LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

Variance Modeling for FMpCT

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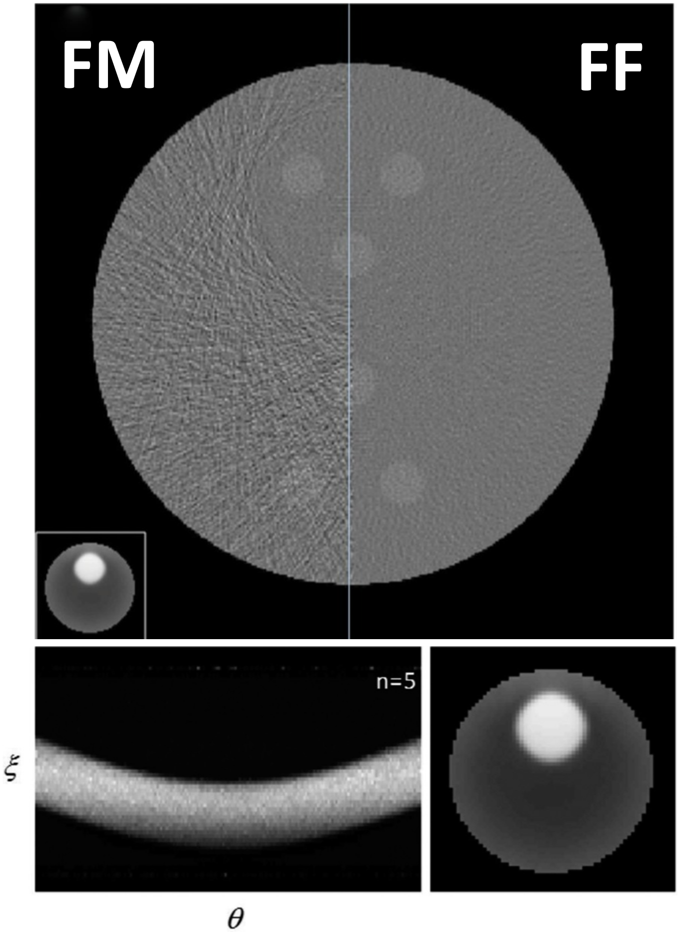
4th Loma Linda Workshop

Fluence Modulation

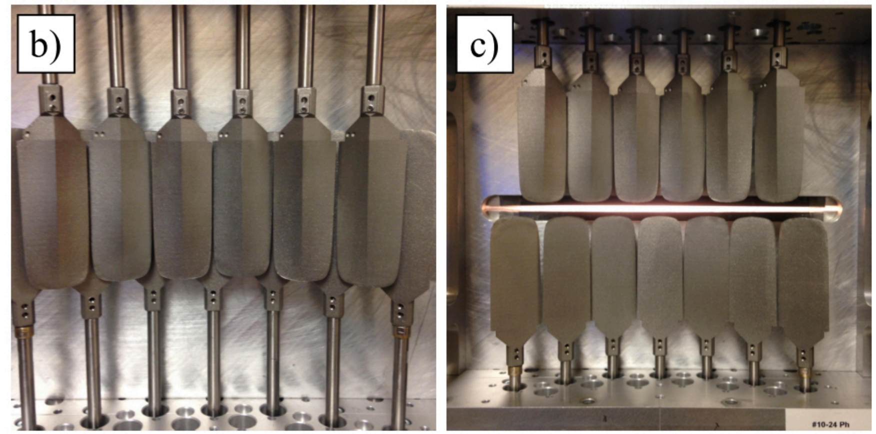
- Fluence modulation for CT aims for a **reduction of imaging dose** by reducing fluence outside a **region of interest**.



Bartolac et al. 2011 *Med Phys*

Dose Reduction in X-ray CT

Shunhavanich et al. 2018 *SPIE Med Imaging*



Clinical X-ray CT

- Bowtie filters
- Automatic exposure control

Fluence Modulation in X-ray CT

- digital beam attenuator[1]
- binary collimator (Tomotherapy)[2]
- multiple aperture devices[3]
- piecewise-linear dynamic attenuators[4]

[1] Szczykutowicz and Mistretta 2014 *Phys Med Biol*
[2] Szczykutowicz et al. 2015 *Phys Med Biol*
[3] Stayman et al 2016 *SPIE Med Imaging*
[4] Shunhavanich et al. 2018 *SPIE Med Imaging*

Fluence Modulated Proton CT (FMpCT)

- High precision beam delivery using treatment system

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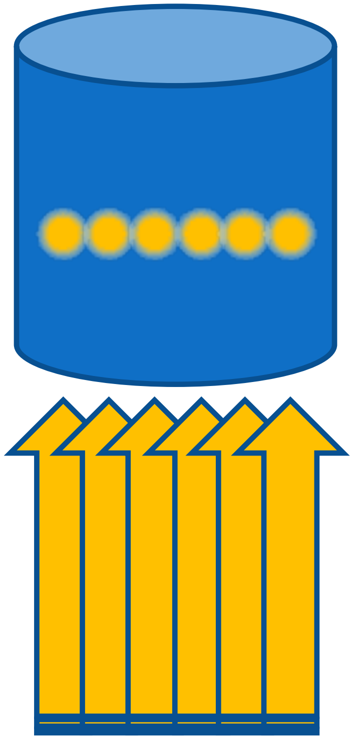
- Fluence modulation using pencil beams



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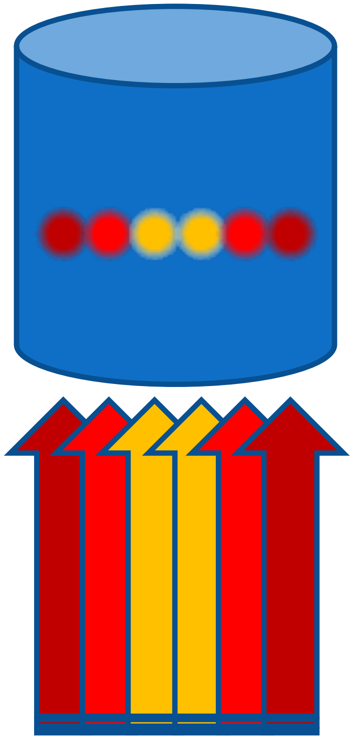
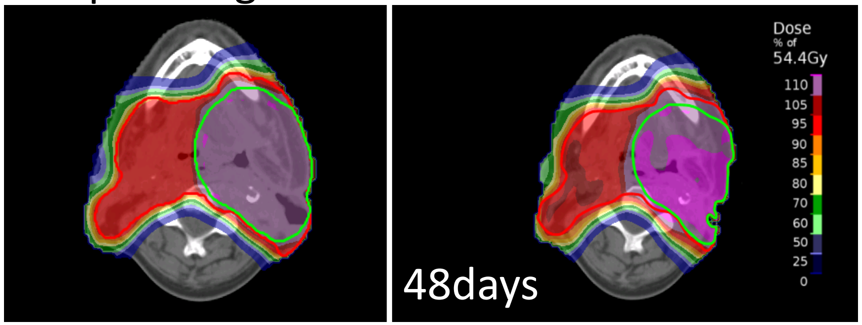


