Deformable Scintillator Array Dosimetry for *in vivo* Volumetric Dose and Dose-Rate Validation of UHDR Proton Therapy

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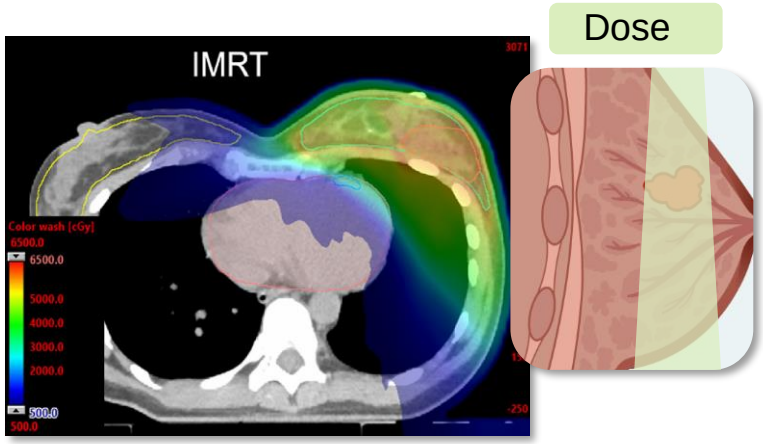
Pre-Treatment Quality Assurance
Daily, monthly, annual QA
Patient specific QA

Real-Time Beam Monitoring
Flatness/Output/Symmetry Checks
Automatic Safety Interlocks

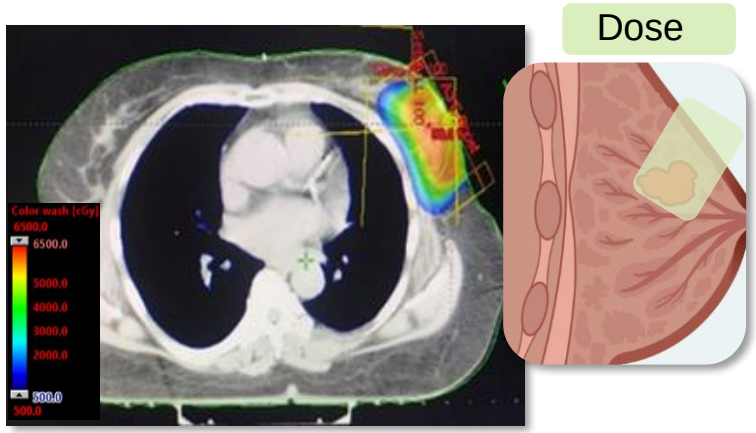
Patient Monitoring
Surface Guidance
On-Patient *In Vivo* Dosimetry

Photon

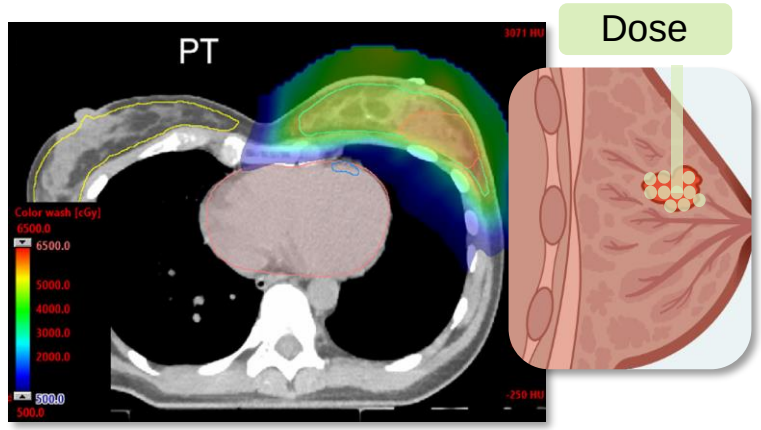


Karmanos Cancer Institute

Electron



Proton



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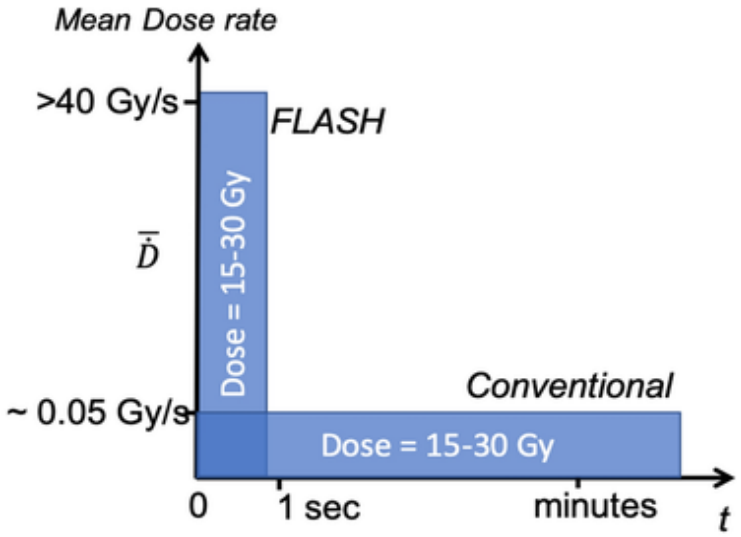

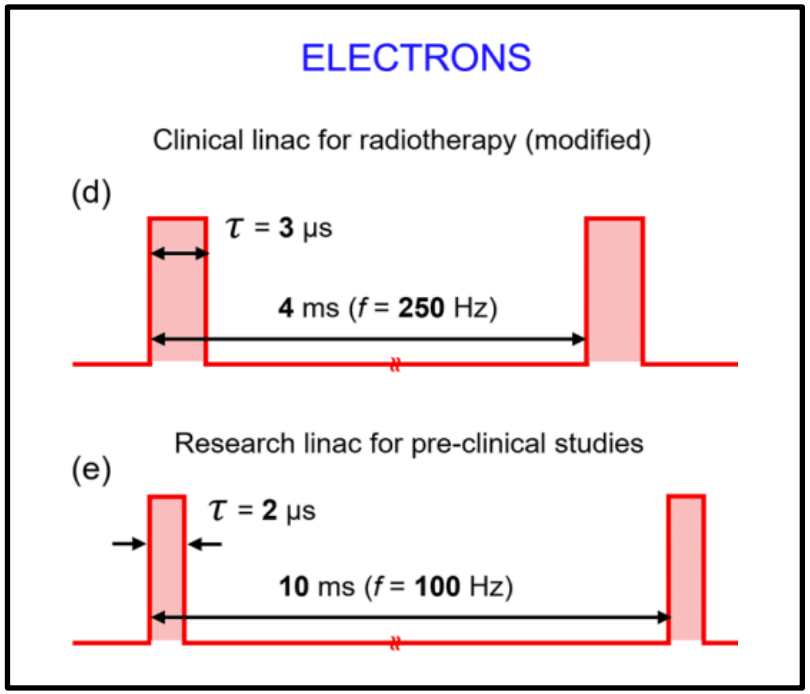

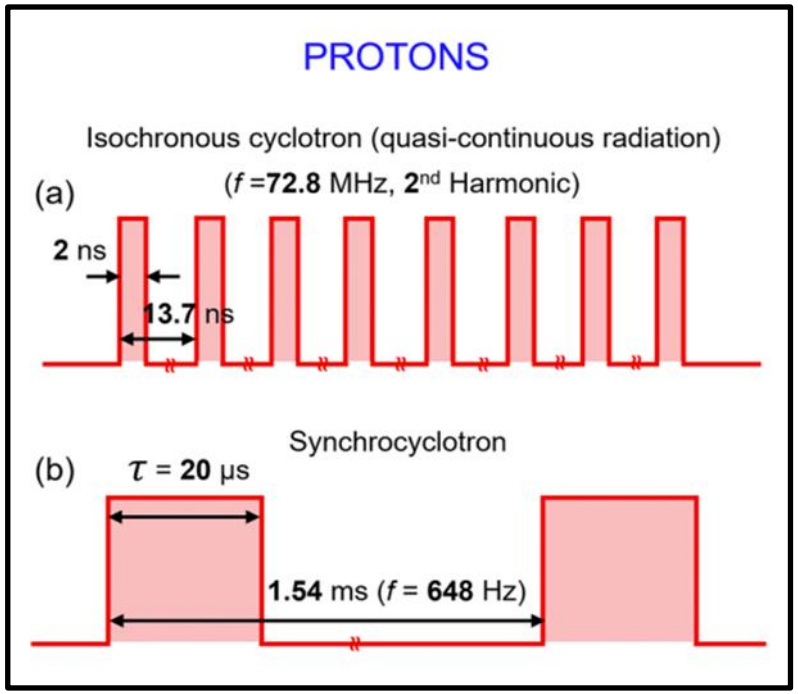

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Romano et al. Medical Physics. 49. 10.1002/mp.15649.
Esplen et al. Scientific Reports. 14. 10.1038/s41598-023-50412-w.

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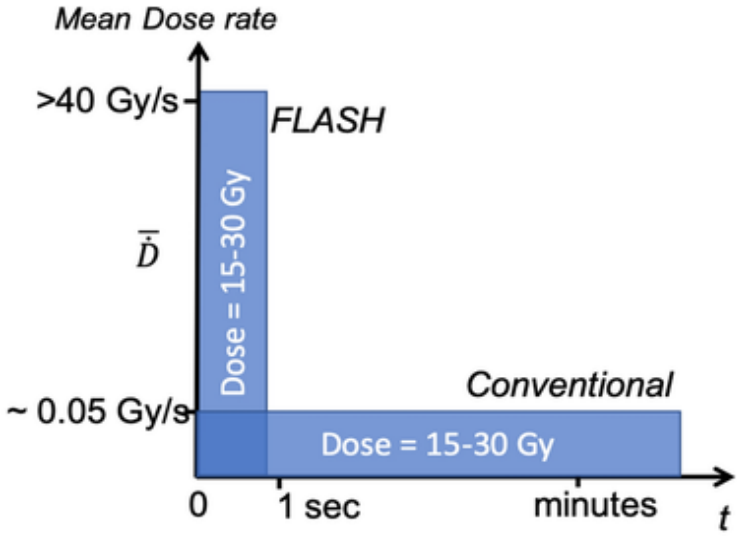
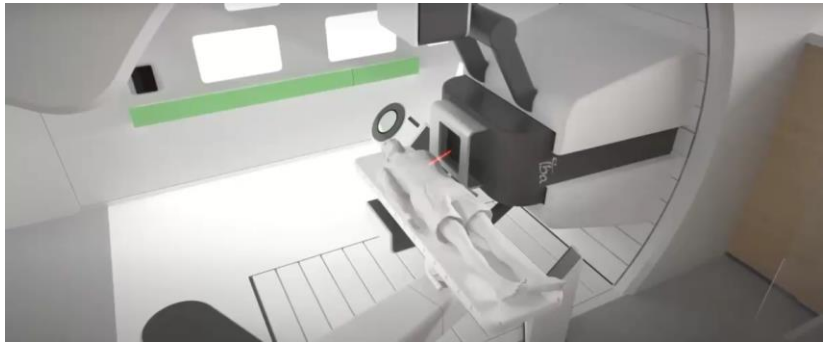
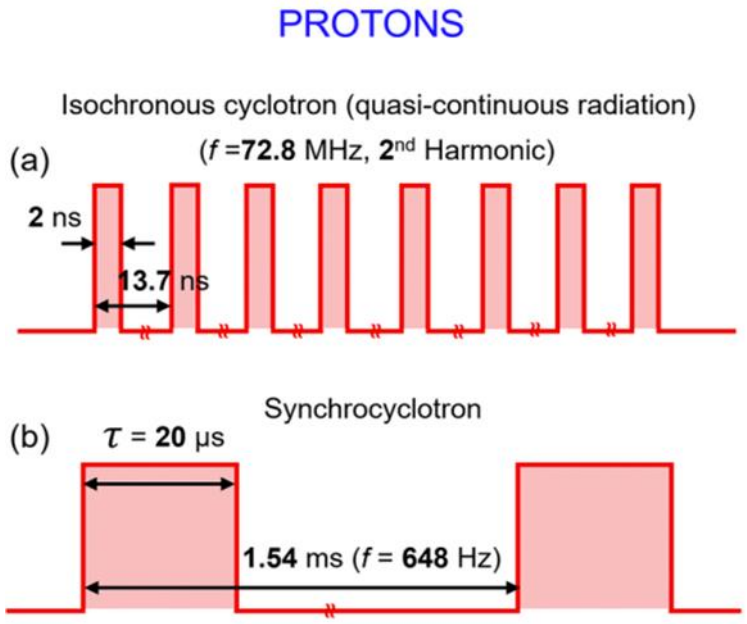




UHDR PBS Beam Conditions			
Spot dwell time: <3ms	Spot scanning speed: >25m/s[1,2]	Ø1.1cm FWHM[3]	**<1sec** deliveries

