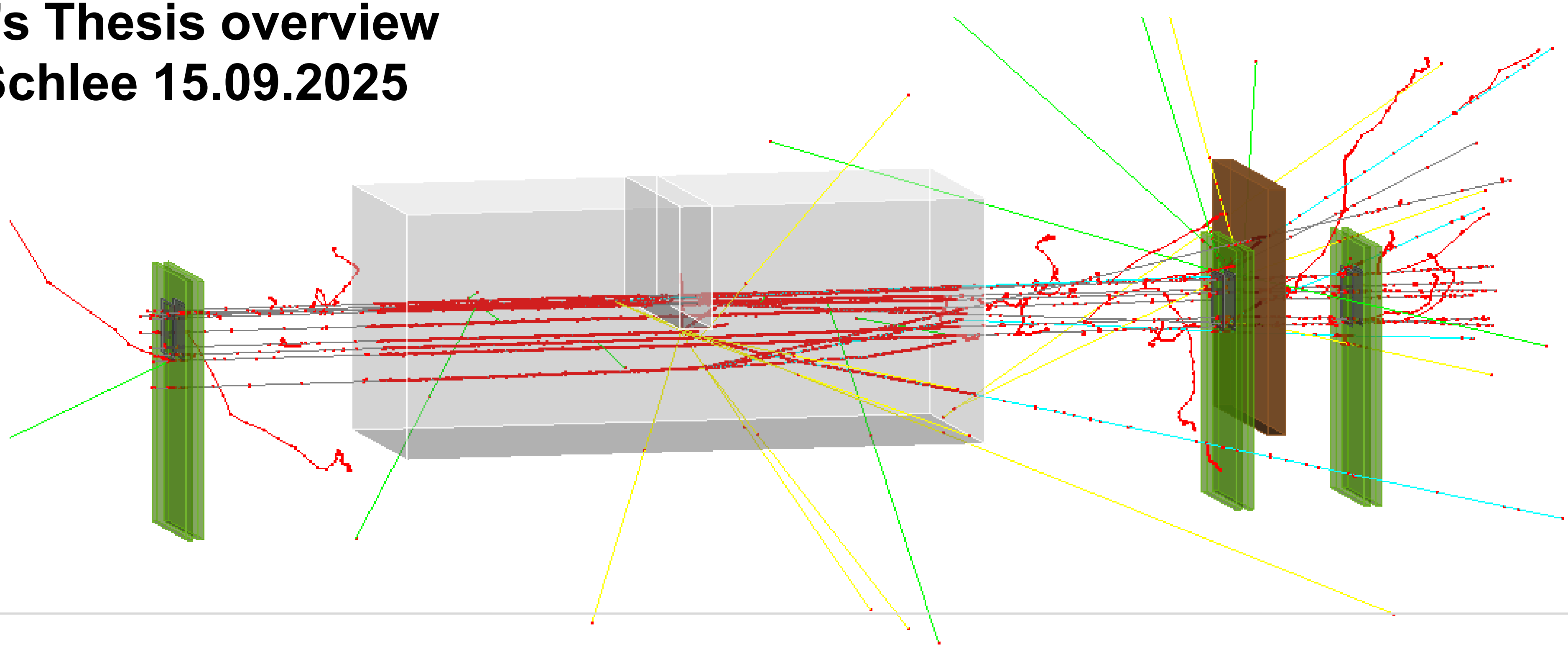
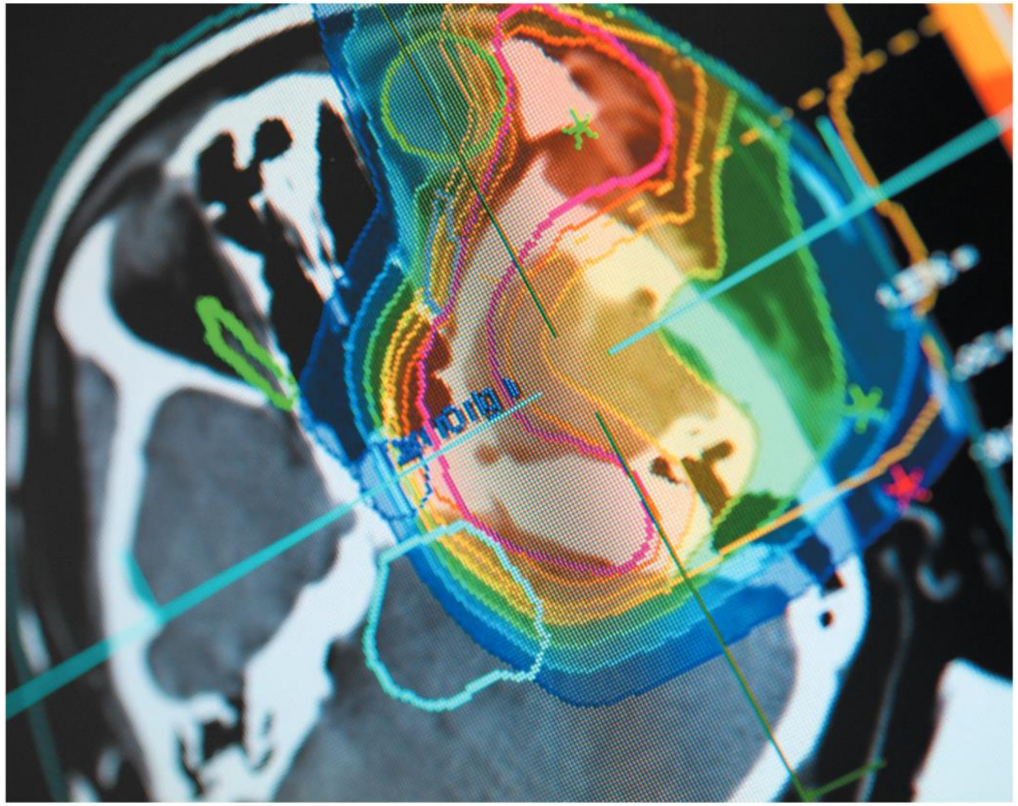
Optimisation of a detector setup for Helium-CT

Master's Thesis overview
Linus Schlee 15.09.2025



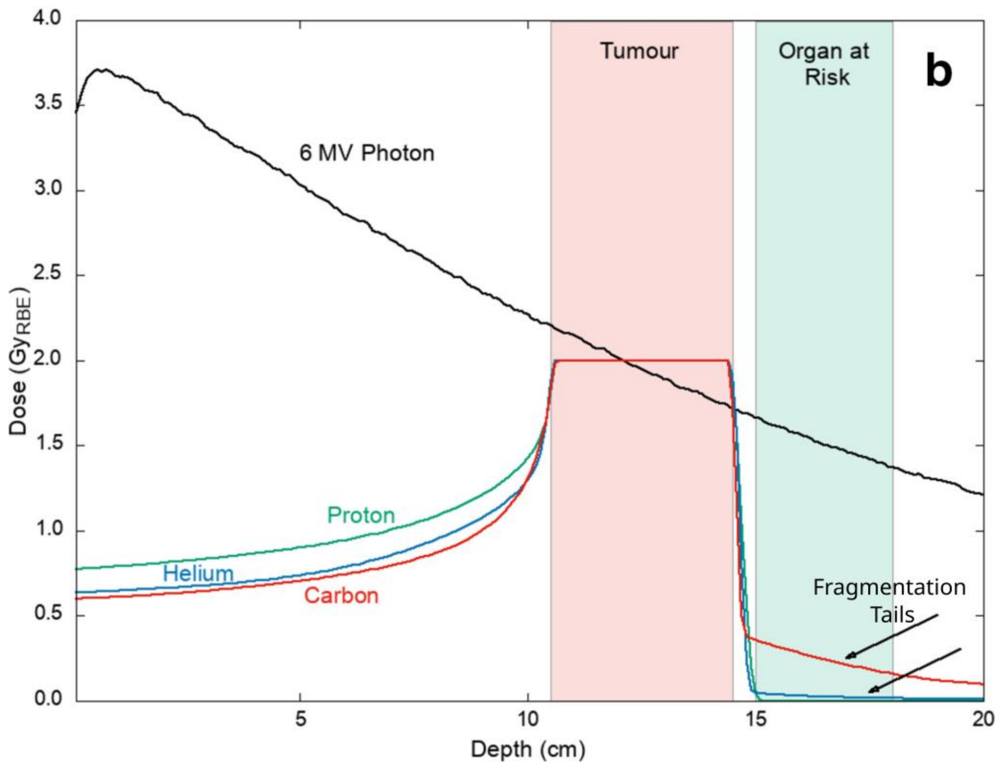
Motivation – medical therapy and imaging

- radiotherapy and radiographic imaging
- diagnosis and treatment of **cancerous diseases**
- compromise between **effective radiation dose** and **minimal damage** to healthy tissue



CT for treatment planning Heidelberg University Hospital

Advantages of Helium in Ion-Beam Therapy



Dose relative to depth in human tissue
Br J Radiol. 2020 Nov; 93(1116): 20200247

- Ion-Beam Therapy enables treatment with highly conformal dose distribution
- Helium as compromise between Hydrogen and Carbon

- more massive than protons
  → steep Bragg Peak
  → less Coulomb Scattering
- less massive than carbon
  → smaller Fragmentation Tail (secondary radiation)

Medical Ion-Beam-Radiotherapy

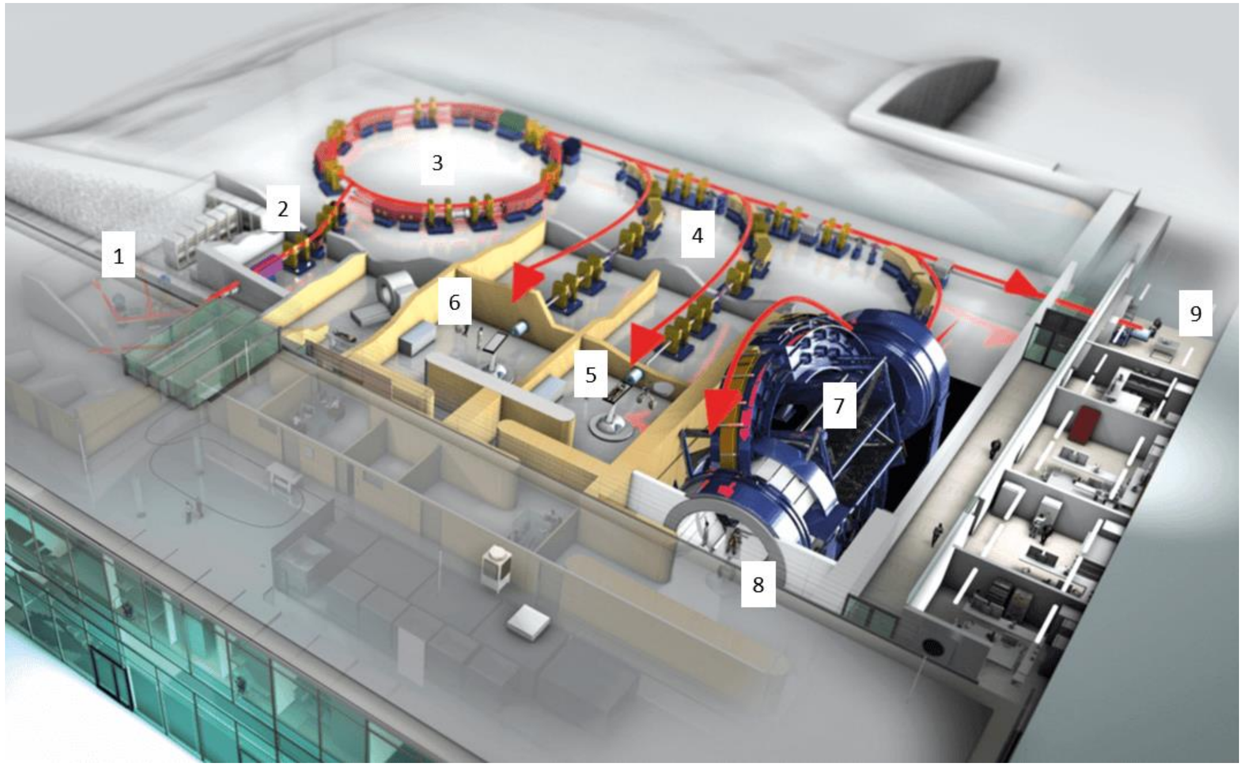
DKFZ/HIT Heidelberg

Ion Therapy

- Heavy Ion Therapy at Heidelberg Ion Beam Therapy Center with **H**, **He** and **C**

