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RSP accuracy and Spatial Resolution Comparison of Two Proton Computed Tomography Scanners

G. Dedes[1], H. Drosten[1], S. Götz[1], J. Dickmann[1], C. Sarosiek[2], M. Pankuch[3], N. Krah[4], S. Rit[4], V. Bashkirov[5], R. W. Schulte[5], R.P Johnson[6], K. Parodi[1], E. DeJongh[7] and G. Landry[8,9]

[1] Ludwig-Maximilians-Universität München
[2] Medical College of Wisconsin
[3] Northwestern Medicine Chicago Proton Center
[4] Université de Lyon
[5] Loma Linda University
[6] U.C. Santa Cruz
[7] ProtonVDA Inc
[8] University Hospital, LMU Munich
[9] German Cancer Consortium (DKTK)

DFG Deutsche Forschungsgemeinschaft German Research Foundation

BaCaTeC

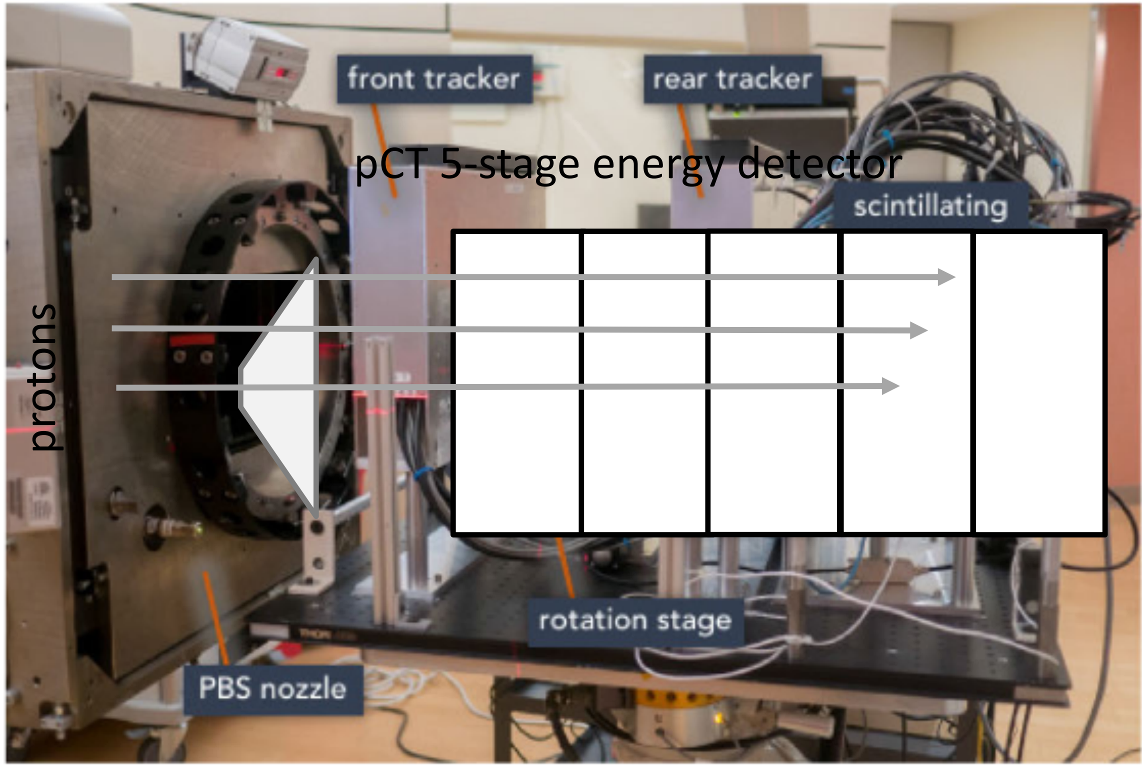
Introduction

- Different pCT prototype concepts:
  - “Full” vs. “partial” tracking
  - Energy detection, range detection, time-of-flight, detector segmentation etc.
  - Cost and complexity
  - Speed
  - …

- Performance of two pCT scanners of different design approaches
  - At the same facility (Northwestern Medicine Chicago Proton Center)
  - Scanned the same object of known RSP
  - Reconstructed with the same algorithm
  - Quantify RSP accuracy and spatial resolution (SRes)

pCT Scanners

phase-II prototype scanner (LLU/UCSC)[1]

