Acquisition of integrated-mode ion radiographs in clinical beam lines

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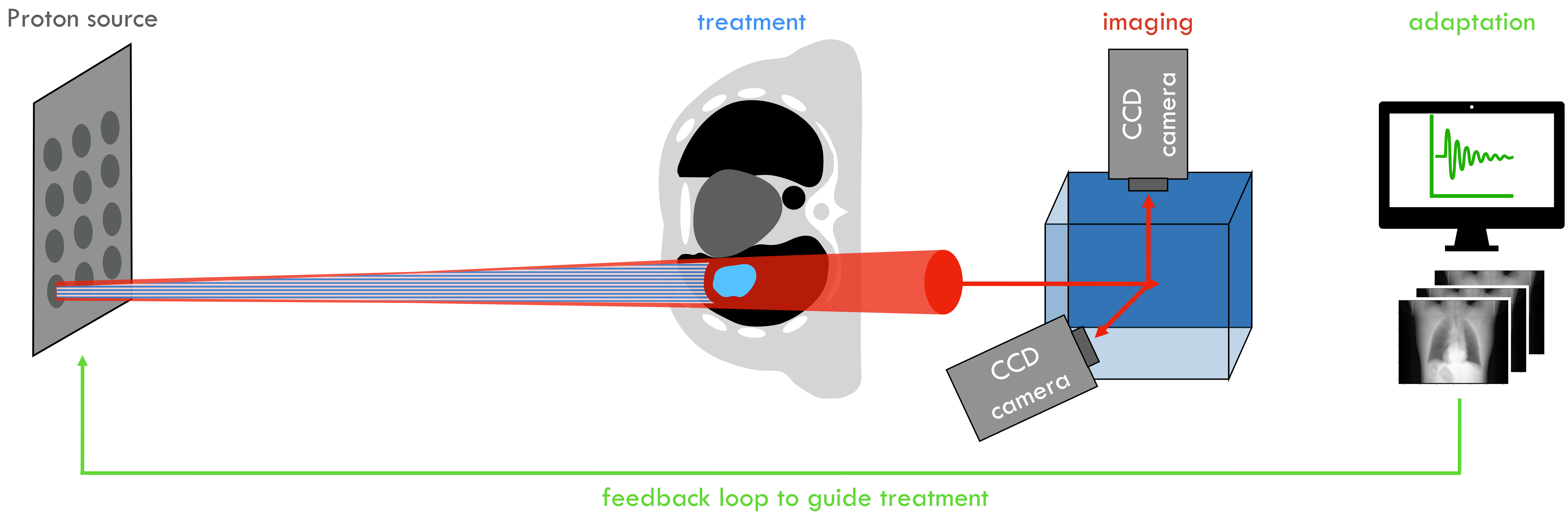
Introduction

Transmission imaging with ion beams

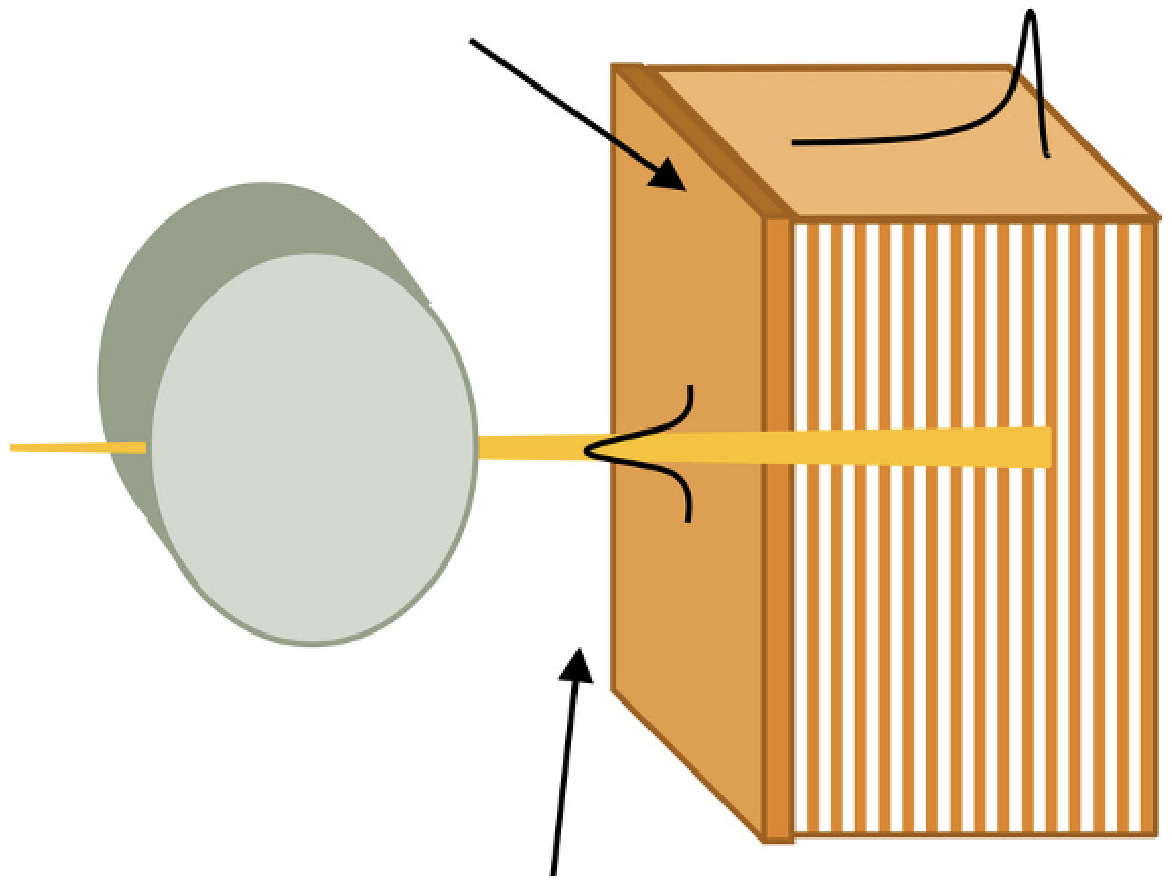
- Using the treatment source at high energy to capture **ion radiographs** is an attractive imaging solution, as it provides images (1) **fully registered** with the treatment beam, and (2) **high water equivalent thickness** (WET) **accuracy**.



Introduction

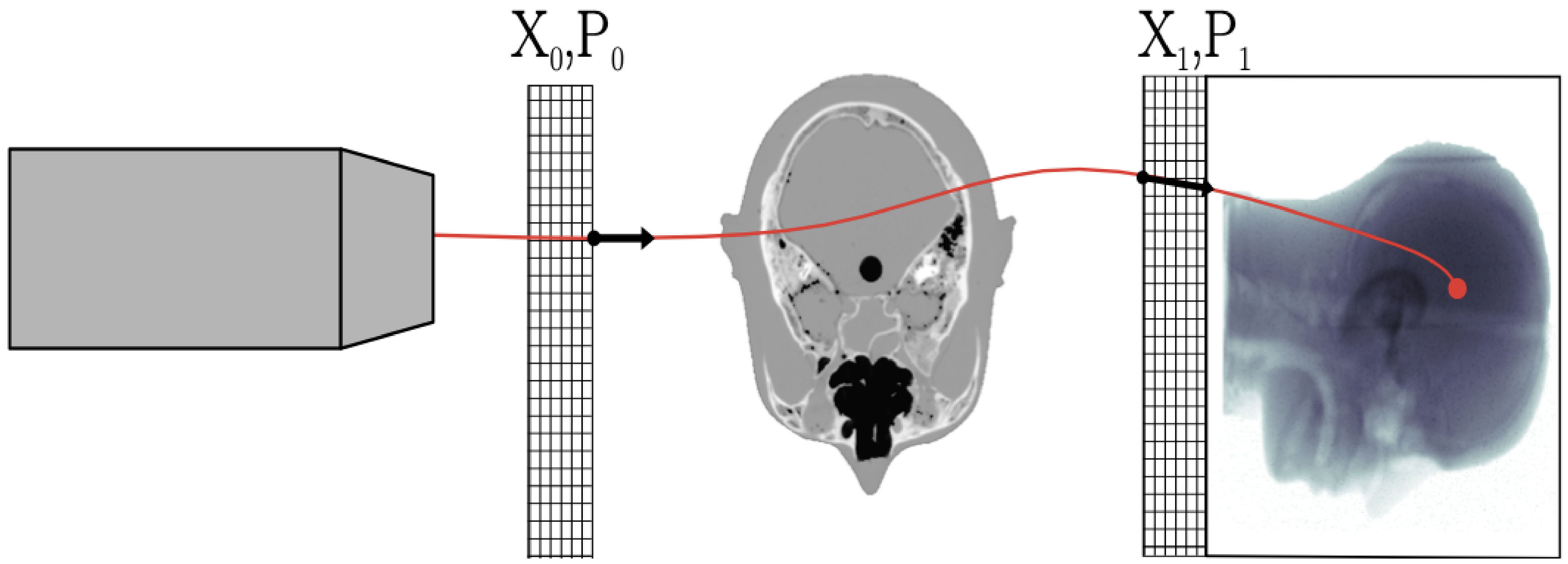
Two approaches for transmission imaging

Integrated mode



- Every pencil beam is tracked
- Low dose efficiency
- Spatial resolution limited by the number of pencil beams/scattering
- Low-cost / simple equipment
- Compatible with clinical beams

Single-event mode



- Every proton is tracked
- Very high dose efficiency
- Impact of scattering is minimised by multiple position measurements
- Requires complex equipment
- Cannot be used in clinical practice

Introduction

Applications of ion imaging

- Ion radiographs (iRads) could be useful to mitigate uncertainties in ion beam therapy.

1. In-situ measurement of RSP/WET [1,2]
2. Refinement of SECT stopping power calibration curves with proton radiographs [3]
3. Inter-fraction WET monitoring / patient positioning [4,5]
4. Metal artifact reduction [6]
5. Motion tracking [7,8]
6. Indirect in vivo range verification

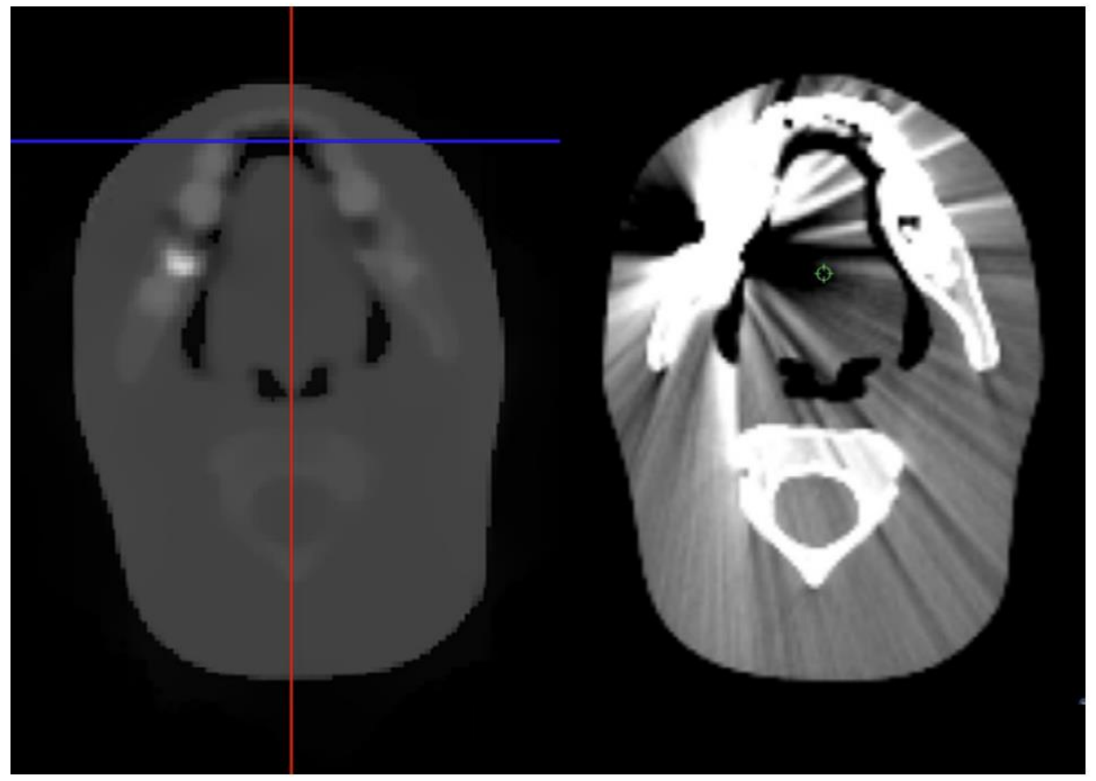
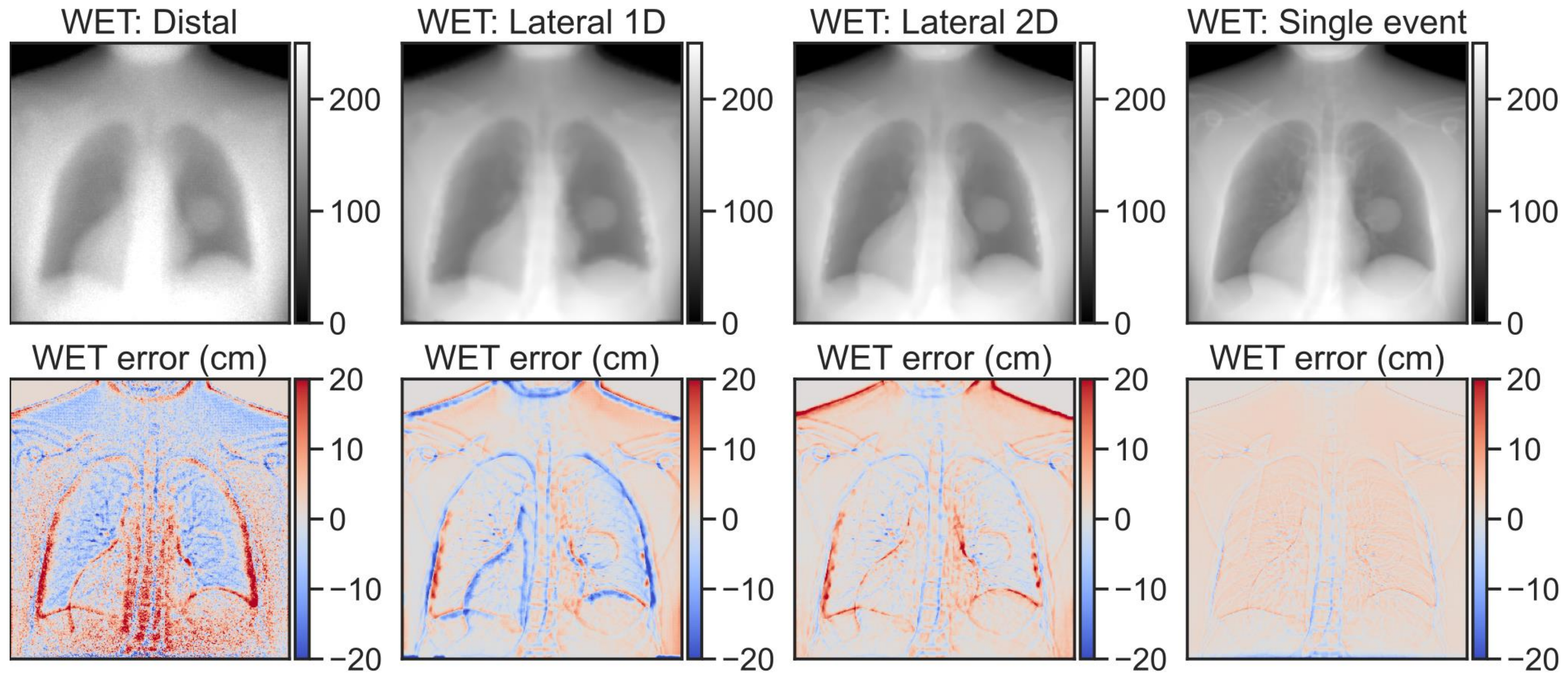


Figure 14. A comparison of pCT (left) and x-ray (right) CT images of a pediatric head phantom in which a gold tooth is visible in the slice displayed. The x-ray image, but not the pCT image, shows severe artifacts due to beam hardening caused by the gold. Reproduced from [71]. CC BY 3.0.

