Image reconstruction in proton computed tomography

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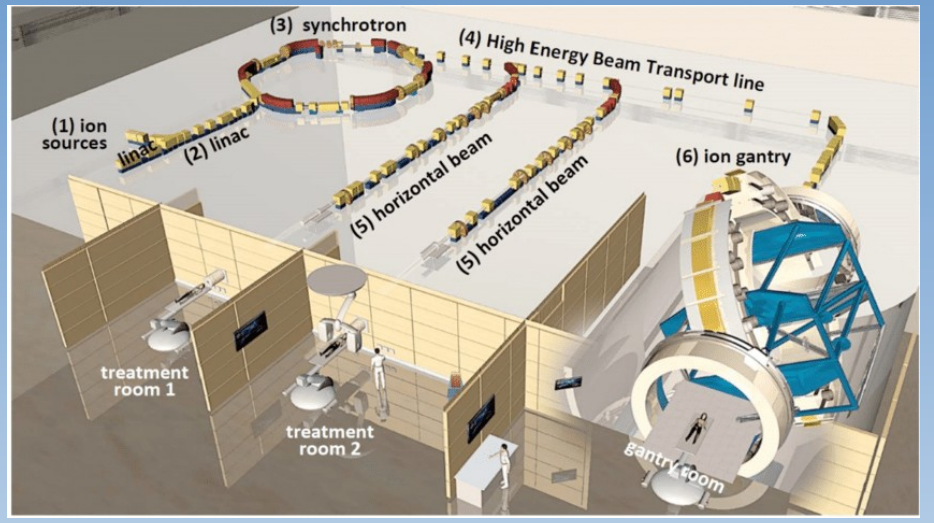
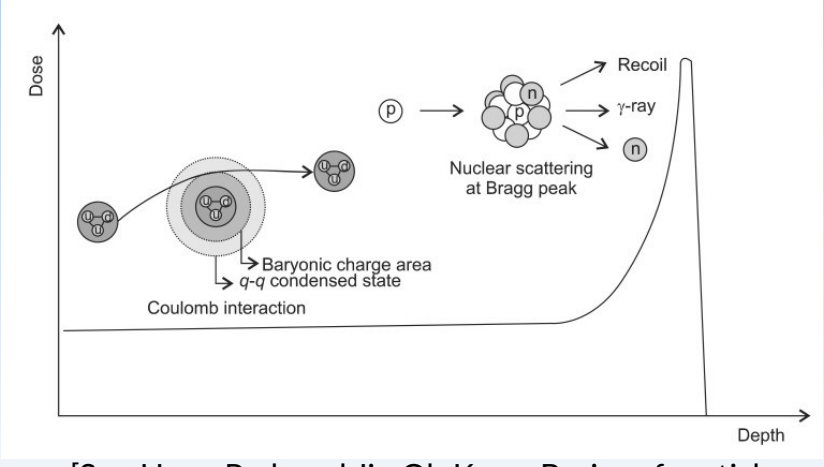
Motivation

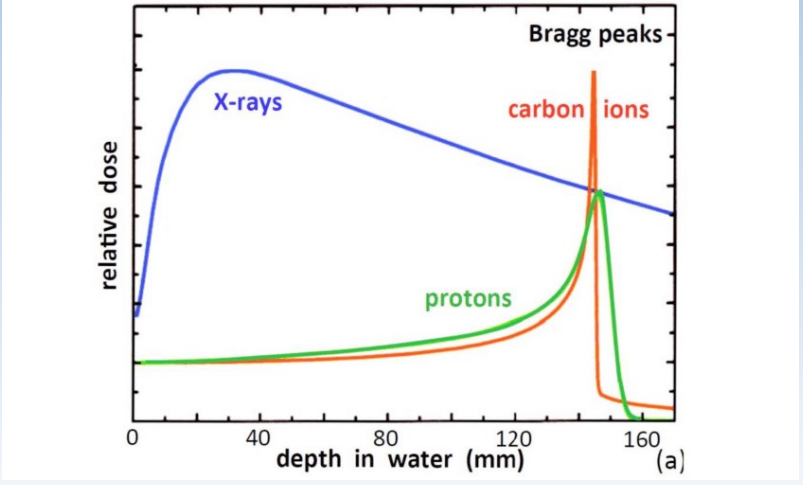
- Cancer treatment: surgery, chemotherapy, radiotherapy, immunotherapy
- Radiotherapy: uses ionizing particles
- What kind of particles?
  - Photons
  - Protons
  - Heavy ions



Layout figure of HIT Centre (Heidelberg)

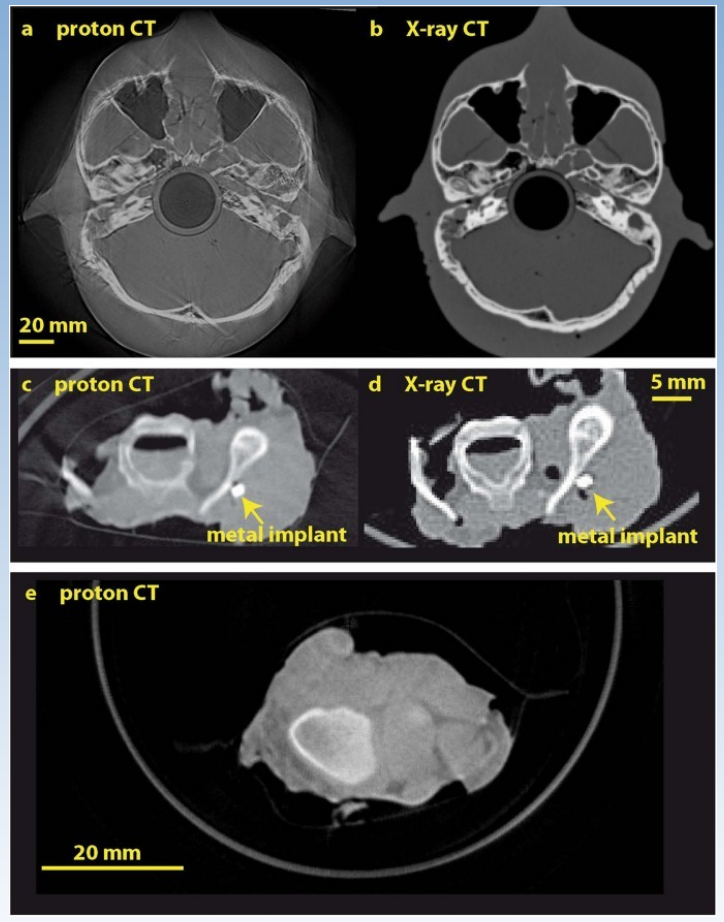


[Seo Hyun Park and Jin Oh Kang. Basics of particle therapy i: physics. Radiation oncology Journal, 29(3):135, 2011.]



