Prescribing image noise using dynamic fluence field optimization

experimental results using the pre-clinical proton CT phase-II scanner

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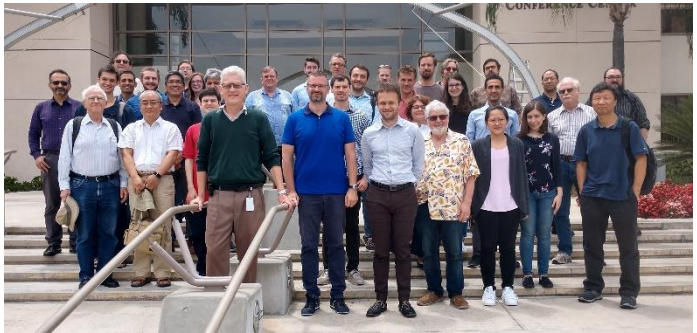
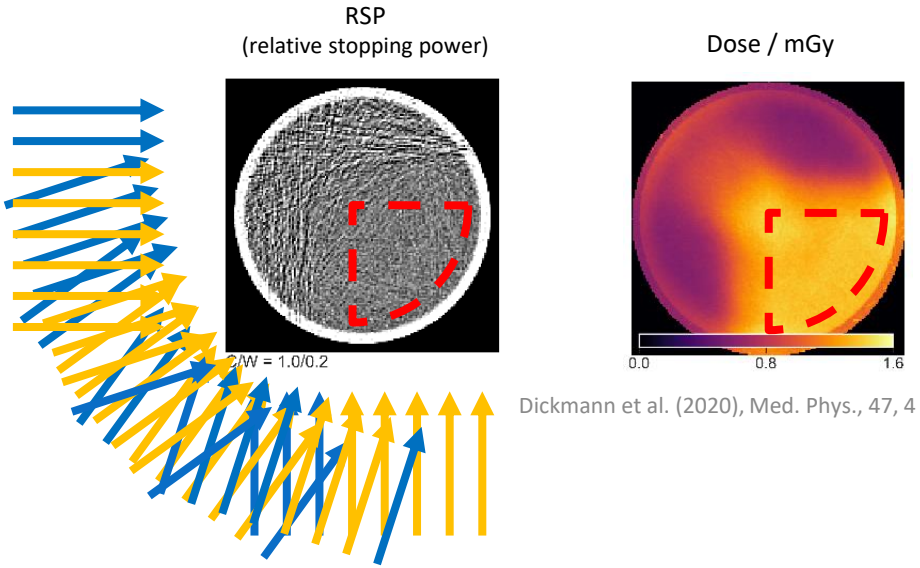
6th Loma Linda (virtual) workshop

July 2020



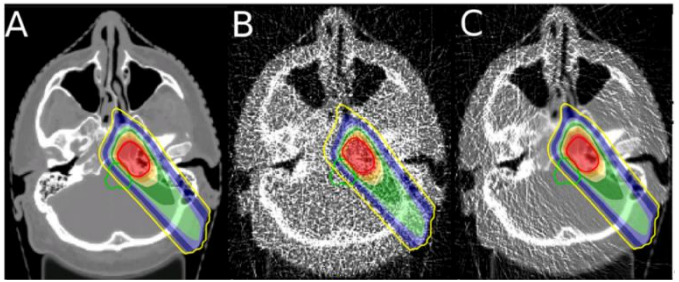
Fluence-modulated proton CT (FMpCT)

Aim: to show **experimental feasibility** of achieving arbitrary **image noise targets** with FMpCT.



