

Focus stacking particle radiography

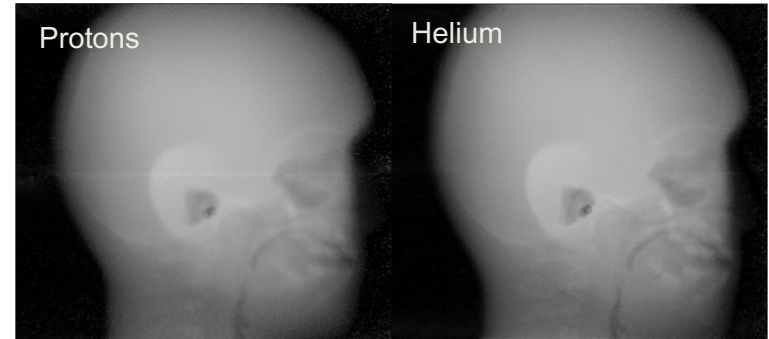
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² University College London, London, UK

Single-event particle radiography

- ✓ Patient alignment
- ✓ Water equivalent thickness (WET) check
- ✓ HLUT optimization
- ✓ Faster + cheaper compared to pCT
- But spatial resolution is limited by scattering¹



Experimental pRads @HIT (Volz et al. 2017)

For visual feedback: improved reconstruction algorithms needed

Available pRad algorithms

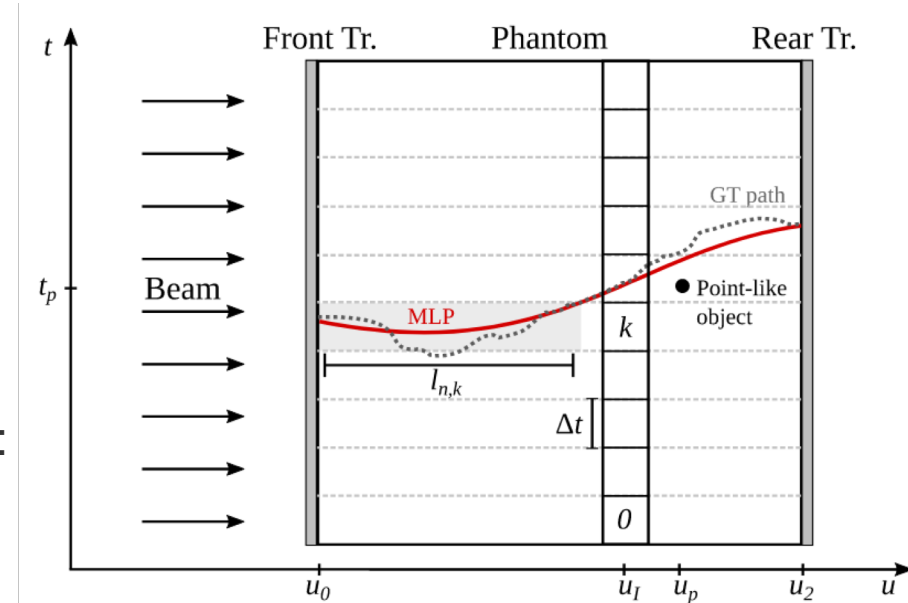
- Binning in depth¹ u :

$$\text{➤ } WET_k = \frac{\sum_{n=0}^N \chi_k(MLP_n(u_I)) \times WET_n}{\sum_{n=0}^N \chi_k(MLP_n(u))}$$

