ProtonVDA

TRANSFORMING PROTON THERAPY

Experimental Results from a Prototype Clinical Proton Imaging System

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Proton Imaging can help reduce range uncertainties by directly measuring proton stopping power

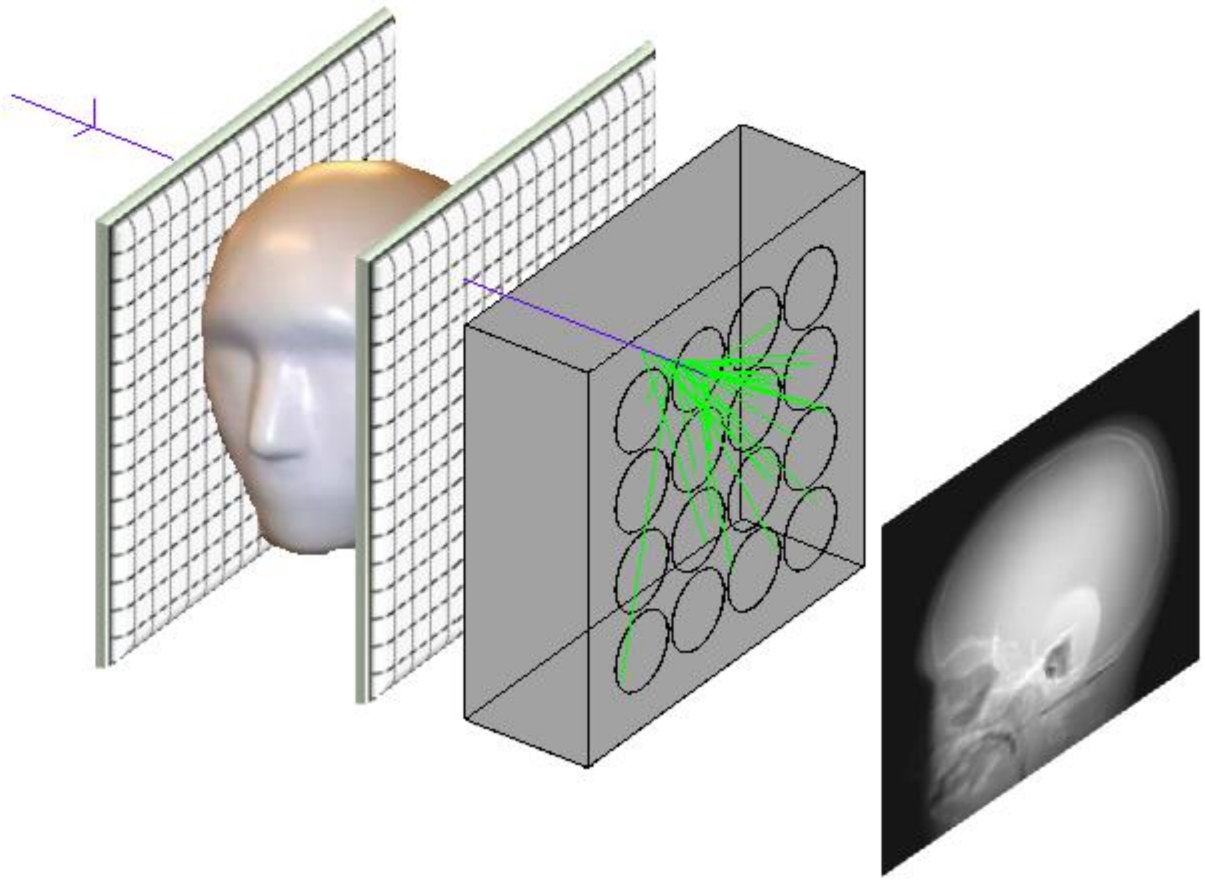
We aim to:

Develop a proton imaging system based on well-established fast scintillator technology.

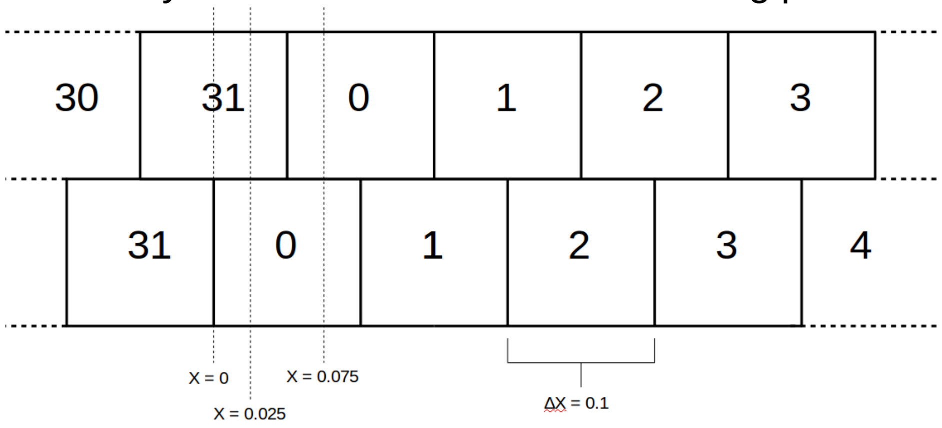
1. $\rightarrow$ High-performance, low-cost measurements of proton range.
2. Achieve lower dose to the patient relative to equivalent x-ray images.
3. Produce spatially sharp images.
4. Images free of artifacts from high-Z implants.

Multidisciplinary team of detector physicists, medical physicists, computer scientists, and radiation oncologists:

- ProtonVDA: Fritz DeJongh, Ethan DeJongh, Victor Rykalin, Igor Polnyi
- Loyola Stritch School of Medicine: James Welsh
- Northwestern Medicine Chicago Proton Center: Mark Pankuch
- Northern Illinois University, Dept. of Computer Science: Nick Karonis, Cesar Ordonez, John Winans, Kirk Duffin. Dept. of Physics: George Coutrakon, Christina Sarosiek
- Loma Linda University: Reinhard Schulte



Fiber layout cross-section for one tracking plane:

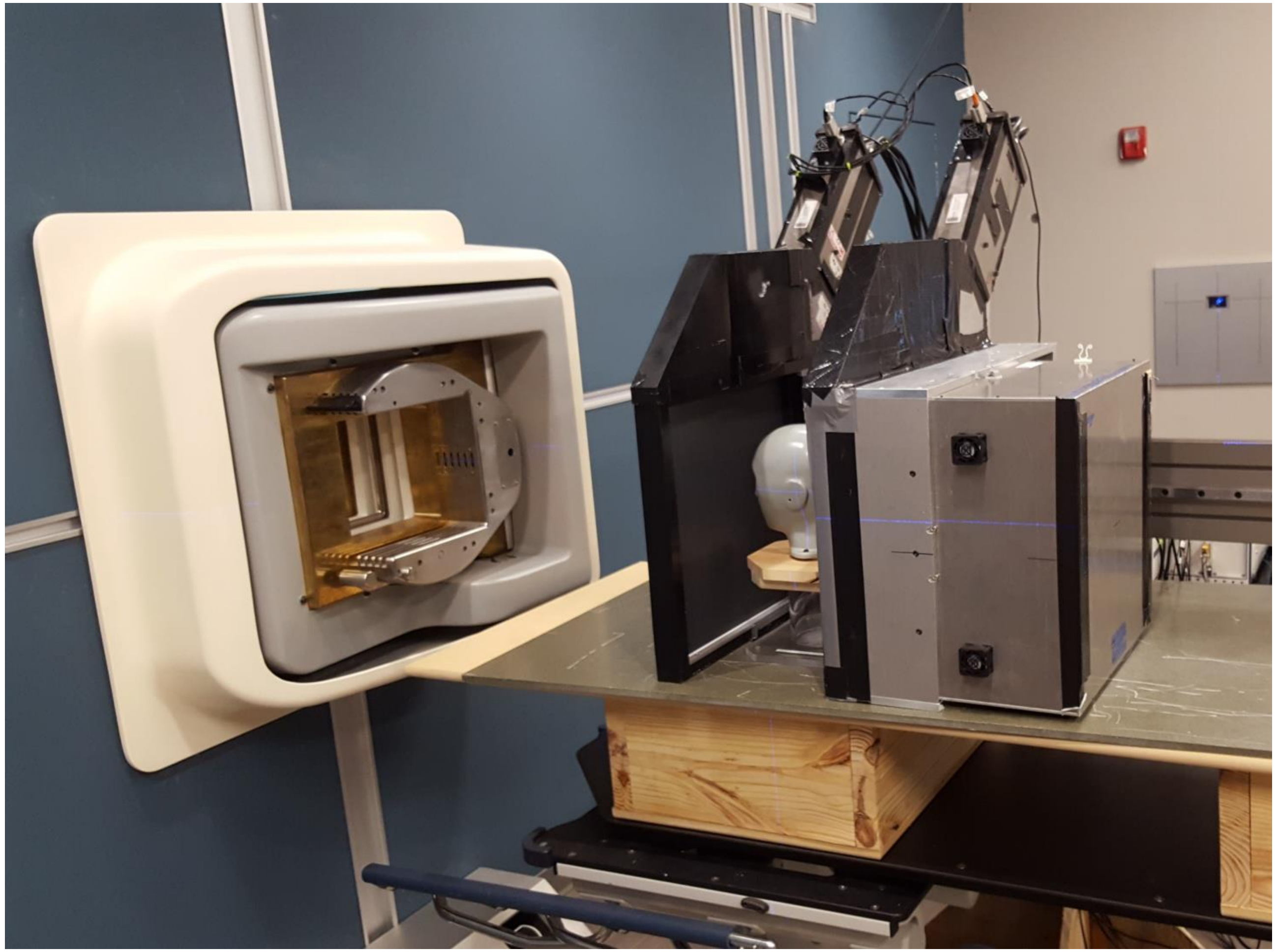


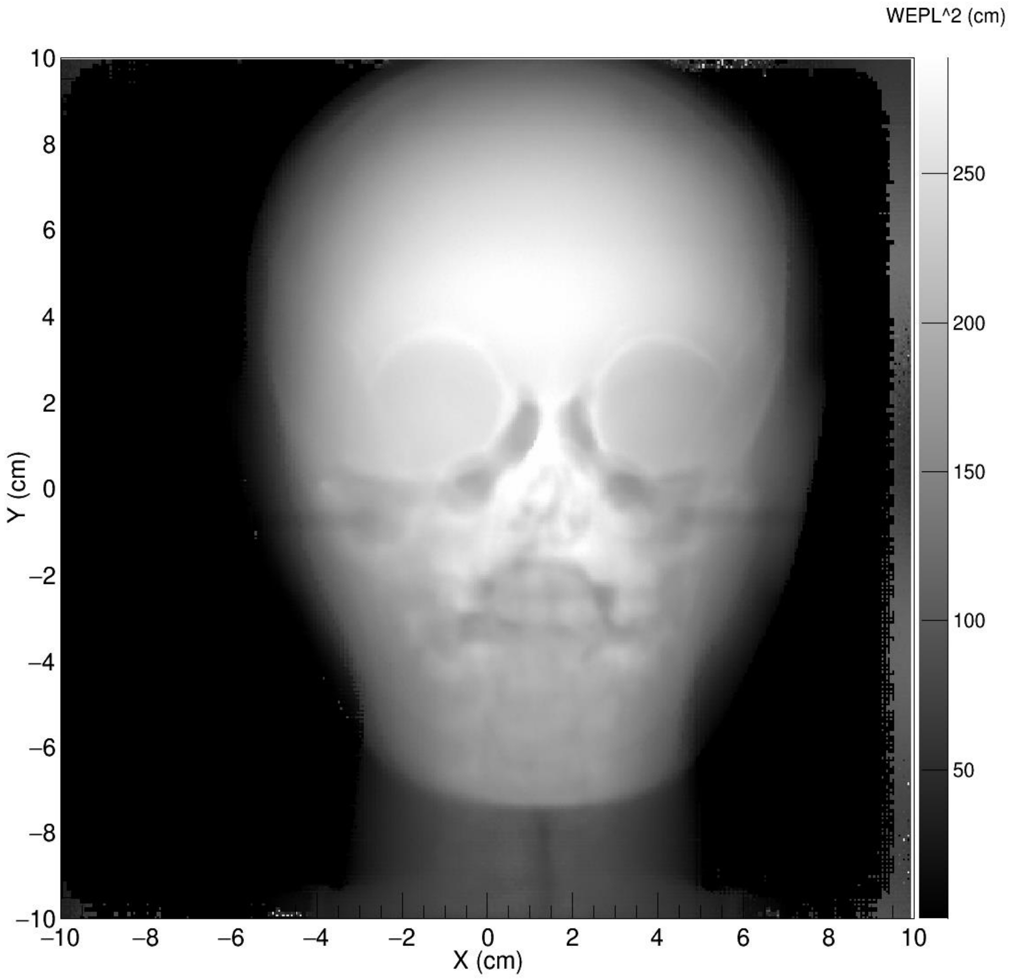
- X-Y tracking planes upstream and downstream

- Multiplexed fiber readout
  - 32 digitized channels per tracking plane
  - position ambiguities resolved using pencil beam targeting information
  - reduces amount of electronics needed

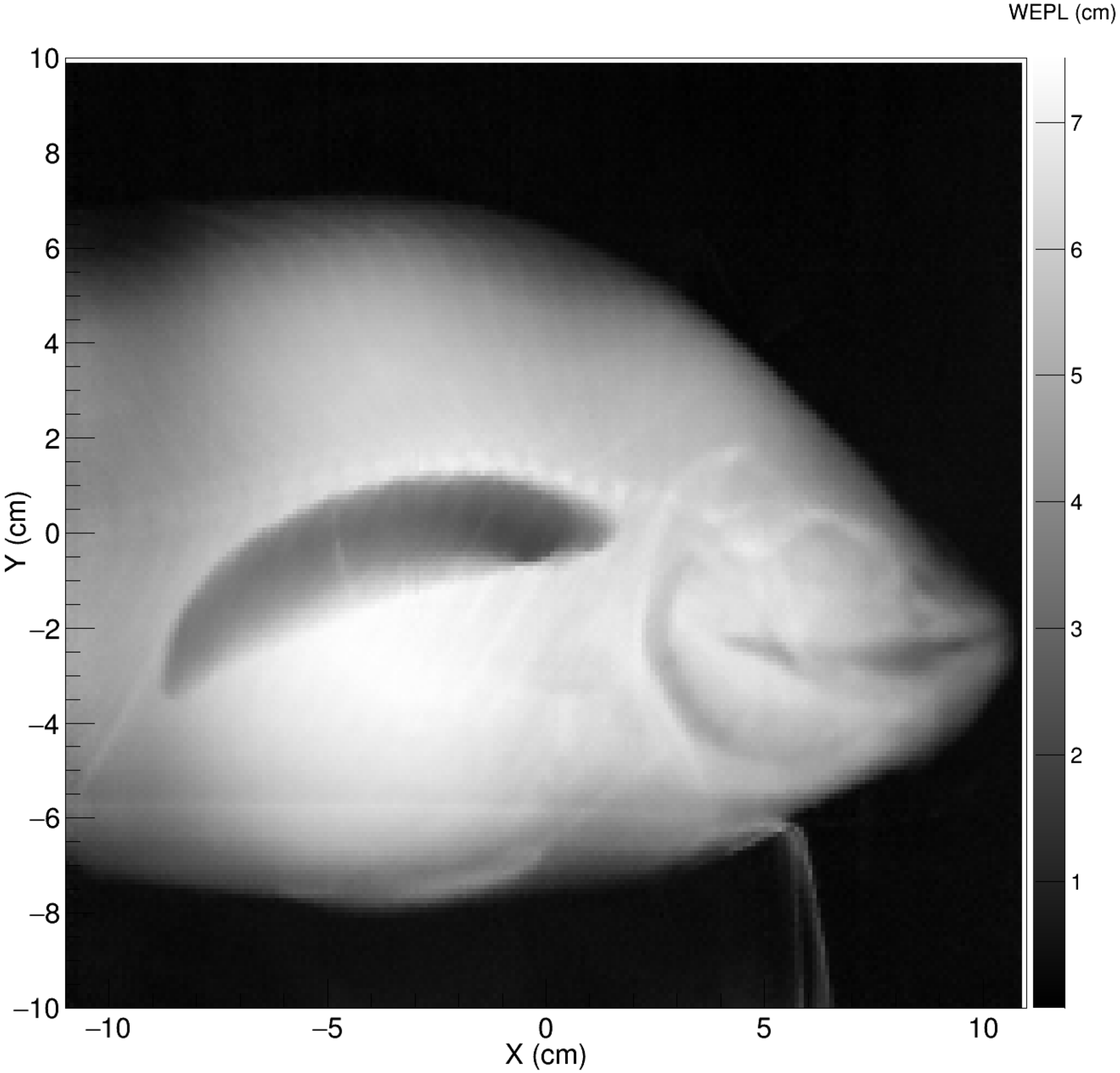
- 40 x 40 x 13 cm block of scintillator for range detector
  - 4 x 4 array of PMTs
  - Output digitized into four channels: E, U, V,C

- Individual protons tracked at up 10 MHz
- > 99% tracking efficiency
- WEPL resolution ~ 3 mm per proton
- 40 x 40 cm image field size
- Fast (<1 min) image reconstruction for radiograph



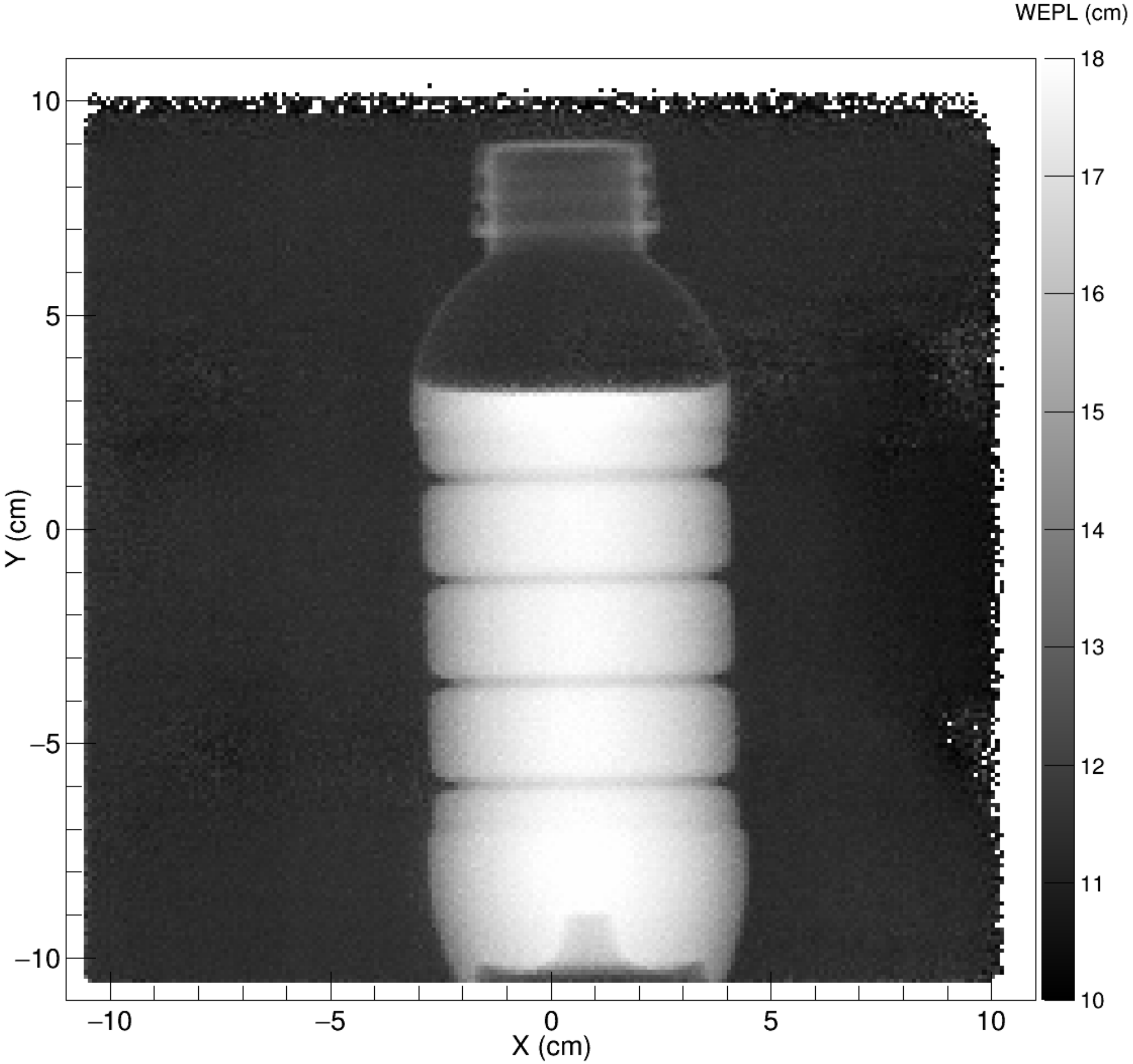

WEPL^2 (cm)
250
200
150
100
50
Y (cm)
10
8
6
4
2
0
−2
−4
−6
−8
−10
X (cm)
−10
−8
−6
−4
−2
0
2
4
6
8
10

Frozen fish image – 120 MeV

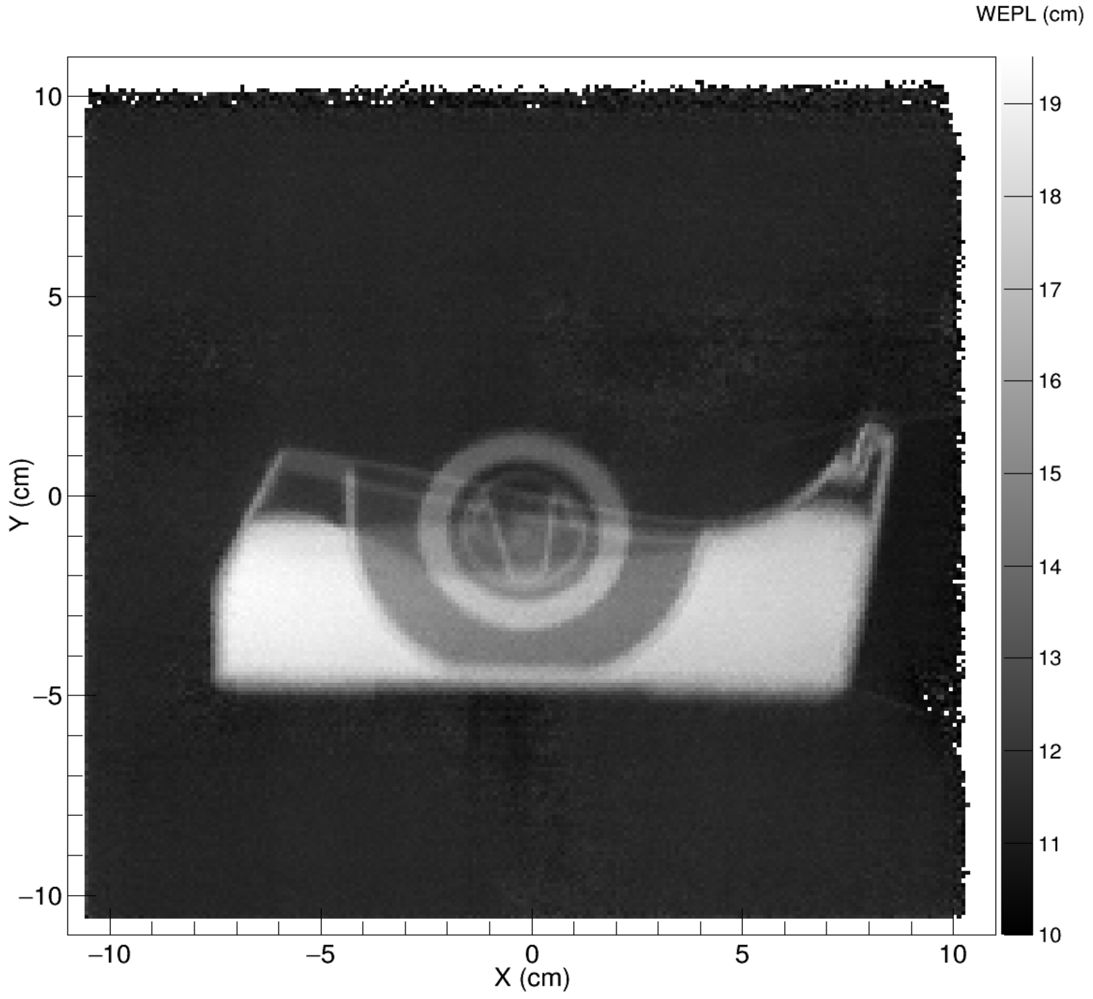


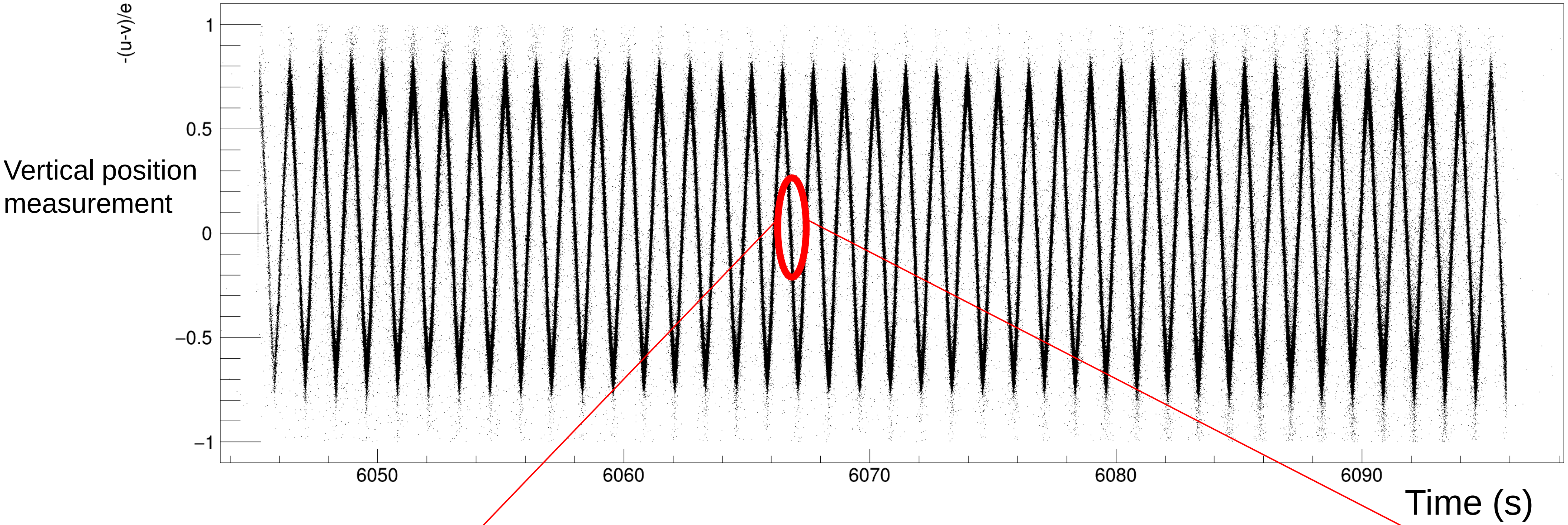
Fast (~ 1 min) online image reconstruction