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

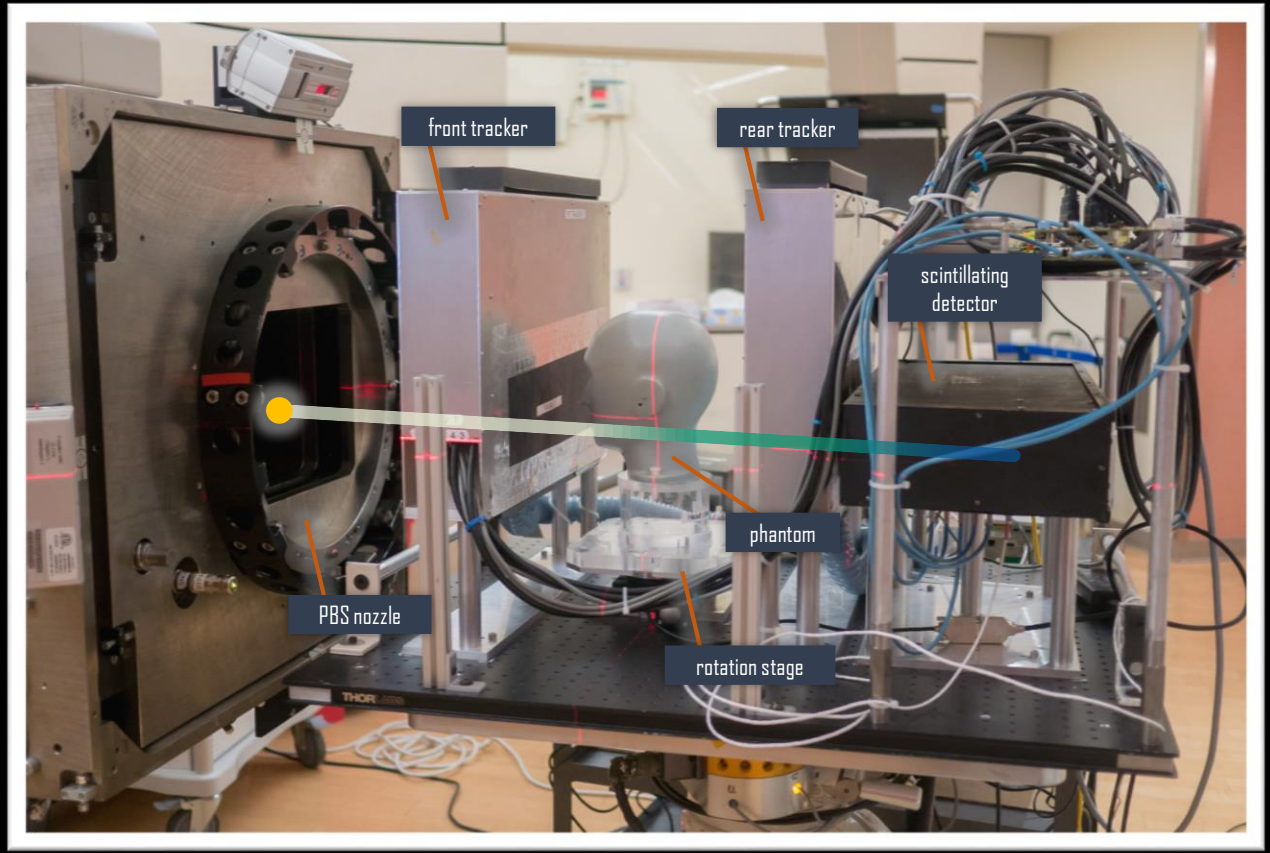
Motivation: frequent imaging for particle therapy



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

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

Proton computed tomography



Johnson et al. (2016), IEEE, 63, 1

Bashkirov et al. (2016), Med. Phys., 43, 2

RSP and variance reconstruction

- Relative stopping power (RSP) reconstruction:
  - Based on registered WEPLs: $\mathrm{WEPL} = \int_L \mathrm{RSP}\,\mathrm{d}l$
  - Filtered backprojection along curved proton paths

- WEPL variance in a projection: $$\sigma^2_{p_{\gamma_n}}(j\Delta\xi, k\Delta\eta) = \frac{\sigma^2_{E_{\mathrm{out}},\gamma_n}(j\Delta\xi, k\Delta\eta)}{N_{\gamma_n}(j\Delta\xi, k\Delta\eta)\cdot S^2_{\mathrm{W}}(\bar{E}_{\mathrm{out},\gamma_n}(j\Delta\xi, k\Delta\eta))}.$$

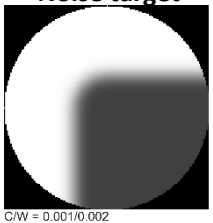
- RSP variance reconstruction: $$\mathrm{Var}\left[f(x_p, y_p)\right] = f_{\mathrm{interp},\mu}\left(\frac{\pi}{N_p}\Delta\xi\right)^2 \sum_{n=1}^{N_p} V_{\gamma_n}(j\Delta\xi)$$

  with $V_{\gamma n}$ being the variance in a pixel in the projection

Rit S et. al. (2013), Med Phys, 40(3):031103
Rädler et al. (2018), PMB, 63(21):215009

