Image reconstruction in proton computed tomography*

for the Bergen Proton CT Collaboration

Theory and Experiment in High Energy Physics
V4-HEP, Warsaw
28-30/10/24

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

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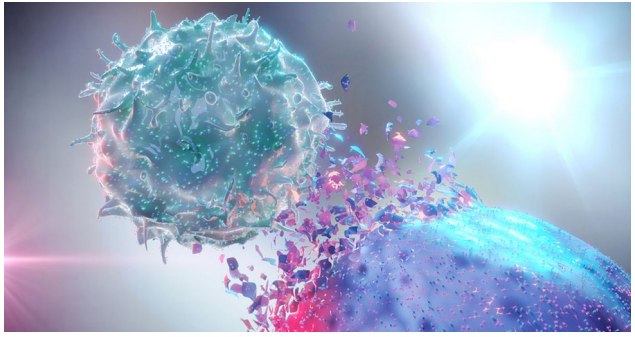
Motivation

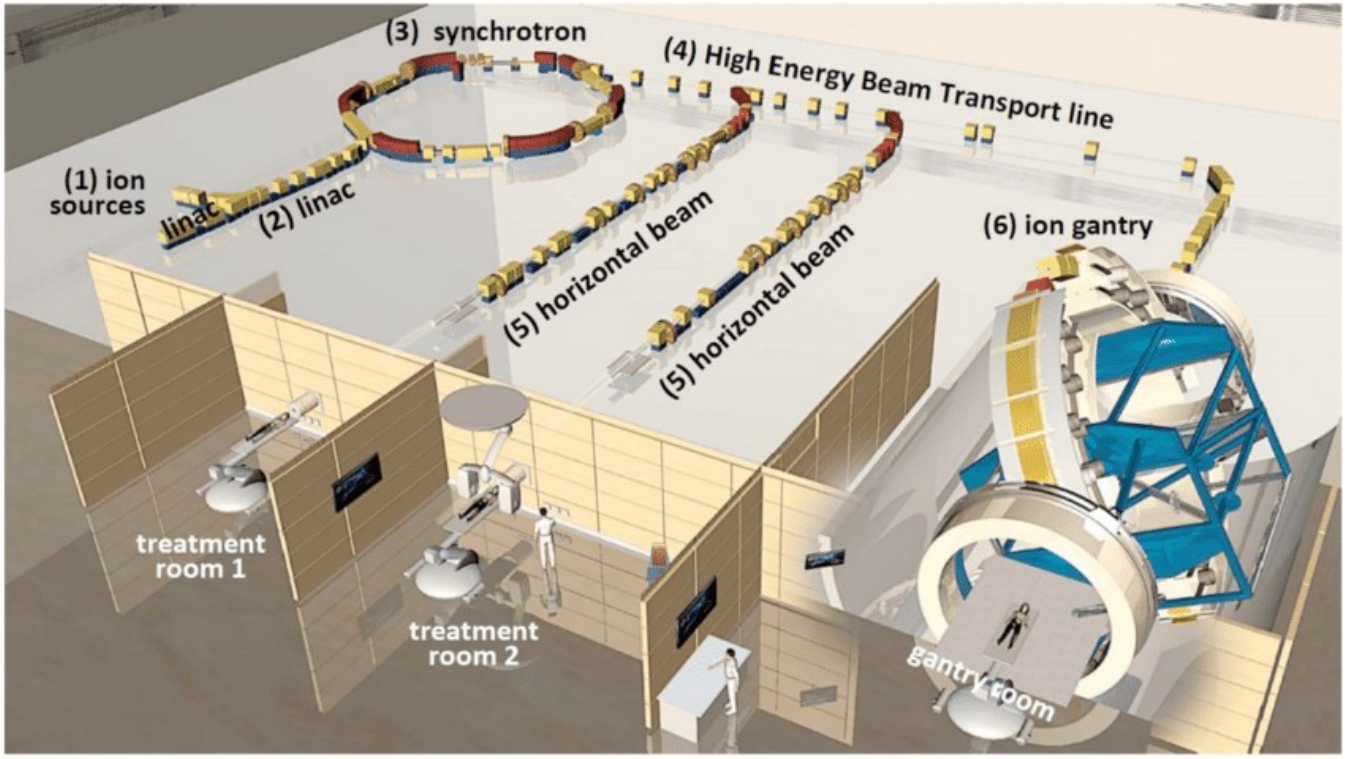
Motivation

- 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

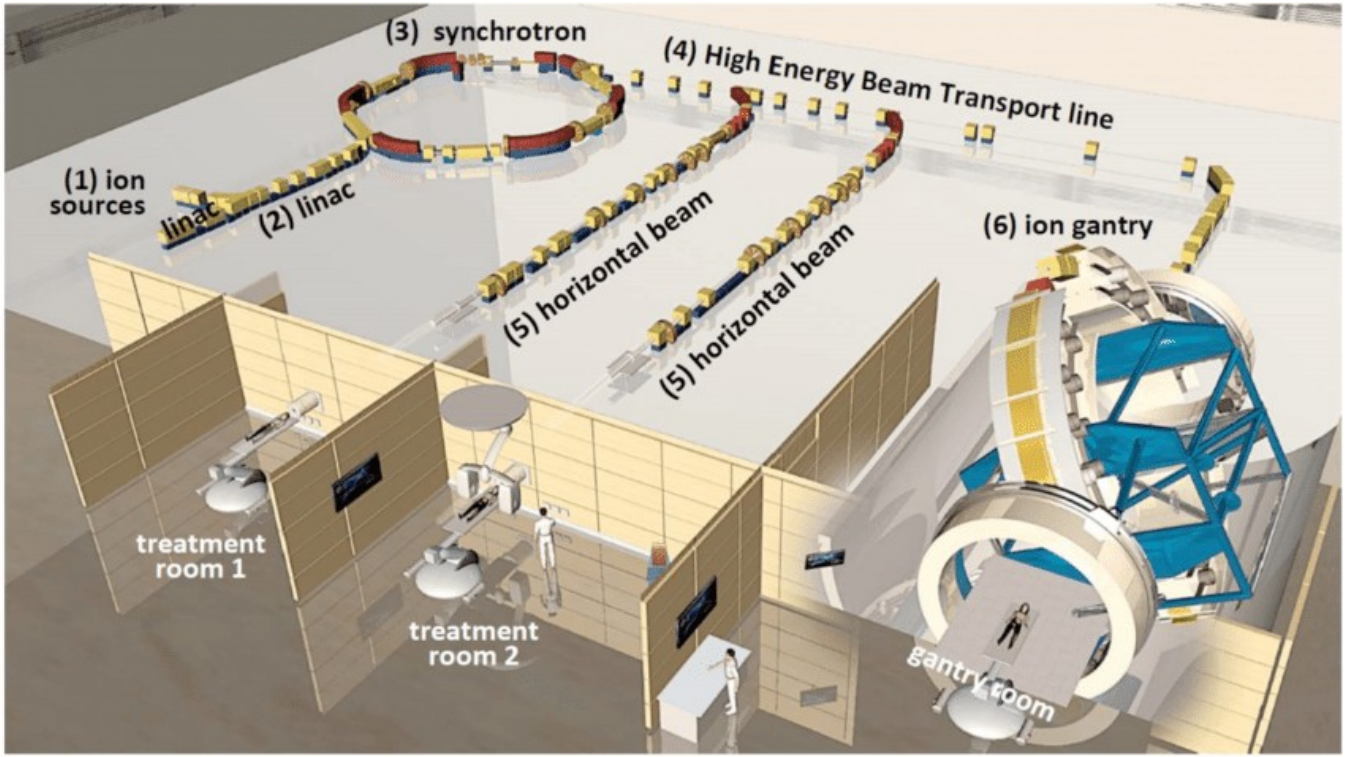


Layout figure of HIT Centre (Heidelberg)

Hadron (proton) therapy

Hadron therapy

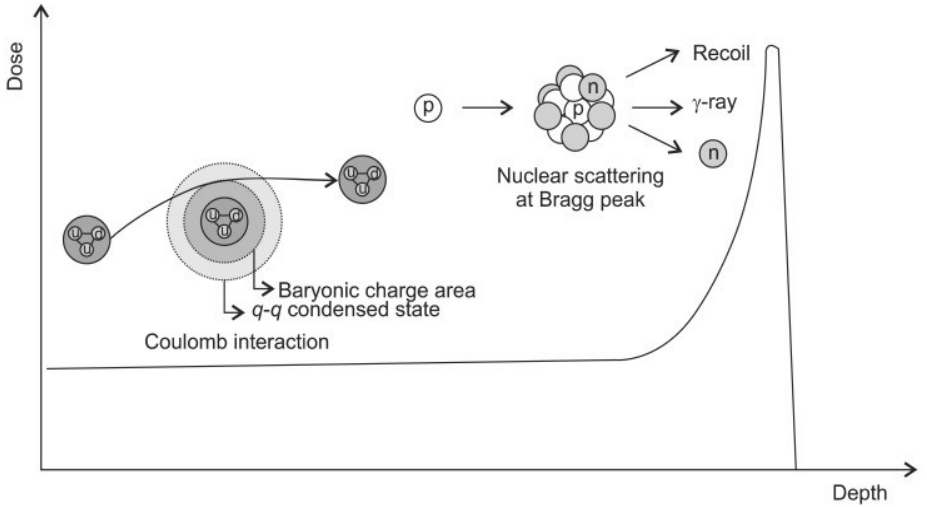
- 2024: 120 proton, 14 carbon ion centres in operation (more under construction)[1]
- End of 2022: >350000 patients treated[2]
- 5-year survival estimates: 19% for conventional radiotherapy, 40% for proton, 42% for carbon ion therapy[3]



Layout figure of HIT Centre (Heidelberg)

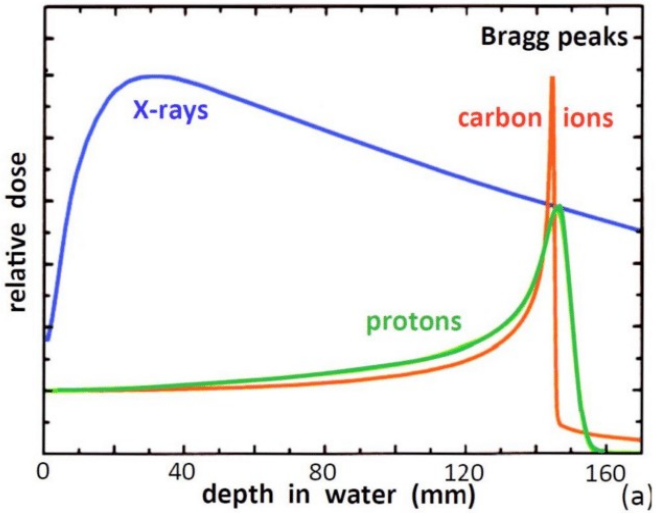
[1]PTCOG, Particle therapy facilities in operation. (2024).
[2]PTCOG, Patient statistics. (2022).
[3]Grutters, Janneke PC, et al. "Comparison of the effectiveness of radiotherapy with photons, protons and carbon-ions for non-small cell lung cancer: a meta-analysis." Radiotherapy and Oncology 95.1 (2010): 32-40.

