Particles against cancer – Iterative Image Reconstruction Algorithm for Proton Computed Tomography

Ákos Sudár [1,2]

Gergely Gábor Barnaföldi [1] and Dávid Légrády [2]

[1] Wigner Research Centre for Physics
[2] Budapest University of Technology and Economics

Margaret Island Symposium 2022 on Vacuum Structure, Particles, and Plasmas, 17 May 2022

The Bergen pCT Collaboration

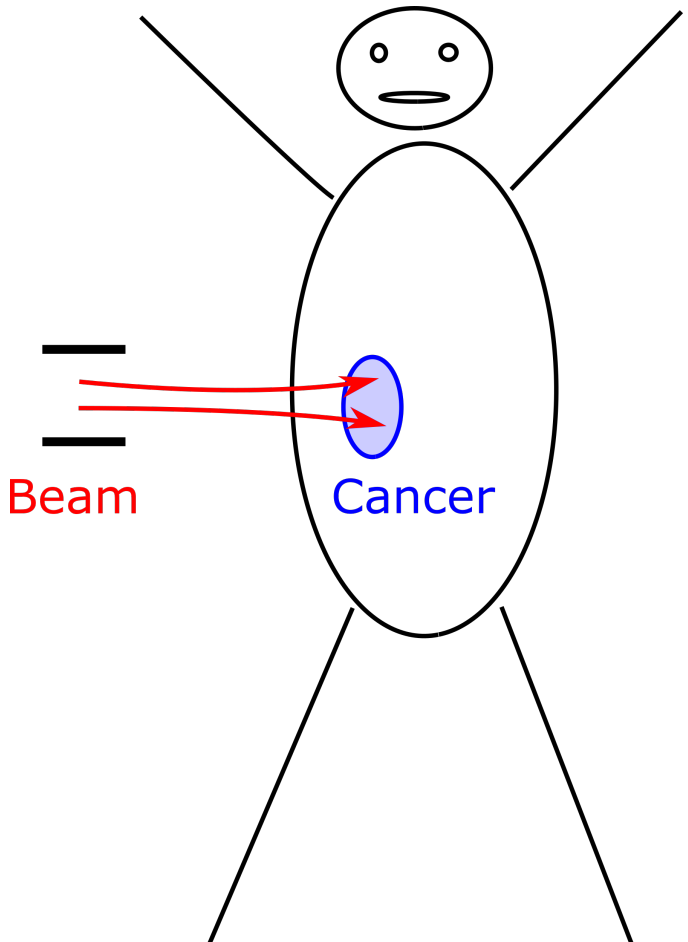
Members of the Bergen pCT collaboration: [a]Department of Physics and Technology, University of Bergen, 5020 Bergen, Norway [b]Department of Oncology and Medical Physics, Haukeland University Hospital, 5021 Bergen, Norway [c]Department for Theoretical Physics, Heavy-Ion Research Group, Wigner RCP of the Hungarian Academy of Sciences, 1121 Budapest, Hungary [d]Institute for Subatomic Physics, Utrecht University/Nikhef, Utrecht, Netherlands [e]Department of Computing, Mathematics and Physics, Western Norway University of Applied Science, 5020 Bergen, Norway [f]Department of Electrical Engineering, Western Norway University of Applied Sciences, 5020 Bergen, Norway [g]Institute for Physics, Eötvös Loránd University, 1/A Pázmány P. Sétány, H-1117 Budapest, Hungary [h]Department of Physics, University of Oslo, 0371 Oslo, Norway [i]Department of Biomedical Physics in Radiation Oncology, German Cancer Research Center, Heidelberg, Germany [j]Department of Physics and Astronomy, Heidelberg University, Heidelberg, Germany [k]Center for Technology and Transfer (ZTT), University of Applied Sciences Worms, 67549 Worms, Germany [l]LTU, Kharkiv, Ukraine [m]Institute of Science, Suranaree University of Technology, Nakhon Ratchasima, Thailand [n]College of Mechanical & Power Engineering, China Three Gorges University, Yichang, China [o]Chair for Scientific Visualization Lab, Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany [p]Chair for Scientific Computing, Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany [q]St. Petersburg University, St. Petersburg, Russia

