QUALITY ASSURANCE OF RADIOTHERAPY USING SCATTERED X-RAY

PROJECT UPDATE

TEAM 3
Students: Tatiana Kashtanova, Samuel Ydenberg

Mentors: Dr. Xun Jia, Dr. Lin Su (JHH)
Dr. Yujie Chi (UT Arlington); Dr. Youfang Lai, Dr. Xiaoyu Hu (JHH)

BACKGROUND

- **Radiation Therapy (RT):** maximum dose to the tumor, minimum dose to the normal tissue
- **Quality Assurance (QA)**[1,2]: the procedures ensuring the precise and safe dose delivery to the tumor while sparing the normal tissue and minimizing personnel exposure:

https://images.app.goo.gl/Y4493cVg6LhvWzEC7

Treatment planning
- Contour delineation
- Dose calculation

Treatment delivery
- Equipment calibration
- Patient positioning

Treatment delivery verification
- Simulations
- Physical measurements

Challenges[3]**:**
- Patient mispositioning
- Organ movements
- Anatomical morphological changes

→

Consequences[3]**:**
- Underdose
- Overdose

→

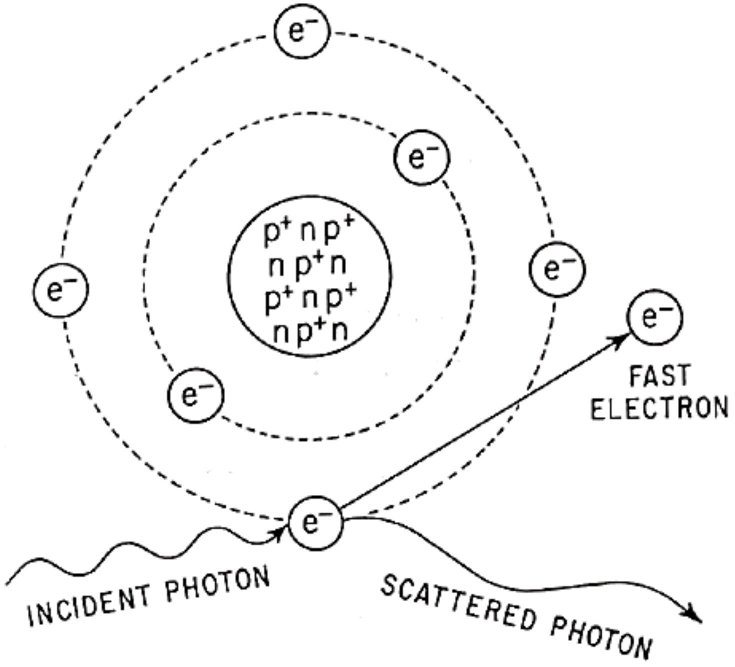
Current solutions[3]**:**
- IGRT, ART

Side effect:
Extra-dosage

1. World Health Organization. (1988). Quality Assurance in Radiotherapy: a Guide Prepared Following a Workshop Held at Schloss Reisensburg, Federal Republic of Germany, 3-7 December1984. Geneva.
2. Glide-Hurst, C.K., & Chetty, I.J. (2014). Improving radiotherapy planning, delivery accuracy, and normal tissue sparing using cutting edge technologies. *Journal of Thoracic Disease*, *6*(4), p.303–318.
3. Cunha, M., et al. (2013). Dose-free monitoring of radiotherapy treatments with scattered photons: Concept and simulation study. *IEEE Transactions on Nuclear Science, 60*(4), p. 3119-3126

Project Importance: A system for real time depth-dose verification without extra-dosage using scattered photons registration

Compton scattering



Hall, E.J. (2000). Radiobiology for the radiologist. 5th edition. Philadelphia, PA: Lippincott Williams & Wilkins

Monte Carlo Simulation

- Photon energy
- Photon position
- Photon momentum direction
- Material density

↓

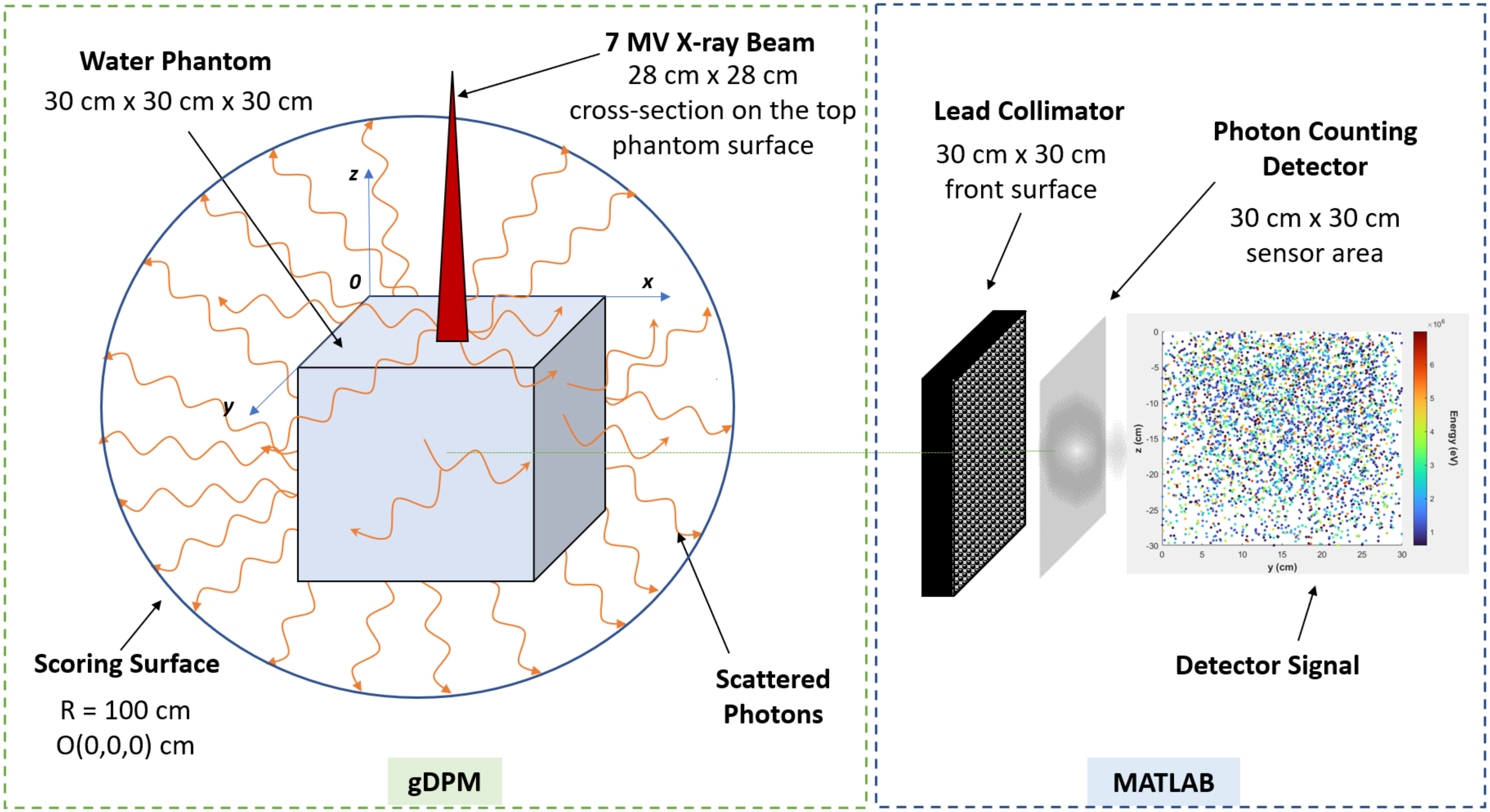
- Probabilities of different interactions
- Interaction type