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.]

Interactions of proton in a medium

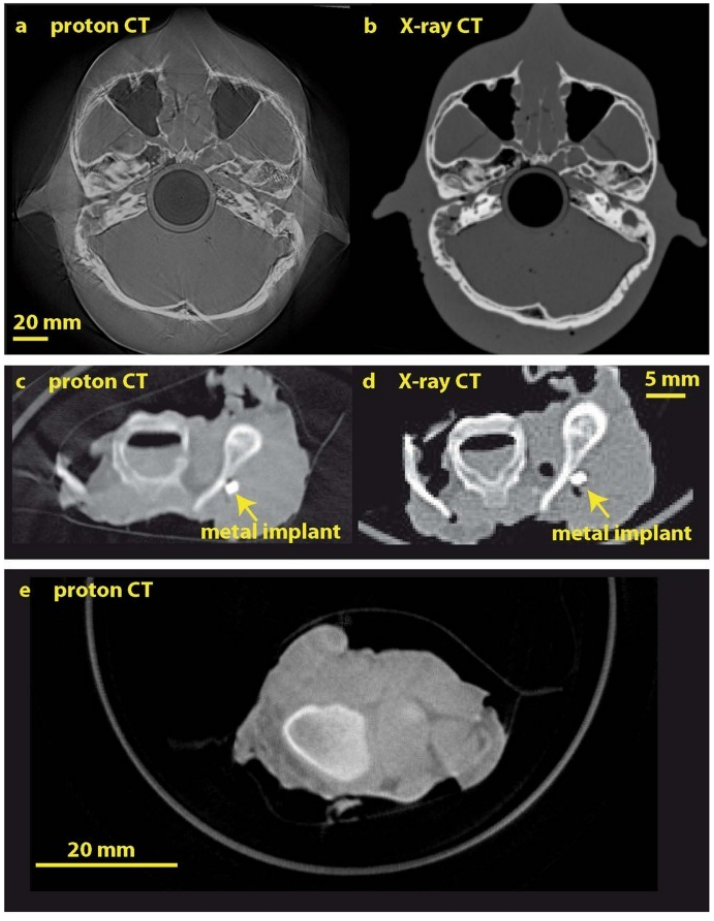


[Ugo Amaldi, Manjit Dosanjh, Jacques Balosso, Jens Overgaard, and Brita Sørensen. A facility for tumour therapy and biomedical research in south-eastern europe. 09 2019.]

Dose deposit characteristics → less radiation for healthy tissues

Energy loss in matter: $$-\frac{dE}{dx} = \frac{4\pi e^4 z^2 NZ}{(4\pi\varepsilon_0)^2 M_e v^2}\left[\ln\left(\frac{2M_e v^2}{I}\right) - \ln(1-\beta^2) - \beta^2\right]$$

Problems with imaging – and the solution



X-ray CT vs. proton CT

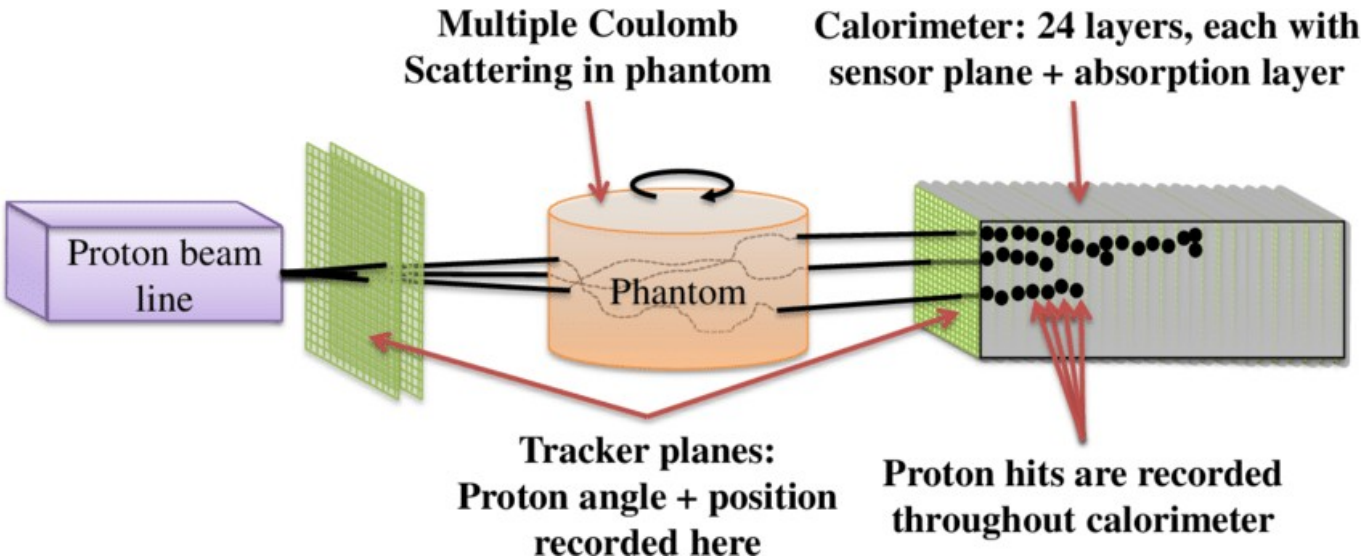
- Today X-ray CT is used
- We need to know the range of the protons → Relative Stopping Power (RSP): how much does it slow down in a material compared to water
- Difference between the absorption of photons and the energy loss of protons → conversion is not accurate between Hounsfield units* and RSP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

*The quantitative scale of X-ray absorption

Proton computed tomography

What is proton CT?

- Cross-sectional images → information about energy absorption
- What do we need?
  - Proton beam
  - Tracker detector(s)
  - Calorimeter
- Very promising results: RMSE of estimation of the RSP was 0.2-0.5%*



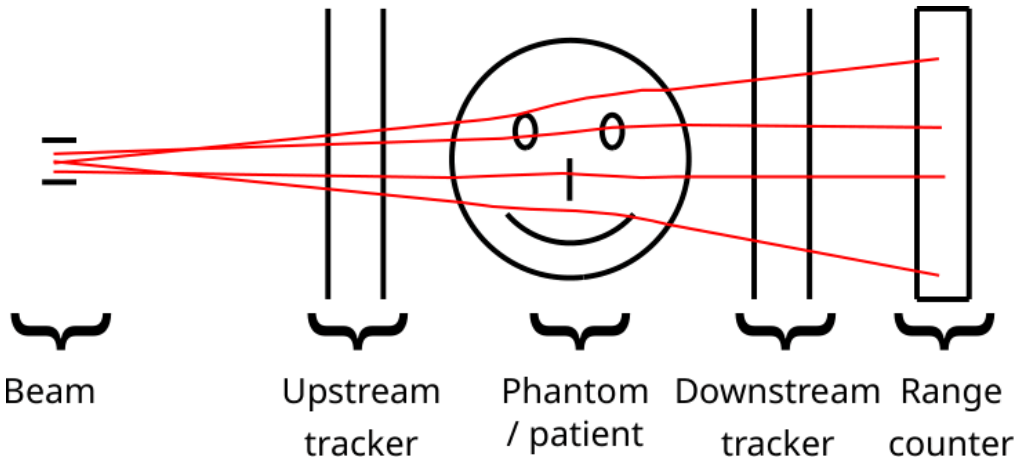
Pettersen, Helge Egil Seime. (2018). A Digital Tracking Calorimeter for Proton Computed Tomography.

David C Hansen et al. Acta oncologica, 54(9):1638–1642, 2015.

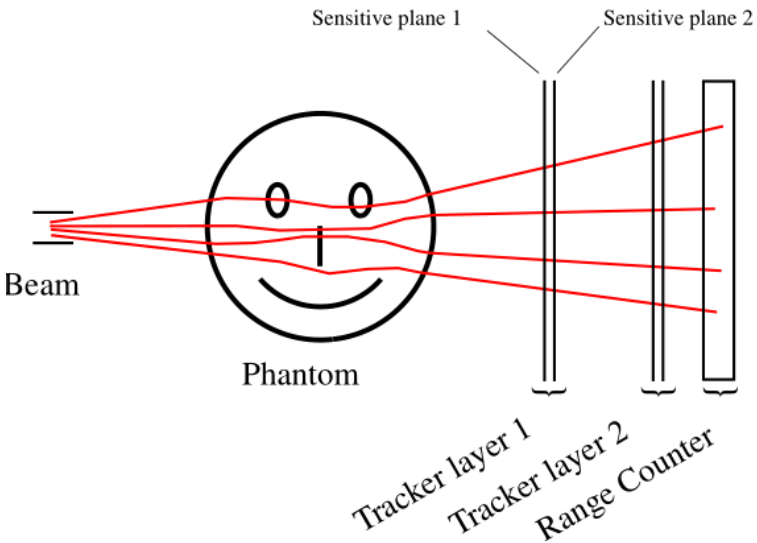
What is proton CT?