Fluence field optimization

Noise target



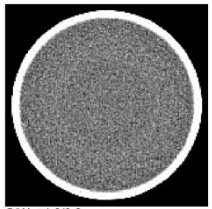
C/W = 0.001/0.002

iterative variance forward projection

$\mathrm{Var}[p_{\mathrm{presc.}}]$

target variance projection stack

Image guide



C/W = 1.0/0.2

variance simulation

$\mathrm{Var}[p_{\mathrm{unit}}]$

expected variance at unit fluence

$$\mathrm{Var}[p] \propto \frac{1}{f}$$

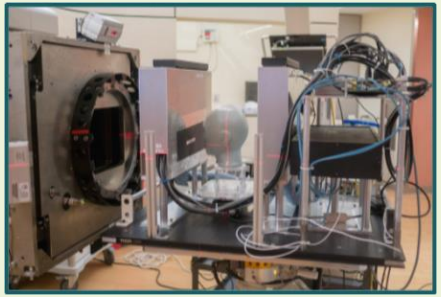
$$f_{\mathrm{rel}} = \frac{\mathrm{Var}[p_{\mathrm{unit}}]}{\mathrm{Var}[p_{\mathrm{presc.}}]}$$

per-pixel relative fluence

pencil beam weight optimization

{}

pencil beam weight vector



Interface to PBS beamline

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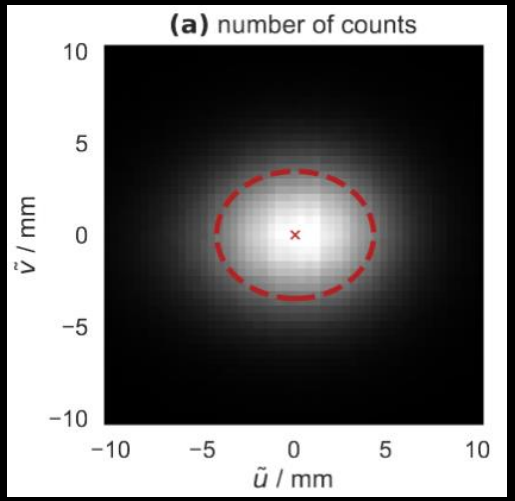
Experimental acquisition

Dickmann et al. (2020), Med. Phys., 47, 4
Dickmann et al. (2019), PMB, 64, 14

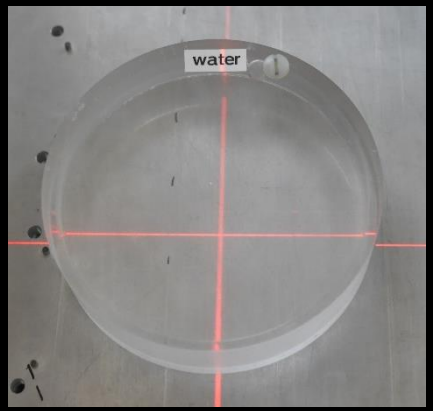
Proton therapy facility

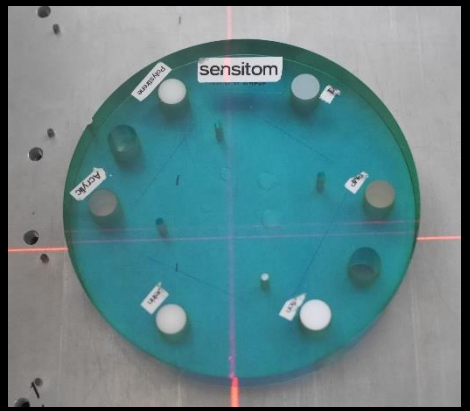
- Northwestern Medicine Chicago Proton Center
- **PROTEUS®PLUS IBA Cyclotron**
- Full Pencil Beam (PB) scanning capability
- Used **fixed** beamline room in “research” mode
- **1.3 nA, 8.6 and 6.9 mm FWHM, variable dwell time**

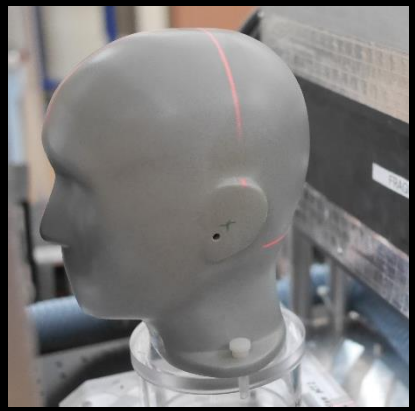


Phantoms

- Water phantom in polystyrene container
- CTP404 module of the Catphan®600 phantom (RSP: 0.883 – 1.79)
- Pediatric (5-year old) head phantom







