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# Image reconstruction in proton computed tomography

## Theory and Experiment in High Energy Physics

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HUN-REN
Hungarian Research Network

MTA
Centre of Excellence

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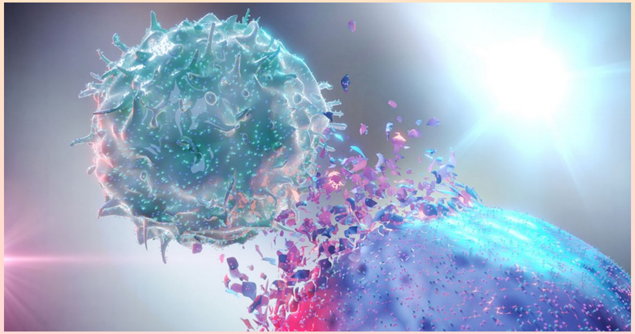
EÖTVÖS LORÁND UNIVERSITY | BUDAPEST

# 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

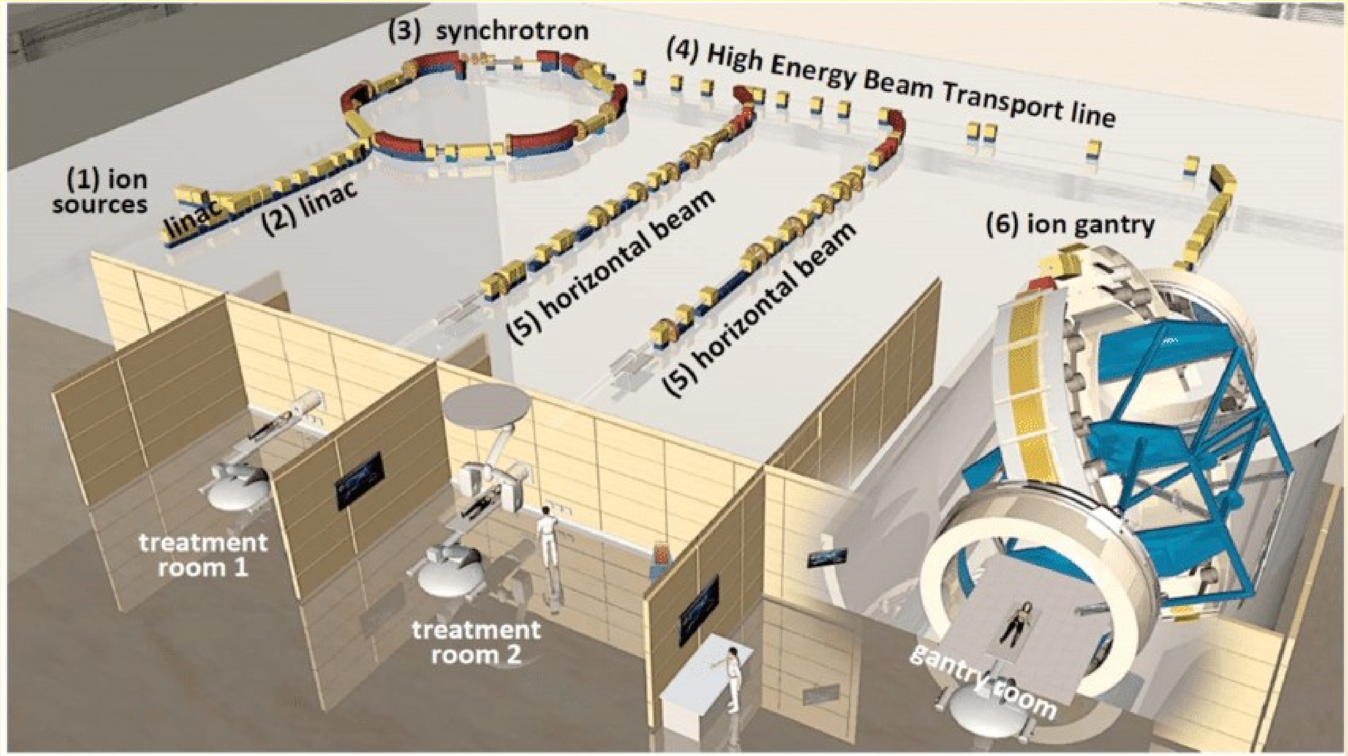