Proton therapy against cancer

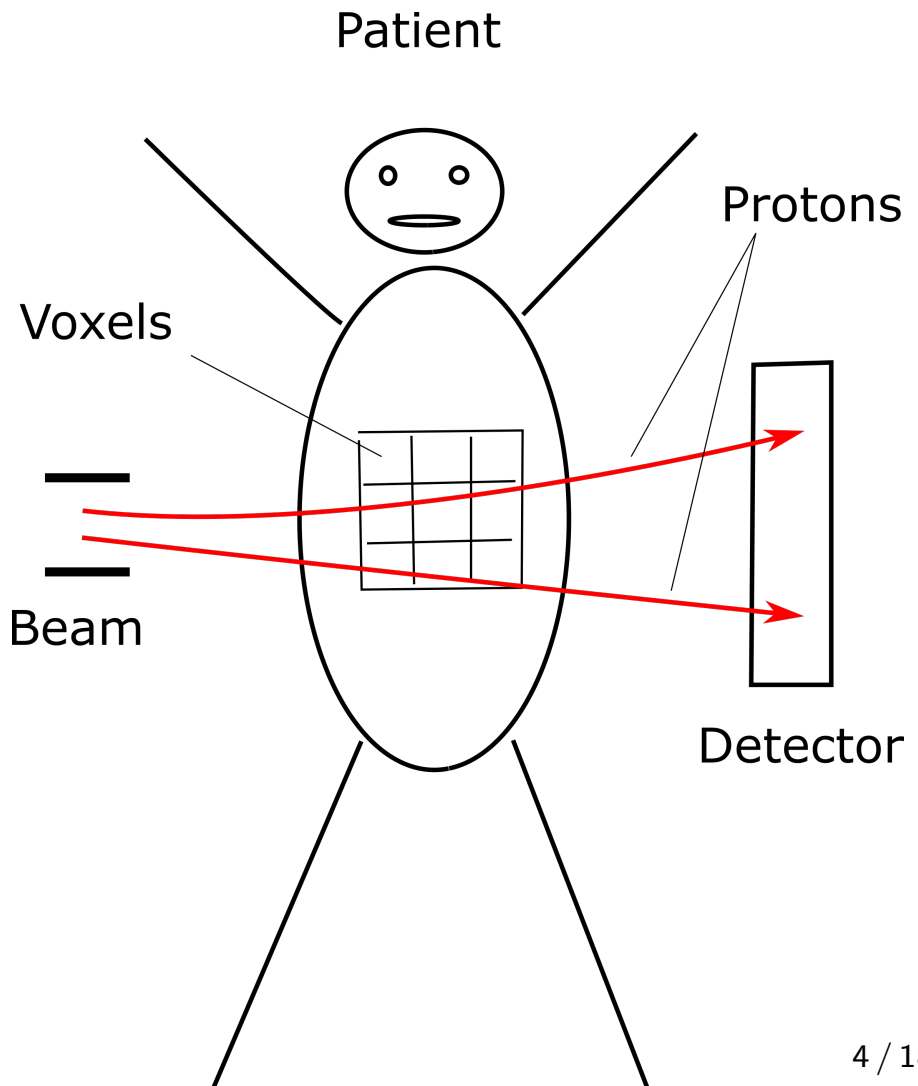
Goal: minimize the uncertainties of the treatment

Why proton therapy requires imaging?

Therapy:



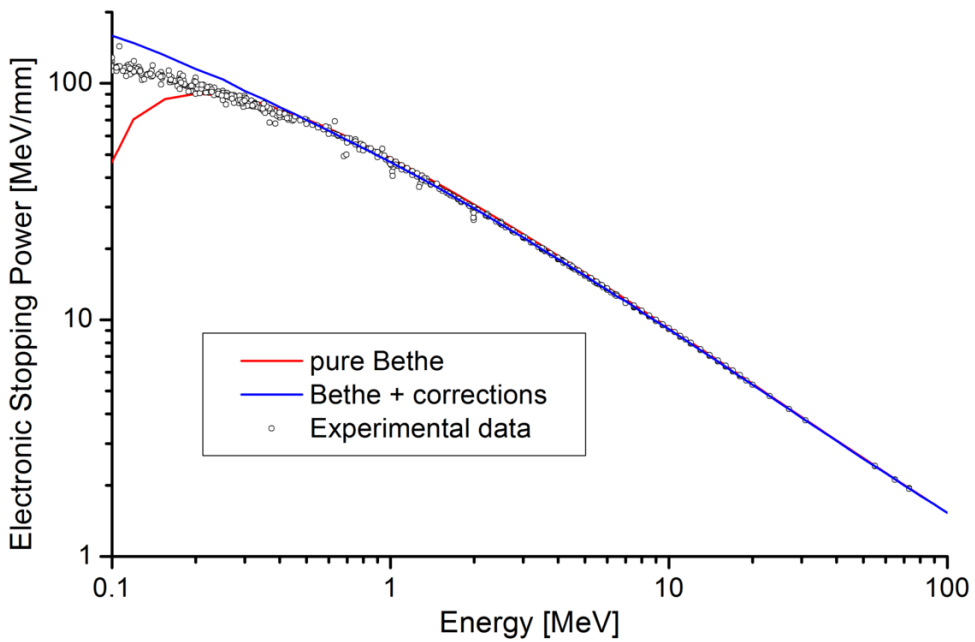
Imaging:



