The 5th ion imaging workshop

Experimental Proton and Helium Scanning Beam Radiography with Clinical Scanner Prototype

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Agenda

1. **Helios project**
2. Imaging detector features
3. Beam delivery features
4. First results of the integration
5. Conclusion

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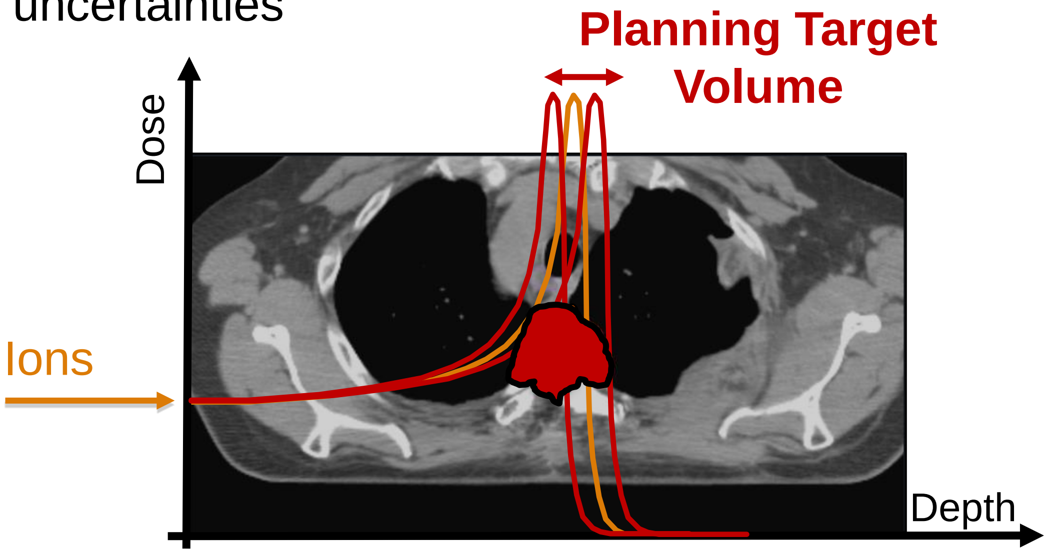
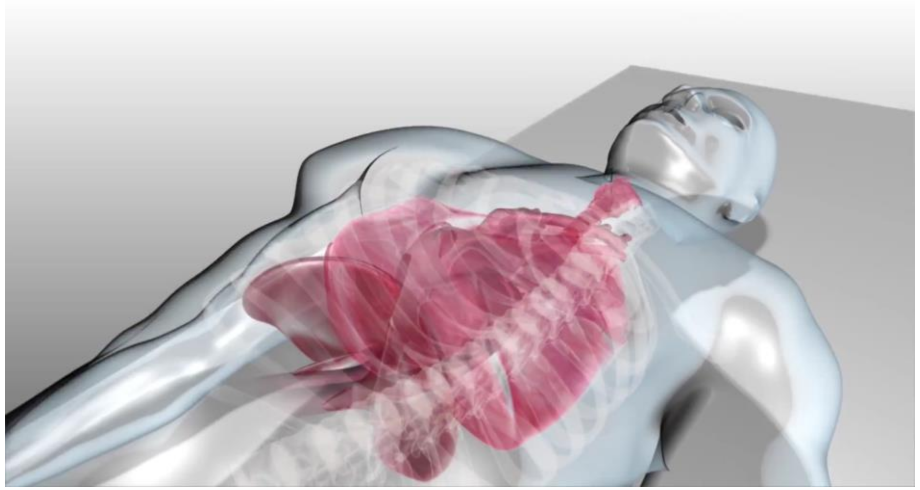
Motivation and research question

Current problems in proton therapy	**Range uncertainties in ion delivery reduce treatment efficiency and increase toxicity [1]**	**Use of X-ray CT to avoid geometric uncertainties in adaptive radiotherapy leads to unnecessary dose**
Problem background	Ions are sensitive to geometric and dosimetric uncertainties 	Frequent X-ray CTs increase the risk of secondary blood cancers [2] 
Clinical requirements	Need to **reduce % range uncertainties** in proton therapy	Need to **reduce the dose** to healthy organs of radiotherapy
Research question	**Is it possible to use low-dose ion imaging for real time monitoring of anatomical changes?**	

[1] Liao Z et al. Clin Oncol. 2018; 36(18):1813-1822.
[2] Bosch de Basea Gomez M et al. Nat. Med. 2023; 29:3111–3119.