[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

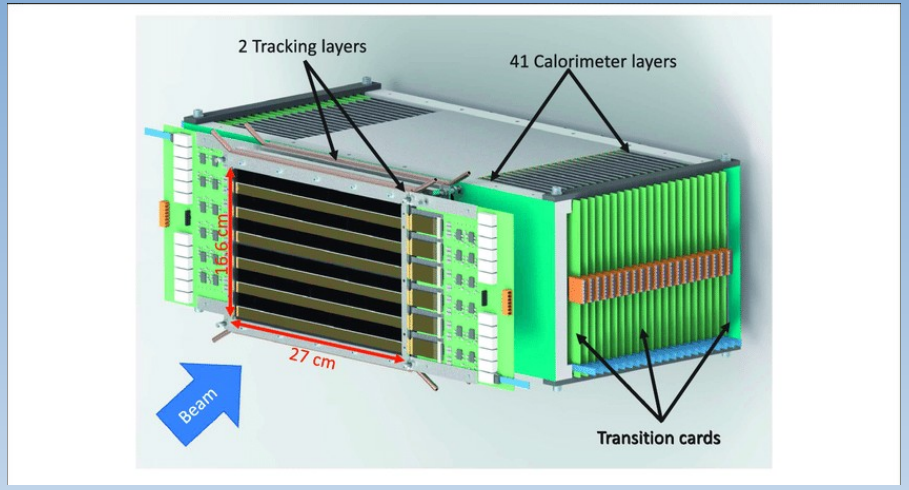


X-ray CT vs. proton CT

- 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

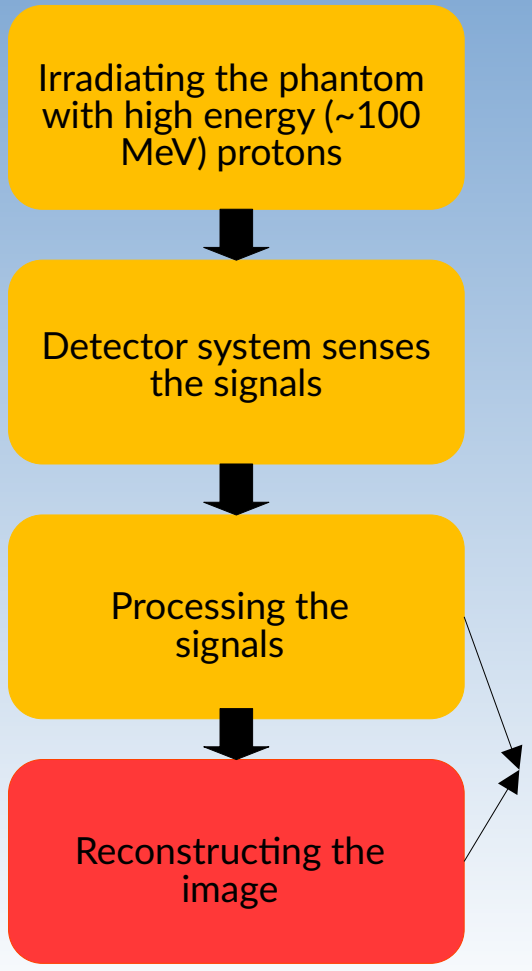
*The quantitative scale of X-ray absorption

The Bergen pCT Collaboration



The Bergen pCT

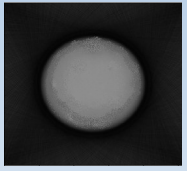
- Based at the University of Bergen
- Goal: to build a proton CT based on the high-energy particle detectors used in the CERN ALICE collaboration (technology transfer)



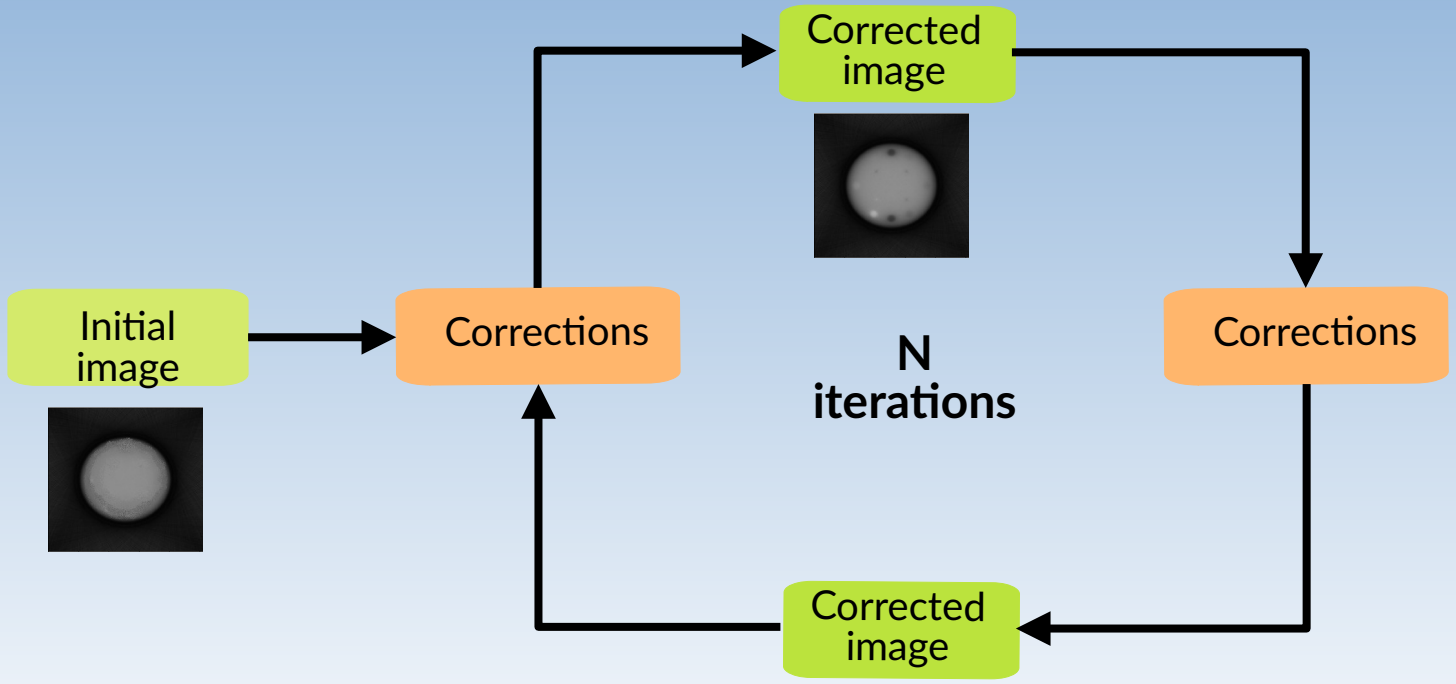
Computation time plays a huge role → we have to find the compromise between speed and quality

