Application of a Statistically Based, Iterative Image Reconstruction Algorithm for Proton Computed Tomography

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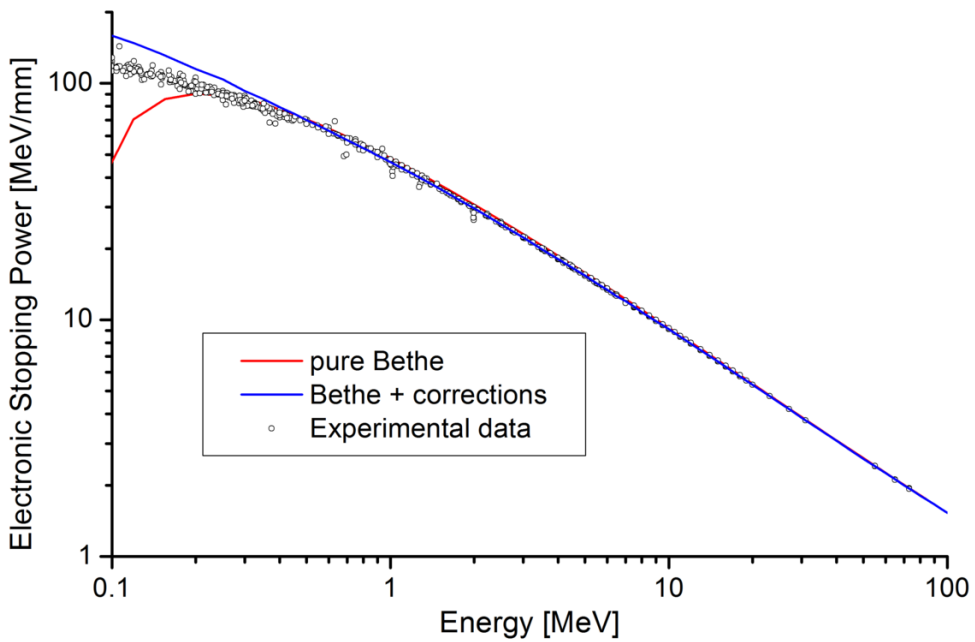
on behalf of Bergen proton CT collaboration
(full collaboration list)

Ref: Front. in Phys. Med. Phys. Im. ID: 568243, Phys. in Med. & Bio. ID: 110623.R3, NIM A 860 (2017) 51–6152, Phys. Med. 63 (2019) 87–97

The Bethe Formula – How to Apply?

The Bethe formula describes the energy loss of charged particle travelling through material. The non relativistic version of formula was introduced by Bethe in 1930, and the relativistic in 1932.

$$-\left\langle \frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle = K\, z^2\, \frac{Z}{A}\, \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right],$$

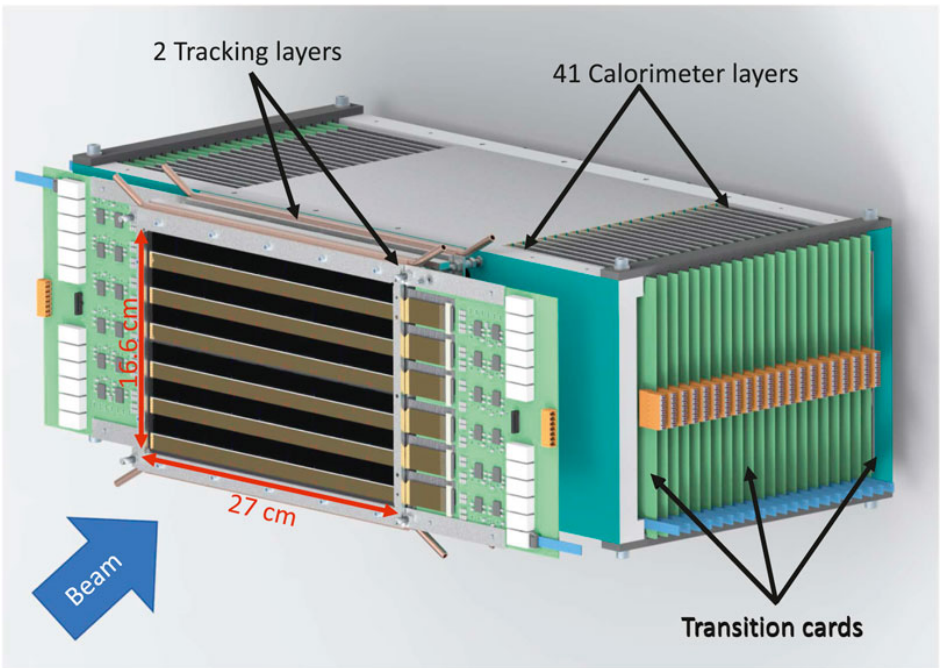


The Importance of Proton CT Imaging

- A CT measures the distribution of a material property
  - Relative stopping power (RSP) in case of pCT
- Nowadays RSP distribution is converted from X-ray CT
  - Large uncertainty $\Rightarrow$ significant reduction with pCT
    $\Rightarrow$ reduced safety zone around the tumour
- The number of proton facilities is rapidly increasing
  $\Rightarrow$ Increasing importance to develop this technique