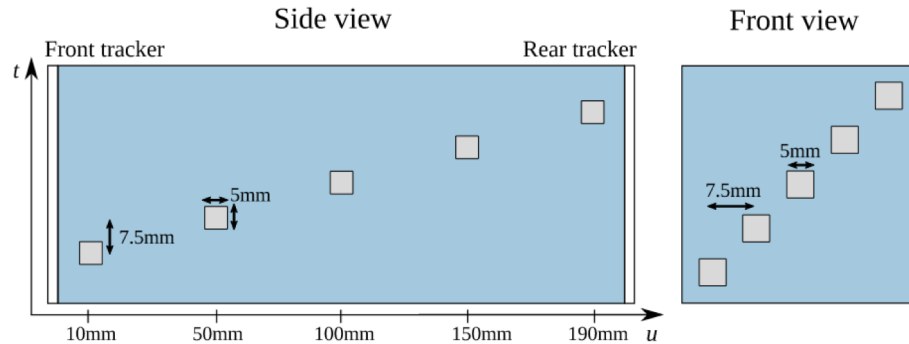
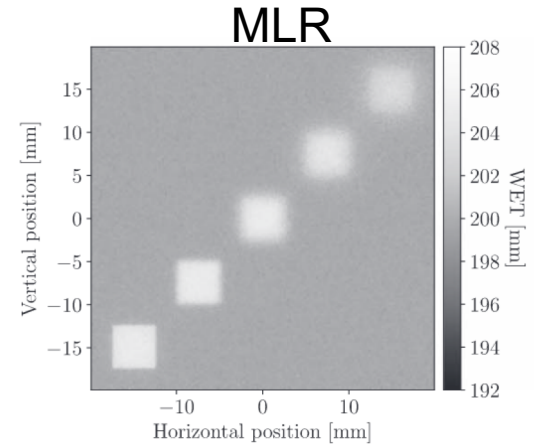
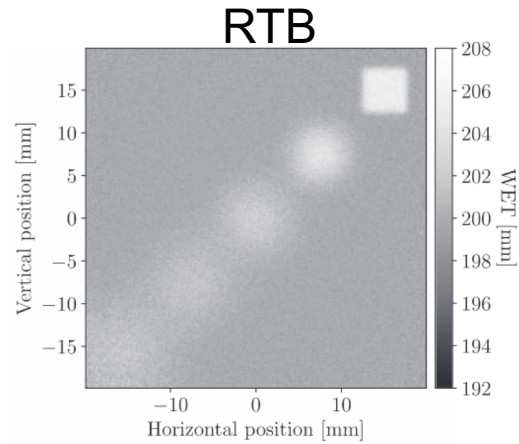
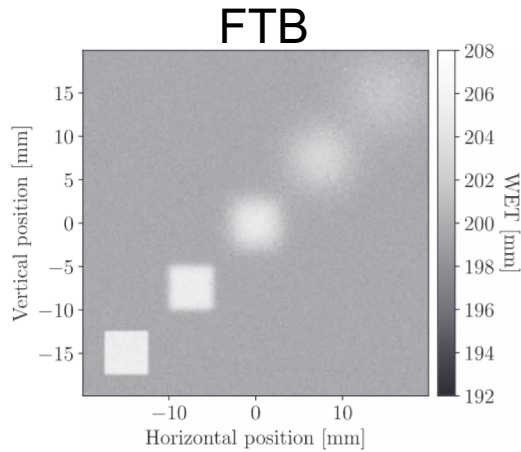
- Binning on the front/rear tracker
special cases of BID

- Maximum likelihood reconstruction² (MLR):

$$\text{➤ } WET_k = \frac{\sum_{n=0}^N WET_n \times \left(\frac{l_{n,k}}{L_n}\right)^2}{\sum_{n=0}^n \left(\frac{l_{n,k}}{L_n}\right)^2}$$