Ordonez et al 2016

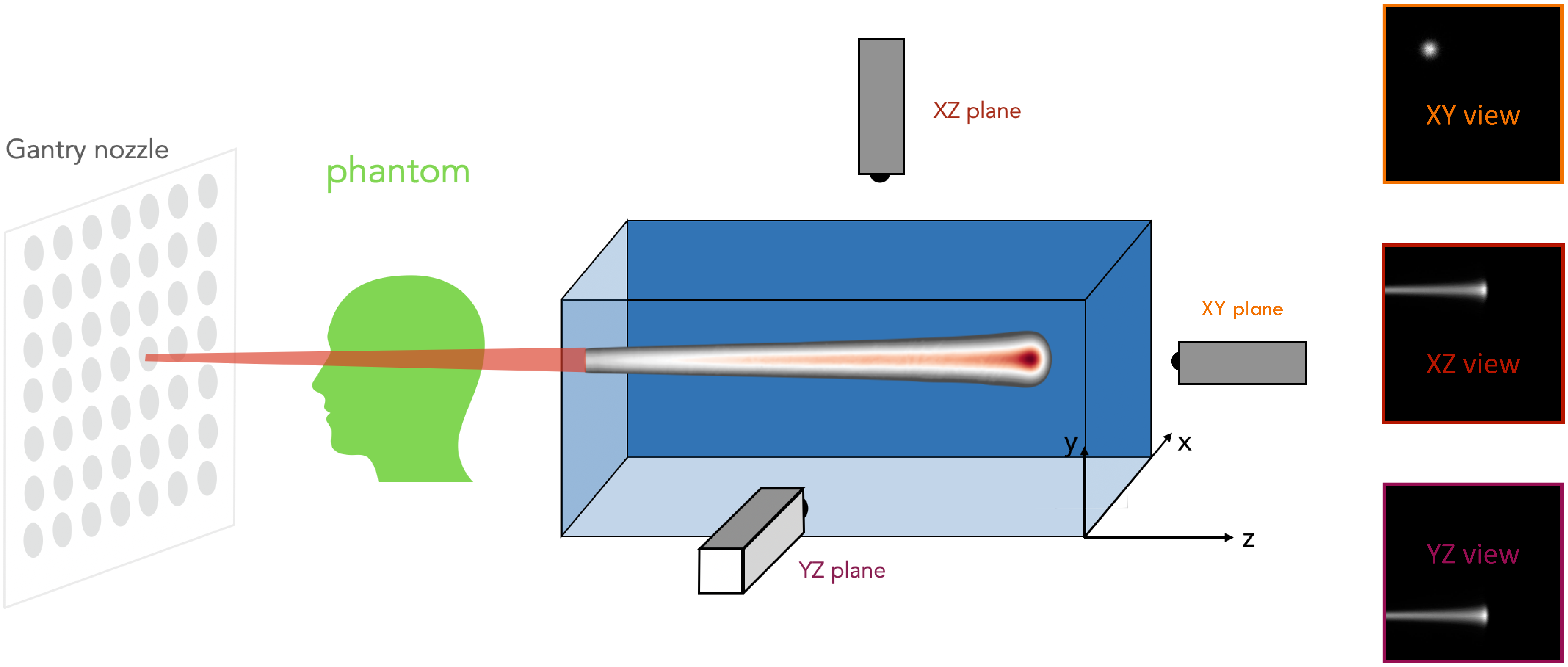


Simard et al (under review)

- The purpose of this work is to (1) **demonstrate the imaging capabilities** of an integrated mode ion imaging device, and (2) **quantify image quality metrics** to evaluate applicability.

Methods

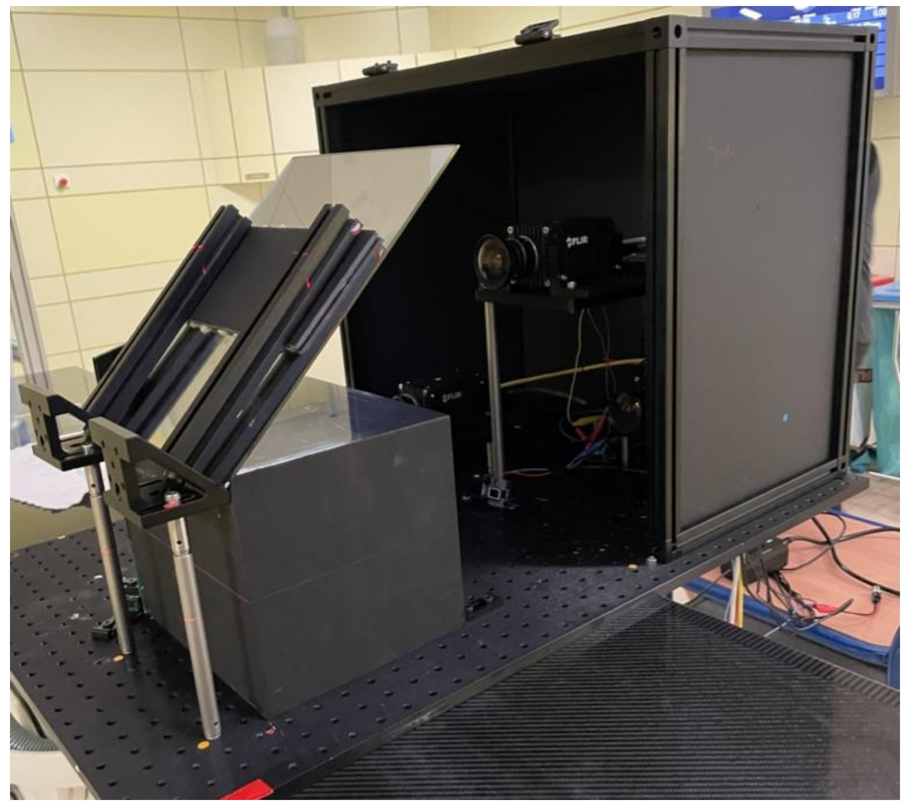
Ion radiography acquisition device - concept

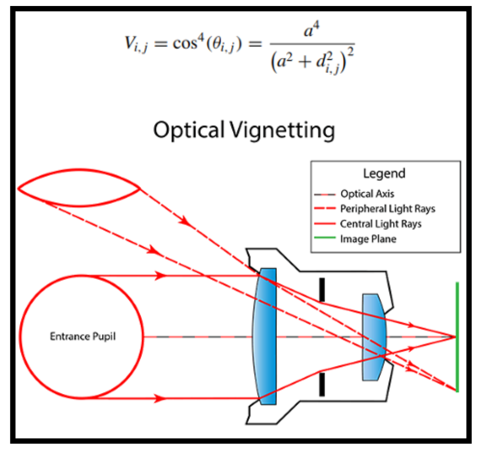


Methods

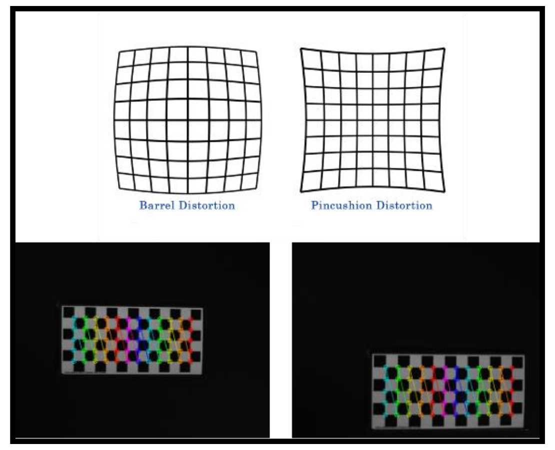
Ion radiography acquisition device

- iRads are acquired using a plastic volumetric scintillator (EJ-260) equipped with 3 CCD cameras capturing orthogonal views of the 3D energy deposition.
- The detector has a 20x20 cm^2 FOV.

