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

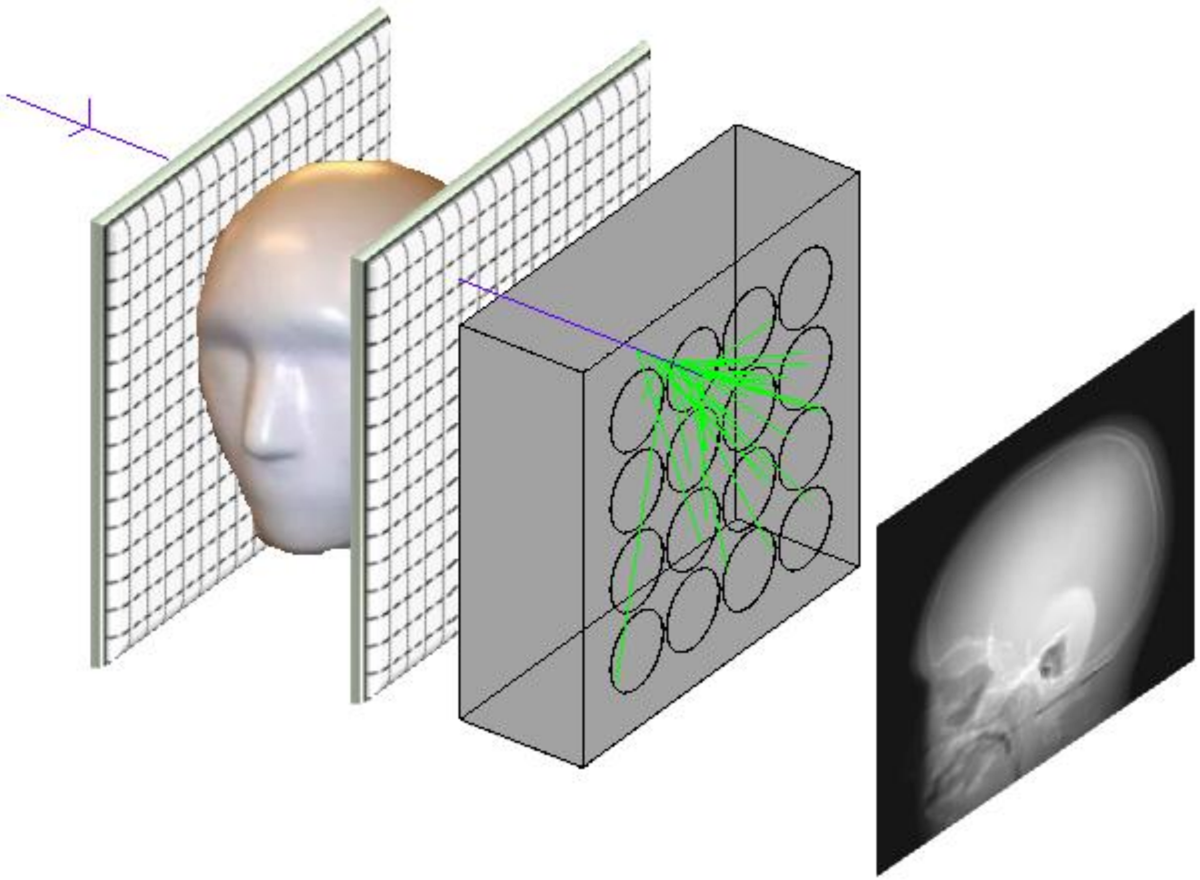
We aim to:

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

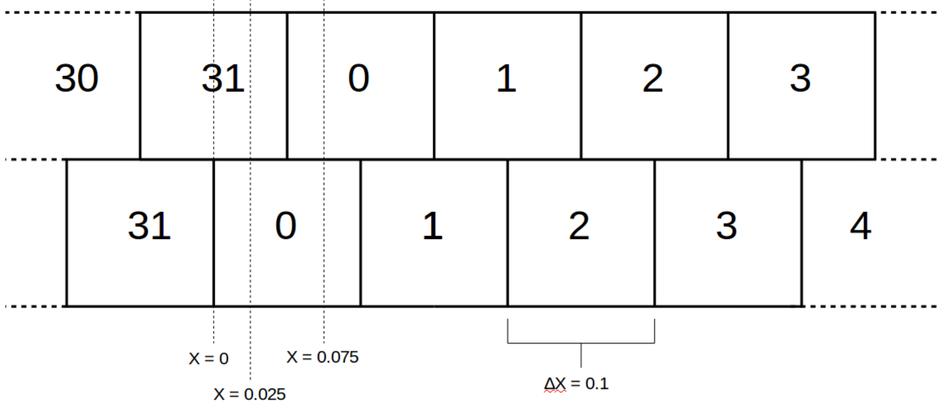
1. $\rightarrow$ High-performance, low-cost measurements of proton range.
2. Achieve lower dose to the patient relative to equivalent x-ray images.
3. Produce spatially sharp images.
4. Images free of artifacts from high-Z implants.

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



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

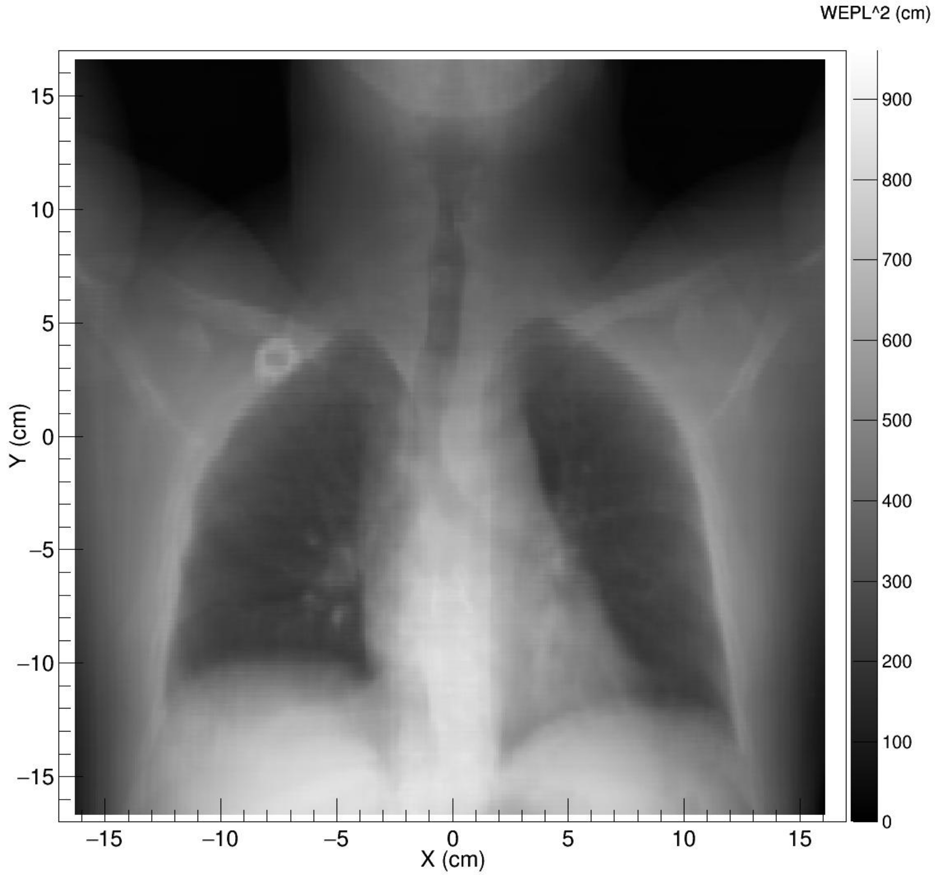
- 40 x 40 x 13 cm block of scintillator for range detector
  - 4 x 4 array of PMTs
  - Output digitized into four channels: E, U, V,C

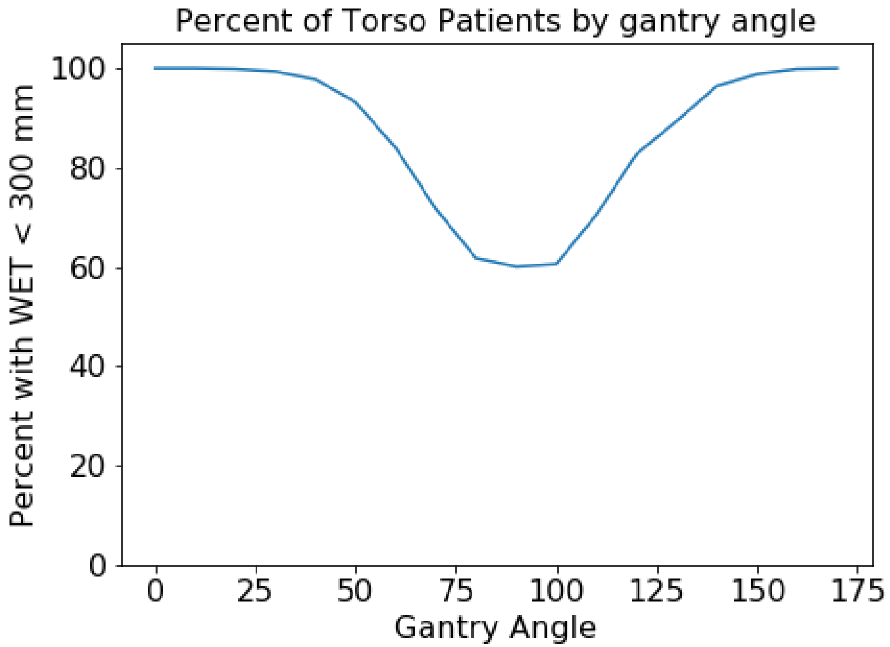
- Individual protons tracked at up 10 MHz
- > 99% tracking efficiency
- WEPL resolution ~ 3 mm per proton
- 40 x 40 cm image field size
- Fast (<1 min) image reconstruction for radiograph

From e-poster, C. Sarosiek M. Pankuch, et al

"Distribution of patients that can be imaged with 235 MeV protons"

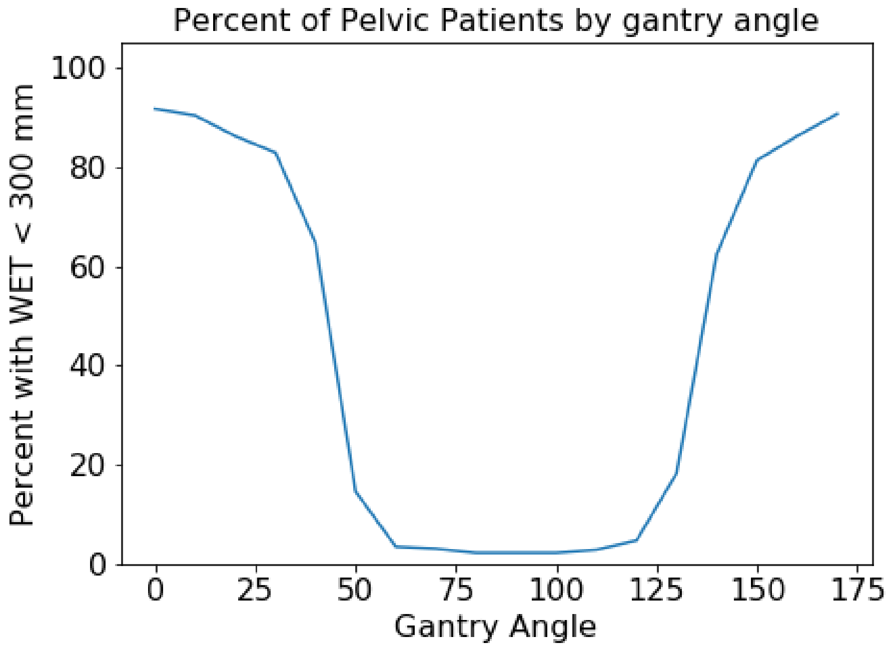
Analysis of recent Northwestern patients
Simulated proton radiographs from x-ray CT scans



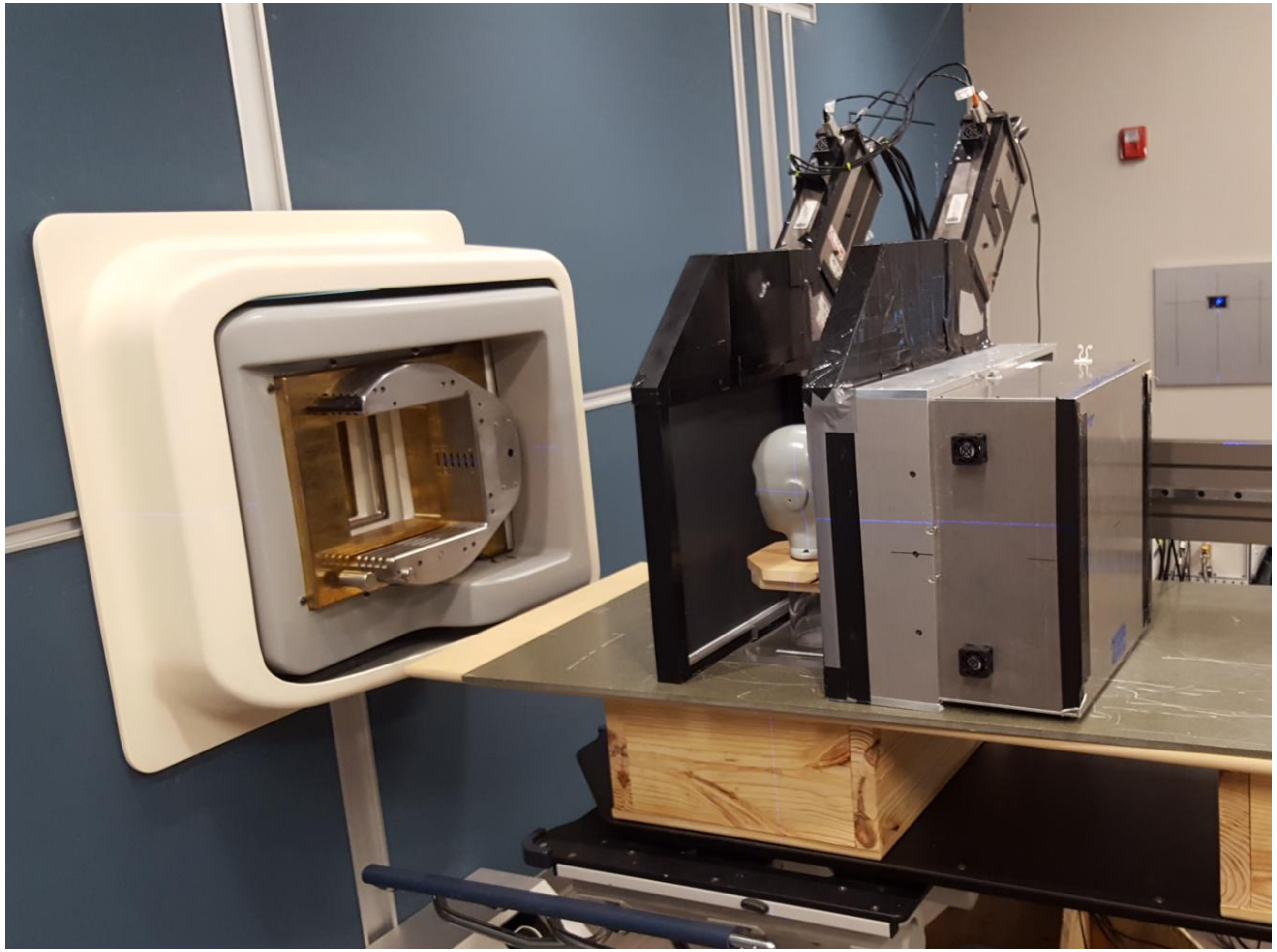


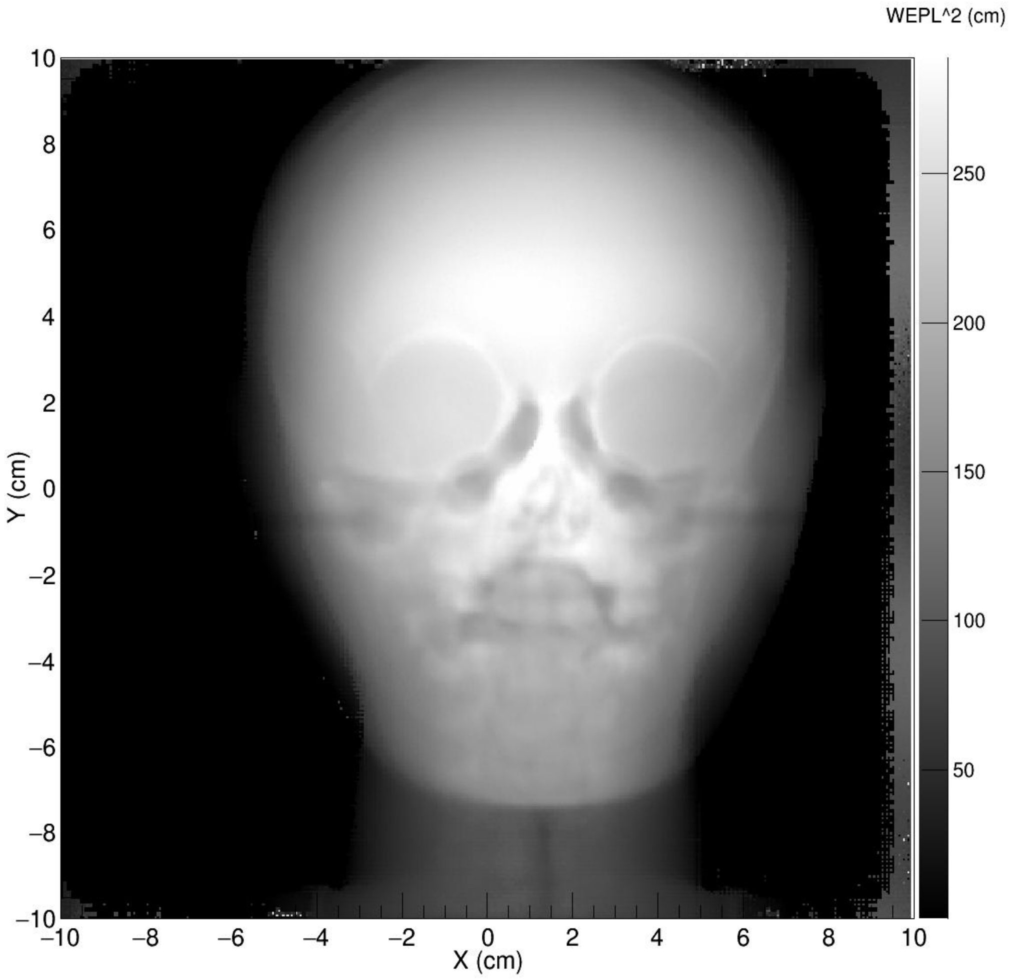
Almost 100% of head/neck patients can be imaged at all angles

Majority of torso patients can be imaged at all angles



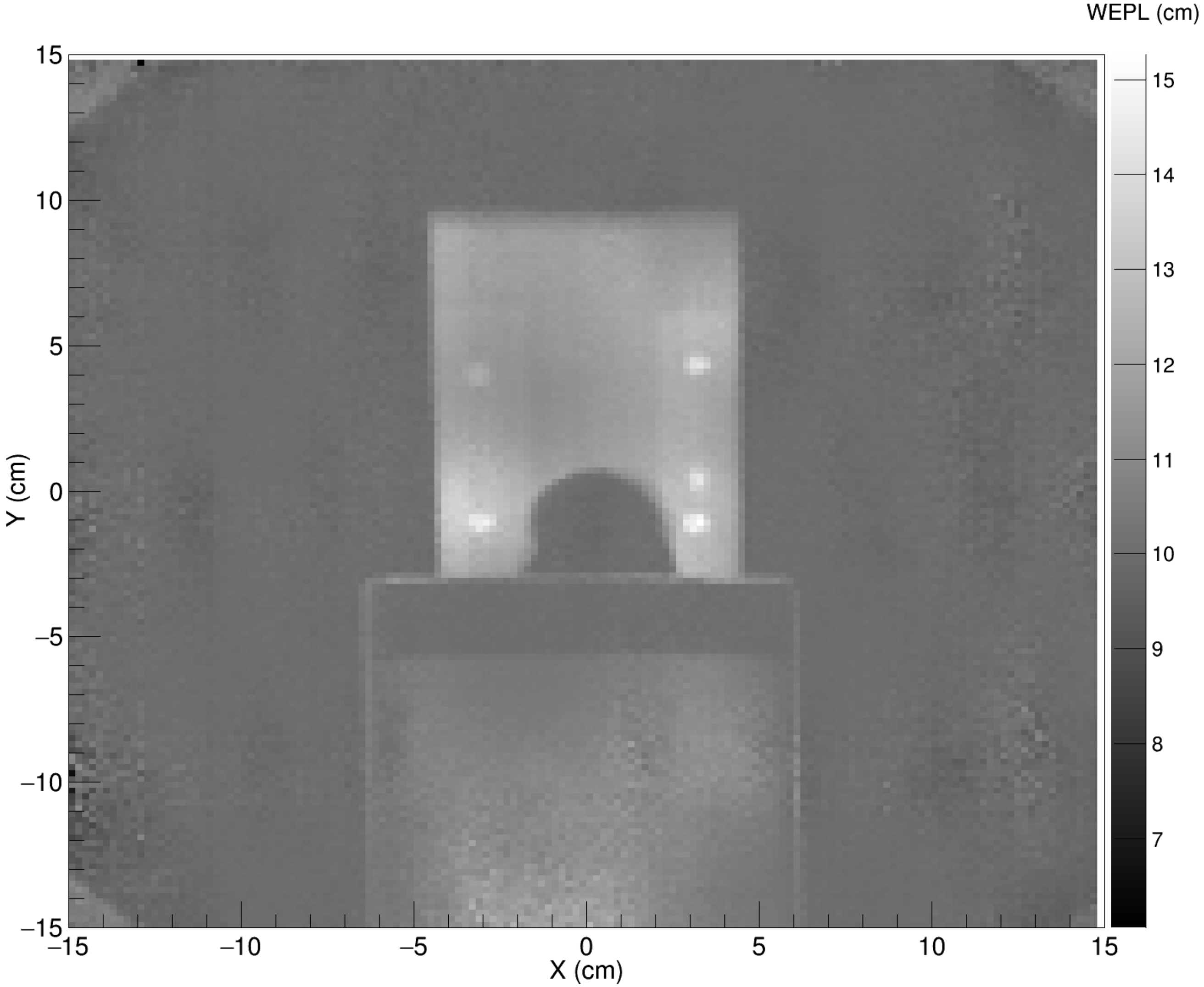
Most pelvic patients can be imaged with a range of angles



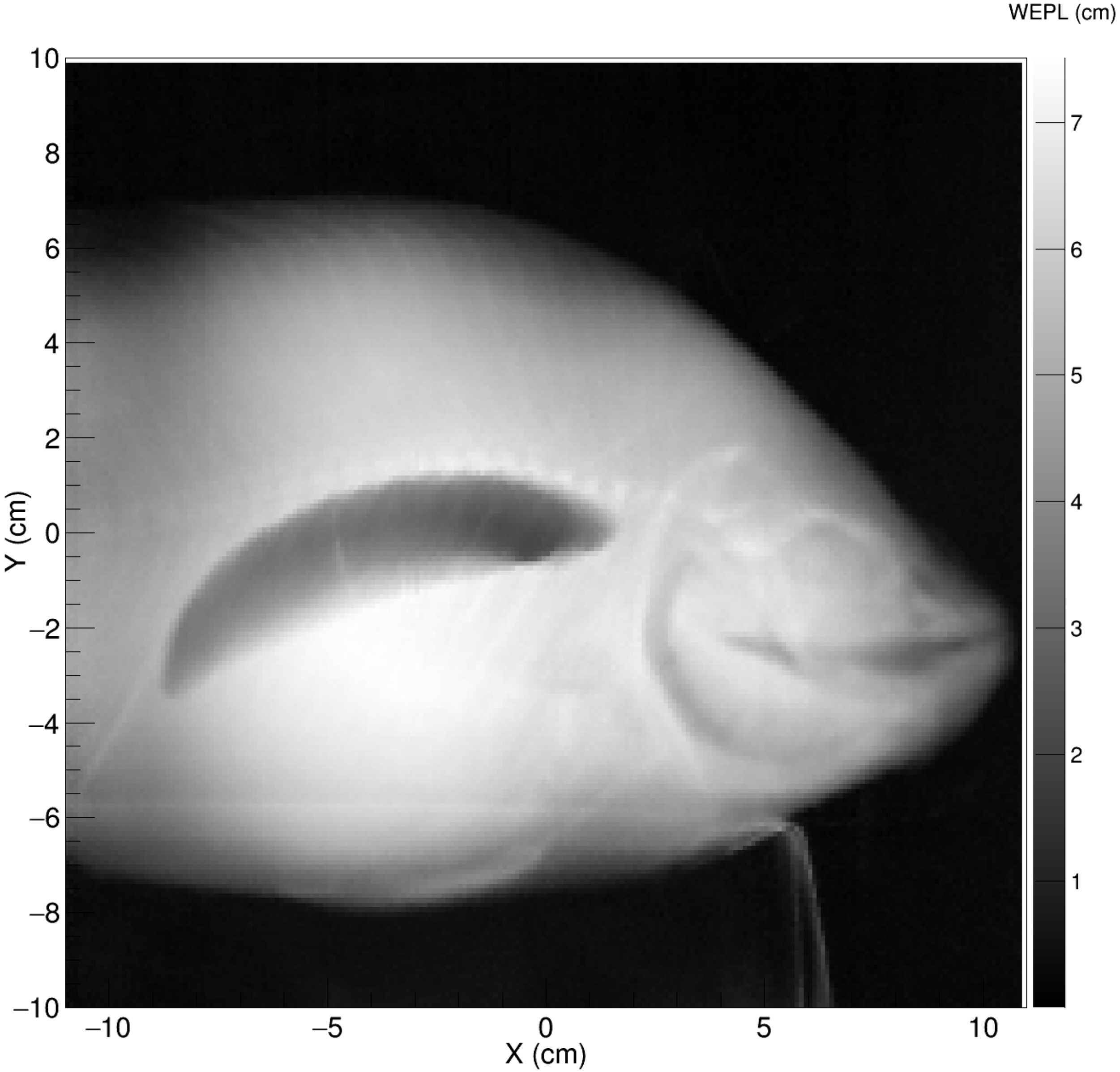

WEPL^2 (cm)
Y (cm)
X (cm)
10
8
6
4
2
0
−2
−4
−6
−8
−10
−10
−8
−6
−4
−2
0
2
4
6
8
10
250
200
150
100
50

Our first real image – block of wood with screws

- Single 120 MeV Scan

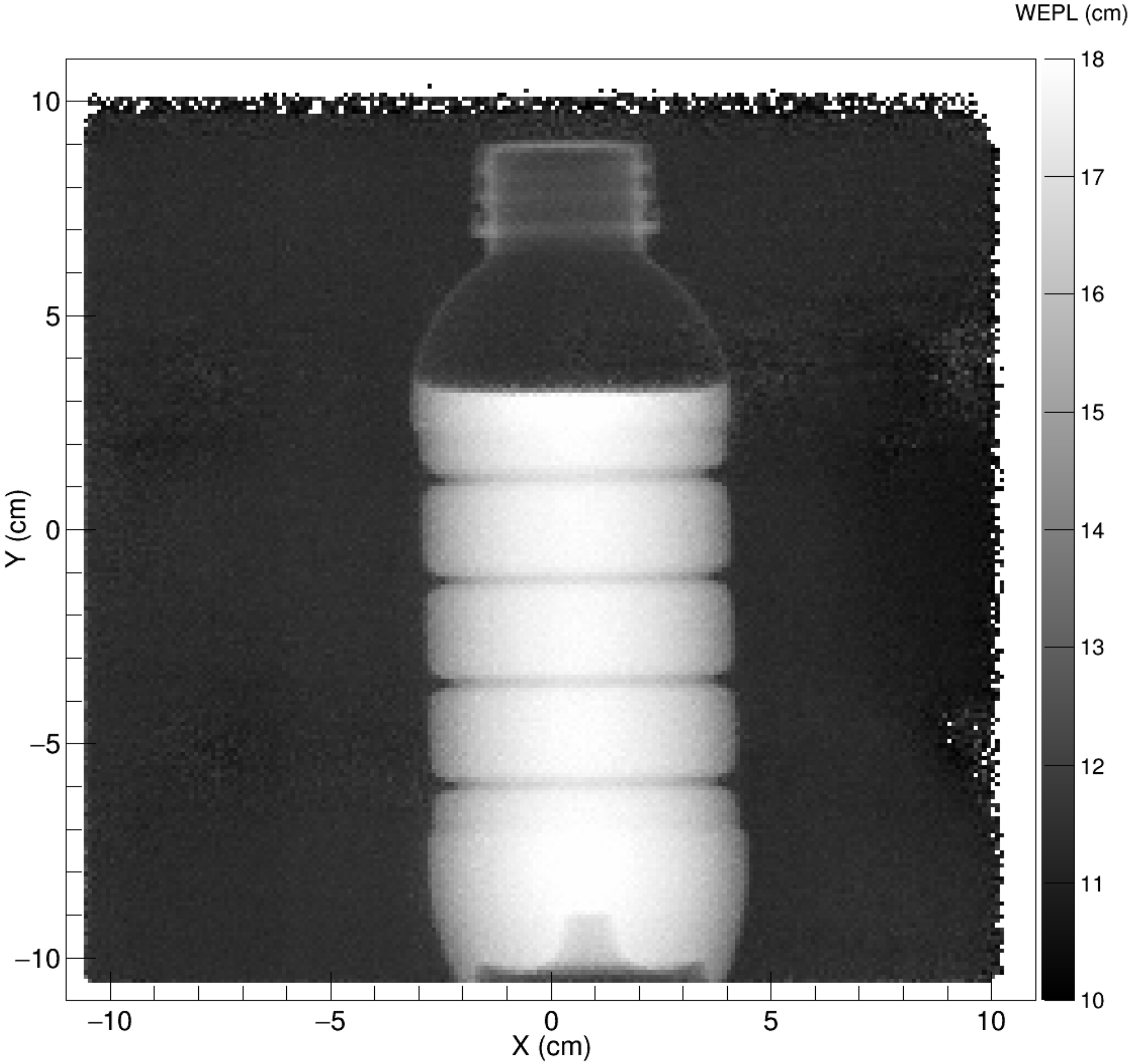


Frozen fish image – 120 MeV

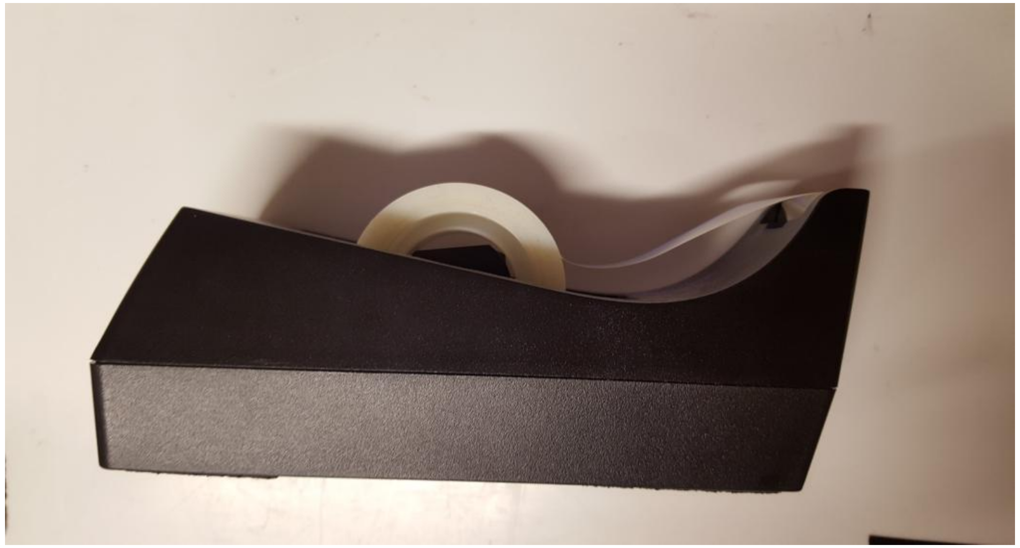


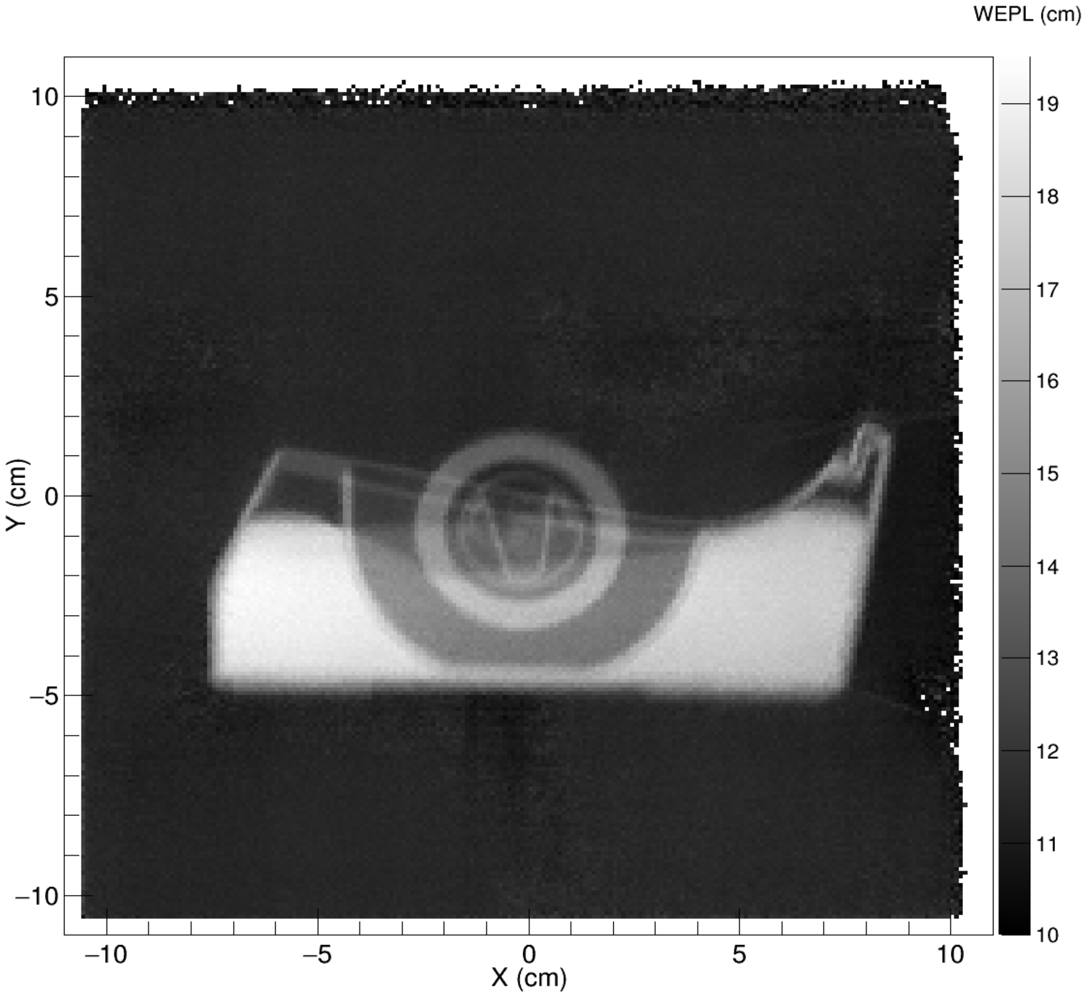
Fast (~ 1 min) online image reconstruction