Iterative methods for image reconstruction

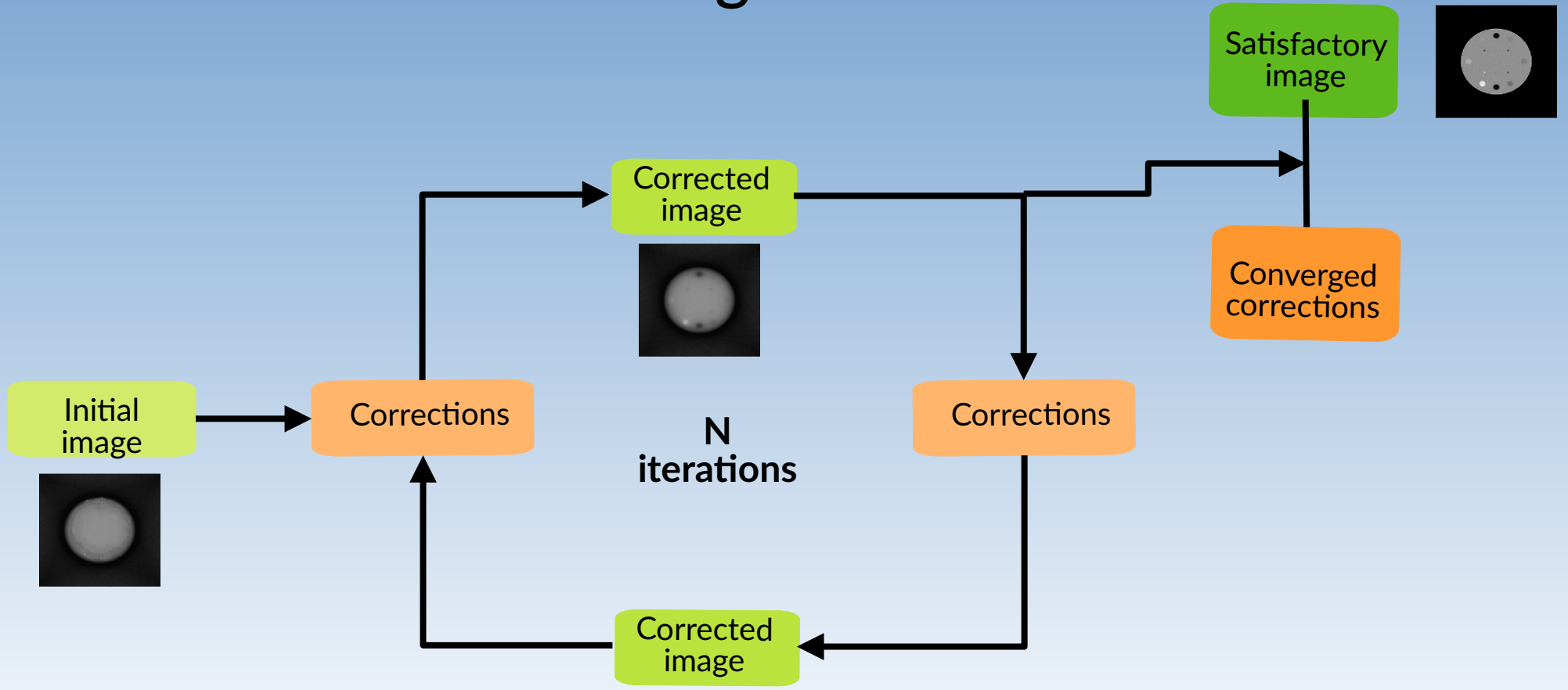
Initial image



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

Very difficult technically (~millions of proton trajectories)