# Motivation

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



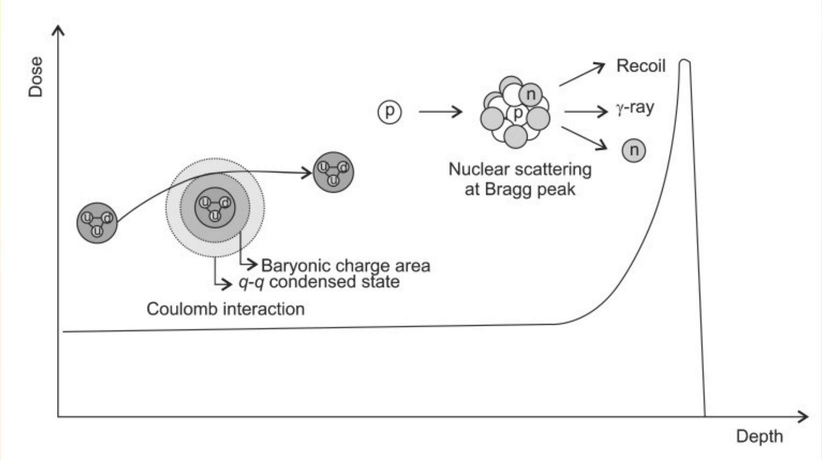
# Motivation

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

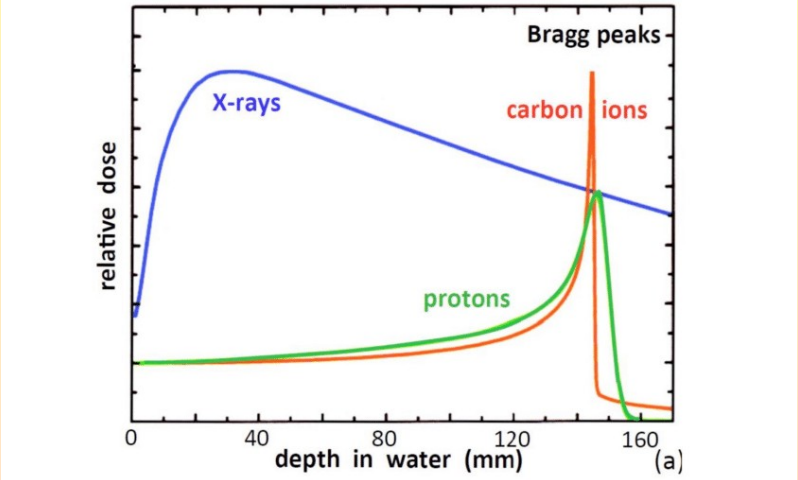



Layout figure of HIT Centre (Heidelberg)

# Why is proton therapy so outstanding?

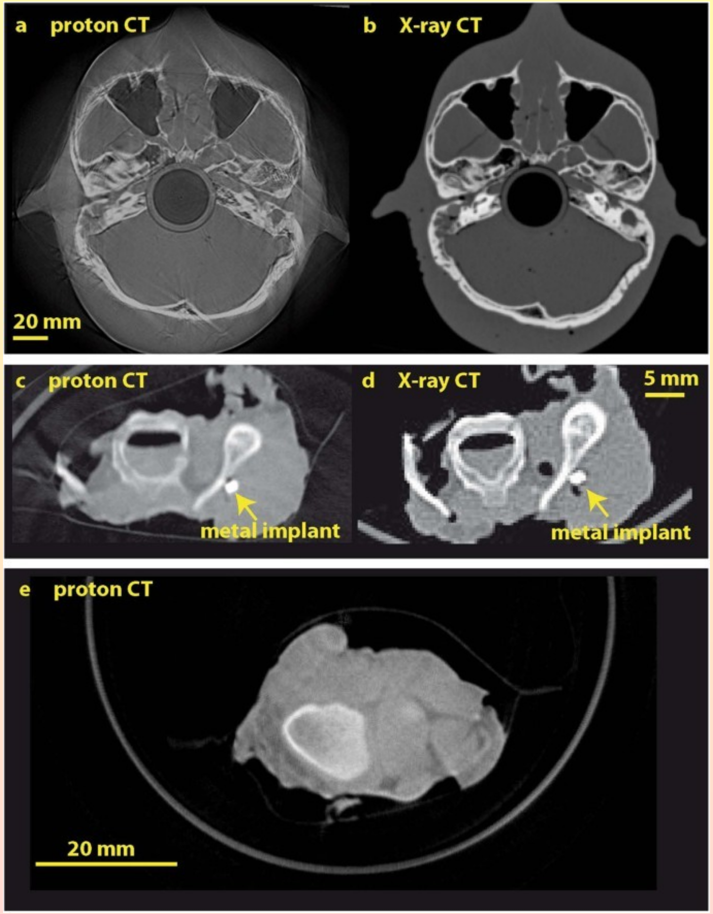



[Seo Hyun Park and Jin Oh Kang. Basics of particle therapy i: physics. Radiation oncology Journal, 29(3):135, 2011.]