1. Kanouta et al. 2022. 2. Poulsen et al. 2018. 3. Darafsheh et al 2021.



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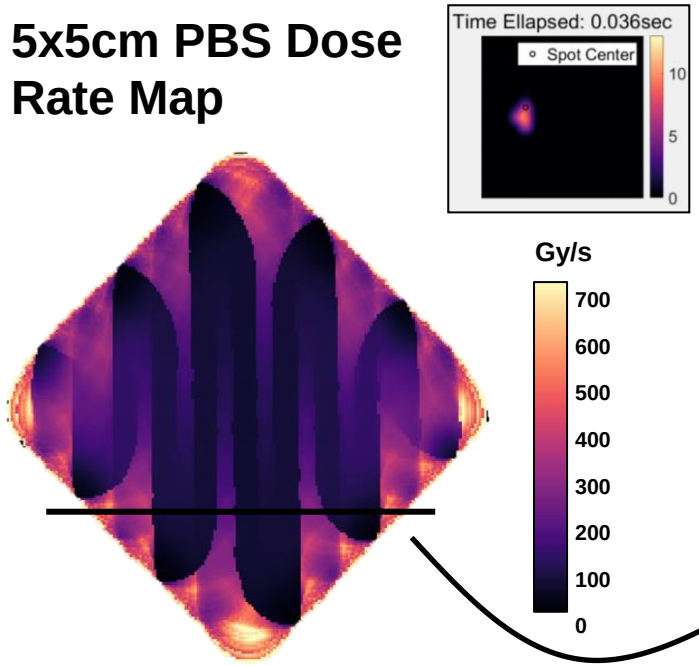
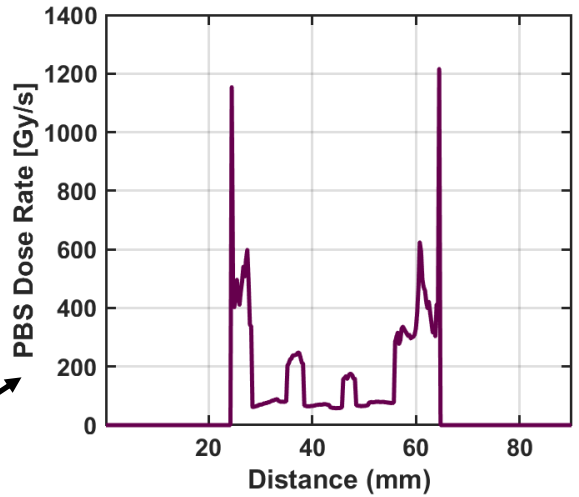
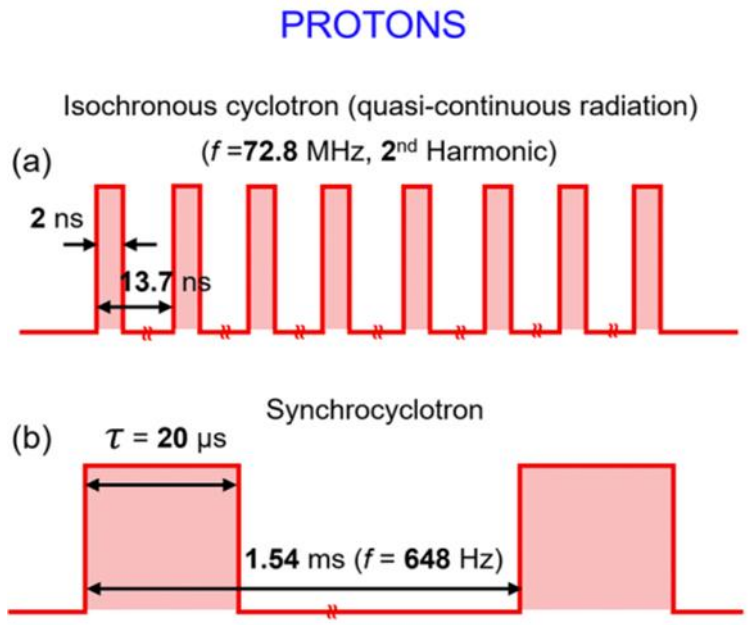
5x5cm PBS Dose Rate Map



$$\dot{D}_{PBS}(\vec{x}) = \frac{\left(D(\vec{x}) - D_{\dagger}\right) - D_{\dagger}}{t(\vec{x})}$$

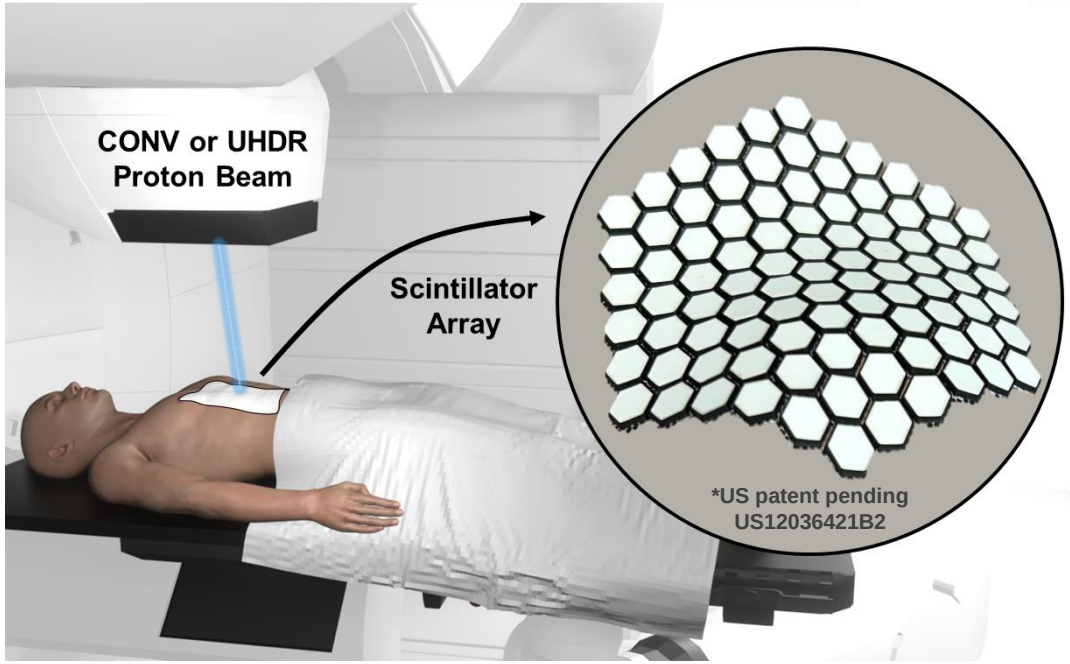
Cross Section Profile

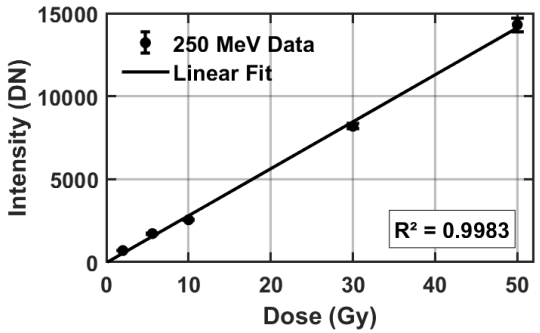


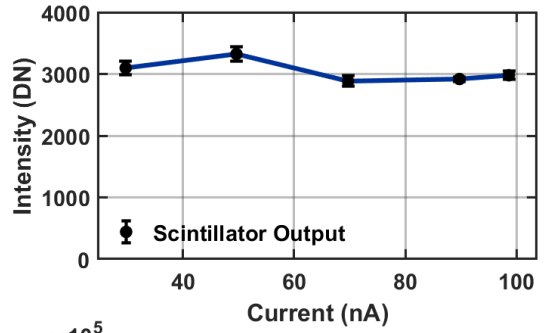


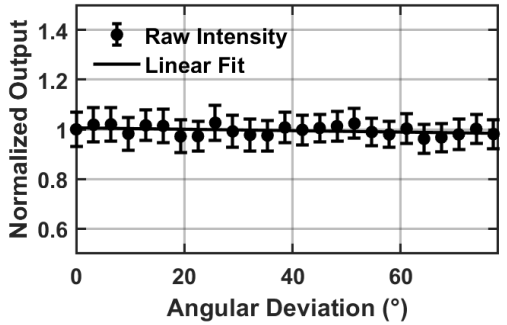
Deformable array application introduces **dynamic surface dose monitoring** during UHDR delivery and **minimal deviation to treatment workflow**

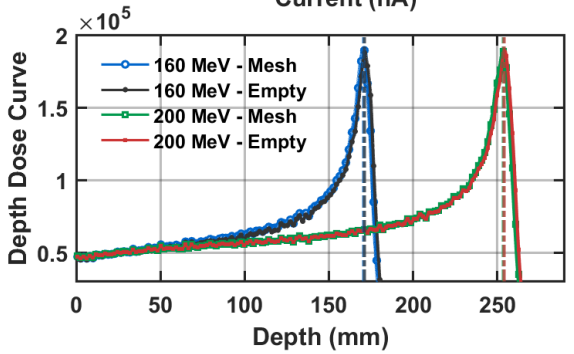
Reponse	Detectors	Measurement Type	Instantaneous Dose-Rate/Dose per Pulse (Dp) Dependence	Spatial Resolution	Temporal Resolution	Type of Dosimetry
	TLD/OSLD	1D (IVD)	Independent (~10^9) Gy/s	~1mm	Passive	Reference
Luminescence	Scintillators	2D+ (IVD)	Independent (~10^6) Gy/s	~1mm	~ns	Reference











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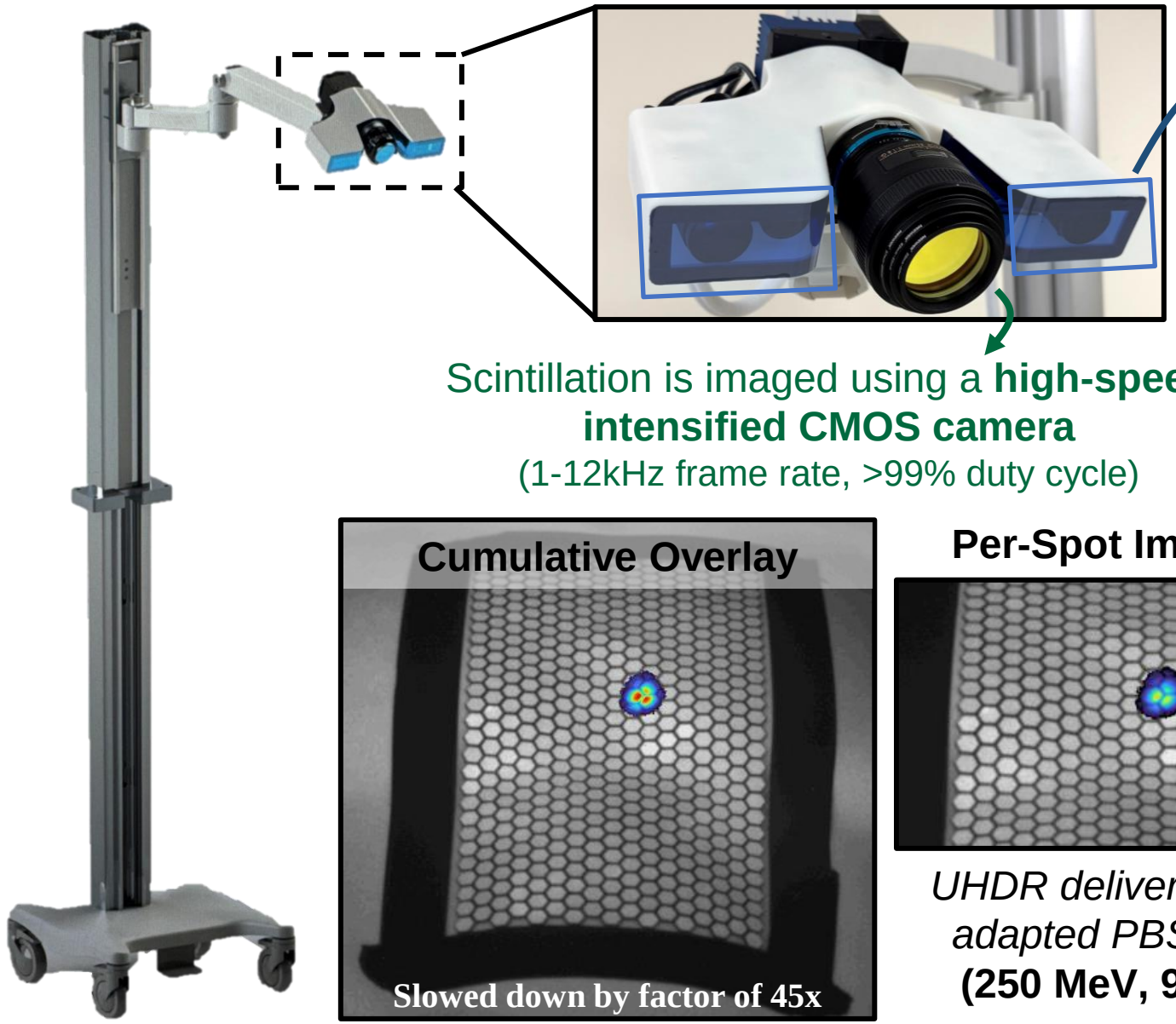
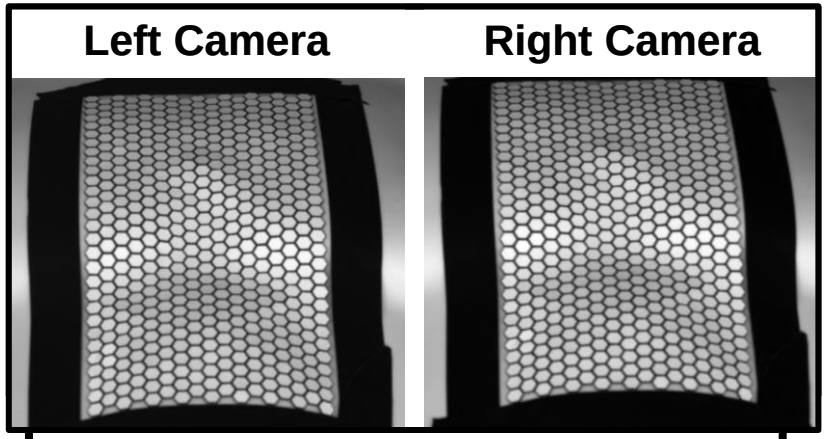
Romano et al. Med Phys. 2022 Jul;49(7):4912-4932. doi: 10.1002/mp.15649
Ashraf et al. Front. Phys. 8:328. doi: 10.3389/fphy.2020.00328



