Inverse-planned fluence field modulation for optimal usage of imaging dose in proton CT

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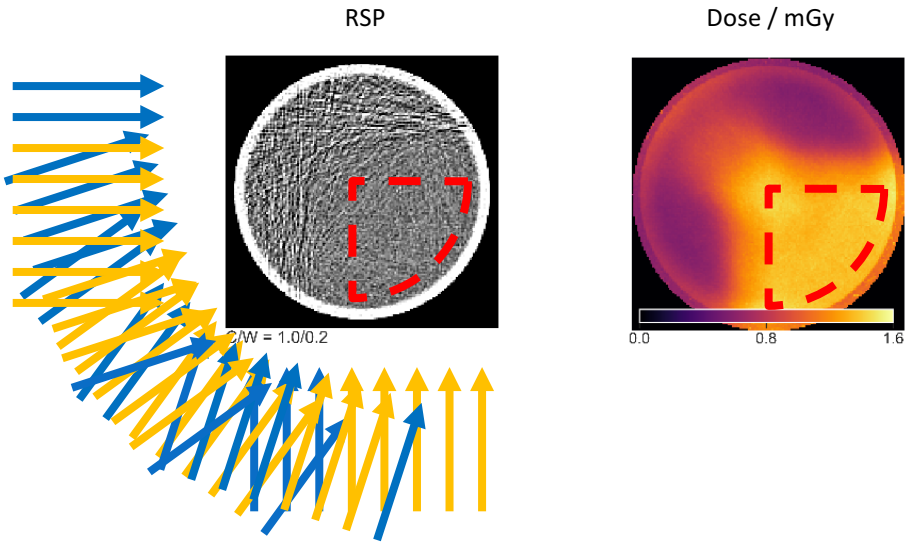
5th annual Loma Linda Workshop on Algorithms for Particle Imaging and Radiation Treatment planning

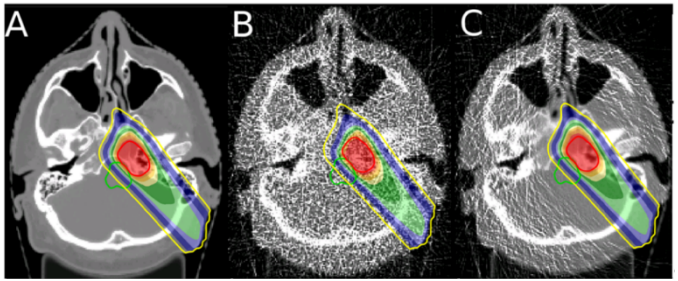
Monday, July 22nd 2019

Fluence-modulated proton CT (FMpCT)

Aim: to achieve arbitrary **image noise targets** with FMpCT



Motivation: frequent imaging for particle therapy



noise in ROI	Low	High	Low
dose outside ROI	High	Low	Low

Dedes et. al. (2017), PMB, 62, 6026

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Part I:

Simulating & understanding noise

Part II:

Optimizing FMpCT plans

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Part I:

Simulating & understanding noise

Part II:

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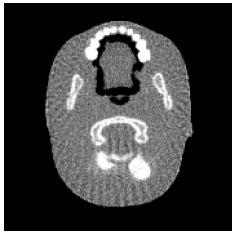
Variance reconstruction

Standard reconstruction

projection

ramp filter → backprojection

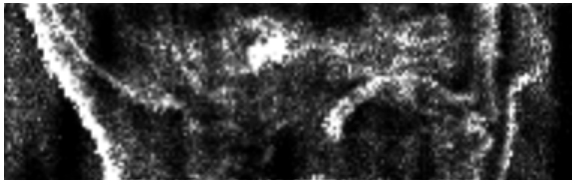


volume

$$f(x,y) = \frac{\pi\Delta\xi}{N_P} \sum_{n=1}^{N_P} \{k \circledast p\}(x\cos(\gamma_n) + y\sin(\gamma_n))$$

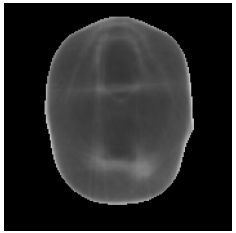
$$\mathrm{Var}[f(x,y)] = f_{\mathrm{interp}} \left(\frac{\pi\Delta\xi}{N_P}\right)^2 \sum_{n=1}^{N_P} \{k^2 \circledast \mathrm{Var}[p]\}(x\cos(\gamma_n) + y\sin(\gamma_n))$$