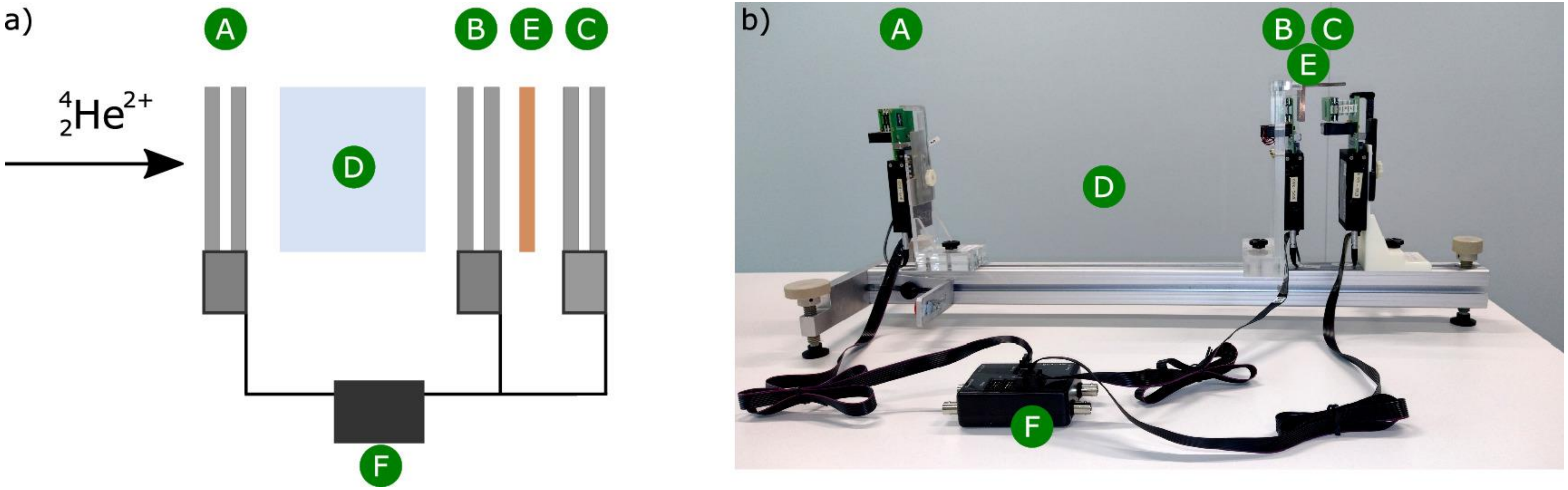
Imaging

- measuring water-equivalent-thickness with thin detectors [Knobloch,MedPhys 49,pp 5347 2022]



HIT facility, Heidelberg
www.klinikum.uni-heidelberg.de (03.2025)

He-Radiography: current setup at DKFZ

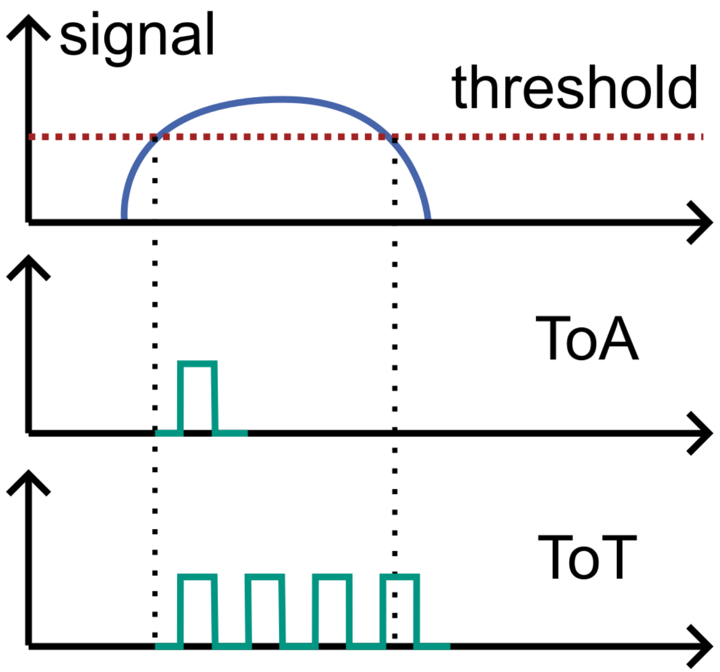


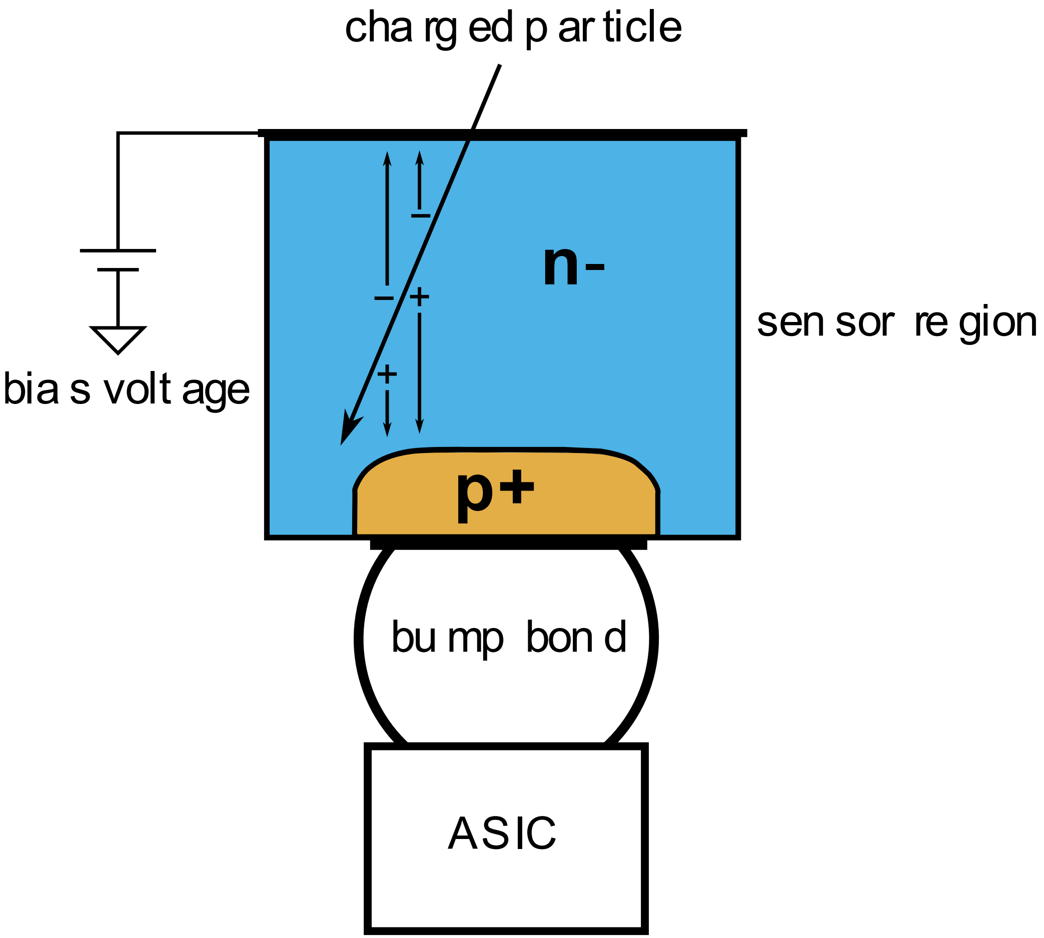
Margareta Metzner et al 2024 Phys. Med. Biol. 69 055002, Fig 2

A,B: tracking detectors **C**: energy, rear tracking detector **D**: phantom **E**: copper degrader **F**: hardware unit

Detectors

- hybrid semiconductor pixel detectors
- signal formation in depleted layer





based on CERN Courier Volume 64, Number 5, September/October 2024

Detectors

- **TimePix**
  - 256x256 px^2, 14x14 mm^2, pitch 55 μm
  - Tracking mode: time-of-arrival
  - Energy mode: time-over-threshold

[Knobloch, MedPhys 49,pp 5347, 2022]

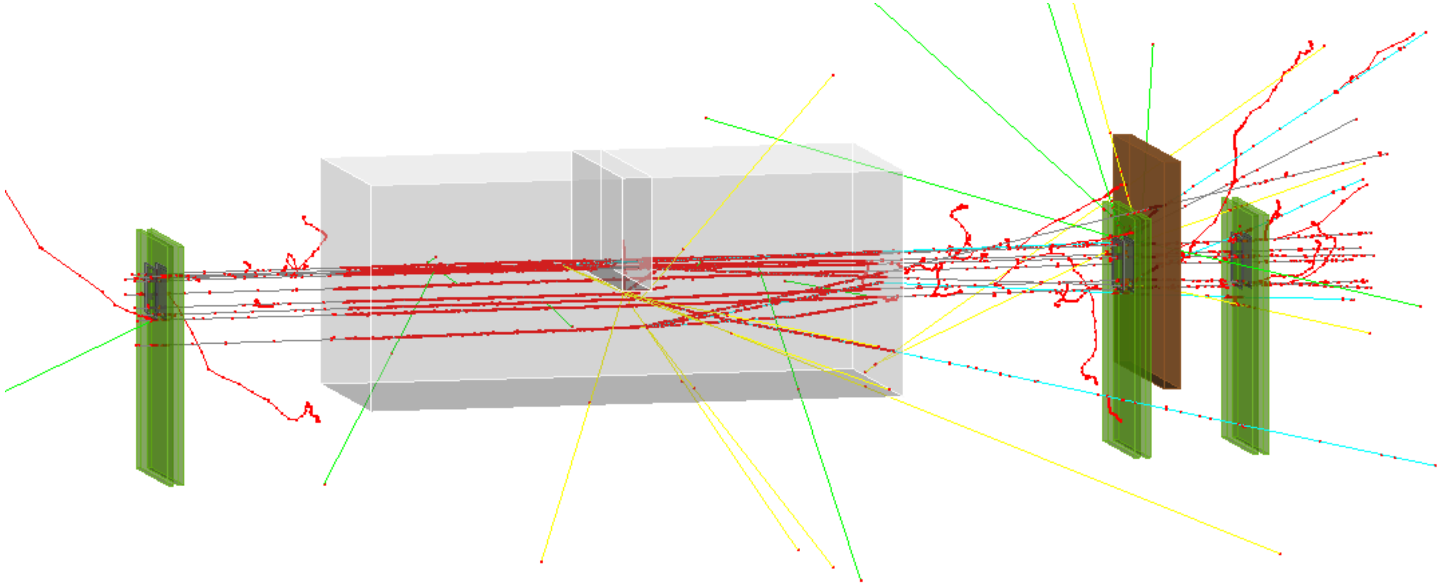
simulation: not using these outputs → **information on deposited charge per pixel**

A. Natochii, PRAE Workshop **2018**, TimePix

Simulation with Allpix^2

- Allpix Squared – Semiconductor Detector Monte Carlo Simulation Framework, developed at CERN
- simulating physical processes with GEANT4
- grounded in real measurement setups from DKFZ

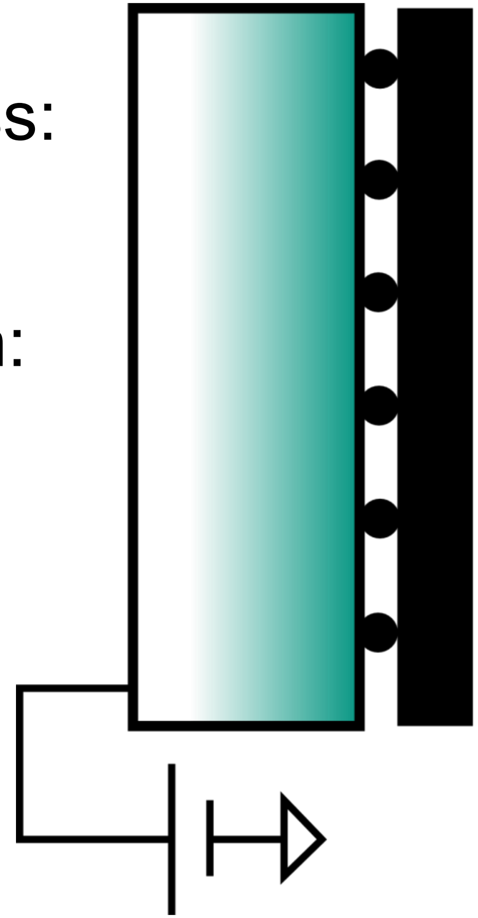
- geometry of setup, detector type, source
- different models to simulate processes inside sensor



Allpix setup: parameters

sensor thickness:
300 µm

depletion depth:
210 µm



chip thickness: 100 µm

reverse bias voltage: -7.4 V

- digitization: charge sensitive amplifier model used for energy sensor
- degrader: 5.45 mm of copper
- phantom: varying length of **PMMA** (poly-methyl metacrylate, "plexiglass")