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

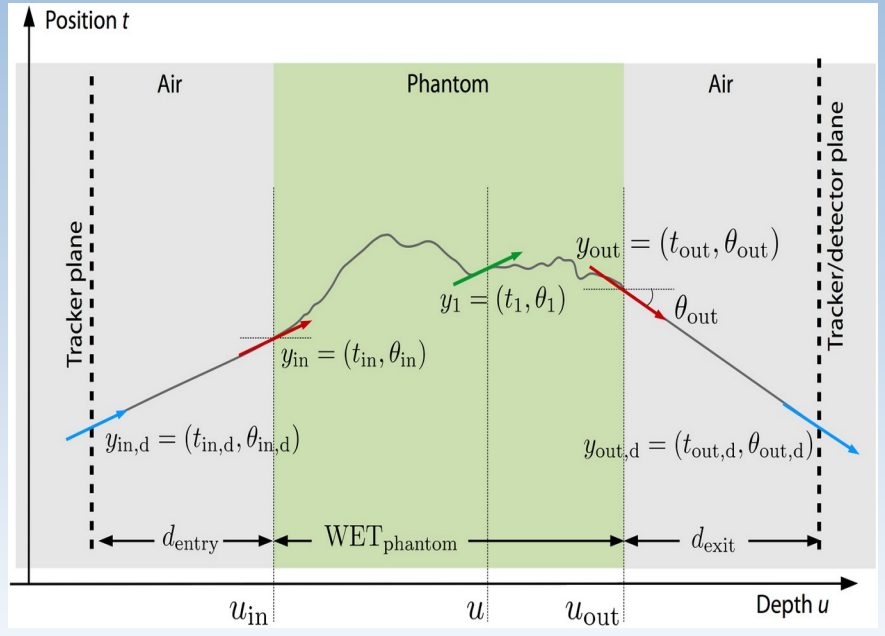
Number of iterations

Vector containing WEPL values

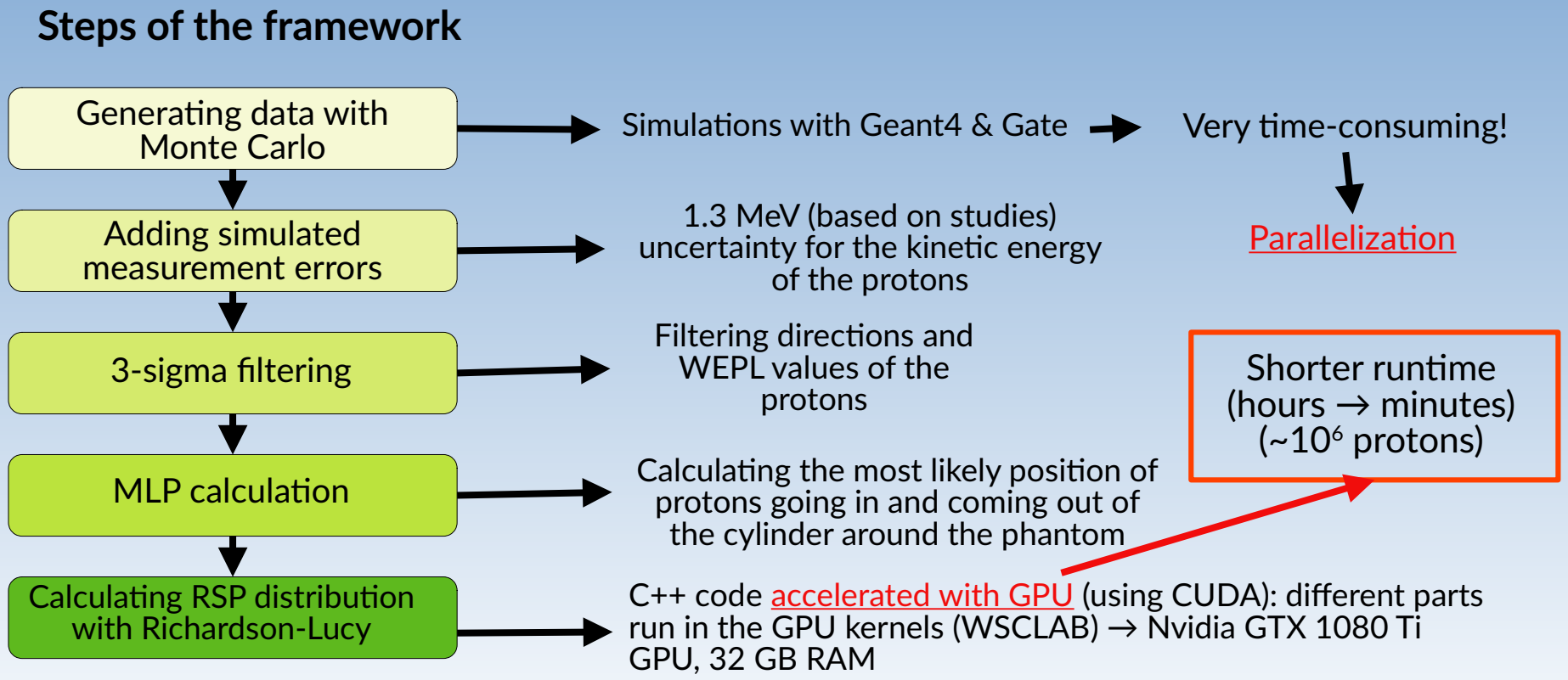
Matrix containing interaction coefficients between proton trajectories and voxels