Water bottle plus solid water – 180 MeV



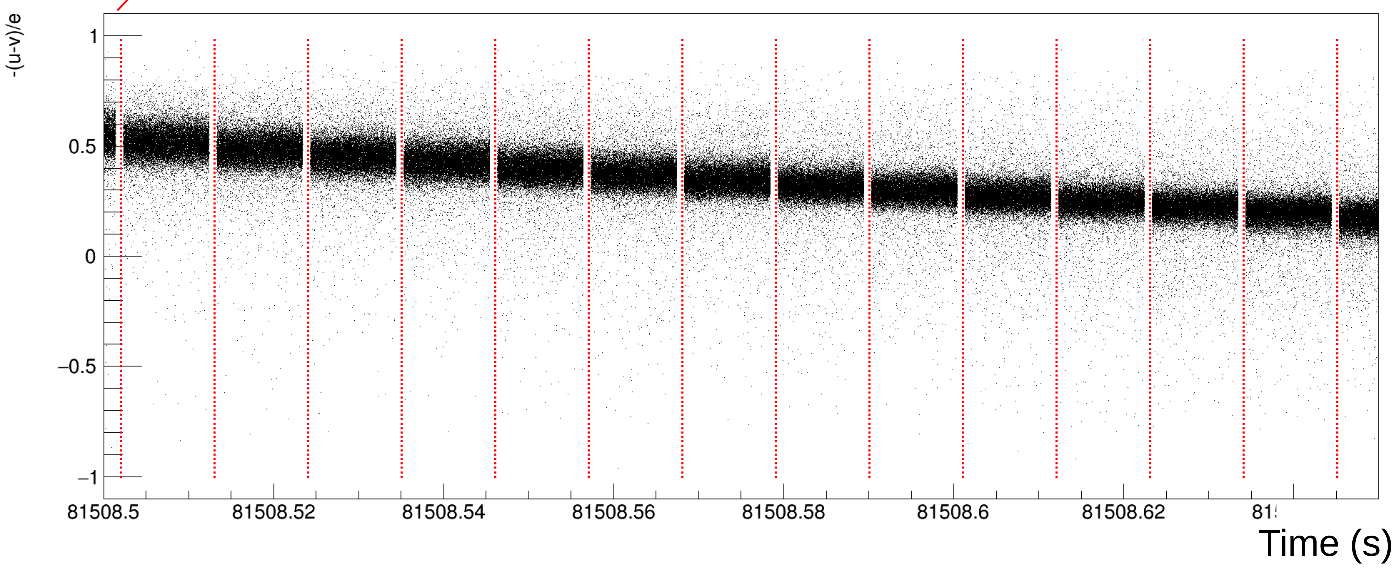
Tape dispenser plus solid water – 180 MeV

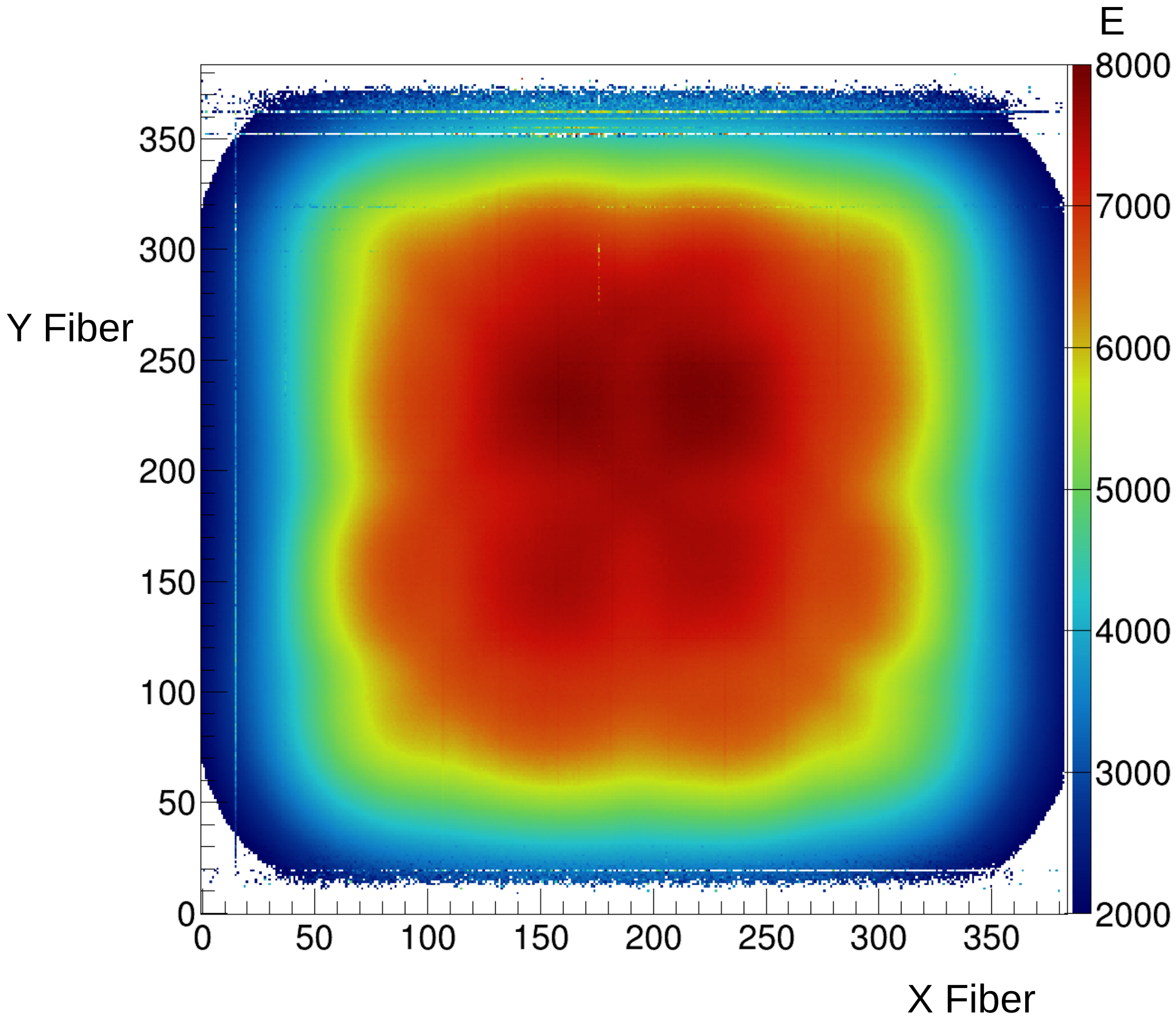


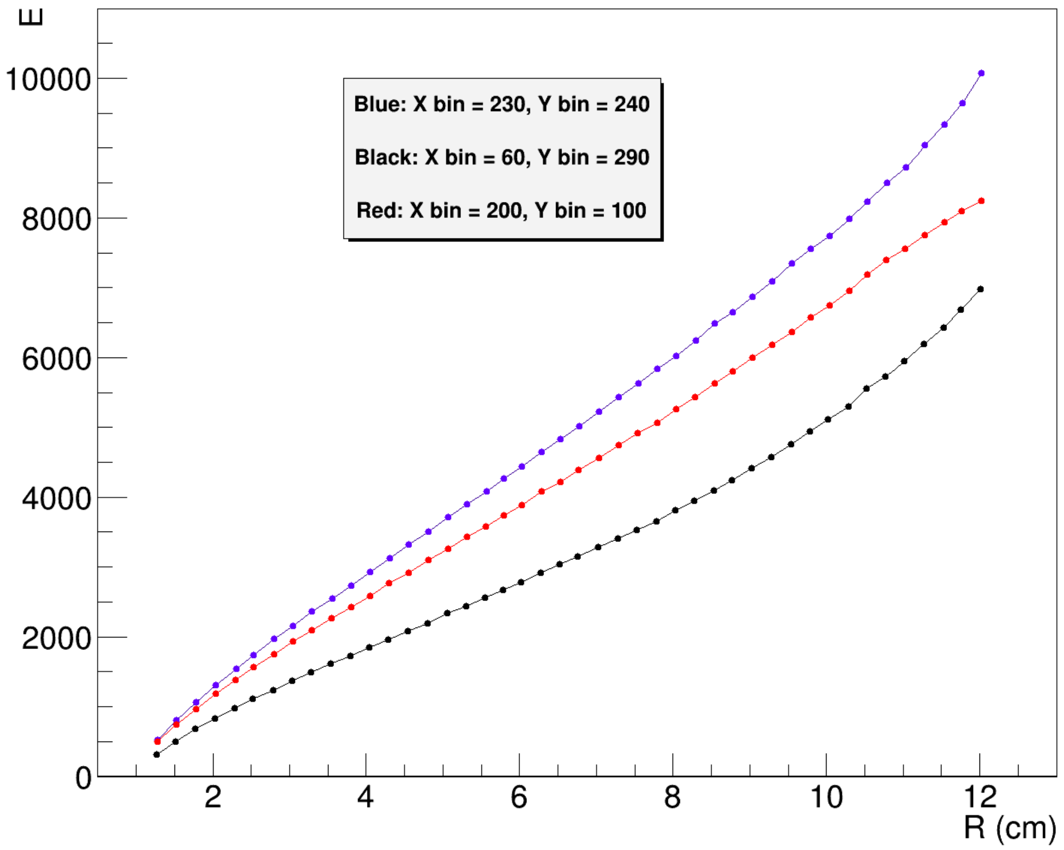


- Individual protons from a pencil beam scan are tracked and sorted into beam spots based on time recorded since the beginning of the scan

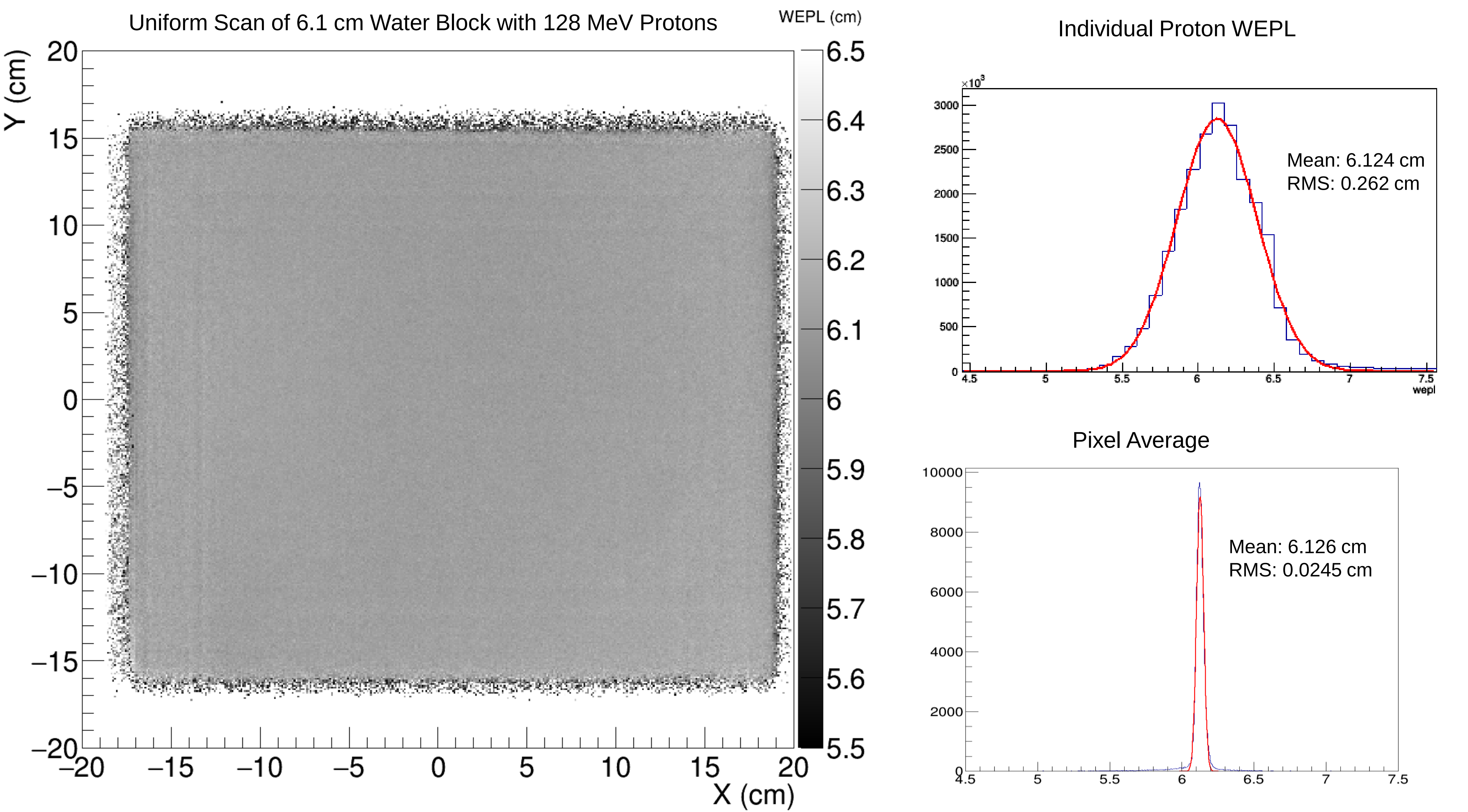
- Vertical lines indicate beam dwell time per spot





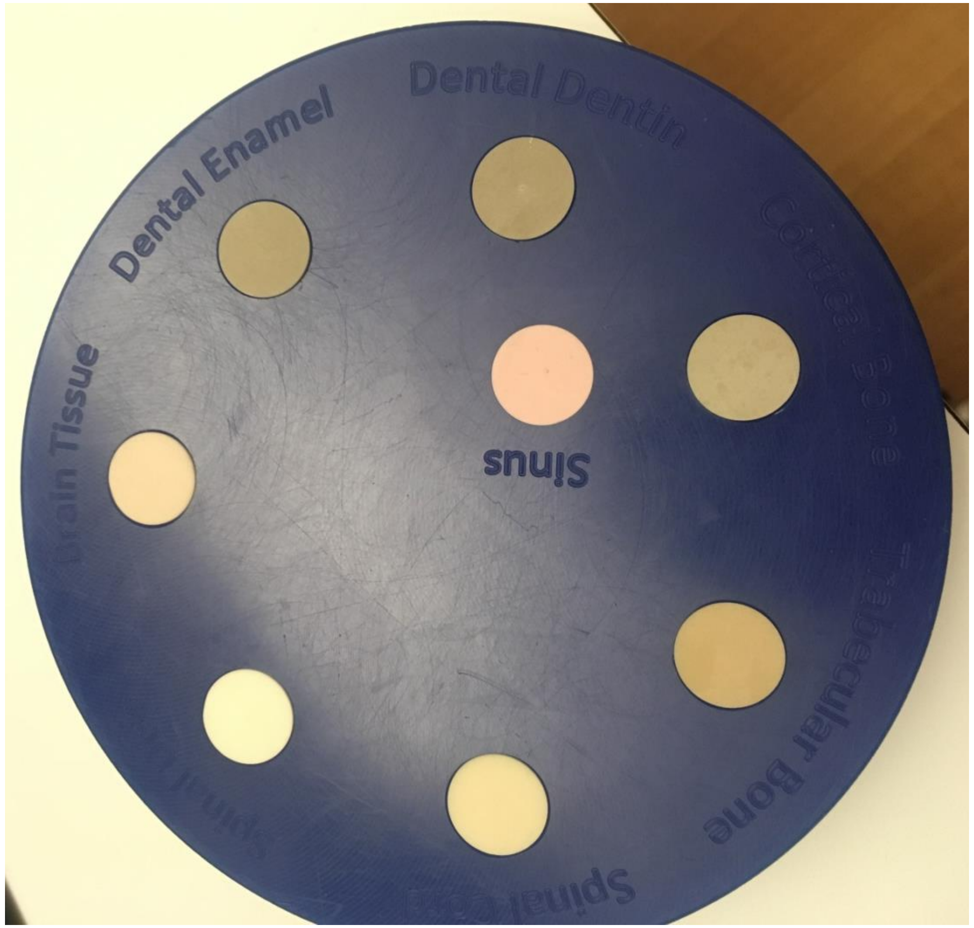


- Linear detector response vs. range gives very good range sensitivity

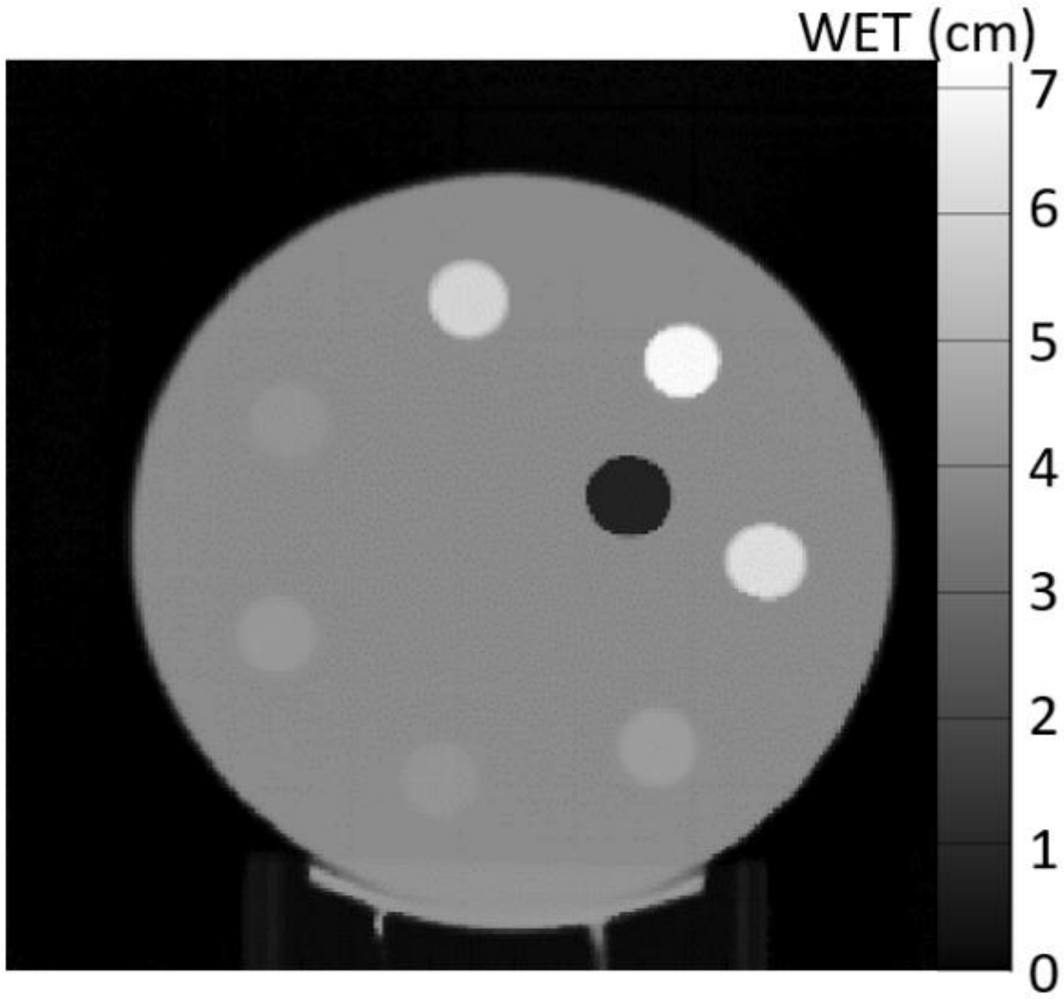


Uniform Scan of 6.1 cm Water Block with 128 MeV Protons
WEPL (cm)
Y (cm)
X (cm)
Individual Proton WEPL
Mean: 6.124 cm
RMS: 0.262 cm
wepl
Pixel Average
Mean: 6.126 cm
RMS: 0.0245 cm

- Absolute WET Measurements
  –



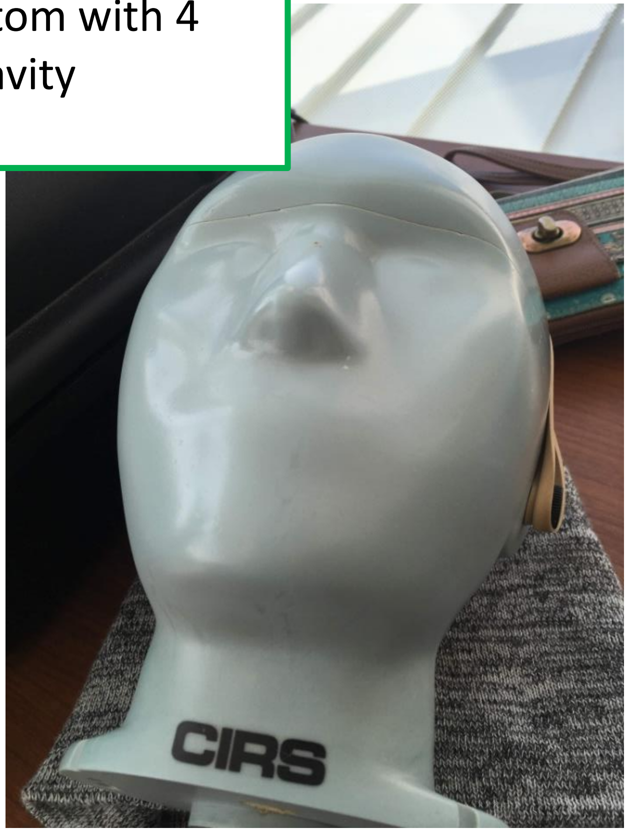
- George phantom
  - Blue bolus wax background, RSP = 0.98
  - 15 cm diameter
  - 4 cm thick
  - 8 CIRS tissue-equivalent materials, RSP = 0.22 – 1.755
  - 1.8 cm diameter inserts

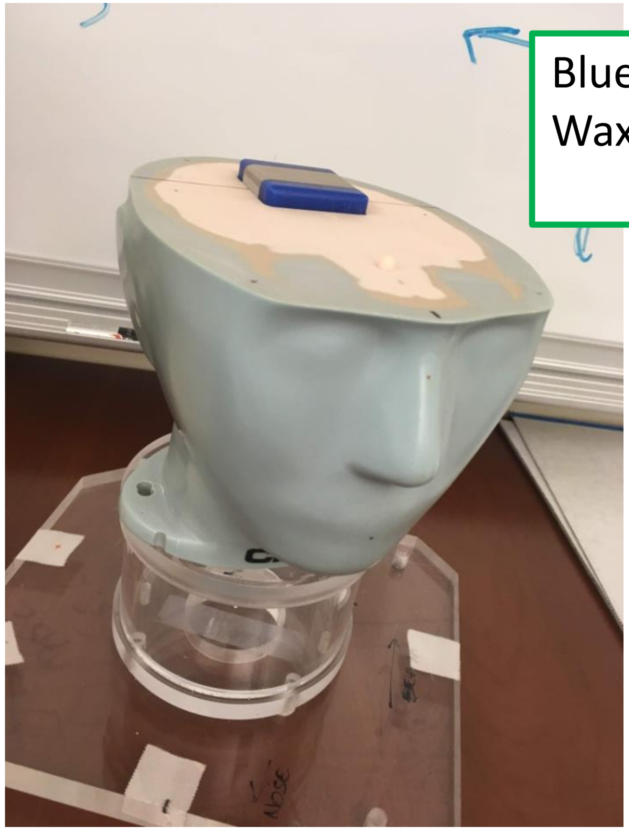


Insert	True WET (cm)	Measured WET (cm)	Difference between True and Measured (cm)
Sinus	0.80	0.80 ± 0.01	0.00
Enamel	7.02	7.01 ± 0.01	-0.01
Dentin	5.98	5.96 ± 0.01	-0.02
Brain	4.16	4.15 ± 0.01	-0.01
Spinal Cord	4.16	4.17 ± 0.01	0.01
Spinal Disc	4.28	4.28 ± 0.01	0.00
Trabecular Bone	4.40	4.41 ± 0.01	0.01
Cortical Bone	6.22	6.21 ± 0.01	-0.01

