Image Reconstruction with Proton Computed Tomography

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ZSÓFIA JÓLESZ
jolesz.zsofia@wigner.hun-ren.hu

HUN REN | wigner

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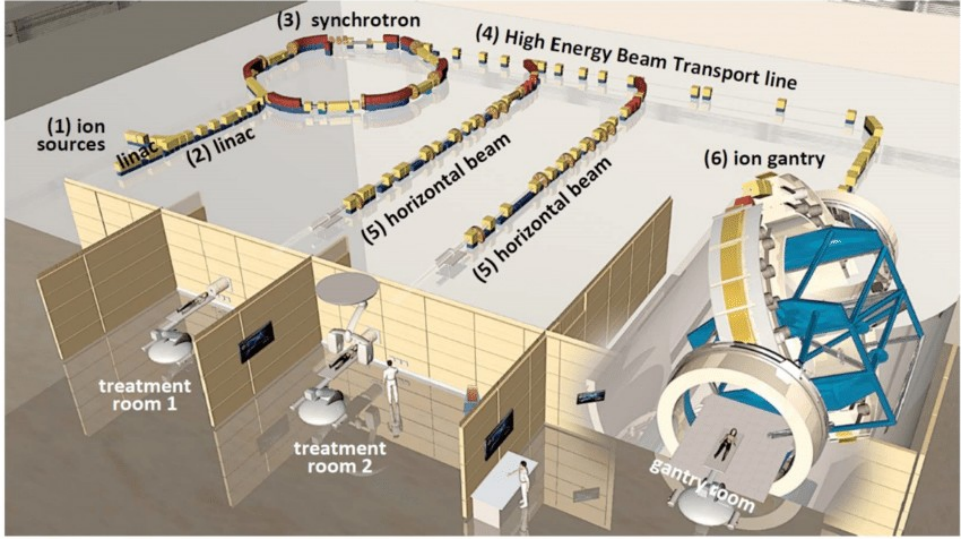
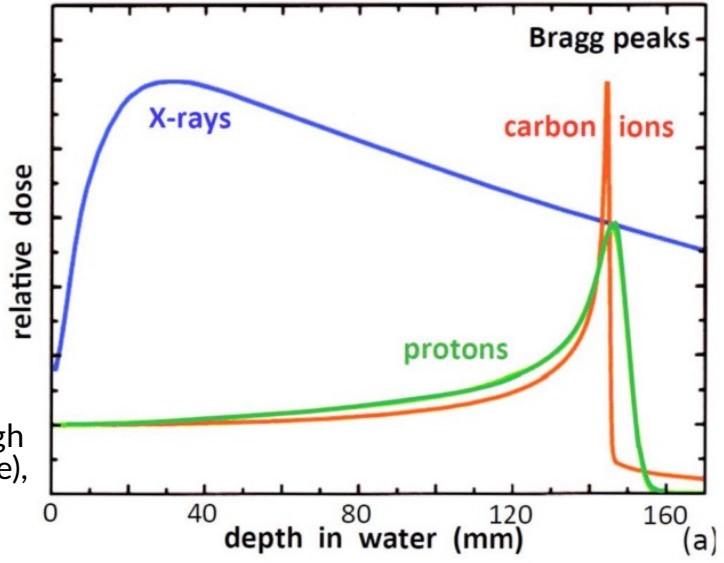
Introduction



Layout figure of the HIT Centre (Heidelberg)

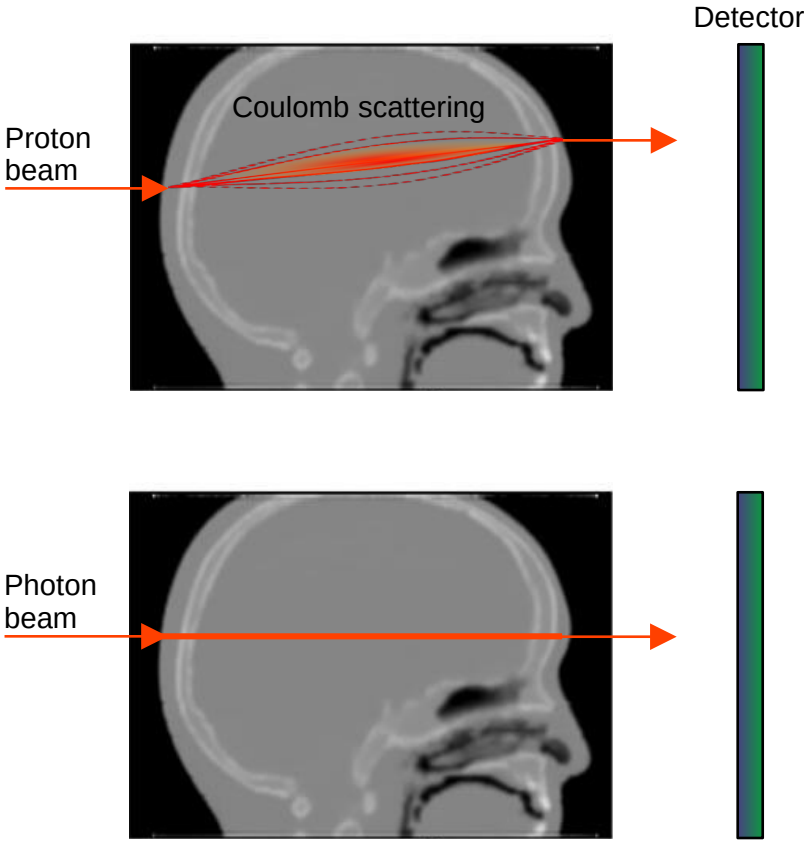
- Cancer therapy: surgery, chemotherapy, radiotherapy, immunotherapy
- Radiotherapy: uses ionizing particles →
- Photons, protons, heavy ions

Coulomb scattering → Bragg peak



Dose deposit characteristics of high energy photons (blue), protons (green), and heavy ions (red)

Problems with imaging – and the solution



Proton CT vs. X-ray CT

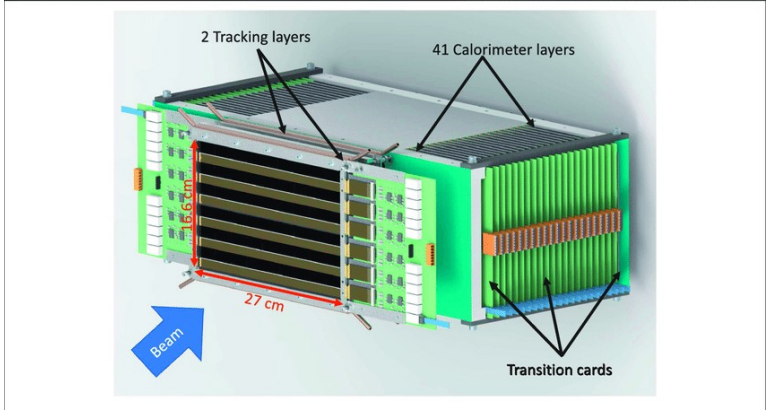
- Today X-ray CT is used
- We need to know the range of the protons → Relative Stopping Power (RSP): how much does it slow down in a material compared to water
- Difference between the absorption of photons and the energy loss of protons → conversion is not accurate between Hounsfield units* and RSP
- Solution: let's do the imaging with protons! → proton CT

*The quantitative scale of X-ray absorption

The Bergen pCT Collaboration

- Goal: to build a proton CT based on the high-energy particle detectors used in the CERN ALICE collaboration (technology transfer)

Granular tracking calorimeter →

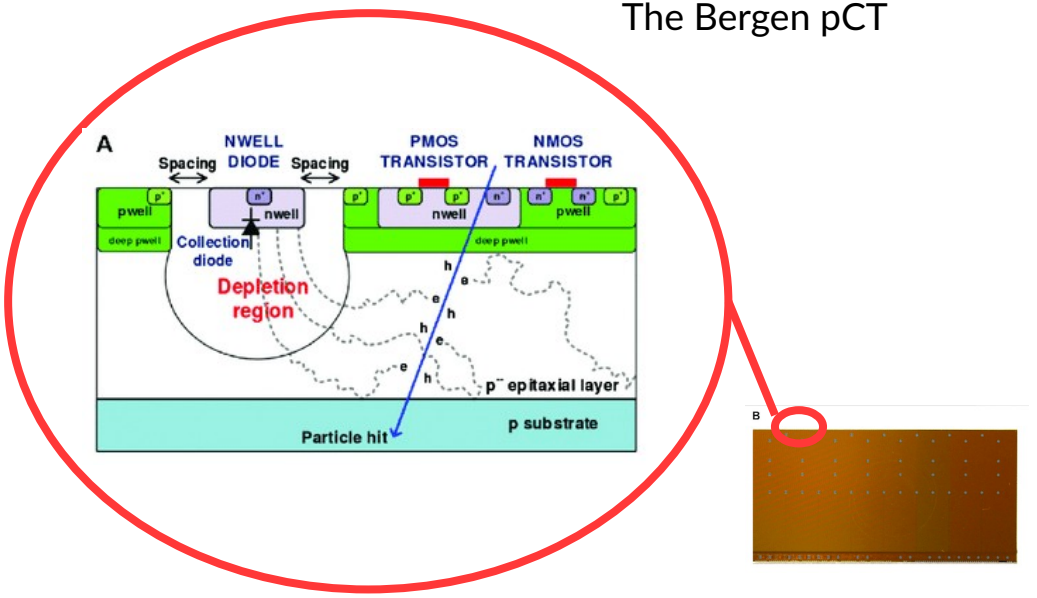


The Bergen pCT

- The detector system is based on the **ALPIDE chip** (part of the ITS in ALICE)