Vector containing RSP values

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



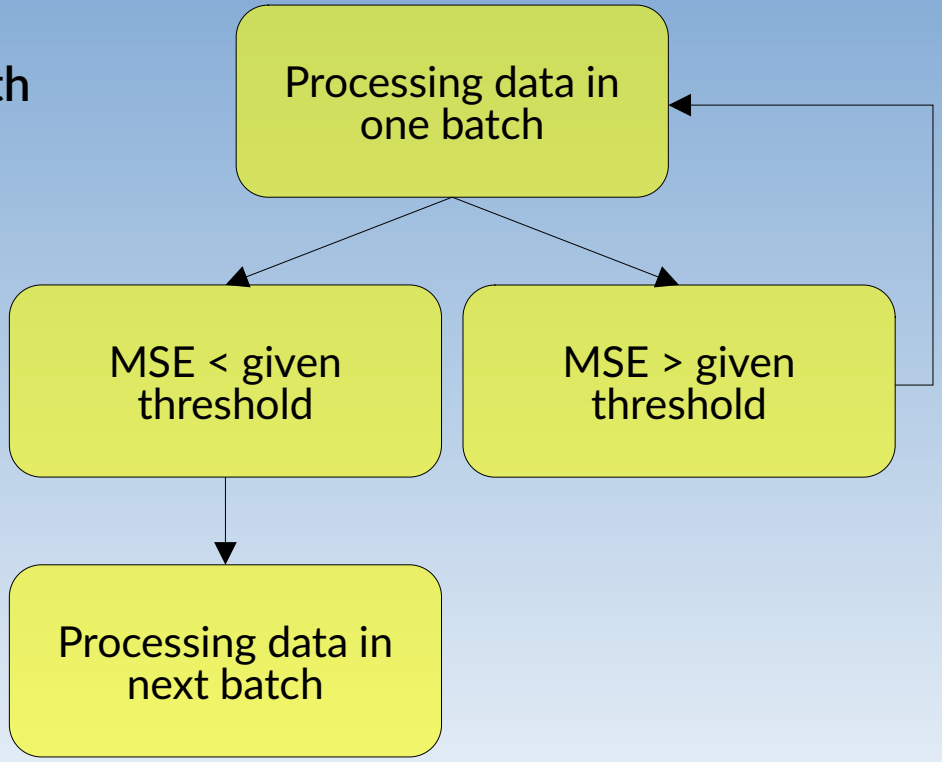
Development of the framework



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

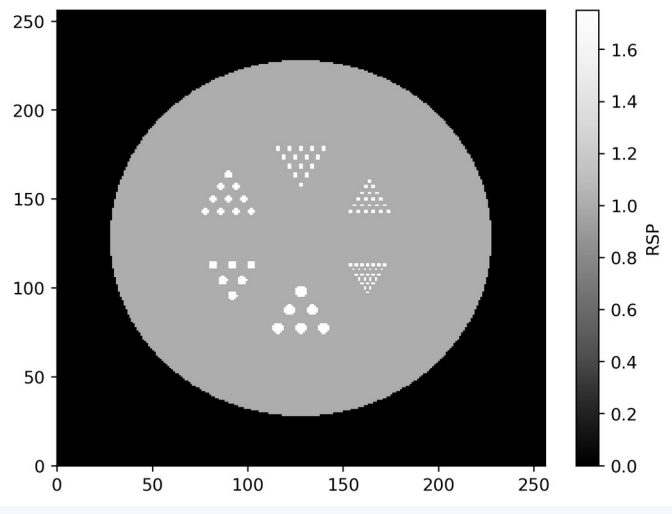


Significant speed-up in runtime

Evaluating the algorithm - phantoms

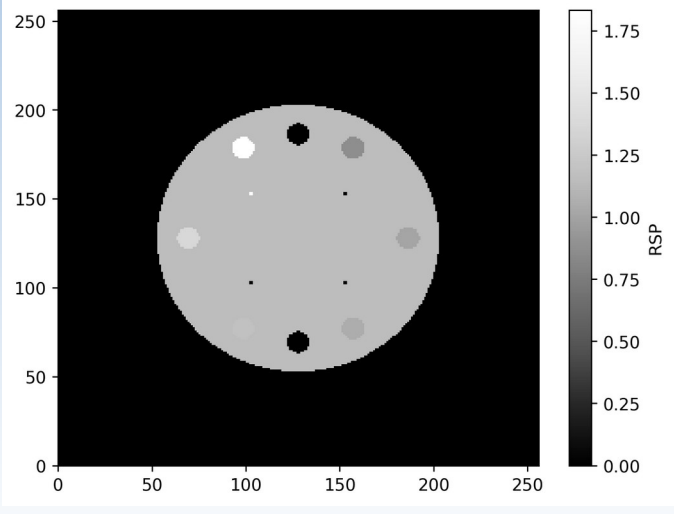
Derenzo phantom

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

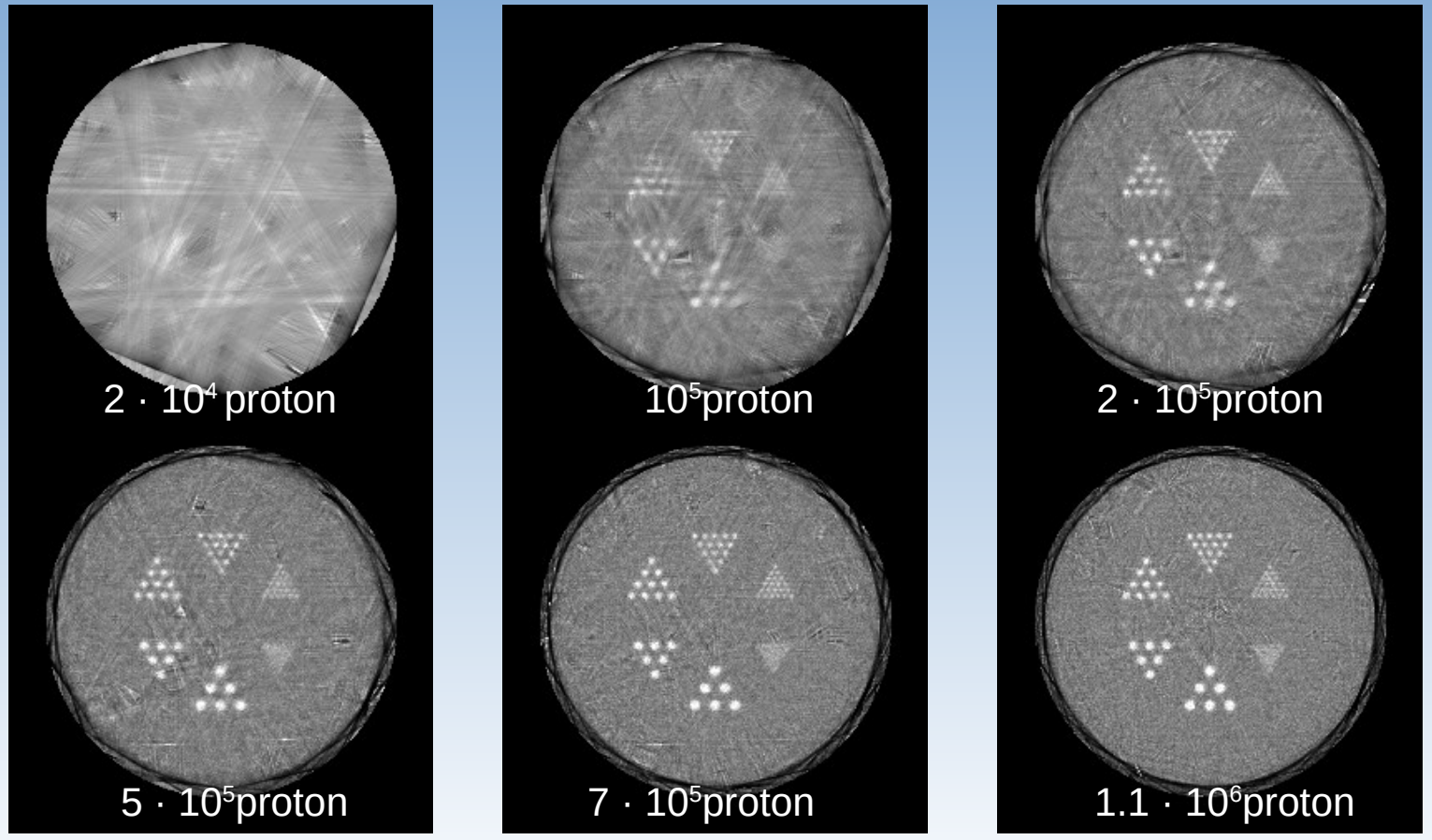