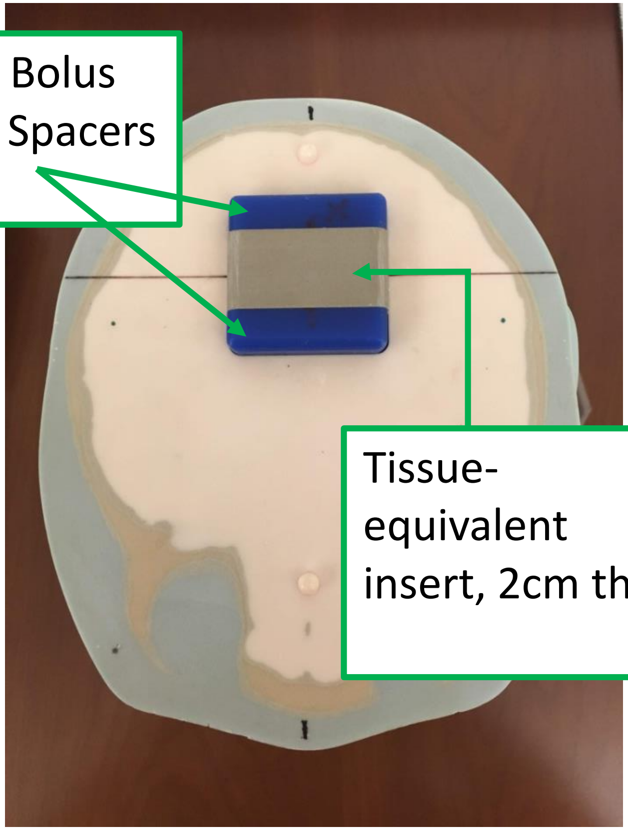
Pediatric Head Phantom with CIRS Inserts

Customized pediatric head phantom with 4 cm cubic cavity

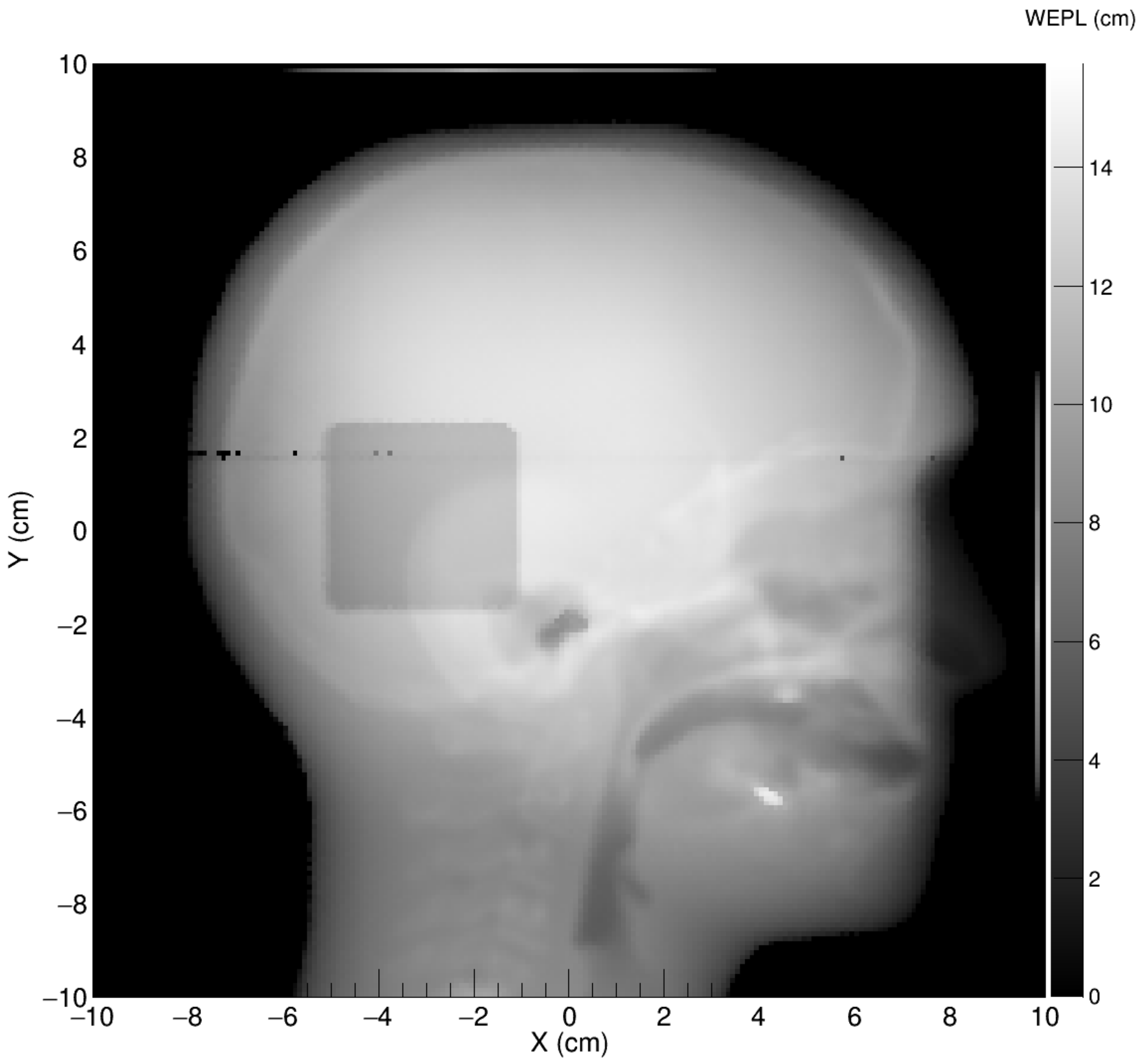




Blue Bolus Wax Spacers



Tissue-equivalent insert, 2cm thick

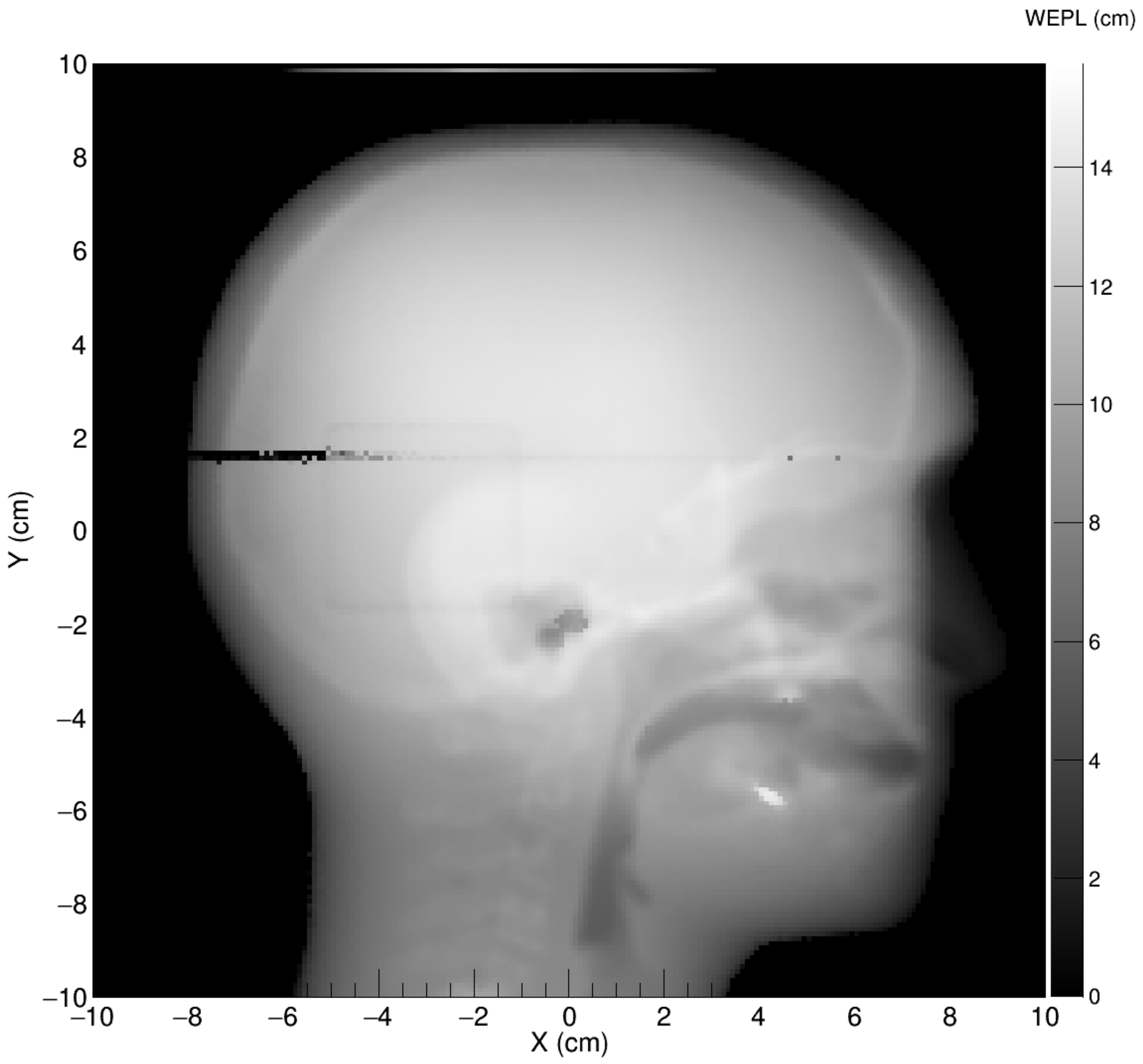


Insert: air (2 cm blue wax)

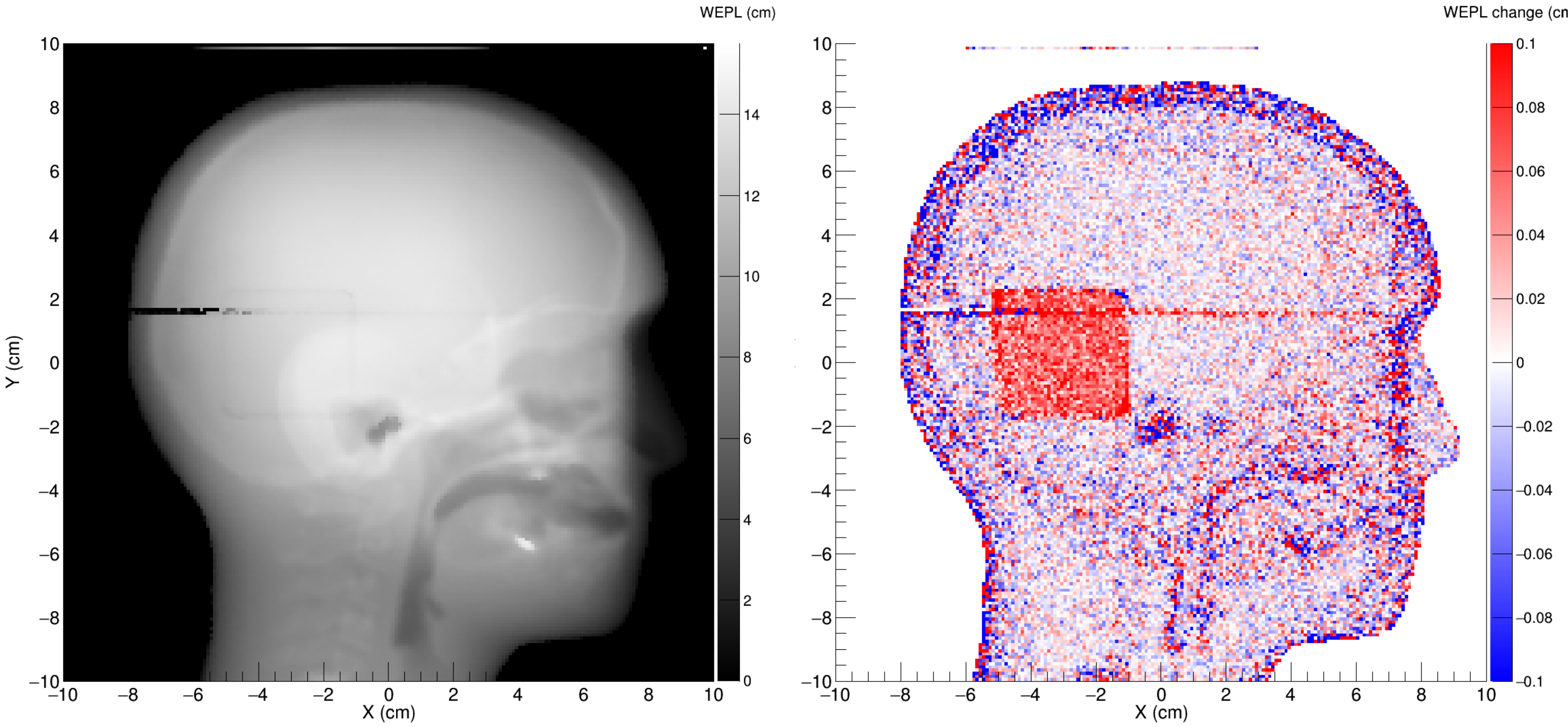
RSP: 0.001

Measuring changes in WET using phantom with known materials inserted into cavity

- Averaging WEPL into pixels based on MLP-determined position on isocenter plane (no iterative solver)



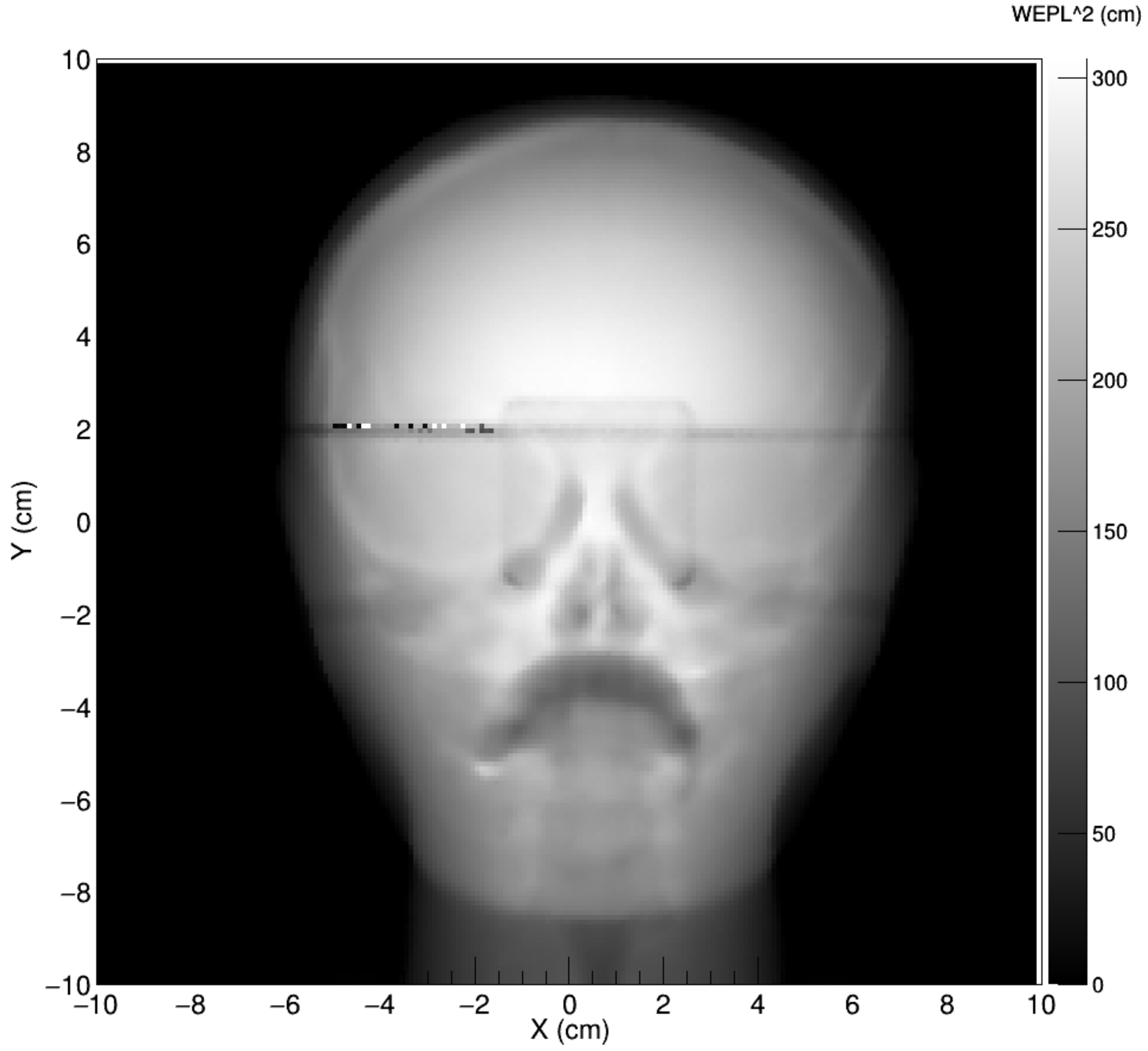
Insert: spinal cord RSP: 1.04

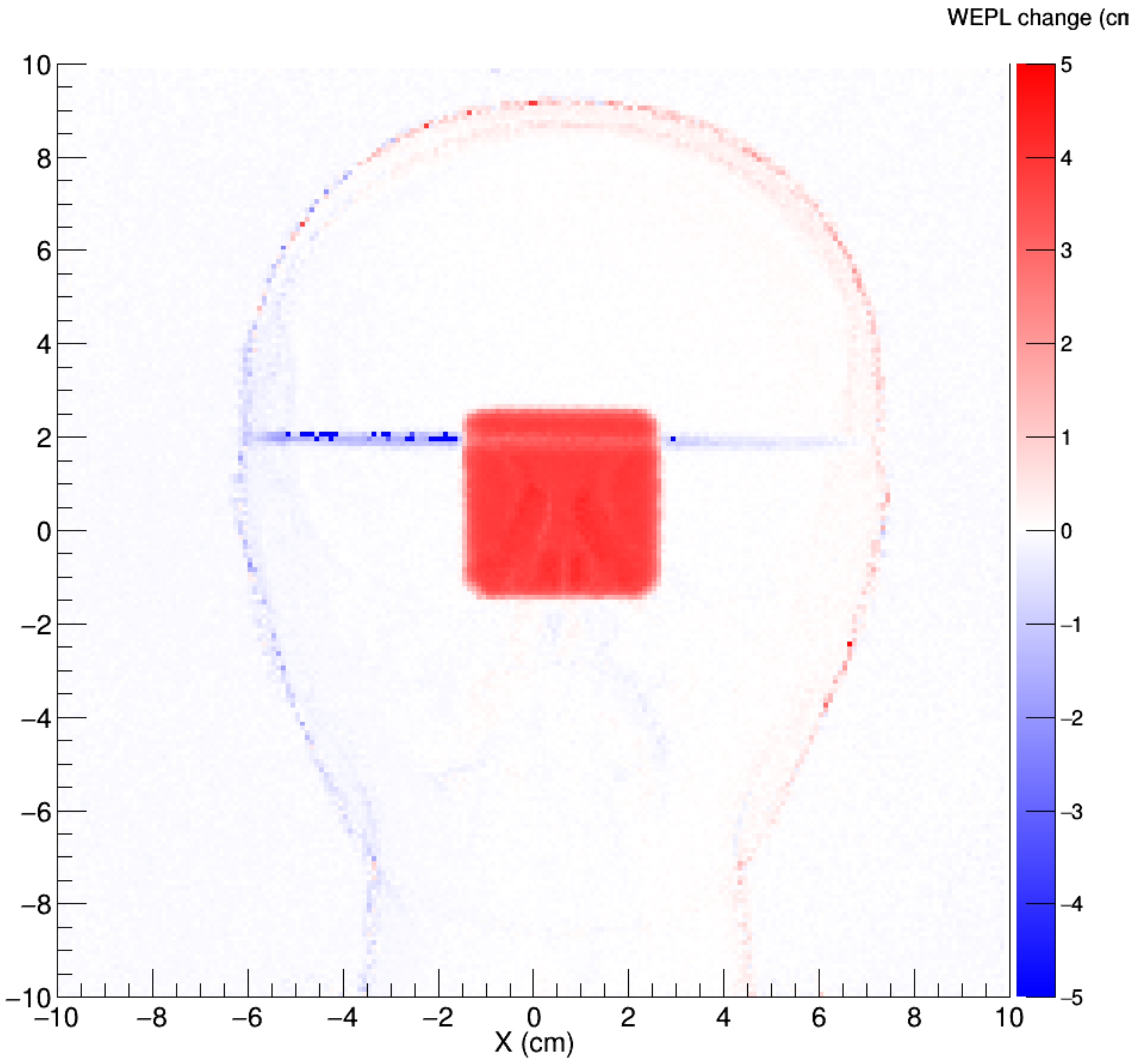


Insert: spinal disc

RSP: 1.07

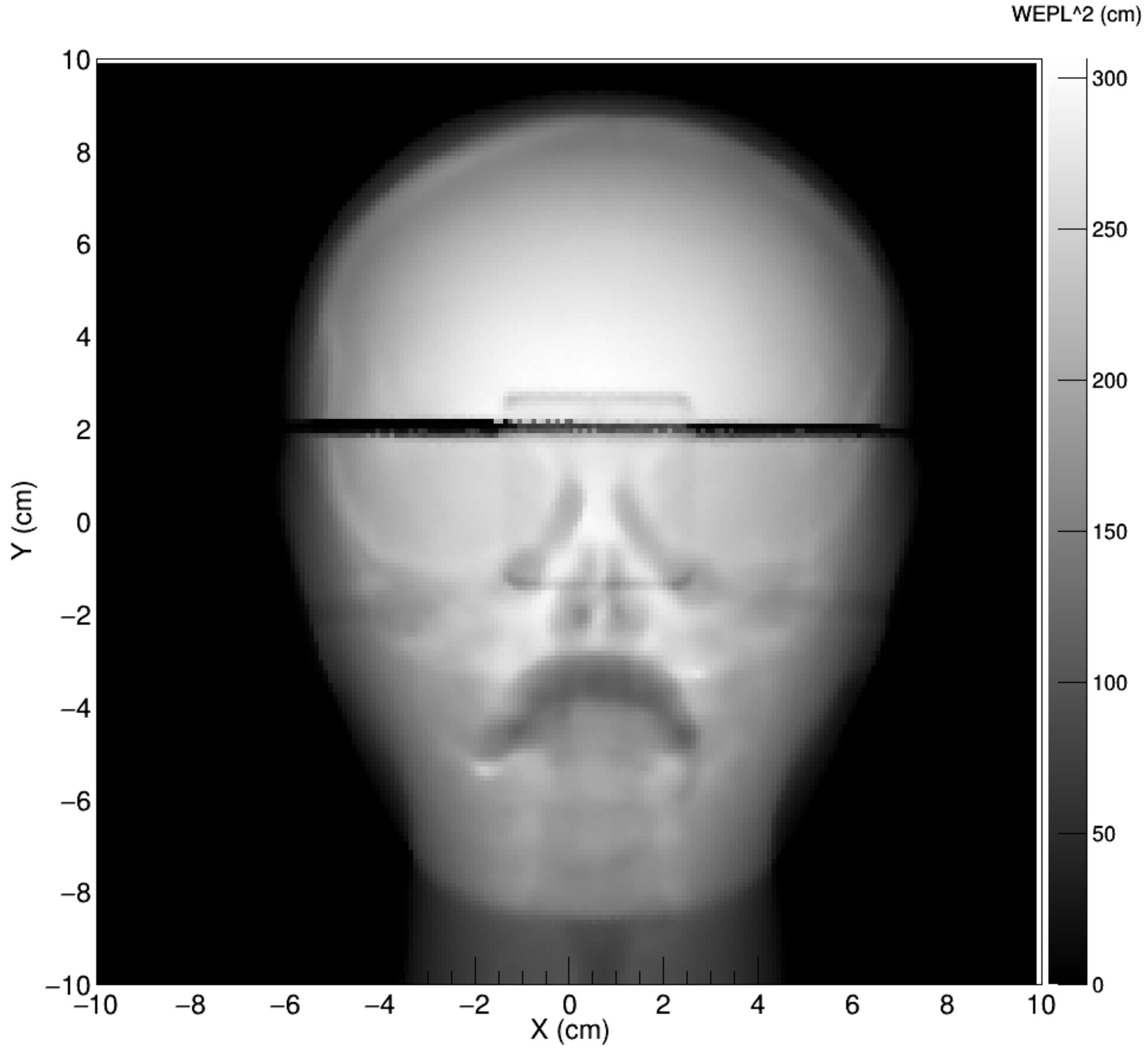
Expected difference: +0.6 mm
Measured difference: +0.58 ± 0.01 mm