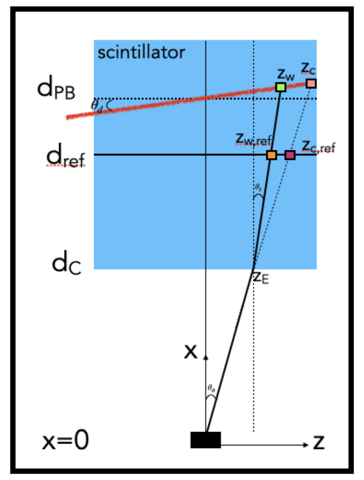




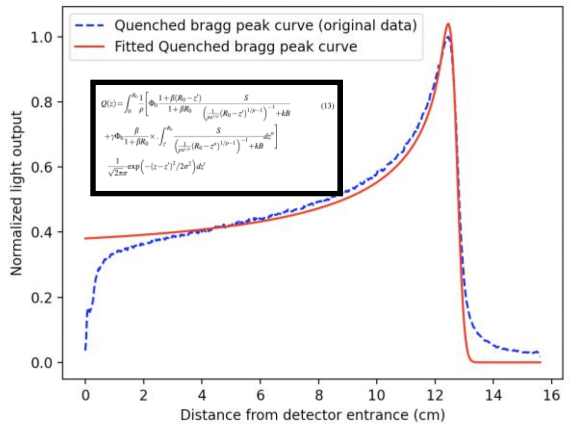
Vignetting



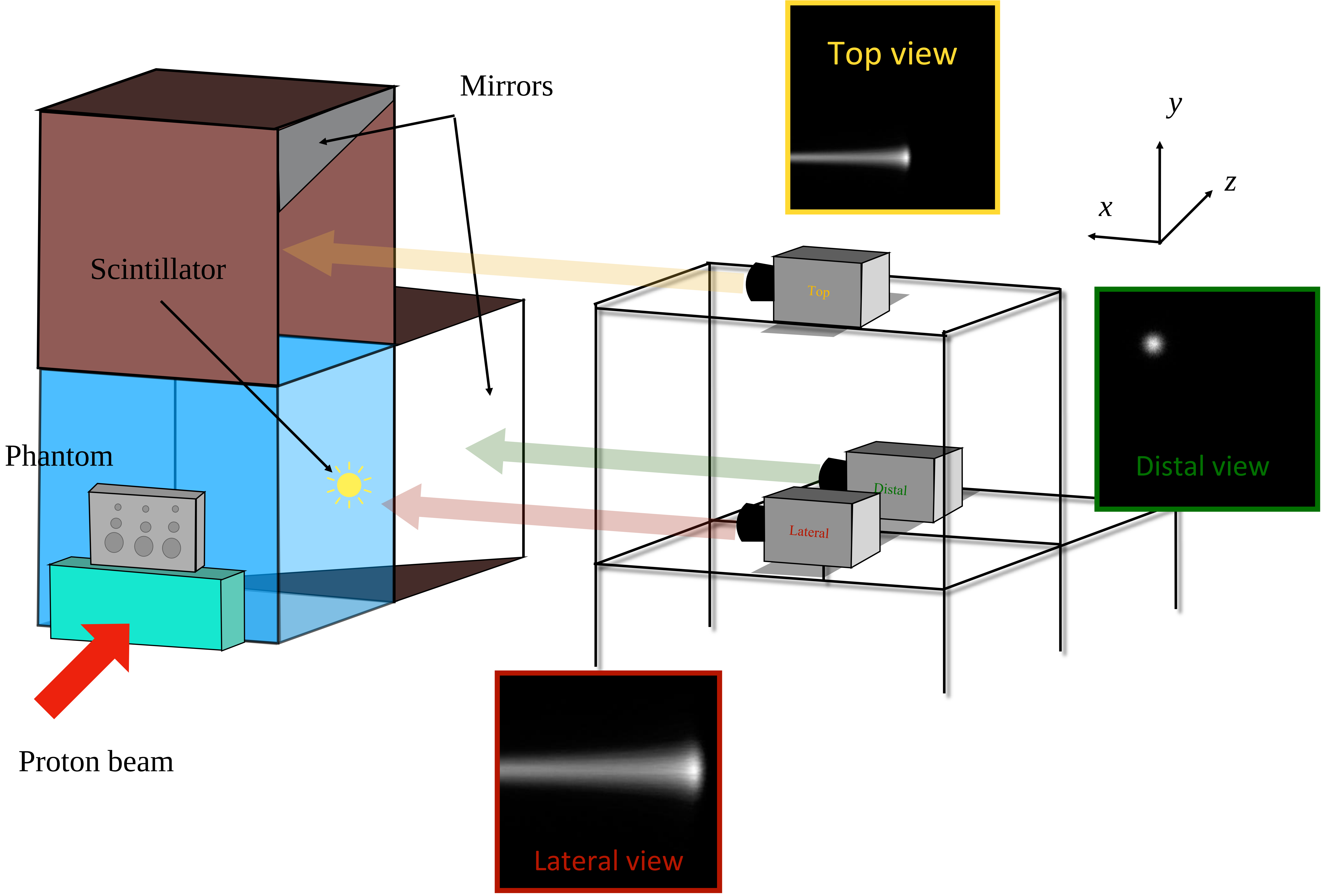
Lens distortion



Perspective & refraction



Scintillator quenching

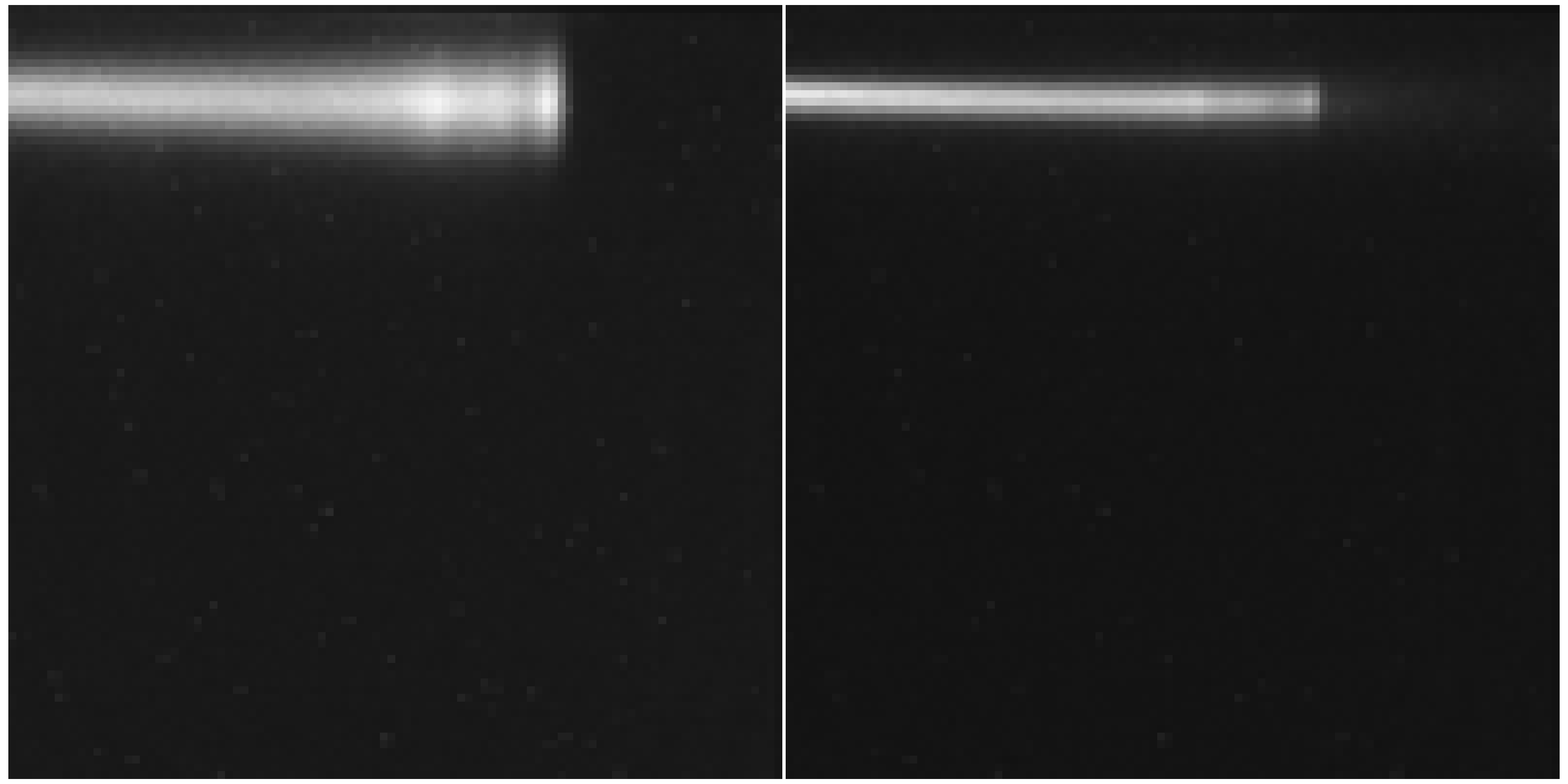


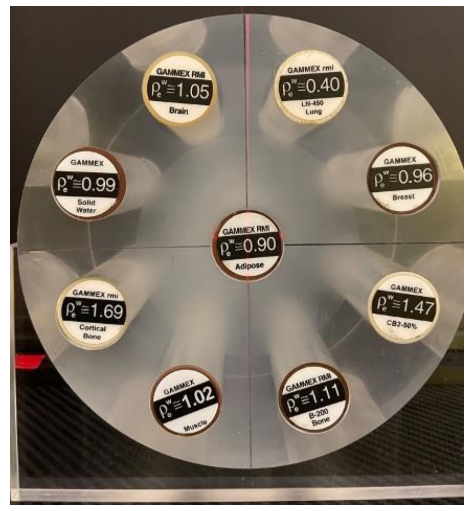
Methods

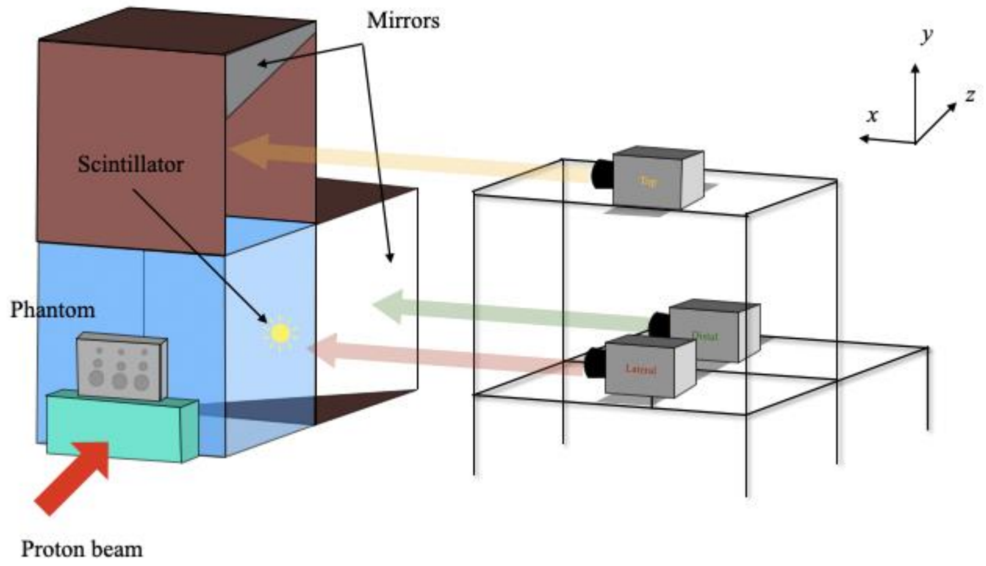
Data acquisition examples

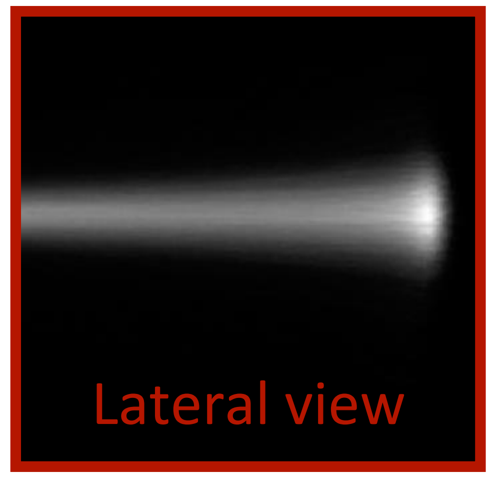
Phantom measurement with lateral view

Protons | Carbon ions

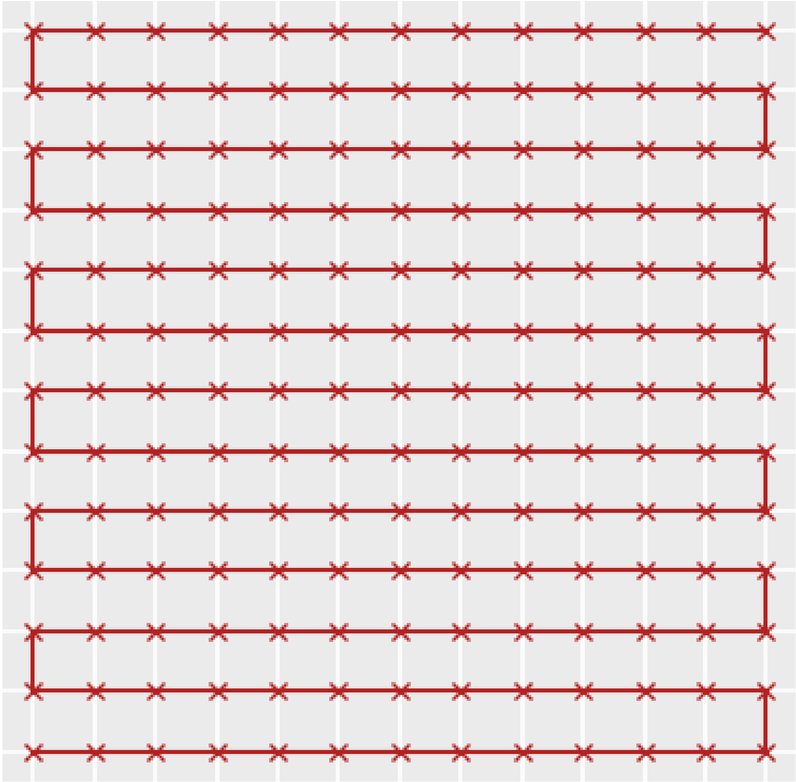


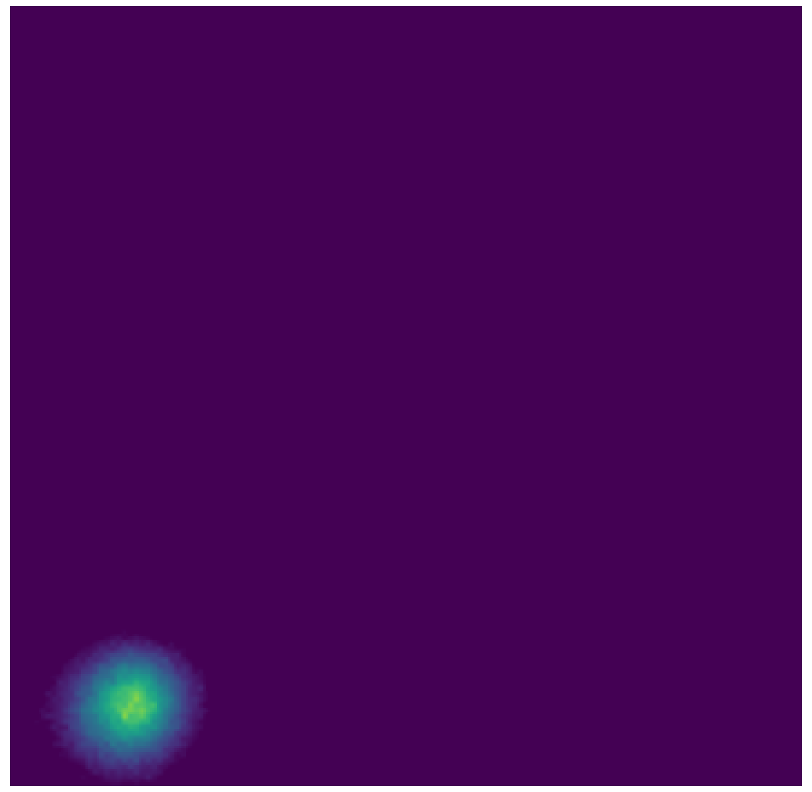






Beam acquisition pattern and distal view

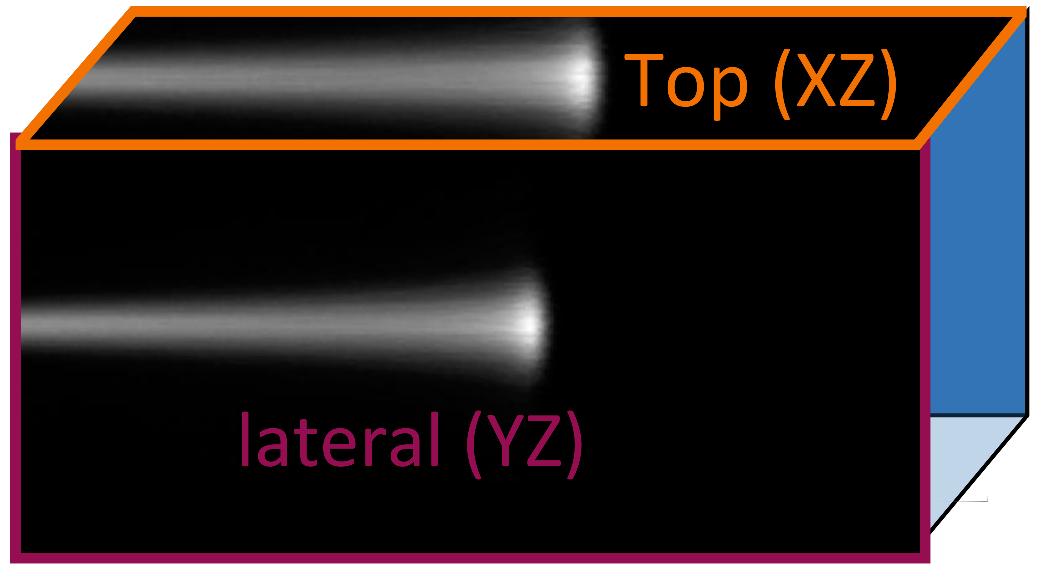


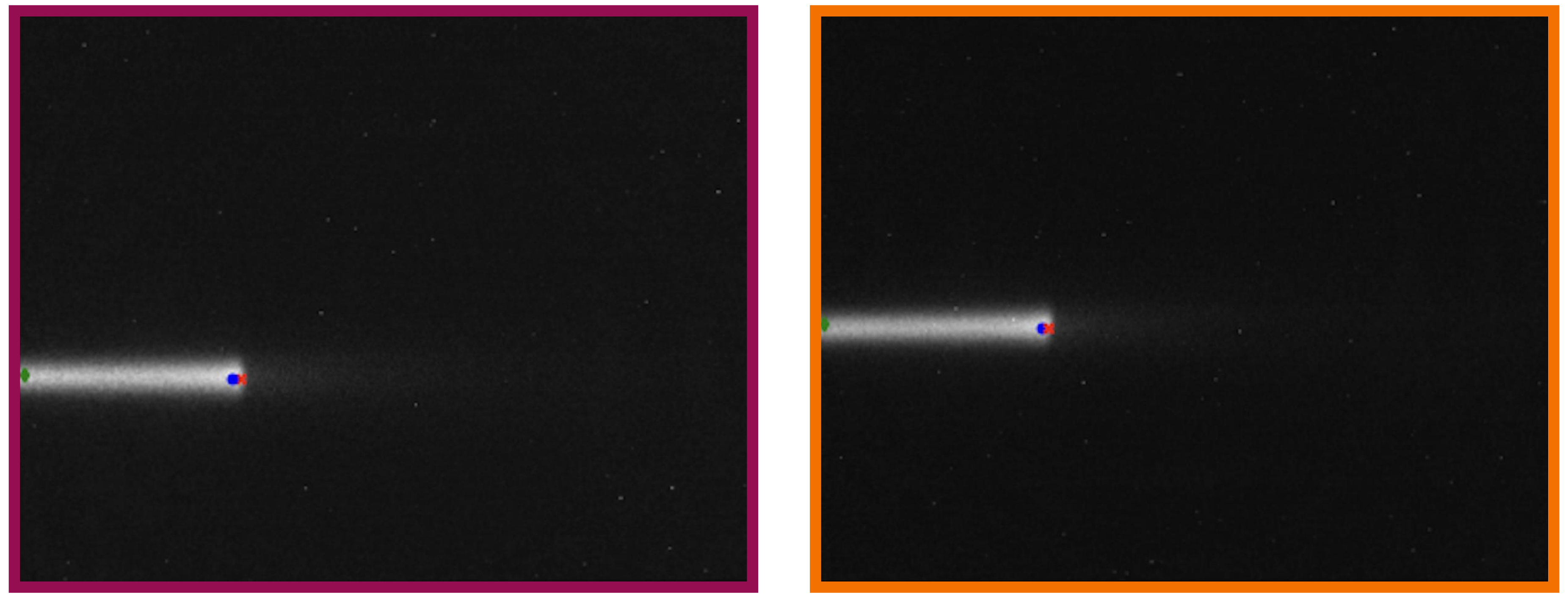


Methods

Image reconstruction

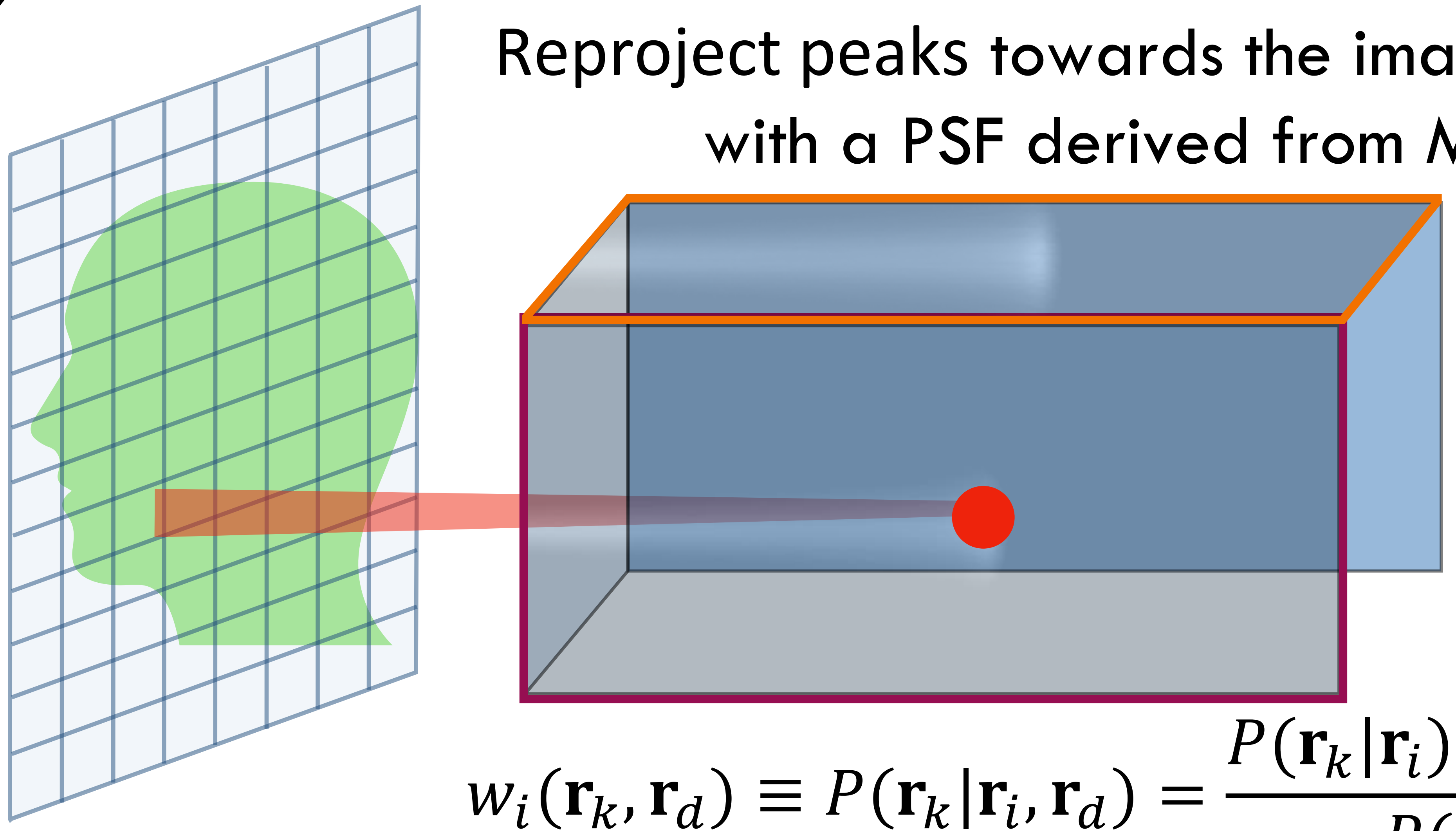
For each PB, process the lateral and top view.





Locate one or more Bragg peaks in the views

