Relative Proton Stopping Power measurements by **proton Computed Tomography** apparatus

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Purpose

- The aim of this work is to build/check a look-up-table (xCT Hounsfield Units vs. SPR) based on the direct proton Computed Tomography (pCT) SPR measurements of CIRS phantom tissue-substitute inserts to be used for dose calculation within a commercial treatment planning system (TPS).
- Materials and Methods:
  - pCT system (INFN-Florence) [1] installed on the APSS-Trento proton beam line [2]
  - CIRS 062M, electron density phantom [3]
  - FDK-like reconstruction with Most Likely Path (MLP) [4]

[1] M. Scaringella et al., Phys. Med. Biol. 68 (2023) 154001 https://doi.org/10.1088/1361-6560/ace2a8

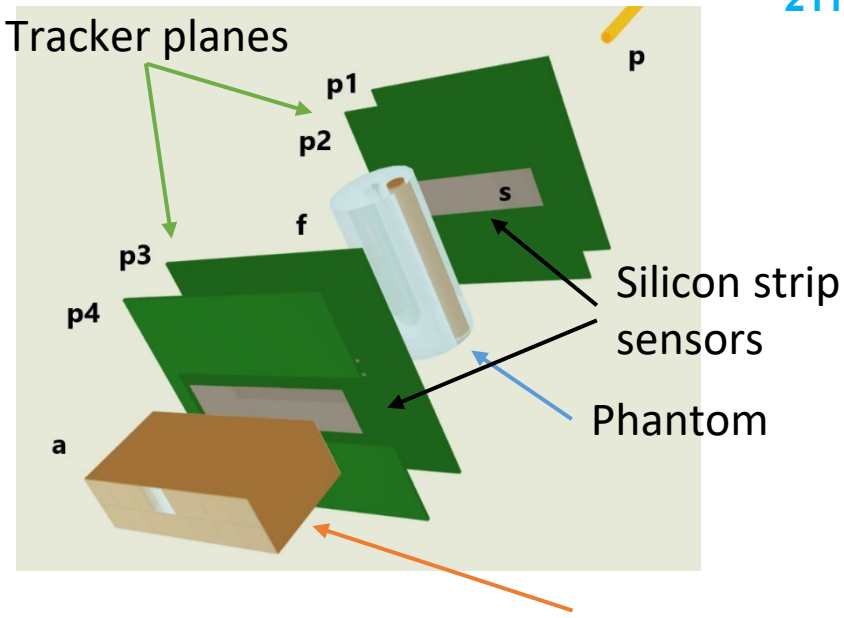
[2] F. Tommasino et al., NIM A 869 (2017) 15-20 https://doi.org/10.1016/j.nima.2017.06.017

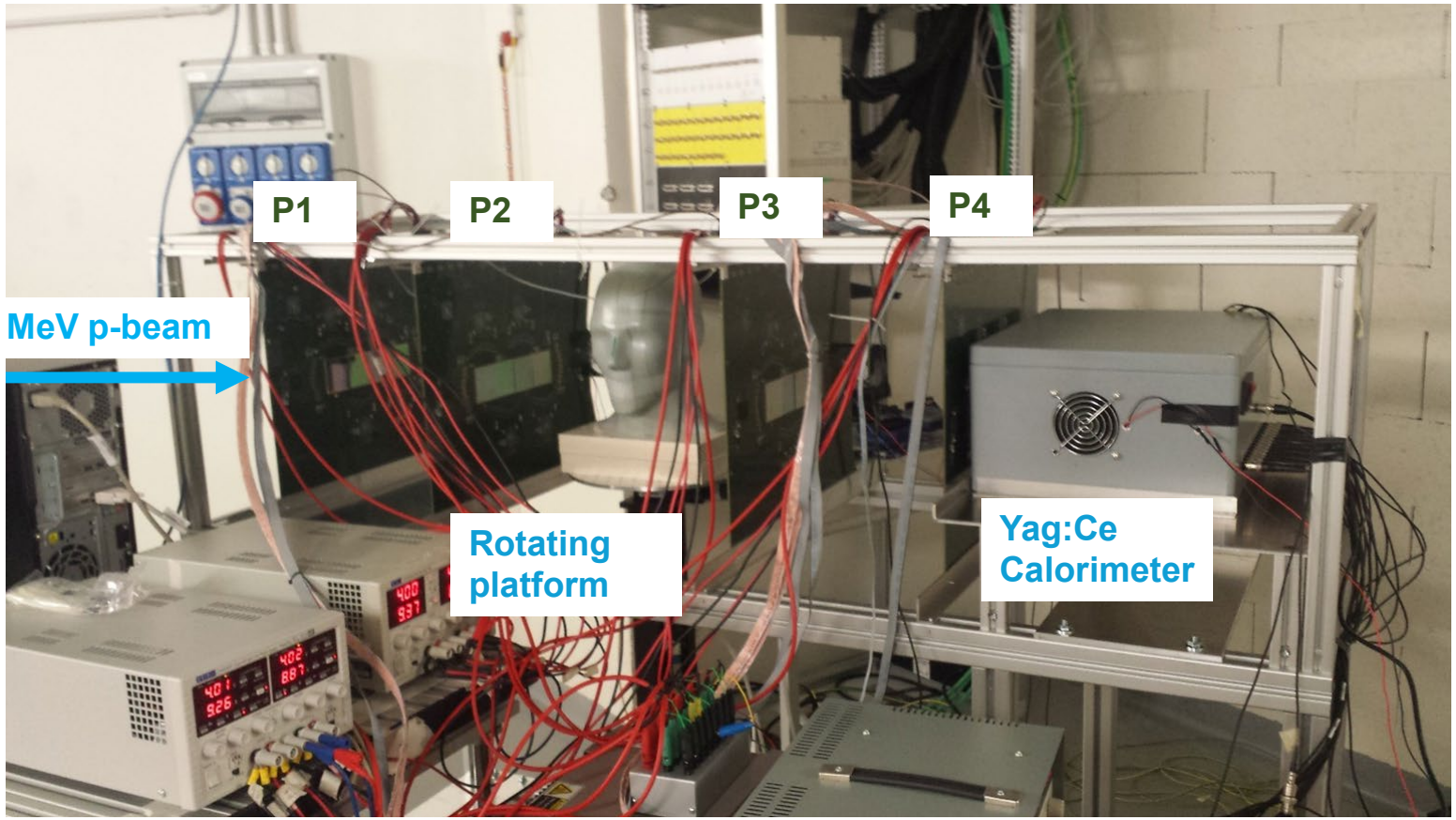
[3] https://www.cirsinc.com/wp-content/uploads/2019/12/062M-DS-121619.pdf

[4] S. Rit et al., Med. Phys. 40 (3), March 2013 https://doi.org/10.1118/1.4789589

The proton CT apparatus

- Silicon strip tracker + YaG:Ce scintillator calorimeter
- Single-event acquisition @ 100kHz





C. Civinini *et al.*, 'Relative stopping power measurements and prosthesis artifacts reduction in proton CT' *Phys. Med. Biol.* **65** (2020) 225012, DOI 10.1088/1361-6560/abb0c8.

CIRS 062M phantom

- Water-equivalent plastic matrix with 9 tissue-substitute inserts
  - 180 mm diameter, 50 mm height (~ fits in the pCT scanner field-of-view)

	g cm^{-3}	x 10^{23} e^{-} cm^{-3}	
material	density	e- density	RED
water eq.	1,029	3,333	0,998
muscle	1,06	3,483	1,043
bone core 1500mg/cc	1,99	6,134	1,837
lung inhale	0,2	0,634	0,2
bone 200mg/cc	1,16	3,73	1,117
breast	0,99	3,261	0,976
bone 800mg/cc	1,53	4,862	1,456
liver	1,07	3,516	1,052
bone 1250mg/cc	1,82	5,663	1,695
lung exale	0,5	1,632	0,496