[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

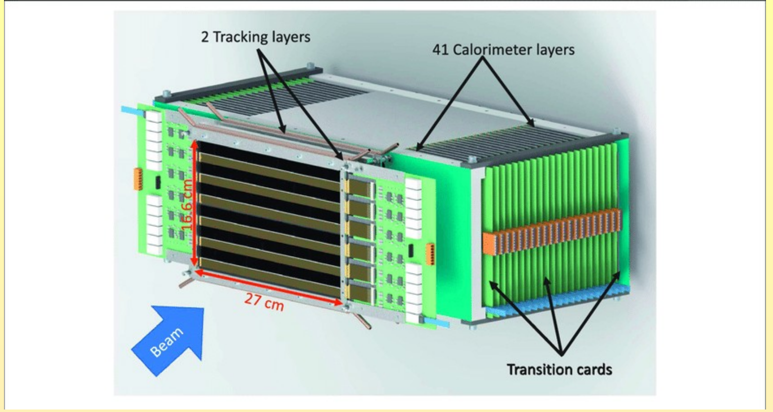
↓

Processing the signals

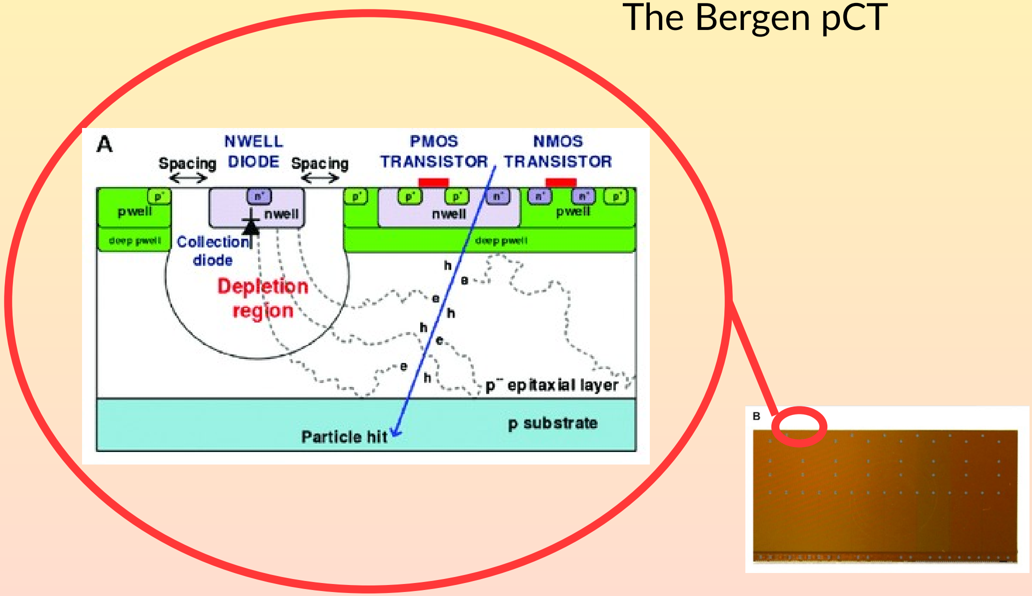
↓

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

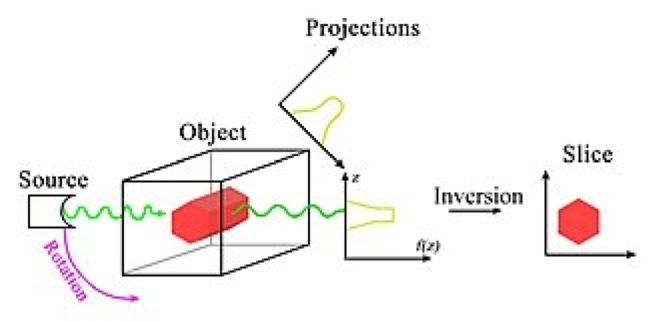


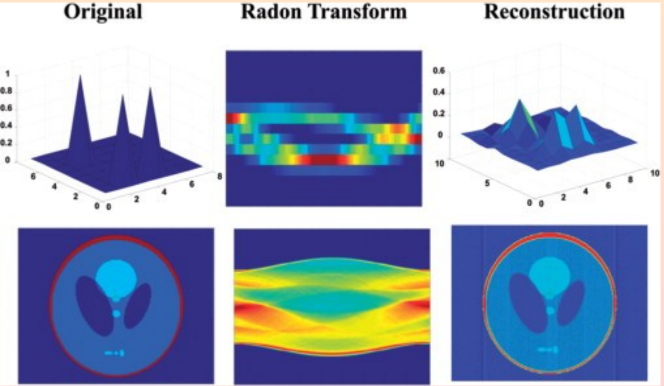

The cross-sectional image (A) and the photograph (B) of the ALPIDE chip

# 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




$$\boldsymbol{A} * \color{red}{x} = y$$

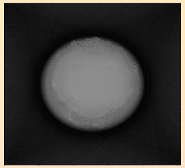
Matrix that contains interaction coefficients between protons and pixels/voxels

Vector that contains estimated proton RSP values

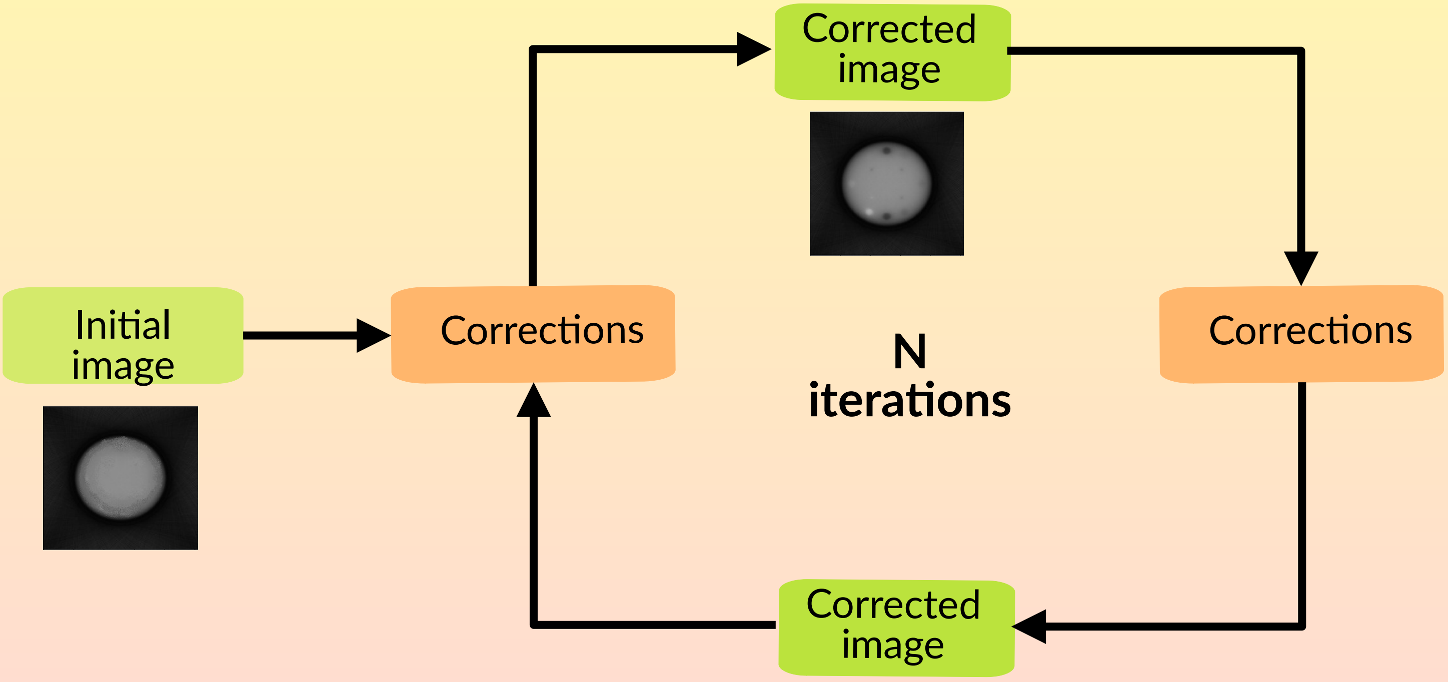
Vector that contains the known WEPL values of the protons