Reproject peaks towards the imaging plane with a PSF derived from MCS



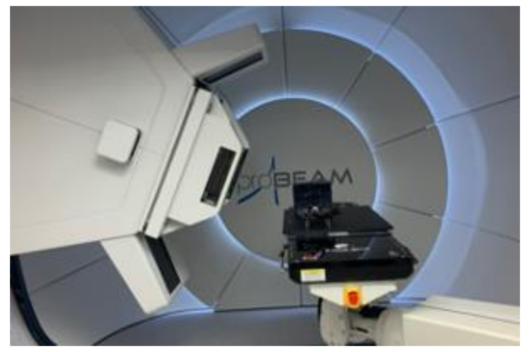
$$w_i(\mathbf{r}_k, \mathbf{r}_d) \equiv P(\mathbf{r}_k | \mathbf{r}_i, \mathbf{r}_d) = \frac{P(\mathbf{r}_k | \mathbf{r}_i) P(\mathbf{r}_d | \mathbf{r}_k, \mathbf{r}_i)}{P(\mathbf{r}_d | \mathbf{r}_i)}$$

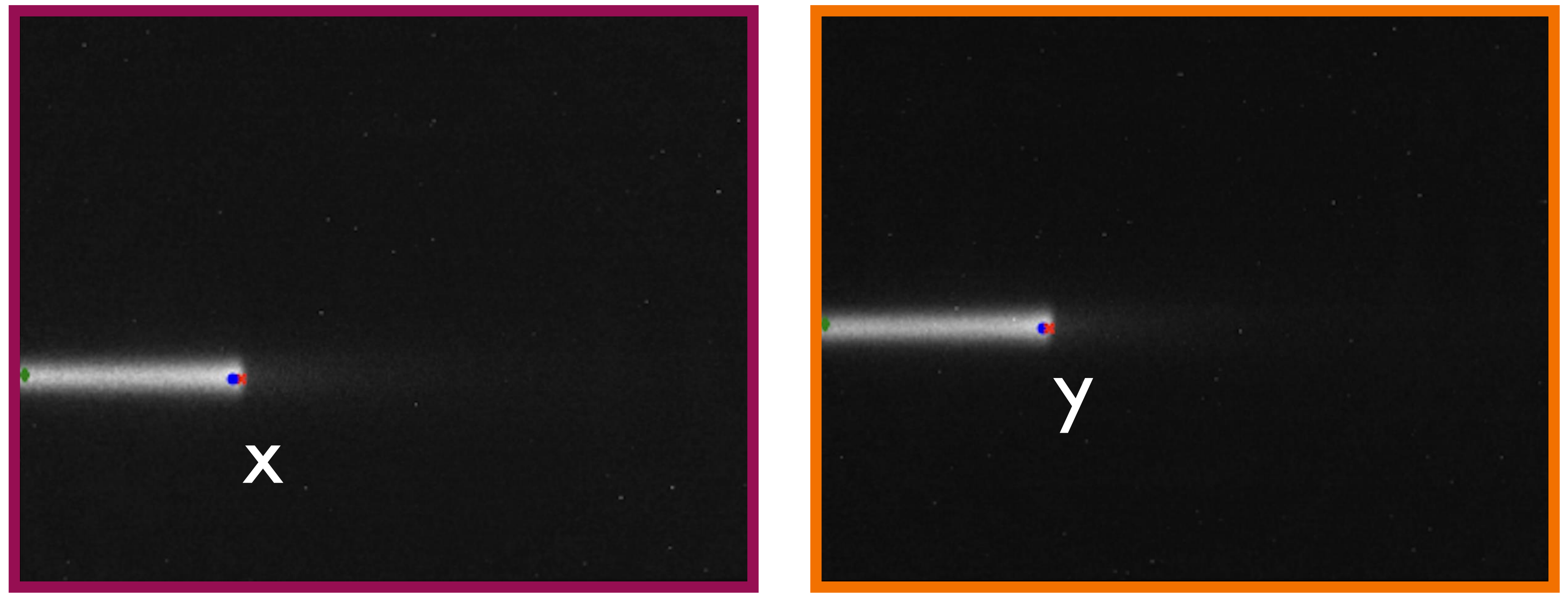
Accumulate over all PBs to get a WET map

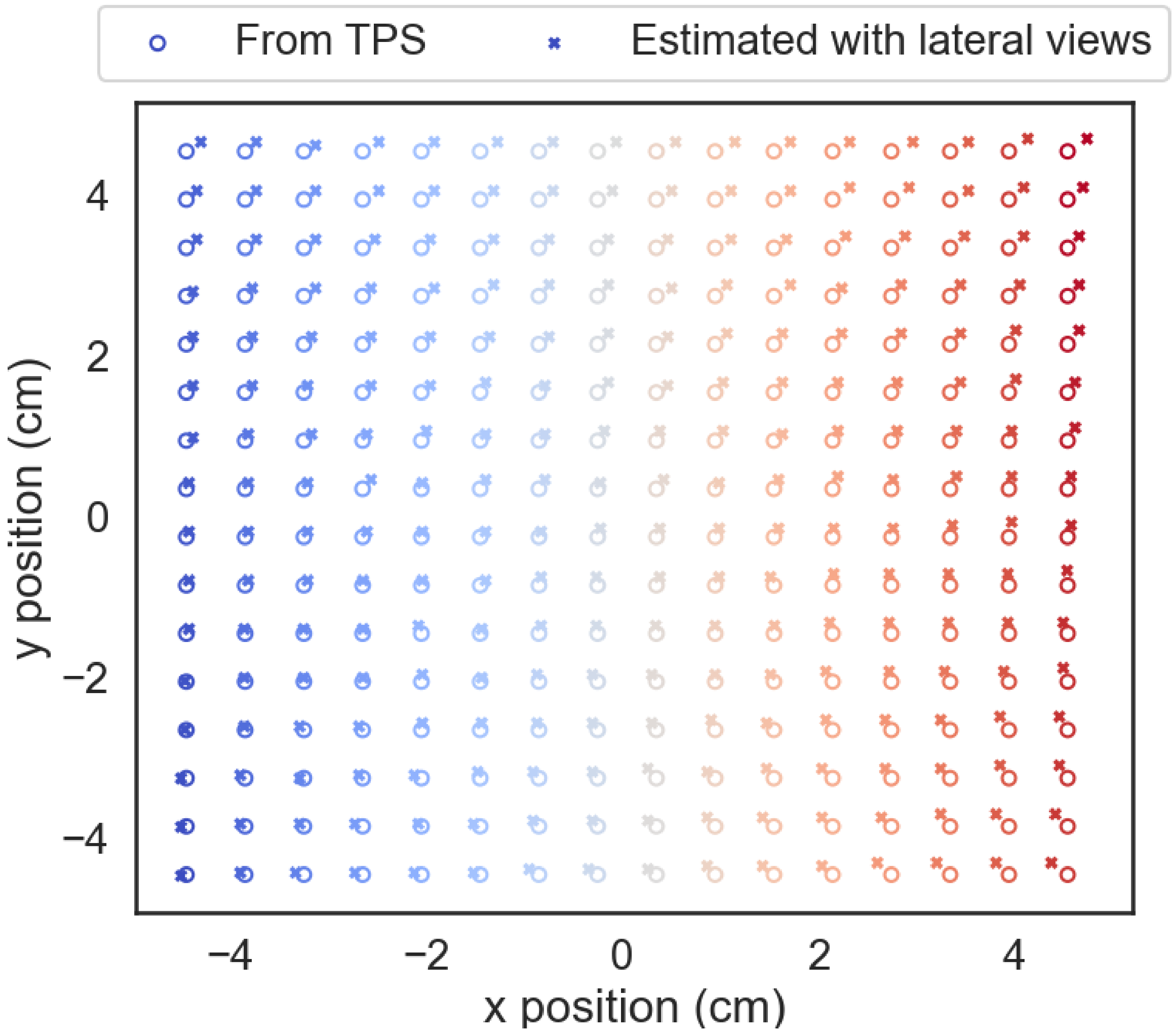
$$g(\mathbf{r}_k) = \frac{\sum_{i=1}^{n_{PB}} \sum_d w_i(\mathbf{r}_k, \mathbf{r}_d) \frac{N_i(\mathbf{r}_d)}{N_{i,\mathrm{tot}}} \mathrm{WET}_i(\mathbf{r}_d)}{\sum_{i=1}^{n_{PB}} \sum_d w_i(\mathbf{r}_k, \mathbf{r}_d) \frac{N_i(\mathbf{r}_d)}{N_{i,\mathrm{tot}}}}$$

Results (@ University College London Hospitals)

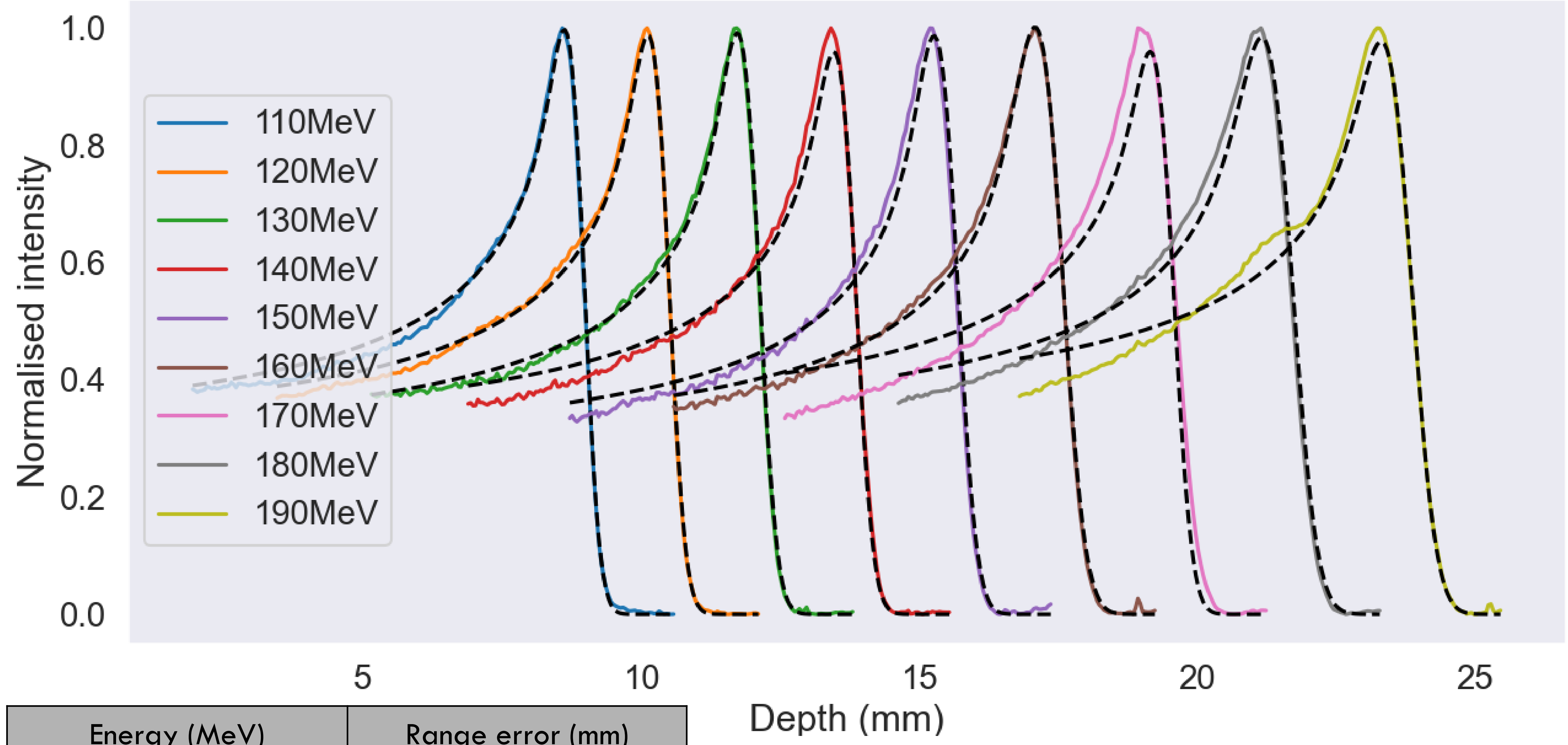
Proton radiographs - pencil beam localisation and range accuracy