Water bottle plus solid water – 180 MeV

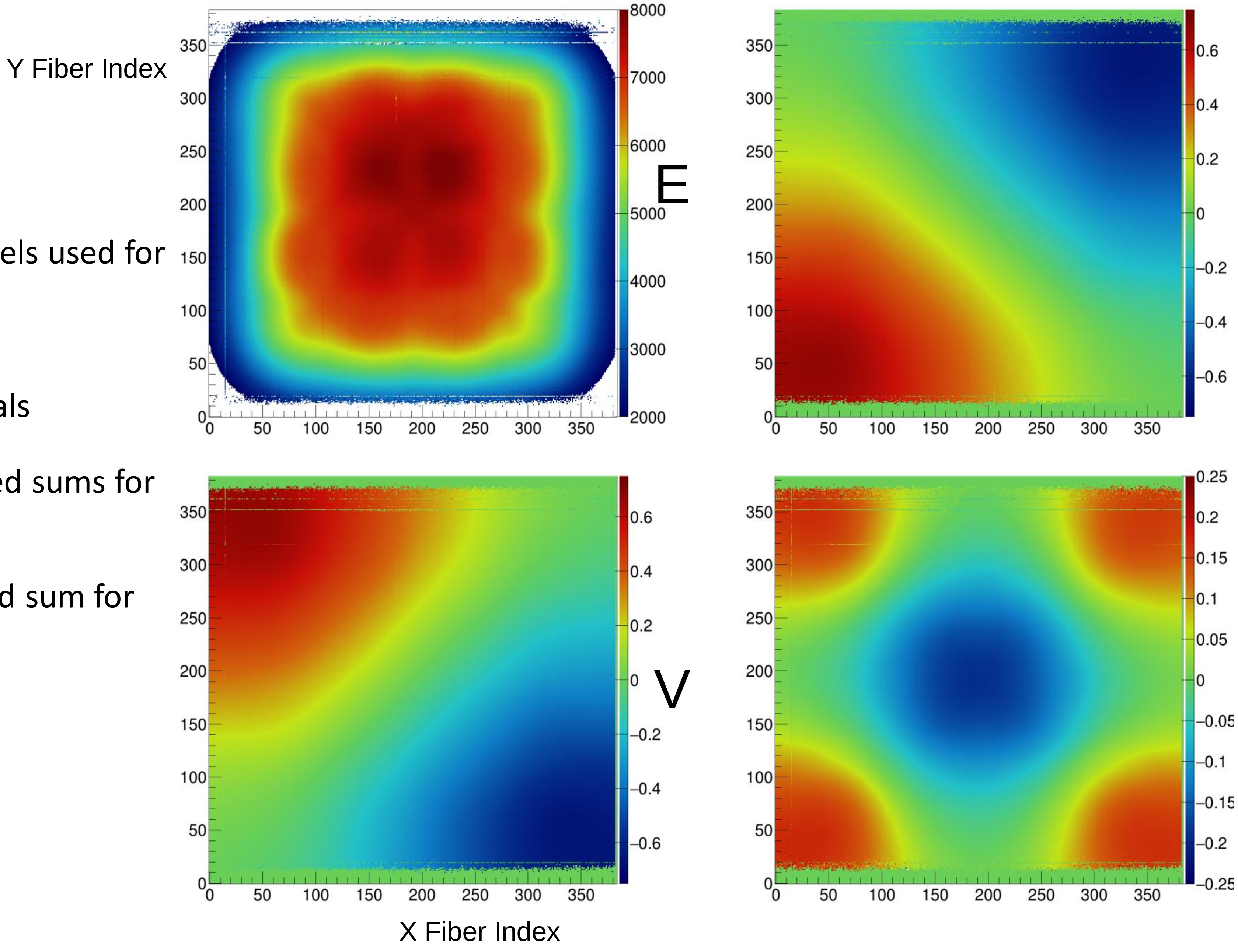


Tape dispenser plus solid water – 180 MeV

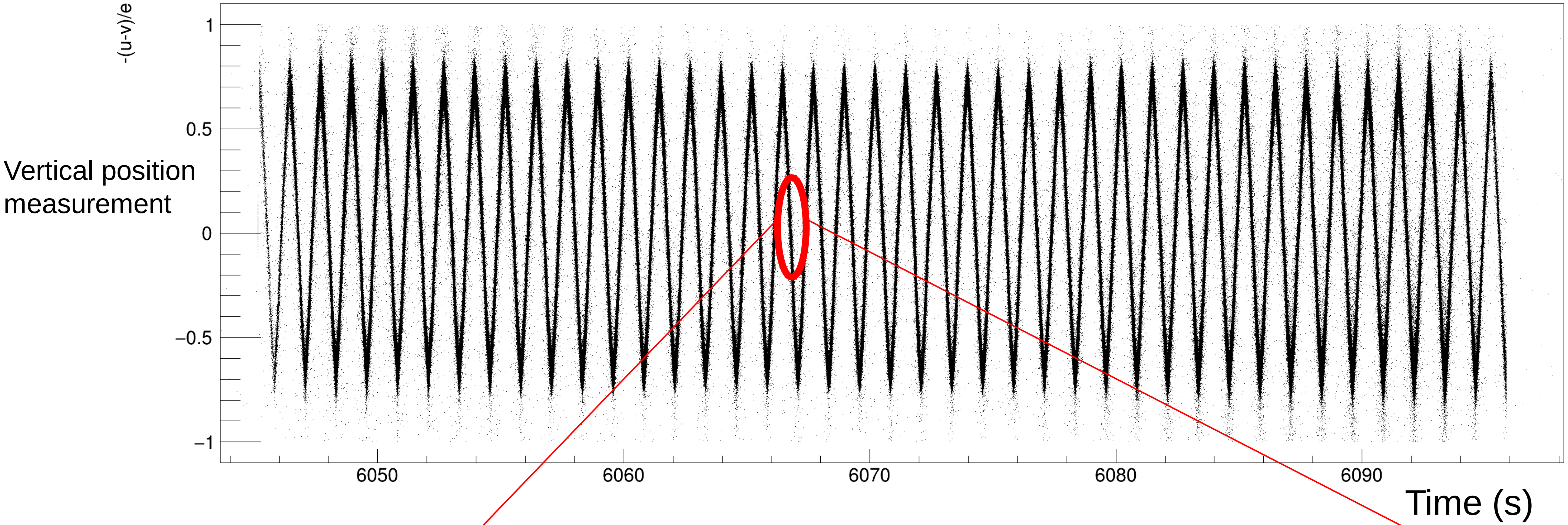




Uniform scan of 116.4 MeV protons across range detector

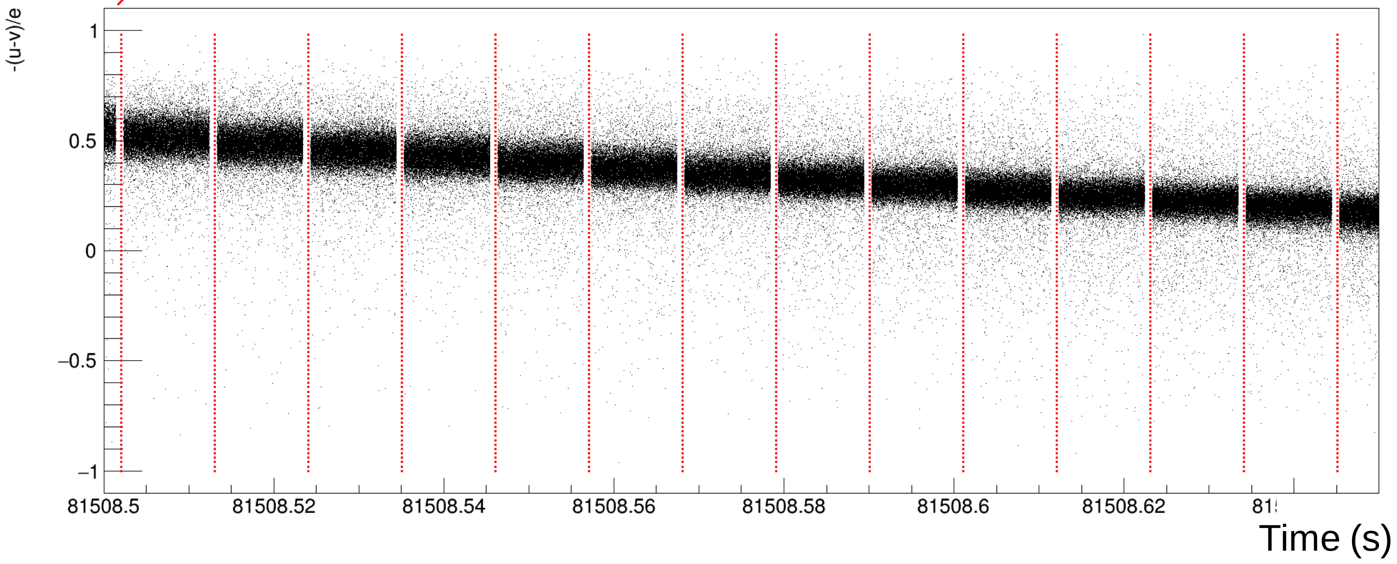


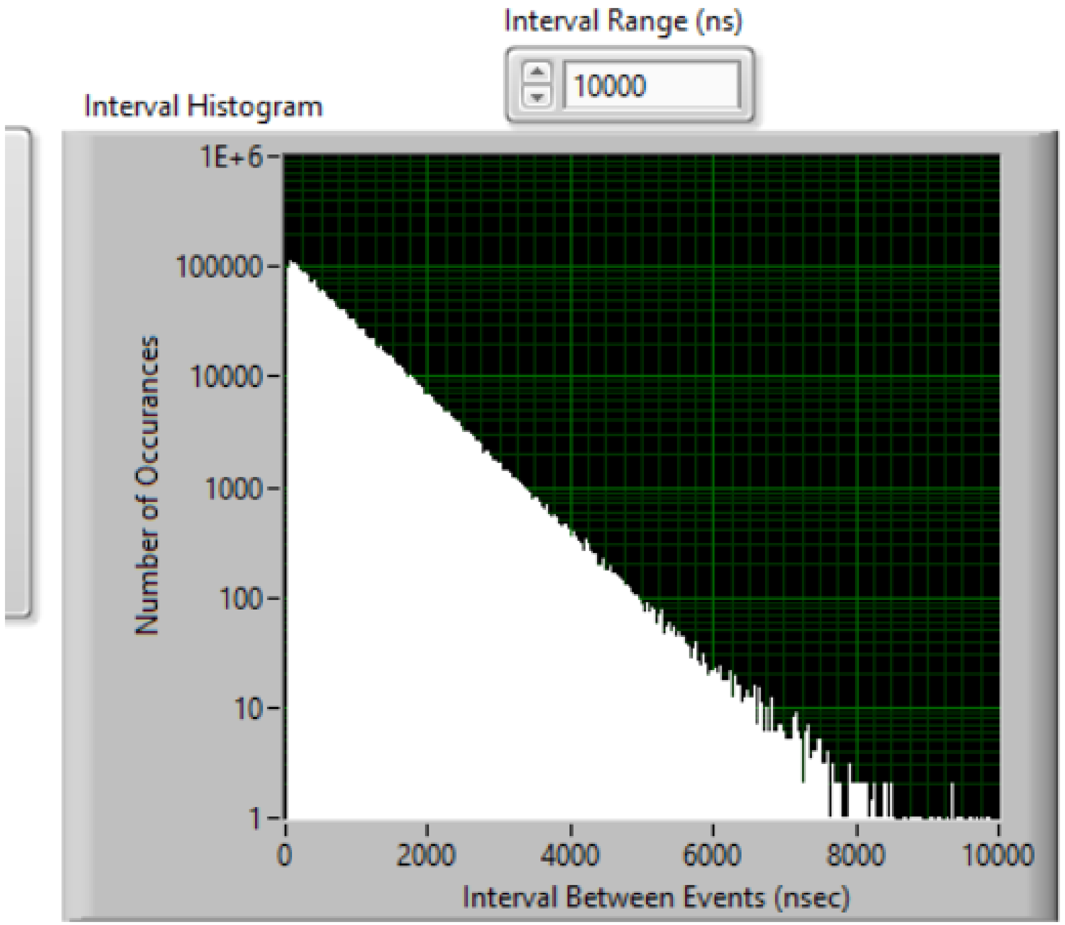
- Four range detector channels used for range measurement and cuts/corrections
- E – sum of all 16 PMT signals
- U & V – diagonally weighted sums for position information
- C – Inside-outside weighted sum for radial information

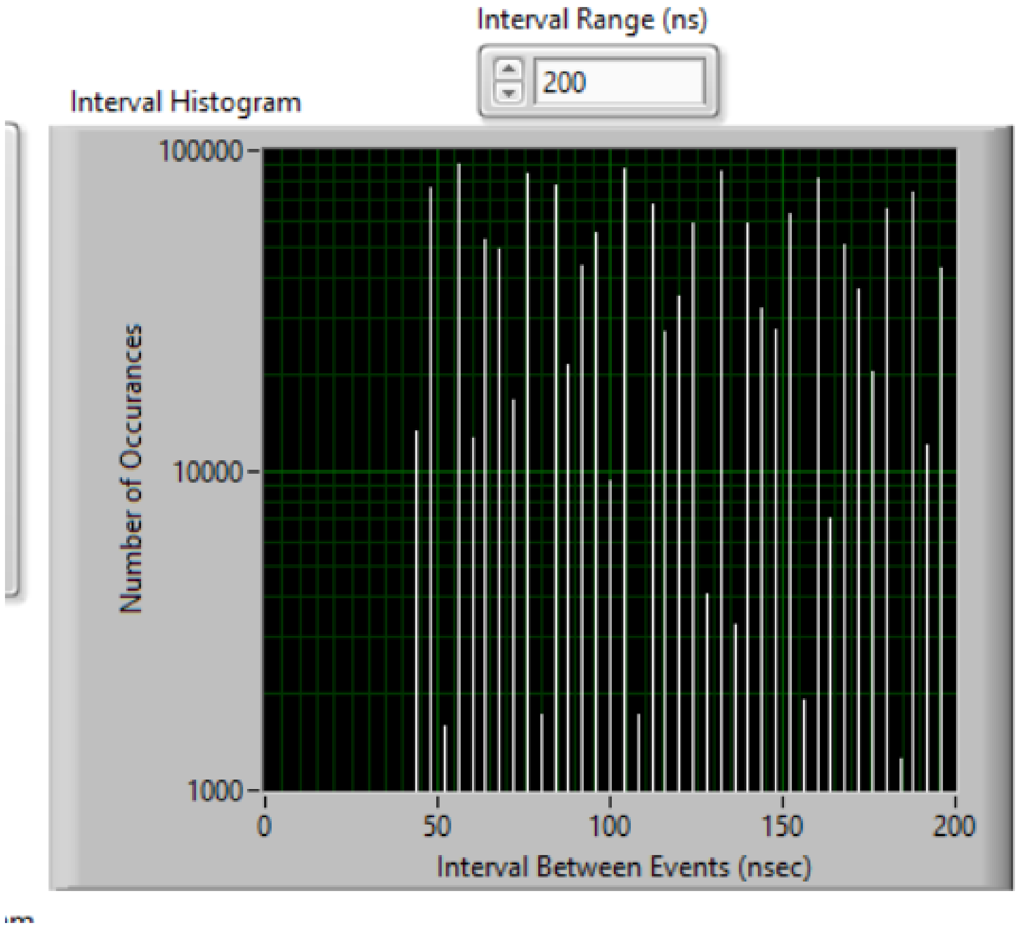


- Individual protons from a pencil beam scan are tracked and sorted into beam spots based on time recorded since the beginning of the scan

- Vertical lines indicate beam dwell time per spot





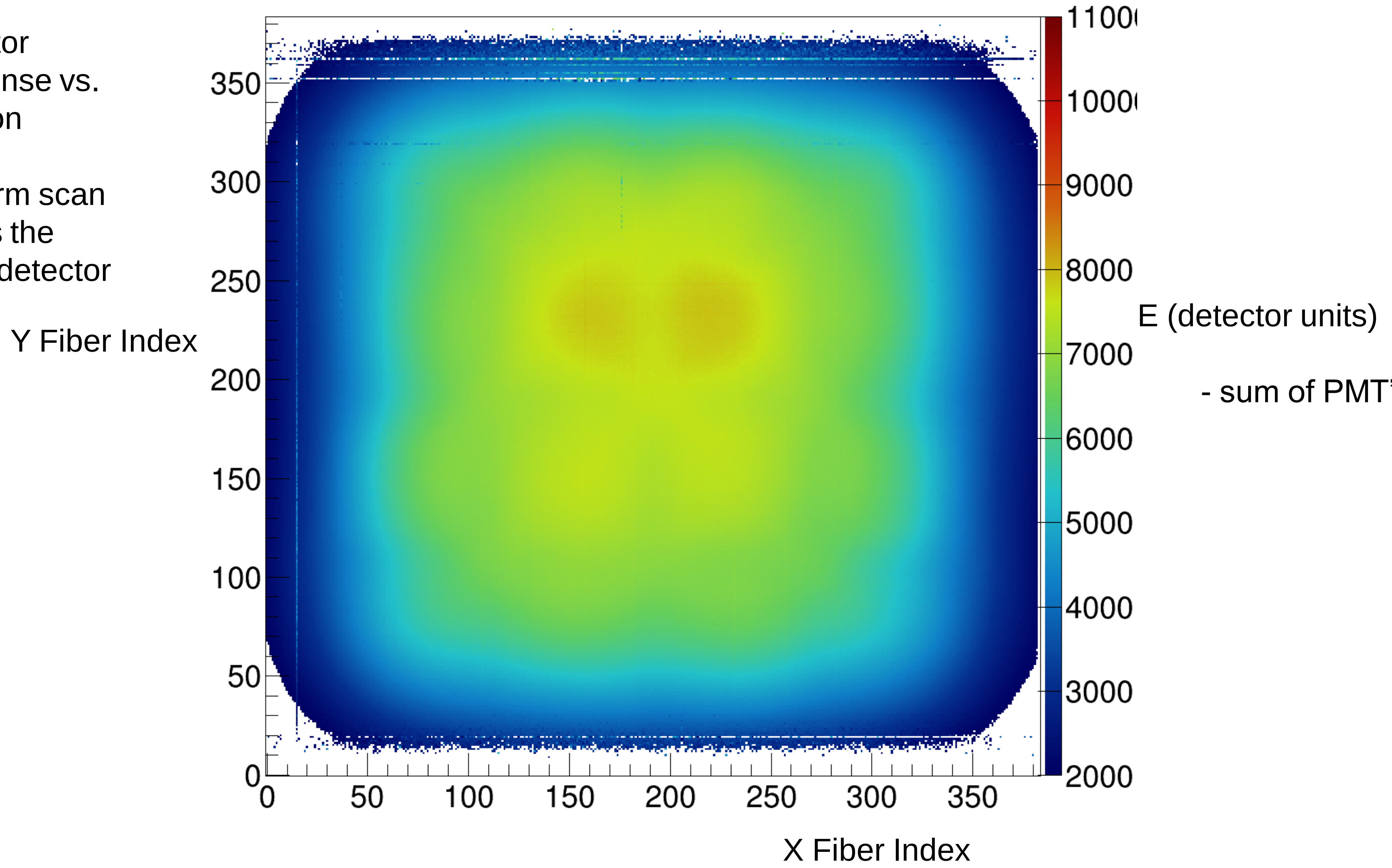


- Time between events is randomly distributed
- Protons arrive one at a time with great consistency (>99% at 1 MHz)

Calibration Energy: 116.4 MeV (Range ~10.1 cm)

Detector Response vs. Position

-Uniform scan across the entire detector

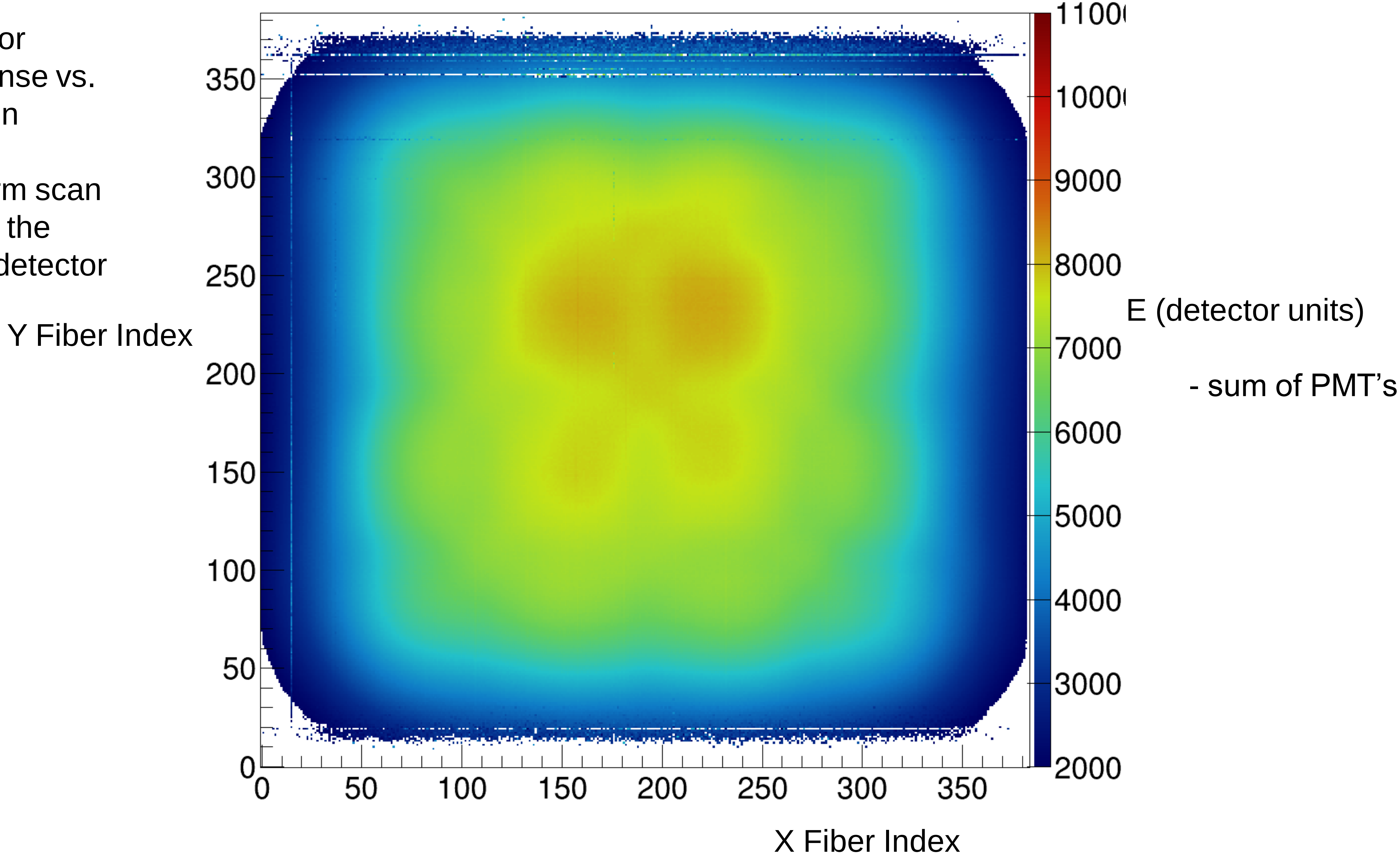


- sum of PMT’s

Calibration Energy: 118 MeV (Range ~10.3 cm)

Detector Response vs. Position

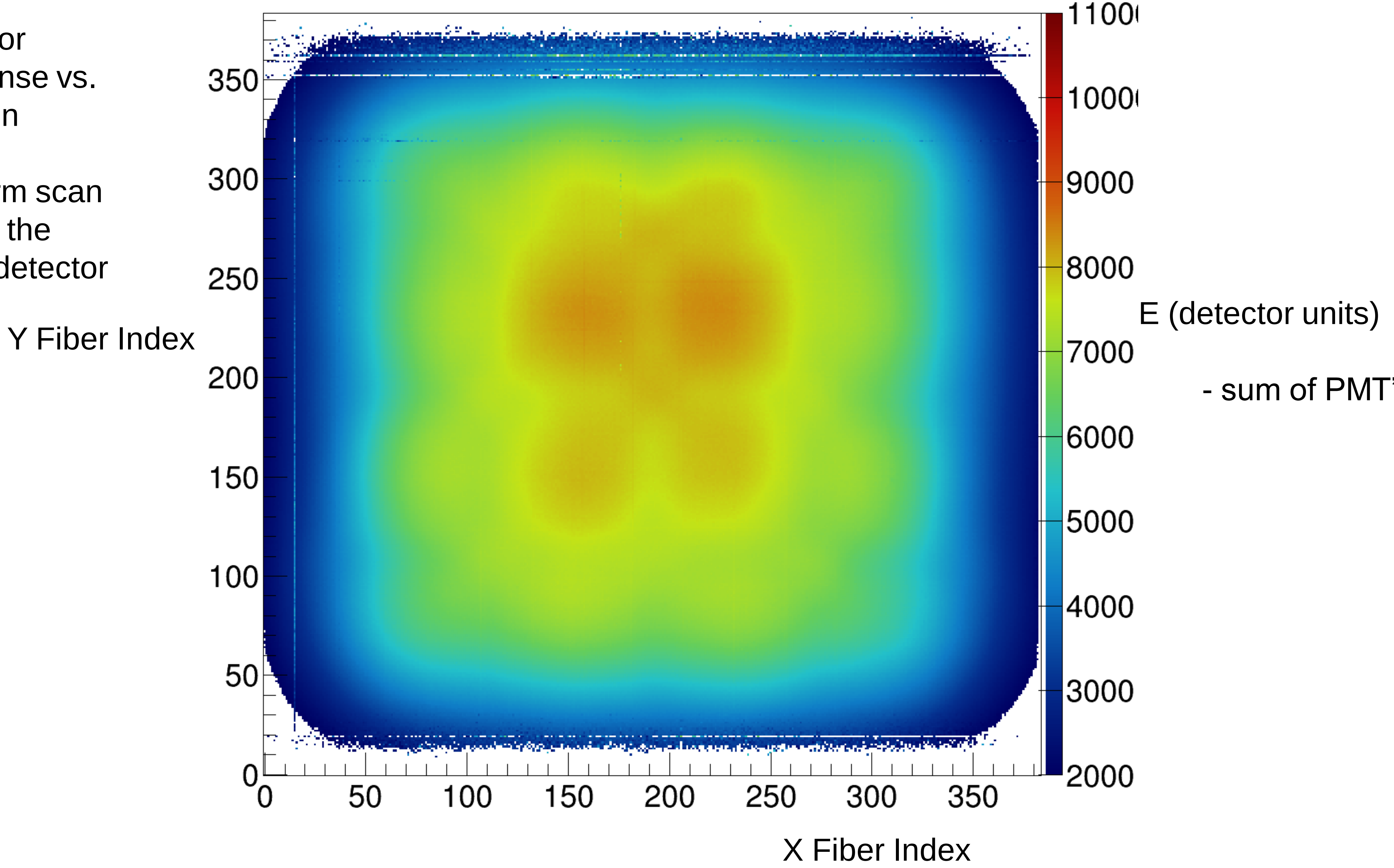
-Uniform scan across the entire detector



Calibration Energy: 119.6 MeV (Range ~10.6 cm)

Detector Response vs. Position

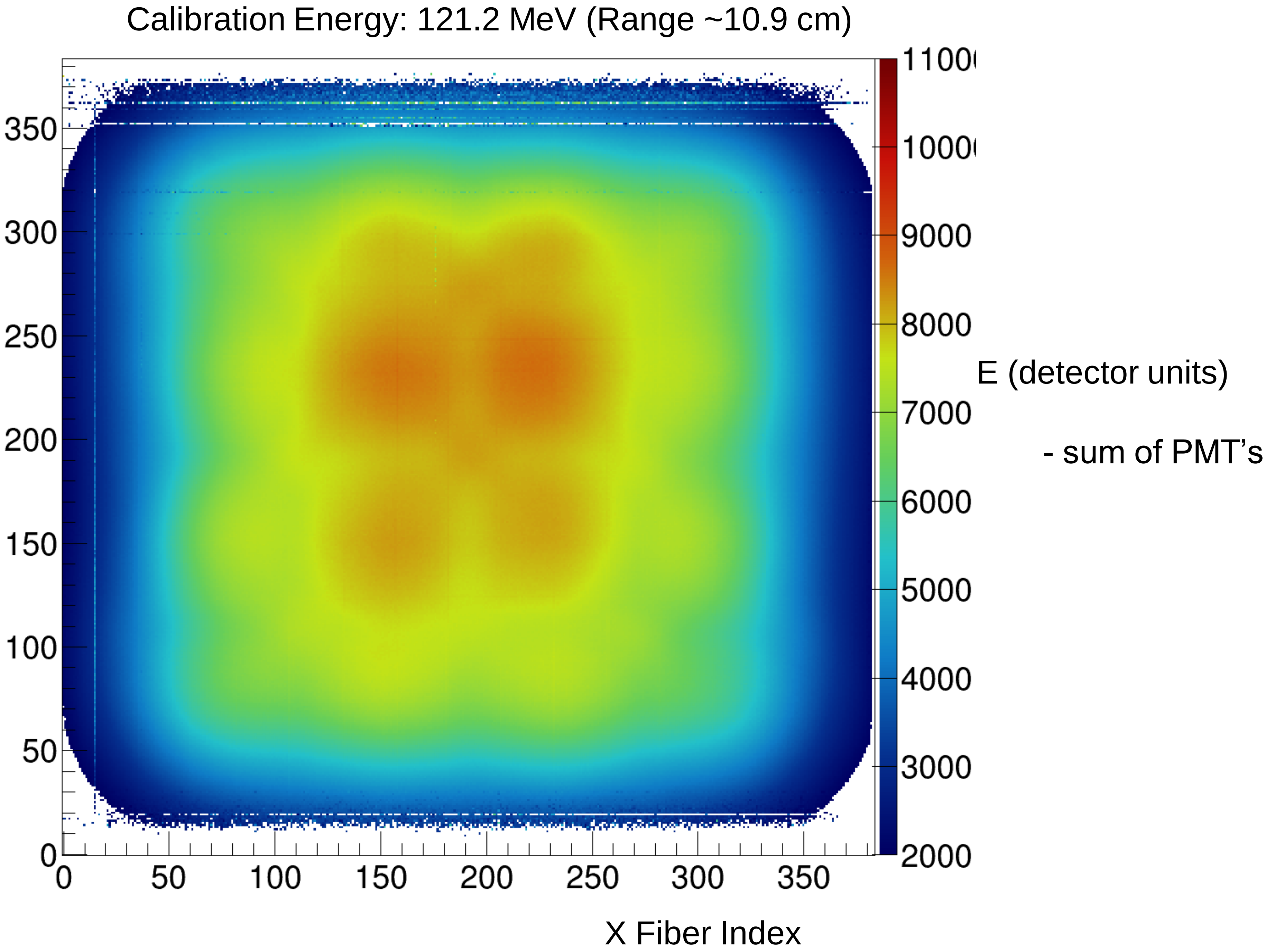
-Uniform scan across the entire detector



- sum of PMT's

Detector Response vs. Position

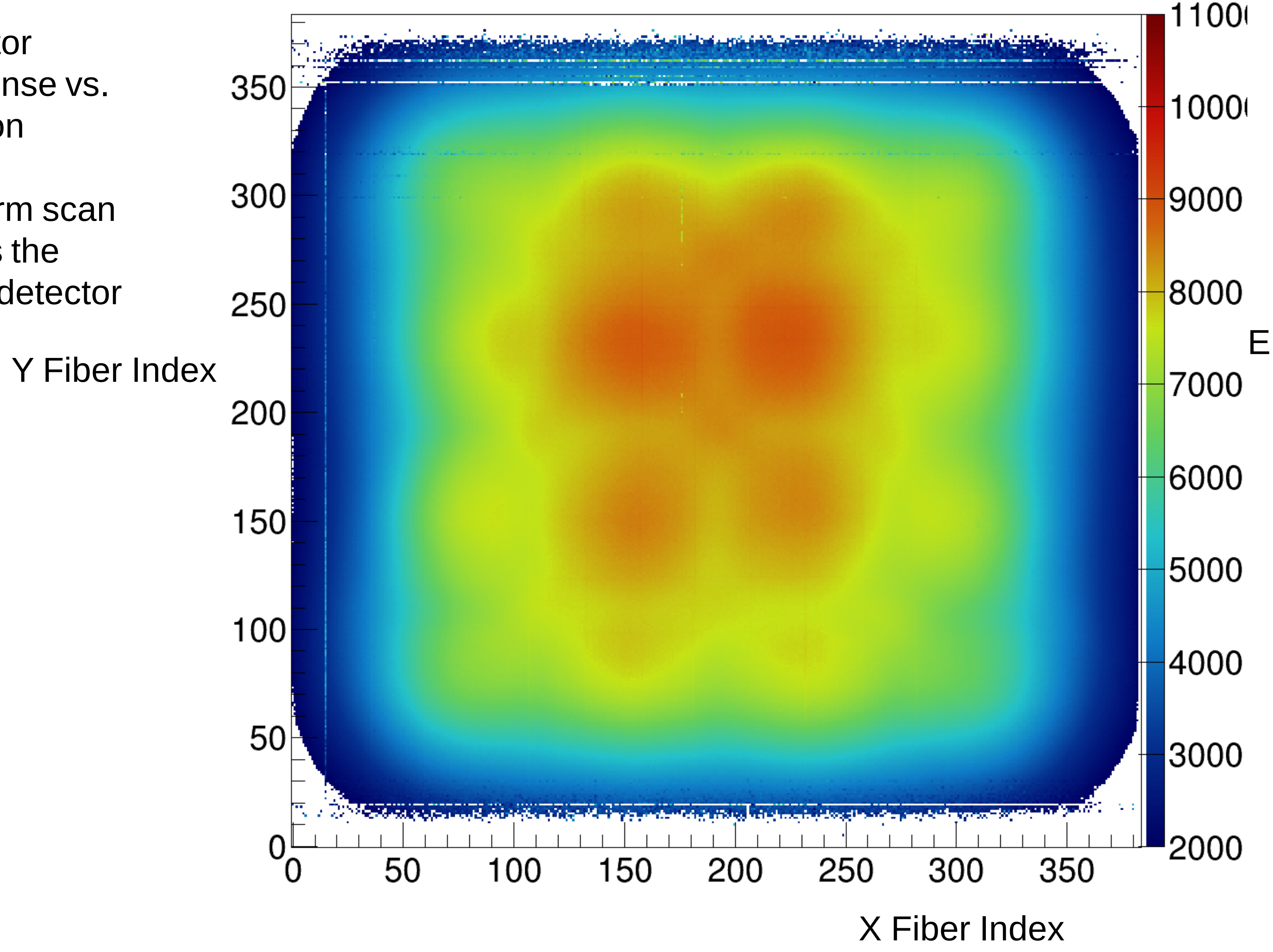
-Uniform scan across the entire detector



Calibration Energy: 122.8 MeV (Range ~11.1 cm)

Detector Response vs. Position

-Uniform scan across the entire detector



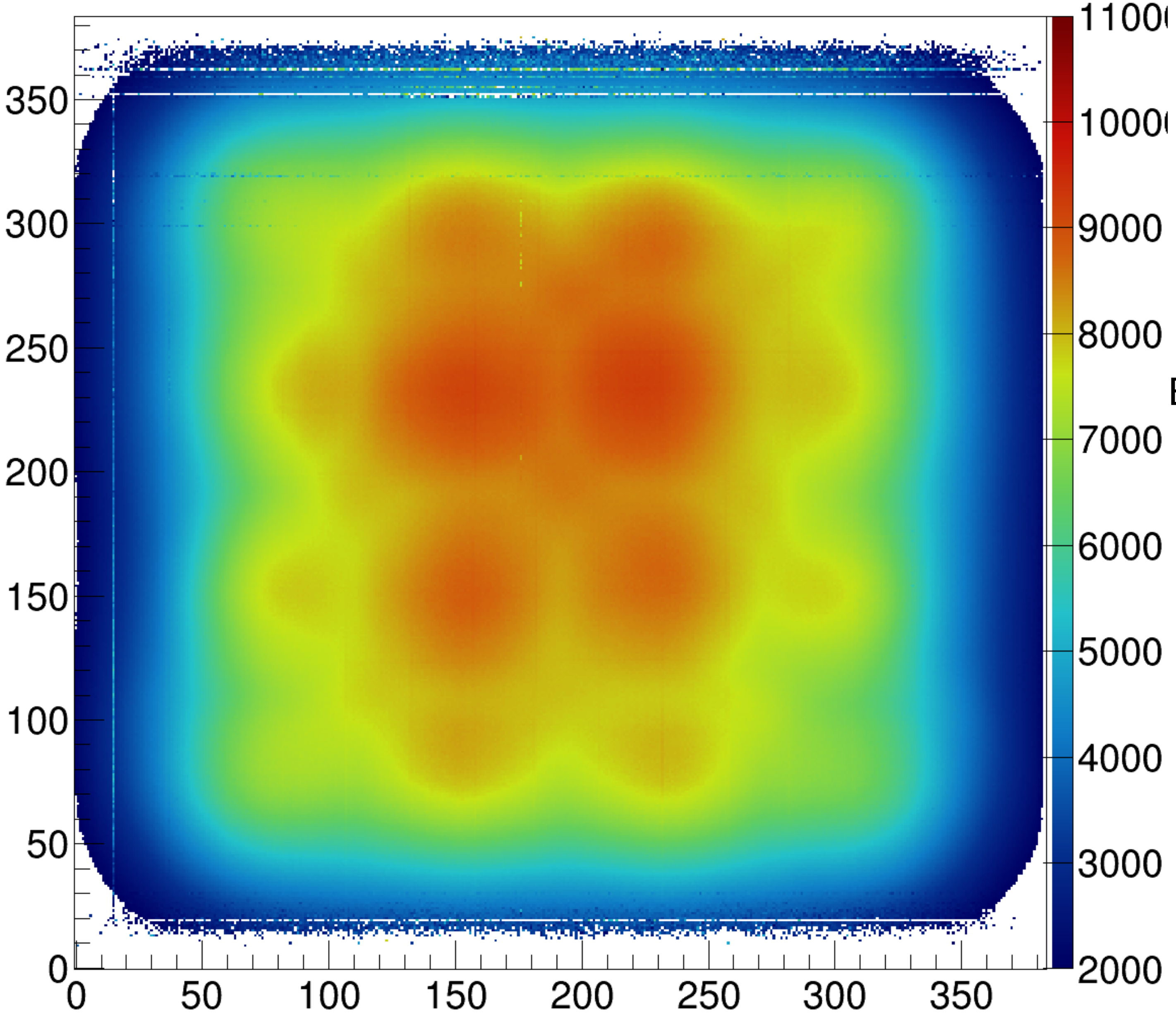
- sum of PMT’s

Calibration Energy: 124.4 MeV (Range ~11.4 cm)

Detector Response vs. Position

-Uniform scan across the entire detector

Y Fiber Index



X Fiber Index

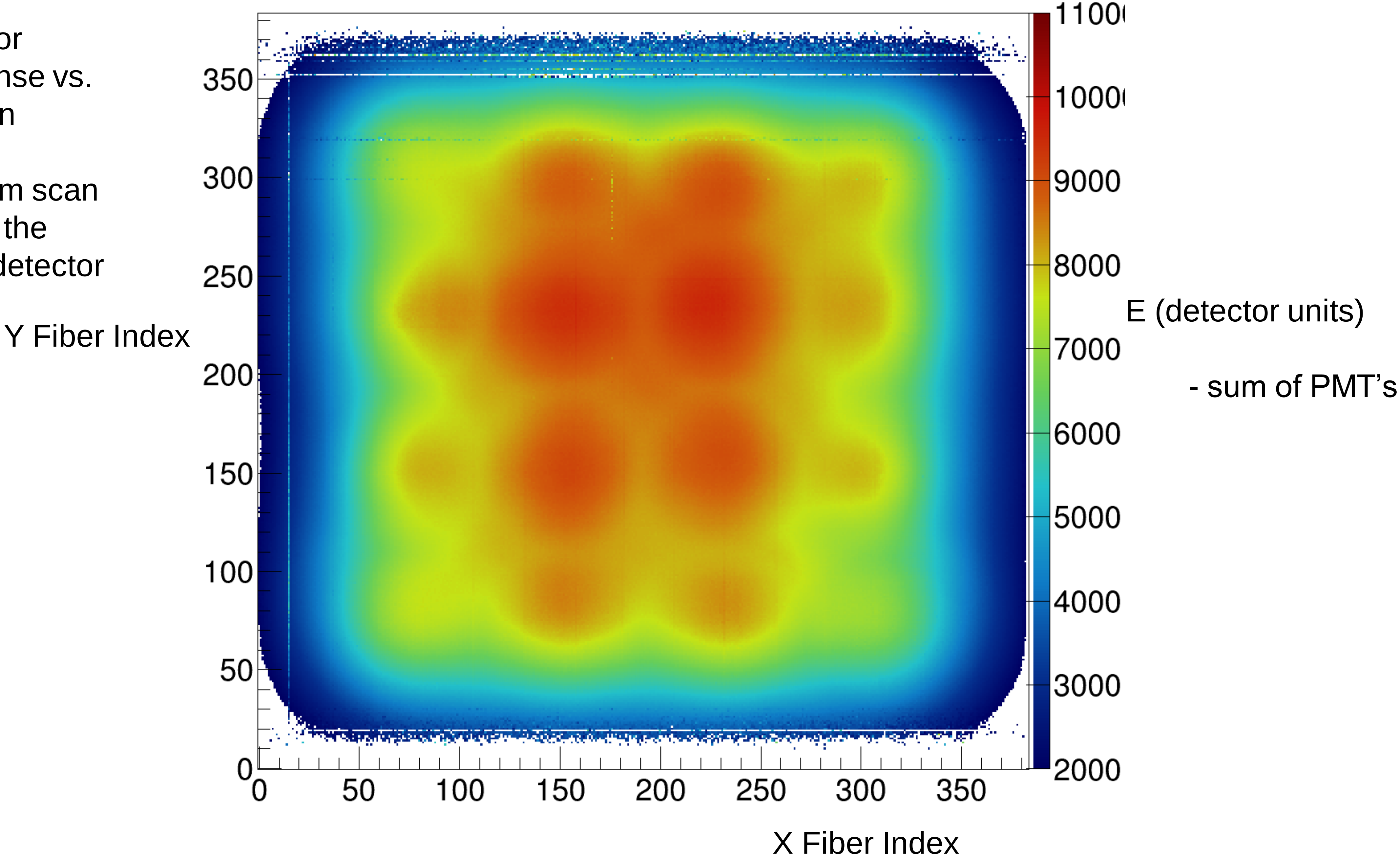
E (detector units)

- sum of PMT's

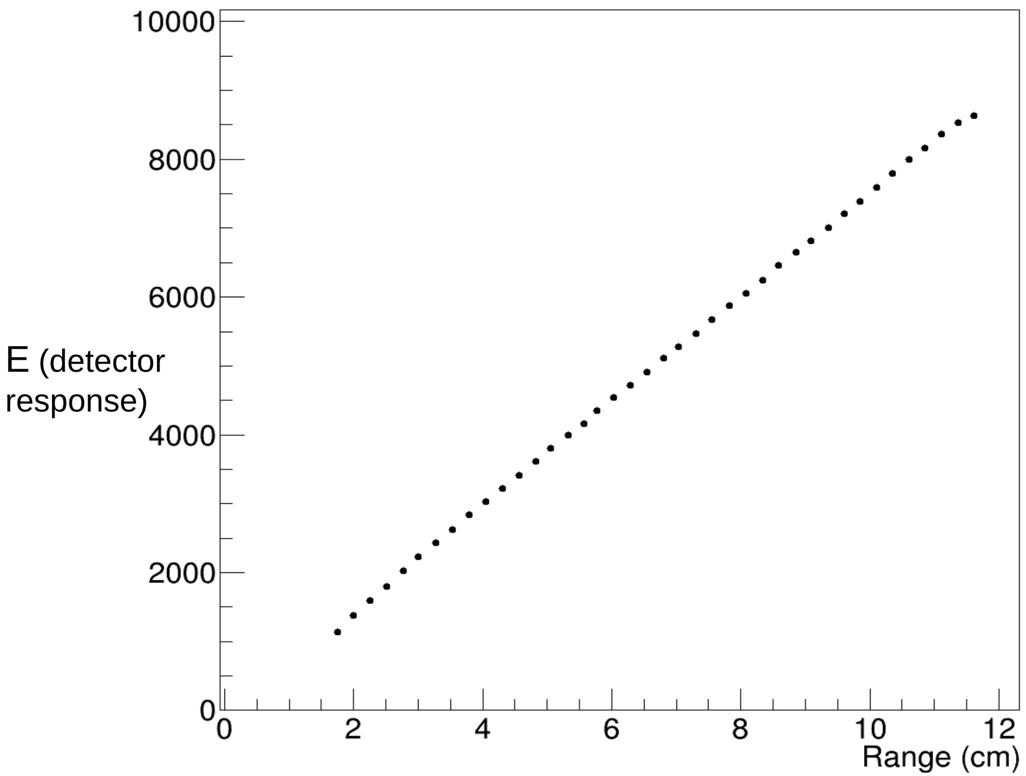
Calibration Energy: 126 MeV (Range ~11.6 cm)

Detector Response vs. Position

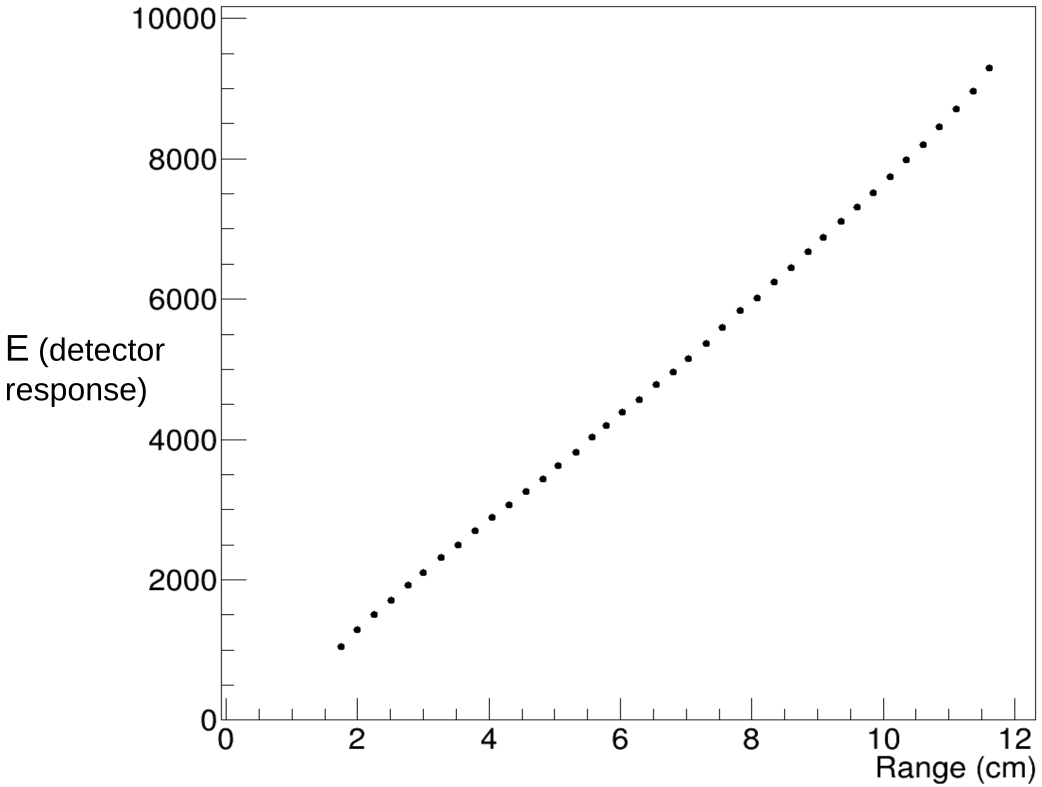
-Uniform scan across the entire detector



