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Imaging dose estimation in ion CT for the image quality comparison of proton CT and helium CT

2025 Ion Imaging Workshop

20.10.2025 | Lei Chen

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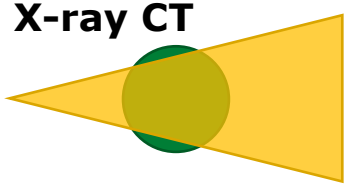
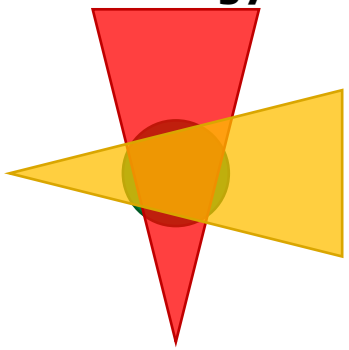
Background
Imaging in Proton Therapy

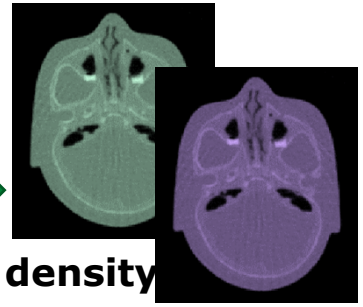


photon attenuation μ

RSP error

(≈ 1-3%)

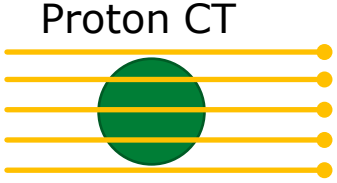




e^- density

Z_{eff}

(0.67%)



ΔE → WEPL = ∫RSP

proton stopping power (RSP)

Proton CT (0.55%)
- Direct measurement of proton interaction
- Low imaging dose
- In treatment position using treatment beam line

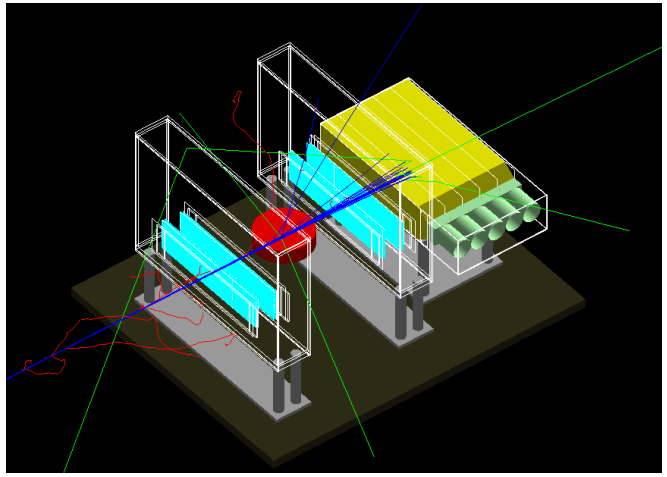
Helium CT (0.78%)
- *Higher spatial resolution*

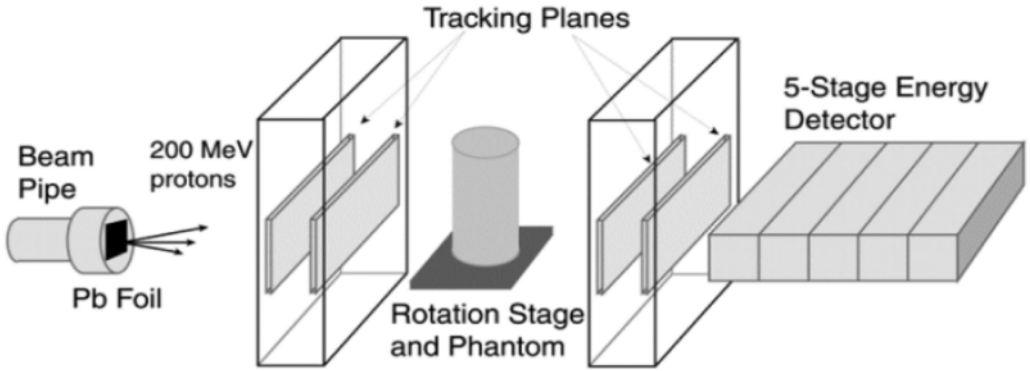
G. Dedes et al. PMB. 2019, 64, 16
Bär E, et al, Med Phys. 2022;49(1)