Variance reconstruction



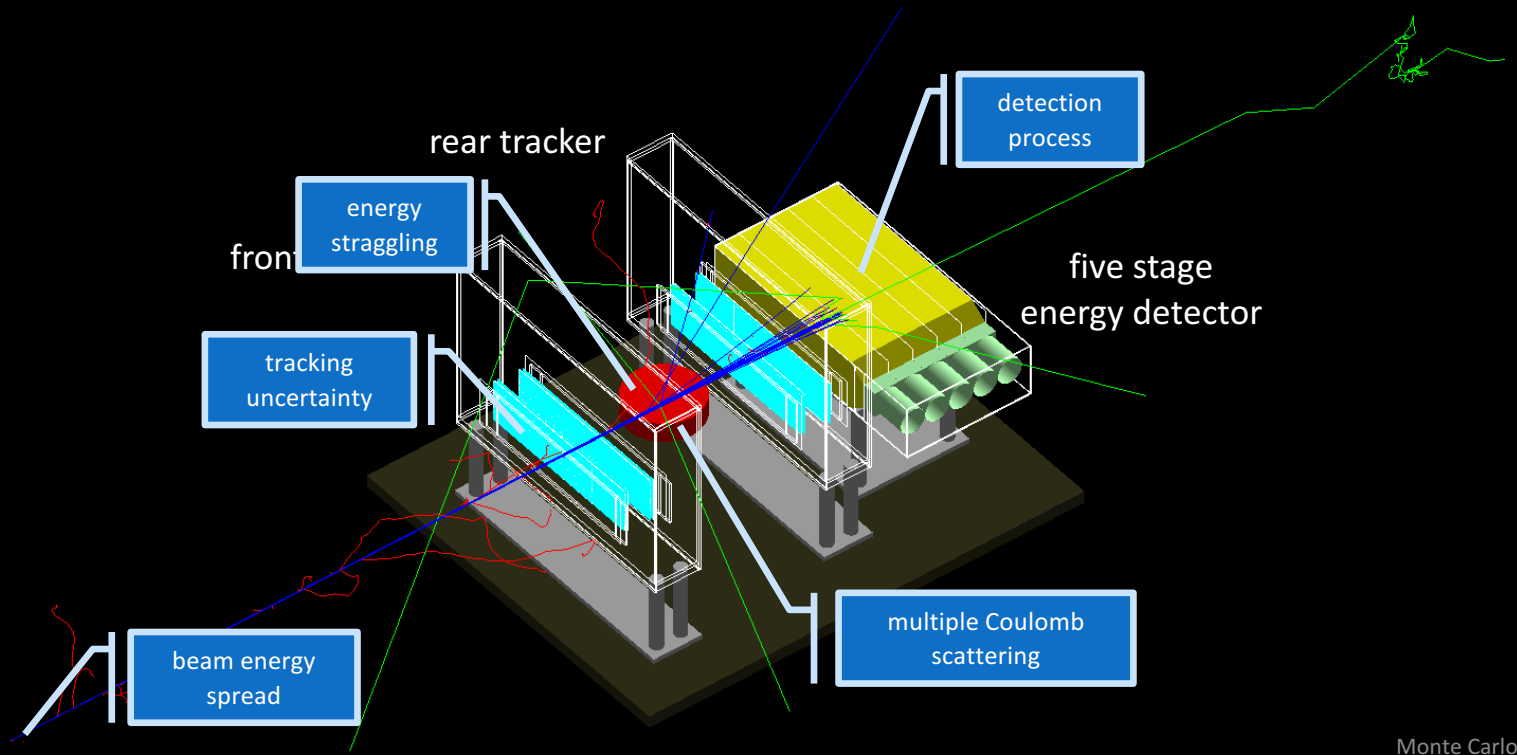
variance projection

(filter) → backprojection



variance volume

Proton computed tomography

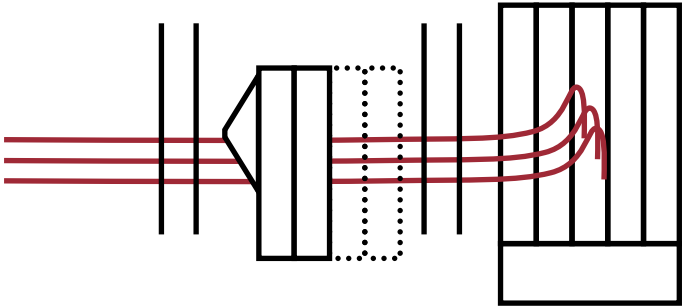


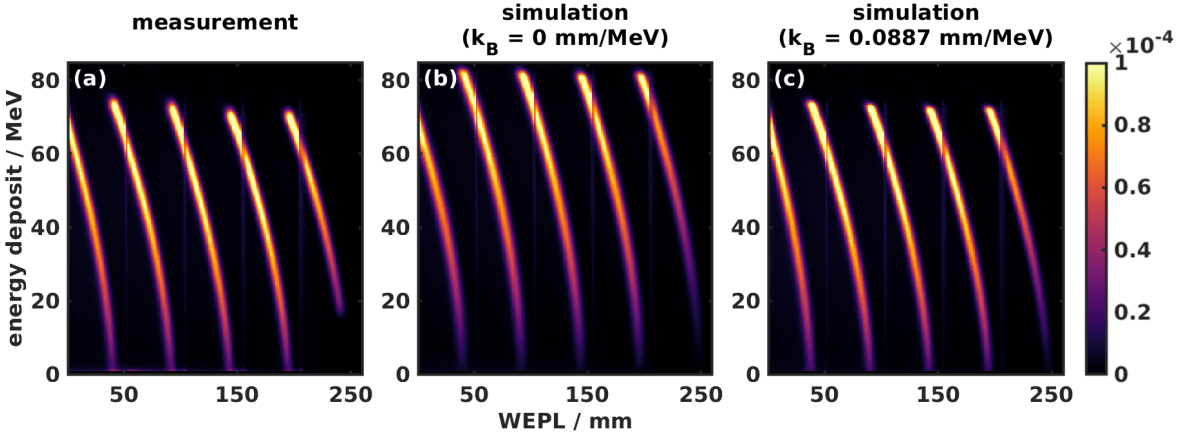
Monte Carlo model:
Giacometti et. al. (2017), Med. Phys, 44, 3
Dickmann et. al. (2019), PMB, in press

Quenching

- Efficiency of **light production** reduces for **high-LET radiation**!