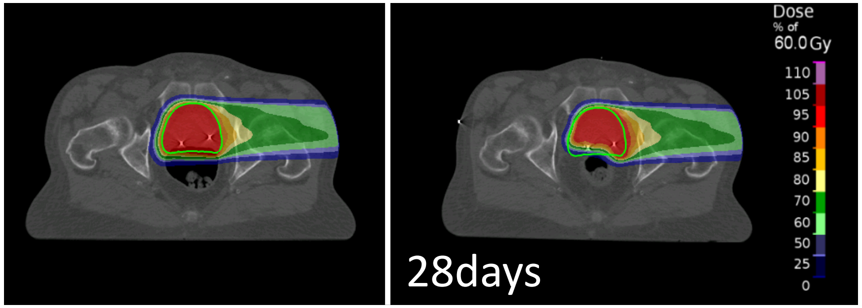
Fluence Modulated Proton CT (FMpCT)

- High precision beam delivery using treatment system
- Fluence modulation using pencil beams
- Benefitial integration into frequent imaging of image-guided proton therapy workflow

planning CT control CT



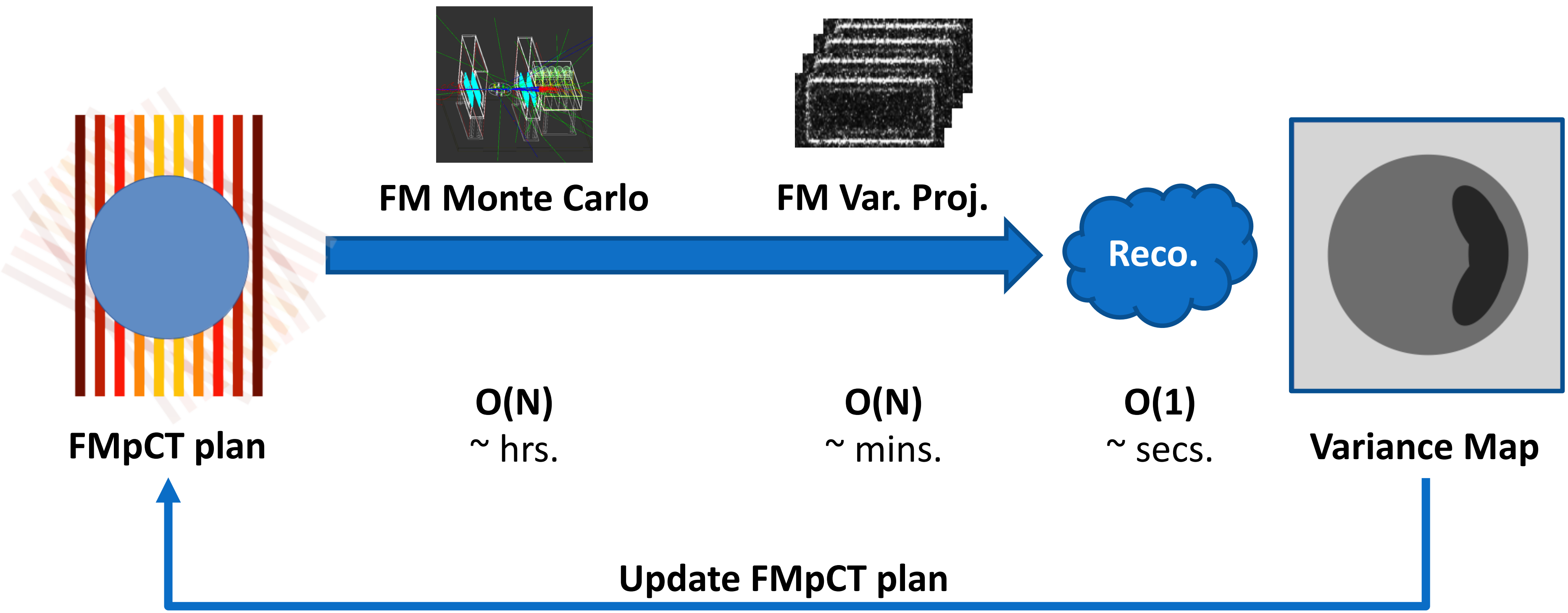
Head and neck:
Timescale: days/weeks



C. Kurz et al., ICTR-PHE 2016

Prostate:
Timescale: minutes/hours/days

Optimizing FMpCT Plans

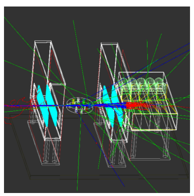


FF = Full fluence
FM = Fluence modulated

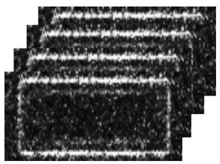
Optimizing FMpCT Plans

$$\mathrm{Var}[p] \propto \frac{1}{N} \;*$$

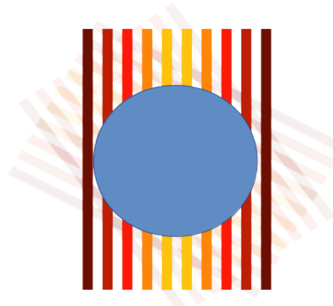
$$\mathrm{Var}[p_{\mathrm{FM}}] = \mathrm{Var}[p_{\mathrm{FF}}] \cdot \frac{N_{\mathrm{FF}}}{N_{\mathrm{FM}}}$$



FF Monte Carlo



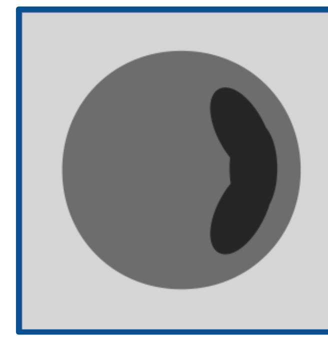
FF Var. Proj.



FMpCT plan

Variance Modulation

Reco.



Variance Map

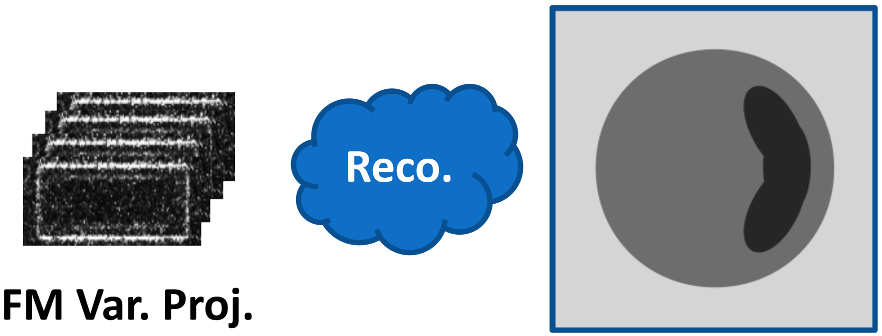
FF Monte Carlo	FF Var. Proj.	FMpCT plan	Reco.
O(N)	**O(N)**	**O(1)**	**O(1)**
~ hrs.	~ mins.	~ secs.	~ secs.