2 main types of detector designs

Double-sided scanner design



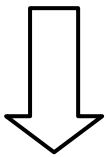
Single-sided scanner design



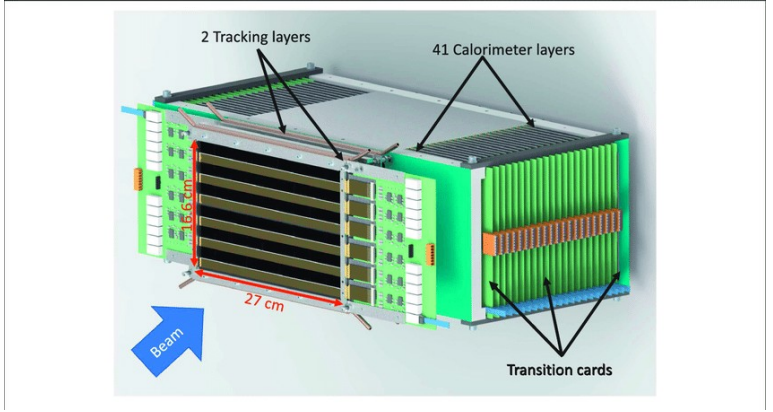
The Bergen pCT Collaboration

The Bergen pCT Collaboration

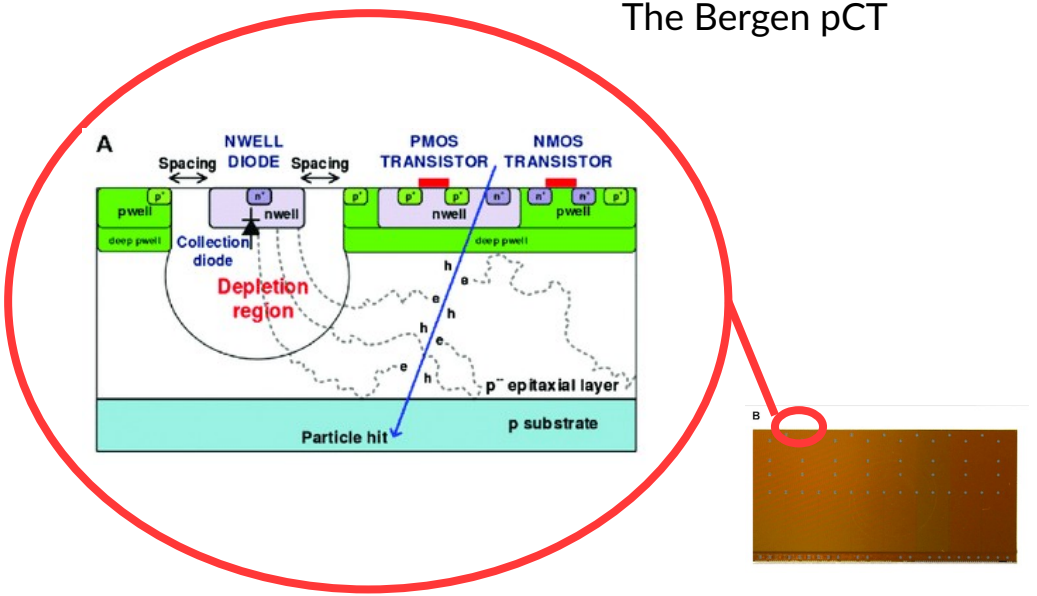
- Goal: to build a proton CT based on the high-energy particle detectors used in the CERN ALICE collaboration (technology transfer)
- The detector system is based on the **ALPIDE chip**



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



The Bergen pCT

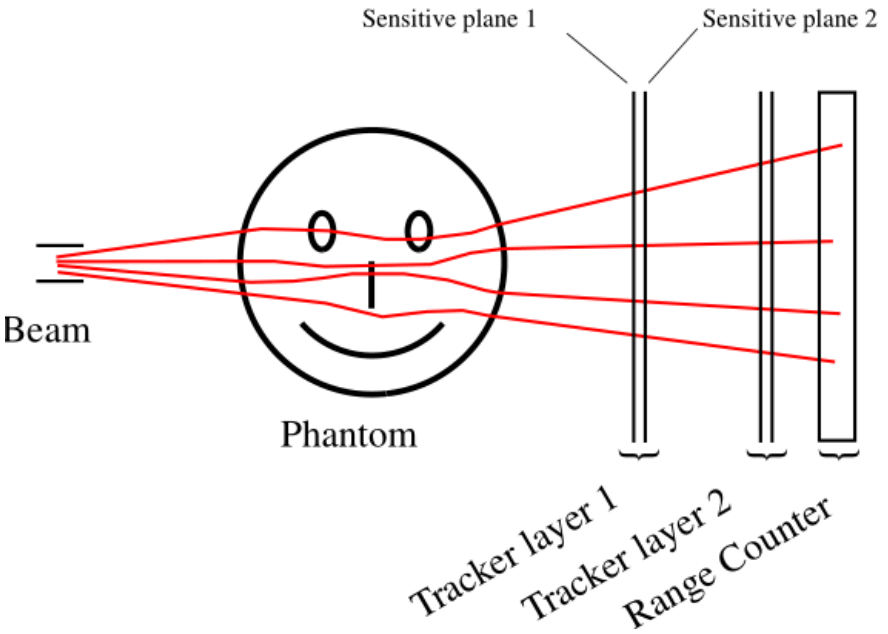


The cross-sectional image (A) and the photograph (B) of the ALPIDE chip

The Bergen pCT Collaboration

- Avoids pairing problem → we can measure more tracks
- 4% accuracy in water equivalent thickness (WET) measurements
- 10^6 protons/sec
- Goals: further optimized detector
  - 2 tracking layers and 41 alternating aluminium absorbing and tracking layers
  - 10^7 protons/sec
  - using ALPIDE

Single-sided scanner design



The Bergen pCT Collaboration

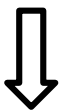
Irradiating the phantom with high energy (~100 MeV) protons

Detector system senses the signals

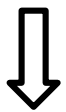
Processing the signals

Reconstructing the image

Currently: Monte Carlo simulations



Tasks:
- Reconstruct trajectories from hits
- Predict energies



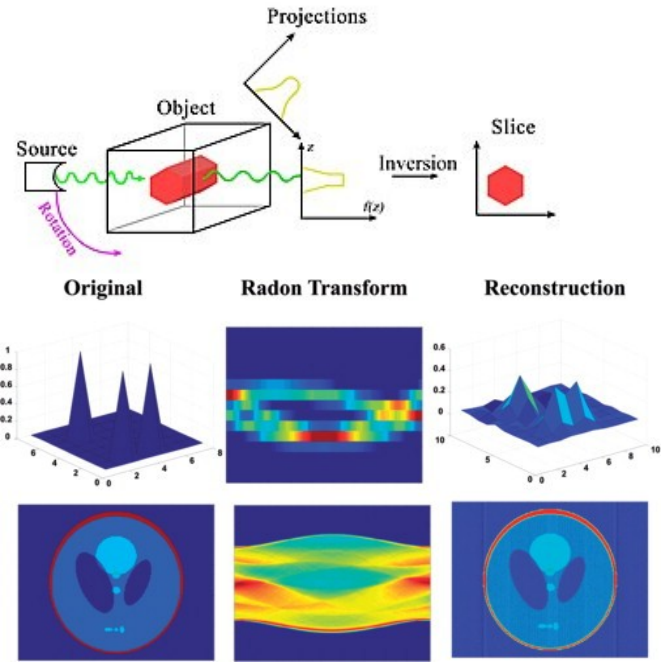
Tasks:
- Determine RSP distribution
- Develop the framework
- Test it on phantoms

Image reconstruction

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

$$A \cdot x = y$$

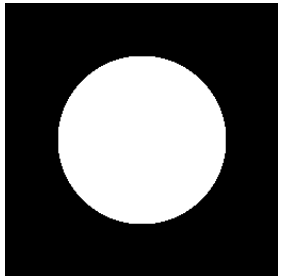
Matrix that contains interaction coefficients between protons and pixels/voxels

Vector that contains estimated proton RSP values

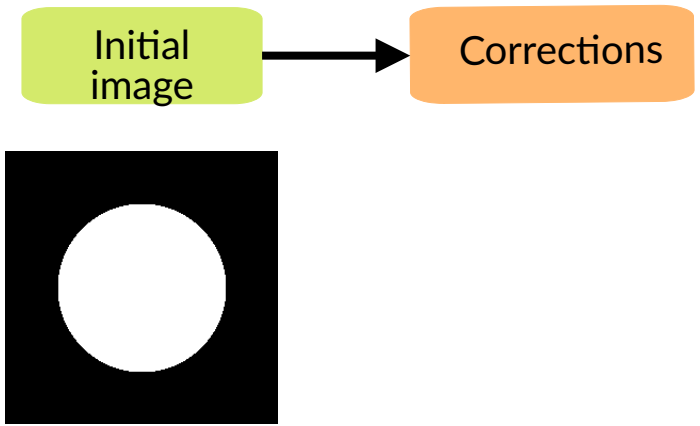
Vector that contains the known WEPL values of the protons