↓

- Photon remaining energy
- Photon new position
- Photon new momentum direction

The Netherlands Commission on Radiation Dosimetry. (2006). Monte Carlo treatment planning. An introduction. Report 16

SYSTEM DESIGN



gDPM (Jia et al., 2011; Jia et al., 2014)

SYSTEM REQUIREMENTS AND FUNCTIONAL SPECIFICATIONS

System Objective: To infer on the delivered radiation dose deposition inside the phantom using information on the photons scattered outside of the phantom

Part I (gDPM)
MV x-ray transport through a phantom and scattered photons registration on a scoring sphere

Inputs:

- Phantom material and dimensions in cm
- Scoring sphere center coordinates and its radius in cm
- The number of simulated photons in the beam
- Beam cross-section on the top phantom surface in cm

Outputs:

- "PSFpos.dat" – photon position on the scoring sphere (x, y, z, r) in cm
- "PSFdir.dat" – photon direction (x, y, z) in cm and photon energy in eV
- "dose.img" – dose in Gy/particle deposited in each phantom voxel
- "dose.header“ – a coefficient for converting the phantom voxels used in "dose.img" to cm

SYSTEM REQUIREMENTS AND FUNCTIONAL SPECIFICATIONS

Part II (MATLAB)
Scattered photons transport from the scoring sphere to a photon counting detector and the relation of the detector signal to the delivered dose

Inputs:

- The outputs of Part I (gDPM)

Outputs:

- A plot with 2D detector signal (.png)
- Plots with the simulated dose and dose-correlated photon longitudinal profiles obtained with and without a collimator present (.png)
- The correlation coefficient between the dose and dose-correlated photon profiles to display on the above-mentioned plots

The system must achieve ≥ 0.9 correlation coefficient between the simulated dose and dose-correlated scattered photon profiles.

CHANGE IN DELIVERABLES & ACTIVITIES

Initial project deliverables

Minimum: Incorporation of the detector section into the gDPM package

Expected:
1. Detector performance verification
2. Depth dose profile simulation

Maximum: Simulated depth dose profile verification

The deliverables & activities got changed. See Wiki-page for details

KEY DATES, RESPONSIBILIES, & STATUS

<table>
<tr><td colspan="6">Minimum Deliverable: Modeling and simulation of scattered photons registration on a photon counting detector without a true collimator present</td></tr>
<tr><th colspan="2">Activities</th><th>Output</th><th>Deadline
Soft
(Hard)</th><th>Status</th><th>Responsible</th></tr>
<tr><td>1</td><td>Perform literature review & explore the gDPM package</td><td>Background reading report</td><td>02/20
(02/23)</td><td>Done on 02/17</td><td>Tatiana & Samuel</td></tr>
<tr><td>2</td><td>Compile the gDPM on our machine</td><td>Screenshot of a successful run of the gDPM package</td><td>02/24
(02/27)</td><td>Done on 02/21</td><td>Samuel</td></tr>
<tr><td>3</td><td>Model a photon counting detector
• Scoring sphere center and radius adjustment
• Detector sensor area geometry and position
• Photon transport to the detector sensor</td><td>A block diagram of the desired code structure</td><td>03/17
(03/19)</td><td>Done on 03/17</td><td rowspan="2">Tatiana</td></tr>
<tr><td>4</td><td>Program the photon counting detector based on the designed block diagram</td><td>MATLAB code with comments, a 2D detector signal, a plot with longitudinal dose and photon counts profiles</td><td>03/27
(03/29)</td><td>Done on 03/28</td></tr>
</table>

KEY DATES, RESPONSIBILIES, & STATUS

Expected Deliverable #1: Modeling and simulation of scattered photons registration on a photon counting detector in the presence of a collimator

	Activities	Output	Deadline Soft (Hard)	Status	Responsible
1	Model a collimator • Collimator geometry • Photon transport through the collimator to the detector sensor	A block diagram of the desired code structure	03/20 (03/22)	Done on 03/20	Samuel & Tatiana
2	Program the collimator based on the designed block diagram	MATLAB code with comments, a 2D detector signal, a plot with longitudinal dose and photon counts profiles	04/05 (04/07)	Done on 04/06	Samuel

KEY DATES, RESPONSIBILIES, & STATUS

Expected Deliverable #2: Modeling and programming of dose-correlated photon depth profile

	Activities	Output	Deadline Soft (Hard)	Status	Responsible
1	Increase the input data for MATLAB system	gDPM output files of a smaller size but containing more useful information	04/12 (04/14)	In progress	Samuel
2	Reduce phantom dimensions and place the detector right next to the phantom	Phantom definition file (C code with comments), MATLAB code with comments for the detector placement	04/12 (04/14)	In progress	Tatiana
3	Find the best relationship between the detector signal and the delivered dose considering • Photon counts • Photon counts per delivered dose (Cunha et al., 2013) • Other mathematical expressions	MATLAB code with comments on the used mathematical expressions, a plot with dose and dose-correlated photon longitudinal profiles	04/18 (04/20)	In progress	Tatiana & Samuel
4	Analyze the correlation between the simulated dose profile and the processed profiles of scattered photons	Analysis report in PDF	04/18 (04/20)	Not started	Tatiana