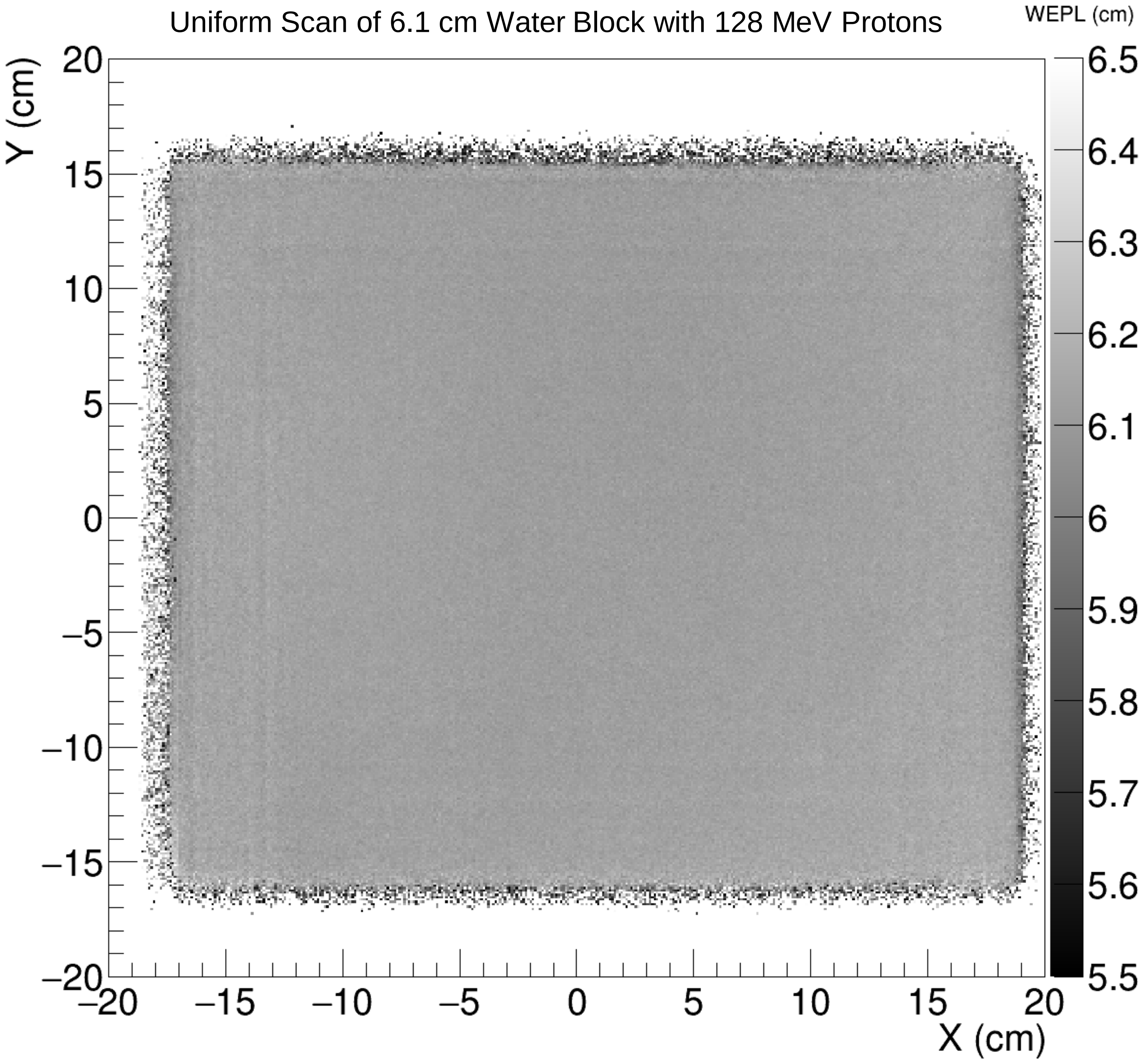
Position near center of detector

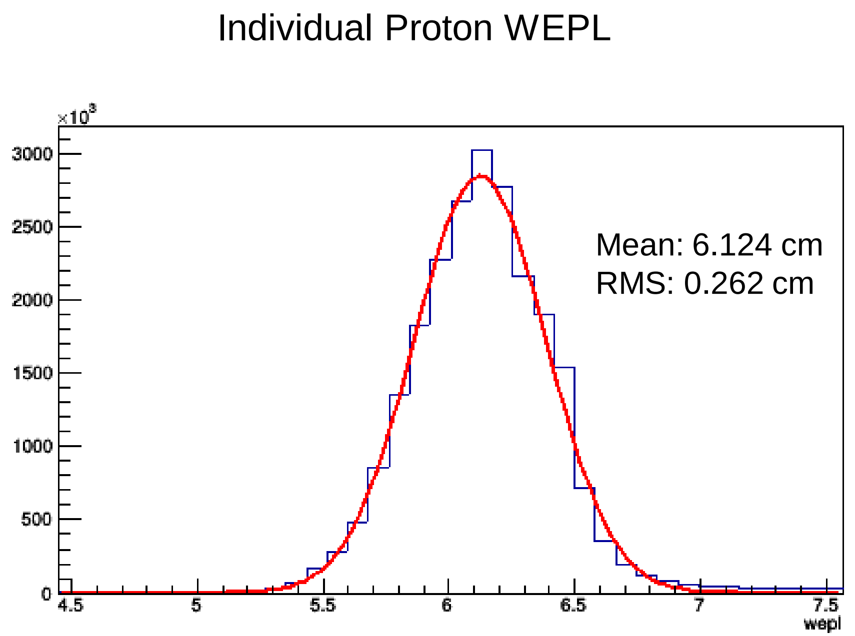


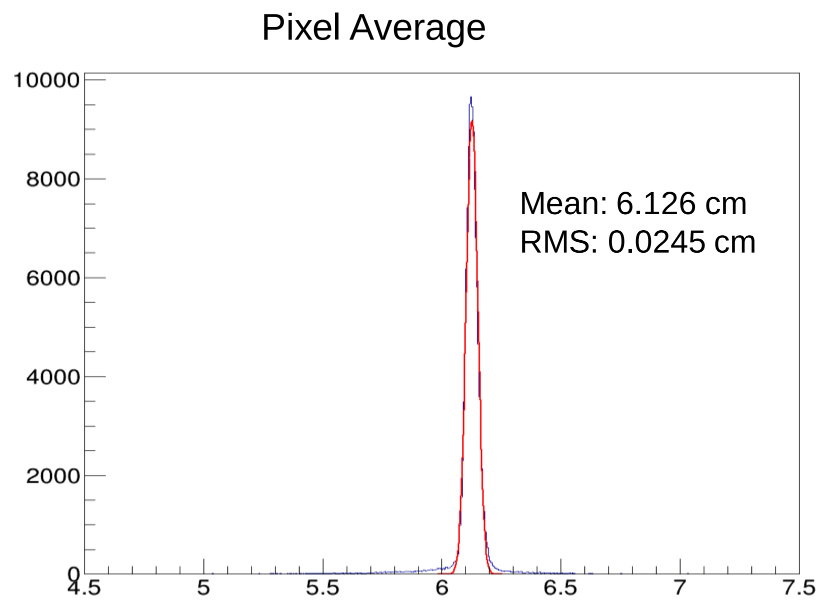
Position near central PMT



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

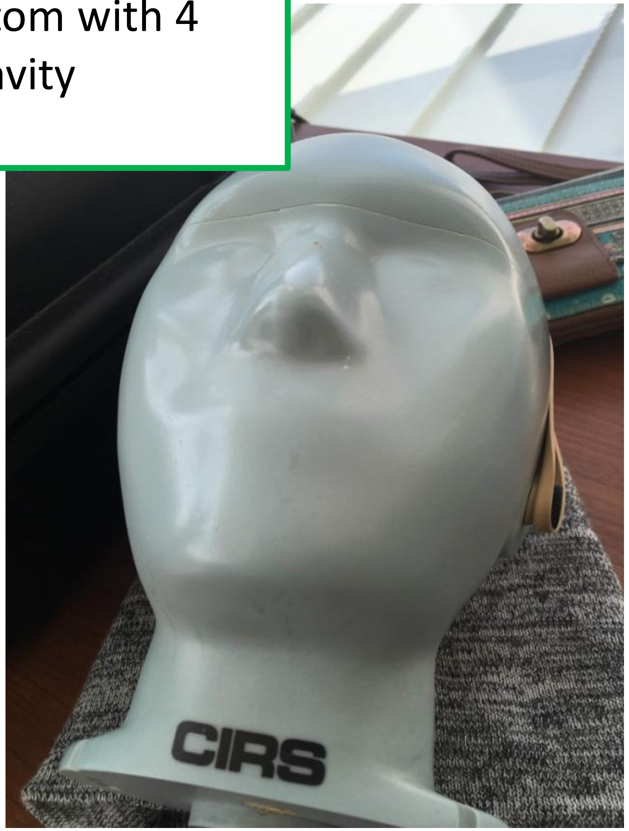

Uniform Scan of 6.1 cm Water Block with 128 MeV Protons
WEPL (cm)
Y (cm)
X (cm)
20
15
10
5
0
−5
−10
−15
−20
6.5
6.4
6.3
6.2
6.1
6
5.9
5.8
5.7
5.6
5.5

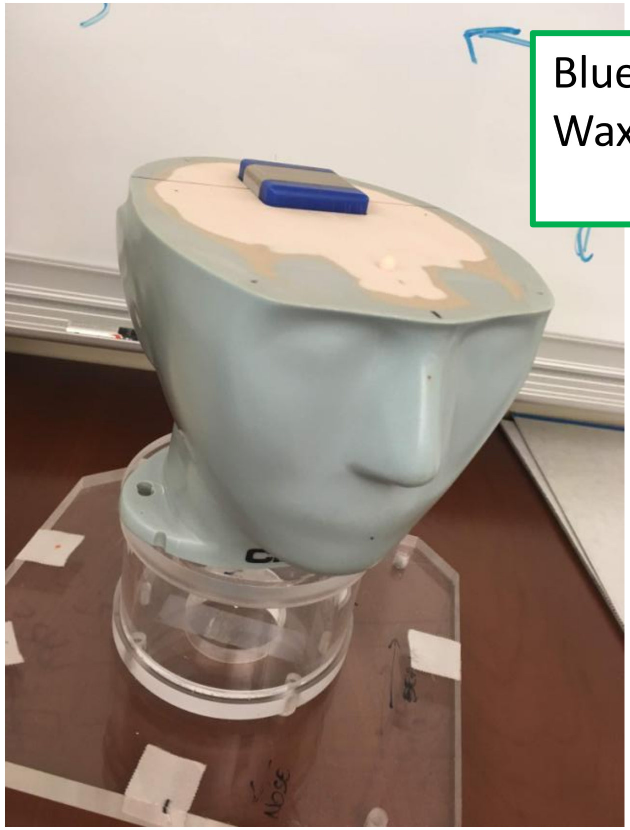

Individual Proton WEPL
×10³
3000
2500
2000
1500
1000
500
0
4.5
5
5.5
6
6.5
7
7.5
wepl
Mean: 6.124 cm
RMS: 0.262 cm


Pixel Average
10000
8000
6000
4000
2000
0
4.5
5
5.5
6
6.5
7
7.5
Mean: 6.126 cm
RMS: 0.0245 cm

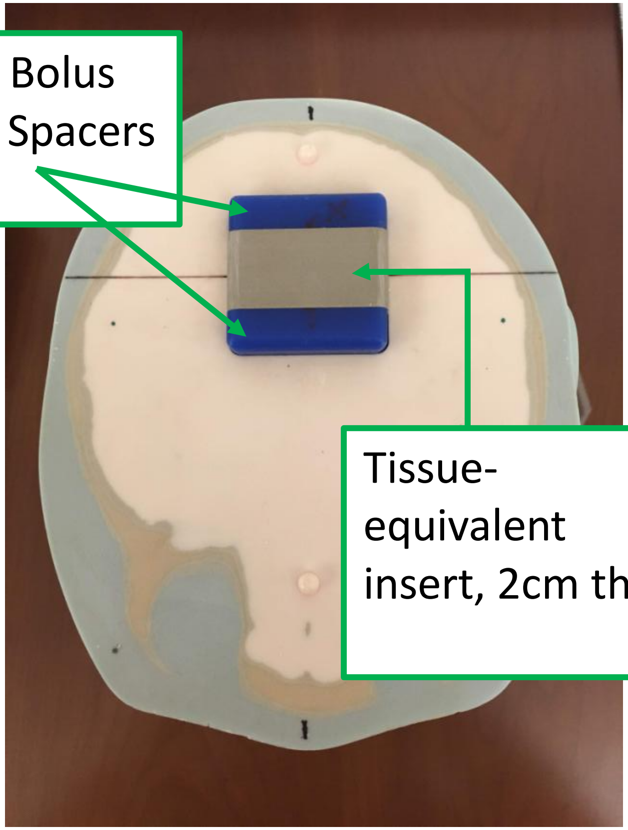
Pediatric Head Phantom with CIRS Inserts

Customized pediatric head phantom with 4 cm cubic cavity



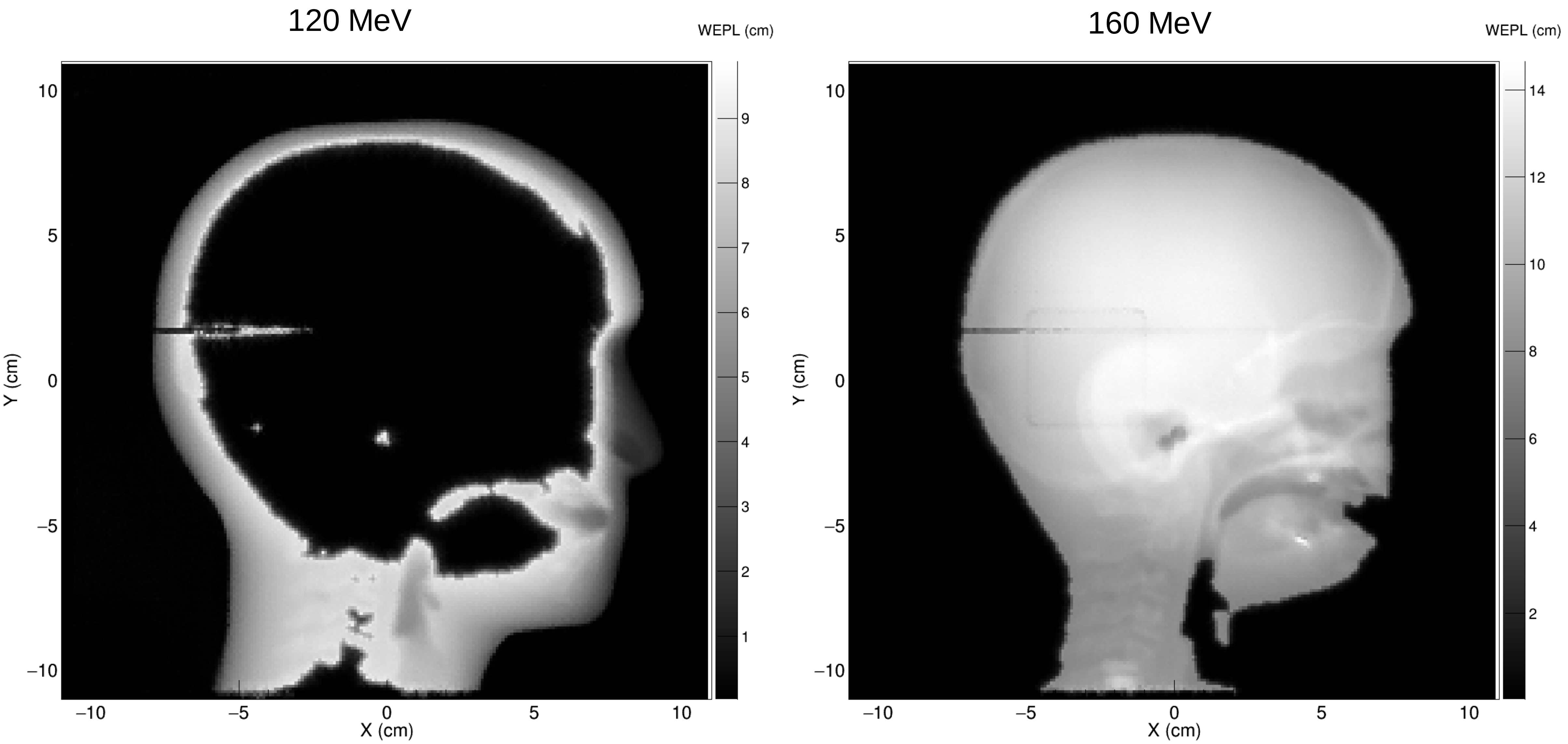


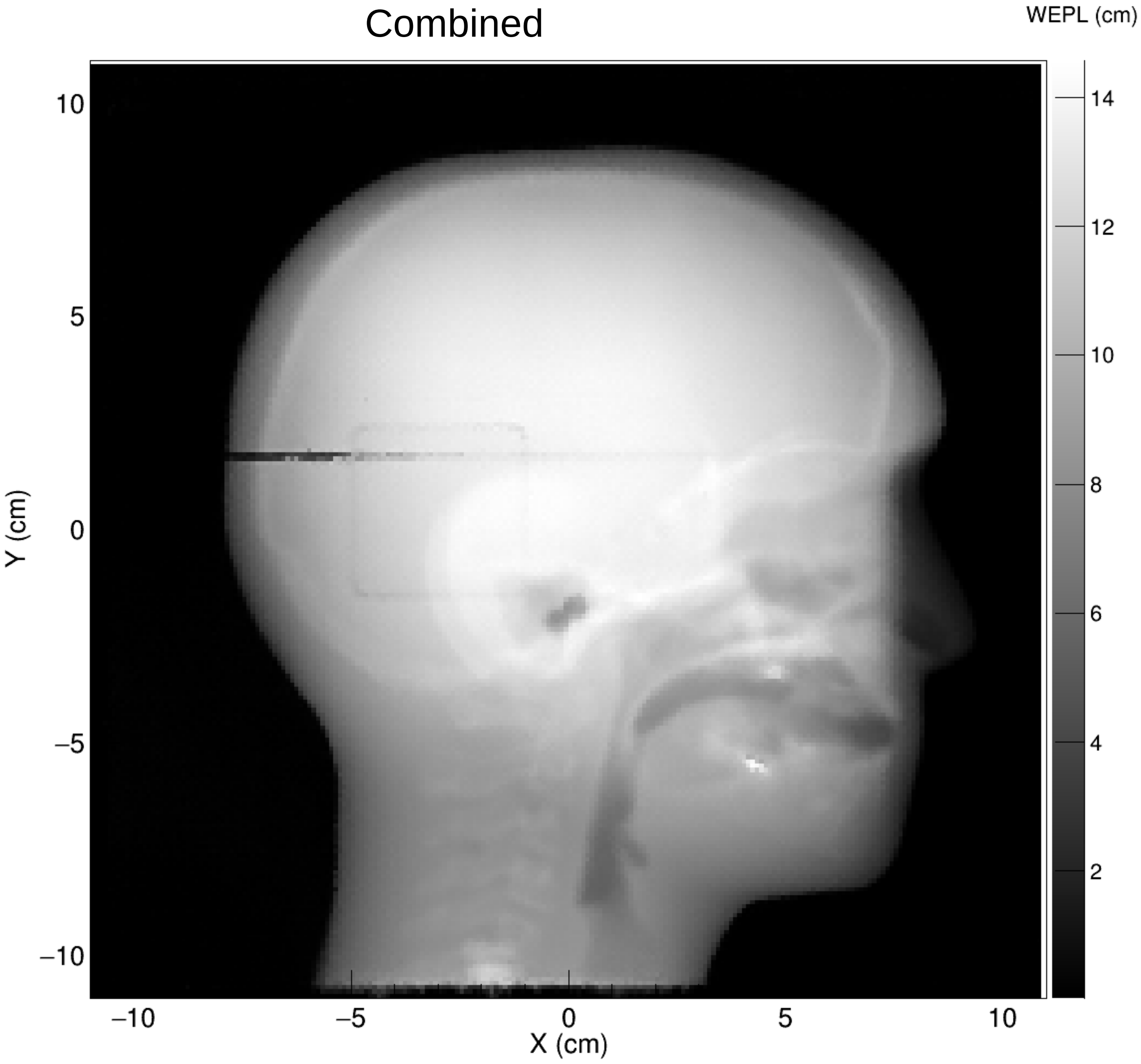
Blue Bolus Wax Spacers



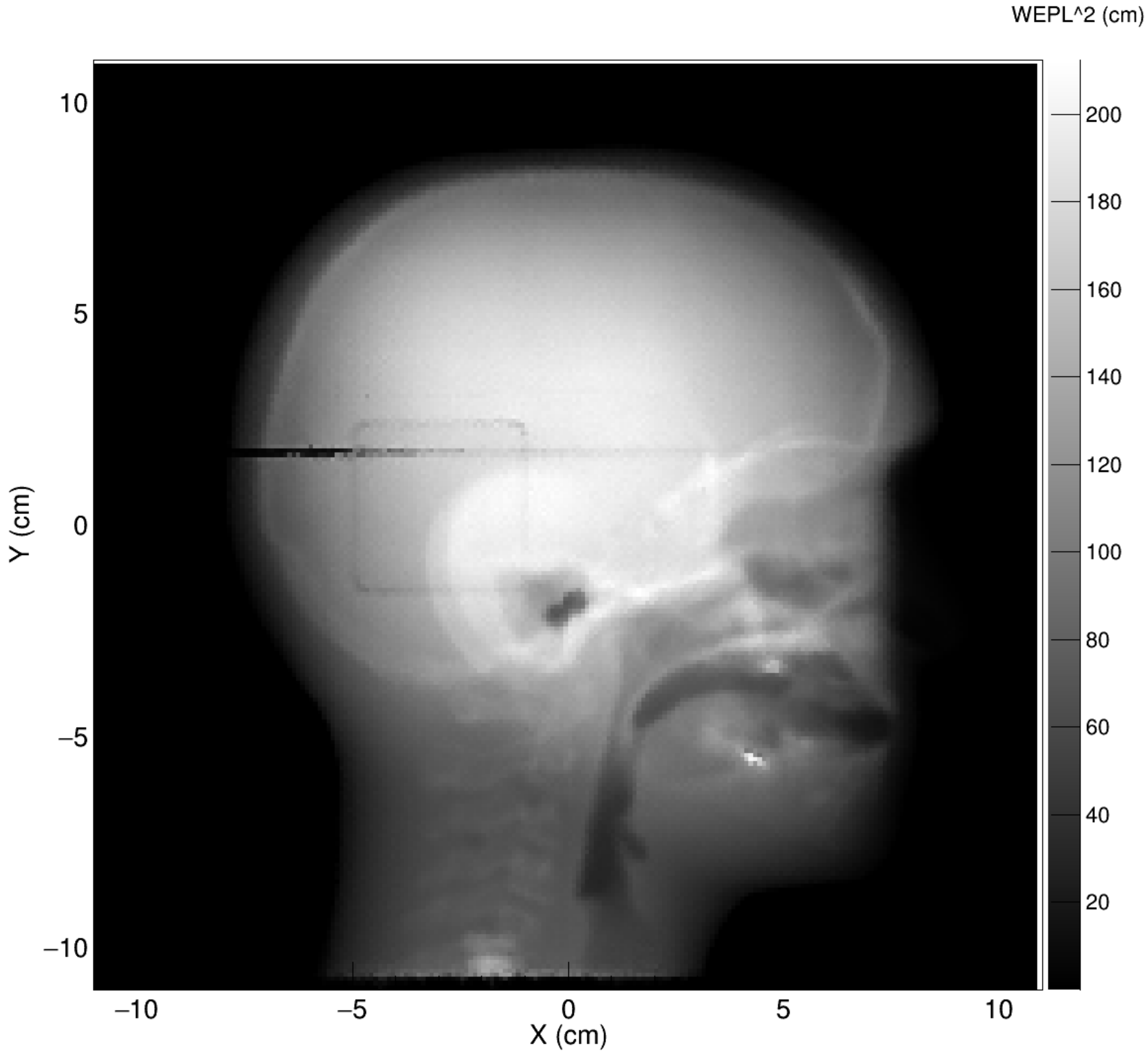
Tissue-equivalent insert, 2cm thick

Imaging with Multiple Proton Energies – Pediatric Head Phantom



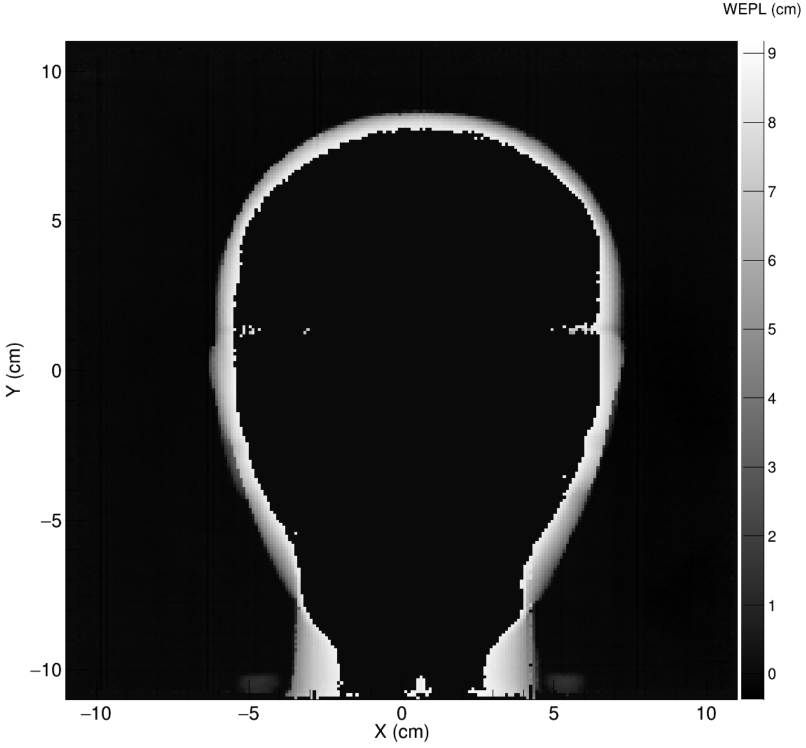


Combined
WEPL (cm)
14
12
10
8
6
4
2
10
5
0
−5
−10
Y (cm)
−10
−5
0
5
10
X (cm)

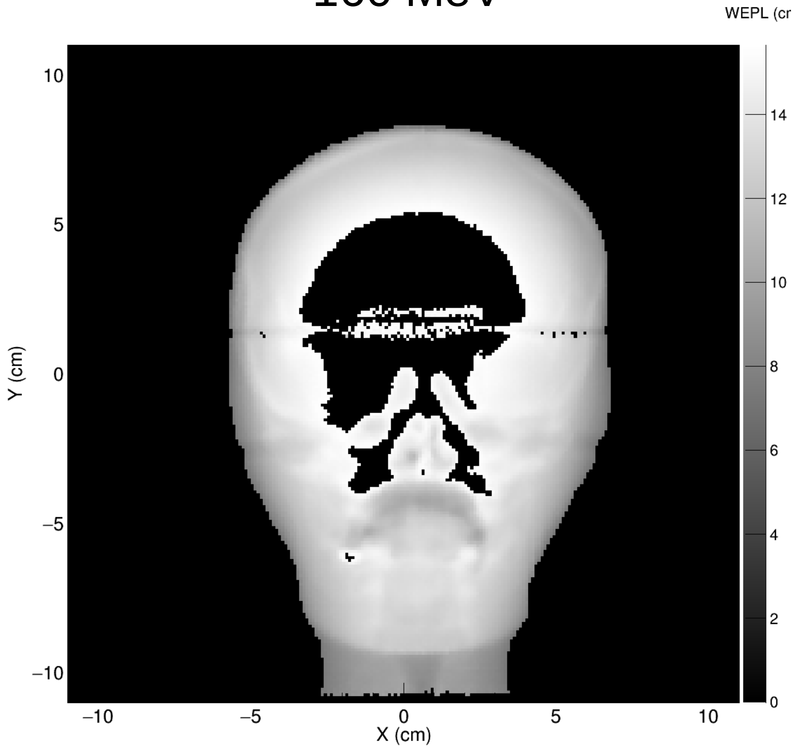


WEPL^2 (cm)
200
180
160
140
120
100
80
60
40
20
10
5
0
−5
−10
Y (cm)
X (cm)

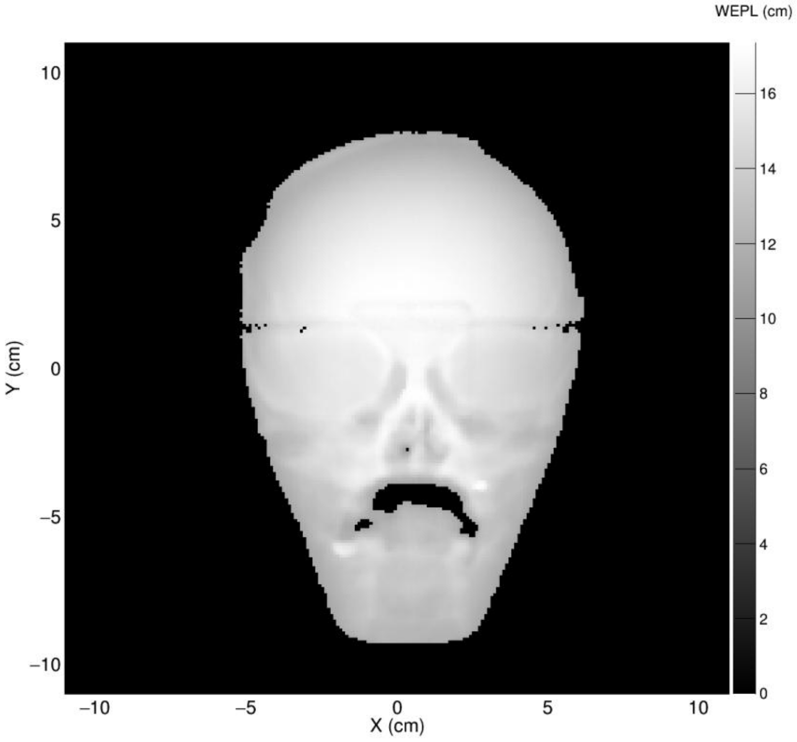
120 MeV

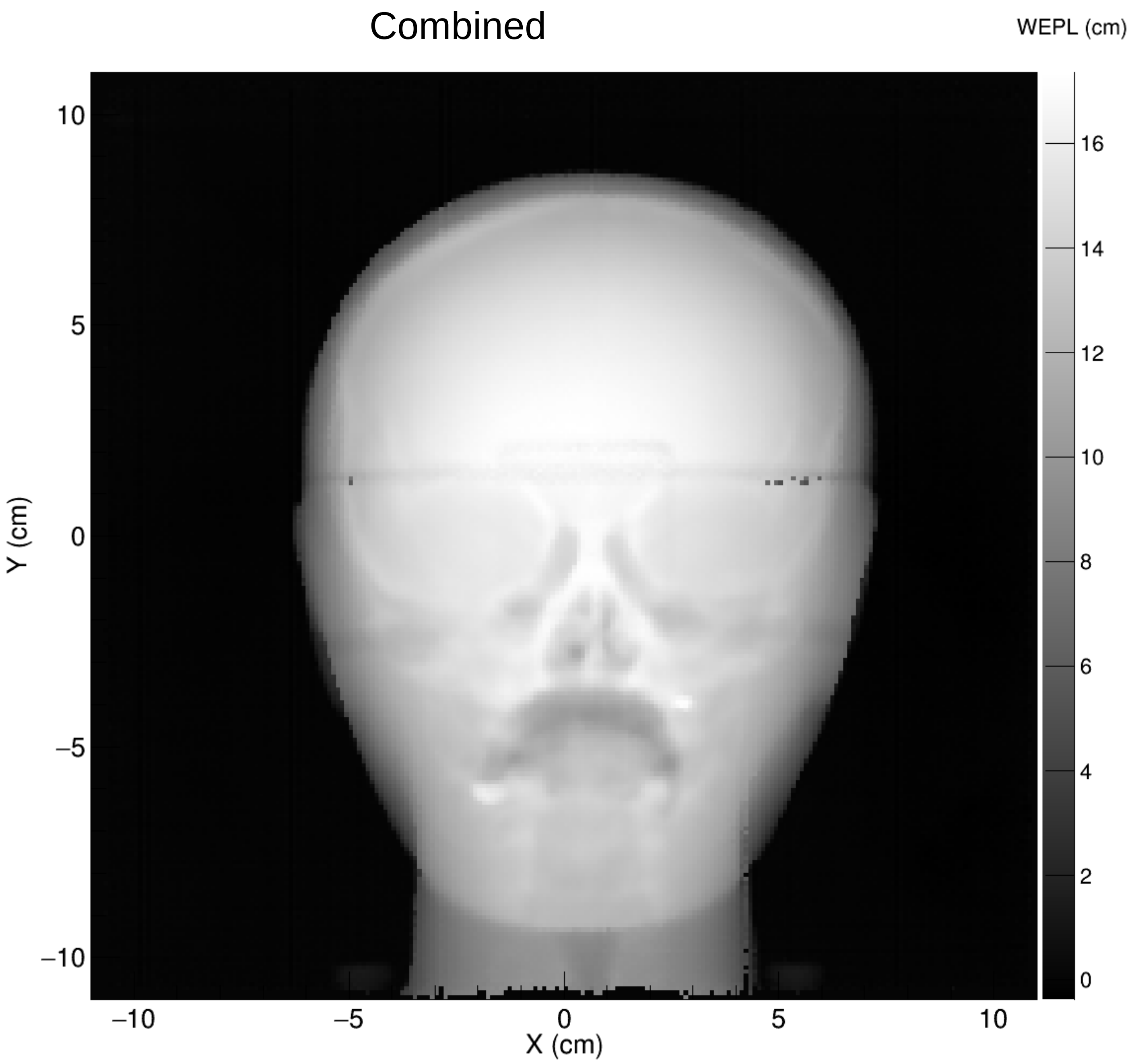


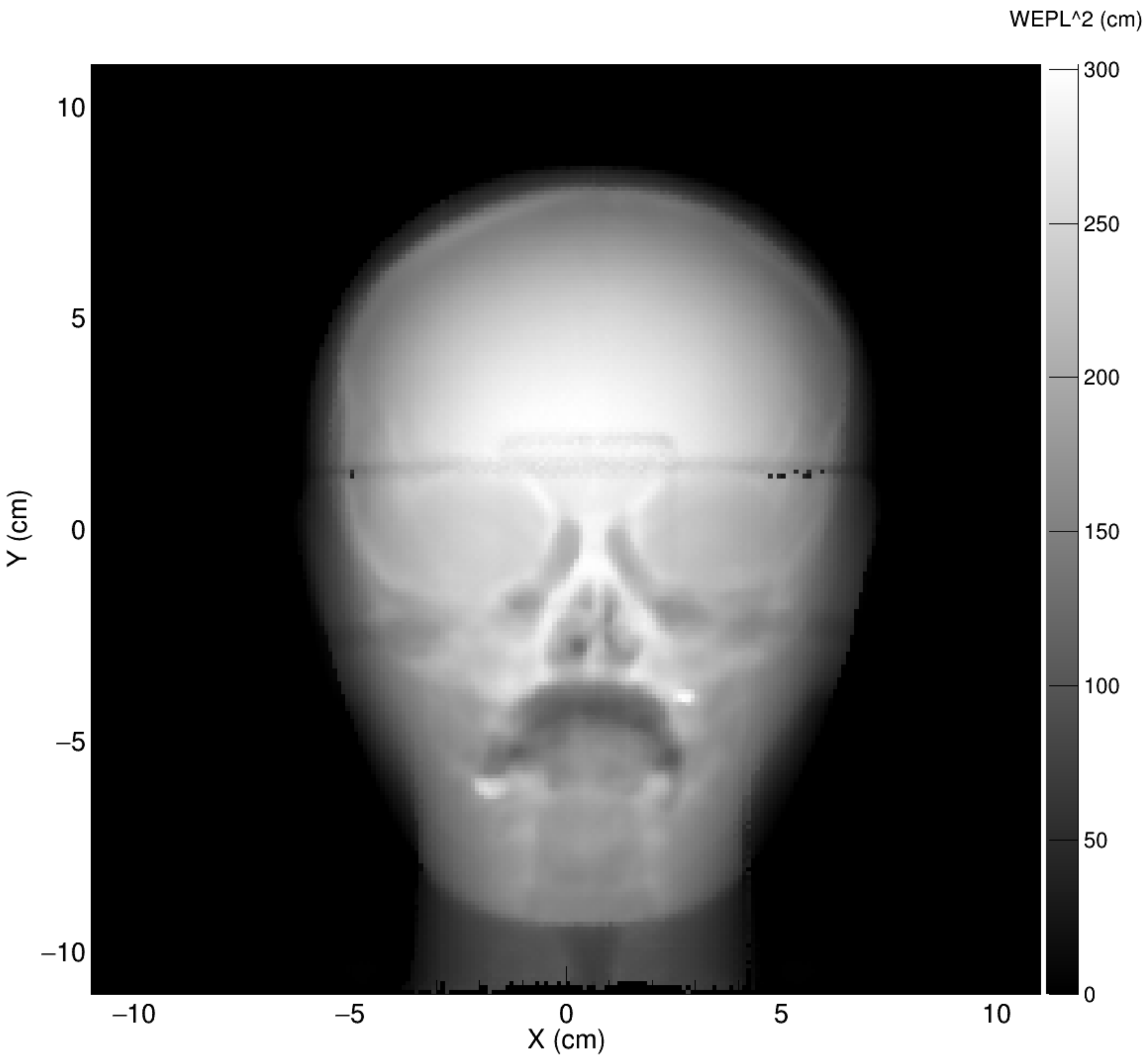
160 MeV



180 MeV



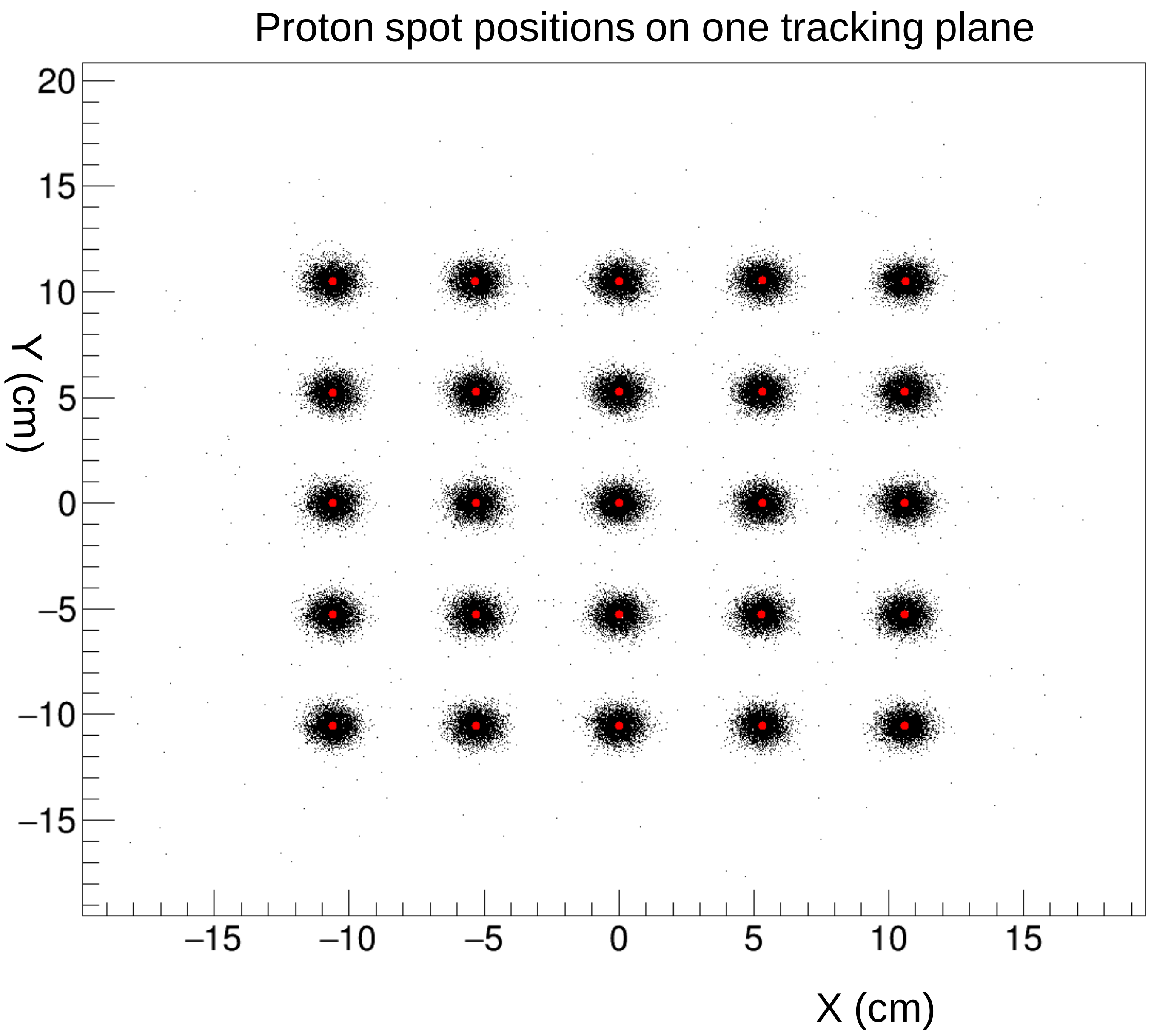

Combined
WEPL (cm)
Y (cm)
X (cm)
10
5
0
−5
−10
−10
−5
0
5
10
16
14
12
10
8
6
4
2
0