Measurement methods

simulation

- distinct events
- single particle from source

- measured quantity: **deposited charges/number of created e-h pairs**
- conversion into deposited energy: E = 3.64 eV per charge

experiment

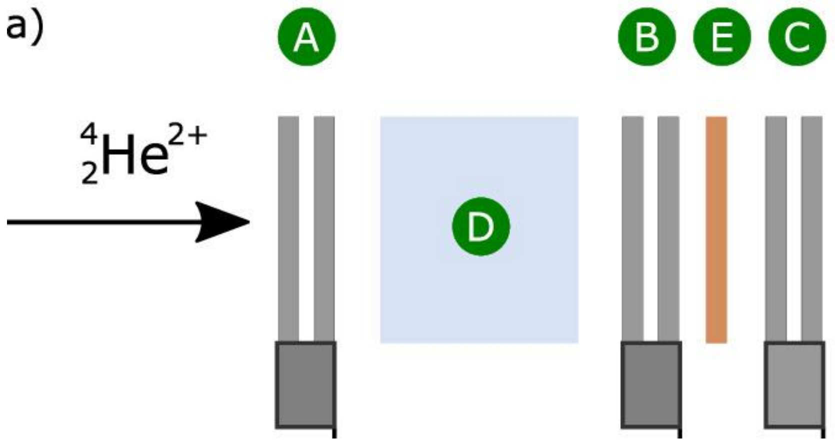
- measuring over time intervall
- high intensity particle flux

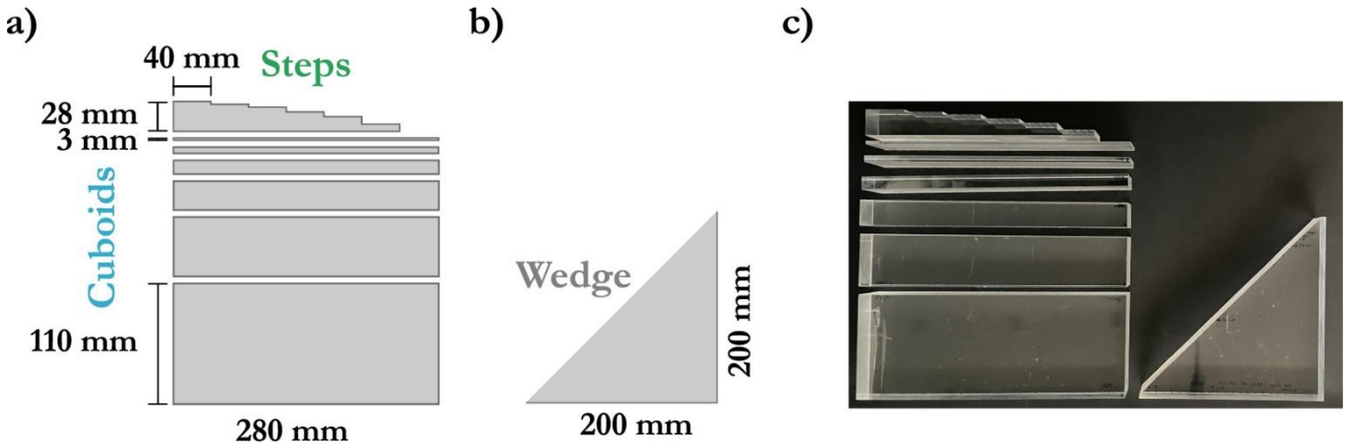
- measured quantity: **time-over-threshold**

- conversion via calibration measurement with known radioactive sources

Overview of experimental data

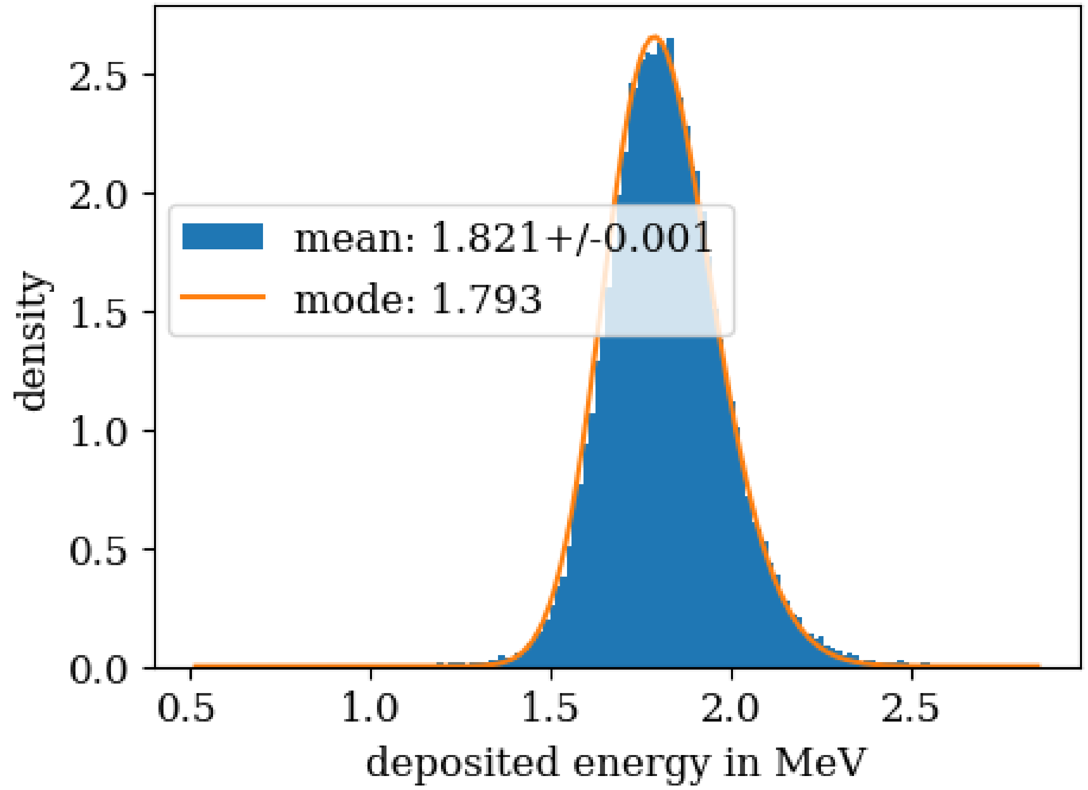
- datasets of deposited energy
- two different beam energies
- 4 different phantom thicknesses per beam energy





Overview of experimental data

- 179 mm PMMA phantom
- 825.4 MeV beam energy
- approximately gaussian peak



Overview of experimental data

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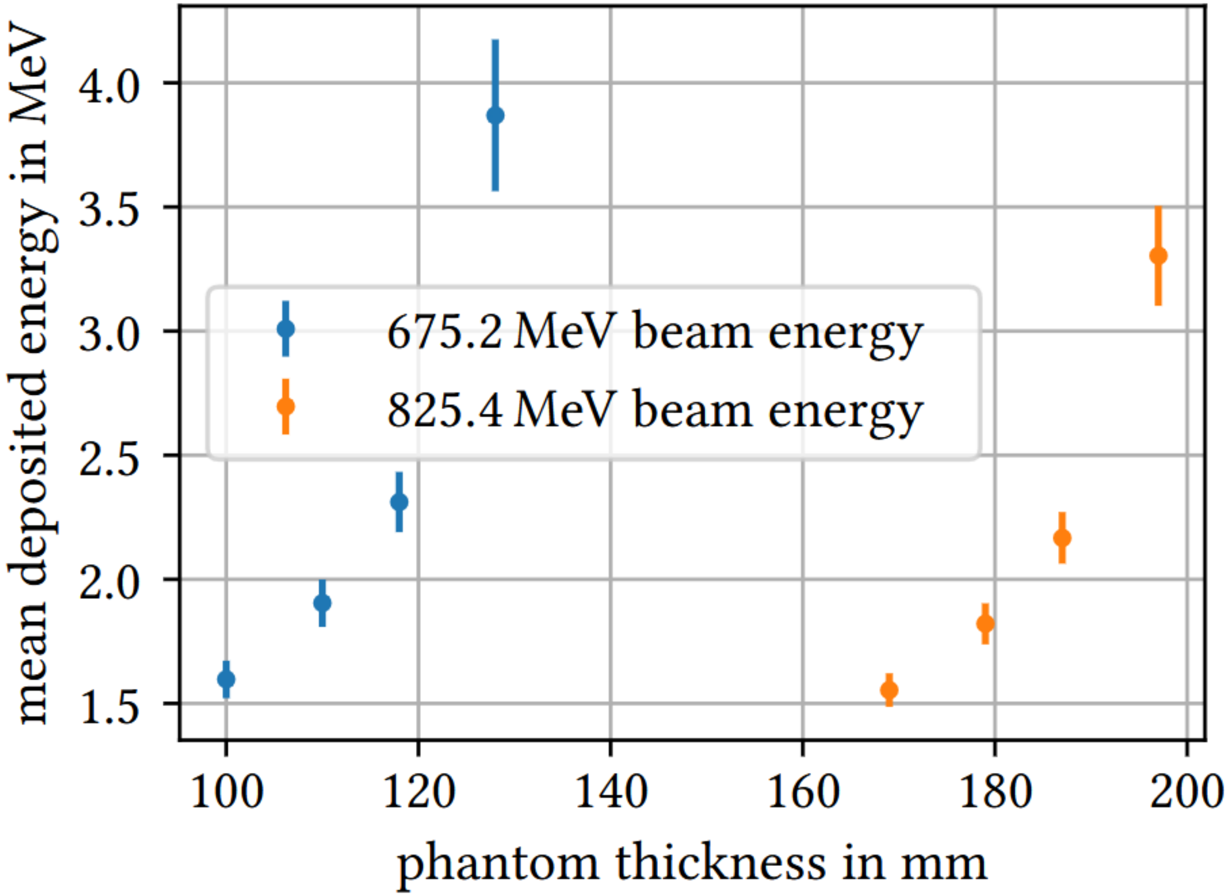
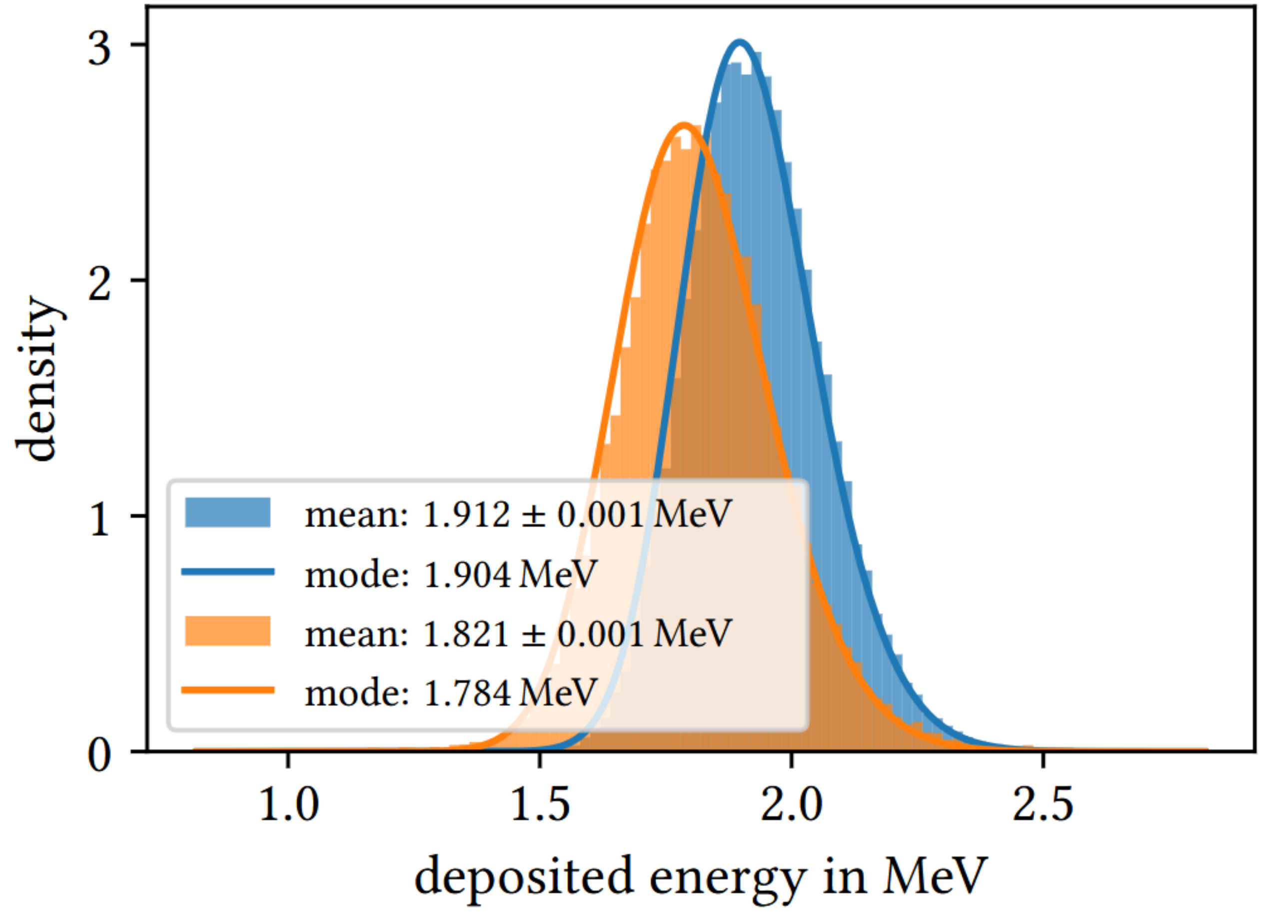


