

CT Imaging with Helium and Carbon Ions

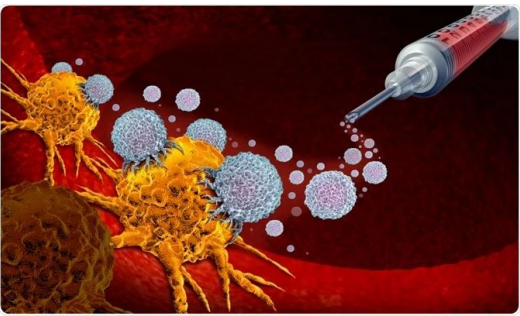
GPU Day, 28/05/26

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Supervisors: Gábor Bíró, PhD. (HUN-REN Wigner Research Centre for Physics) and Gábor Papp, DSc. (Eötvös Loránd University)

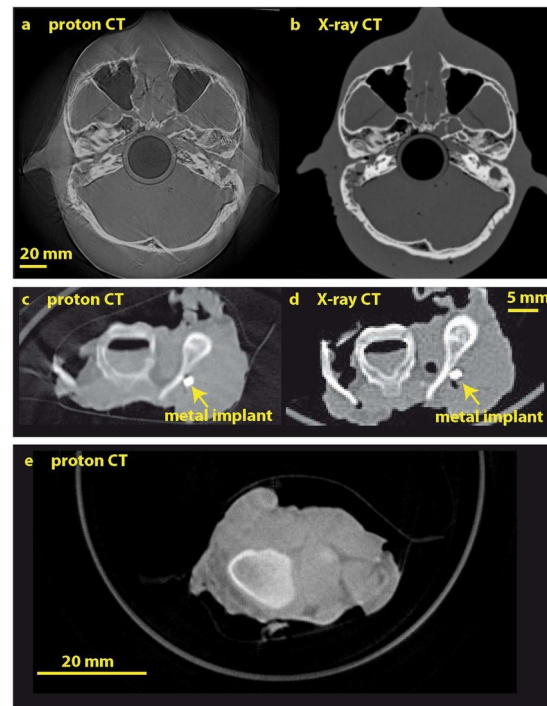
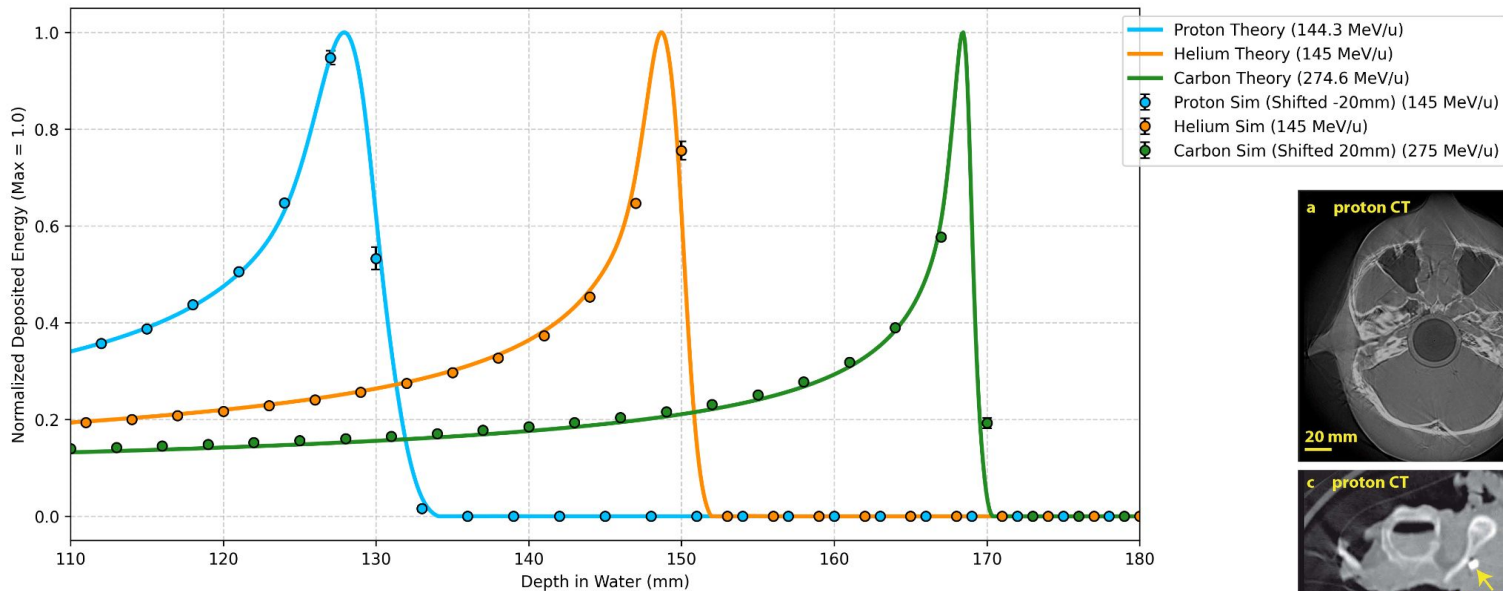
Introduction



Cancer treatment

- Surgery
- Chemotherapy
- Immunotherapy
- **Radiotherapy - uses ionization to destroy the DNA of cancerous cells**

Introduction

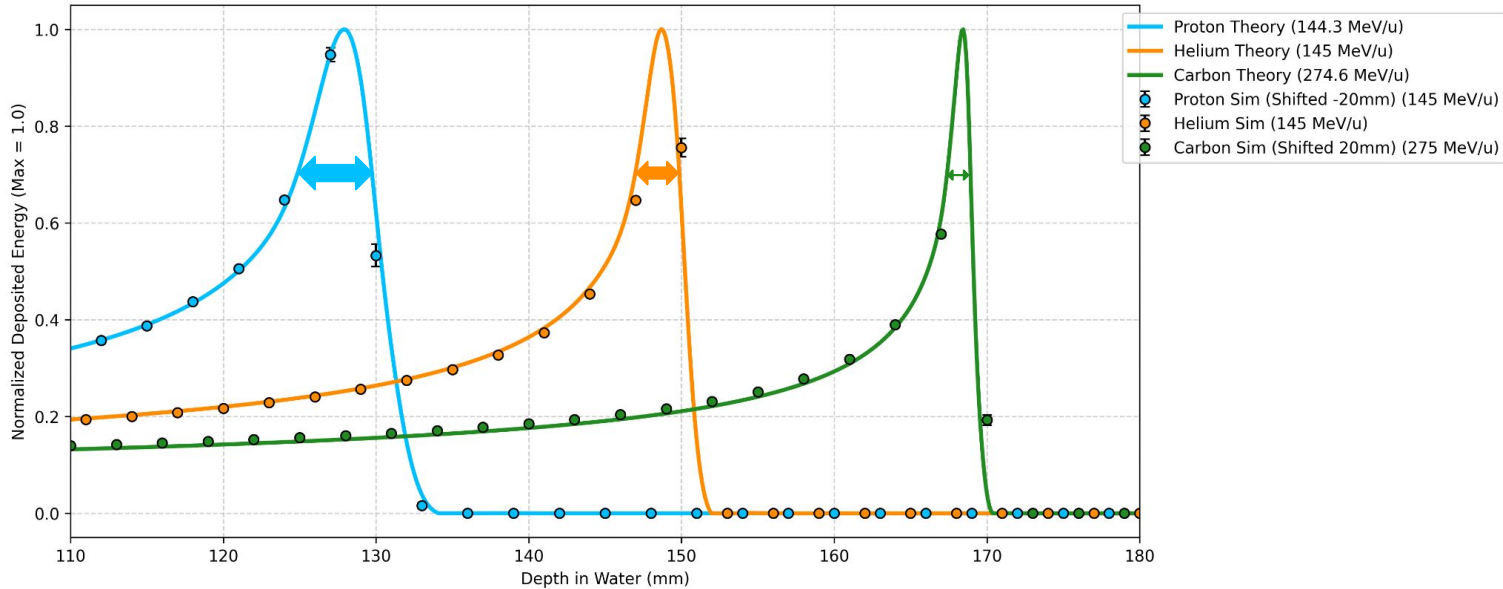


Imaging is a crucial part of radiotherapy

- Currently: X-ray CT
- Problem: errors introduced at the conversion of Hounsfield units to Relative Stopping Power (RSP) units (~7% uncertainty)
- Solution: let's do the imaging with the particle we will use for the treatment! → Position of Bragg peak can be fine-tuned with the initial energy - we simply choose a larger initial energy for imaging

Prall, Matthias et al. (2016). High-energy proton 3 imaging for biomedical applications.

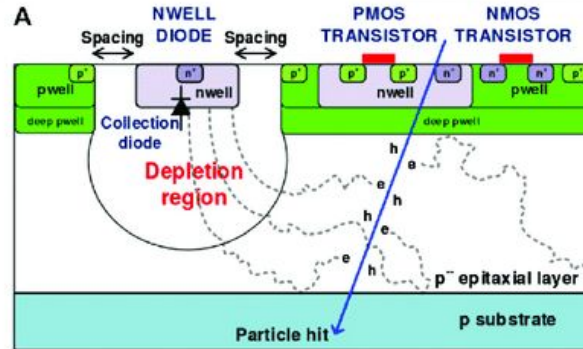
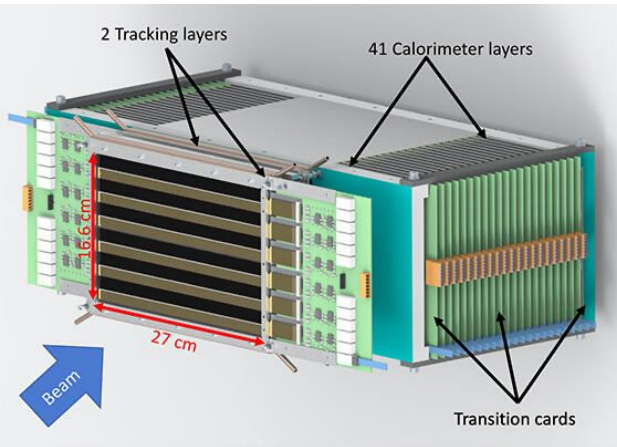
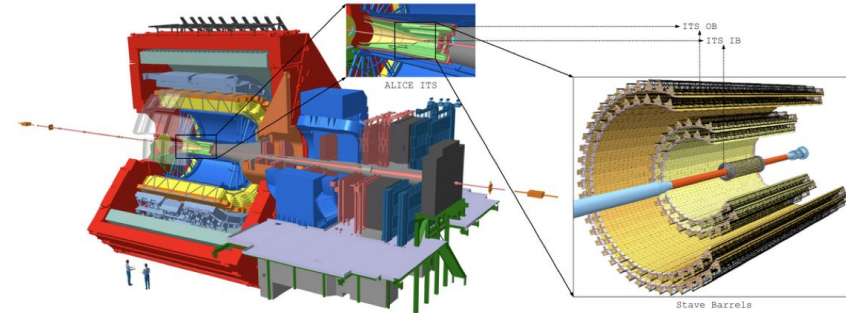
Protons vs. Heavier Ions