CTP404 phantom

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

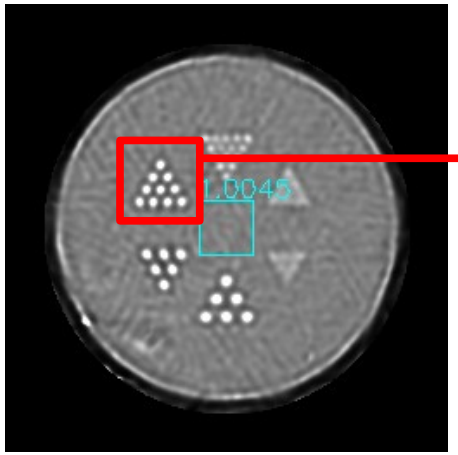


Spatial resolution with Derenzo phantom



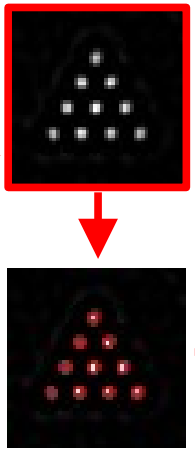
Spatial resolution with Derenzo phantom

(i)



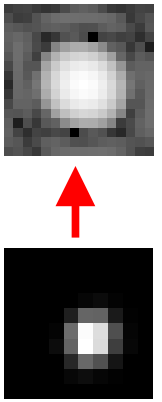
Subtract the mean background

(ii)



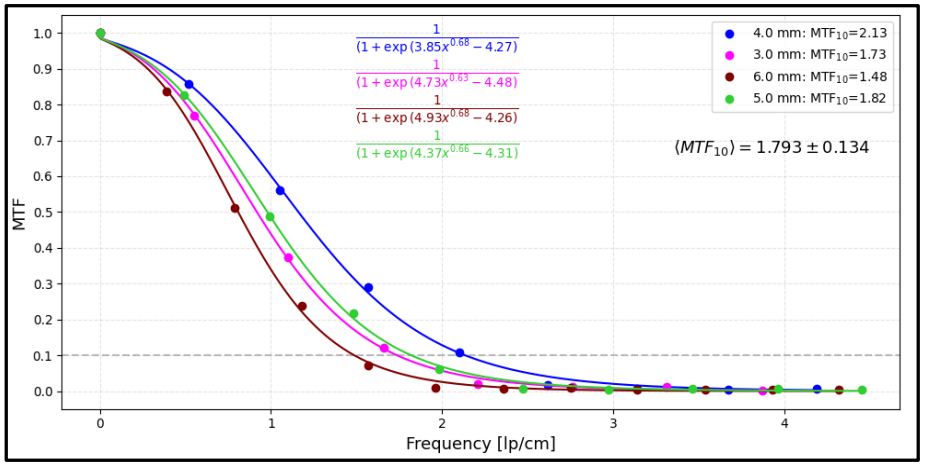
Find individual rods from each sector

(iii)



Average them → Point Spread Function

(iv)-(v)