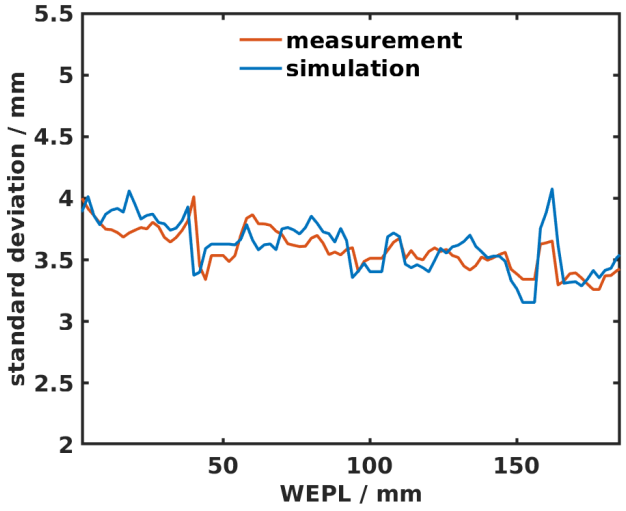
$$E'(R) = S_n \int_R^0 \mathrm{d}x \, \frac{\mathrm{d}E/\mathrm{d}x}{1 + k_B \cdot \mathrm{d}E/\mathrm{d}x}$$

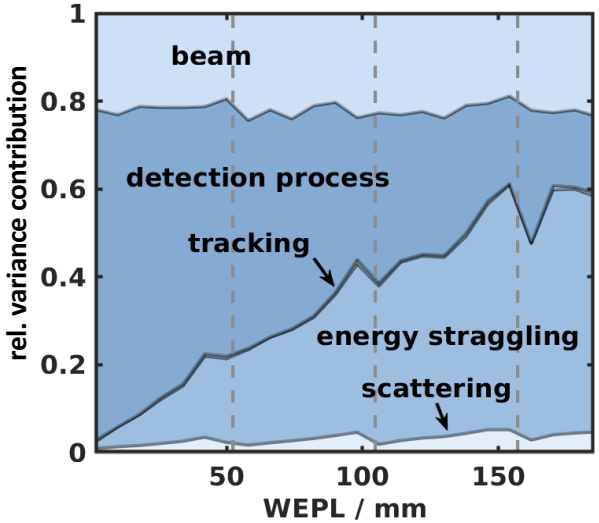




Projection noise contributions

- Noise in projection is **independent of WEPL**.
- For homogeneous phantom, noise is **dominated by energy straggling**.





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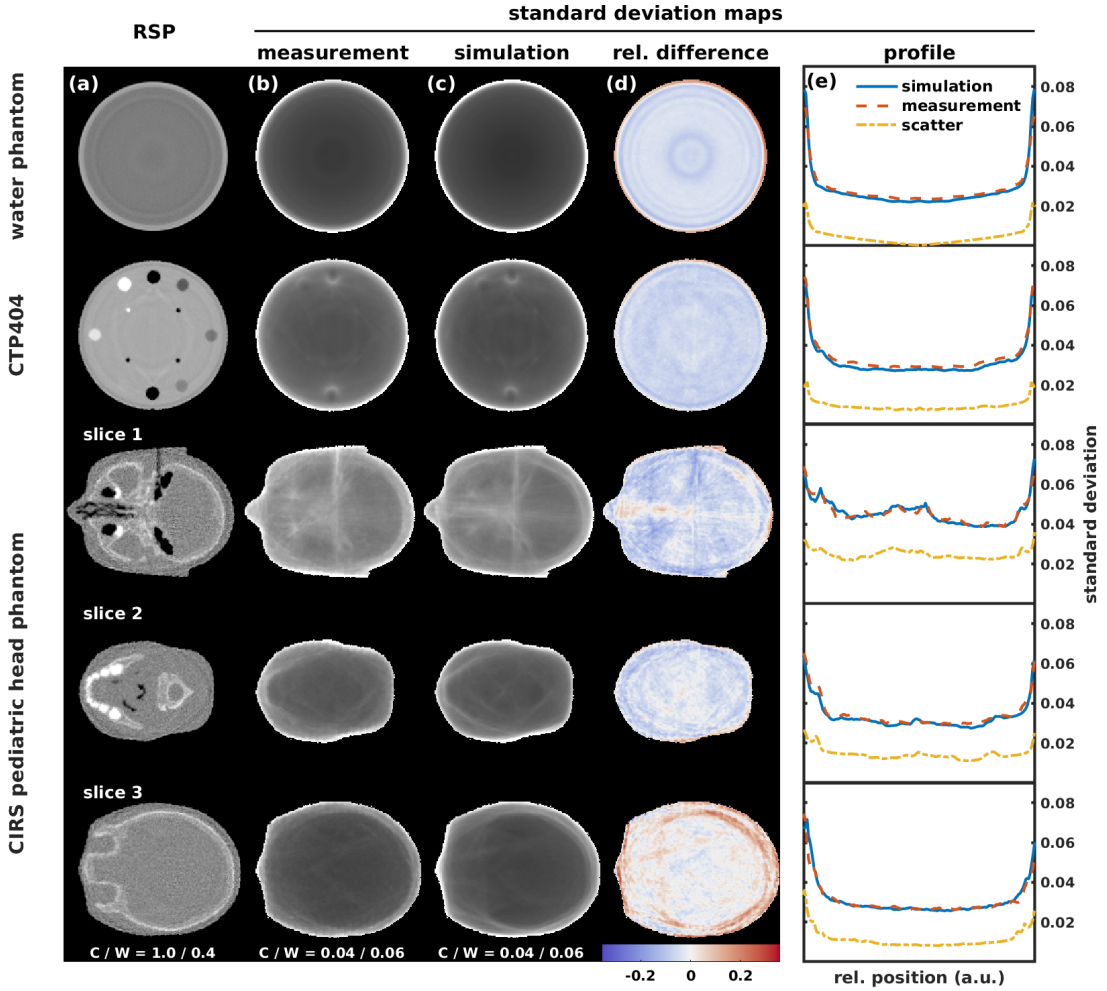
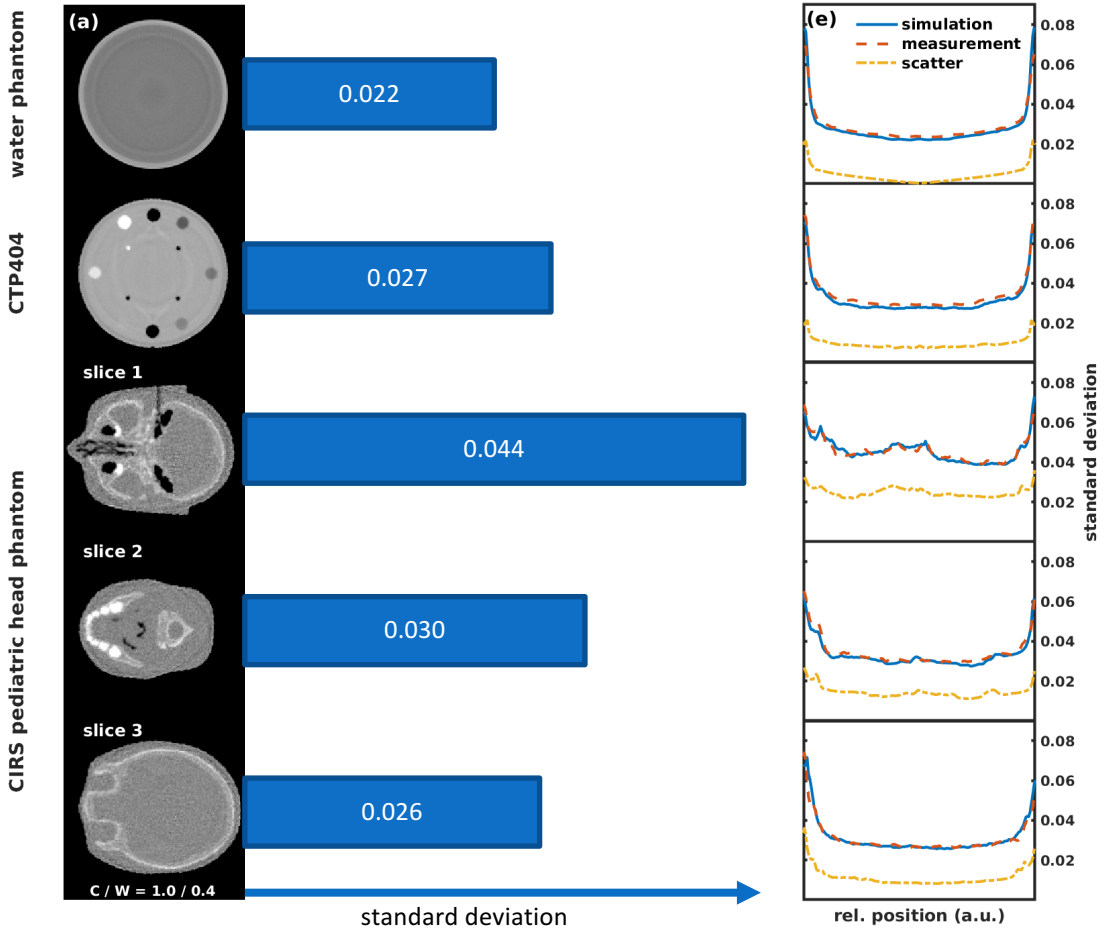
RESULTS