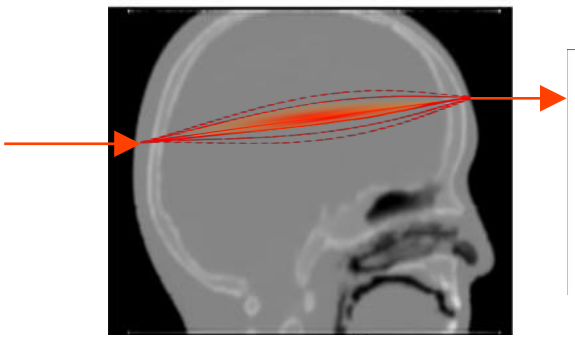
⇩

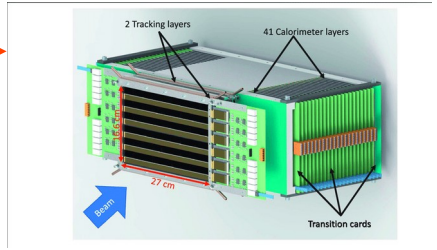
- → Monolithic Active Pixel Sensor (MAPS)
- → Sensors are on the same layer with readout electronics

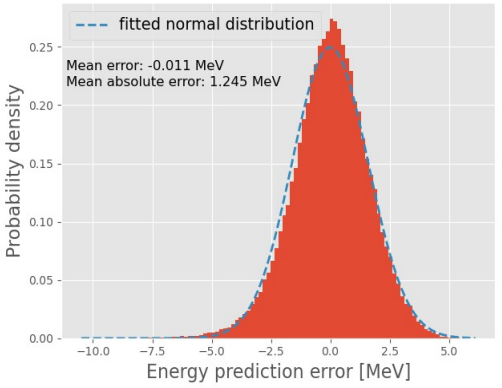


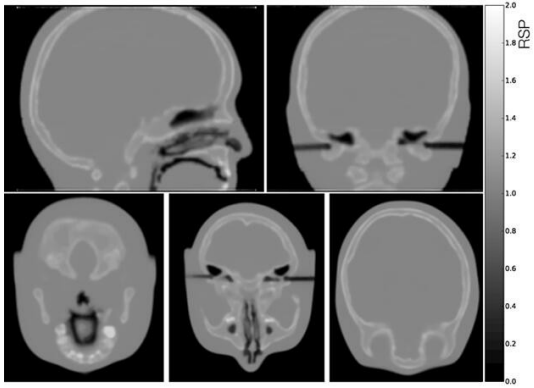
The cross-sectional image (A) and the photograph (B) of the ALPIDE chip

Process of the reconstruction









Irradiating the phantom with high energy (~100 MeV) protons

Detector system senses the signals

Processing the signals

Reconstructing the image

Currently: Monte Carlo simulations

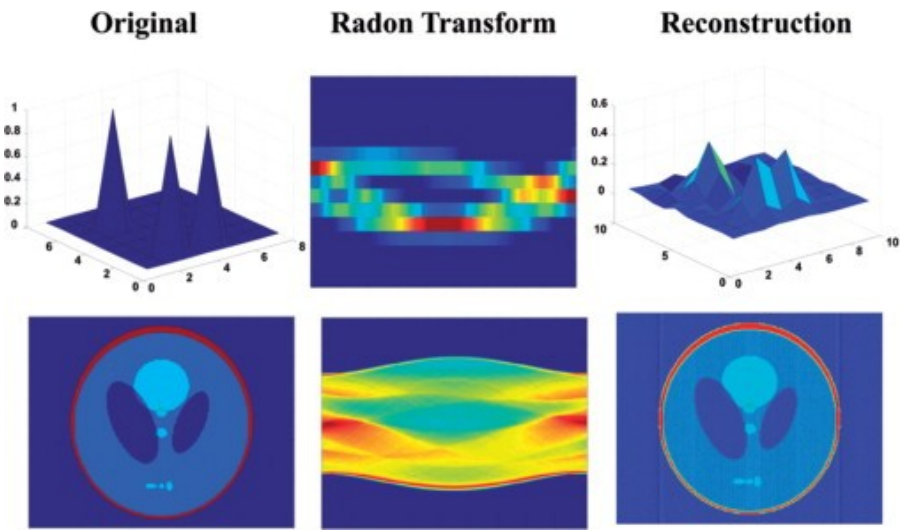
- Reconstructing trajectories from hits
- Predicting energies

- Determining RSP distribution
- Developing framework
- Evaluation with phantoms

Image reconstruction techniques

Integral transformations → Radon, Inverse Radon
- ➔ Cannot be used for proton CT (due to nuclear scattering of protons)

Iterative reconstruction techniques
- ➔ Model the problem as a linear equation system



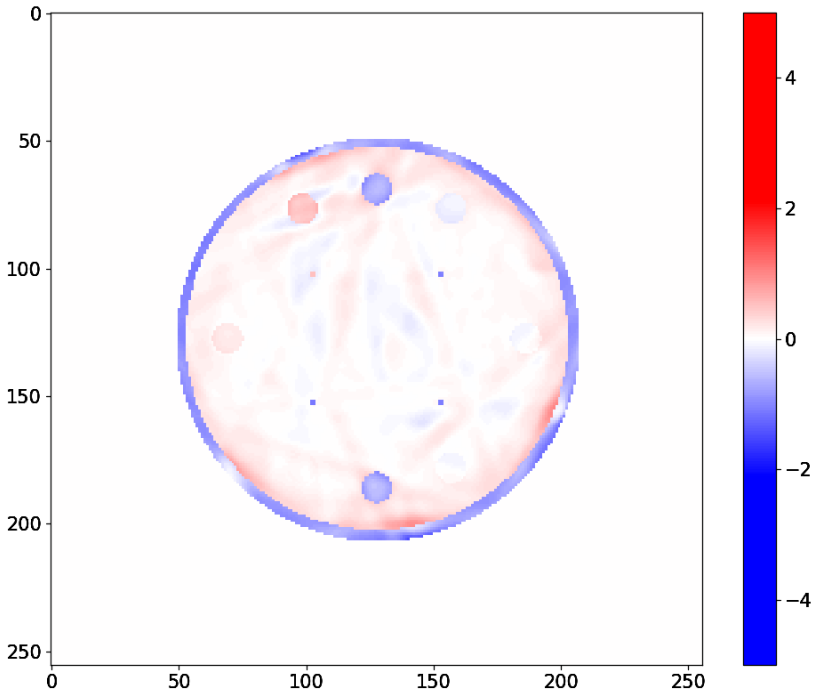
$$A \cdot x = y$$

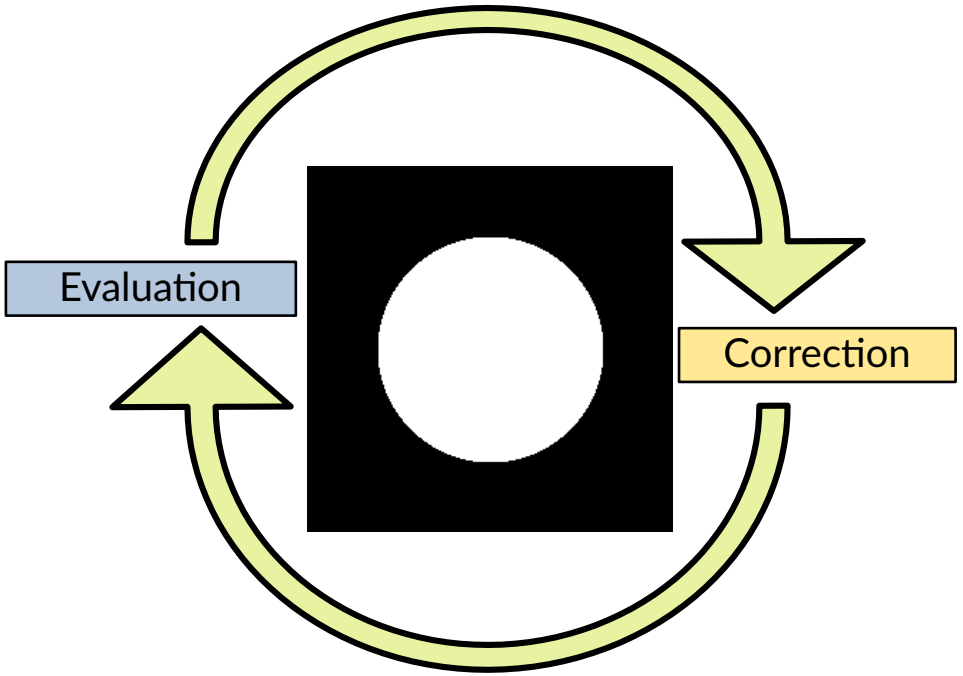
Matrix that contains interaction coefficients between protons and pixels/voxels