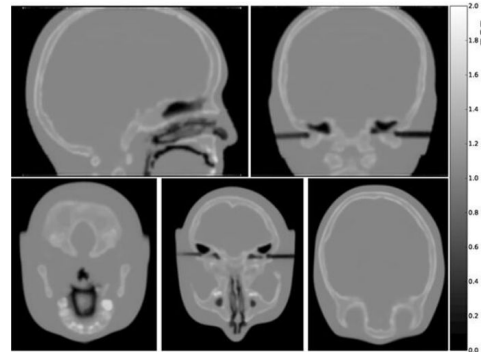
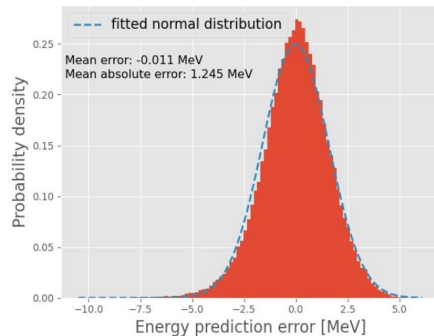
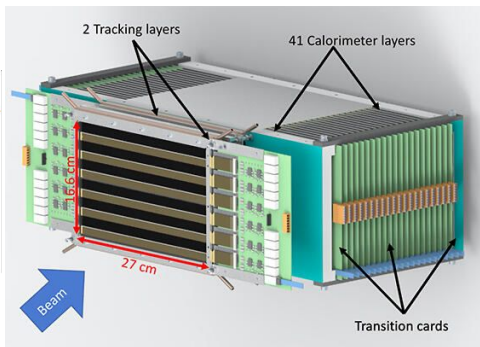
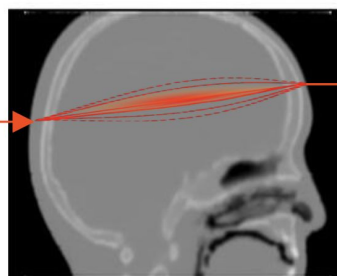
- Proton therapy is more widespread - cheaper, easier to carry out
- Bragg peak is narrower for heavier ions - more precise treatment
- Imaging before heavy ion therapies with the heavy ions? - advantage: same instrument we use for the treatment, but we need to check some parameters
 - Accuracy of imaging
 - Dose deposit of particles

The Bergen pCT Collaboration

- Goal: building and utilizing a proton CT that is based on the high energy particle detectors used in ALICE (CERN)
- Base of the detectors: ALPIDE chip
 - Monolithic Active Pixel Sensor
 - Sensors and readout are on the same layer
 - $3 \times 1.5 \text{ cm}^2$
 - 1024×512 pixels, $29 \times 27 \mu\text{m}^2$
 - 108 ALPIDE/layer in the detector



From the Particles to the Image



Irradiate the phantom with high energy (~100 MeV) hadrons

Detector system senses the signals

Currently: MC simulations

GPU usage

Signals get processed

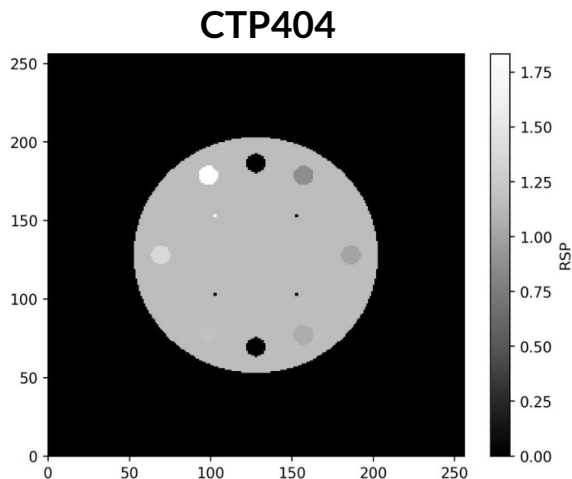
Reconstructing trajectories and predicting energies

Image reconstruction

Getting the RSP map of the irradiated object

GPU usage

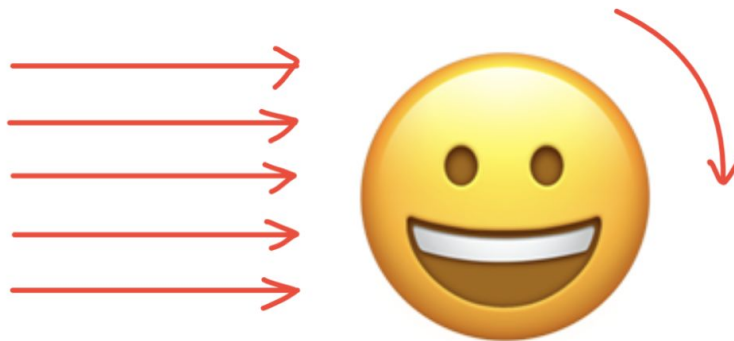
Monte Carlo Simulations of the Phantom



- D=150 mm
- 8 rods of 12,2 mm diameter, different materials
- RSP reconstruction accuracy

Geant4 & GATE simulations using GPUs of WSCLAB

- scanning the phantom
 - for 360°, in every 1°
 - for 155 mm, in every 1 mm
 - with 1000 primaries
- initial energies:
 - protons: 230 MeV/u
 - helium ions: 230 MeV/u
 - carbon ions: 430 MeV/u
- Very time consuming, GPU usage is needed



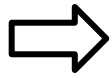
DISCLAIMER: This is only 2D!!

Image Reconstruction

2 main reconstruction techniques

Image Reconstruction

2 main reconstruction techniques



Integral transformations: Radon, Inverse Radon Transformation

→ Cannot be used for hadron CT (due to nuclear scattering of particles)

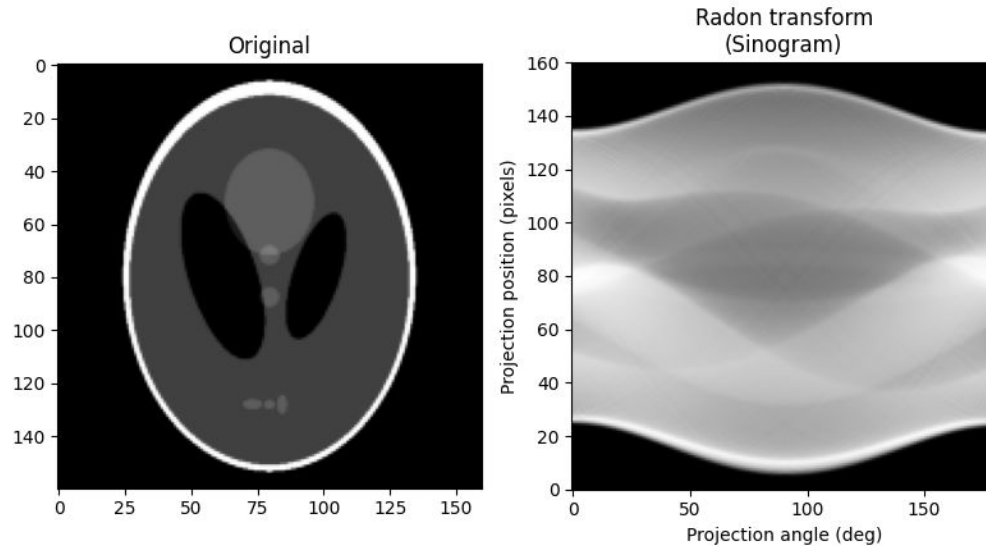


Image Reconstruction

2 main reconstruction techniques



Iterative techniques: Model the problem as a linear equation system

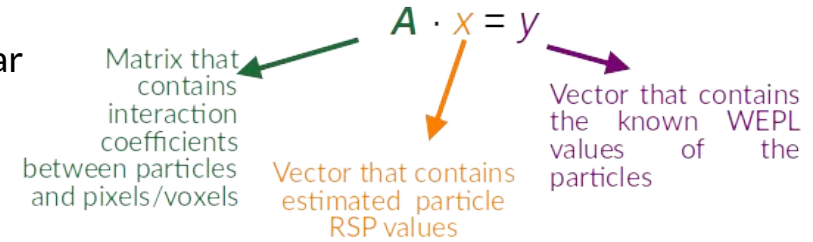


Image Reconstruction

2 main reconstruction techniques



Iterative techniques: Model the problem as a linear equation system

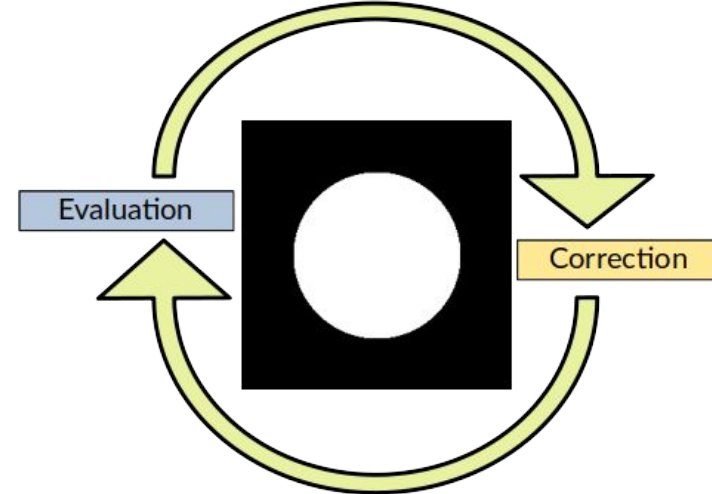
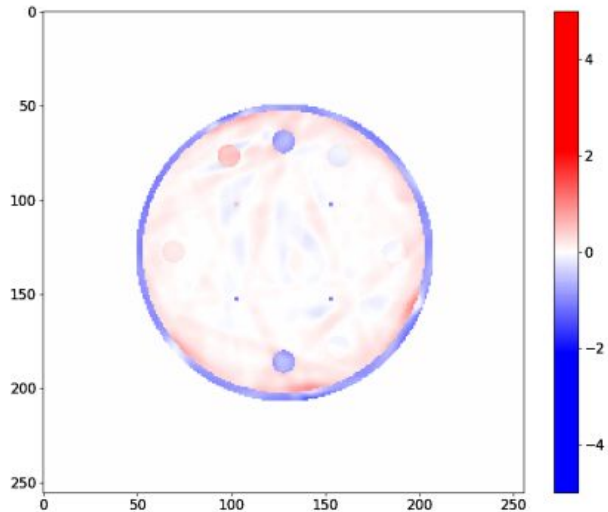
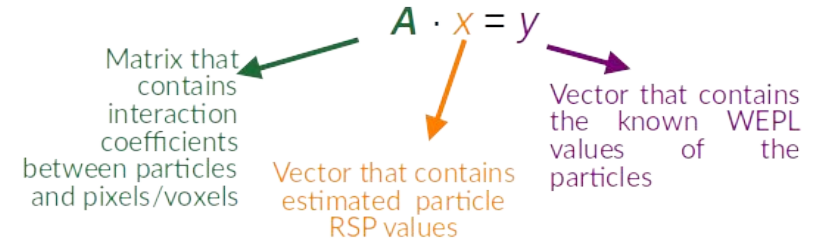