Noise prescription

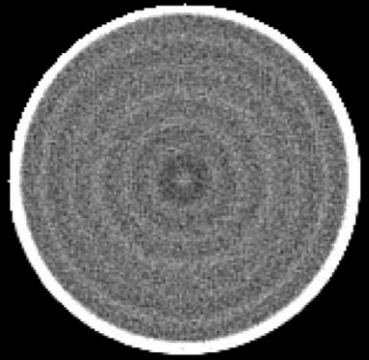
- **Unit fluence scans** with pencil beam weights set to **1**
- **Constant noise scans** with V_{ROI} noise everywhere the image
  (in general pCT noise is not constant for unit fluence)
- **A ROI imaging task (FMpCT)** with V_{ROI} in a quadrant of the image

- V_{ROI} prescriptions:
  - Water phantom: 4.6×10^{-4}
  - CTP404 phantom: 5.9×10^{-4}
  - Head phantom: 12.0×10^{-4}

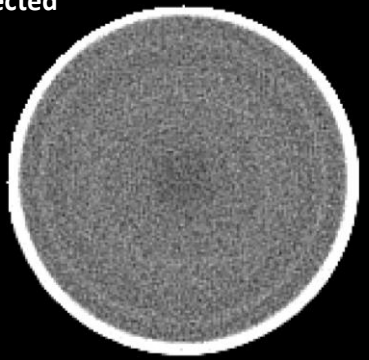
- The exact value of V_{ROI} is the peak variance at unit fluence for each phantom