Scintillation is imaged using a **high-speed intensified CMOS camera**
(1-12kHz frame rate, >99% duty cycle)

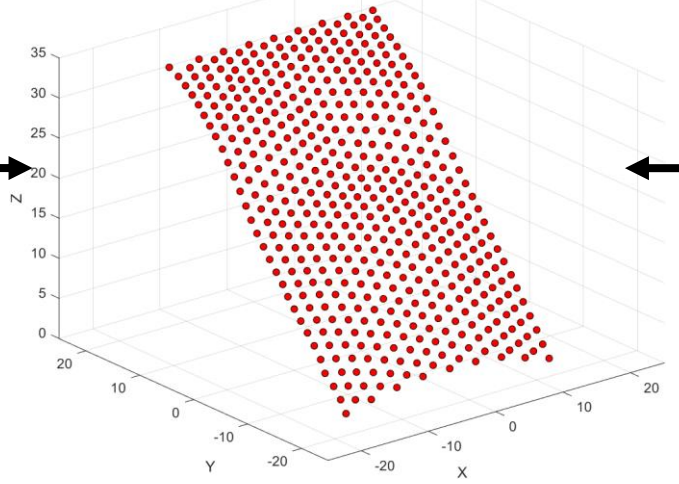
Stereovision constructs a structural array profile to retain **geometric reference**



Per-Spot Imaging

UHDR delivery of an adapted PBS plan
(250 MeV, 99nA)

3D Centroid Point Cloud

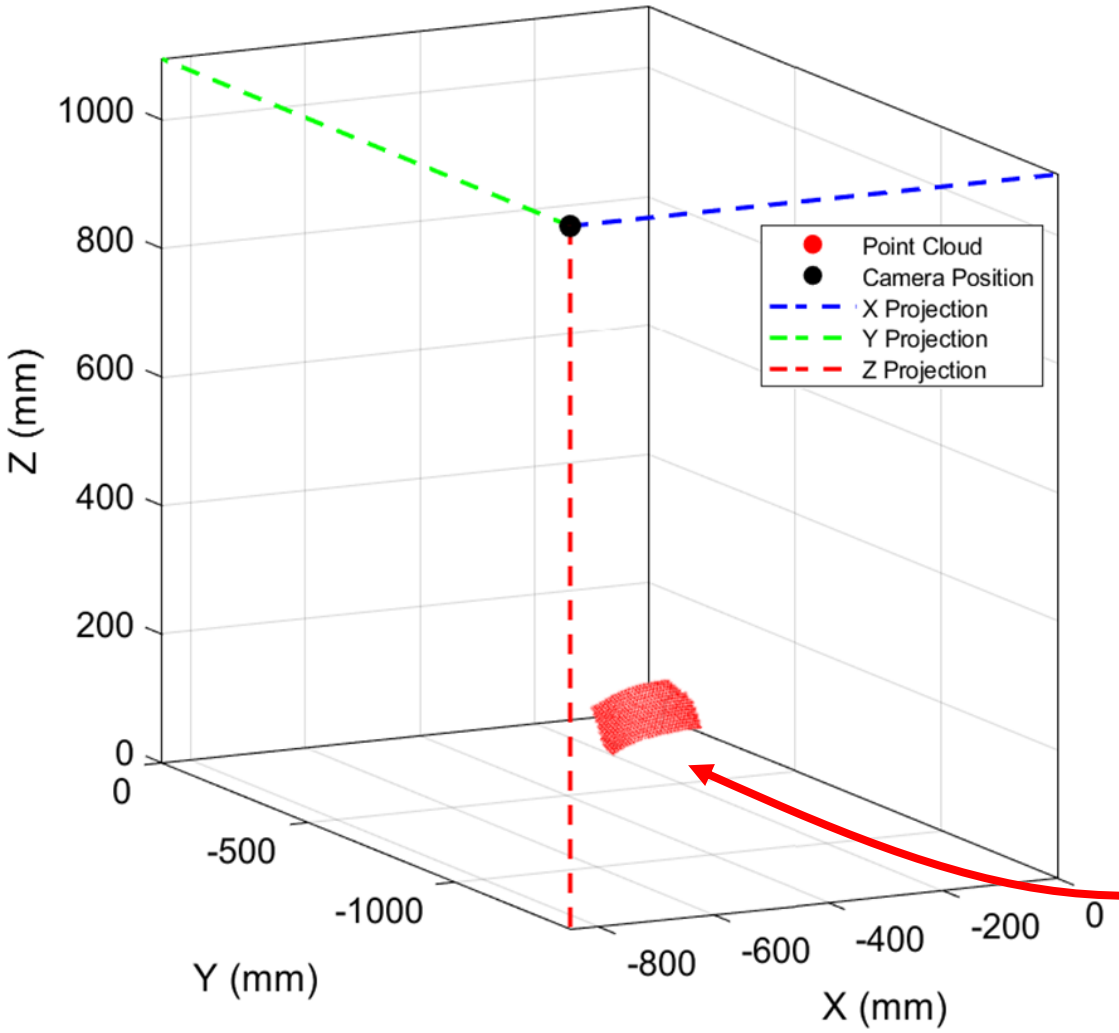


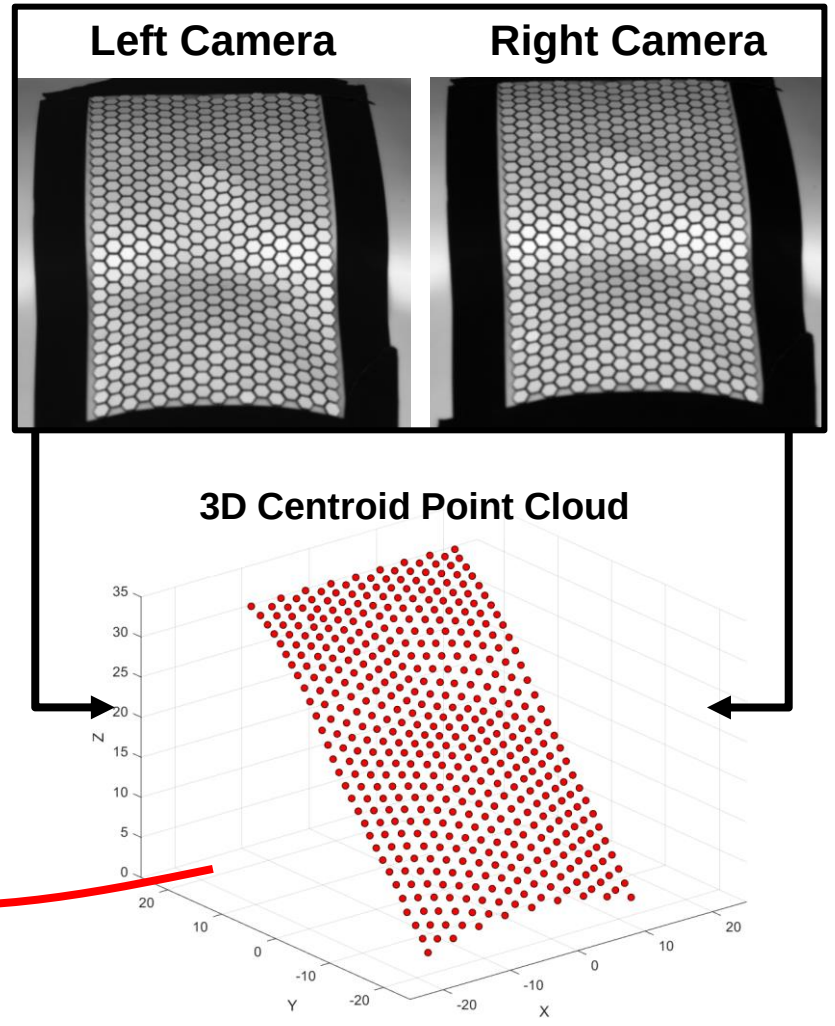
Extrinsic camera calibration maps the array to be **in 3D room coordinates**

Isocenter calibration maps array with respect to **target**

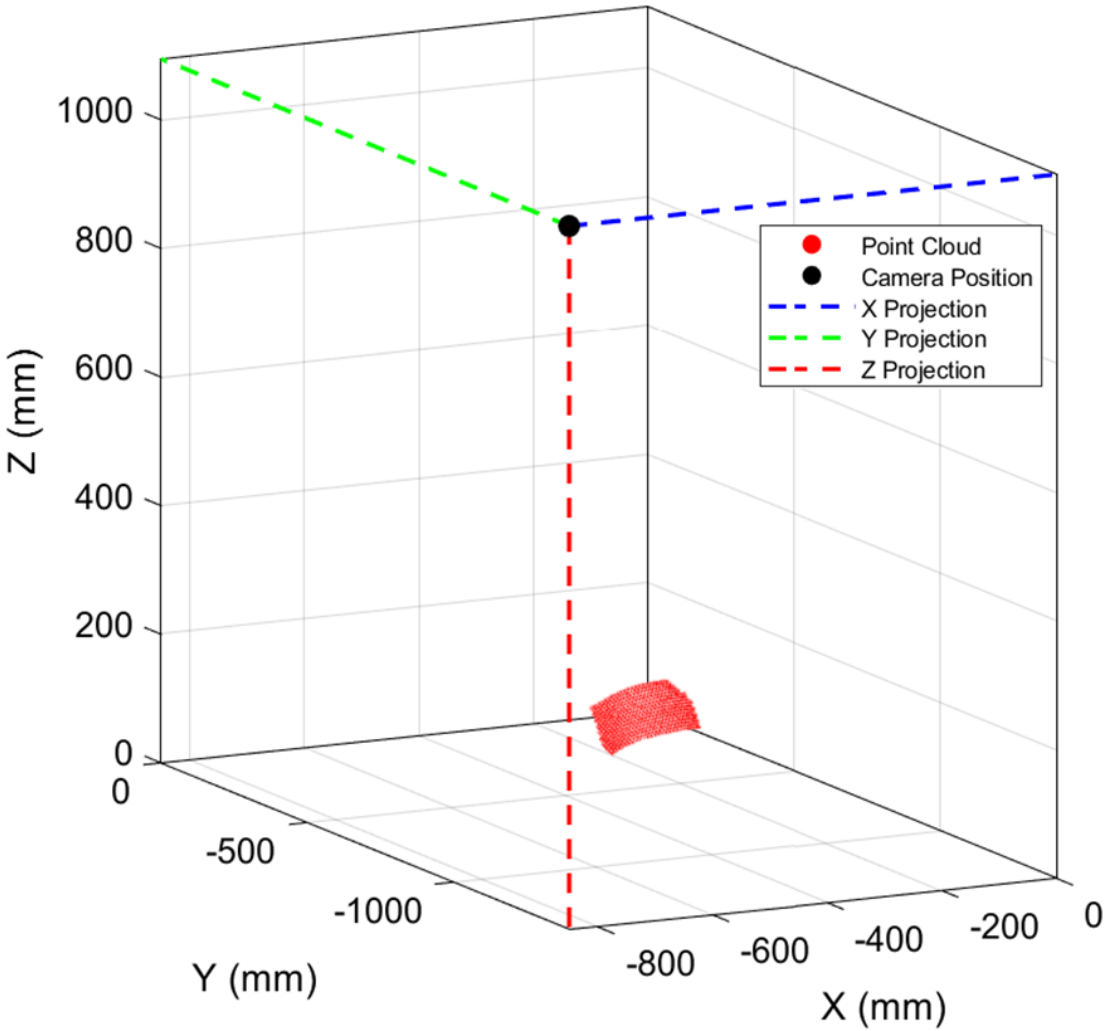
Planned gantry position maps array with respect to **beam** propagation **path**

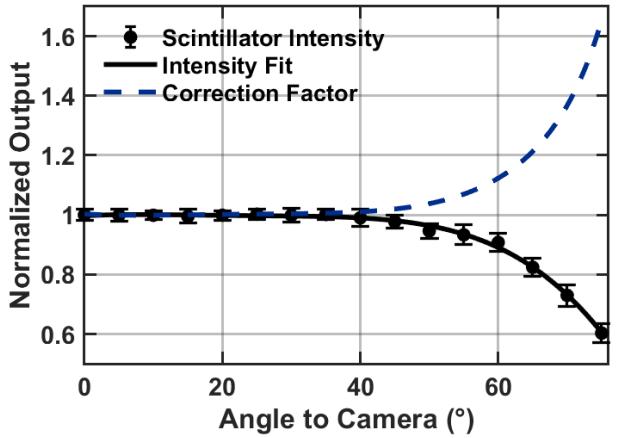
Array localization is **independent** of setup or pre-Tx positioning