Image Reconstruction

2 main reconstruction techniques



Iterative techniques: Model the problem as a linear equation system

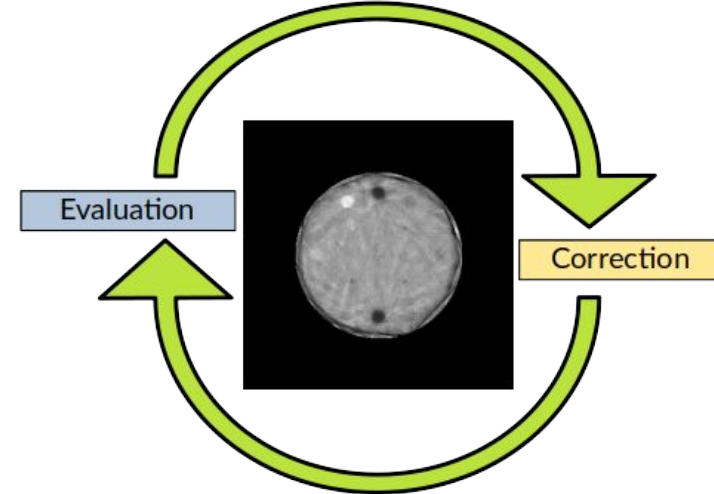
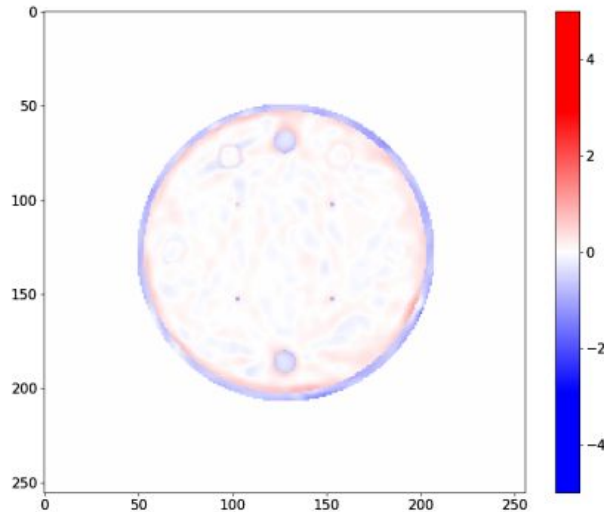
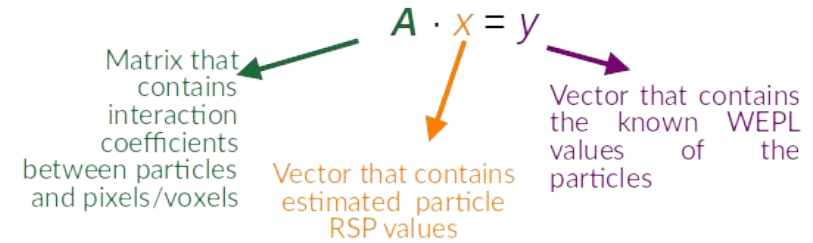


Image Reconstruction

2 main reconstruction techniques



Iterative techniques: Model the problem as a linear equation system

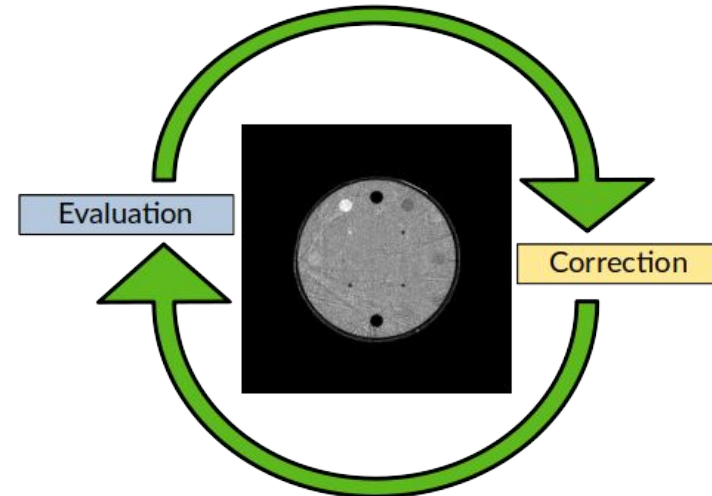
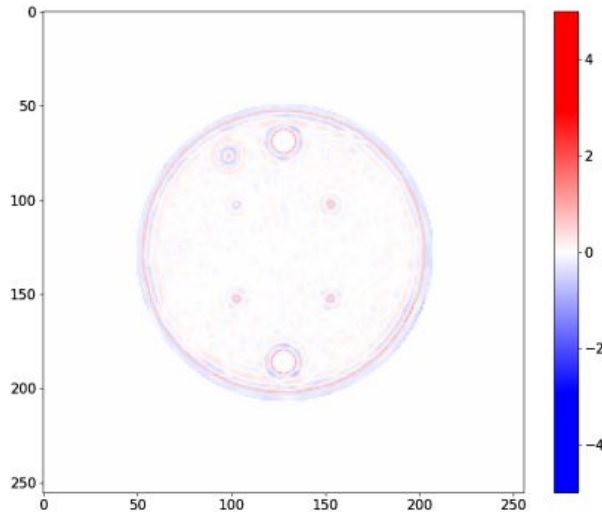
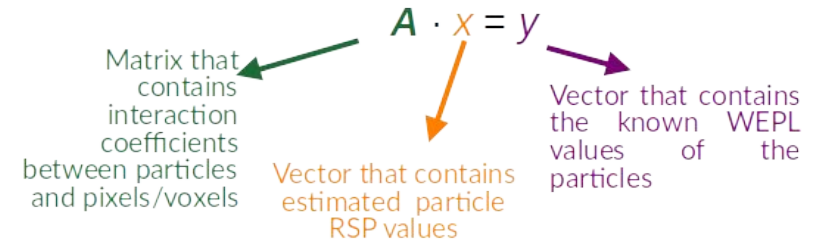
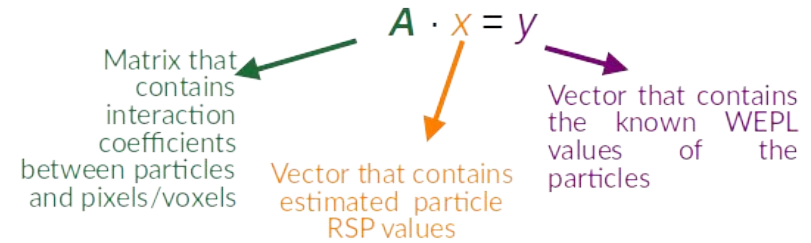


Image Reconstruction

2 main reconstruction techniques



Iterative techniques: Model the problem as a linear equation system



Algebraic Reconstruction Technique
(ART)

Parallel ART
(PART)

Simultaneous ART
(SART)

Diagonally Relaxed Orthogonal
Projection
(DROP)

Image Reconstruction

2 main reconstruction techniques



Iterative techniques: Model the problem as a linear equation system

What we use: **Richardson-Lucy iteration**

- Originally used in optics and astronomy for Poisson-distributed measurements
- Technically challenging: millions of particle trajectories
- Using GPU: C++ code sped up with CUDA
 - ◆ Iteration cycle is executed in the GPU kernels (WSCLAB) → Nvidia GTX 1080 Ti GPU, 32 GB RAM
 - ◆ Goal: maximize resolution + minimize runtime

$A \cdot x = y$

Matrix that contains interaction coefficients between particles and pixels/voxels

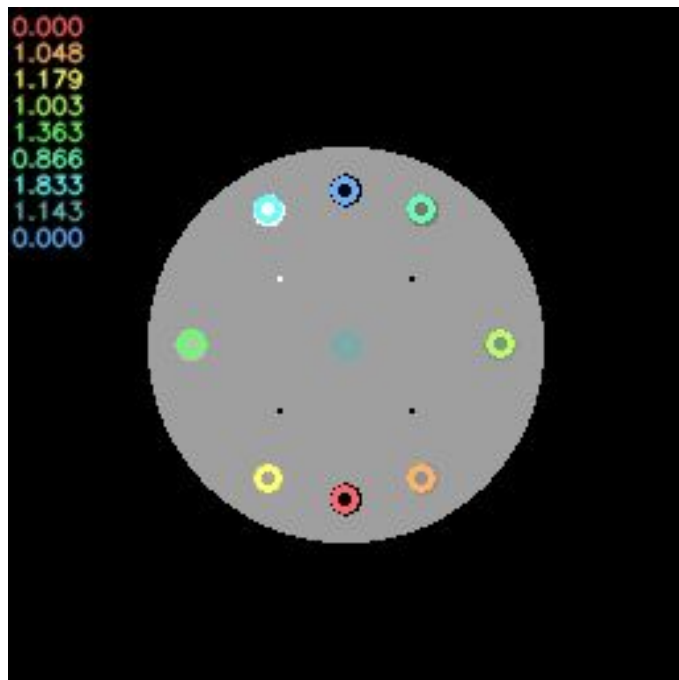
Vector that contains estimated particle RSP values

Vector that contains the known WEPL values of the particles

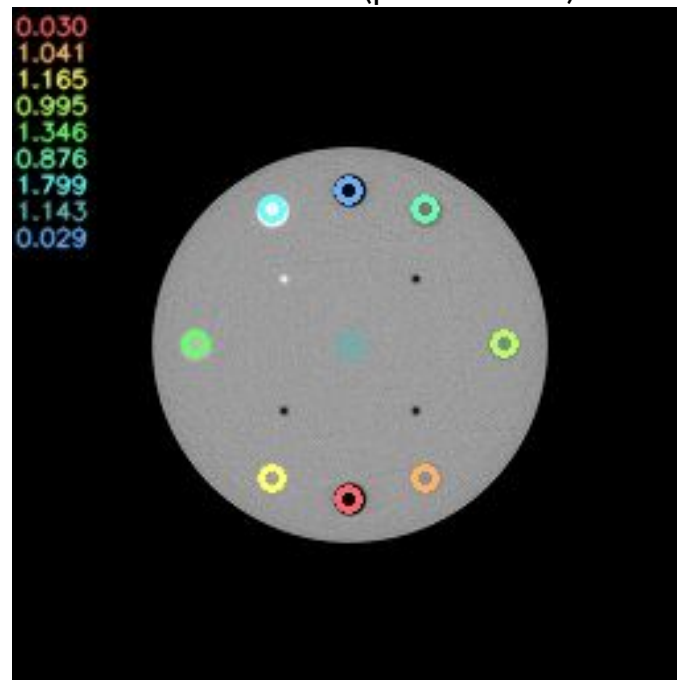
$$x_i^{k+1} = \frac{x_i^k}{\sum_j A_{i,j}} \sum_j \frac{y_j}{\sum_l A_{l,j} x_l^k} A_{i,j}$$

Evaluation of the Reconstruction: RSP

Ground truth



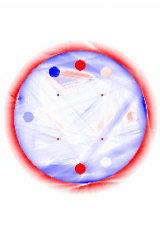
Reconstruction (proton beam)



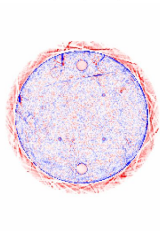
1. At given reconstruction resolution (determined by mm/pixel values), we determine the **exact center position** of each insert on the **ground truth image** (perfect contrast, zero noise and blurring)
2. On the **reconstructed image**: **mean RSP** of previously determined positions