Bergen pCT Collaboration

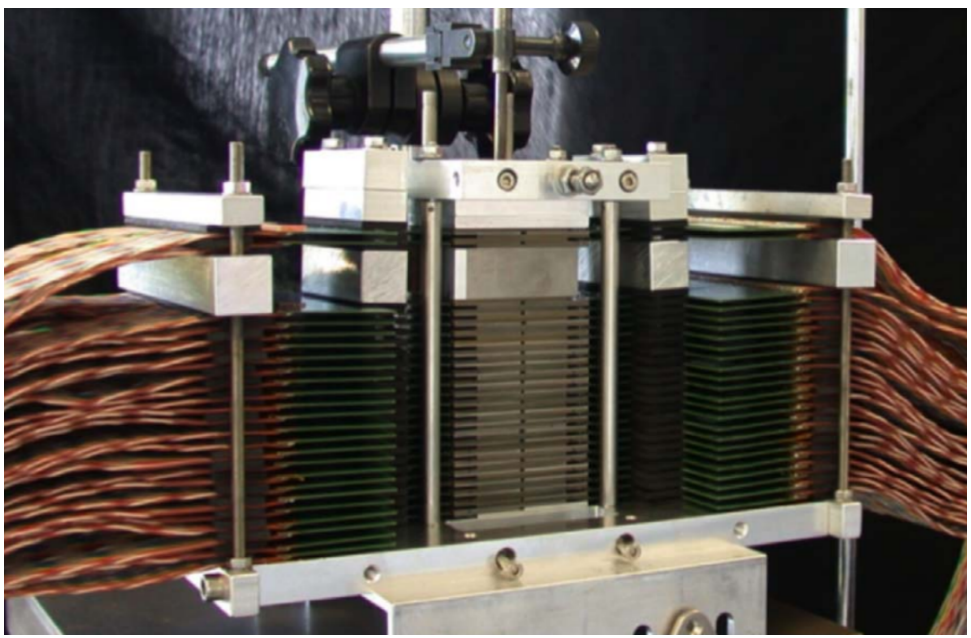
- Goal: reach the clinical testing with a prototype pCT detector
- Monolithic active pixel sensor (MAPS)
- Pencil beam ($\sim$ 7 mm)
- Individual measurement of 10^7 proton per second

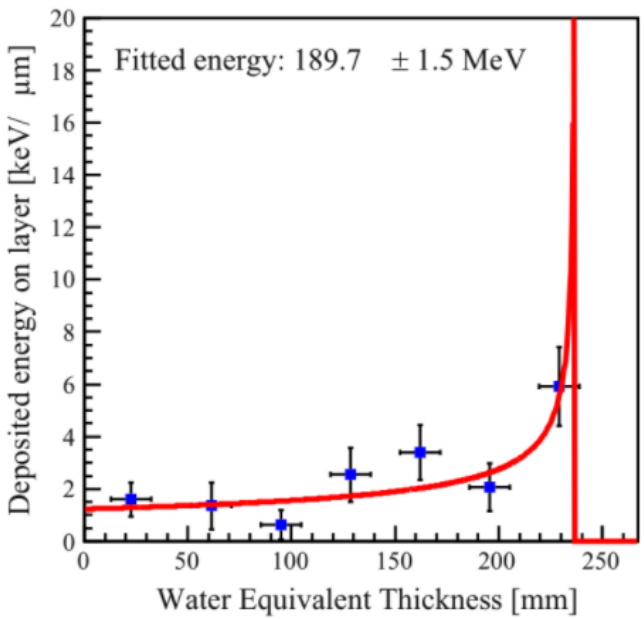


Bergen pCT Collaboration – Previous Results

Proof of concept detector:

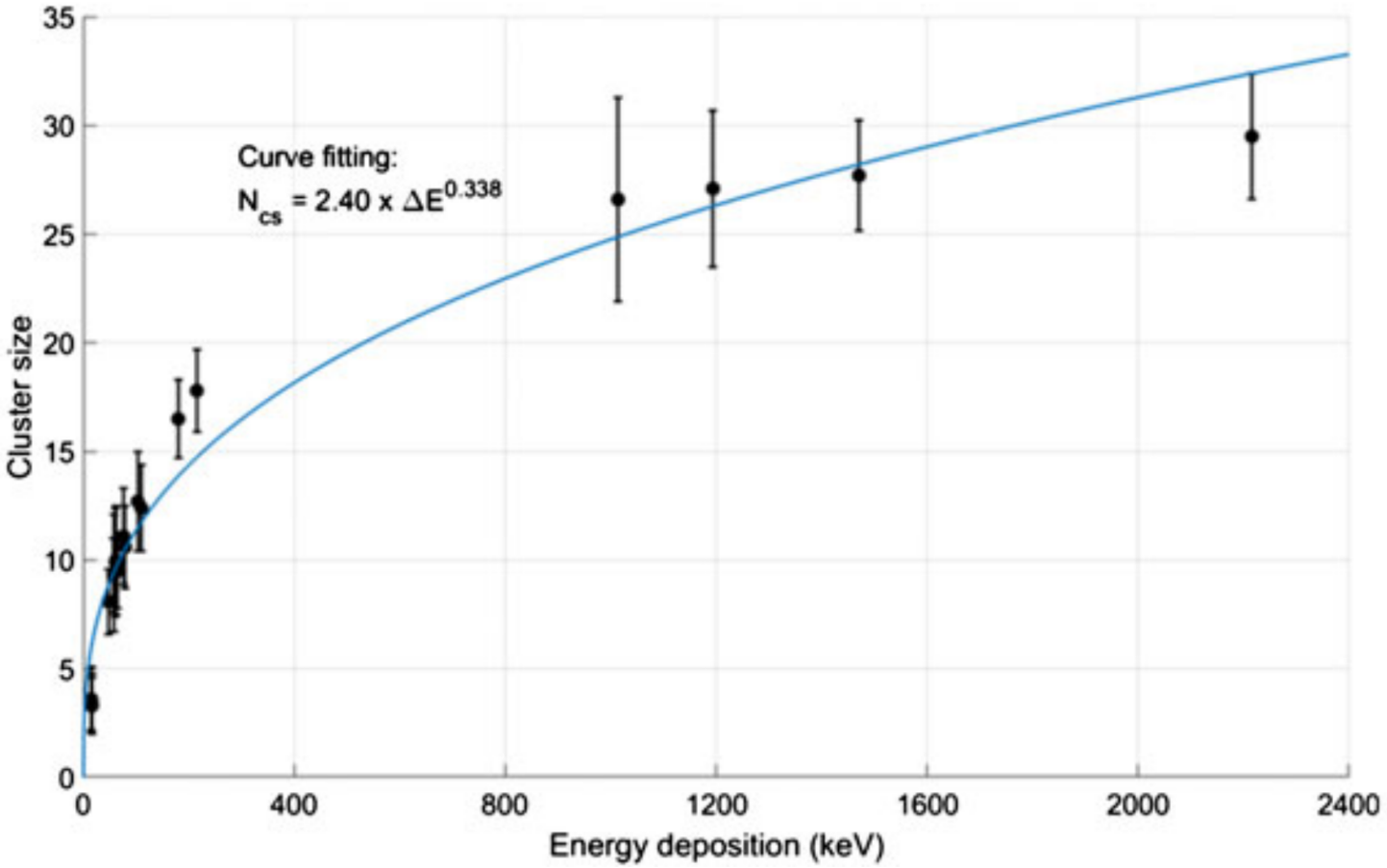
- Prototype of the high-granularity digital tracking calorimeter for pCT application
- MC simulation 10^6 proton per second
- 4 % water equivalent thickness (WET) range resolution for individual protons





Bergen pCT Collaboration – Previous Results

- Cluster size – deposited energy
- Measured in Heidelberg Ion Beam Therapy Center (HIT)
- Proton, helium and carbon; energy: 50-230 MeV/u



Bergen pCT Collaboration – Wigner Contribution

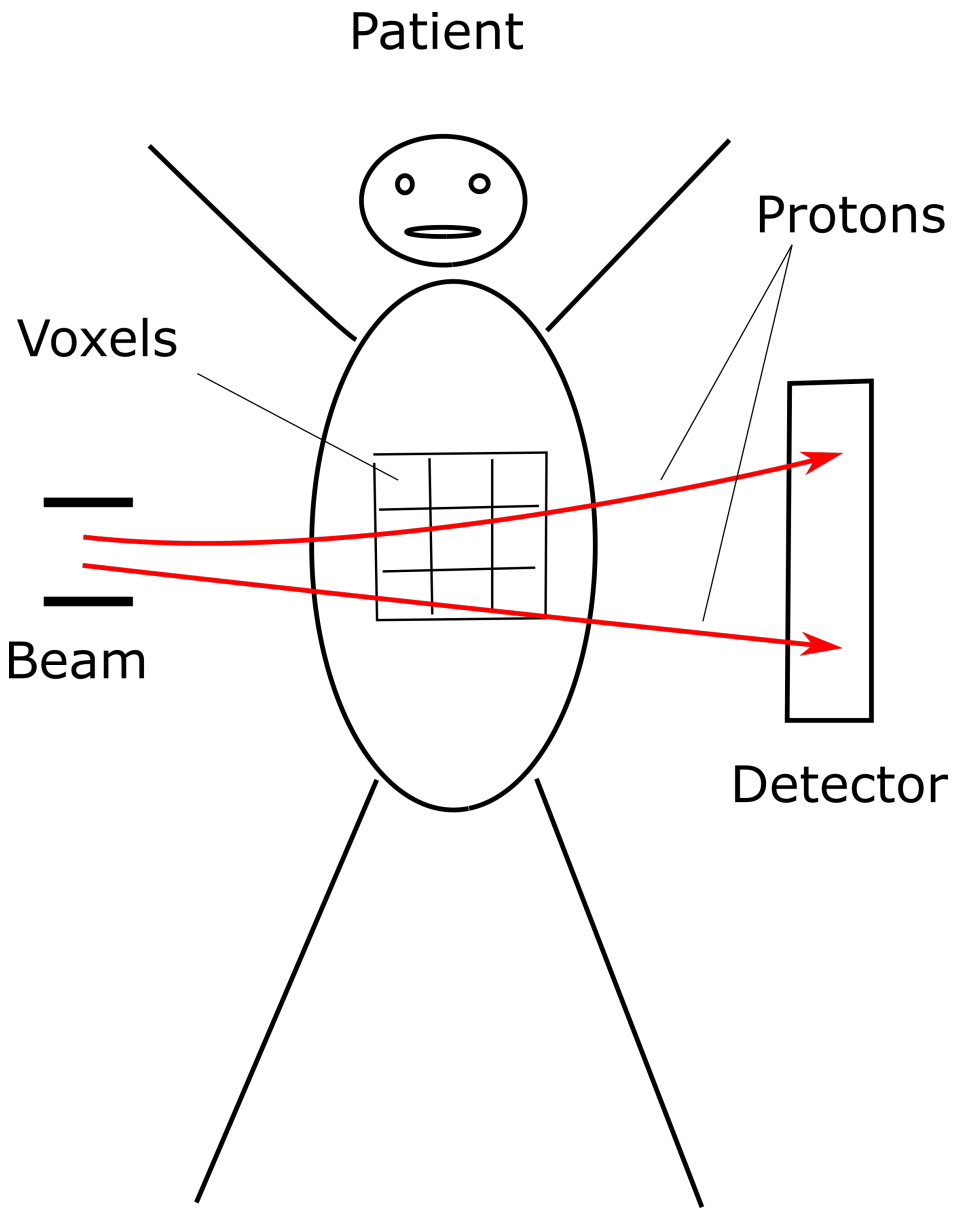
- **Data analysis of test beam measurements: ALPIDE characterization:**
  G. Tambave *et al* (included Á. Sudár), Characterization of monolithic CMOS pixel sensor chip with ion beams for application in particle computed tomography, Nuclear Instruments and Methods in Physics Research Section A, **958**, 2020, doi: 10.1016/j.nima.2019.162626.
- **Numerical analysis of the cooling system:**
  J. Alme *et al* (included Á. Sudár), A High-Granularity Digital Tracking Calorimeter Optimized for Proton CT, Frontiers in Physics, **8**, 2020, doi: 10.3389/fphy.2020.568243.