Update FMpCT plan

FF = Full fluence
FM = Fluence modulated

Variance Reconstruction

- Variance reconstruction is equivalent to image reconstruction.



FM Var. Proj.

Variance Map

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

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

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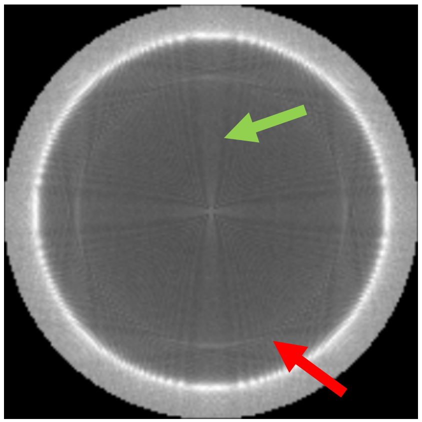
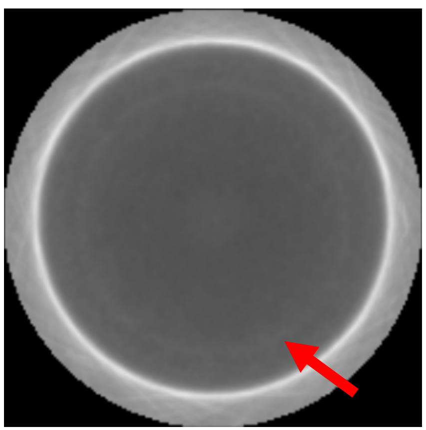
Variance Reconstruction

- Validation of the method:
  Voxel-wise variance of N = 100 noise realisations
- Phantom: Water cylinder