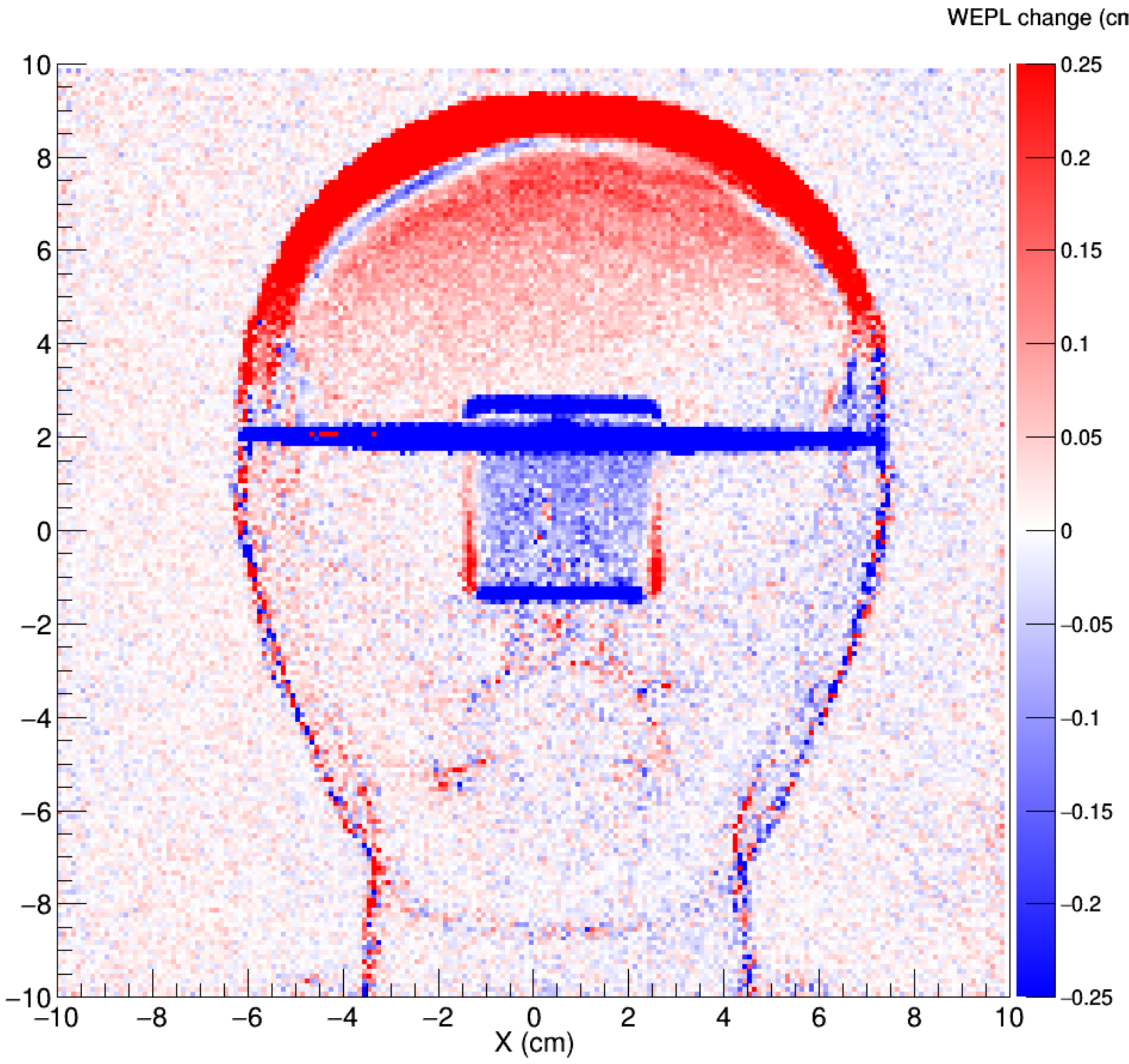




Change in insert thickness: +39.98 mm

Expected difference: +39.06 mm
Measured difference: +38.57 ± 0.07 mm

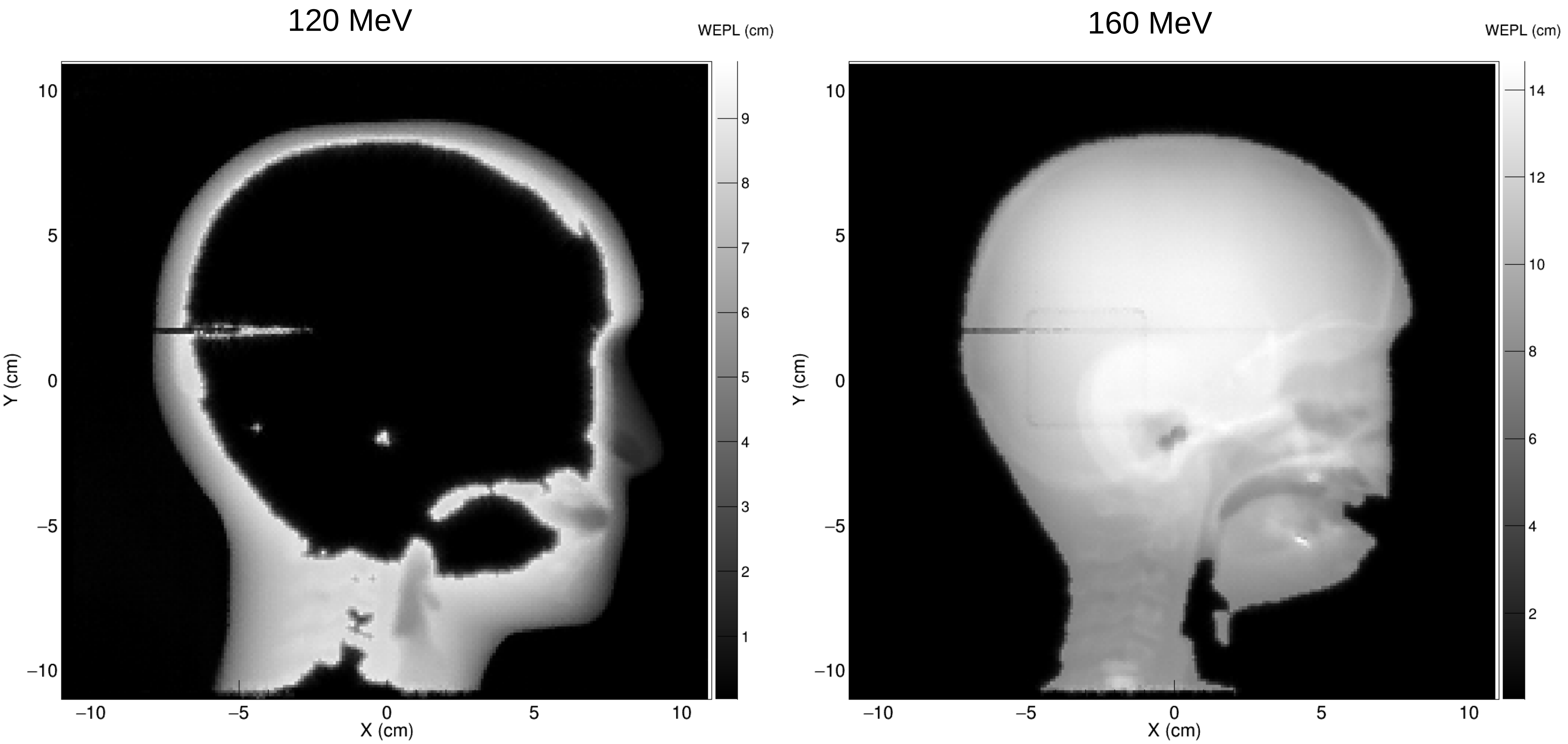


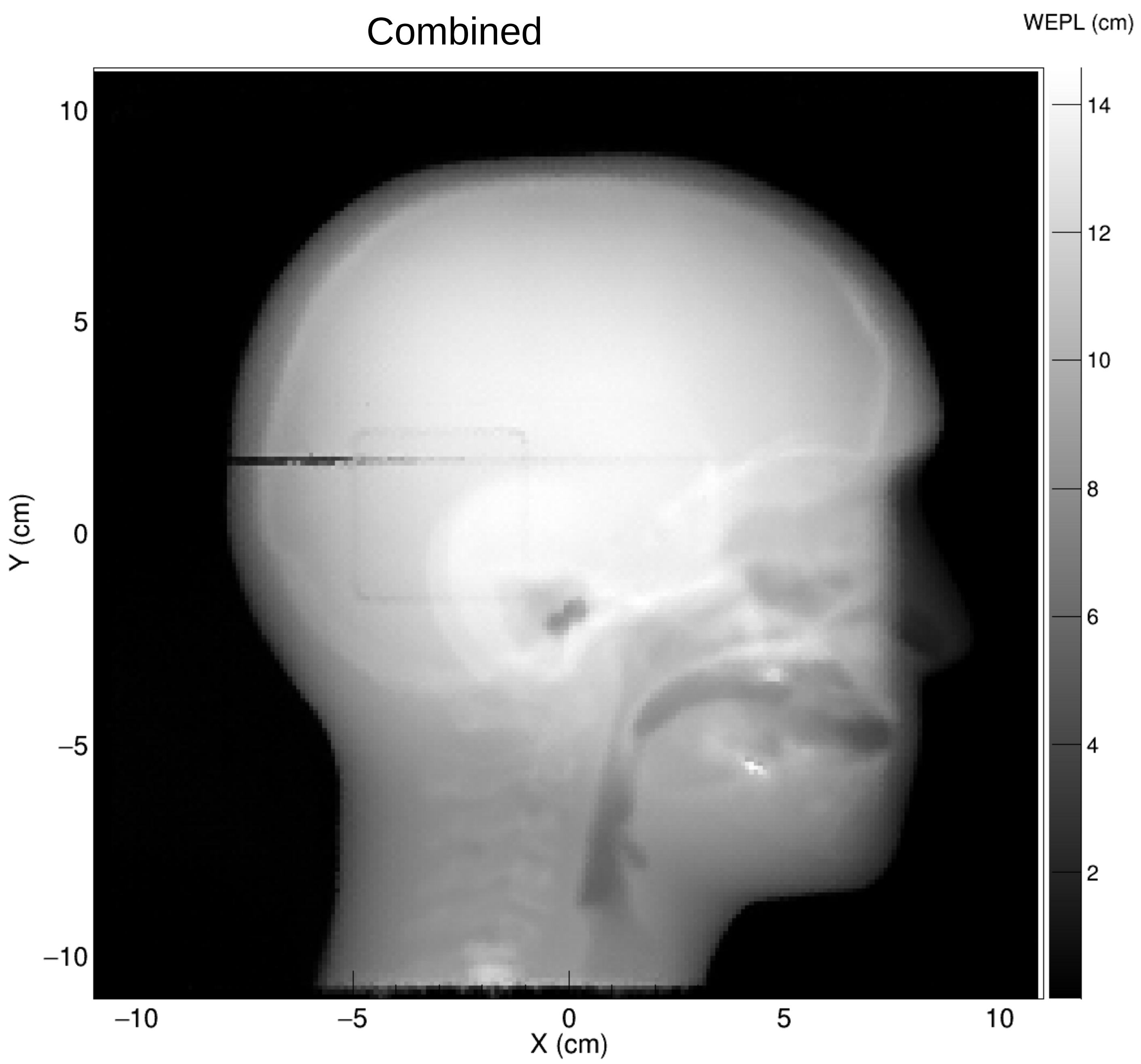


Change in insert thickness: -0.88 mm

Expected difference: -0.86 mm
Measured difference: -0.82 ± 0.03 mm

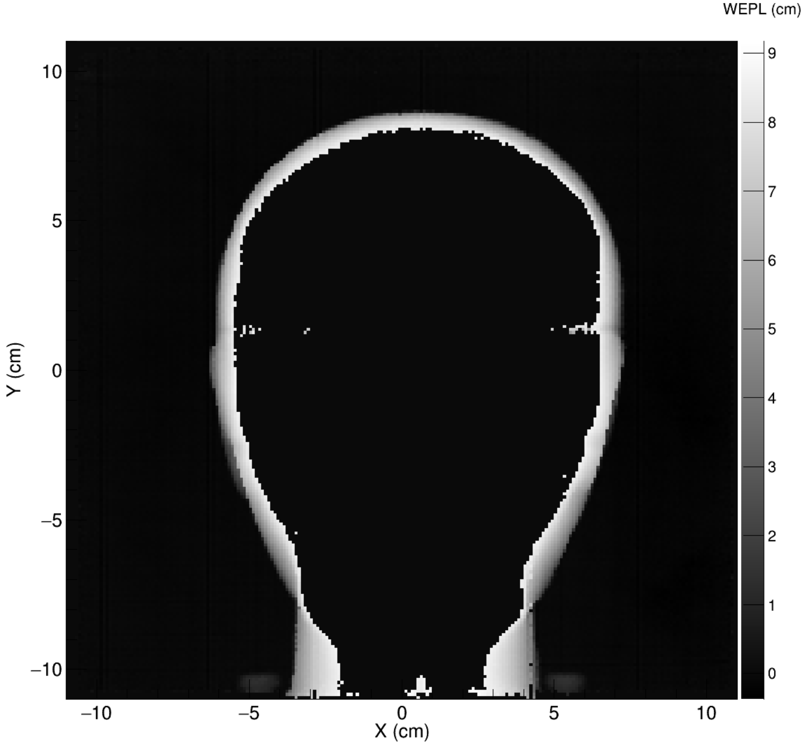
Imaging with Multiple Proton Energies – Pediatric Head Phantom



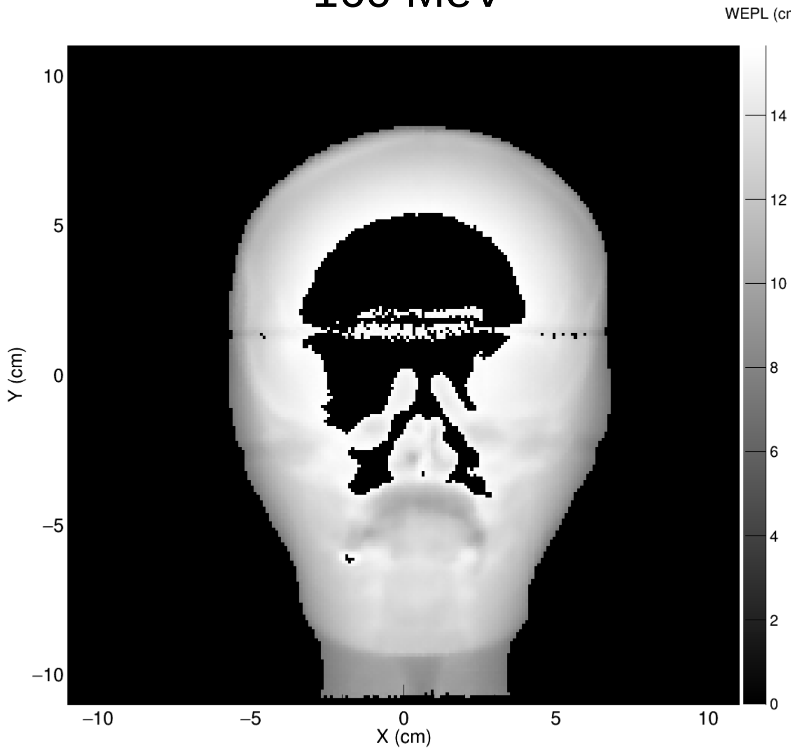


Combined
WEPL (cm)
14
12
10
8
6
4
2
10
5
0
−5
−10
Y (cm)
−10
−5
0
5
10
X (cm)

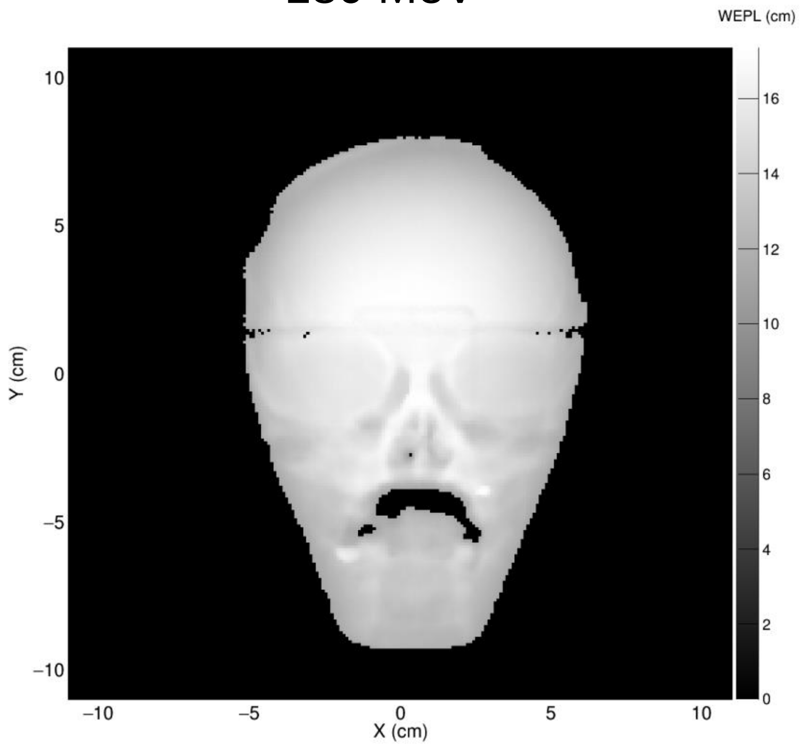
120 MeV

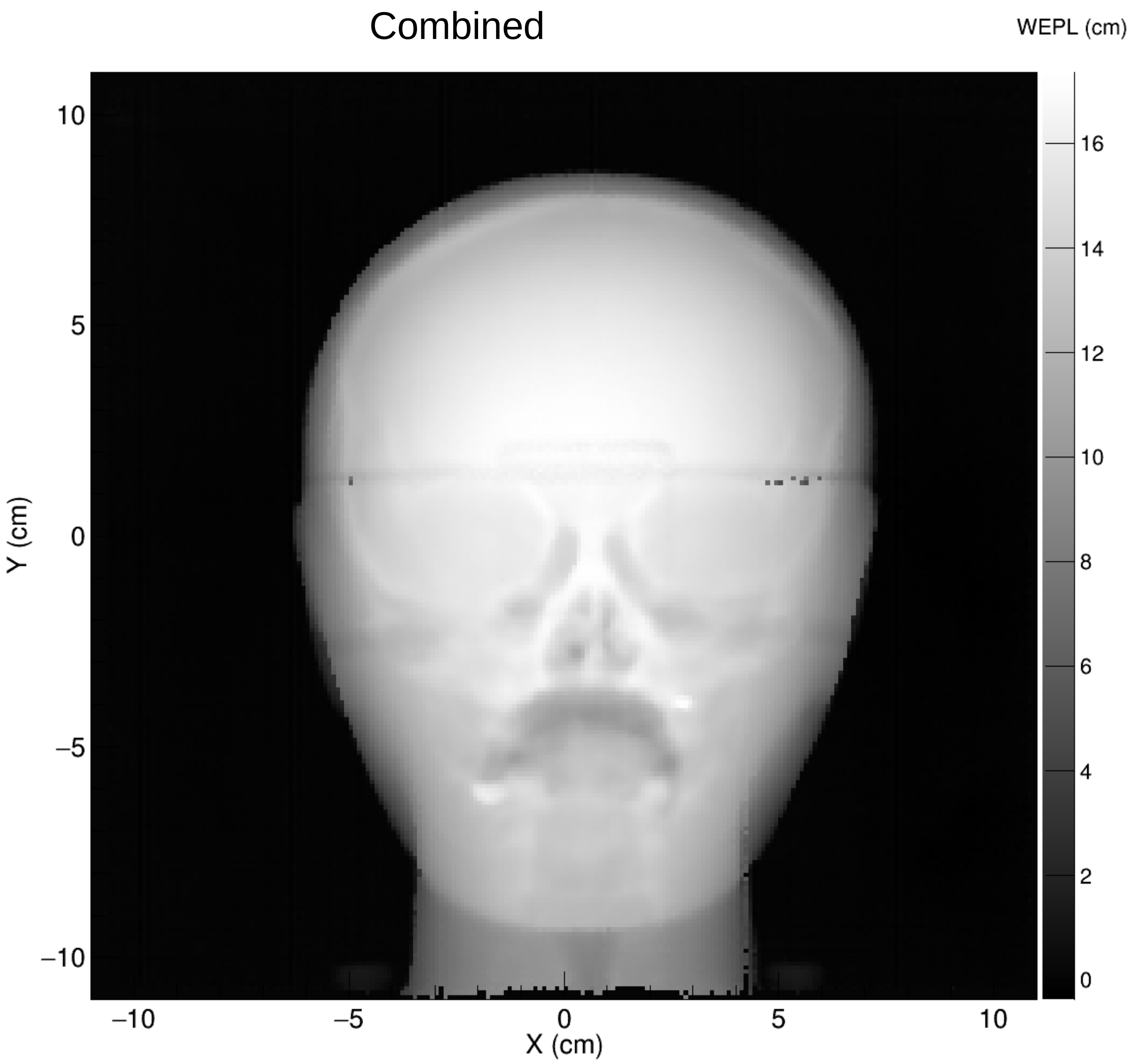


160 MeV



180 MeV

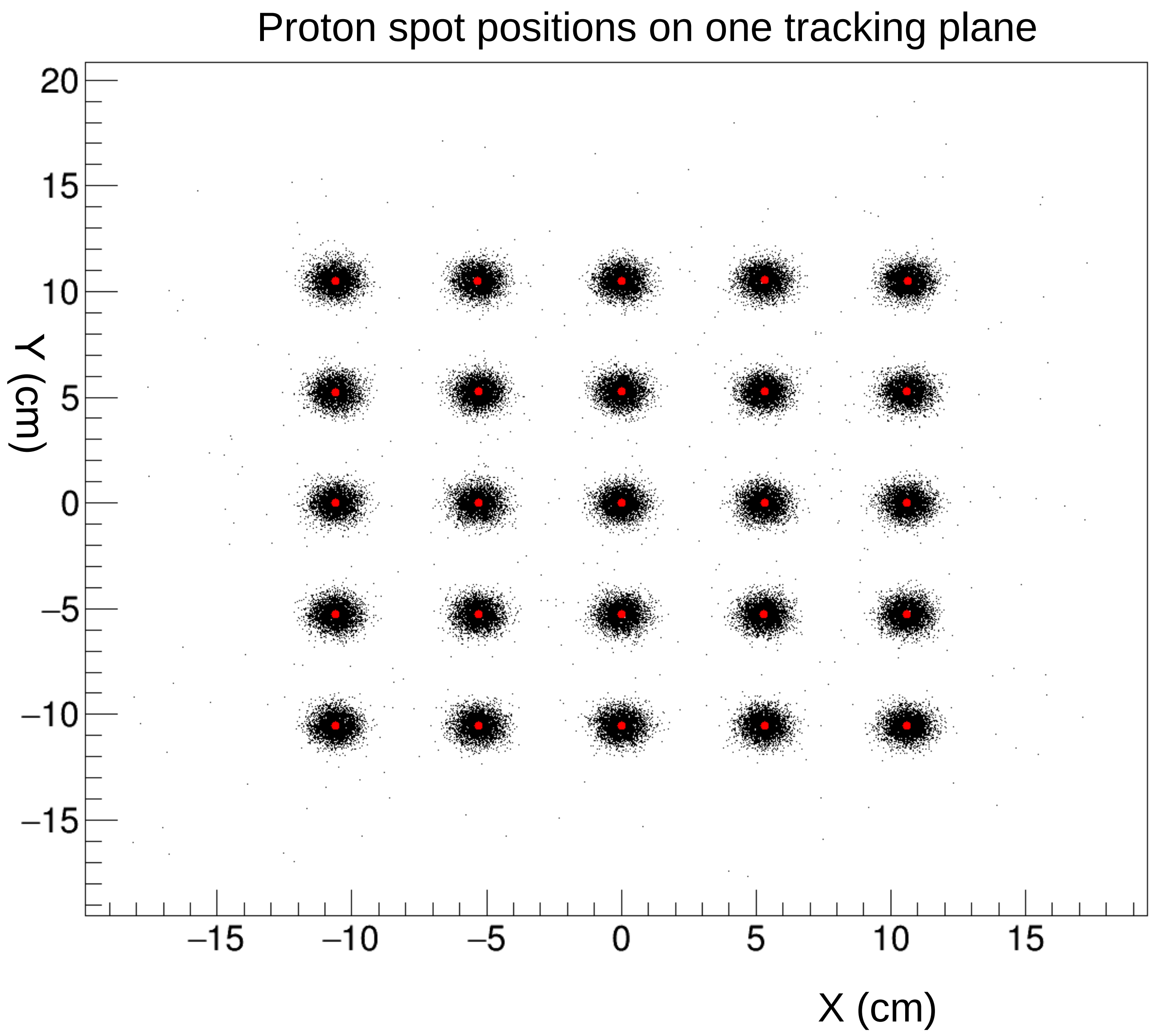




Combined
WEPL (cm)
16
14
12
10
8
6
4
2
0
10
5
0
−5
−10
Y (cm)
−10
−5
0
5
10
X (cm)

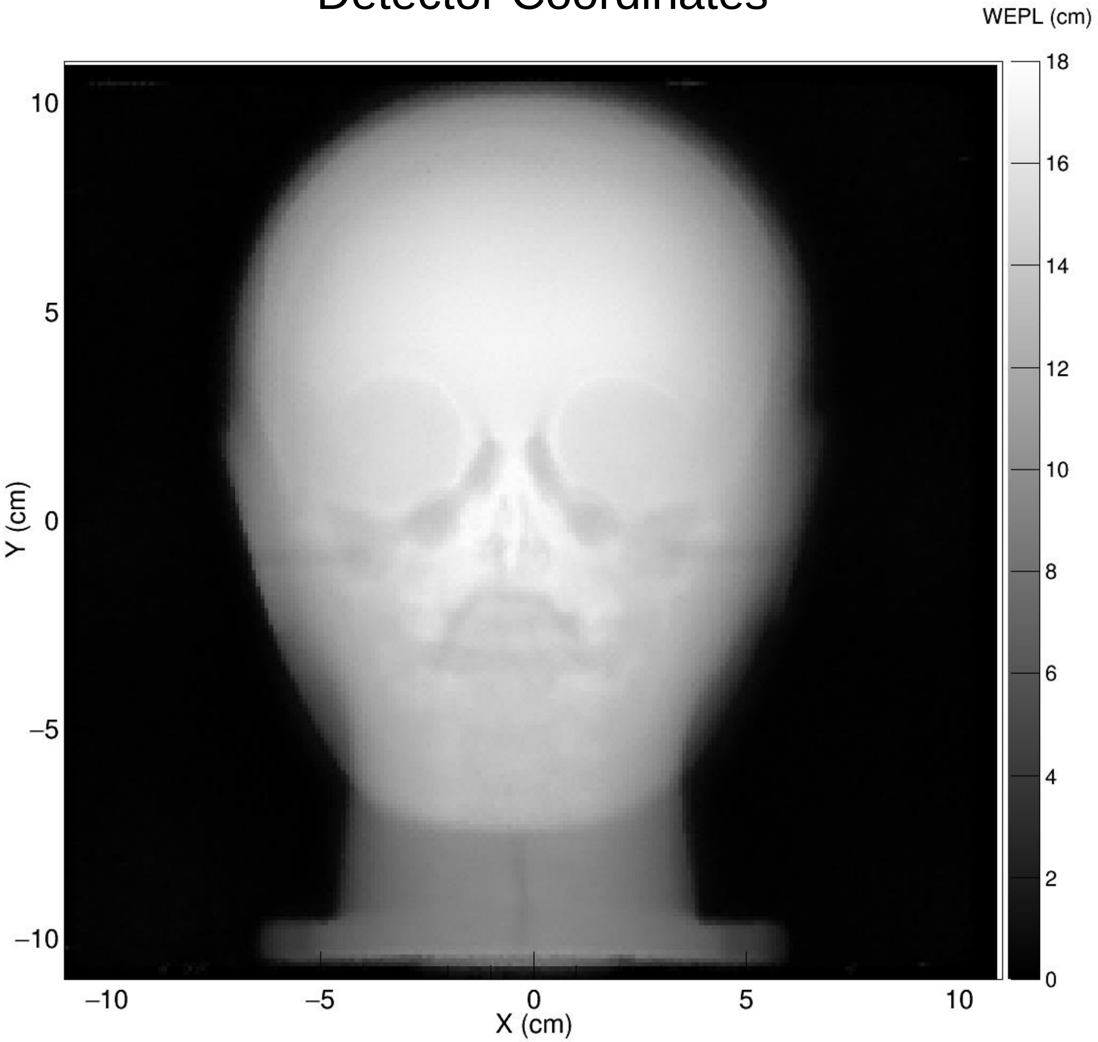
Detector Alignment Procedure

- Pencil beam targets an array of spots prior to imaging scans.
    - Beam is aimed at locations specified in isocenter coordinates.
- Software compares measured spot positions to expected positions
- Allows for automatic transformation of detector coordinates to isocenter coordinates, accounting for detector positioning.
    - Image is automatically presented in isocenter coordinates, with no need for QA on detector alignment.