RESULTS


(a)
water phantom
CTP404
CIRS pediatric head phantom
slice 1
slice 2
slice 3
C / W = 1.0 / 0.4
0.022
0.027
0.044
0.030
0.026
standard deviation
(e)
simulation
measurement
scatter
0.08
0.06
0.04
0.02
standard deviation
rel. position (a.u.)

More on this…

Paper in PMB

Prediction of image noise contributions in proton computed tomography and comparison to measurements

DOI: 10.1088/1361-6560/ab2474

IOP Publishing Phys. Med. Biol. 64 (2019) 145016 (19pp) https://doi.org/10.1088/1361-6560/ab2474

Physics in Medicine & Biology

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PAPER

Prediction of image noise contributions in proton computed tomography and comparison to measurements

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Keywords: proton CT, proton therapy, relative stopping power, dose reduction, fluence-modulated proton CT, quenching, Monte Carlo

RECEIVED 27 February 2019
REVISED 9 May 2019
ACCEPTED FOR PUBLICATION 24 May 2019
PUBLISHED 16 July 2019

Abstract

We present a method to accurately predict image noise in proton computed tomography (pCT) using data generated from a Monte Carlo simulation and a patient or object model that may be generated from a prior x-ray CT image. This enables noise prediction for arbitrary beam fluence settings and, therefore, the application of fluence-modulated pCT (FMpCT), which can achieve prescribed noise targets and may significantly reduce the integral patient dose.

We extended an existing Monte Carlo simulation of a prototype pCT scanner to include effects of quenching in the energy detector scintillators and constructed a beam model from experimental tracking data. Simulated noise predictions were compared to experimental data both in the projection domain and in the reconstructed image. Noise prediction agreement between simulated and experimental data in terms of the root-mean-square (RMS) error was better than 7% for a homogeneous water phantom and a sensitometry phantom with tubular inserts. For an anthropomorphic head phantom, modeling the anatomy of a five-year-old child, the RMS error was better than 9% in three evaluated slices. We were able to reproduce subtle noise features near heterogeneities. To demonstrate the feasibility of Monte Carlo simulated noise maps for fluence modulation, we calculated a fluence profile that yields a homogeneous noise level in the image. Unlike for bow-tie filters in x-ray CT this does not require constant fluence at the detector and the shape of the fluence profile is fundamentally different.

Using an improved Monte Carlo simulation, we demonstrated the feasibility of using simulated data for accurate image noise prediction for pCT. We believe that the agreement with experimental data is sufficient to enable the future optimization of FMpCT fluence plans to achieve prescribed noise targets in a fluence-modulated acquisition.