Range guided adaptive particle therapy (RGAPT)

pRad/HeRad

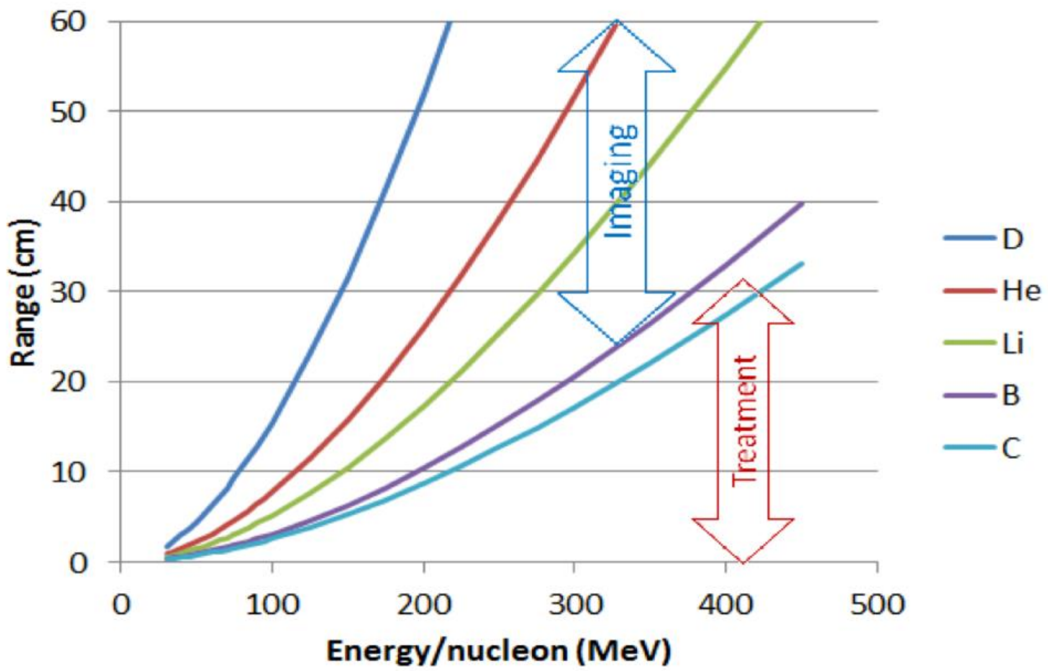
Particles from a single angle

Relative to RSP map

- Check integrated range
- Check alignment

~ Online Validation

- WET check
- Transverse ROI position (small FOV)



The idea is to use two particles with close to a constant mass/charge ratio for simultaneous imaging and treatment :