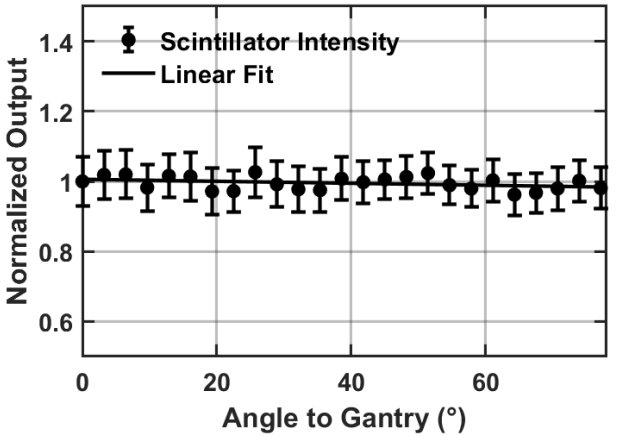


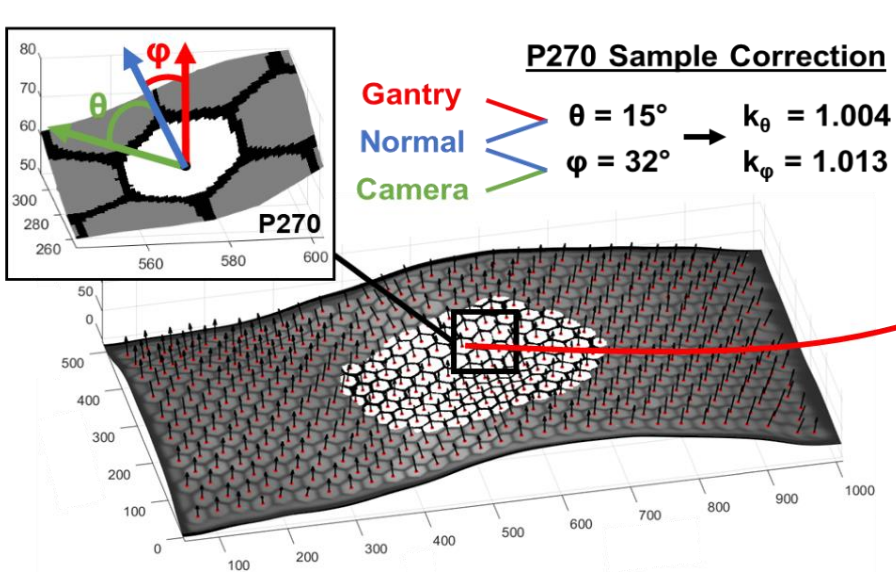


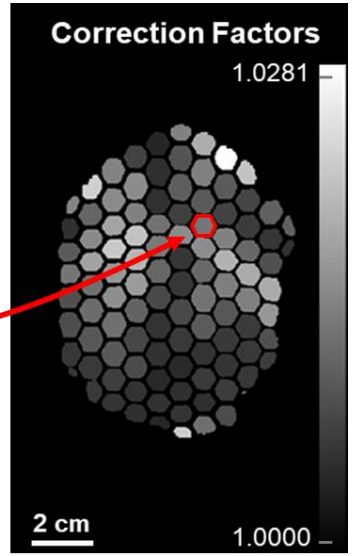
Intensity **variation at high incidence and imaging angles** is corrected using known **single element orientation** from stereovision mapping











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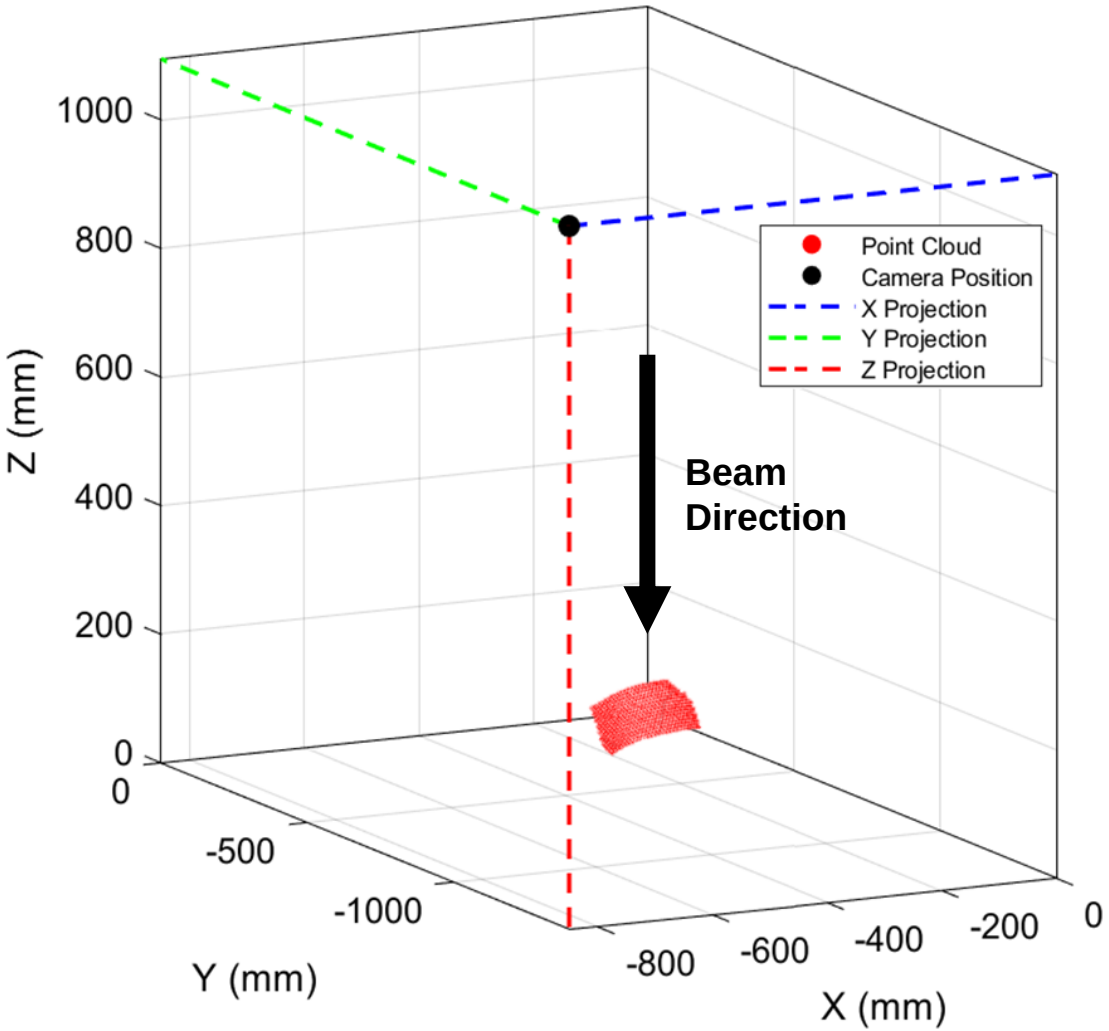
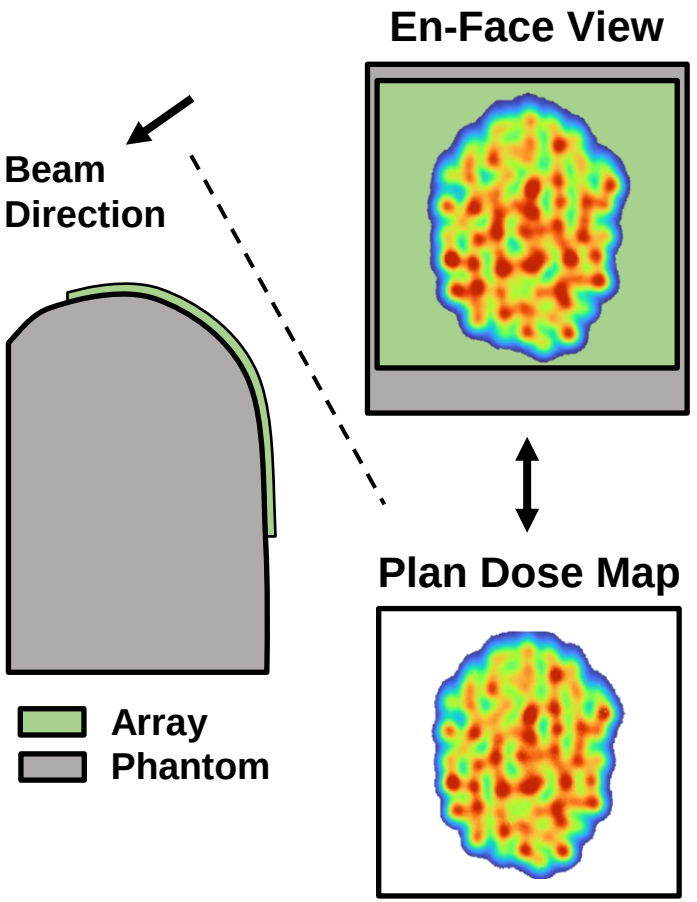
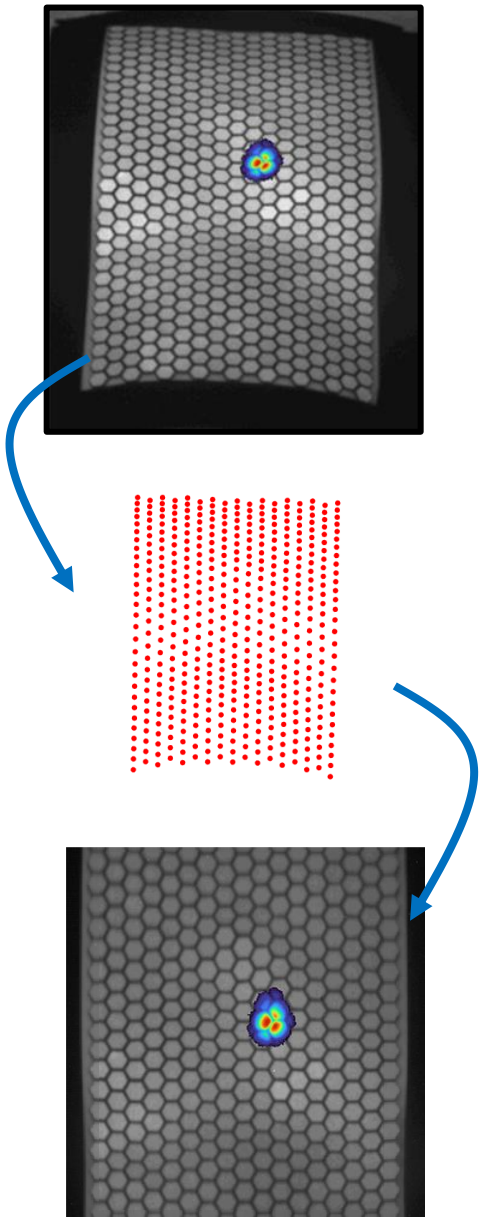
Angular information is used to **correct for geometric deviation** and **transform image to the desired POV** (e.g. Beam's Eye View)