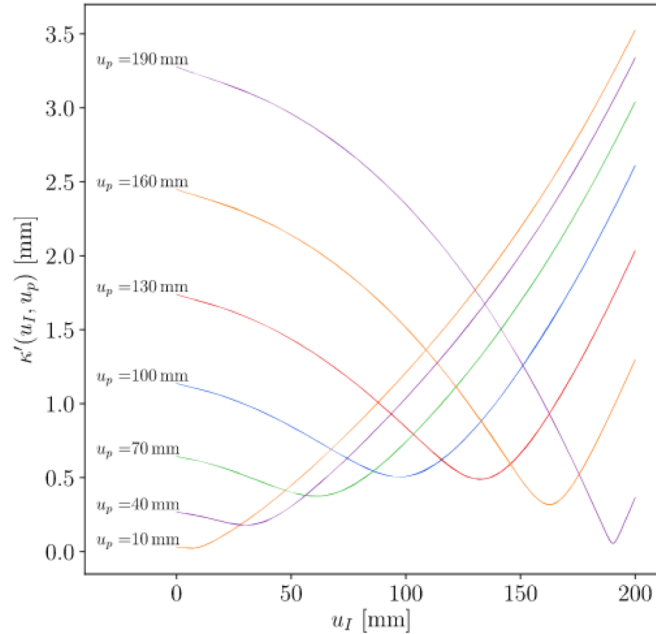
Limitations of available methods



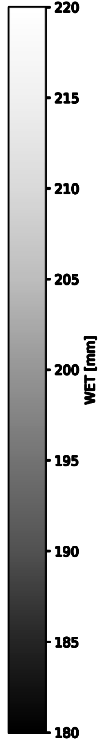
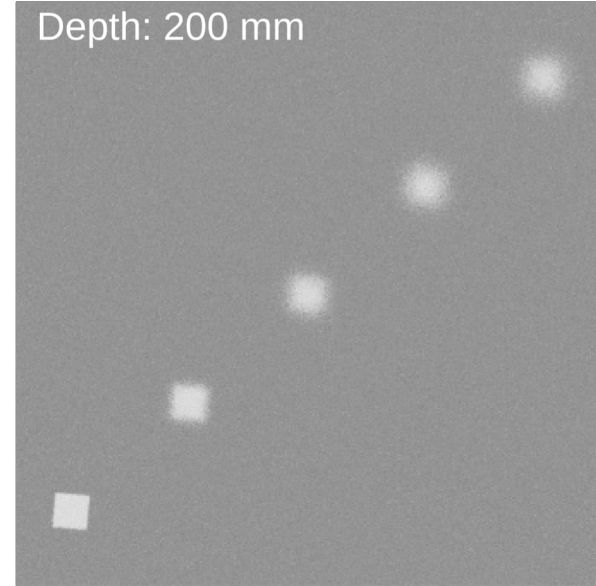
Binning at depth

Front Tracker

Rear Tracker



ge detector



➤ Spatial resolution highest at ~ object depth

¹Volz, Collins-Fekete, Solie, Seco (2020) Biomed. Phys. Engin. Express
Khellaf et al. (2022) IEEE Trans. Nuk. Med.

Rit et al. (2013) Med. Phys.

Focus stacking

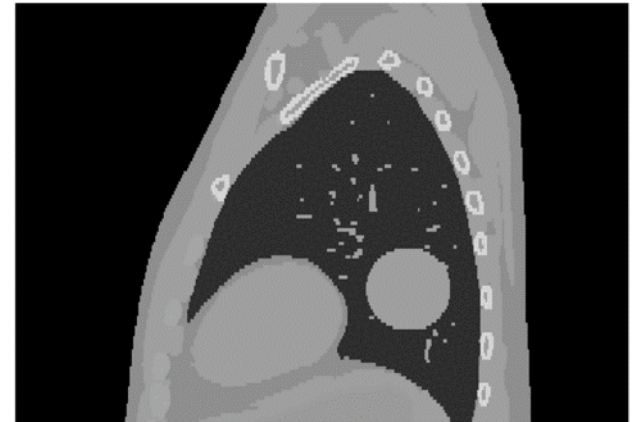
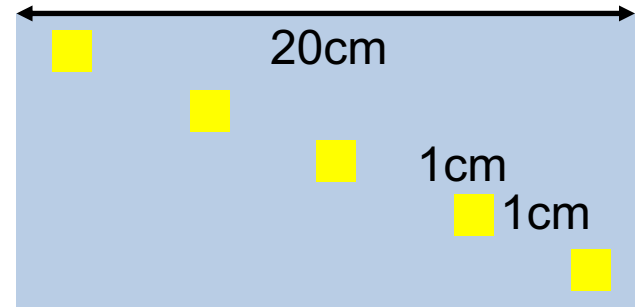
- Idea: join different 'focal depths' to single image



