Image reconstruction in proton computed tomography

Theory and Experiment in High Energy Physics

Supervisors:
Gábor Bíró, Ph.D.
Gábor Papp, Ph.D.

Zsófia Jólesz
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HUN-REN Hungarian Research Network

MTA Centre of Excellence

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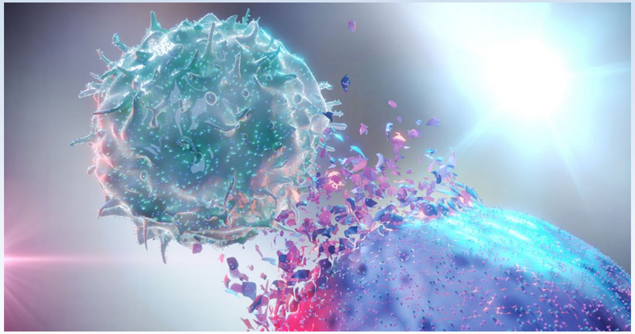
Outline

- Proton therapy – advantages and difficulties
- The Bergen Proton CT Collaboration
- Image reconstruction techniques
- Iterative methods
- The Richardson-Lucy algorithm
- Development of the framework
- Testing the algorithm with phantoms, results
- Summary

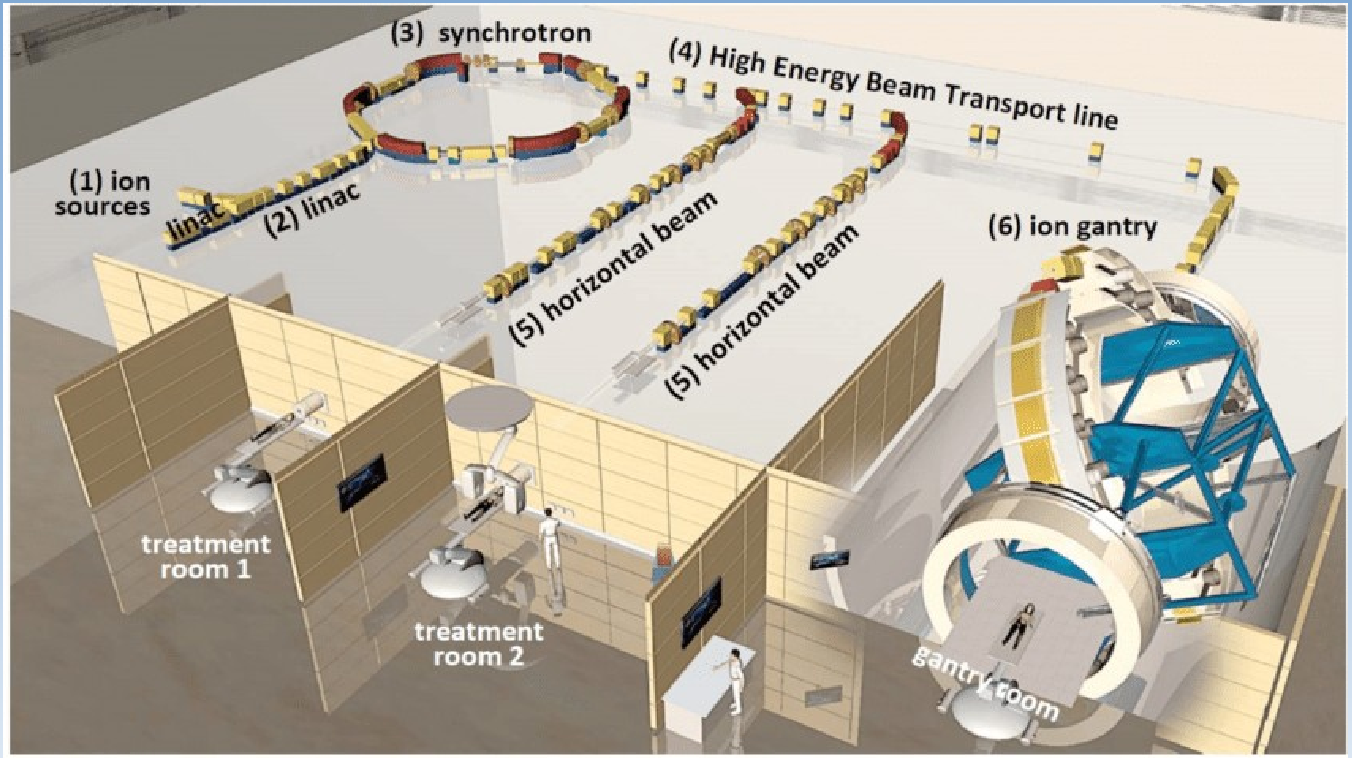
Motivation

- Cancer treatment: surgery, chemotherapy, radiotherapy, immunotherapy
- Radiotherapy: uses ionizing particles



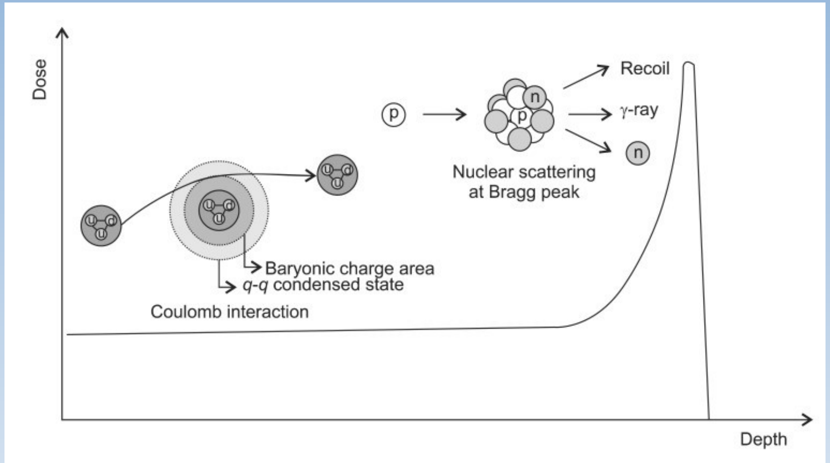
Motivation

- Cancer treatment: surgery, chemotherapy, <u>radiotherapy</u>, immunotherapy
- Radiotherapy: uses ionizing particles
- What kind of particles?
  - Photons
  - <u>Protons</u>
  - Heavy ions

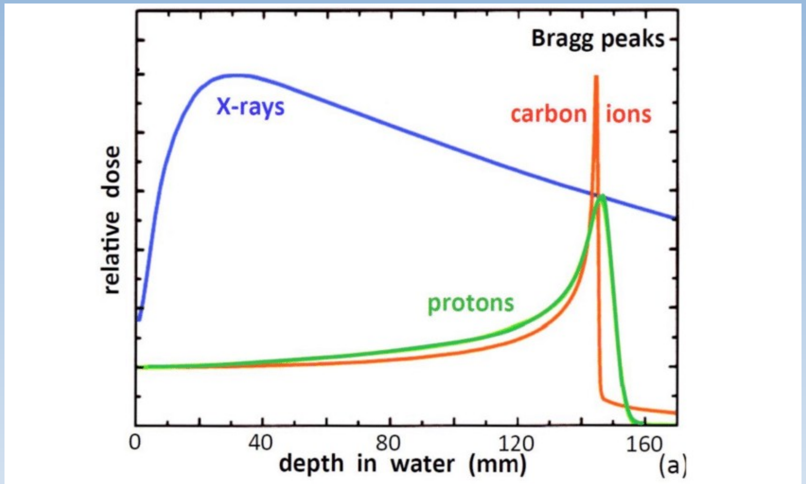


Layout figure of HIT Centre (Heidelberg)

Why is proton therapy so outstanding?