Pencil beam energy correction

uncorrected

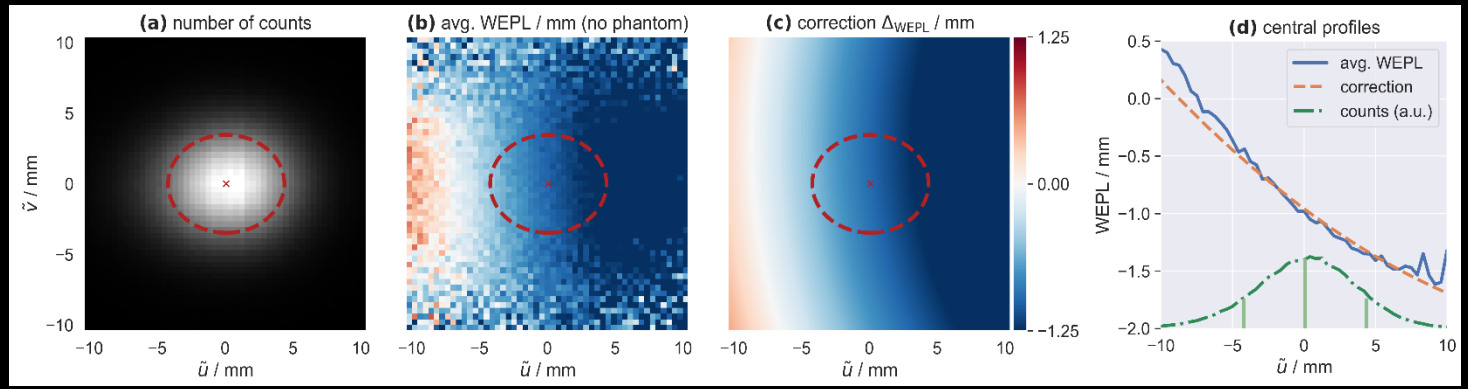


corrected



C/W = 1.0/0.2

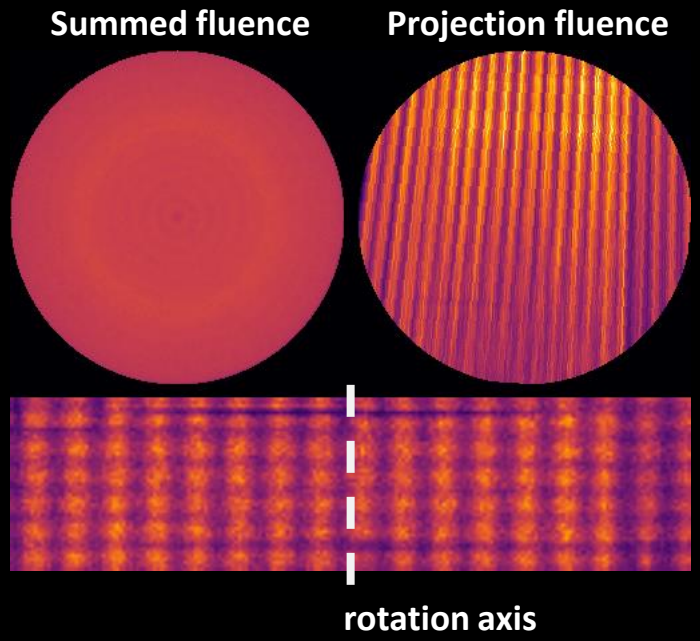
- Analysis revealed **an intra-PB spatially varying energy distribution**
- **Correction** based on data without phantom



Fluence delivery

- To **reduce the degrees of freedom** in the optimization, pencil beams
  - had a larger interspace
  - were offset by a quarter of the interspace

- With a 360-degree acquisition, summed fluence was **homogeneous**.



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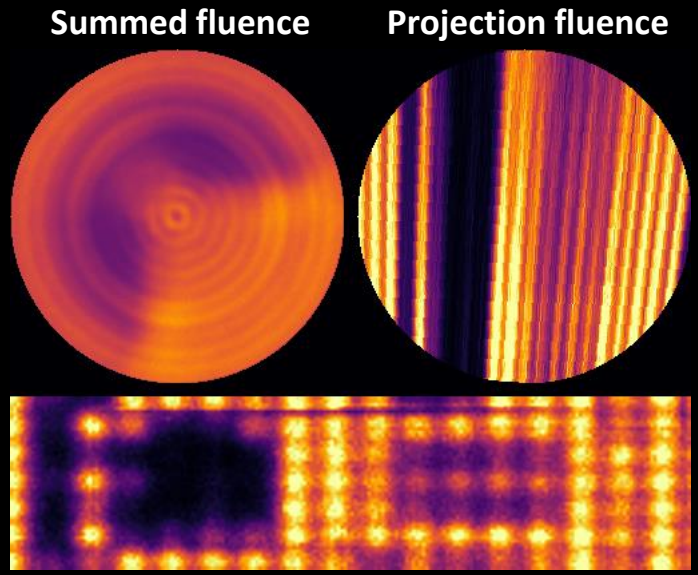