Vector that contains estimated proton RSP values

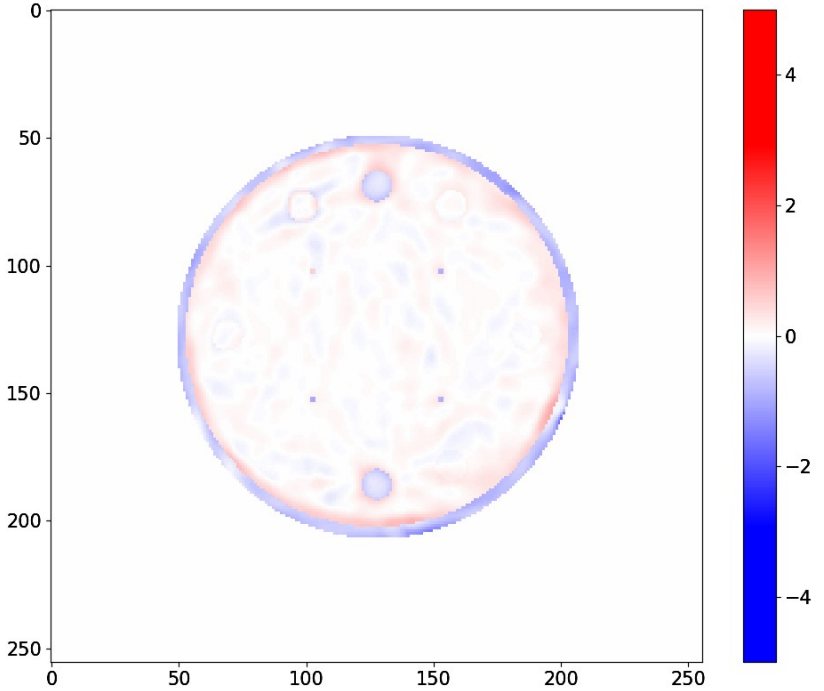
Vector that contains the known WEPL values of the protons