1. Introduction

The use of proton computed tomography (pCT), initially proposed by Cormack (1963), promises superior accuracy of relative stopping power (RSP) images required for proton therapy dose calculations employed in treatment planning or for various adaptive proton therapy strategies. Instead of using a stoichiometric calibration to convert x-ray linear attenuation coefficients to proton stopping power (Paganetti 2012, Yang *et al* 2012), pCT scanners directly measure RSP line integrals, which can be used to reconstruct RSP images using

Part I:

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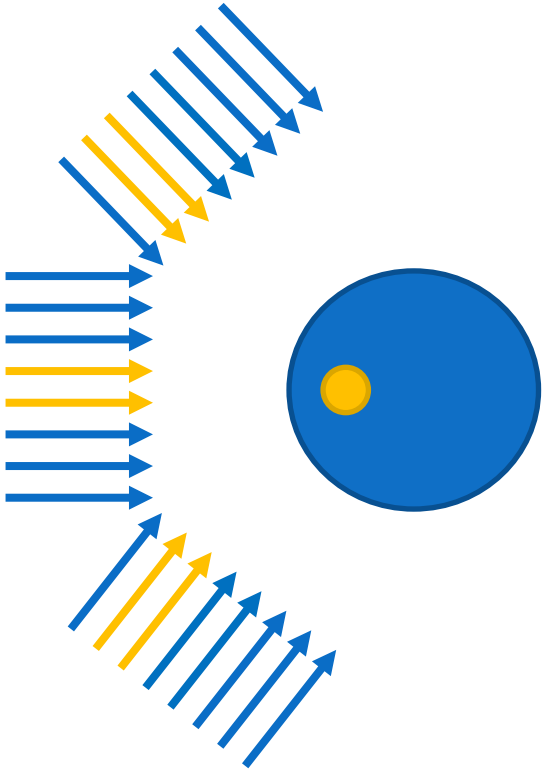
Fluence field optimization



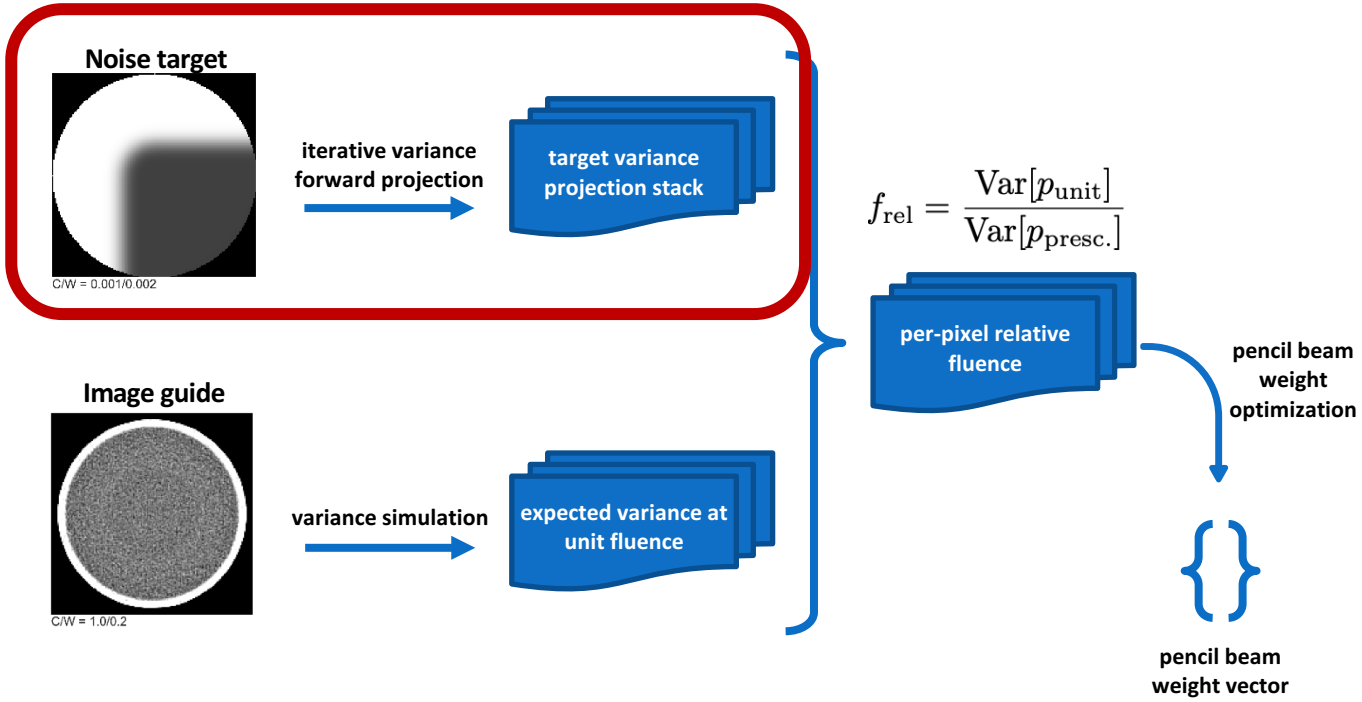
Simple fluence field optimization:
beams intersecting ROI

Drawbacks:

- Only convex shapes
- No absolute noise prescription

Dedes et. al. (2017), PMB, 62, 6026

Fluence field optimization



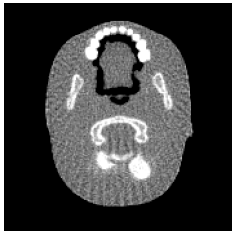
Variance forward projection

Standard forward projection = line integrals

projection

ramp filter → backprojection

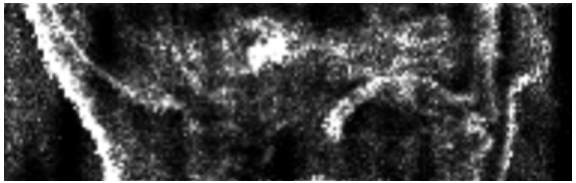
line integrals



volume

Variance forward projection p filter

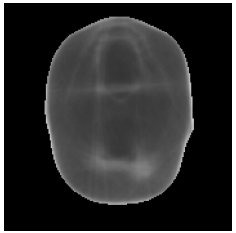
unphysical result:
- high frequencies
- negative