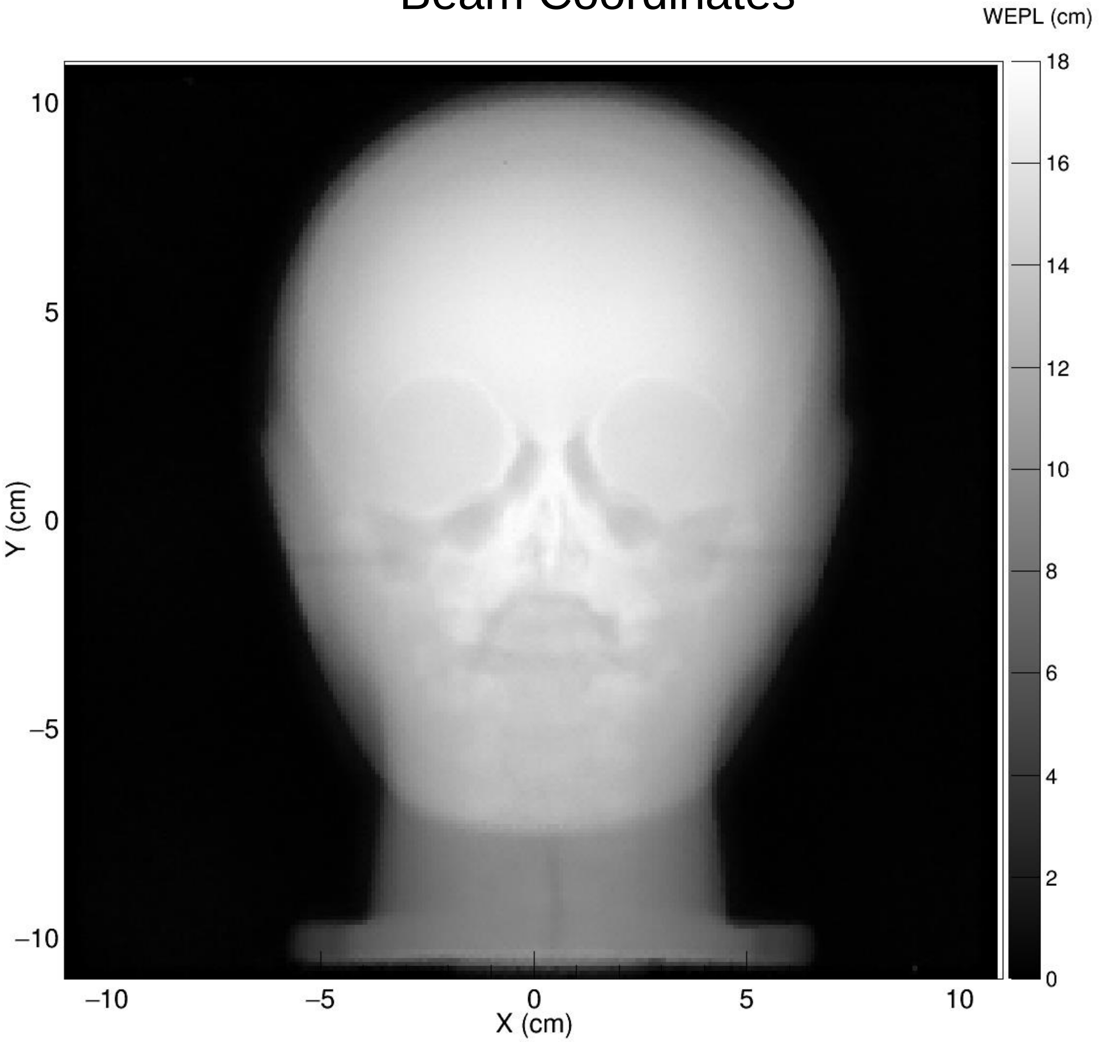


Nominal

Detector Coordinates

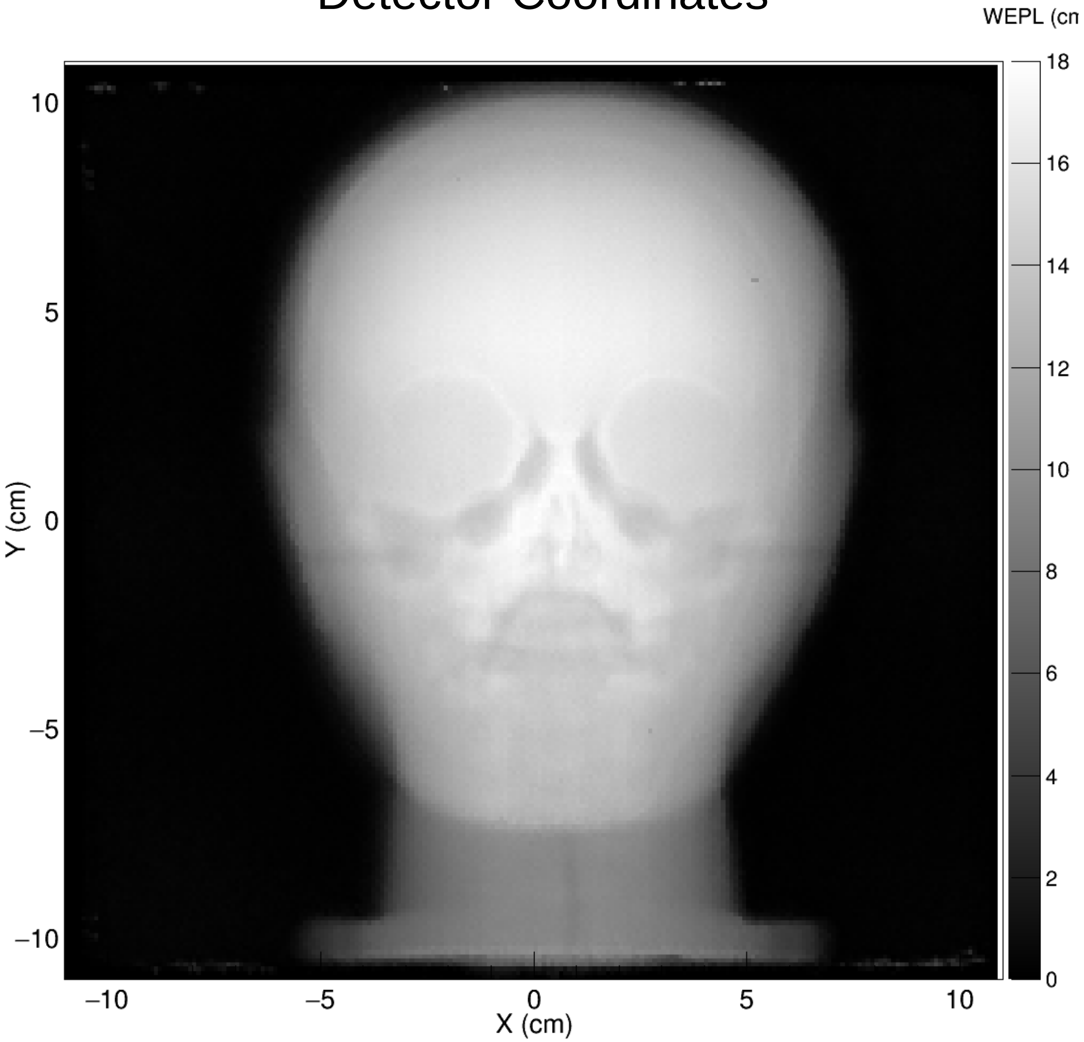


Beam Coordinates

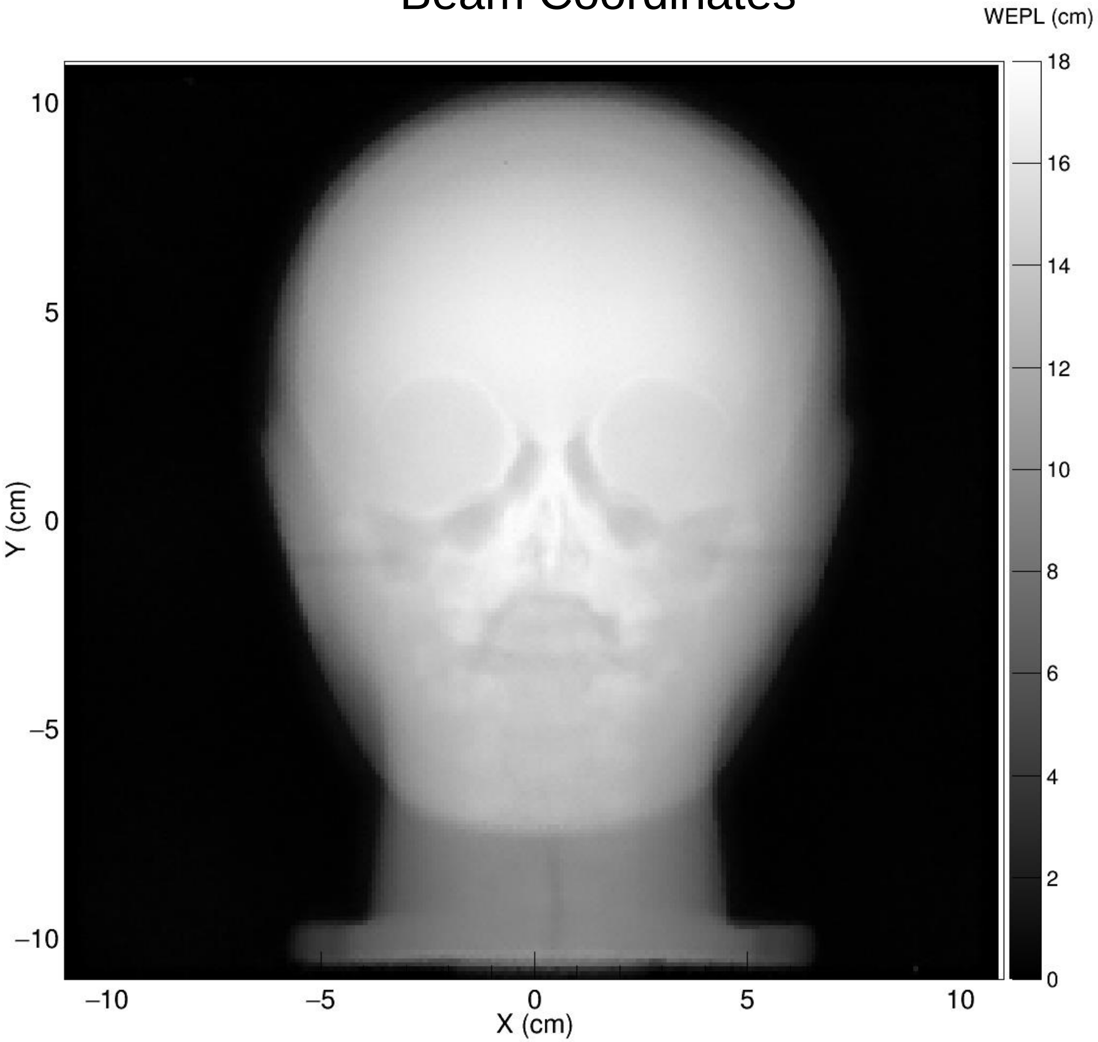


Detectors Shifted left, Phantom in Same Position

Detector Coordinates

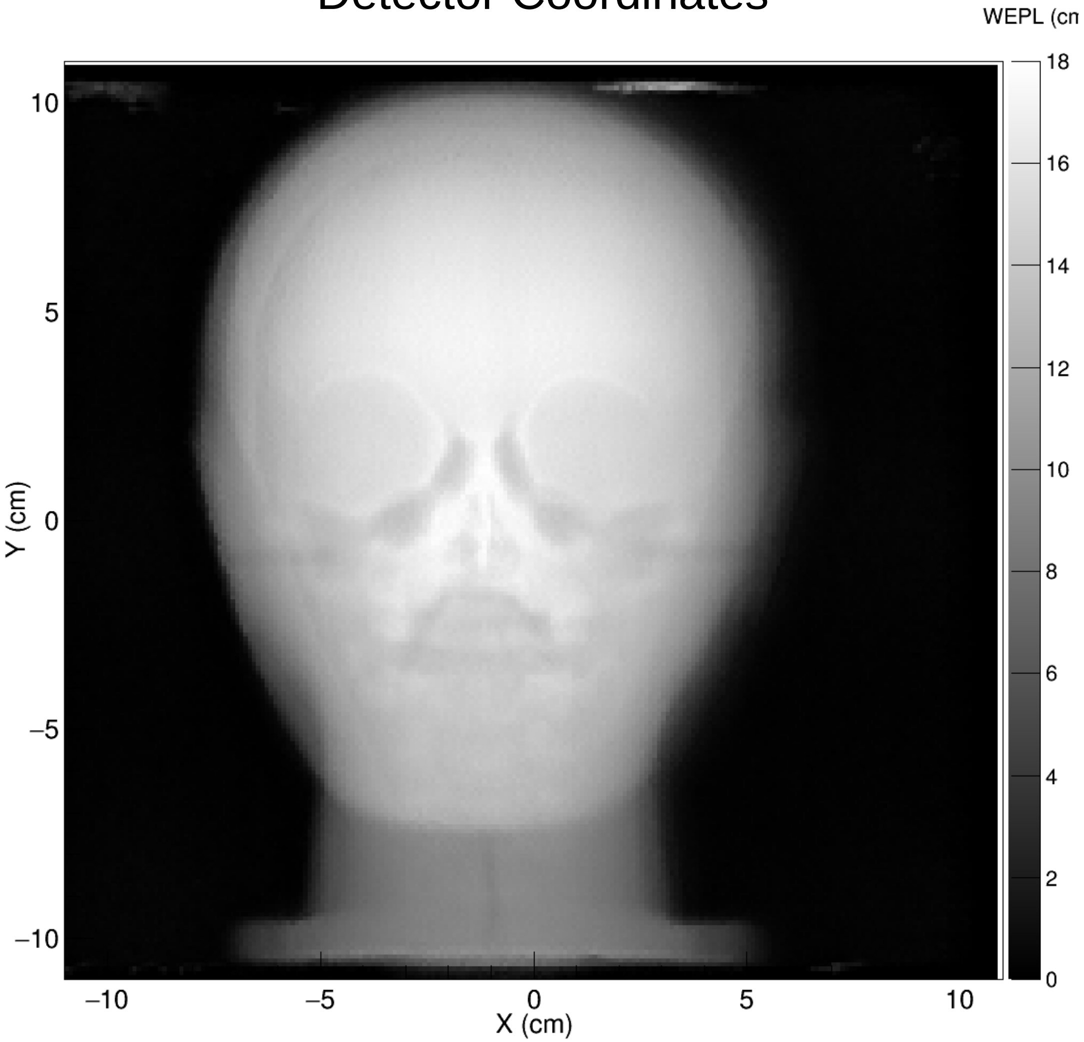


Beam Coordinates

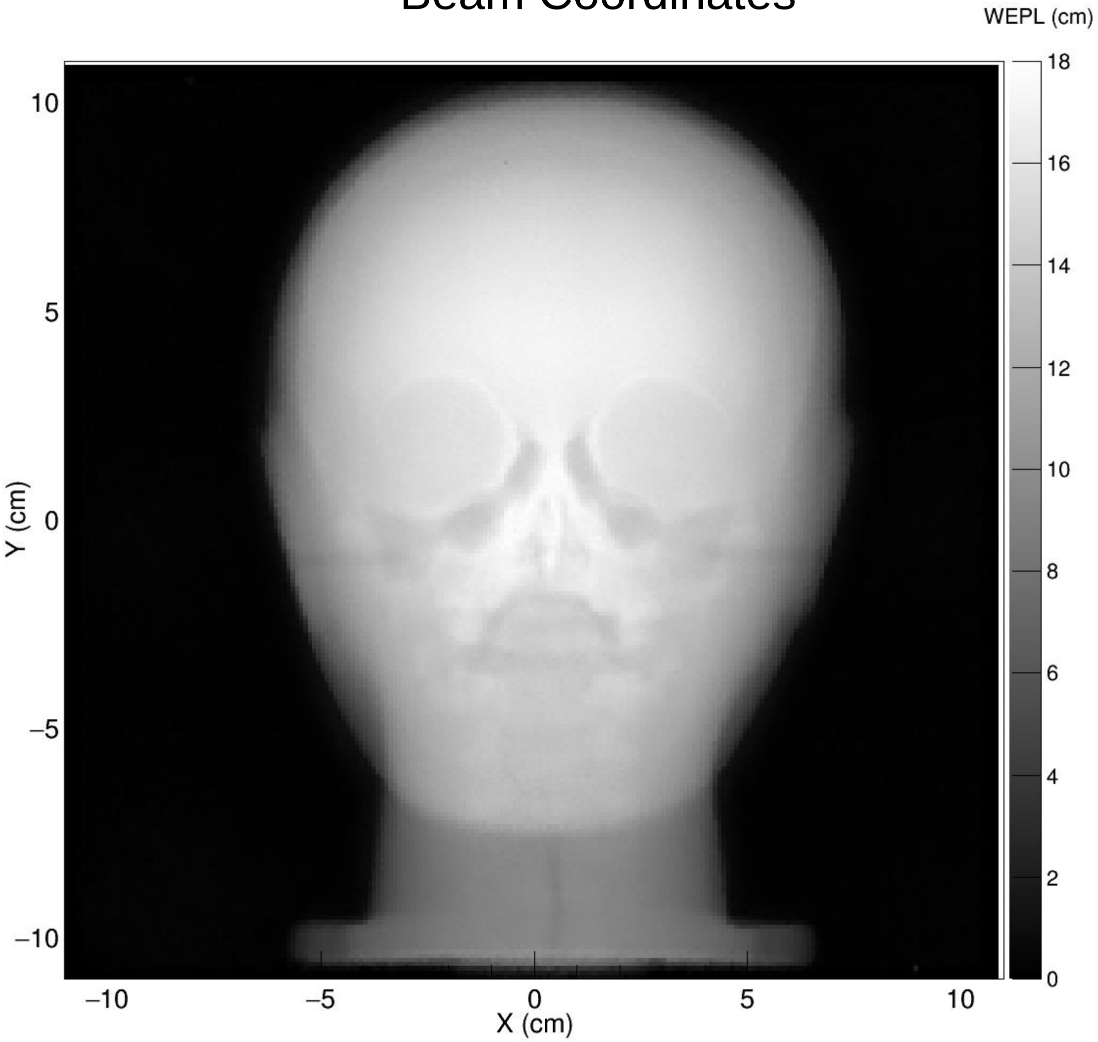


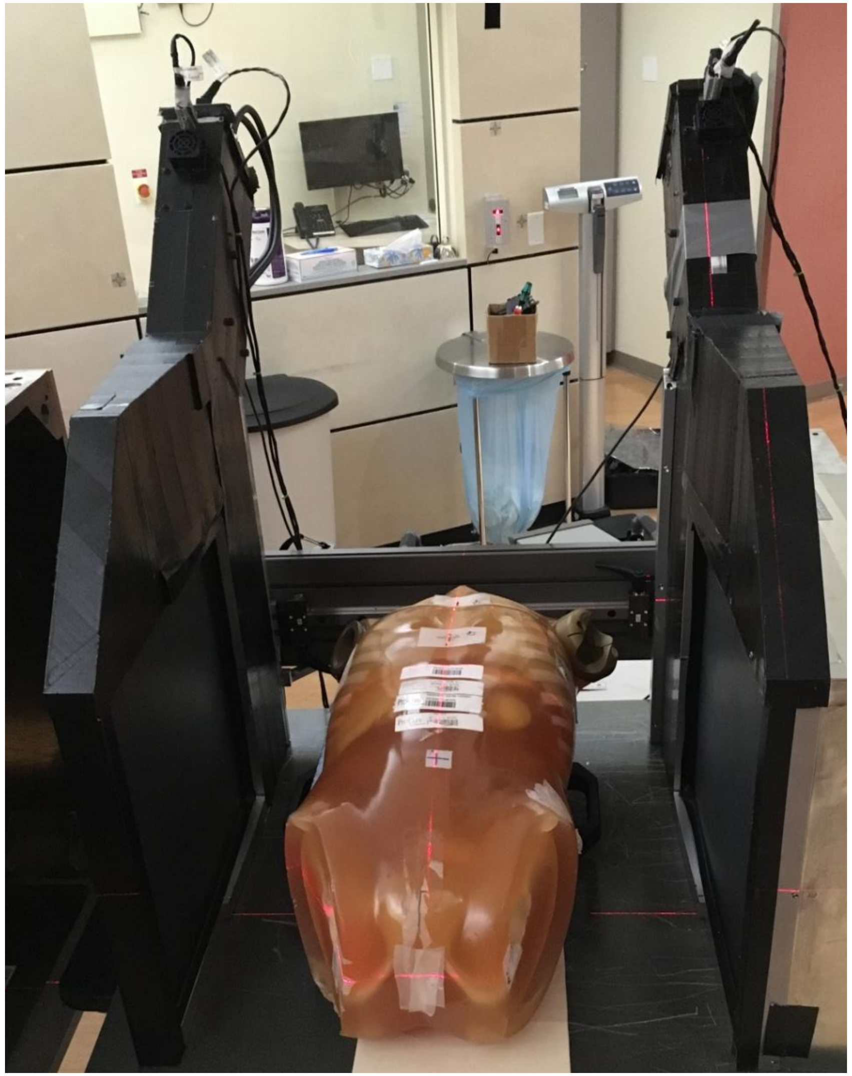
Detectors shifted right, phantom in same position