Iterative methods for image reconstruction

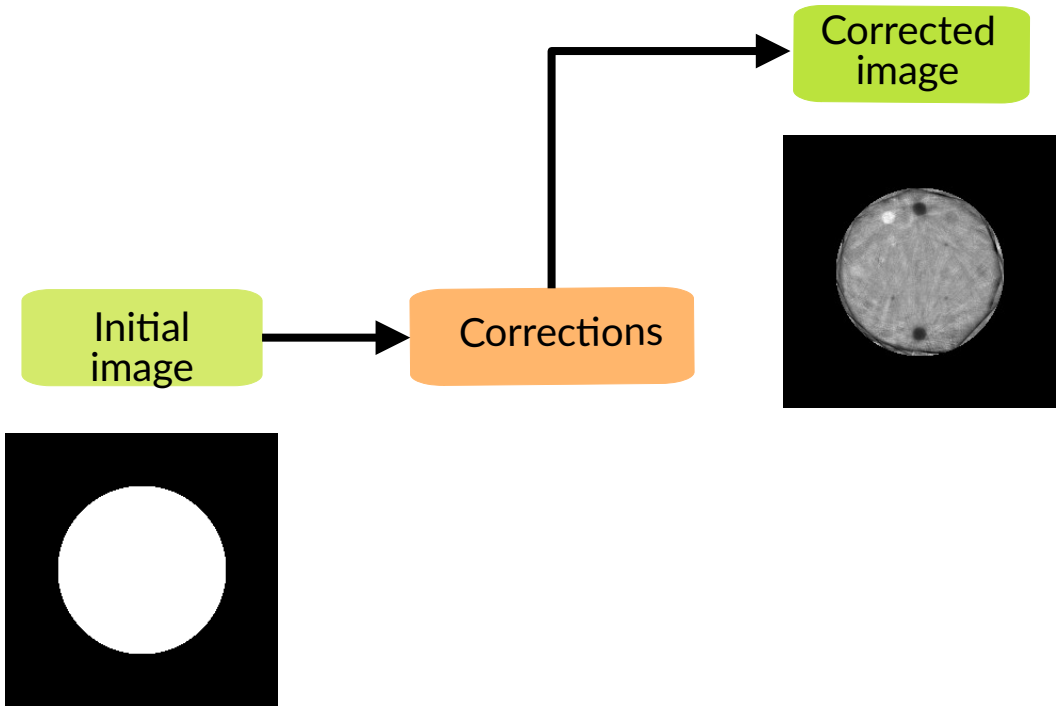
Initial image



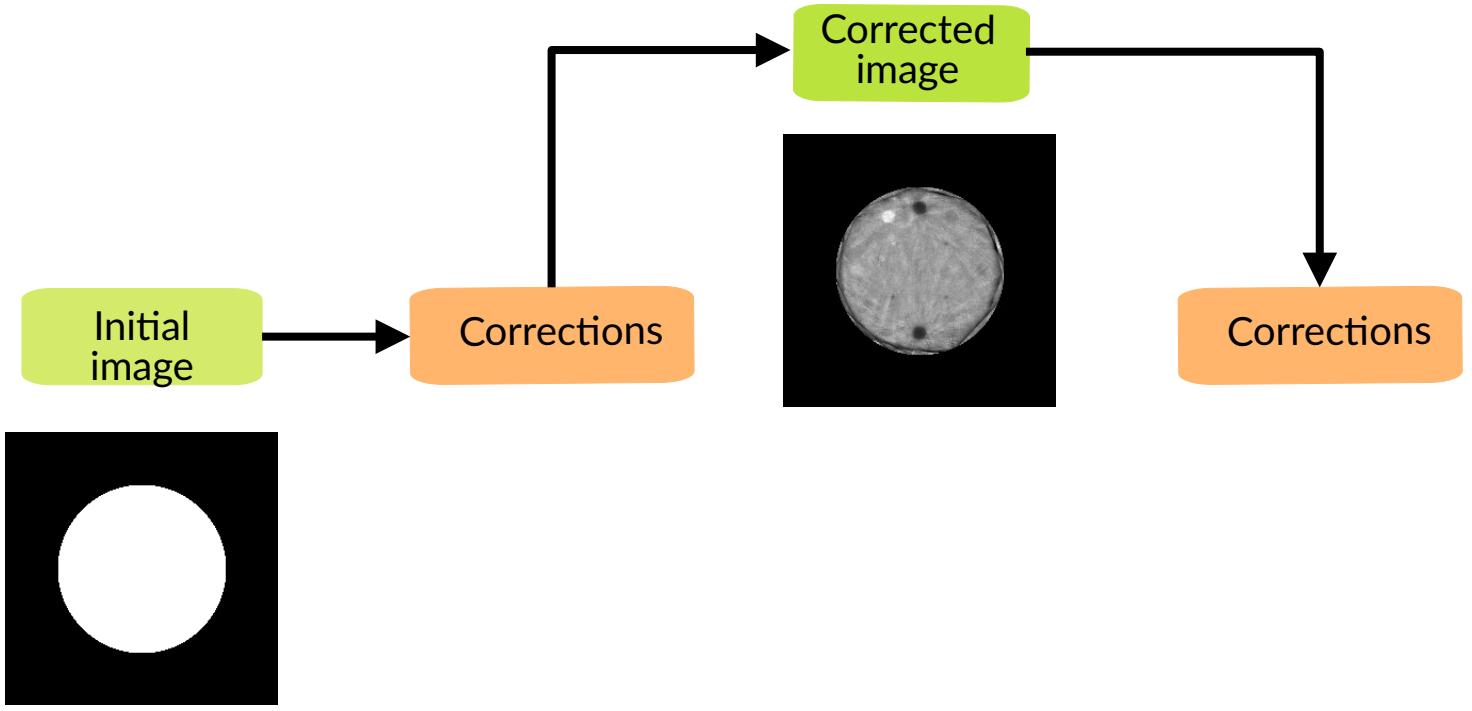
Iterative methods for image reconstruction



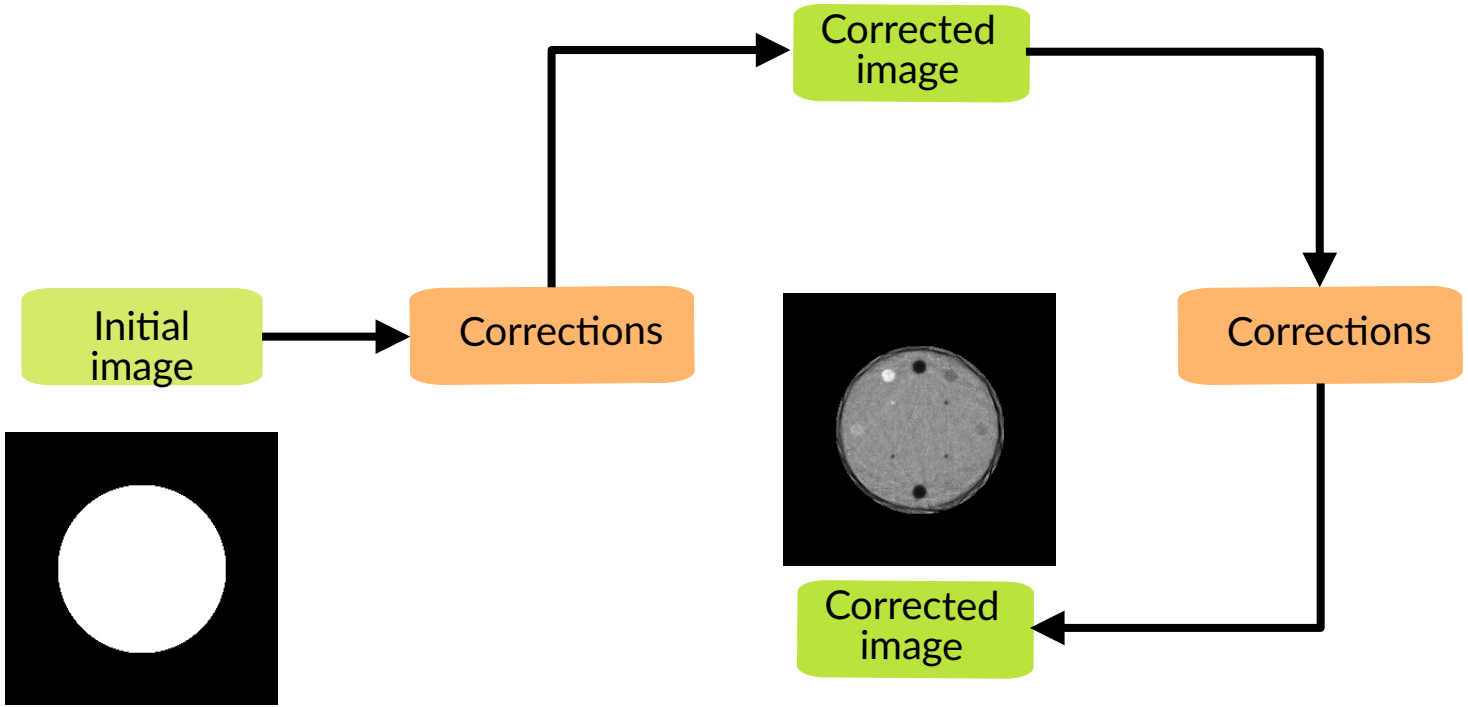
Iterative methods for image reconstruction



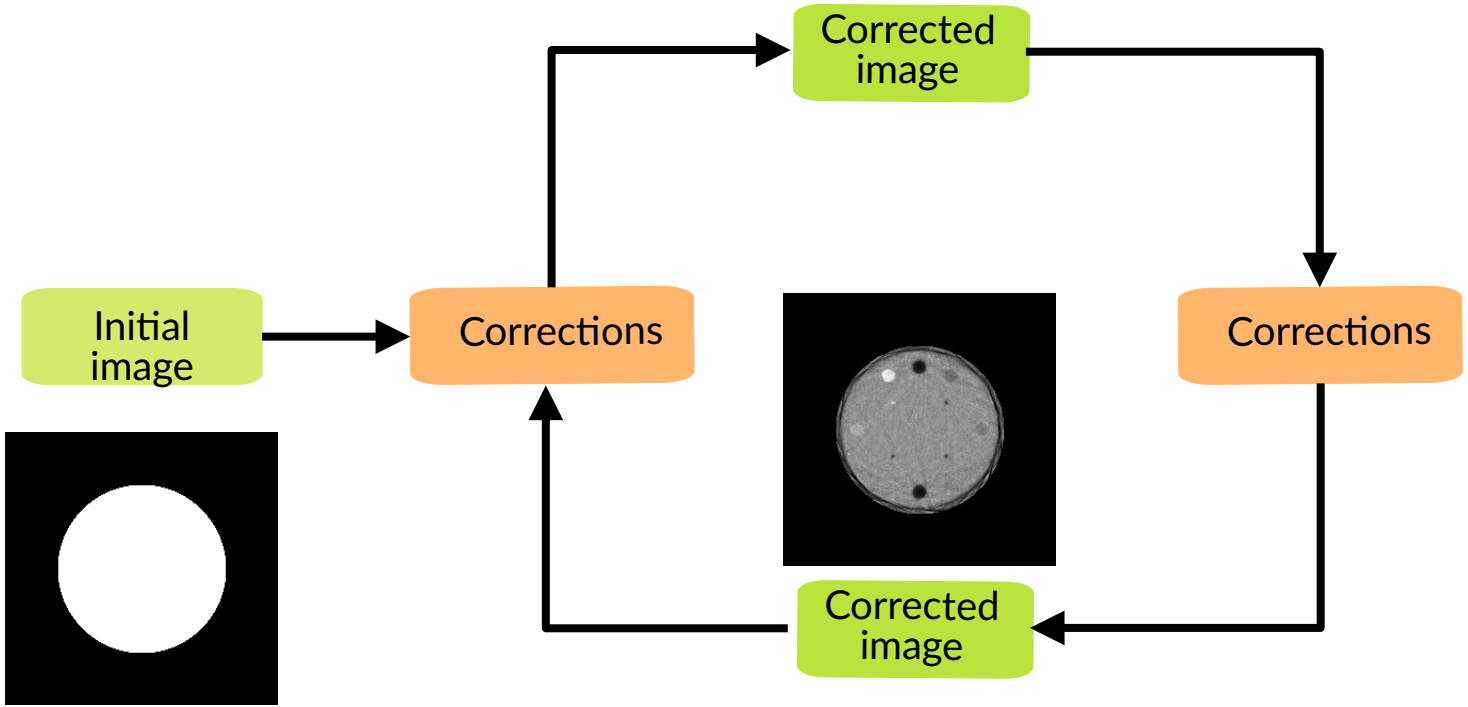
Iterative methods for image reconstruction