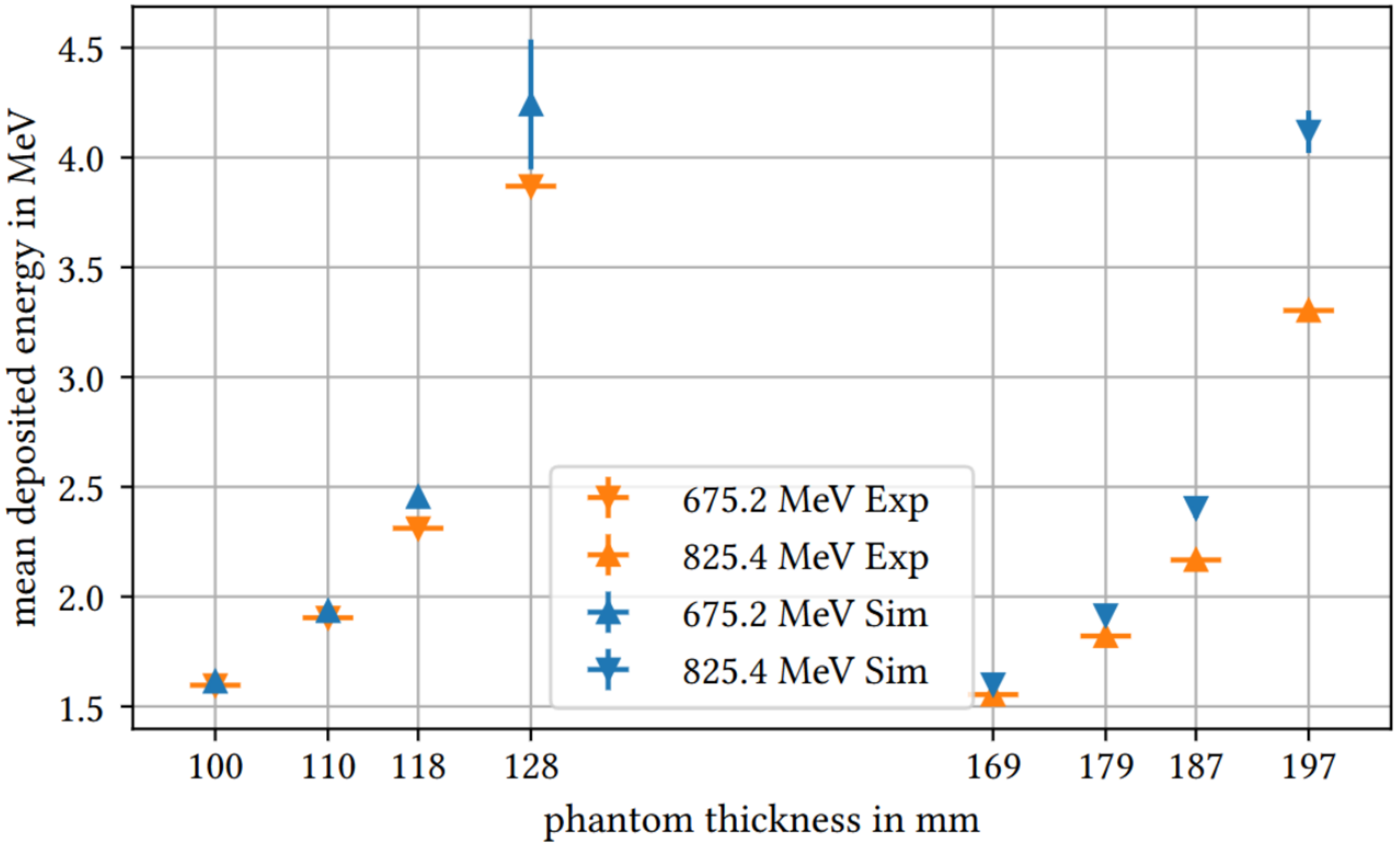
Simulation – comparison with experimental results



- example at 825.4 MeV
- simulating phantom with 179 mm of PMMA

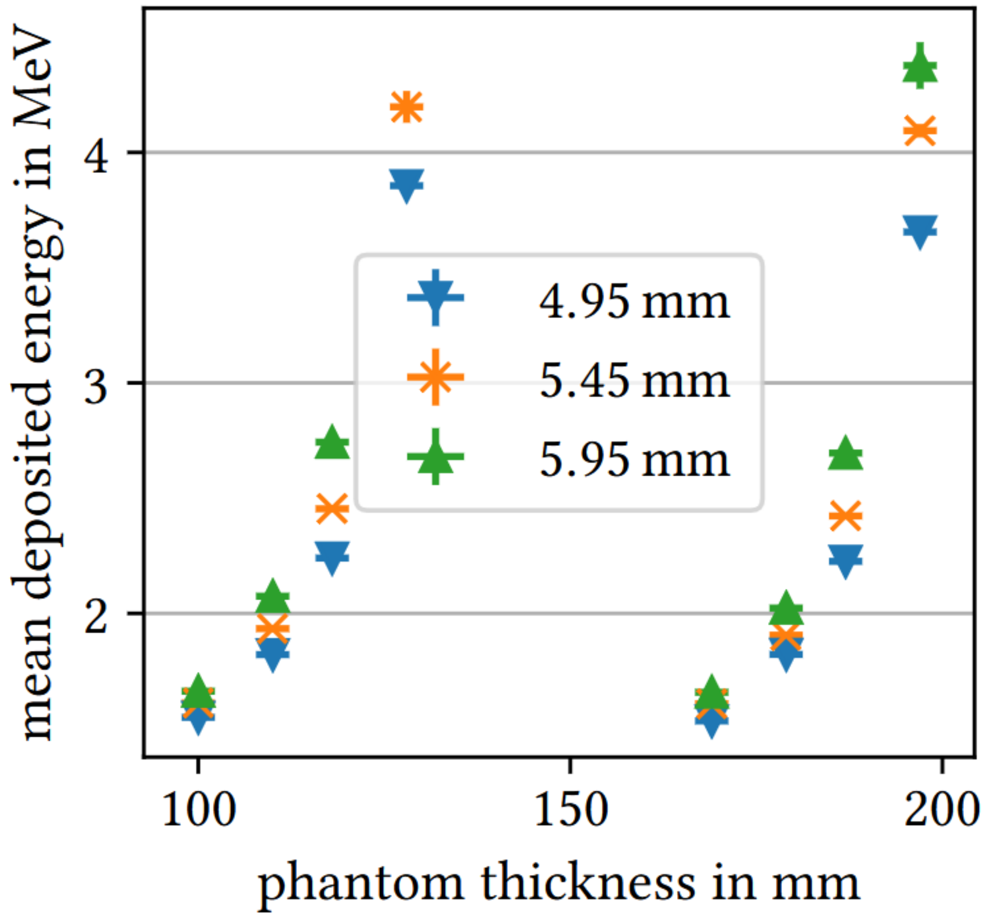
Results – comparison between simulation and experiment

- simulation overestimates deposited energy
- higher dispersion of deposited energy at larger thickness