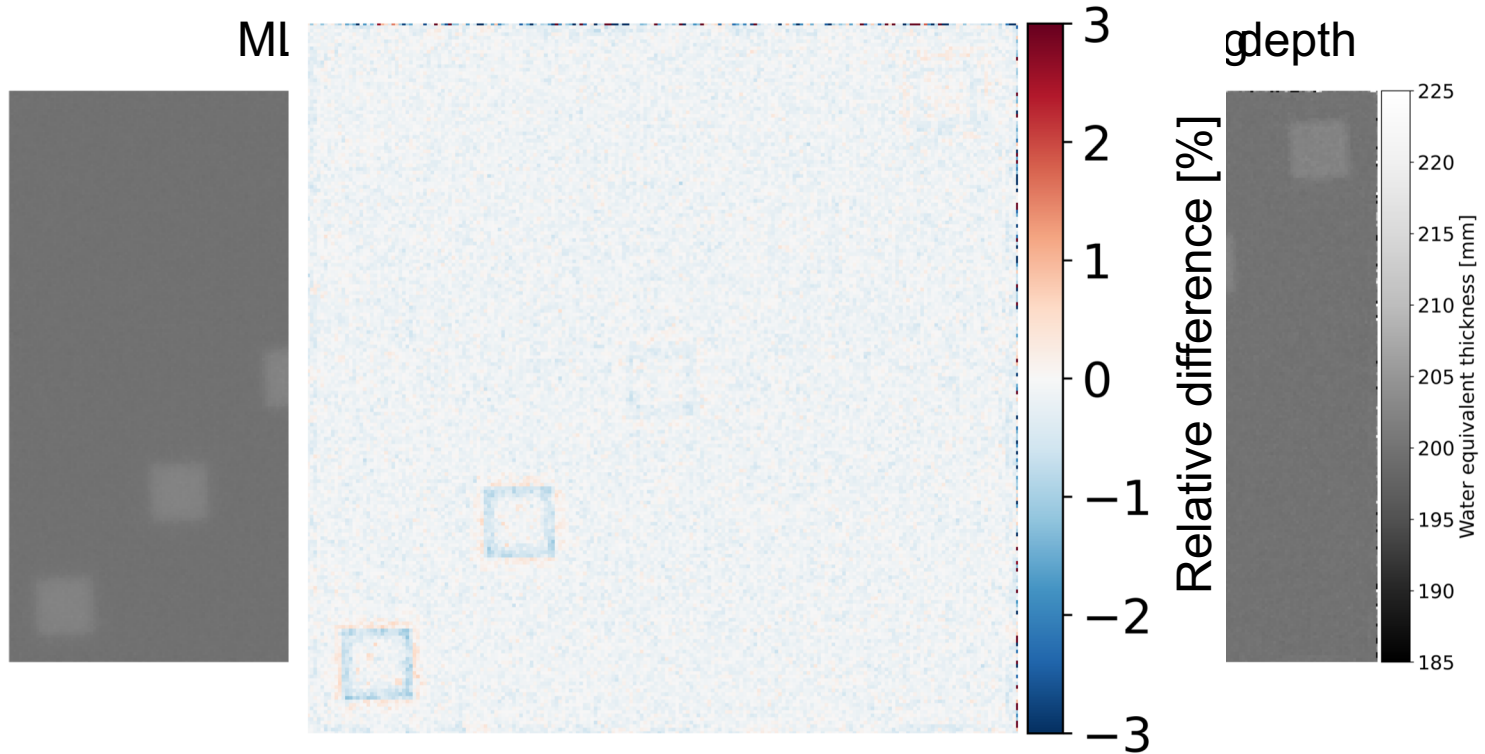
1. Generate 3D pRad (multiple BID planes)
2. For each depth perform edge detection
 - Convolve with Gaussian and then Laplace operator (5x5 kernels)
3. Join image pixels from the depth of their highest gradient