# Iterative methods for image reconstruction

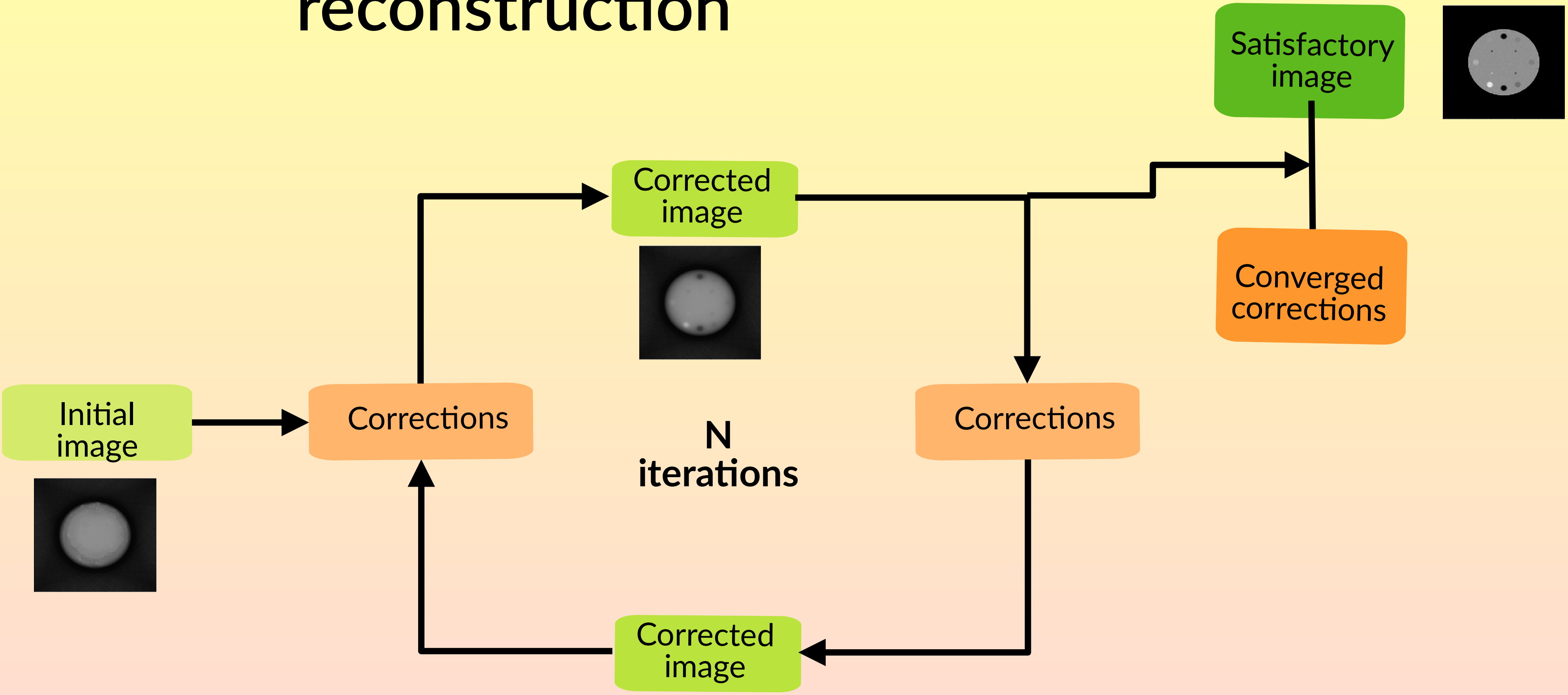
Initial image



# 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 <u>Monte Carlo</u>
- MLP calculation
- <u>RSP-distribution calculation</u>

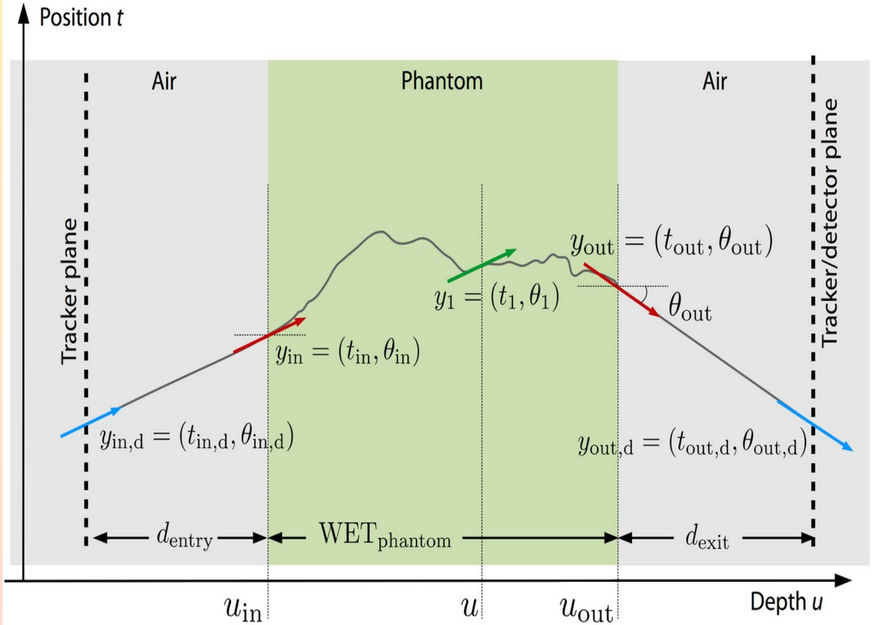
Number of iterations

Vector containing WEPL values

Matrix containing interaction coefficients between proton trajectories and voxels