~ 1.2 mm error on pencil beam position

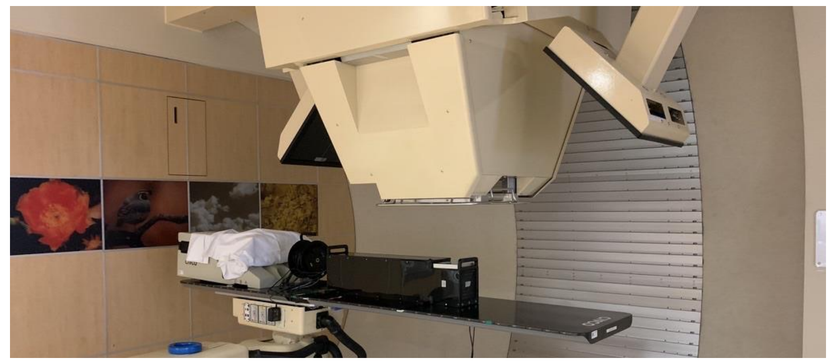


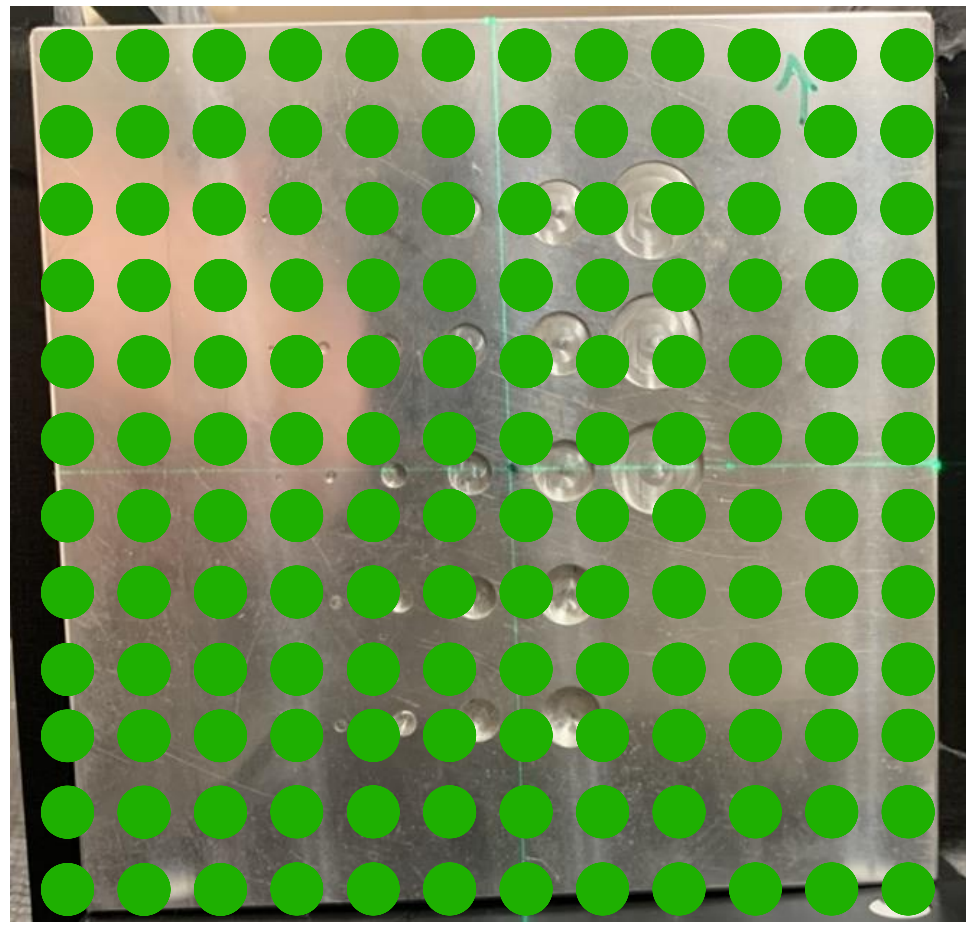
Energy (MeV)	Range error (mm)
110	1.6
120	1.5
130	1.5
140	0.9
150	1.0
160	0.7
170	-0.1
180	-0.1
190	1.0
MAE	0.9

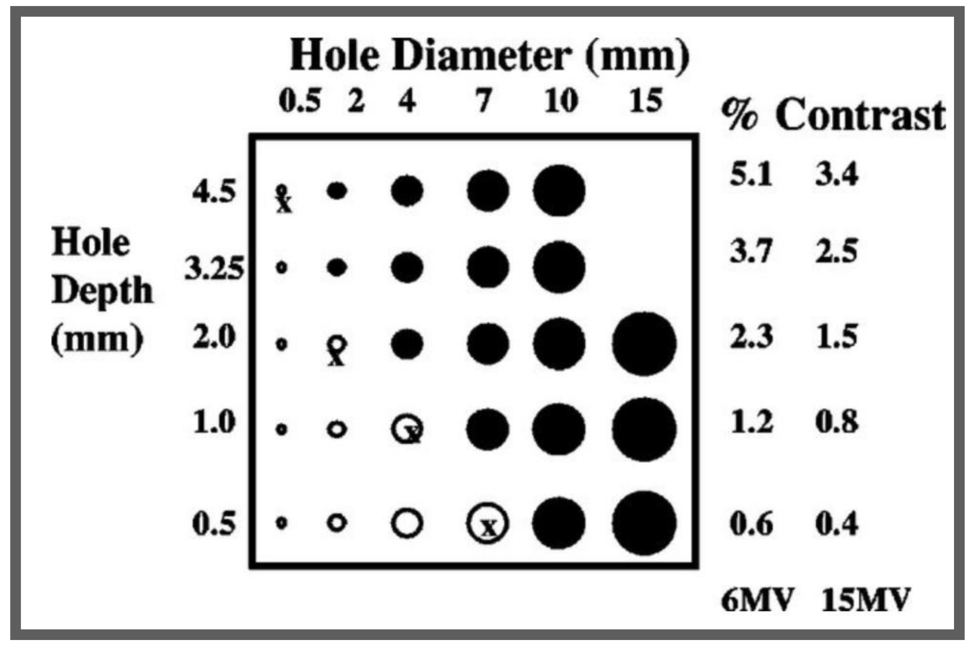
Mean absolute error of 0.9 mm on range of pristine beams

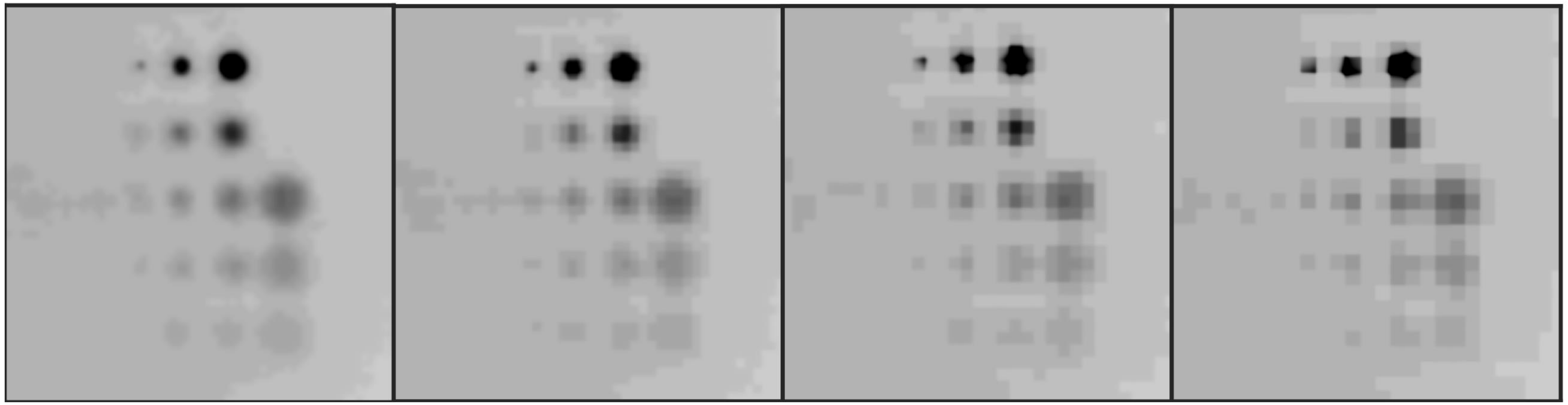
Results (@ Mayo clinic Arizona)

Proton radiographs - low contrast phantom









	2 mm	3 mm	4 mm	5 mm
# of PBs	2500	1089	625	400
Imaging time (s)*	7.5	3.3	2.1	1.2
Dose (cGy)**	6.2	2.8	1.5	1.0

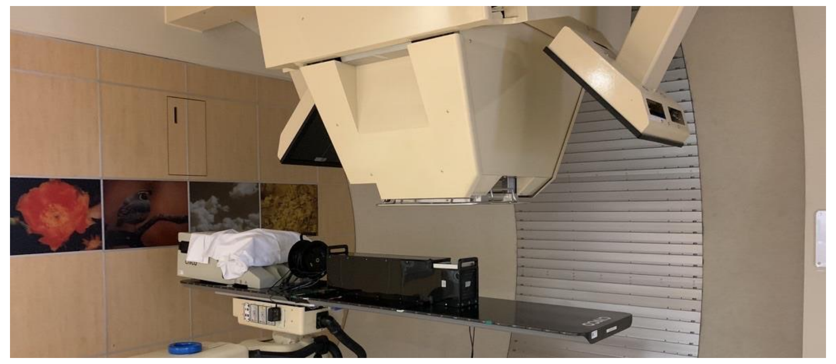
Beam parameters: 10x10cm^2 field size, 135.6 MeV, 3.1 mm spot size, beam spacings of 2, 3, 4, 5 mm.

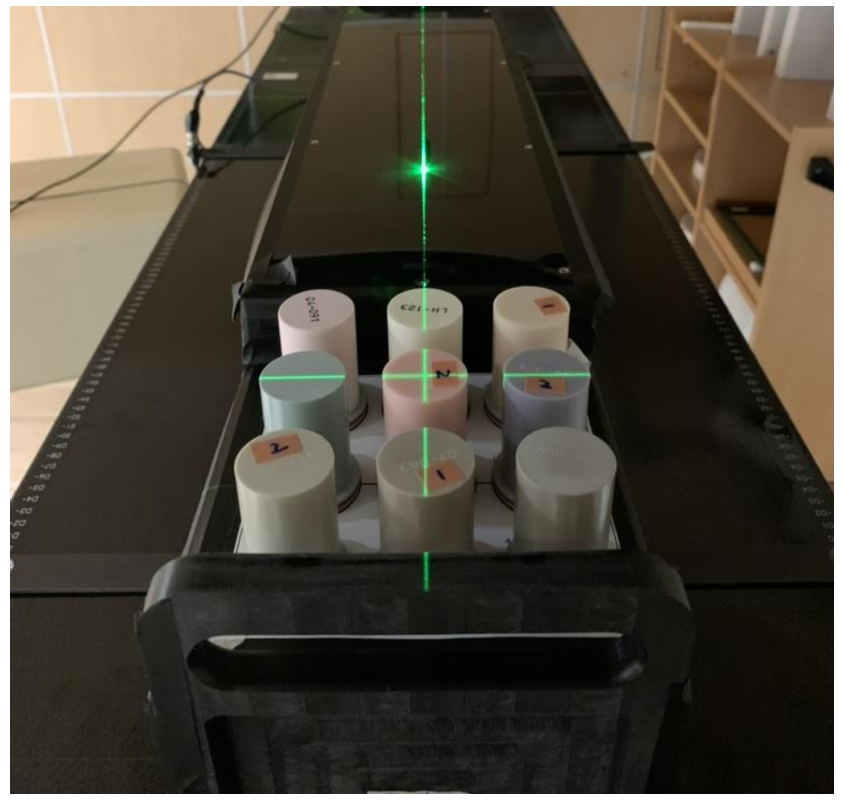
* Assuming 3 ms per spot

** (PTW30010) - Limited by commissioned beam lowest MU (not by the device)

Results (@ Mayo clinic Arizona)

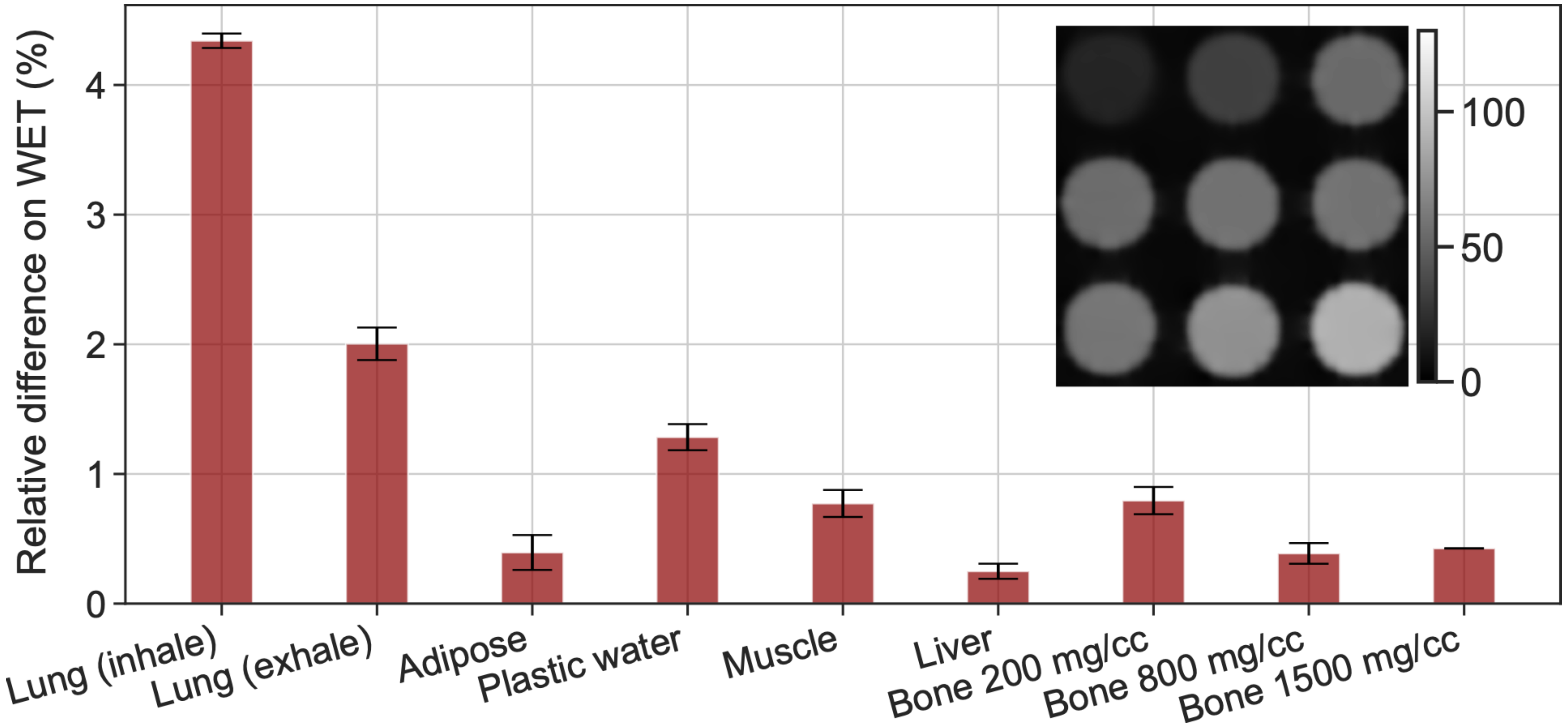
Proton radiographs - WET accuracy and general image quality