Ground Truth



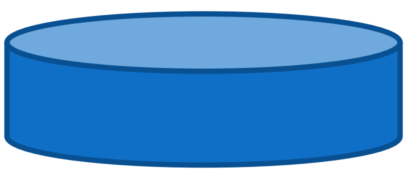
Var. Reconstruction



C / W = 0.02 / 0.01

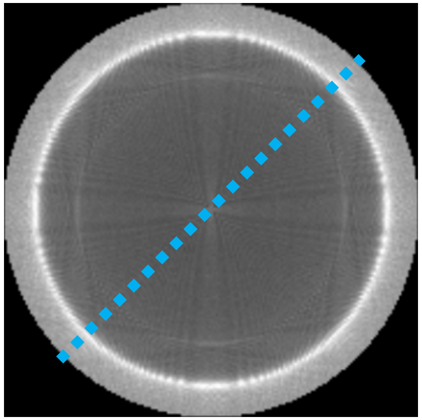
RSP Map

C / W = 1.0 / 0.2

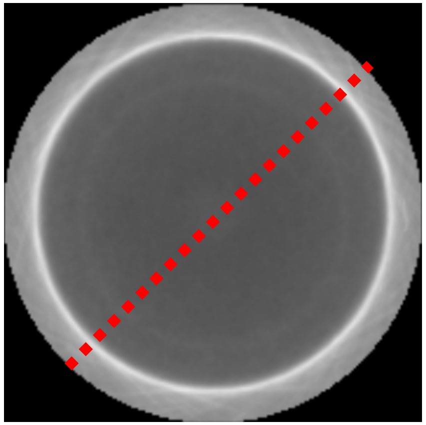


Variance Reconstruction

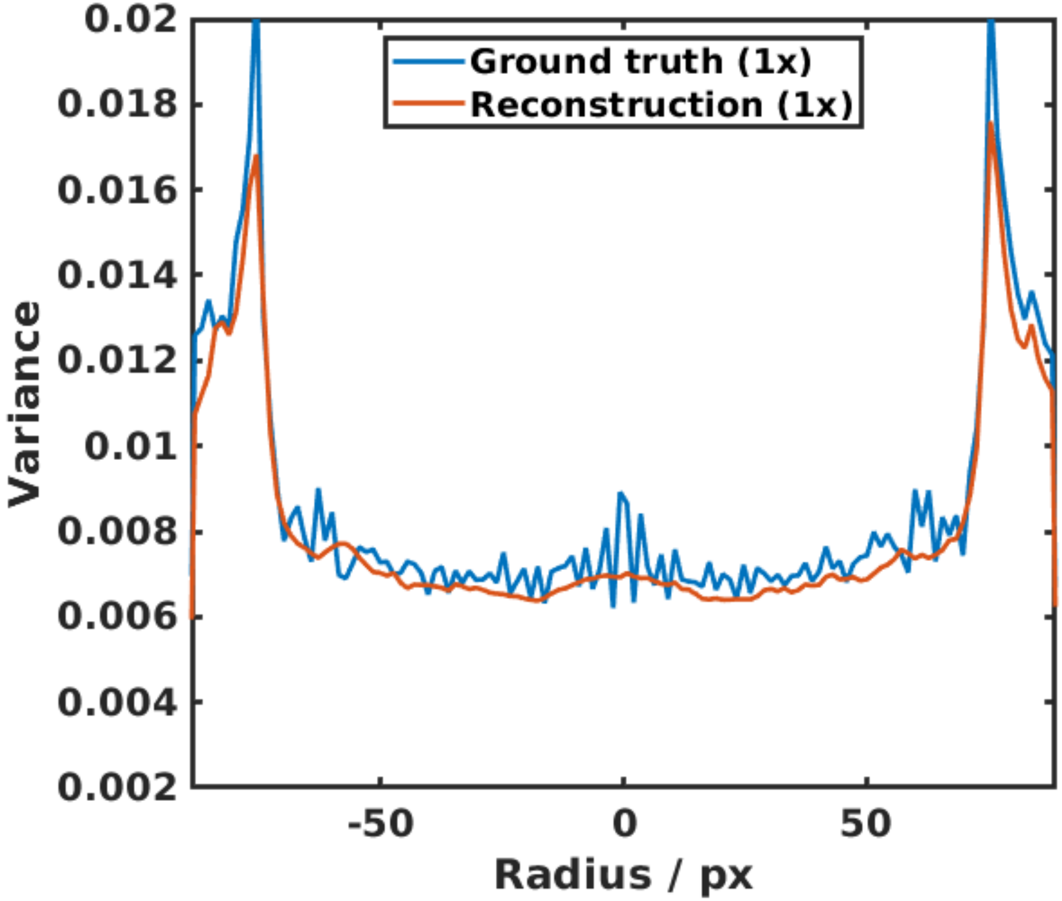
Ground Truth



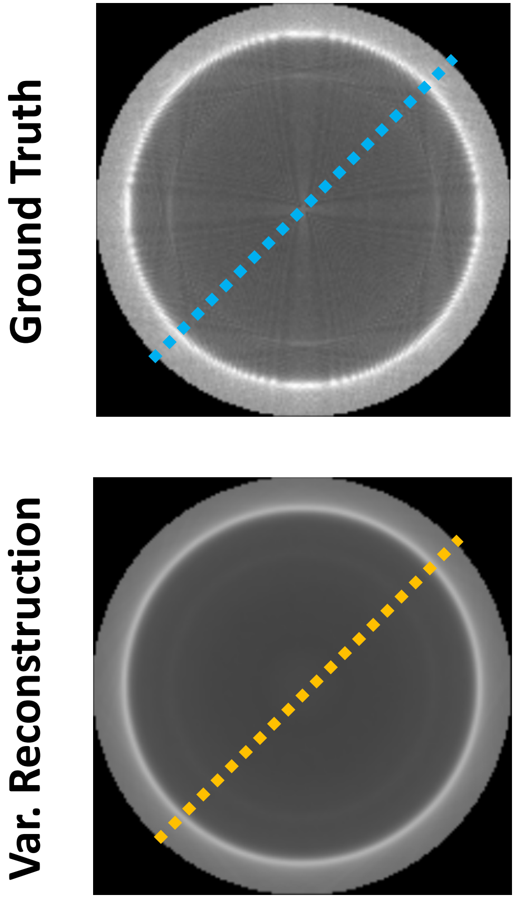
Var. Reconstruction



C / W = 0.02 / 0.01



Variance Reconstruction



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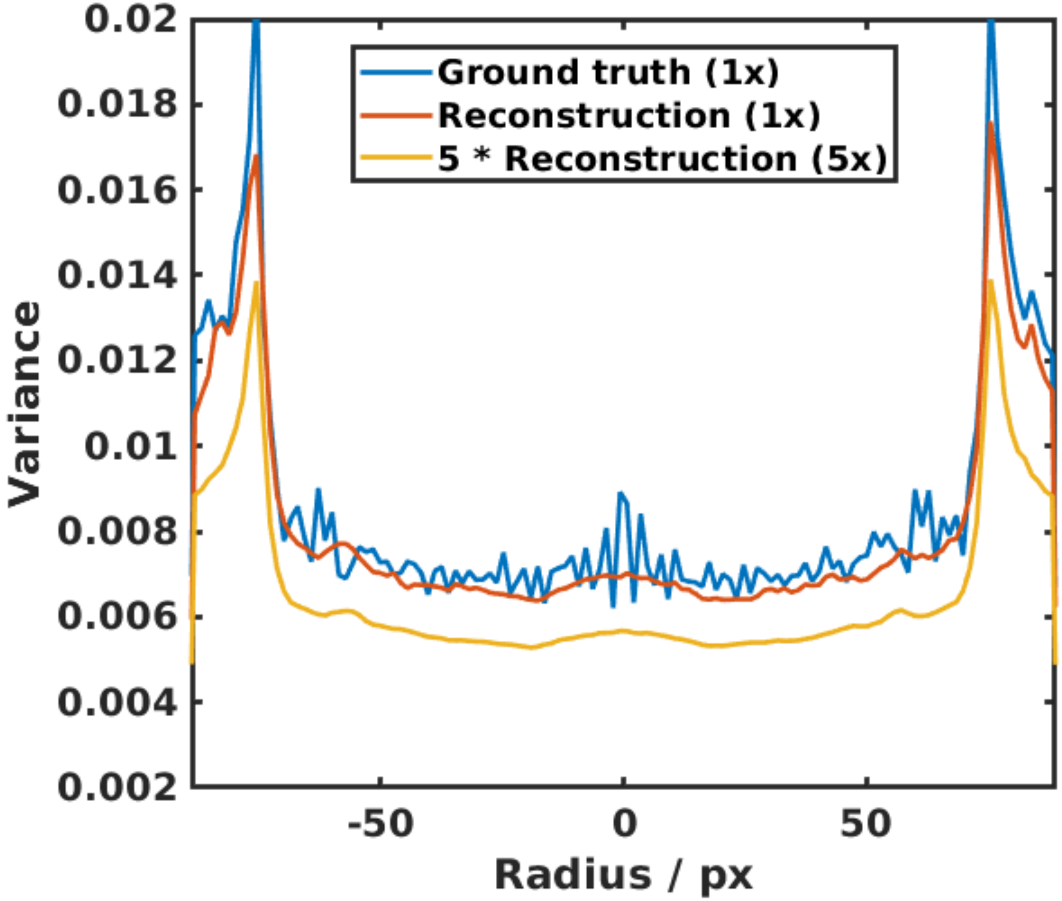
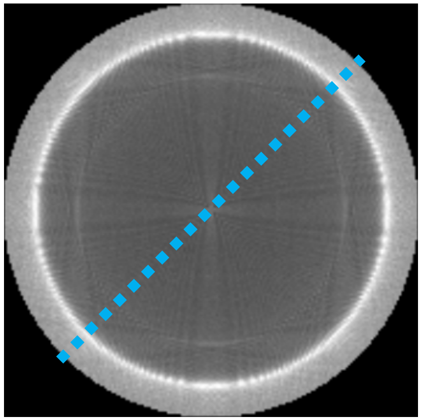
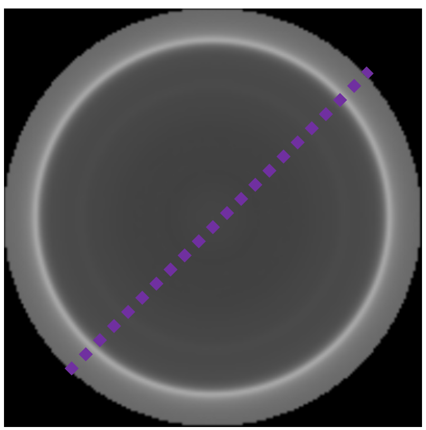