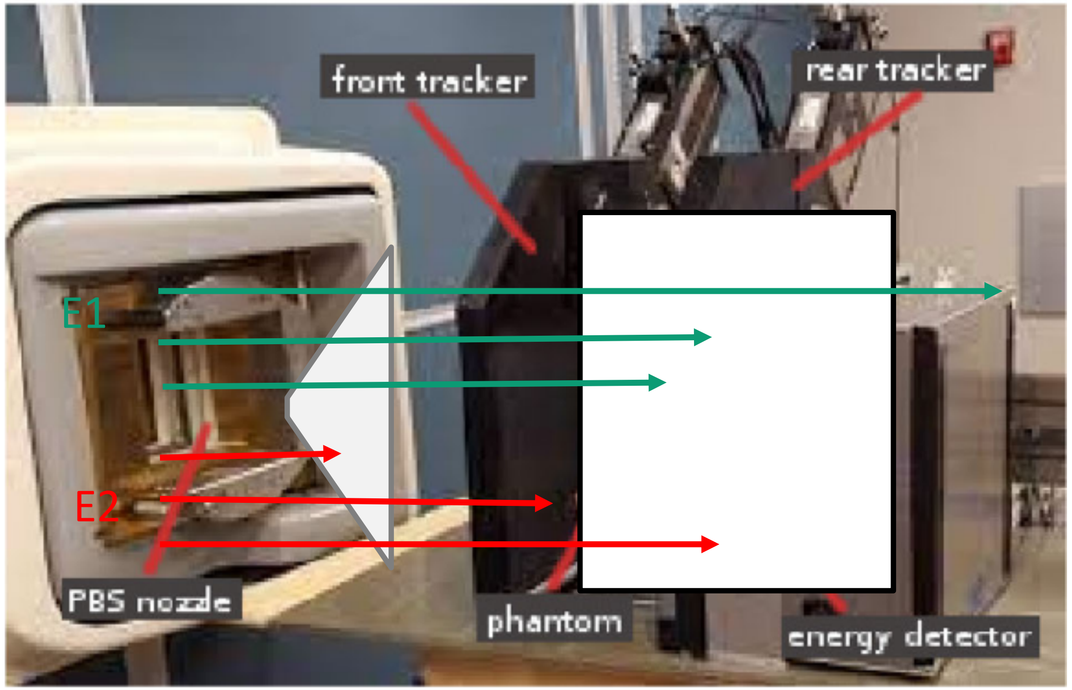


- Position and direction upstream and downstream (full tracking)
- 5-stage scintillator - hybrid energy detector
- ~1 MHz count rate
- 9 cm x 32 cm FOV
- 200 MeV protons (for this acquisition)

[1] Johnson et al., IEEE Trans Nucl Sci 63(1): 52-60

pCT Scanners

ProtonVDA scanner[2]

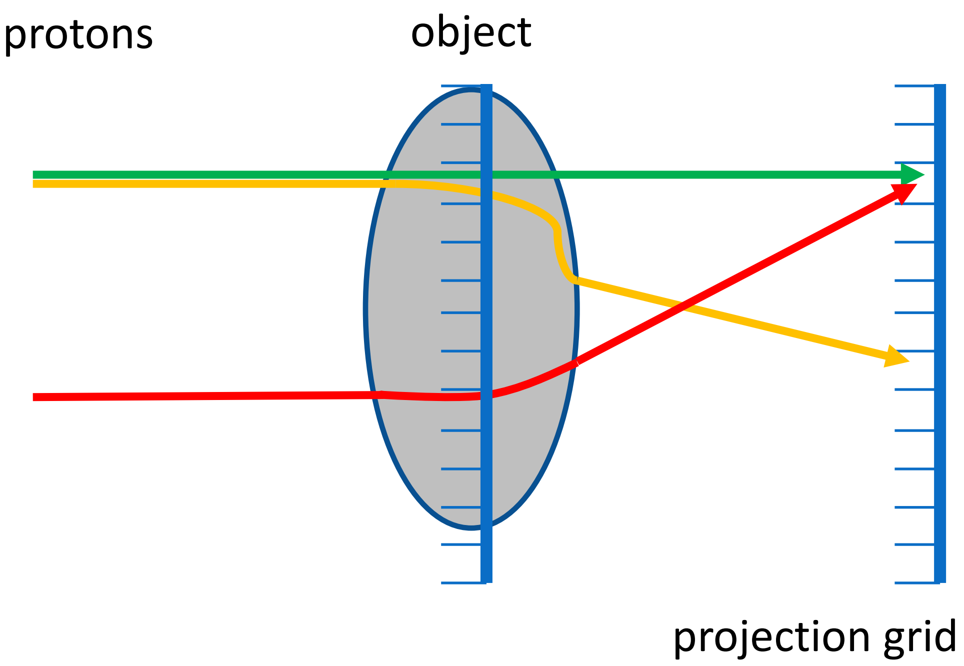


- Single position upstream and downstream
- Direction upstream by virtual source (accelerator) and position
- Direction downstream by position and MLP
- Compact energy detector
- Energy modulation (118, 160, 187 MeV)

[2] DeJongh et al., Med Phys. 2021;48:1356-136

Image reconstruction

- Filtered backprojection accounting for curved proton paths[3]
- Based on the concept of “Distance driven binning”



[3] Rit et al., Med Phys . 2013 Mar;40(3):031103.