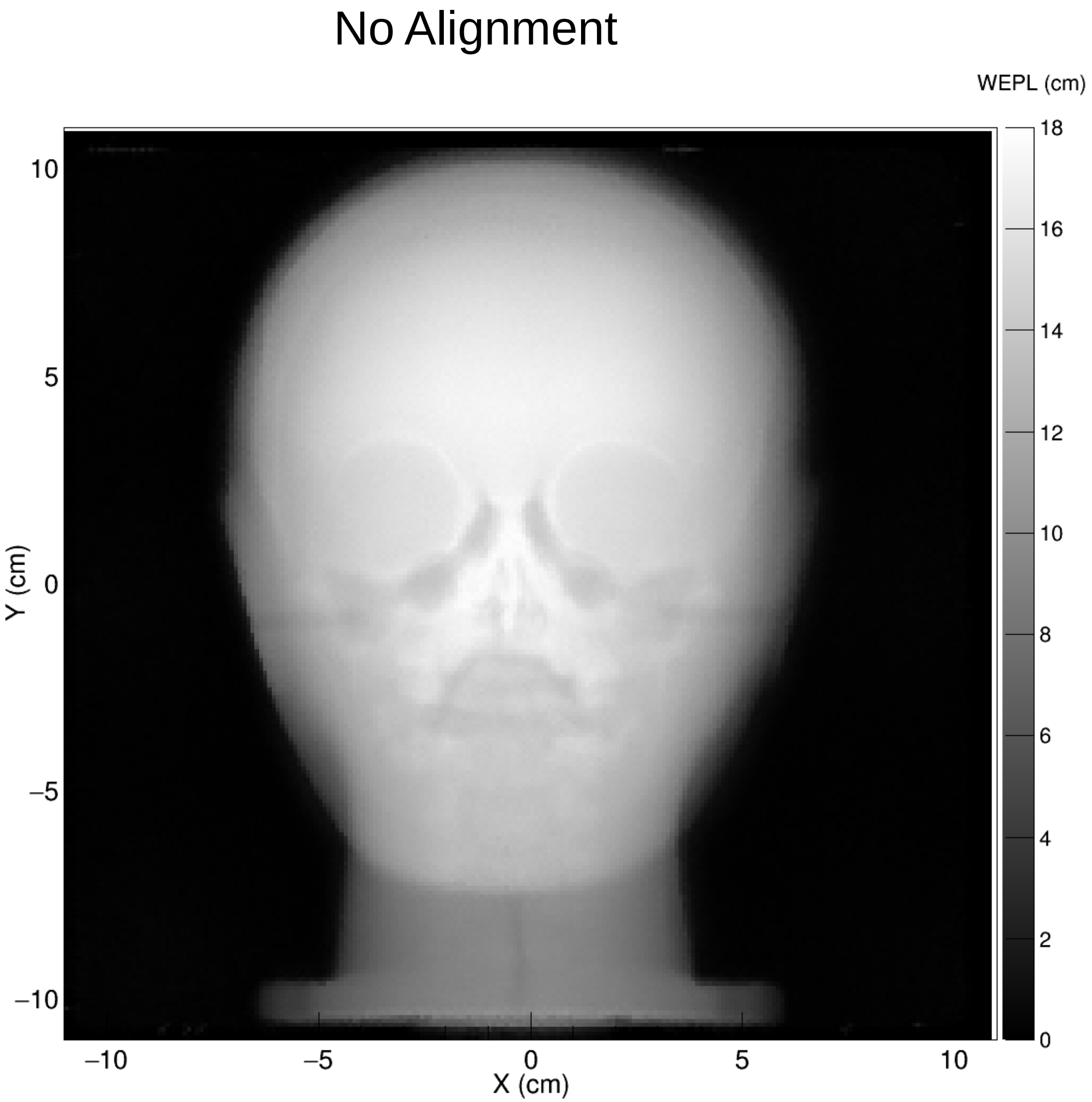
WEPL^2 (cm)
300
250
200
150
100
50
0
10
5
0
−5
−10
Y (cm)
−10
−5
0
5
10
X (cm)

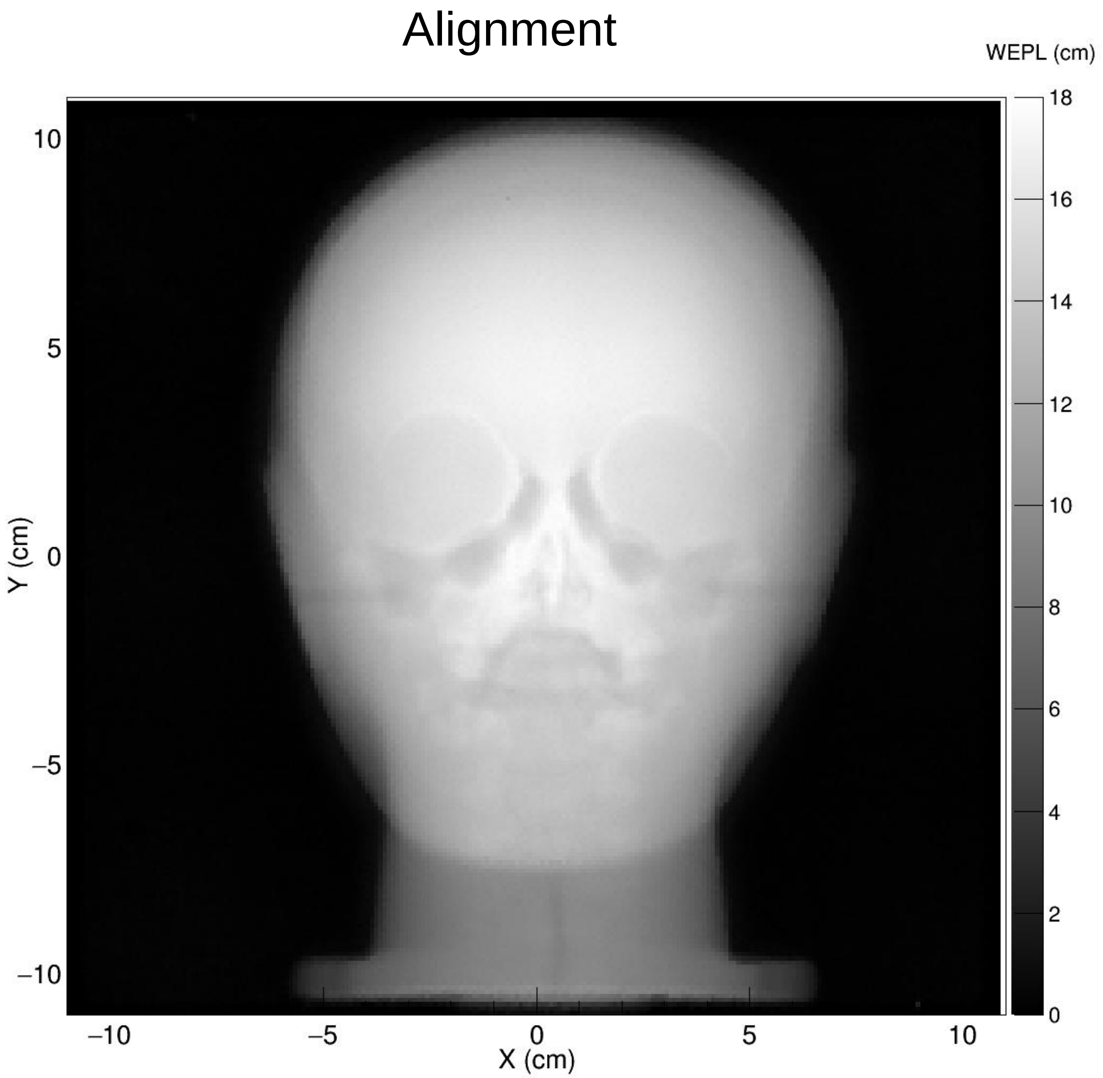
Detector Alignment Procedure

- 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.

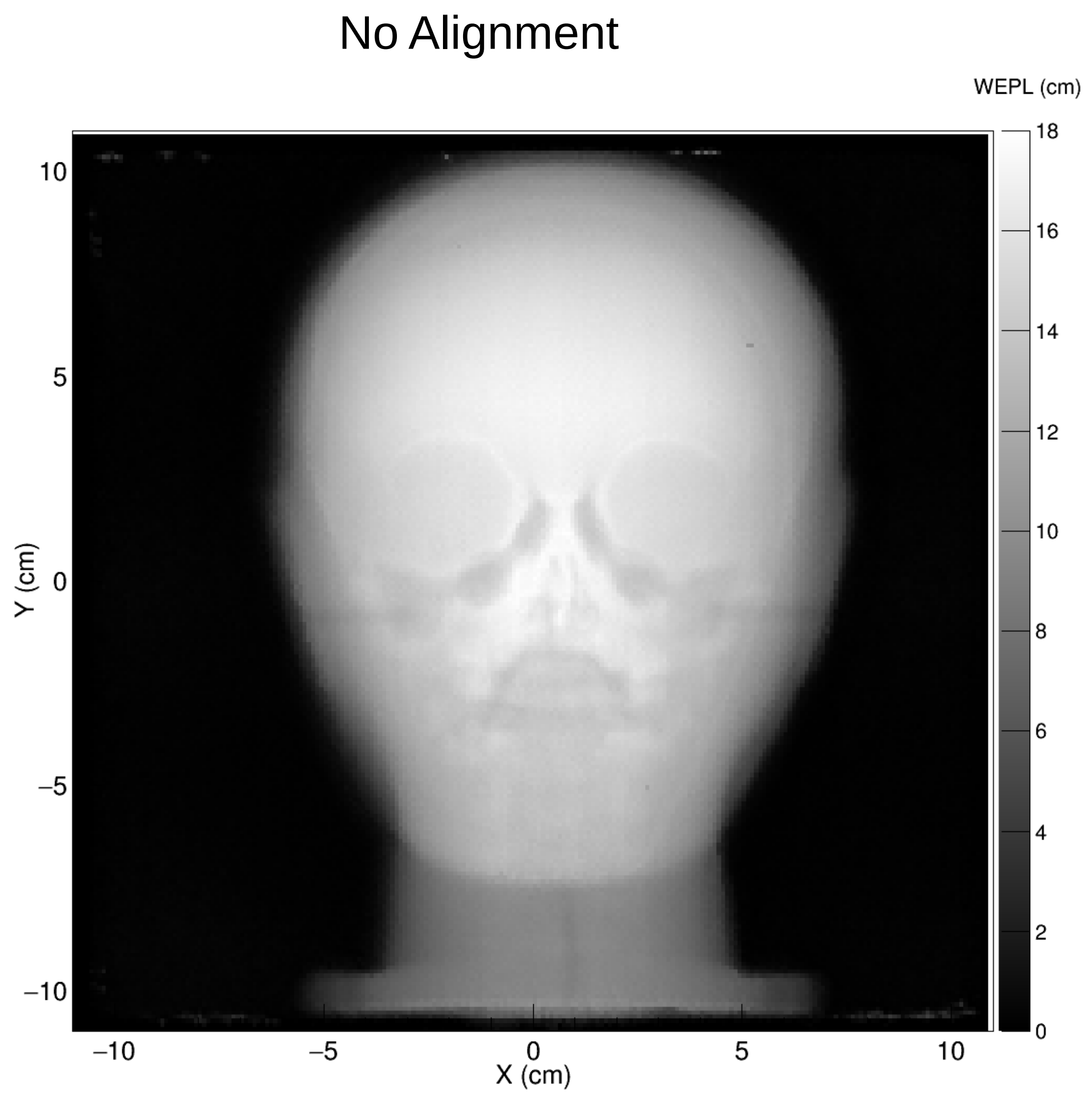


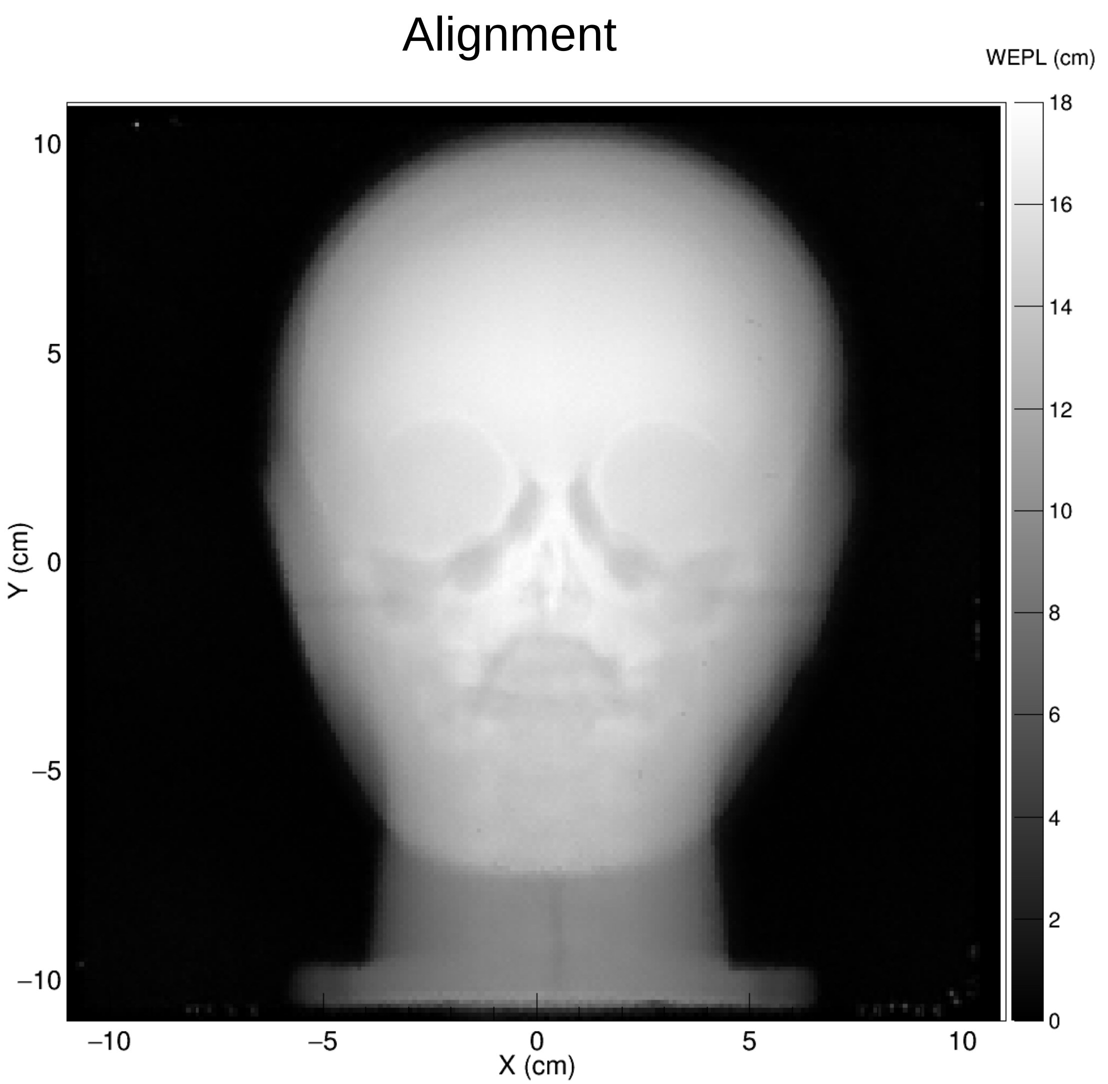
Nominal


No Alignment
WEPL (cm)
Y (cm)
X (cm)
10
5
0
−5
−10
18
16
14
12
10
8
6
4
2
0

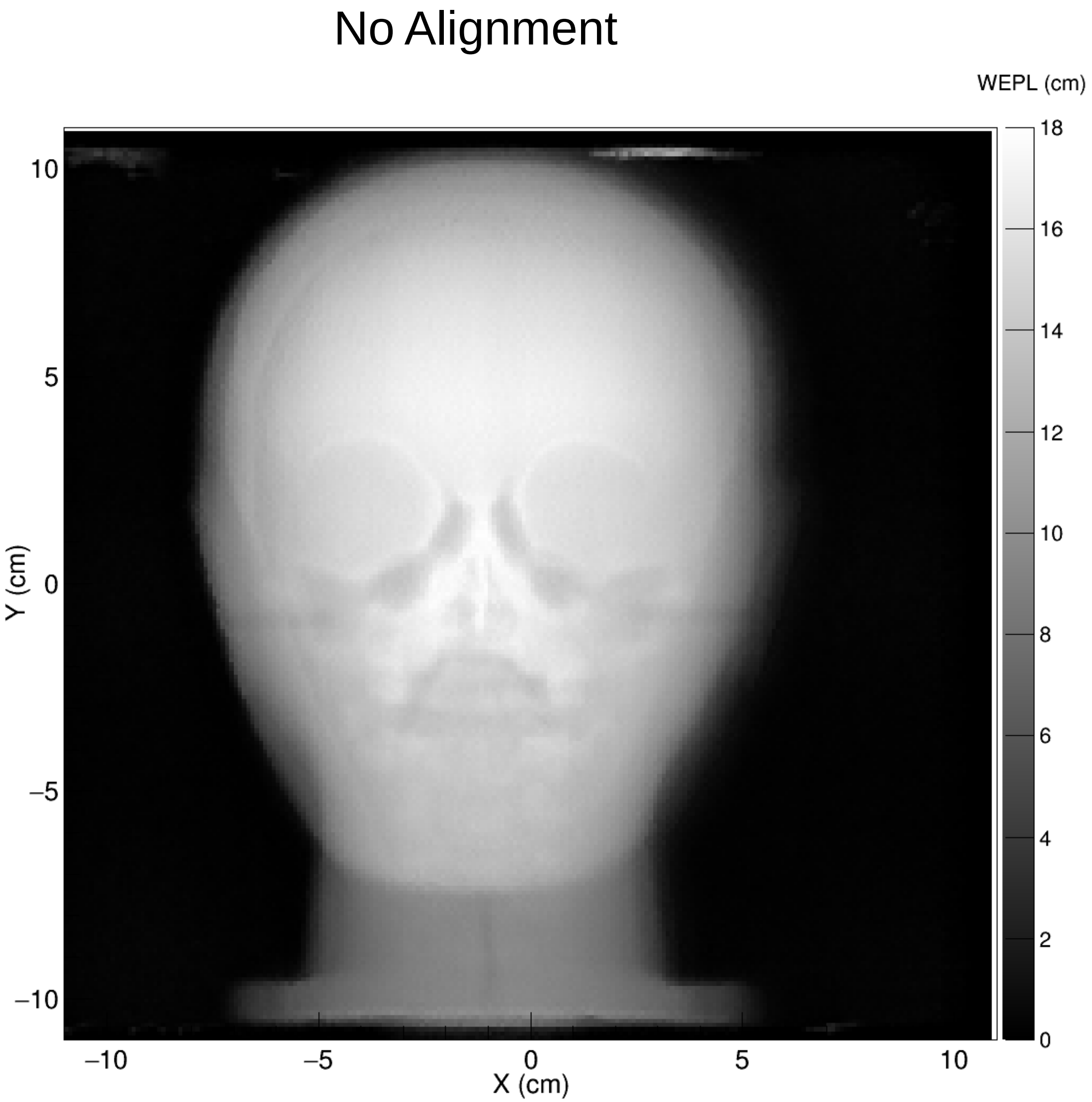

Alignment
WEPL (cm)
Y (cm)
X (cm)
10
5
0
−5
−10
18
16
14
12
10
8
6
4
2
0

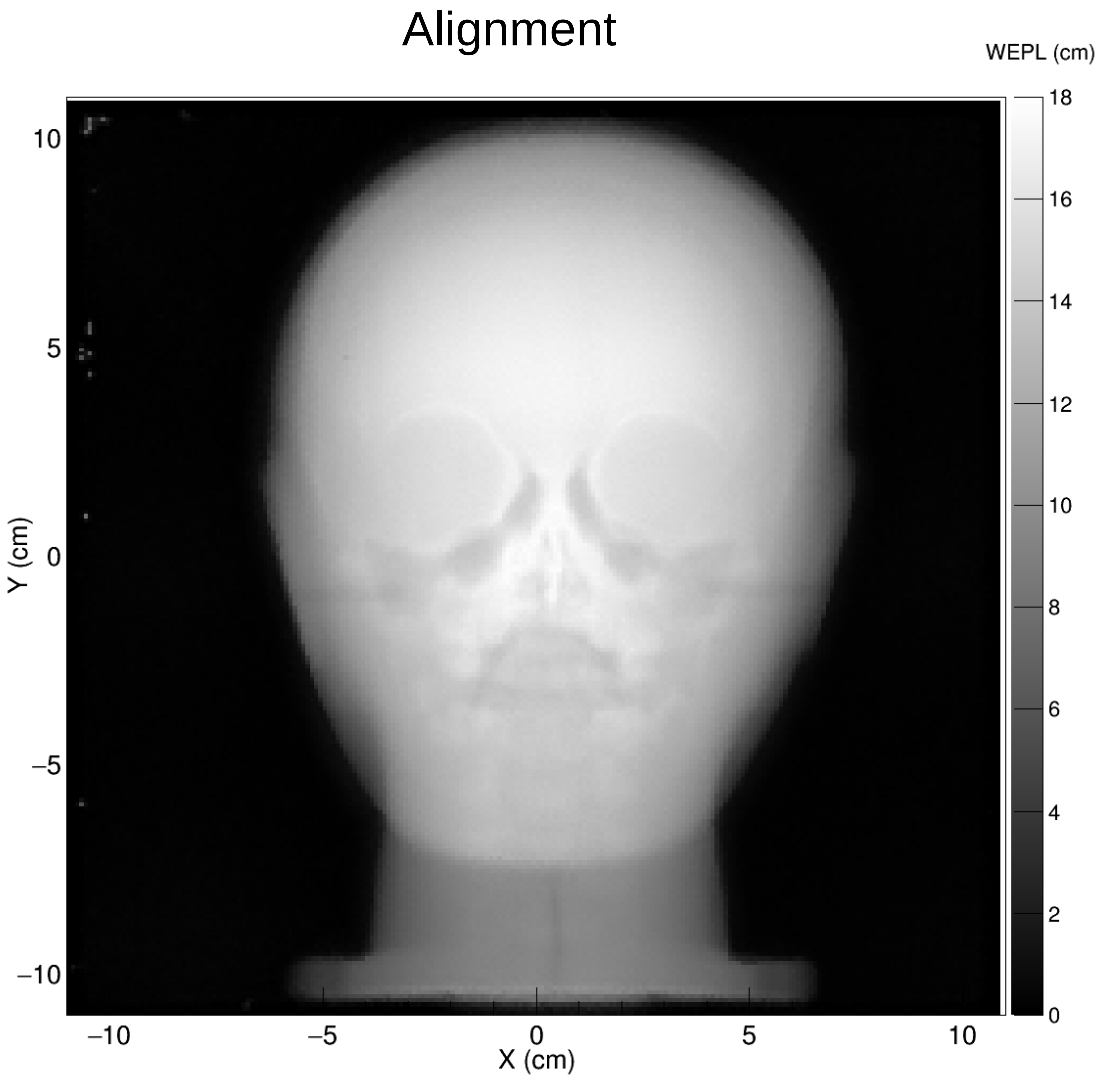
Detectors Shifted left, Phantom in Same Position

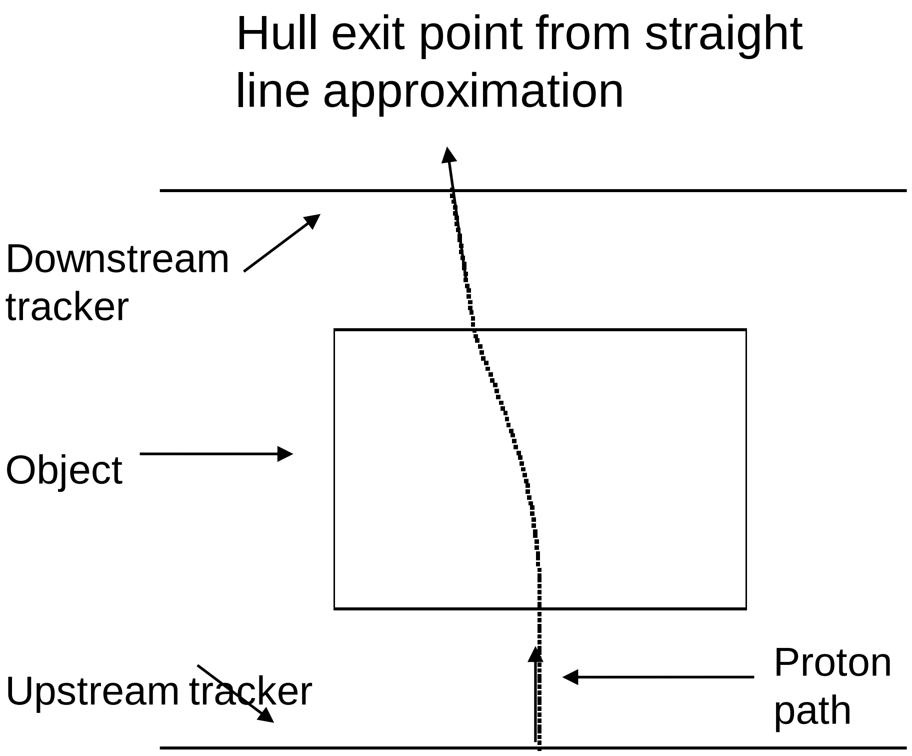


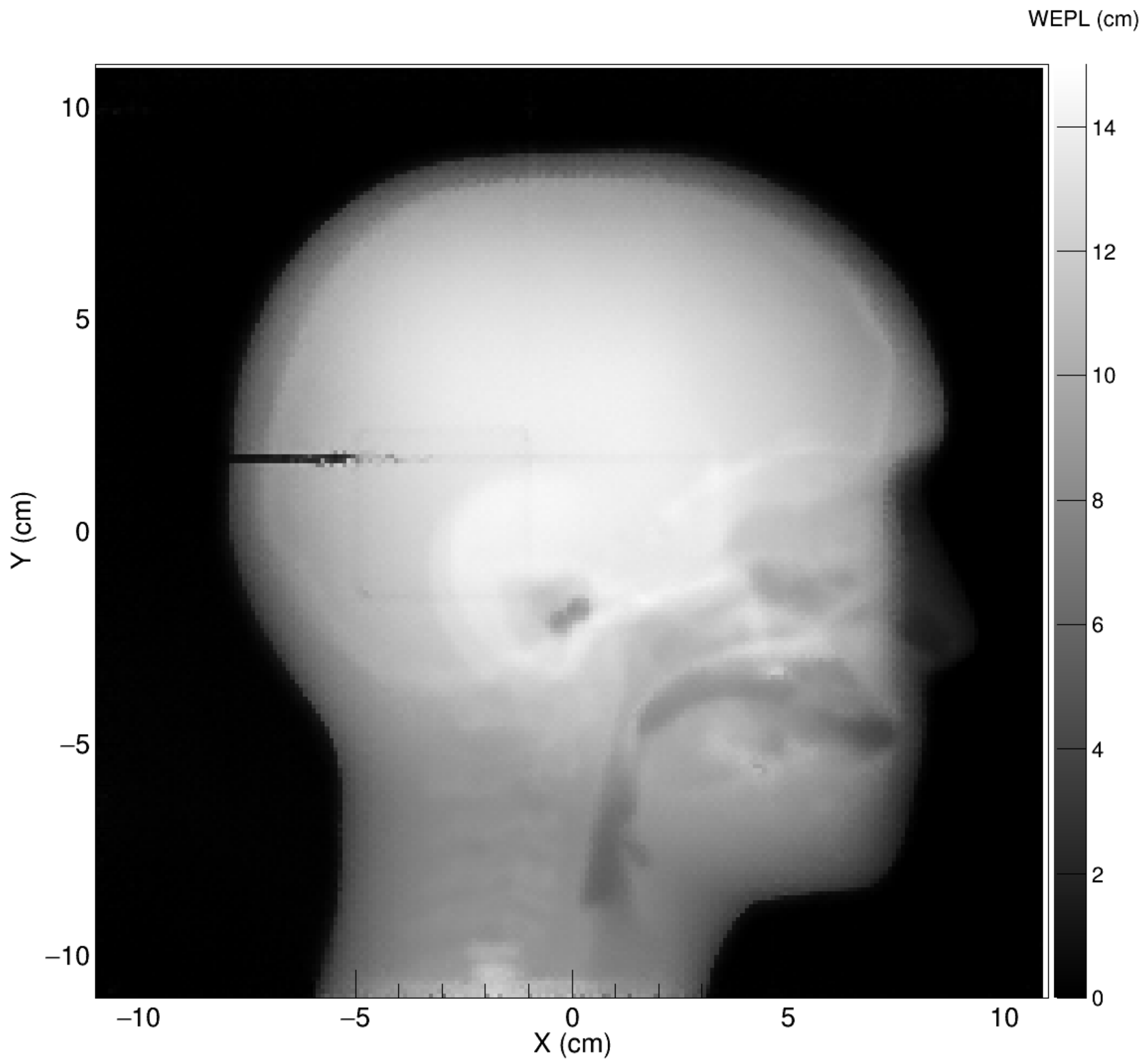


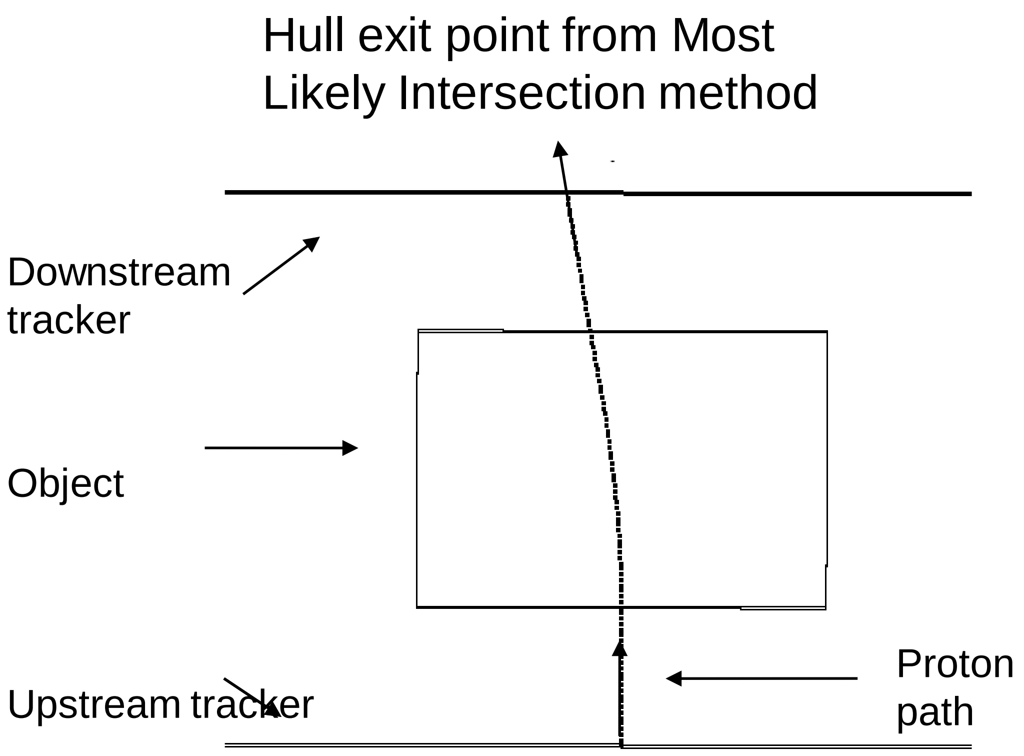
Detectors shifted right, phantom in same position

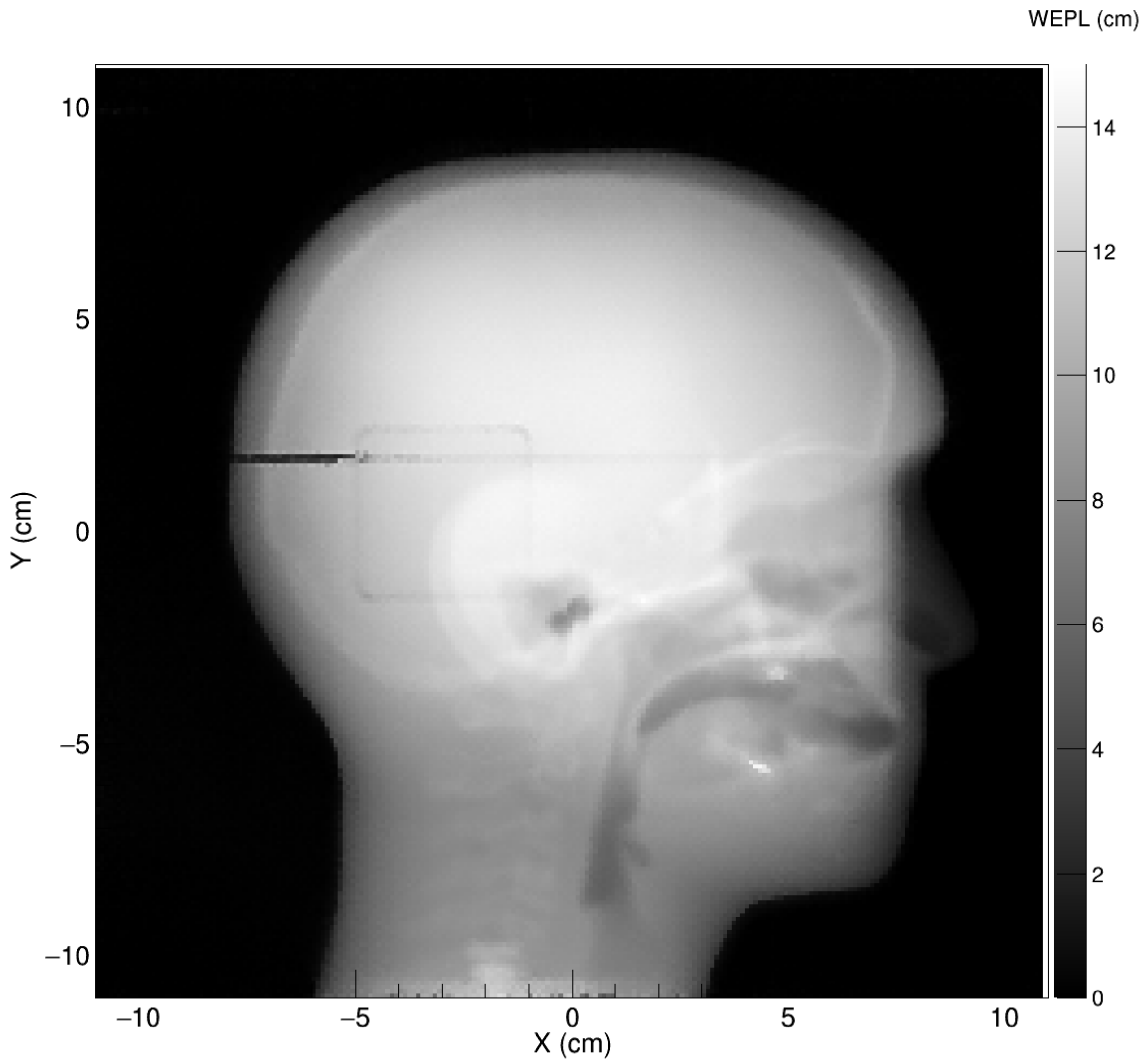




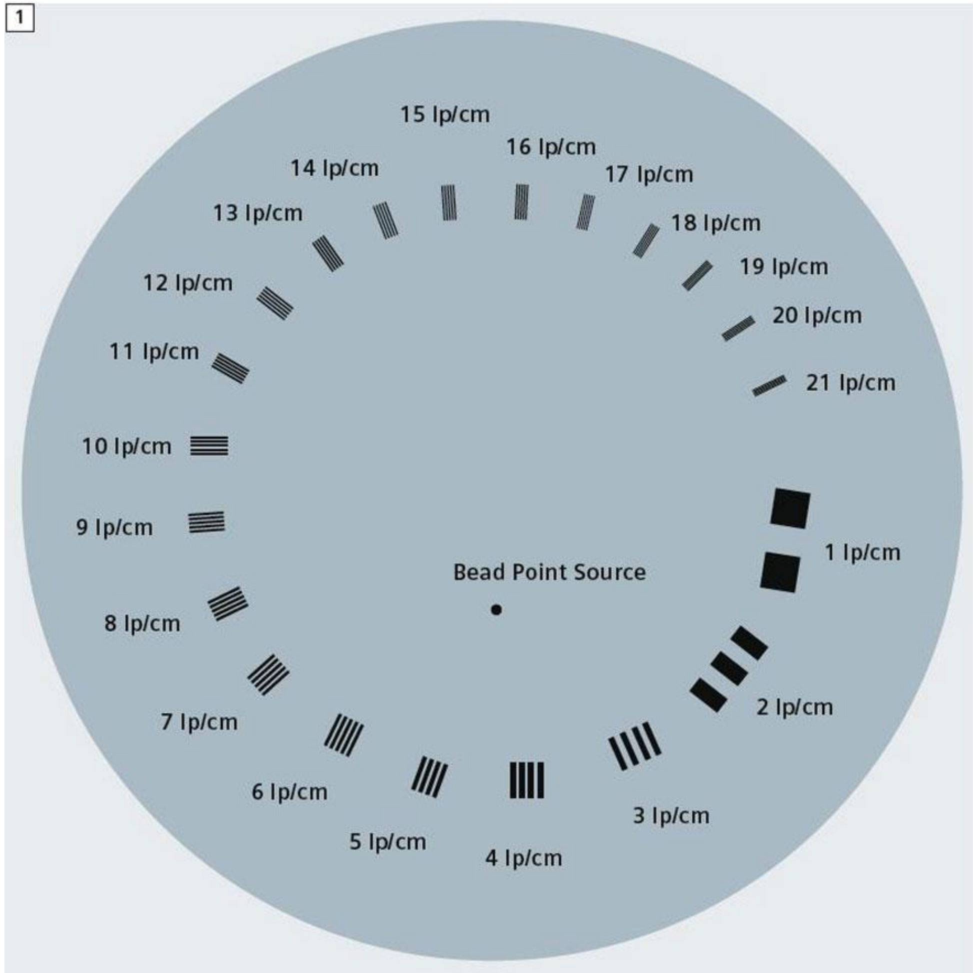

Hull exit point from straight line approximation
Downstream tracker
Object
Upstream tracker
Proton path


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


Hull exit point from Most
Likely Intersection method
Downstream
tracker
Object
Upstream tracker
Proton
path

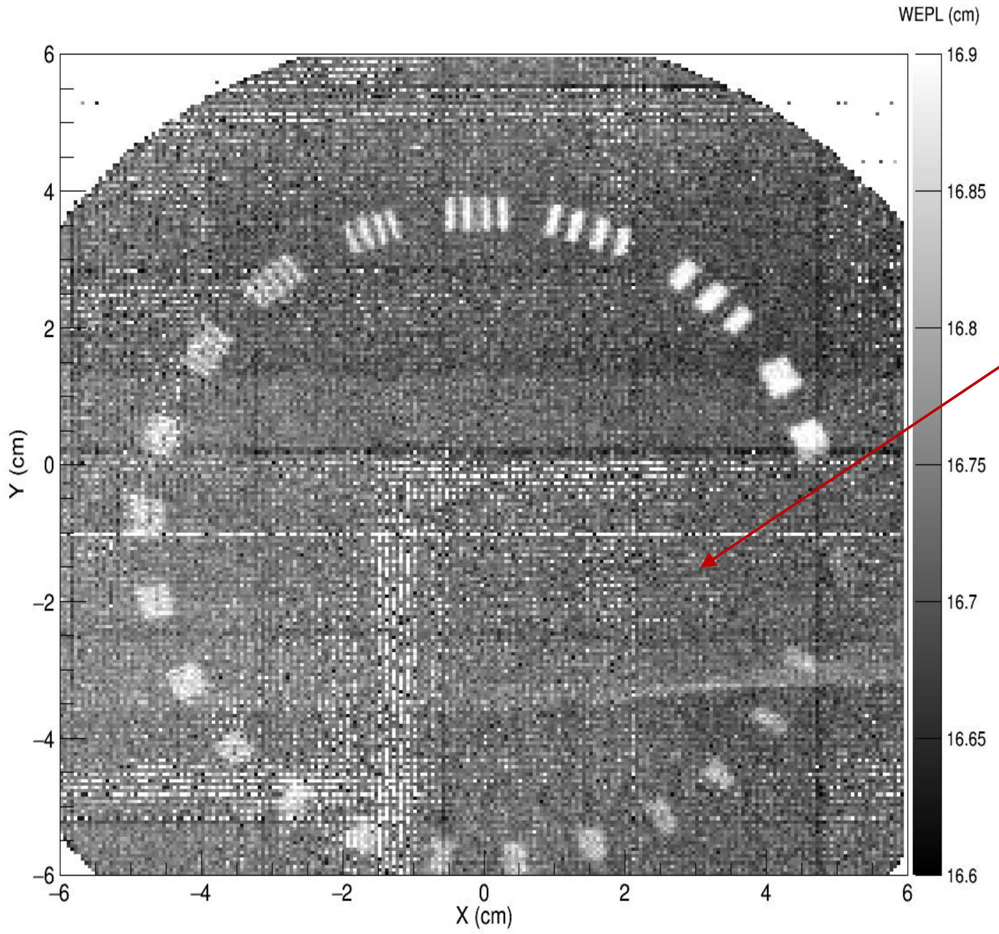

WEPL (cm)
Y (cm)
X (cm)
10
5
0
−5
−10
14
12
8
6
4
2

CATPHAN Line Pair Phantom

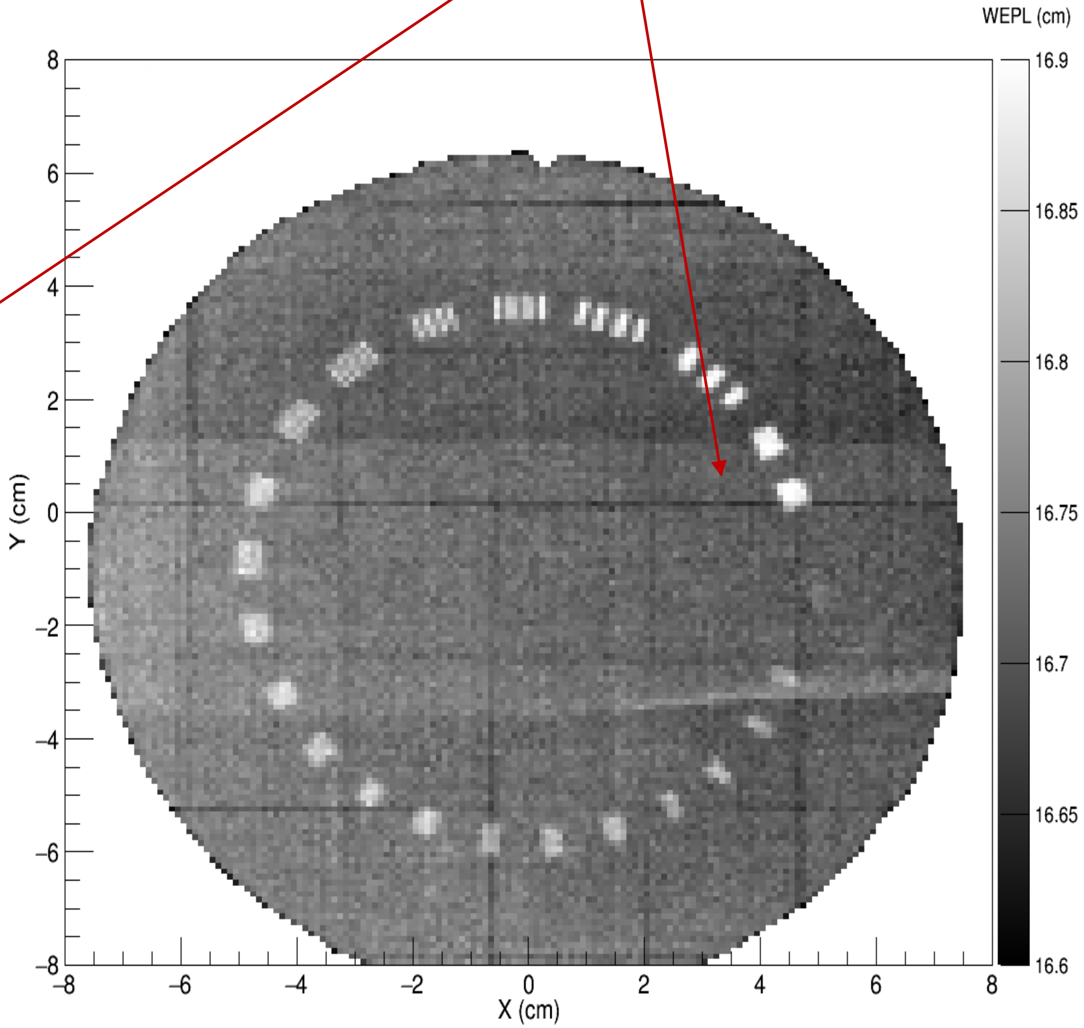


Offline reconstruction
Note: grey scale range only 3 mm!