KEY DATES, RESPONSIBILIES, & STATUS

<table>
<tr><th colspan="6">Expected Deliverable #3: Project documentation</th></tr>
<tr><th colspan="2">Activities</th><th>Output</th><th>Deadline
Soft (Hard)</th><th>Status</th><th>Responsible</th></tr>
<tr><td>1</td><td>System design</td><td>PDF document</td><td>03/07
(03/10)</td><td>Done on 03/10</td><td rowspan="2">Tatiana</td></tr>
<tr><td>2</td><td>System requirements and functional specifications</td><td>PDF document</td><td>03/07
(03/10)</td><td>Done on 03/10</td></tr>
<tr><td>3</td><td>System testing</td><td>PDF document</td><td>04/28
(05/10)</td><td>Done for the current version on 04/10</td><td>Samuel</td></tr>
<tr><td>4</td><td>Project code</td><td>Link to GitHub project</td><td>04/28
(05/10)</td><td>Done for the current version on 04/10</td><td rowspan="2">Tatiana & Samuel (by written functions)</td></tr>
<tr><td>5</td><td>Project report
• Mathematics/Physics
• Algorithmic steps
• Program structure
• Program testing
• Results
• Discussion
• Conclusion</td><td>PDF document</td><td>04/28
(05/10)</td><td>Not started</td></tr>
<tr><td>6</td><td>Project poster</td><td>PDF document</td><td>04/28
(05/10)</td><td>Not started</td><td>Tatiana & Samuel</td></tr>
</table>

KEY DATES, RESPONSIBILIES, & STATUS

Maximum Deliverable #1: Depth-dose profile retrieval in heterogeneous phantoms using scattered photons					
	Activities	**Output (Wiki-page)**	**Deadline Soft (Hard)**	**Status**	**Responsible**
1	Design two heterogeneous phantoms • A water phantom with a bone inside • A water phantom with a bone and an air cavity inside	Phantoms' diagrams, phantoms' definition files (C codes with comments)	04/18 (04/20)	Not started	Samuel
2	Run the MATLAB detector codes (with and without a collimator) with the integrated detector signal - dose relationship using the gDPM output files obtained with the constructed phantom definition files as inputs	Plots with dose and dose-correlated photon longitudinal profiles	04/20 (04/21)	Not started	Tatiana
3	Analyze the correlation between the simulated dose profiles and the obtained profiles of scattered photons	Analysis report in PDF	04/20 (04/21)	Not started	

KEY DATES, RESPONSIBILIES, & STATUS

Maximum Deliverable #2: Comparison of the simulated system results with physical measurements					
Activities		**Output**	**Deadline Soft (Hard)**	**Status**	**Responsible**
1	Adjust the simulation to match the setup of the prospective MV x-ray physical experiments following the mentor's guidance	C and MATLAB codes with comments	04/24 (04/25)	Not started	Samuel
2	Compare the simulation and experimental data	MATLAB code with comments and data visualizations Analysis report in PDF	04/25 (04/27)	Not started	Tatiana

DEPENDENCIES

Need	Dependencies	Source	Responsible	Deadline Soft (Hard)	Status	Contingency Plan
The gDPM compilation	The gDPM simulation package	Dr. Youfang Lai, Dr. Yujie Chi	Dr. Lin Su	02/10 (02/13)	Done on 02/09	NA
	The gDPM compilation	Google Colab	Samuel	02/13 (02/15)	Done on 02/13	NA
Photon counting detector modeling	Phase Space File (photon registration on the spherical surface)	Dr. Yujie Chi	Dr. Lin Su	02/15 (02/27)	Done on 02/26	NA
Comparison of the simulated system results with physical measurements	Physical measurements	Dr. Xun Jia, Dr. Lin Su		04/20 (04/24)	Not started	Do not do the corresponding maximum deliverable

MANAGEMENT

Tatiana and Samuel:

- Individual assigned work, upload to the OneDrive Shared folder/GitHub
- Meetings on Monday and Wednesday for 1-2 hours via Zoom or at JHU

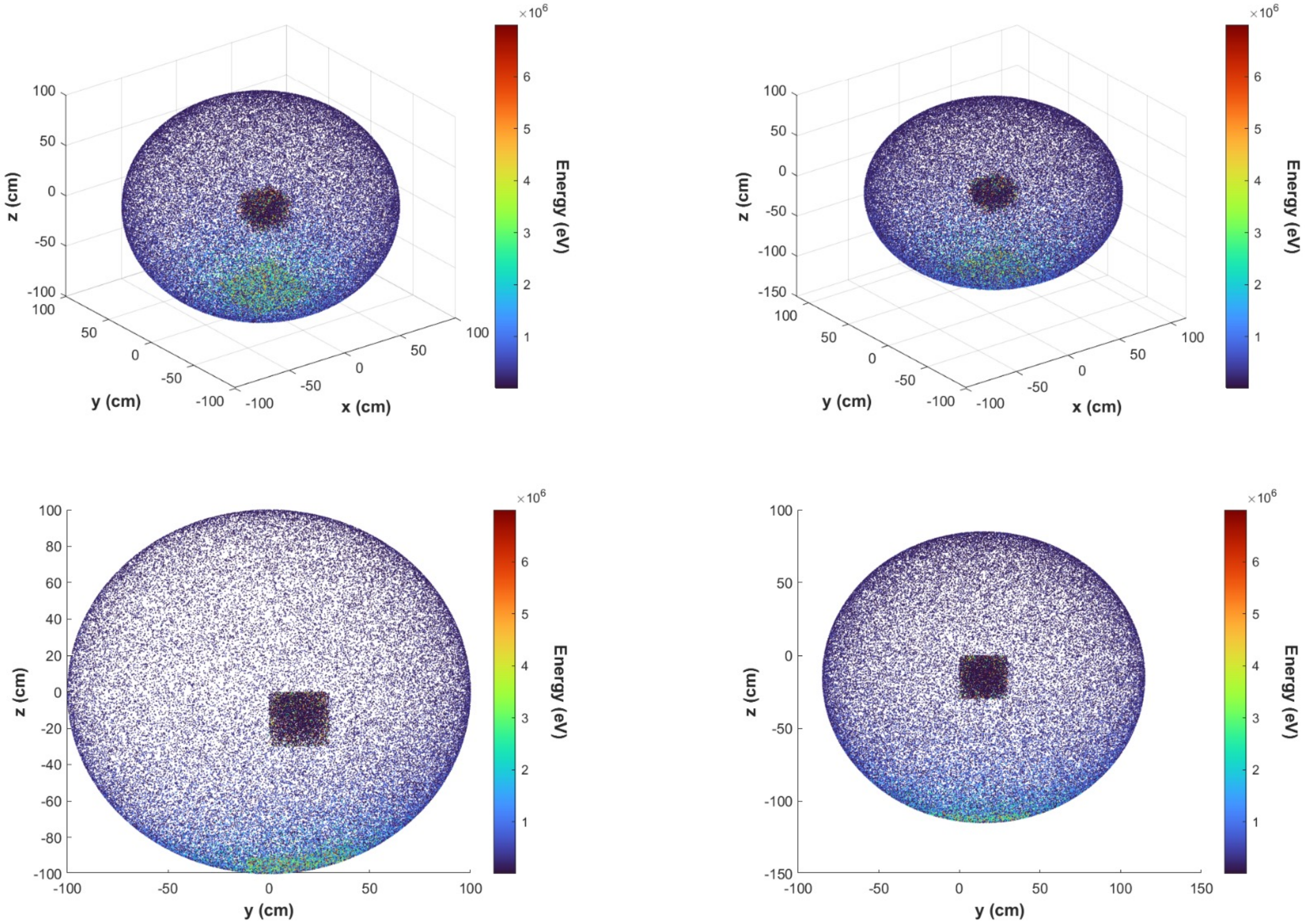
Communication with mentors (weekly):