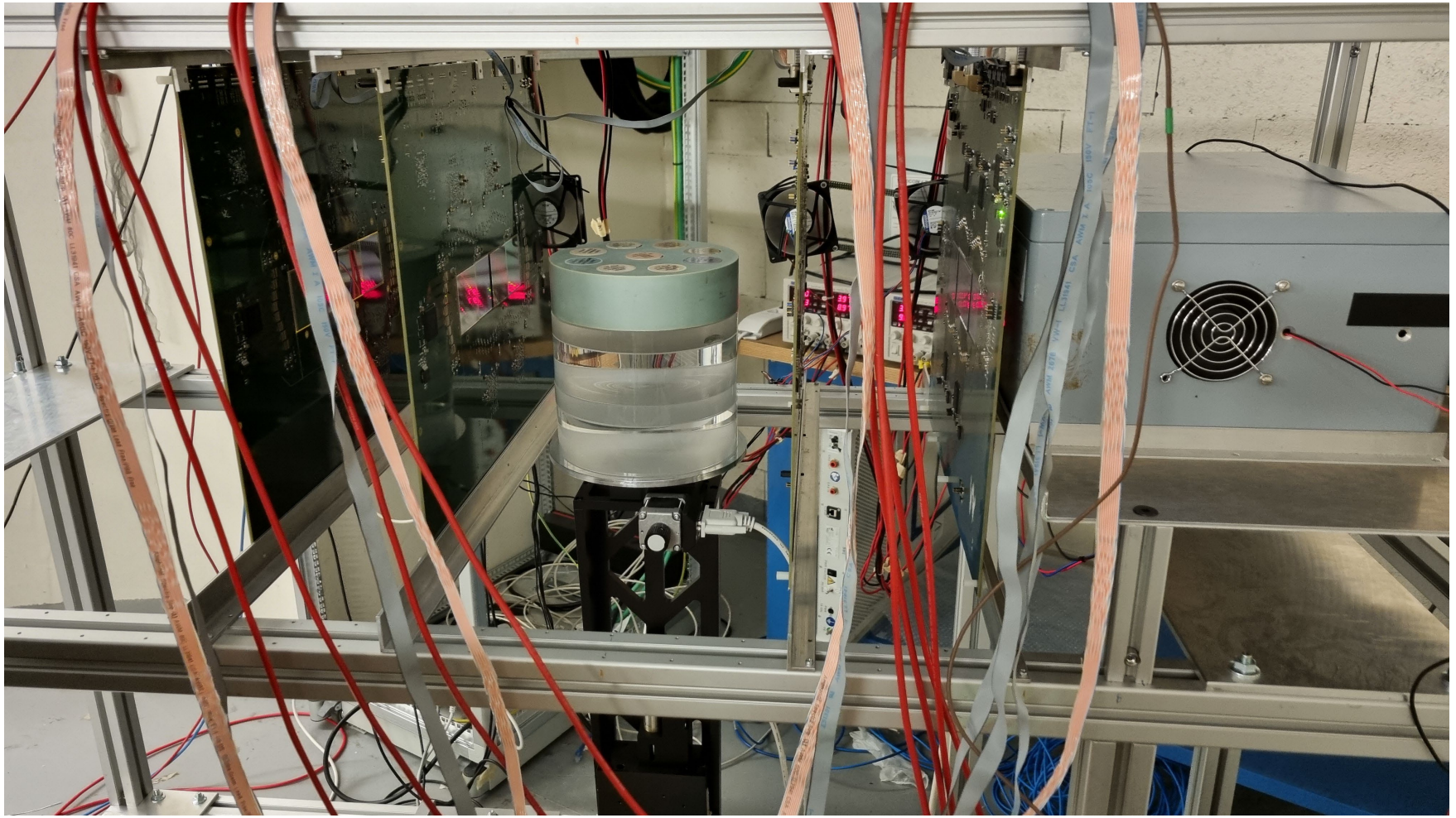
Data acquisition

- July 2025 test at APSS-Trento experimental beam line
- CIRS phantom:
  - Statistics:10 complete turns → $\mathbf{1 \times 10^9}$ triggers
  - Total dose: **14 mGy**
  - Acquisition rate: **70-100 kHz**
- Demineralized water phantom (used for calibration):
  - Statistics: 3 complete turn → **3**$\times \mathbf{10^8}$ triggers
  - Cylinder diameter: **115 mm**
- Proton beam:
  - **211 MeV** (2.5mm Tantalum plate to spread the beam)
  - Phantoms (rot. axis) at **~ 4.432 m** from the beam exit window

Data acquisition

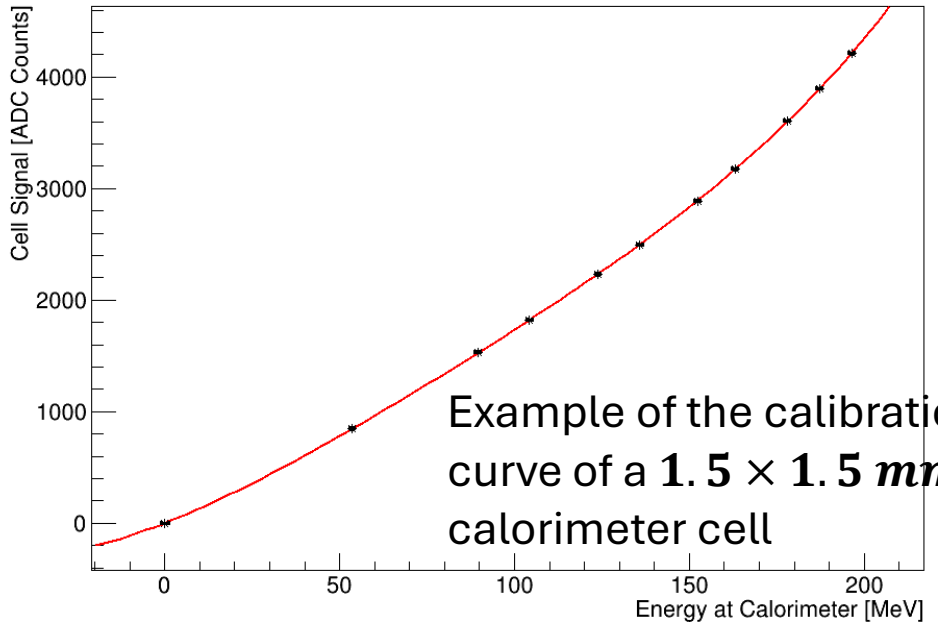
Picture of the CIRS phantom mounted on the remotely controlled rotating platform positioned between plane #2 and #3 of the pCT system.

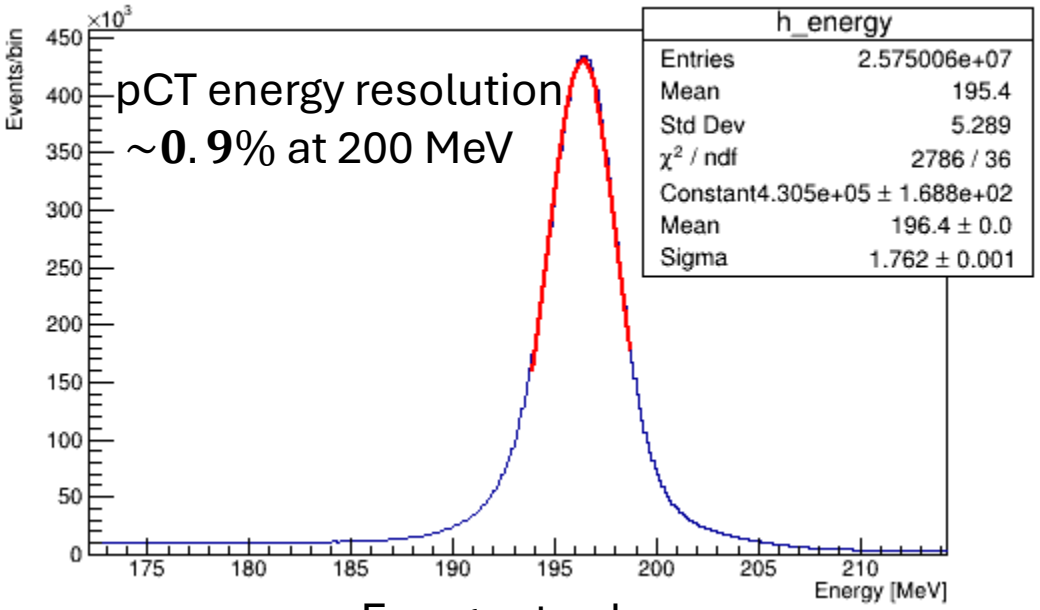
The proton beam enters the system from left.



Energy calibration

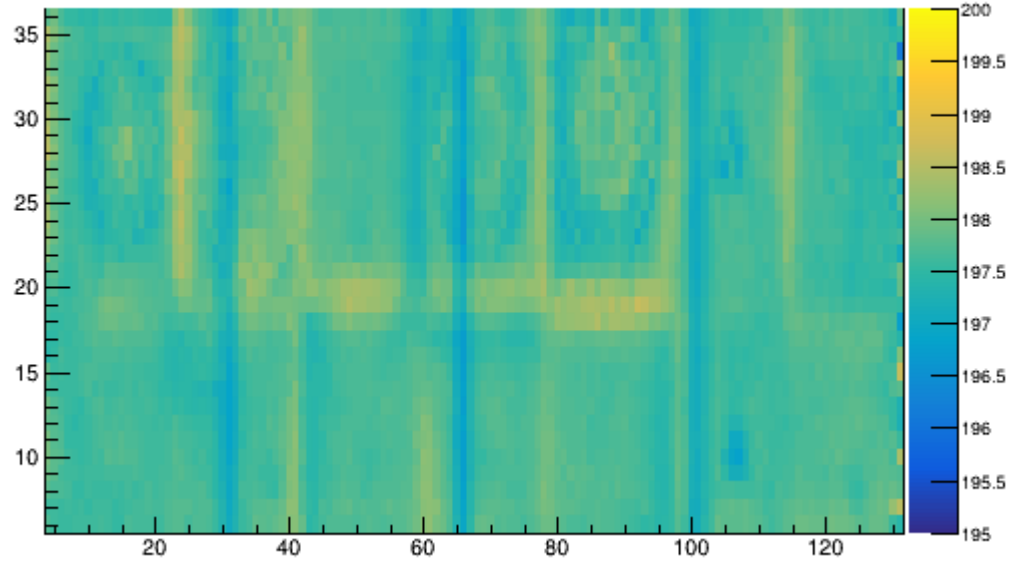
- 10 runs without phantom
  - Proton energy from 80 up to 211 MeV
  - 4×10^7 triggers/run
  - Rate 80-90 kHz (8'-10' for point)





Energy at calo

peak fit



pCT calorimeter uniformity

Energy calibration

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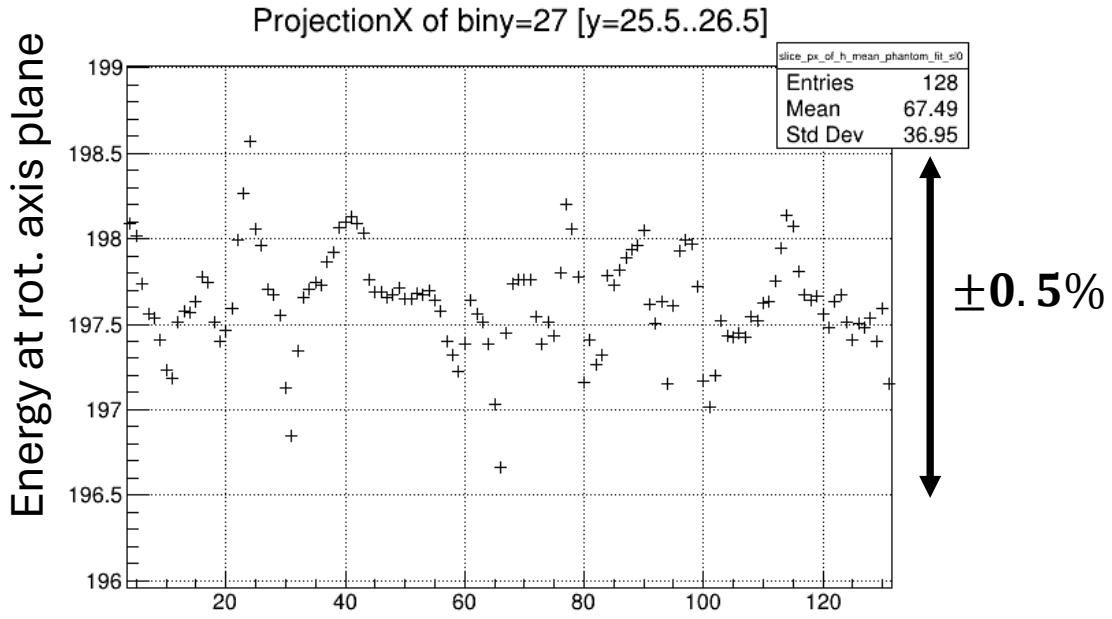