Characterize proton energy loss – The Bethe Formula

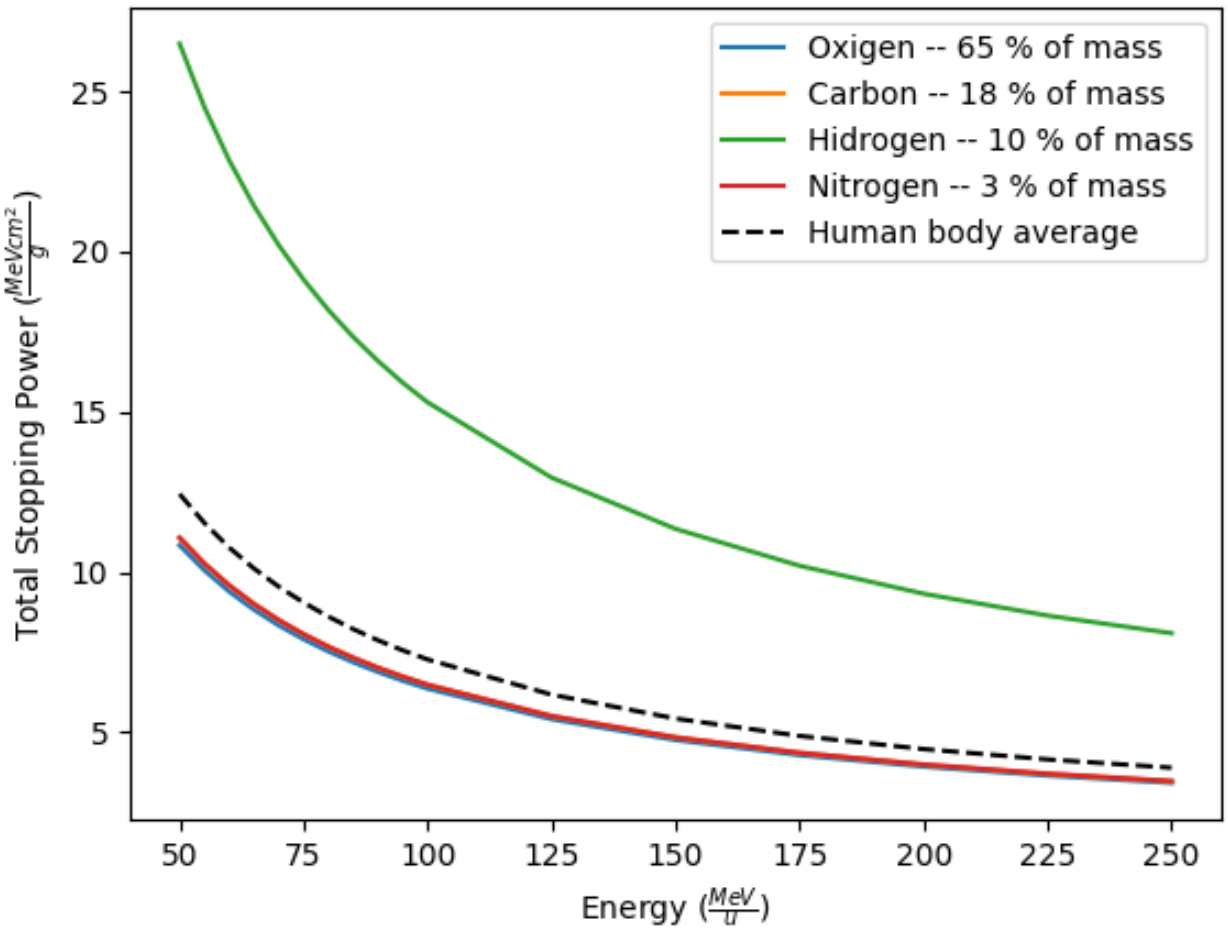
The Bethe formula describes the energy loss of charged particle travelling through material. The non relativistic version of formula was introduced by Bethe in 1930, and the relativistic in 1932.

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



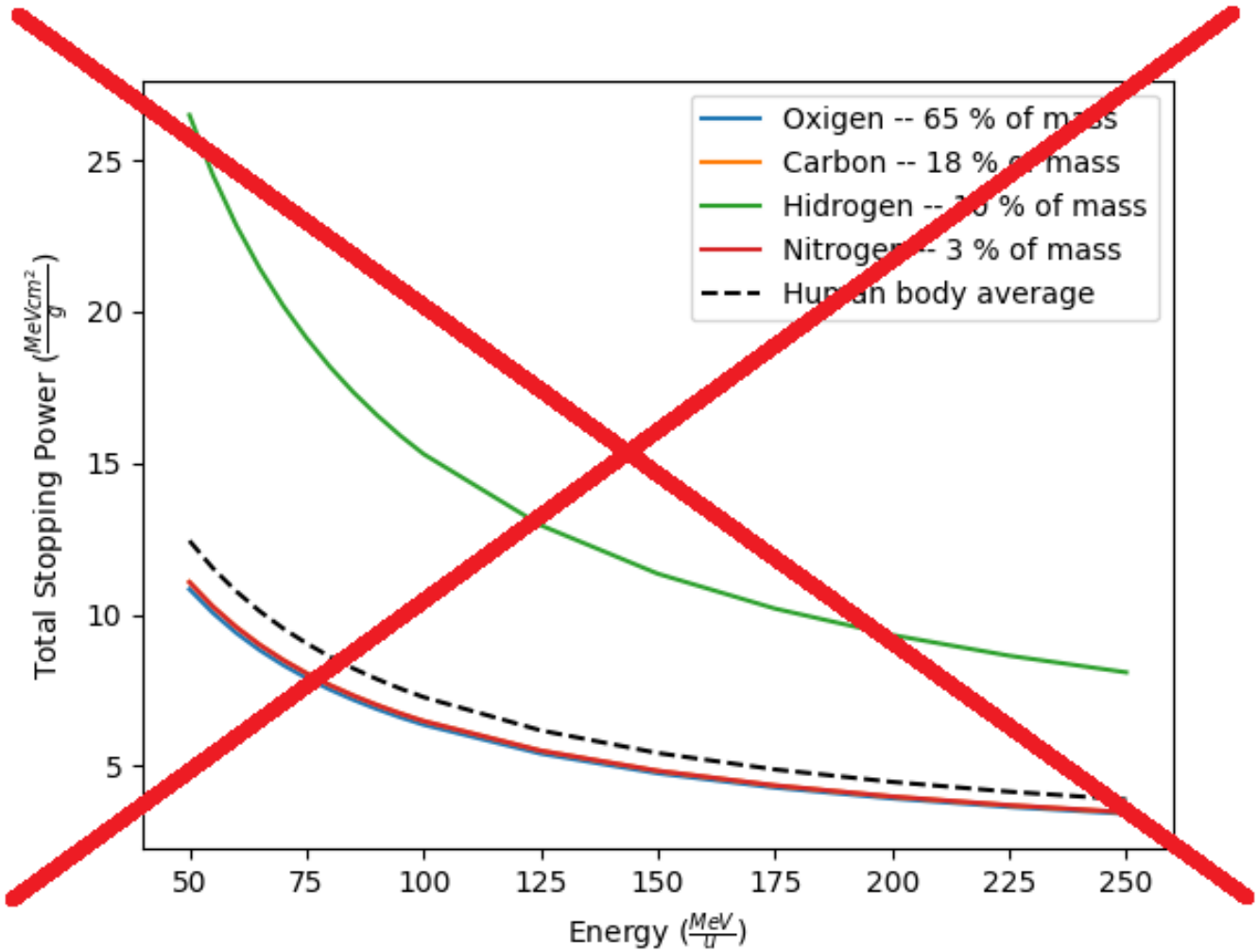
What are we reconstructing? – Stopping Power