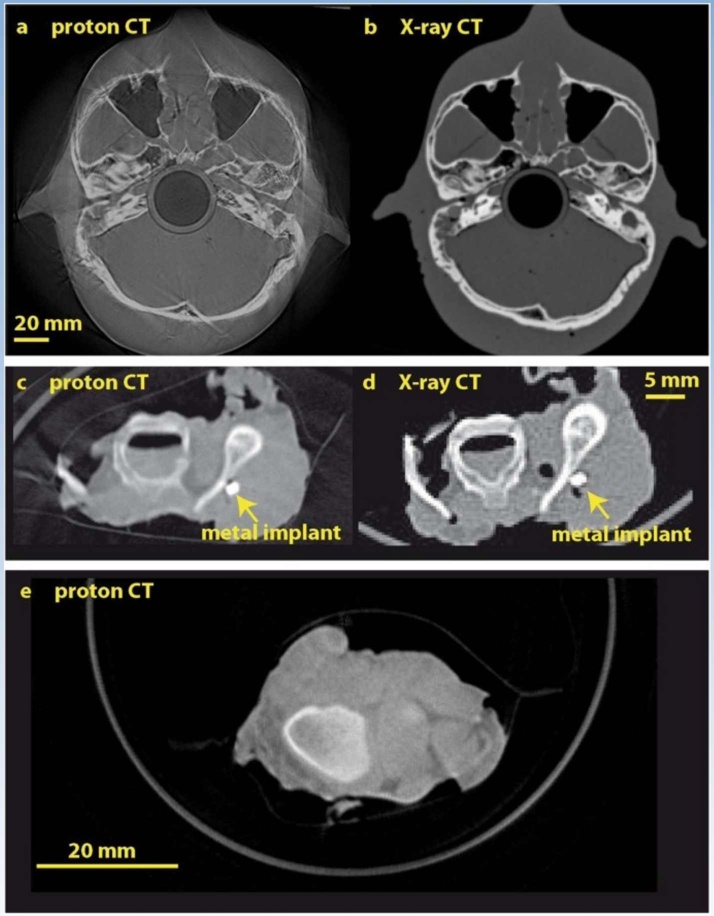


[Seo Hyun Park and Jin Oh Kang. Basics of particle therapy i: physics. Radiation oncology Journal, 29(3):135, 2011.]



[Ugo Amaldi, Manjit Dosanjh, Jacques Balosso, Jens Overgaard, and Brita Sørensen. A facility for tumour therapy and biomedical research in south-eastern europe. 09 2019.]

Problems with imaging – and the solution



X-ray CT vs. proton 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

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

↓

Detector system senses the signals

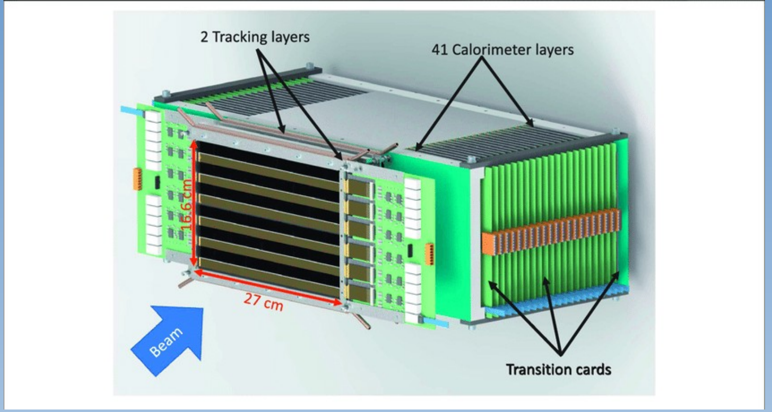
↓

Processing the signals

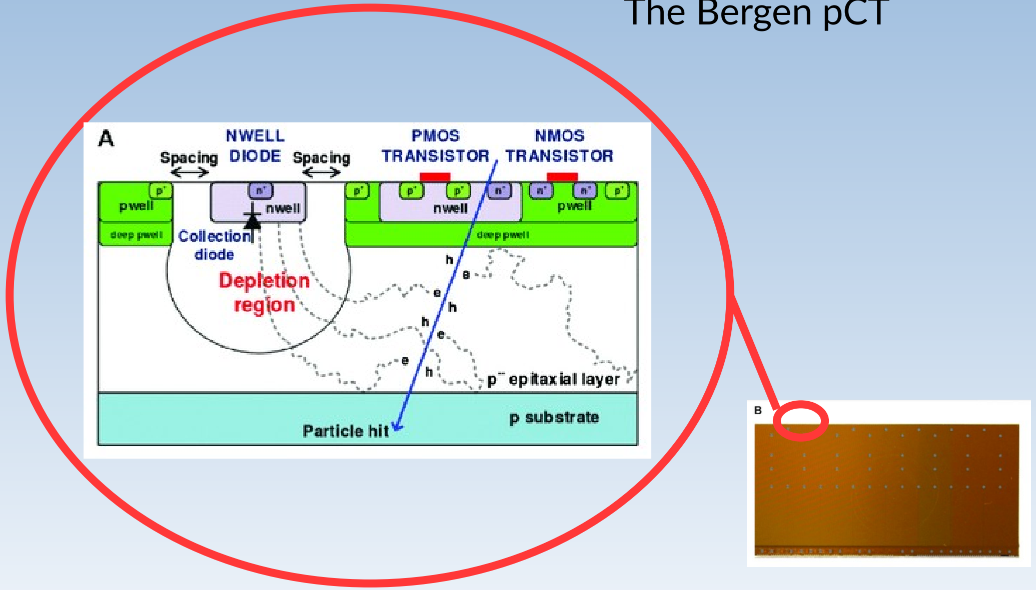
↓

Reconstructing the image

- Based at the University of Bergen
- Goal: to build a proton CT based on the high-energy particle detectors used in the CERN ALICE collaboration (technology transfer)
- The detector system is based on the ALPIDE chip



The Bergen pCT



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

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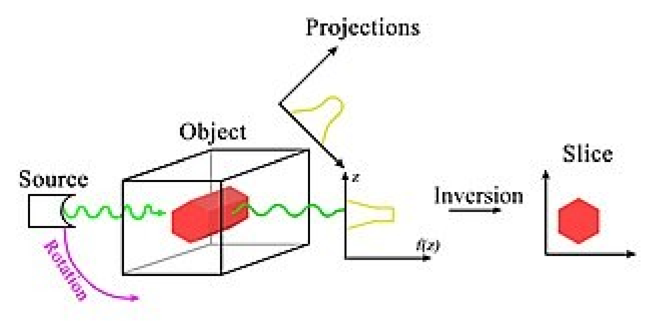
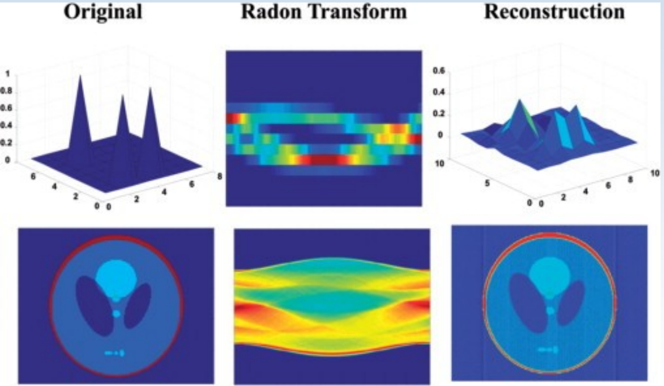
Particles & Plasmas Symposium, 2024

Image reconstruction techniques

Integral transformations → Radon, Inverse Radon

- Cannot be used for proton CT (due to nuclear scattering of protons)





Iterative reconstruction techniques

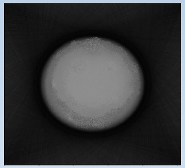
- Model the problem as a linear equation system

$$A \cdot x = y$$

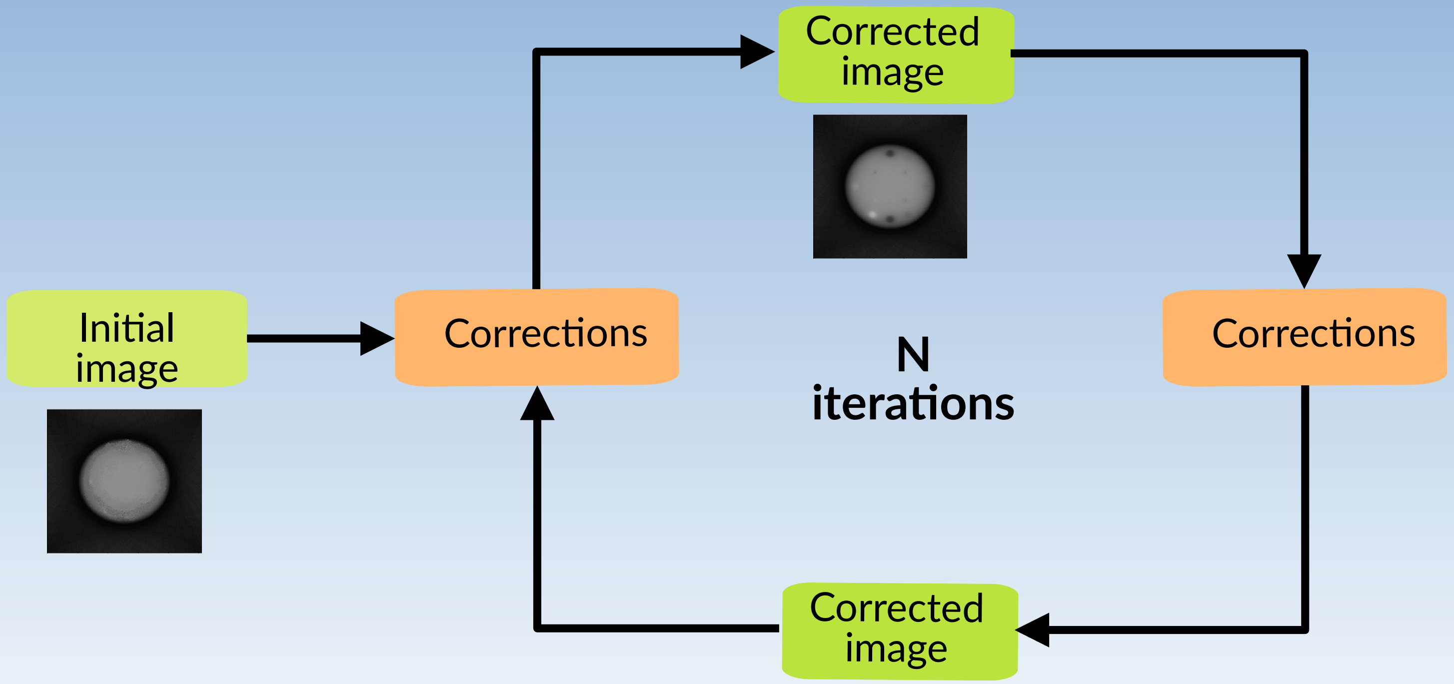
- A: Matrix that contains interaction coefficients between protons and pixels/voxels
- x: Vector that contains estimated proton RSP values
- y: Vector that contains the known WEPL values of the protons