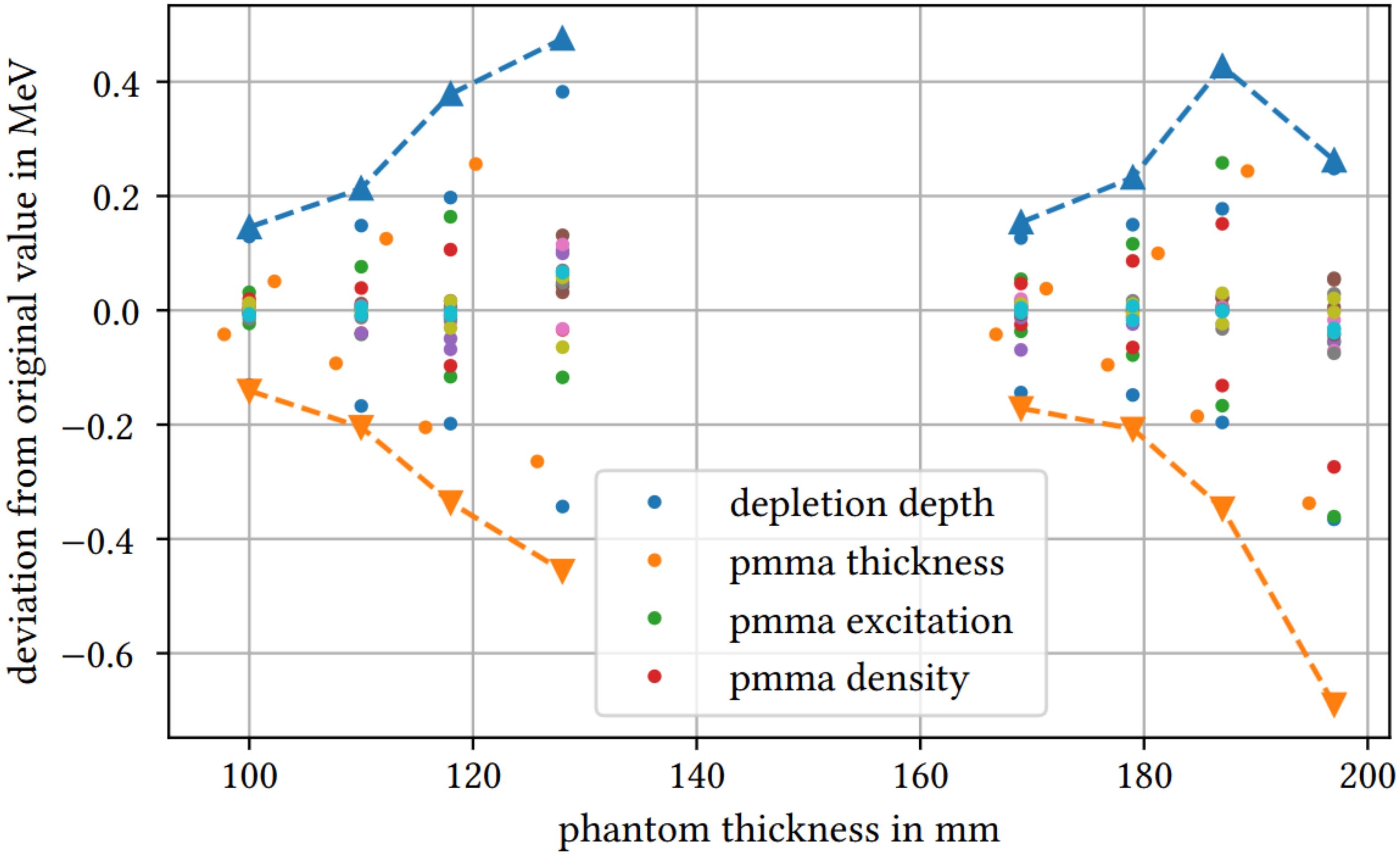


Study on simulation parameters

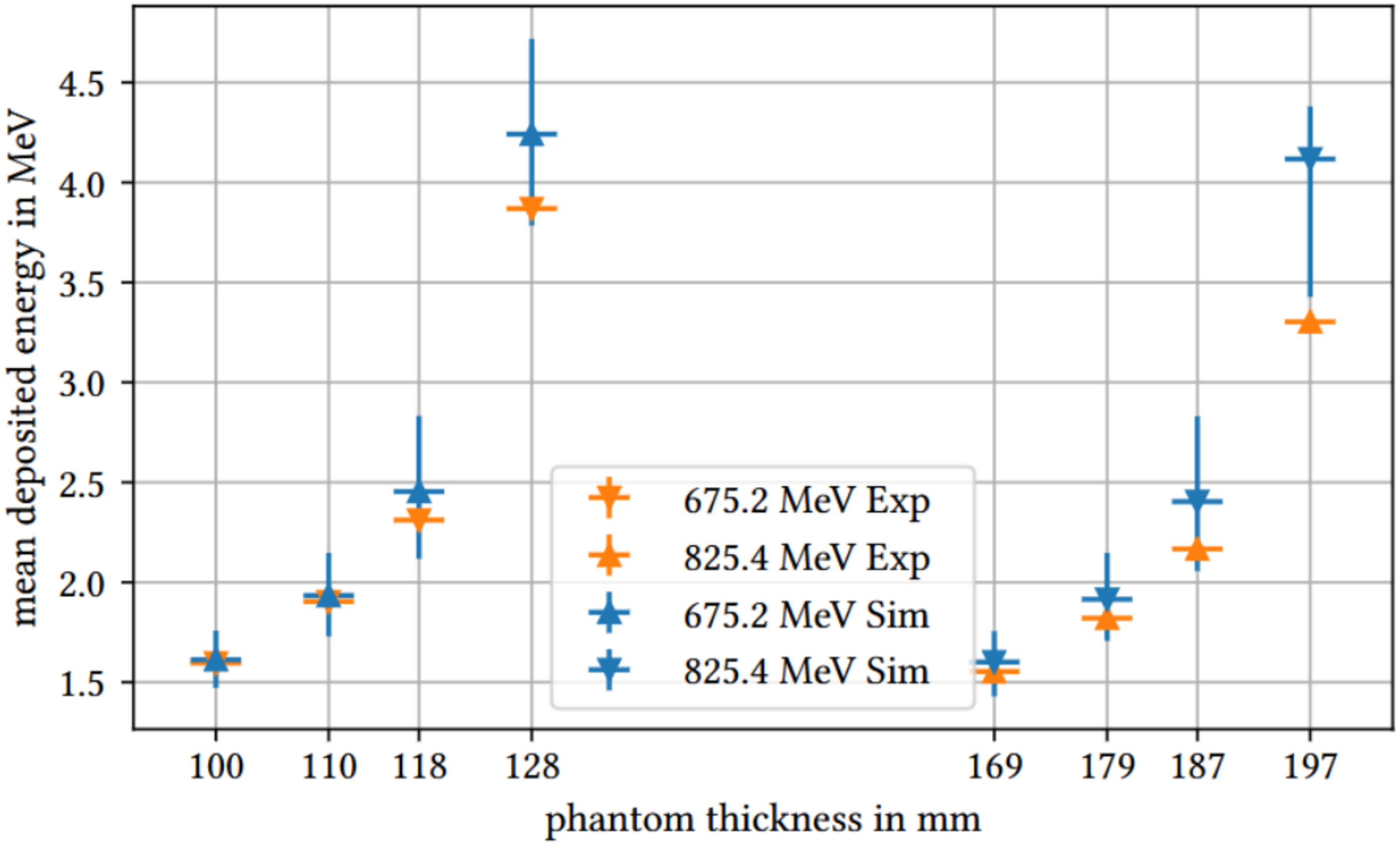
- example: **degrader thickness**
- varying given value by the uncertainty ($\pm\sigma$)
- rough estimate of probable upper and lower bounds on simulated energy



Study on simulation parameters

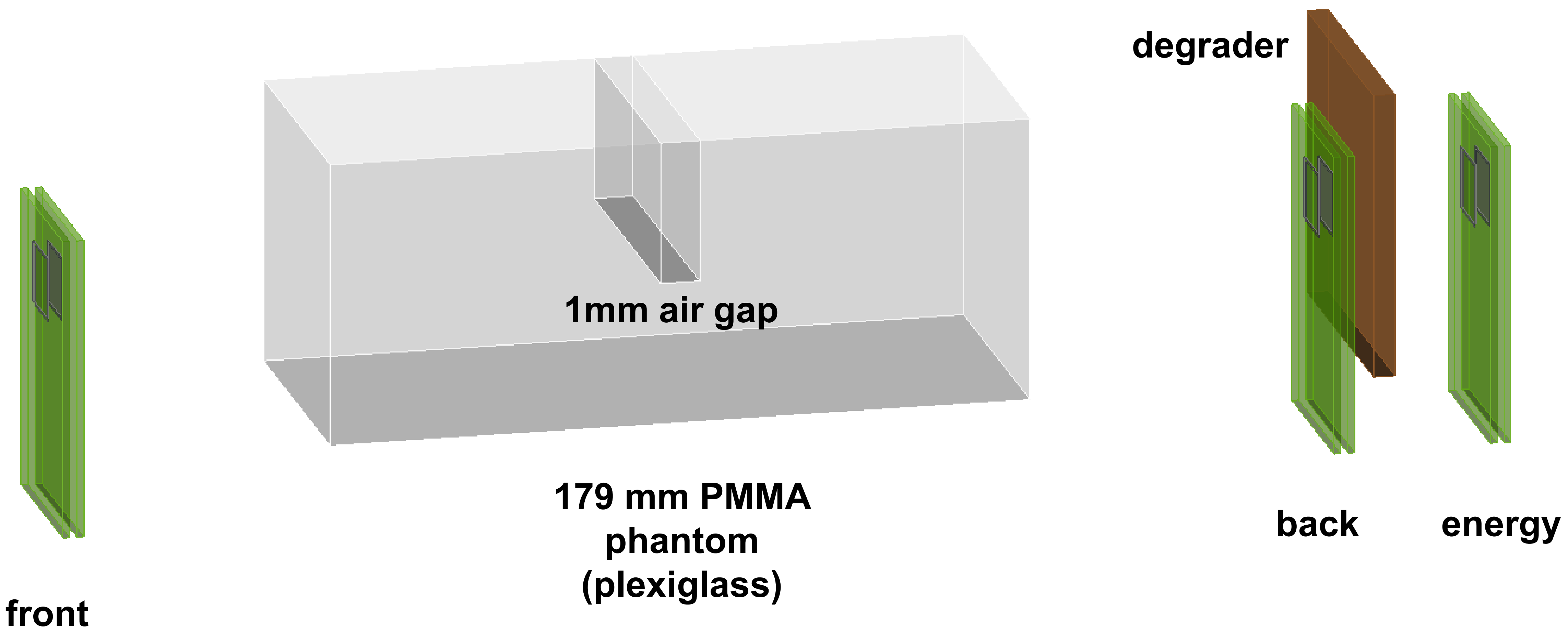


Revised comparison with experimental results



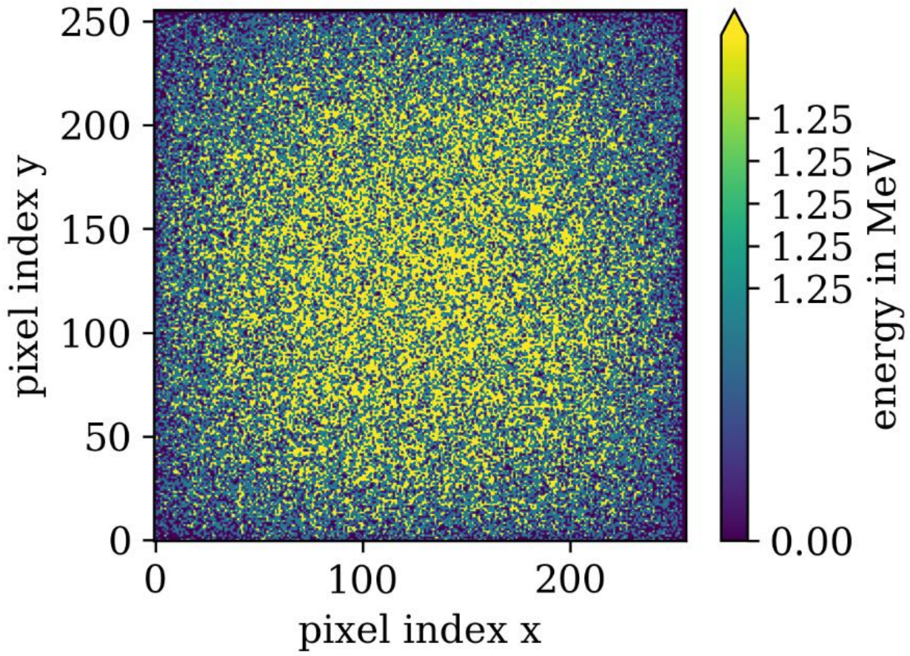
- wide margin between upper and lower bounds
- no accurate representation of experimental data achieved
- physical simulation models rely on precisely known parameters → missing information

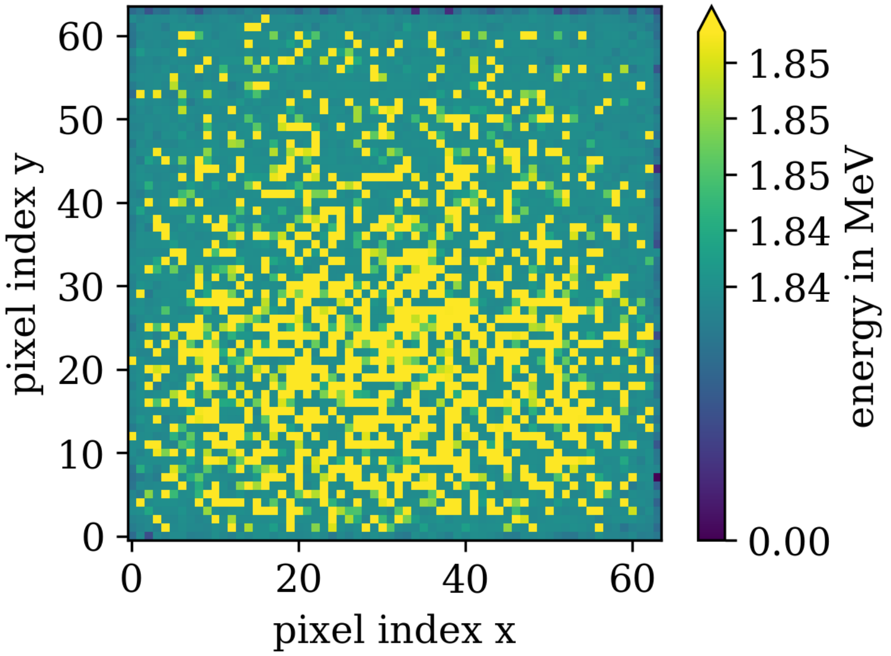
Imaging – visualisation in Allpix²



Imaging

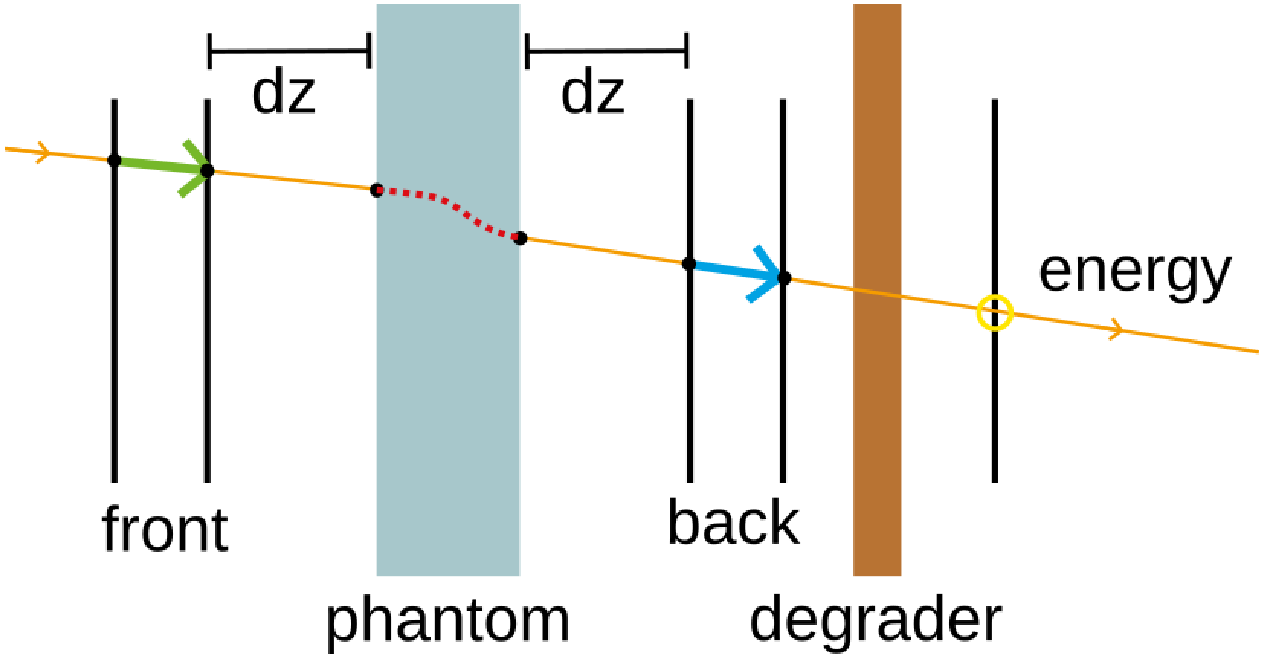
- **2-D** radiography
- generate image from 2D per pixel energy deposition