Stopping power $\Rightarrow$ strong energy dependence (50 - 250 MeV/u)



What are we reconstructing? – Stopping Power

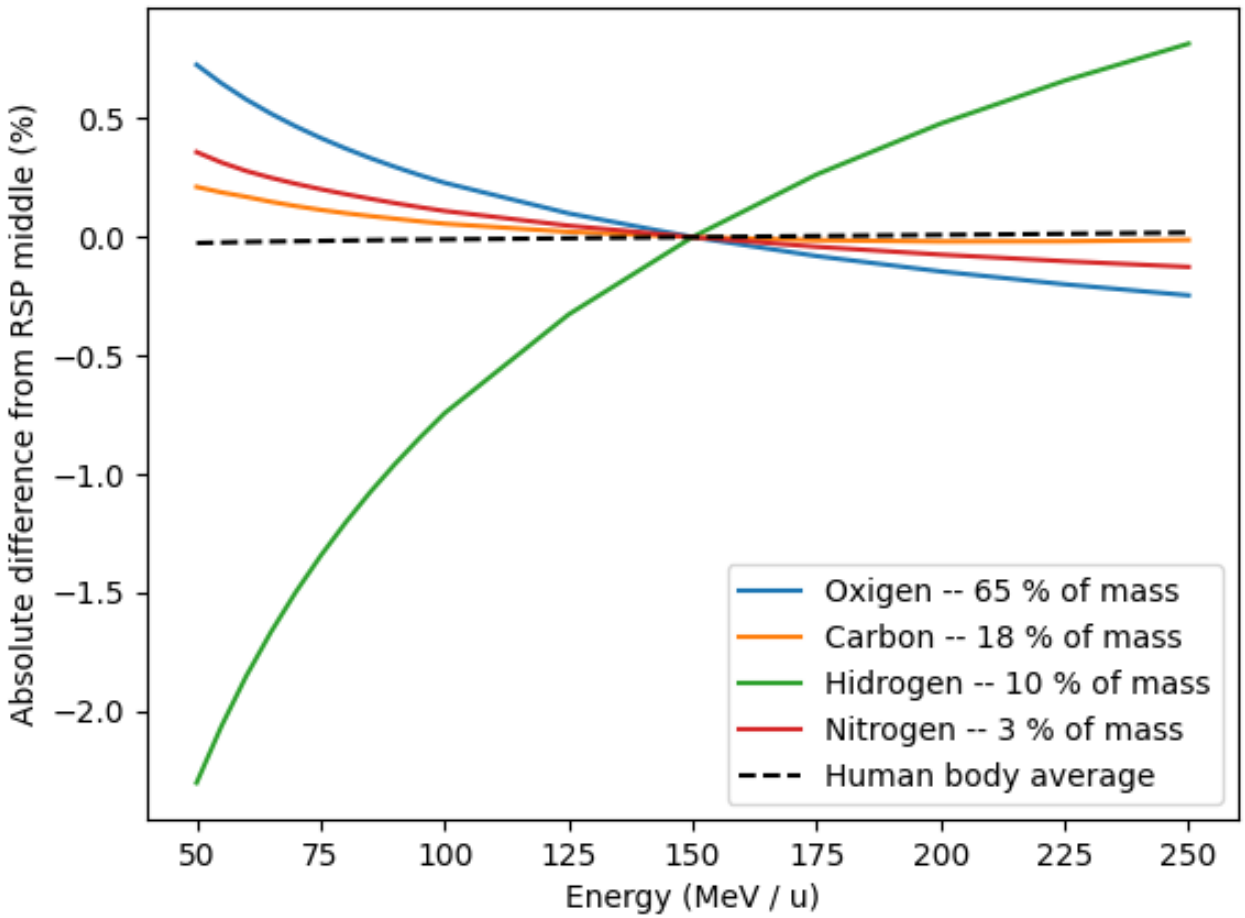
Stopping power ⇒ strong energy dependence (50 - 250 MeV/u)