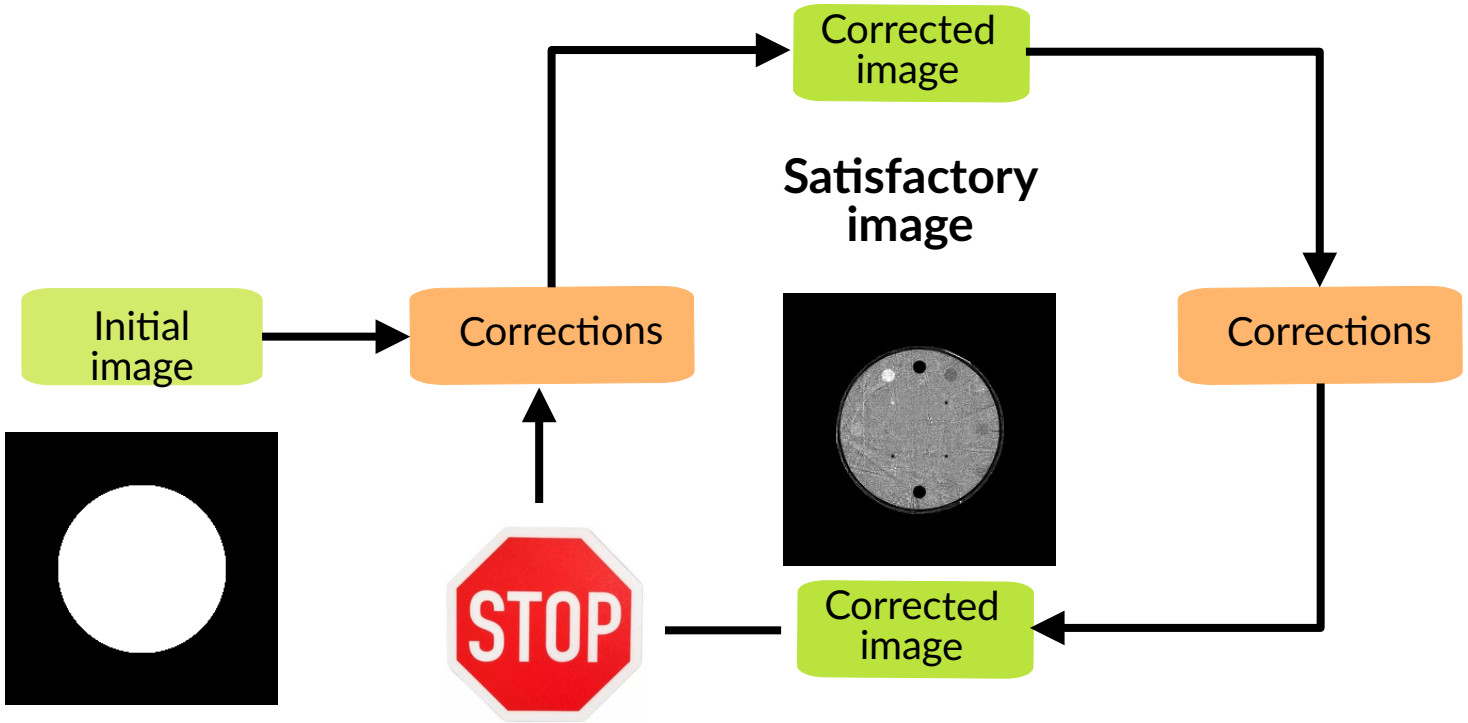
Iterative methods for image reconstruction



Iterative methods for image reconstruction



Iterative methods for image reconstruction



Development of the framework

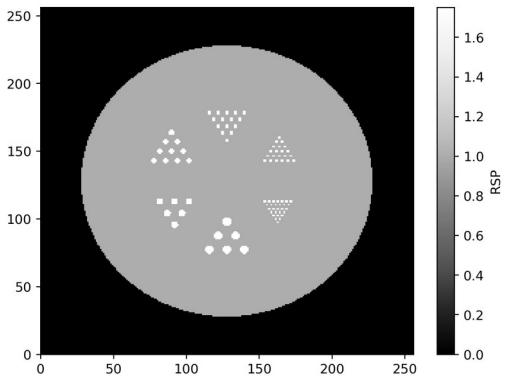
Development of the framework

Steps of the framework

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

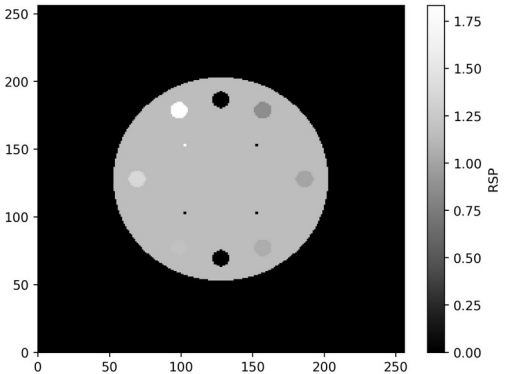
- Adding simulated measurement errors
- 3-sigma filtering
- MLP calculation
- Calculating RSP distribution with Richardson-Lucy algorithm

Derenzo



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

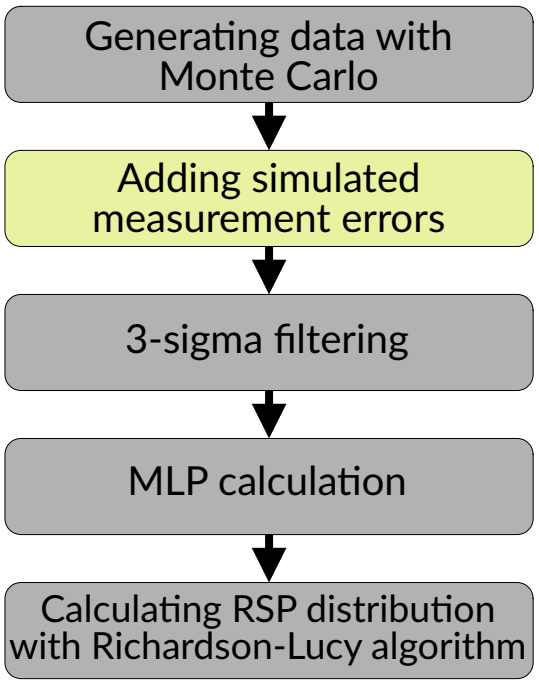
CTP404



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

Development of the framework

Steps of the framework



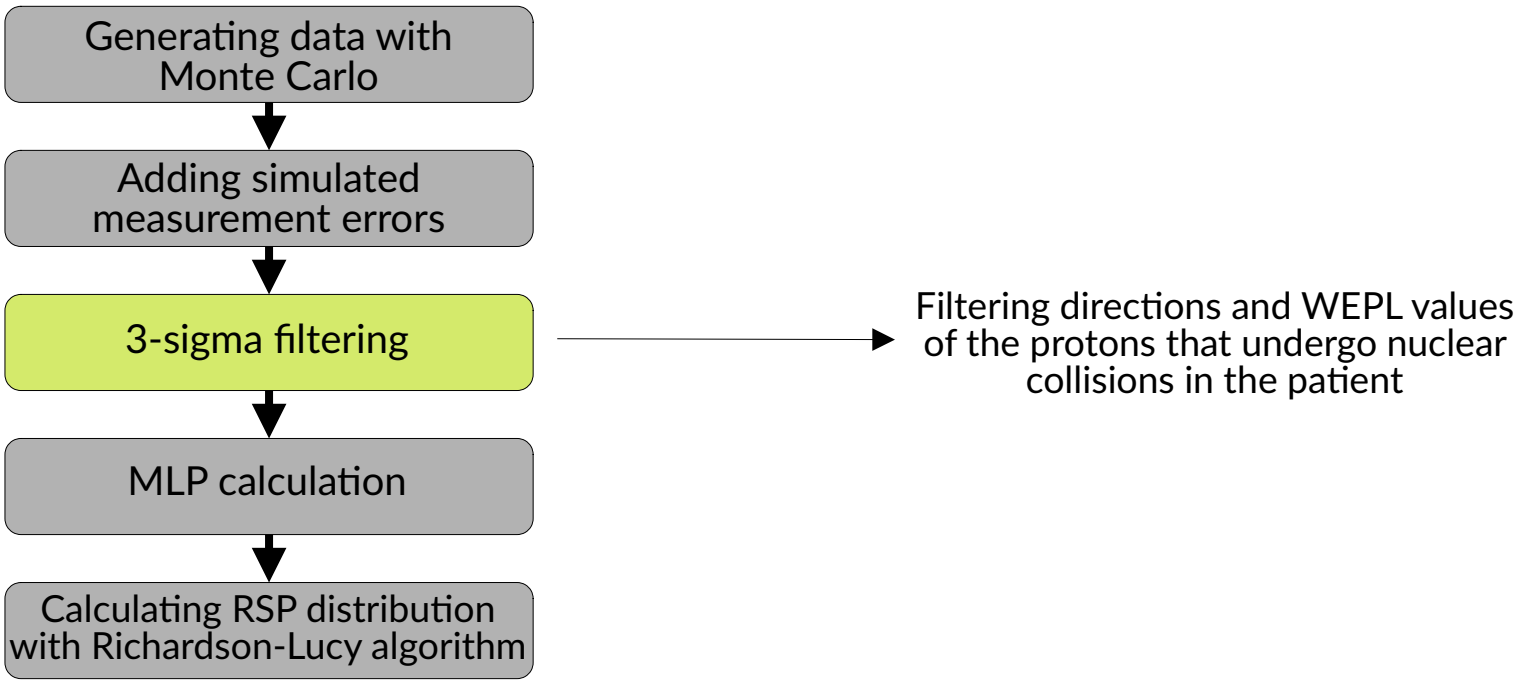
3 different setups compared

- Idealized detector (no measurement errors)
- Silicon pixel tracker (after the design of the Bergen pCT Collaboration*) → 3 water equivalent mm resolution in WEPL
- Silicon strip detector (after the LLU/UCSC Phase-II Scanner design**) → 3 water equivalent mm resolution in WEPL

