Image reconstruction in proton computed tomography

SciComp Conference - Szeged
17-19 10 2024
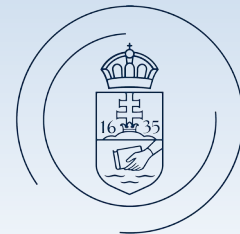
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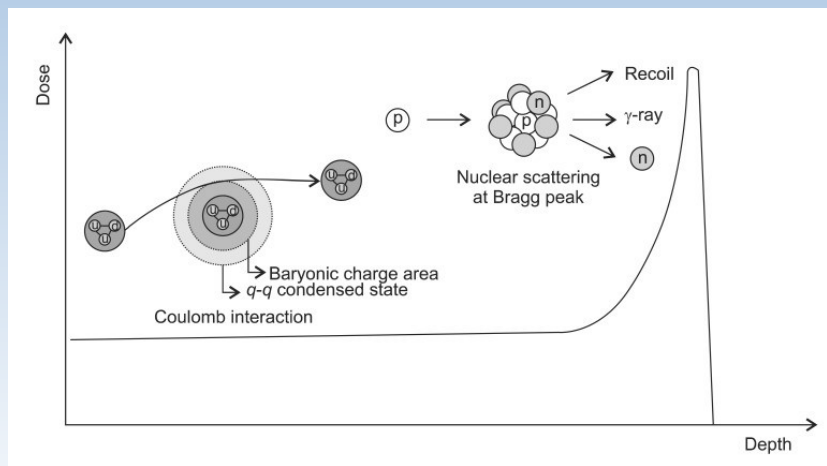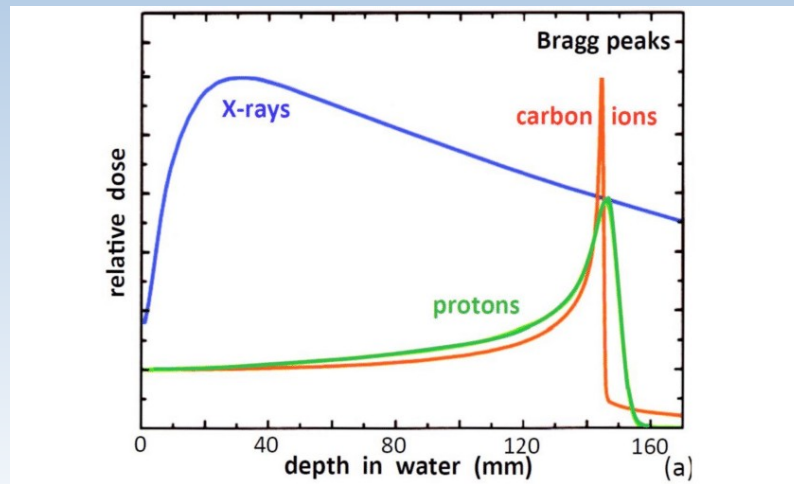
Motivation

- Cancer treatment: surgery, chemotherapy, <u>radiotherapy</u>, immunotherapy
- Radiotherapy: uses ionizing particles
- What kind of particles?
  - → Photons
  - → <u>Protons</u>
  - → Heavy ions
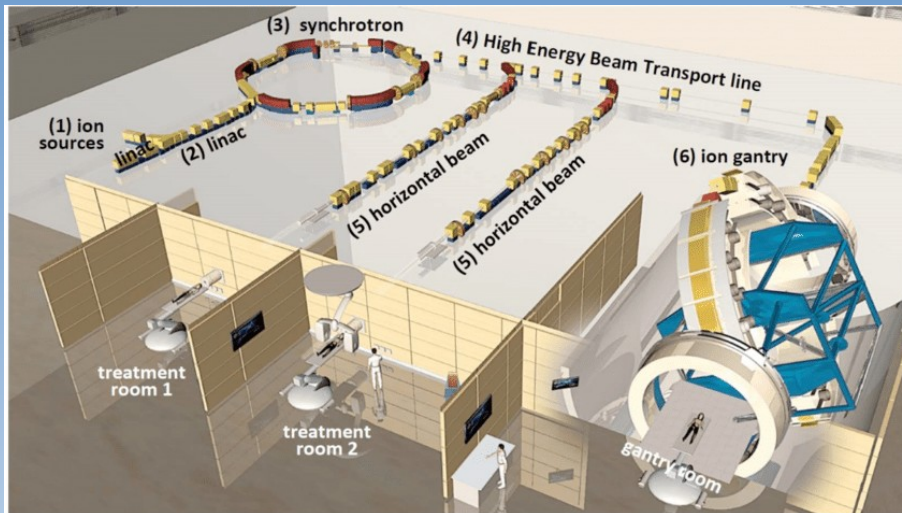
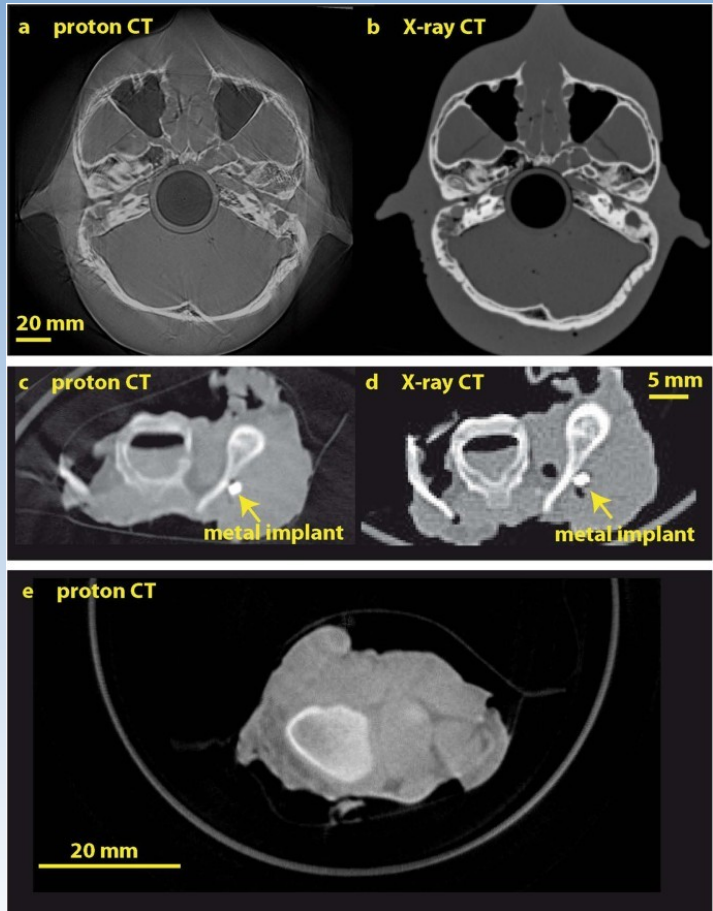Layout figure of HIT Centre (Heidelberg)