As to range sensitivity.. We clearly see the 0.2 mm tape supporting the phantom. The density of this tape is slightly above water density.



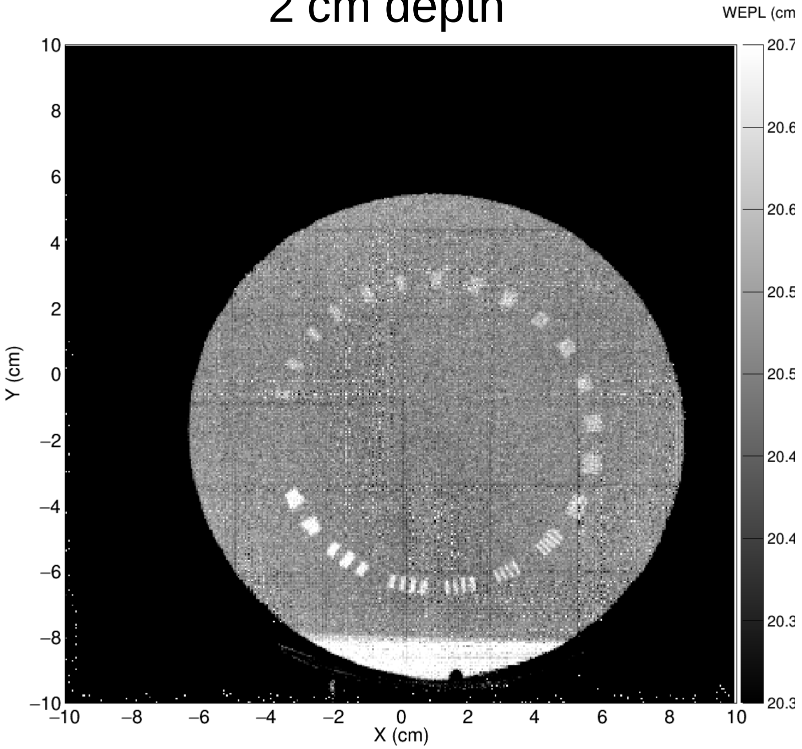
We see 7 line pairs/cm with 0.5 mm pixel size



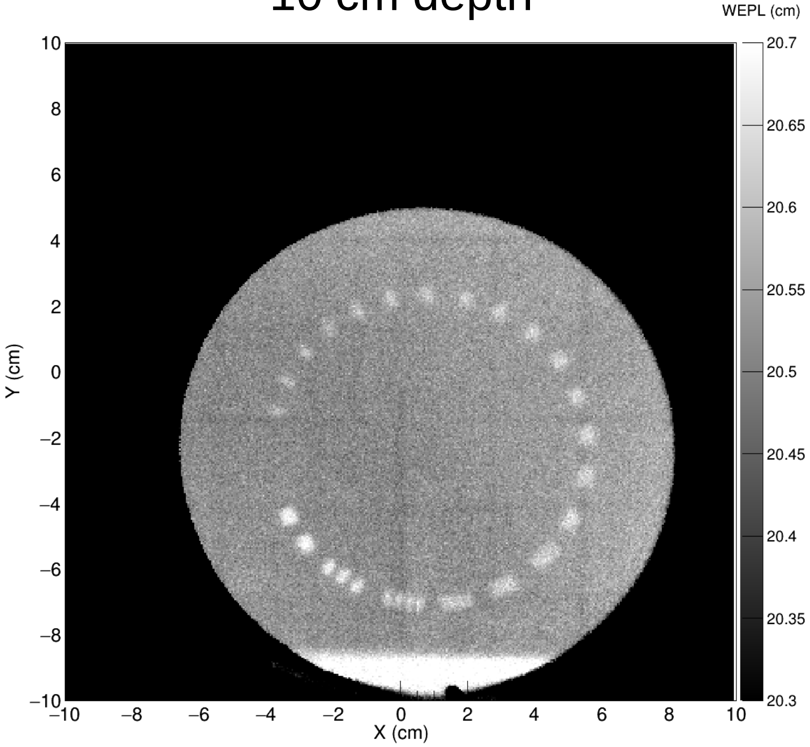
We see 6 line pairs/cm with 1 mm pixel size

Measuring spatial resolution at different depths in water – line pair phantom plus 16 cm water

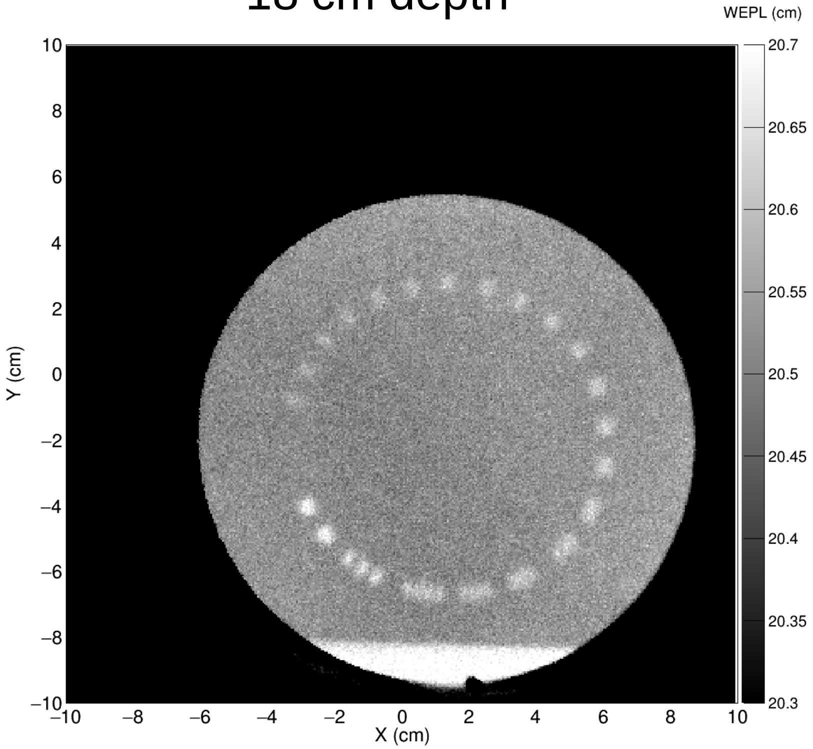
2 cm depth



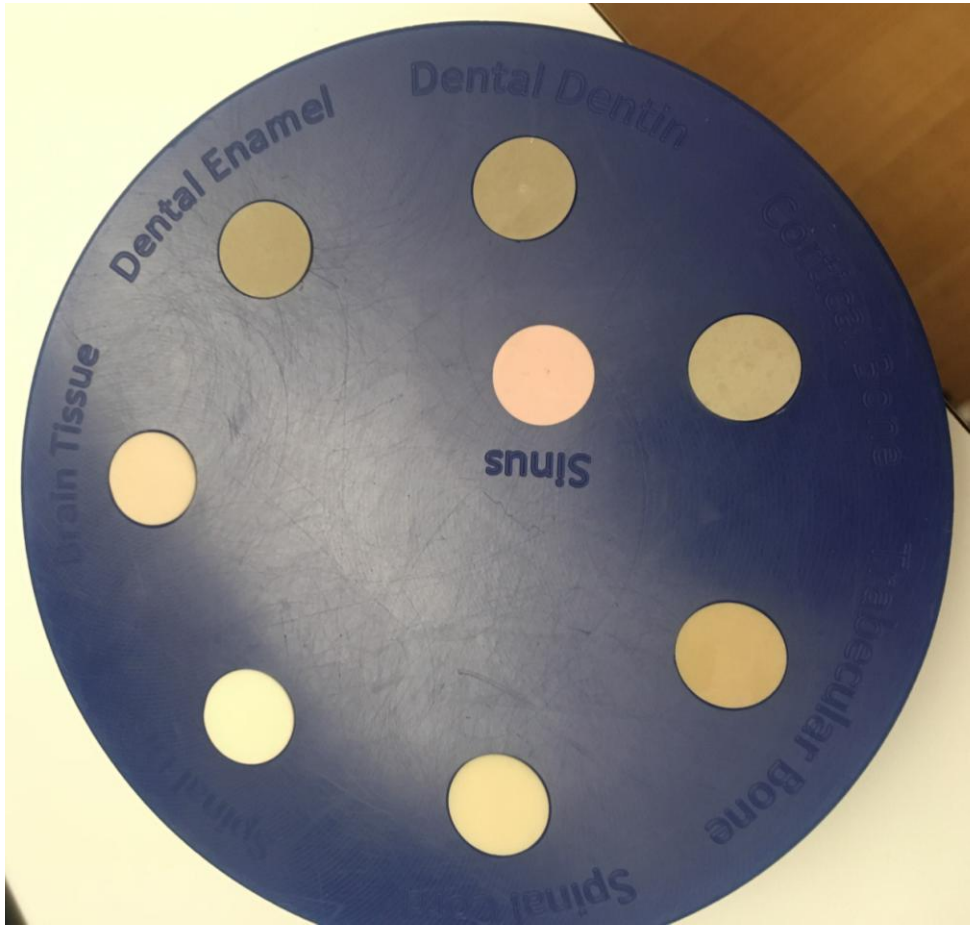
10 cm depth



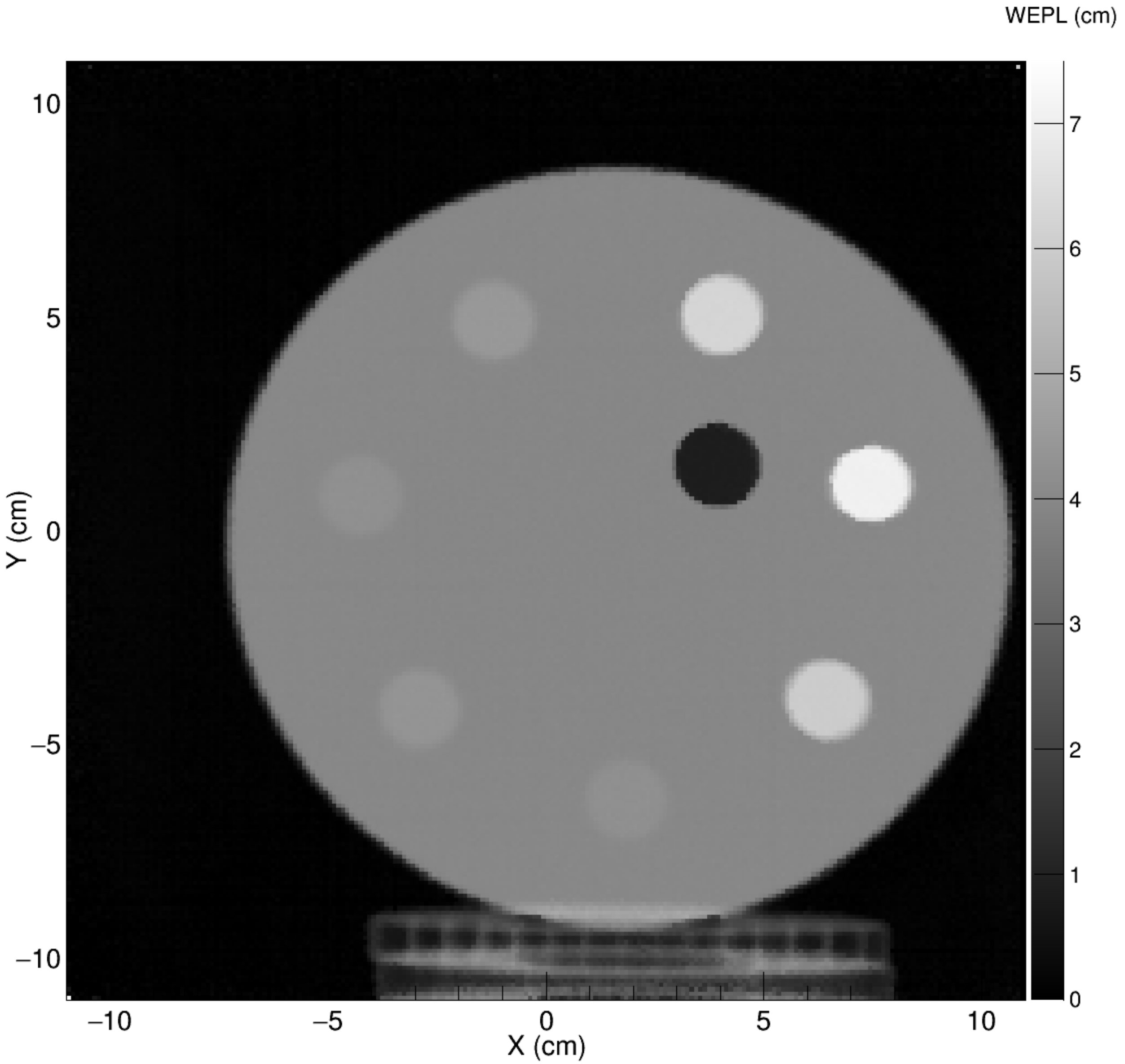
18 cm depth



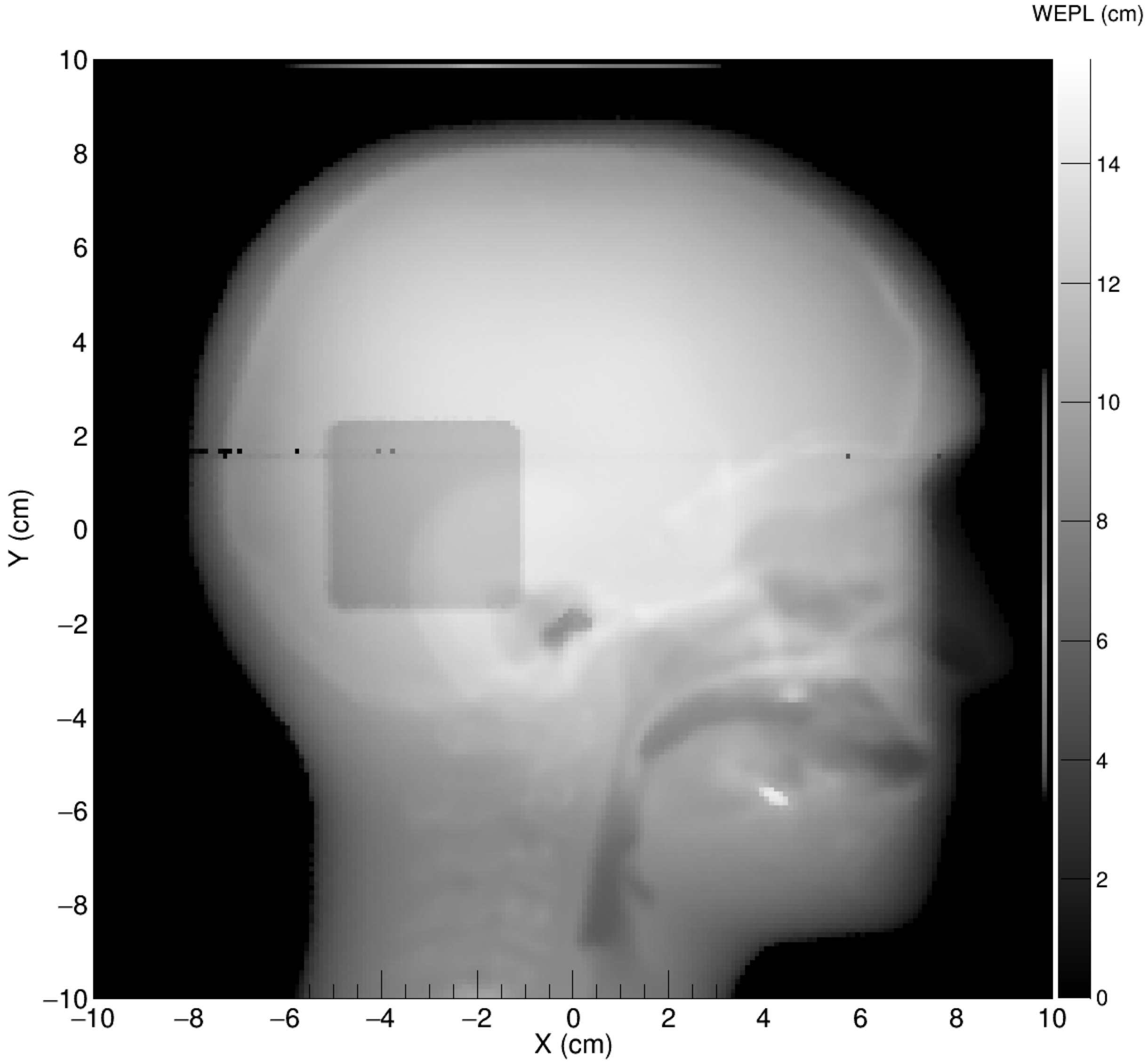
- Absolute WET Measurements
  –



- 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	Truth (cm)	Mean (cm)	Physical Error (cm)	Percent Error (%)
Sinus	0.88	0.84	-0.04	4.54
Enamel	7.02	7.04	0.02	0.28
Cortical Bone	6.22	6.25	0.03	0.48
Spinal Cord	4.16	4.22	0.06	1.44
Spinal Disc	4.28	4.34	0.06	1.40
Brain	4.16	4.22	0.06	1.44
Dentin	5.98	5.98	0.0	0.0

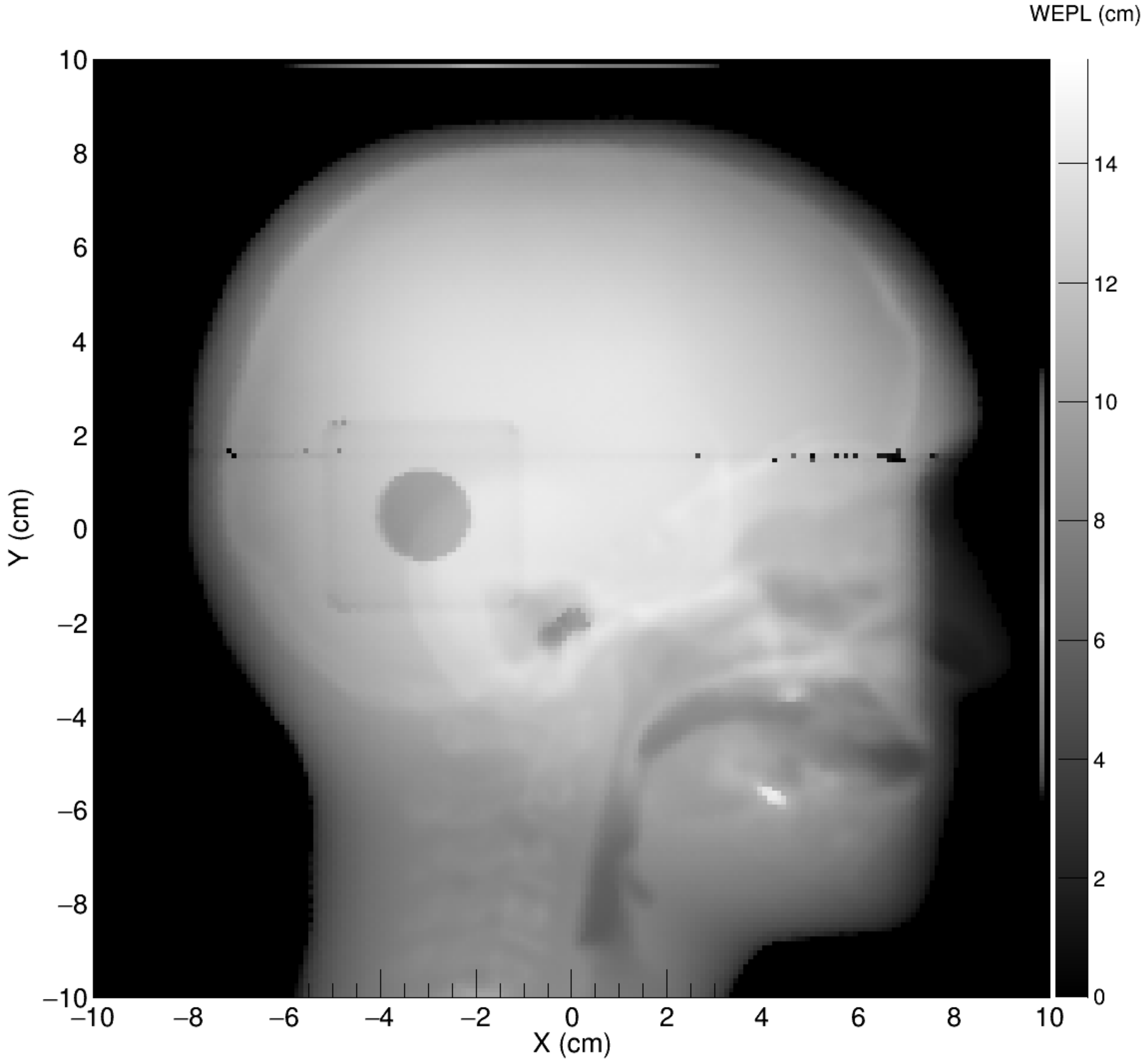


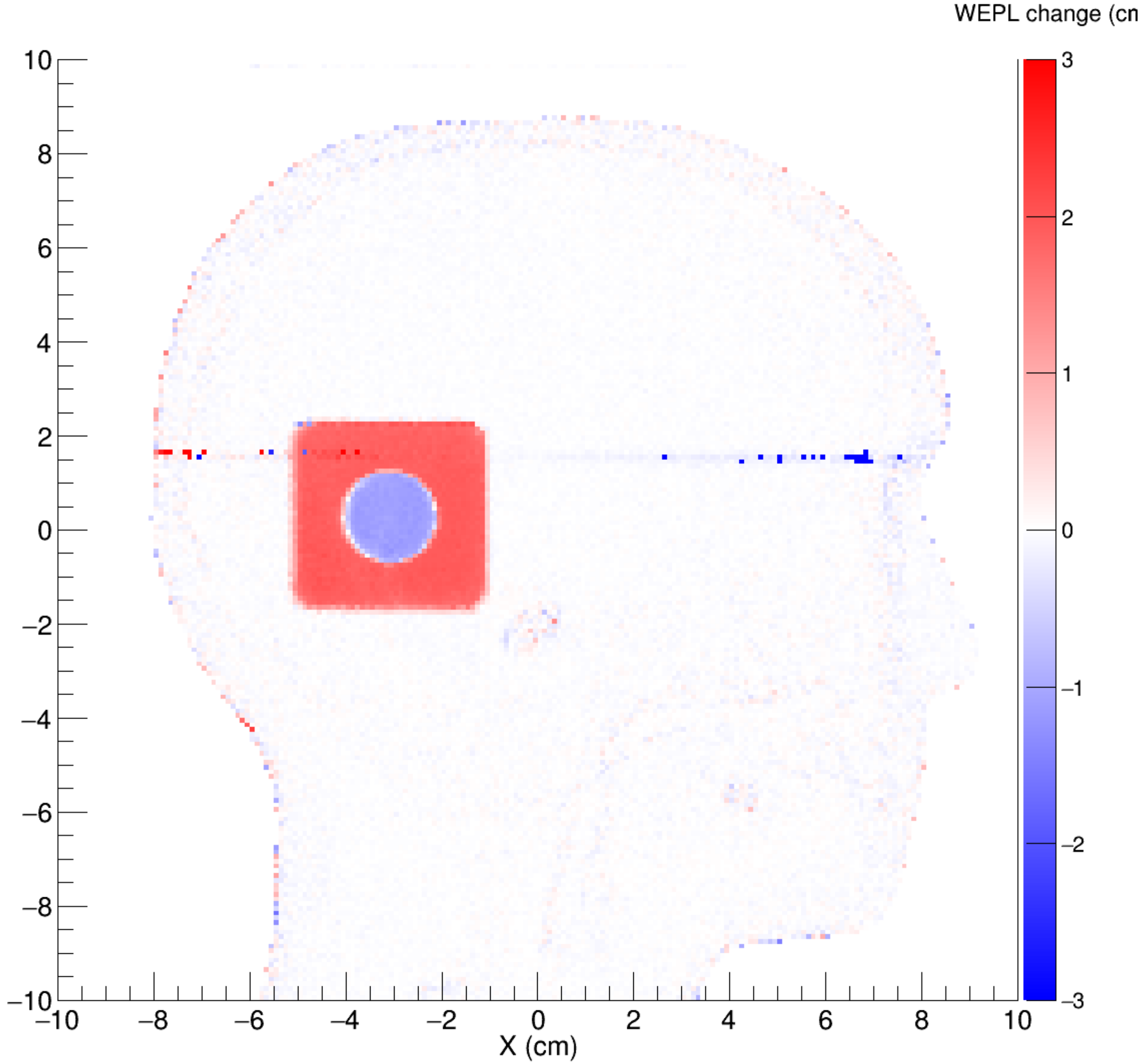
Insert: air (2 cm blue wax)

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)

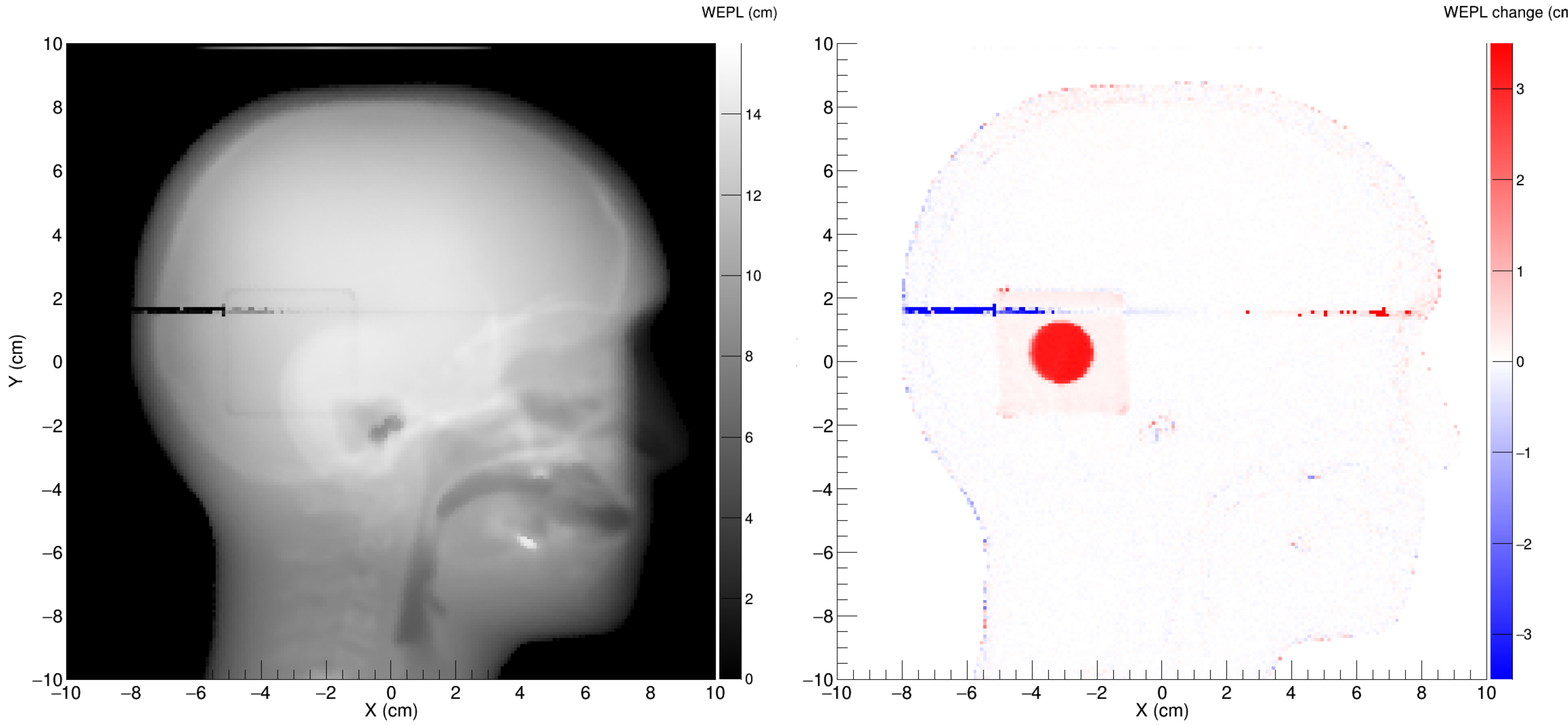




Insert: sinus (4 cm)

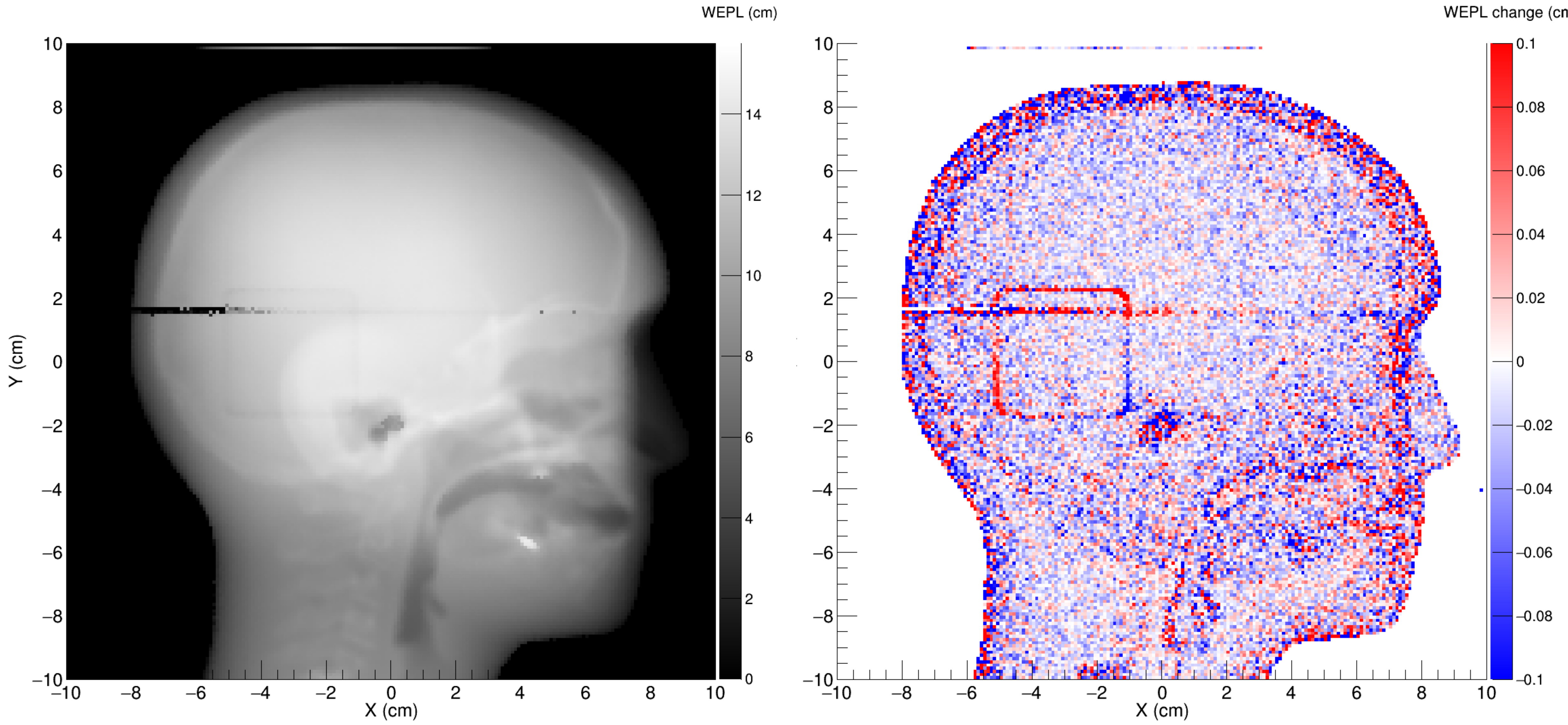
RSP: 0.22

Expected difference: -10.8 mm
Measured difference: -10.82 ± 0.04 mm



Insert: brain tissue RSP: 1.04

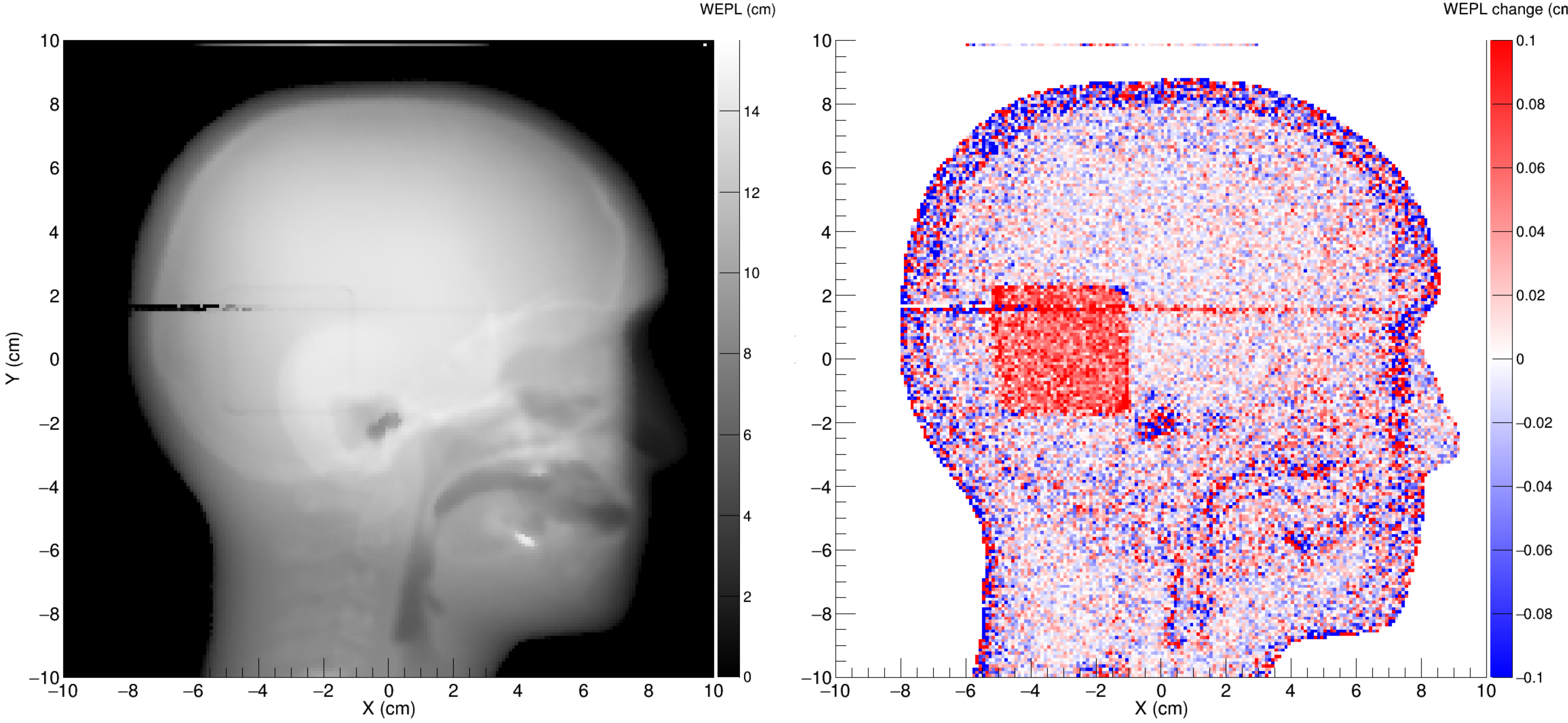
Expected difference: +31.6 mm
Measured difference: +31.31 ± 0.04 mm