Method

Imaging dose estimation method

Farmer Ionization Chamber 30010





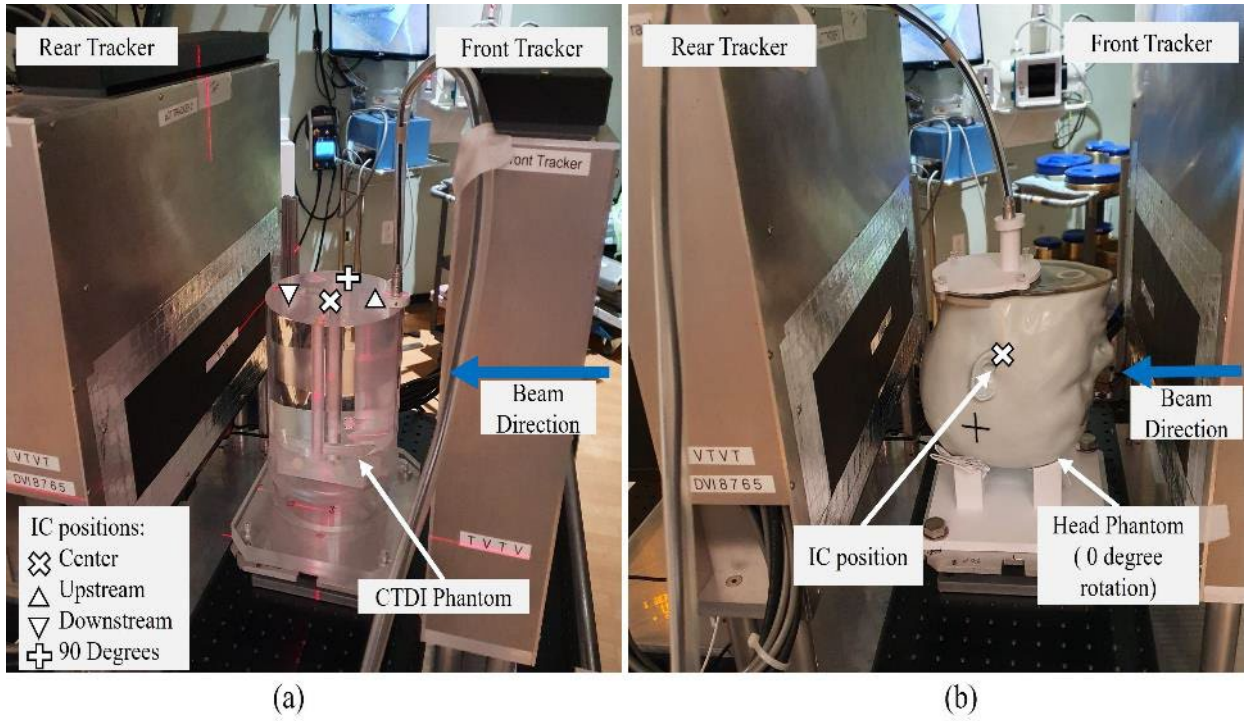
- Estimation by simulation
  - Front-tracker-triggered method
  - Energy-detector-triggered method

Monte Carlo model: Giacometti et al. (2017), Med. Phys, 44, 3
Dickmann et al. (2019), PMB, 64, 14

Method

Front-tracker-triggered method

- The Phase II prototype pCT scanner at the Northwestern Medicine Chicago Proton Center



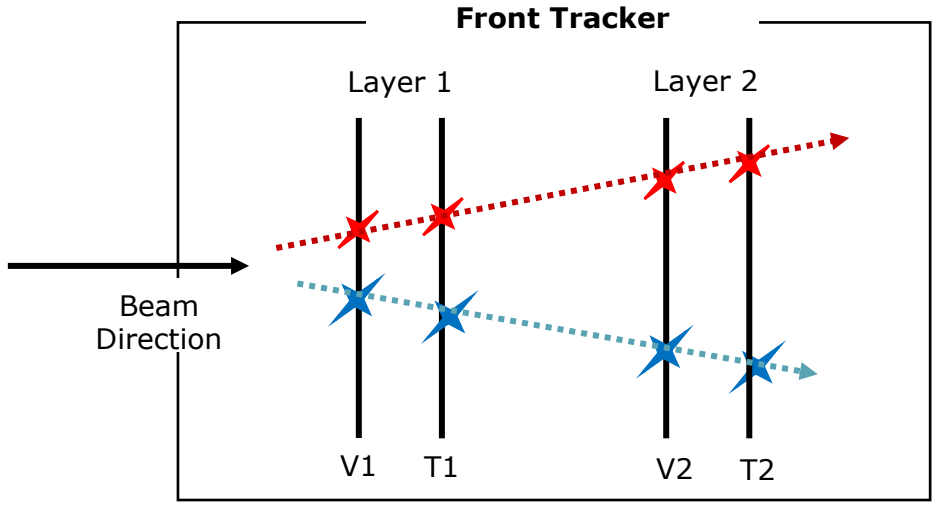
Phantom Type	Rotation	IC position	Beam on duration [s]	Trigger rate [MHz]	Trigger type	IC Measurement repetition
CTDI	no	center	30	1.00	energy detector	8
phantom	no	upstream	30	1.00	energy detector	3
	no	downstream	30	1.00	energy detector	3
	no	90 degrees	30	1.00	energy detector	3
	360 degree	center	360	1.00	energy detector	2
	no	upstream	30	1.20	front tracker	1
	no	downstream	30	1.18	front tracker	1
	no	90 degrees	30	1.18	front tracker	1
Head	0 degree	center	30	1.03	energy detector	1
phantom	45 degrees	center	30	1.05	energy detector	1
	90 degrees	center	30	1.05	energy detector	1
	360 degrees	center	360	1.00	energy detector	1
No phantom (× 5)	/	/	30	1.20	front tracker	/

L Chen et al. Submitted, 2025.