Reconstruction Accuracy

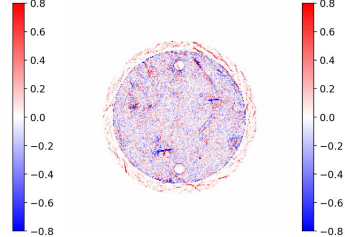
Proton - 20,000 particles



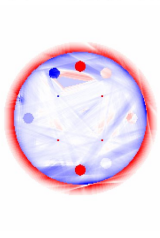
Proton - 1,000,000 particles



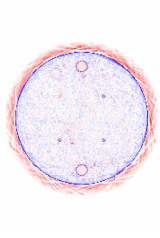
Proton - 25,000,000 particles (Final Picture)



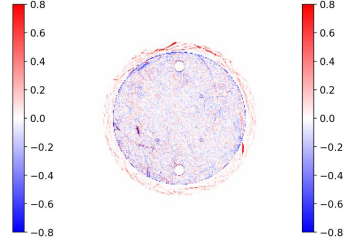
Helium - 20,000 particles



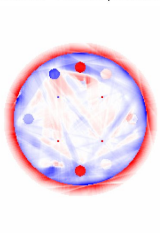
Helium - 1,000,000 particles



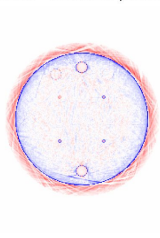
Helium - 25,000,000 particles (Final Picture)



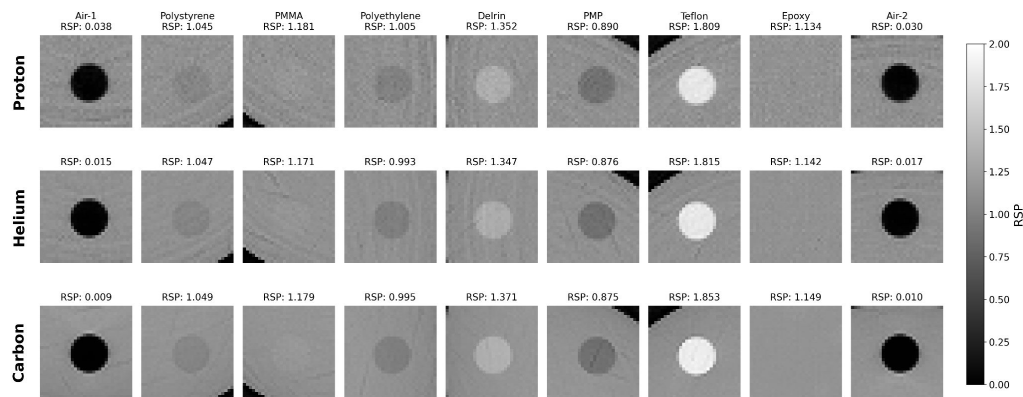
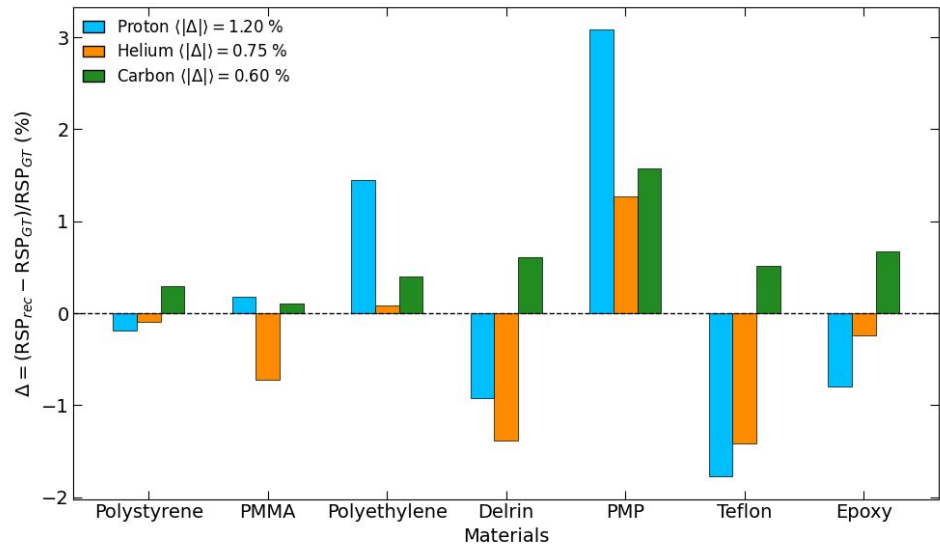
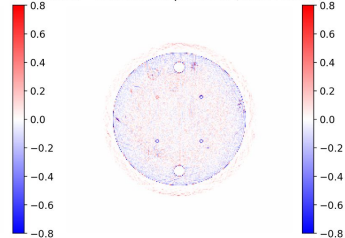
Carbon - 20,000 particles



Carbon - 1,000,000 particles

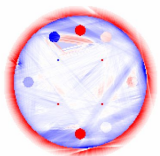


Carbon - 25,000,000 particles (Final Picture)

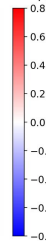
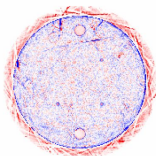


Reconstruction Accuracy

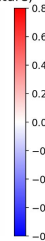
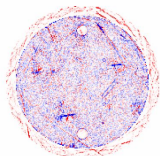
Proton - 20,000 particles



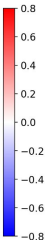
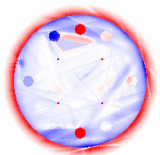
Proton - 1,000,000 particles



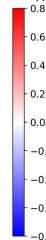
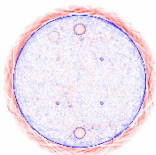
Proton - 25,000,000 particles (Final Picture)



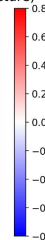
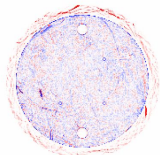
Helium - 20,000 particles



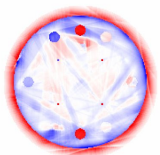
Helium - 1,000,000 particles



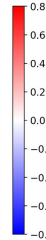
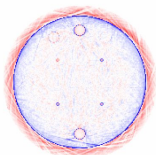
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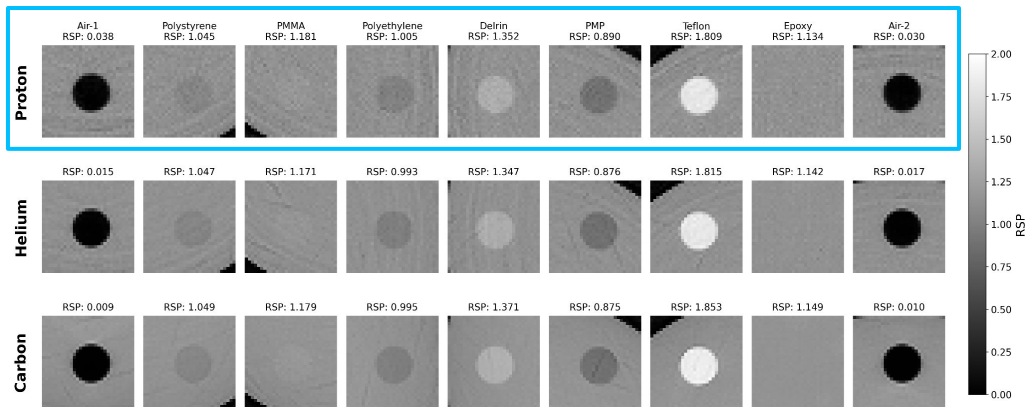
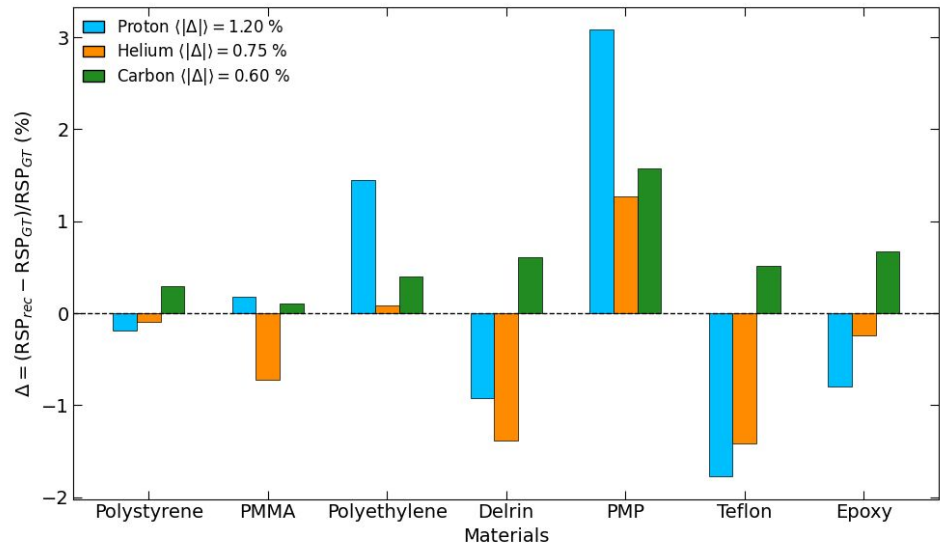
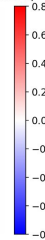
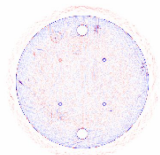
Carbon - 20,000 particles



Carbon - 1,000,000 particles

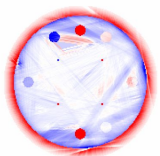


Carbon - 25,000,000 particles (Final Picture)

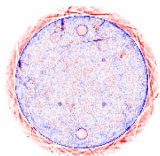


Reconstruction Accuracy

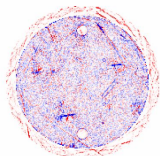
Proton - 20,000 particles



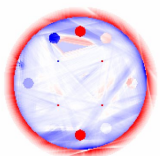
Proton - 1,000,000 particles



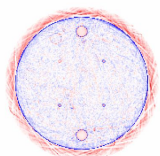
Proton - 25,000,000 particles (Final Picture)



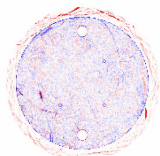
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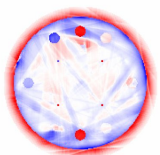
Helium - 1,000,000 particles