WET accuracy - 9 CIRS inserts

135.6 MeV / 3.1 mm spot size

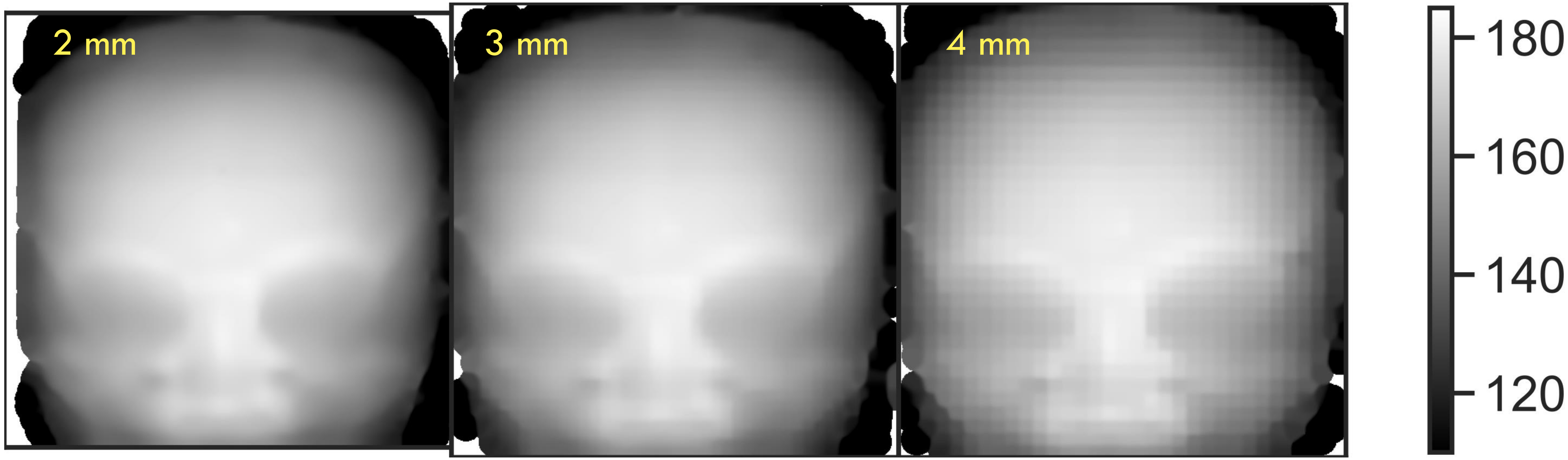


Mean absolute error (MAE) over all plugs

Relative: 1.2%
Absolute: 0.4 mm

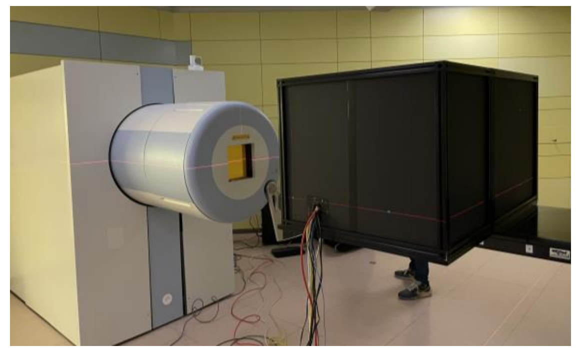
General image quality - paediatric head

189 MeV / 2.5 mm spot size

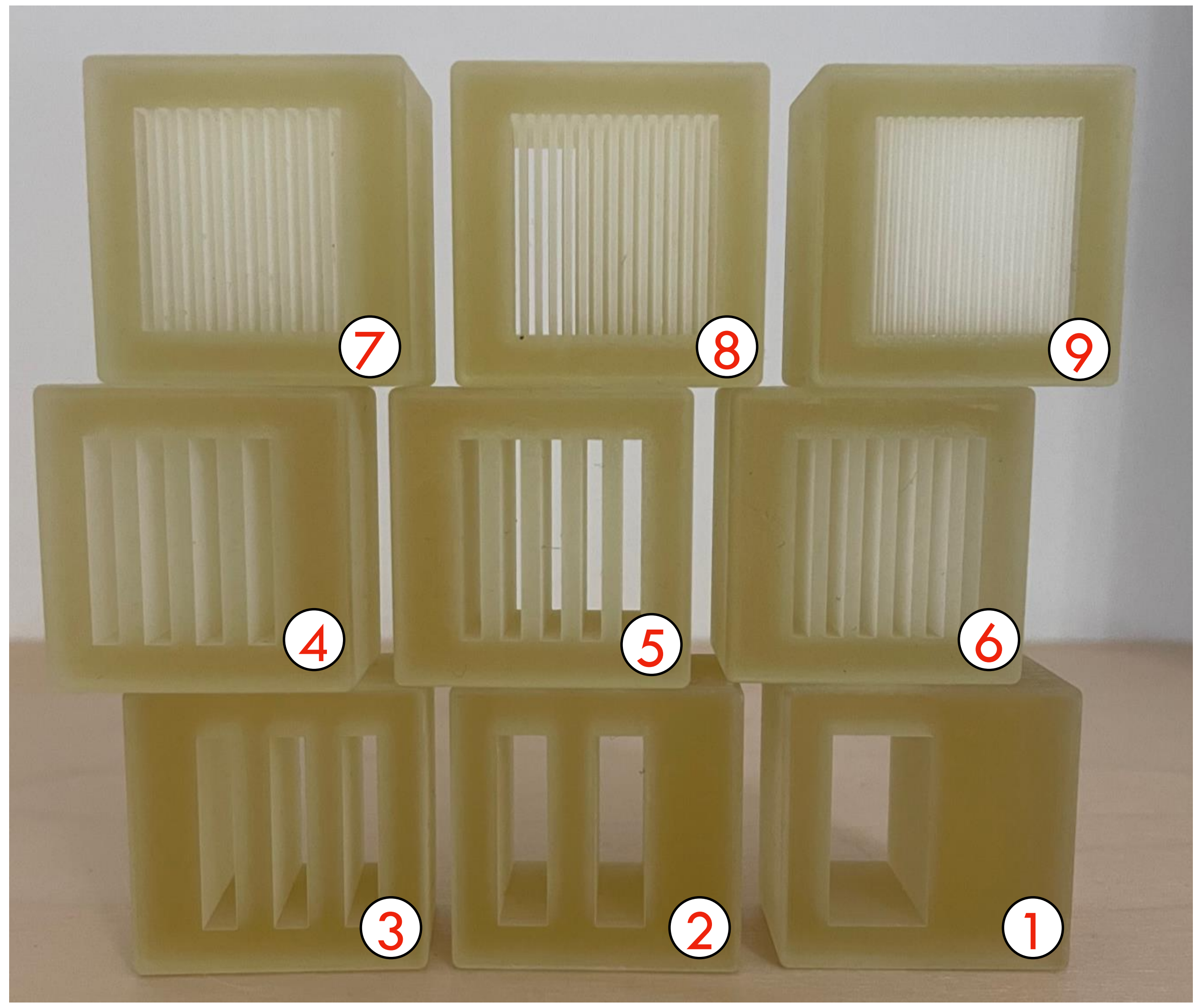


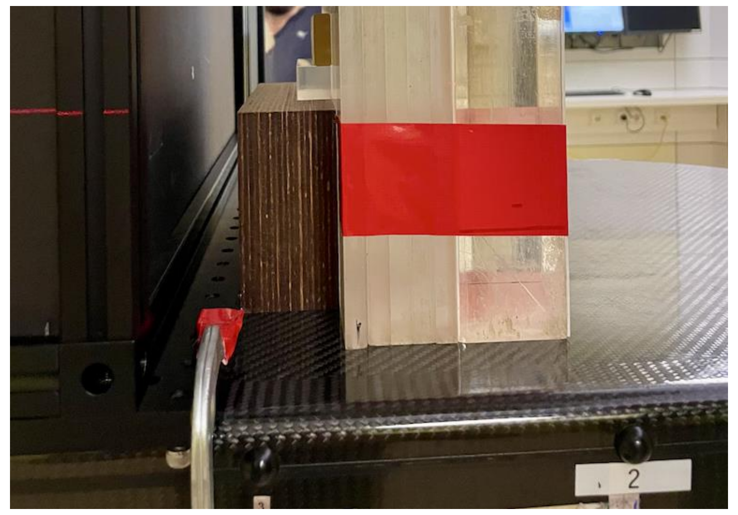
Results (@ Marburg ion therapy centre)

Proton and carbon ion radiographs – spatial resolution



Line pair modules (spatial resolution)
+ 10 cm solid water



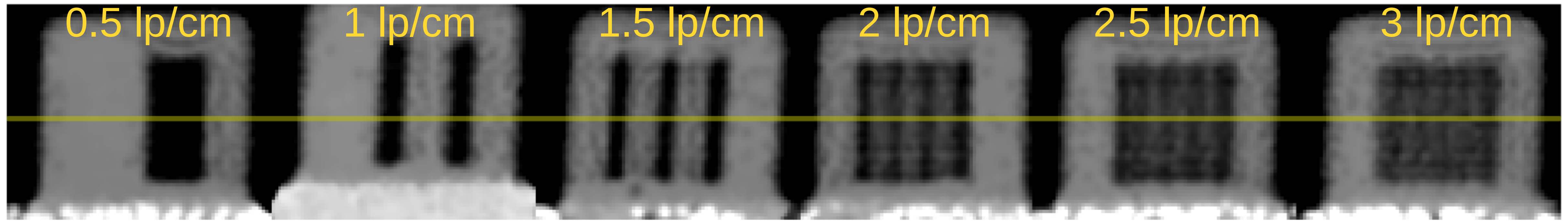


Module	Resolution (lp/cm)
1	0.5
2	1
3	1.5
4	2
5	2.5
6	3
7	5
8	7
9	10

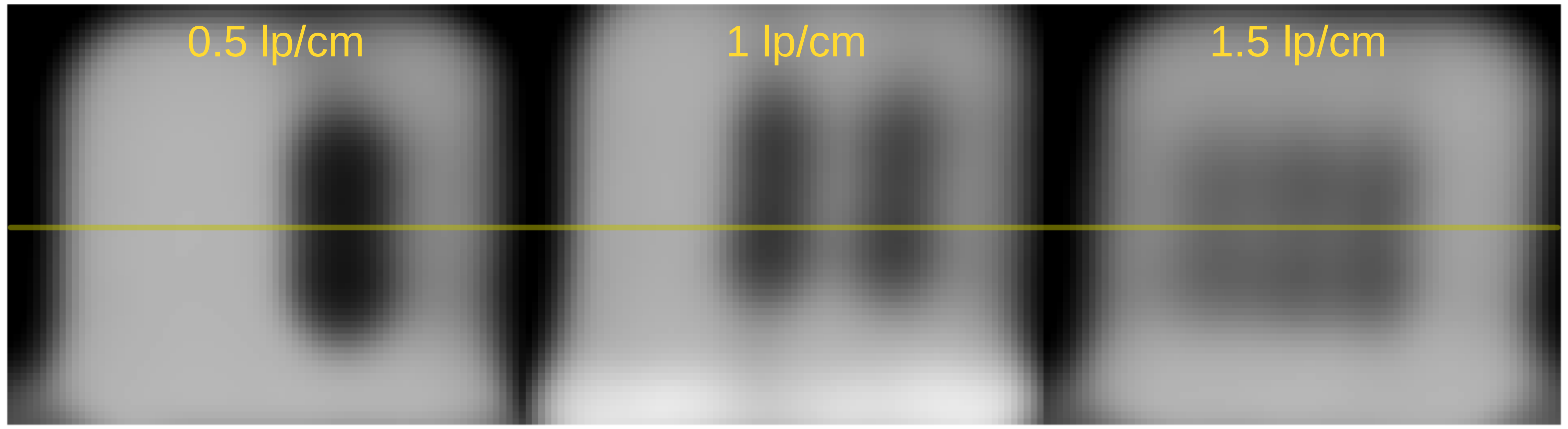
Species	Protons	Carbon ions
Estimated resolution (lp/cm)	1.5 - 2.0	3.0 - 5.0

For reference: He single event: 5 lp/cm (Knobloch et al Med Phys 2022)