Bergen pCT Collaboration – Recent Studies

Image reconstruction

Application of the Richardson – Lucy algorithm

Imaging with protons



Relative Stopping Power

Stopping power in units of stopping power of water

$\Rightarrow$ Advantage: almost energy independent (50 - 250 MeV/u)

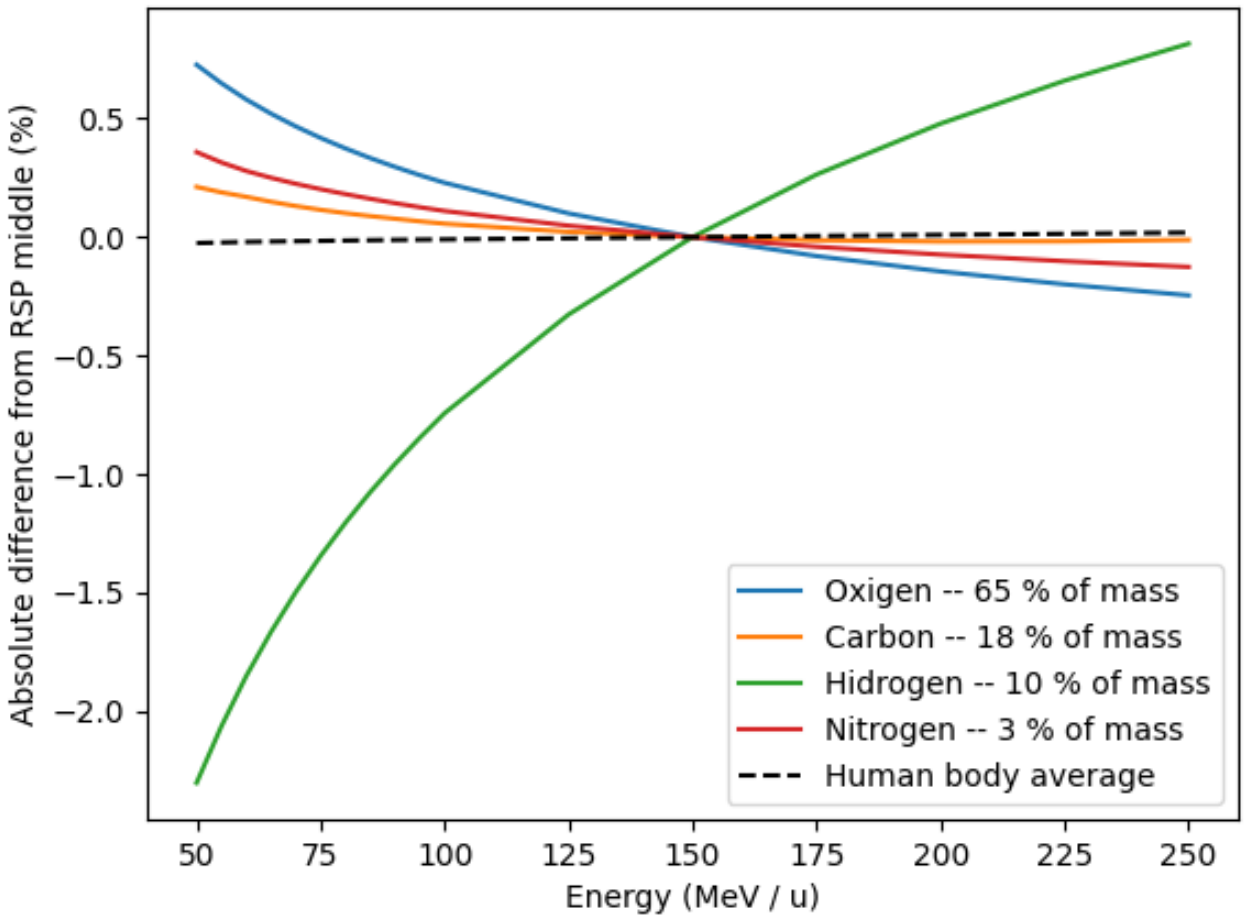


Image Reconstruction – a Huge Linear Problem

The image reconstruction is a huge linear problem:

$$\mathbf{y} = \mathbf{A}\,\mathbf{x}\ ,$$

where:

- $\mathbf{y}$ is the energy loss of protons $\Leftrightarrow$ track integral of RSP
- $\mathbf{x}$ RSP value of voxels
- $\mathbf{A}$ system matrix: proton – voxel interaction coefficients

Goal: Solve the linear problem

$$\mathbf{x} = \mathbf{f}\,(\,\mathbf{y},\ \mathbf{A}\,)\ .$$

Image Reconstruction – the Richardson – Lucy algorithm

- First application in the field of proton CT imaging
- Originally developed for astrophysics image reconstruction
- It is a fixed point iteration for sparse systems
- Initialization: arbitrary positive vector
  Usually unit vector or approximate solution

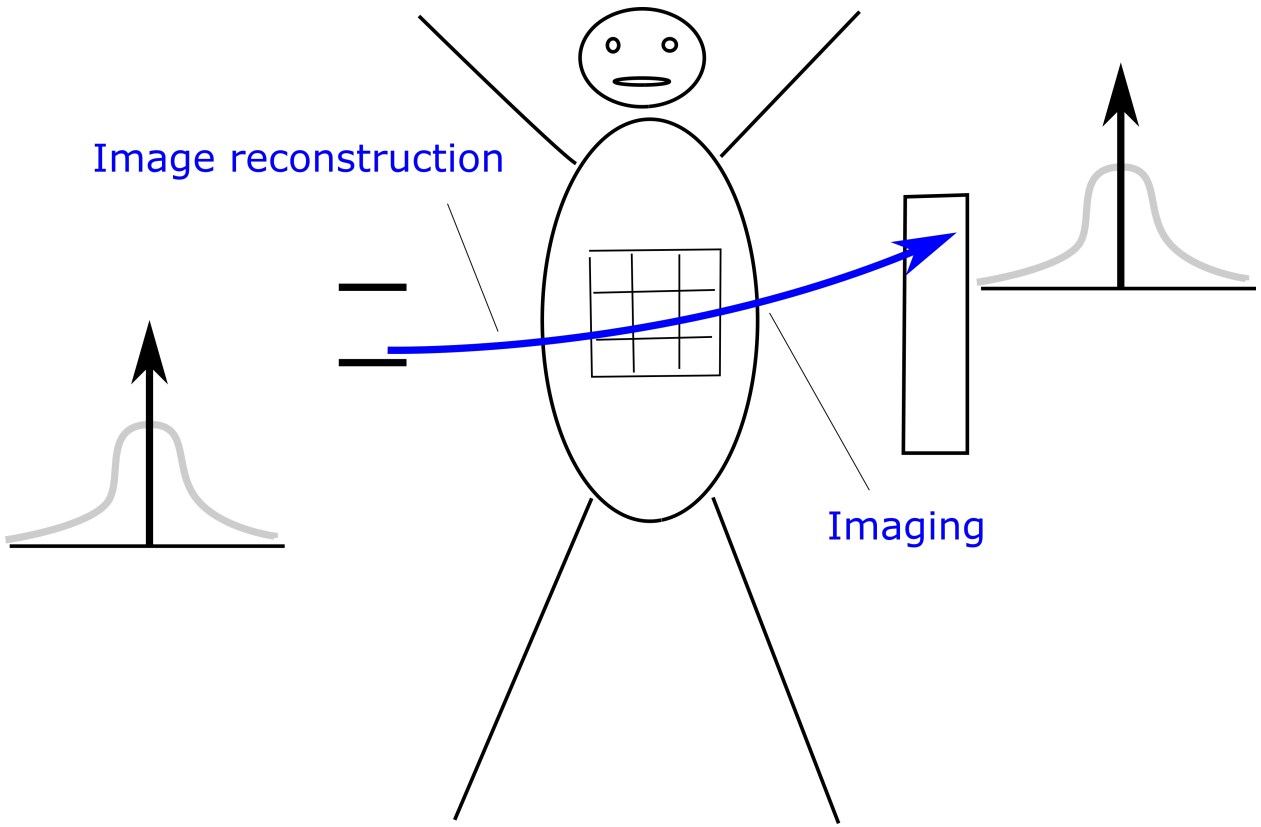
Approximation of the i$^{\text{th}}$ voxel of the next iteration:

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

where k is the iteration number. Typically takes 20-300 iterations.