Method

Front-tracker-triggered method

- Precise quantification of the proton fluence in each measurement is crucial for accurate dose estimation through MC simulations
  - Created tracks from complete events
  - Potential tracks from incomplete events
    - the same probability of creating single/multiple proton tracks
  - Potential tracks from complete events
    - additional hits

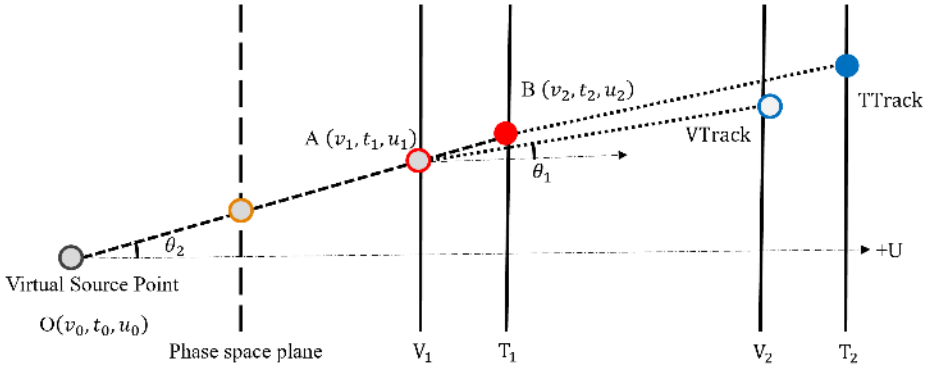


L Chen et al. Submitted, 2025.

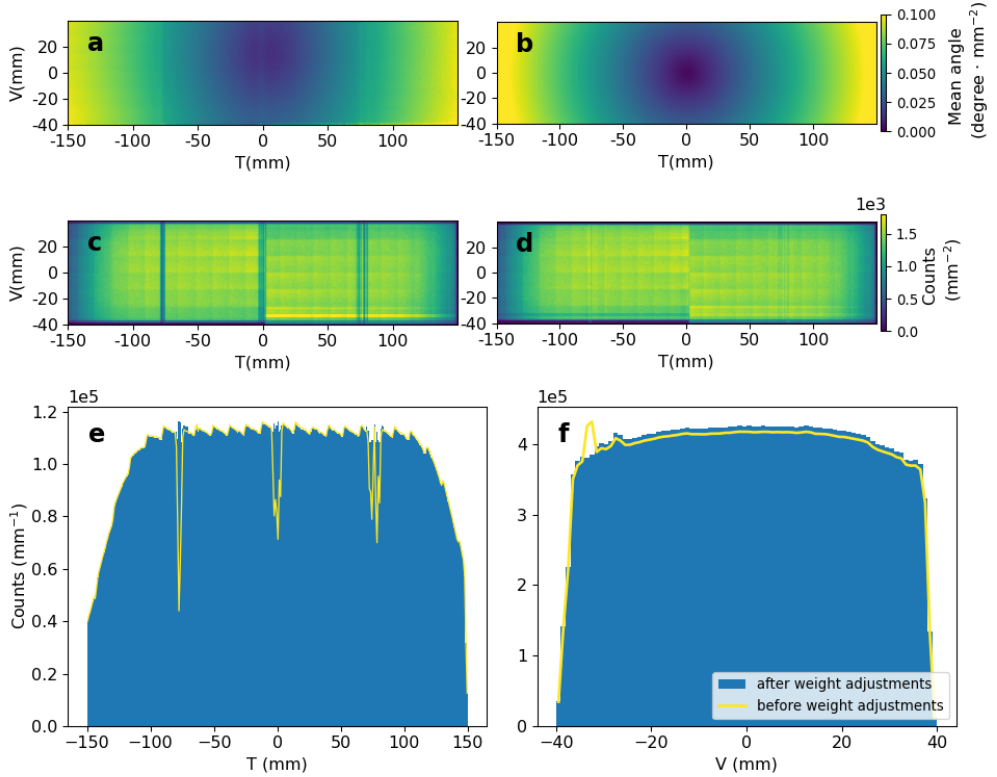
Method

Front-tracker-triggered method

- Created tracks from complete events
  - V/T hits -> V/T track -> Tracks
  - smallest-angle selection
  - virtual source point introduction



$$\frac{v_1 - v_0}{v_2 - v_0} = \frac{t_1 - t_0}{t_2 - t_0} = \frac{u_1 - u_0}{u_2 - u_0} \qquad \left(v_1, \frac{u_1 - u_0}{u_2 - u_0} \times (t_2 - t_0) + t_0, u_1 \right)$$



- Angular
- Position

L Chen et al. Submitted, 2025.