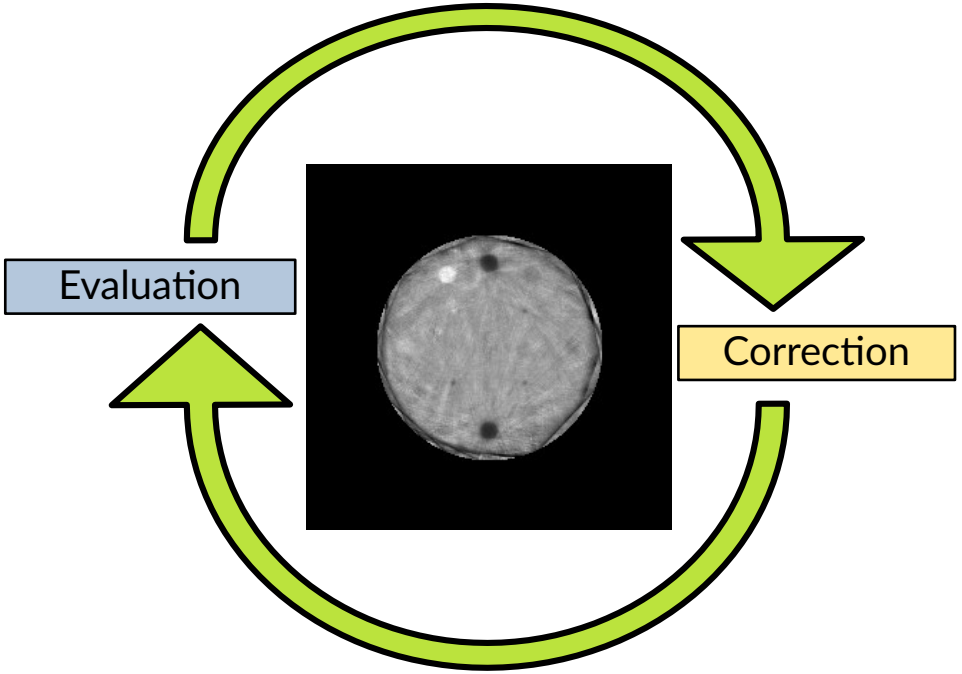
Iterative reconstruction techniques



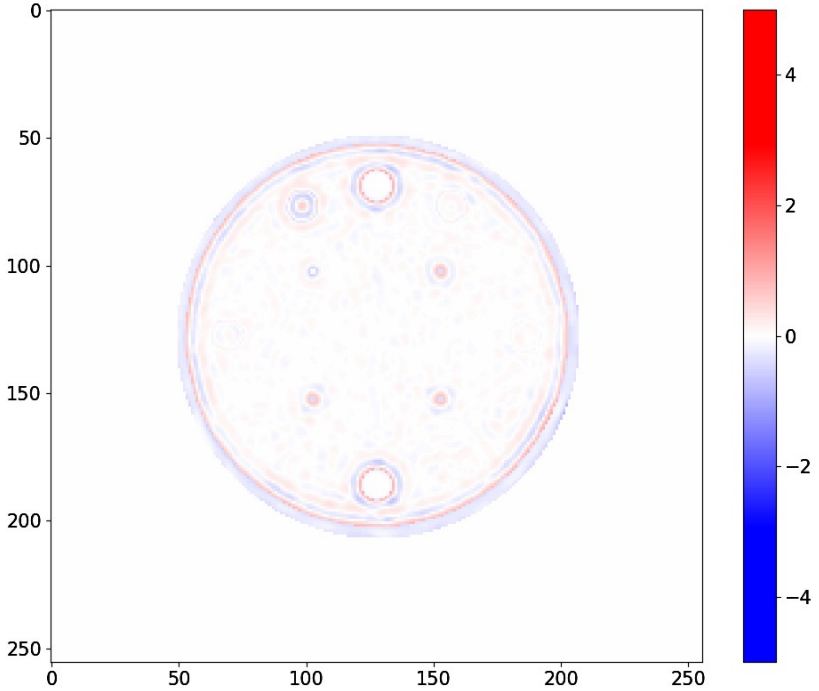


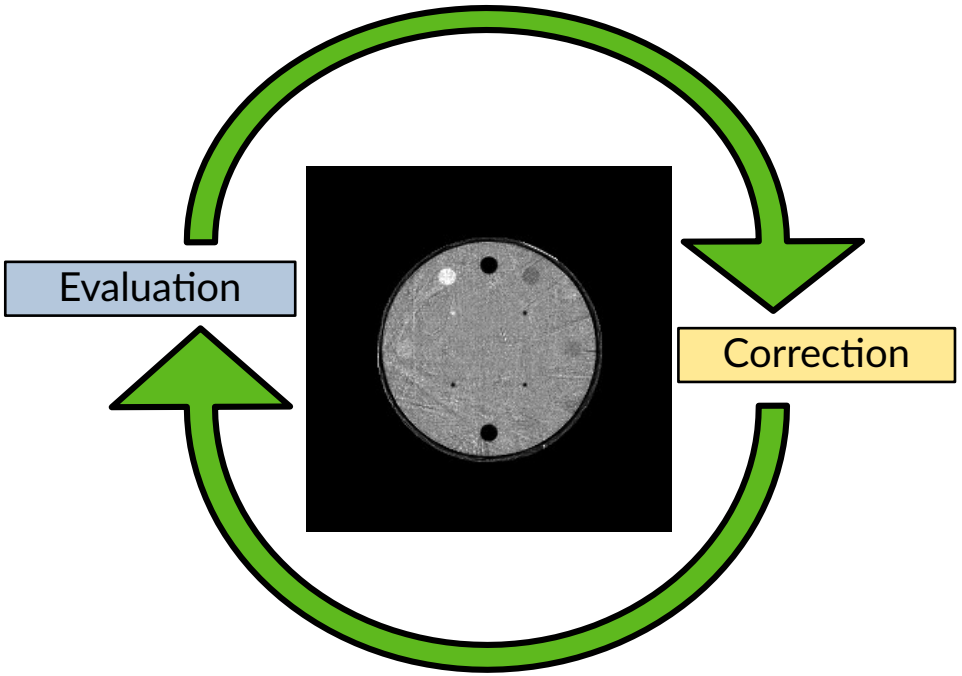
Iterative reconstruction techniques





Iterative reconstruction techniques

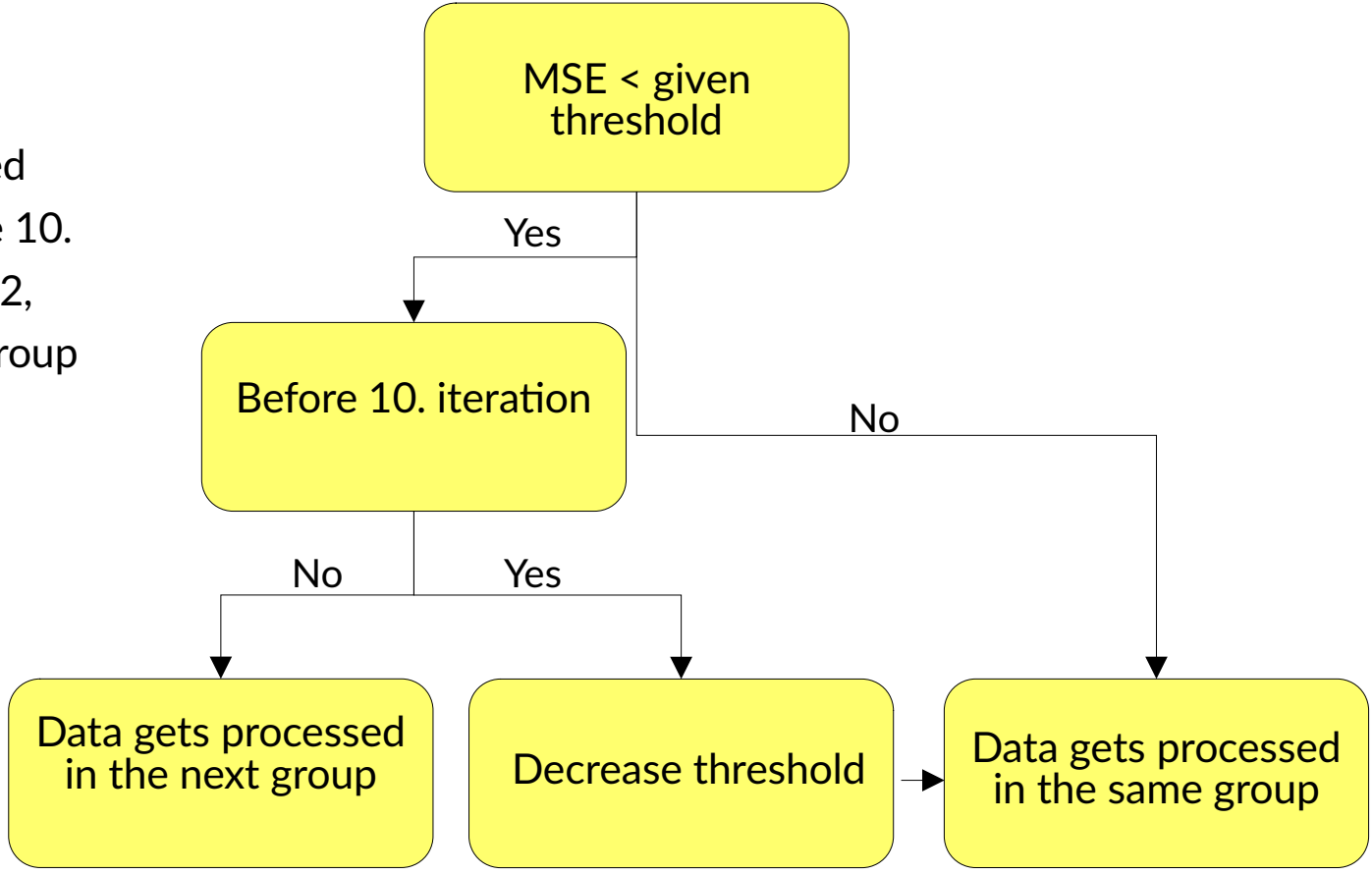




Adaptive grouped processing of proton trajectories

- Data to be processed is grouped
- Consecutive iterations are compared
- If MSE < given threshold before the 10. iteration, threshold gets divided by 2, otherwise continue with the next group

Runtime got significantly shorter
(hours → minutes)
(~10^6 protons)



Steps of the framework

Generating data with Monte Carlo → Simulations with Geant4 & Gate → Very time-consuming!

- 360˚, rotation per degree
- 2 mm steps

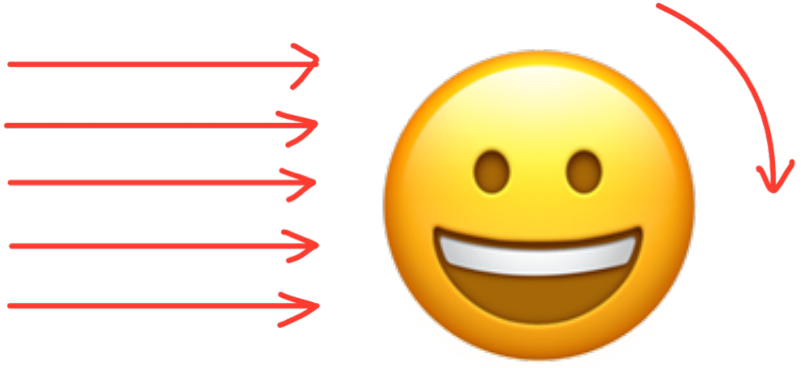
Parallelization

Adding simulated measurement errors

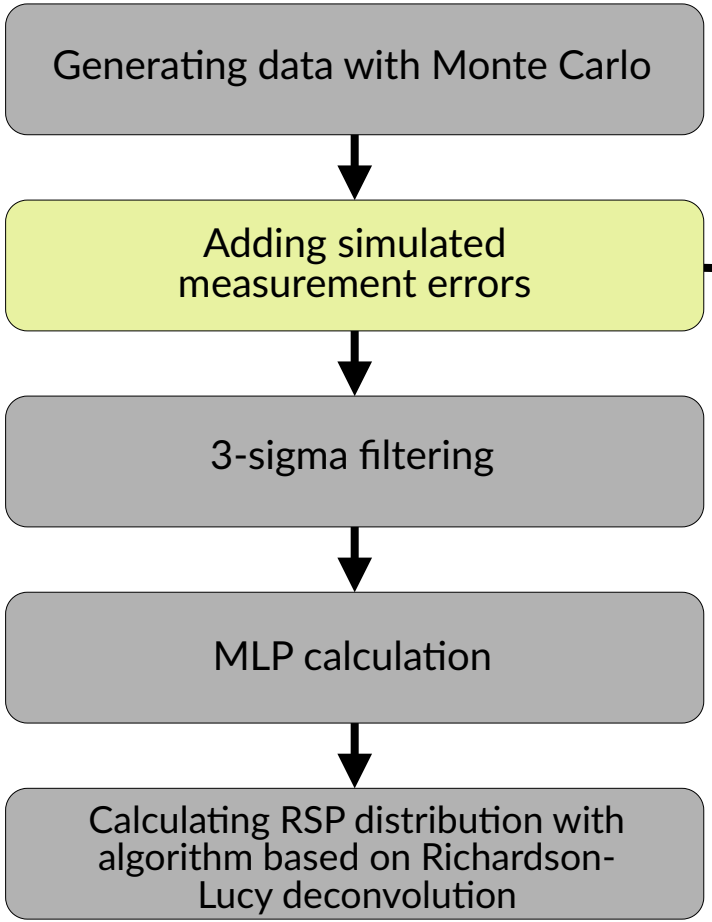
3-sigma filtering

MLP calculation

Calculating RSP distribution with algorithm based on Richardson-Lucy deconvolution



Steps of the framework



Simulating energy and position uncertainties of proton trajectories

- From correlated Gaussian distributions
- ~2 MeV energy uncertainty

Steps of the framework

Generating data with Monte Carlo

↓

Adding simulated measurement errors

↓

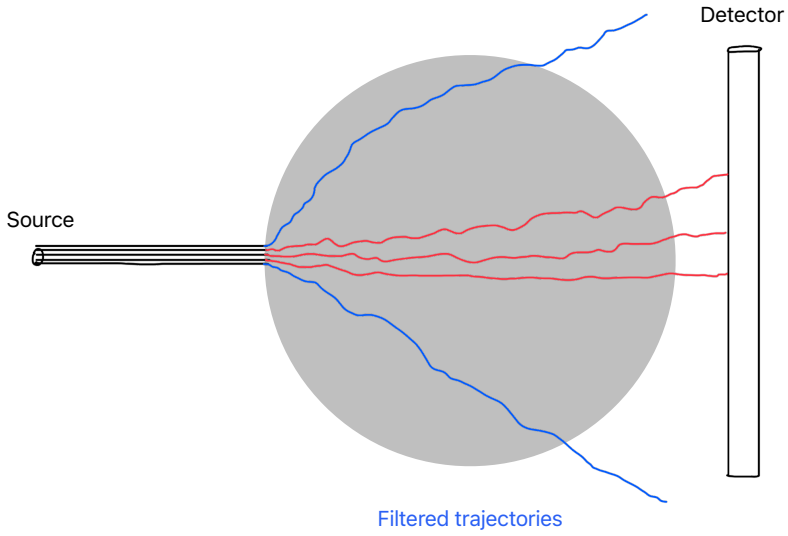
3-sigma filtering → Filtering out protons that scattered with a large angle

↓

MLP calculation

↓

Calculating RSP distribution with algorithm based on Richardson-Lucy deconvolution



Steps of the framework

Generating data with Monte Carlo

↓

Adding simulated measurement errors

↓

3-sigma filtering

↓

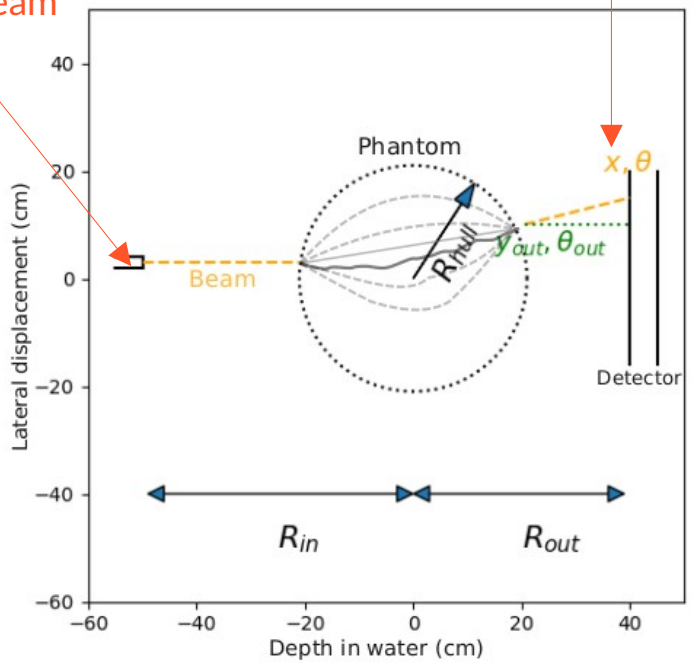
MLP calculation → Calculating the most likely position of protons going in and coming out of the cylinder around the phantom

↓

Calculating RSP distribution with algorithm based on Richardson-Lucy deconvolution

Beam position from the detector

Initial position of the beam



Compromise between speed and accuracy!