Insert: spinal cord

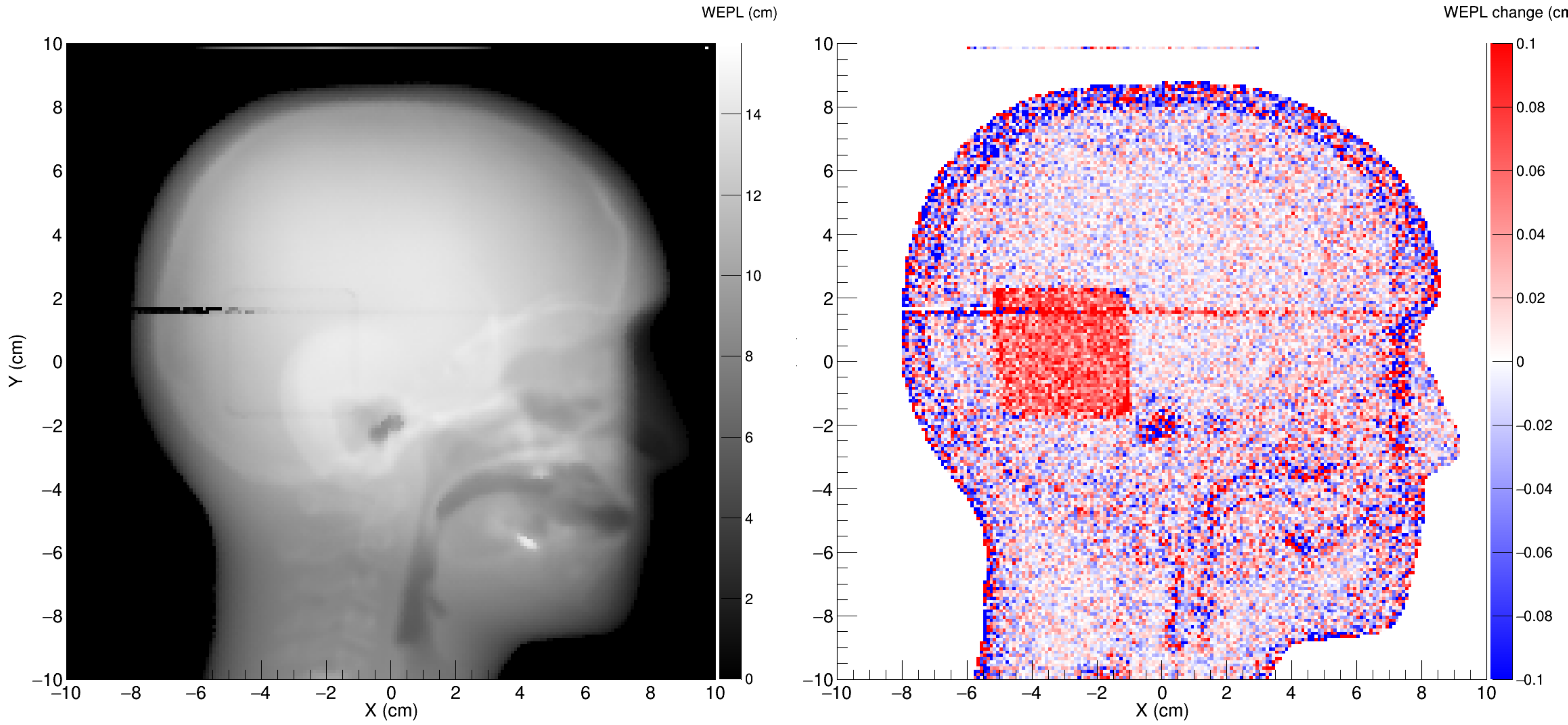
RSP: 1.04

Expected difference: 0 mm
Measured difference: -0.05 ± 0.01 mm



Insert: spinal disc RSP: 1.07

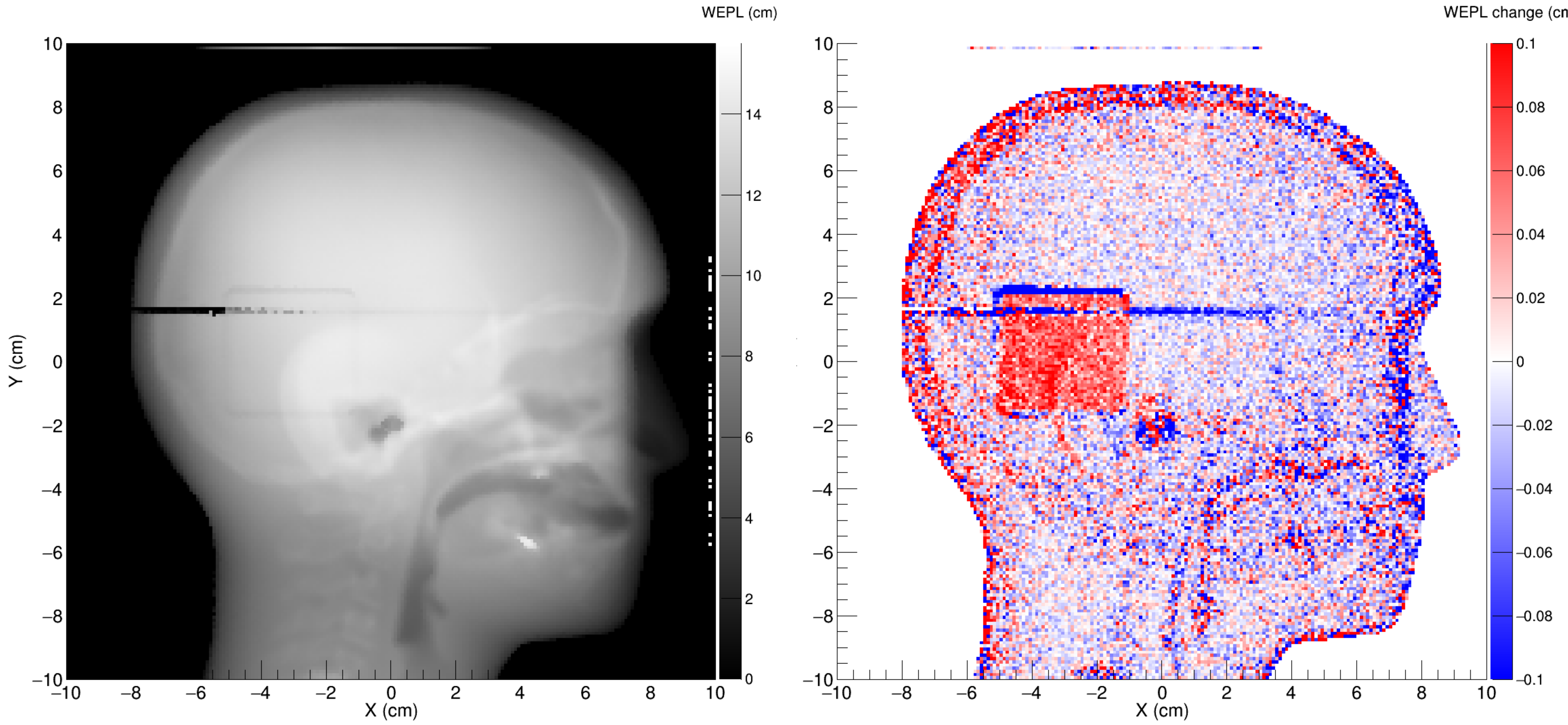
Expected difference: +0.6 mm
Measured difference: +0.58 ± 0.01 mm



Insert: spinal disc

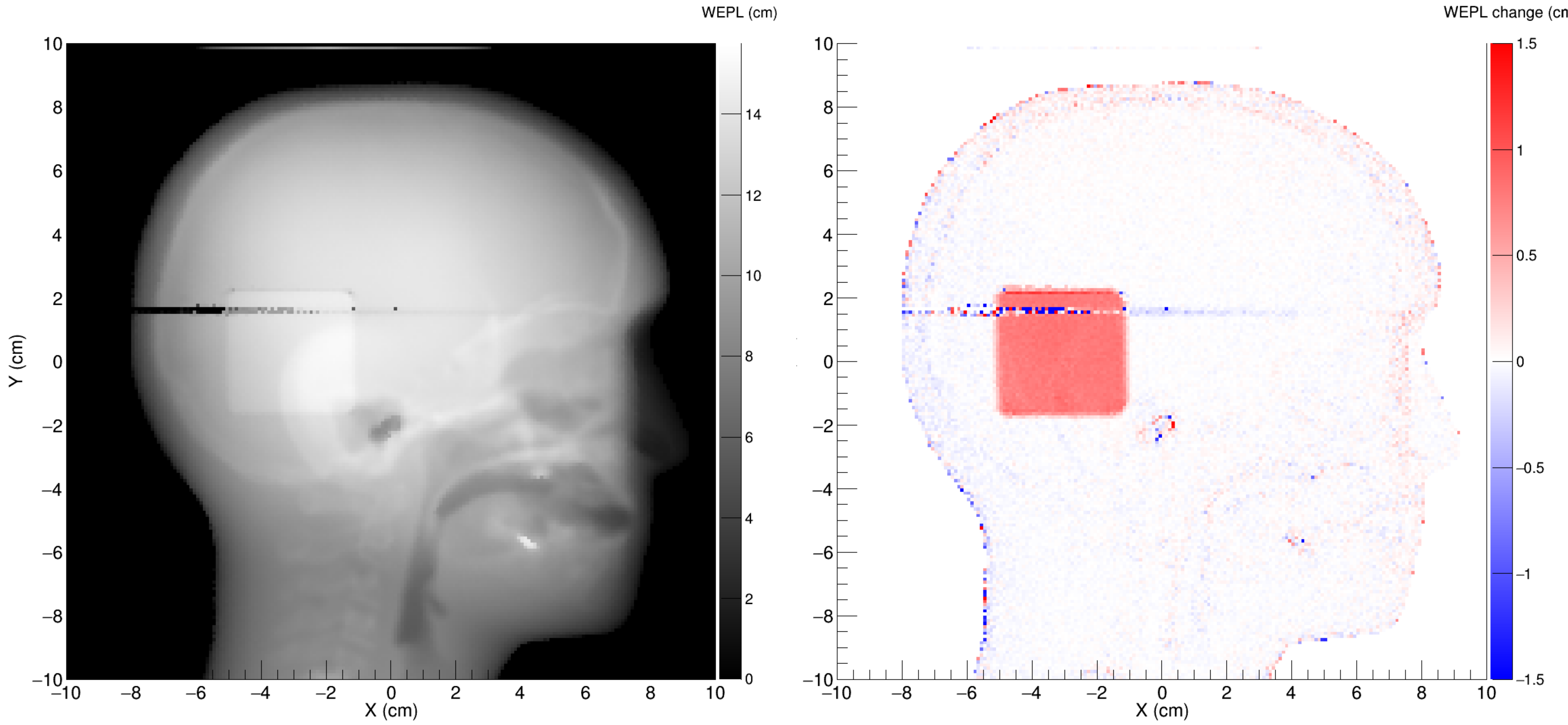
RSP: 1.07

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



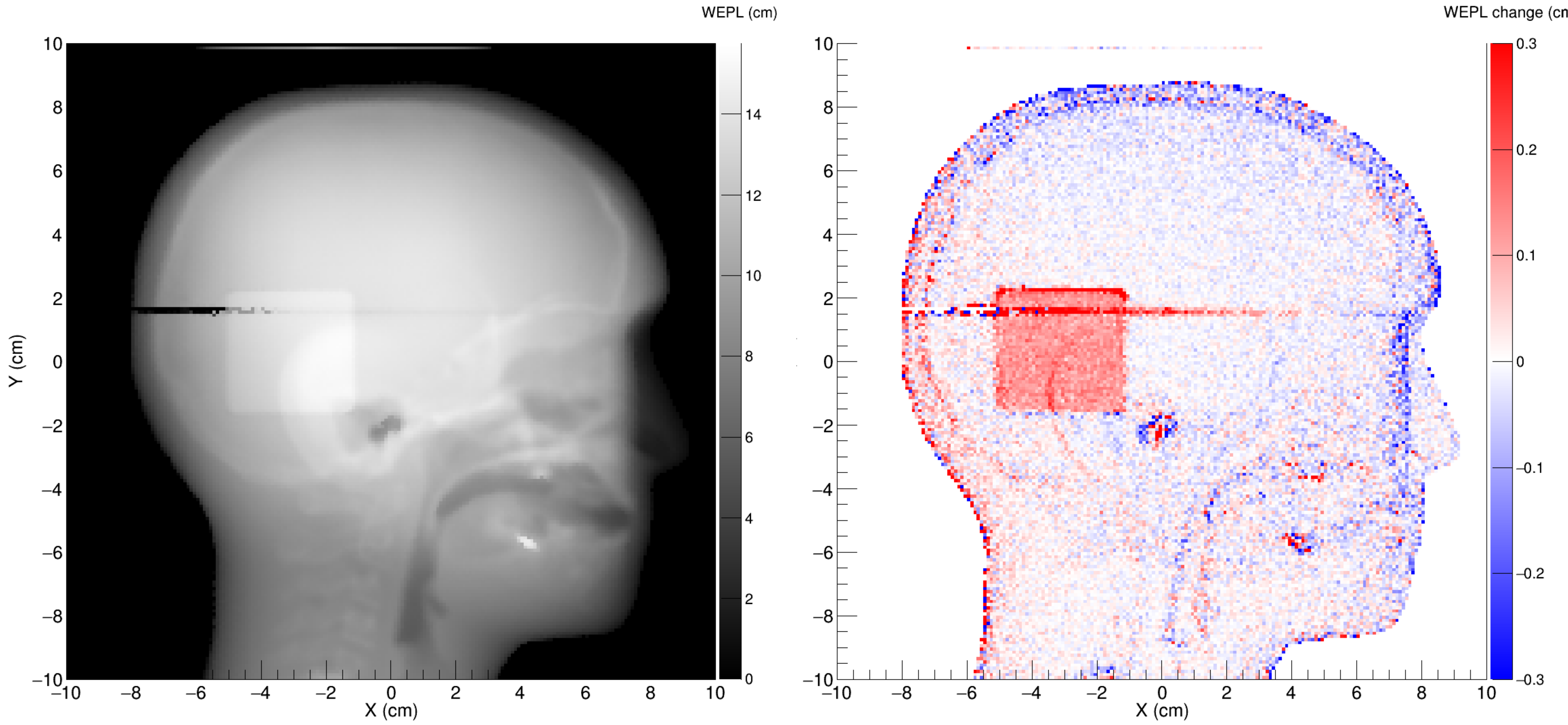
Insert: trabecular bone RSP: 1.10

Expected difference: +0.6 mm
Measured difference: +0.64 ± 0.01 mm



Insert: dental enamel RSP: 1.495

Expected difference: +7.9 mm
Measured difference: +7.83 ± 0.01 mm

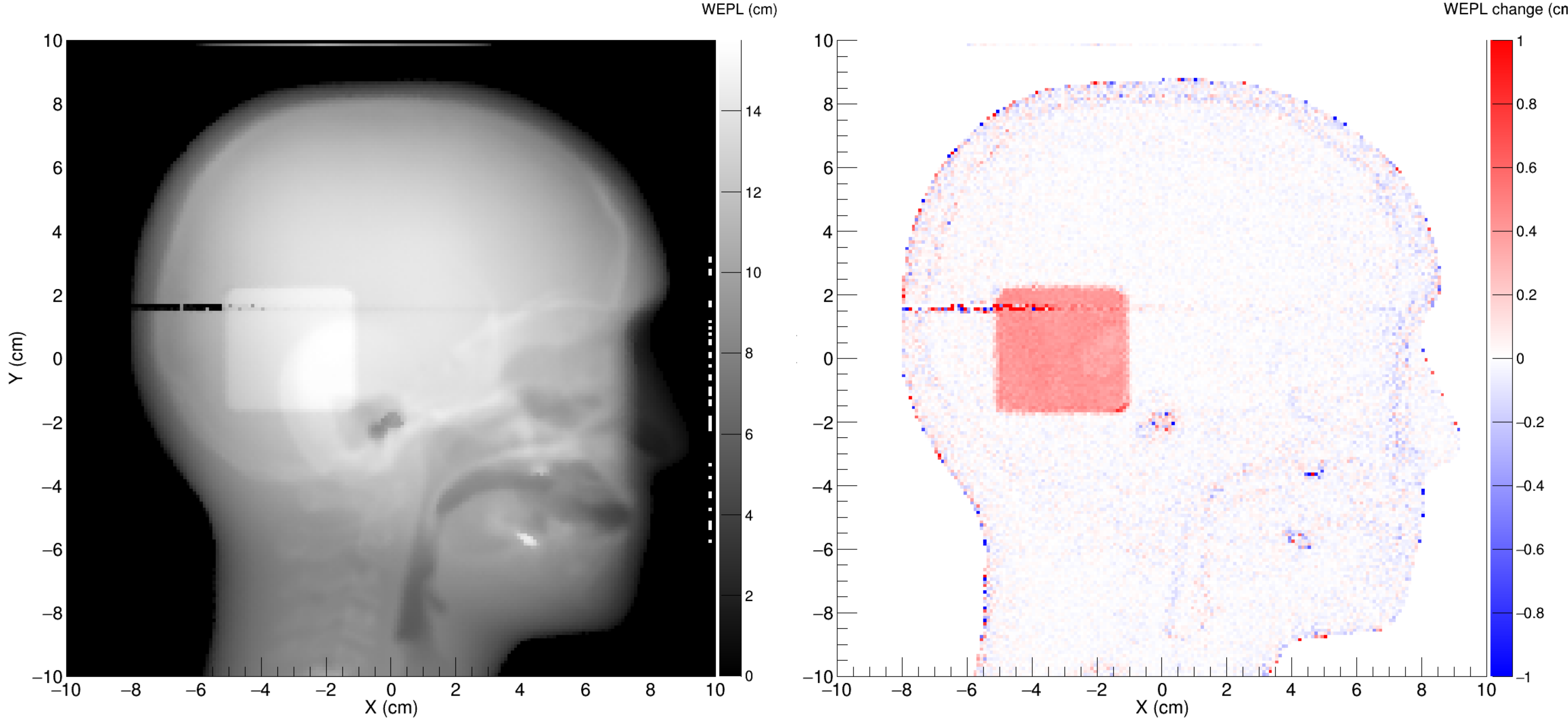


Insert: cortical bone

RSP: 1.555

Expected difference: +1.2 mm

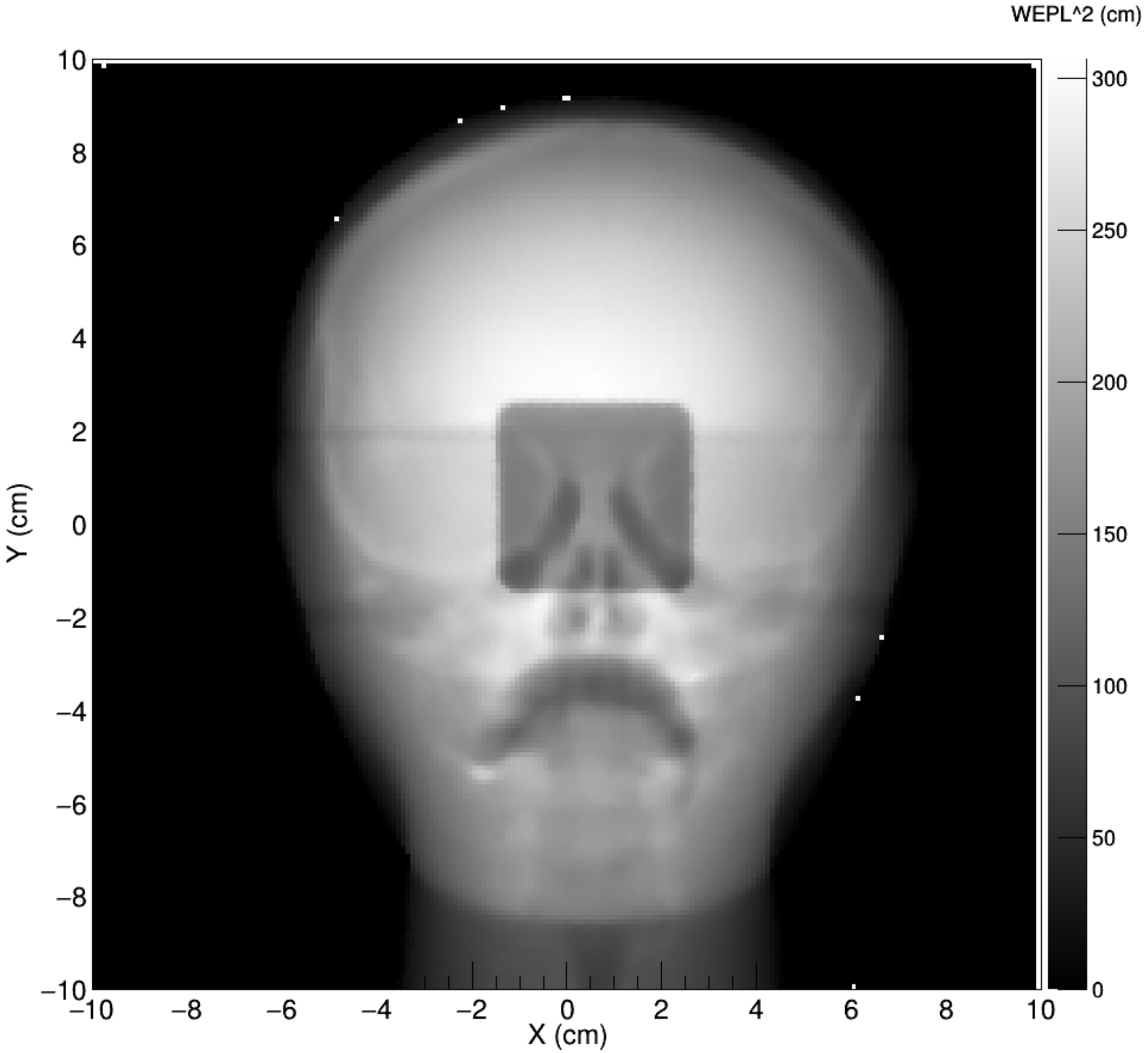
Measured difference: +1.26 ± 0.01 mm



Insert: dentin

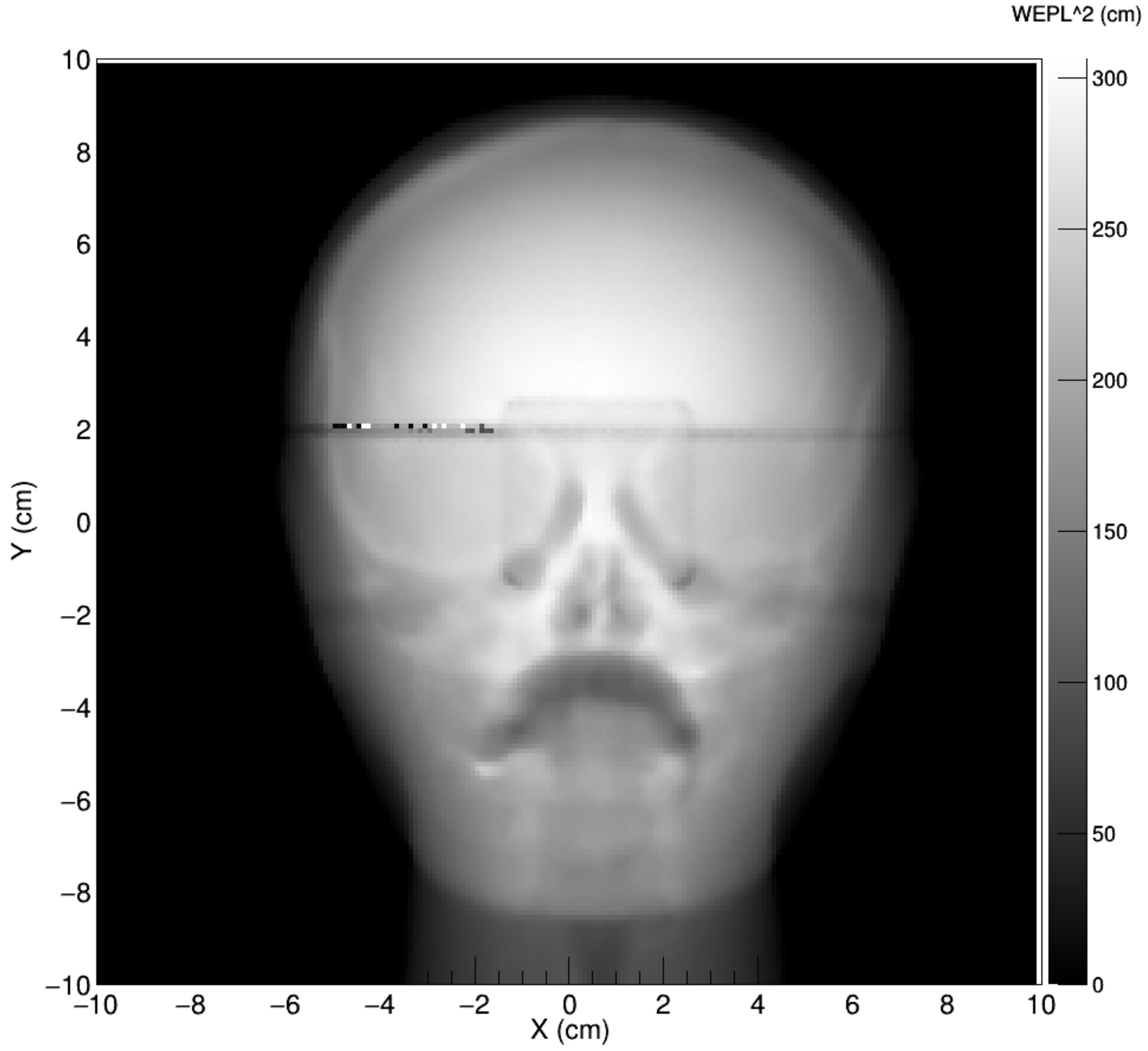
RSP: 1.755

Expected difference: +4.0 mm
Measured difference: +4.04 ± 0.01 mm

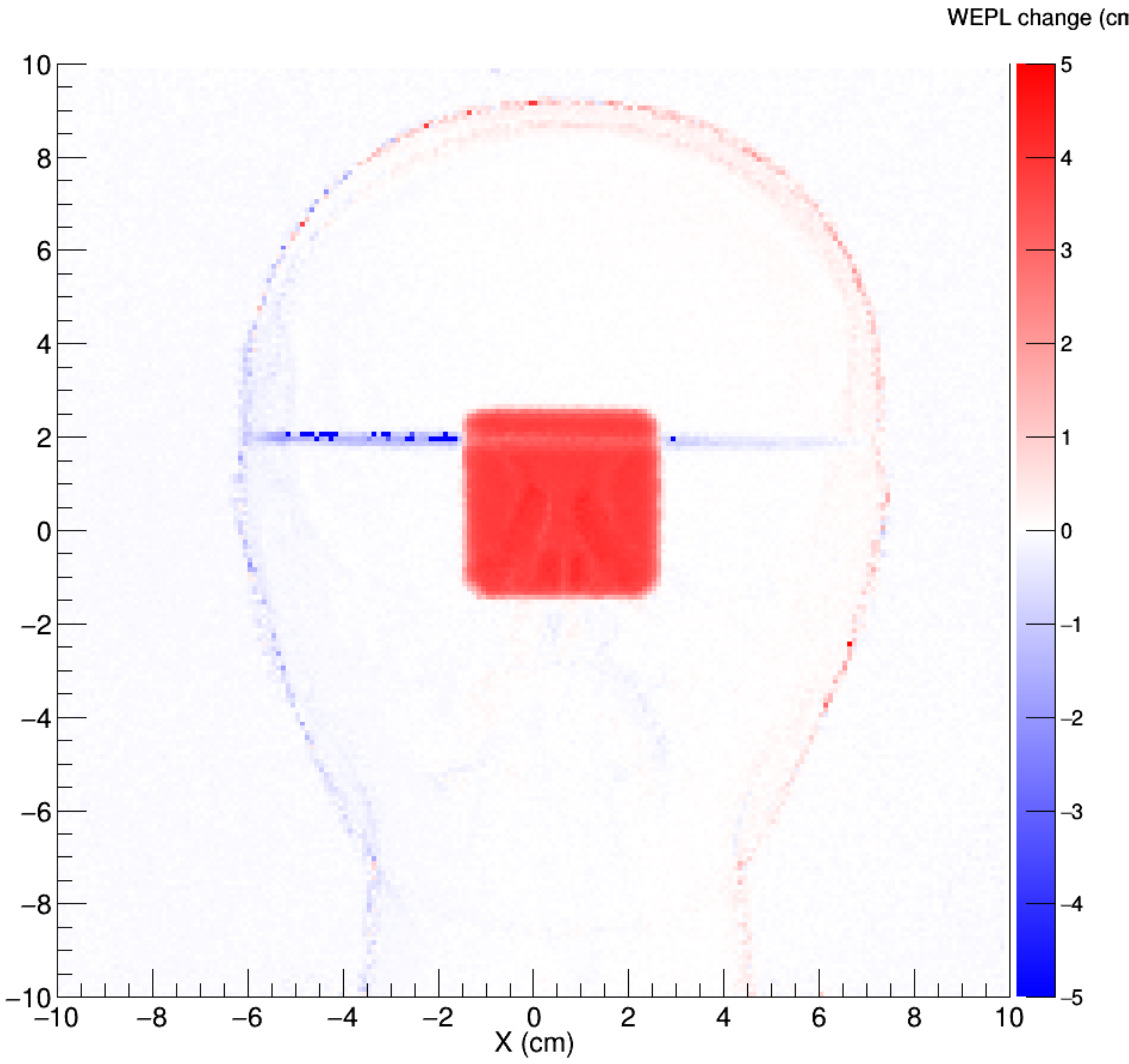


Blue wax inserts (RSP 0.977) of varying lengths

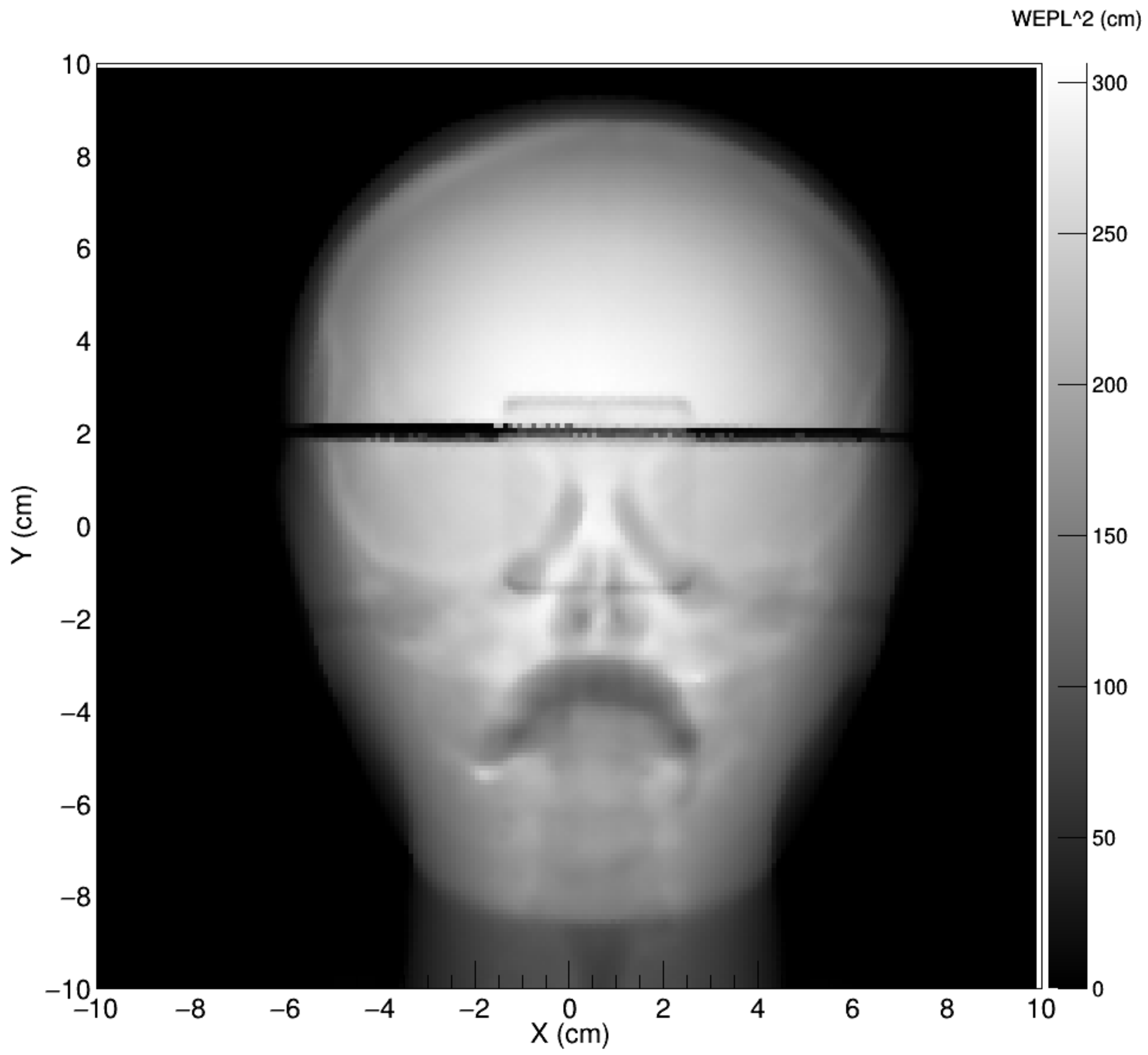
Insert: air

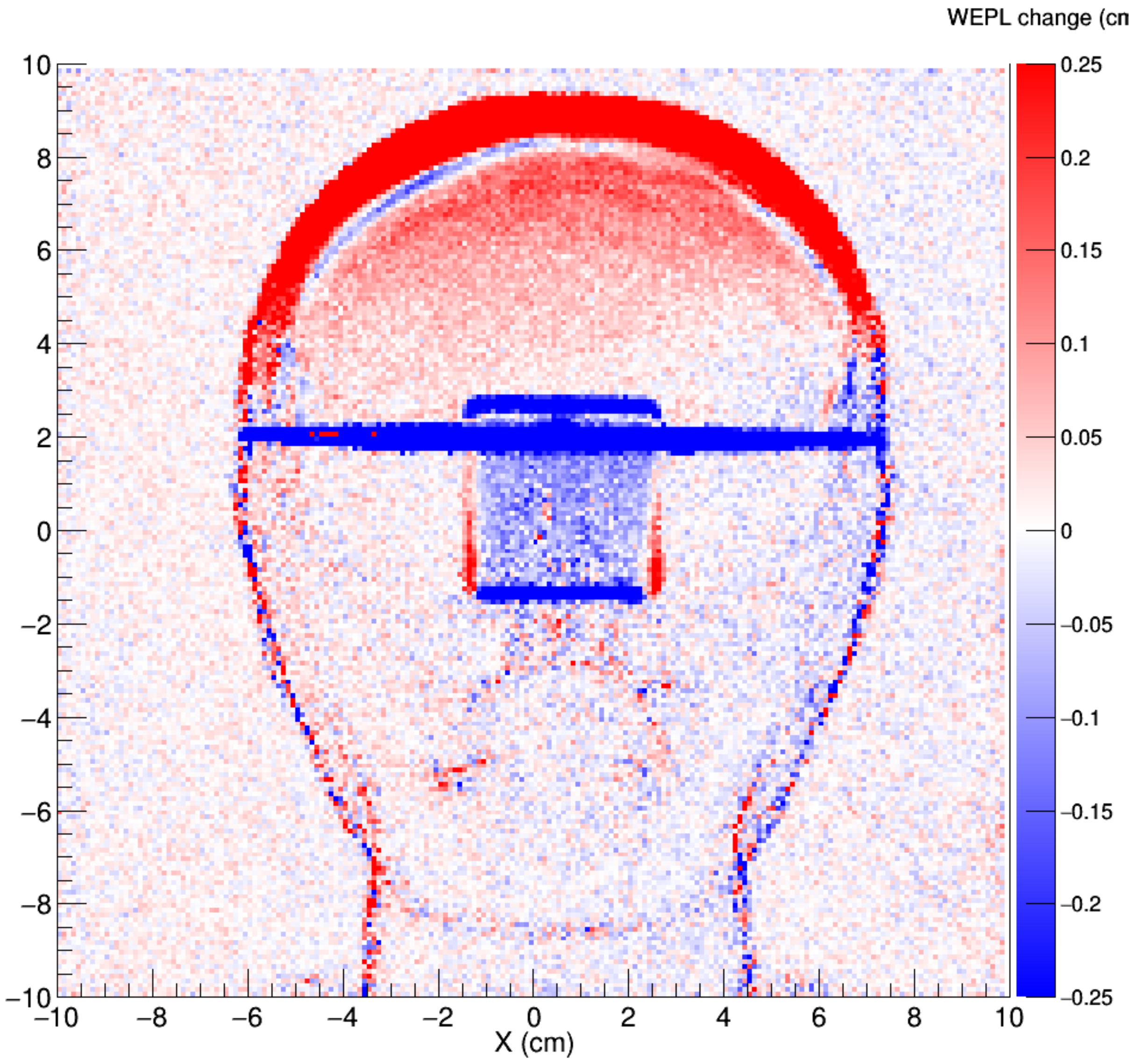


Change in insert thickness: +39.98 mm



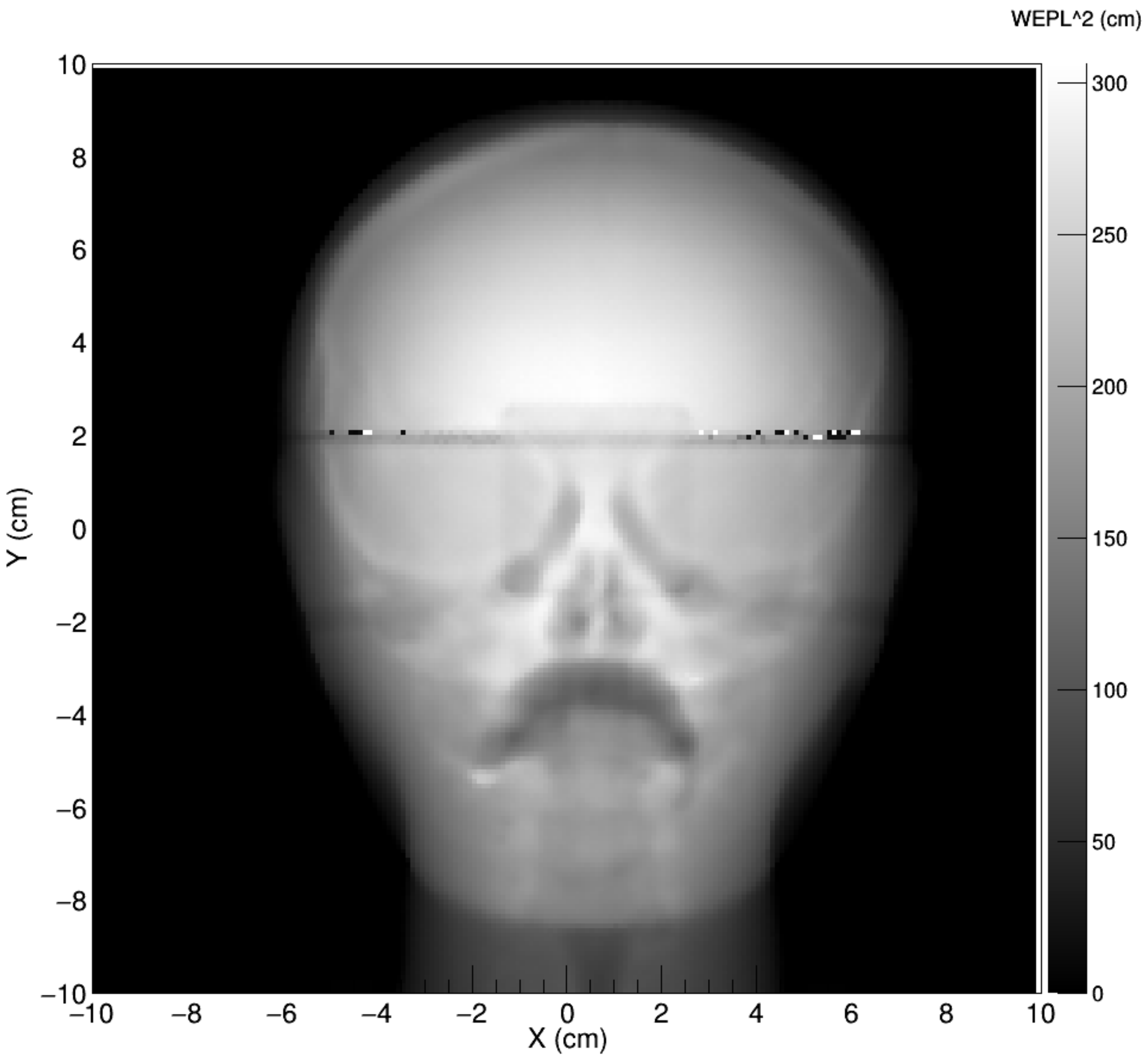
Expected difference: +39.06 mm
Measured difference: +38.57 ± 0.07 mm