Method

Front-tracker-triggered method

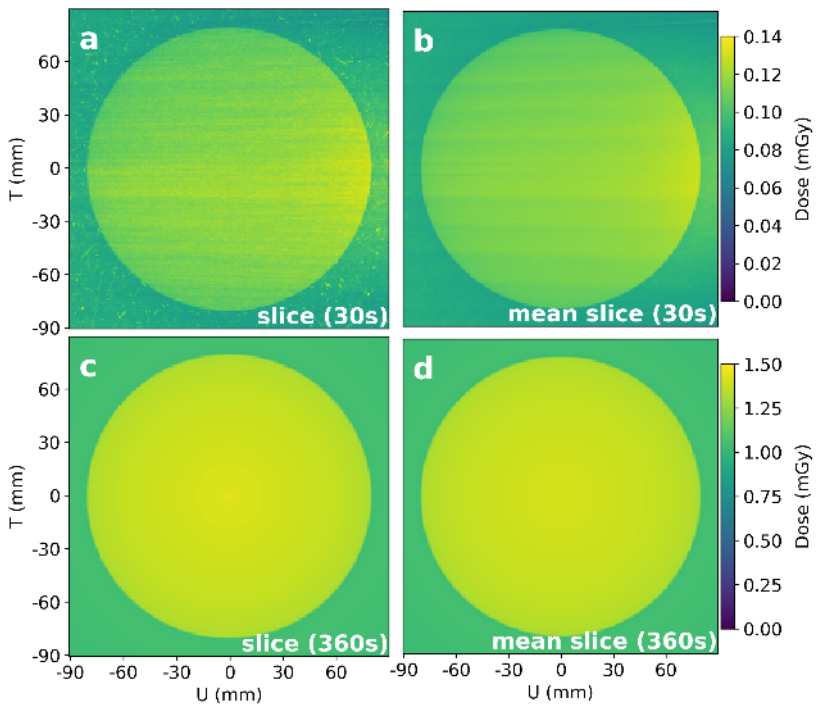
- Simulation, Geant4
  - Input source: averaged phase space file from 8 front tracker triggered measured data.
  - Phantom: CTDI/Head phantom and IC were filled with water.
  - Renormalisation: simulated dose(arbitrary number) renormalised to estimated proton tracks(measured proton fluence).

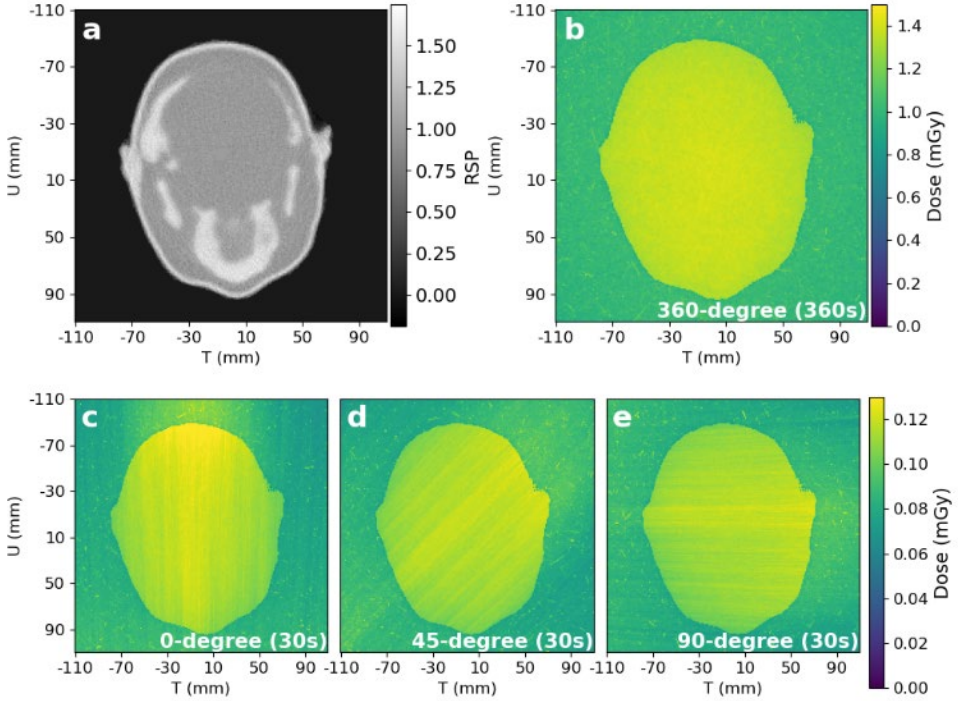
L Chen et al. Submitted, 2025.

Results

Front-tracker-triggered method

- Simulated dose distributions on the T-U plane at a V-coordinate of 0 mm.
  - CTDI phantom with the IC positioned at the centre.
  - Head phantom from 360-degree rotation and single-projections.





L Chen et al. Submitted, 2025.

Results
Front-tracker-triggered method

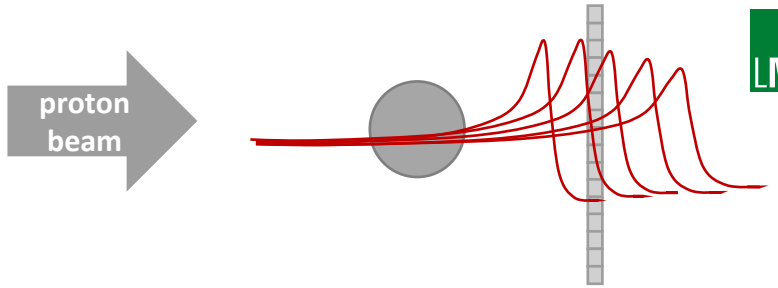
- Dose in satisfactory agreement with IC measurements
- Up to 2% relative difference in CTDI, up to 4.6% in head phantom
- Exception: 6.7% in a single head phantom full scan