Variance projection

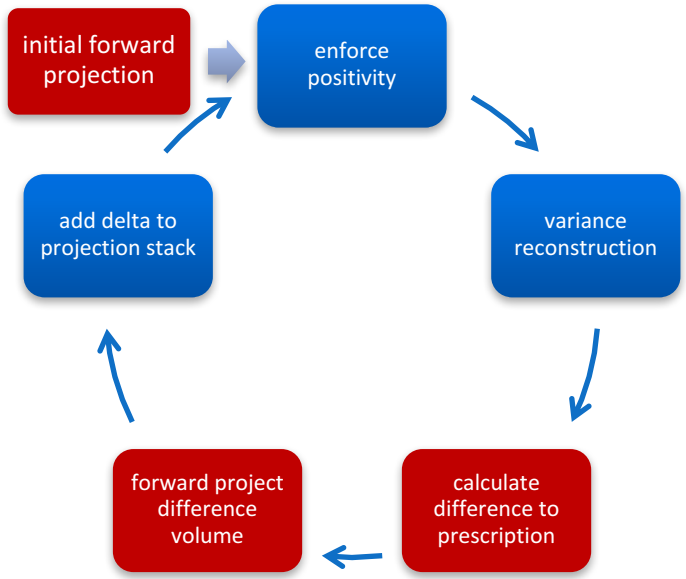
backprojection

ramp filter ← line integrals



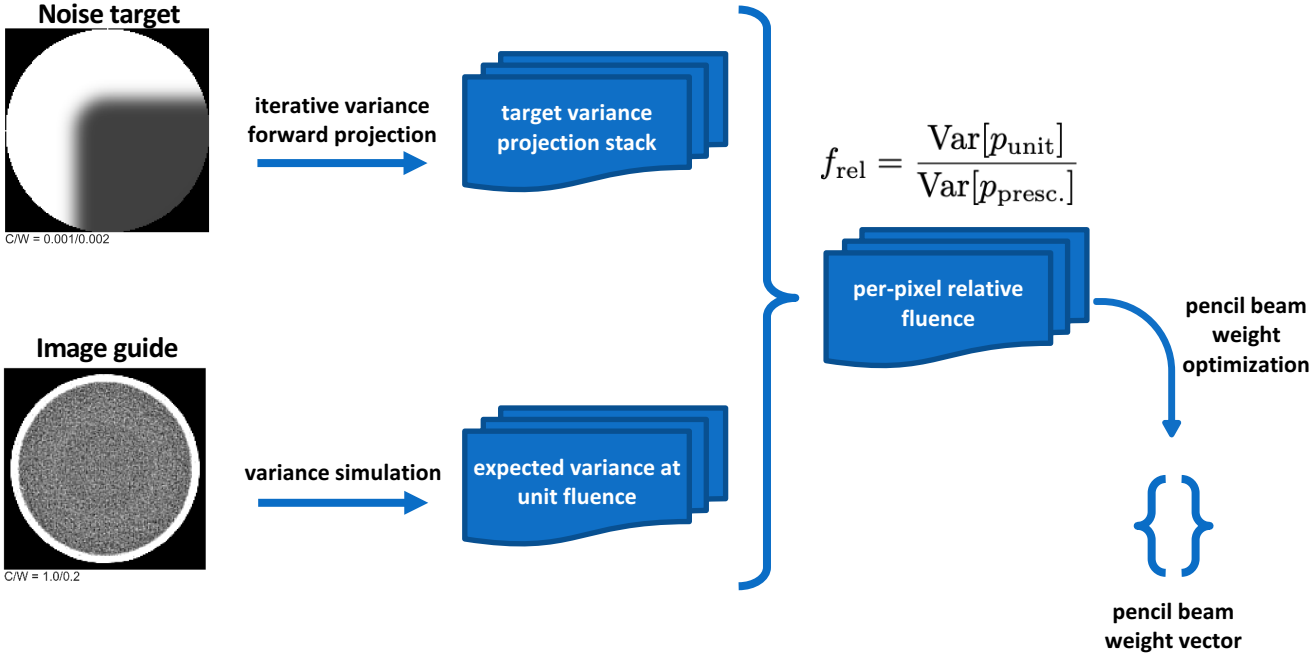
Variance volume

Iterative variance forward projection

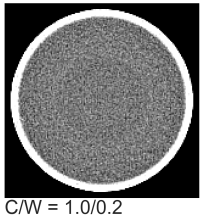
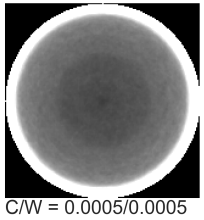
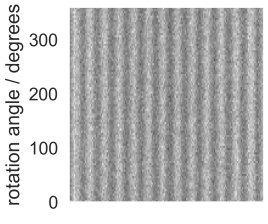
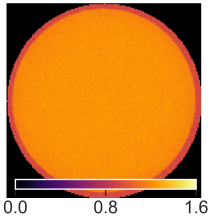
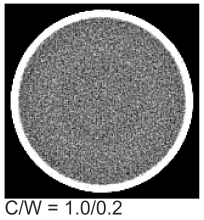
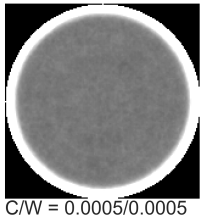
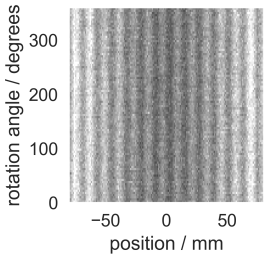
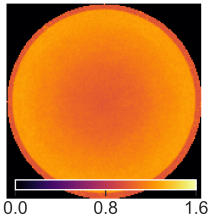