[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.]

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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
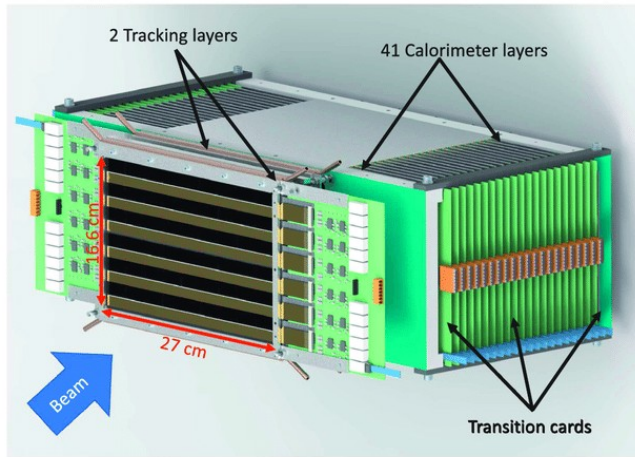
The Bergen pCT

- 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)

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

↓
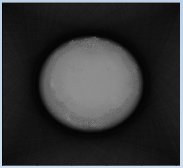
Detector system senses the signals

↓

Processing the signals

↓

Reconstructing the image
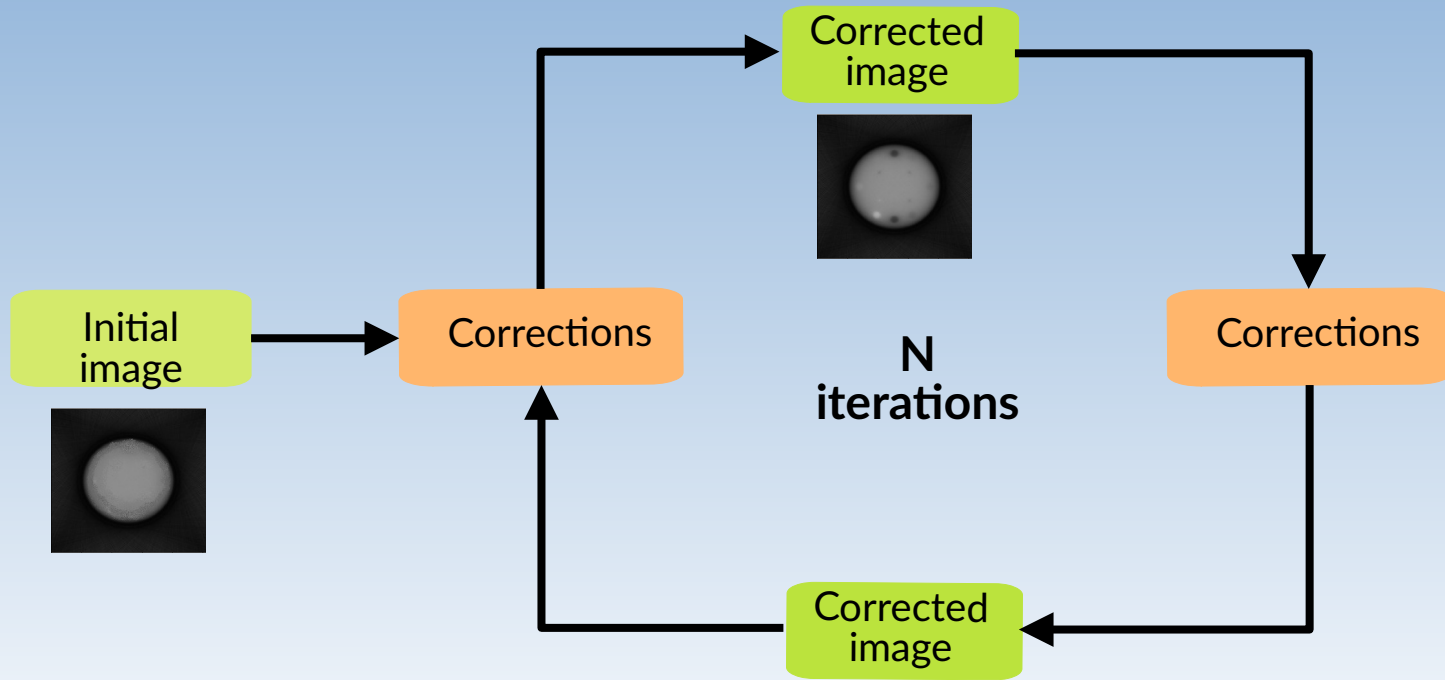
Computation time plays a huge role → we have to find the compromise between speed and quality
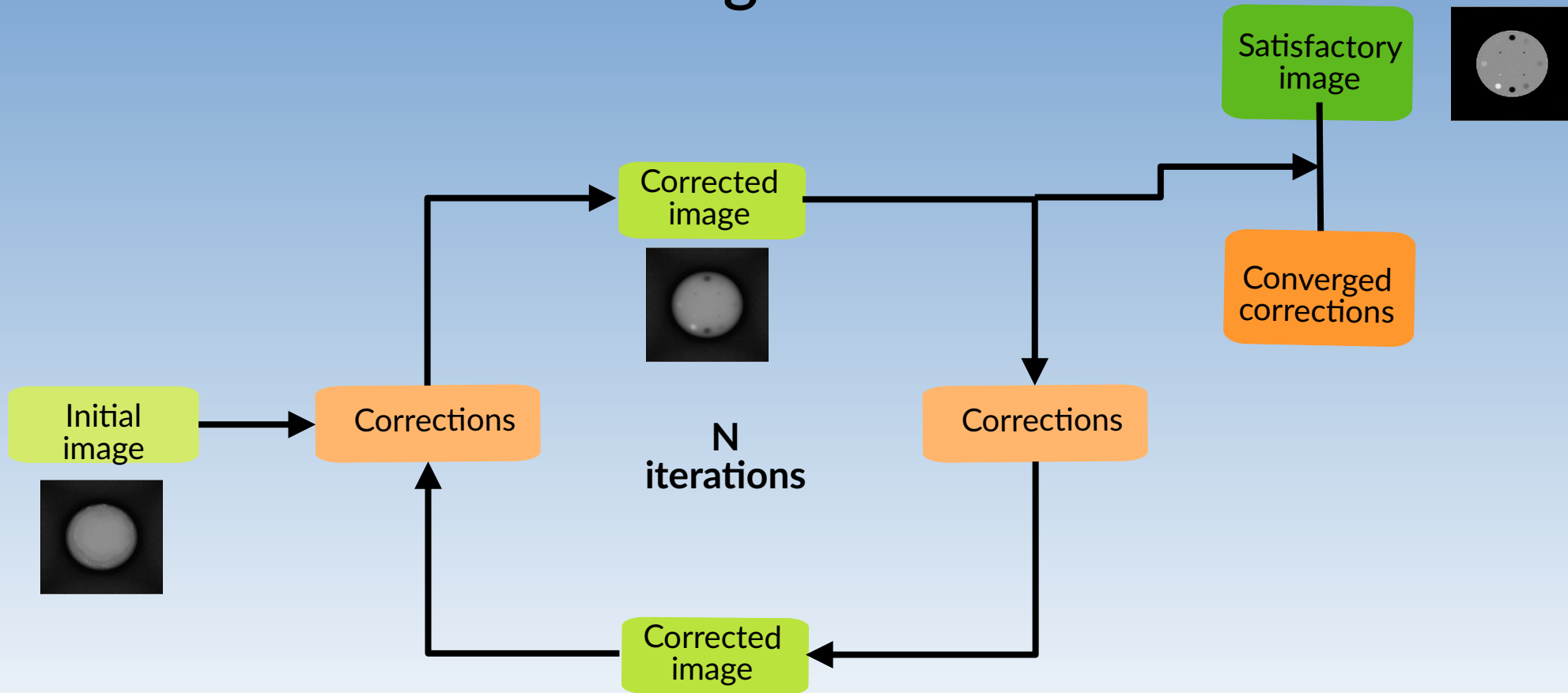
Iterative methods for image reconstruction