*Pettersen et al., 2019; Alme et al., 2020
**Johnson et al., 2016

Development of the framework

Steps of the framework



Development of the framework

Steps of the framework

Generating data with Monte Carlo

↓

Adding simulated measurement errors

↓

3-sigma filtering

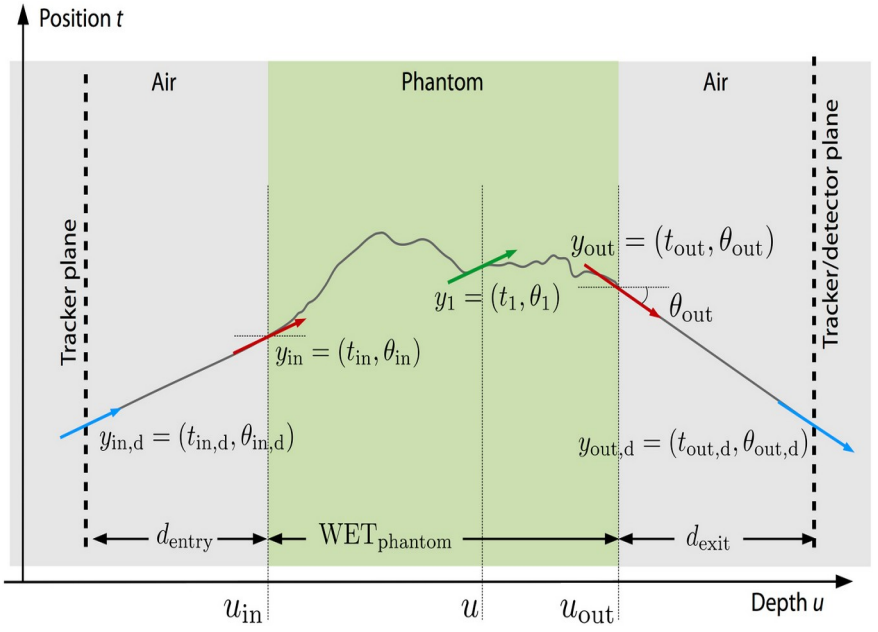
↓

MLP calculation

↓

Calculating RSP distribution with Richardson-Lucy algorithm

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

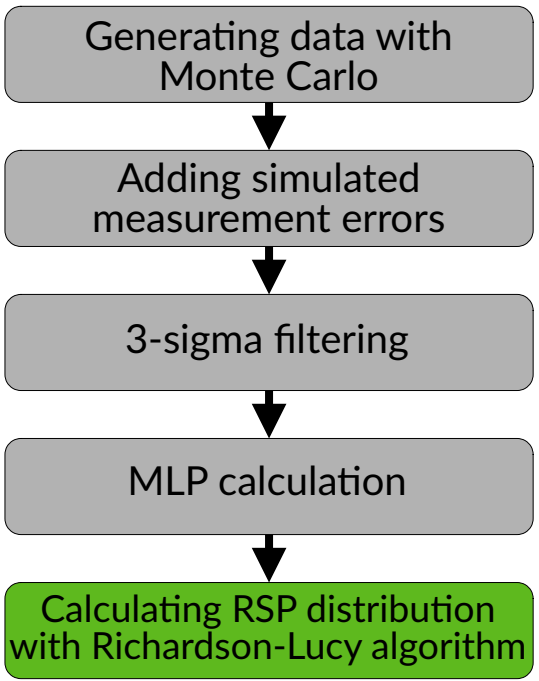


Compromise is needed between runtime and accuracy!

*Krah et al., 2018.
Schulte et al., 2008.
Williams, 2004.

Development of the framework

Steps of the framework



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

Number of iterations

Vector containing WEPL values

Matrix containing interaction coefficients between proton trajectories and voxels

Vector containing RSP values

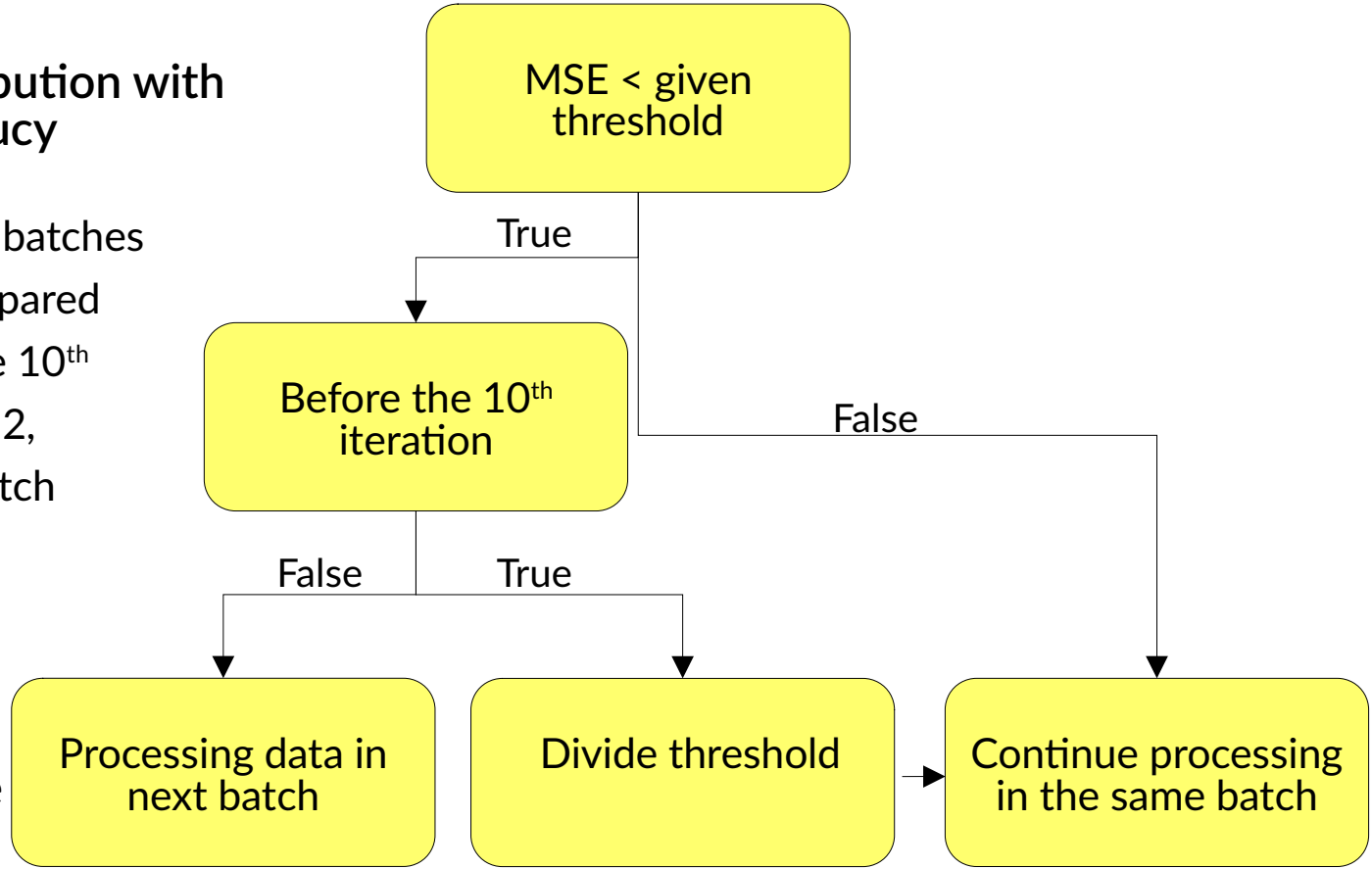
- Statistical iterative algorithm
- Maximum Likelihood - Expectation Maximization (ML-EM)
- Originally used in optics
- Very difficult technically (~millions of proton trajectories)
- Using GPU (CUDA): C++ code: different parts run in the GPU kernels (WSCLAB) → Nvidia GTX 1080 Ti GPU, 32 GB RAM
  - ➔ Goal: Finding optimization regarding the number of iterations and protons

Development of the framework

Calculating RSP distribution with Richardson-Lucy

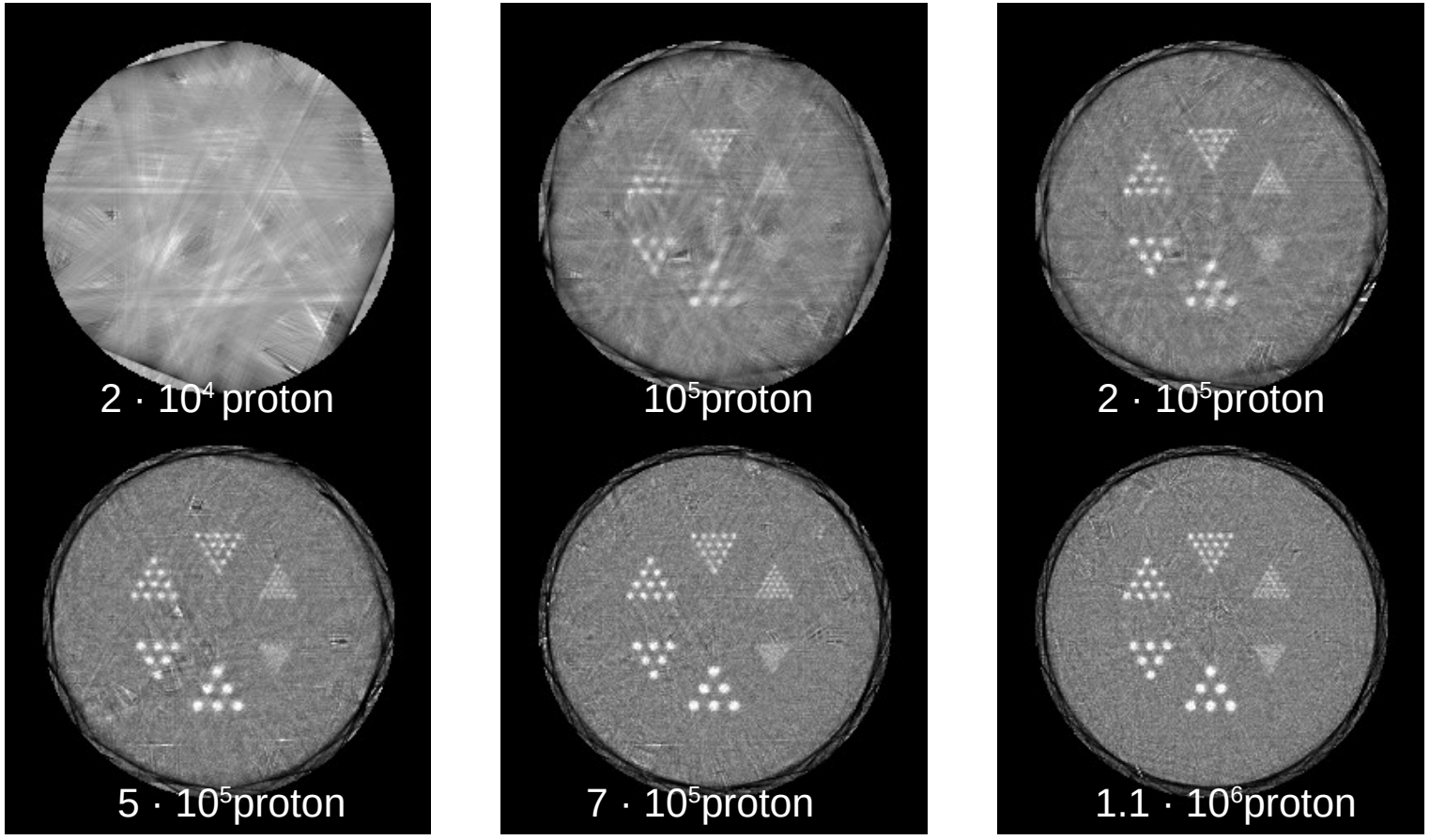
- Data to be processed is grouped in batches
- The consecutive iterations are compared
- If MSE < given threshold before the 10th iteration, threshold gets divided by 2, otherwise iterations stop in that batch