Iterative methods for image reconstruction

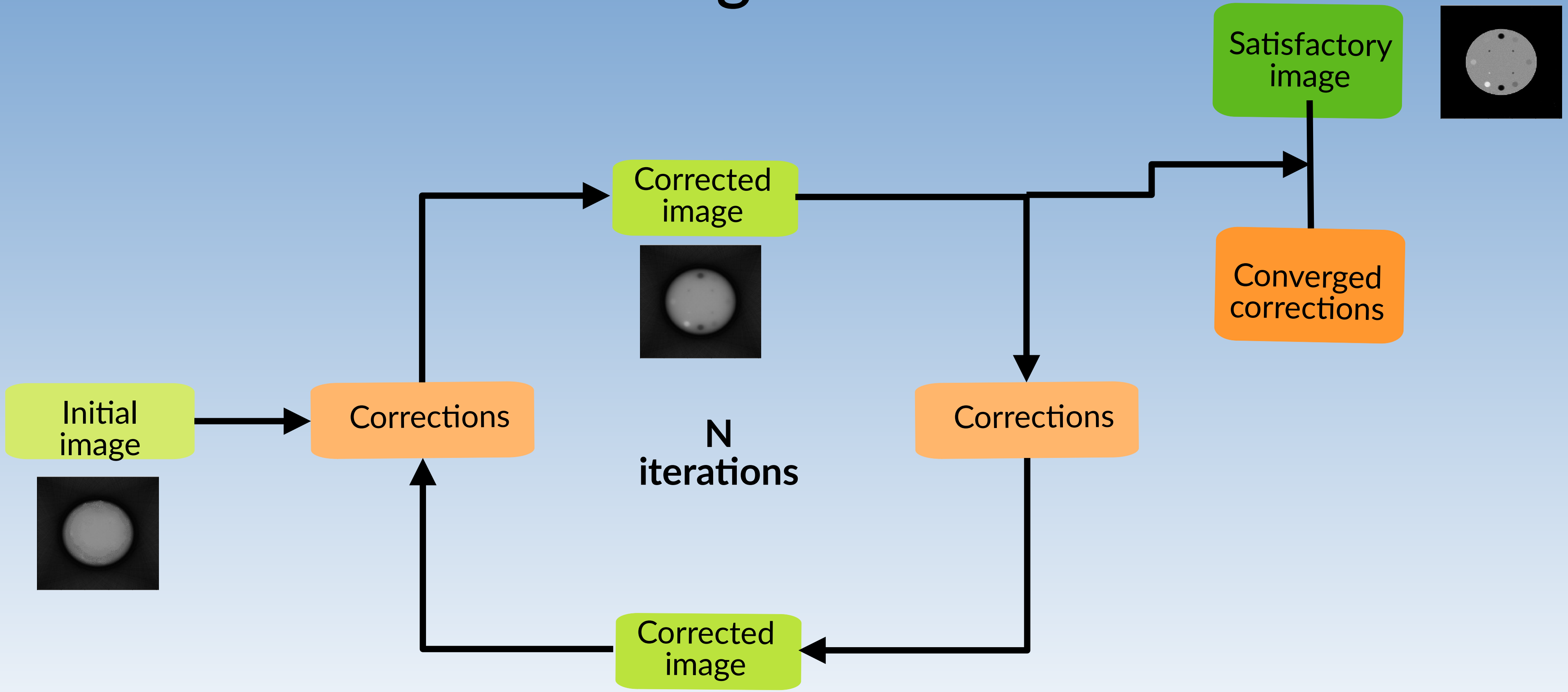
Initial image



Iterative methods for image reconstruction



Iterative methods for image reconstruction



The Richardson-Lucy algorithm

- Statistical iterative algorithm
- Maximum Likelihood - Expectation Maximization (ML-EM)
- Originally used in optics
- Input data: from detector or Monte Carlo
- MLP calculation
- RSP-distribution calculation

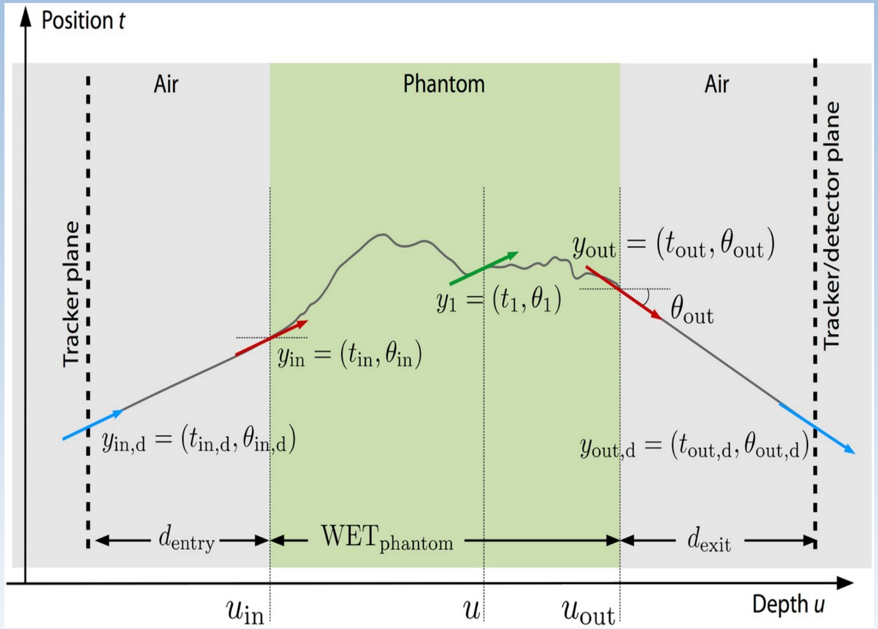
$$x_i^{k+1} = x_i^k \frac{1}{\sum_j A_{i,j}} \sum_j \frac{y_j}{\sum_l A_{l,j} x_l^k} A_{i,j}$$

Number of iterations

Vector containing WEPL values

Matrix containing interaction coefficients between proton trajectories and voxels

Vector containing RSP values



Very difficult technically (~millions of proton trajectories)

- Using GPU (CUDA)
- Goal: Finding optimization regarding the number of iterations and protons

Development of the framework

Steps of the framework

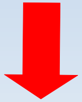
- **Generating data with Monte Carlo** → Simulations with Geant4 & Gate → Very time-consuming! → Parallelization
- **Adding simulated measurement errors** → 1.3 MeV (based on studies) uncertainty for the kinetic energy of the protons
- **3-sigma filtering** → Filtering directions and WEPL values of the protons
- **MLP calculation** → Calculating the most likely position of protons going in and coming out of the cylinder around the phantom
- **Calculating RSP distribution with Richardson-Lucy** → C++ code accelerated with GPU (using CUDA): different parts run in the GPU kernels (WSCLAB) → Nvidia GTX 1080 Ti GPU, 32 GB RAM

Shorter runtime (hours → minutes) (~10^6 protons)