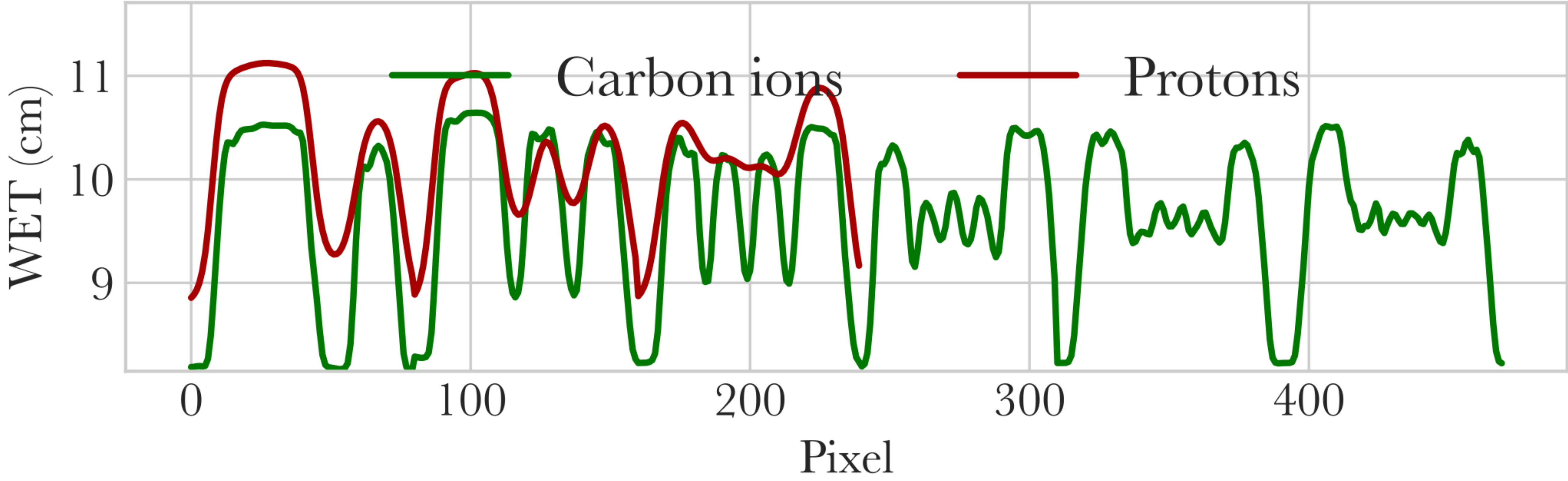
Carbon ions



Protons

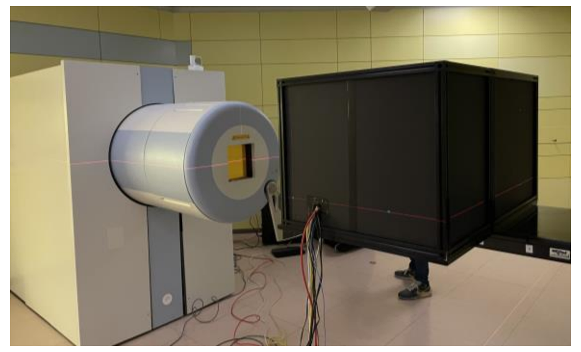


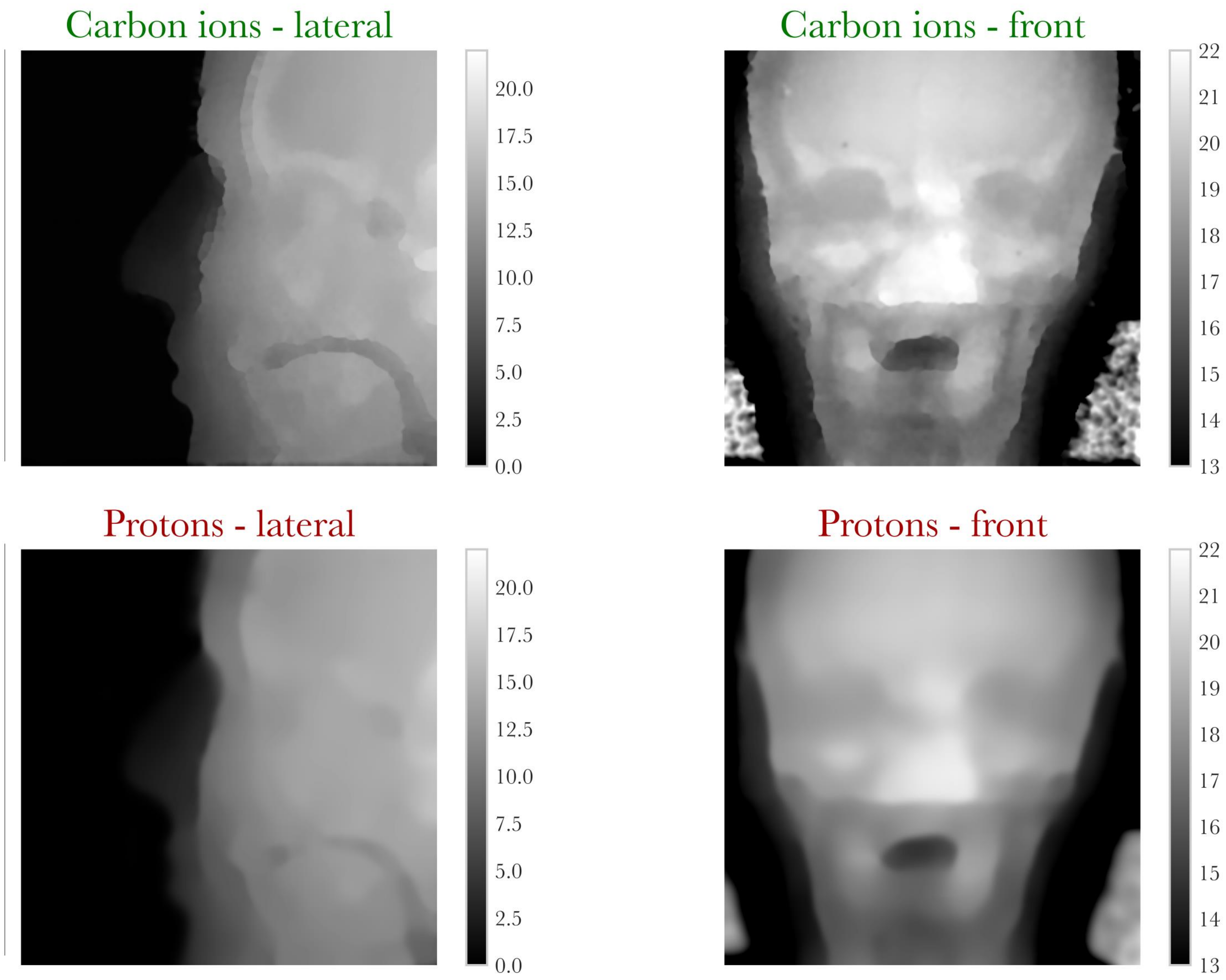
Profile along line

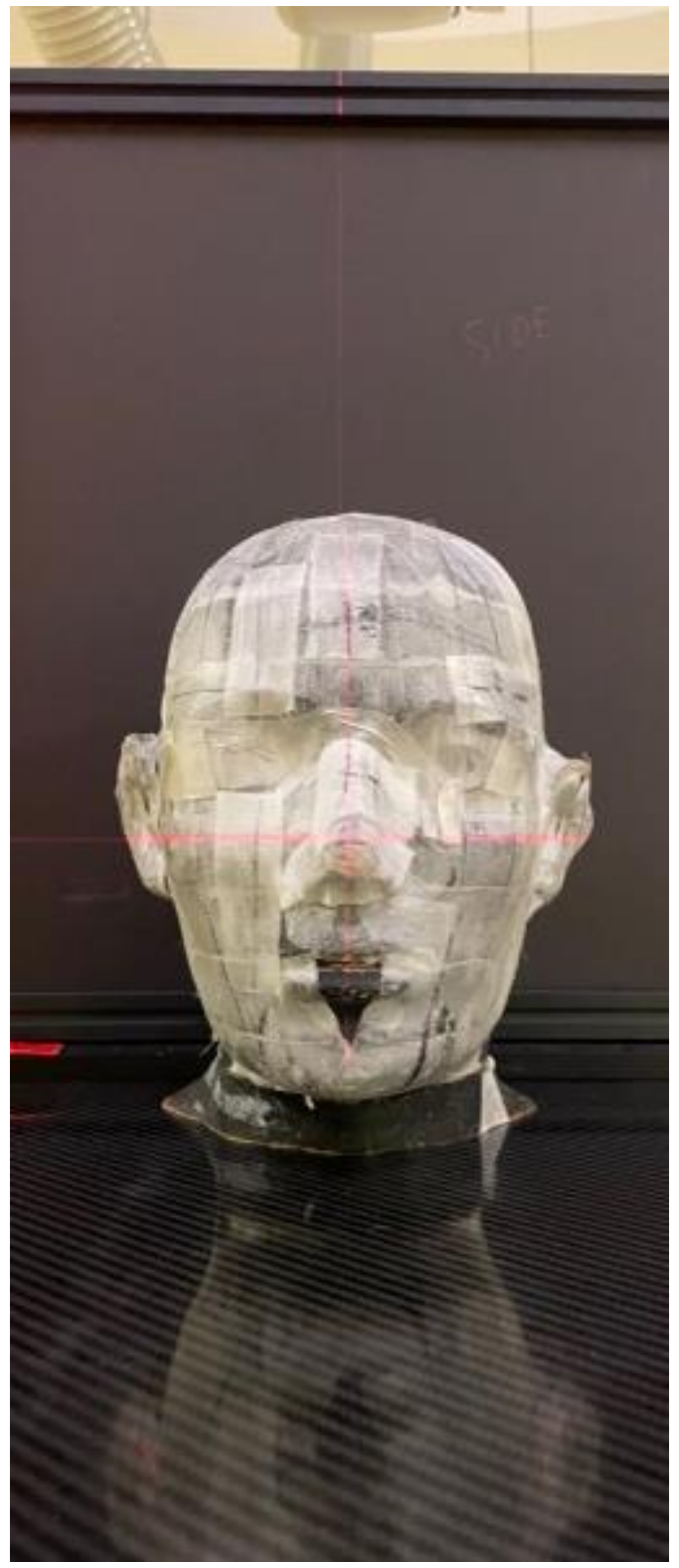


Results (@ Marburg ion therapy centre)

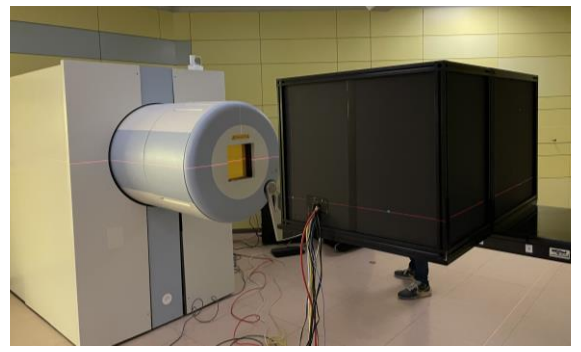
Proton and carbon ion radiographs – Alderson head phantom





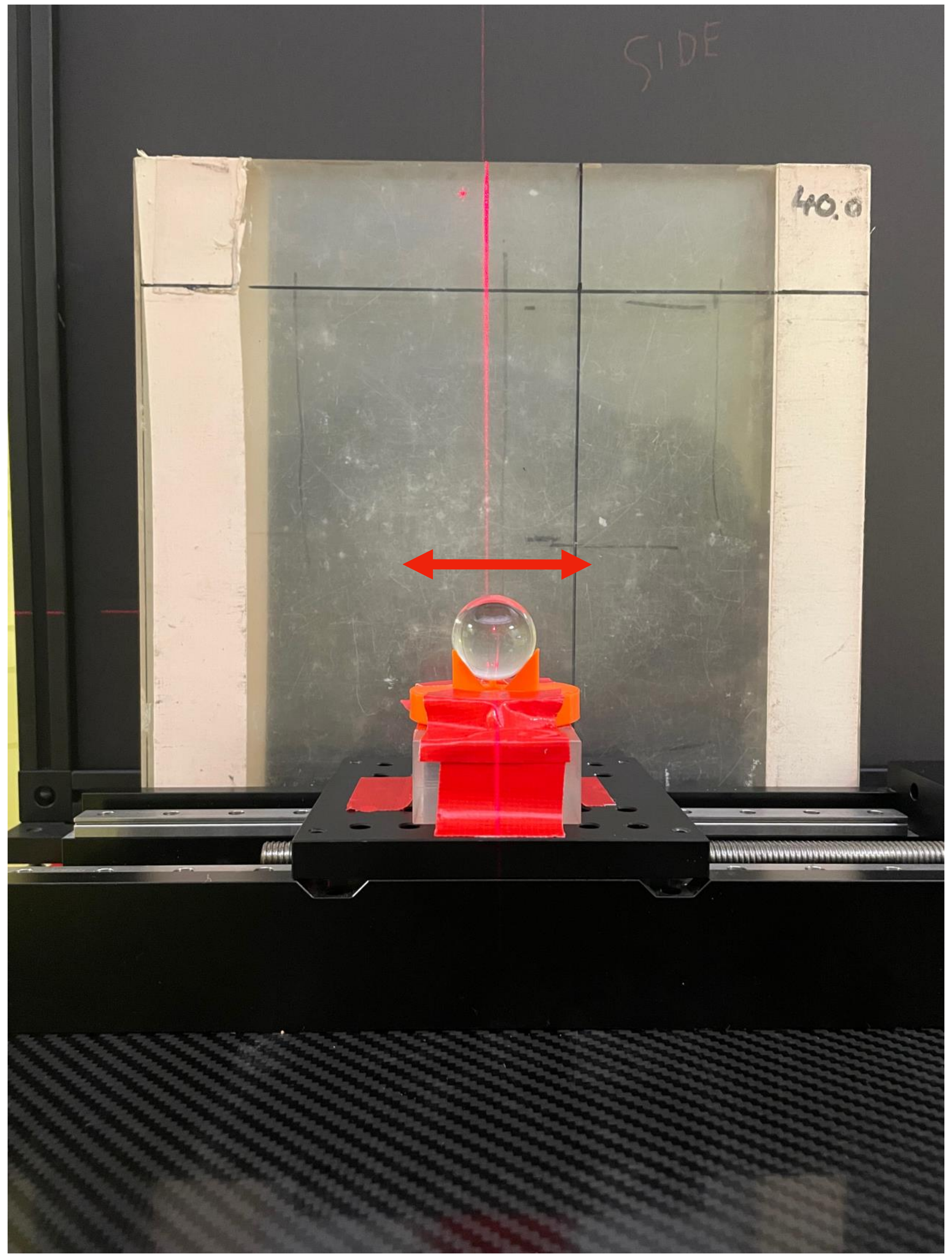


Results (@ Marburg ion therapy centre)
Towards motion management with carbon ion radiographs

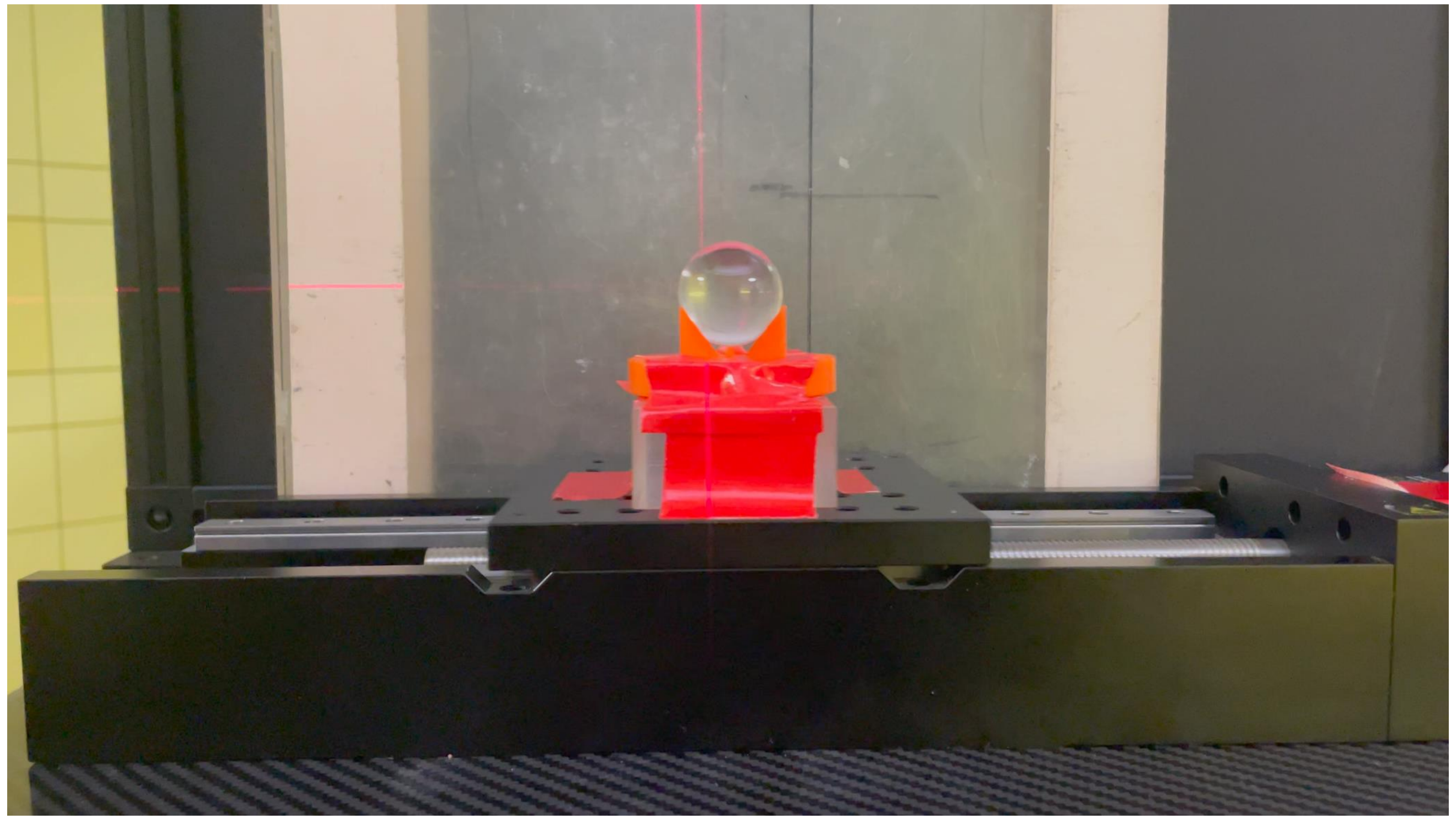


- **Beam parameters:** carbon ions, 6x6 cm^2 field, 345 MeV/u, 2.6 mm spot size, beam spacing of 5 mm
- **Imaging time per frame:** ~900 ms