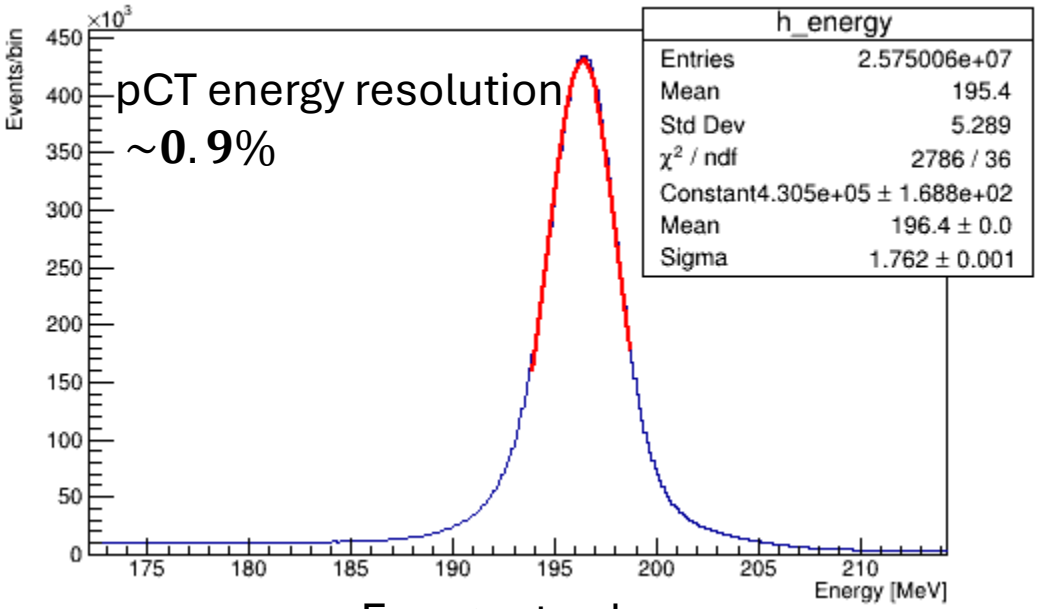

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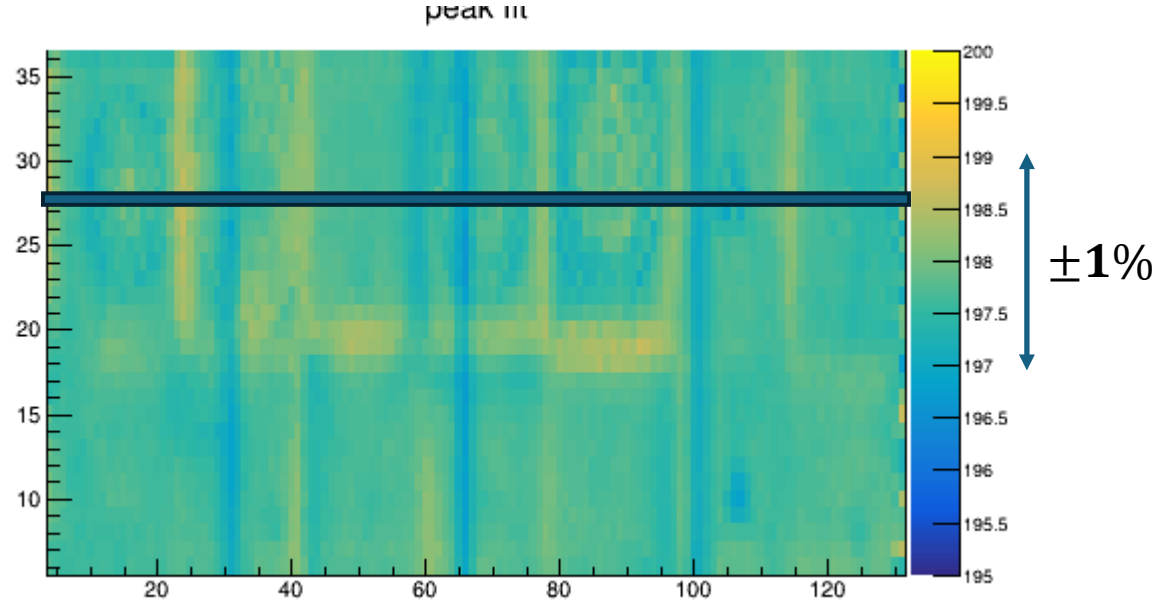


pCT calorimeter uniformity

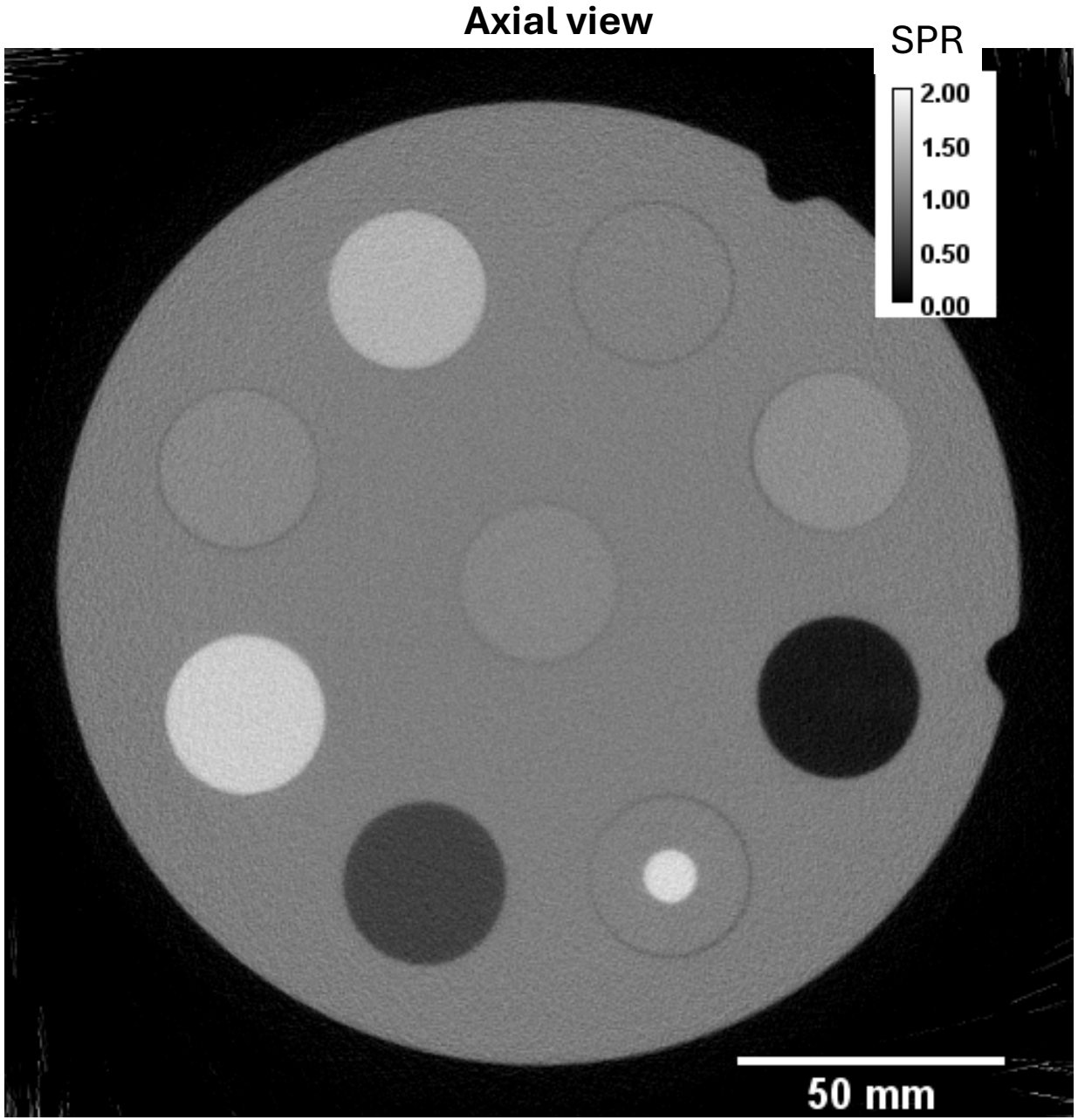
CIRS pCT image

- SPR of the phantom CIRS-062M
- Axial slice #15
- Voxel dimensions: **0.39x0.39x1.5** mm^3
- Statistics: **$1x10^9$** triggers
- Total dose: **14 mGy**
- FDK-like reconstruction with MLP

  Simon Rit, George Dedes, Nicolas Freud, David Sarrut, Jean Michel Létang

  Filtered backprojection proton CT reconstruction along most likely paths

  Med. Phys. 40 (3), March 2013
  https://doi.org/10.1118/1.4789589
- No Hann additional filter applied