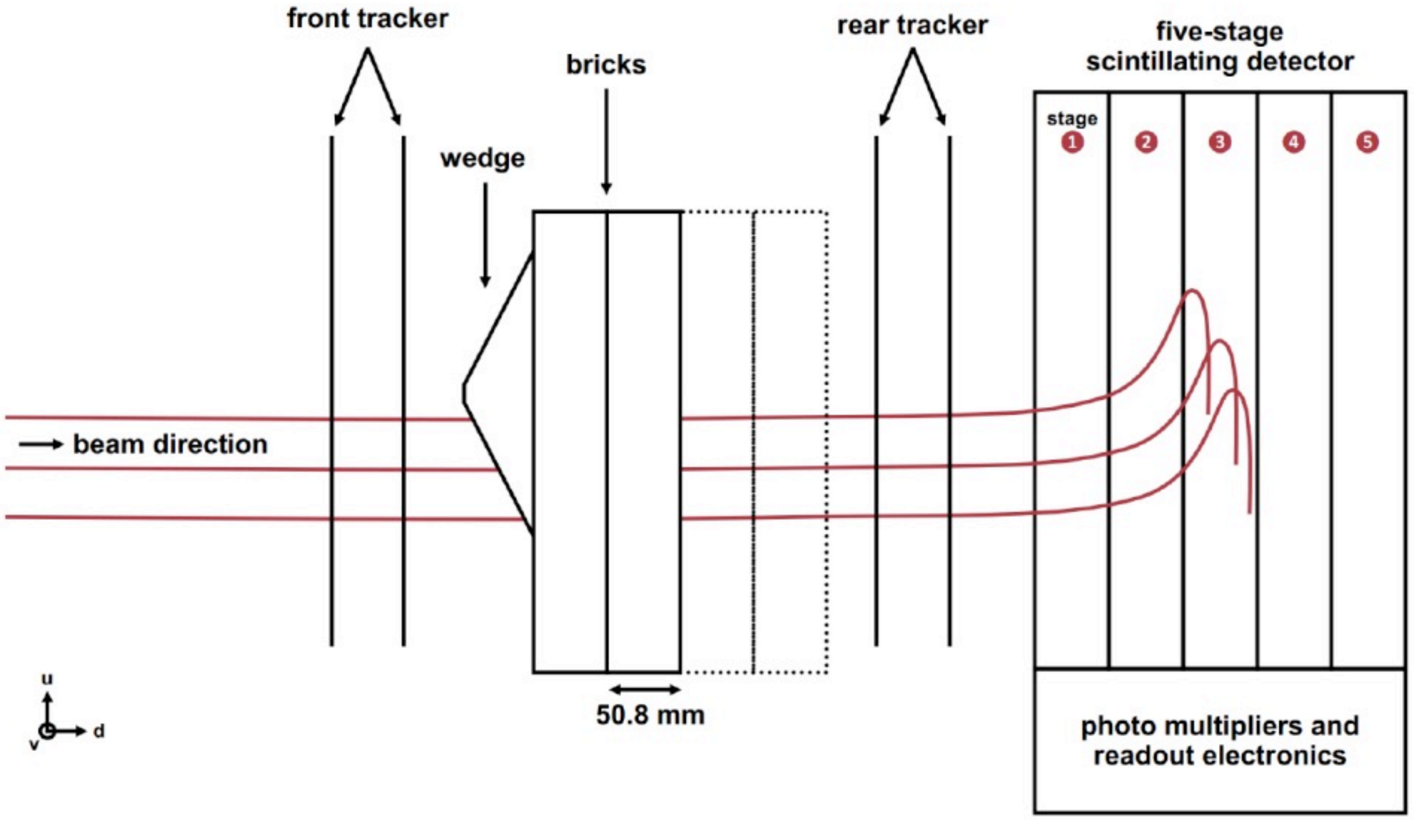
Phantom

Insert	RSP_{ref}
Cortical bone	1.555 ± 0.004
Trabecular bone	1.100 ± 0.003
Spinal disc	1.070 ± 0.003
Enamel	1.755 ± 0.004
Dentin	1.495 ± 0.004
Sinus	0.200 ± 0.005
Phantom body	0.980 ± 0.002
Spinal cord	1.040 ± 0.003
Brain	1.040 ± 0.003

- Wax body and **8** cylindrical **plastic tissue equivalent** inserts
- RSP range from **0.20** to **1.76**
- Insert radii: **18 mm**
- Phantom diameter: **180 mm**

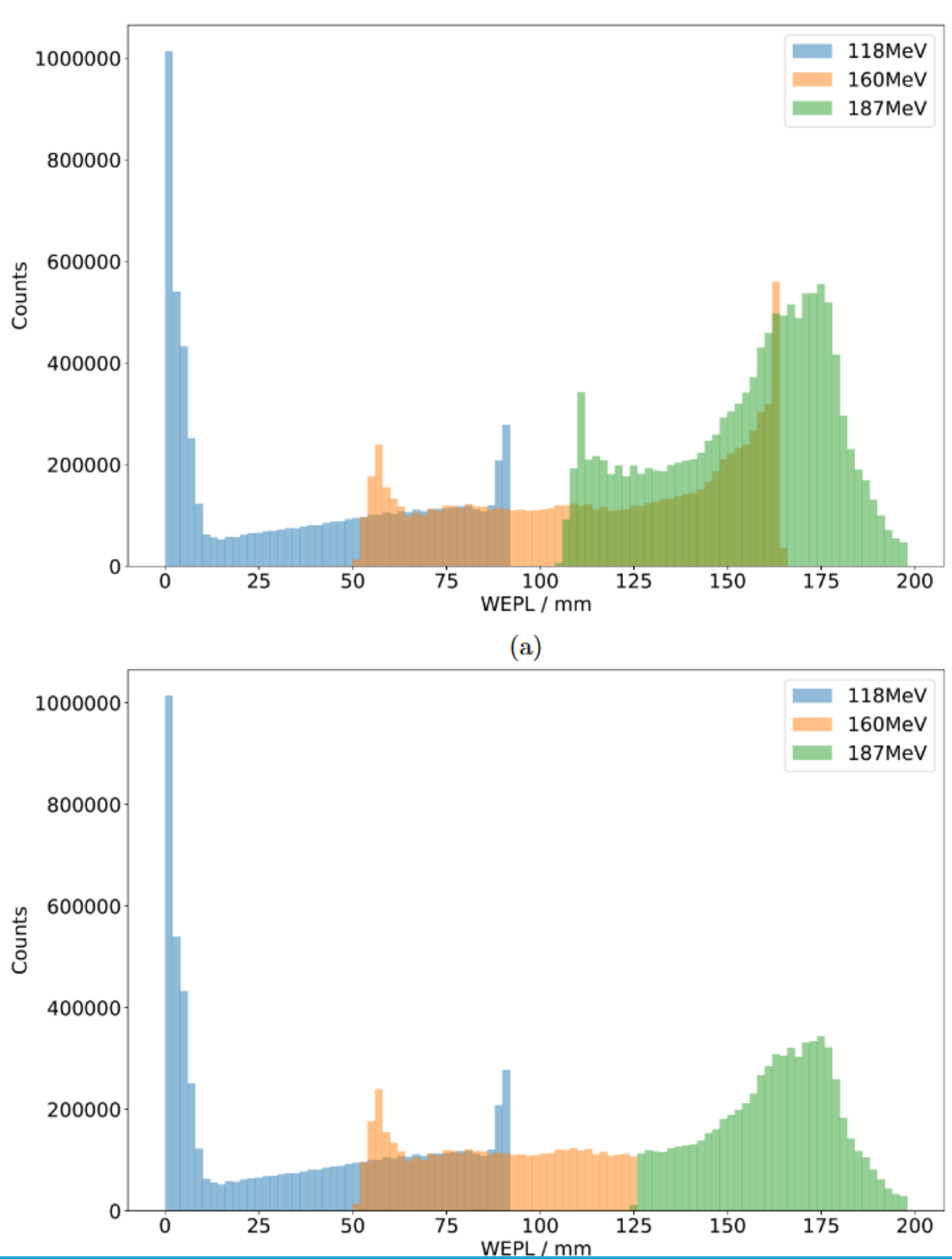
Data processing

- Phase-II scanner:
    - ➢ Track quality cuts
    - ➢ ADC signal to WEPL calibration
    - ➢ 3-sigma in WEPL and angle