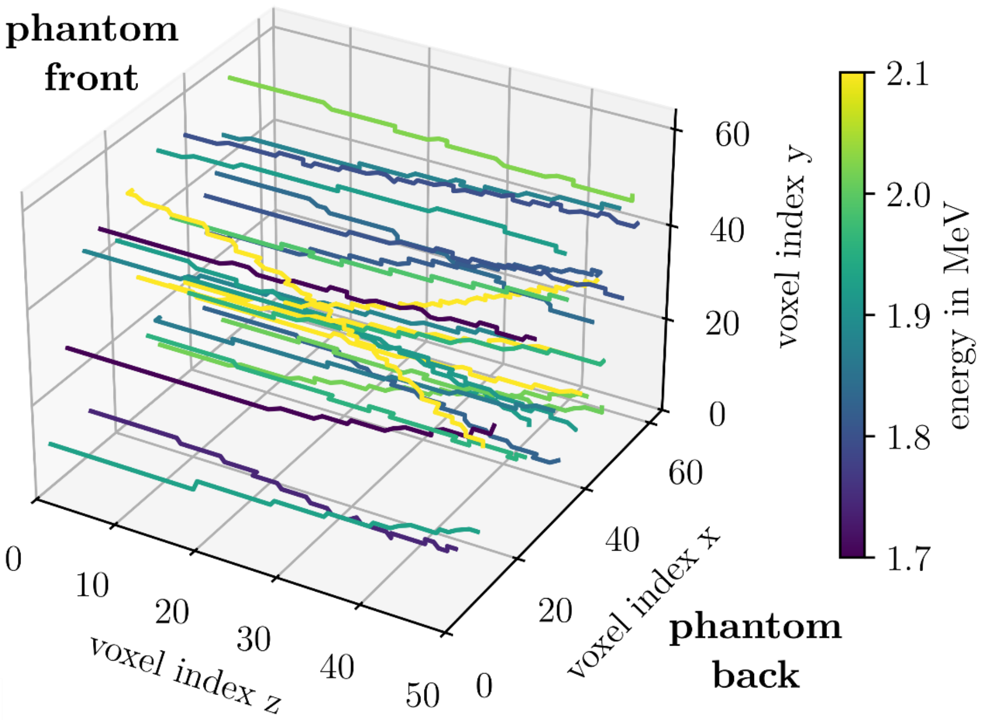


Imaging – method

- methods used from [Gehrke, PhysMedBiol 63, 2018]
- path through phantom approximated through cubic spline path [Fekete, PhysMedBiol 60, 2015]
- path is calculated with estimated parameters from the **WET** and **w**ater-**e**quivalent-**p**ath-**l**ength at the specified **beam energy**



imaging - method

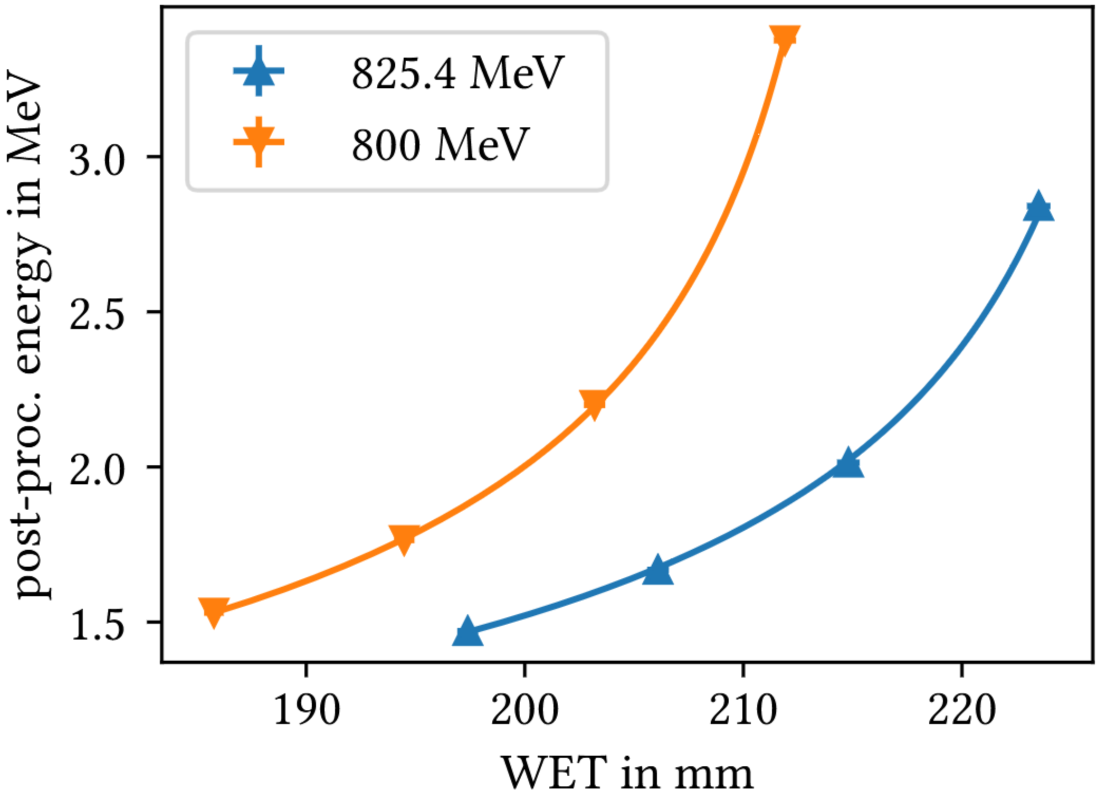


- 3-D path conversion to voxels
- mean energy value calculated for each voxel
- integration along z-axis for 2D picture

Conversion of energy into WET

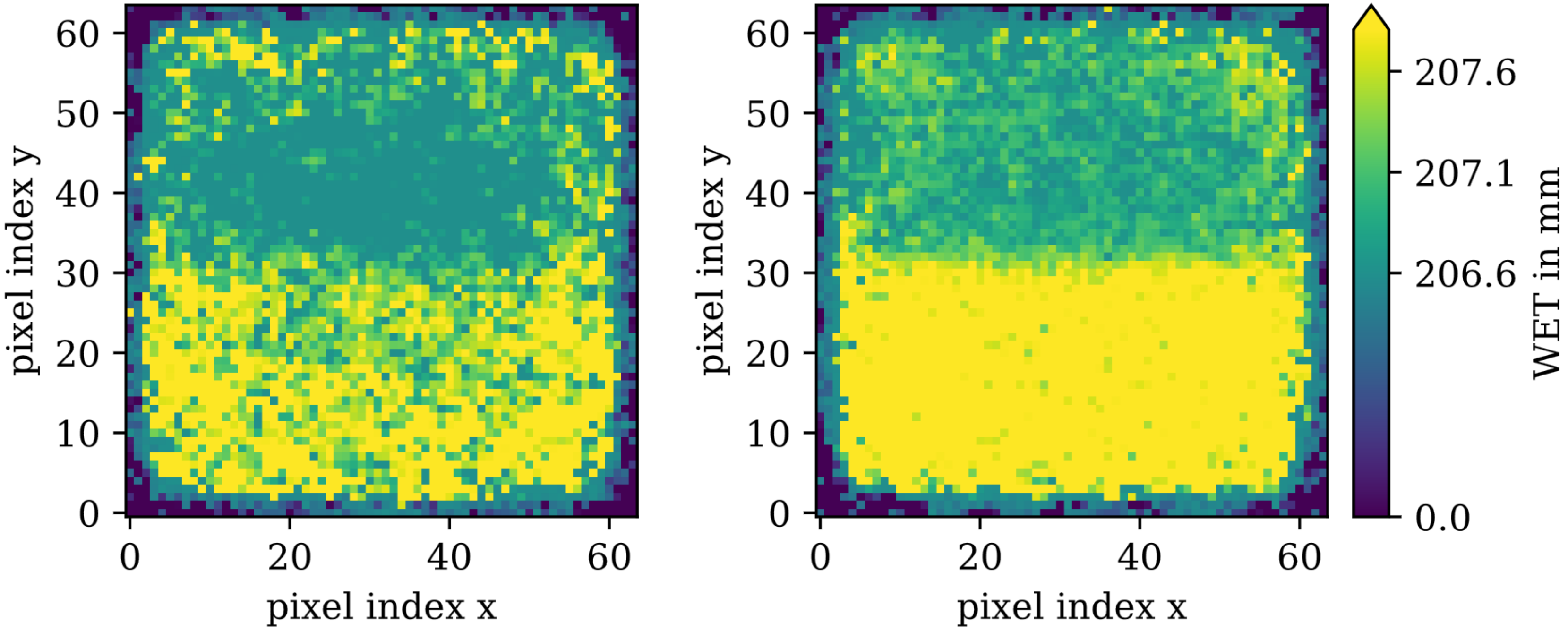
- **WET:** water-equivalent-thickness
- length of water needed to achieve the same effect
- measure of radiological thickness independent of incident energy

- repeated simulations with PMMA phantoms of known WET



Imaging - results

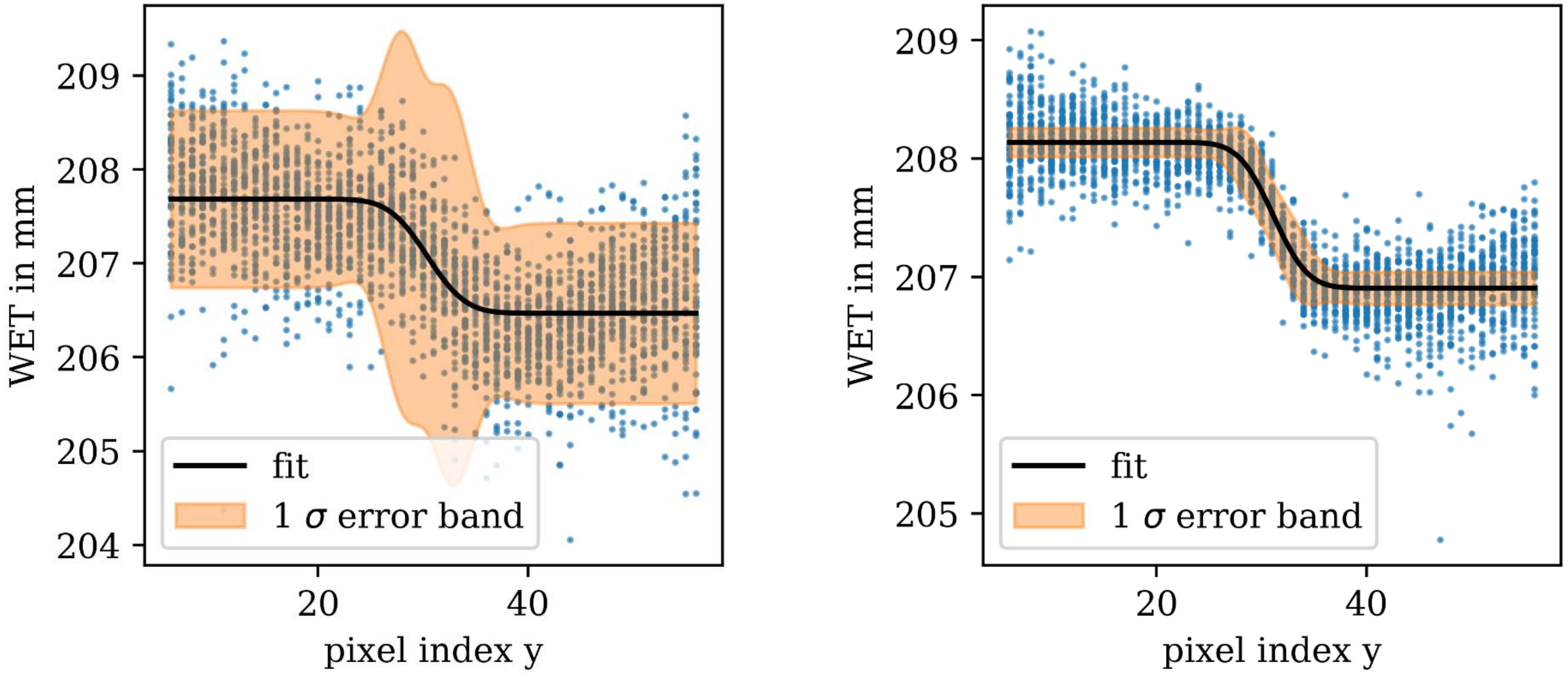
- 1 mm gap at 825.4 and 800 MeV beam energy