Phantom type	Rotation	IC position	$D_{measured}$ [mGy]	$D_{estimated}$ [mGy]	σ_{voxel}	$\Delta_{diff,max}$	$\overline{\Delta}_{diff}$	σ_{diff}
CTDI	no	center	0.116	0.117	0.2%	3.9%	0.6%	1.9%
phantom	no	upstream	0.109	0.111	0.2%	3.1%	1.4%	1.7%
	no	downstream	0.125	0.127	0.2%	2.3%	1.3%	0.8%
	no	90 degrees	0.106	0.108	0.2%	3.5%	1.4%	1.3%
	360 degrees	center	1.429	1.403	0.2%	-2.3%	-1.8%	0.5%
Head	0 degree	center	0.120	0.120	0.3%	-3.4%	/	/
phantom	45 degrees	center	0.119	0.117	0.2%	-4.6%	/	/
	90 degrees	center	0.117	0.116	0.2%	-3.6%	/	/
	360 degrees	center	1.451	1.391	0.2%	-6.7%	/	/

L Chen et al. Submitted, 2025.

Method

Energy-detector-triggered method



Experiment without phantom

Two simulation with/without phantom

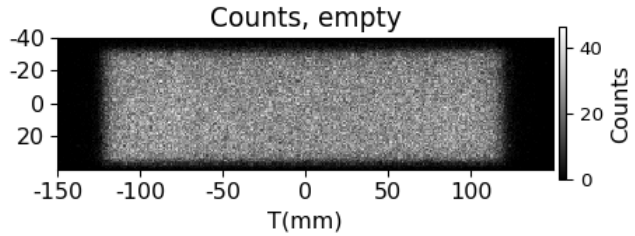
Creating phase space source

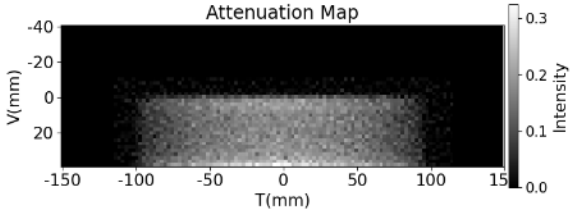
Creating attenuation correction

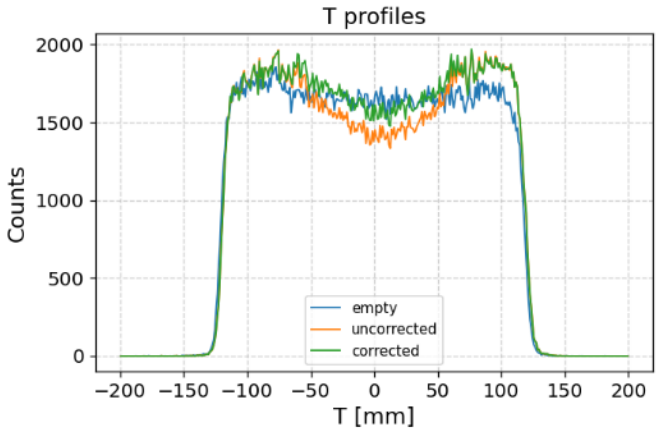
Apply attenuation correction on run with phantom