Simulation setup

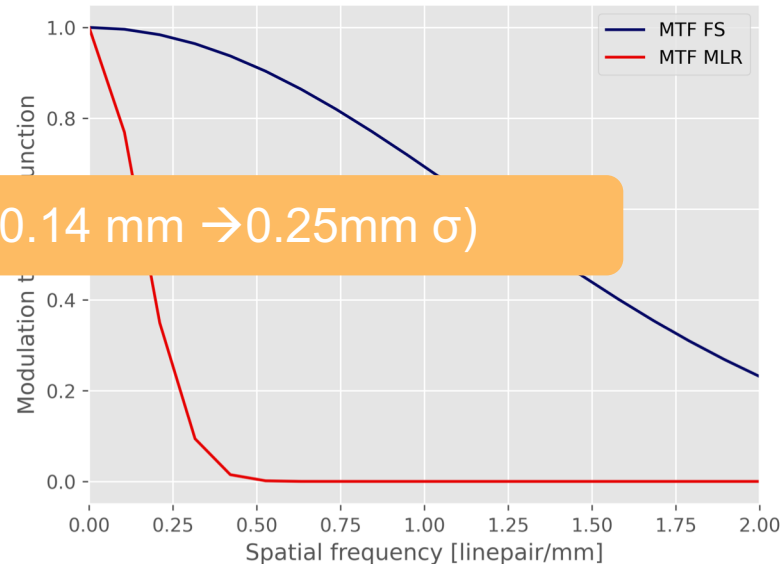
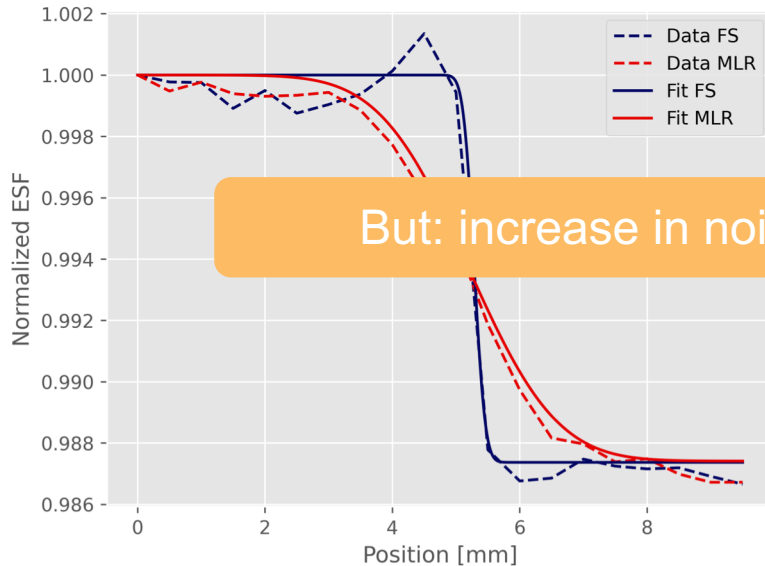
- Geant4 simulations of cortical bone cubes in water tank and anthropomorphic lung phantom
- 10^7 primaries on $10 \times 10 \text{ cm}^2$ field (both ideal and clinically realistic beams)
- Path reconstruction with cubic spline path
- 3σ -filtering and particle identification