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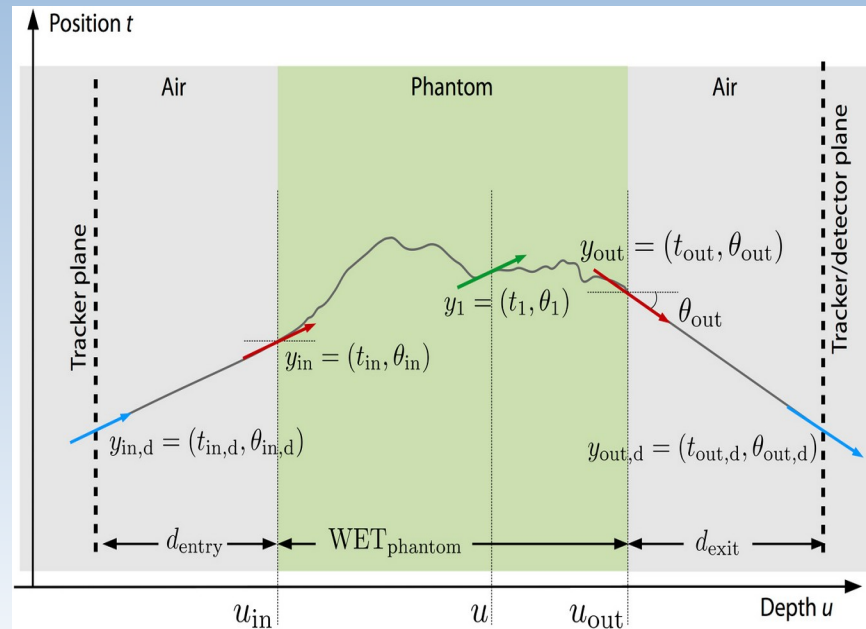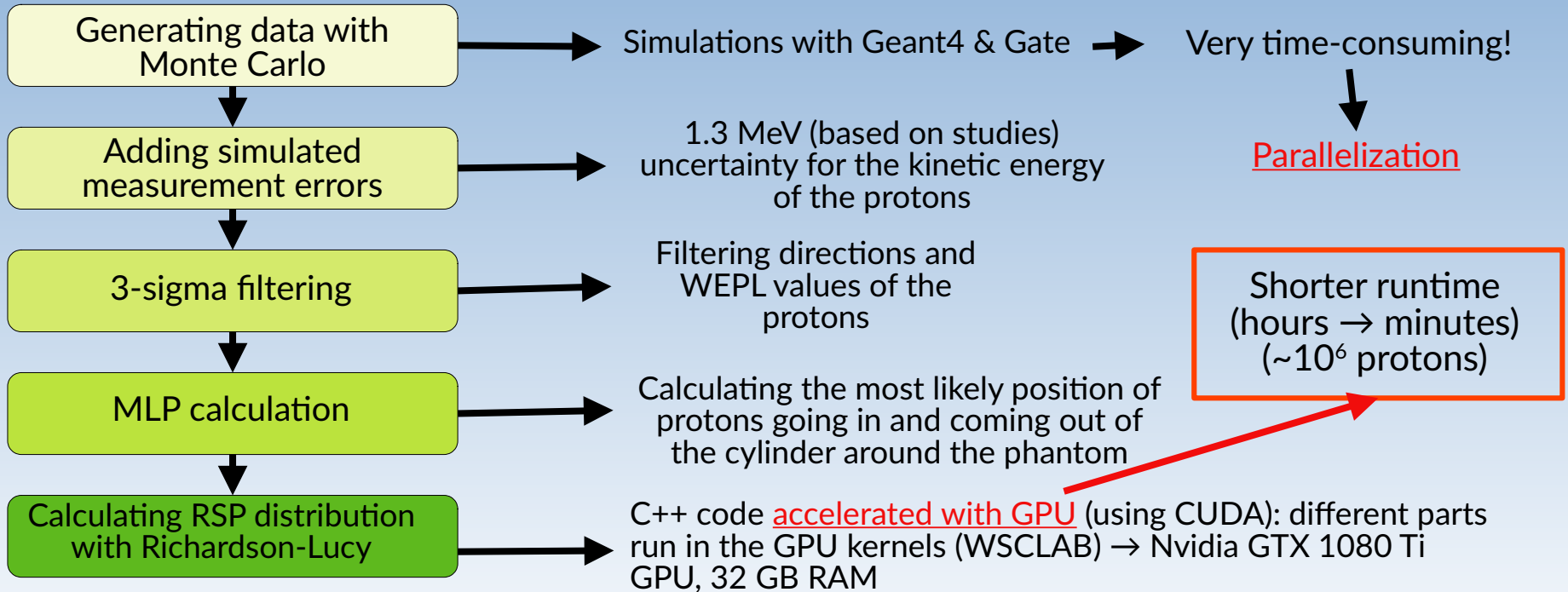
$$x_i^{k+1} = x_i^k \frac{1}{\sum_j A_{i,j}} \sum_j \frac{y_j}{\sum_l A_{l,j} x_l^k} A_{i,j}$$