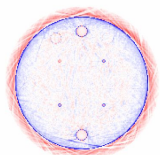
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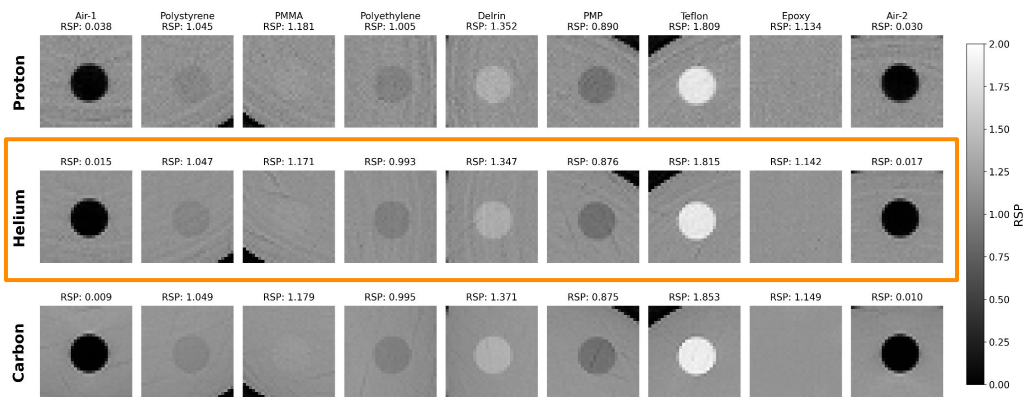
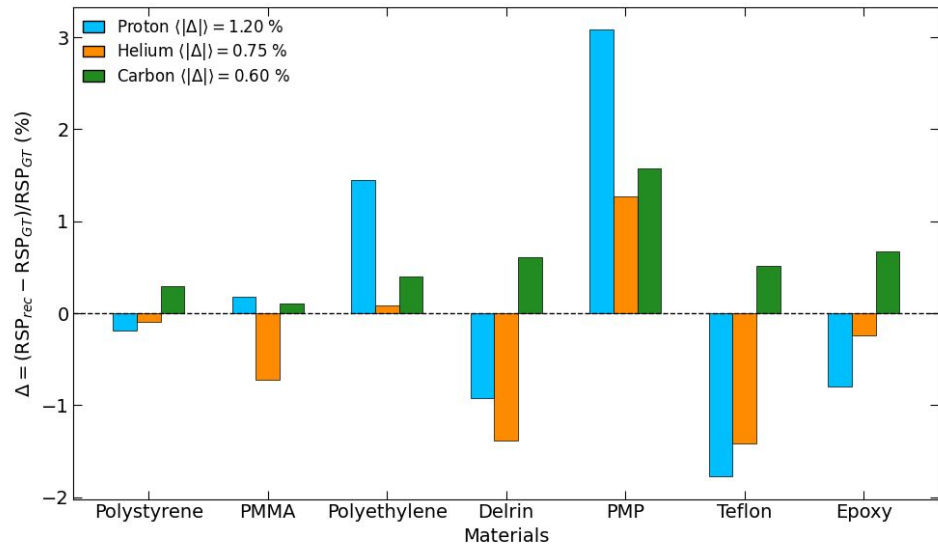
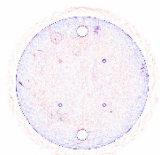
Carbon - 20,000 particles



Carbon - 1,000,000 particles

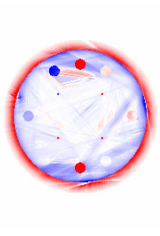


Carbon - 25,000,000 particles (Final Picture)

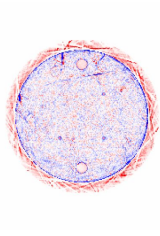


Reconstruction Accuracy

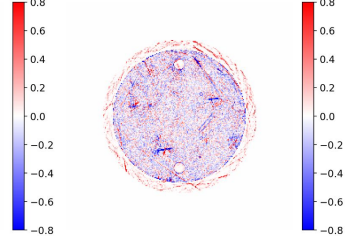
Proton - 20,000 particles



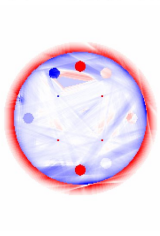
Proton - 1,000,000 particles



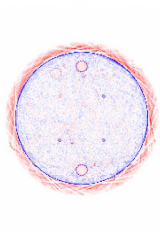
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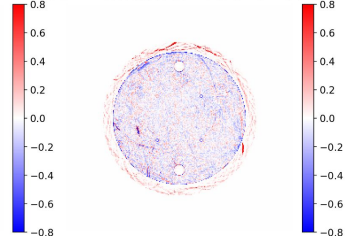
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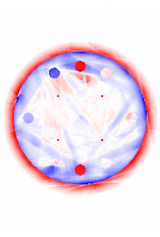
Helium - 1,000,000 particles



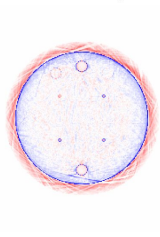
Helium - 25,000,000 particles (Final Picture)



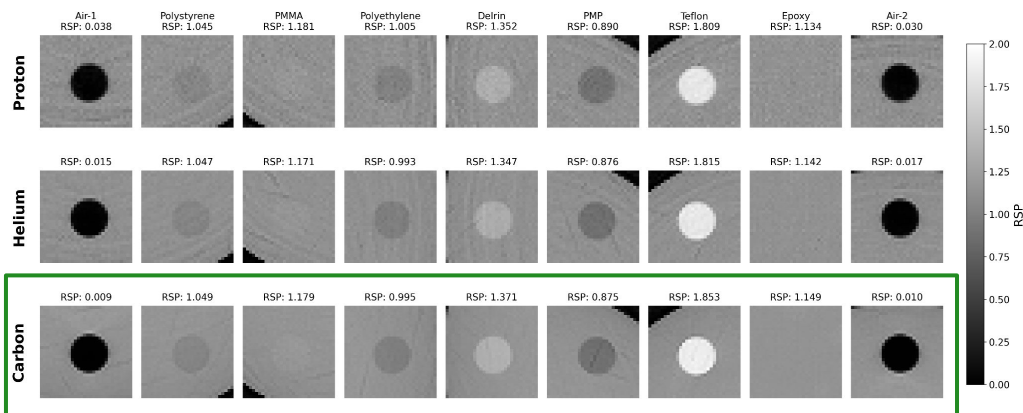
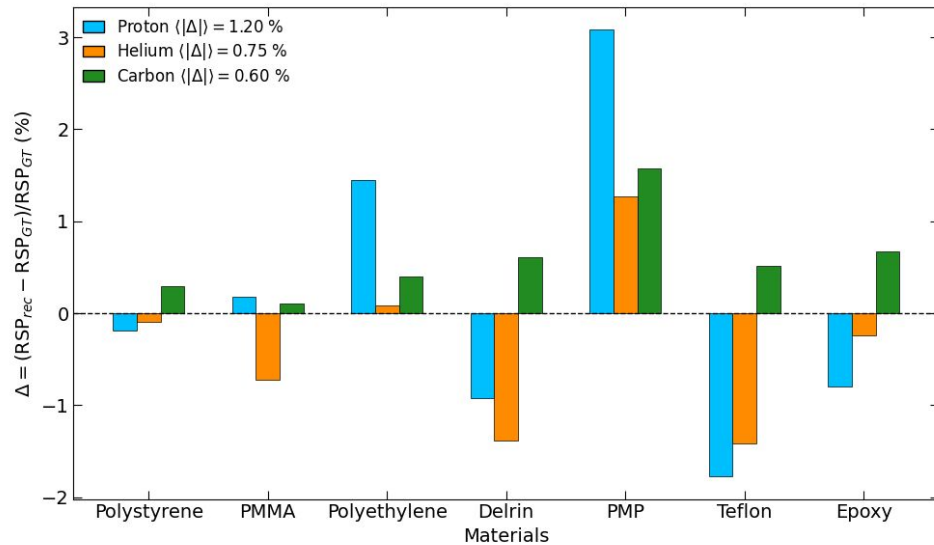
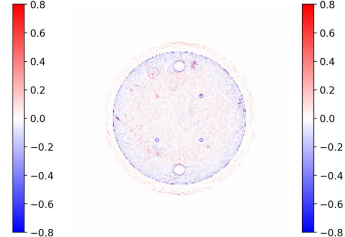
Carbon - 20,000 particles



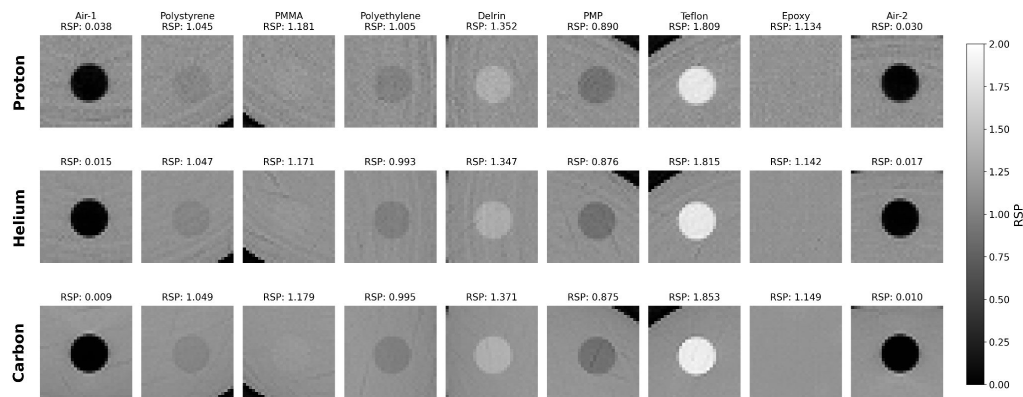
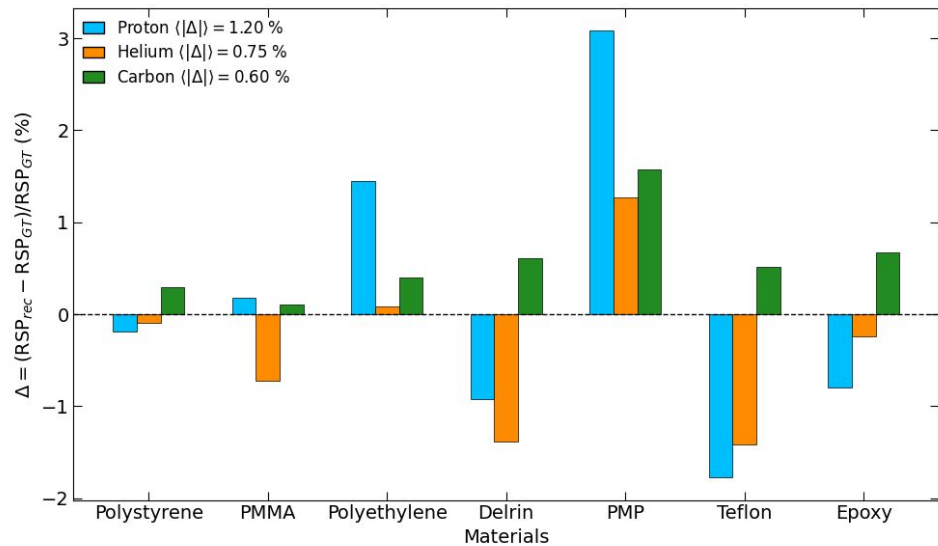
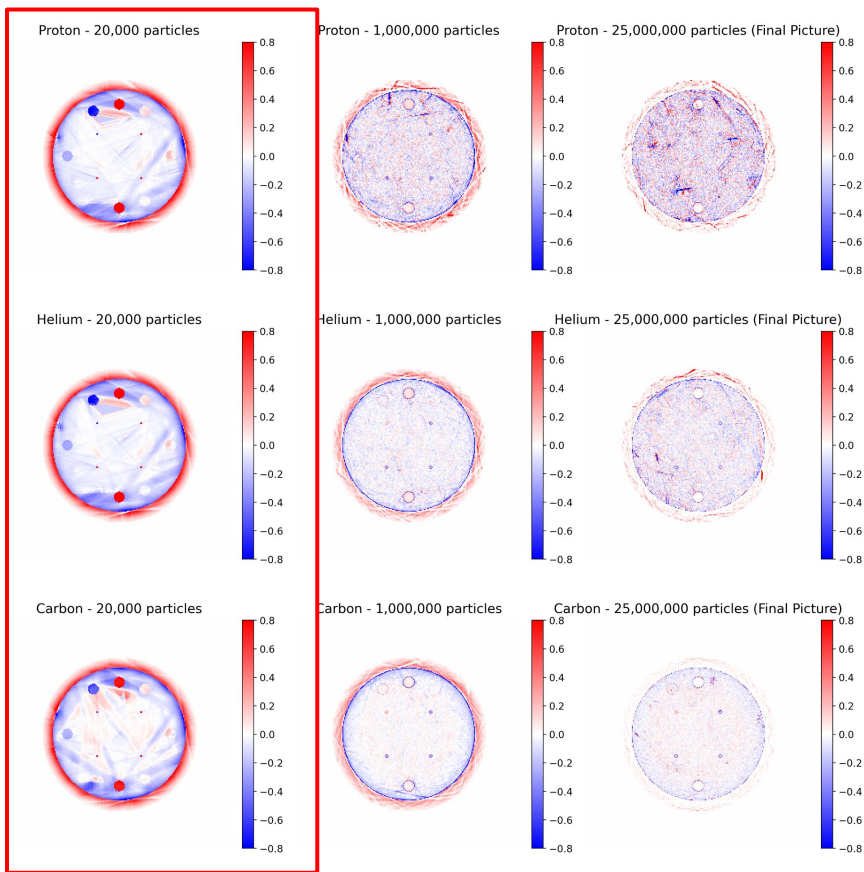
Carbon - 1,000,000 particles