$$x_i^{k+1} = x_i^k \frac{1}{\sum_j A_{i,j}} \sum_j \frac{y_j}{\sum_1 A_{l,j} x_1^k} A_{i,j}$$

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 → From correlated Gauss distributions, for every proton’s direction & position

3-sigma filtering → Filtering directions and WEPL values of the protons

Shorter runtime (days → hours)

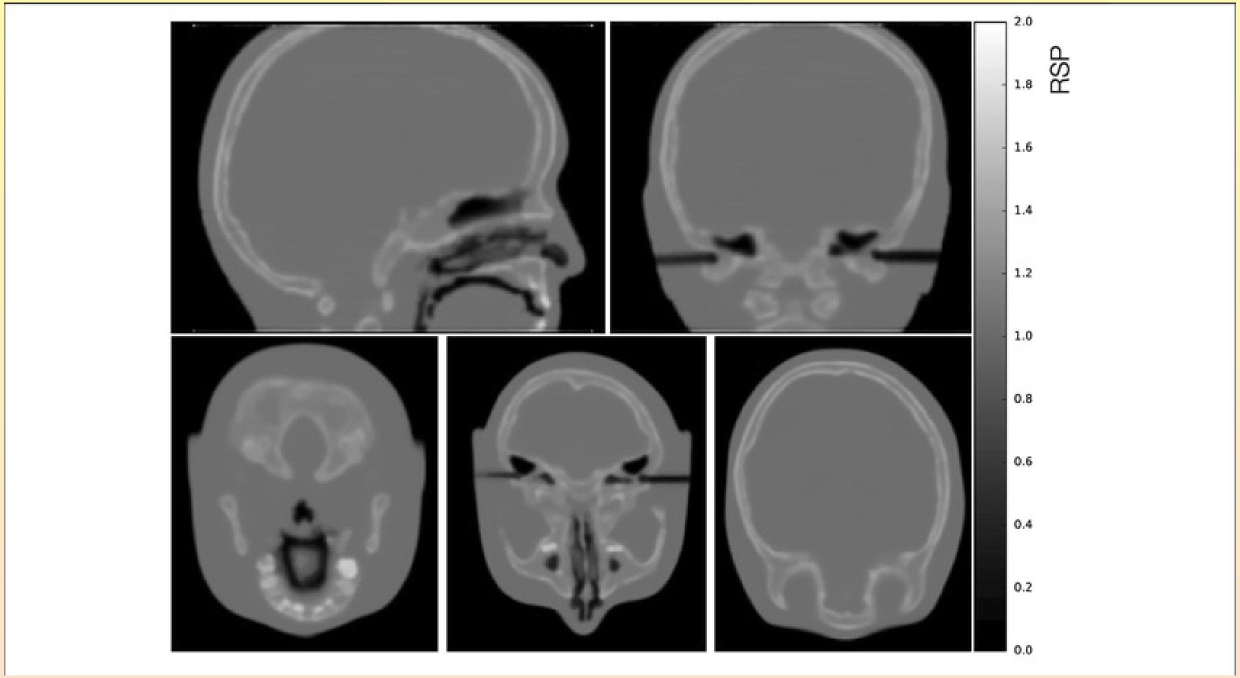
MLP calculation → Calculating the most likely position of protons going in and coming out of the cylinder around the phantom

Calculating RSP distribution with Richardson-Lucy → C++ code accelerated with GPU (using CUDA): Hadamard ratios are calculated for every trajectory in the GPU kernels (WSCLAB)

# Evaluating the algorithm

What aspects do we have to consider?

- Spatial resolution
- Accuracy of RSP reconstruction (~density)

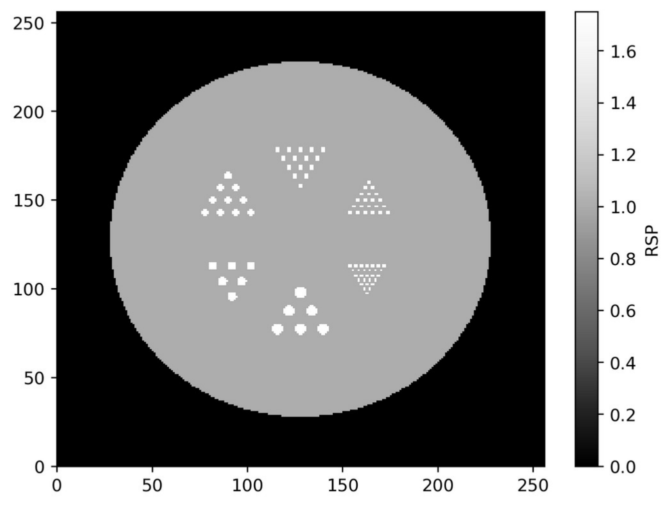



[Alme J, et al., Frontiers in Physics. 2020;8(460)]