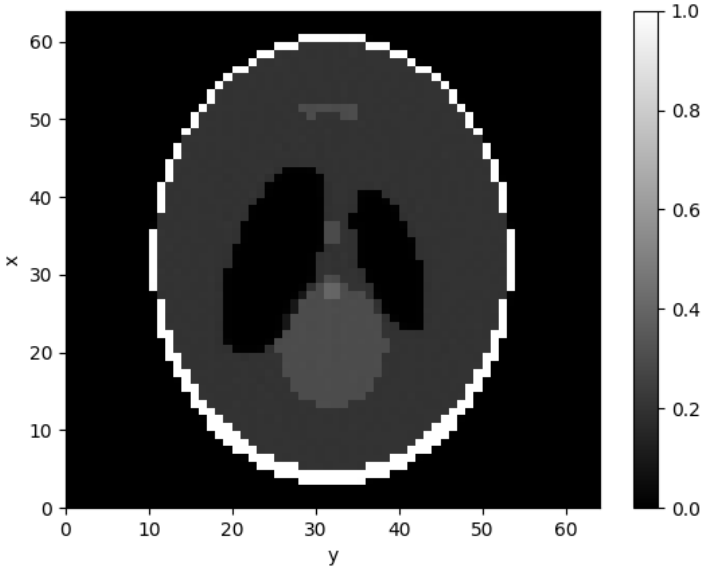
Ideal Imaging

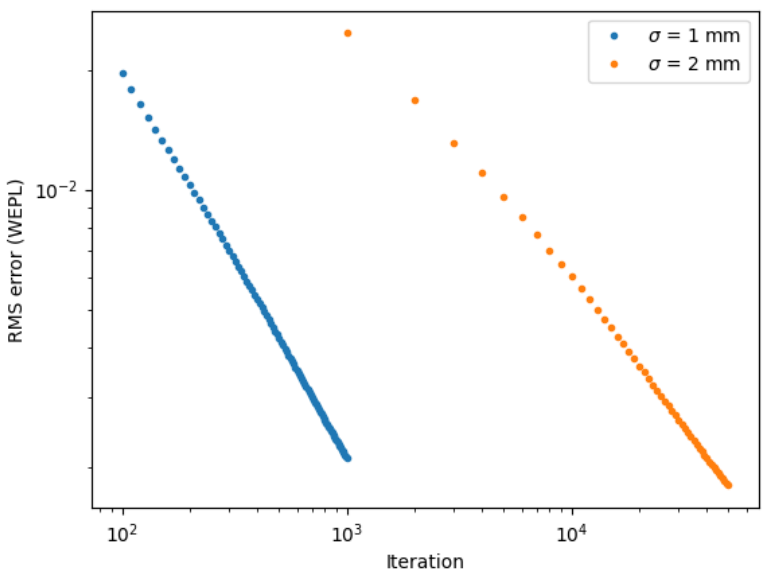
No angular end spatial error in the endpoints



Ideal Imaging – Shepp–Logan Phantom

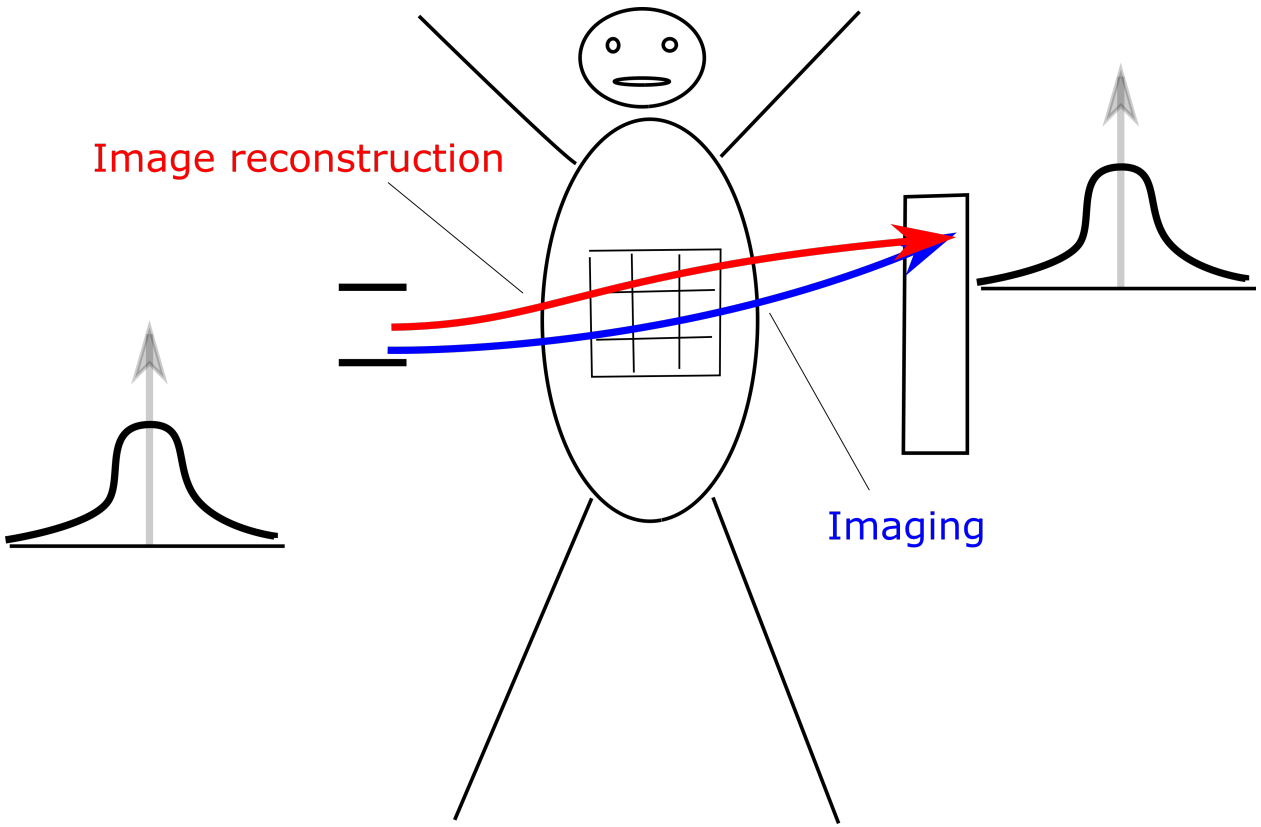
- Reconstructed RSP distribution and convergence