- Correspondence via JHU email and Microsoft Teams group chat
- Meetings via Microsoft Teams on Tuesdays

PROJECT PROGRESS
1. System set-up

Scoring Sphere Center

Original Center
(0,0,0) cm



Shifted Center

(15,15,15) cm
in gDPM system

(15,15,-15) cm
in MATLAB system

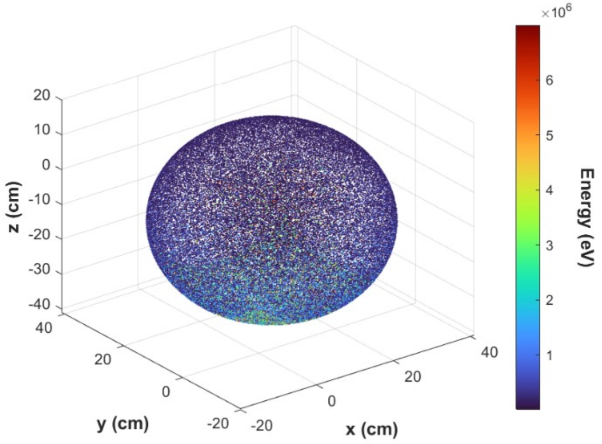
PROJECT PROGRESS
1. System set-up

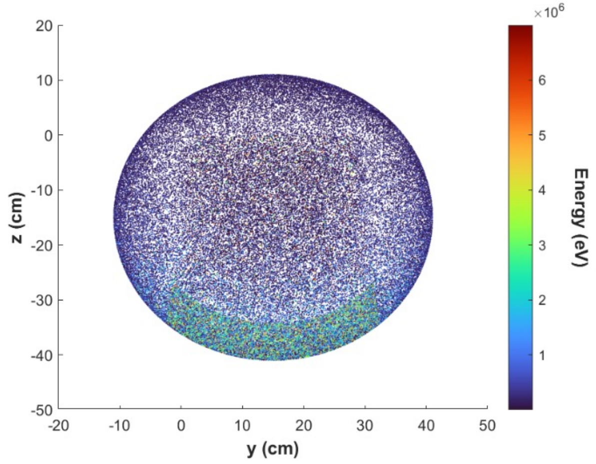
Scoring Sphere Radius

- The phantom side length: 30 cm
- The circumscribed sphere radius:

$$\frac{\sqrt{3}\cdot 30}{2} = 25.98\ cm$$

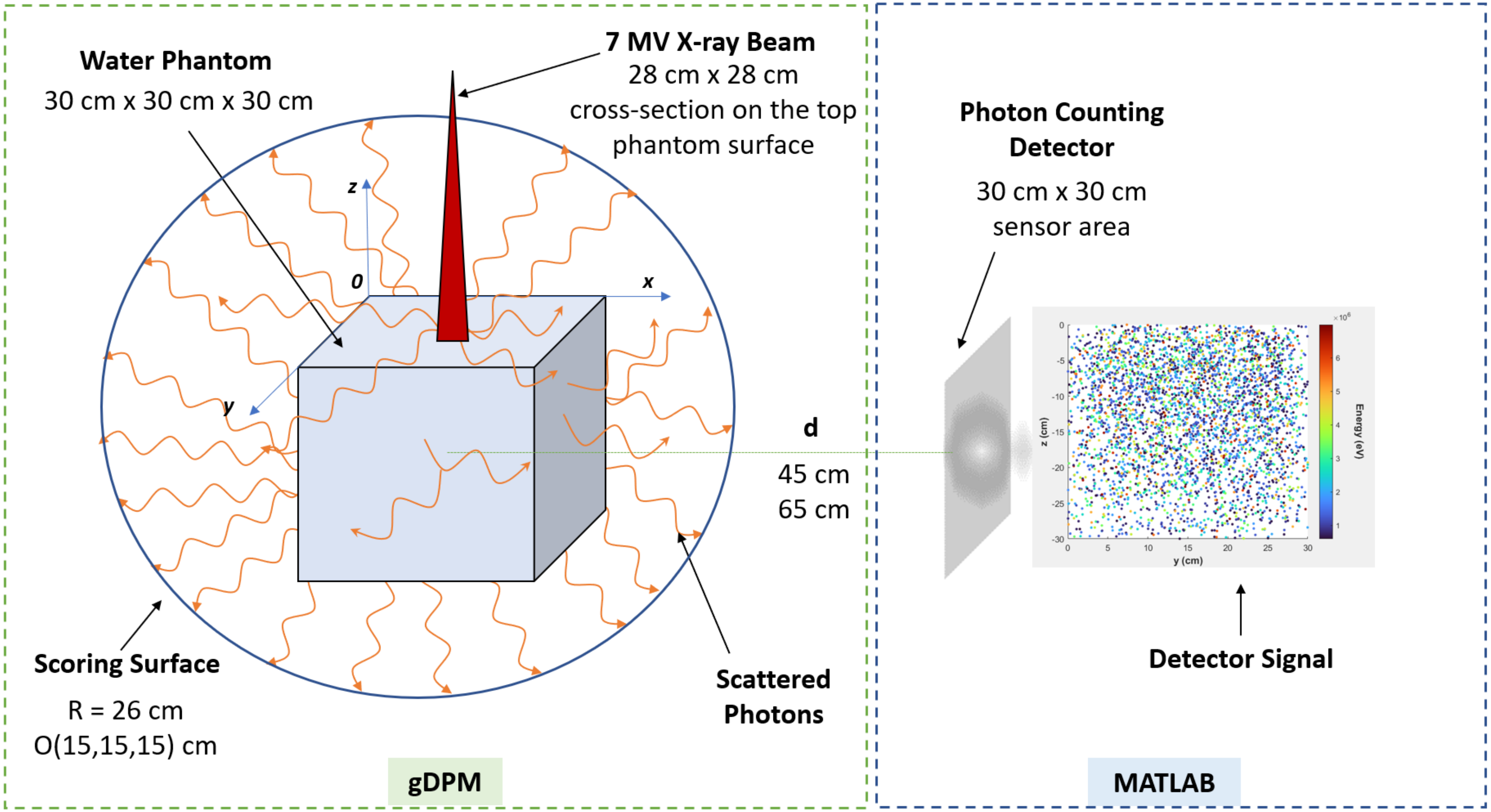
- Scoring sphere radius: 26 cm





PROJECT PROGRESS

2. Photon Counting Detector (no collimator)



PROJECT PROGRESS
2. Photon Counting Detector (no collimator)