Variance Reconstruction

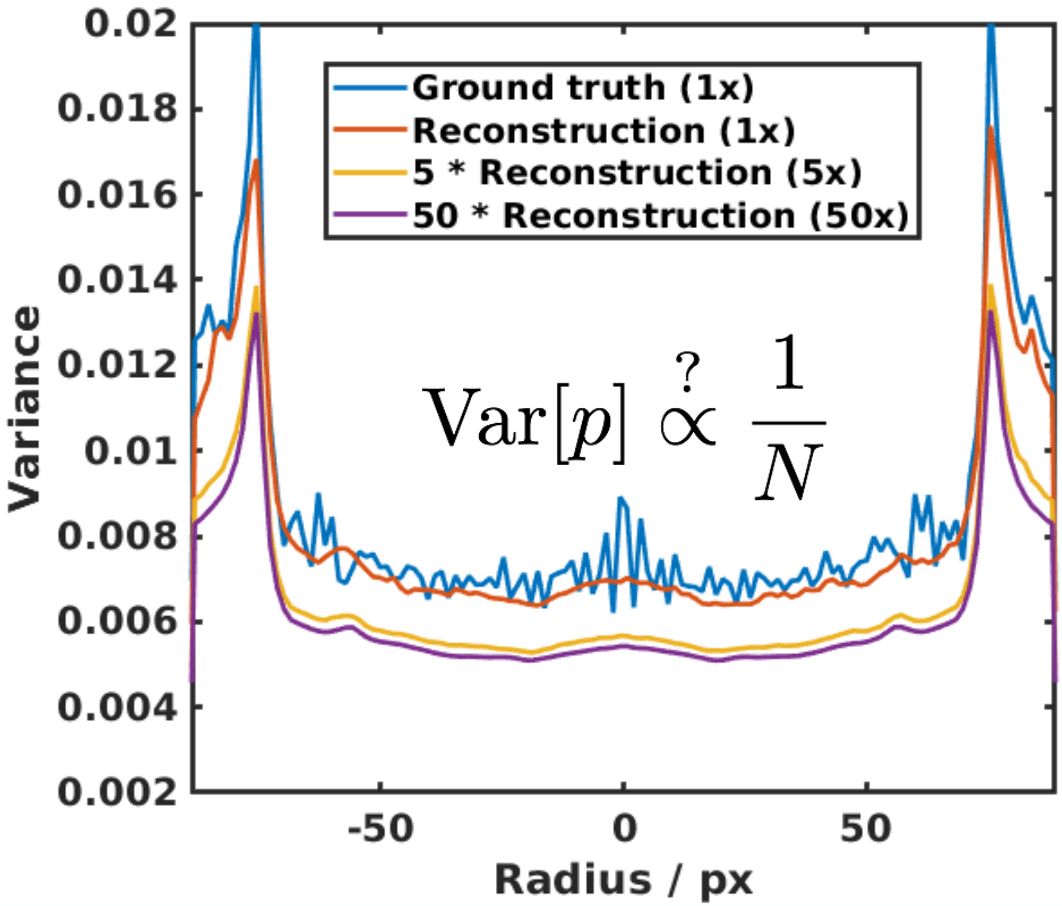
Ground Truth



Var. Reconstruction

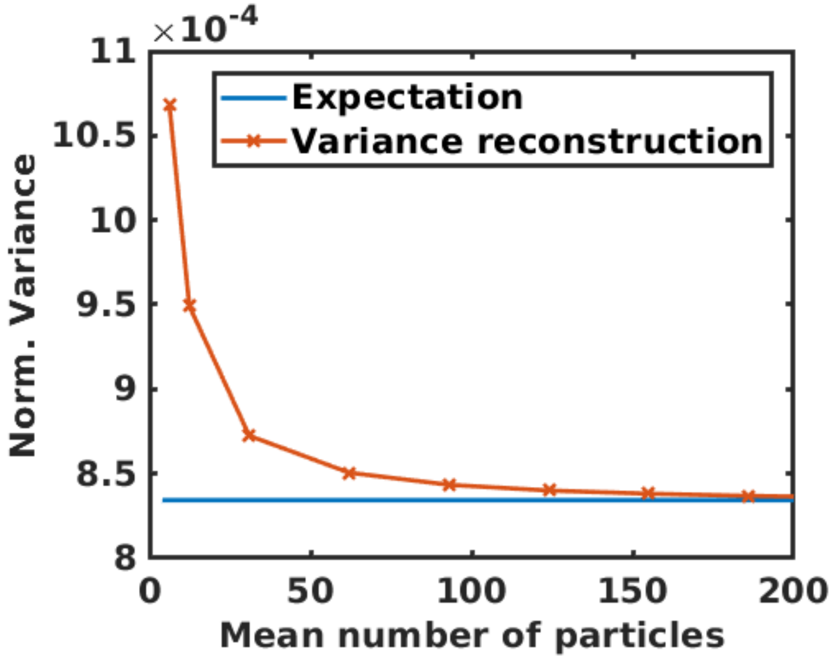


C / W = 0.02 / 0.01



Variance at Low Fluence

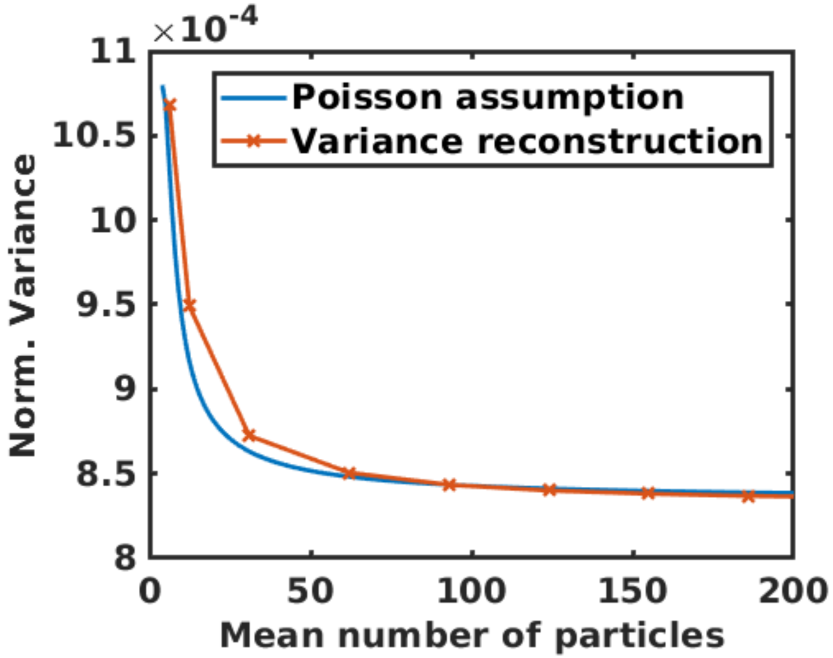
- The definition of the variance of the mean assumes a **constant number** of particles per pixel.



$$\left.\begin{array}{lcl} p_1 & = & \text{mean}(x_1, x_2, x_3) \\ p_2 & = & \text{mean}(x_4, x_5, x_6) \\ p_3 & = & \text{mean}(x_7, x_8, x_9) \end{array}\right\} \implies \text{Var}_N[p] = \frac{\text{Var}[x]}{N}$$