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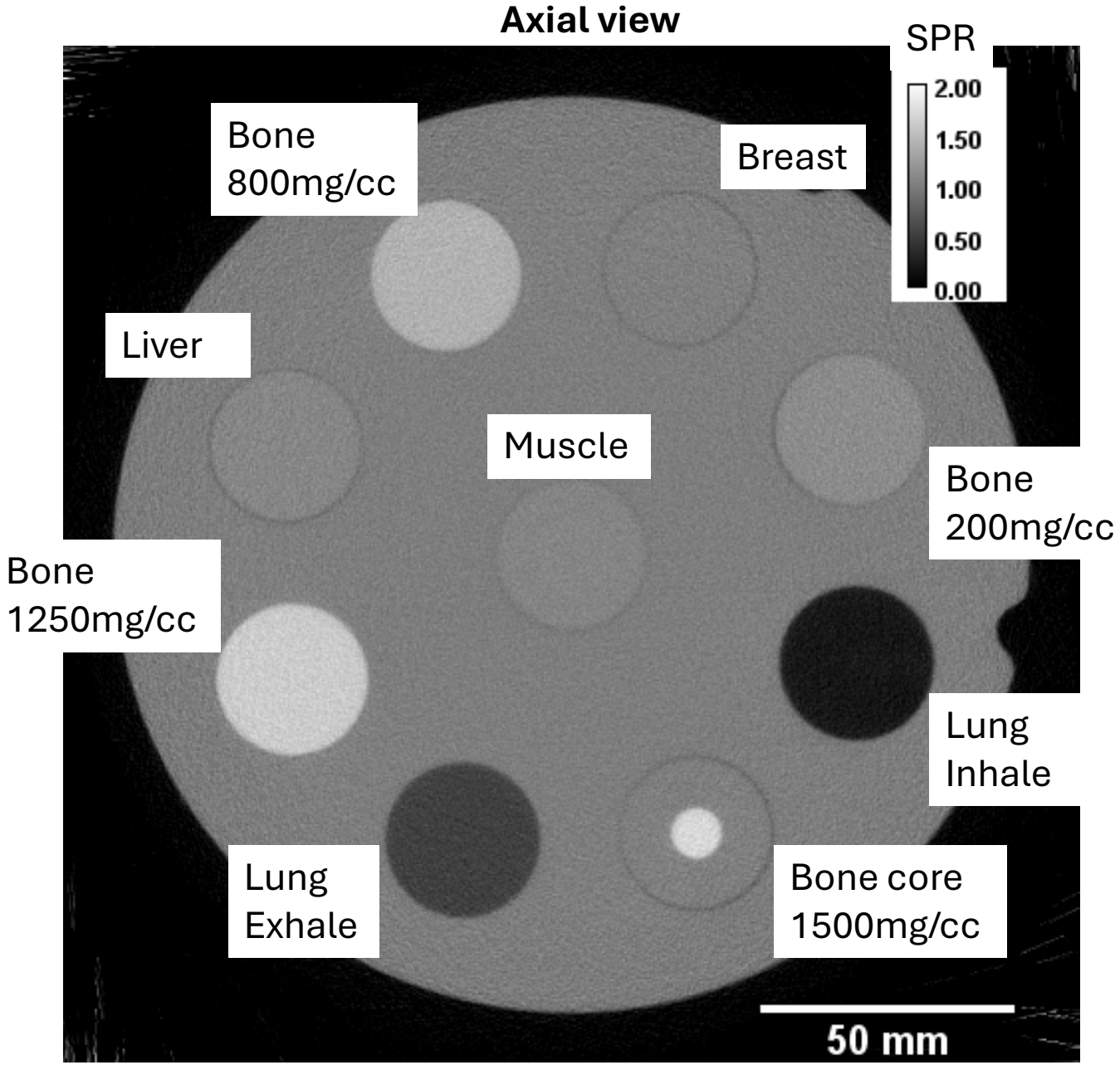

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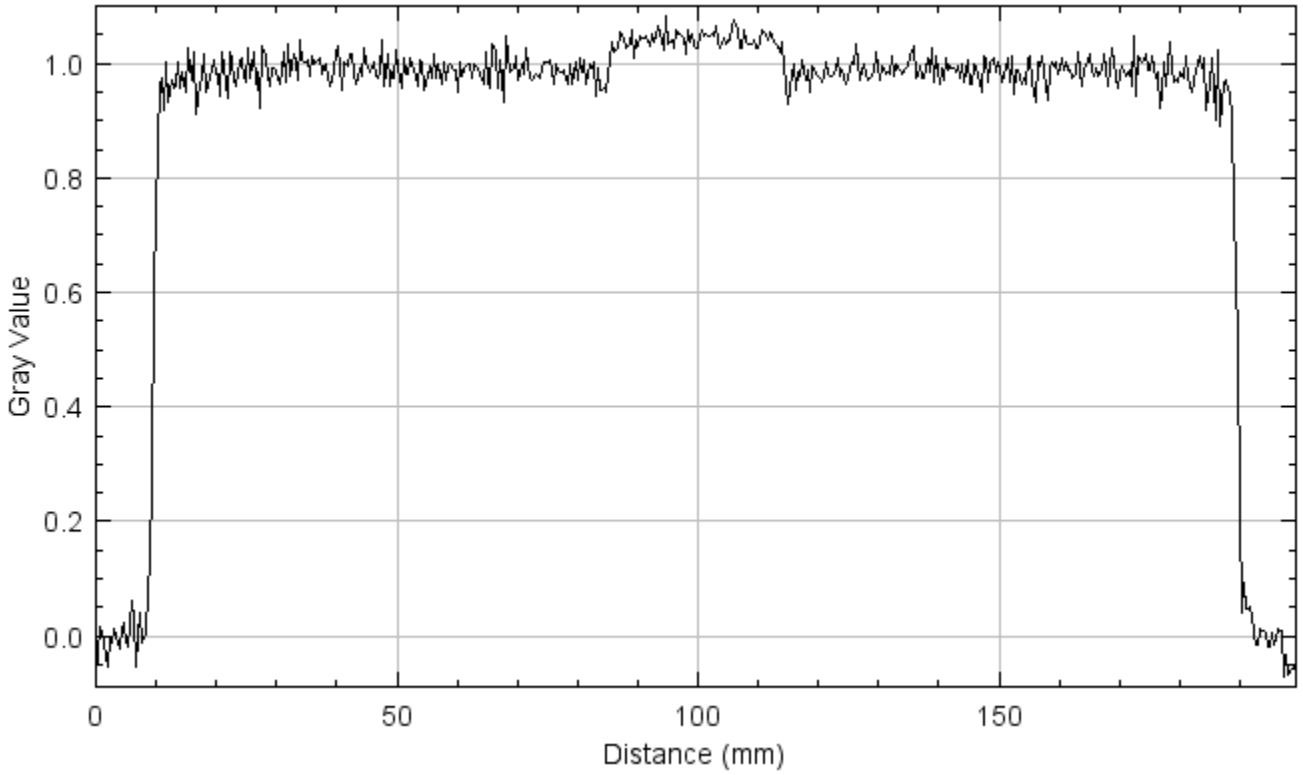

SPR profile along the phantom diameter of slice #15

CIRS pCT image

- SPR of the phantom CIRS-062M
- Z-projection from slice #2 to #26
- Voxel dimensions: **0.39x0.39x37.5** mm^3
- Statistics: **$1x10^9$** triggers
- Total dose: **14 mGy**
- FDK-like reconstruction with MLP

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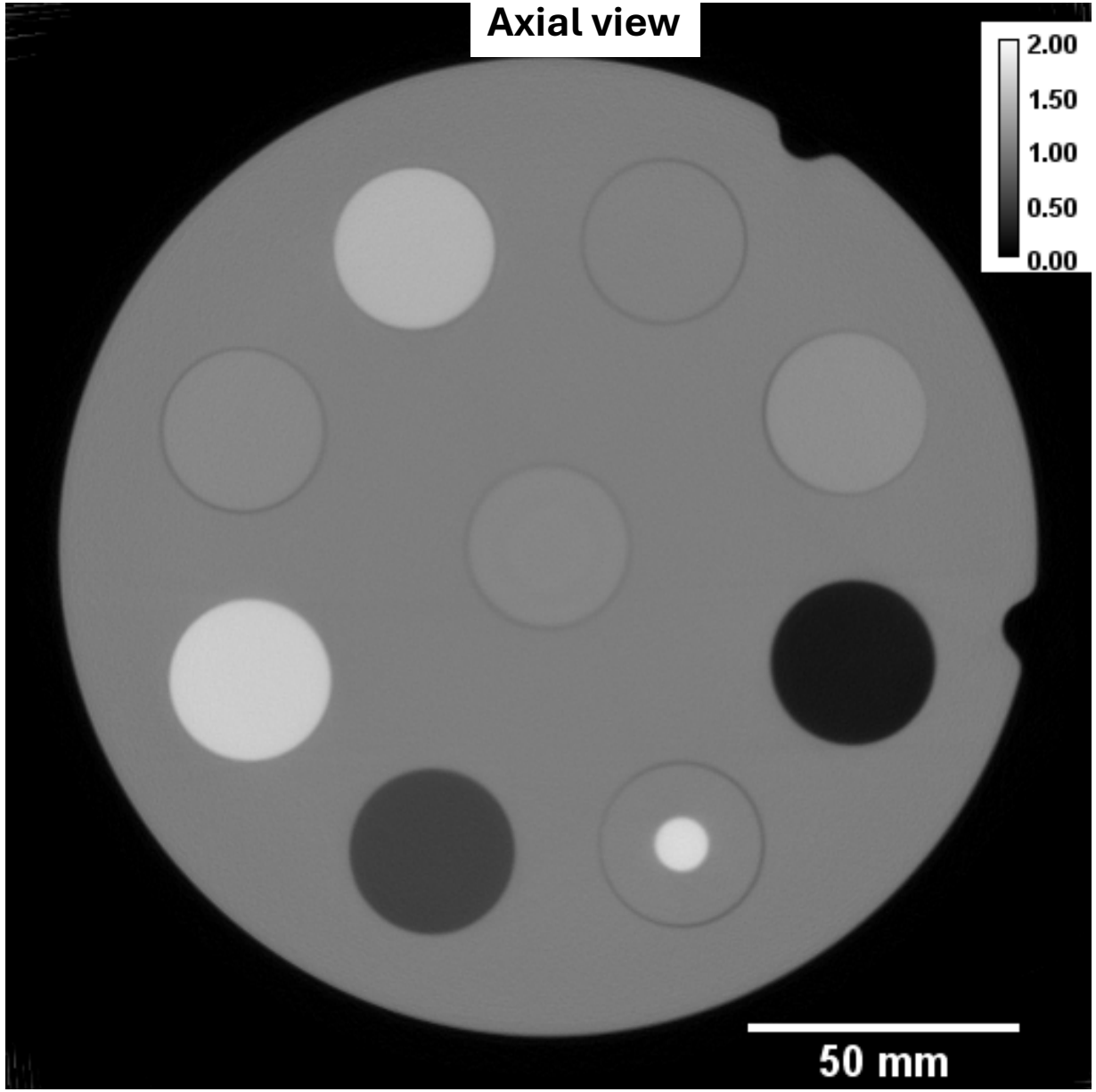
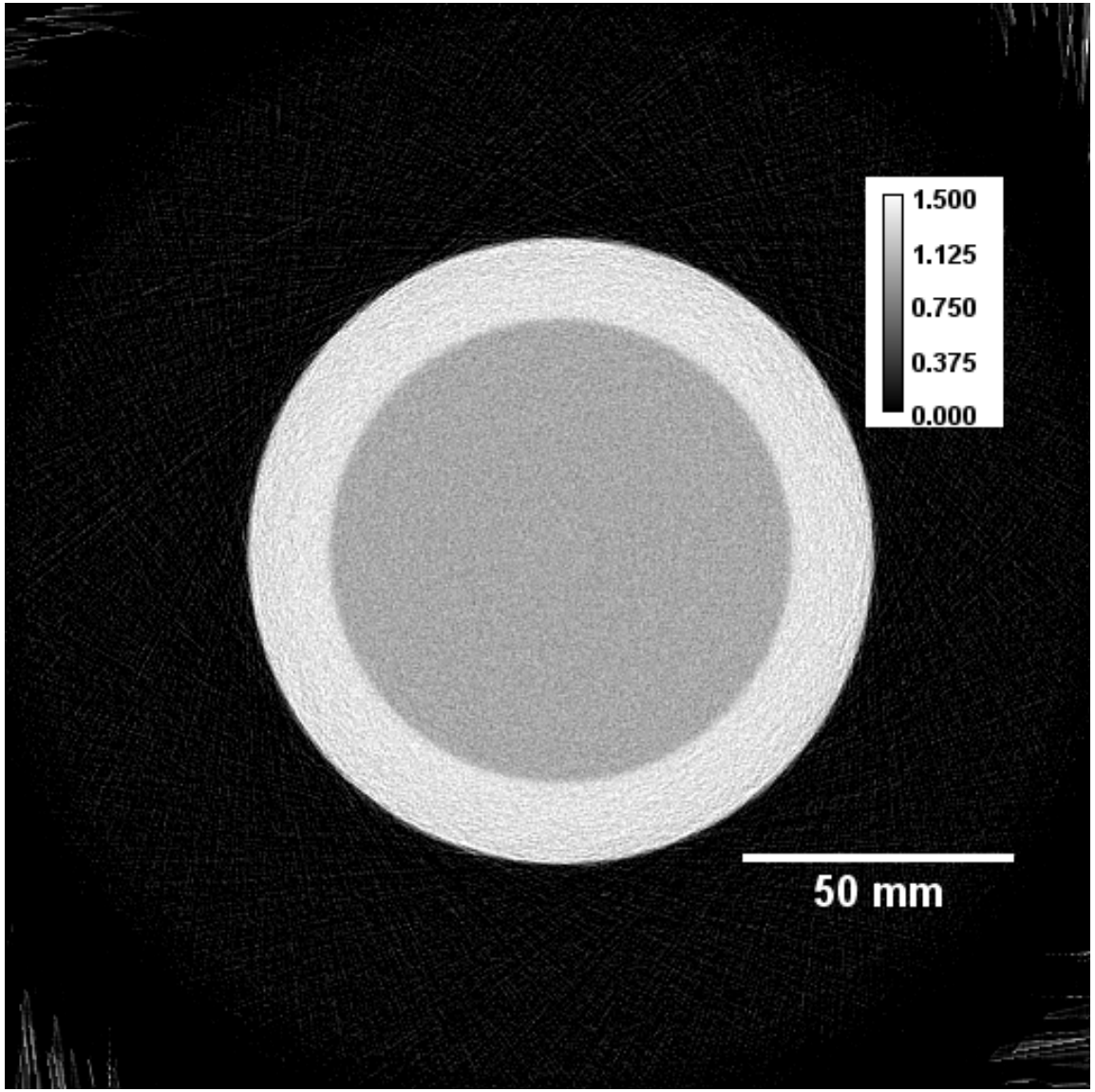