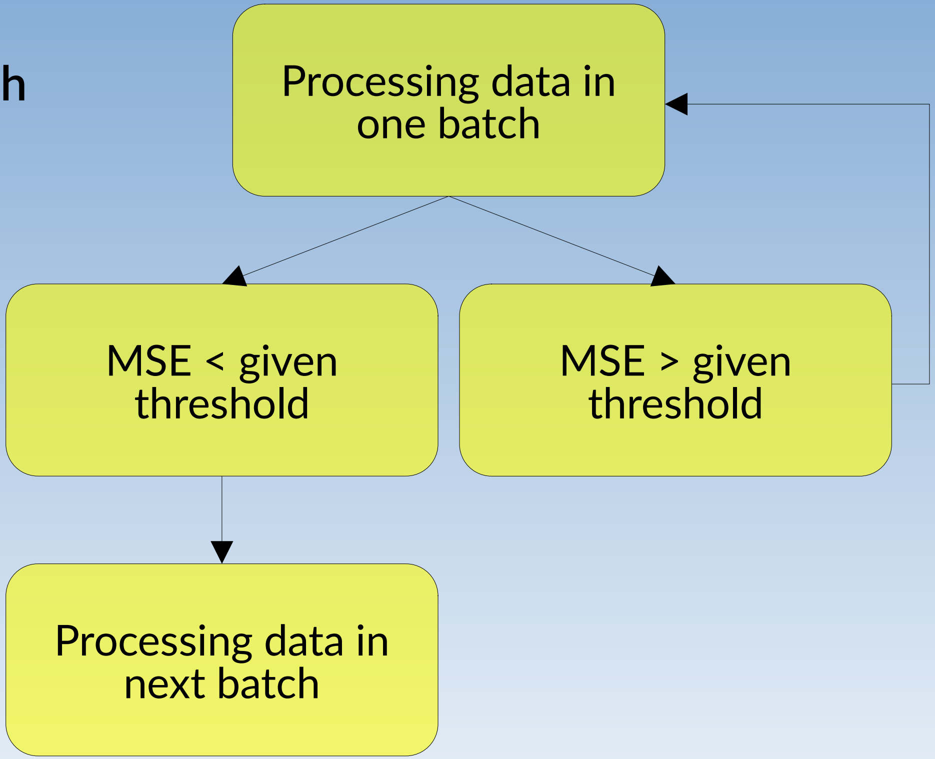
Development of the framework

Calculating RSP distribution with Richardson-Lucy

- Data to be processed is grouped in batches
- The consecutive iterations are compared
- If MSE < given threshold before the 10th iteration, threshold gets divided by 2, otherwise iterations stop in that batch



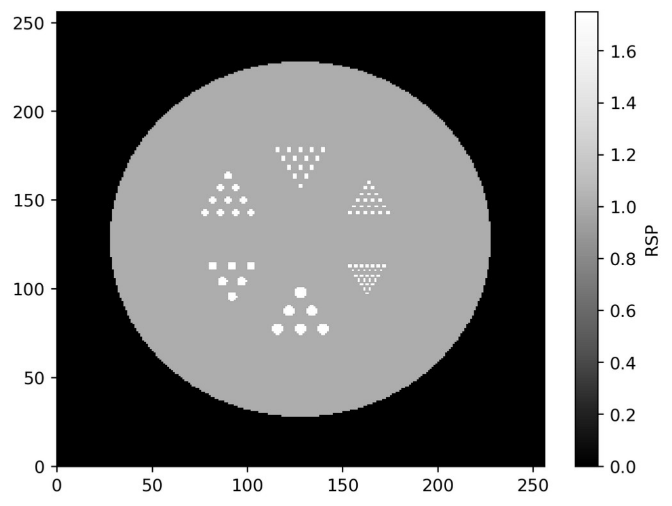
Significant speed-up in runtime



Evaluating the algorithm - phantoms

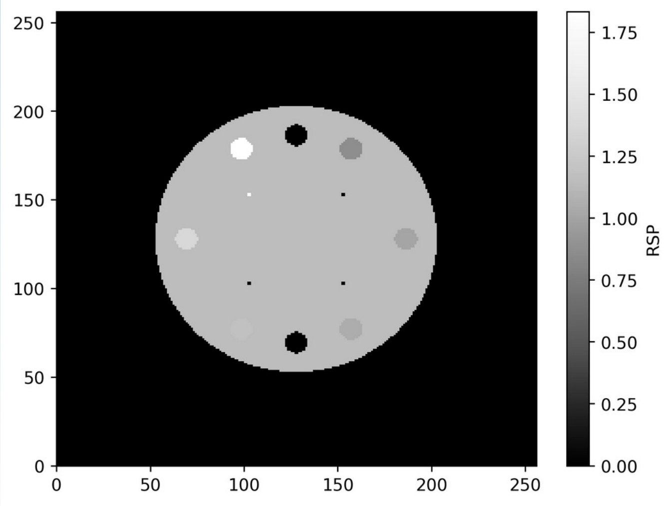
Derenzo phantom

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

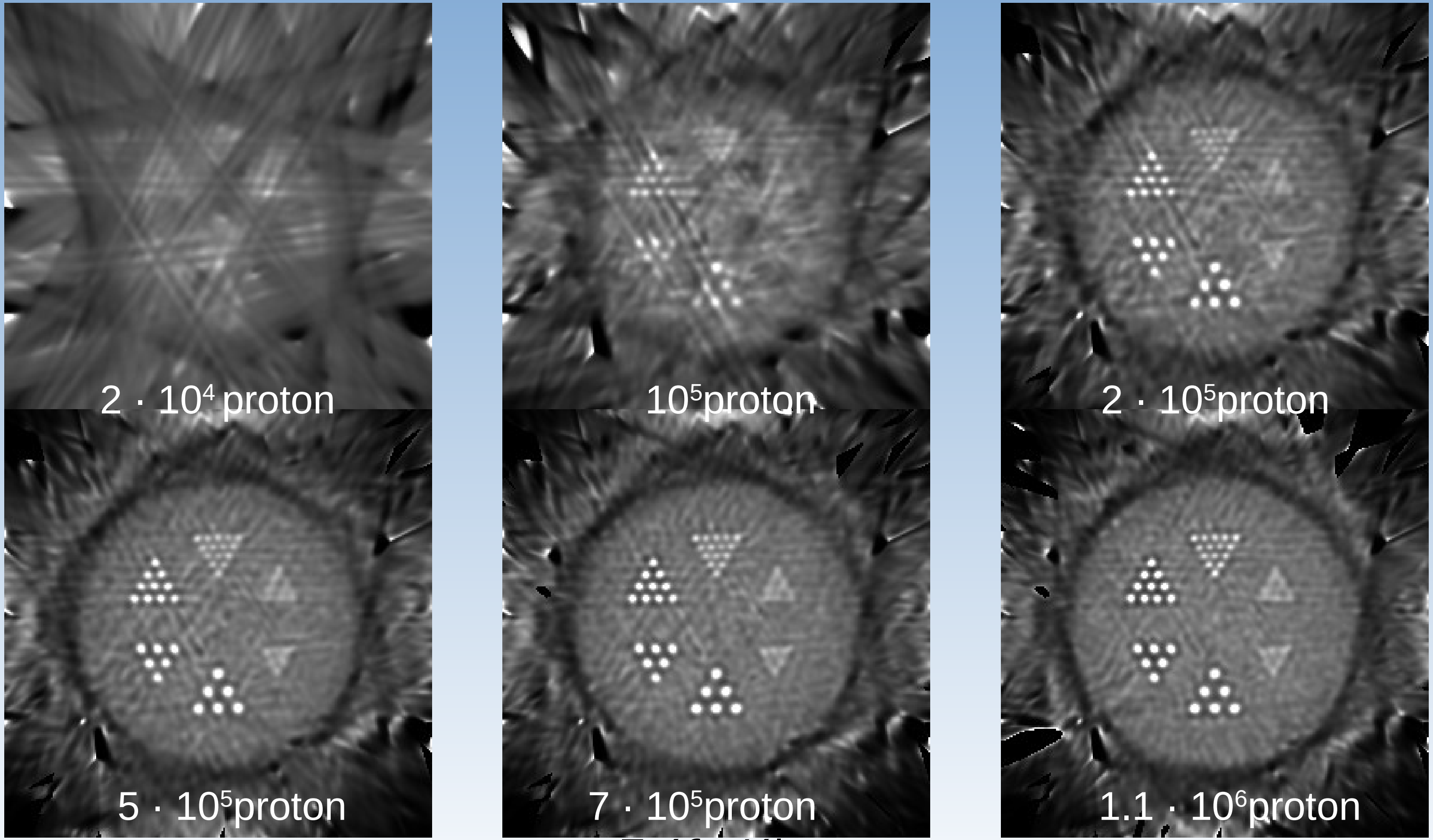


CTP404 phantom

- 150 mm diameter epoxy cylinder with 8 different material inserts with 12.2 mm diameter
- Used for measuring reconstruction accuracy for RSP