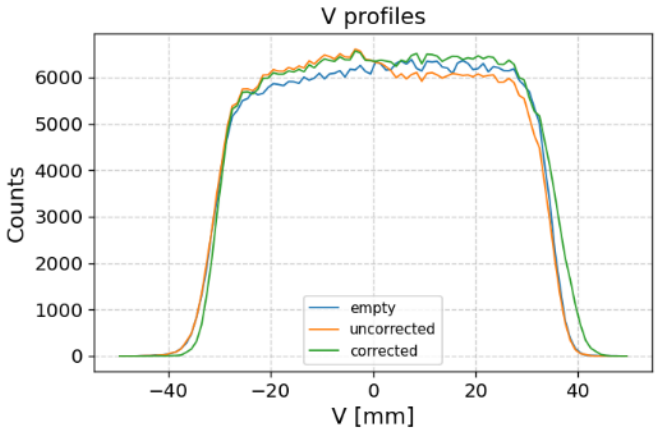
Creating phase space source

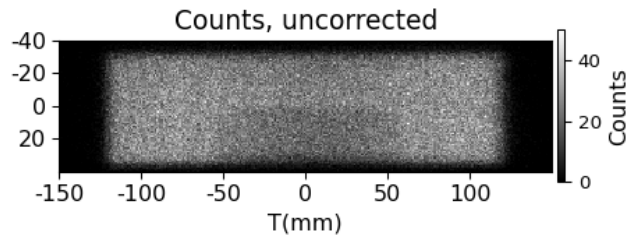
Simulation with source from this source

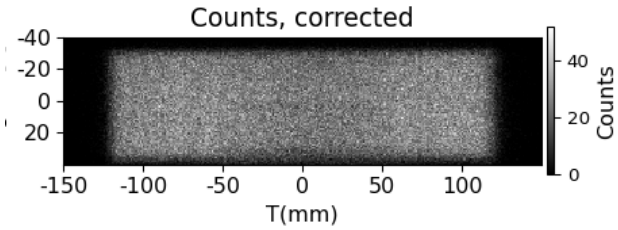








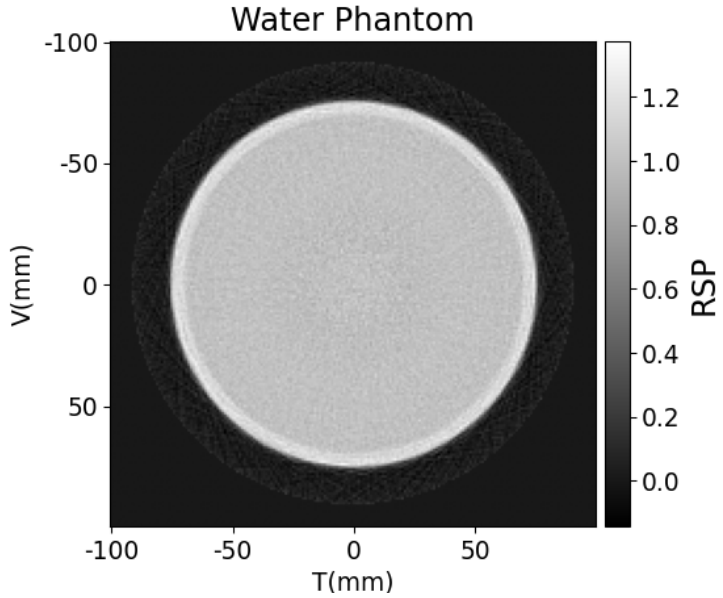


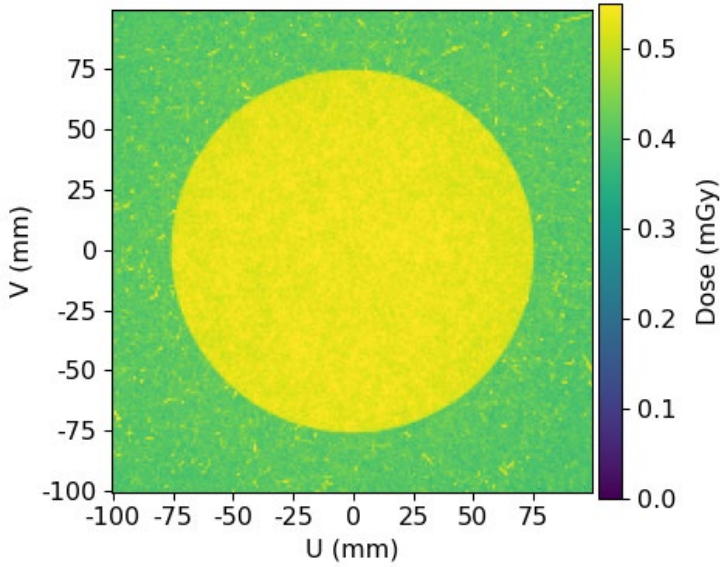


Results

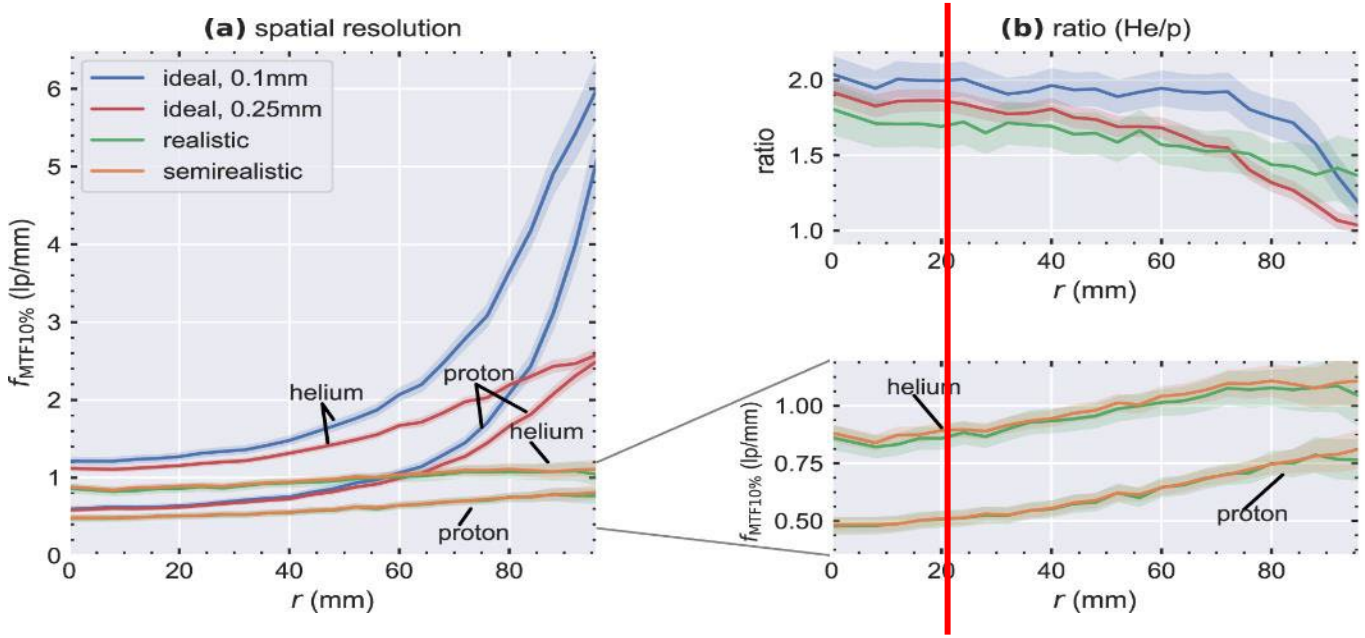
Energy-detector-triggered method

- Simulation
  - Corrected phase space source for each projection, and used it to the corresponding rotation angle
- Renormalisation
  - Total proton number after preprocessing
  - Constant factor due to cut during preprocessing