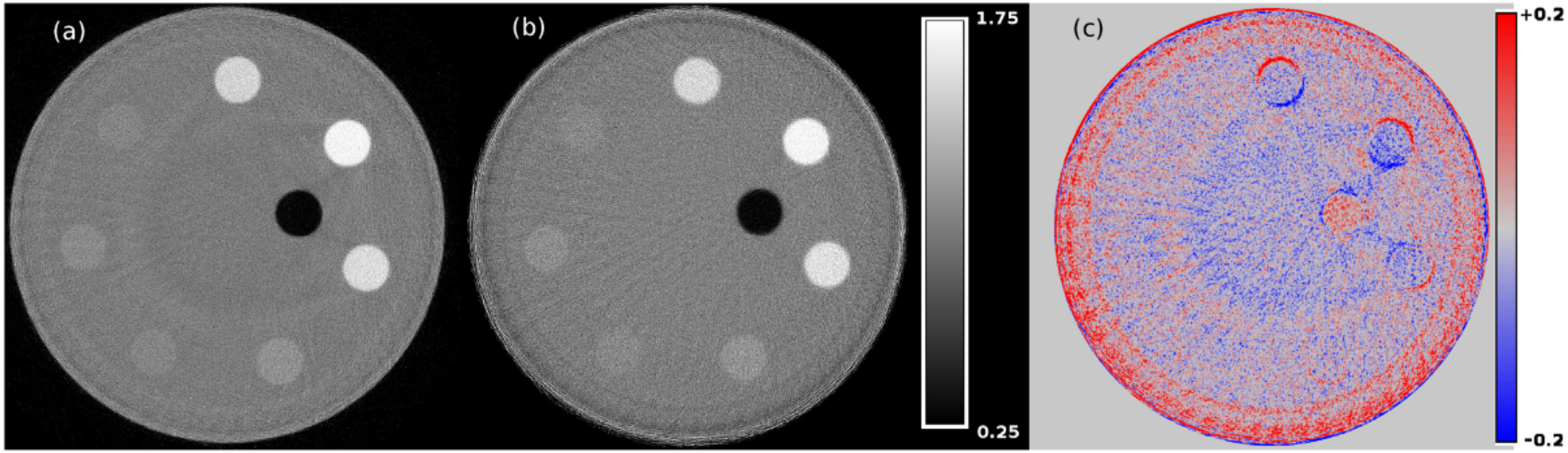
Data processing

- ProtonVDA scanner:
  - ➢ Estimation of entry/exit directions
  - ➢ Merging of the different energy datasets
  - ➢ 3-sigma in WEPL and angle



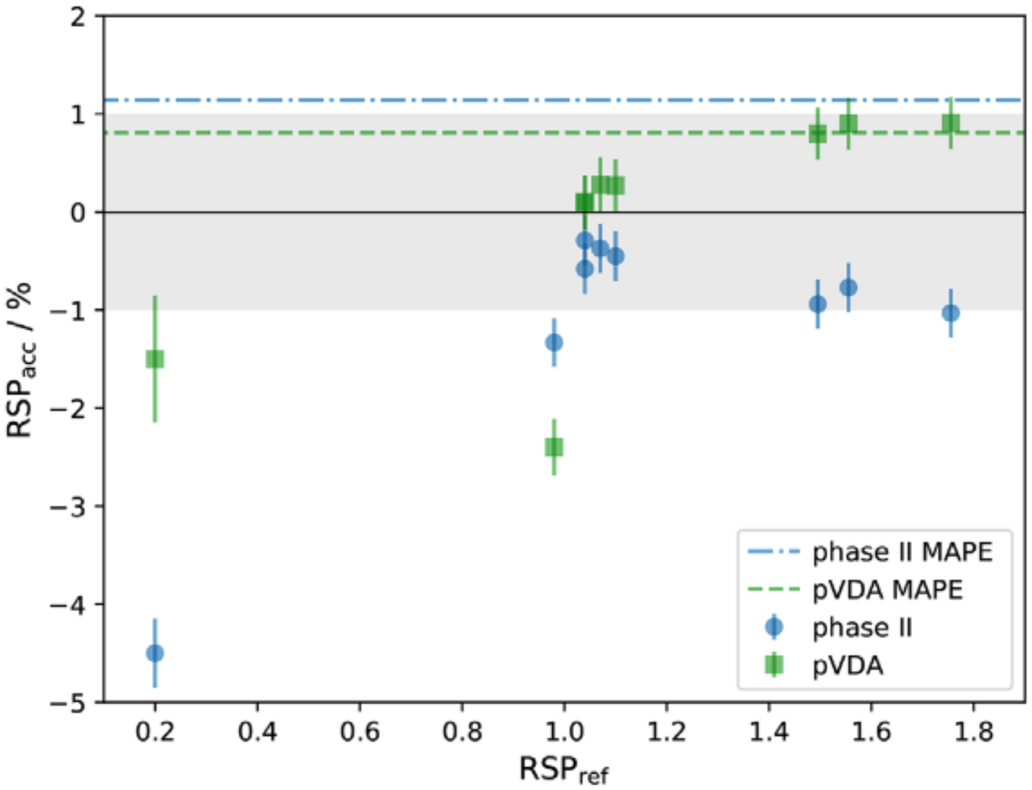
RSP images

phase-II ProtonVDA Difference



- 90 projections at 4 deg steps (for time reasons)
- Ring shaped artifacts
- Undersampling streak artifacts vanish in 360 projection acquisition
- Scan duration: **300 sec** for phase-II and **120 sec** for ProtonVDA