Significant speed-up in runtime
(hours → minutes)
(~10^6 protons)



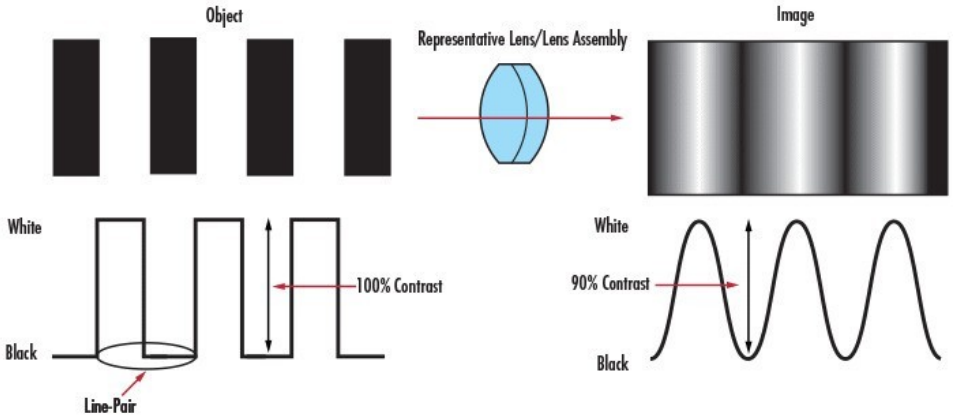
Evaluation of the framework

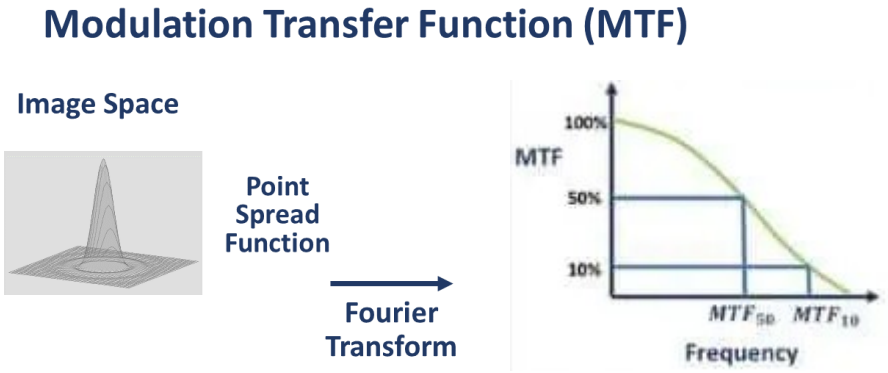
Spatial resolution with Derenzo phantom



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

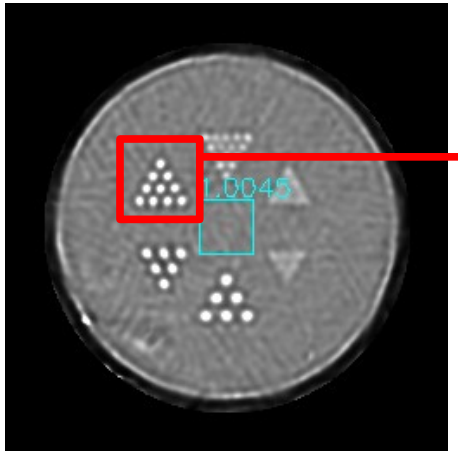




The more linepairs we can differentiate, the better the resolution is

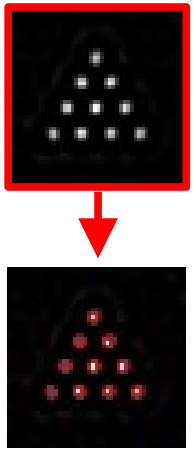
Spatial resolution with Derenzo phantom

(i)



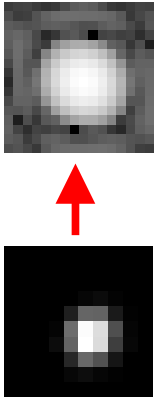
Subtract the mean background

(ii)



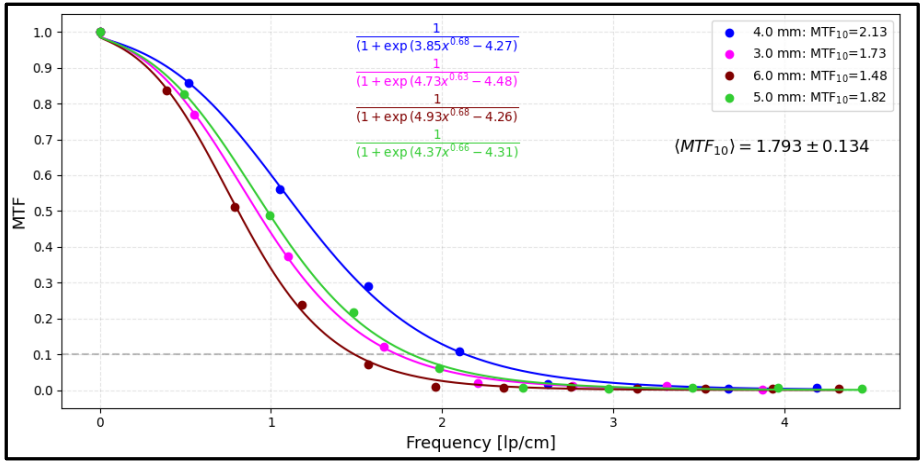
Find individual rods from each sector

(iii)



Average them → Point Spread Function

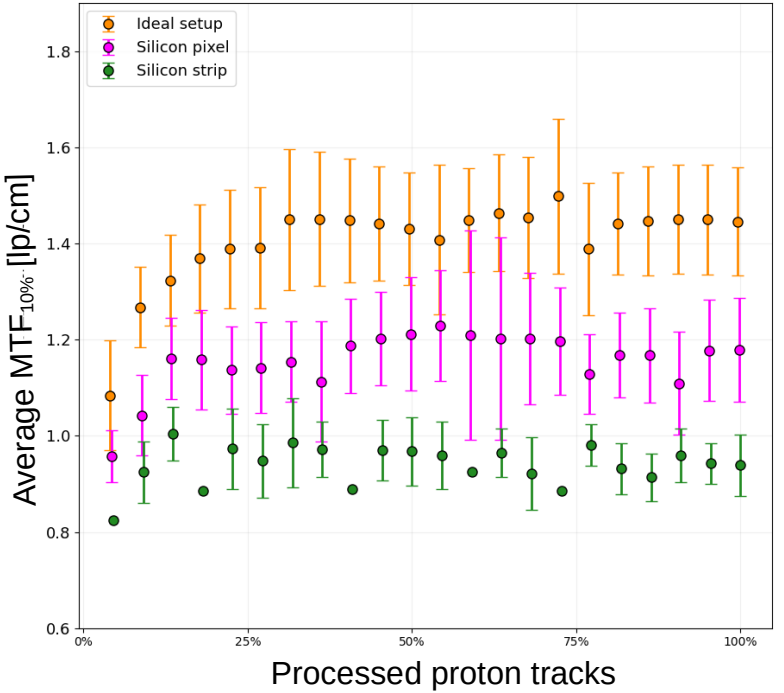
(iv)-(v)



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

Spatial resolution with Derenzo phantom

	Ideal	Reference - ideal	Realistic	Reference - realistic
MTF10% [lp/cm]	1.43	3.8	1.17 (pixel) 0.94 (strip)	3.2