Steps of the framework

Generating data with Monte Carlo

Adding simulated measurement errors

3-sigma filtering

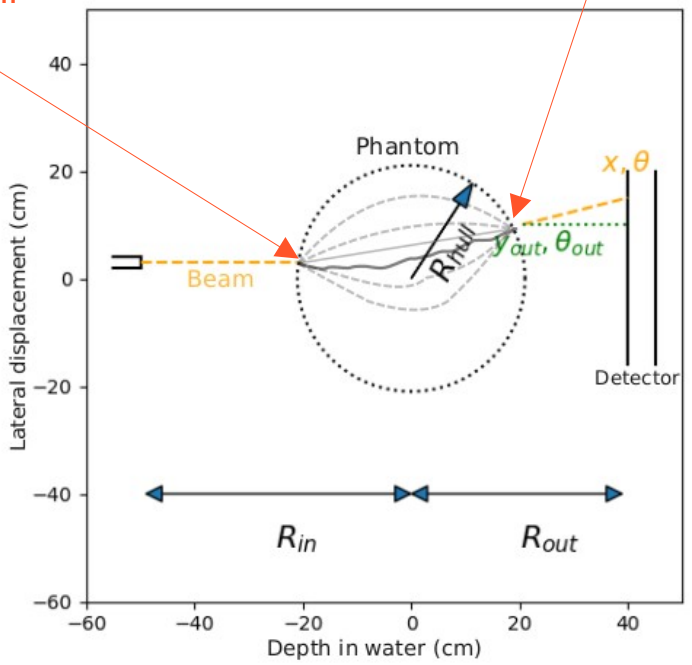
MLP calculation

Calculating RSP distribution with algorithm based on Richardson-Lucy deconvolution

Calculating the most likely position of protons going in and coming out of the cylinder around the phantom

Intersection of the beam with the known phantom hull

Intersection of the beam with the known phantom hull



Compromise between speed and accuracy!

Steps of the framework

Generating data with Monte Carlo

↓

Adding simulated measurement errors

↓

3-sigma filtering

↓

MLP calculation → Calculating the most likely position of protons going in and coming out of the cylinder around the phantom

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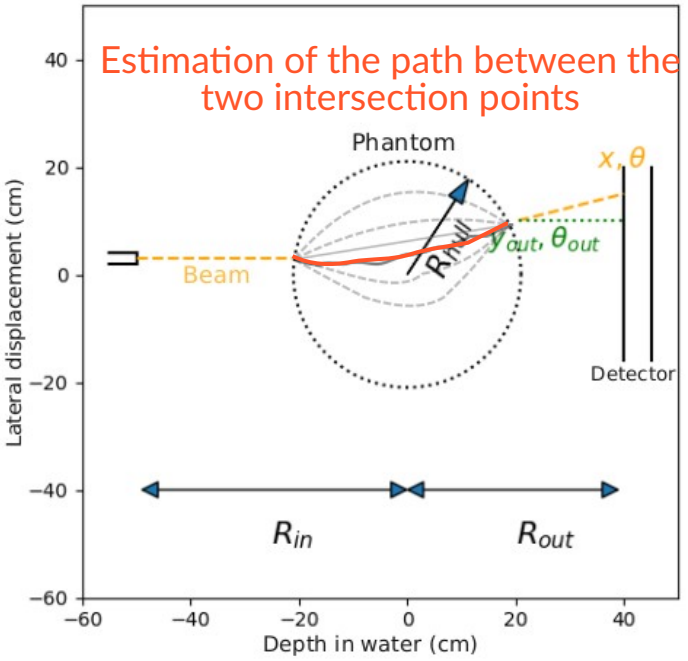
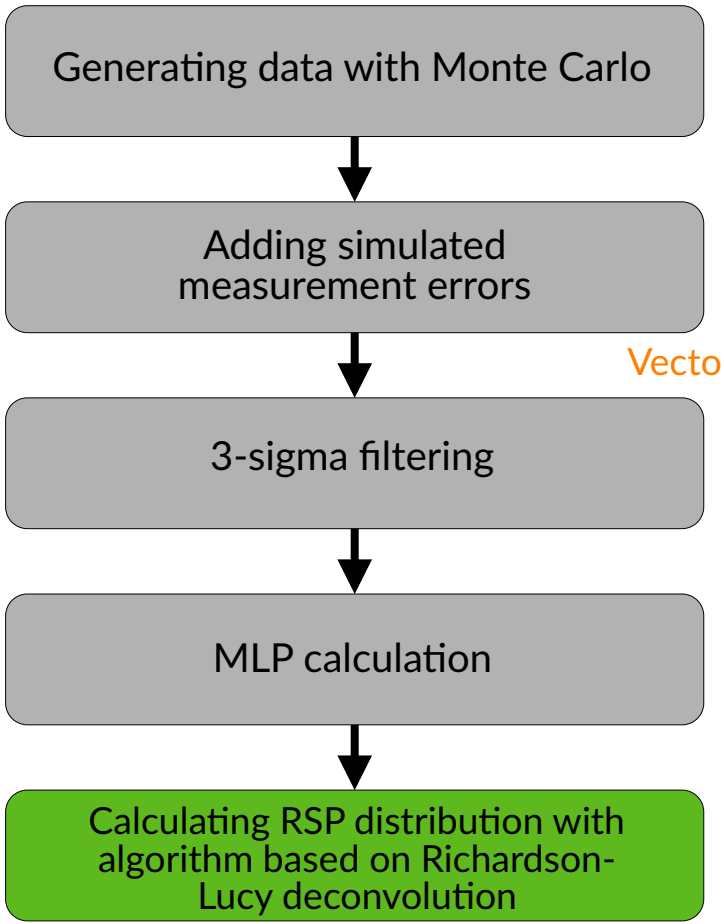
Calculating RSP distribution with algorithm based on Richardson-Lucy deconvolution



Compromise between speed and accuracy!

Steps of the framework



Number of iterations

Vector containing WEPL values (from detector)

Matrix containing interaction coefficients between proton trajectories and voxels

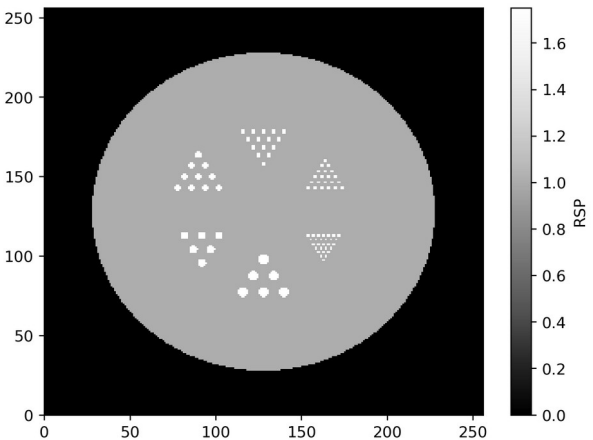
$$x_i^{k+1} = x_i^k \frac{1}{\sum_j A_{i,j}} \sum_j \frac{y_j}{\sum_l A_{l,j} x_l^k} A_{i,j}$$

Vector containing RSP values

- Statistical iterative algorithm, Maximum Likelihood - Expectation Maximization (ML-EM)
  - → Originally used in optics
- Technical challenge (~millions of proton trajectories)
- Using GPU: C++ code sped up with CUDA
  - → The equation is evaluated for every trajectory and iteration in the GPU kernels (WSCLAB) → Nvidia GTX 1080 Ti GPU, 32 GB RAM
  - → Goal: maximize resolution + minimize runtime → adaptive grouped processing of proton trajectories → runtime is shortened to minutes

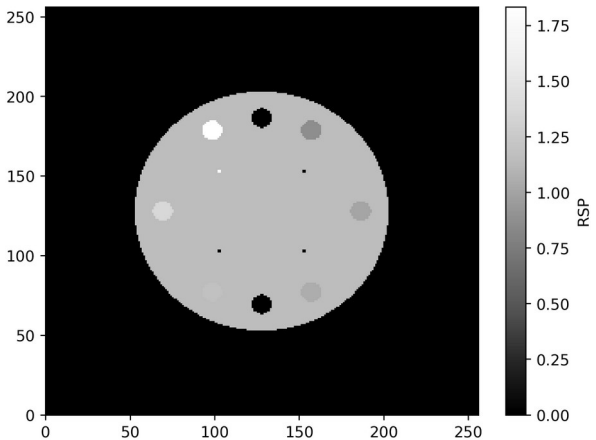
Evaluation of the algorithm - phantoms

Derenzo



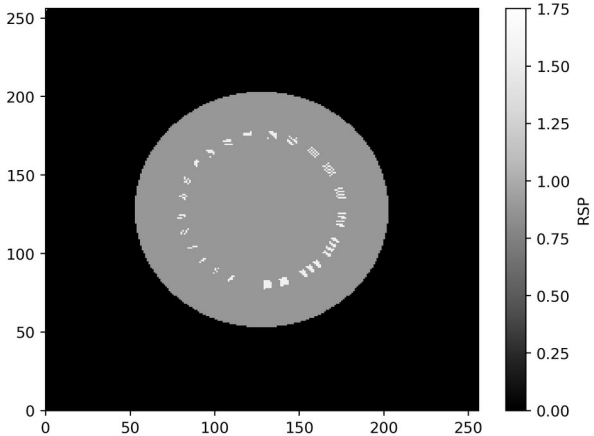
- 200 mm diameter water cylinder
- 6 sectors with 1.5-6 mm diameter aluminium rods
- Used for measuring spatial resolution

CTP404



- 150 mm diameter epoxy cylinder
- 8 different material inserts, 12.2 mm diameter cylinders
- Used for measuring reconstructed RSP accuracy