Water pCT image

- SPR proton tomography of a demineralized water phantom, 115 mm diameter, 15 mm tick delrin walls
- Axial slice #12
- Voxels: **0.39x0.39x1.5** mm^3
- Statistics: **$3x10^8$** triggers
- Total dose: **4.2 mGy**
- FDK-like reconstruction with MLP

Axial view



SPR: error discussion

- The uncertainty in the SPR value measured in **ROI** with sizes of $\mathbf{N} \gg \mathbf{100}$ pixels is fundamentally driven by systematic
- Statistical error → $std.dev.(SPR)/\sqrt{N}$ with $std.dev.(SPR) \cong 1.1\%$
  - $\boldsymbol{\sigma^{SPR}_{Stat.ROI}} \ll \mathbf{0.1\%}$
- Uncertainty due to residual non-uniformities in energy measurement by the calorimeter → $\mathbf{0.5\%}$
- Uncertainty due to the event selection cuts → $\mathbf{0.4\%}$
- Total syst. uncertainties: $\mathbf{0.7\%}$
- Vertical coordinate (z) dependency
  - This is the most important part of the calorimeter's non-uniformity (in principle, it could be corrected since it is a systematic bias)

Dimensional calibration

- If the image is not correctly reconstructed in its actual dimensions, the SPR changes accordingly:
- $+\mathbf{1}\%\ \boldsymbol{\Delta x} \Rightarrow -\mathbf{1}\%\ \boldsymbol{\Delta SPR}$
- Incorrect determination of the position of the axis of rotation in the direction of the beam produces a dimensional variation in the image.

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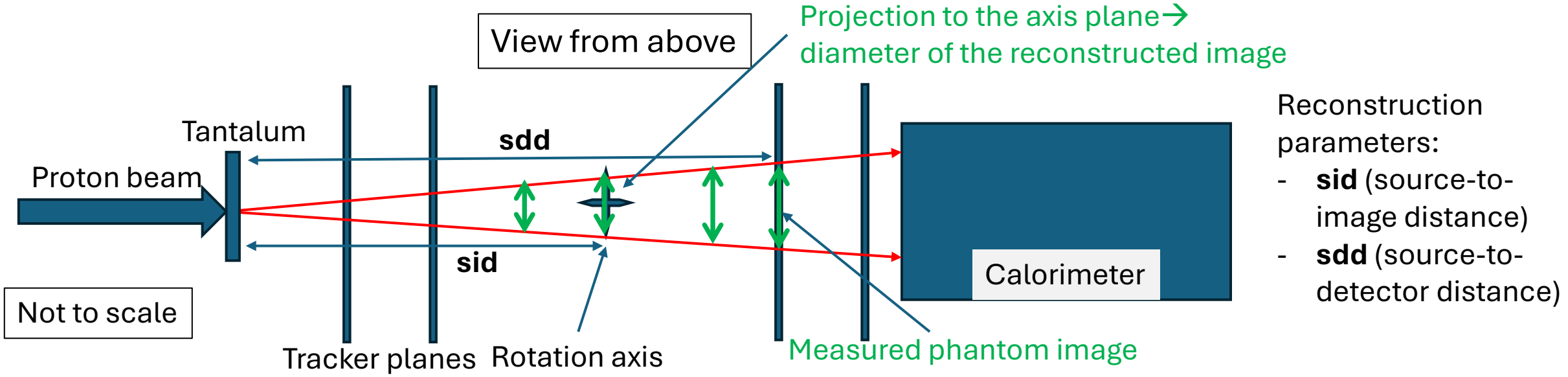
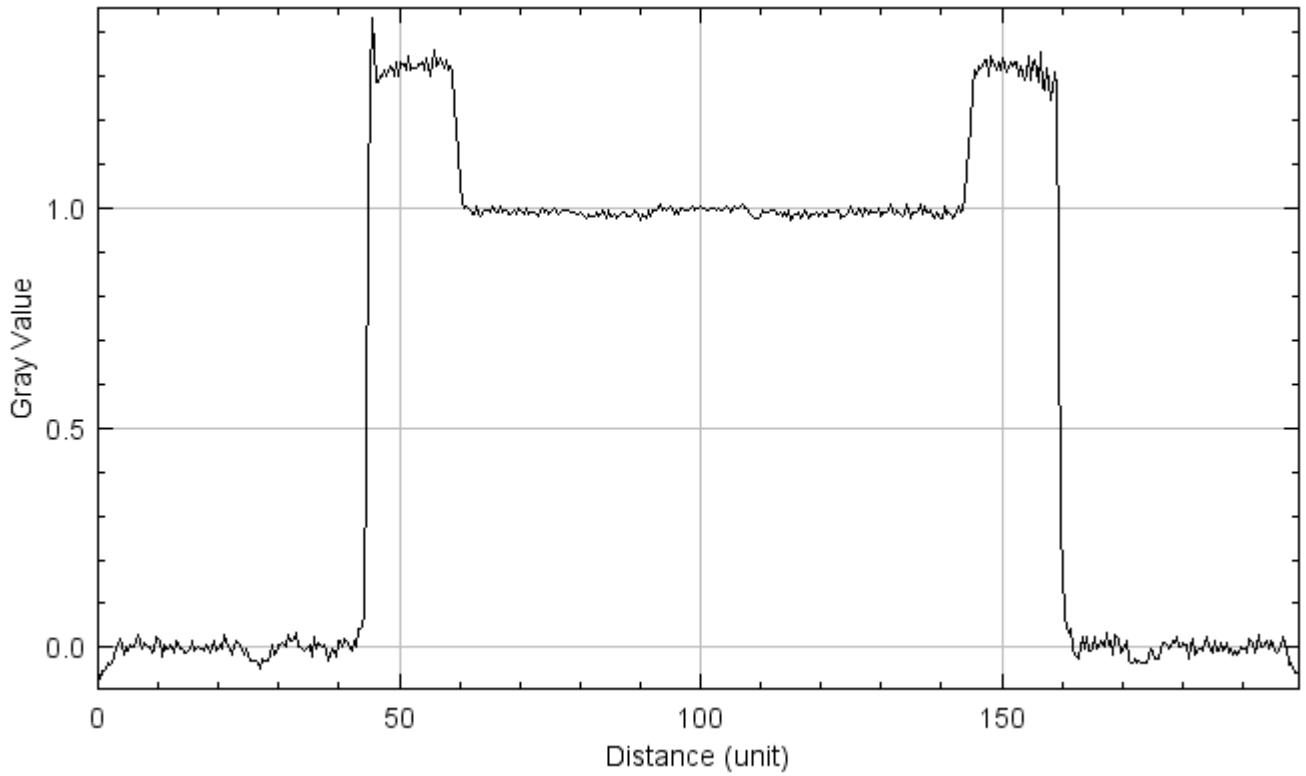


Dimensional calibration

- Using the water phantom (SPR profile along its diameter)