Simple geometry

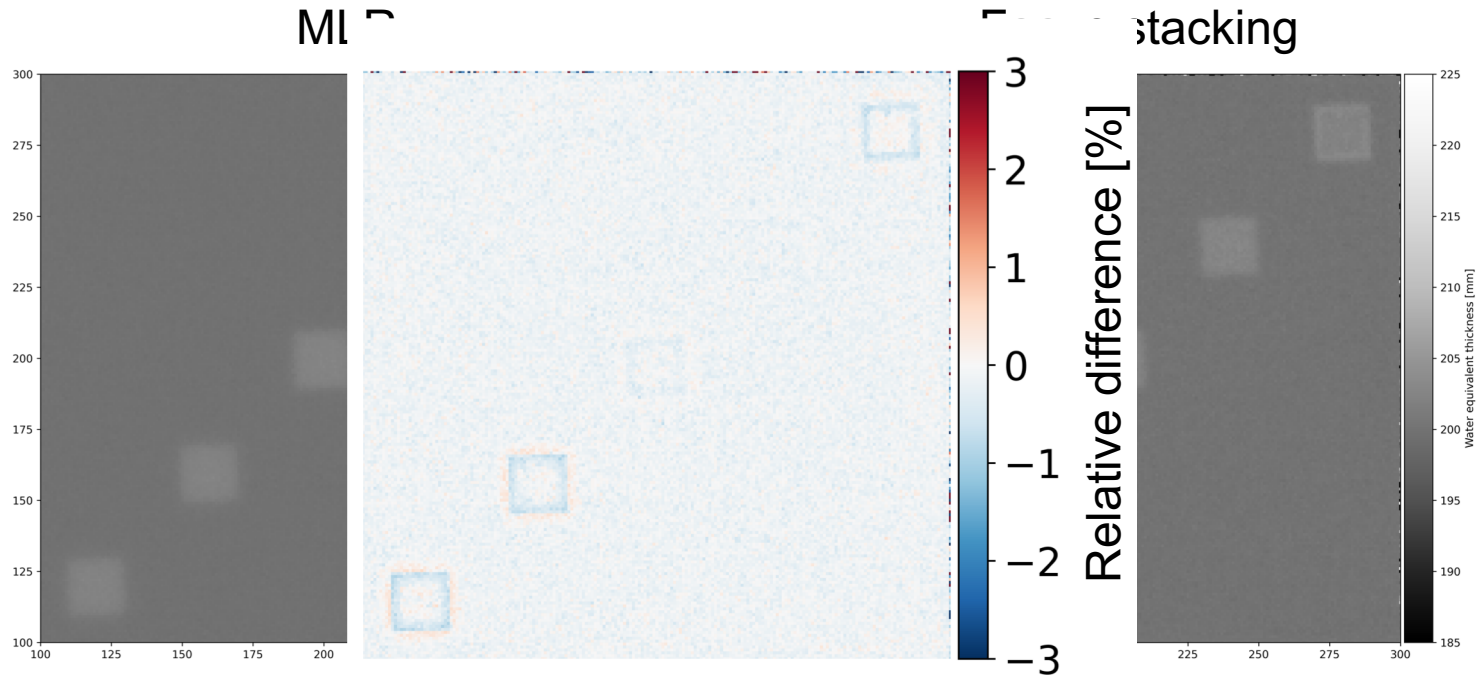


- Median spatial resolution improvement @200MeV proton radiography: 50%
- Greatest benefit (0.3lp/mm \rightarrow 2.5 lp/mm) for deep features where MLR is worst
- No loss in accuracy