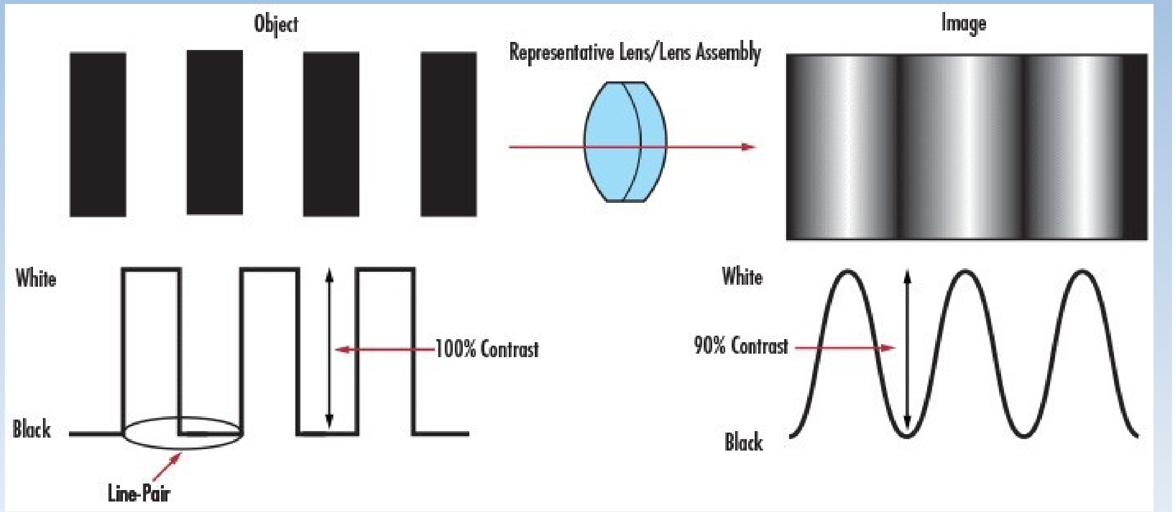


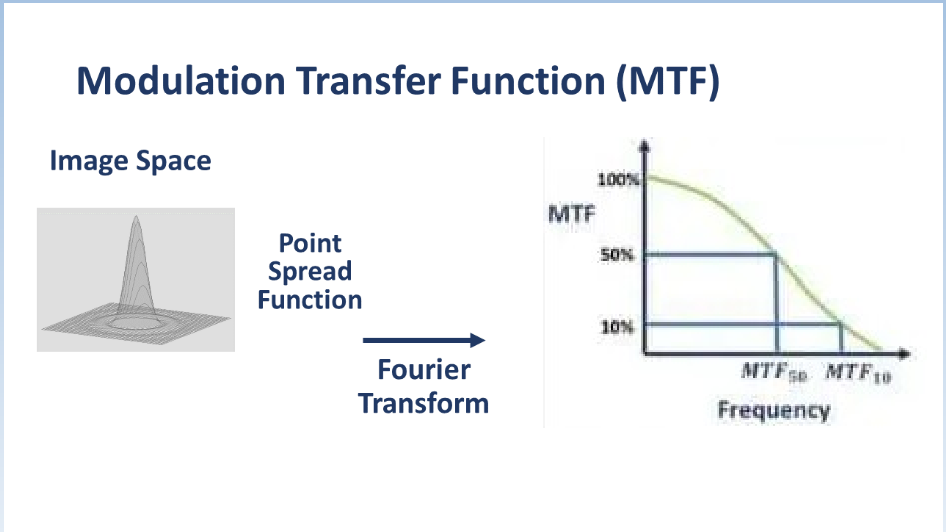
Spatial resolution with Derenzo phantom



Spatial resolution with Derenzo phantom

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

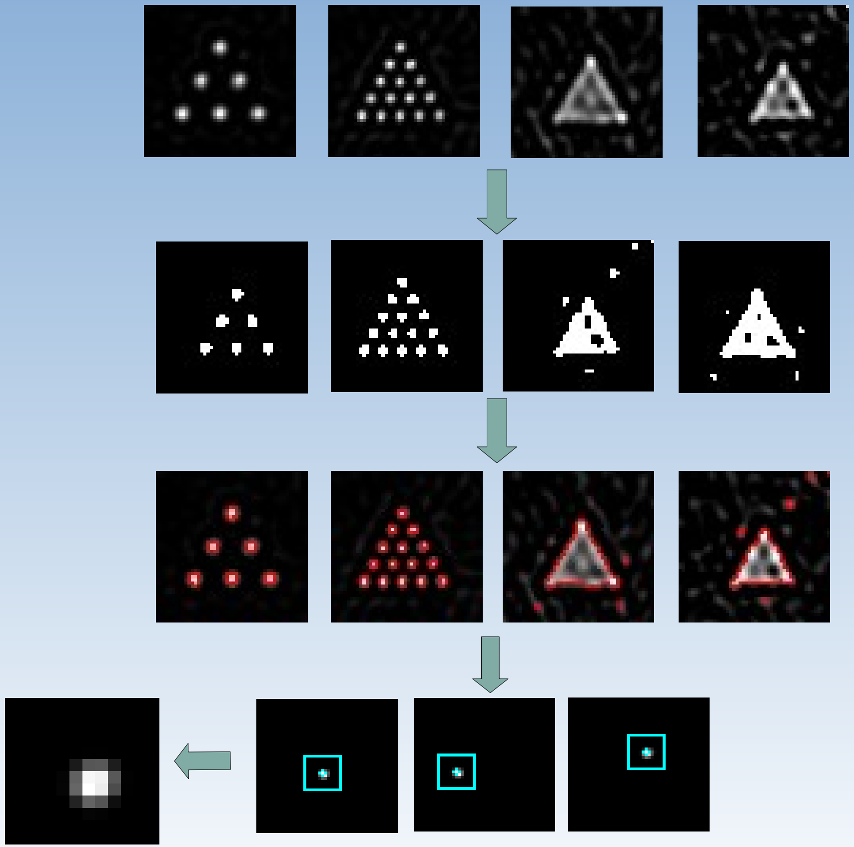




Spatial resolution with Derenzo phantom

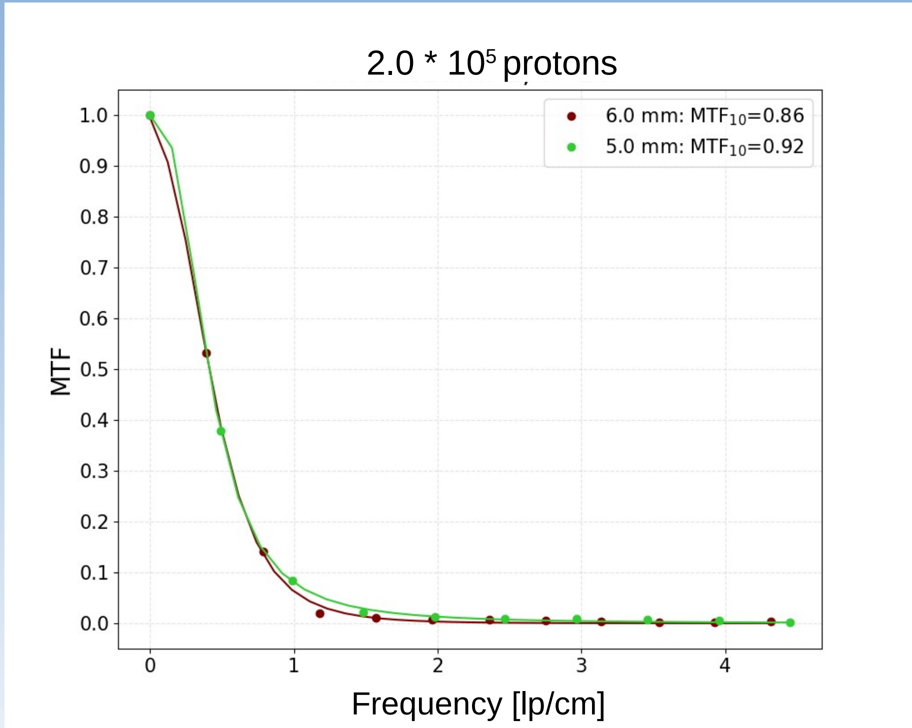
Determination of the $MTF_{10\%}$

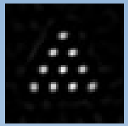
1. Get the (avg) PSF from each rod size (that is still distinguishable[1])
   i. Subtract the mean background
   ii. Rotate and cut the Area Of Interest (AOI)
   iii. Try to search for the unique blobs
   iv. Avg. the blobs
2. Get the MTF from the PSF
   i. 2d Fourier transform of the PSF
   ii. Radial profile
   iii. Sigmoid fit
   iv. Take the 10% value