Photon Transport

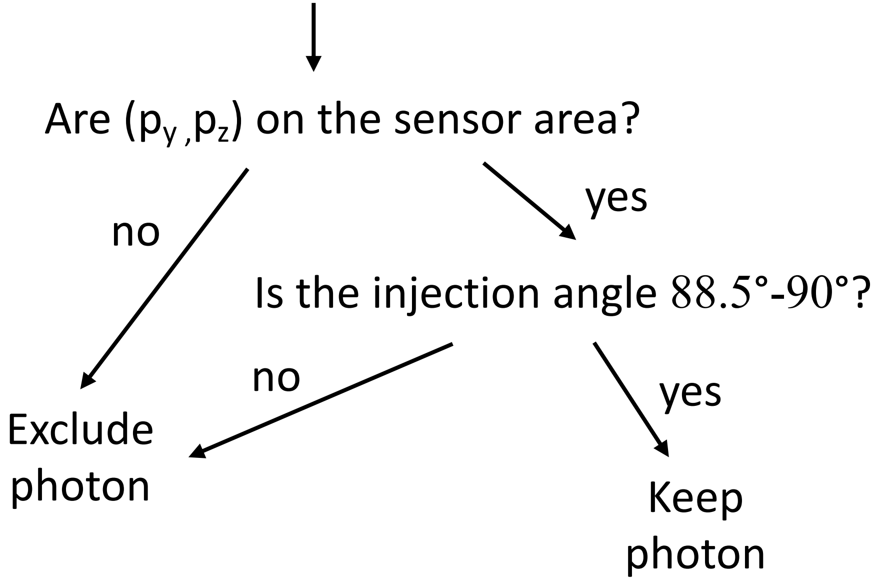
Action	# Photons on the scoring sphere
Run gDPM with 10^8 histories	104,302,756
Keep photons which left the phantom (radius ≥25.98 cm)	90,267,708
Keep photons that collided with the sensor area at approximately right angle	9,861
Energy threshold ≥ 100 keV	7,791