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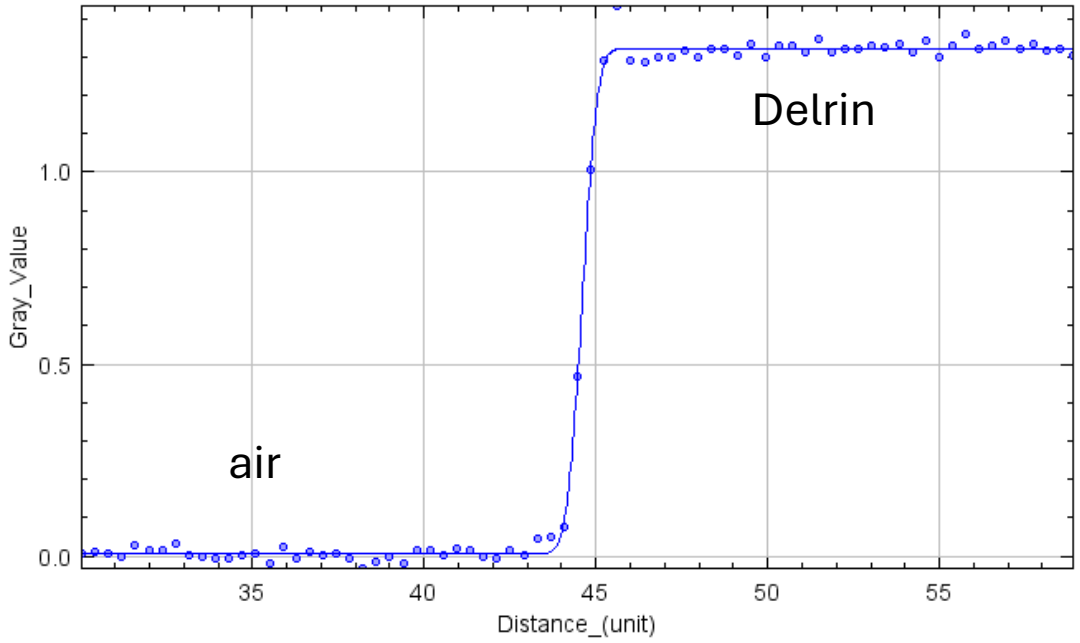
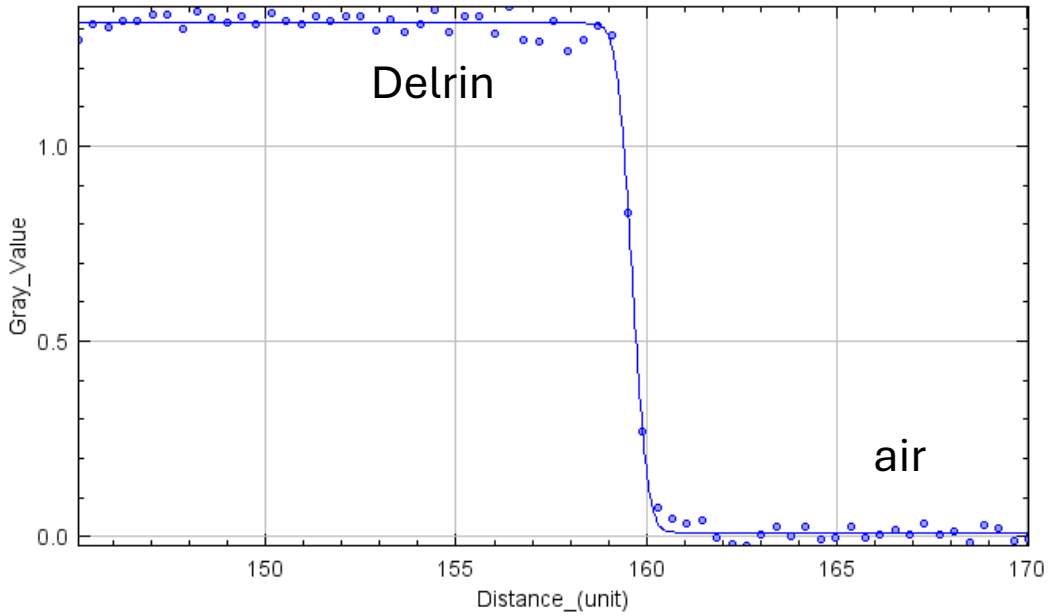




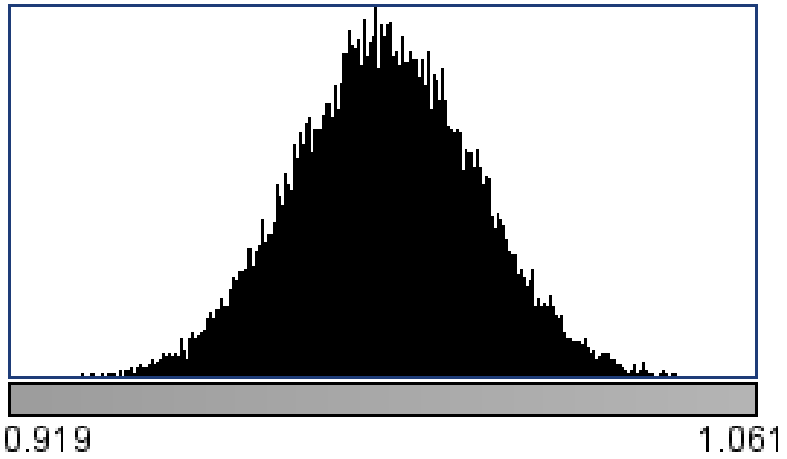
Left edge: erf fit 44.596 mm

Diameter: **115.029** mm

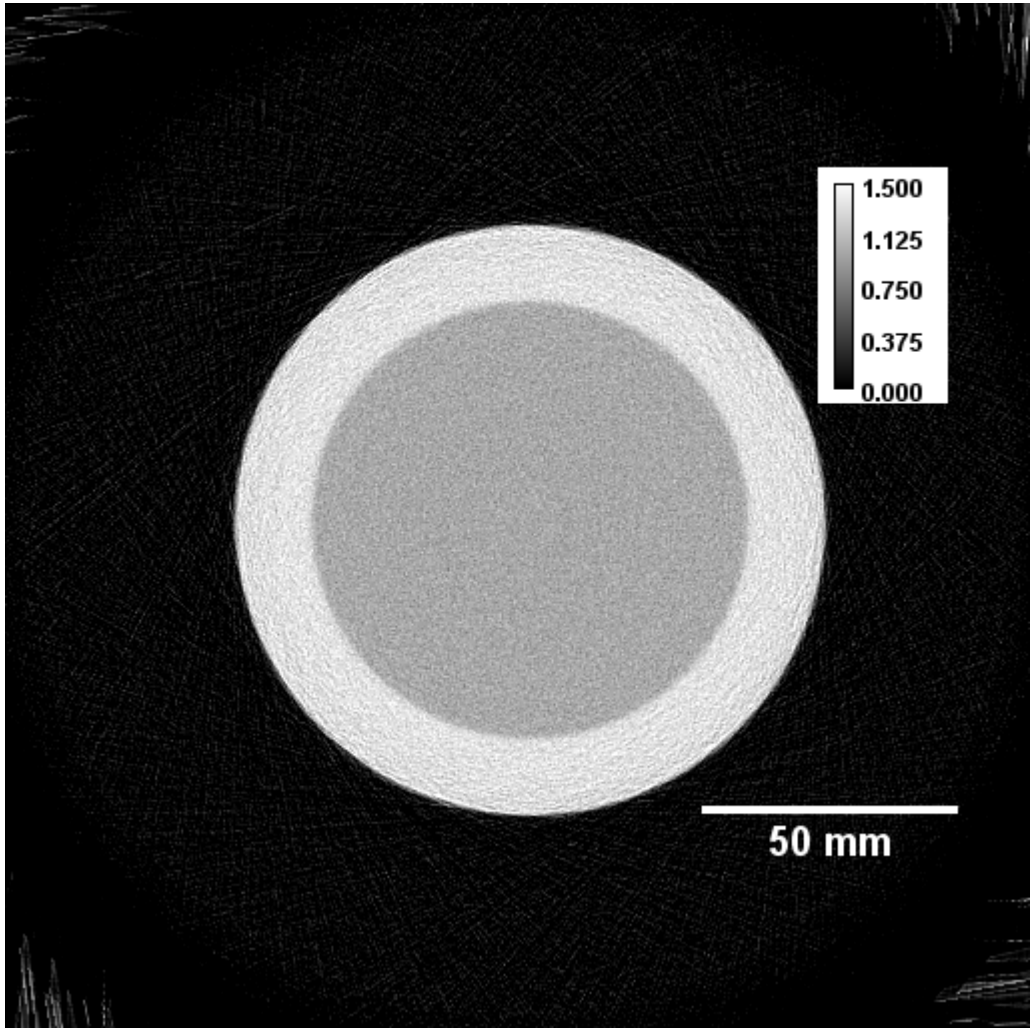
Right edge: 159.627 erf fit mm

SPR check using the water phantom

- Demineralized water phantom:
  - diameter 115 mm
  - delrin walls: 15 mm
  - Slice n. 12
- **SPR = 0.99**



N: 30184	Min: 0.919
Mean: 0.990	Max: 1.061
StdDev: 0.0176	Mode: 0.989 (416)
Bins: 256	Bin Width: 0.000553
Value: 1.052	Count: 0