# Evaluating the algorithm - phantoms

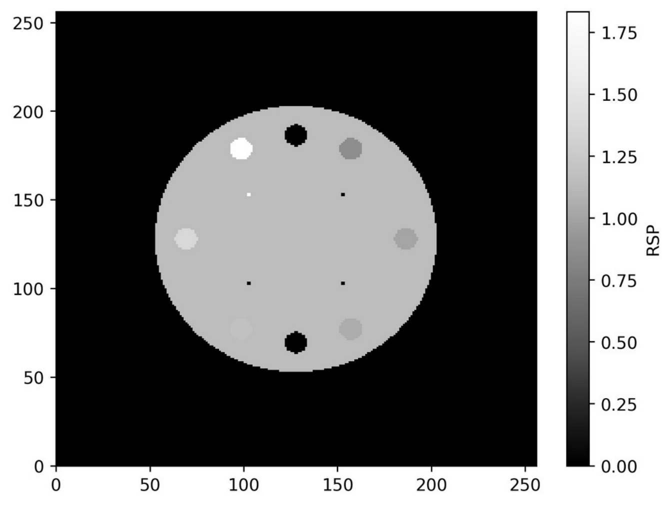
## Derenzo phantom

- 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

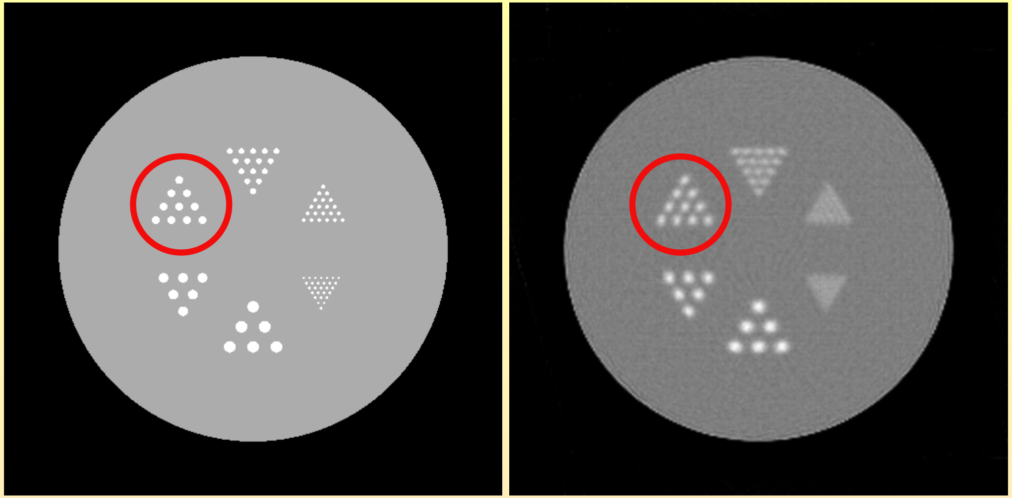


# Results

| | X axis | Y axis |
|---|---|---|
| Original | 0.78 | 0.78 |
| Reconstructed | 0.71 | 0.69 |

The *valley-to-peak* intensity ratios

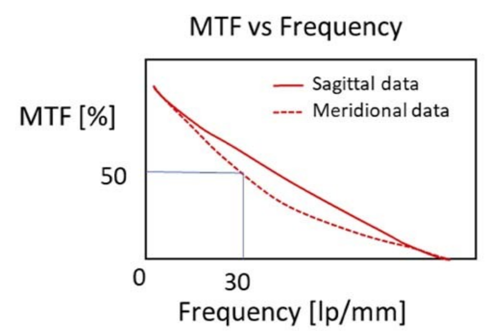
$$r = \frac{\bar{v} - \bar{b}}{\bar{p} - \bar{b}}$$

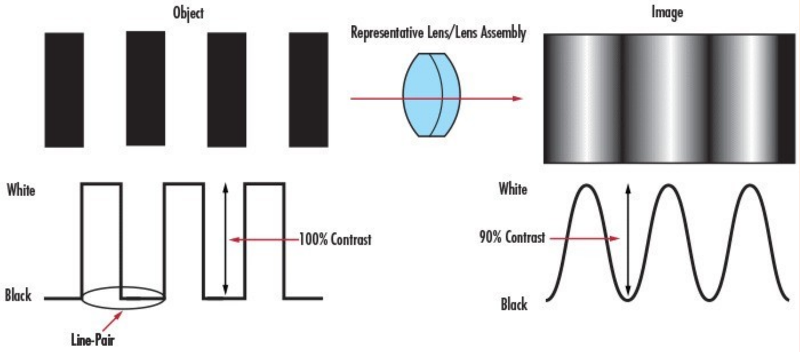


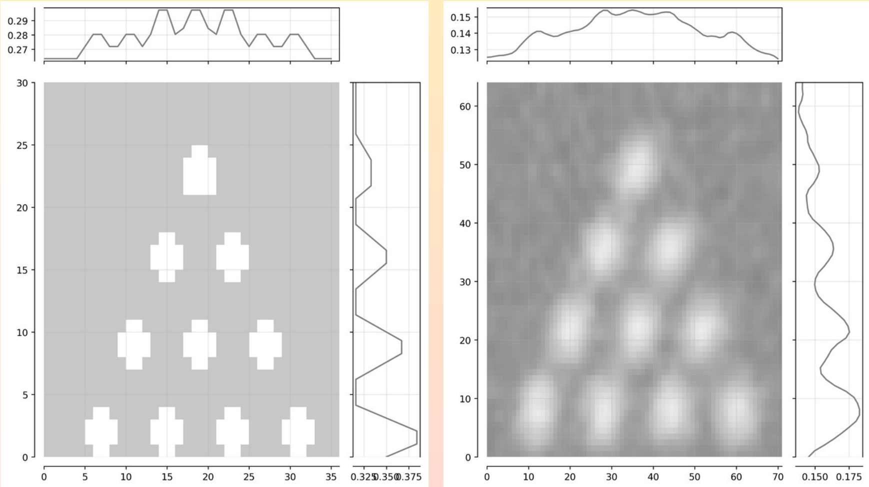
The original (left) and the reconstructed (right) Derenzo phantom

| | $MTF_{10\%}$ |
|---|---|
| Original | 1.69 |
| Reconstructed | 0.95 |

$MTF_{10\%}$ values
(x and y values averaged)