Parametric representation of photon trajectory

$p_x = pos_x + \mathbf{t}*dir_x = dx$

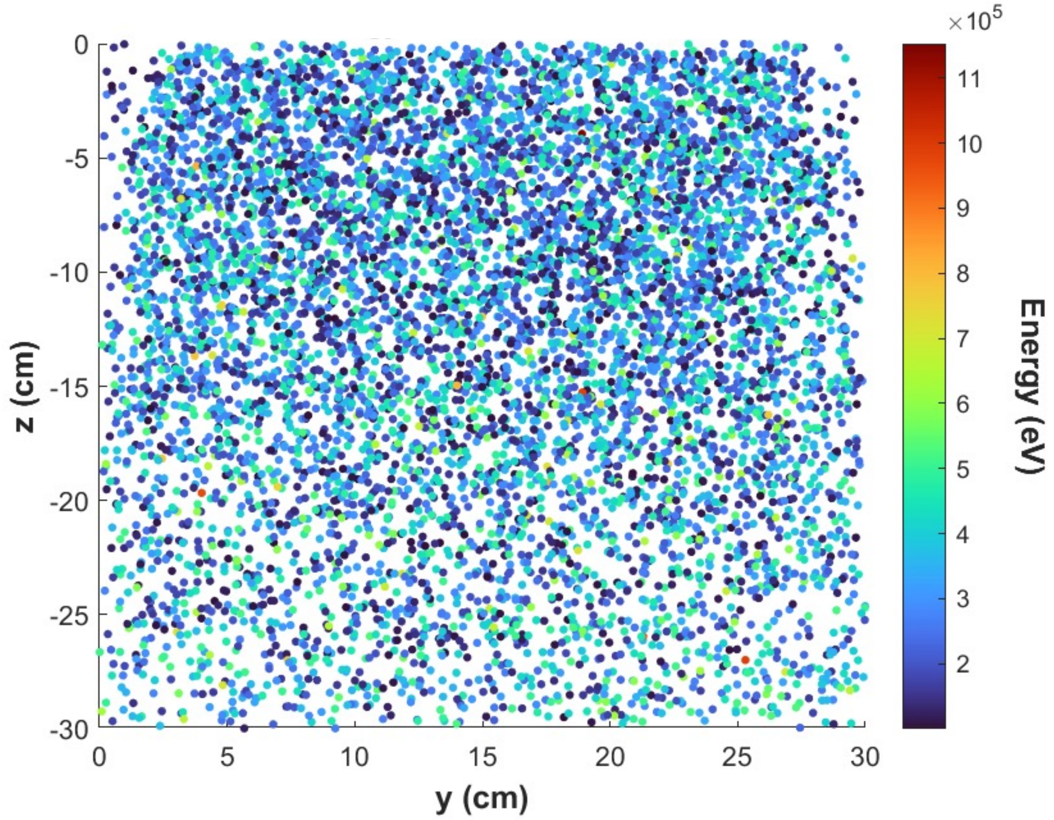
$p_y = pos_y + t*dir_y$

$p_z = pos_z + t*dir_z$

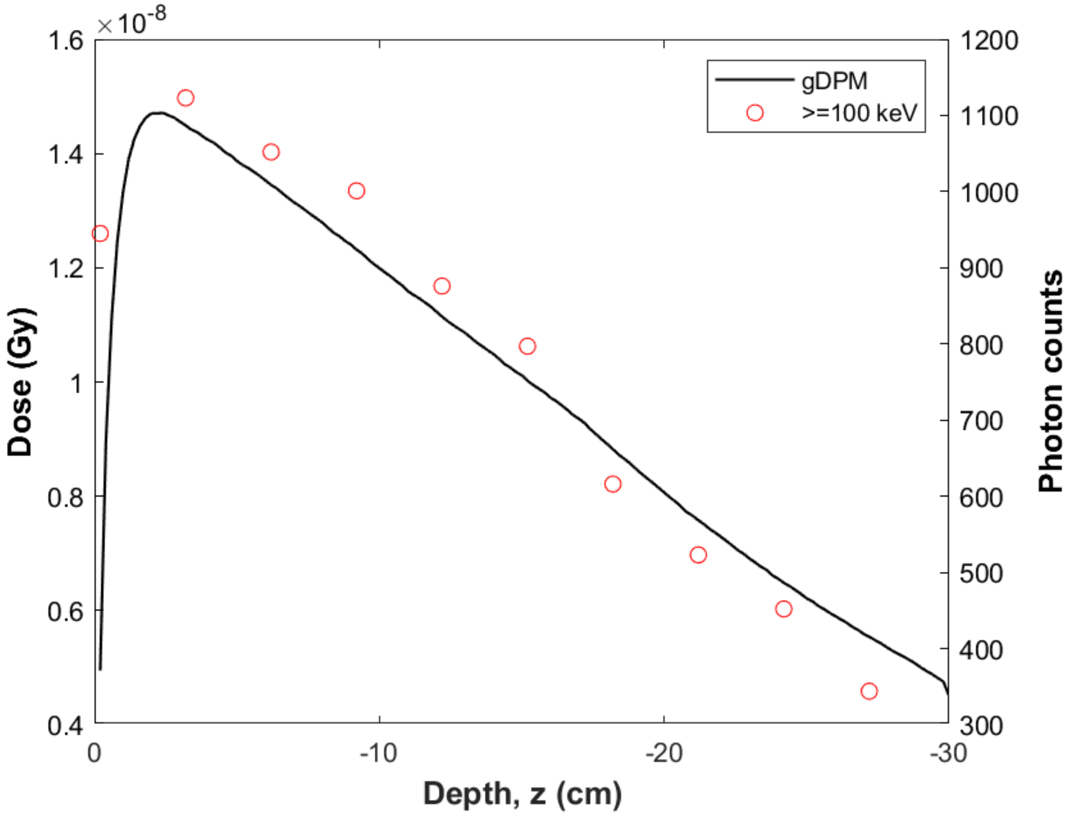


PROJECT PROGRESS
2. Photon Counting Detector (no collimator)

Nominal photon energy ≥ 100 keV; Distance between the phantom and the detector 45 cm



2D Detector Signal



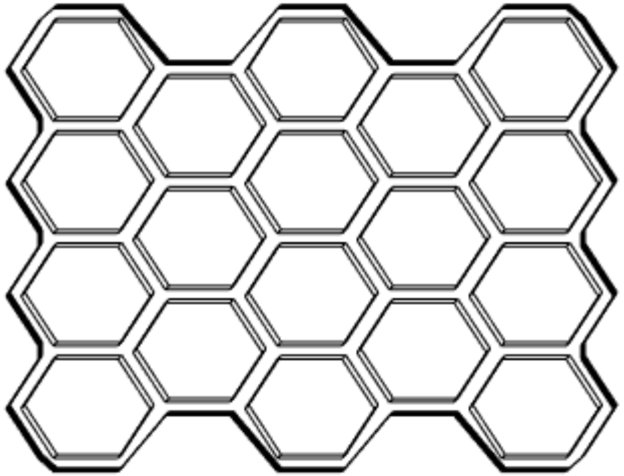
Longitudinal dose and photon counts profiles

PROJECT PROGRESS
3. Photon Counting Detector (with a collimator)

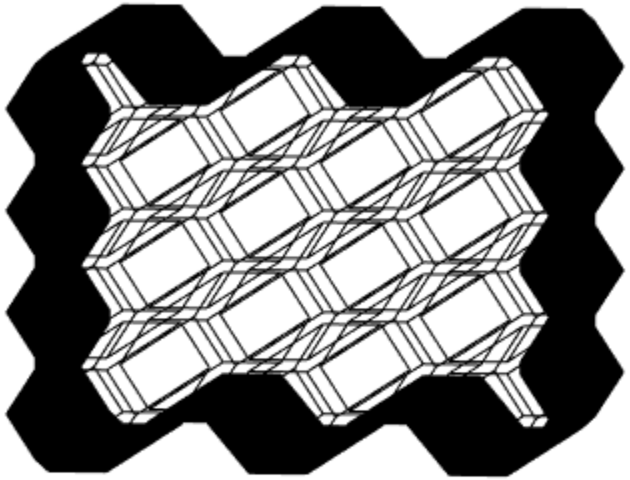
Collimator Geometry

- Multi-hole collimator with hexagonal holes

- Collimator front surface: 30 cm x 30 cm
- Collimator thickness: 3.5 cm
- F2F distance: 1.5 mm
- Septa thickness: 0.2 mm



Modelled collimator
front view



Modelled collimator
depth view

PROJECT PROGRESS
3. Photon Counting Detector (with a collimator)

Photon Transport

For 100 keV*:

Mass-attenuation coefficient: $\frac{\mu}{\rho} = 5.461\ [cm^2/g]$

Lead density: $\rho = 11.36\ [g/cm^3]$

Attenuation coefficient: $\mu = 62.04\ [1/cm]$

Half-value layer: $\text{HVL} = \frac{\ln(2)}{\mu} = 0.01\ cm$

For 800 keV*:

Mass-attenuation coefficient: $\frac{\mu}{\rho} = 0.0872\ [cm^2/g]$

Lead density: $\rho = 11.36\ [g/cm^3]$

Attenuation coefficient: $\mu = 0.99\ [1/cm]$

Half-value layer: $\text{HVL} = \frac{\ln(2)}{\mu} = 0.7\ cm$

*Johns, H.E. & Cunningham, J.R.(1983). The Physics of Radiology, 4th Edition, Table A-4i. Radiological Properties of Lead, p. 736