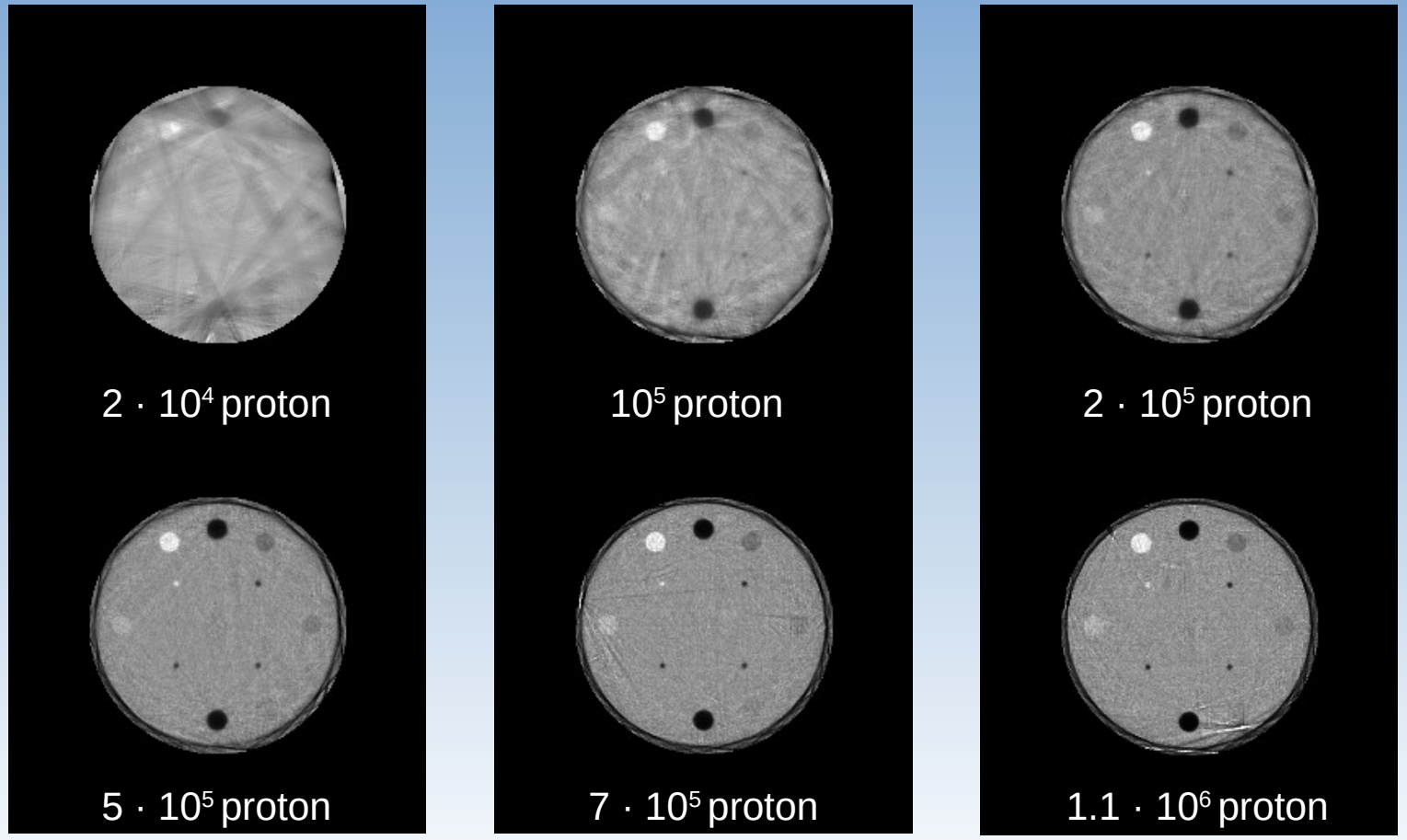


- 2D Fourier transform PSF → Modulation Transfer Function (MTF)
- MTF10% averaged for the sections represents spatial resolution

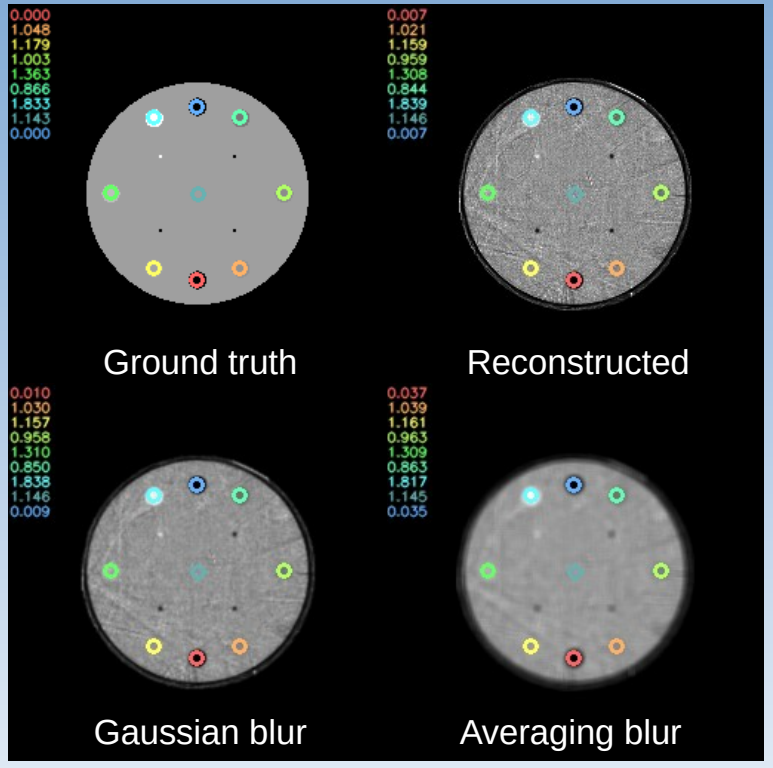
	Ideal	Reference - ideal	Realistic	Reference - realistic
MTF10% [lp/cm]	1.43	2.6-3.7	1.17	2.4-3.0