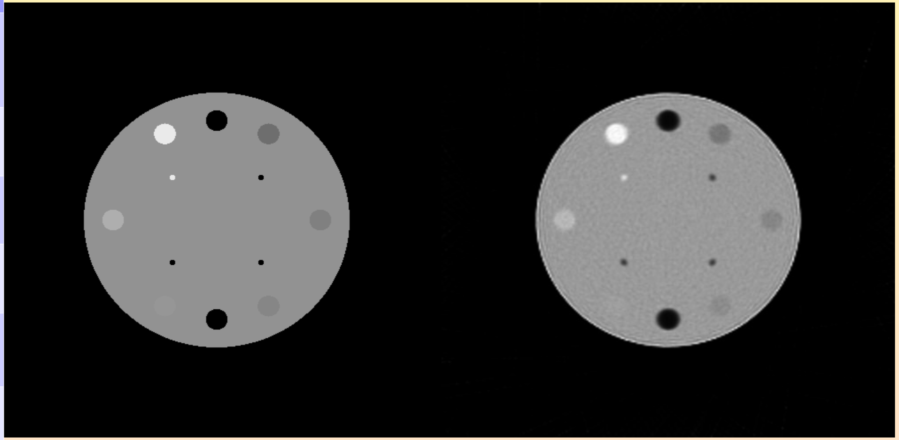



One slice of the original (left) and reconstructed (right) Derenzo phantom and the intensities projected onto the x, y axis

# Results

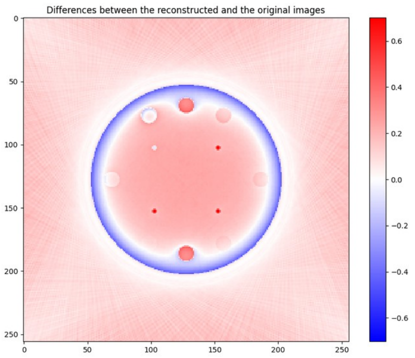
| Material | RSP (original phantom) | RSP (reconstructed phantom) | Relative difference |
|---|---|---|---|
| Air | 0.000 | $5.324*10^{-4}$ | $5.324*10^{-4}$ |
| Teflon | 1.833 | 1.749 | 0.046 |
| Delrin | 1.363 | 1.289 | 0.054 |
| PMMA | 1.179 | 1.124 | 0.047 |
| Polystyrene | 1.048 | 0.987 | 0.058 |
| Polyethylene | 1.003 | 0.919 | 0.084 |
| PMP | 0.866 | 0.813 | 0.061 |

The difference between the real and reconstructed RSP values of the different materials