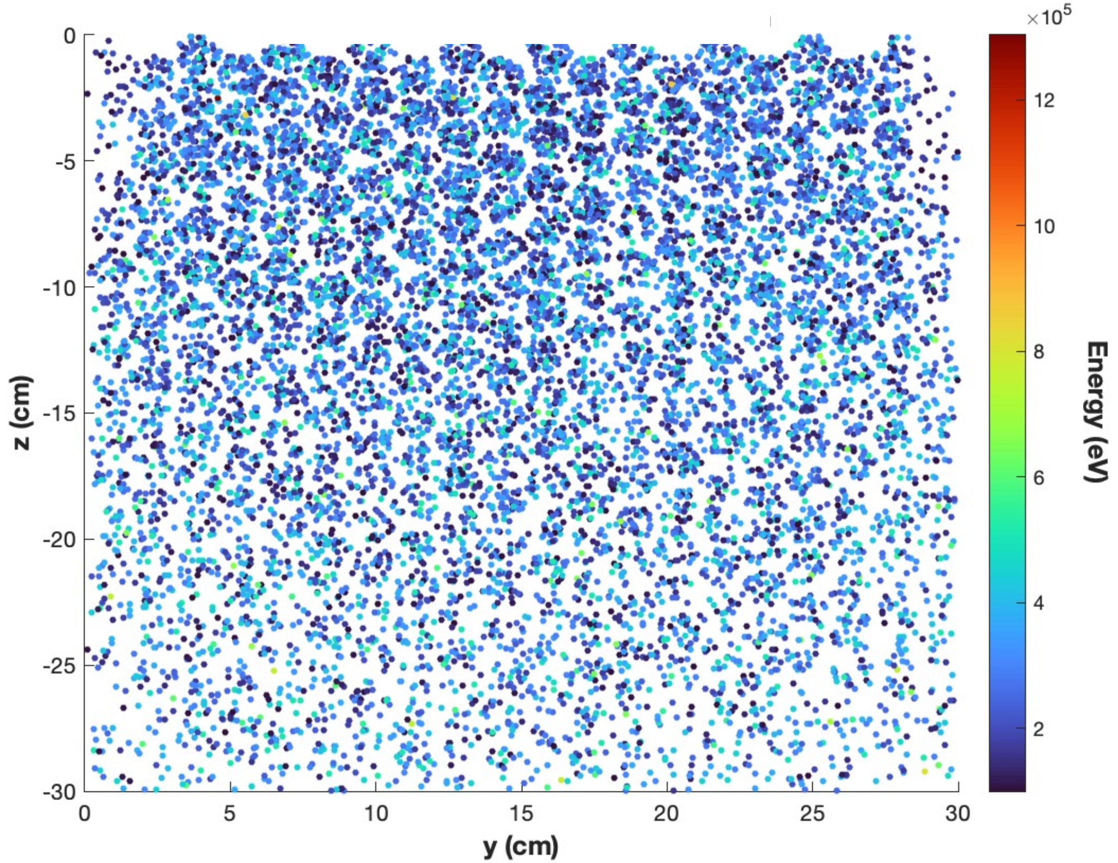
Strategy:

- Keep photons passed through the holes
- Exclude photons collided with the septa material on the collimator face side or inside the holes

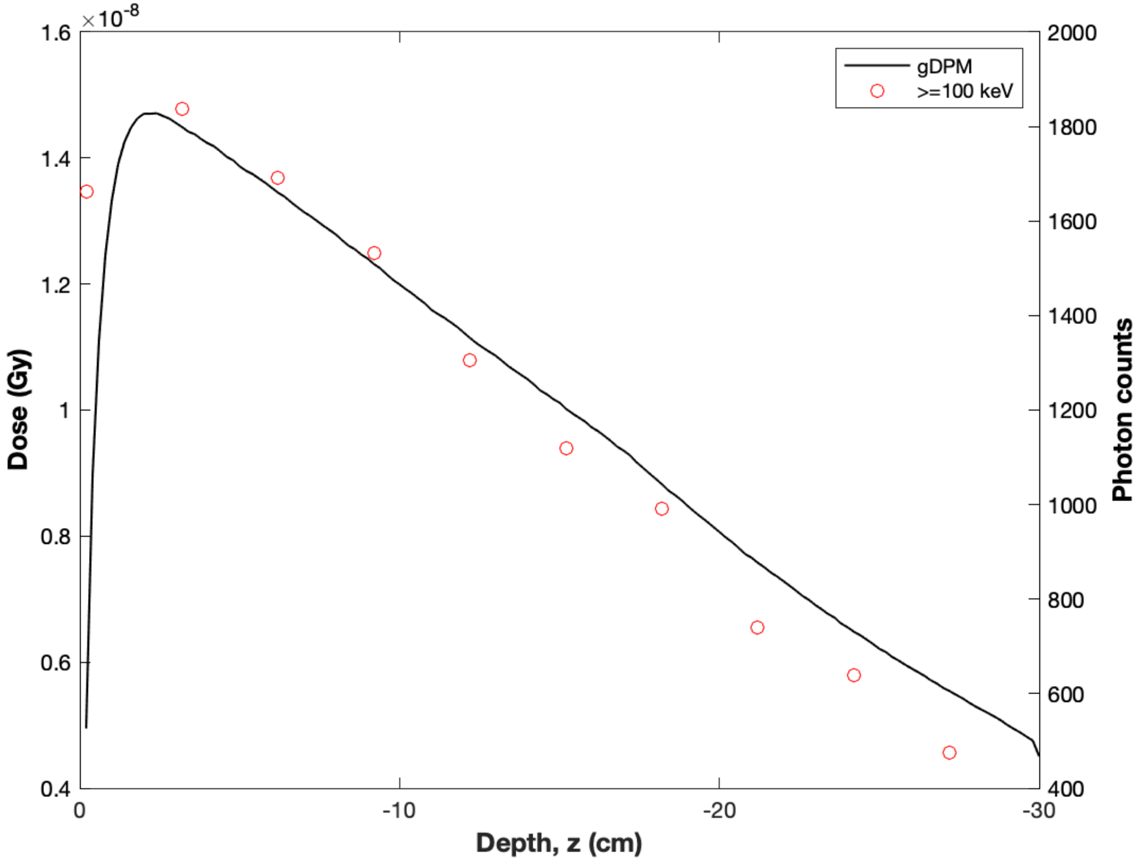
PROJECT PROGRESS

3. Photon Counting Detector (with a collimator)

Nominal photon energy ≥ 100 keV; Distance between the phantom and the detector 45 cm