Detector Coordinates



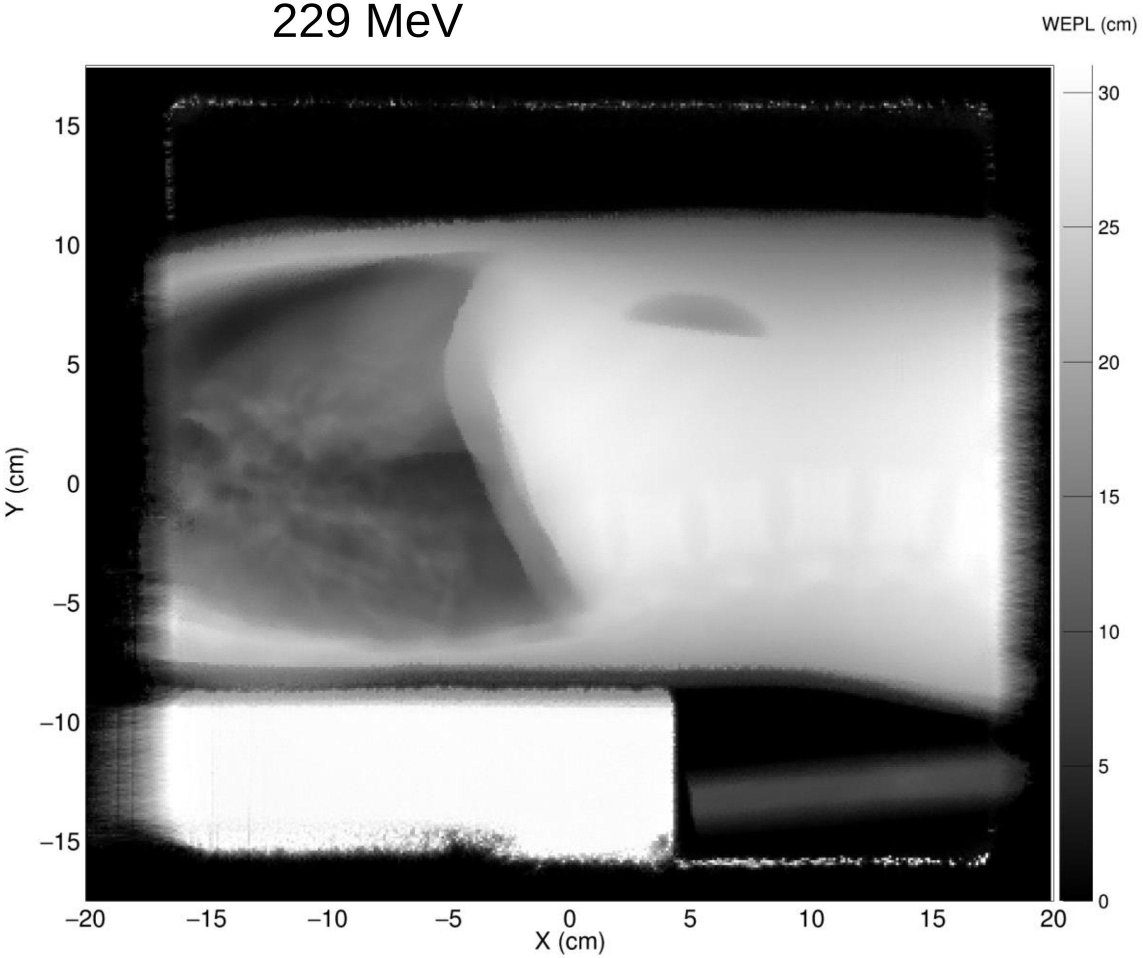
Beam Coordinates

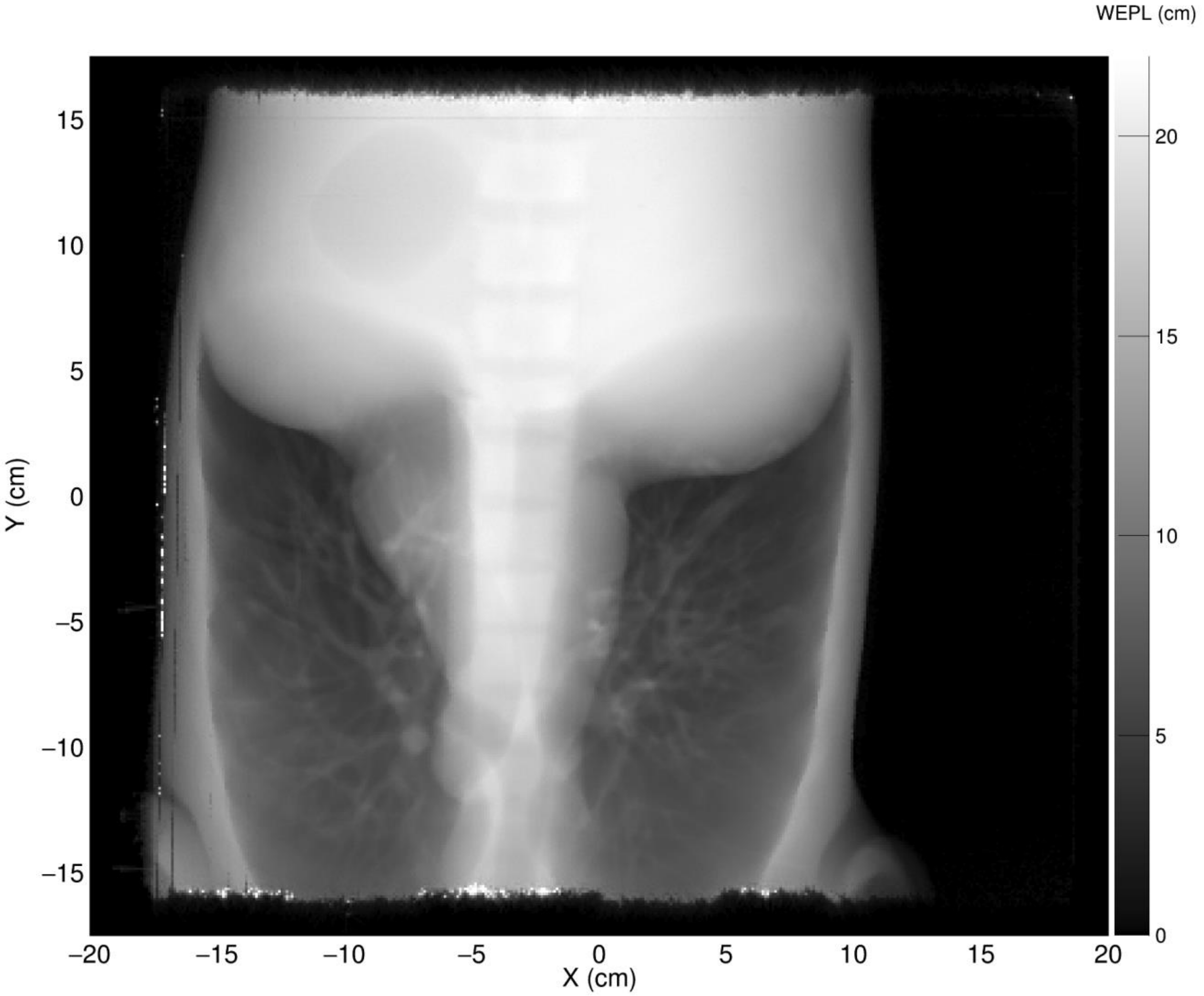




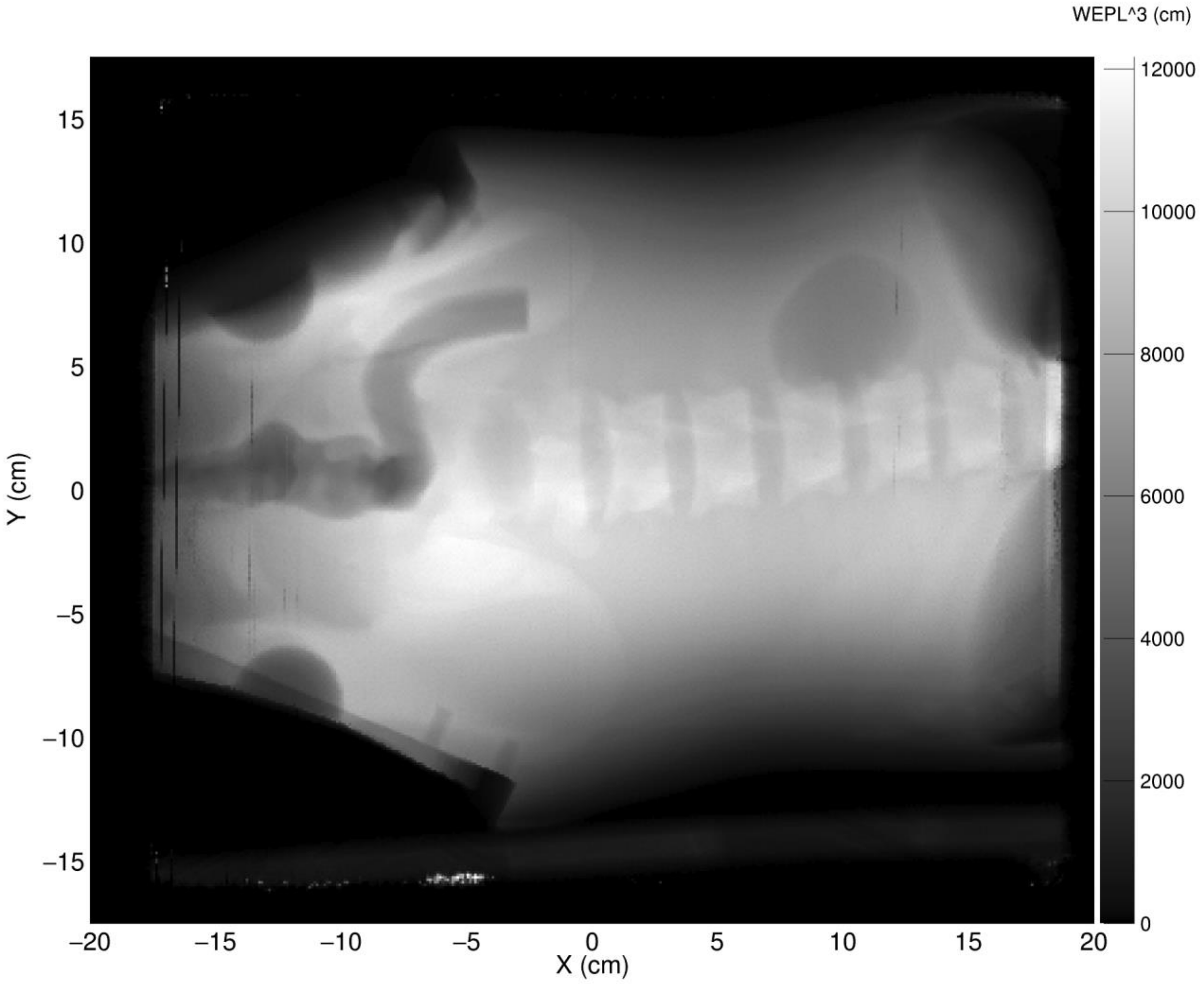
30 x 40 cm scan of torso phantom

- 4 energies: 120, 163, 200, 229 MeV

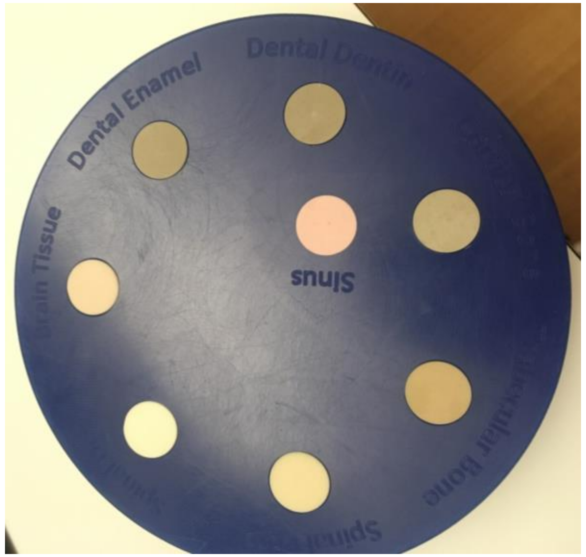




WEPL (cm)
Y (cm)
X (cm)

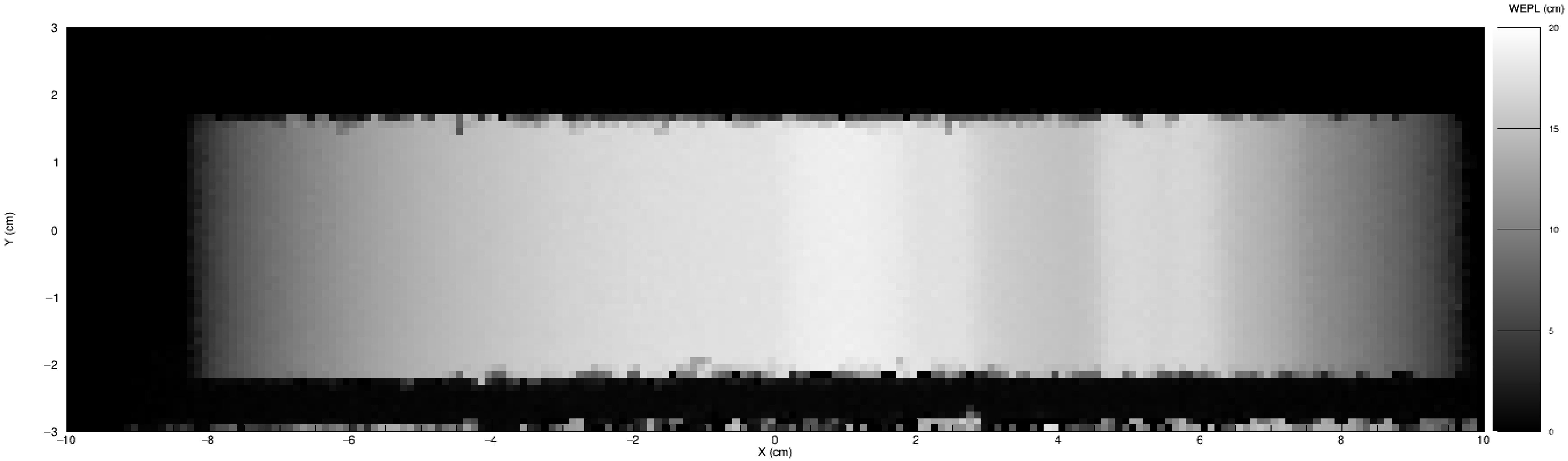


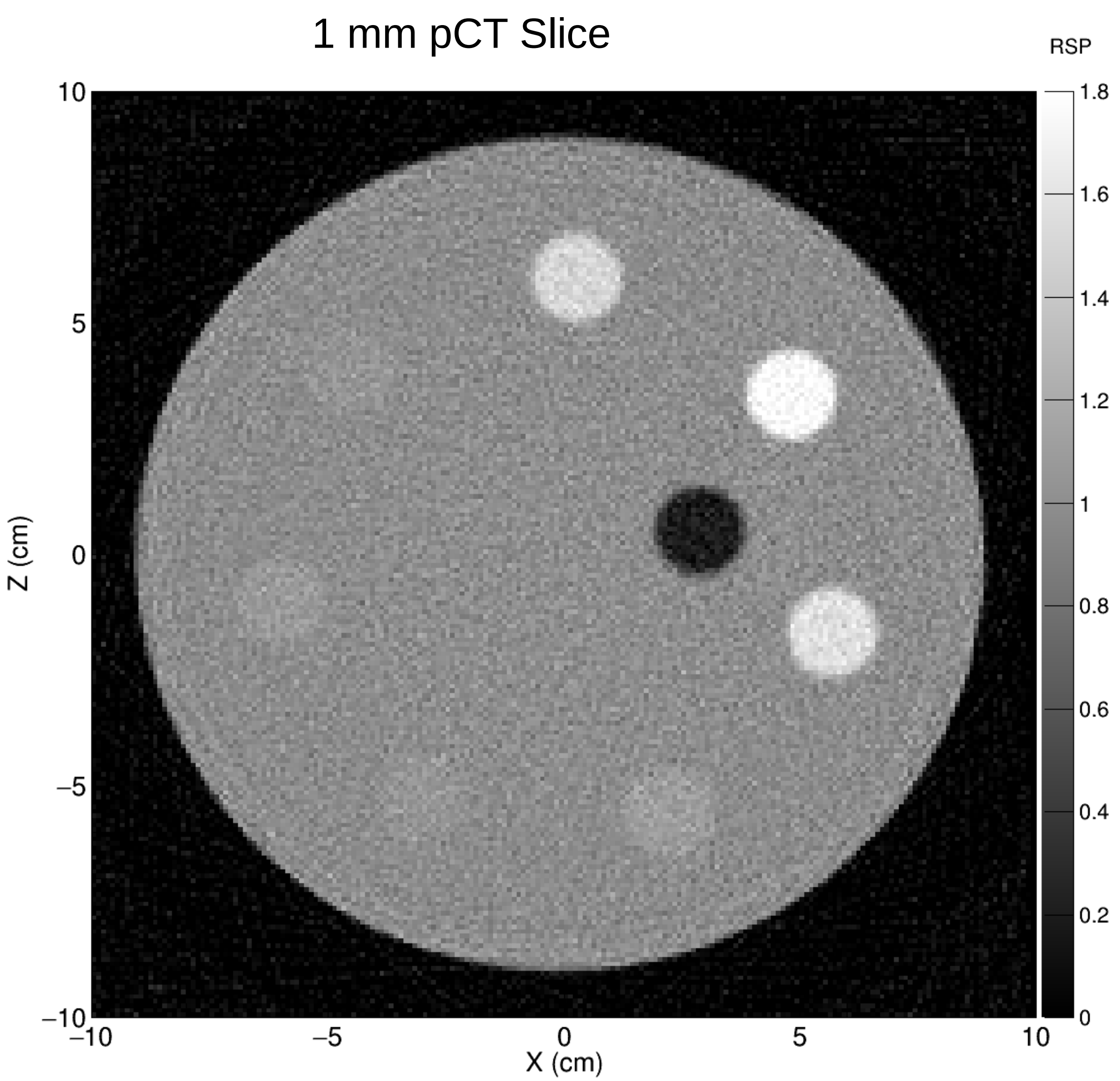
WEPL^3 (cm)
Y (cm)
X (cm)



George Phantom pCT data (projections)

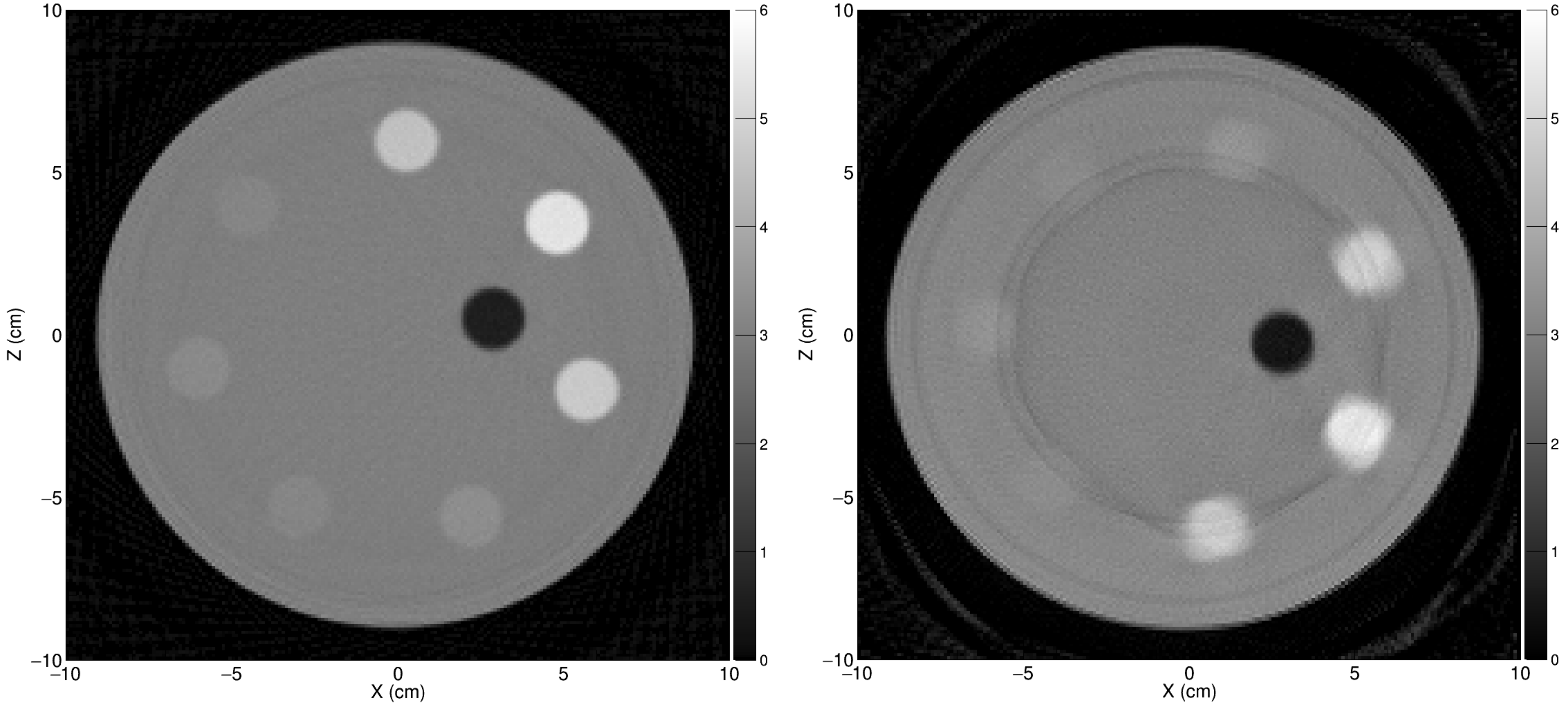
- Made with 3 energies: 195, 160, and 118 MeV
- Data taken every 4 degrees
- 1 mm^3 voxels
- ~20 million protons in final cut





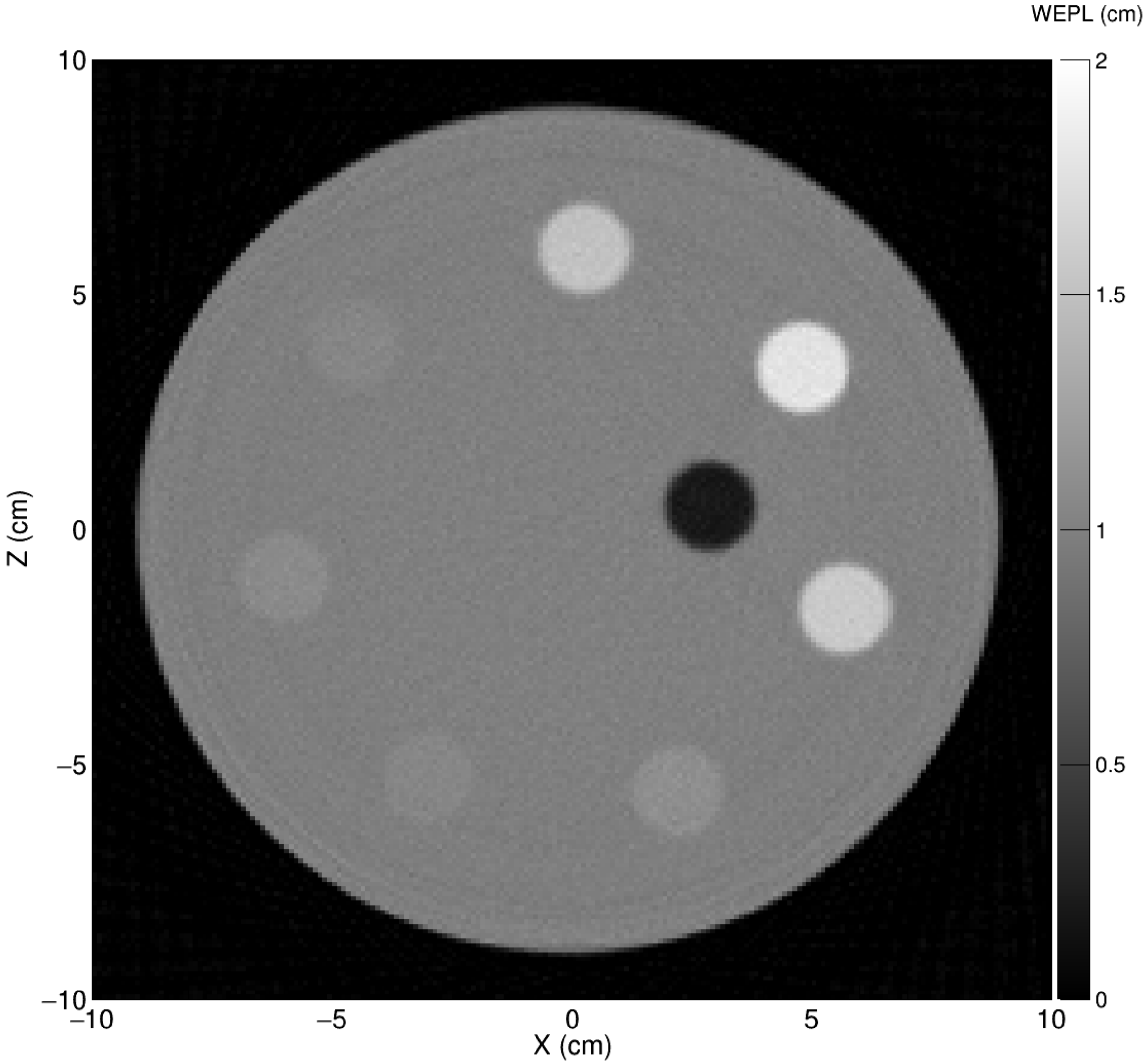
Insert	RSP	RSP from pCT image In ROI for each insert (Statistical uncertainty only)	Difference (pCT – Nominal)
Sinus	0.200	0.192 ± 0.002	-0.008
Enamel	1.755	1.768 ± 0.002	0.013
Dentin	1.495	1.504 ± 0.002	0.009
Brain	1.040	1.043 ± 0.002	0.003
Spinal Cord	1.040	1.046 ± 0.002	0.006
Spinal Disc	1.070	1.079 ± 0.002	0.009
Trabecular Bone	1.100	1.106 ± 0.002	0.006
Cortical Bone	1.555	1.570 ± 0.002	0.015

Comparison to last year



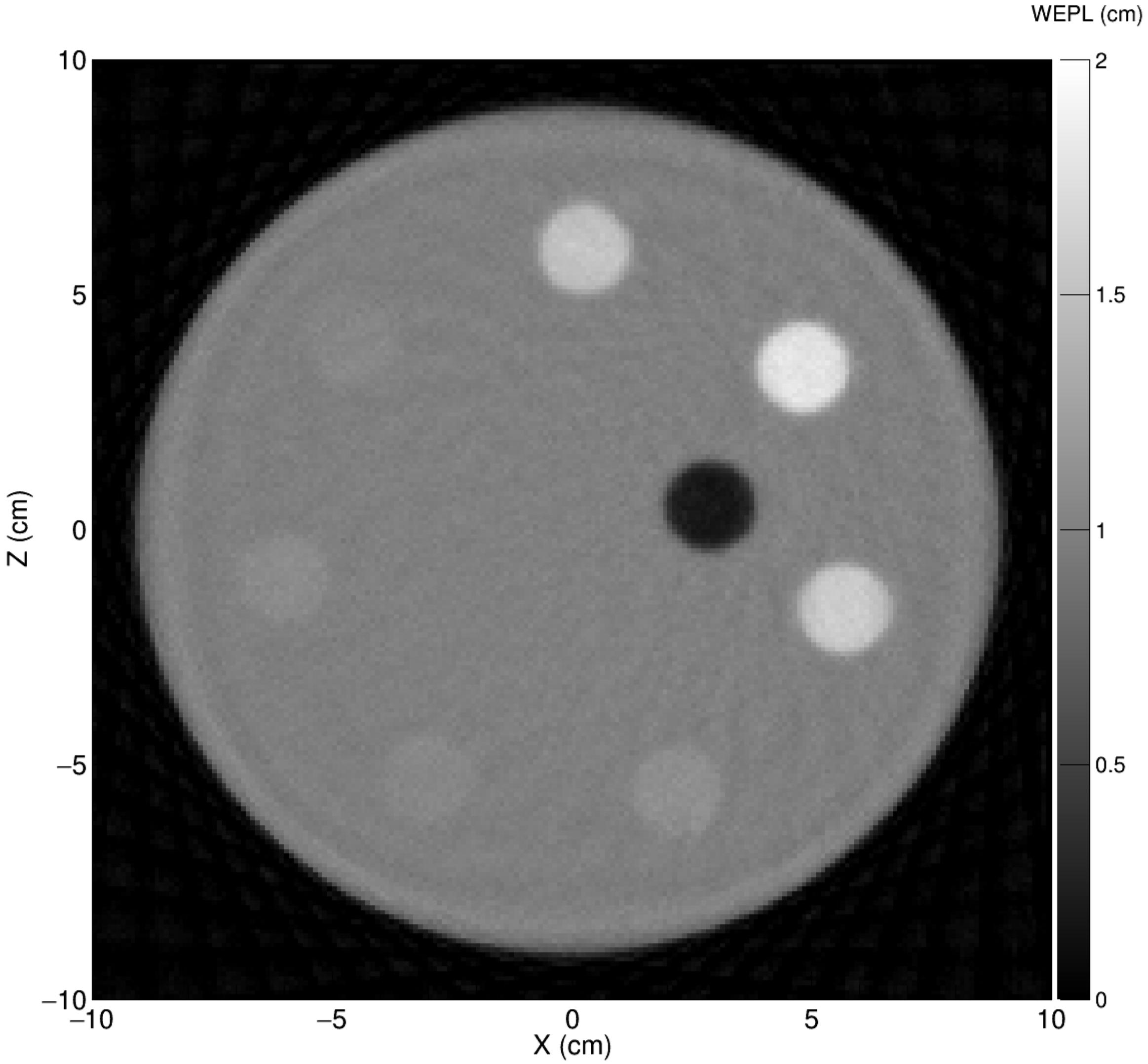
4 degree intervals

How many angles of data do we need?