Outlook
Proton CT vs Helium CT



- the scanner prototype would produce higher spatial resolution for HeCT than pCT by a factor 1.8 (0.86 $lp\,mm^{-1}$ versus 0.48 $lp\,mm^{-1}$ at the center of a 20 cm water phantom).
- HeCT required a factor 2.9 more dose than pCT to achieve the same noise

Table 1. The first three columns report the dose ratio of helium ions to protons at equal variance at the central ROI of the water phantom and for the two ROIs of the head phantom (nasal cavity and center of brain). The ratio is taken using helium and proton data from the same phantom using reconstructions without Hann windowing. The last two columns report the doses for realistic simulations required to achieve the reference variance at the center of the water cylinder for protons without Hann windowing ($V_{p,w/o\,Hann} = 0.0022$).

ROI	Ideal	Rrealistic w/o ΔE–E	Realistic w/ ΔE–E	pCT dose (mGy)	HeCT dose w/ ΔE–E (mGy)
Water phantom	1.3	3.7	2.9	5.00	14.29
Nasal cavity	2.1	3.8	2.9	11.29	32.34
Center of brain	1.3	3.1	2.8	5.52	15.31

Physics in Medicine & Biology

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Evaluation of the impact of a scanner prototype on proton CT and helium CT image quality and dose efficiency with Monte Carlo simulation

S Götz, J Dickmann, S Rit, N Krah, F Khellaf, R W Schulte, K Parodi, G Dedes and G Landry

Published 21 February 2022 • © 2022 The Author(s). Published on behalf of Institute of Physics and Engineering in Medicine by IOP Publishing Ltd

Physics in Medicine & Biology, Volume 67, Number 5

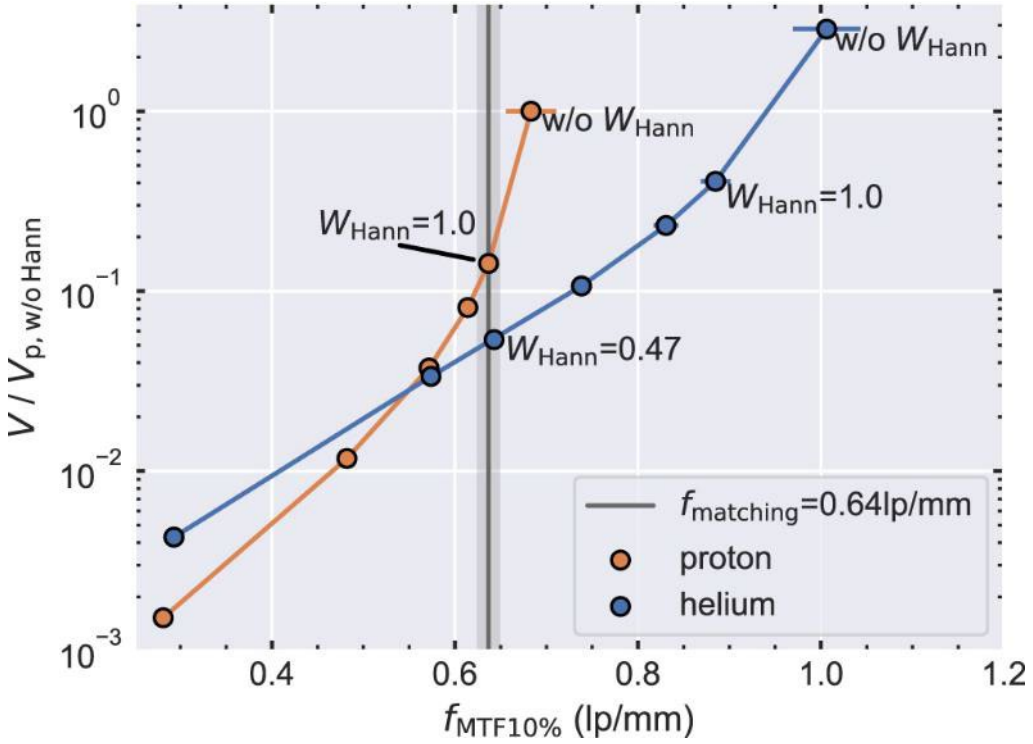
Citation S Götz *et al* 2022 *Phys. Med. Biol.* **67** 055003

DOI 10.1088/1361-6560/ac4fa4

Realistic condition

Götz S et al. *Phys Med Biol*. 2022;67(5):10.