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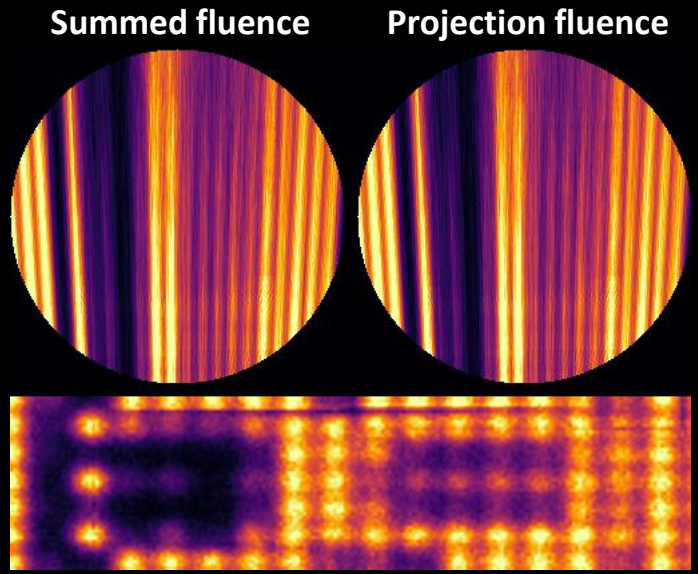
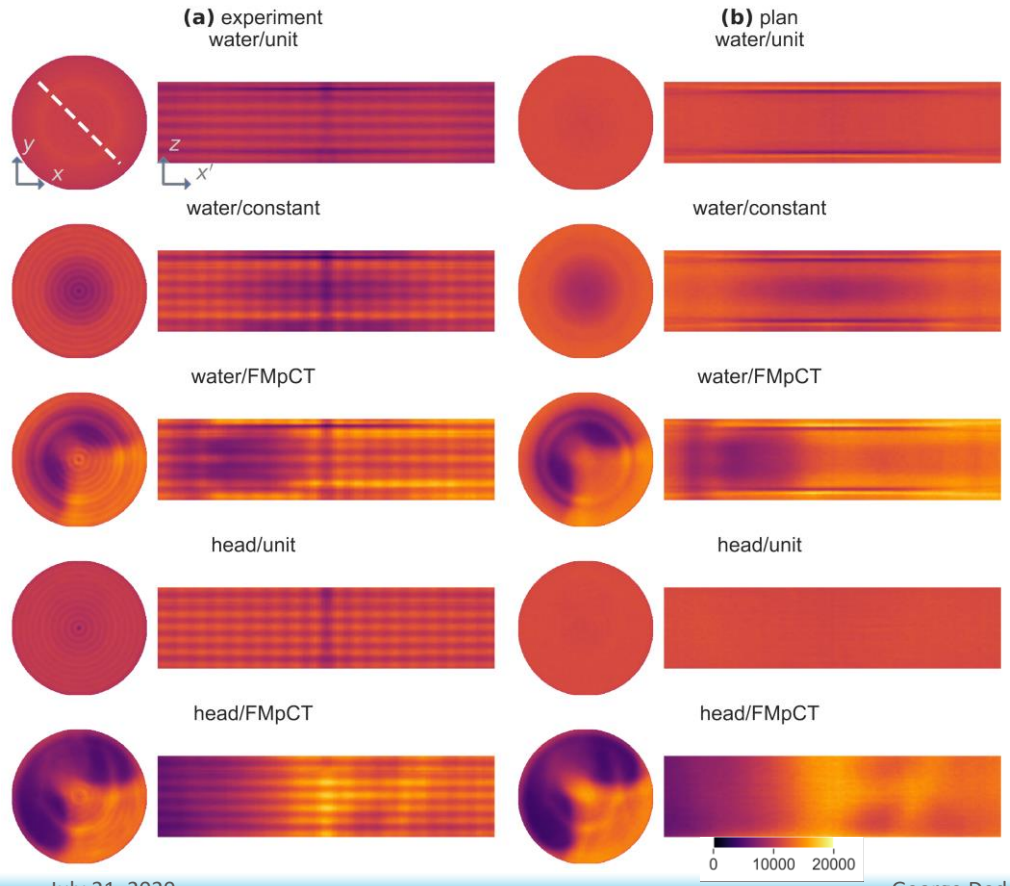
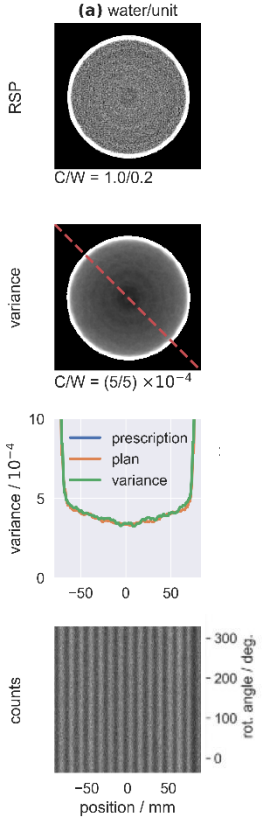


Experimental results: water phantom



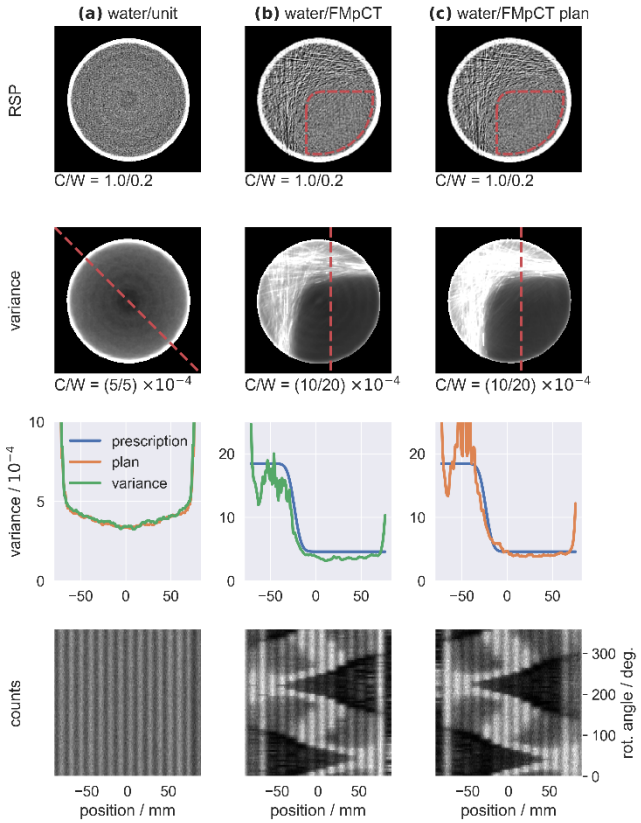
- Example of the effect of differences between planned and delivered beams
  - Misalignment
    (rings in fluence and variance)
  - Smaller beam size