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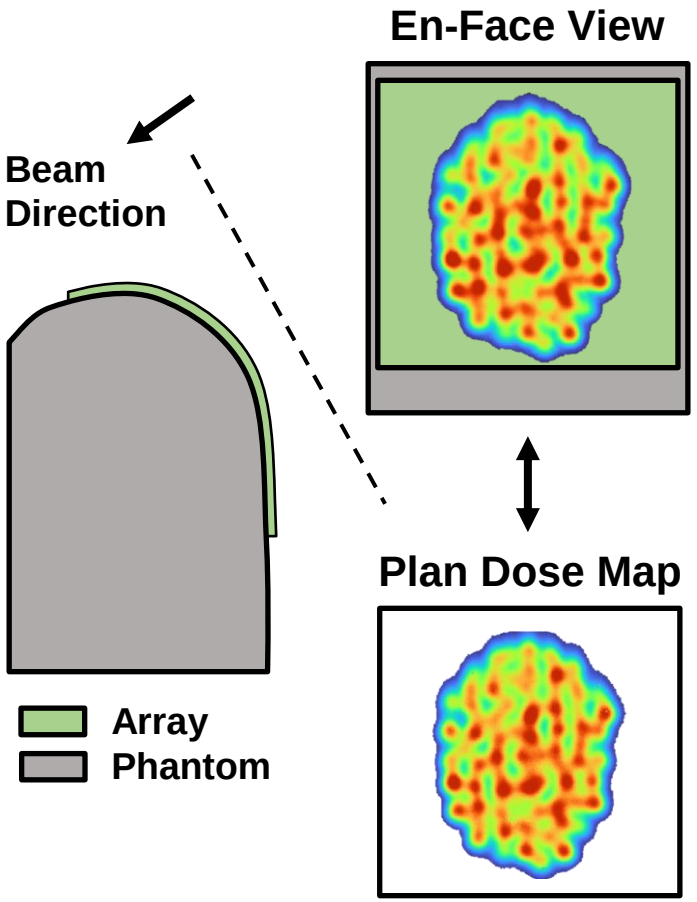
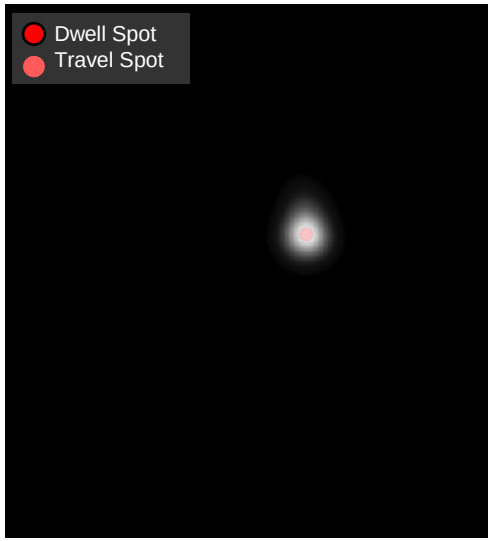
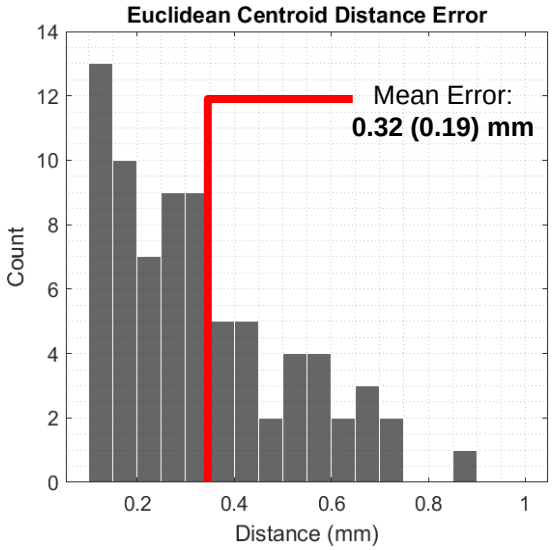
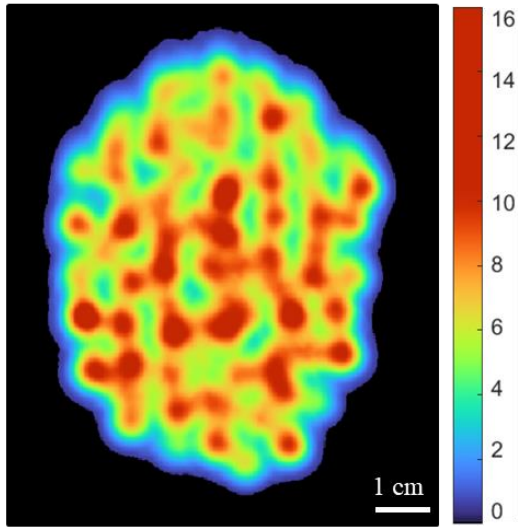
Projected comparison against plan or flat field delivery

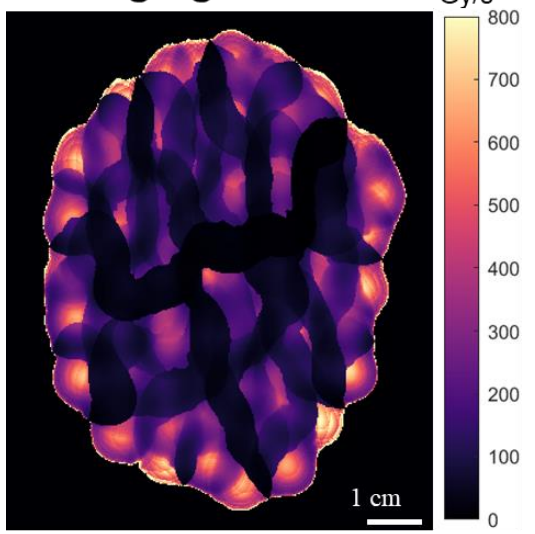
Position - Dose - Dose rate

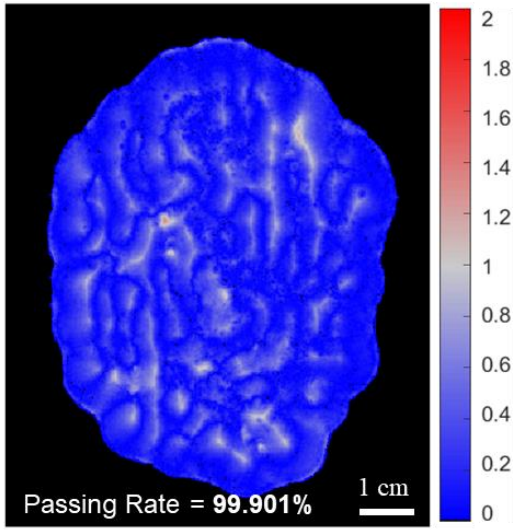


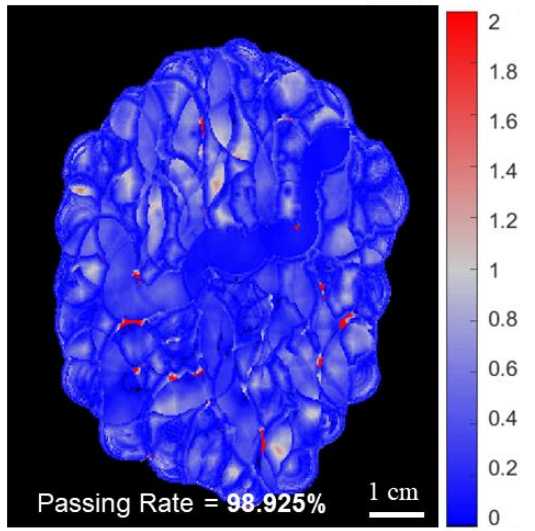












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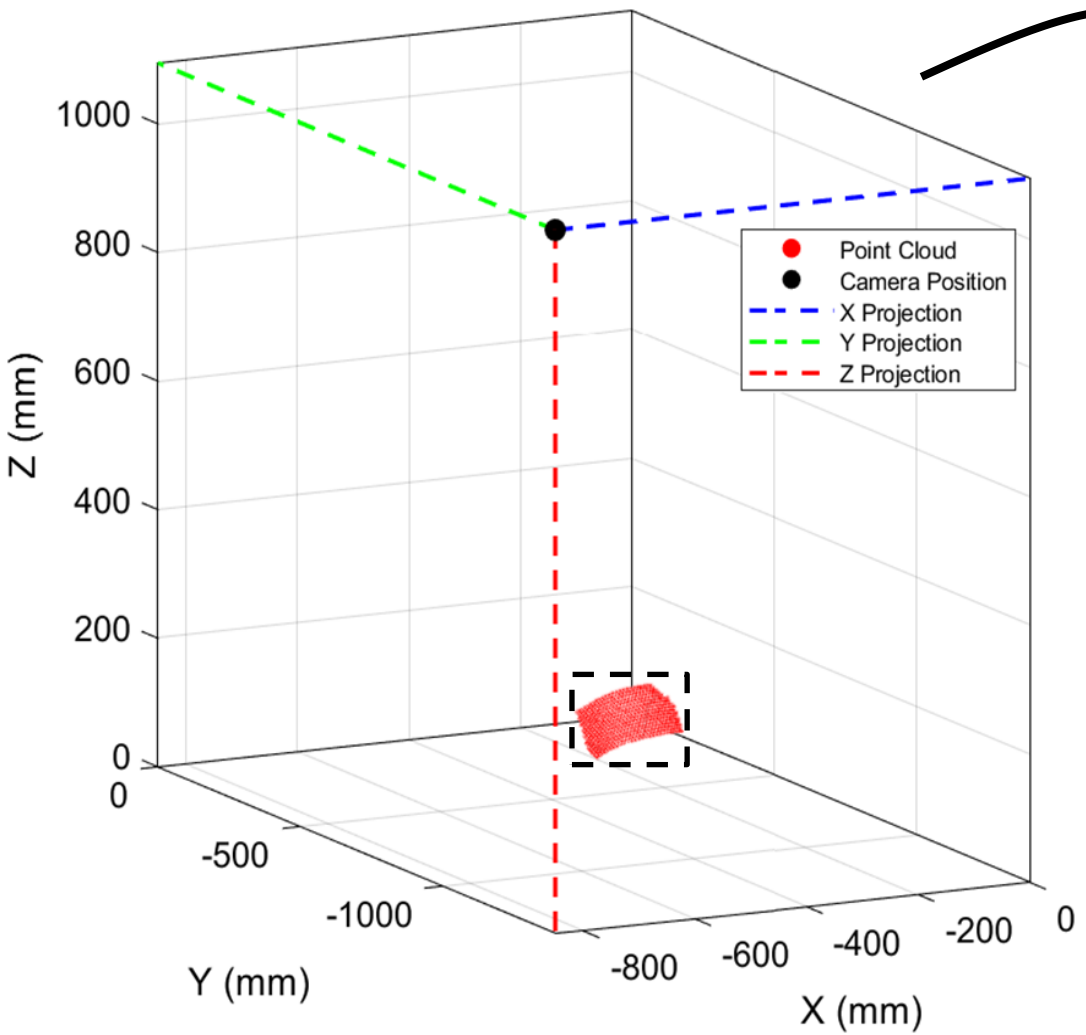
Independent 3D array localization with respect to isocenter allows **direct overlay of observed surface dose dynamics** and the planning CT