What are we reconstructing? – Relative Stopping Power

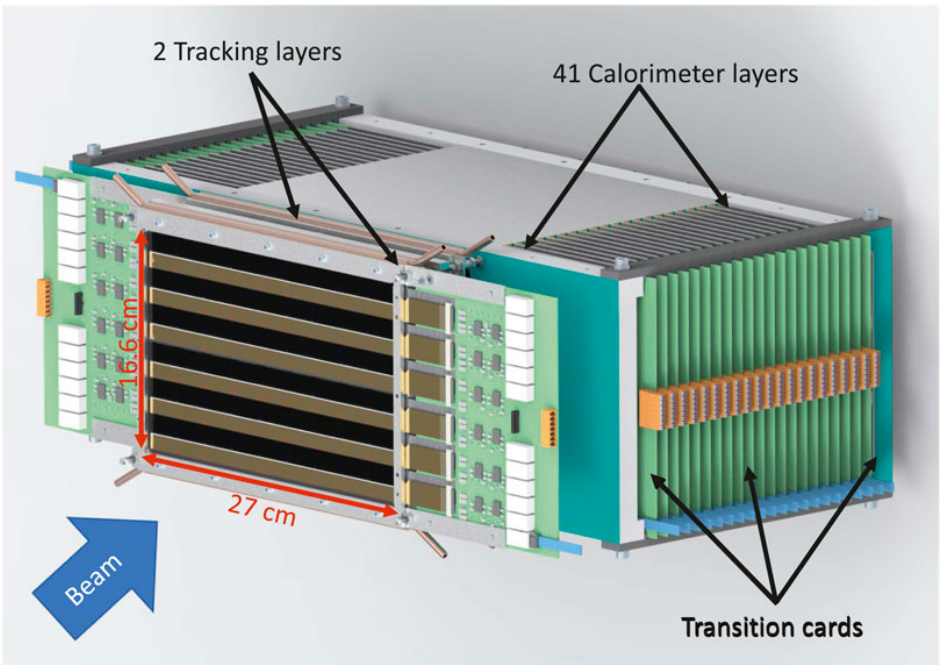
Stopping power in units of stopping power of water

$\Rightarrow$ almost energy independent (human body avg. < 0.03 %)

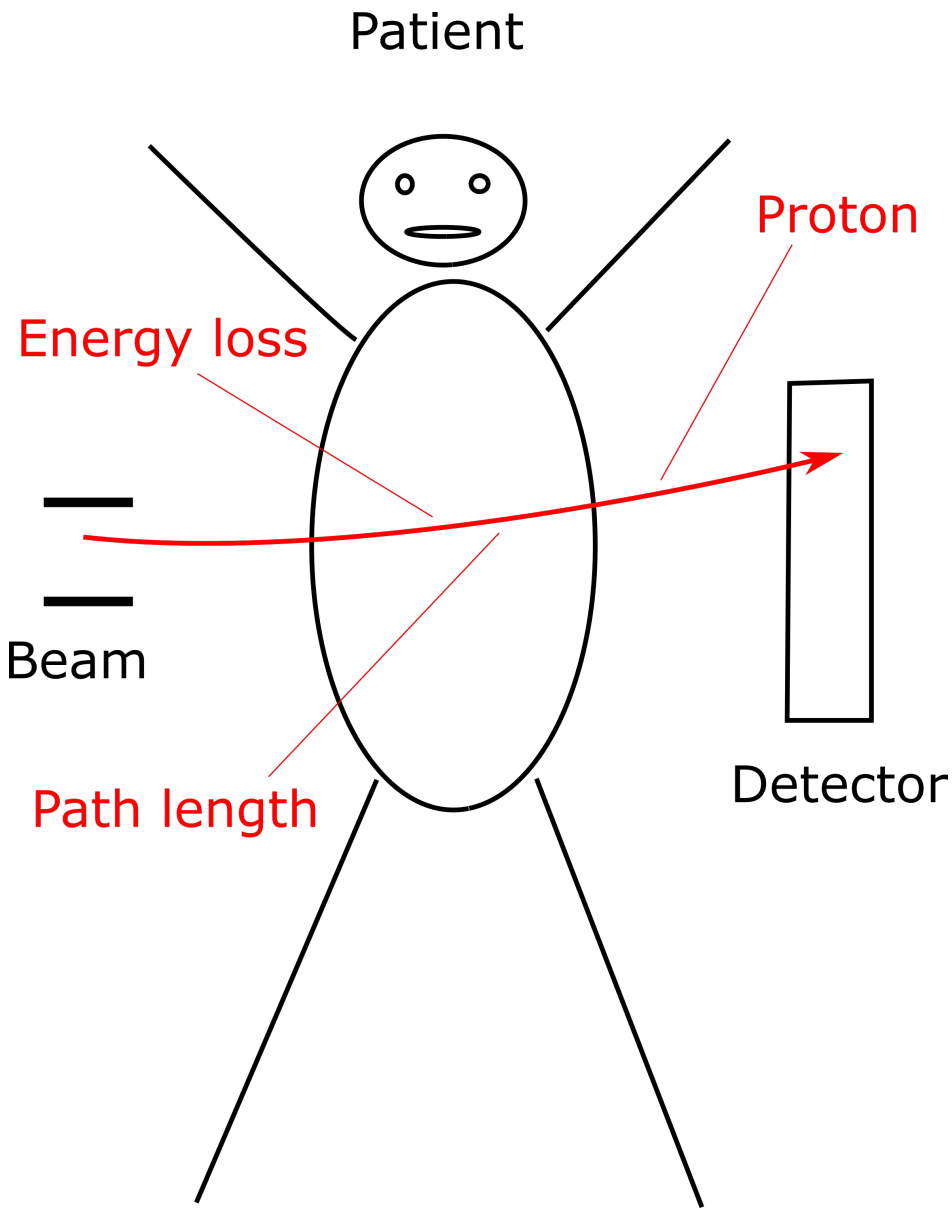


Bergen pCT Collaboration

- 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



How to calculate Relative stopping power (RSP)?