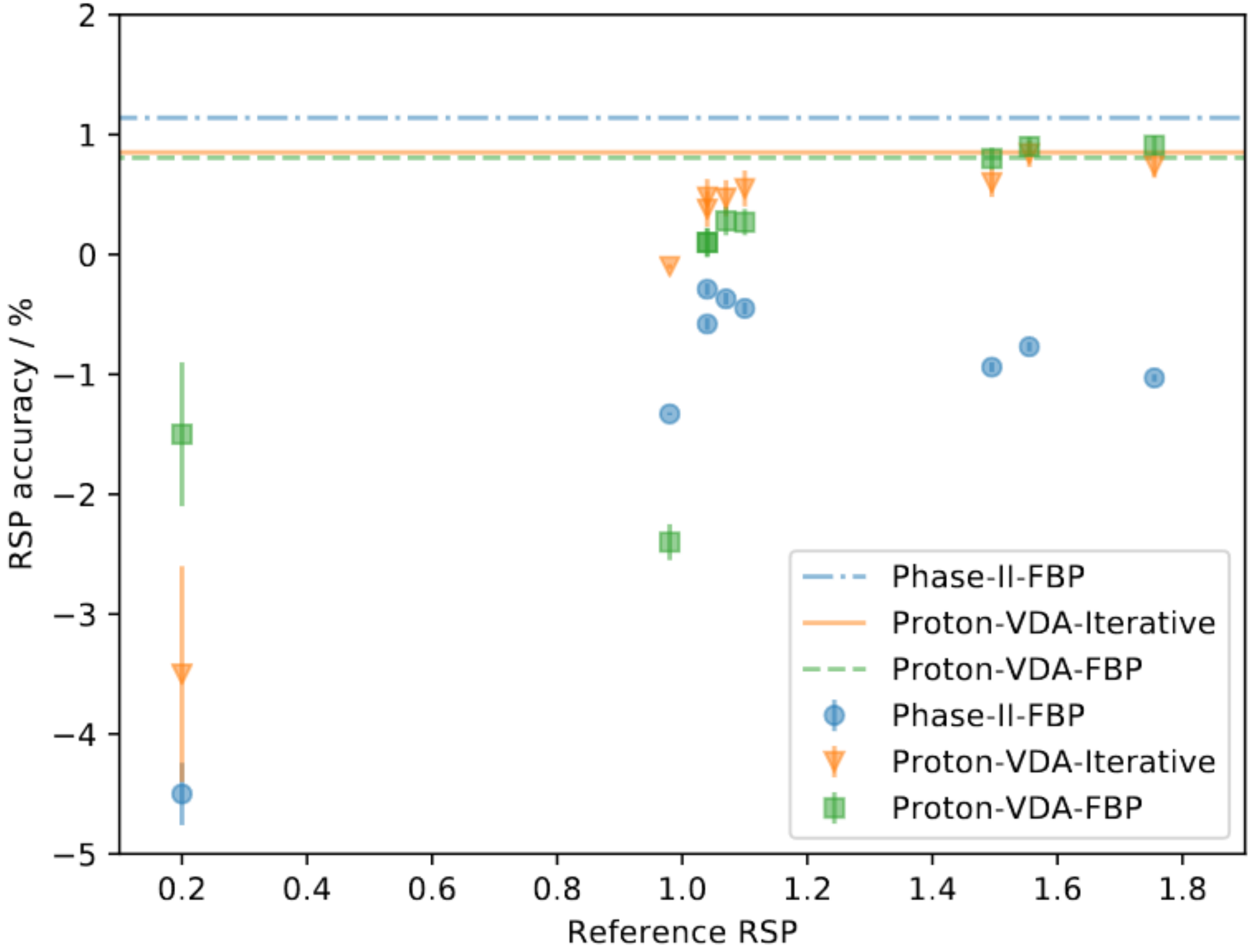
RSP accuracy



- RSP accuracy mostly within ±1% for both scanners
- Above 1% errors for phase-II:
  - ➢ Sinus: **-4.50%**, RSP_{ref} = 0.20 (porous insert)
  - ➢ Phantom body: **-1.33%**, RSP_{ref} = 0.98 (ring artifacts)
- Above 1% errors for ProtonVDA:
  - ➢ Sinus: -**1.50%**, RSP_{ref} = 0.20 (porous insert)
  - ➢ Phantom body: -**2.40%**, RSP_{ref} = 0.98 (ring artifacts)
- Mean absolute percent error (MAPE):
  - ➢ over all materials: **1.14%** for phase-II, **0.81%** for ProtonVDA
  - ➢ excluding sinus insert: **0.72%** for both

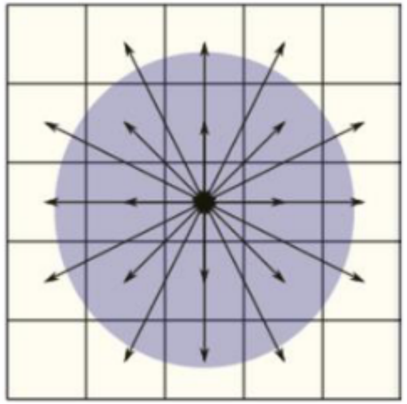
RSP accuracy

- Comparing also against an iterative reconstruction algorithm
- Image was provided by ProtonVDA
  - ➢ Less artifacts
  - ➢ Same RSP MAPE