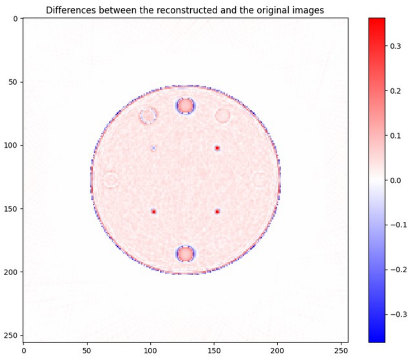


The original (left) and the reconstructed (right) CTP404 phantom

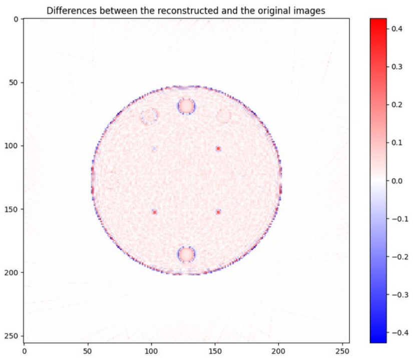
# Results



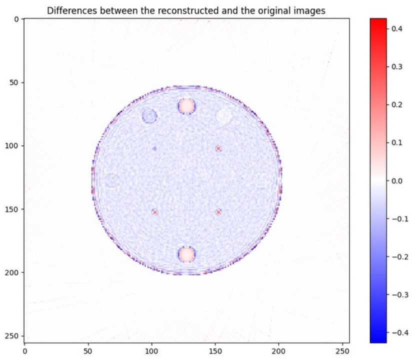

10. iteration




100. iteration

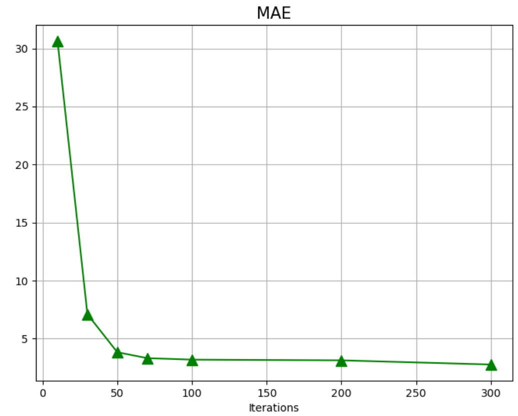



200. iteration



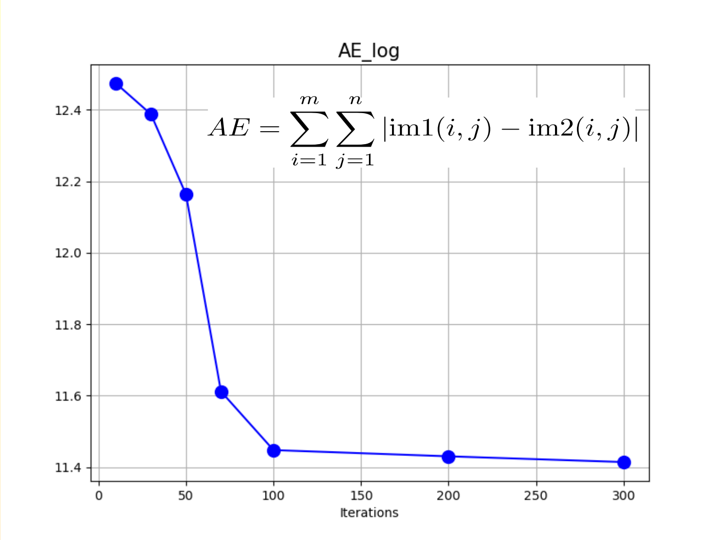

300. iteration

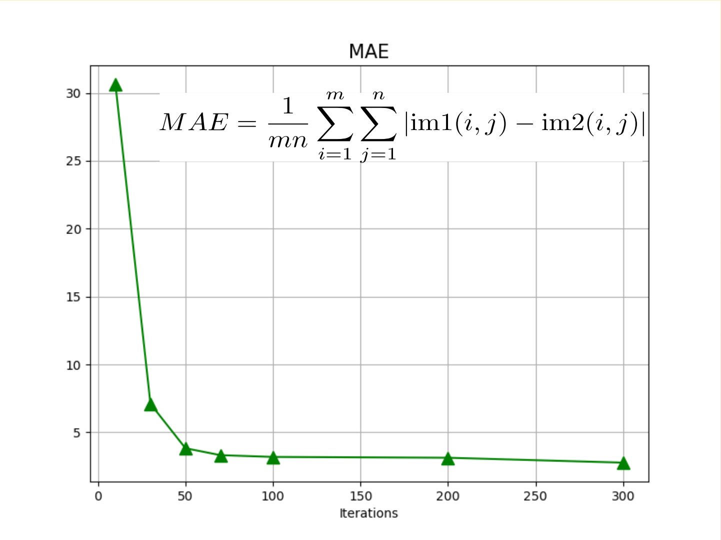
The differences between the original and the reconstructed images



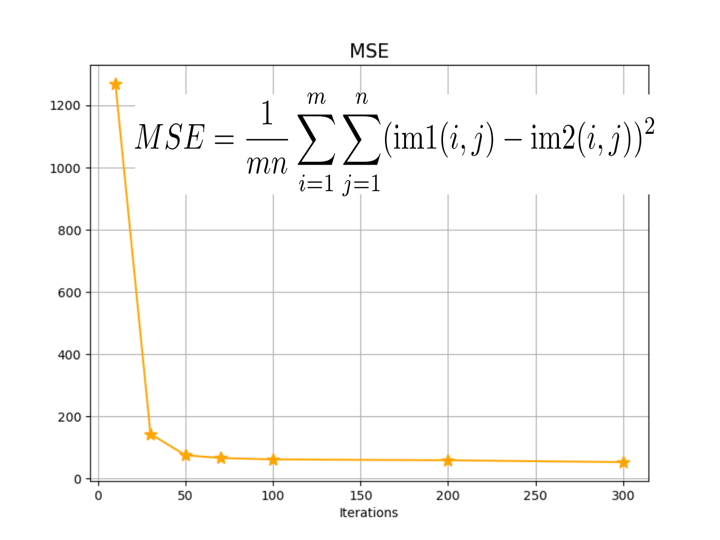

$$MAE = \frac{1}{mn}\sum_{i=1}^{m}\sum_{j=1}^{n}|\mathrm{im1}(i,j) - \mathrm{im2}(i,j)|$$

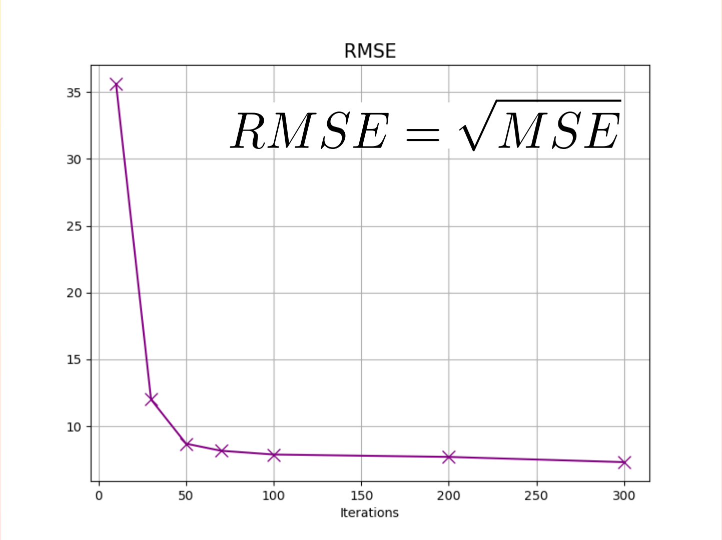
# Results




- **Absolute Error**: number of pixels that differ
- **Mean Absolute Error**: the average absolute difference between corresponding pixels
- **Mean Squared Error**: the average squared difference between corresponding pixels
- **Root Mean Squared Error**: square root of the above



# 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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