Sølie et al., 2020

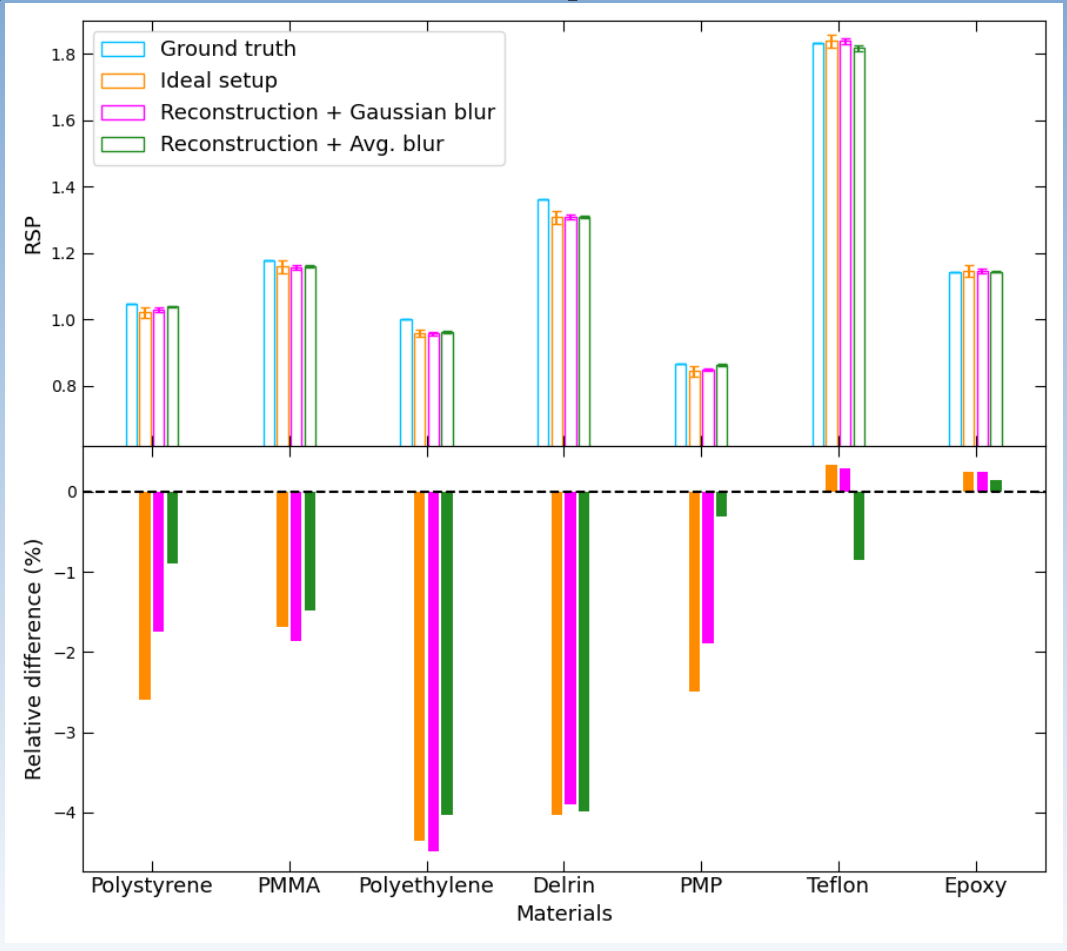
RSP reconstruction accuracy with CTP404 phantom



RSP reconstruction accuracy with CTP404 phantom



Comparing ground truth RSP values with reconstructed RSP values



- ~1% for Wang et al., 2010, runtime is more (Bayesian interference-based proton path probability map for MLP calculation)
- ~-4% for our research, runtime is less (Cubic spline fitting for MLP calculation)

Summary of achievements and future plans

- Richardson-Lucy algorithm used for the first time in medical imaging*
- Promising results, comparable with other used algorithms
- But still needs further developments for clinical usability → Using Machine Learning for noise filtering, MLP calculation, realistic phantoms, etc.; achieving shorter runtime

*Gábor Bíró, Ákos Sudár, Zsófia Jólesz, Gábor Papp, Gergely Gábor Barnaföldi. Proton Computed Tomography Based on Richardson-Lucy Algorithm. ArXiv:2212.00126.

Thank you for your attention!

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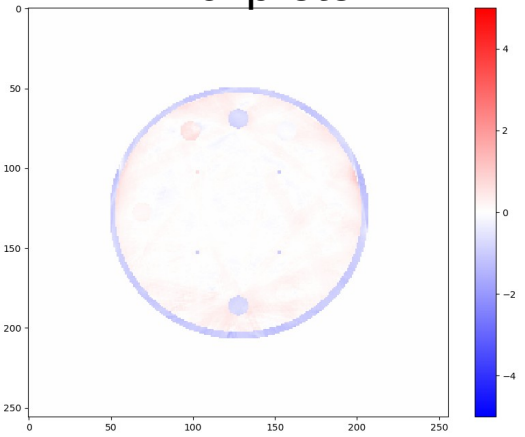
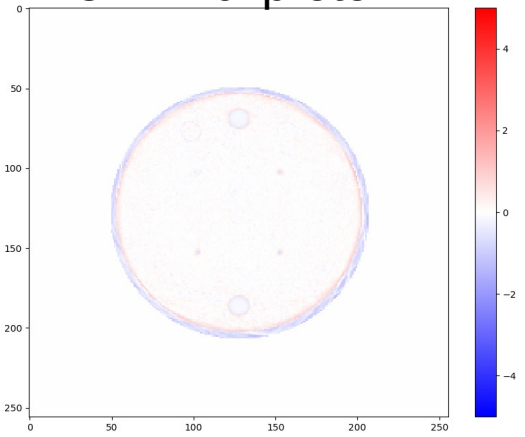
Backup - Differences between the RSP values

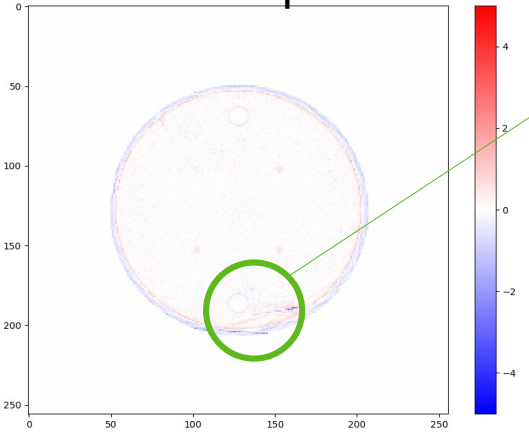
$2 \cdot 10^4$ proton



$3.4 \cdot 10^5$ proton

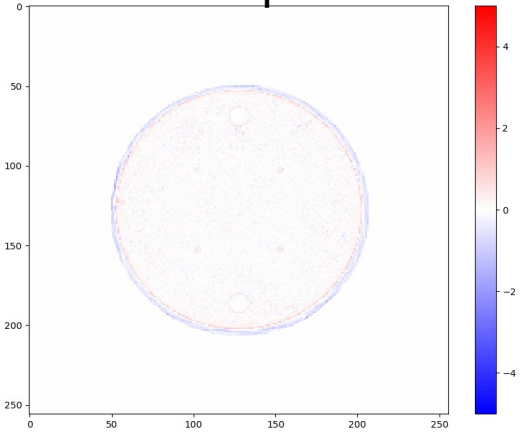


$1.14 \cdot 10^6$ proton



Some outlier pixels

$1.5 \cdot 10^6$ proton



Backup - Mean Absolute Error

Mean Absolute Error: the average absolute difference between corresponding pixels

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