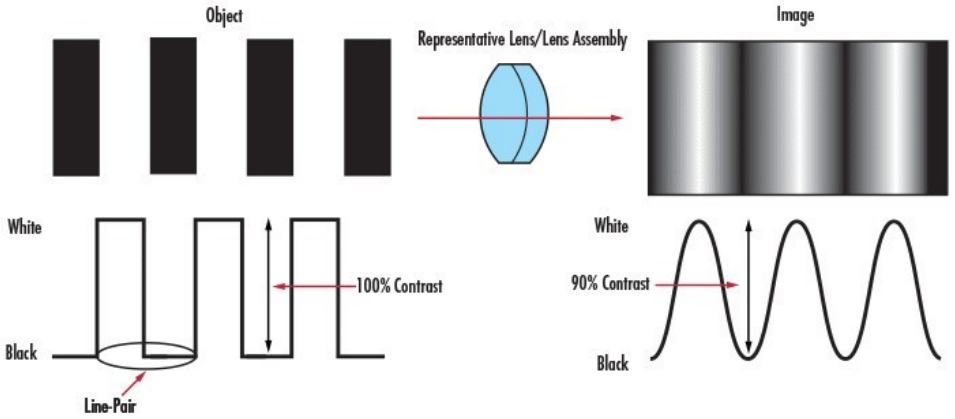
CTP528

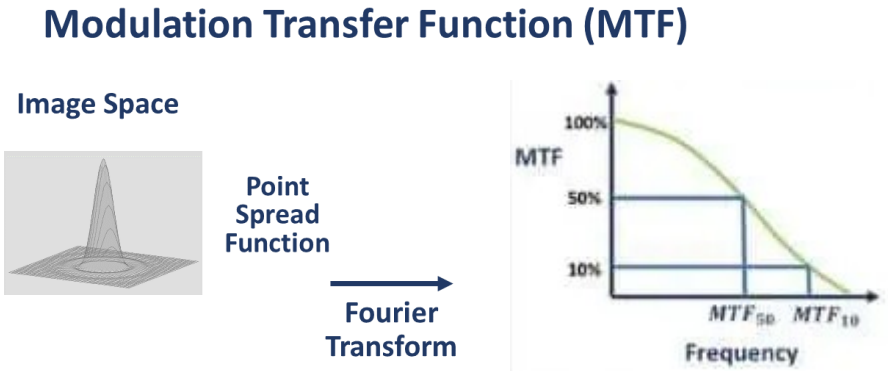


- 150 mm diameter water cylinder
- 1-21 aluminium linepairs per cm
- Used for measuring spatial resolution

Spatial resolution

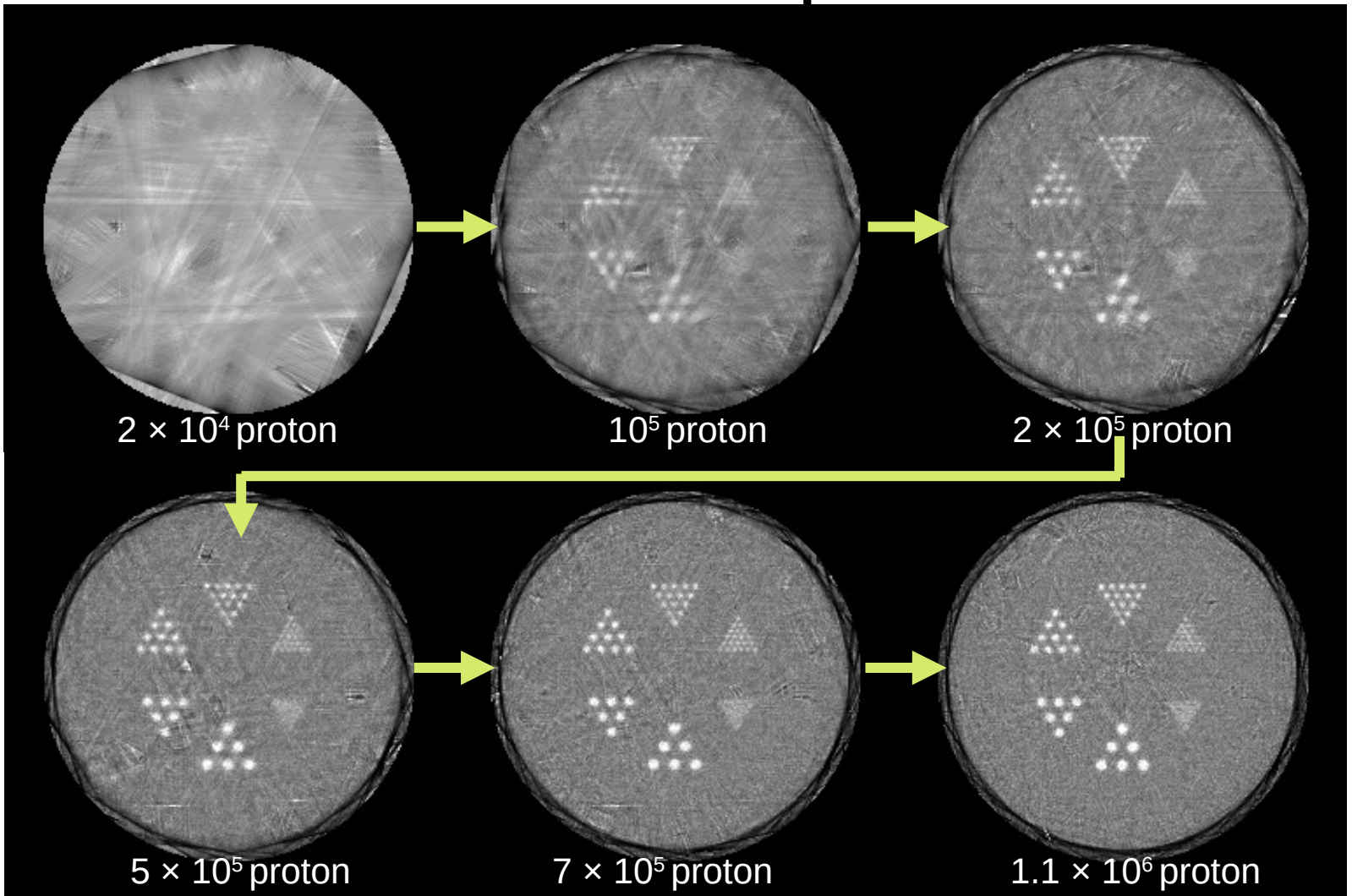
Good measure for spatial resolution: **Modulation Transfer Function** [lp/mm] → how well can we differentiate between two objects on an image





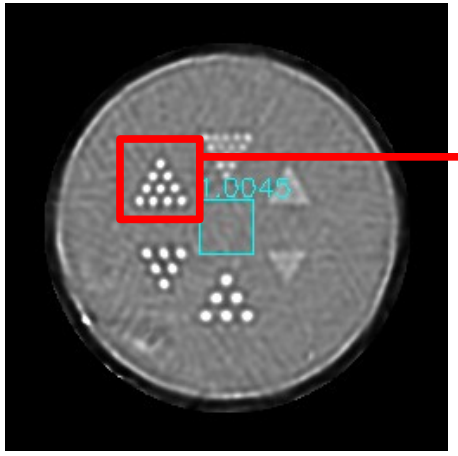
The more linepairs we can differentiate, the better the resolution is

Spatial resolution with Derenzo phantom



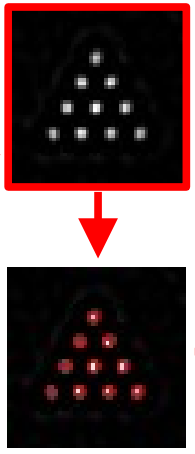
Spatial resolution with Derenzo phantom

(i)



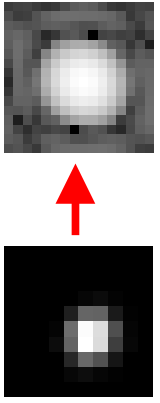
Subtract the mean background

(ii)



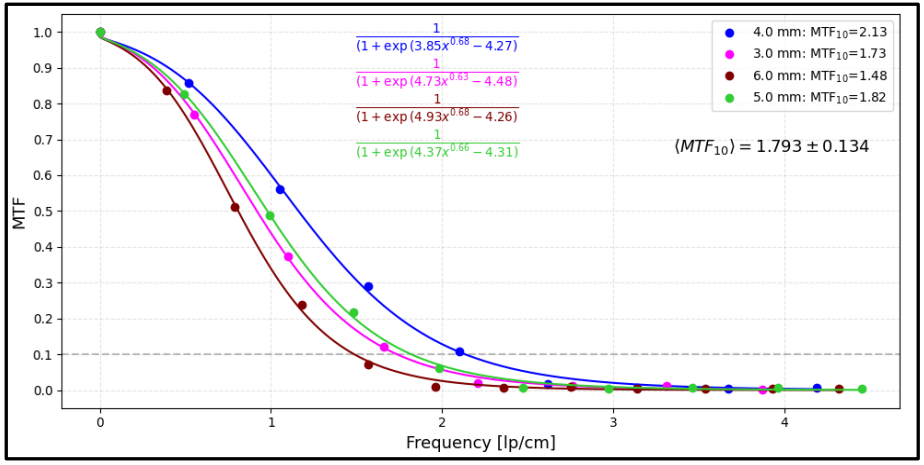
Find individual rods from each sector

(iii)