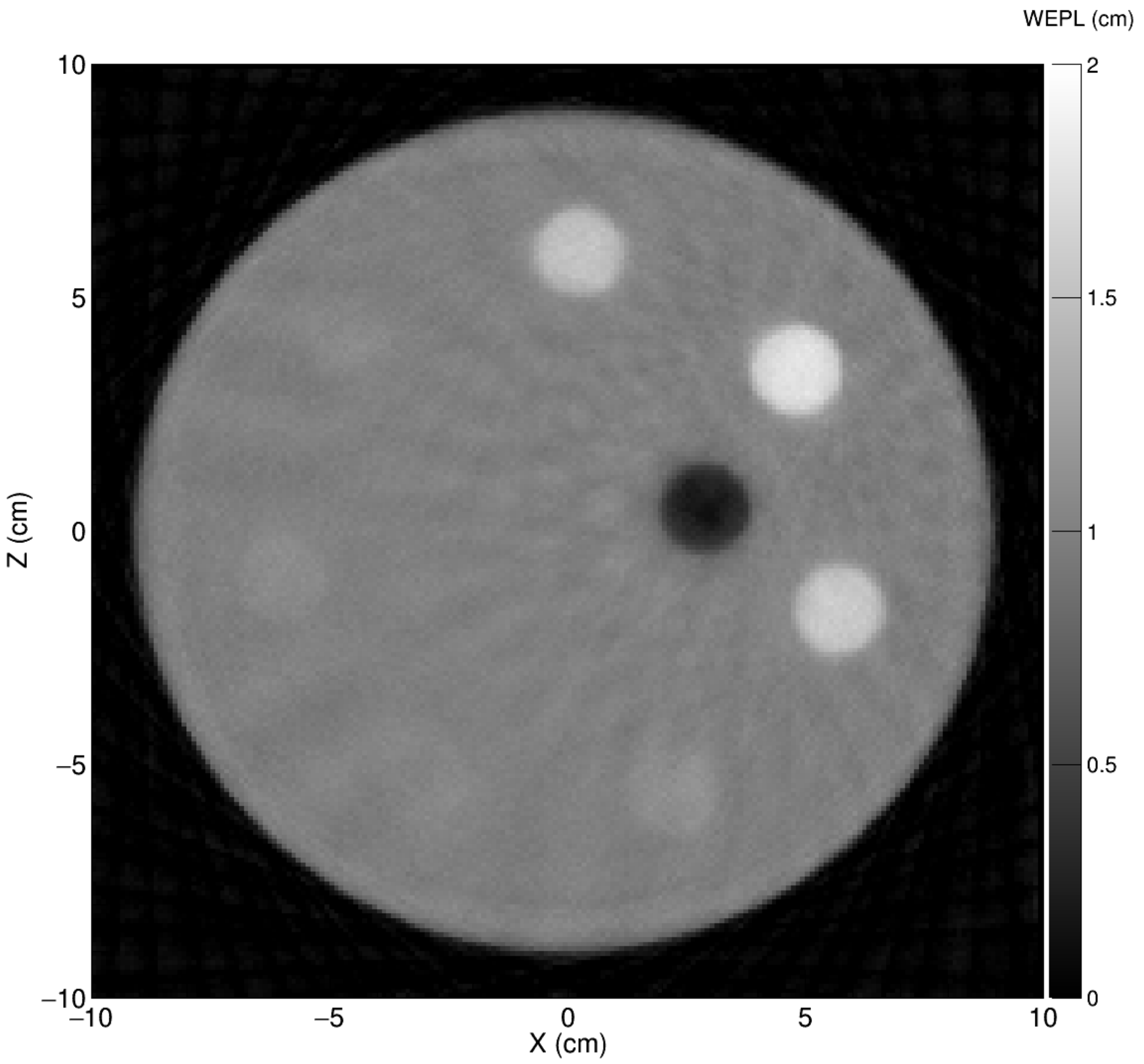
8 degree intervals

How many angles of data do we need?



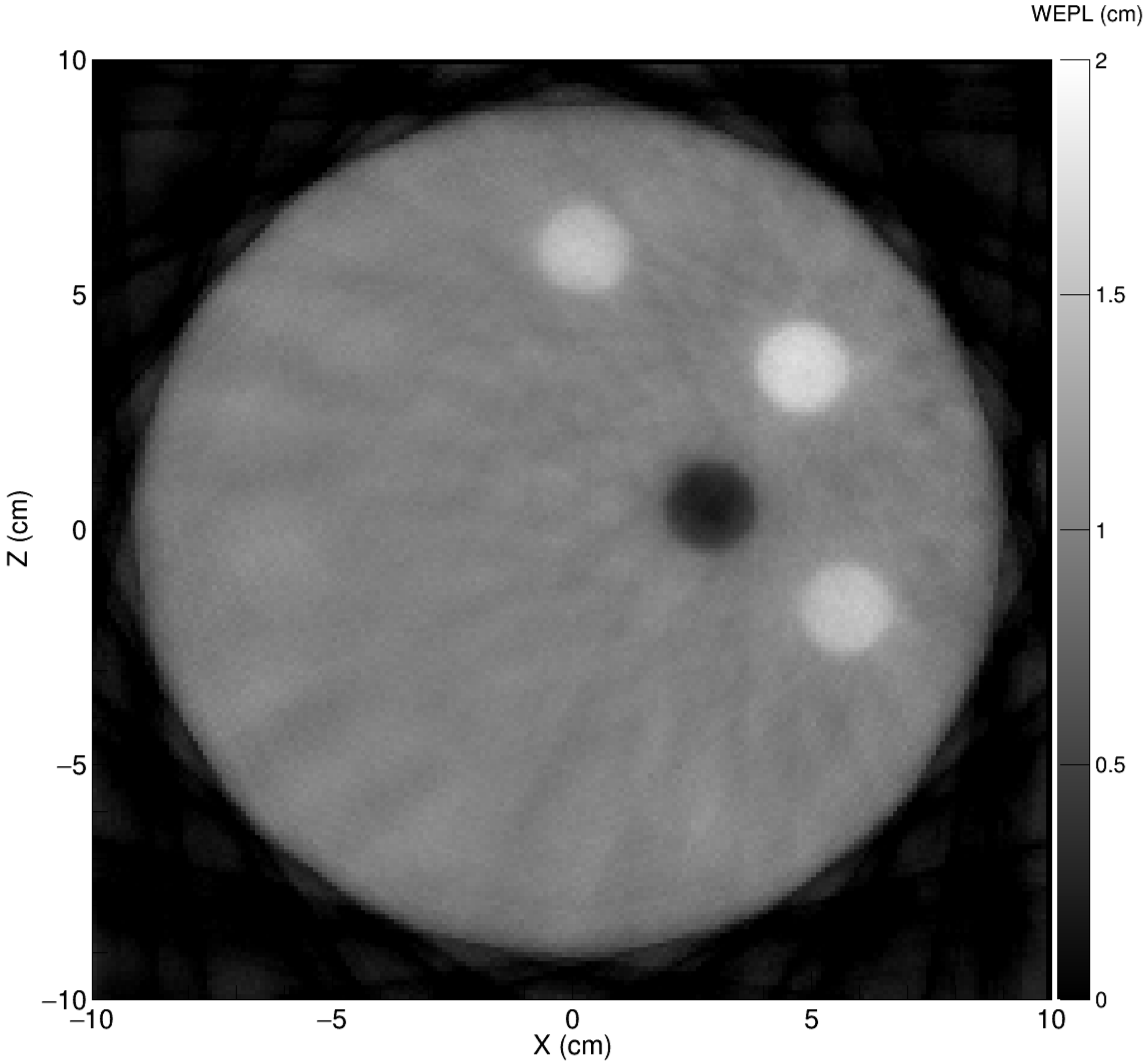
12 degree intervals

How many angles of data do we need?



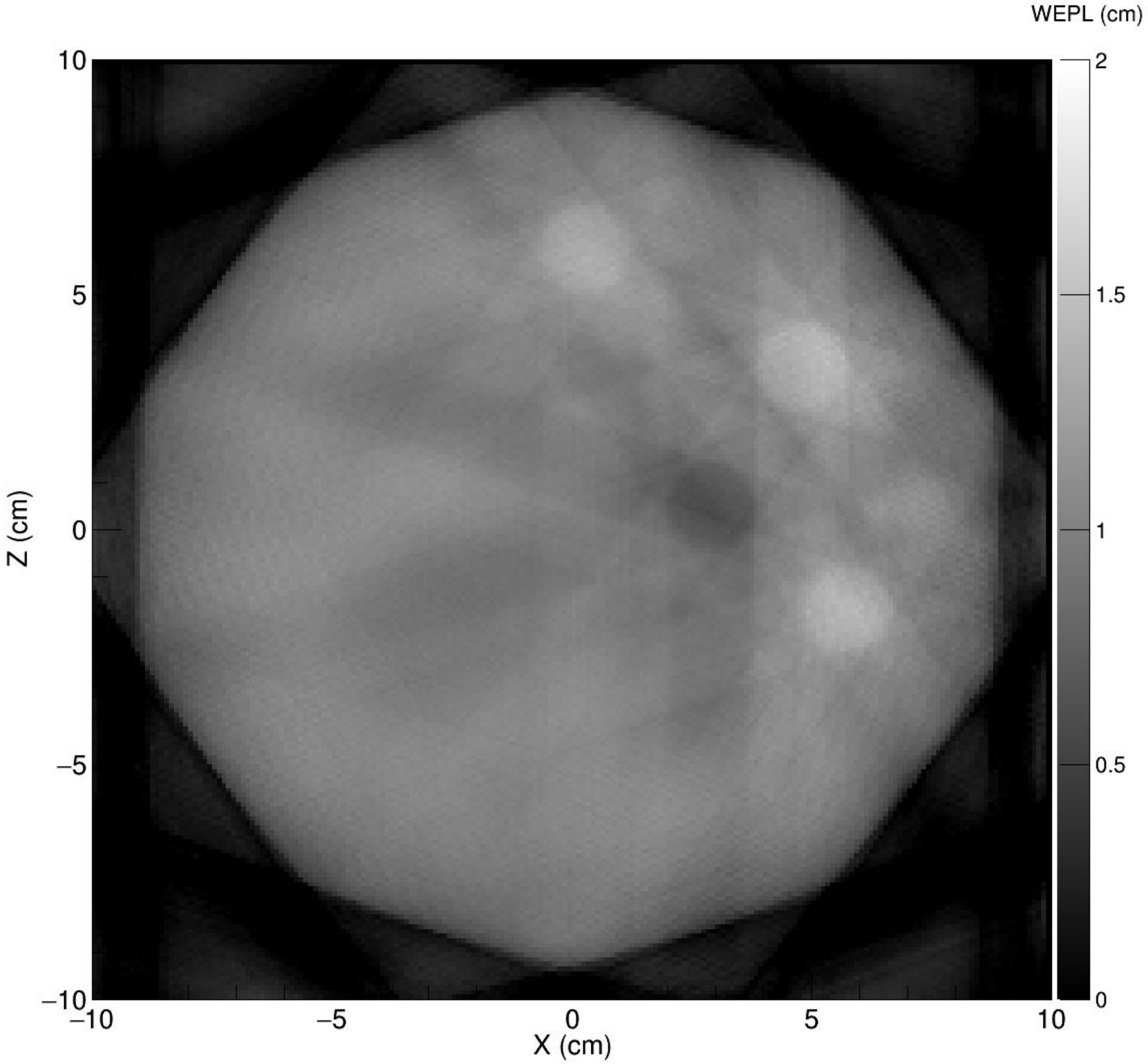
24 degree intervals

How many angles of data do we need?



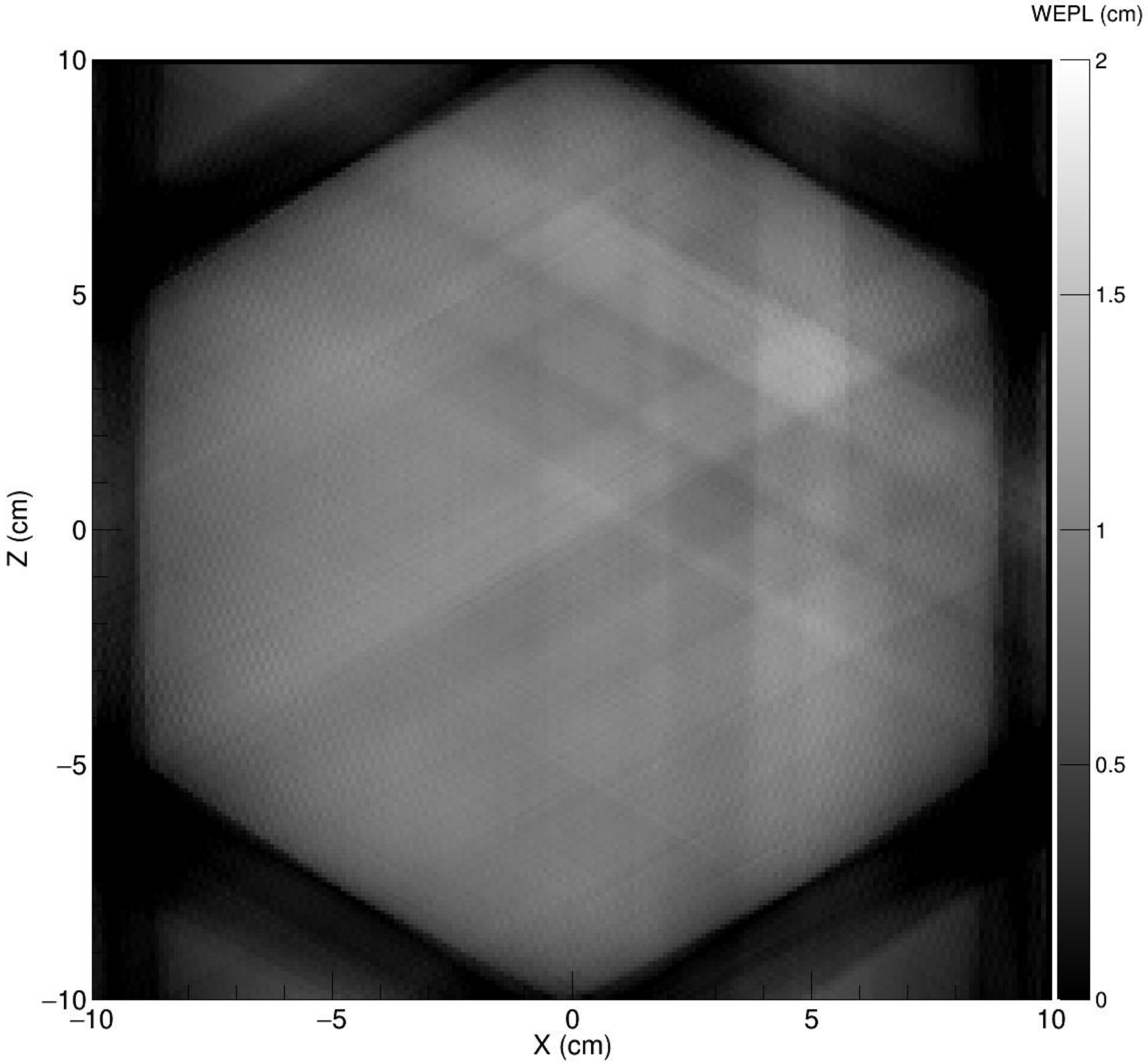
36 degree intervals

How many angles of data do we need?

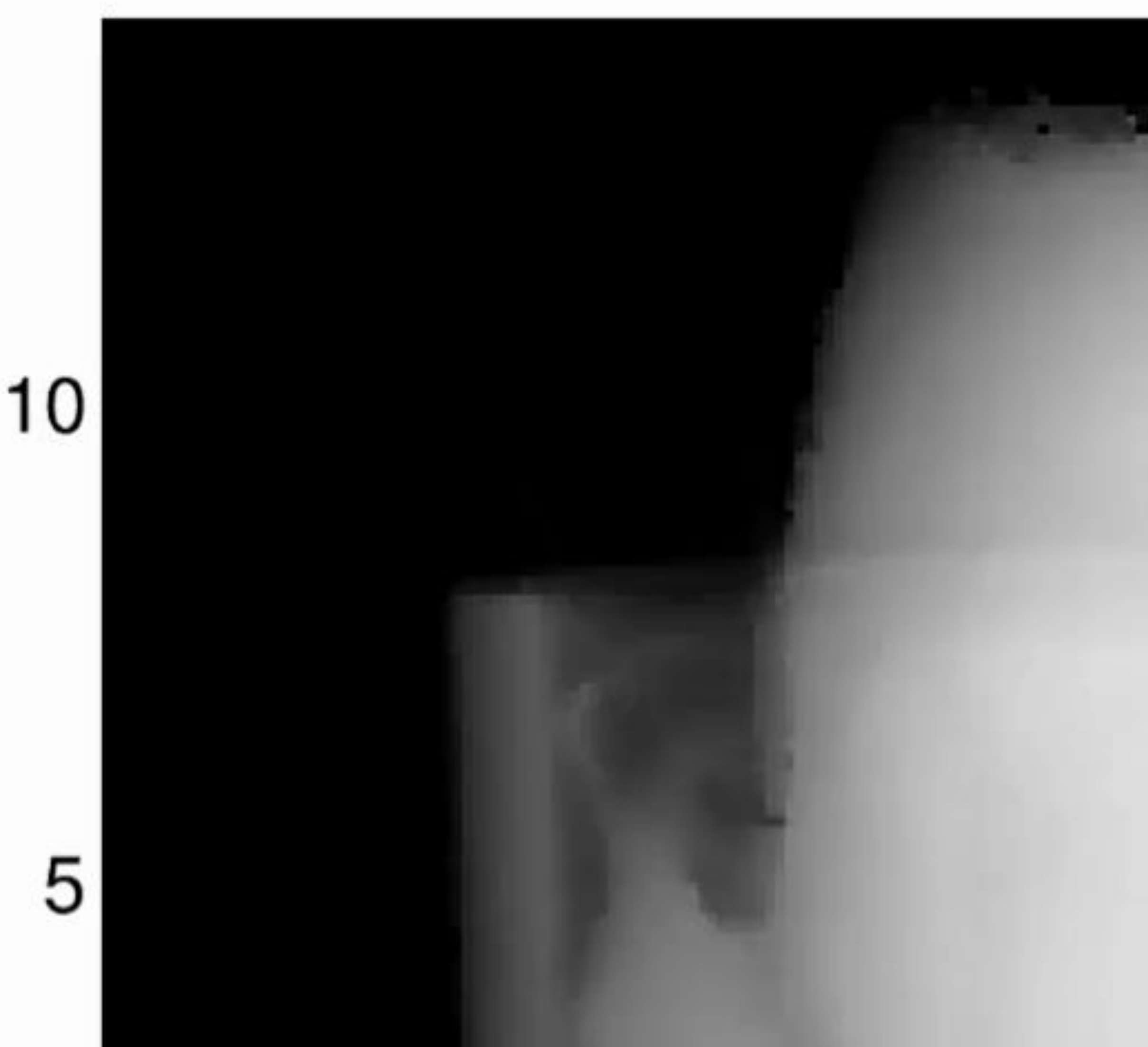


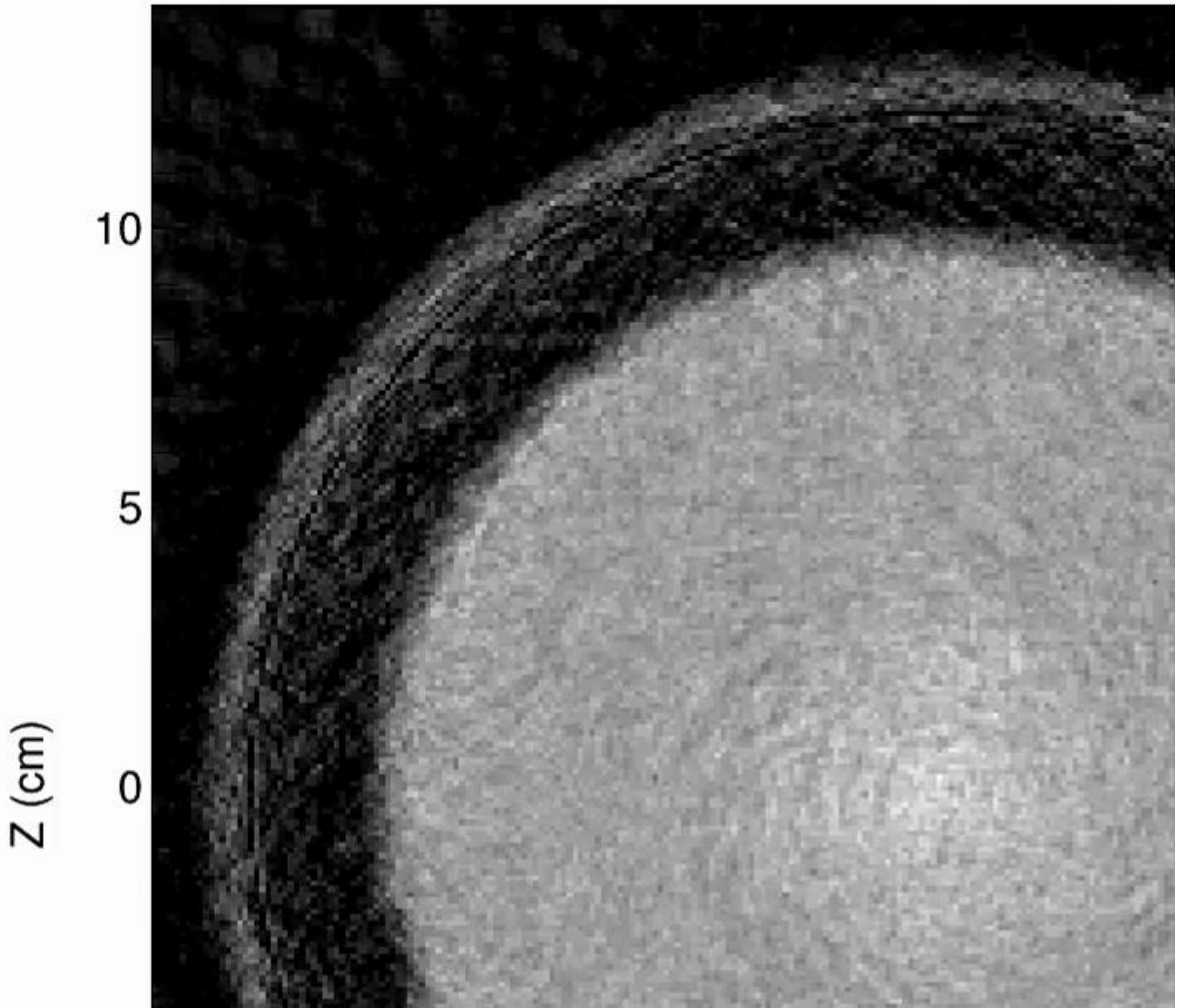
60 degree intervals

How many angles of data do we need?