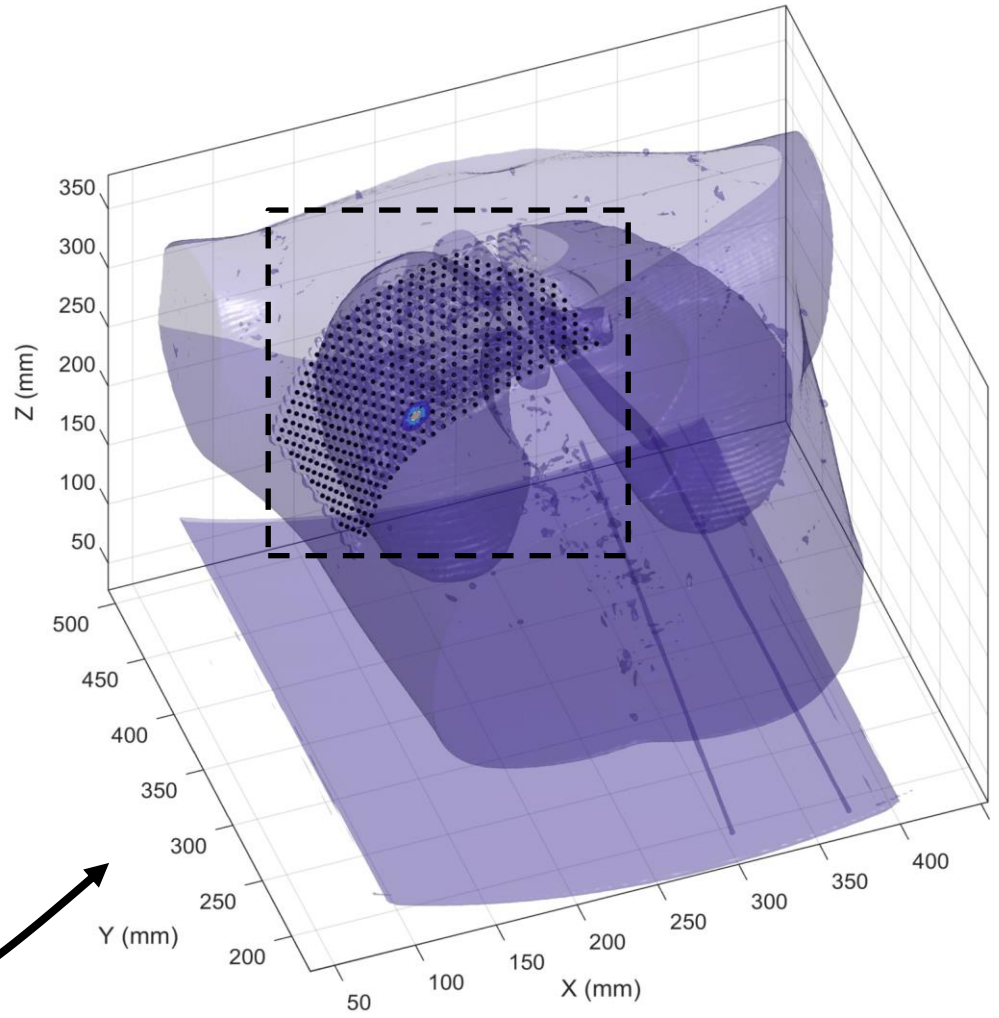
Array PC mapped to the room isocenter

↓

Planning CT mapped to the room isocenter

↓

Direct overlay of time resolved surface dose



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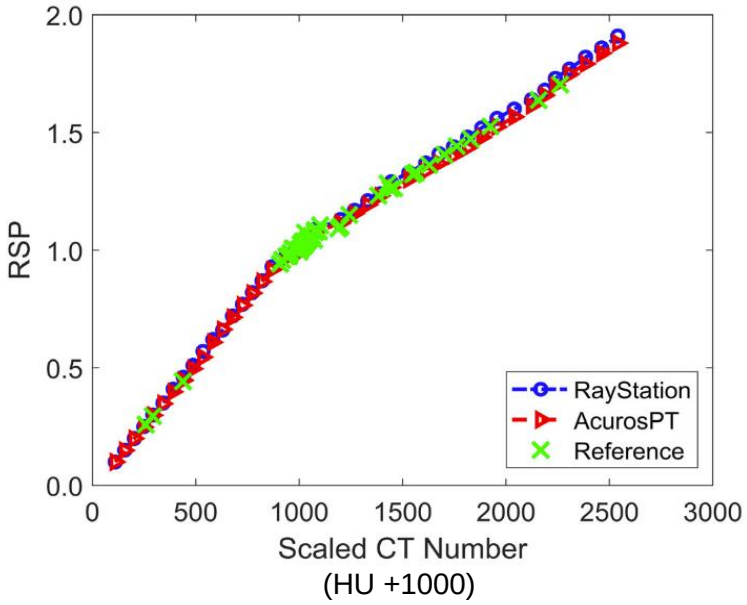
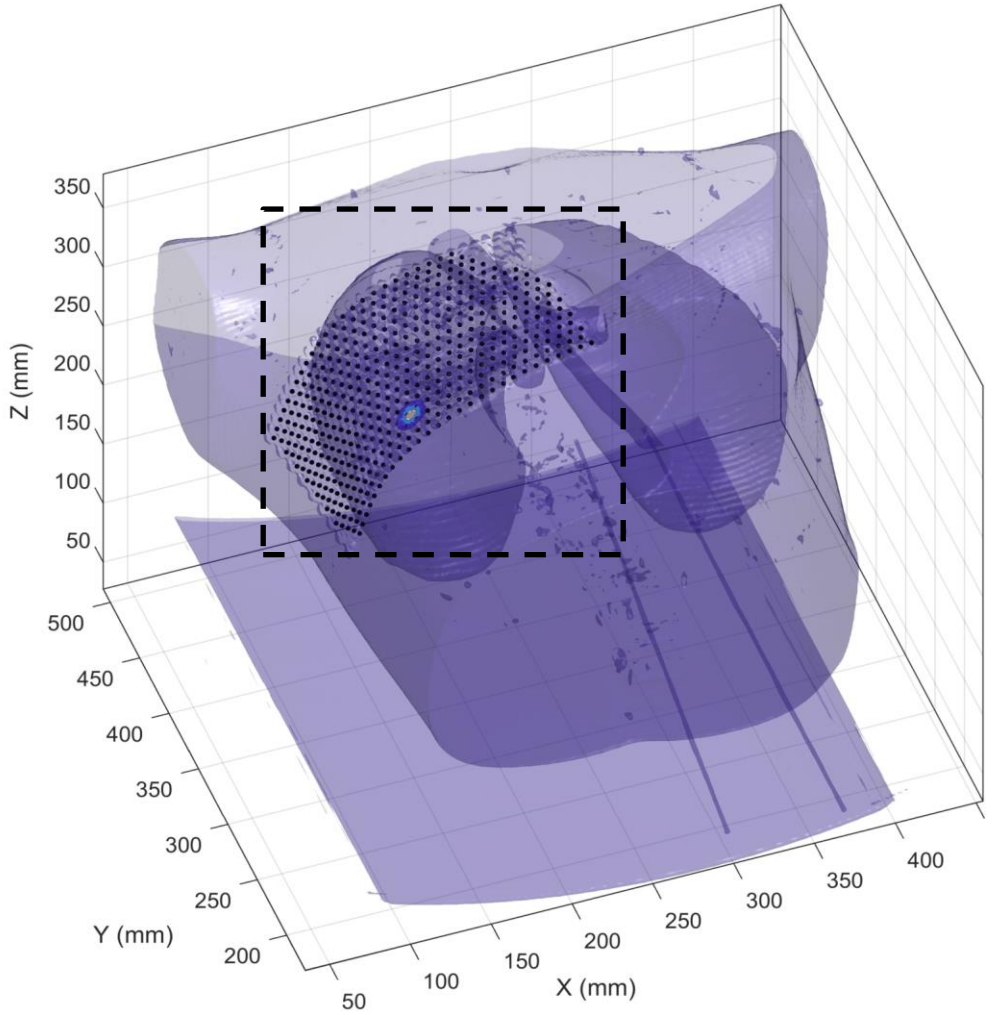
Surface dose was projected through target volume based on known **beam energy, geometry, dose build-up effects, and scatter-based blurring**

CT Conversion to WET

Relative stopping power relationship to HU used to convert each CT layer to WET along beam path





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https://aapm.onlinelibrary.wiley.com/doi/epdf/10.1002/mp.14021

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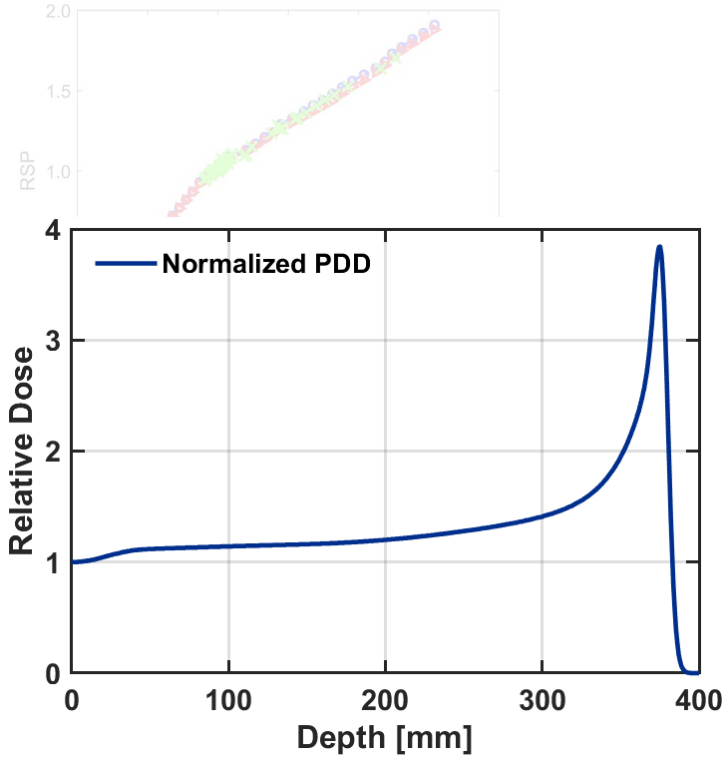
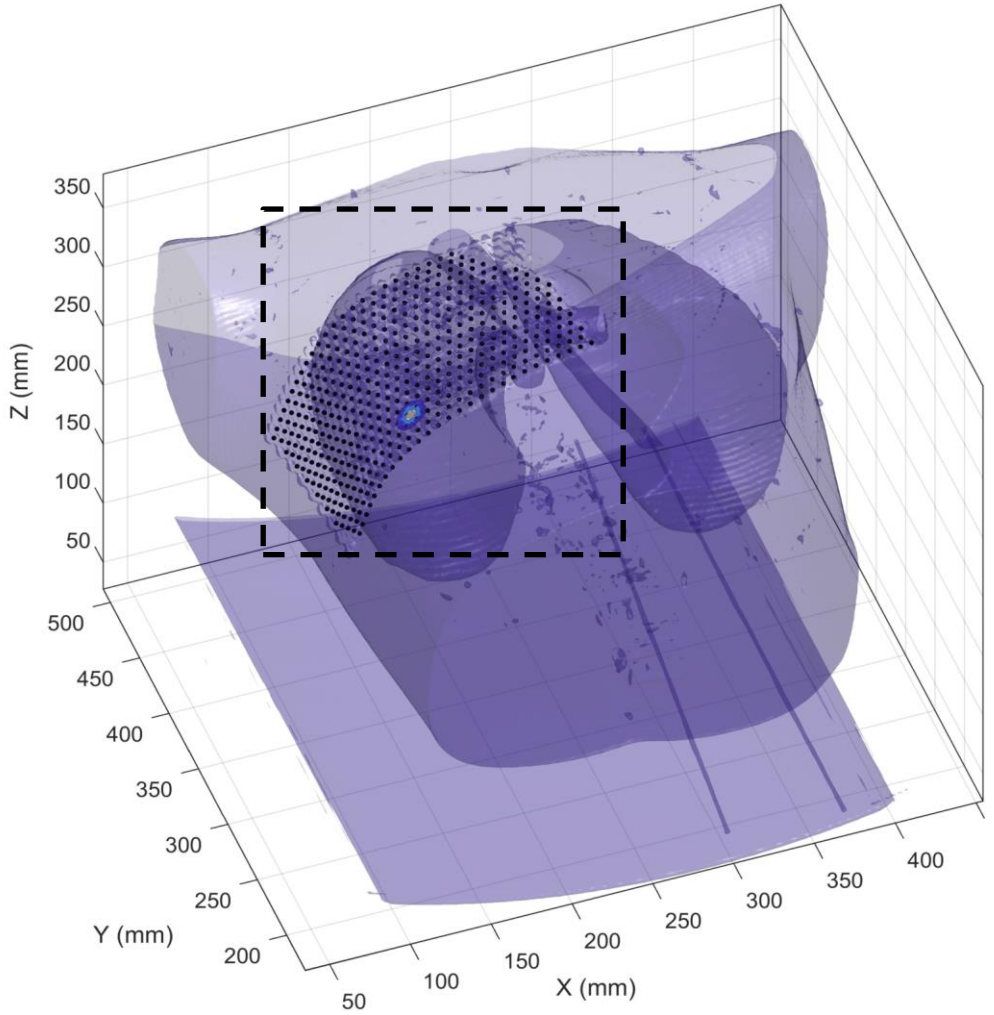
Relative stopping power relationship to HU used to convert each CT layer to WET along beam path

PDD Intensity Scaling

Surface dose spot profile scaled with depth based on energy-specific PDD





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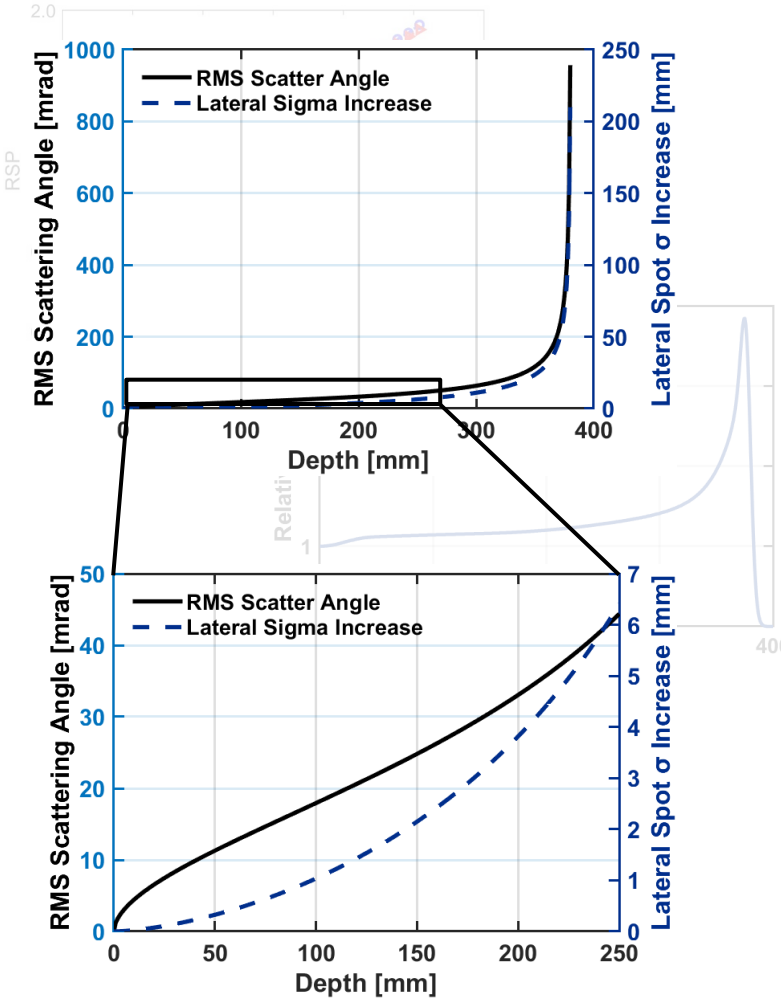
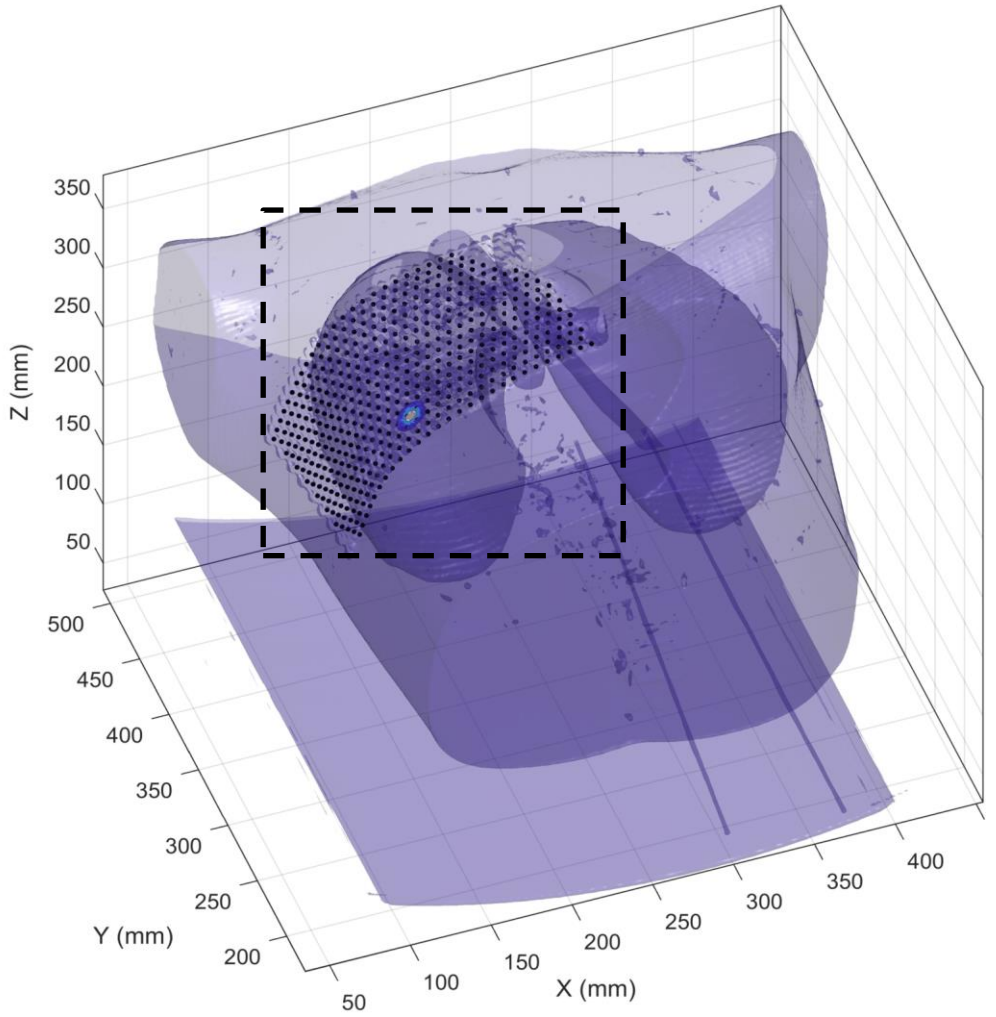
PDD Intensity Scaling