Vector containing RSP values

Development of the framework

Steps of the framework

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

Parallelization

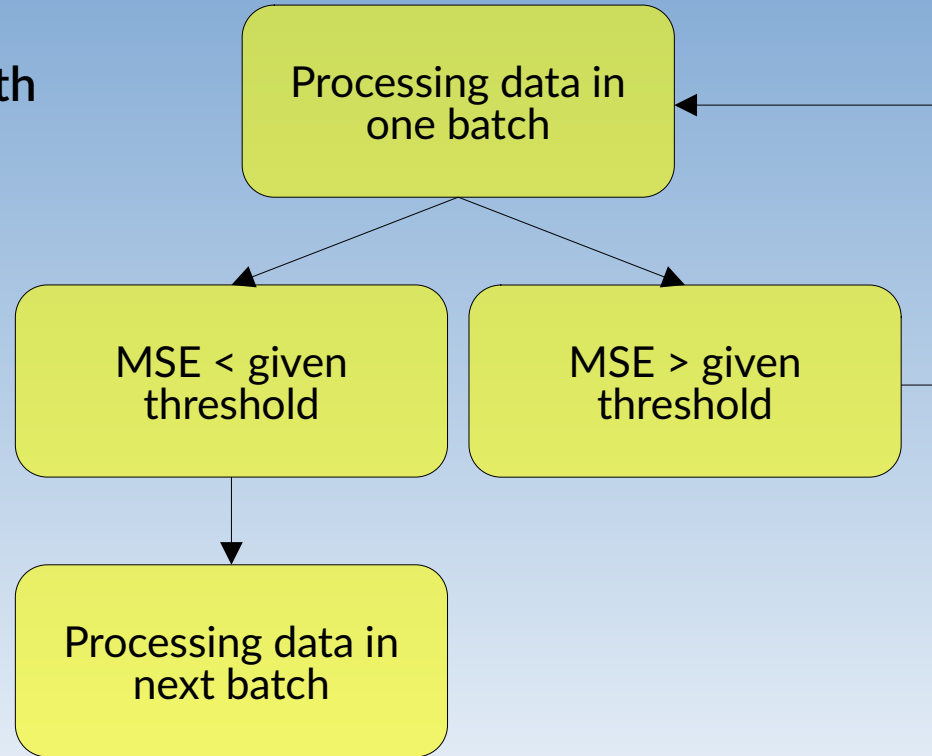Shorter runtime (hours → minutes) (~10^6 protons)

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
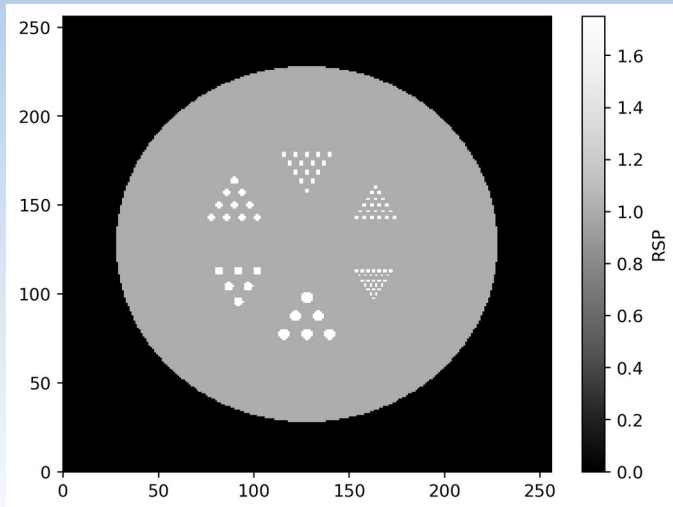
Significant speed-up in runtime

```
Processing data in
one batch
       |
   ┌───┴───┐
MSE < given   MSE > given
threshold     threshold
   |
Processing data in
next batch
```
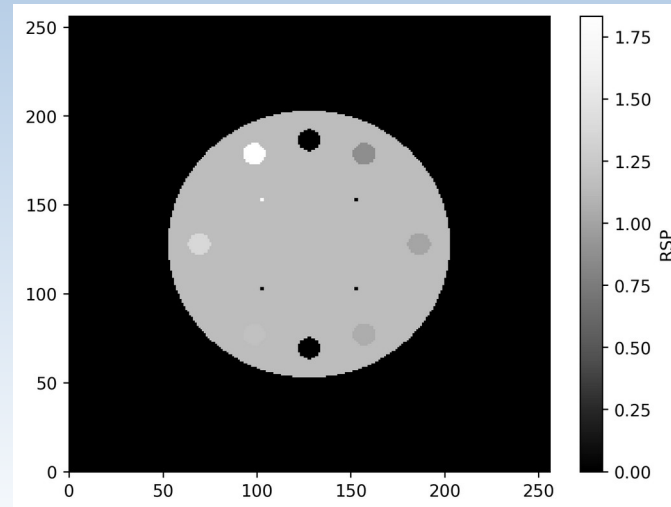
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Evaluating the algorithm - phantoms