Variance at Low Fluence

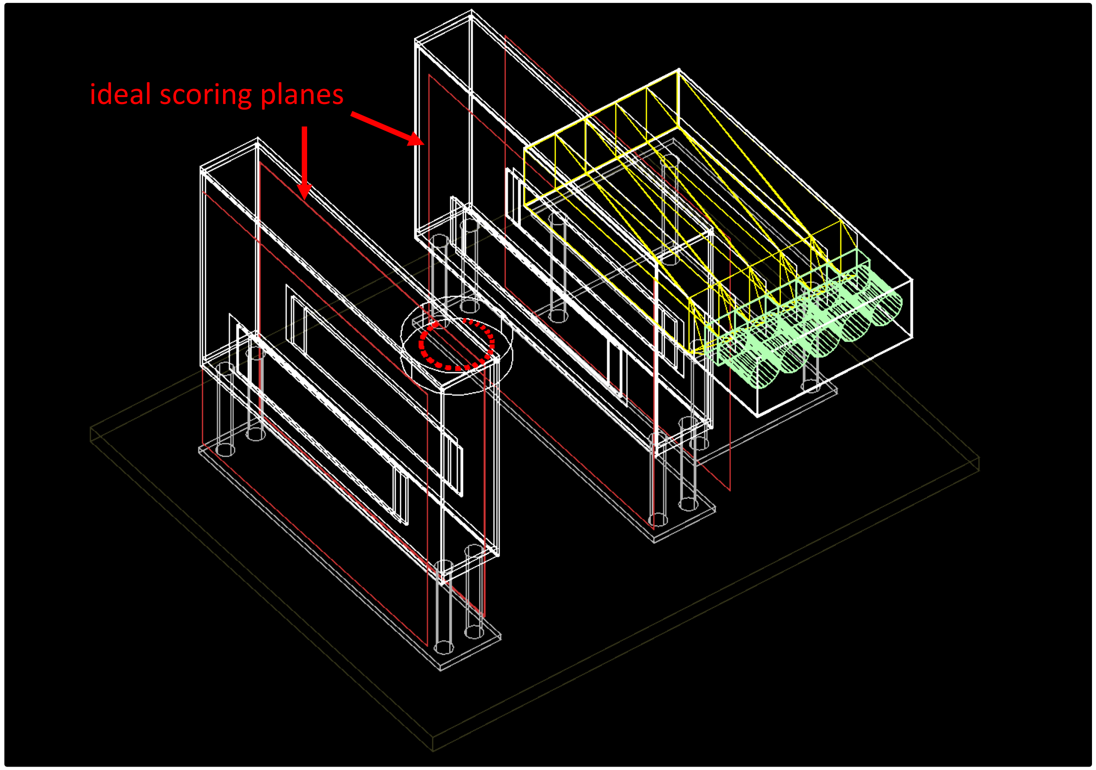
- In reality the number of particles per pixel follows a **Poisson distribution**.
- This causes an increased noise at low fluence.



$$\left.\begin{aligned} p_1 &= \text{mean}(x_1, x_2, x_3, x_4) \\ p_2 &= \text{mean}(x_5, x_6) \\ p_3 &= \text{mean}(x_7, x_8, x_9) \end{aligned}\right\} \Longrightarrow \text{Var}_{\bar{N}}[p] = \sum_{n=1}^{\infty} P_{\bar{N}}(n) \frac{\text{Var}[x]}{n}$$

Variance Contributions

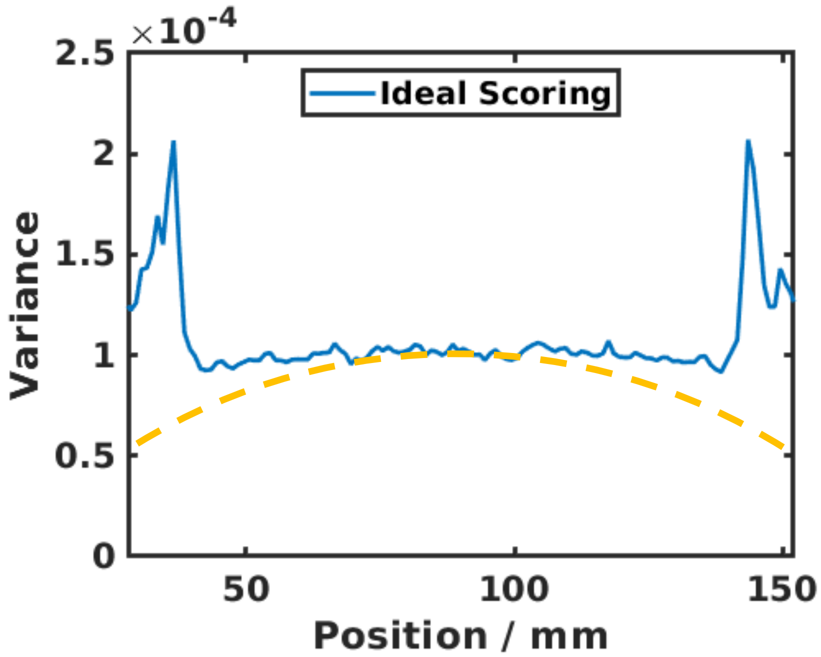
- In simulations, investigate the variance contributions of…
  - Energy straggling (ES) in object and detector
  - Multiple Coulomb Scattering (MCS)
  - Beam energy spread
- Compare to measurement

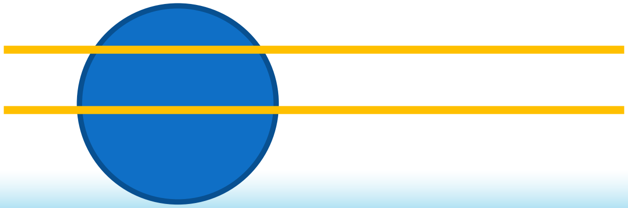


software platform courtesy of the pCT collaboration,
Giacometti et al. 2017 *Med Phys*

Variance Contributions

- Ideal scoring considers only **ES in the object** and **MCS** at the edges.





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Variance Contributions

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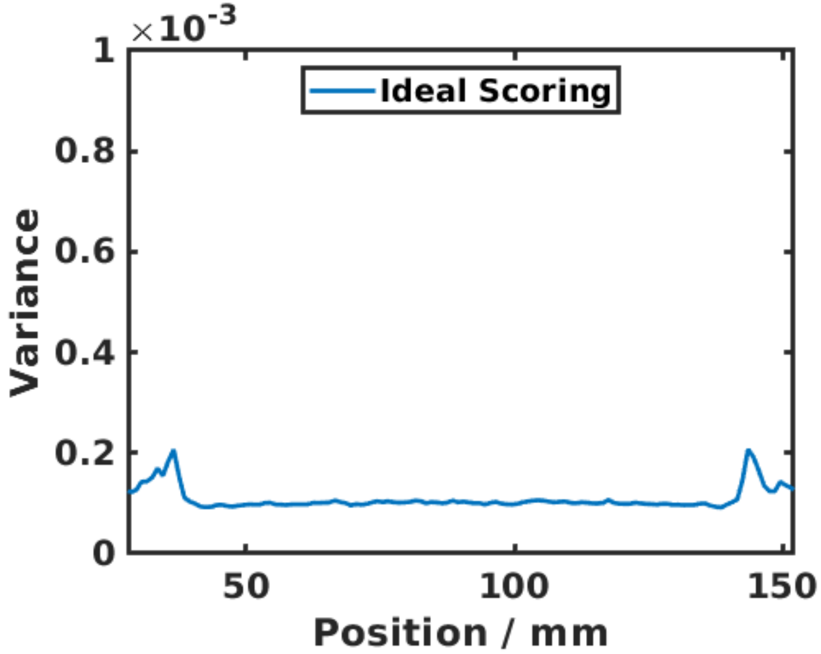
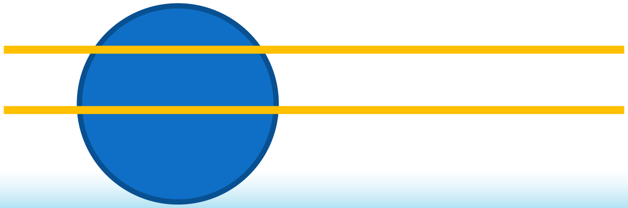
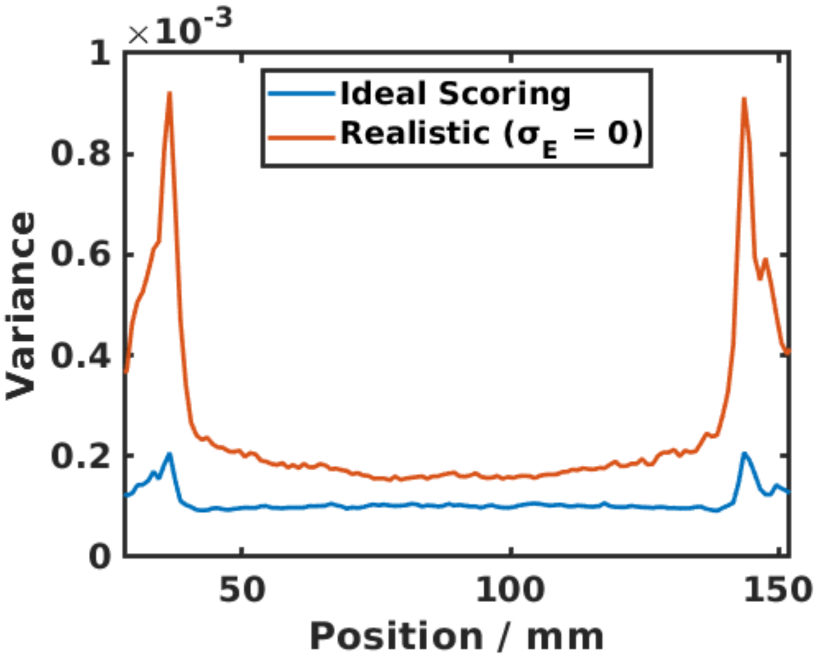
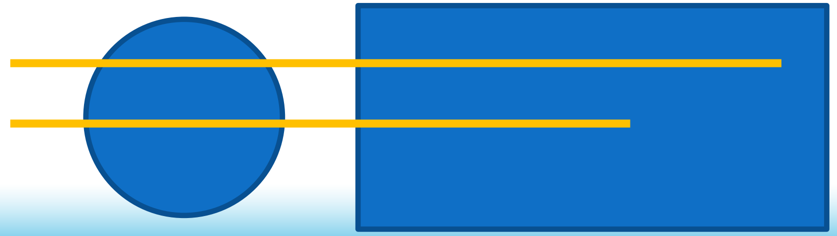