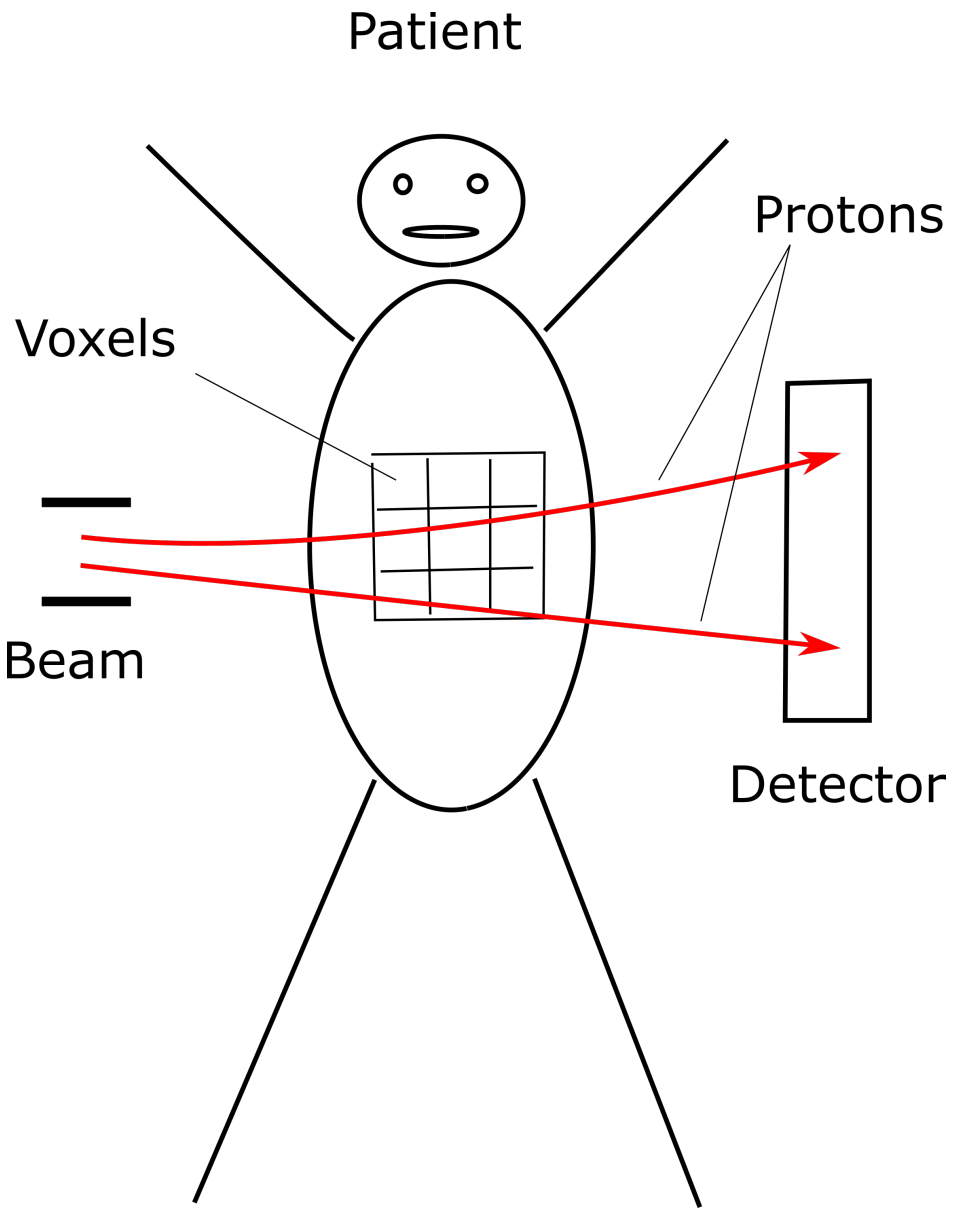
- Energy loss $\Rightarrow$ WEPL

  WEPL: water equivalent path length

- Proton trajectory avg RSP:

  $\overline{RSP} = \frac{WEPL}{Pathlength}$

Image Reconstruction



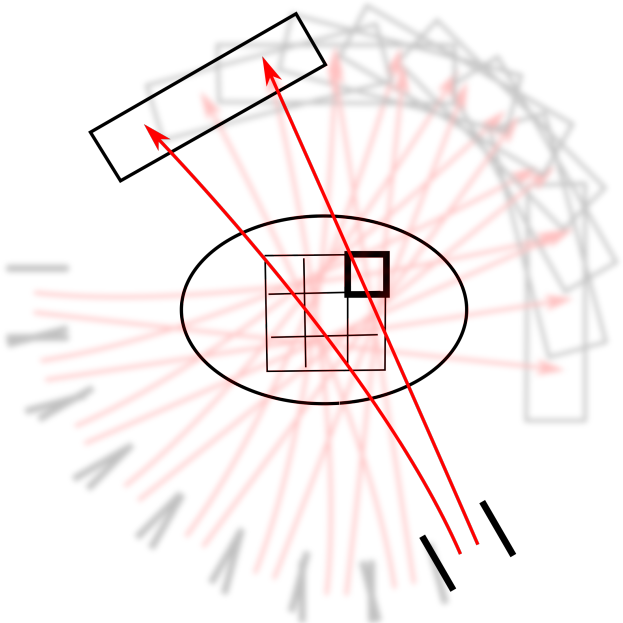


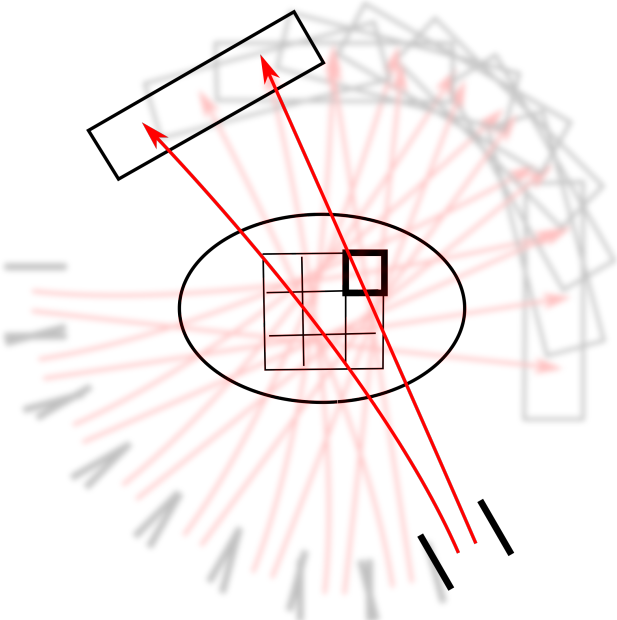
Image Reconstruction – a Huge Linear Problem

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
- $\mathbf{A}$ 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

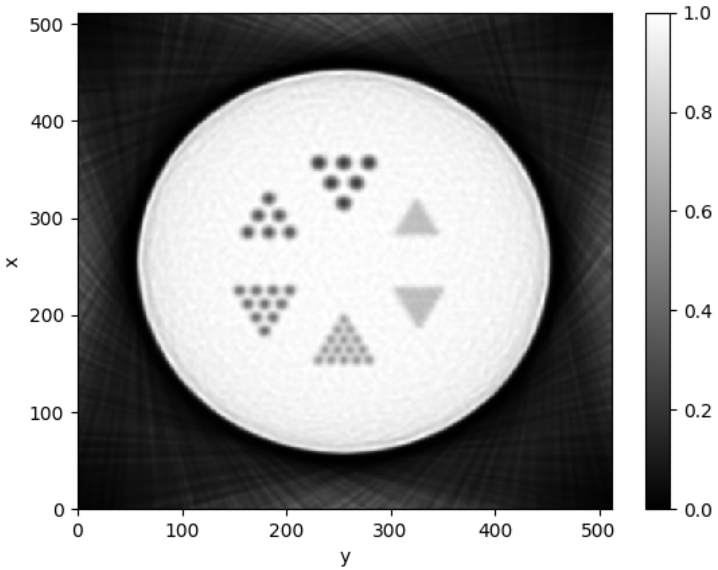
Approximation of the i$^{\text{th}}$ voxel of the next iteration:

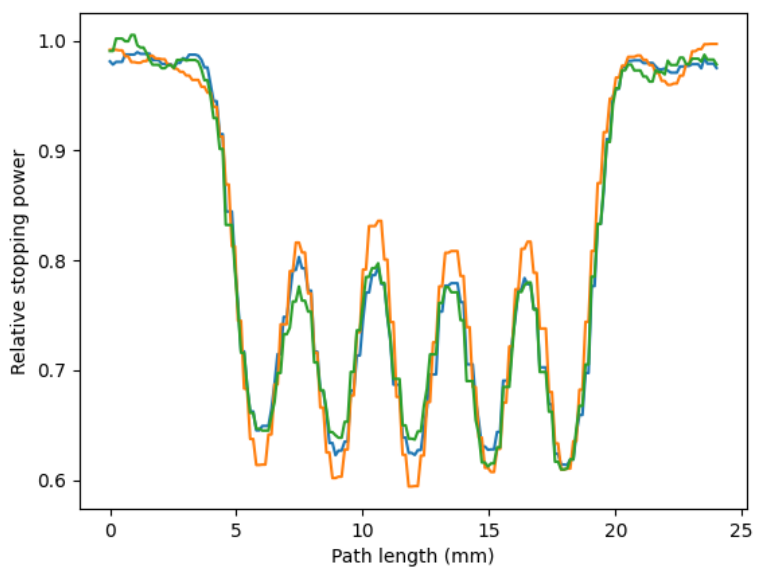
$$x_i^{k+1} = x_i^k \frac{1}{\sum_j A_{i,j}} \sum_j \frac{y_j}{\sum_l A_{l,j} x_l^k} A_{i,j} \ ,$$

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

Derenzo Phantom – Spatial Resolution

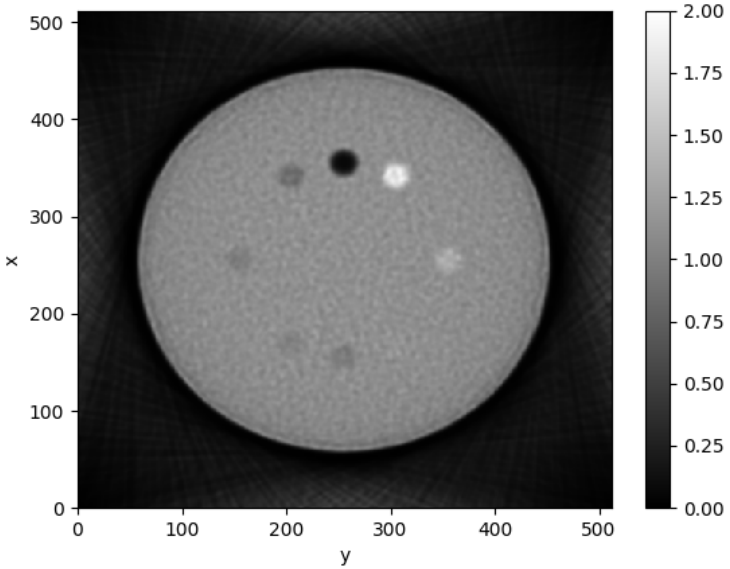
- Reconstructed RSP distribution and valley-to-peak distribution
- Spatial resolution is the FWHM of the point spread function
- Proton CT literature: 3.1 mm $<$ my algorithm: 4.3 mm