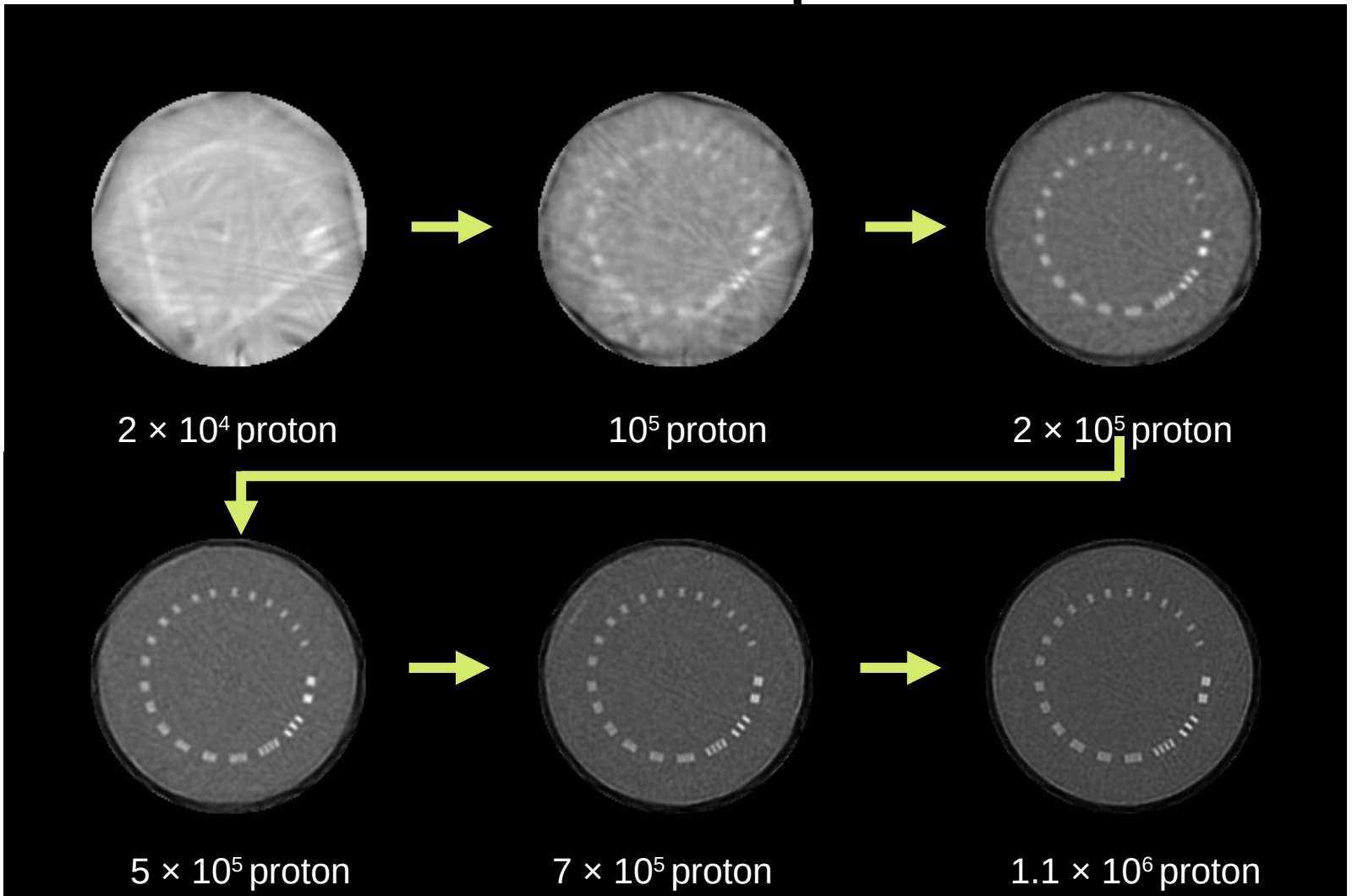
Average them → Point Spread Function

(iv)-(v)

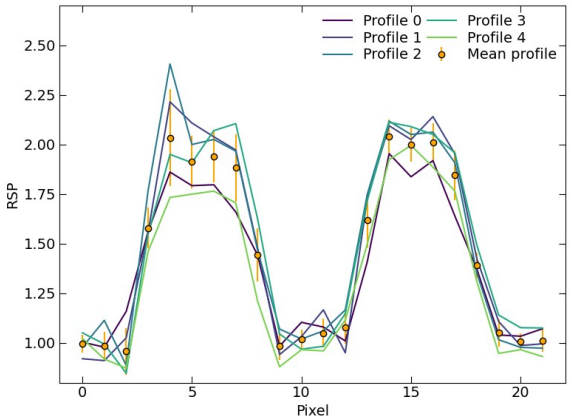


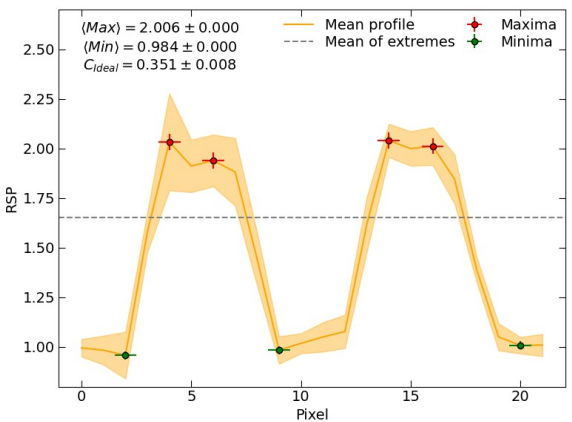
- 2D Fourier transform PSF → Modulation Transfer Function (MTF)
- MTF10% averaged for the sections represents spatial resolution