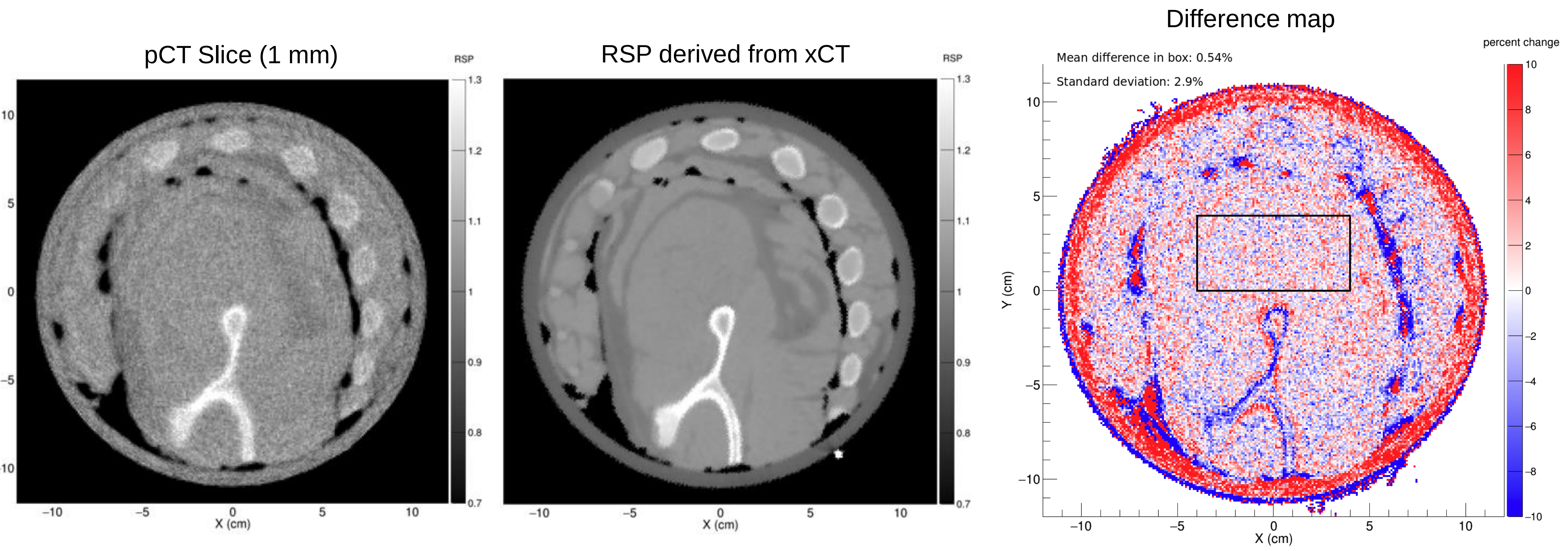


Pork shoulder and ribs
- 4 energies, data taken in 4 degree intervals
- Vertical CT taken for comparison

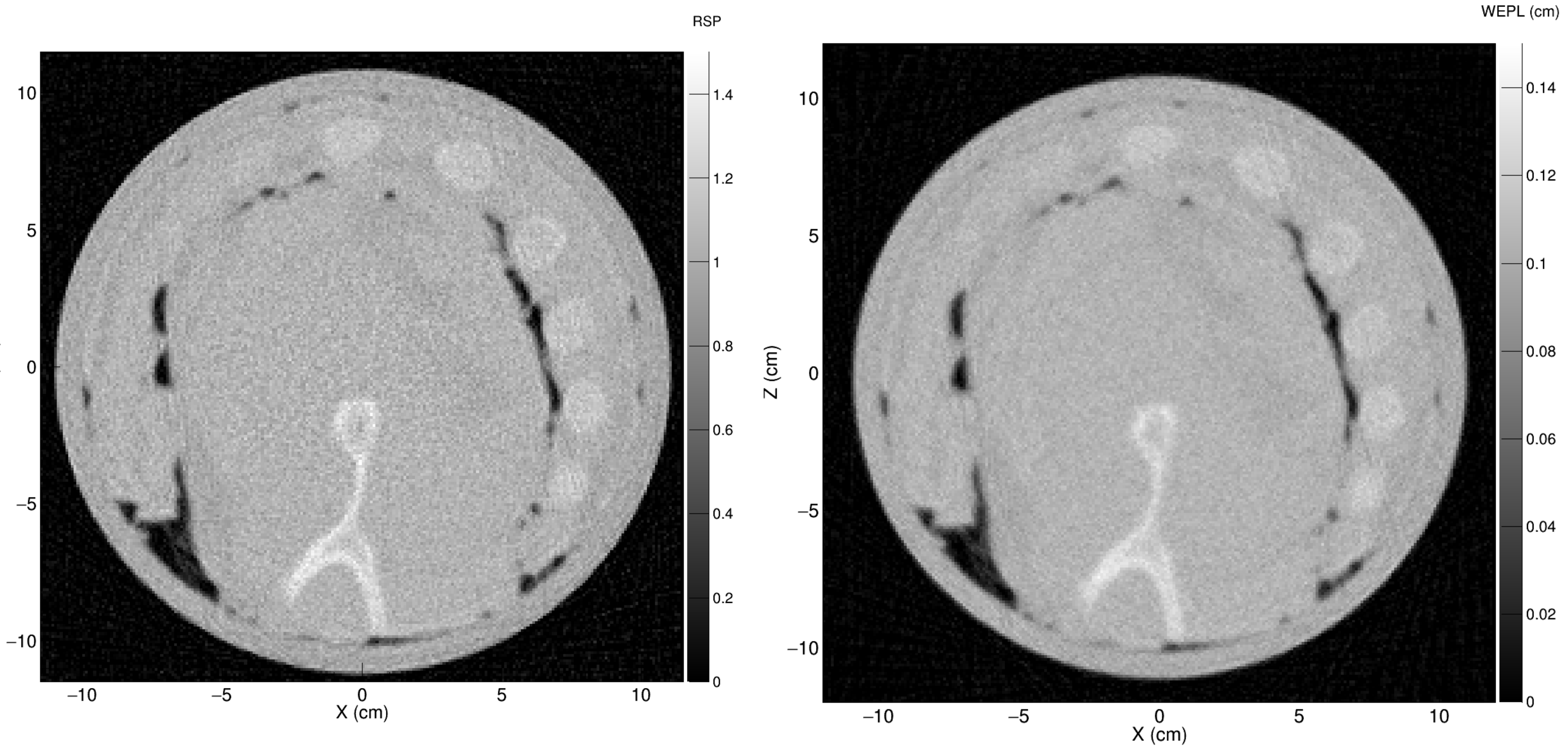




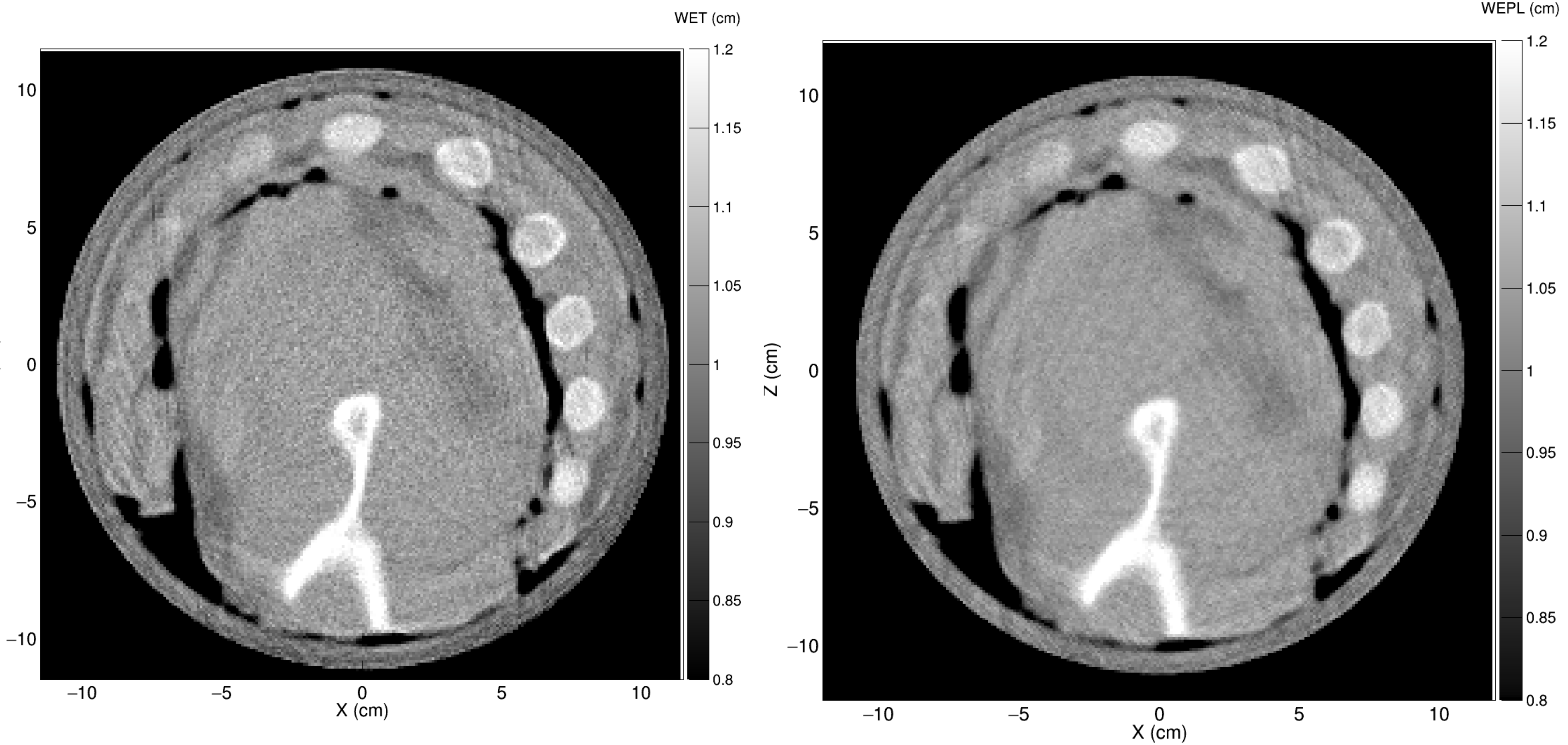
10
5
0
Z (cm)



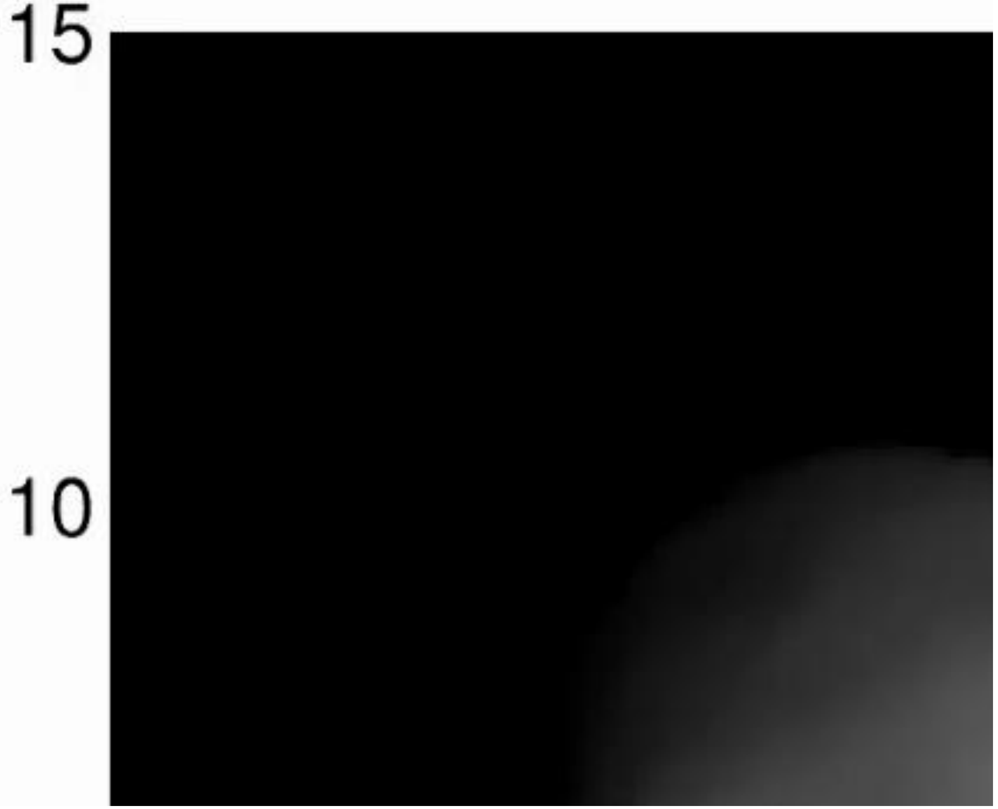
pCT Slice (1 mm)
RSP
1.3
1.2
1.1
1
0.9
0.8
0.7
10
5
0
-5
-10
X (cm)
RSP derived from xCT
Difference map
Mean difference in box: 0.54%
Standard deviation: 2.9%
percent change
Y (cm)



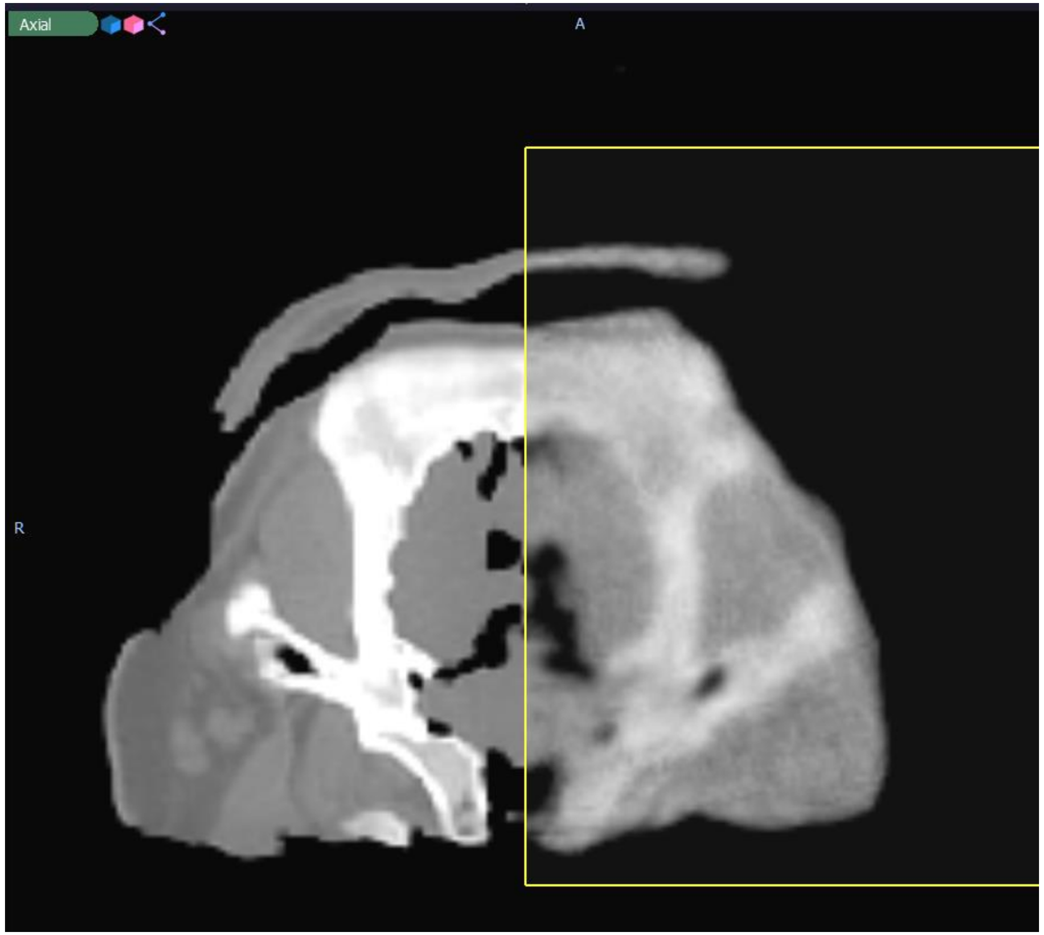
RSP
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10
5
0
−5
−10
X (cm)
WEPL (cm)
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Z (cm)
10
5
0
−5
−10
X (cm)



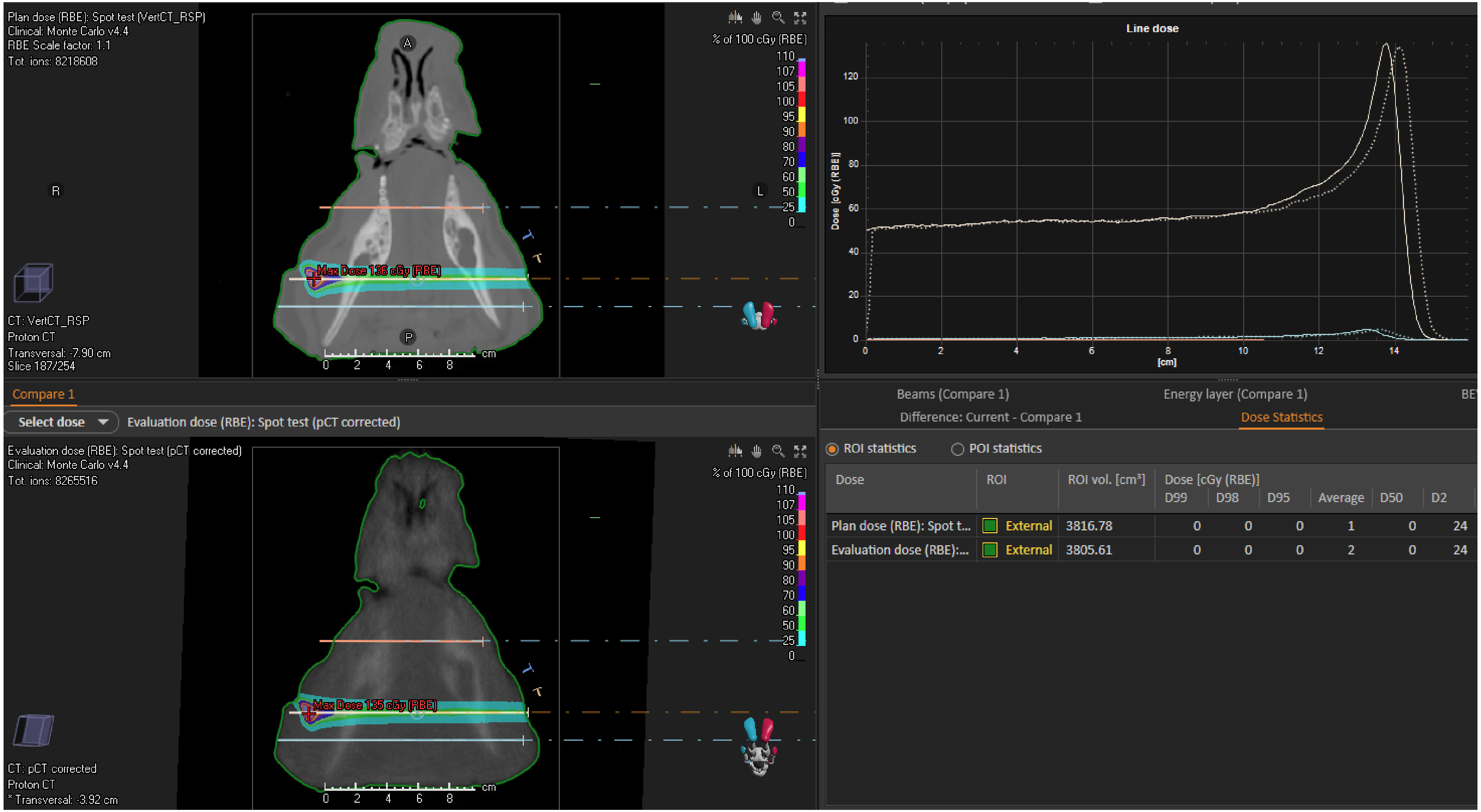
WET (cm)
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
10
5
0
−5
−10
−10
−5
0
5
10
X (cm)
WEPL (cm)
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
Z (cm)
10
5
0
−5
−10
−10
−5
0
5
10
X (cm)


15
10


15
10
10
5
10
5

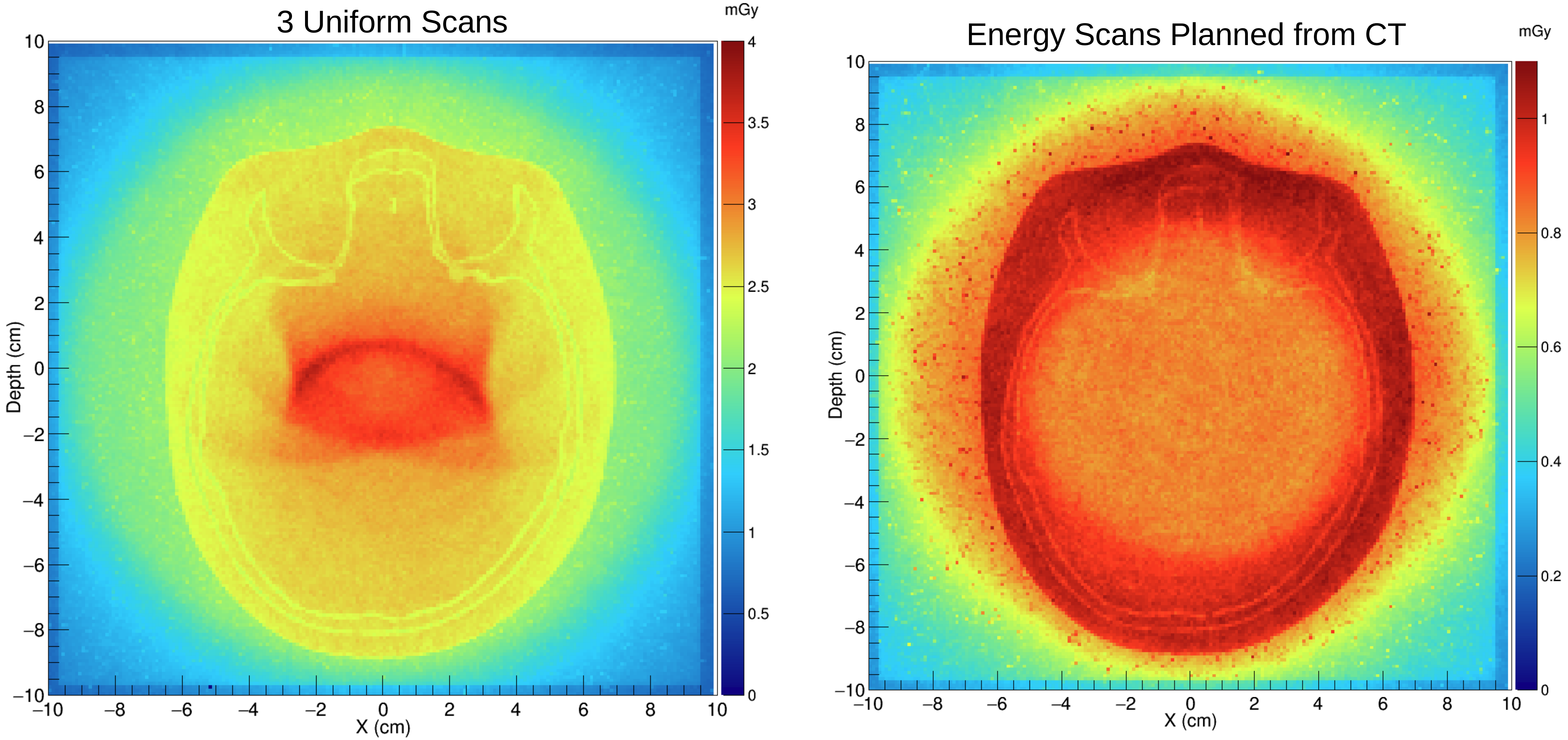

Axial
A
R


Axial
A
R



Plan dose (RBE): Spot test (VertCT_RSP)
Clinical: Monte Carlo v4.4
RBE Scale factor: 1.1
Tot. ions: 8218608
% of 100 cGy (RBE)
110 107 105 100 95 90 80 70 60 50 25 0
R
L
A
P
Max Dose 136 cGy (RBE)
CT: VertCT_RSP
Proton CT
Transversal: -7.90 cm
Slice 187/254
0 2 4 6 8 cm
Line dose
Dose [cGy (RBE)]
[cm]
Compare 1
Select dose
Evaluation dose (RBE): Spot test (pCT corrected)
Evaluation dose (RBE): Spot test (pCT corrected)
Clinical: Monte Carlo v4.4
Tot. ions: 8265516
Max Dose 135 cGy (RBE)
CT: pCT corrected
Proton CT
* Transversal: -3.92 cm
Beams (Compare 1)
Energy layer (Compare 1)
Difference: Current - Compare 1
Dose Statistics
ROI statistics
POI statistics
Dose | ROI | ROI vol. [cm³] | Dose [cGy (RBE)] D99 | D98 | D95 | Average | D50 | D2
Plan dose (RBE): Spot t... | External | 3816.78 | 0 | 0 | 0 | 1 | 0 | 24
Evaluation dose (RBE):... | External | 3805.61 | 0 | 0 | 0 | 2 | 0 | 24

Simulated pCT dose for pediatric head phantom using three energies



ProtonVDA

TRANSFORMING PROTON THERAPY

Summary/Conclusions

- Our prototype proton radiography system produces accurate WET maps through an automatic, clinically practical process
- Images can be automatically reconstructed and displayed in isocenter coordinates
- Our system is capable of detecting very small variations and changes in WET
- Spatial resolution of <1 mm has been achieved, offering the potential for proton radiographs to be used for patient alignment in addition to range verification
- Initial pCT results show good RSP accuracy and ability to detect small features
- Work is being planned for automating pCT reconstruction
- We look forward to seeing this technology integrated into clinical use