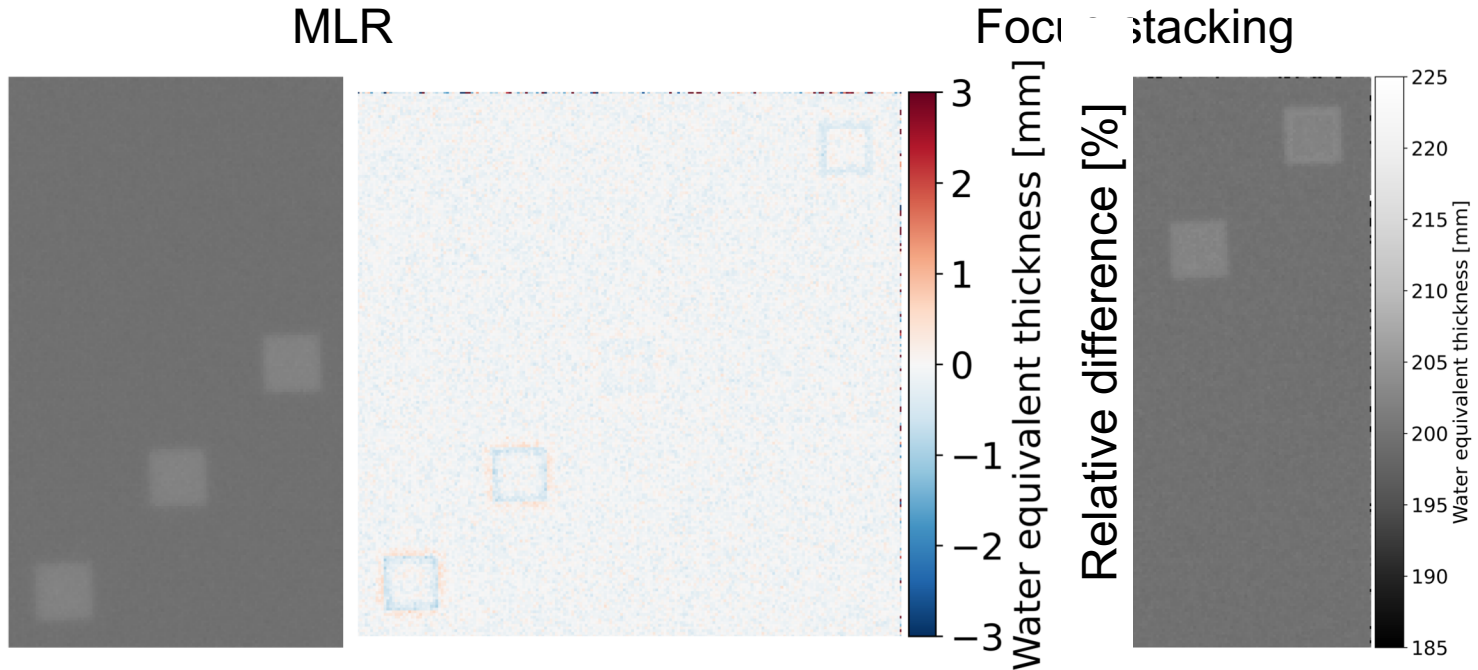
For different energies

Protons @190 MeV



For different energies

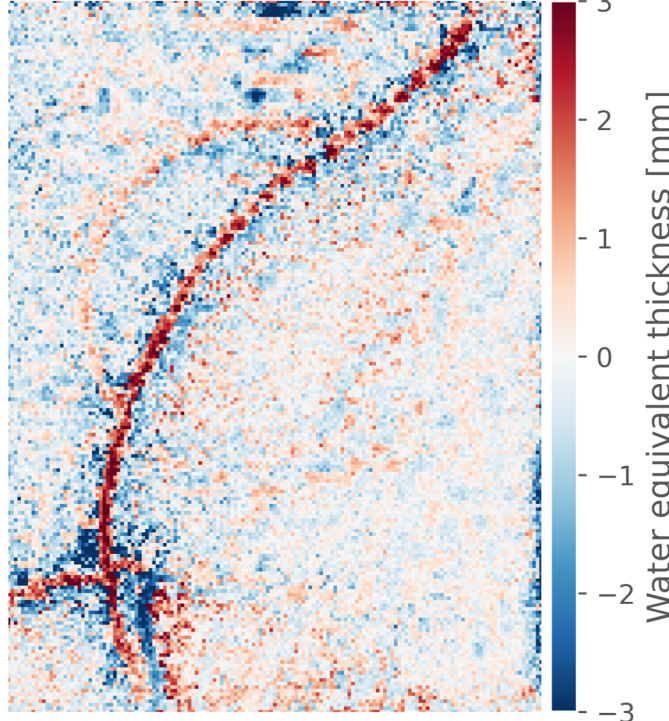
Protons @230 MeV



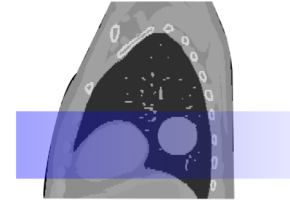
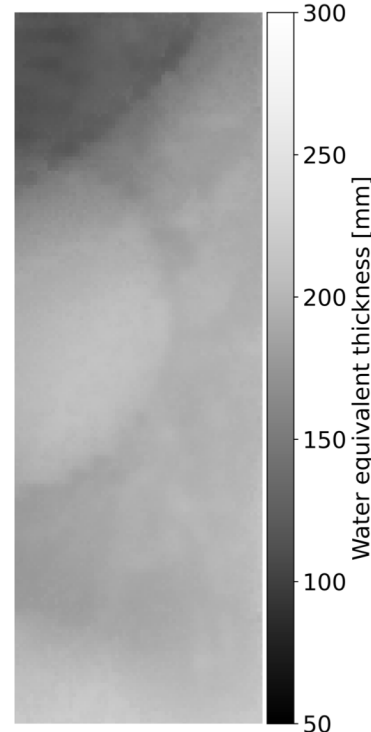
Anthropomorphic lung phantom