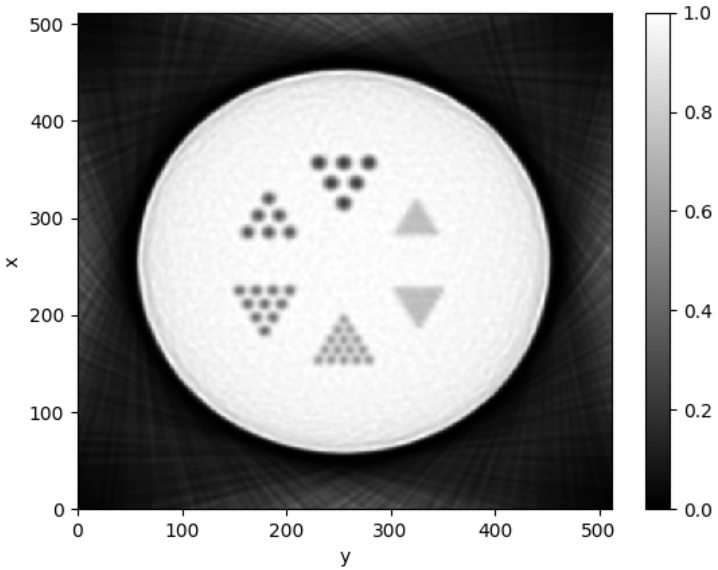
Realistic Imaging – Taking into Account Errors

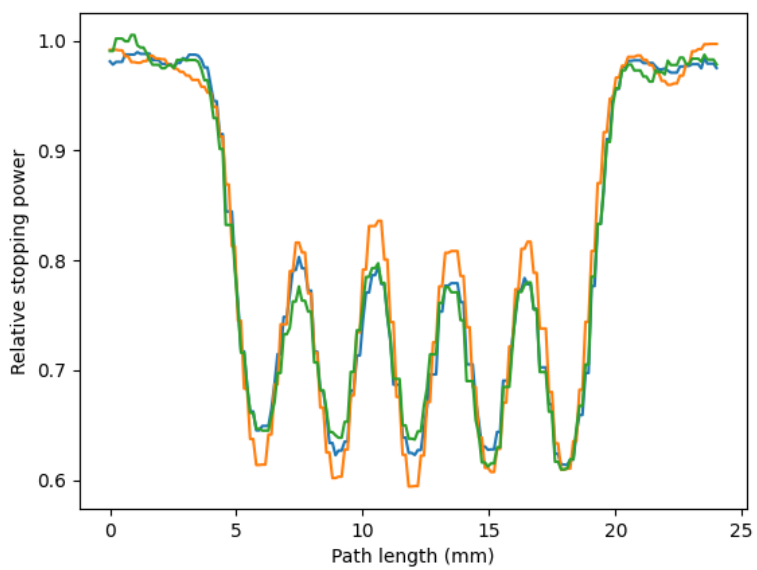
Analytically calculated angular end spatial error in the endpoints