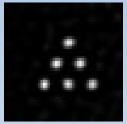


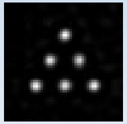
[1]Hard limit determined by the pixel size, e.g. 256x256 geometry → 1mm/px

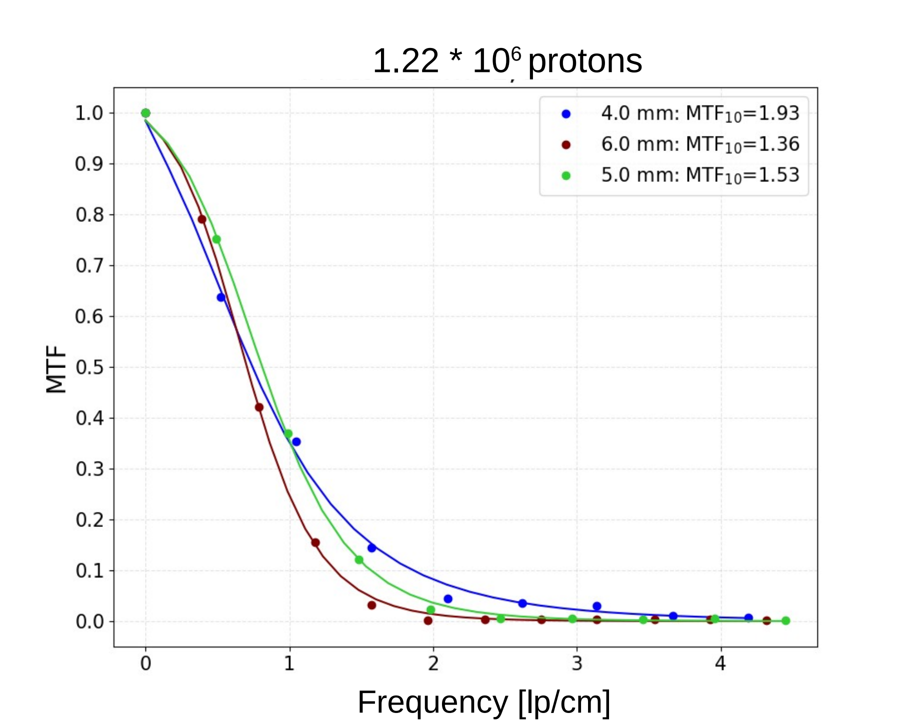
Spatial resolution with Derenzo phantom



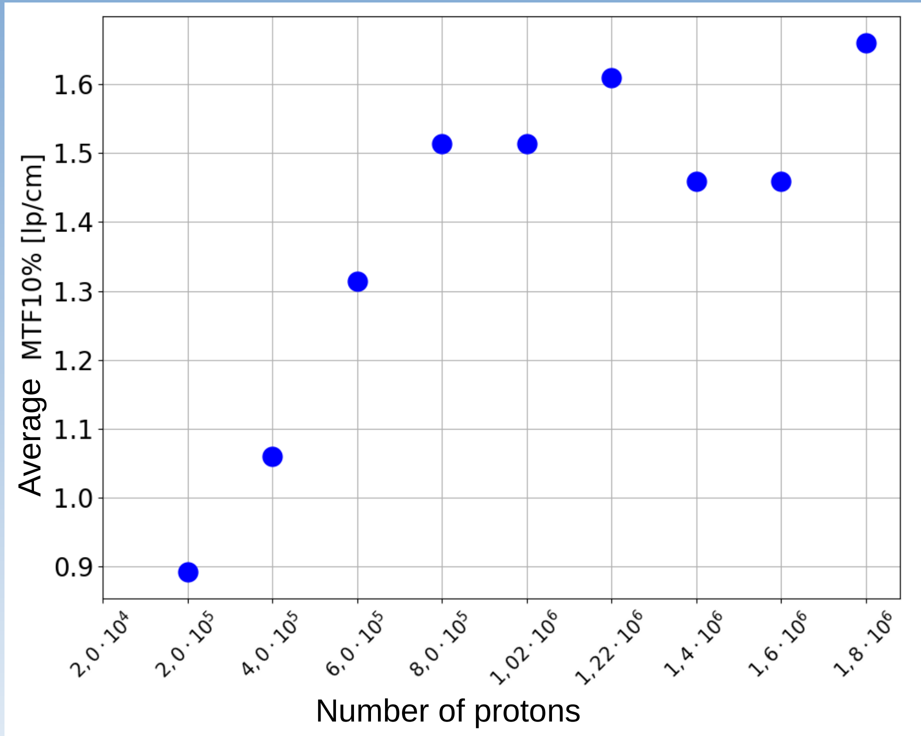