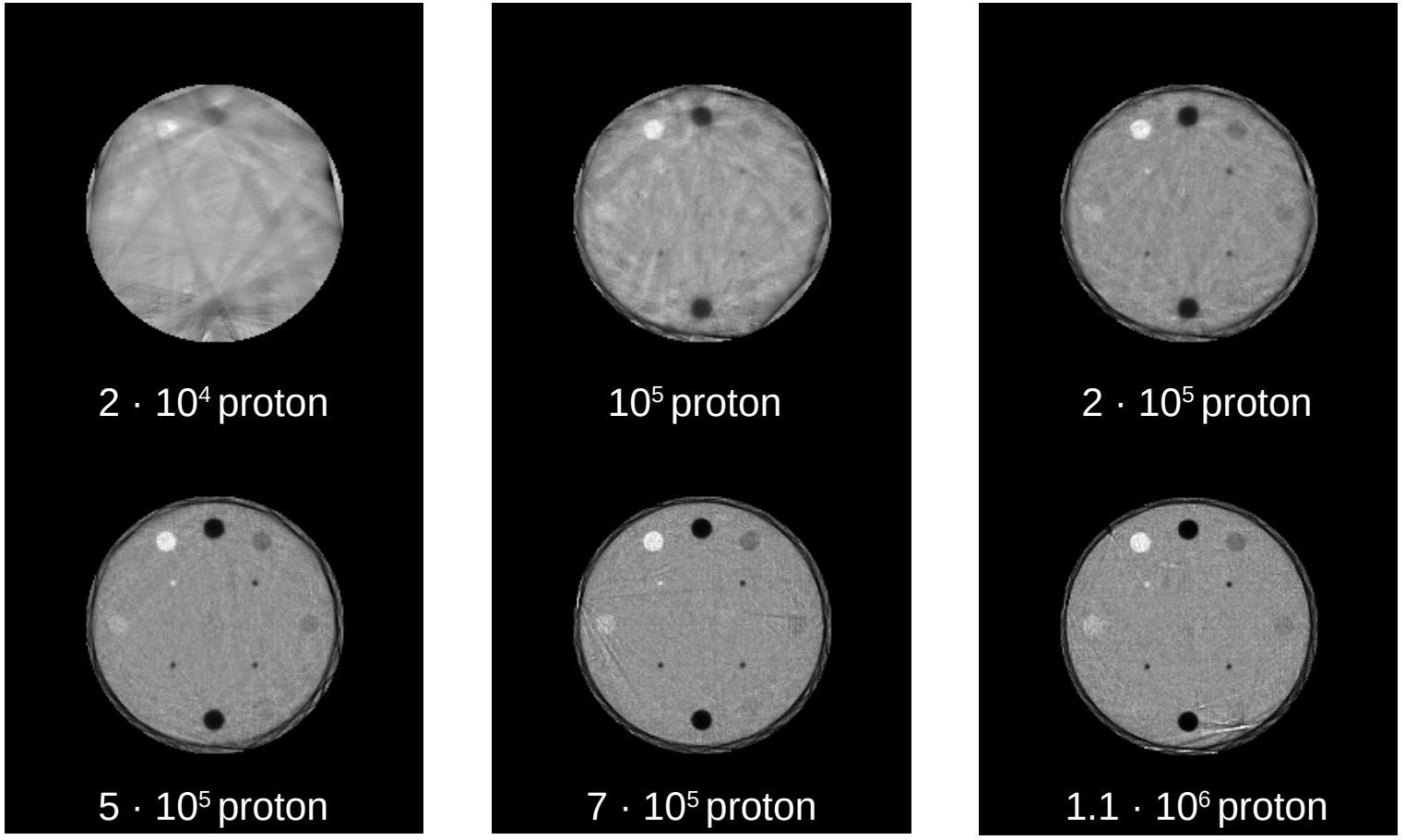


Results compared to literature: promising, but still need development

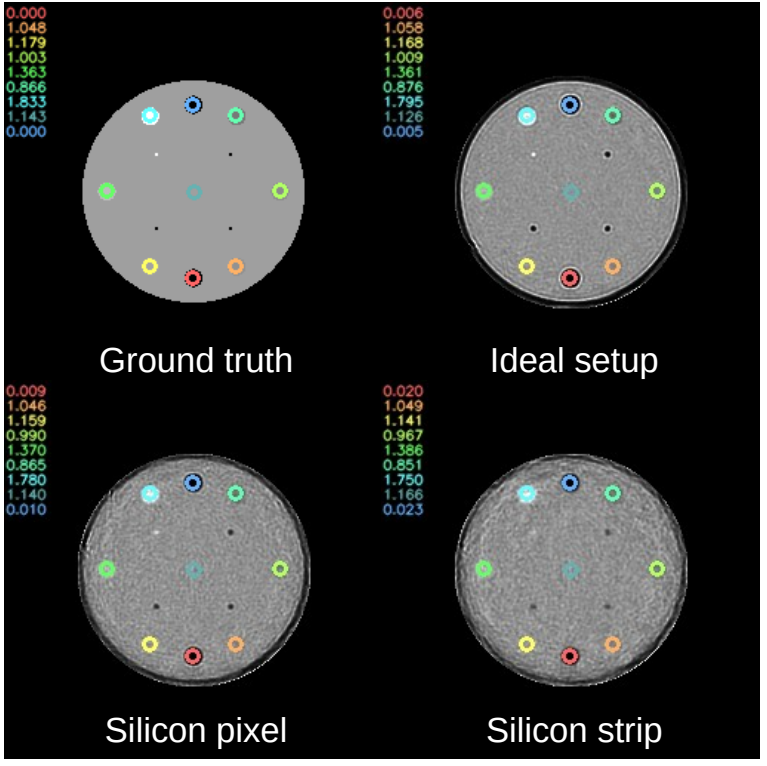
Sølie et al., 2020

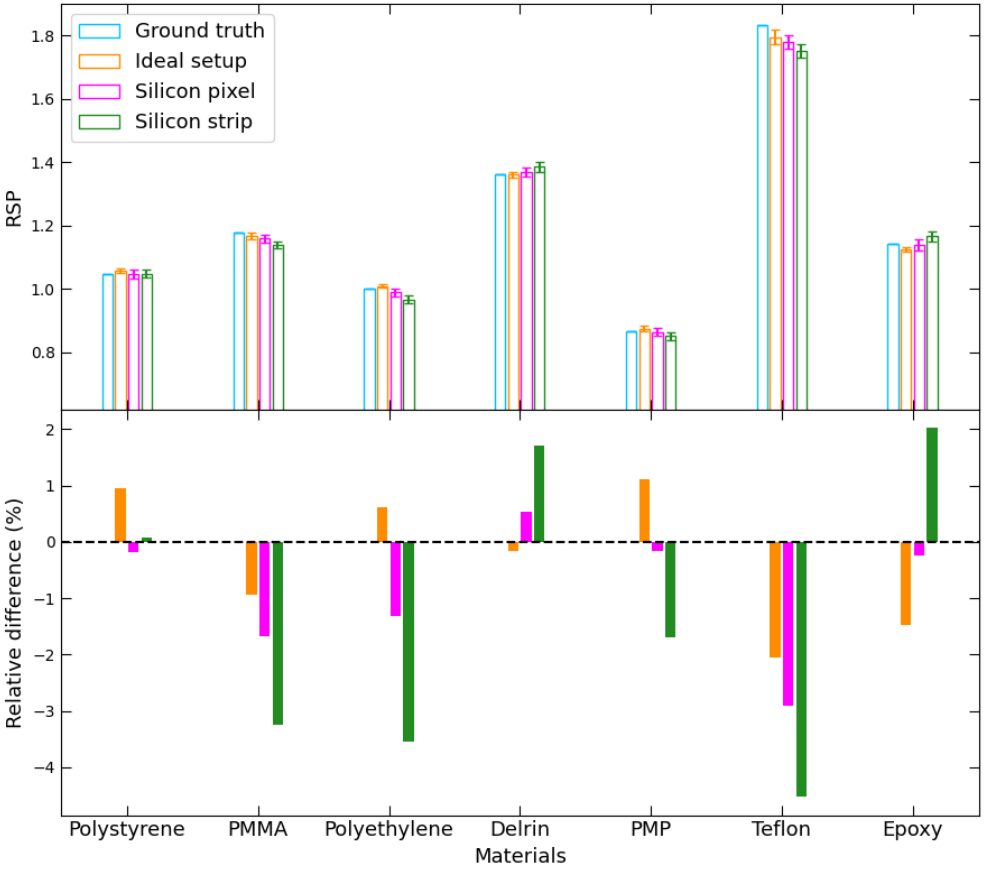
Gábor Bíró, Ákos Sudár, Zsófia Jólesz, Gábor Papp, Gergely Gábor Barnaföldi. Proton Computed Tomography Based on Richardson-Lucy Algorithm. ArXiv:2212.00126.

RSP reconstruction accuracy with CTP404 phantom



RSP reconstruction accuracy with CTP404 phantom





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

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

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
- 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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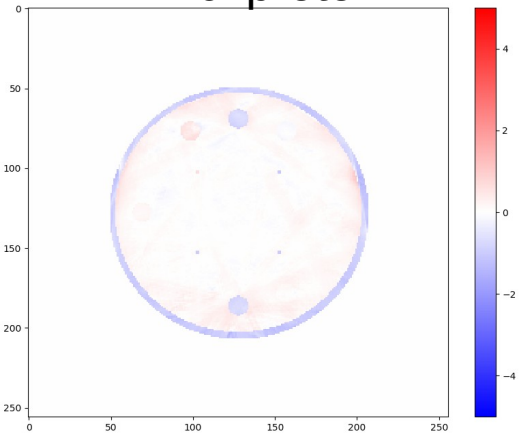
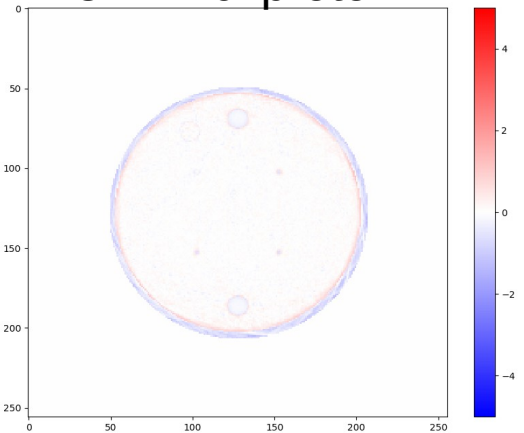
Backup - Differences between the RSP values

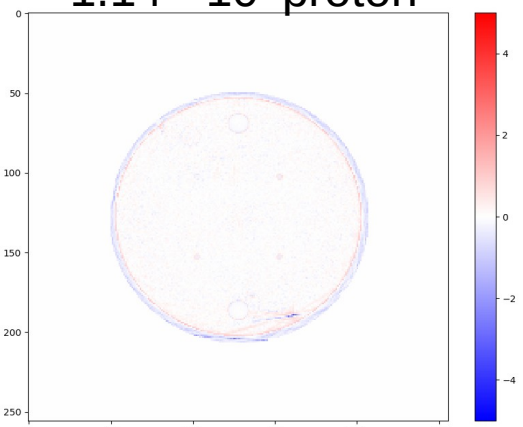
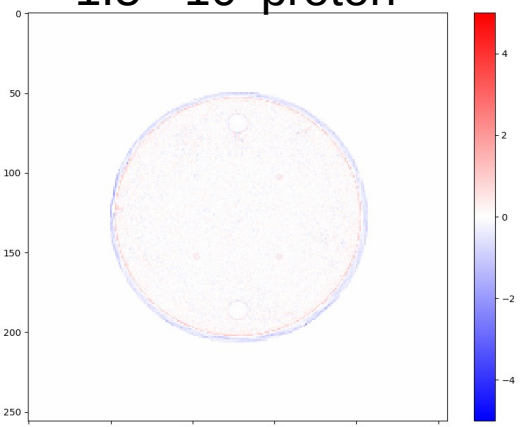
$2 \cdot 10^4$ proton



$3.4 \cdot 10^5$ proton



$1.14 \cdot 10^6$ proton



$1.5 \cdot 10^6$ proton