2D Detector Signal

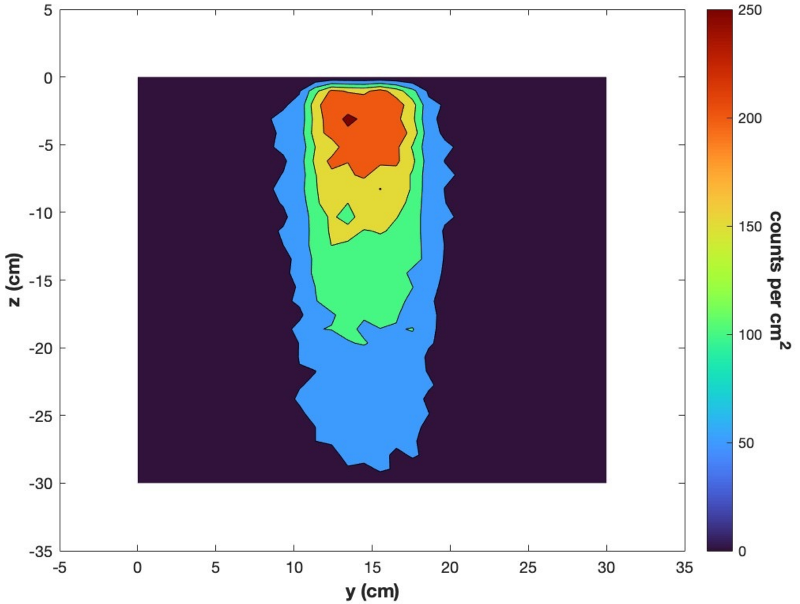


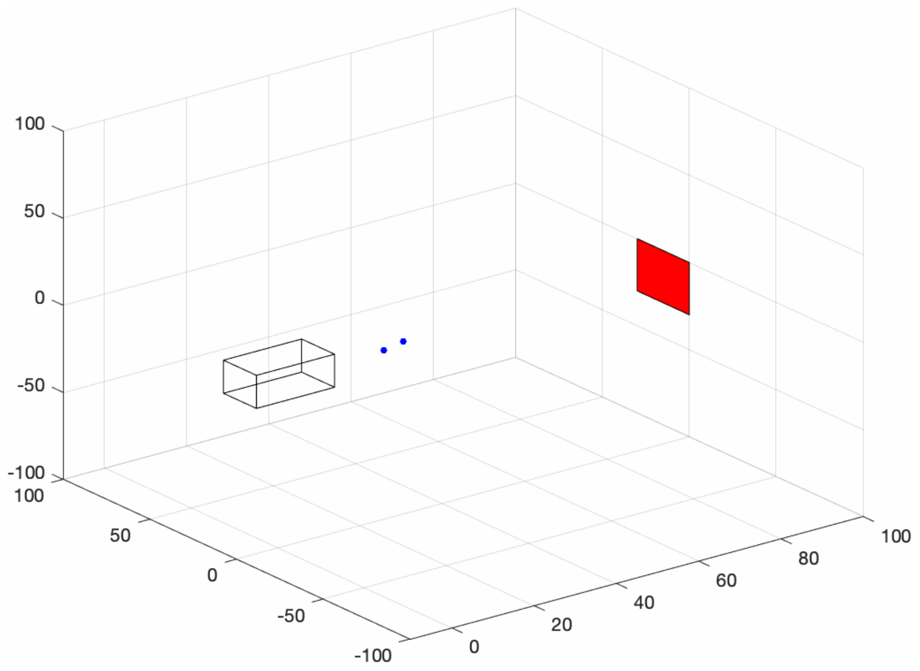
Longitudinal dose and photon counts profiles

PROJECT PROGRESS
4. System testing

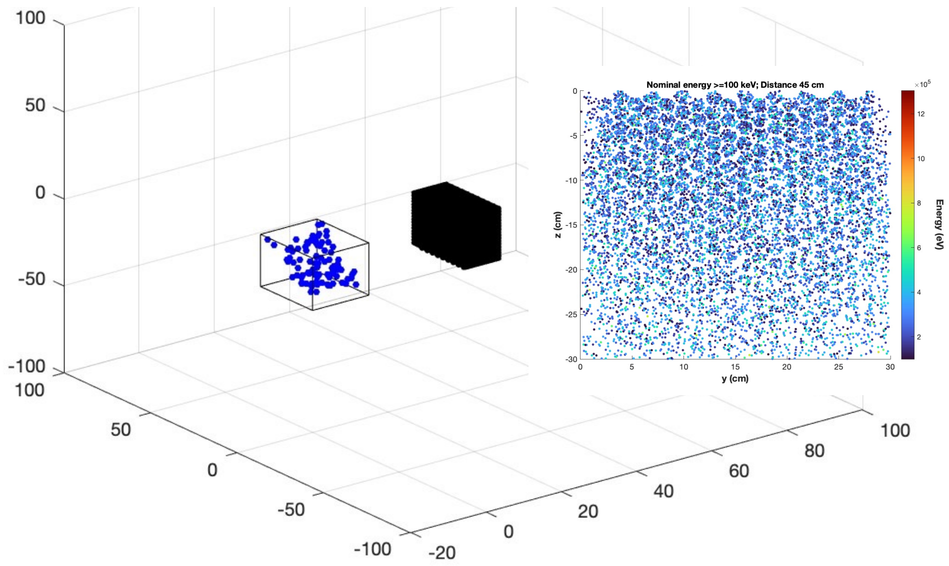
- Unit testing to verify code functions via static data visualizations and animations
- Full system verification

Heatmap of 7x7 beam





Animation of photons interacting with detector



Experiment Setup with Sensor signal output

PROJECT PROGRESS
5. Documentation

Project Code*
GitHub: https://github.com/samydenberg/RQA_Simulation

**Headers, Inputs and Outputs, Comments*
** Instructions, README*

- **System Design**
- **System Requirements and Functional Specifications**
- **System Testing**

See Wiki-page for details

REFERENCES

1. World Health Organization. (1988). Quality Assurance in Radiotherapy: a Guide Prepared Following a Workshop Held at Schloss Reisensburg, Federal Republic of Germany, 3-7 December1984. Geneva.
2. Glide-Hurst, C.K., & Chetty, I.J. (2014). Improving radiotherapy planning, delivery accuracy, and normal tissue sparing using cutting edge technologies. *Journal of Thoracic Disease*, *6*(4), p.303–318.
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4. Hall, E.J. (2000). Radiobiology for the radiologist. 5th edition. Philadelphia, PA: Lippincott Williams & Wilkins.
5. The Netherlands Commission on Radiation Dosimetry. (2006). Monte Carlo treatment planning. An introduction. Report 16.
6. Jia, X. & Jiang, S.B. (2011). gDPM v2.0. A GPU-based Monte Carlo simulation package for radiotherapy dose calculation. The Center for Advanced Radiotherapy Technologies (CART), UCSD.
7. Jia, X., Ziegenhein, P., & Jiang, S. B. (2014). GPU-based high-performance computing for radiation therapy. Physics in Medicine and Biology, 59(4), p. R151–R182.
8. Johns, H.E. & Cunningham, J.R.(1983). The Physics of Radiology, 4th Edition, Table A-4i. Radiological Properties of Lead, p. 736