Carbon - 25,000,000 particles (Final Picture)

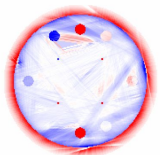


Reconstruction Accuracy

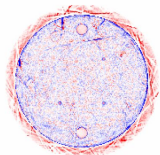


Reconstruction Accuracy

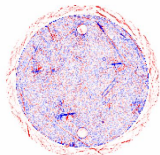
Proton - 20,000 particles



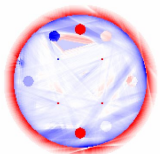
Proton - 1,000,000 particles



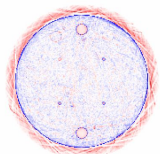
Proton - 25,000,000 particles (Final Picture)



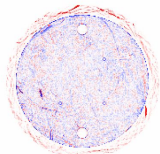
Helium - 20,000 particles



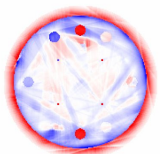
Helium - 1,000,000 particles



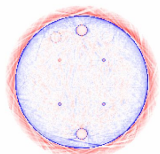
Helium - 25,000,000 particles (Final Picture)



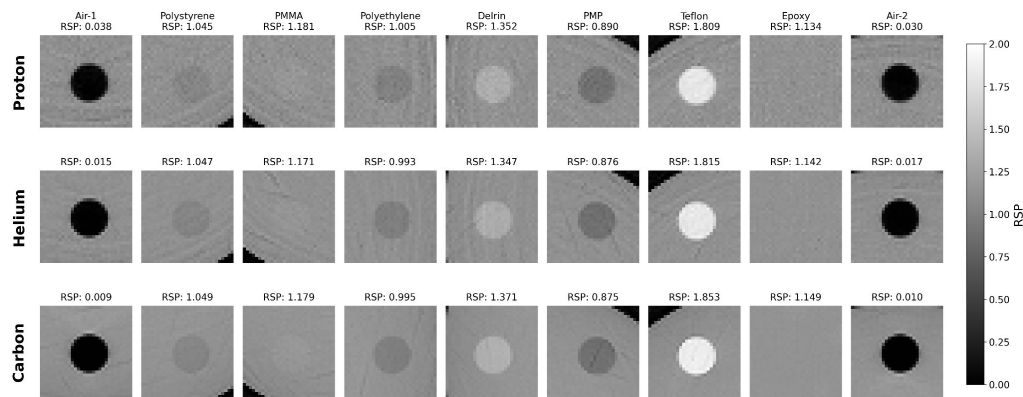
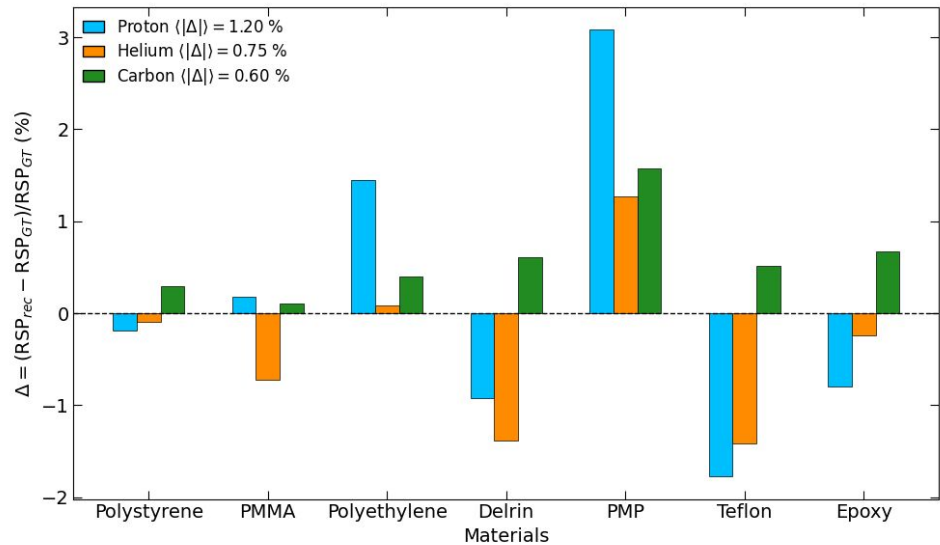
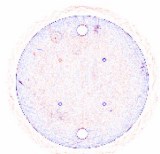
Carbon - 20,000 particles



Carbon - 1,000,000 particles

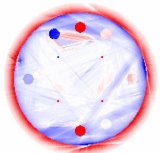


Carbon - 25,000,000 particles (Final Picture)

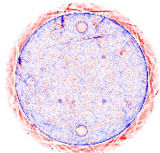


Reconstruction Accuracy

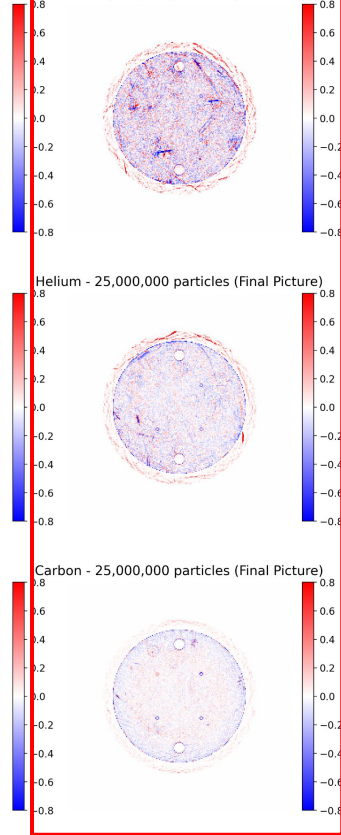
Proton - 20,000 particles



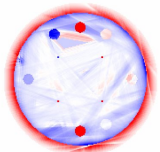
Proton - 1,000,000 particles



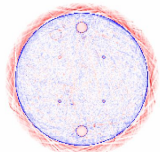
Proton - 25,000,000 particles (Final Picture)



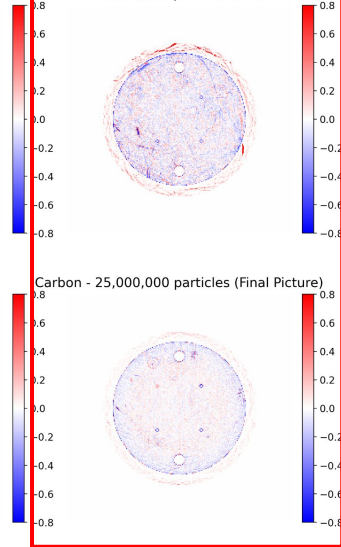
Helium - 20,000 particles



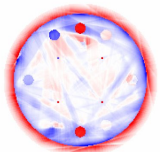
Helium - 1,000,000 particles



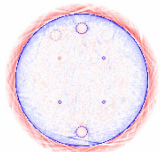
Helium - 25,000,000 particles (Final Picture)



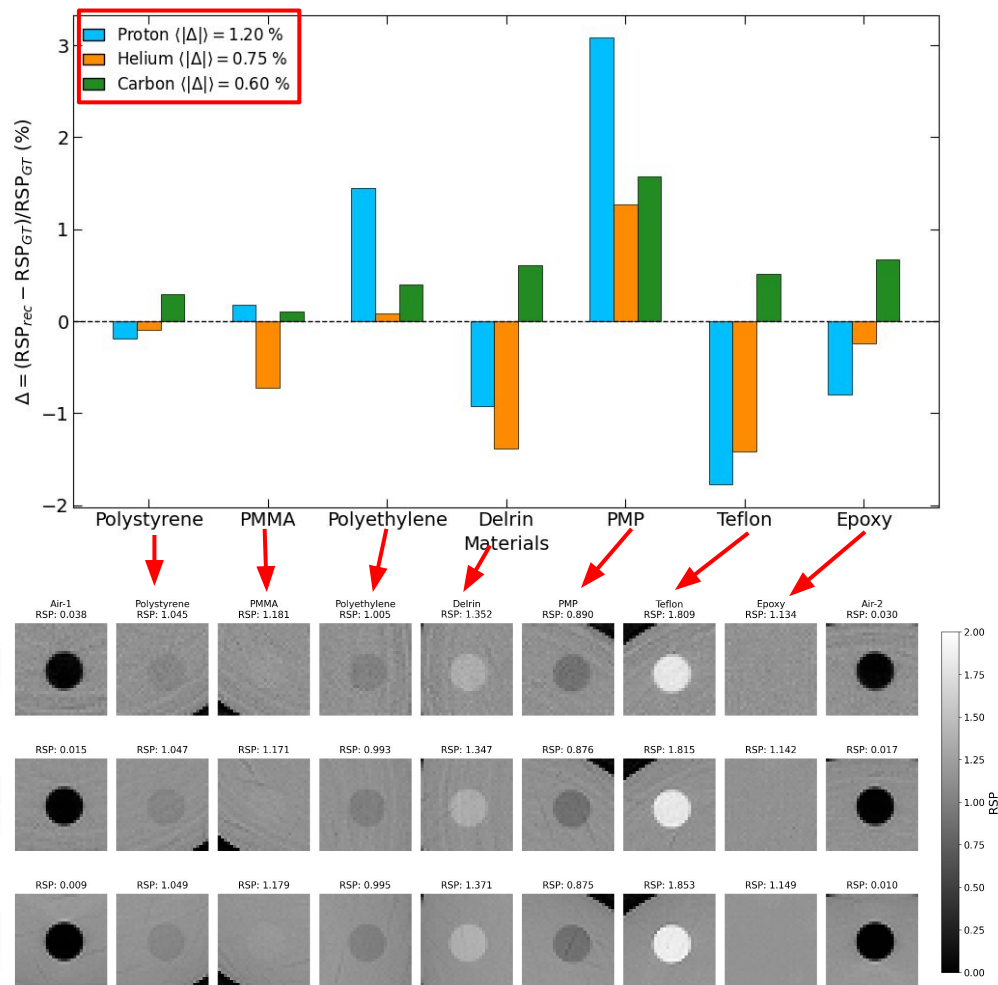
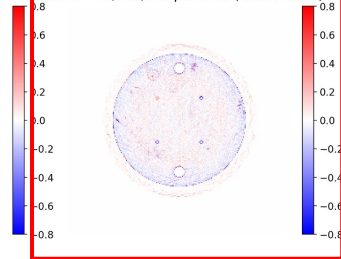
Carbon - 20,000 particles