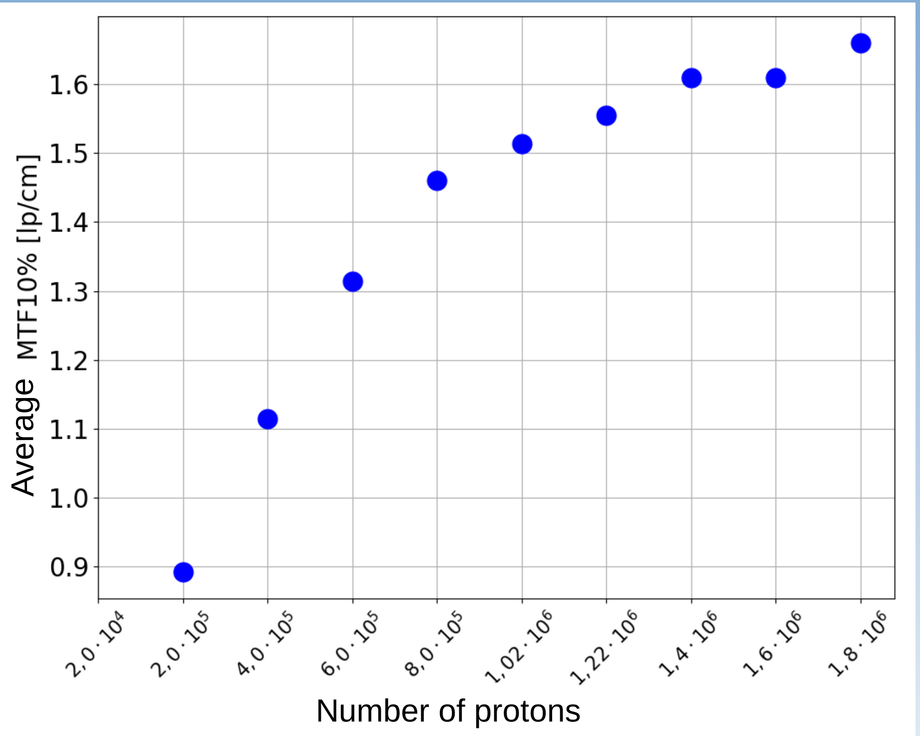




Spatial resolution with Derenzo phantom

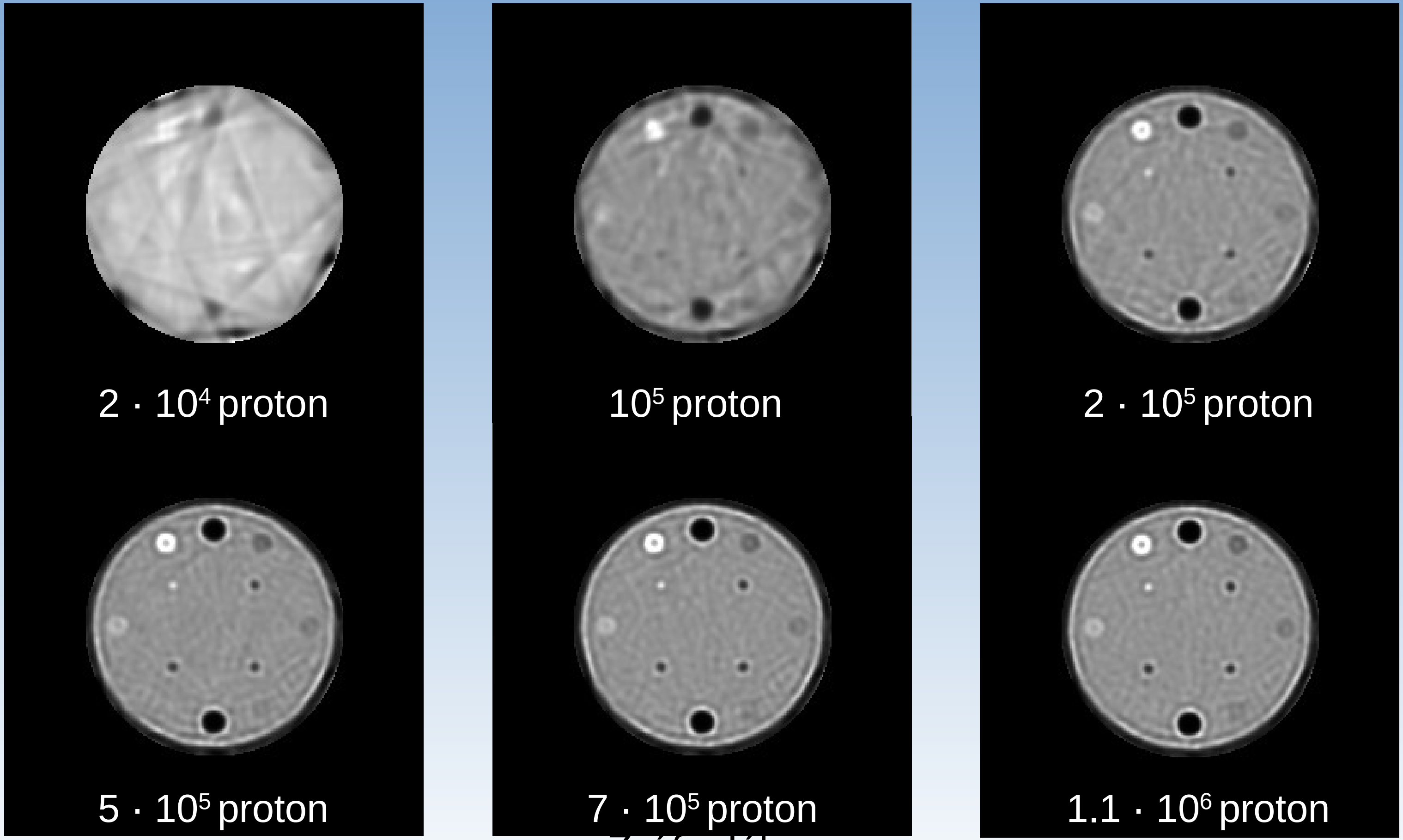


"Realistic" case

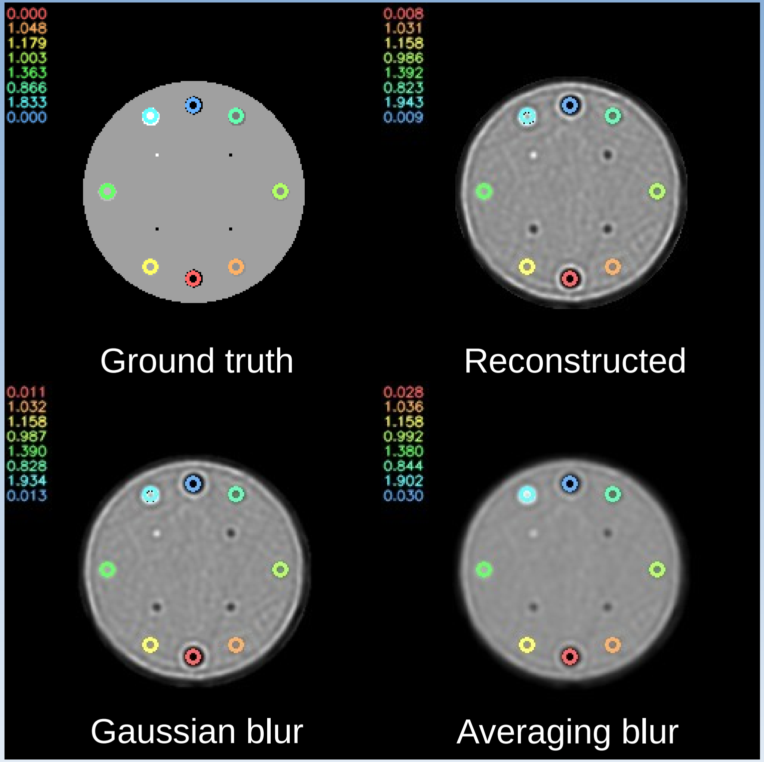


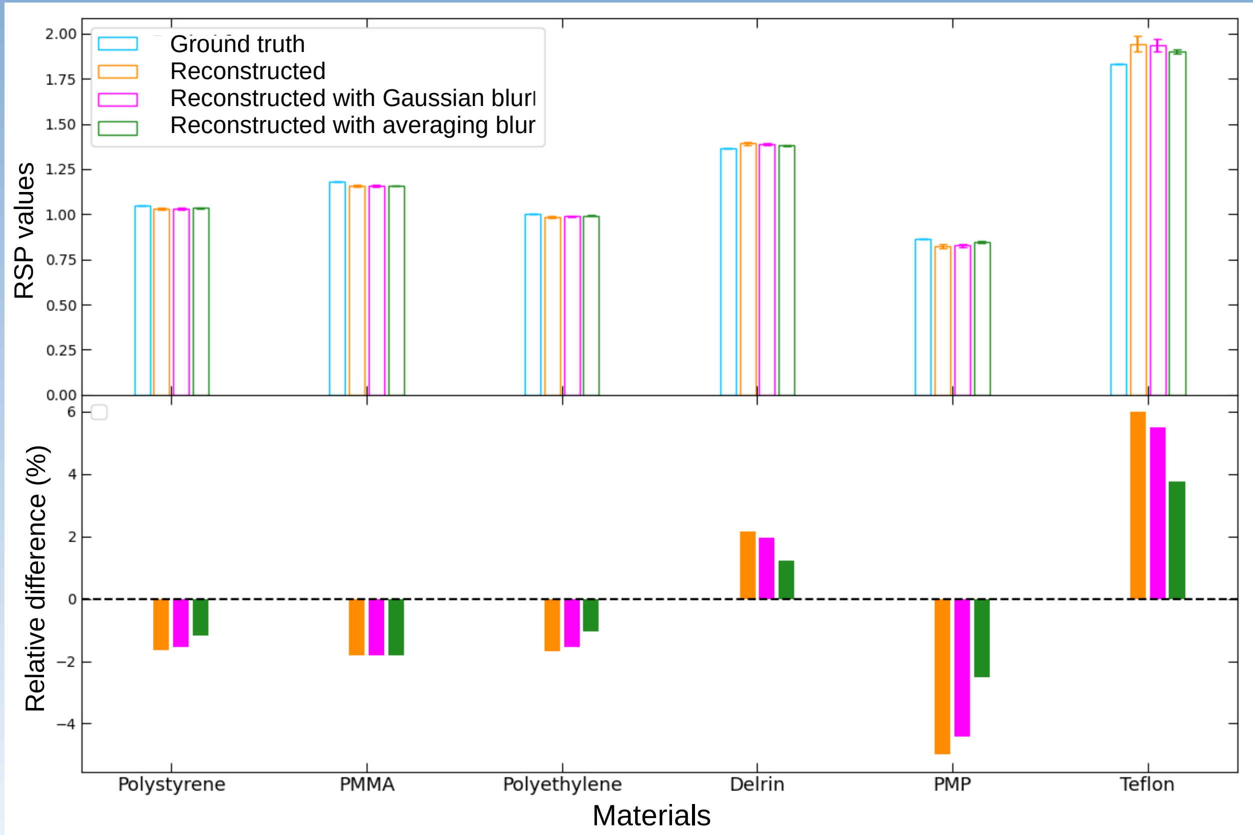
"Ideal" case
(no added error in energy)