Derenzo phantom

- 200 mm diameter water cylinder with 6 sectors of 1.5-6 mm diameter aluminium rods
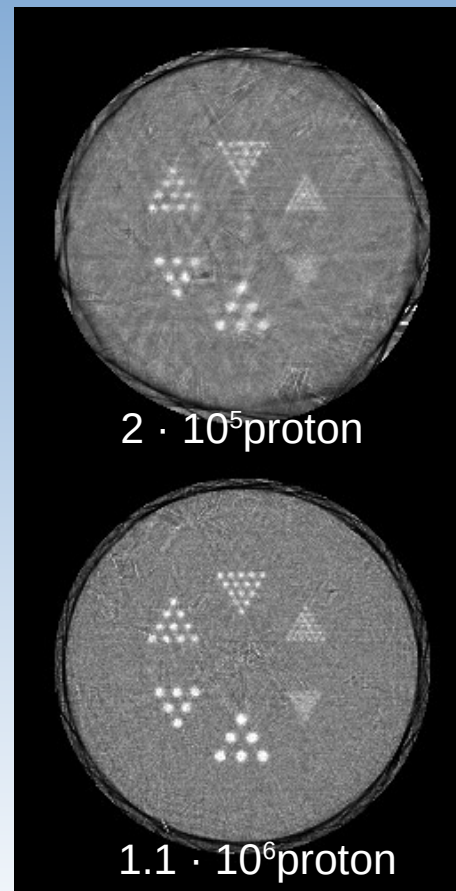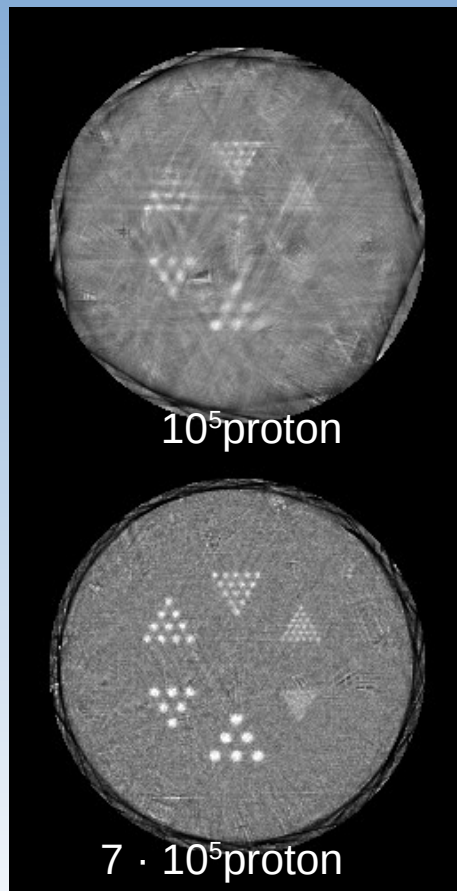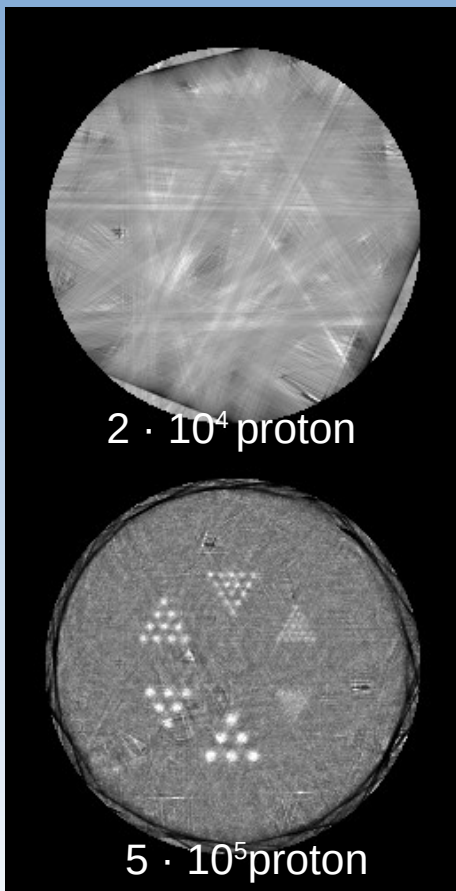- Used for measuring spatial resolution
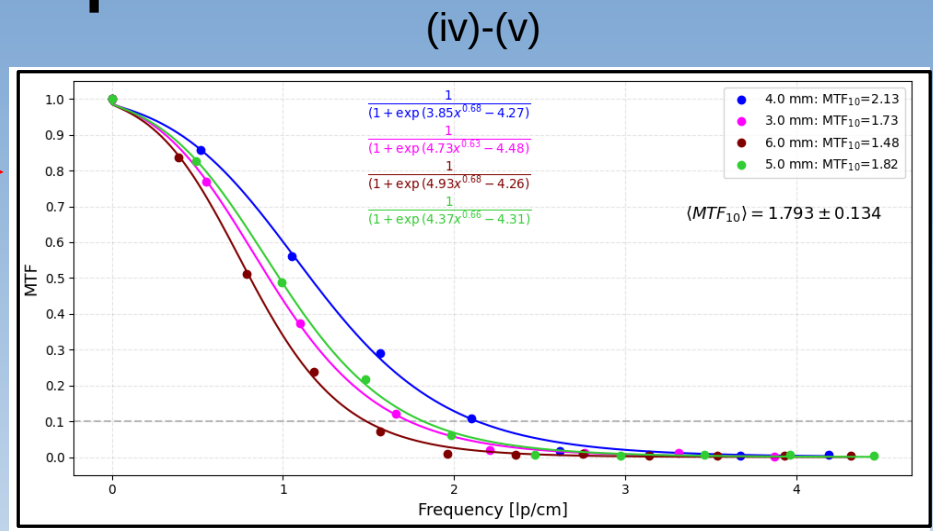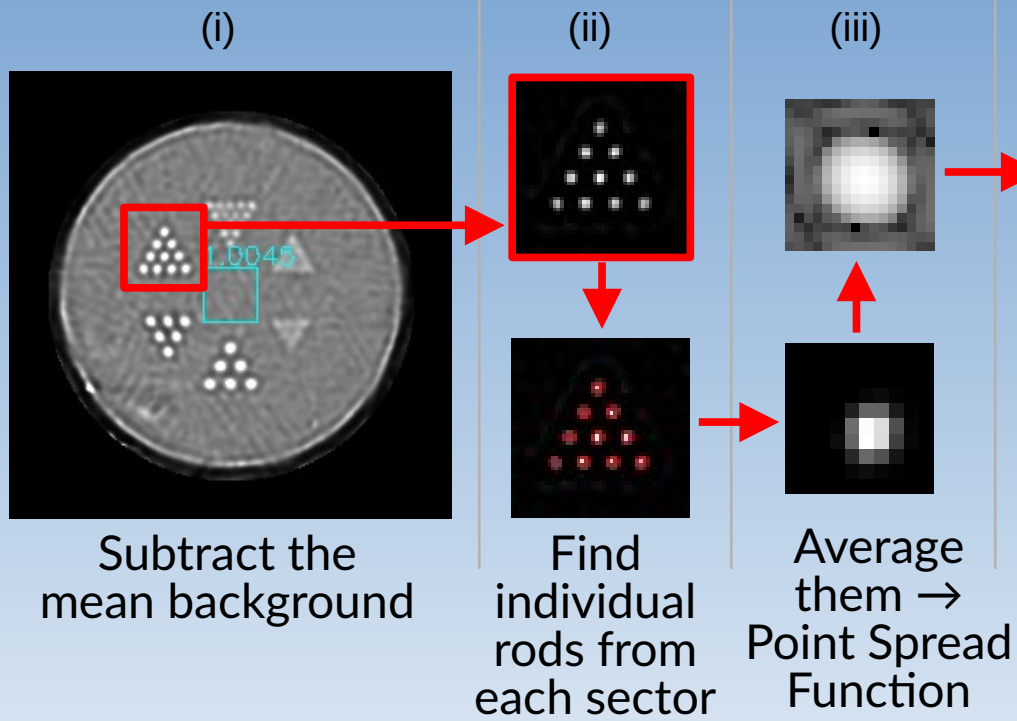
CTP404 phantom