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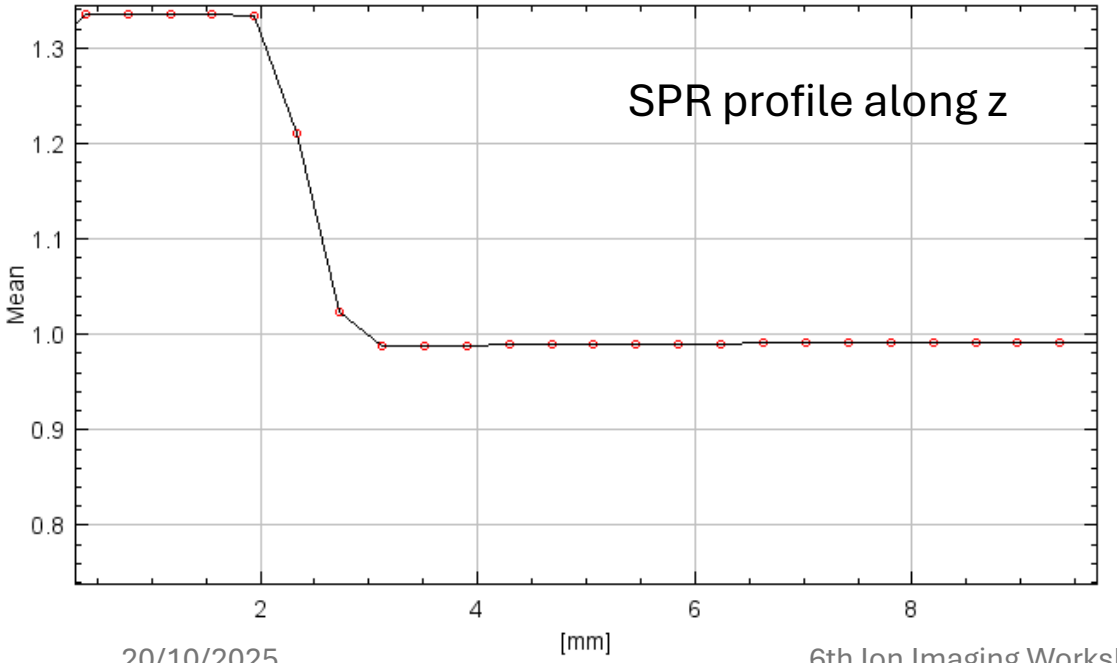
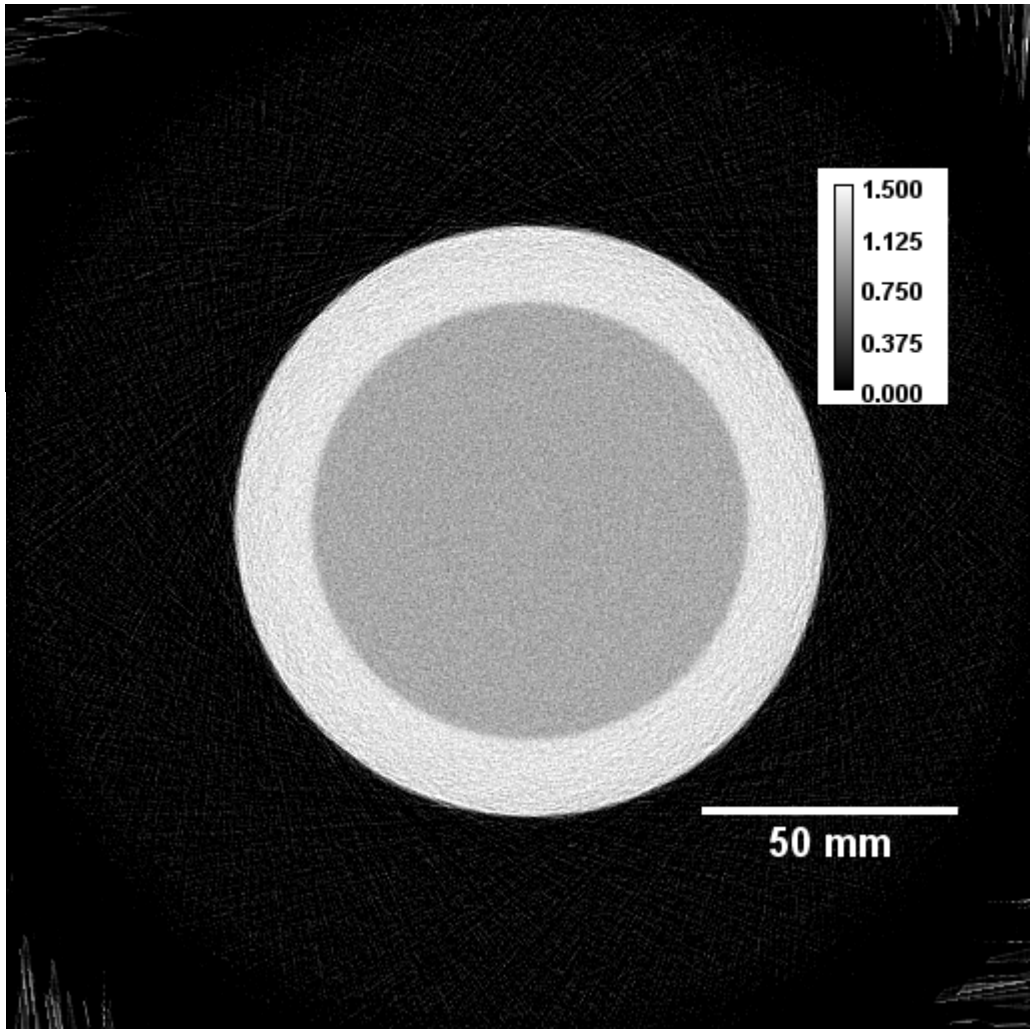




Preliminary

SPR values of the CIRS materials from the pCT image

MATERIAL	g/cc DENSITY	x10^{23} e-/cc E- DENSITY	RED	SPR PCT 2025
water eq.	1,029	3,333	0,998	0,989
muscle	1,06	3,483	1,043	1,04
bone core 1500mg/cc	1,99	6,134	1,837	1,709
lung inhale	0,2	0,634	0,2	0,184
bone 200mg/cc	1,16	3,73	1,117	1,098
breast	0,99	3,261	0,976	1
bone 800mg/cc	1,53	4,862	1,456	1,392
liver	1,07	3,516	1,052	1,053
bone 1250mg/cc	1,82	5,663	1,695	1,6
lung exale	0,5	1,632	0,496	0,506

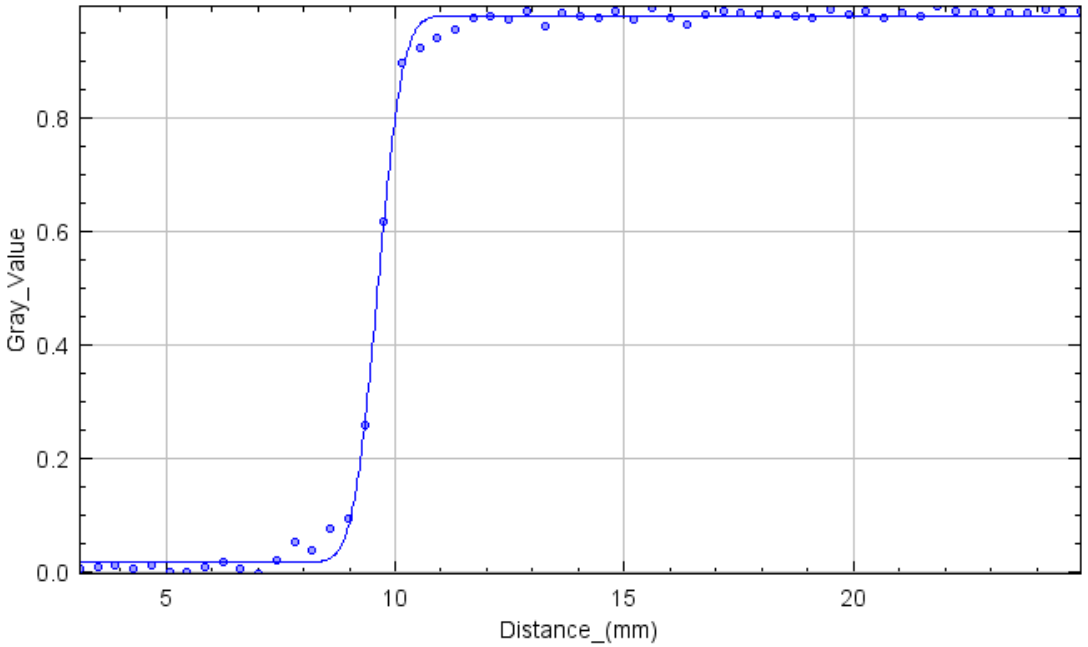
- The table shows the **average SPR value** in a region of interest with a diameter of 90% of the CIRS inserts with a length of 37.5 mm along its axis.
- On these SPR values, the **systematic error** is approximately **0.7%**
- Since the measured **SPR value of water is 0.99** compared to the **expected value of 0.998 at 20°C**, we can consider multiplying the values found by 1.008 to normalize the response of the pCT system to ‘measured SP of the water’.

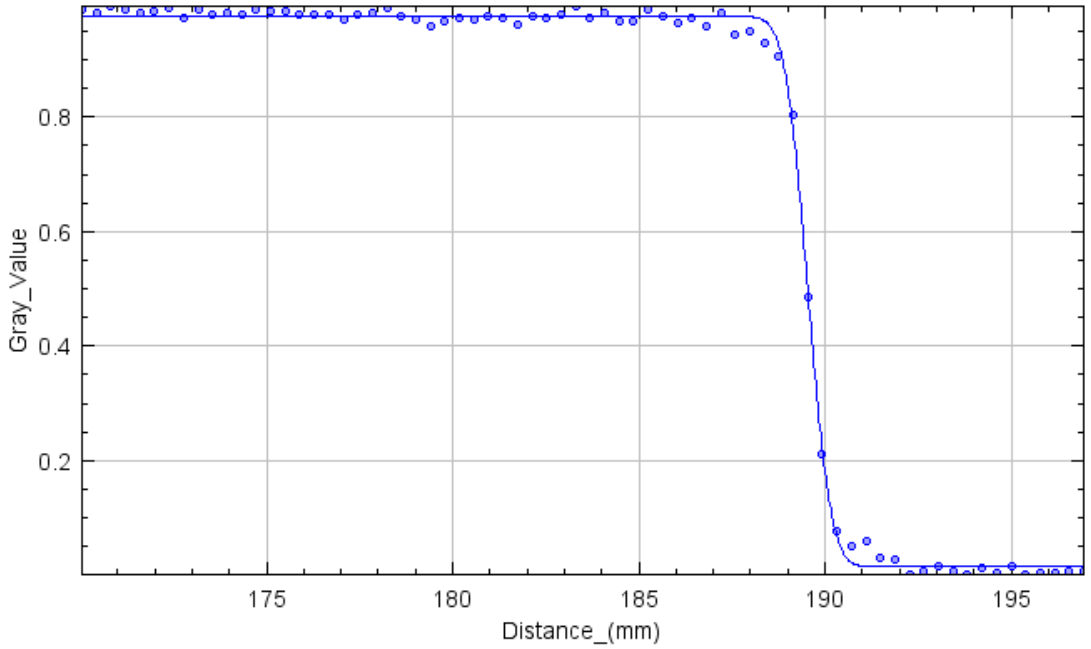
Conclusion

- The SPR of tissue-equivalent materials have been directly measured with a pCT system
- The uncertanties in these values are $\pm 0.7\%$ (syst.)
- These measurement could be used to build/check a look-up-table (xCT Hounsfield Units vs. SPR) to be used for dose calculation within a commercial treatment planning system (TPS).