RSP reconstruction accuracy with CTP404 phantom

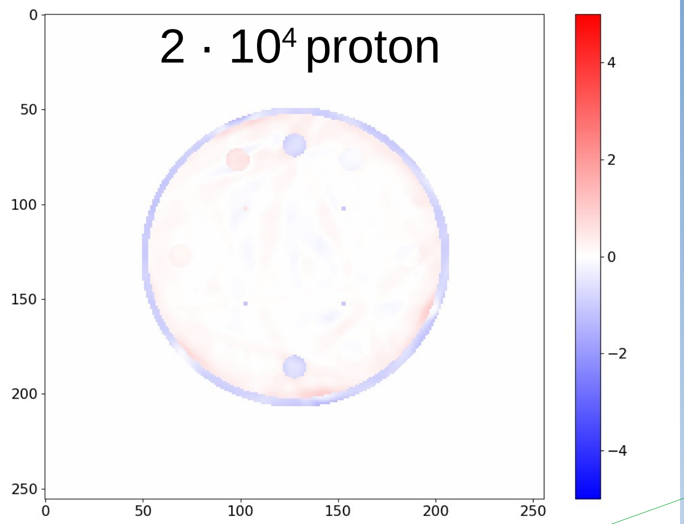


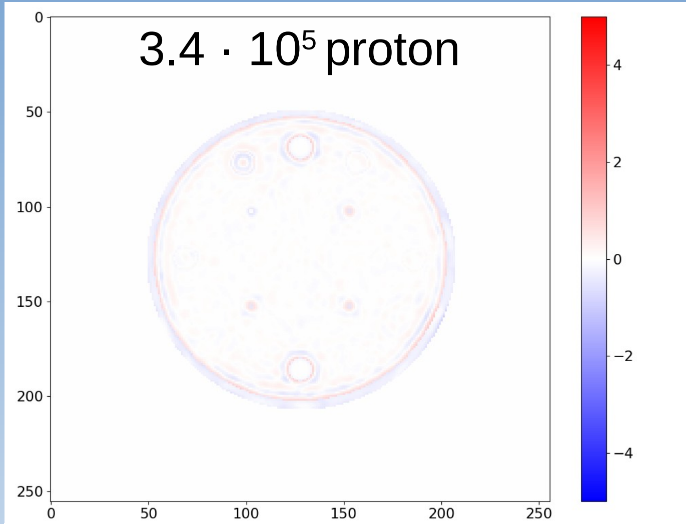
RSP reconstruction accuracy with CTP404 phantom



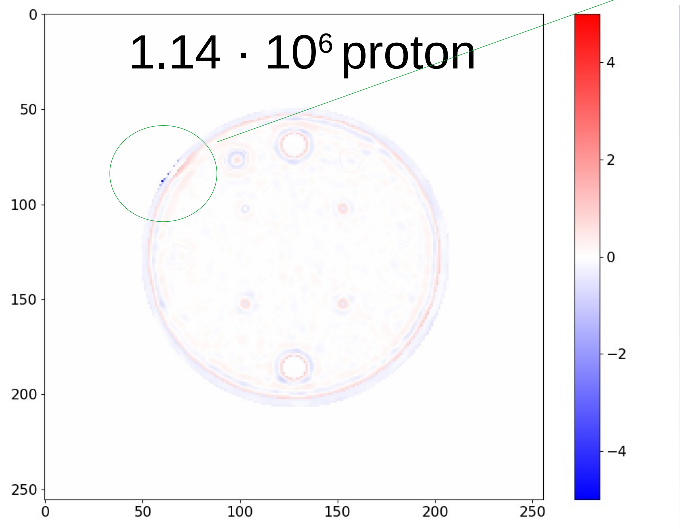


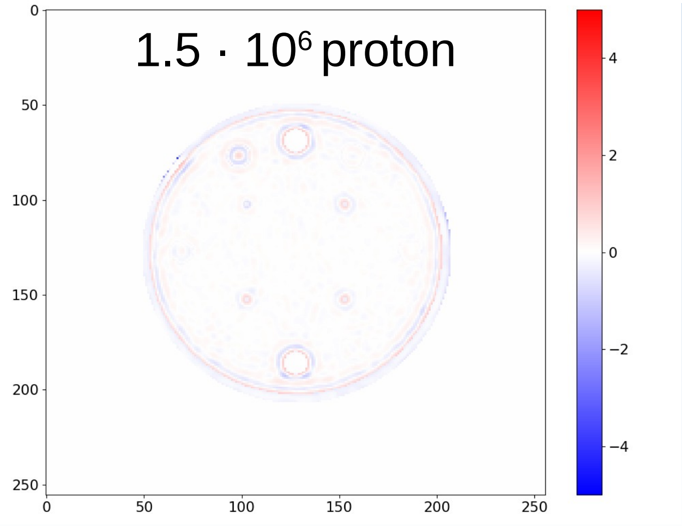
Differences between the RSP values





Some outlier pixels

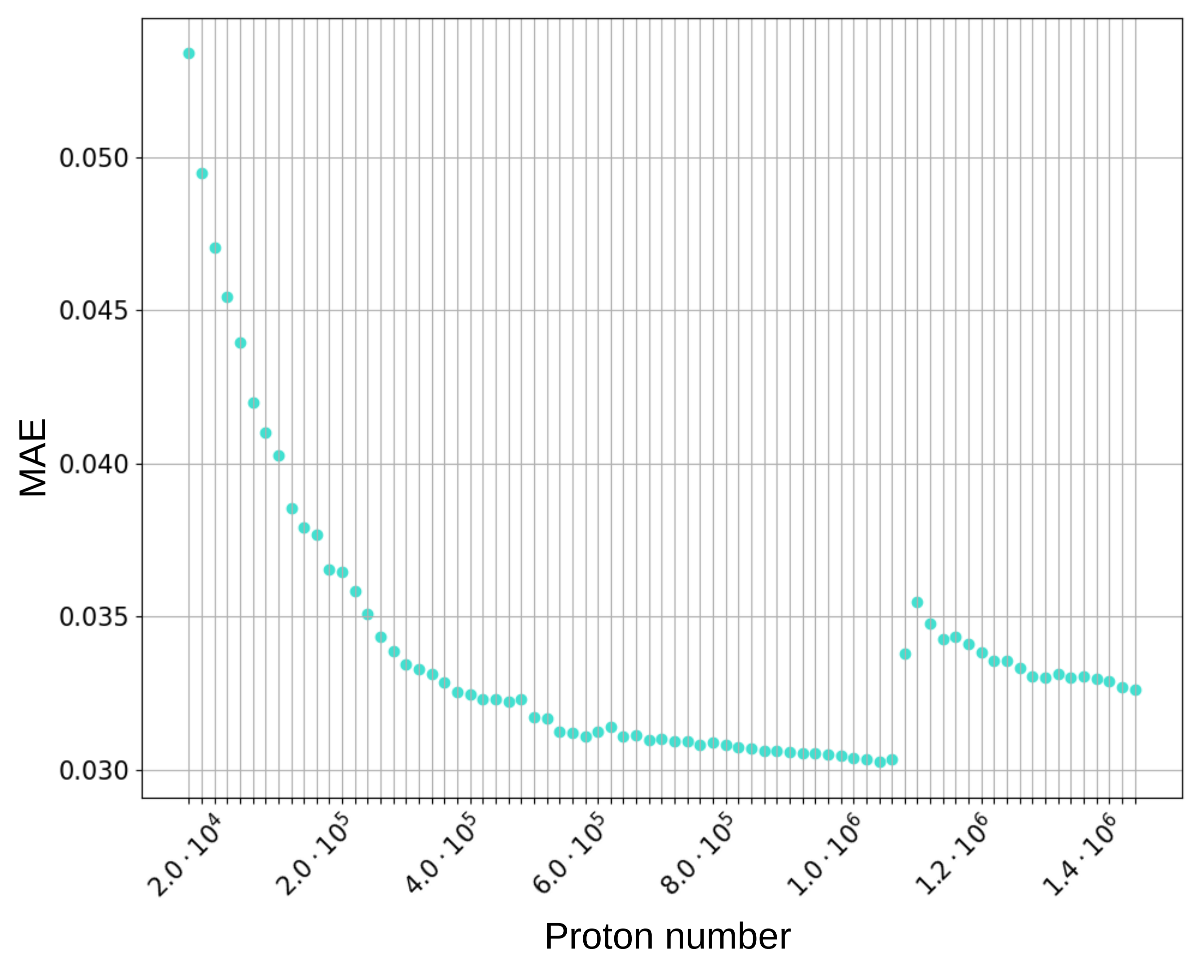




Mean Absolute Error

Mean Absolute Error: the average absolute difference between corresponding pixels

$$MAE = \frac{1}{mn} \sum_{i=1}^{m} \sum_{j=1}^{n} |\mathrm{im1}(i,j) - \mathrm{im2}(i,j)|$$



Comparison to other results in the literature

MTF10% values

	Ideal	Reference - ideal	Realistic	Reference - realistic
MTF10% [lp/cm]	0.9-1.7	2.6-3.7	0.9-1.7	2.4-3.0

Sølie et al., 2020

RSP reconstruction accuracy

- ~1% for Wang et al., 2010, runtime is more (Bayesian interference-based proton path probability map for MLP calculation)
- ~6% for our research, runtime is less (Cubic spline fitting for MLP calculation)

Summary of achievements and future plans

- I have optimized a framework that utilises the Richardson-Lucy algorithm for pCT image reconstruction
- Tested the framework on two phantoms
- TDK Thesis → 3rd place

- Algorithm needs further developments for clinical usability → MLP calculation, shorter runtime, realistic phantoms, etc.
- MSc Thesis

Thank you for your attention!

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