Variance Contributions

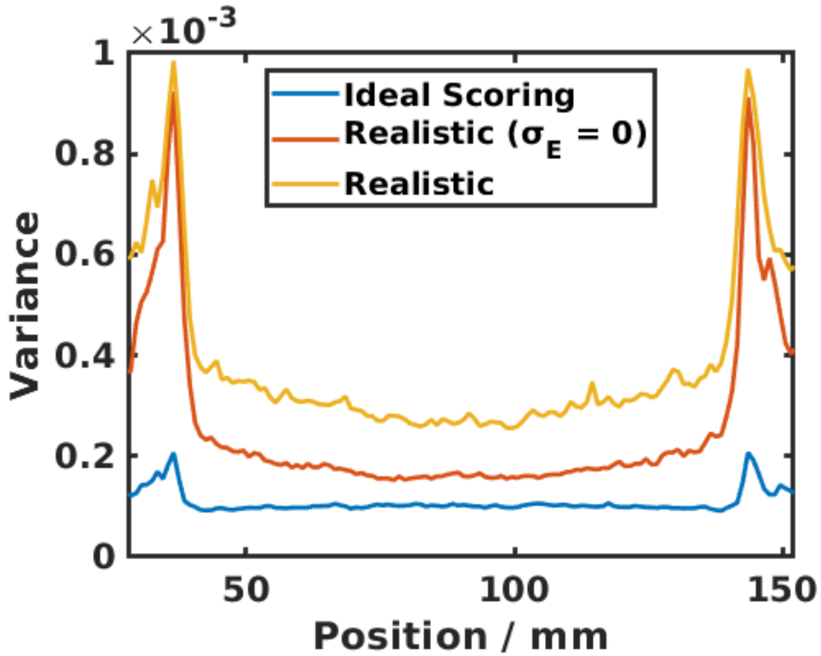
- Realistic scoring considers also **ES in the detector**.
- The beam energy spread is zero.

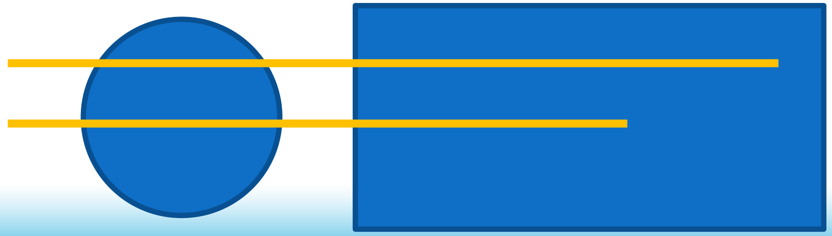




Variance Contributions

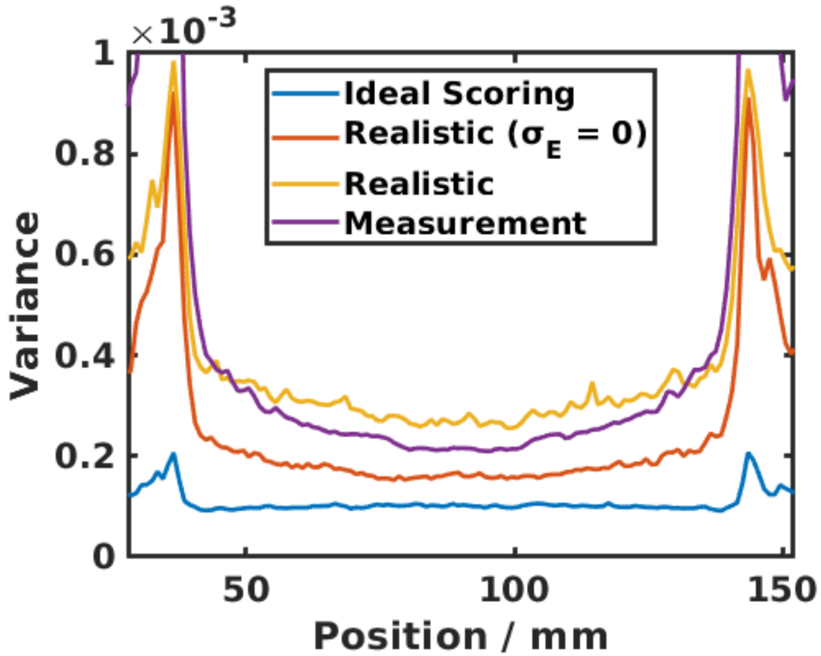
- The fully realistic simulation considers also the **beam energy spread**.