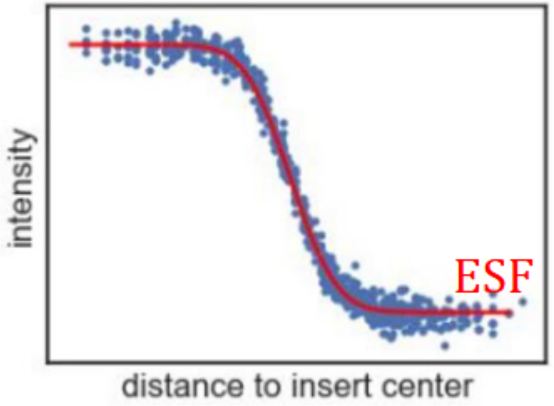


Spatial resolution

- Evaluated as modulation transfer function (MTF) on the radial edge spread function (ESF)[4],[5],[6]



Fit to image intensity



$$\mathrm{ESF}(r) = \frac{A}{2}\left(1 + \mathrm{erf}\left(\frac{r-\mu}{\sqrt{2}\,\sigma}\right)\right) + C$$

- Quantified as frequency at 10% MTF: $f_{\mathrm{MTF10\%}} = \frac{1}{\pi\sigma}\sqrt{\frac{\ln 10}{2}}$

[4] Richard et al., Med Phys.2012;39:4115-412. [5] Talk by Stefanie Götz [6] Khellaf et al., Phys Med Biol. 2020 Jun 1;65(10):105010

Spatial resolution

- Axial SRes for the two scanners at a radial position of ~150 mm:

Insert	$f_{MTF_{10}}^{phase-II}$ (lp/mm)	$f_{MTF_{10}}^{pVDA}$
Cortical bone	0.61 (0.02)	0.47 (0.02)
Dentin	0.62 (0.02)	0.44 (0.02)
Enamel	0.59 (0.01)	0.48 (0.02)
Mean	0.61 (0.01)	0.46 (0.01)

- Phase-II SRes comparable to that quantified in a different study, using same scanner and a slightly different object[7]

- Phase-II higher SRes, reflecting full tracking

- Deterioration of SRes consistent with past theoretical predictions[8]

[7] Plautz et al., Med Phys.2016;43:6291-6300. [8] Krah et al., Phys Med Biol. 2018;63:135013.

Conclusions

- Direct experimental comparison of two pCT scanners/different designs:
  - ➢ RSP accuracy equal or better than 1% for both
  - ➢ Position measurement only, factor 1.2-1.4 lower SRes

LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN
Faculty of Physics
Chair of Medical Physics
Prof. Dr. Katia Parodi

or's Thesis

ical Scanners for Proton
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des, Jannis Dickmann
a Parodi

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RESEARCH ARTICLE

MEDICAL PHYSICS

Comparative accuracy and resolution assessment of two prototype proton computed tomography scanners

George Dedes[1] | Hubertus Drosten[1] | Stefanie Götz[1] | Jannis Dickmann[1] | Christina Sarosiek[2] | Mark Pankuch[3] | Nils Krah[4] | Simon Rit[4] | Vladimir Bashkirov[5] | Reinhard W. Schulte[5] | Robert P. Johnson[6] | Katia Parodi[1] | Ethan DeJongh[7] | Guillaume Landry[1,8,9]