Outlook
Proton CT vs Helium CT



$$V \cdot D = \text{constant}$$

- Spatial resolution matching
  - helium spatial resolution was reduced to the spatial resolution of protons at W_{Hann} = 1
- While at matched resolution, HeCT required only 38% of the pCT dose at equal-area and equal variance.
- HeCT might therefore help reduce the dose exposure of patients with comparable image noise to pCT

Table 2. Dose ratio of helium ($W_{Hann} = 0.47$) to protons ($W_{Hann} = 1.0$) at resolution matching (0.64 lp·mm^{-1} at equal-area insert) and equal variance. The last two columns report the doses for realistic simulations required to achieve the reference variance at the center of the water cylinder for protons ($V_{p,w_{Hann}=1.0} = 0.00031$).

ROI	Dose ratio (He/p)	pCT dose (mGy)	HeCT dose (mGy)
Water phantom	0.38	5.00	1.89
Nasal cavity	0.38	11.28	4.24
Center of brain	0.36	5.52	2.01

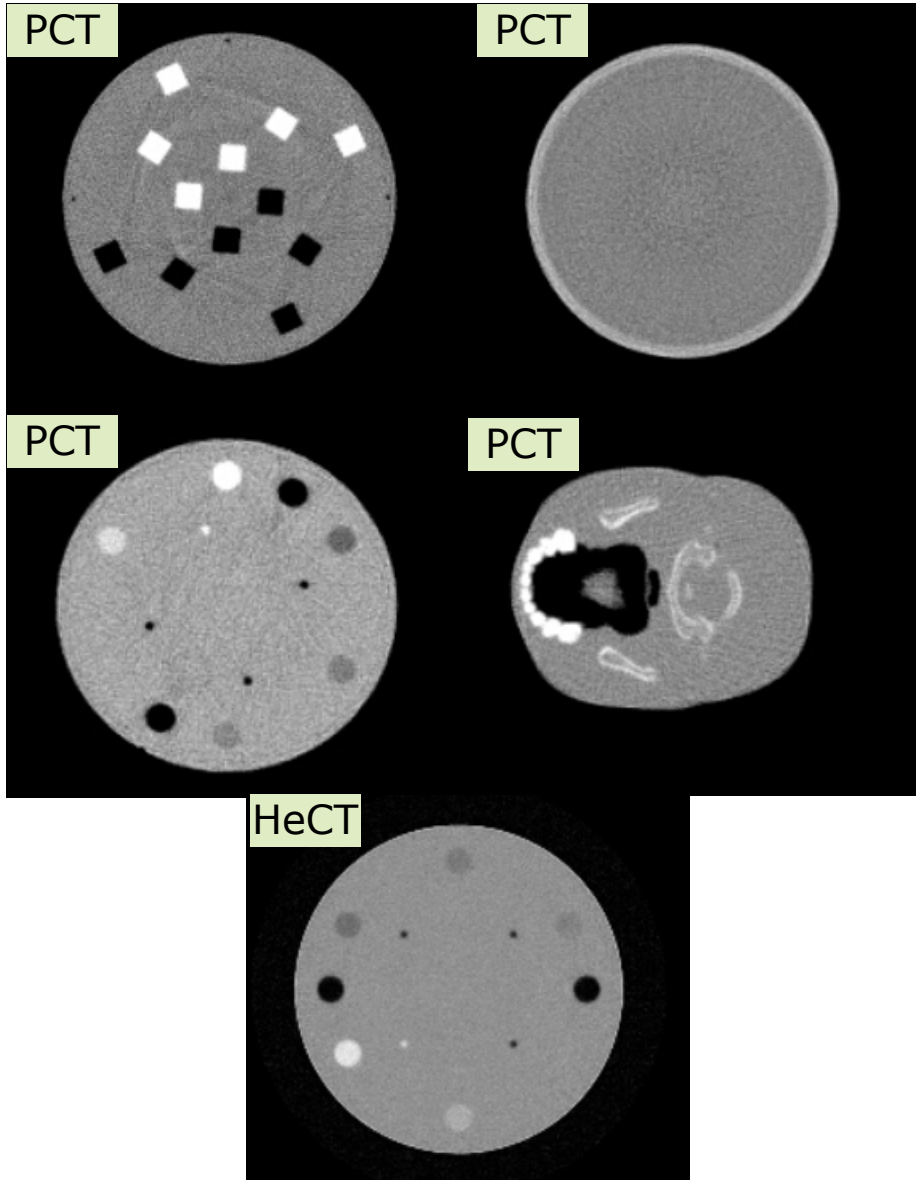
Dickmann et al. Med. Phys. 2020, 47, 4

Götz S et al. *Phys Med Biol*. 2022;67(5):10

Outlook
Proton CT vs Helium CT

- Under equivalent **experimental condition**
  - same scanner geometry and phantom configurations
  - Phantom: water phantom, sensitometry, head phantom, Edge phantom.
  - pCT: Northwestern Medicine Chicago Proton Centre
  - HeCT: Heidelberg/GSI(L Volz)

- Aim of study: Quantitative evaluation of both modalities in terms of:
  - Spatial resolution
  - Imaging dose
  - RSP accuracy



Conclusion

- Successfully developed and implemented a front-tracker-triggered acquisition method.
- Initial validation of energy-detector-triggered method within the pCT scanner

- Development of a unified framework to compare HeCT and pCT at identical experimental conditions

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Vielen Dank
für Ihre Aufmerksamkeit!

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