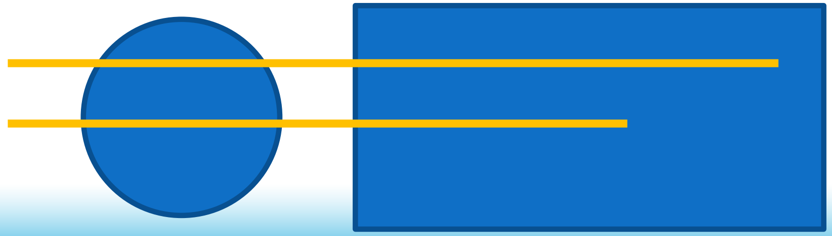




Variance Contributions

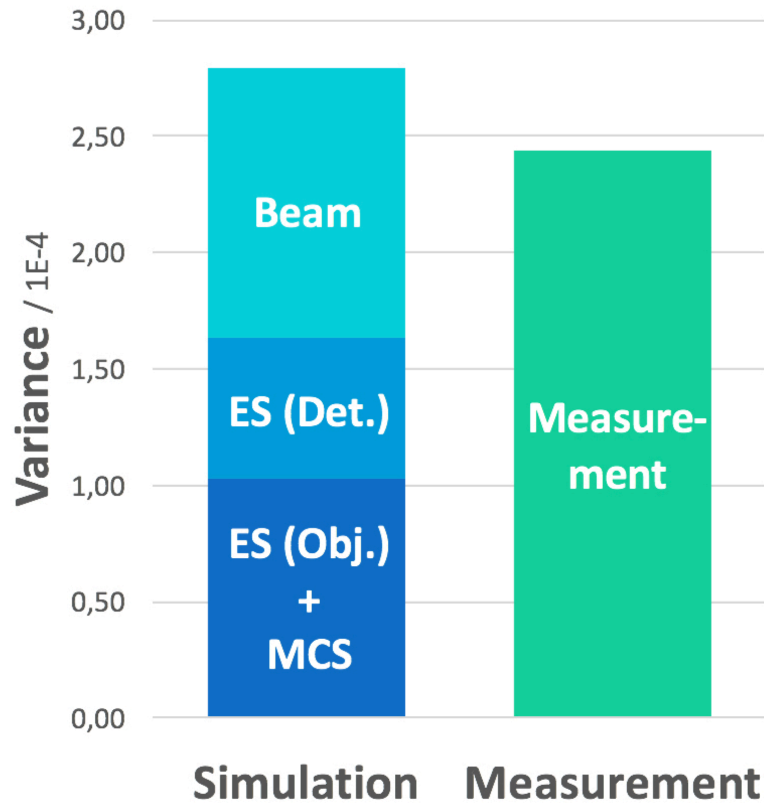
- The **measurement** is at a comparable noise level.
- Differences result from an **inhomogeneous fluence** and distortions in the **beam model**.



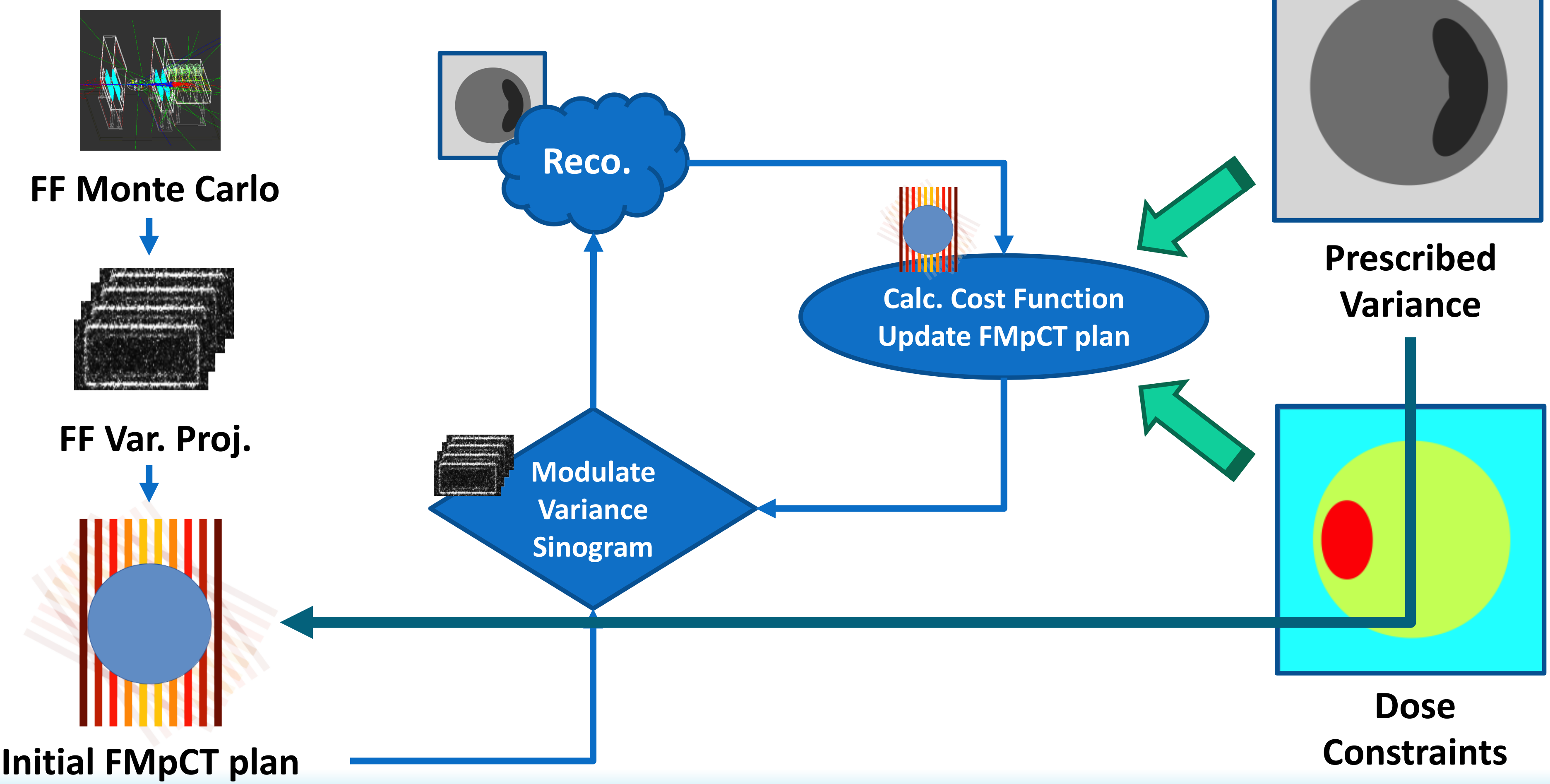


Variance Contributions

- The **measurement** is at a comparable noise level.
- Differences result from an **inhomogeneous fluence** and distortions in the **beam model**.
- Beam model is not negligible.



Optimizing FMpCT Plans



Outlook

Variance Modeling

- Better beam model
  - Impact of divergence?
- Heterogeneous/clinical geometries

Experimental FMpCT

- Implement optimized fluence patterns
- Synchronize with scanner rotation

Fluence modulation patterns

- Optimization of FMpCT plans

Comparison to X-ray CT

- Fan-beam and CBCT

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Simon Rit

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