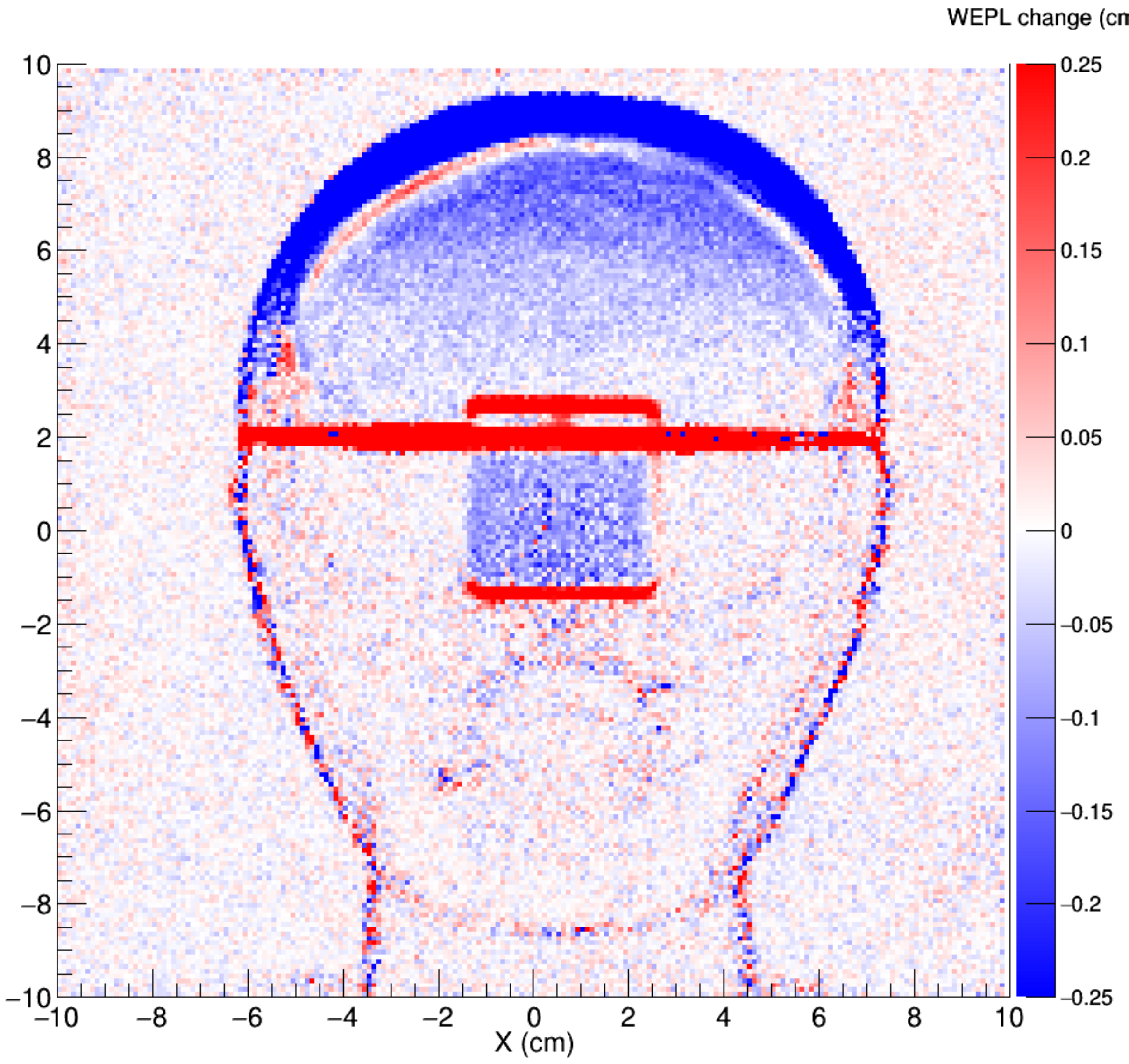




Change in insert thickness: -0.88 mm

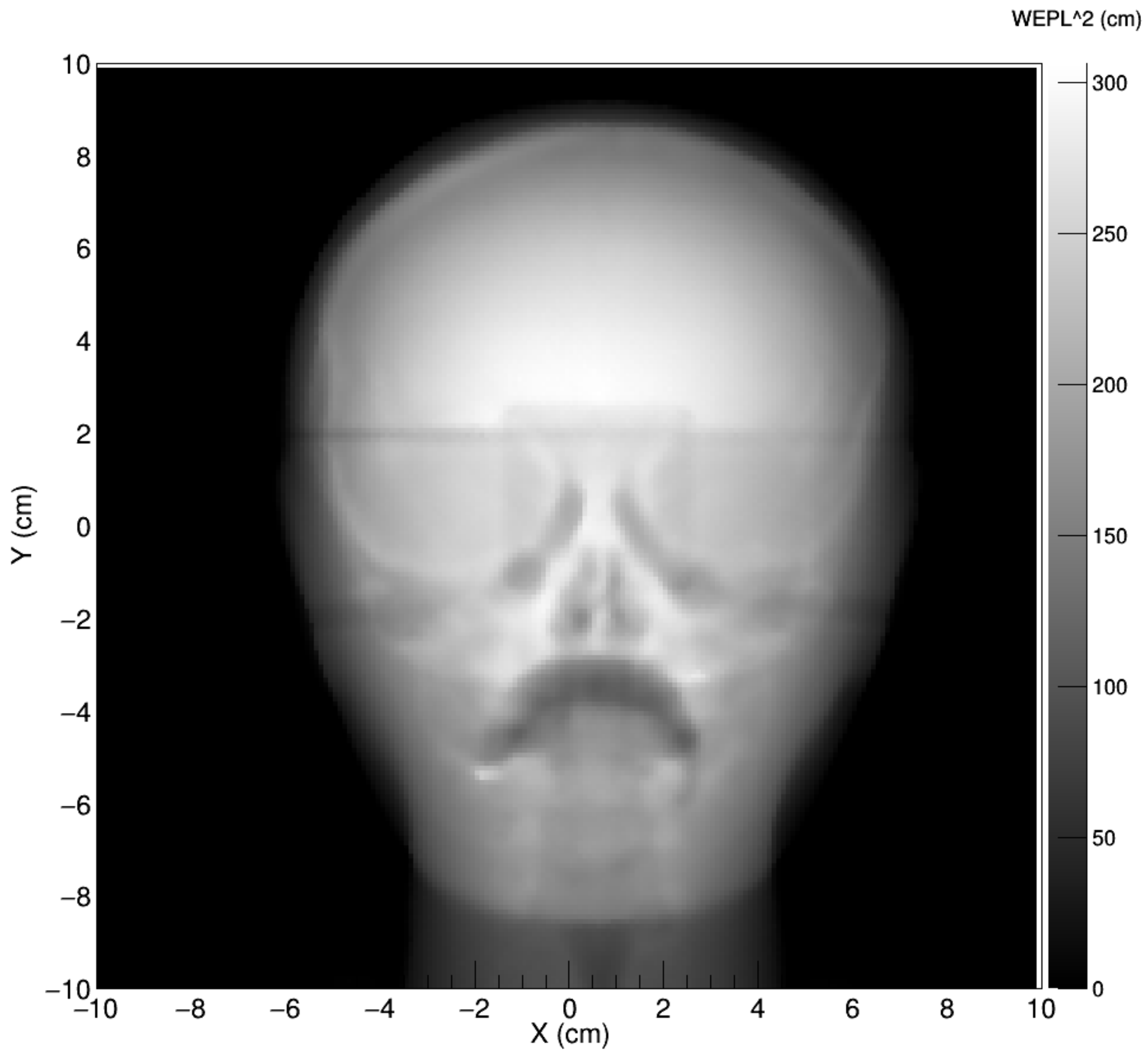
Expected difference: -0.86 mm
Measured difference: -0.82 ± 0.03 mm

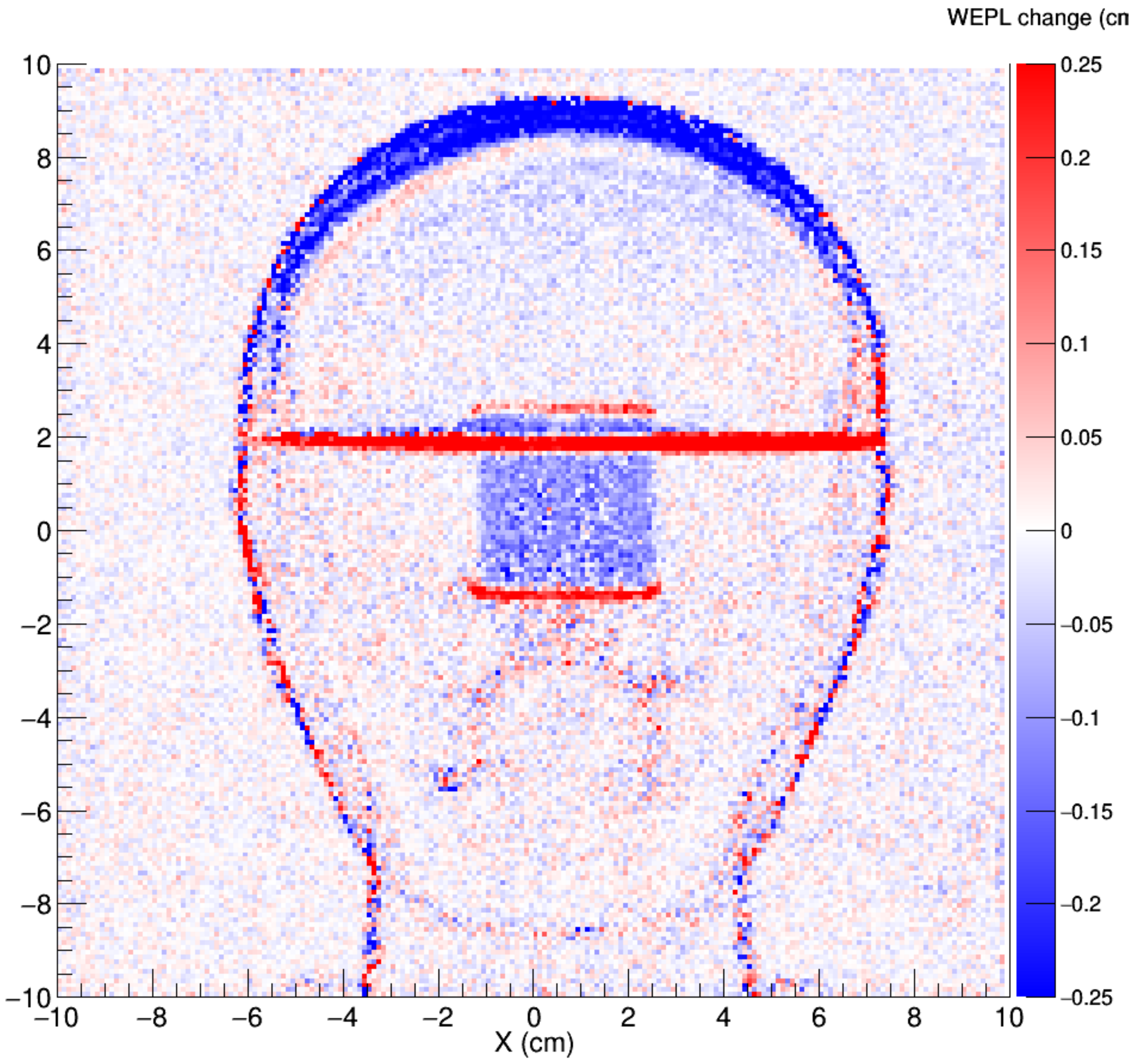




Change in insert thickness: -1.01 mm

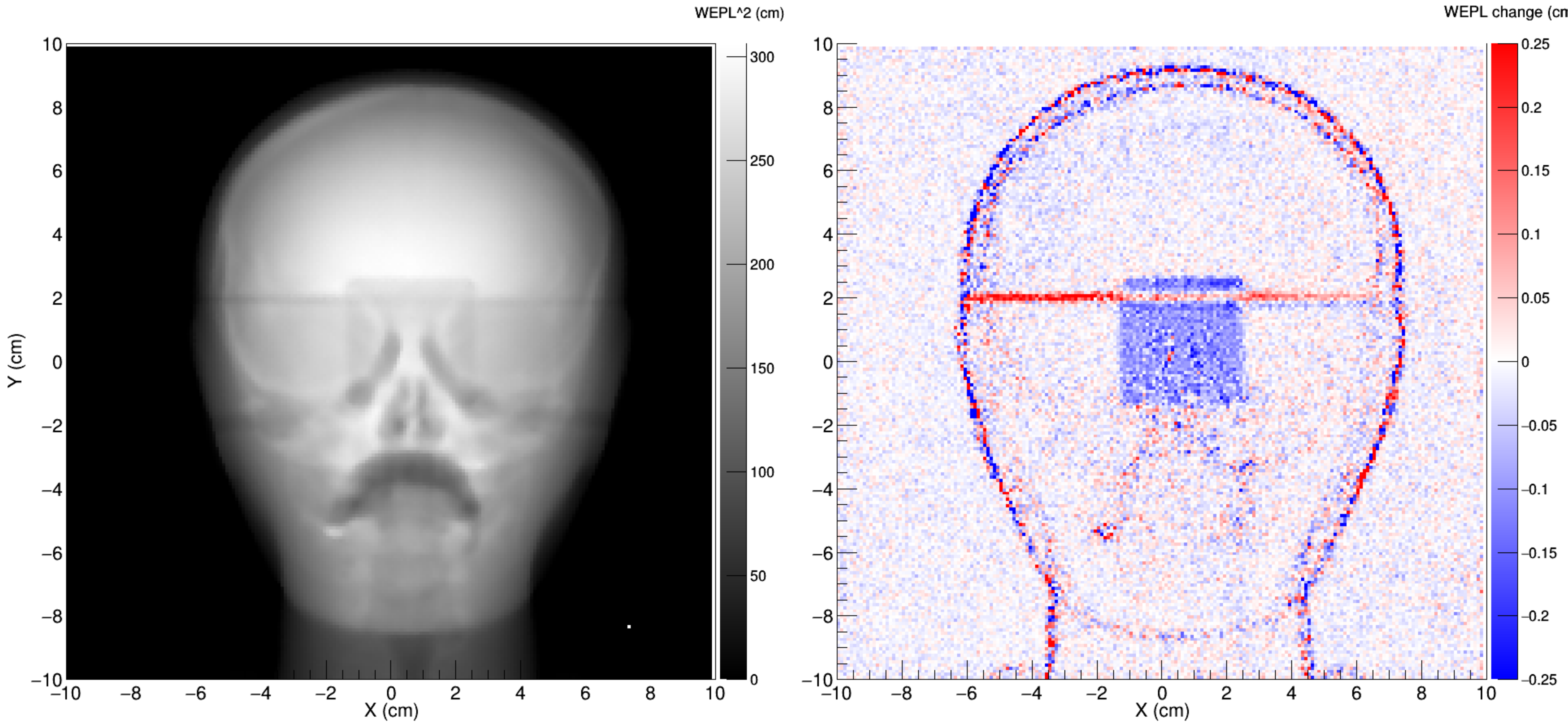
Expected difference: -0.99 mm
Measured difference: -0.88 ± 0.04 mm





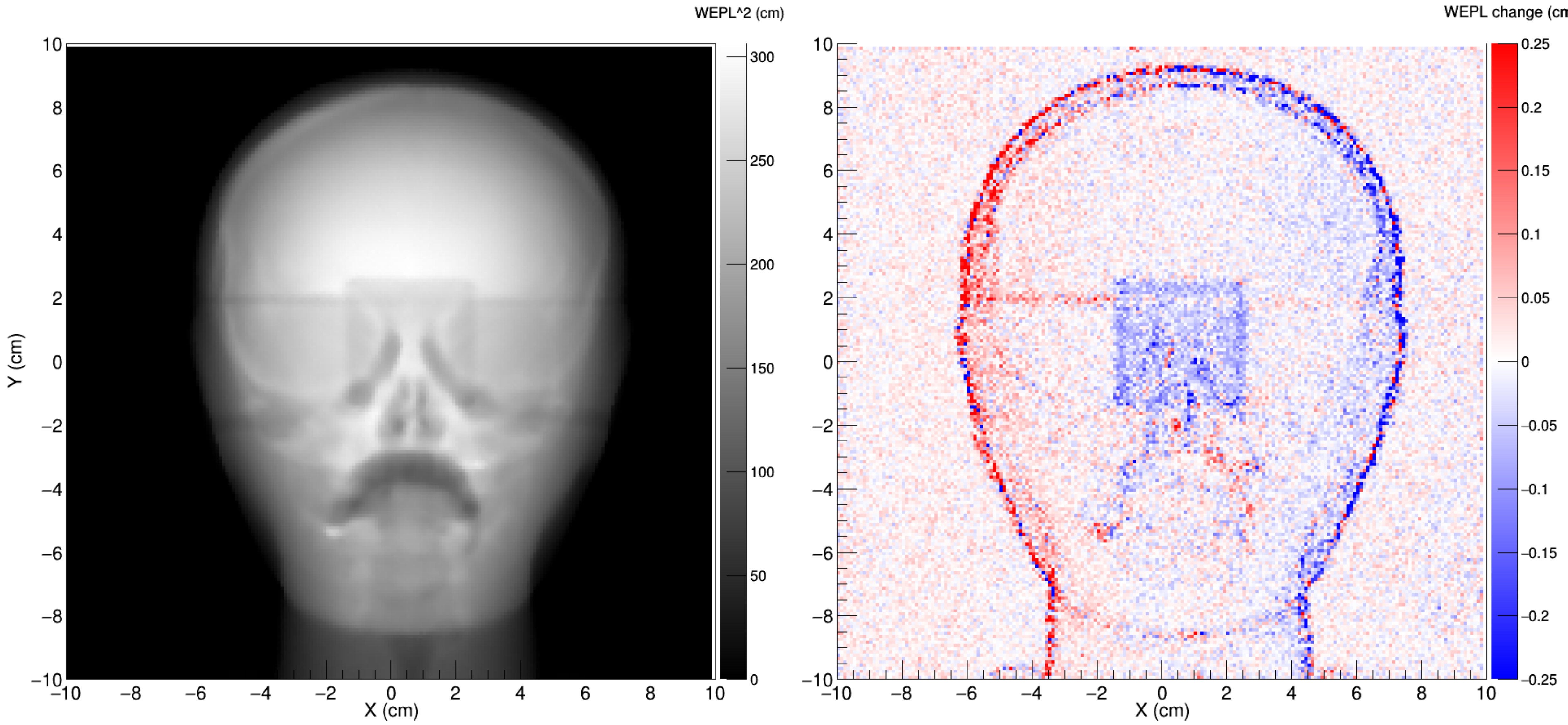
Change in insert thickness: -1.02 mm

Expected difference: -1.00 mm
Measured difference: -1.00 ± 0.03 mm



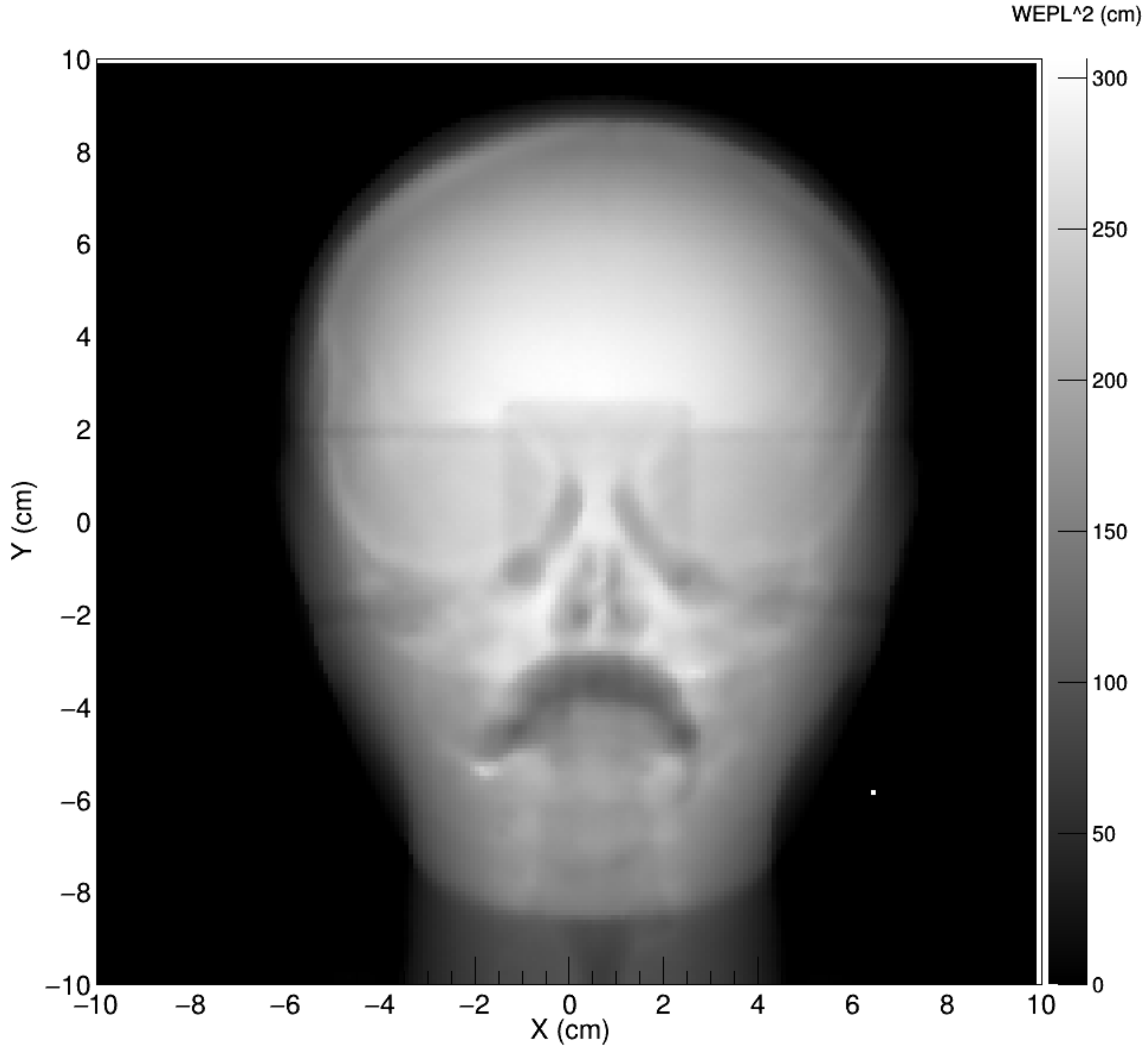
Change in insert thickness: -1.04 mm

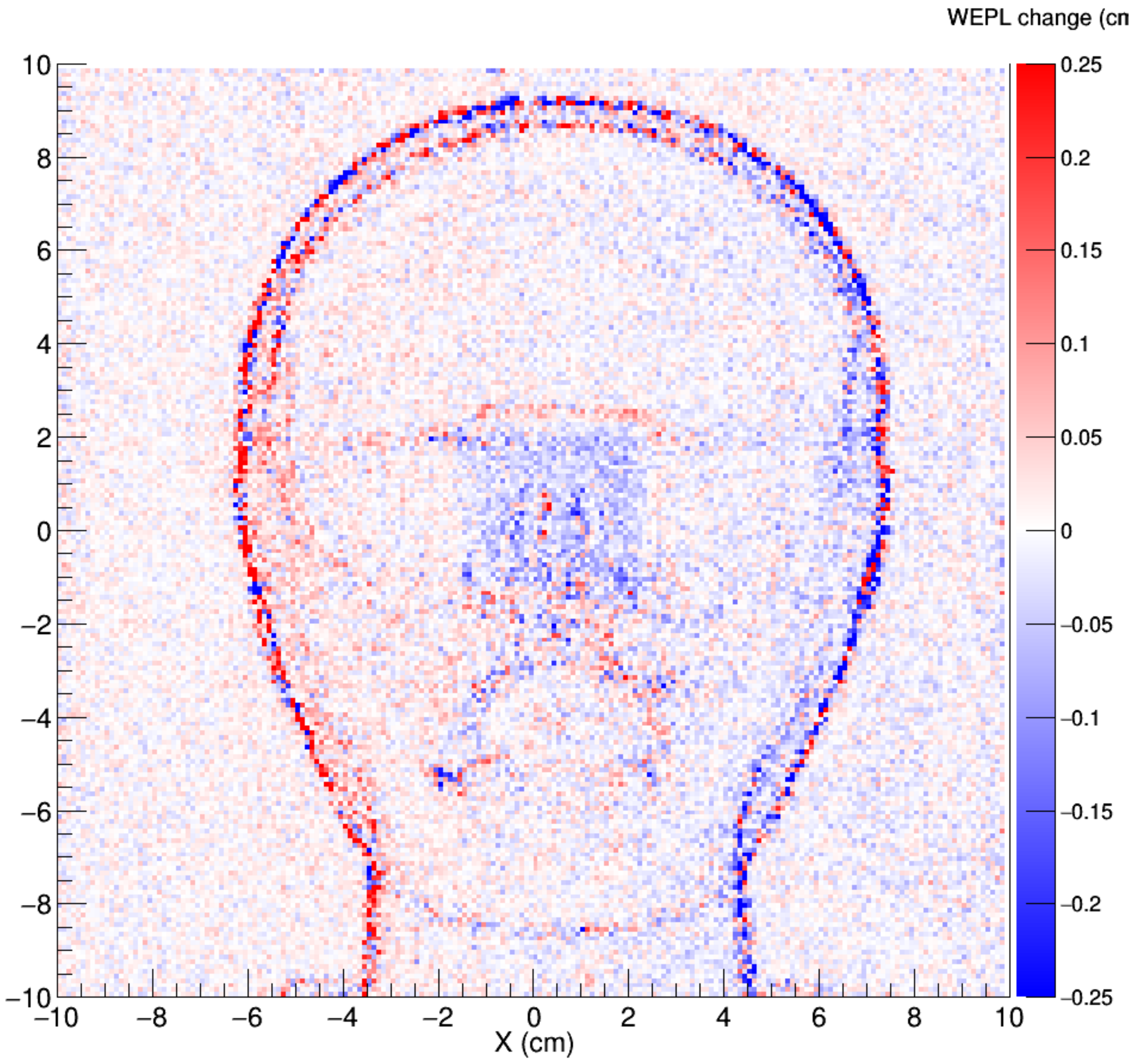
Expected difference: -1.02 mm
Measured difference: -0.97 ± 0.03 mm



Change in insert thickness: -0.51 mm

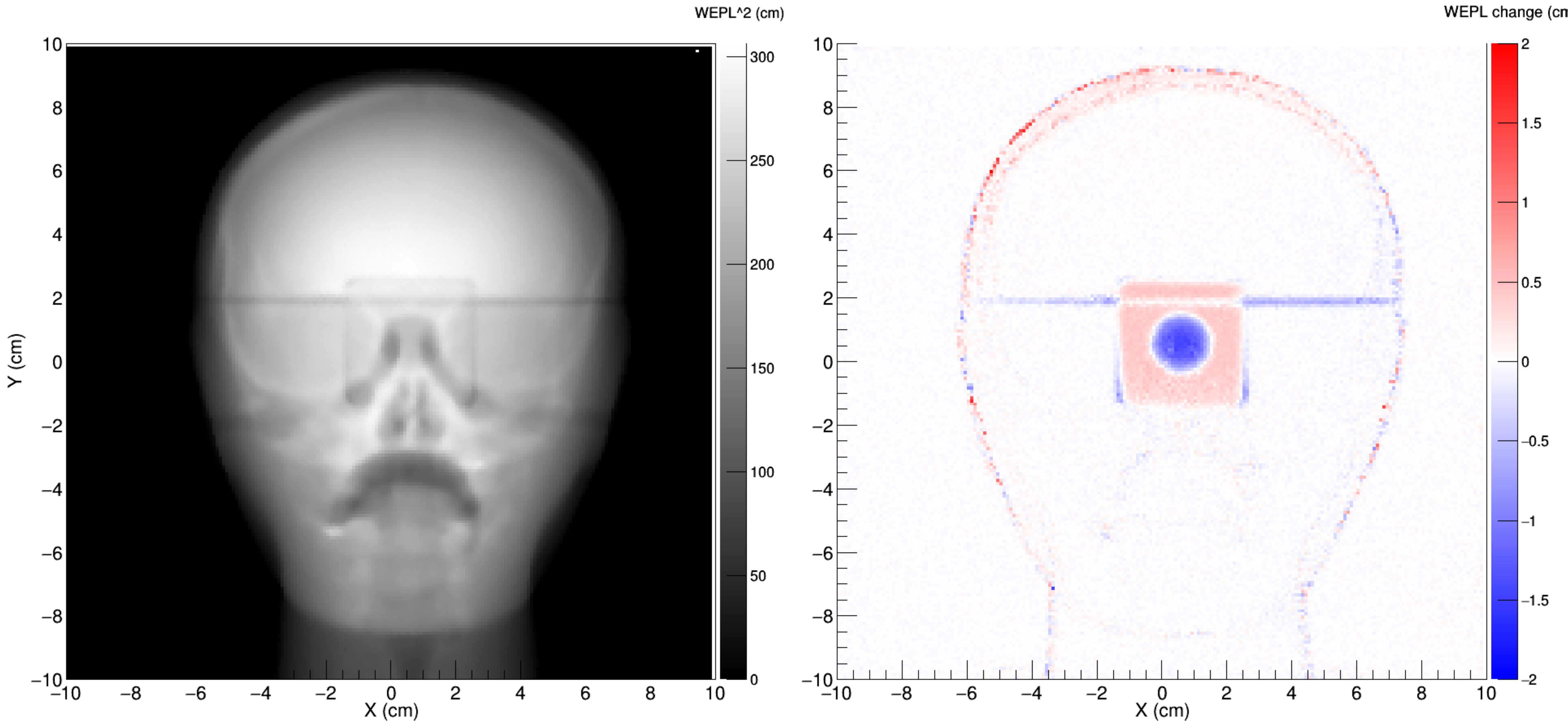
Expected difference: -0.50 mm
Measured difference: -0.52 ± 0.04 mm



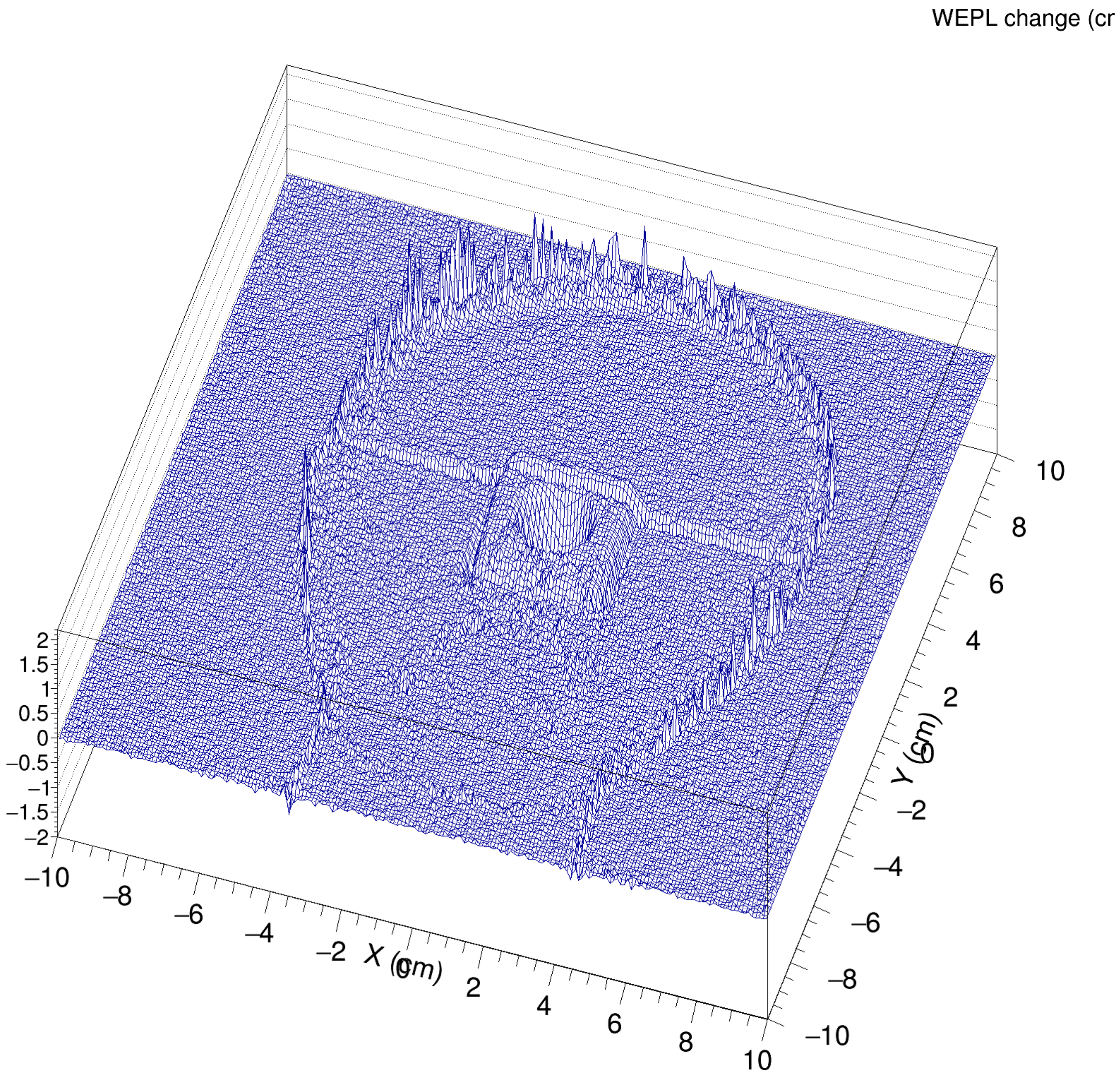


Change in insert thickness: -0.43 mm

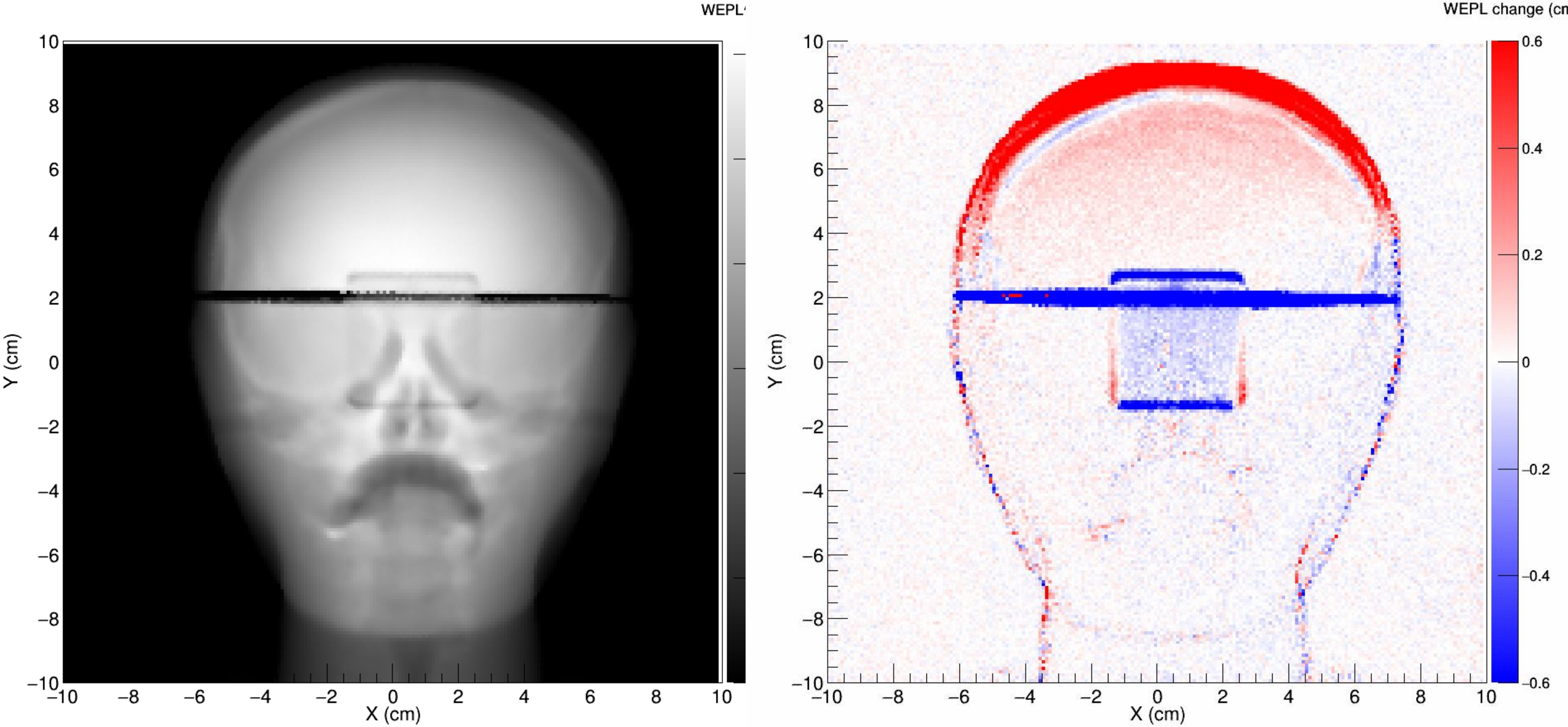
Expected difference: -0.42 mm
Measured difference: -0.34 ± 0.03 mm



WEPL^2 (cm)
Y (cm)
X (cm)
WEPL change (cm
X (cm)

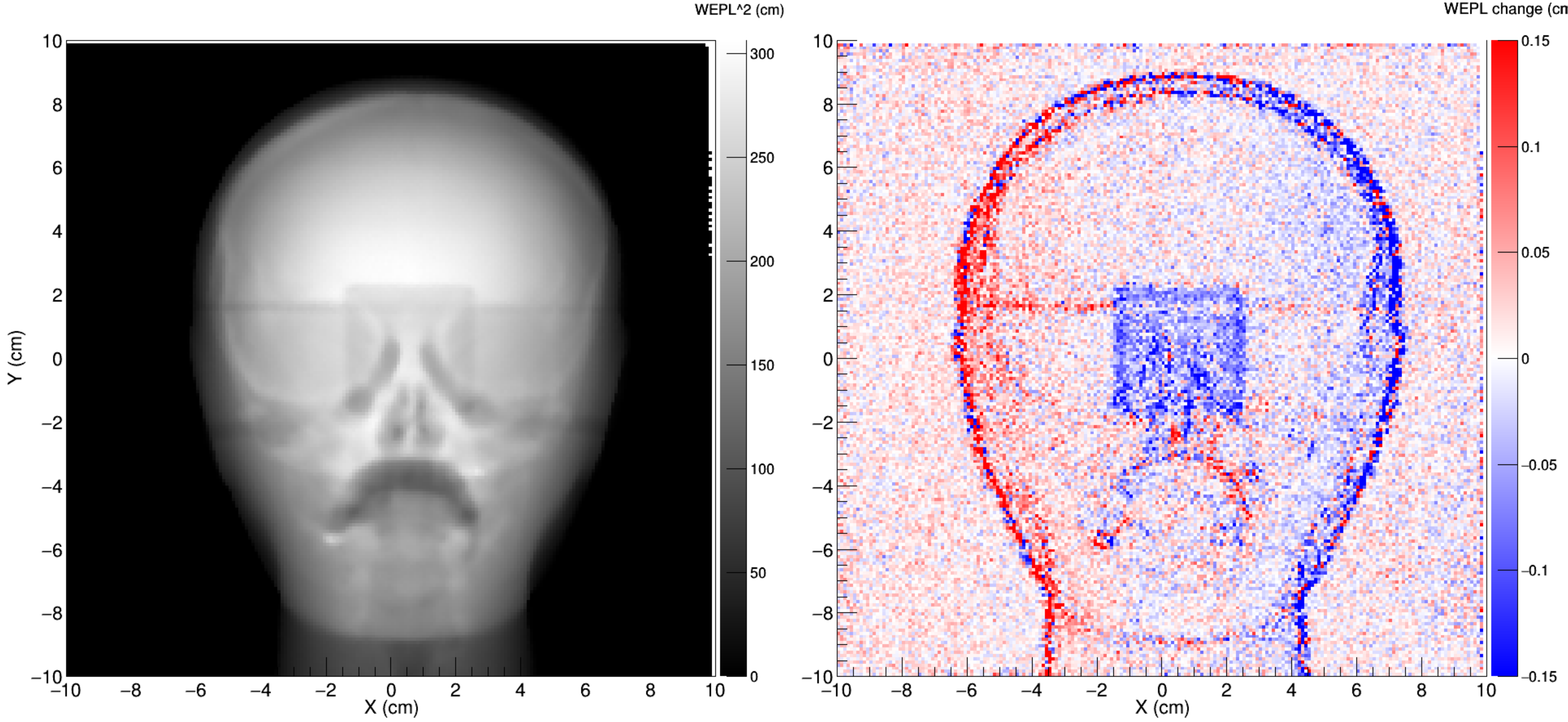


WEPL change (cr
X (cm)
Y (cm)