Experimental results: water phantom



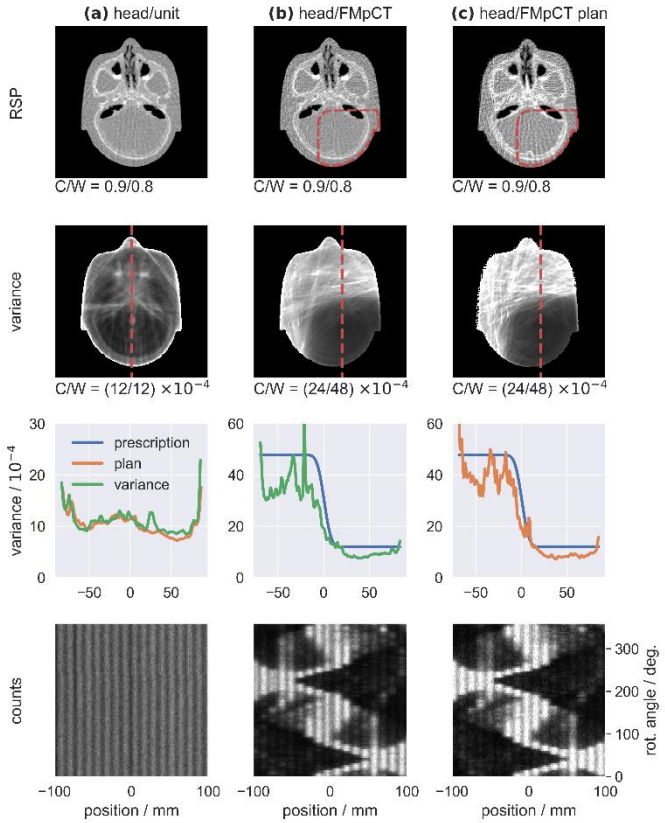
- Unit fluence: **variance reduced** in the center of the phantom

Experimental results: water phantom



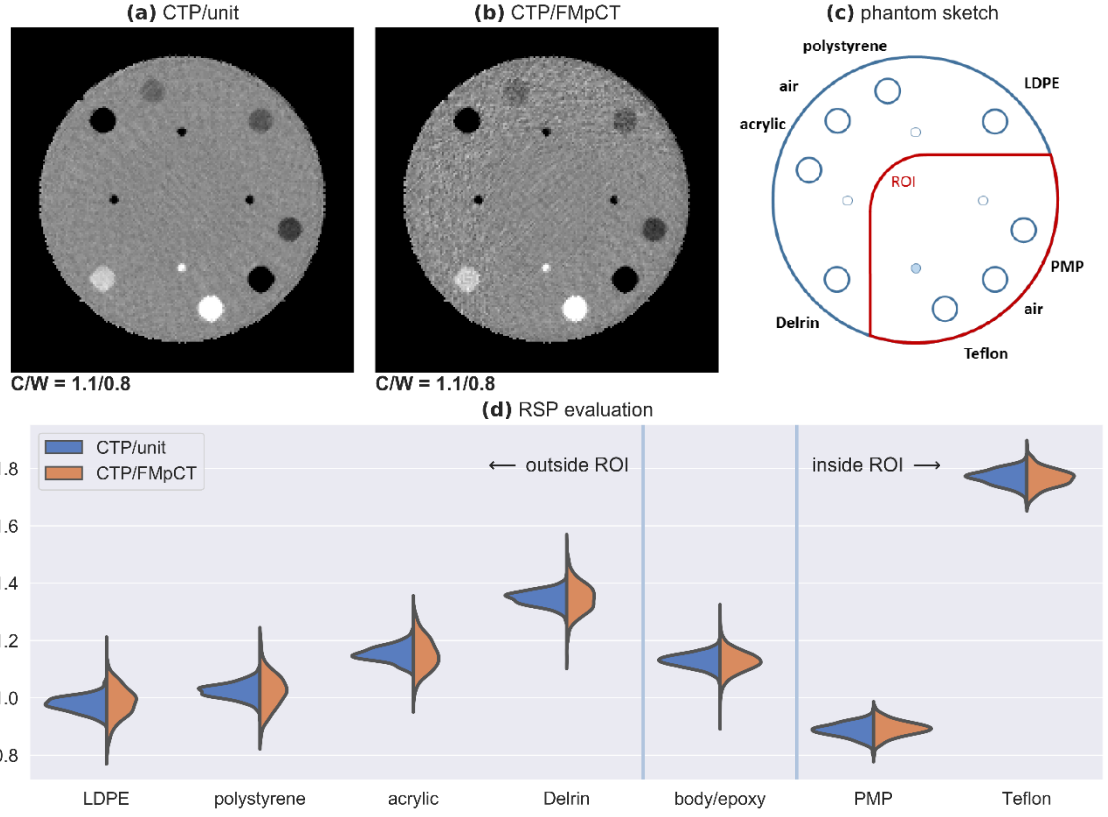
- Unit fluence: **variance reduced** in the center of the phantom
- Good agreement of **FMpCT acquisition**
  - with noise prescription
  - with Monte Carlo plan
- **Dose reduction** outside of ROI 41%