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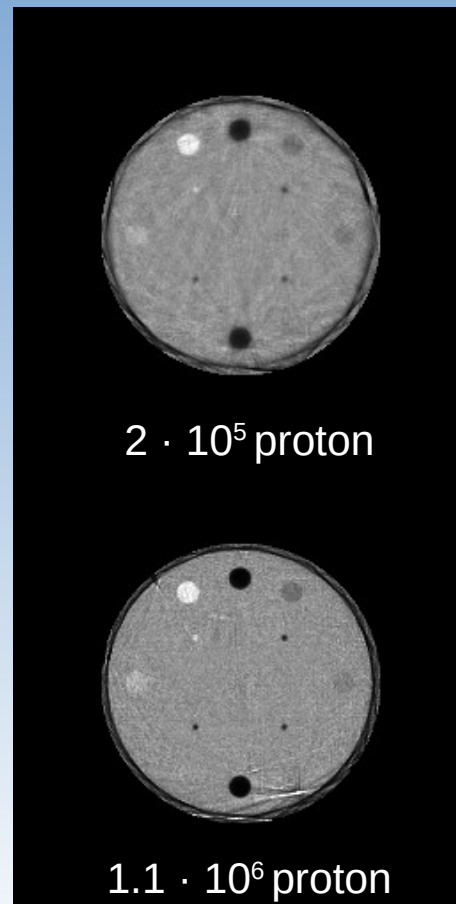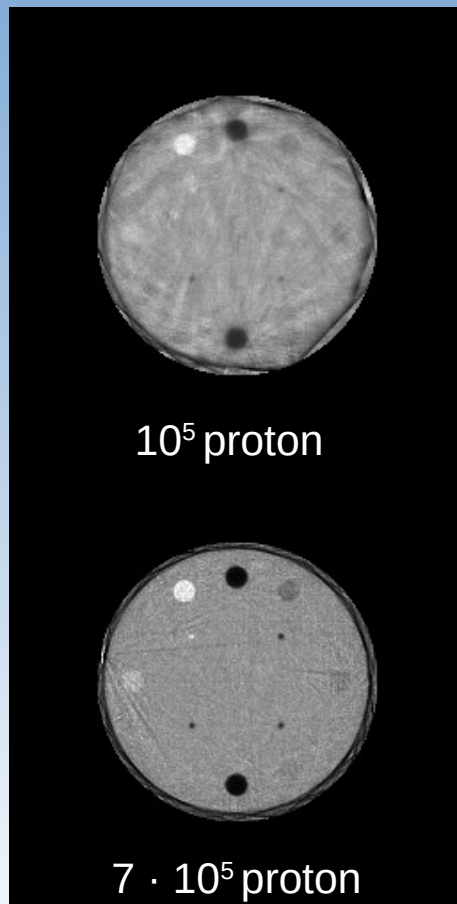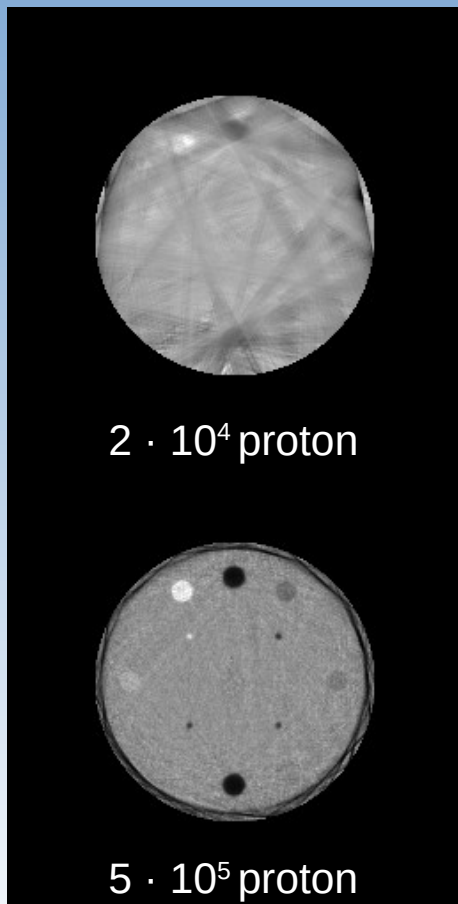
Spatial resolution with Derenzo phantom