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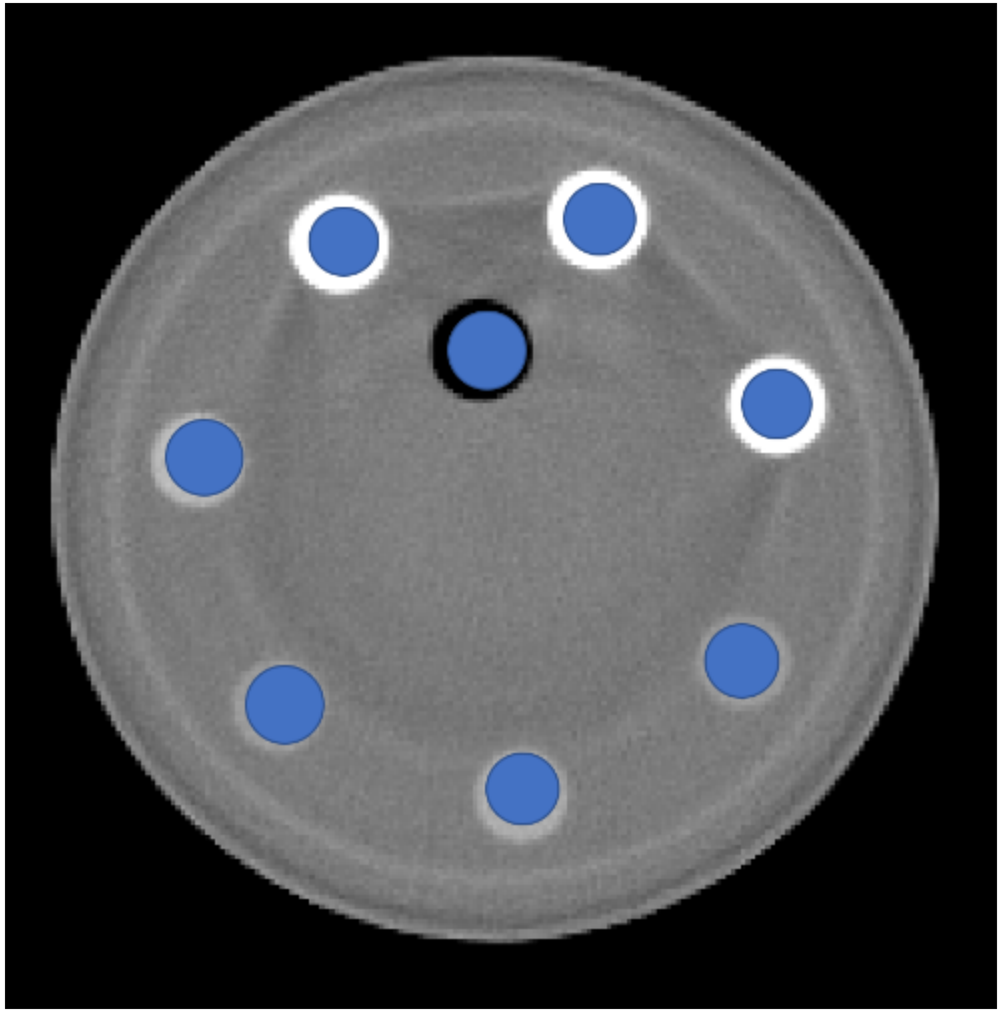
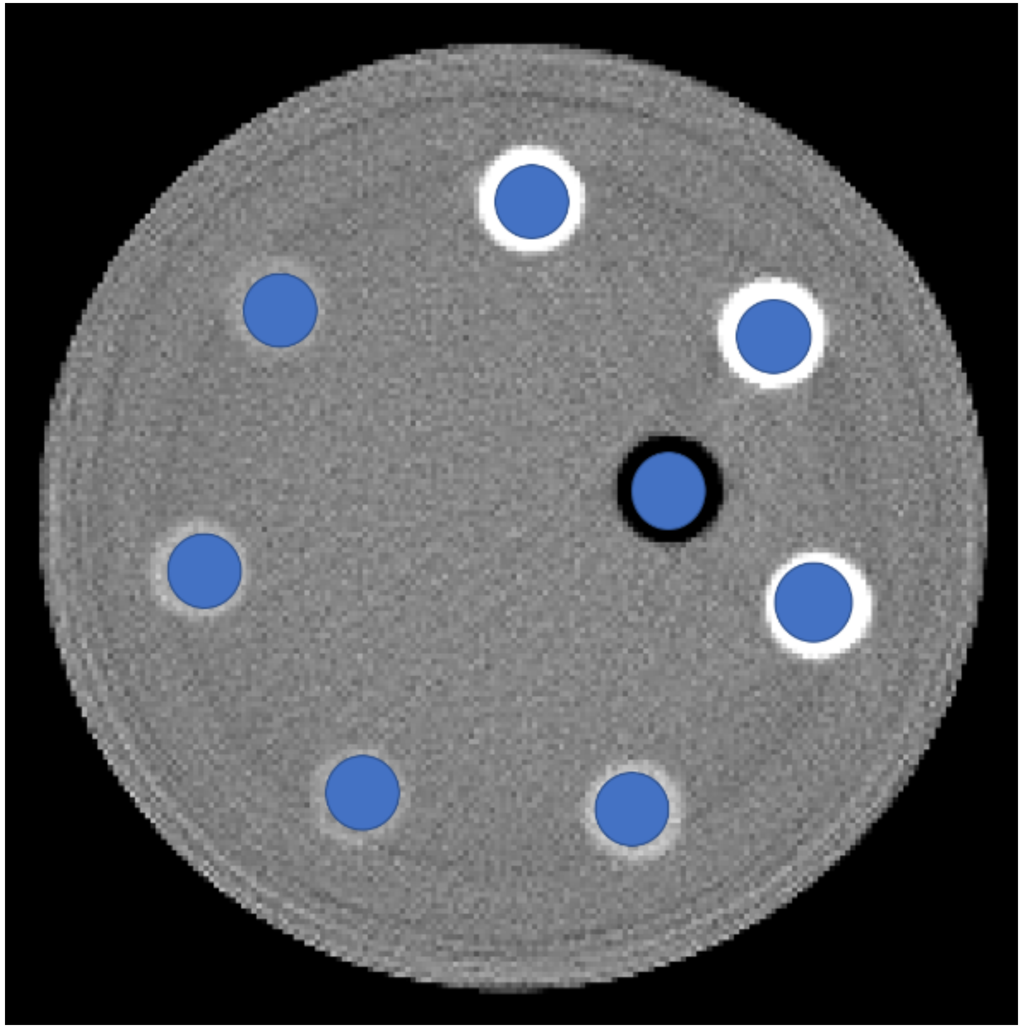
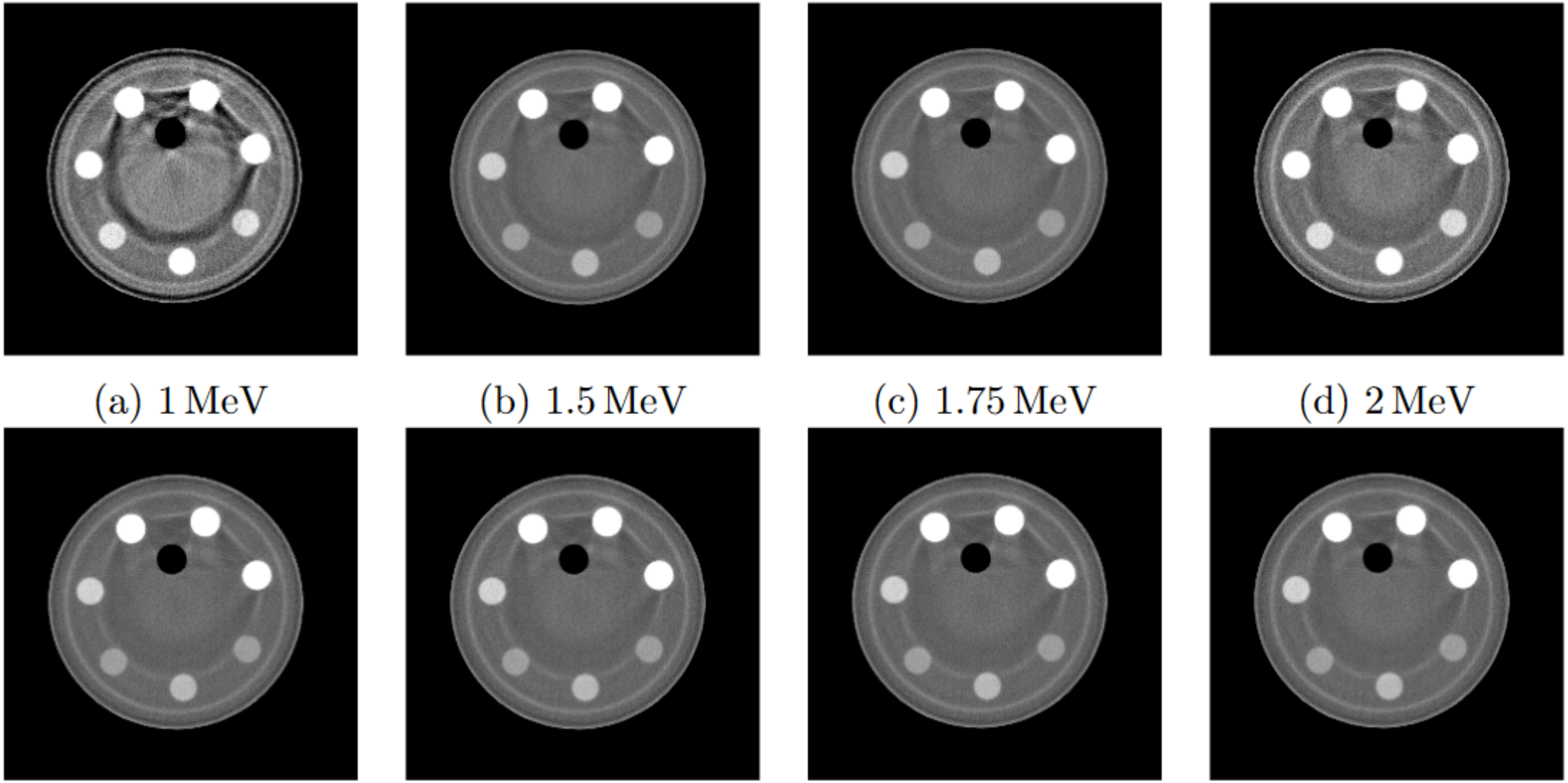
Backup