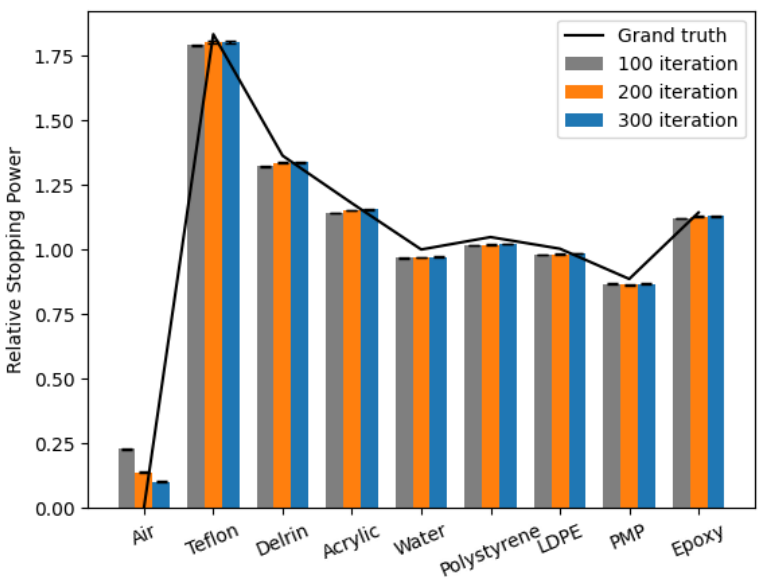




CTP404 Phantom – RSP Accuracy

- 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:

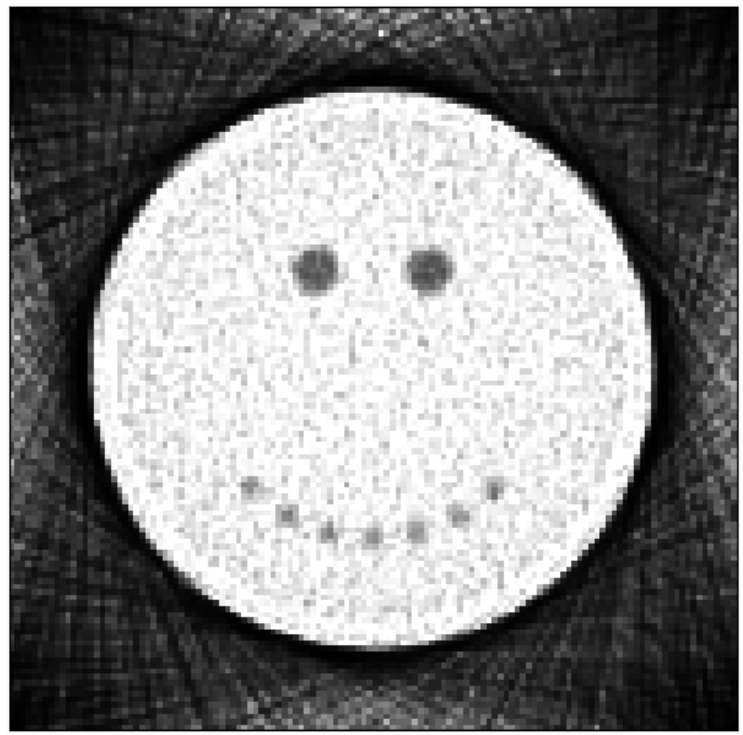
- Works well, promising results
- Further investigations is required

Bergen pCT Collaboration:

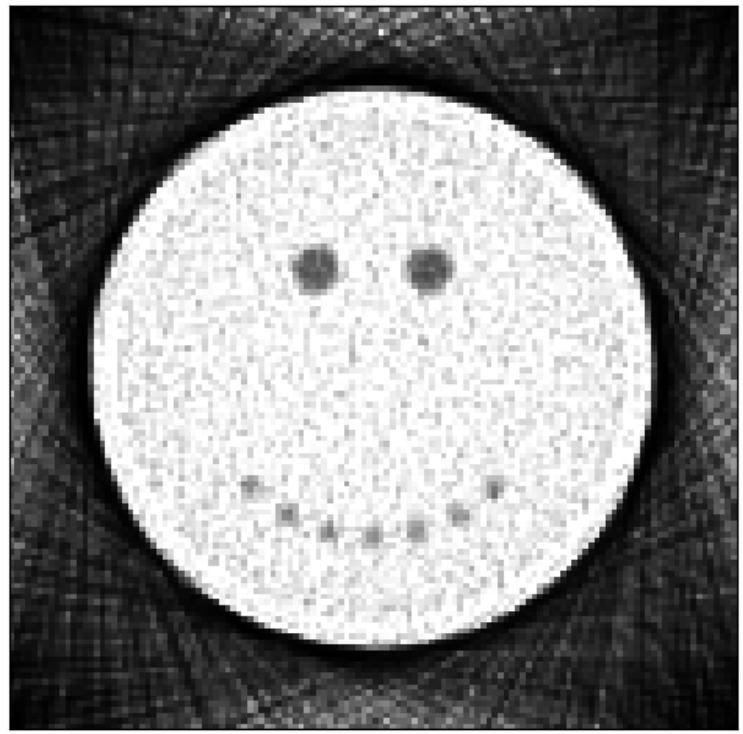
- Develop a pCT detector for clinical testing

Reached results:

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



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.