Protons @230MeV

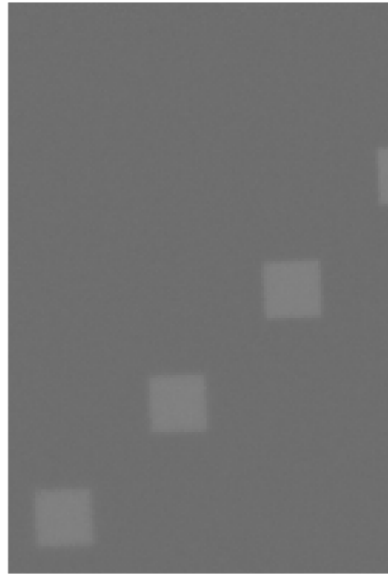
MLR



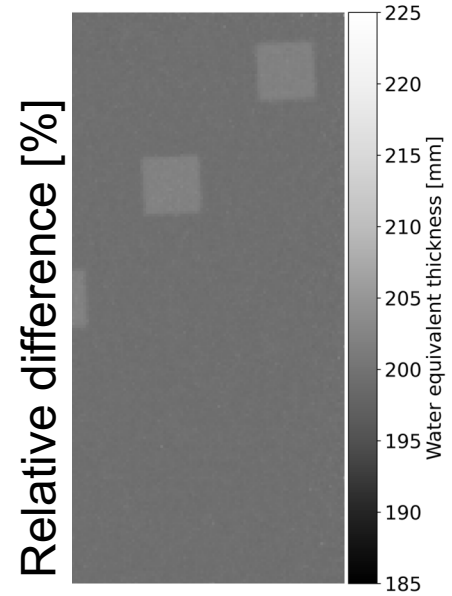
Focus stacking



MLR

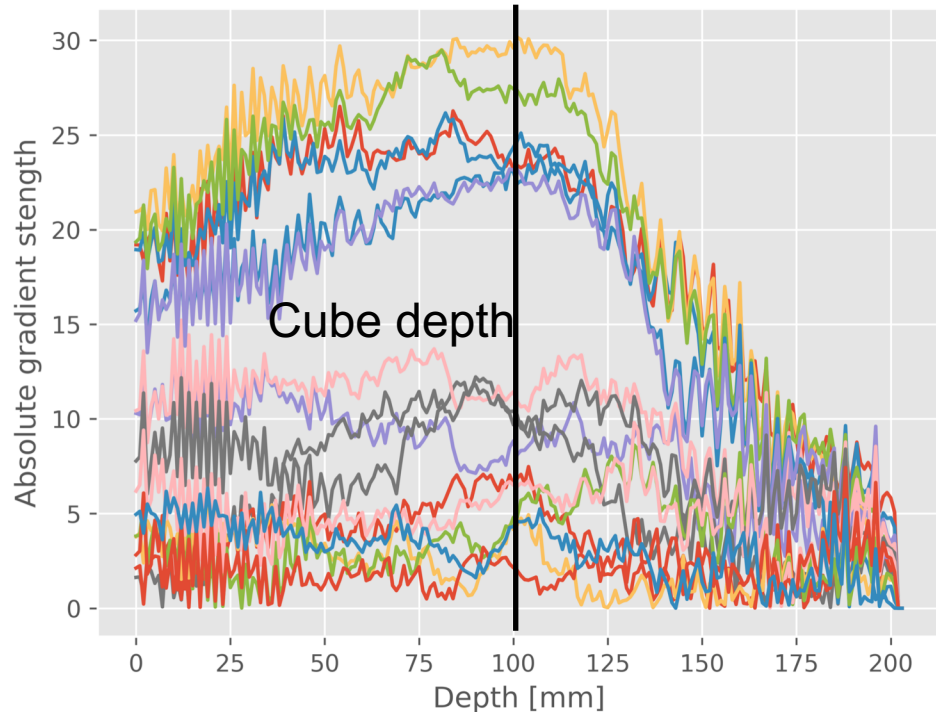


Focus stacking



Can we use it for feature depth detection?

Gradient strength for 16 pixels around central cube corner



- Possibly useful for 3D feature location
- Seems to depend on spatial resolution: The more the better
- Seems to depend on noise: the less the better

- Focus stacking can improve spatial resolution in pRad
- Practically for free: utilizes the full available 3D particle path information
- Limitations in terms of noise, i.e., image dose
 - Better edge detection technique compared to Laplace operator?
- Open questions:
 - 3D feature localization?
 - Combination with projection deconvolution by Khellaf et al.?

Promising technique for further investigations