Carbon - 1,000,000 particles



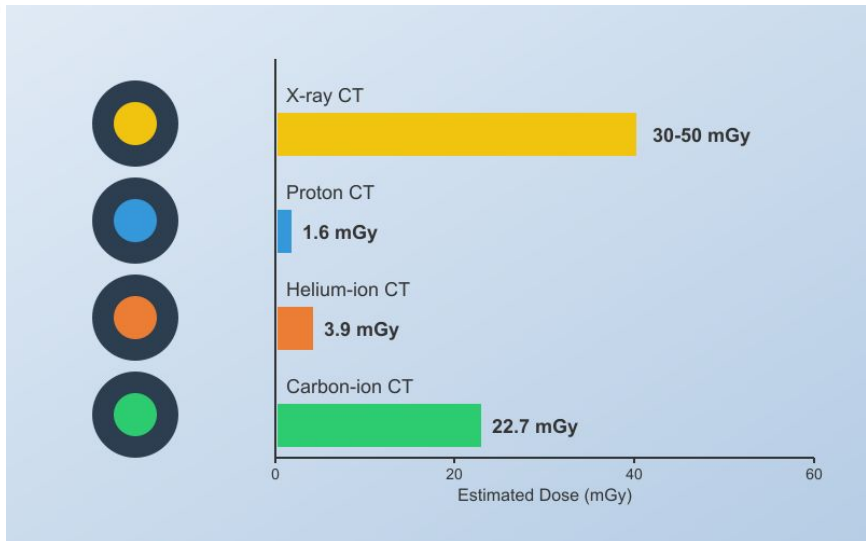
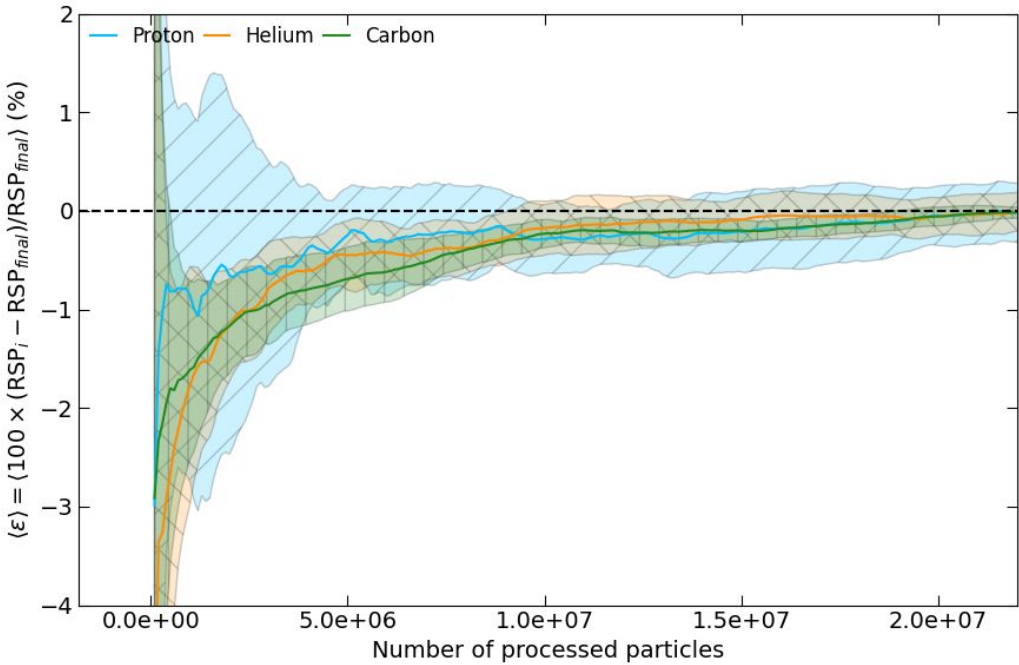
Carbon - 25,000,000 particles (Final Picture)



Dosimetric Performance

We saw that imaging is feasible with helium and carbon ions → It is worth checking what it means for the doses

- Taken into account that the reconstruction accuracy converges → less than 25 million particles needed
- ...and extrapolating to a 3D human head
- Even for carbon ions, the **doses are less** than in the case of an X-ray CT + the **resolution is better**



Summary and Acknowledgements

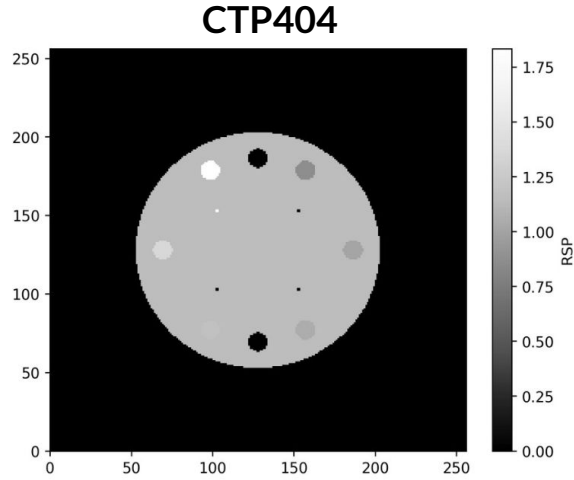
- We compared CT imaging with different particles used in hadron therapies, utilizing GPU for the GATE simulations and the image reconstruction (arXiv:2605.XXYYZZ)
- Used a novel, but already tested image reconstruction method and evaluated on the CTP404 phantom
- Good RSP reconstruction accuracy (outstanding for helium and carbon ions, <1% error)
- Deposited dose is negligible (protons) or comparable with the standard X-ray CT (carbon ions)
- It could be worth utilizing heavy ions for imaging!
- Future plans: more extensive testing, 3D phantoms, etc.

Thank you for your attention!

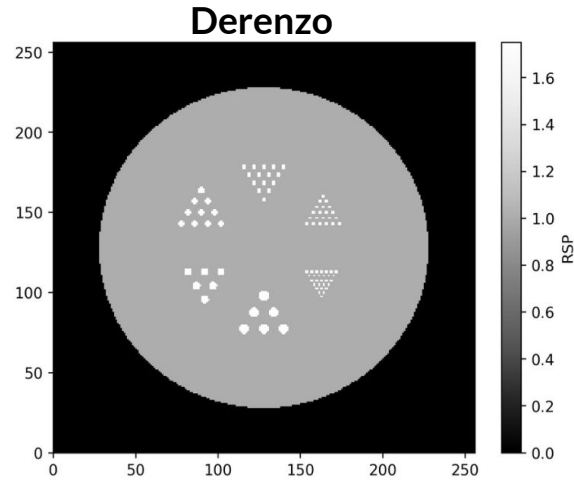
Supported by the EKÖP-25 University Research Scholarship Program of the Ministry for Culture and Innovation from the source of the National Research, Development and Innovation Fund; the ELTE Eötvös Loránd University, Budapest, Hungary and grants NKKP ADVANCED_25-153456, 2025-1.1.5-NEMZ_KI-2025-00005, 2025-1.1.5-NEMZ_KI-2025-00013.

Computational resources were provided by the Wigner Scientific Computing Laboratory (WSCLAB).

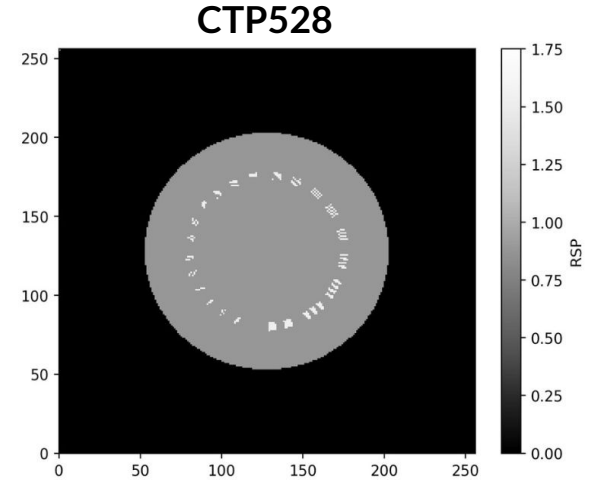
Backup - Phantoms



- D=150 mm
- 8 rods of 12,2 mm diameter, different materials
- RSP reconstruction accuracy