$2 \cdot 10^4$ proton

10^5 proton

$2 \cdot 10^5$ proton

$5 \cdot 10^5$ proton

$7 \cdot 10^5$ proton

$1.1 \cdot 10^6$ proton

Spatial resolution with Derenzo phantom

(i)   (ii)   (iii)   (iv)-(v)

Subtract the mean background

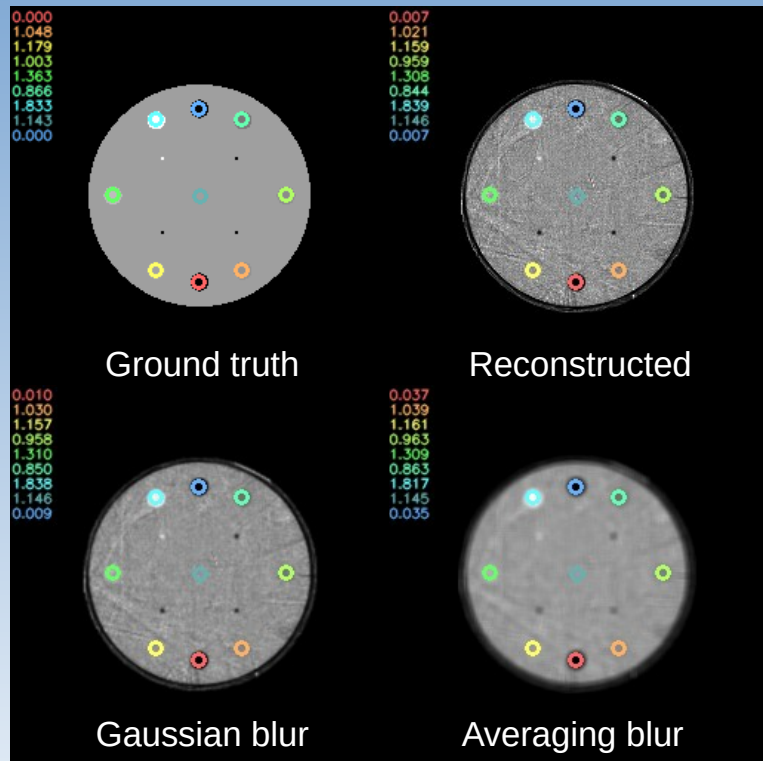Find individual rods from each sector

Average them → Point Spread Function

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

The plot legend:
- 4.0 mm: $MTF_{10}=2.13$
- 3.0 mm: $MTF_{10}=1.73$
- 6.0 mm: $MTF_{10}=1.48$
- 5.0 mm: $MTF_{10}=1.82$

$$\frac{1}{(1 + \exp(3.85x^{0.68} - 4.27)}$$
$$\frac{1}{(1 + \exp(4.73x^{0.63} - 4.48)}$$
$$\frac{1}{(1 + \exp(4.93x^{0.68} - 4.26)}$$
$$\frac{1}{(1 + \exp(4.37x^{0.66} - 4.31)}$$

$\langle MTF_{10} \rangle = 1.793 \pm 0.134$

	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

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RSP reconstruction accuracy with CTP404 phantom