Dimensional calibration

- Using the CIRS phantom (SPR profile along its diameter)





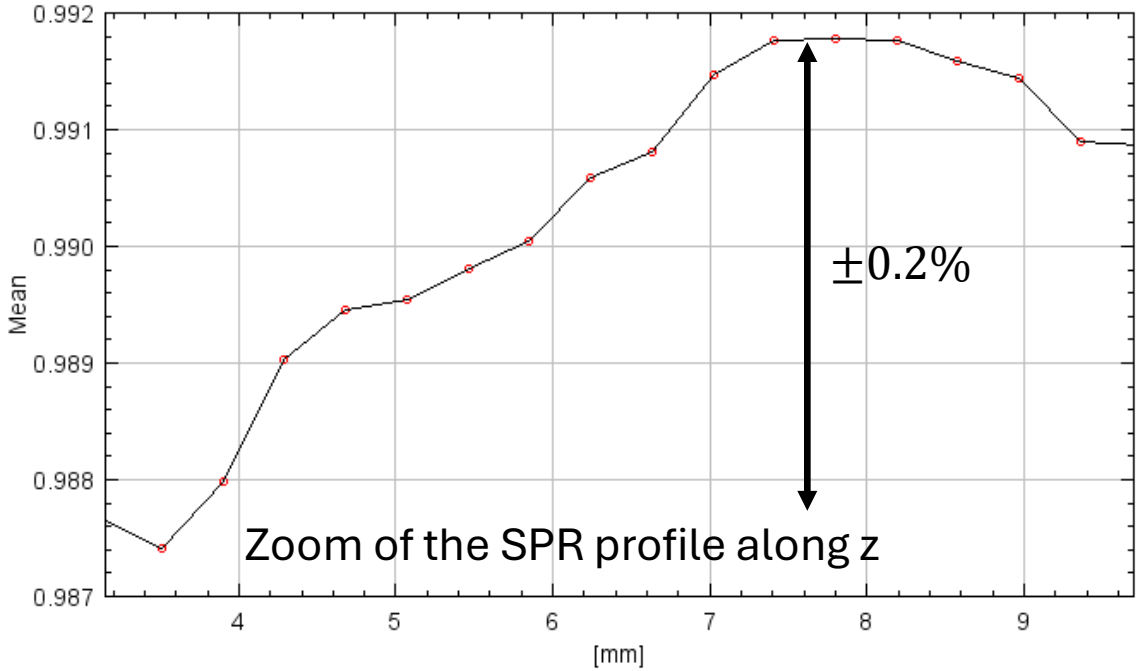
Left edge: erf fit 9.619mm

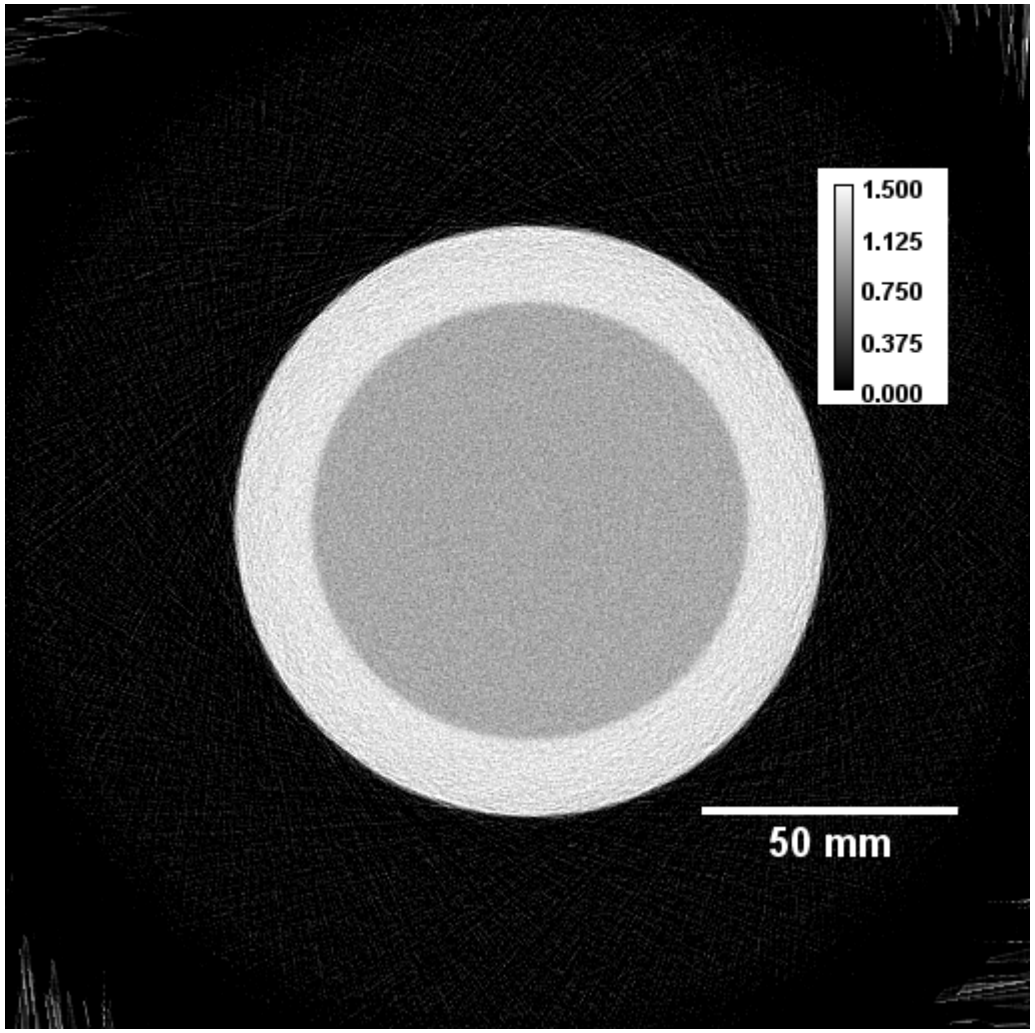
Diameter: **179.924 mm**

Right edge: erf fit 189.543mm

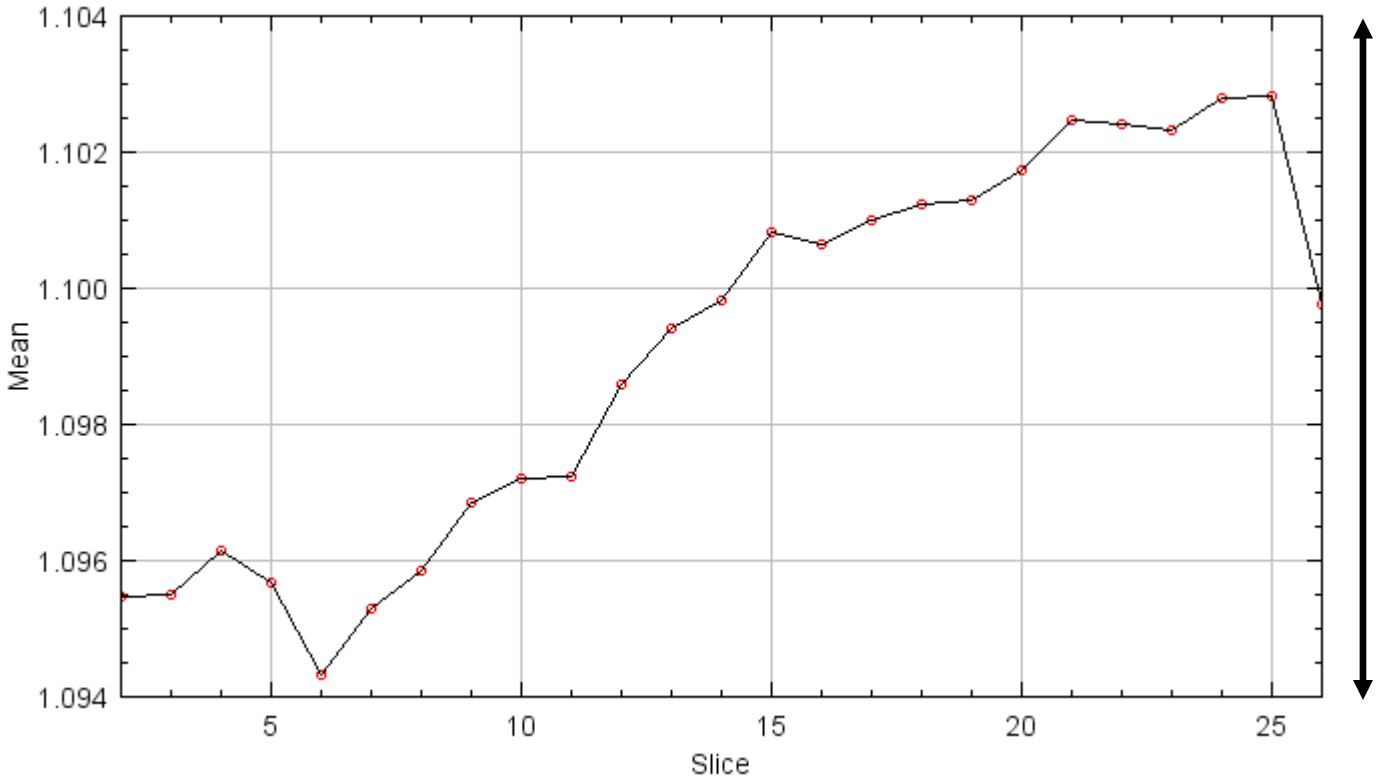
SPR check using the water phantom

- Demineralized water phantom:
  - diameter 115 mm
  - delrin walls: 15 mm
  - Slice n. 12
- **SPR = 0.99**





SPR dependence on the z coordinate



$\pm 0.5\%$

Example:
SPR bone 200mg/cc vs slice