11 cm solid water + 3 cm ball



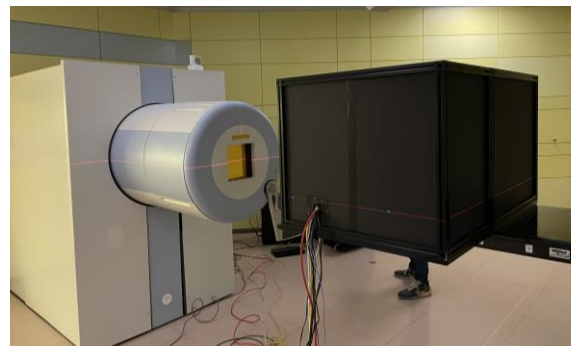
Motion is ± 20 mm in 3s

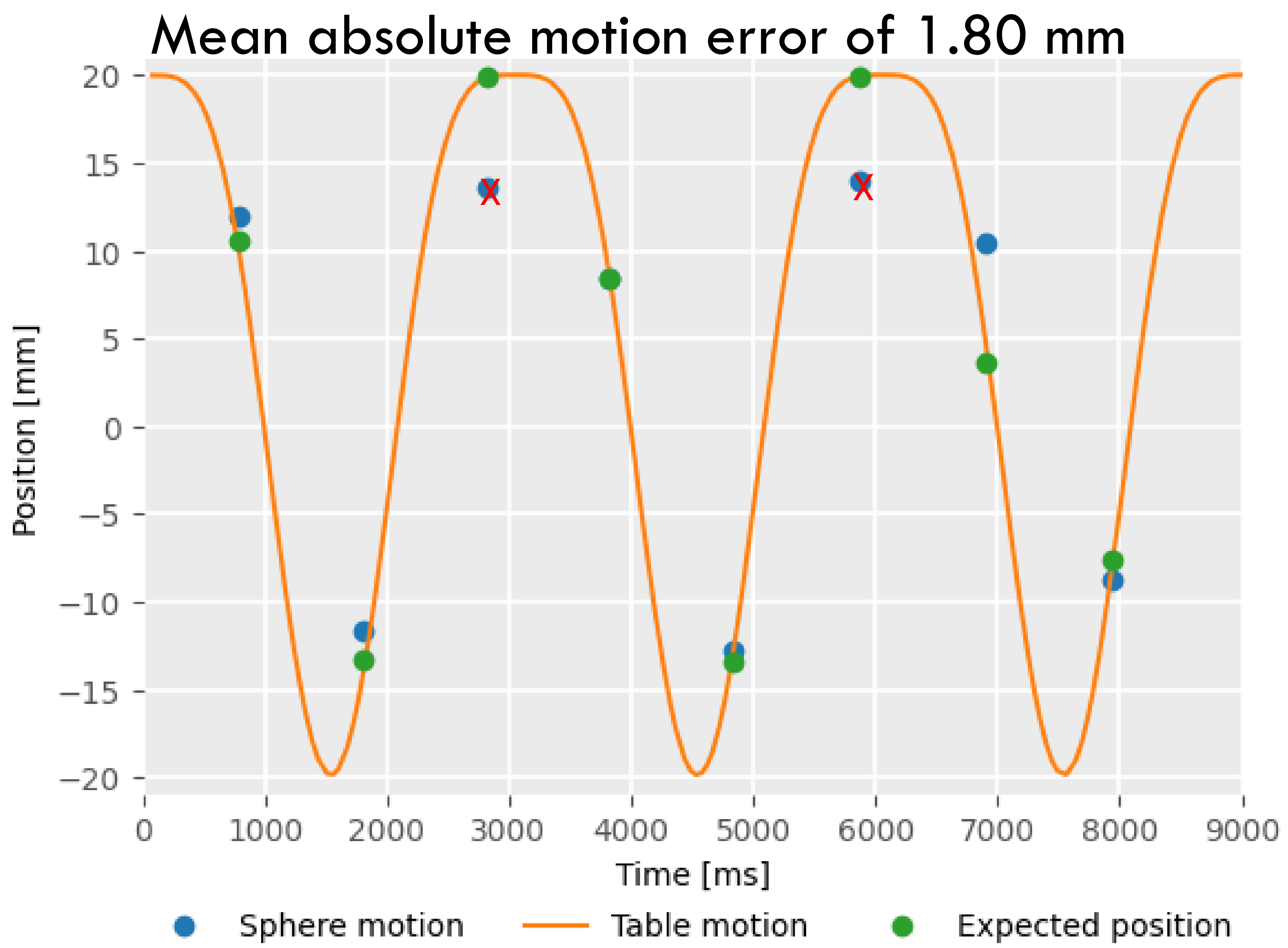


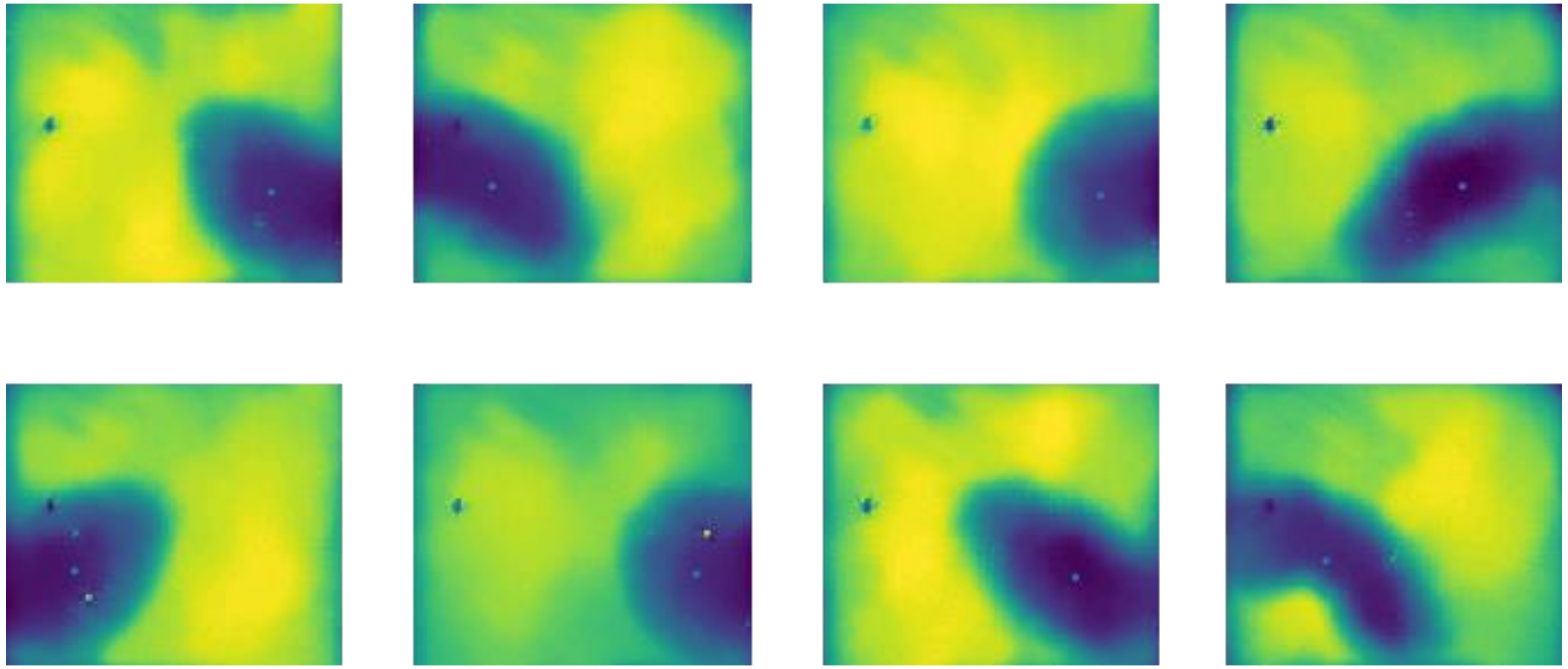
UCL

Results (@ Marburg ion therapy centre)

Towards motion management







Interplay effects (PB scanning as object moves) causing motion artifacts!

<u>Required tracking accuracy for particle therapy < 2 mm</u> (Steinsberger et al 2023 IJROBP)

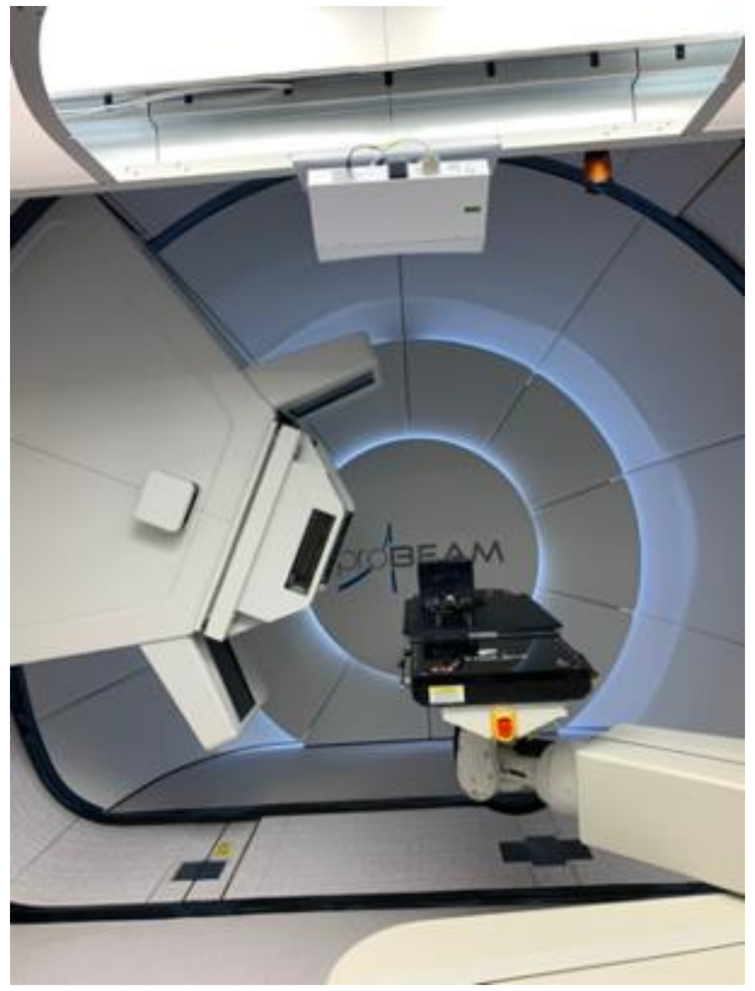
Conclusion

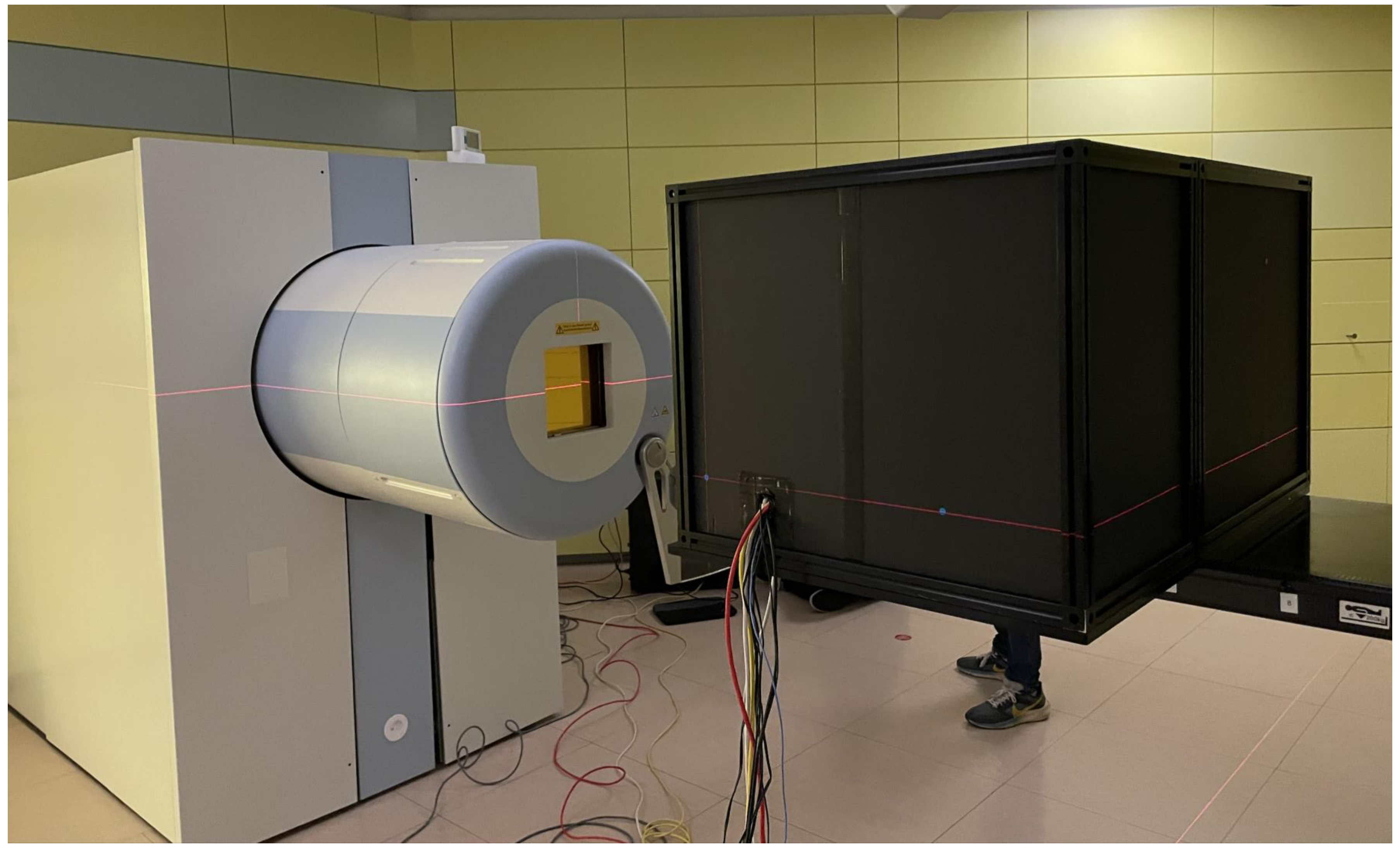
- We have built a low cost (<£10k) and simple device for acquiring integrated mode ion radiographs with clinical beam settings.

- <u>Image quality metrics have been quantified:</u>
  - ➢ High WET accuracy is obtained for pRads.
  - ➢ Enhanced image quality is found for integrated cRads against pRads.
  - ➢ cRad resolution reaches 3-5 lp/cm resolution.

- <u>Motion tracking has been evaluated using a simple spherical object:</u>
  - ➢ A tracking accuracy of ~2 mm is obtained with carbon ion beams.
  - ➢ Images @ MIT can be obtained in 900 ms.

- <u>Future work</u> includes pursuing rapid fluoroscopic imaging for usage in adaptive workflows, and potential use for PBT QA.





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