Derenzo Phantom – Spatial Resolution

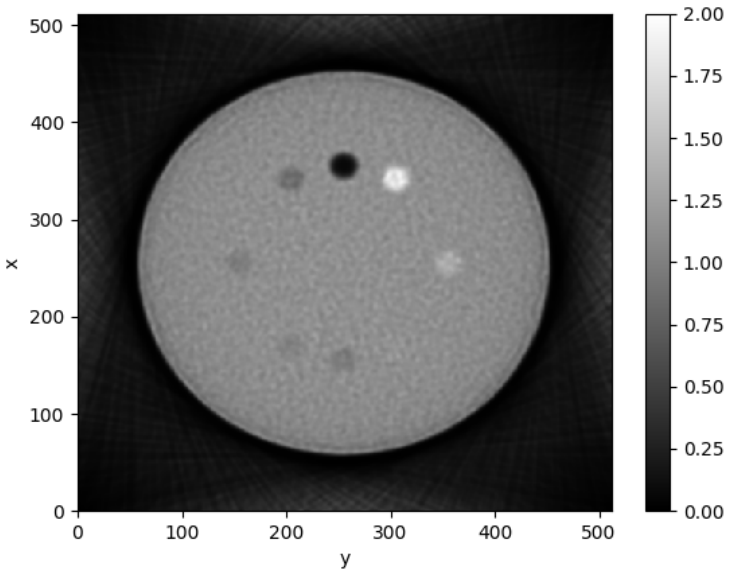
- Reconstructed RSP distribution and valley-to-peak distribution
- Spatial resolution is the FWHM of the point spread function
- Proton CT literature: 3.1 mm $<$ my algorithm: 4.3 mm

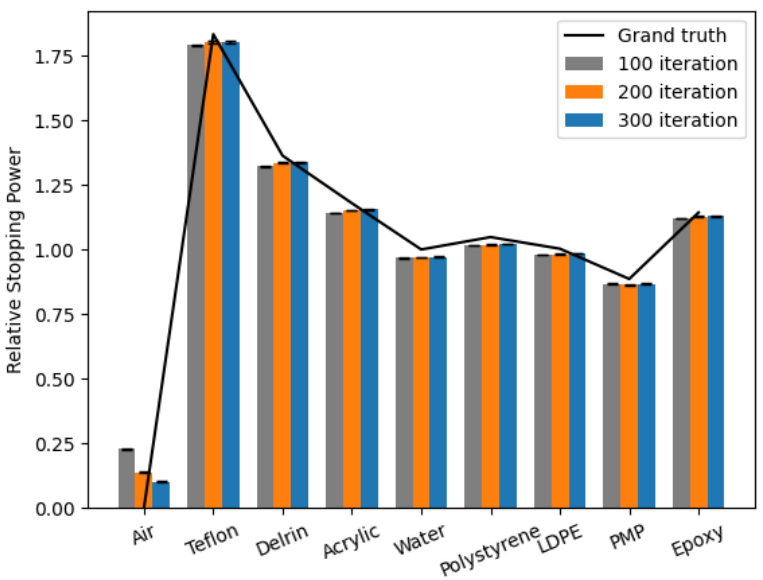




CTP404 Phantom – RSP Accuracy

- Reconstructed RSP distribution and avg. RSP of the inserts
- RSP accuracy: pCT literature: 0.4% < my algorithm: 3%





Summary

Technique:

- Application of Richardson – Lucy algorithm for pCT

Results:

- Works well, promising results
- Further investigations is required

Bergen pCT Collaboration:

- Develop a pCT detector for clinical testing

Reached results:

- Working proof of concept detector system
- Measurements for low energy ALPIDE characteristics
- A detailed engineering design $\Rightarrow$ under construction

The Bergen pCT Collaboration

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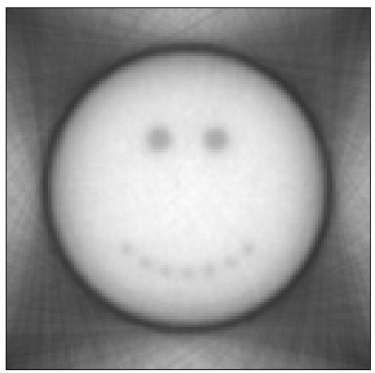
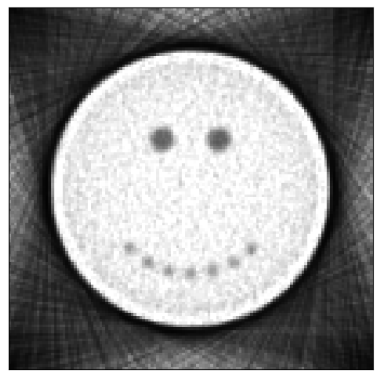
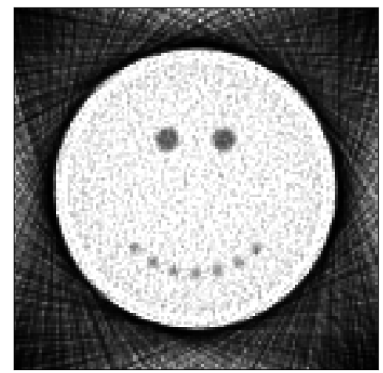
Thank you for your attention!

This work would not be possible without the support of the Research Council of Norway (Norges forskningsråd), grant number 859 250858; the Trond Mohn Foundation, grant number BFS2017TMT07; Hungarian National Research, Development and Innovation Office (NKFIH) grants under the contract numbers OTKA K135515 and 2019-2.1.6-NEMZ_KI-2019-00011. Computational resources were provided by the Wigner GPU Laboratory.