Surface dose spot profile scaled with depth based on energy-specific PDD

MCS/Beam Divergence

Spot profile augmented following MCS gaussian sigma spread and empirically observed beam divergence





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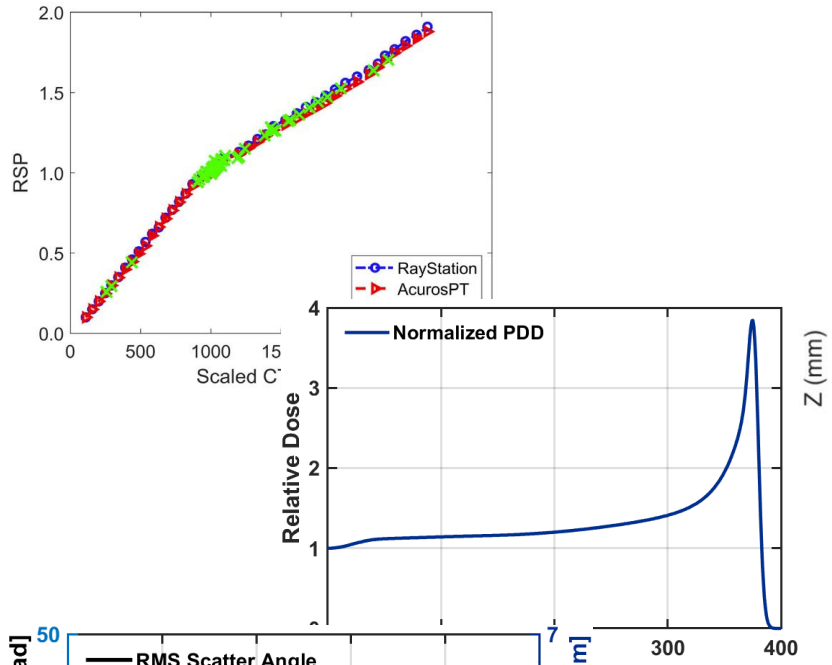

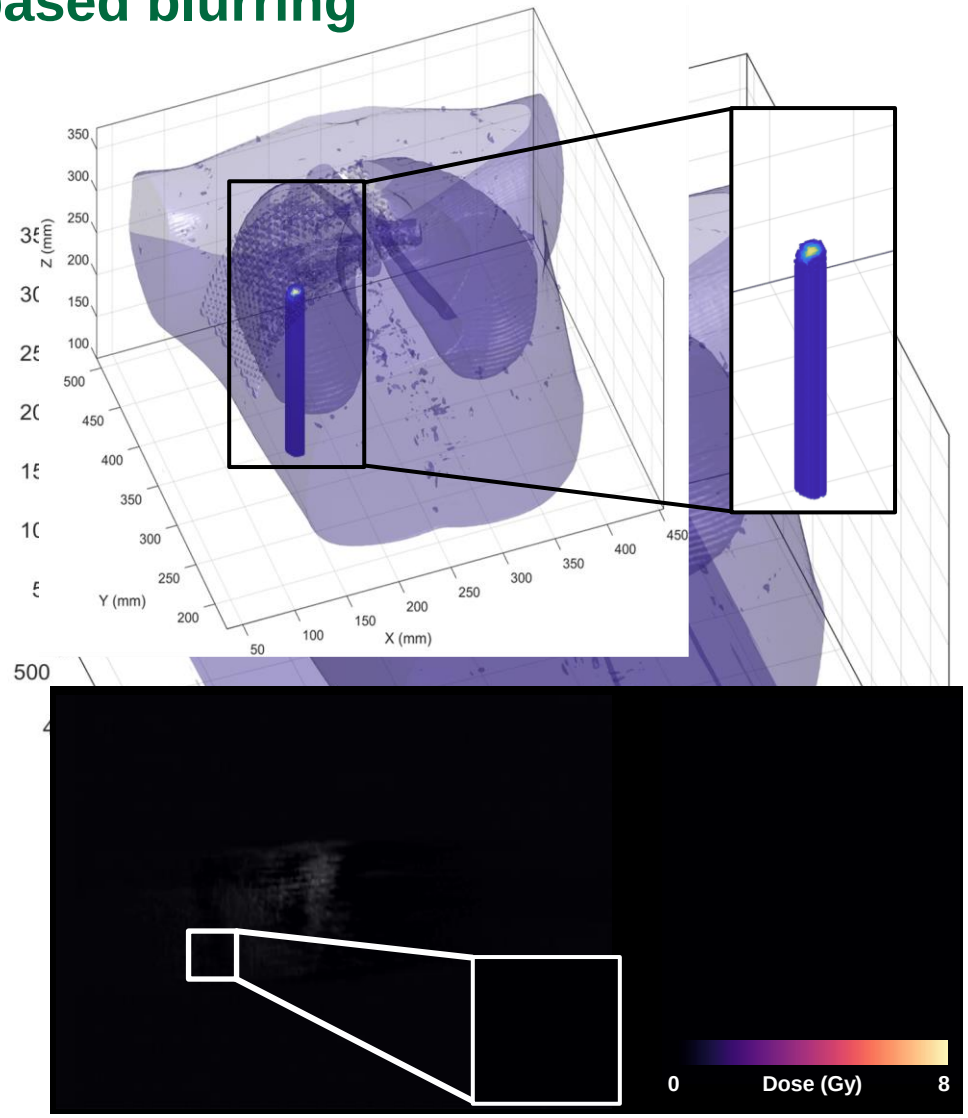

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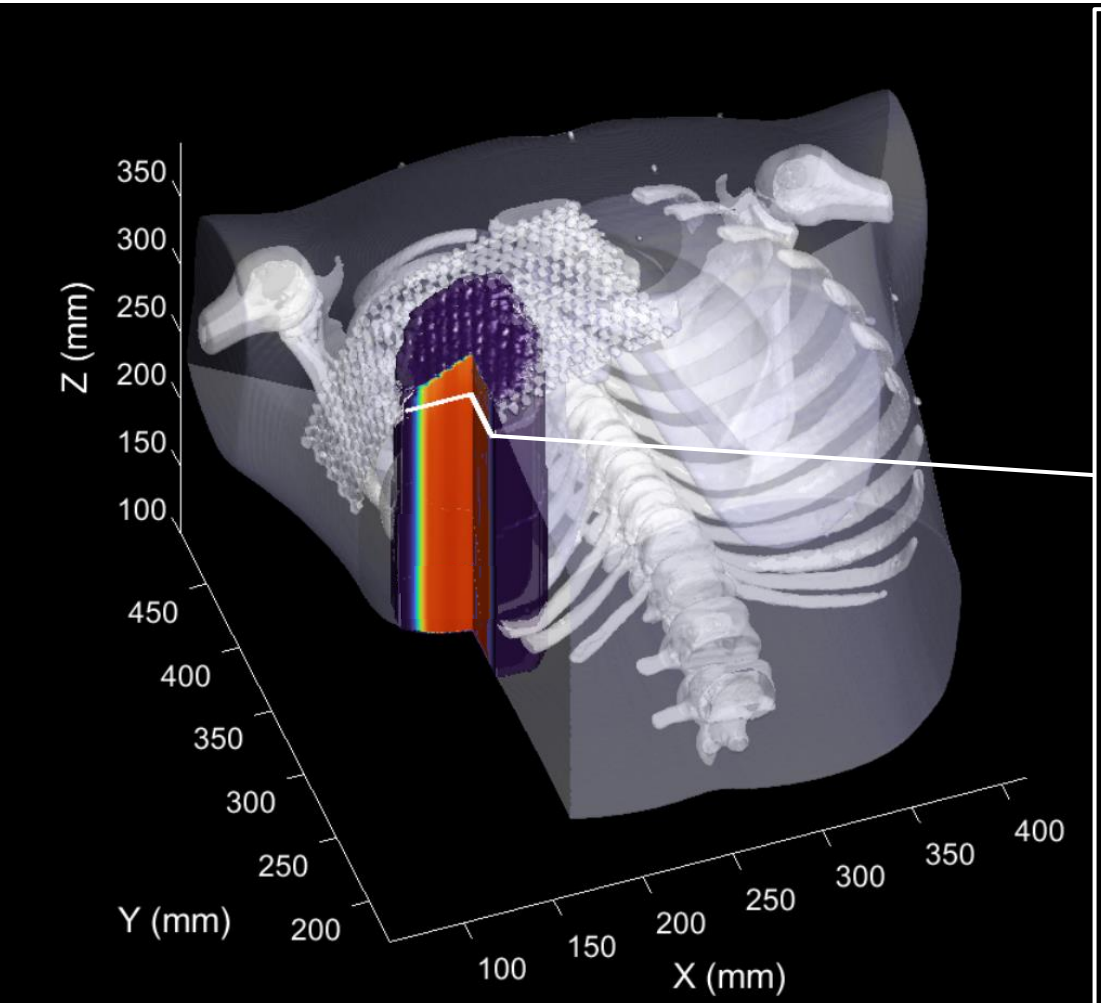
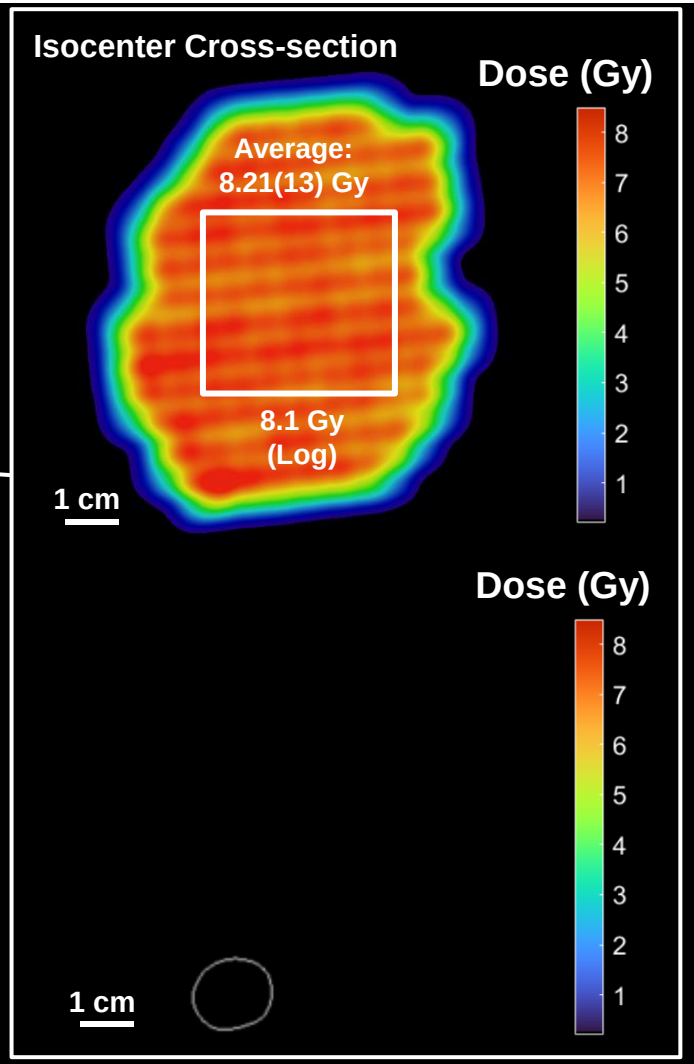
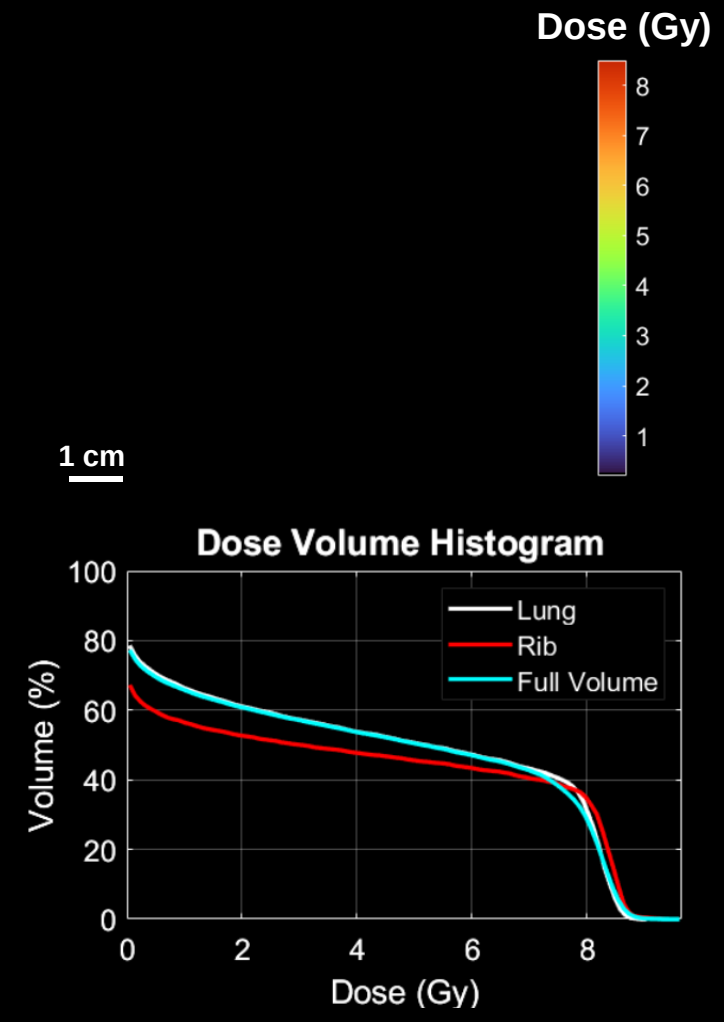
Following depth projection from time resolved surface dosimetry, **volumetric dose maps are derived with reference to the target volume** at the 1000Hz imaging rate