Imaging - results

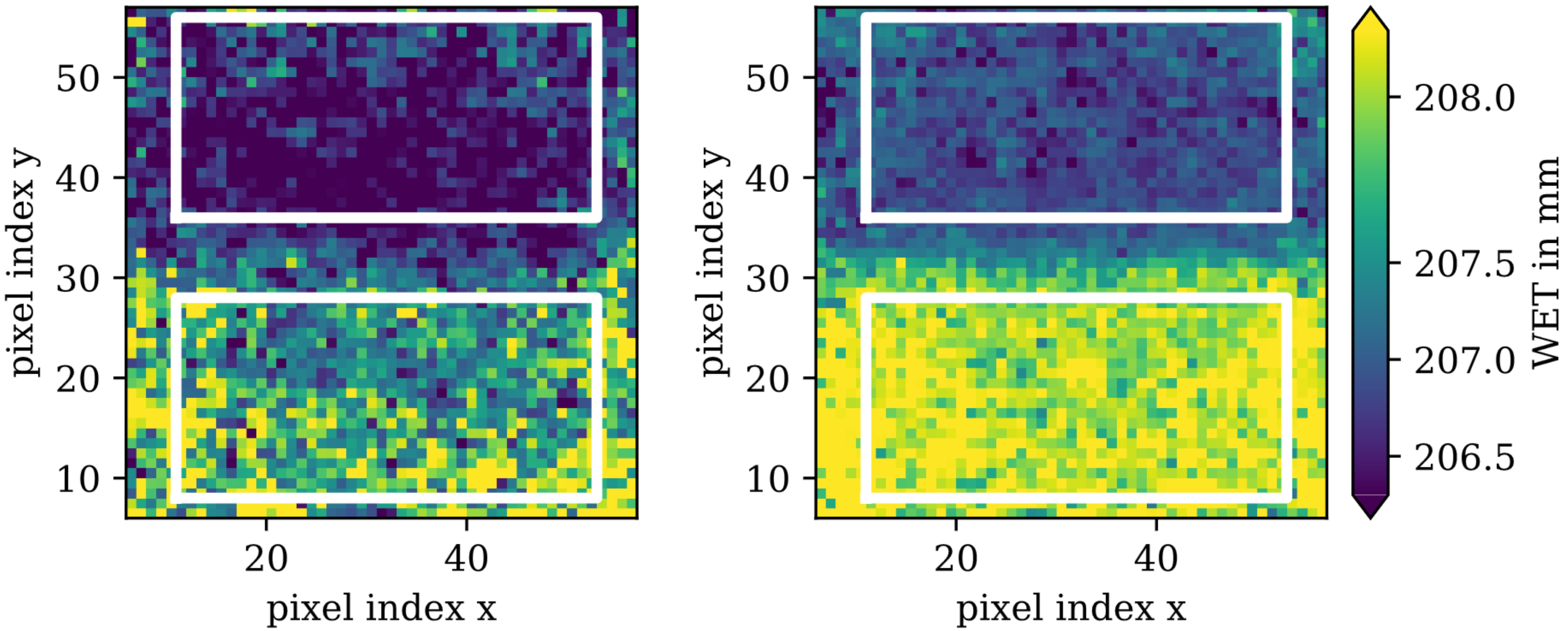
- use error function as fit function

$$\mathrm{erf}(x) = a \cdot \frac{2}{\sqrt{\pi}} \int_0^{(x-z)f} e^{-t^2} dt + b$$



Imaging – contrast to noise ratio

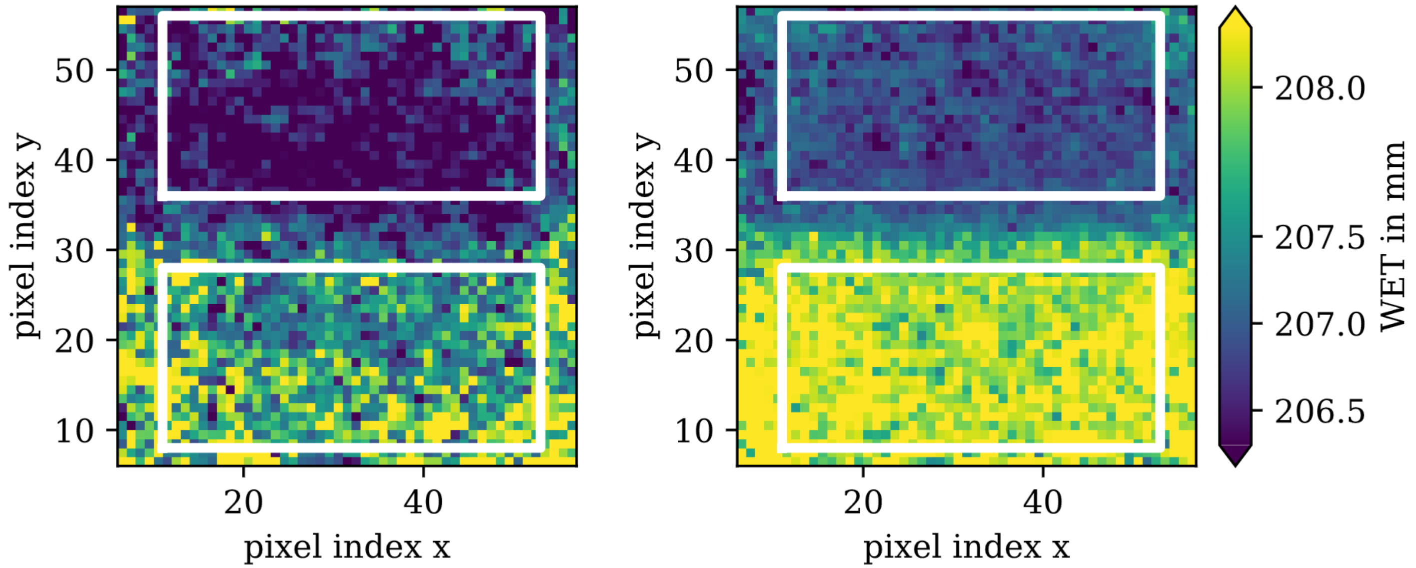
- two equal areas in different regions



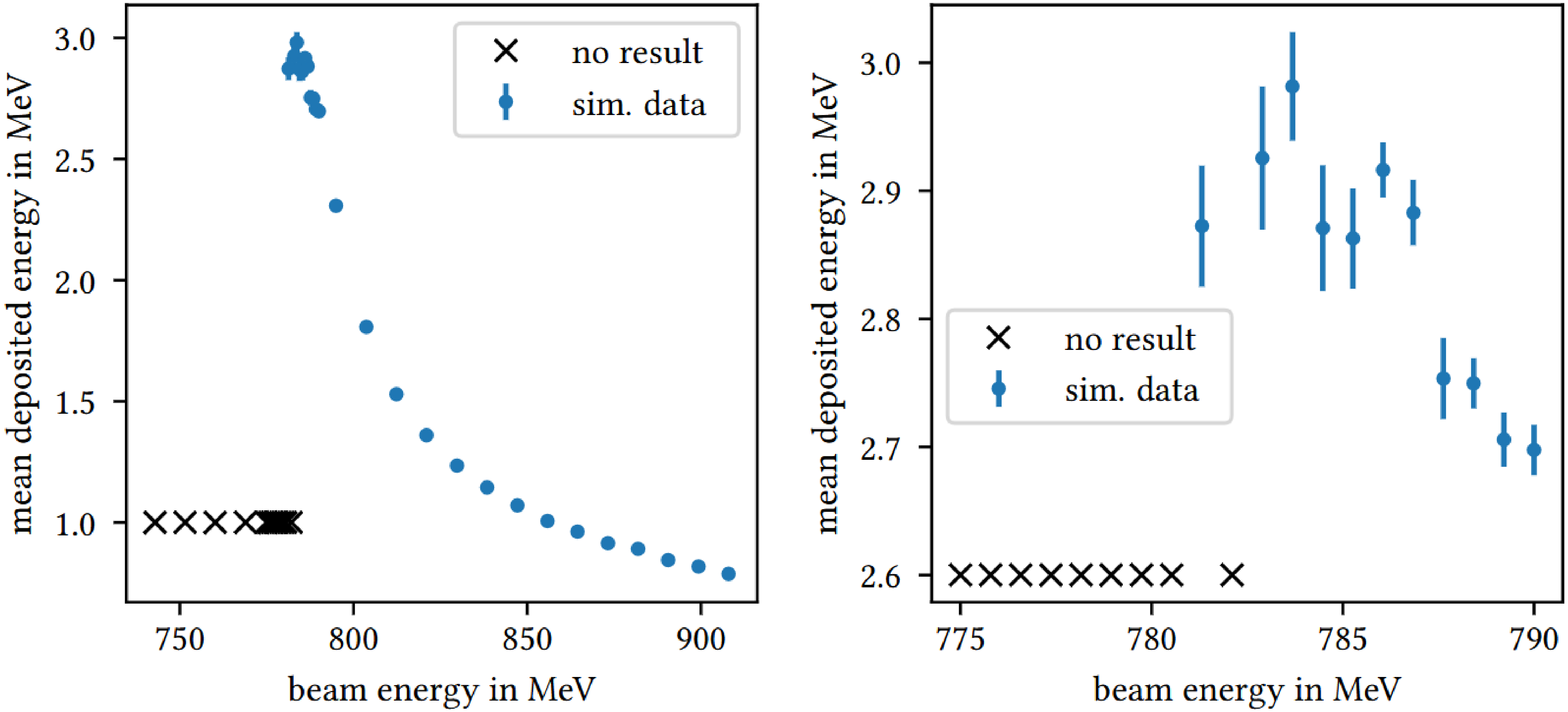
Imaging – contrast to noise ratio

$$\mathrm{CNR} = \frac{|\langle S_a\rangle - \langle S_a\rangle|}{\sqrt{\sigma_a^2 + \sigma_b^2}}$$