$2 \cdot 10^4$ proton

10^5 proton

$2 \cdot 10^5$ proton

$5 \cdot 10^5$ proton

$7 \cdot 10^5$ proton

$1.1 \cdot 10^6$ proton

RSP reconstruction accuracy with CTP404 phantom

Ground truth

Reconstructed

Gaussian blur

Averaging blur

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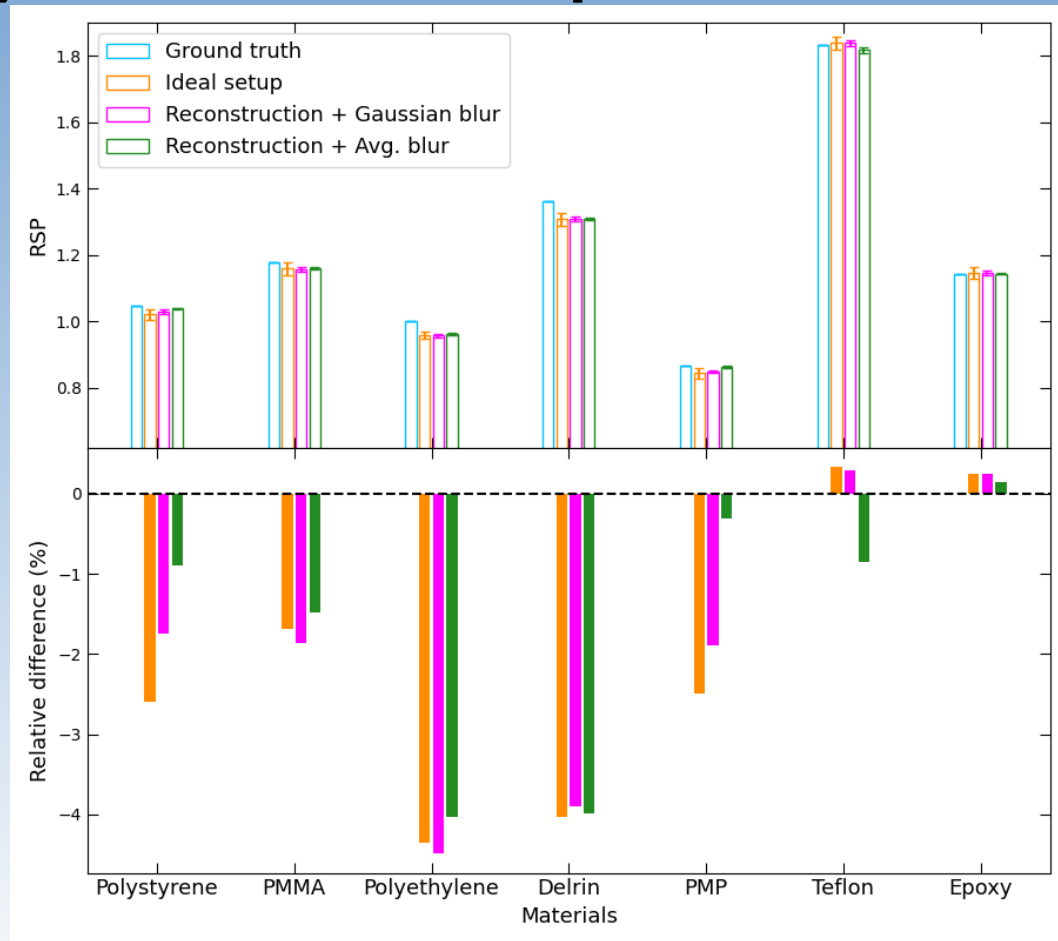
- ~1% for Wang et al., 2010, runtime is more (Bayesian interference-based proton path probability map for MLP calculation)
- ~-4% for our research, runtime is less (Cubic spline fitting for MLP calculation)

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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.
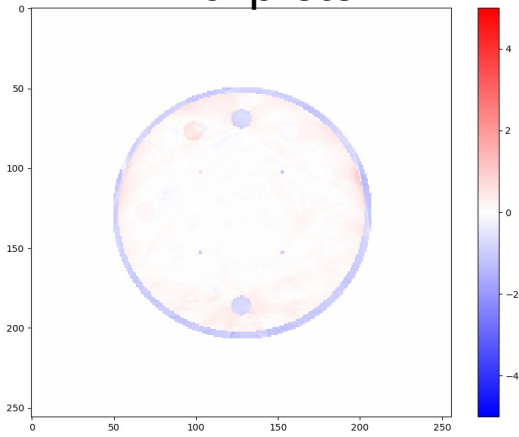
Thank you for your attention!

Backup - Differences between the RSP values
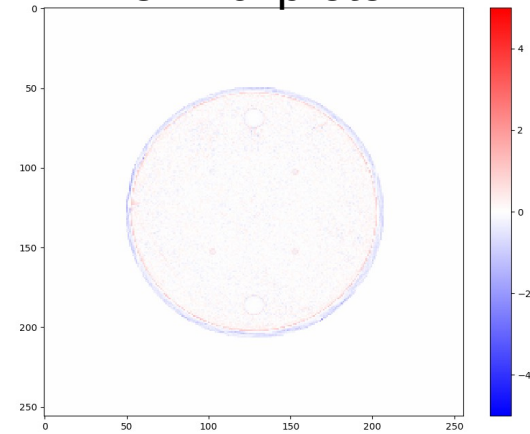

2 · 10^4 proton

3.4 · 10^5 proton
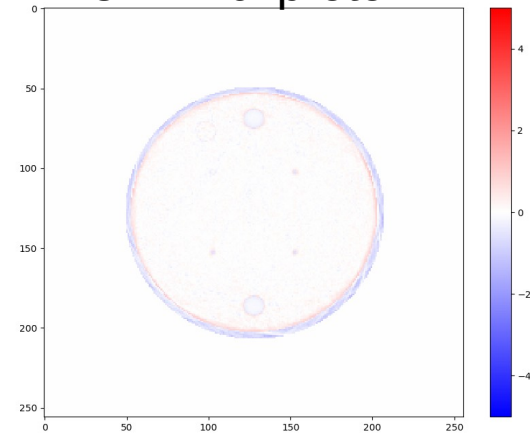
1.14 · 10^6 proton
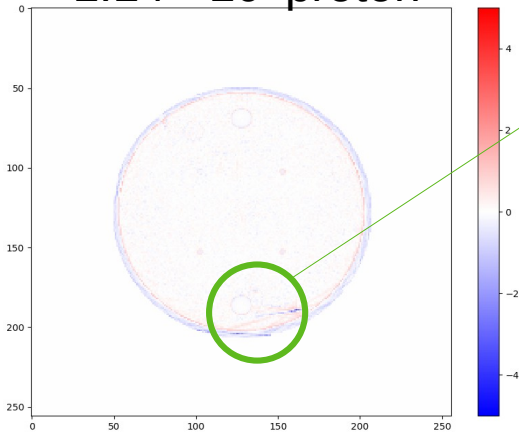
1.5 · 10^6 proton

Some outlier pixels

Backup - Mean Absolute Error

Mean Absolute Error:
the average absolute difference between corresponding pixels

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