- **Enforcement of positivity** in every iteration
- **Forward projection of difference** to noise prescription
- Analogous to **algebraic reconstruction technique** (ART)

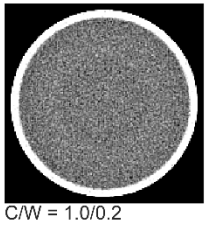
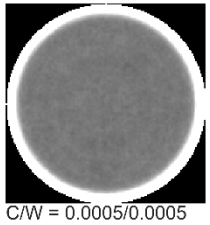
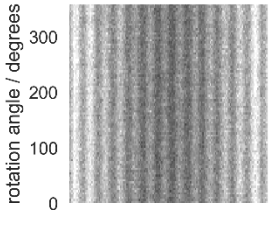
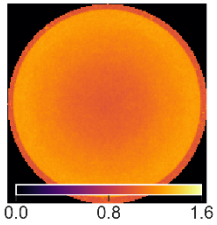
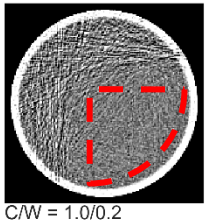
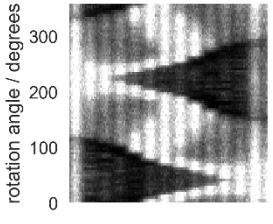
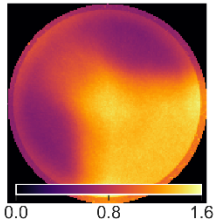
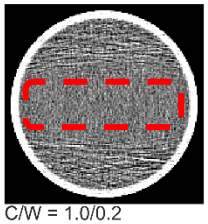
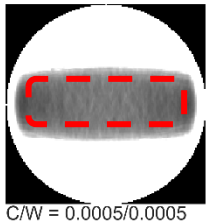
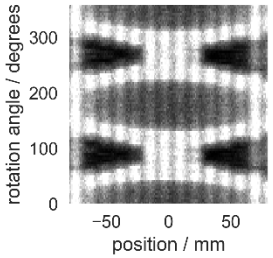
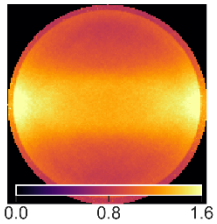
Fluence field optimization



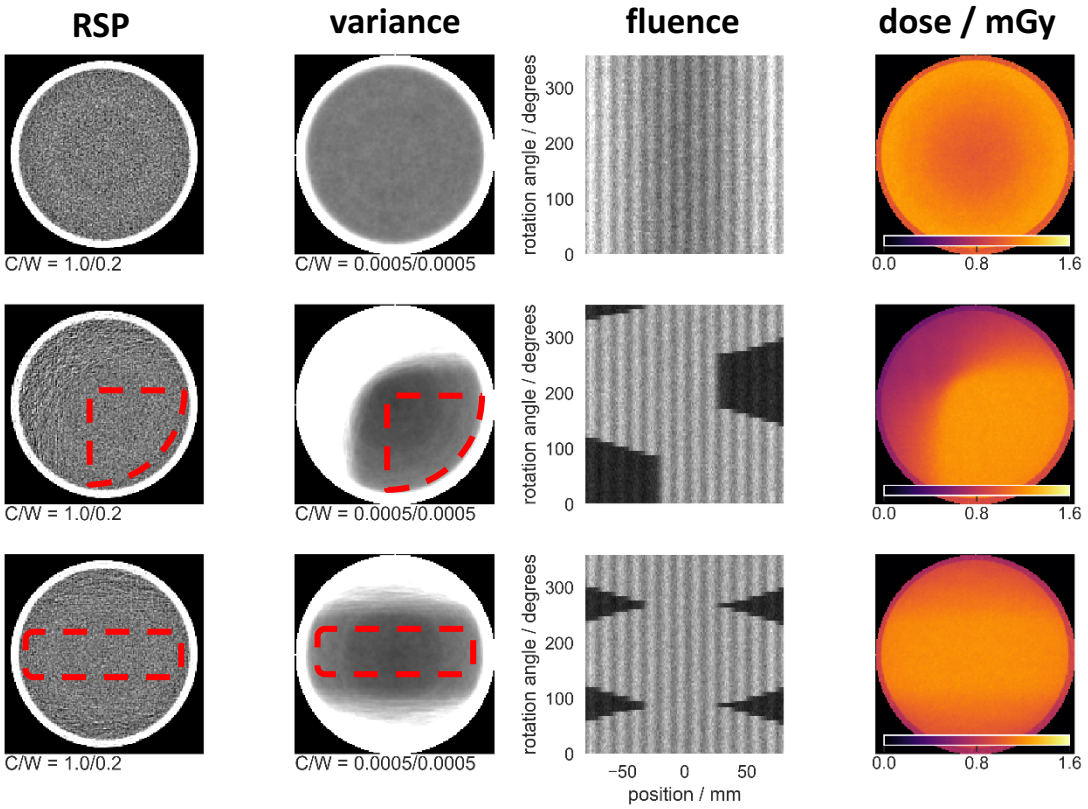
Results: “bowtie” filter

	RSP	variance	fluence	dose / mGy	dose reduction
constant fluence	 C/W = 1.0/0.2	 C/W = 0.0005/0.0005			
constant noise	 C/W = 1.0/0.2	 C/W = 0.0005/0.0005			7 %