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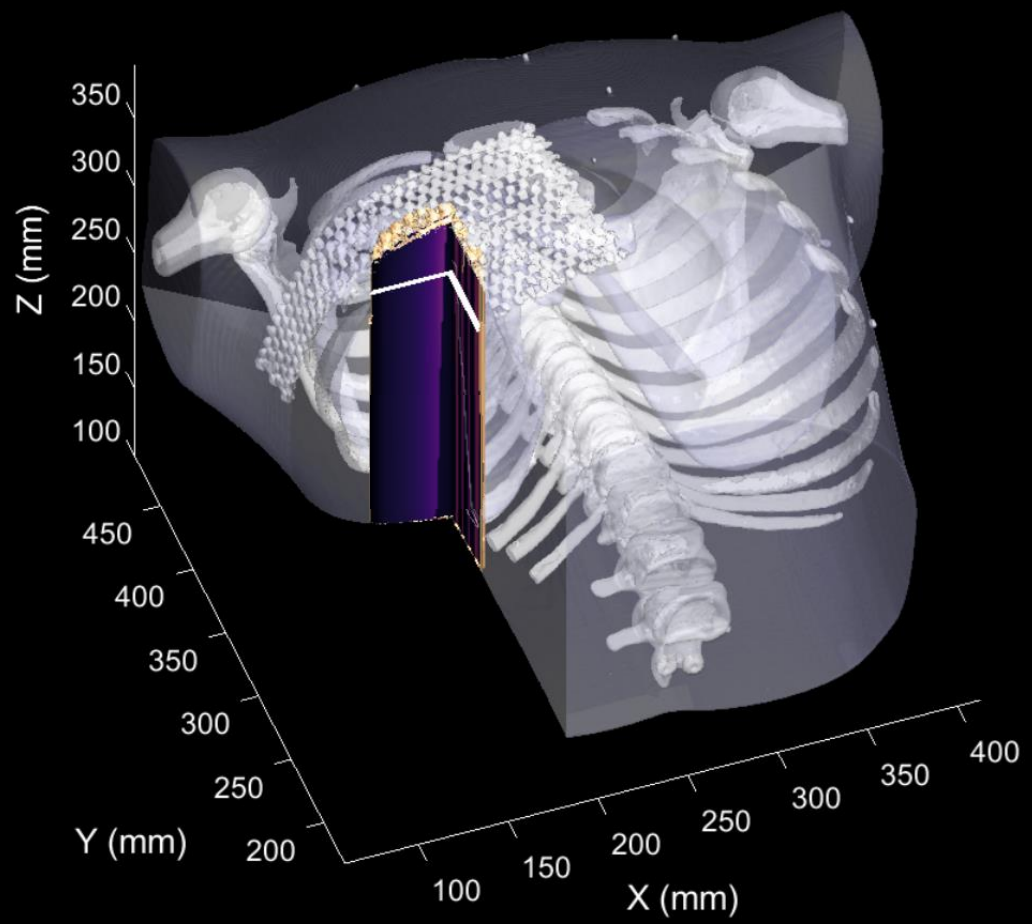
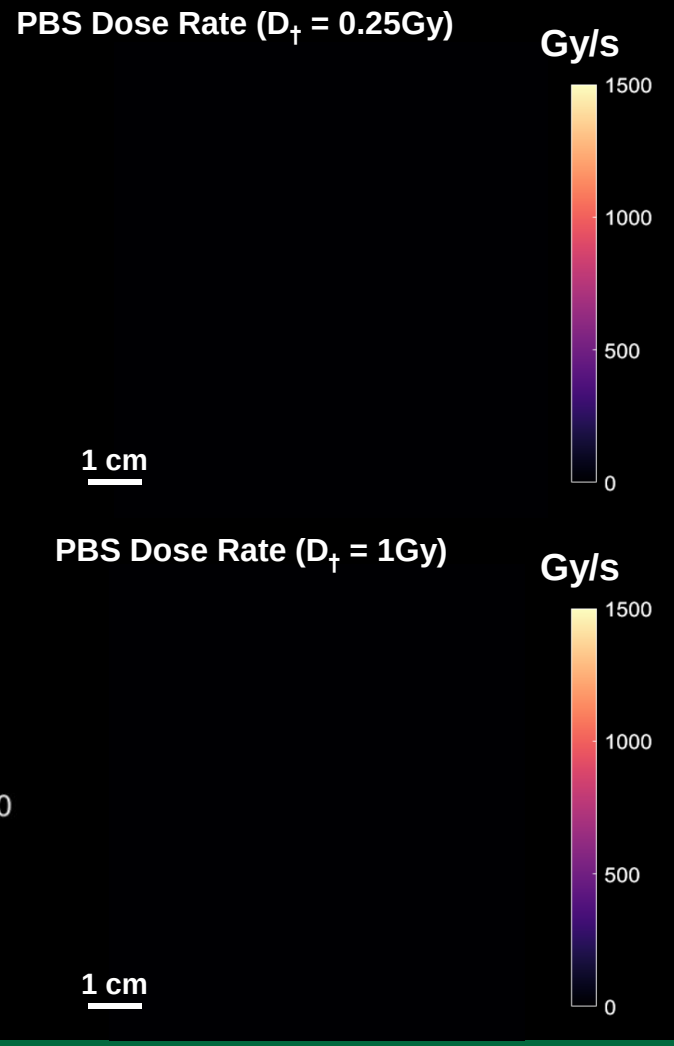
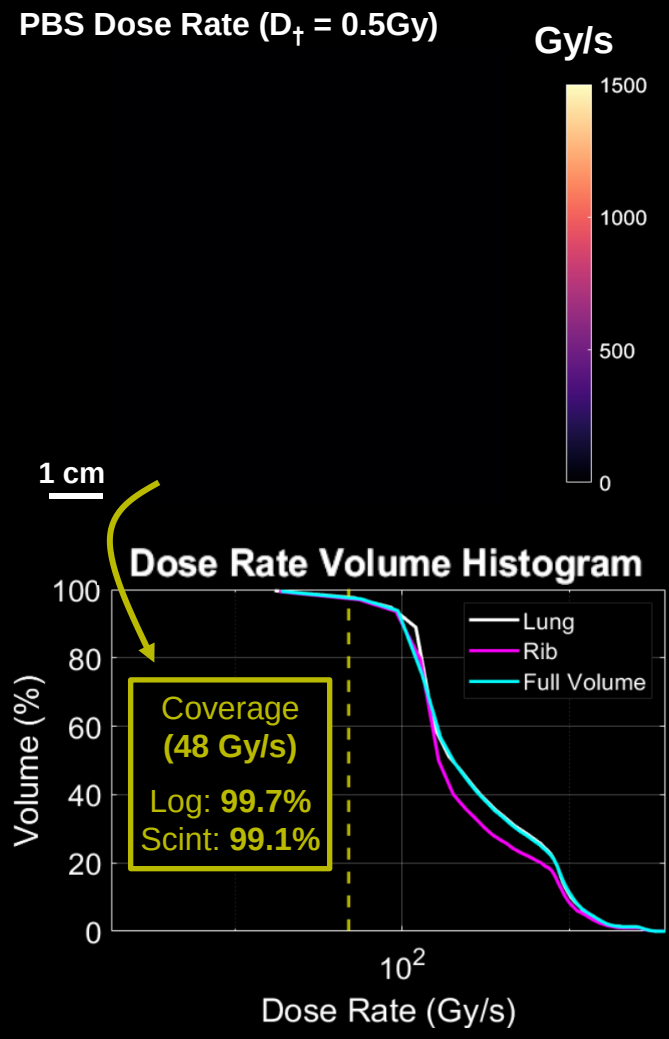
Dynamic surface dose profile used to derive **volumetric PBS dose rate maps**, giving insight to the **dependence on $D_{\dagger}$ selection**

$$\dot{D}_{PBS}(\vec{x}) = \frac{\left(D(\vec{x}) - D_{\dagger}\right) - D_{\dagger}}{t(\vec{x})}$$







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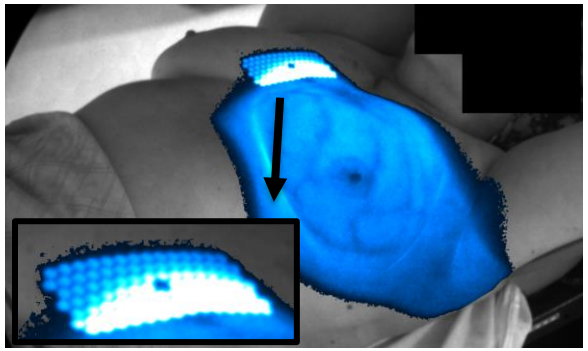
Conclusions

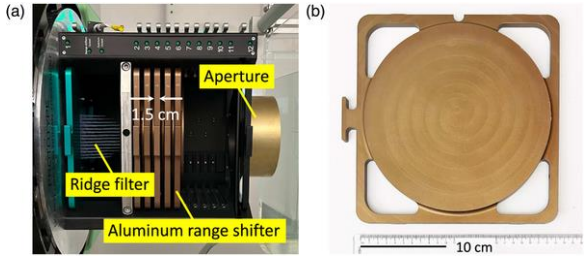
1. Novel dosimeter for *in vivo* application, capable of **real time monitoring** of radiation delivery under UHDR conditions
2. Surface dose maps were constructed from scintillation imaging with **<1ms temporal and 1mm spatial resolution**
3. Dynamic surface dose profiles were localized to the target CT and projected to construct **dose and PBS dose rate volumetric maps**

Future Directions

Conventional EBRT

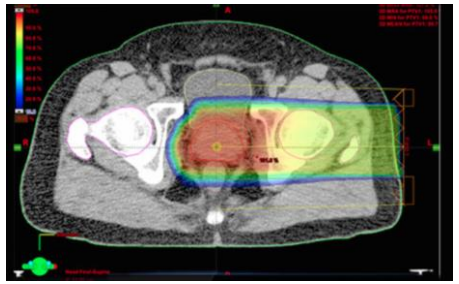


Conformal PBS FLASH

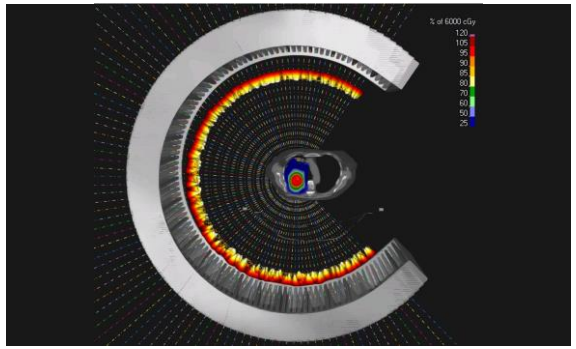


Chen et al. Med Phys DOI: 10.1002/mp.17050

Conventional PT



Proton Arc



Thank You!

DARTMOUTH

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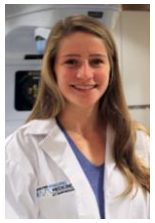

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EXTRA SLIDES