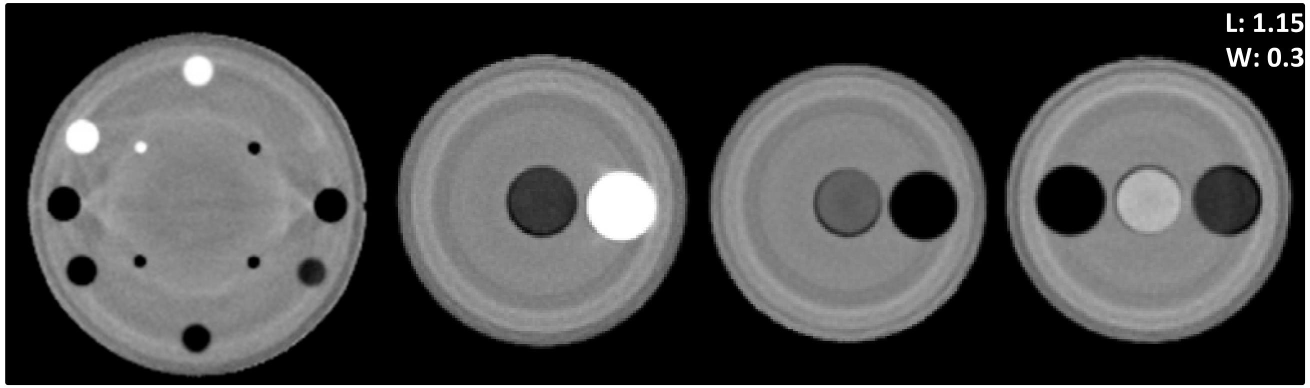


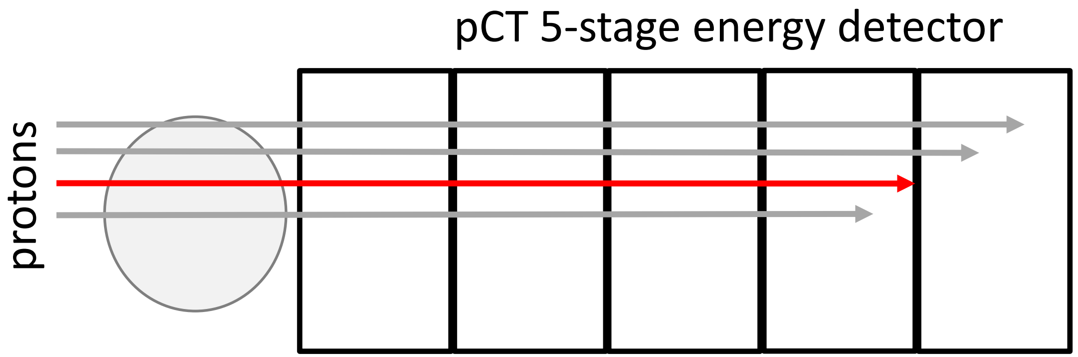


(a) 1 MeV (b) 1.5 MeV (c) 1.75 MeV (d) 2 MeV

(e) 2.25 MeV (f) 2.5 MeV (g) 2.75 MeV (h) 3 MeV

RSP artifacts





- Protons stopping near stage interfaces yield less accurate information
- In homogeneous cylindrical objects this results in ring artifacts

- Calculating for each voxel, the fraction of protons stopping near stage interfaces