Results: FMpCT optimization

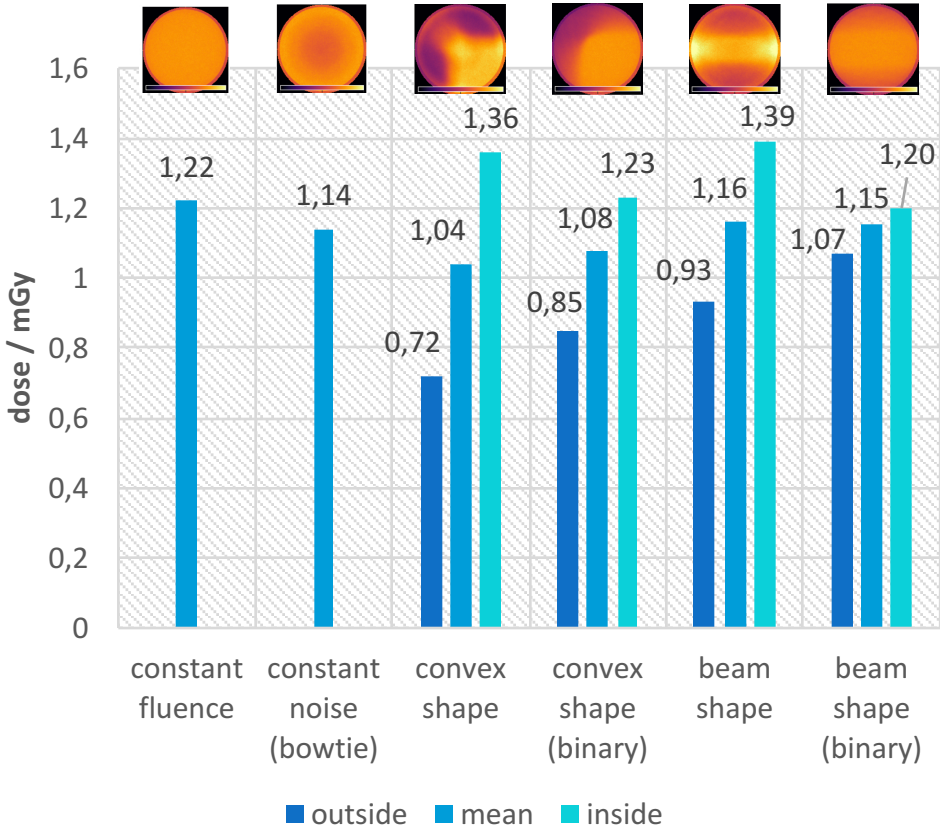
	RSP	variance	fluence	dose / mGy	dose reduction (outside ROI)
constant noise	 C/W = 1.0/0.2	 C/W = 0.0005/0.0005			**7 %**
orthogonal beams	 C/W = 1.0/0.2	 C/W = 0.0005/0.0005			**41 %**
opposing beams	 C/W = 1.0/0.2	 C/W = 0.0005/0.0005			**30 %**

Results: ROI intersection vs. optimization



Results

- Imaging dose **outside** of the ROI can be **considerably decreased**.
- Imaging dose **inside** the ROI **increases**.
- **Mean** imaging dose tends to **decrease**.

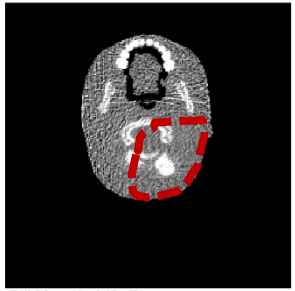


Conclusions

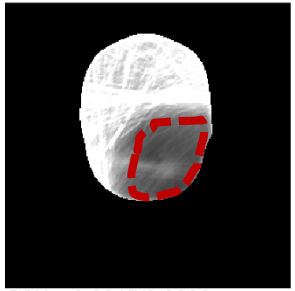
- Proton CT image noise depends on **object's heterogeneity**
  - Fluence should be adapated accordingly
  - Dose comparisons to x-ray CT on homogeneous objects are not necessarily fair
- Noise levels can be **predicted using Monte Carlo** simulations and variance reconstruction.
- Fluence-modulated proton CT (FMpCT) can achieve **prescribed image noise**.
- Inhomogeneous image quality is **meaningful** for frequent imaging in the context of **particle therapy**.
- An **iterative variance optimization** allows to calculate FMpCT plans.
- Dose reductions are **considerable** and depend on the **object** and **prescription ROI**.

Outlook

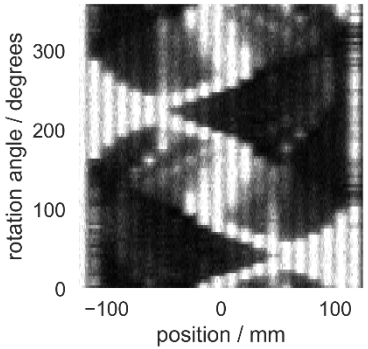
Anthropomorphic phantoms

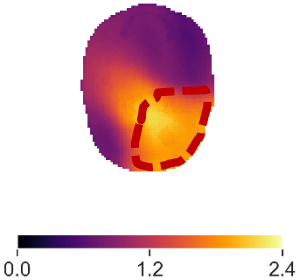


C/W = 1.1/0.5

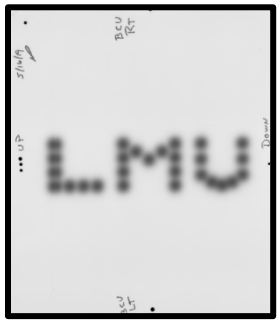


C/W = 0.0015/0.0030





Experimental validation



Outlook

- Include imaging dose in optimization
- Study noise characteristic of other/future scanner designs

Acknowledgements

Prof. Klaus Belka
Dr. Florian Kamp

Mark Pankuch
Nick Detrich
Victor Rykalin

Keith Schubert

Lennart Volz
Joao Seco

Valentina Giacometti
Pierluigi Piersimoni

George Coutrakon
Christina Sarosiek

Thank you for your attention!

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Wednesday, July 17th 2019