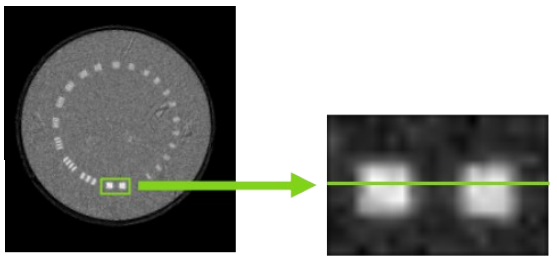
Spatial resolution with CTP528 phantom

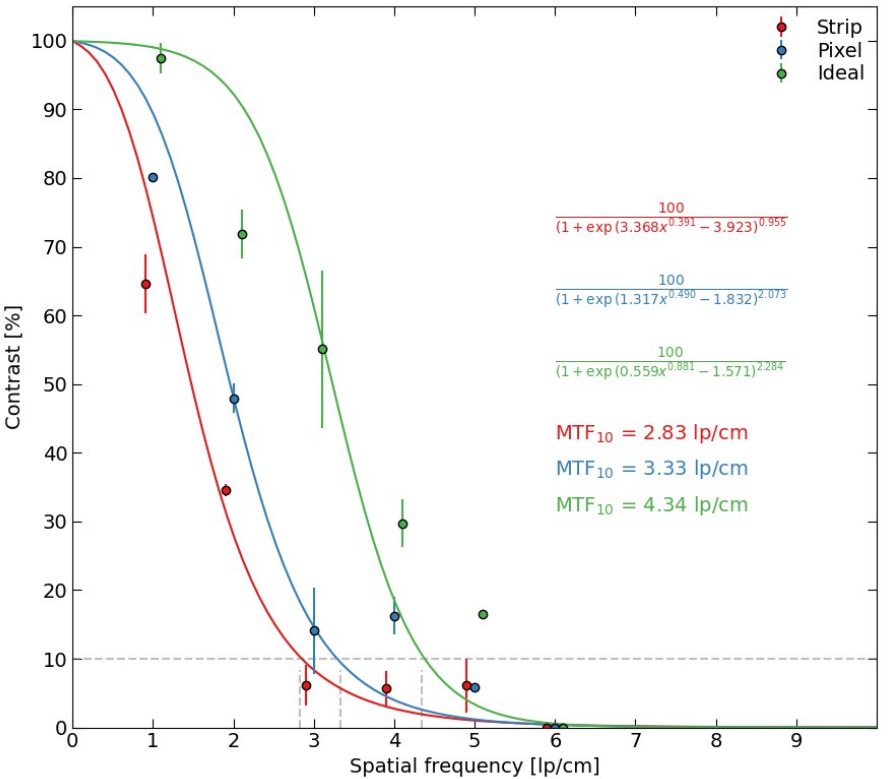


Spatial resolution with CTP528 phantom









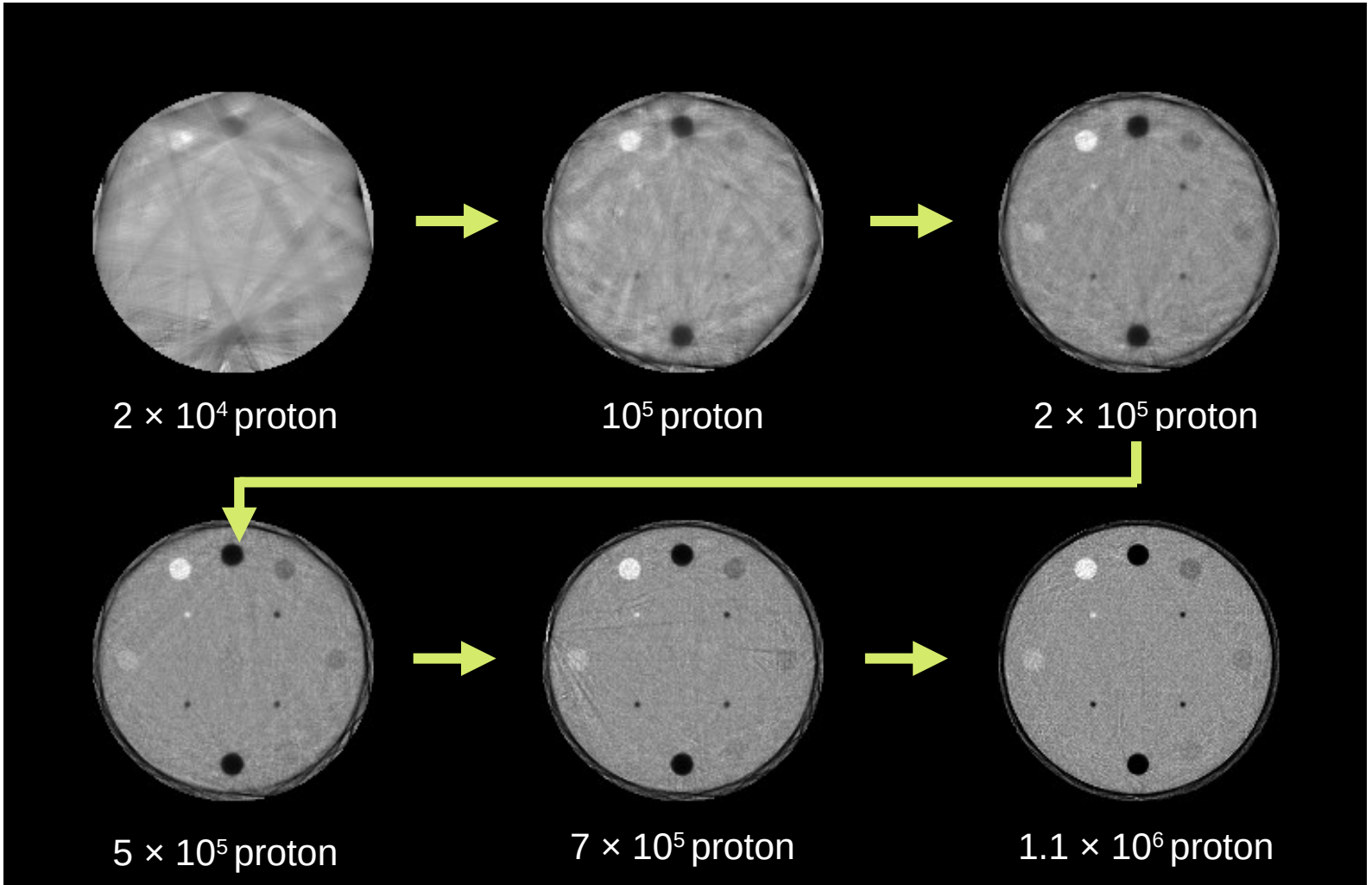
ArXiv:2212.00126v2

Spatial resolution results

Results compared to literature: promising, but still need development

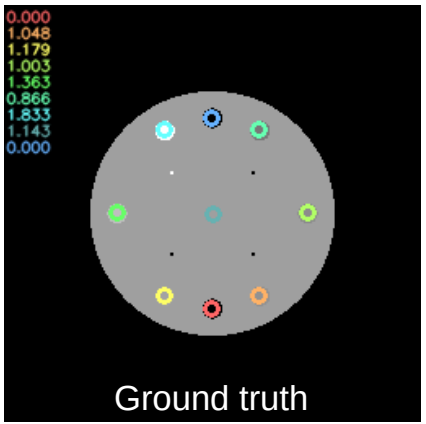
	$MTF_{10\%}$ [lp/cm]	
	Ideal	**Realistic**
Derenzo	1.43	1.17 (pixel)
		0.94 (strip)
CTP528	4.34	3.33 (pixel)
		2.83 (strip)
Reference	3.8	3.2

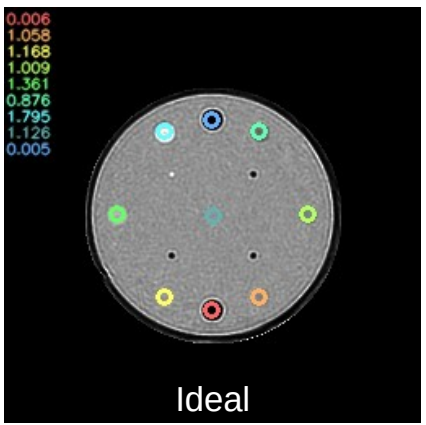
RSP reconstruction accuracy with CTP404 phantom



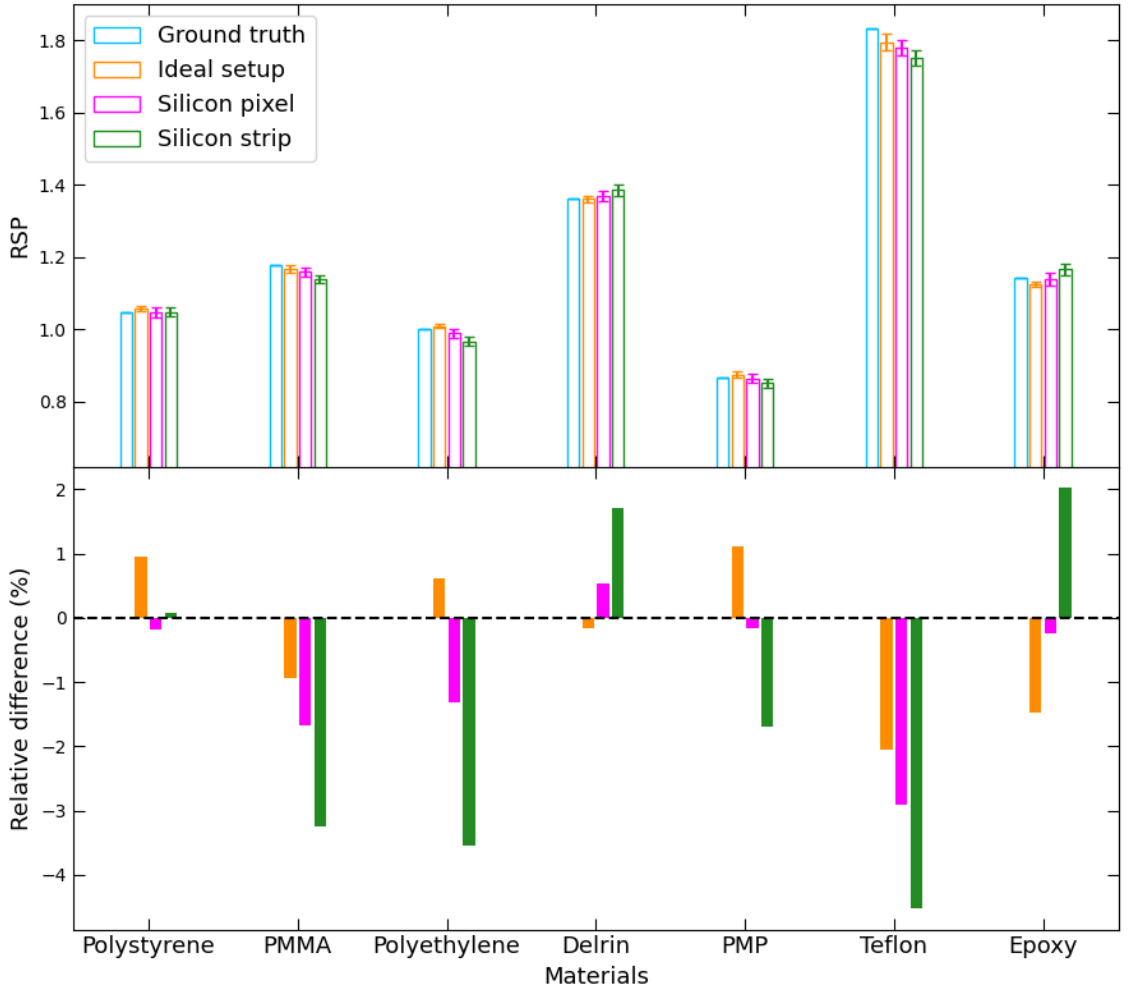
RSP reconstruction accuracy with CTP404 phantom

~-4% relative difference → same order of magnitude as the literature



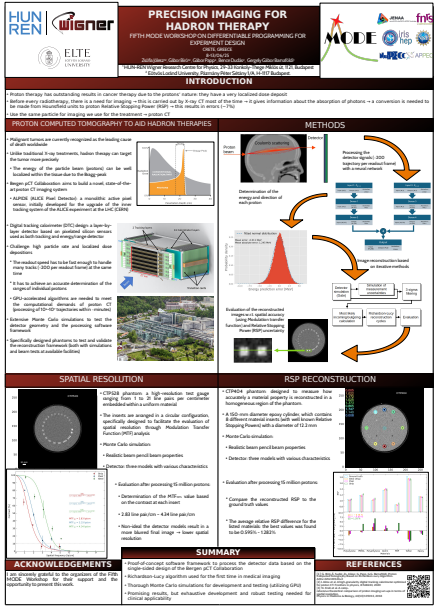


ArXiv:2212.00126v2



Summary of achievements and future plans

- Richardson-Lucy algorithm used for the first time in medical imaging
- Promising results (using ~10^6 protons), comparable with other used algorithms
  - Spatial resolution evaluation with Derenzo & CTP528 phantoms
  - RSP reconstruction accuracy evaluation with CTP404 phantom
- Further developments for clinical usability
  - Precise 3D reconstruction
  - Robust evaluation with realistic phantoms
  - Further improvement in runtime
  - Using Machine Learning for noise filtering, MLP calculation, etc.



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- D. Wang et al., *Medical physics* **37.8** (2010)
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Backup

https://doi.org/10.1142/S0217751X25420084