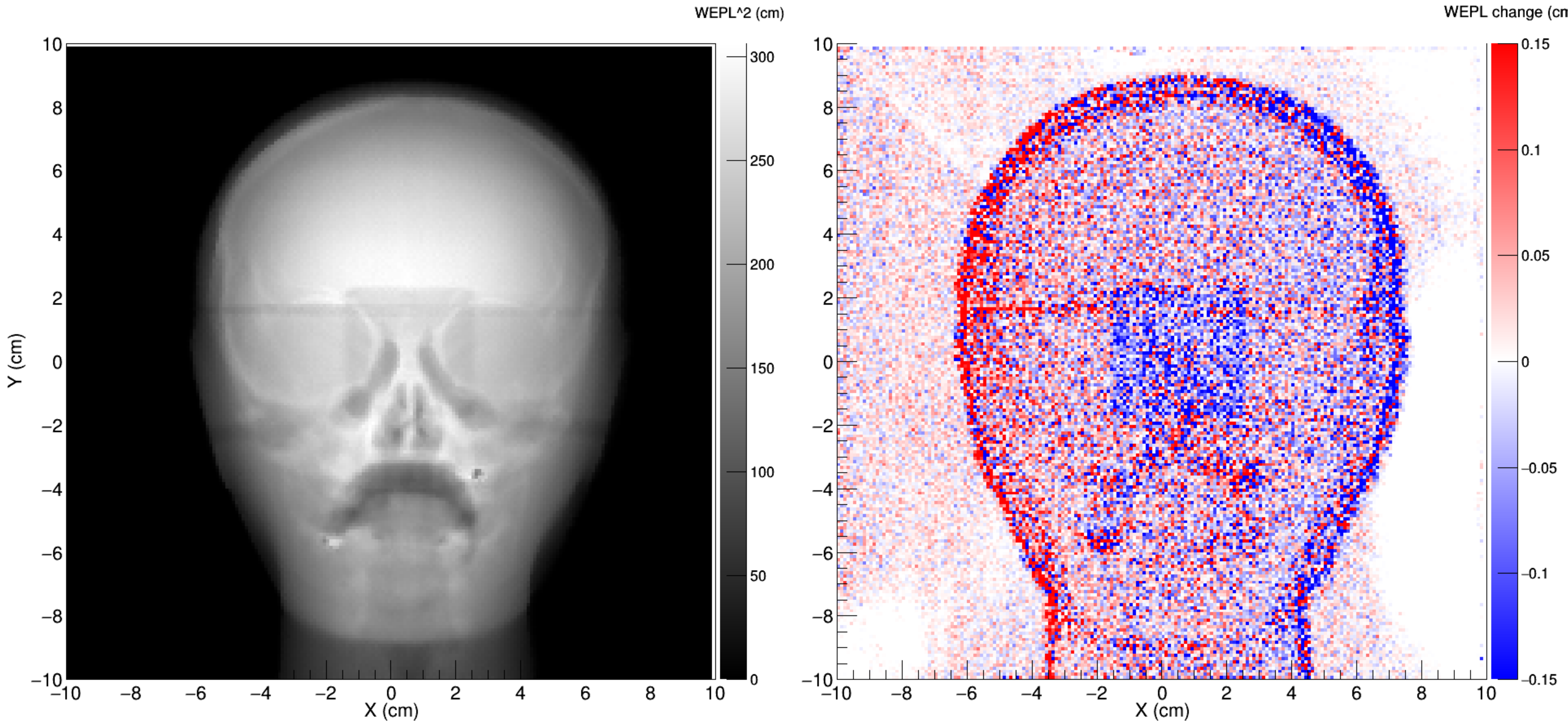
WEPL
WEPL change (cm
Y (cm)
X (cm)
Y (cm)
X (cm)

MLP-binning Reconstruction



Expected difference: -0.50 mm
Measured difference: -0.52 ± 0.04 mm

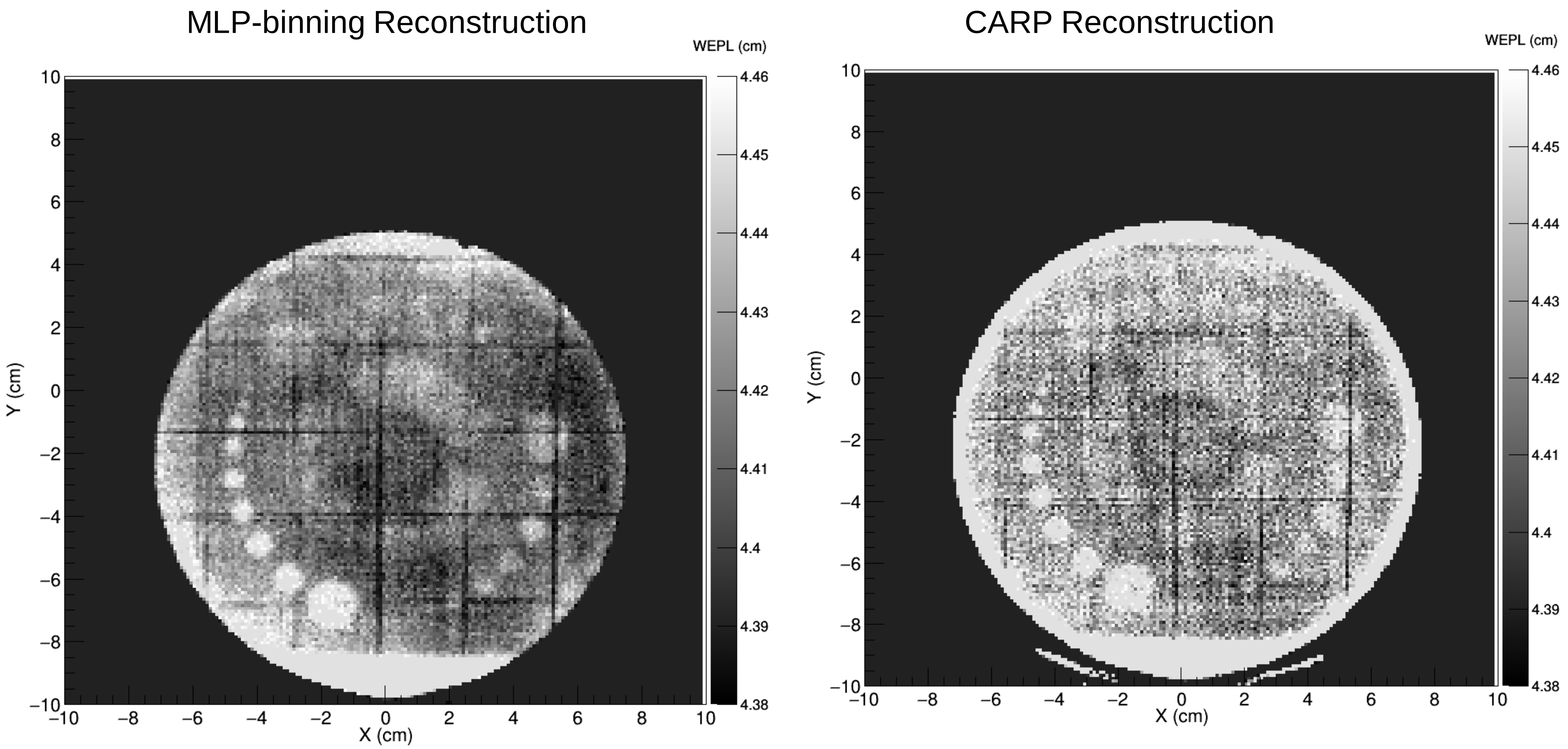
CARP Reconstruction



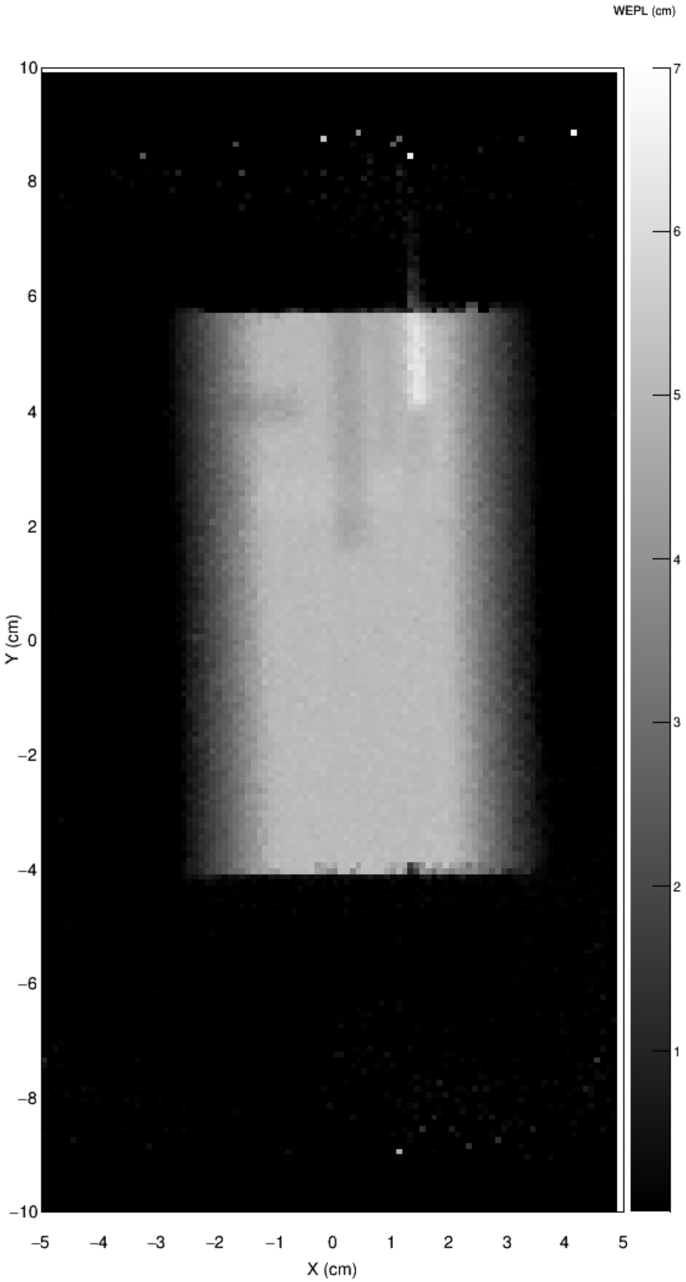
Expected difference: -0.50 mm
Measured difference: -0.52 ± 0.04 mm

Low Contrast Phantom

- Inserts with 0.3% - 1% contrast



Note 0.8 mm greyscale!

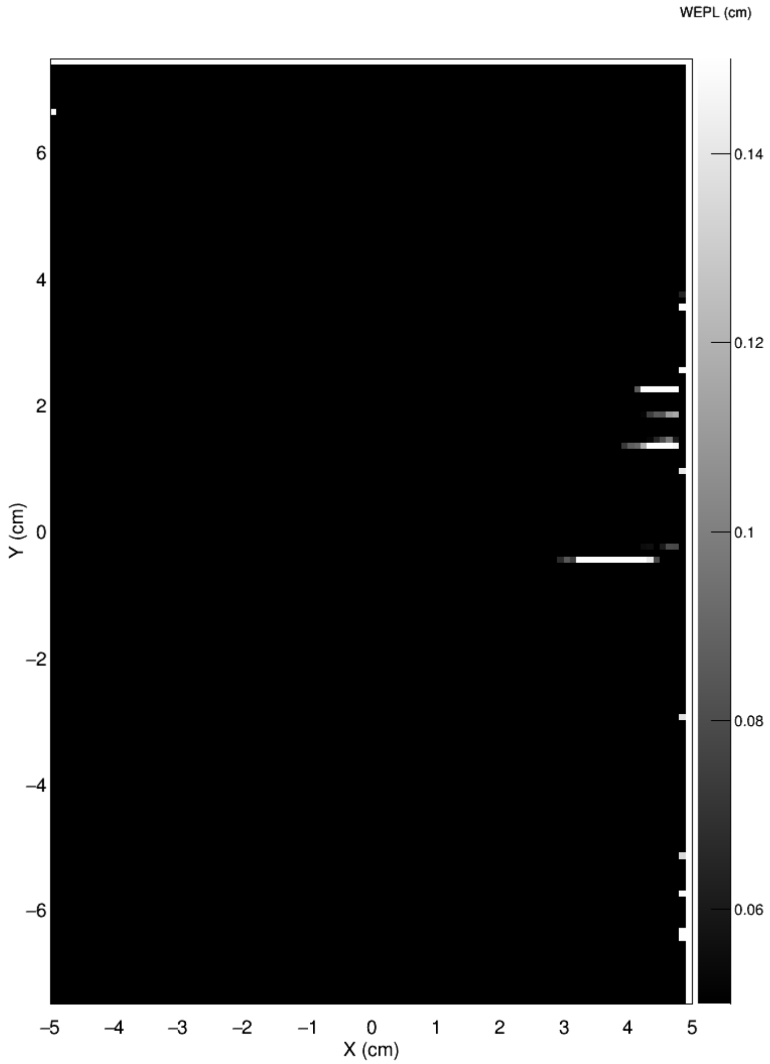


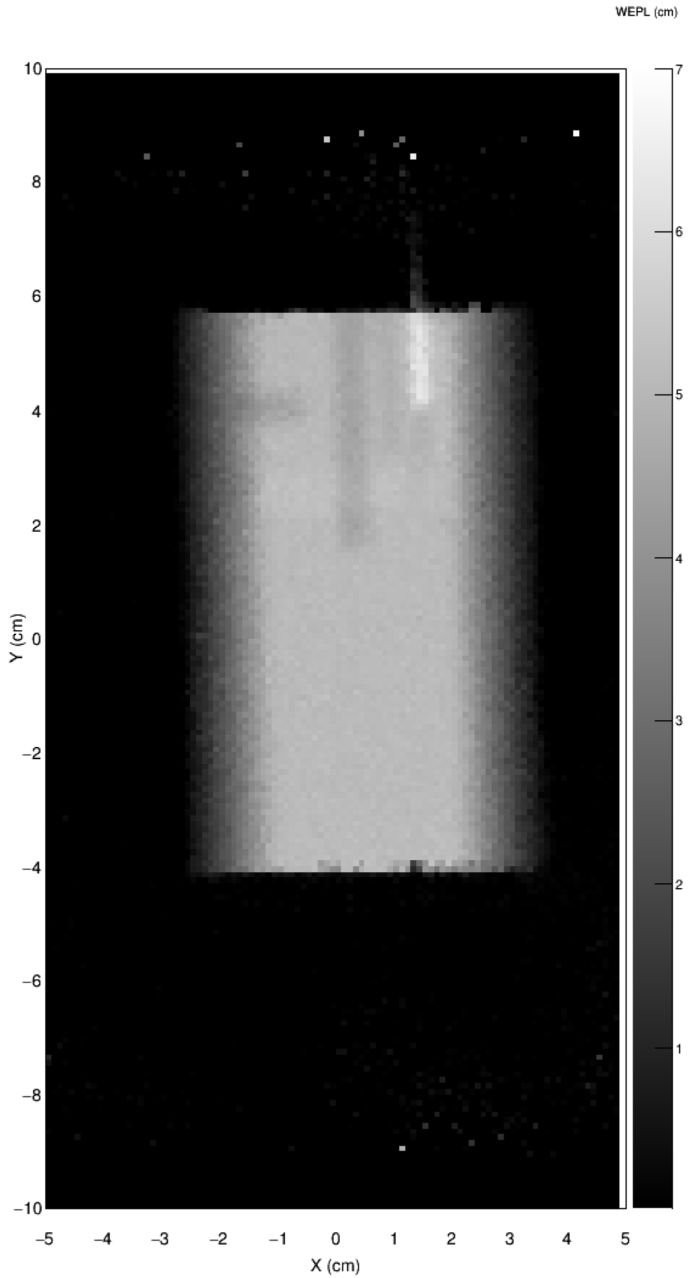
Our First pCT Image!

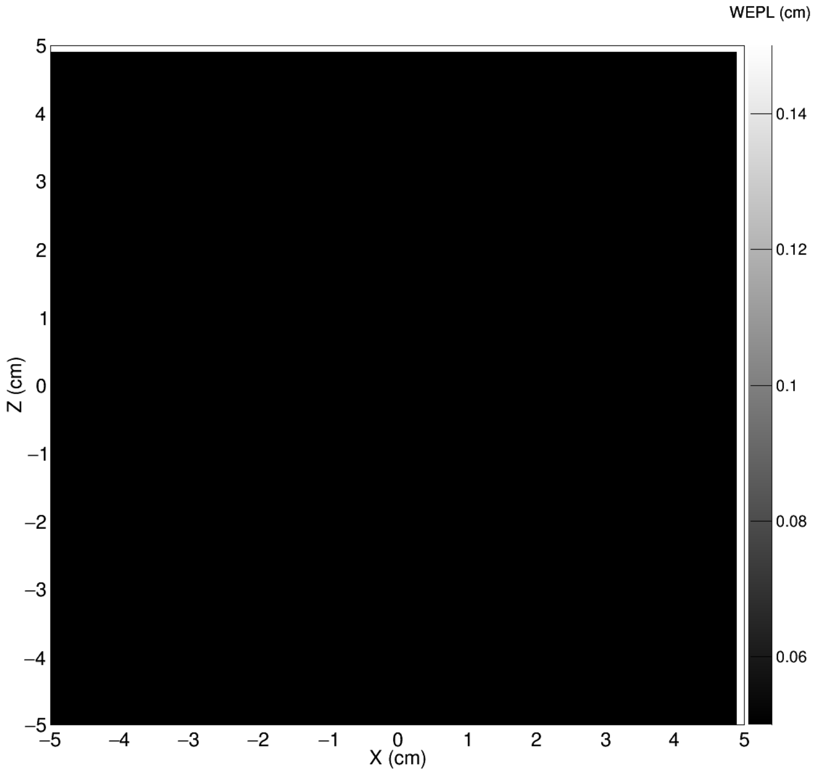
Plastic block with holes and inserts including steel drill bit

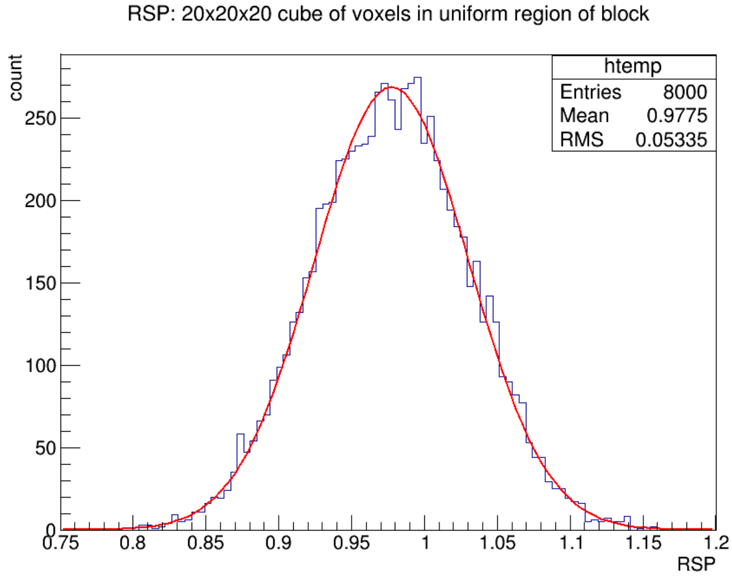
Done with:

- Scanning pencil beam
- Continuous rotation


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


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

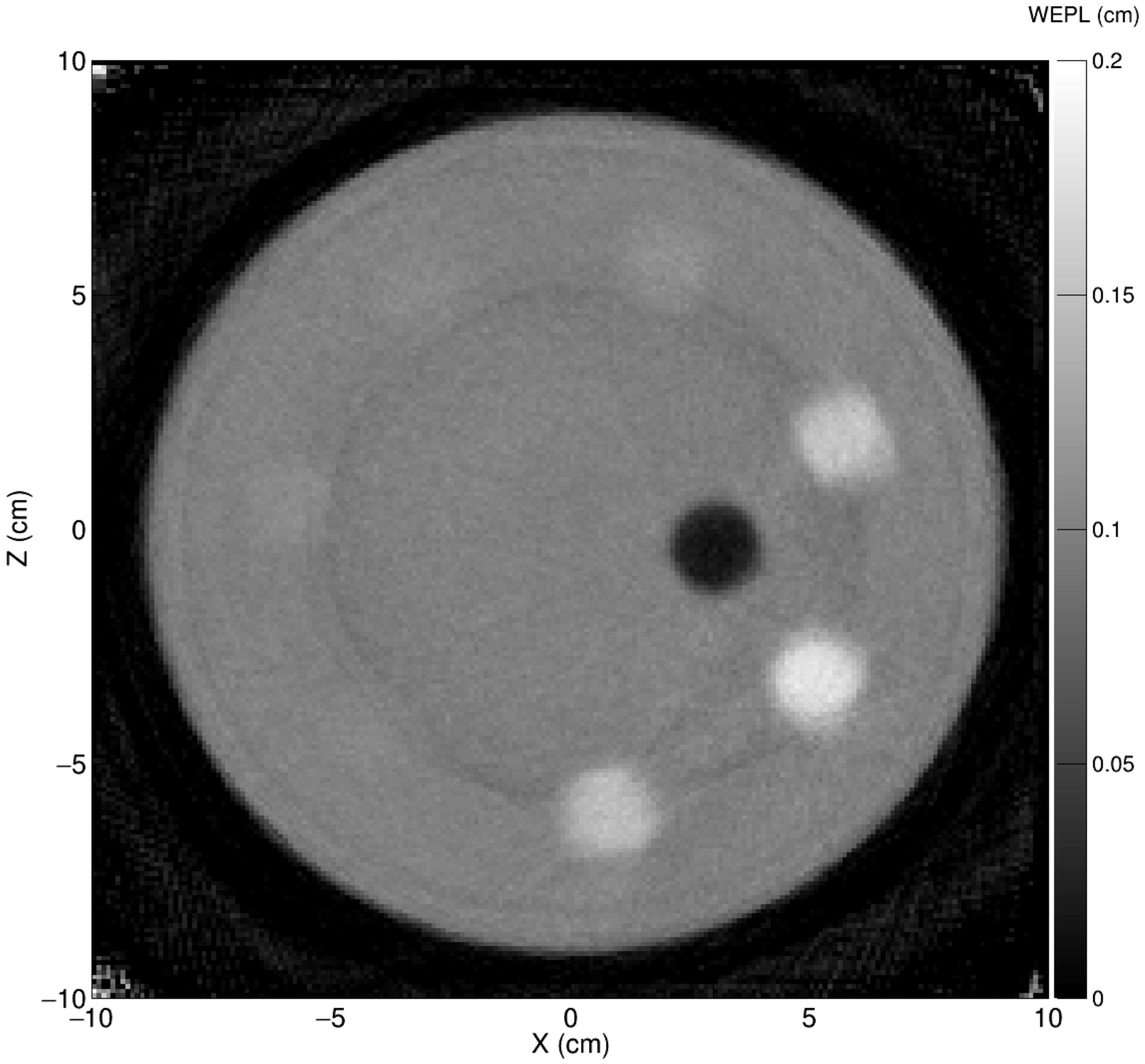

WEPL (cm)
Z (cm)
X (cm)


RSP: 20x20x20 cube of voxels in uniform region of block
htemp
Entries 8000
Mean 0.9775
RMS 0.05335
count
RSP

George Phantom pCT slice

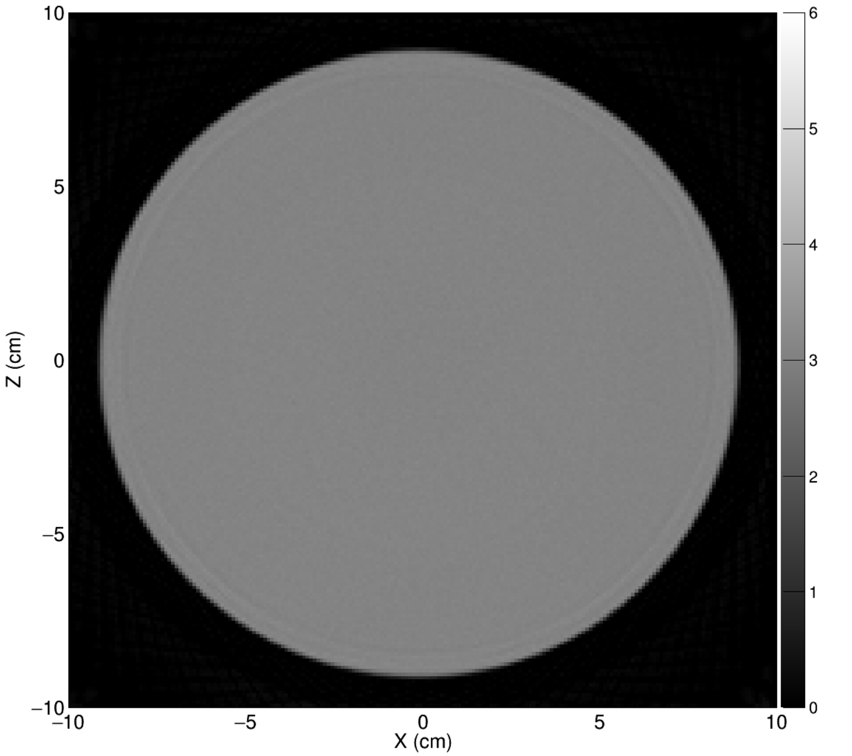
- Made with 3 energies: 195, 160, and 118 MeV

- Continuous rotation on a simple rotating display device

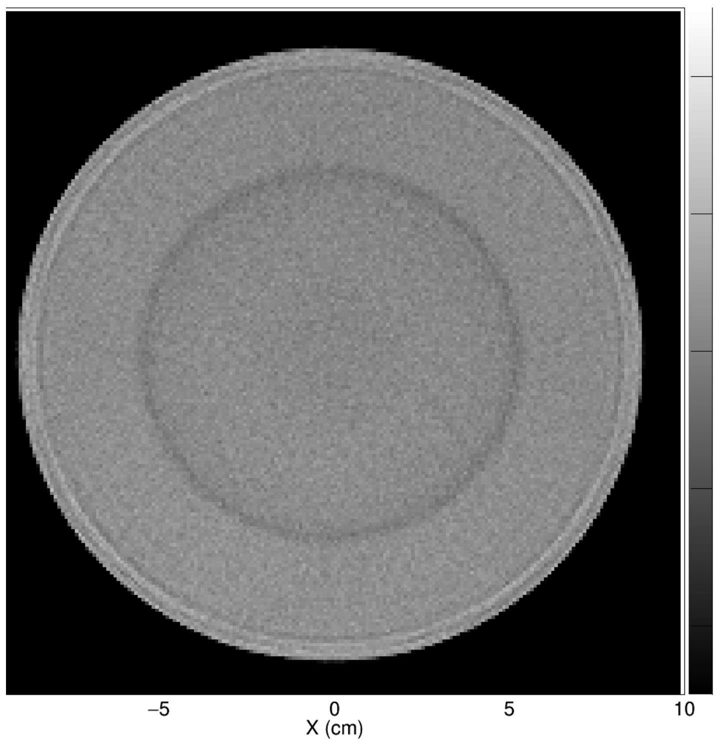


Simulated pCT image of cylinder of water
with the same 3 energies
- sum of 30 slices

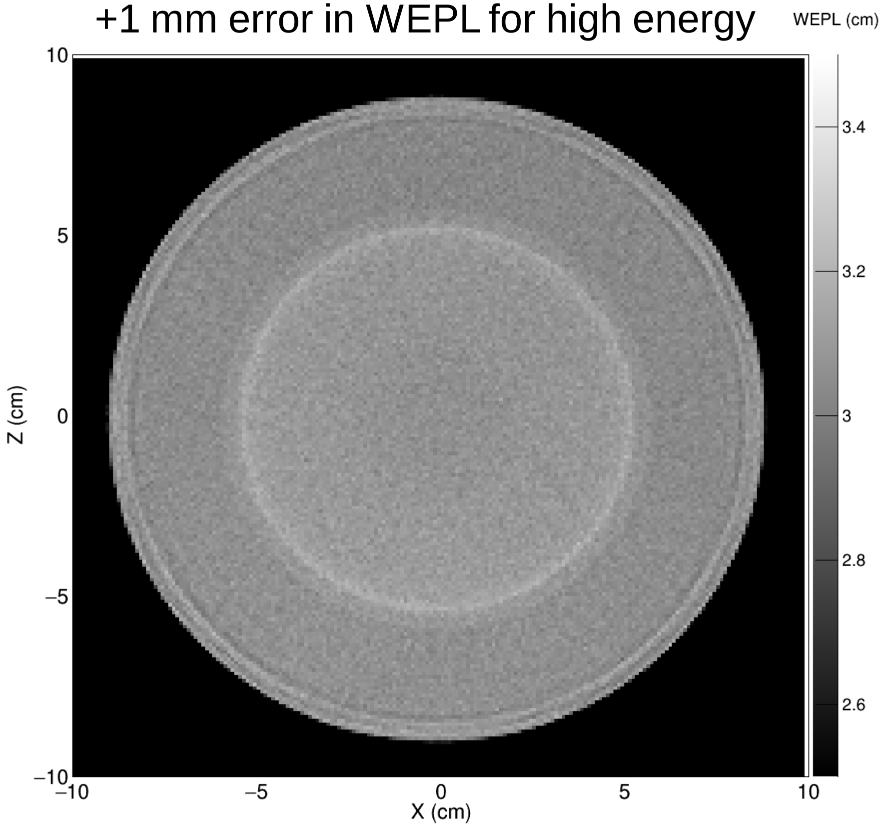
All WEPL's measured correctly



-1 mm error in WEPL for high energy



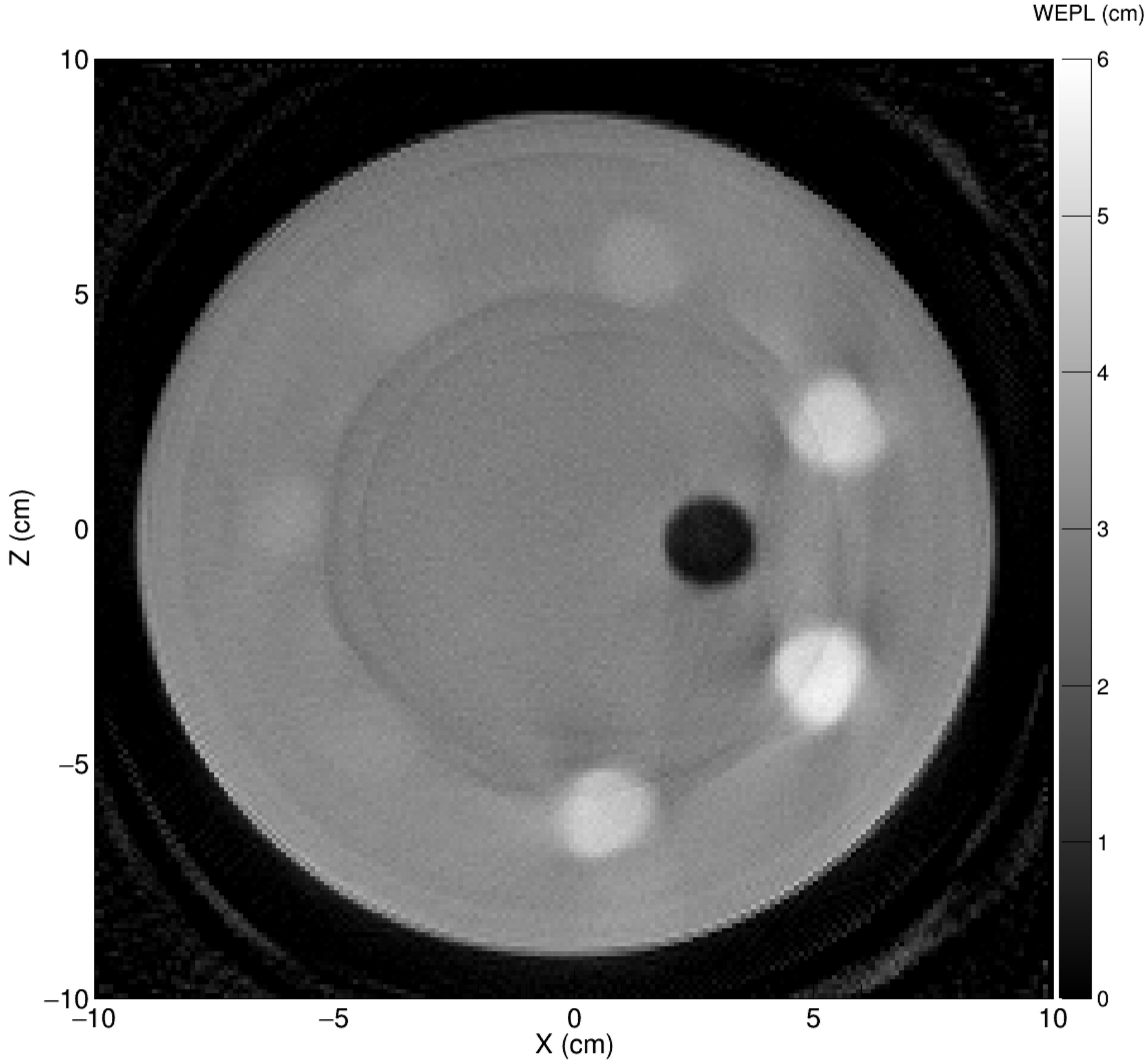
+1 mm error in WEPL for high energy



Back to real image...

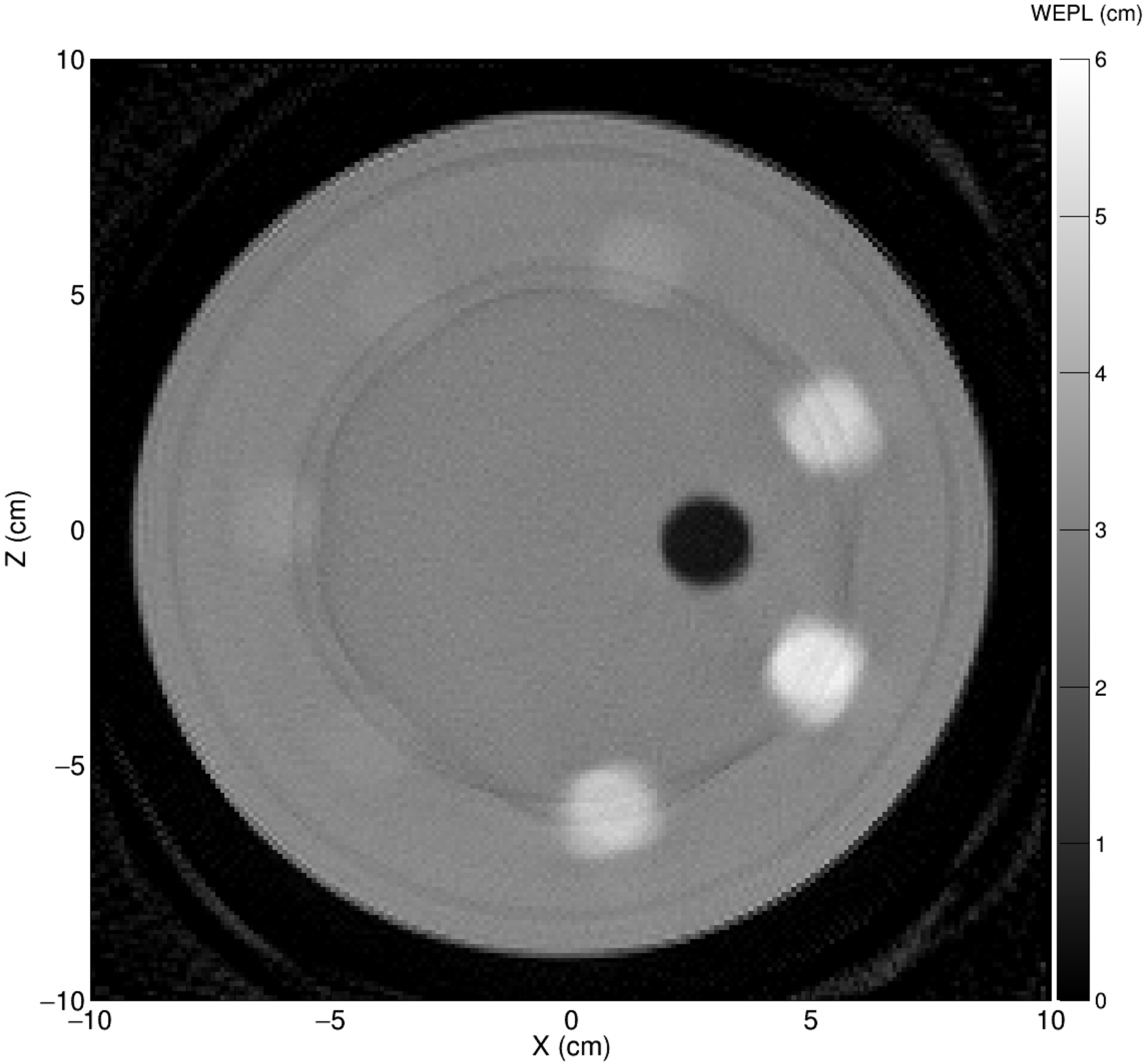
- Residual range limits set to 2-10 cm

- allowing overlap between energies



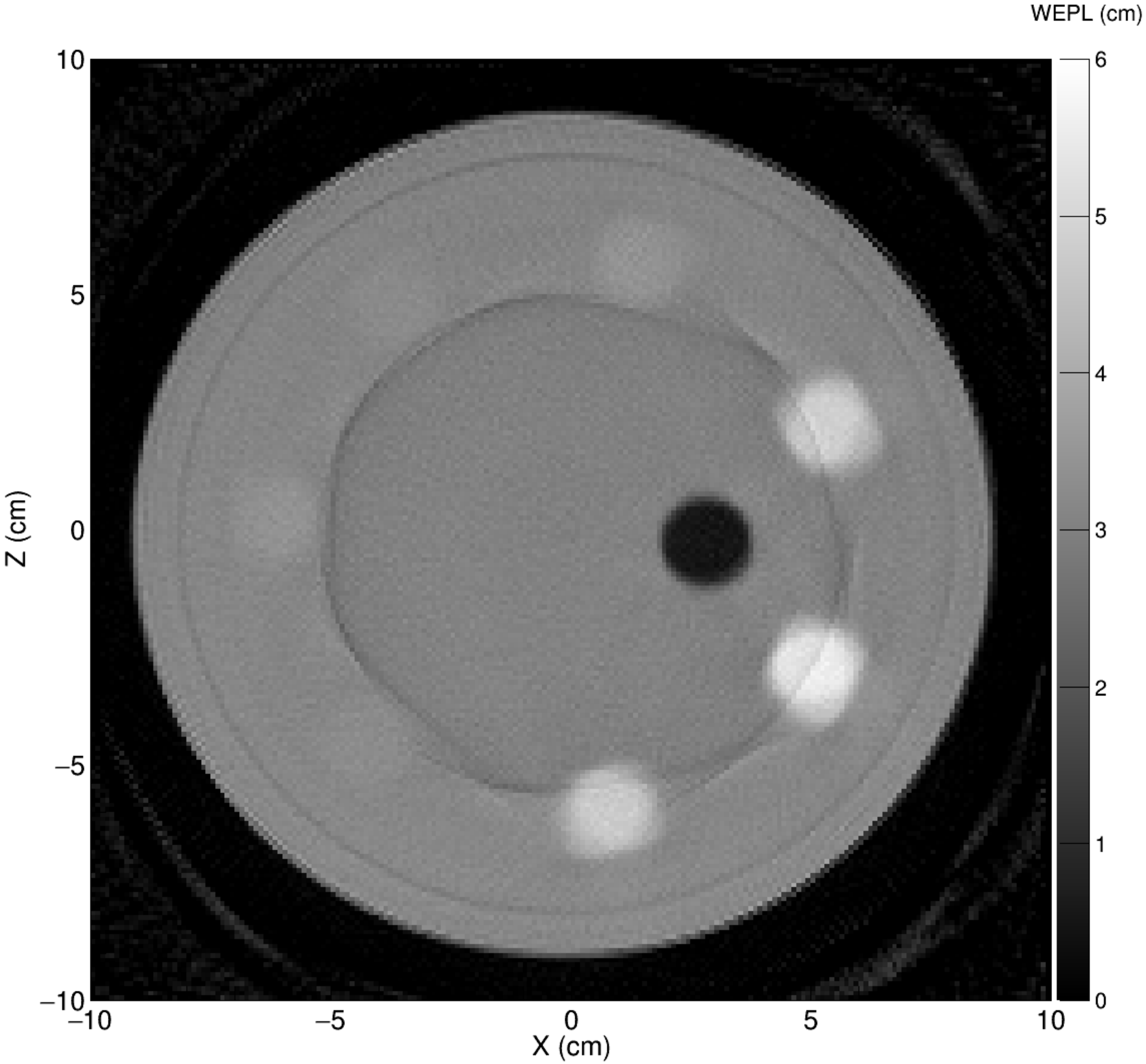
- Residual range limits set to 3-11 cm

- allowing overlap between energies



- Residual range limits set to 3-11 cm

- not allowing overlap between 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
- Work is being planned for automating pCT reconstruction
- We look forward to seeing this technology integrated into clinical use