- $\mathrm{CNR}_{825} = 1.618$
- $\mathrm{CNR}_{800} = 3.923$

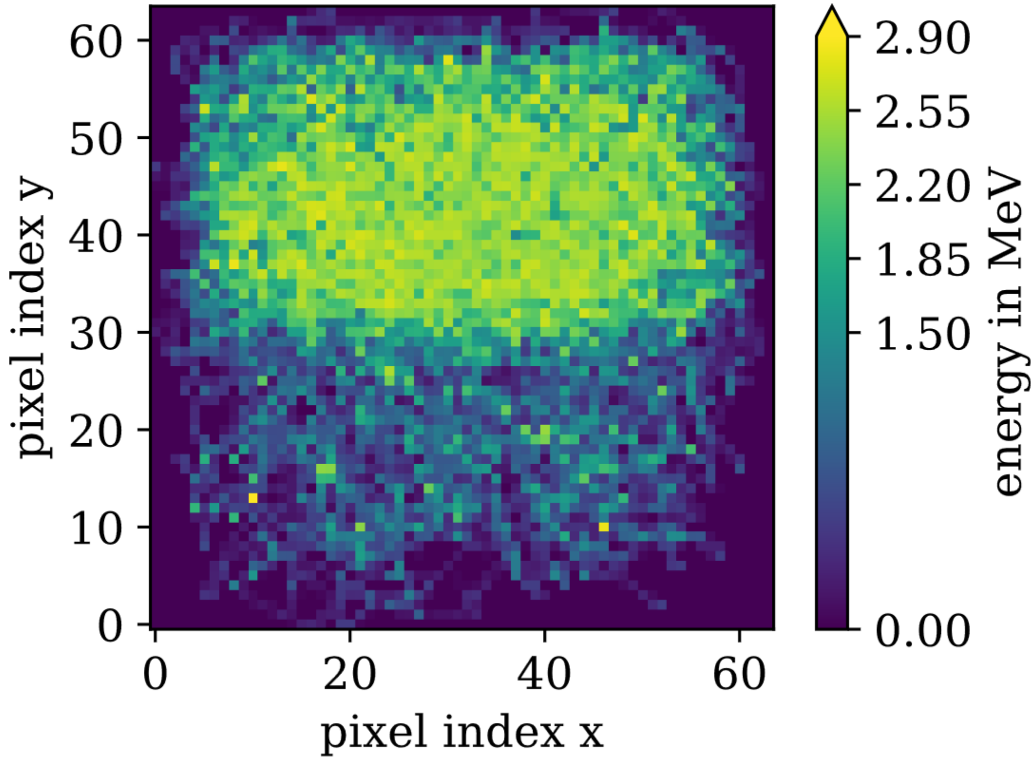


Optimising beam energy



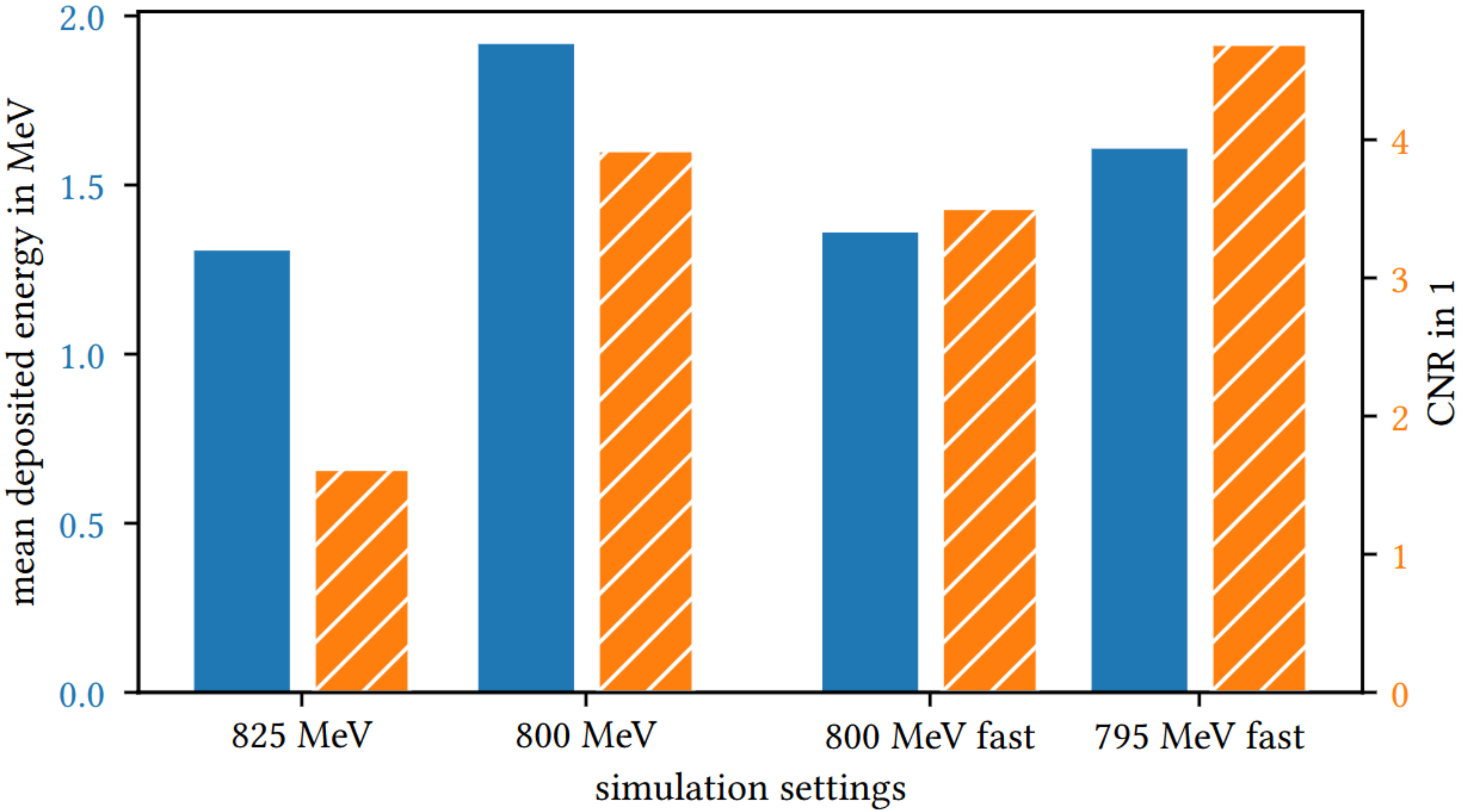
Imaging – insufficient energy

- energy of particles too small
- blocked in region of higher WET



Deposited energy and contrast-to-noise-ratio

Karlsruhe Institute of Technology



Summary

- real world setup has been successfully recreated in Allpix-Squared
- experimental results could not be reproduced with satisfying accuracy
- insufficient data on setup, calibration and depletion region

- 1 mm air gap in PMMA phantom imaged in radiograph
- WET value of 1.2 +/- 0.5 mm, agrees with expected value of 1.16 mm
- improvement of CNR by changing beam energy

- future steps: 3D (CT), efficient simulation, different quantities to optimise, optimisation via Machine Learning

Thanks !

Karlsruhe Institute of Technology

... to Ulrich and Alexander,
... to Lorenzo and Jan,
... to CN 317,

... to ETP for all your support and cake.

Addendum

Locations of medical Ion-Radiotherapy

DKFZ/HIT Heidelberg

- Secondary Radiation: In-ViMo Project [6], Carbon-Ions [5]
- Helium-CT: Imaging, measuring WET [1], Energy Painting [4]

CNAO Italy

- He-Ion facility planned [2]

NIRS: HIMAC Japan

- HIMAC: Heavy Ion Medical Accelerator, Carbon-Radiotherapy
- multi-Ion (He,C,O) radiotherapy planned [3]

MedAustron Austria

- He-Ion facility planned [2]

Imaging – method

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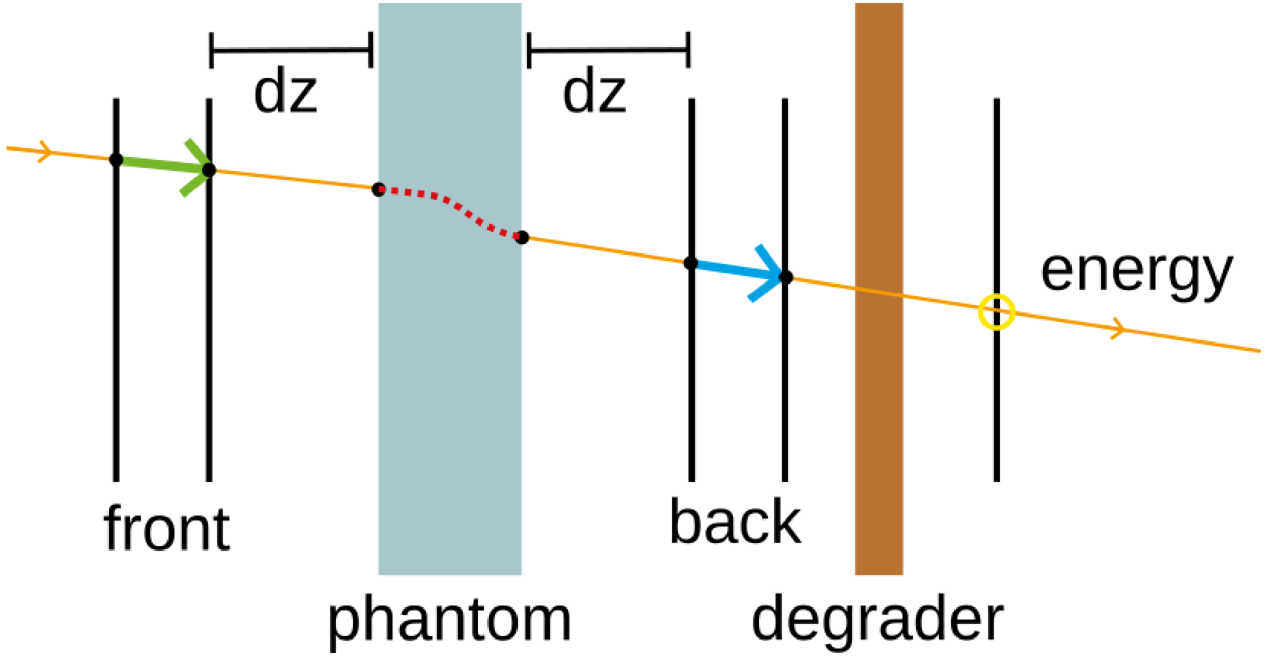
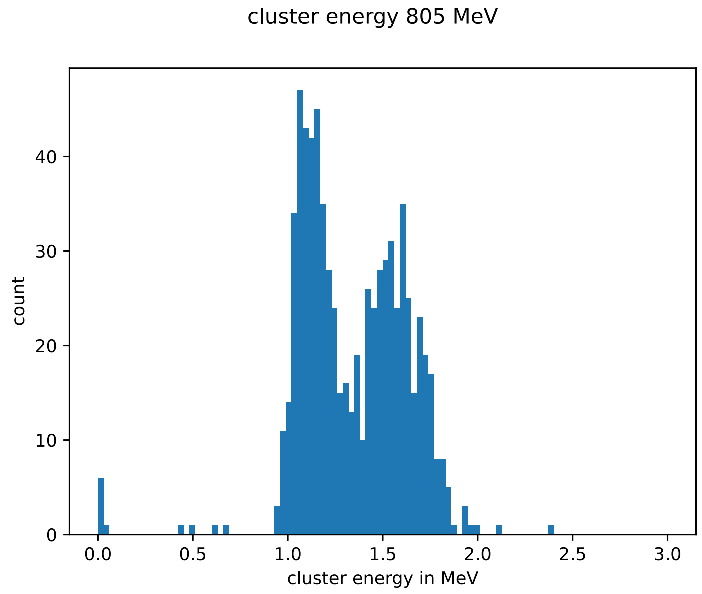


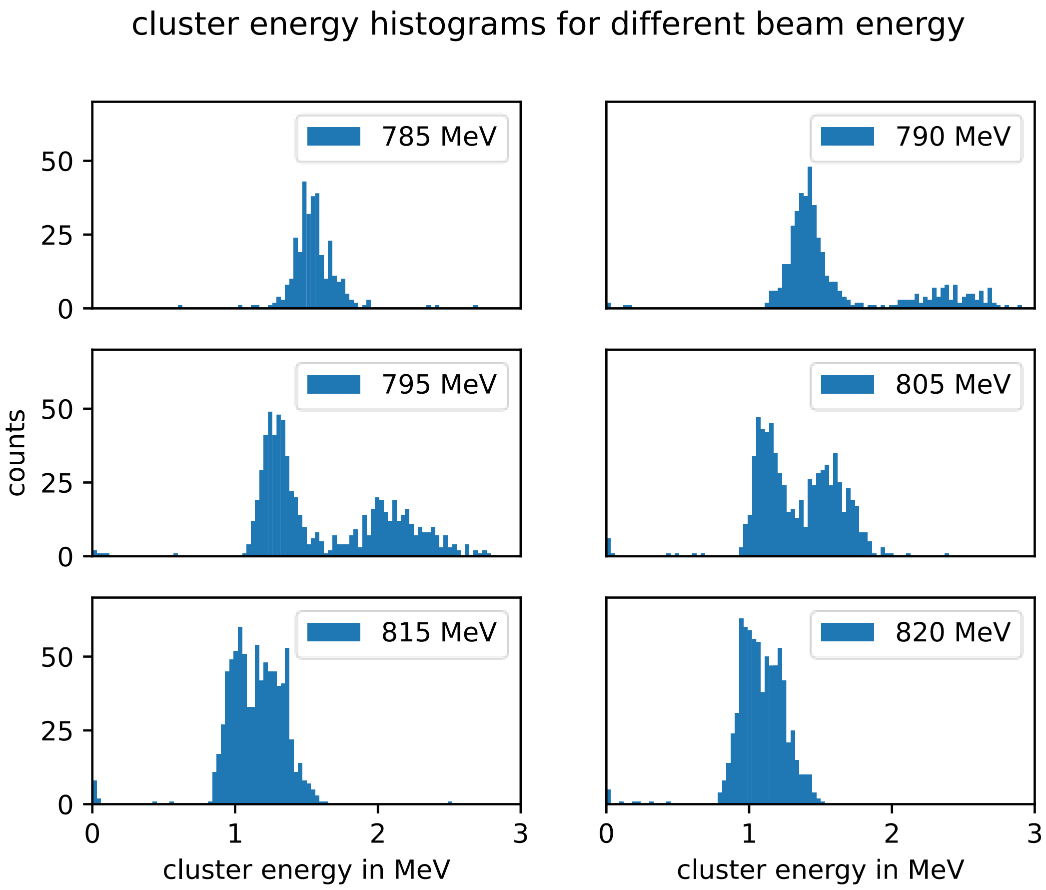
$$r(t) = (2t^3 - 3t^2 + 1) \cdot \vec{p_0} + (t^3 - 2t^2 + t) \cdot \Lambda_0 \cdot \vec{d_0} + (-2t^3 + 3t^2) \cdot \Lambda_1 \cdot \vec{d_1}$$

$$\vec{d_{0,1}} = \hat{d_{0,1}} \left| \vec{p_1} - \vec{p_0} \right|$$

Imaging – different beam energies

- choosing optimal energy
- maximum difference
- still at rising edge of bragg peak





Machine Learning

- established one or multiple parameters and quantities to optimise
- ML: optimisation through gradient descent
  - 🚫 difficult with simulation

- pipeline with Surrogate Model (differentiable) → Jan Kieseler