Experimental results: head phantom



- Good agreement also on **pediatric head phantom**
- **Dose reduction** outside of ROI up to 40%

Experimental results: RSP accuracy



- CTP404 phantom data for RSP evaluation
- RSP **distributions broaden** outside the ROI
- **Errors comparable** to previous study using broad beam [1]
- RSP accuracy **not deteriorated** inside the ROI

[1] Dedes et al. (2019), PMB, 64, 16

Experimental results: RSP accuracy

Insert	RSP	uncorrected error in % unit	uncorrected error in % FMpCT	corrected error in % unit	corrected error in % FMpCT	error in % Dedes (2019)[1]
inside ROI						
PMP	0.883	0.18 ± 0.31	0.79 ± 0.36	0.51 ± 0.31	1.06 ± 0.35	1.08 ± 0.11
Teflon	1.790	-1.31 ± 0.18	-1.49 ± 0.21	-1.16 ± 0.17	-1.32 ± 0.21	-1.31 ± 0.05
outside ROI						
LDPE	0.979	-0.33 ± 0.32	0.24 ± 0.64	-0.12 ± 0.31	0.52 ± 0.65	-0.49 ± 0.11
polystyrene	1.024	-0.12 ± 0.30	-0.25 ± 0.66	0.06 ± 0.29	-0.11 ± 0.67	-0.04 ± 0.10
body/epoxy	1.144	-1.39 ± 0.02	-1.66 ± 0.03	-1.20 ± 0.02	-1.54 ± 0.03	—
acrylic	1.160	-0.80 ± 0.27	-0.80 ± 0.57	-0.54 ± 0.27	-0.63 ± 0.57	-0.30 ± 0.07
Delrin	1.359	-0.93 ± 0.21	-1.02 ± 0.45	-0.78 ± 0.21	-0.83 ± 0.45	-1.32 ± 0.21
MAPE-ALL		0.72 ± 0.09	0.89 ± 0.18	0.63 ± 0.09	0.86 ± 0.18	0.76 ± 0.05
MAPE-ROI		0.74 ± 0.18	1.14 ± 0.21	0.84 ± 0.18	1.19 ± 0.21	1.20 ± 0.06

- FMpCT and full fluence pCT: **same RSP accuracy within the uncertainty margin**
- **RSP accuracy (<1%) comparable** to previous study using broad beam

[1] Dedes et al. (2019), PMB, 64, 16

Conclusions

I. Fluence-modulated proton CT (FMpCT) can deliver **image noise prescriptions** in experiments.

II. Acquisition with pencil beams requires **an energy correction**.

III. Despite minor misalignments **agreement to Monte Carlo plans** was satisfactory.

IV. **No relevant deterioration** of RSP accuracy.

Experimental realization of dynamic fluence field optimization for proton computed tomography

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