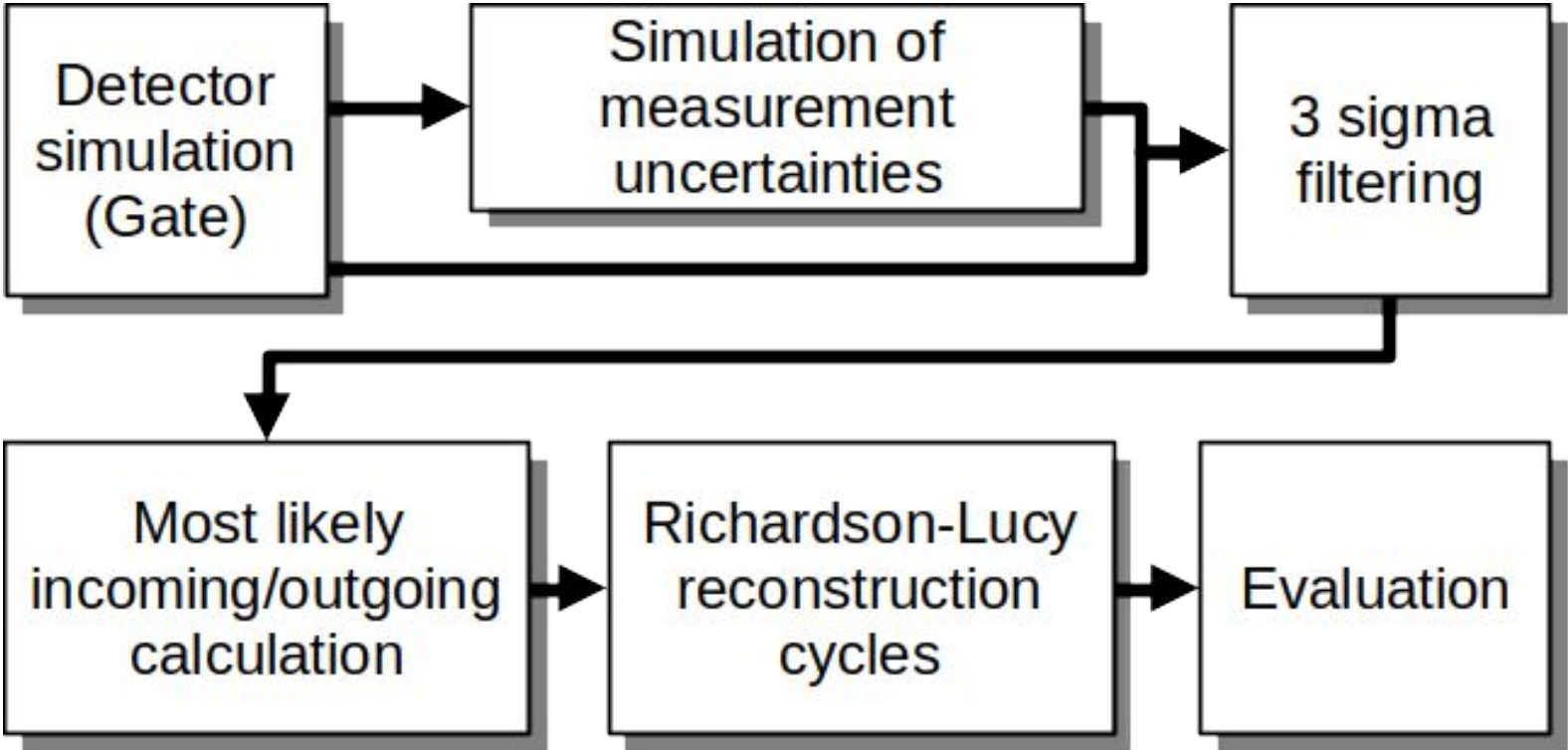


- D=200 mm
- 6 sectors of 1,5-6 mm diameter aluminium inserts
- Spatial resolution

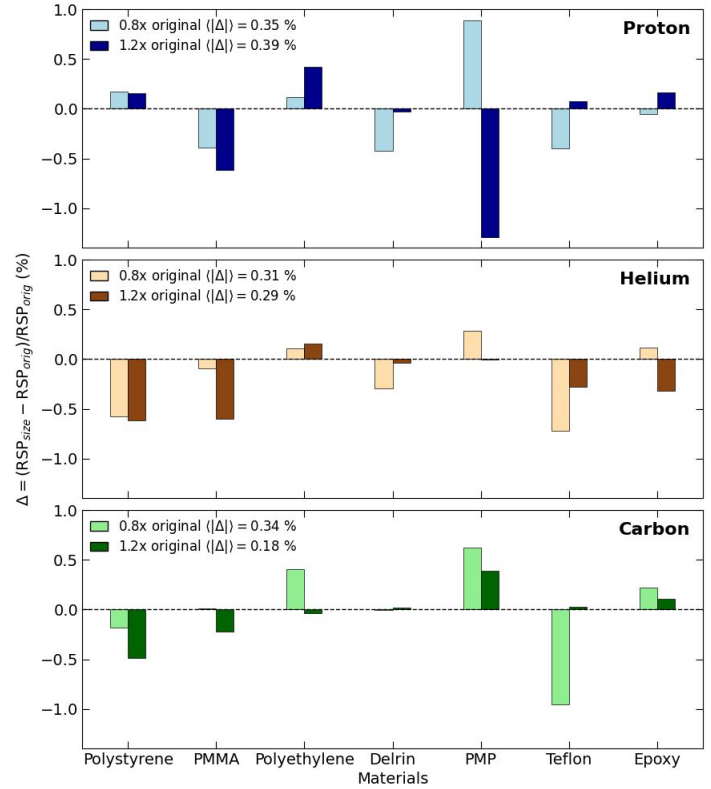


- D=150 mm
- 1-21 aluminium linepairs every cm
- Spatial resolution

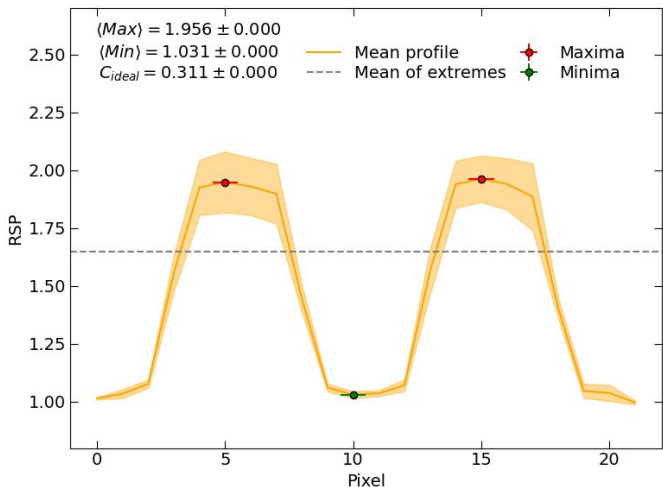
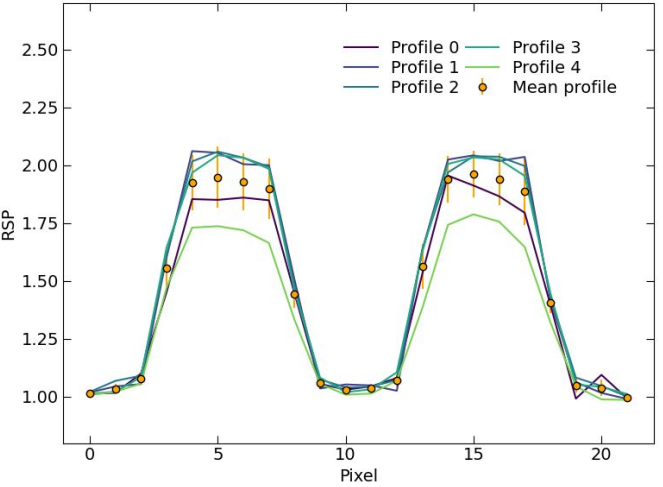
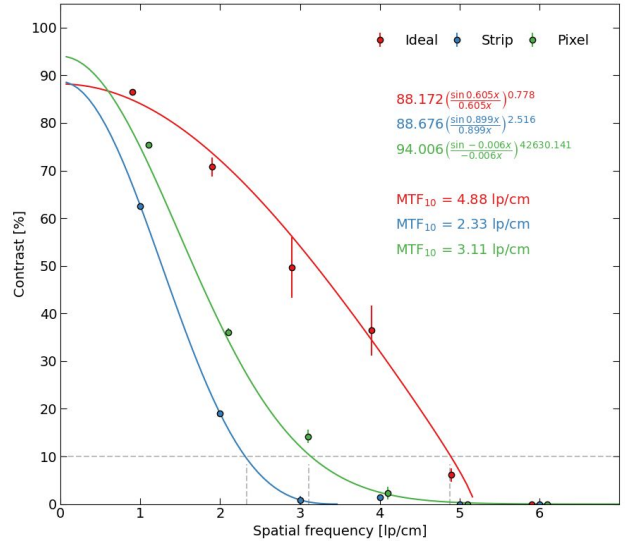
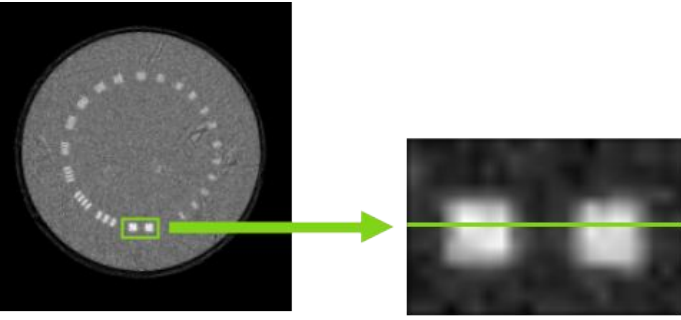
Backup - RL Workflow



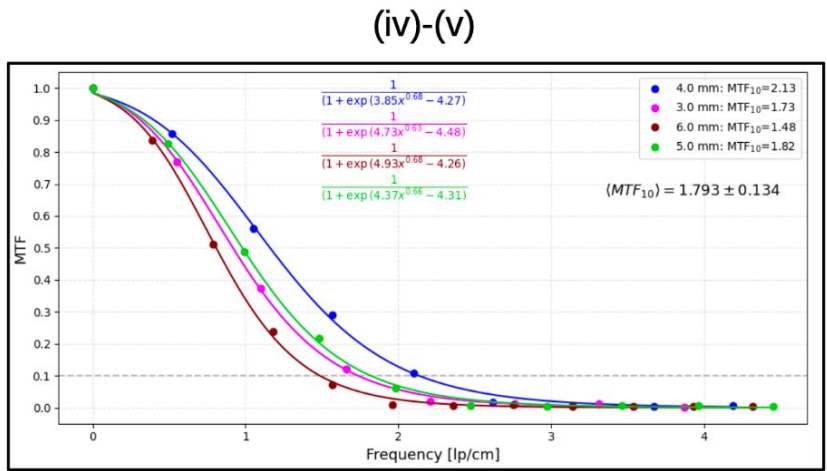
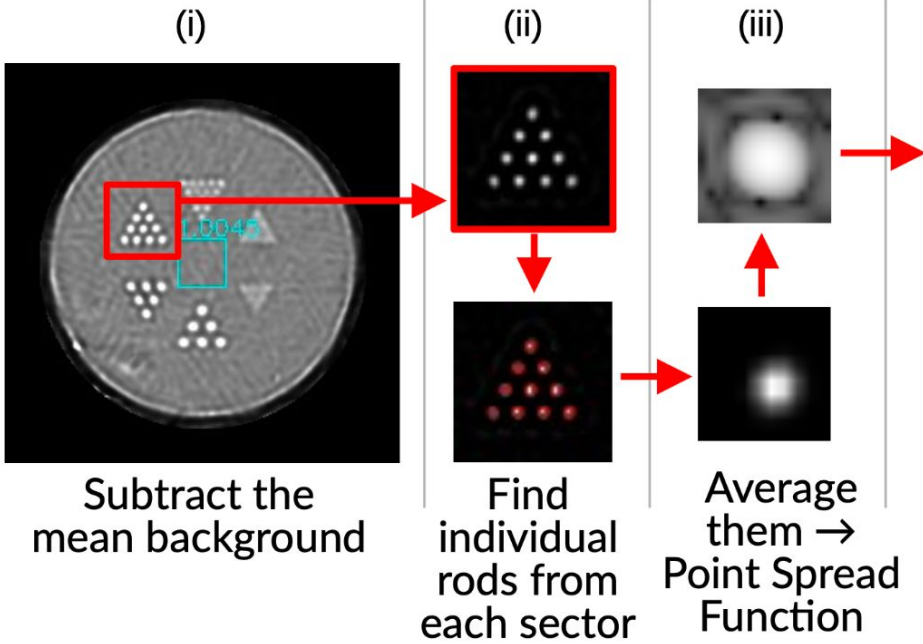
Backup - CTP404 Insert Size Dependence



Backup - Spatial Resolution with CTP528



Backup - Spatial Resolution with Derenzo



- 2D Fourier transform PSF → Modulation Transfer Function (MTF)
- MTF10% averaged for the sections represents spatial resolution