- $^{2}D^{+}$ and $^{4}He^{2+}$
- **$^{4}He^{2+}$ and $^{12}C^{6+}$**

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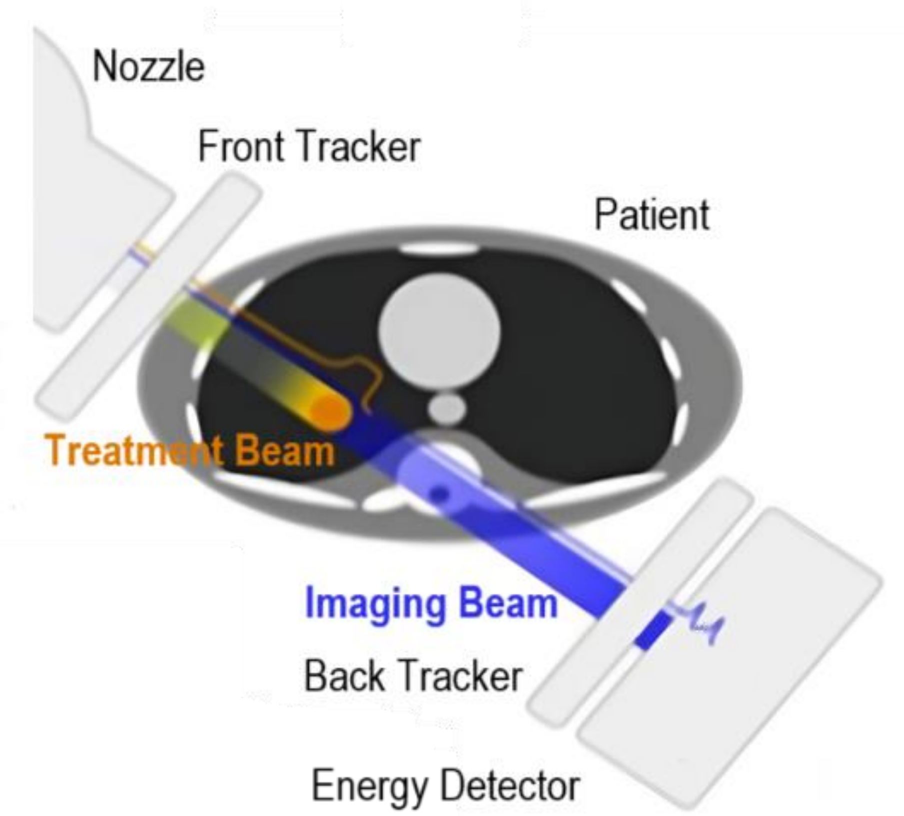
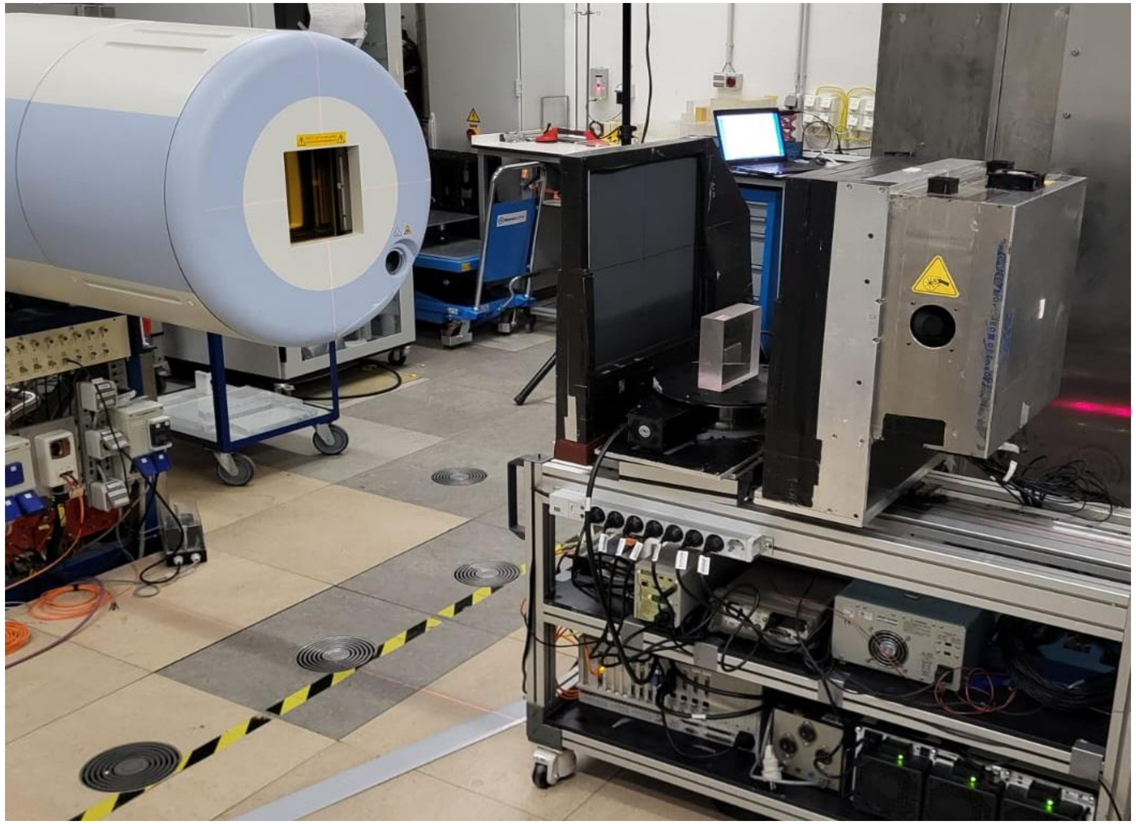
Principle of the experimental setup



Imaging system is requiring:

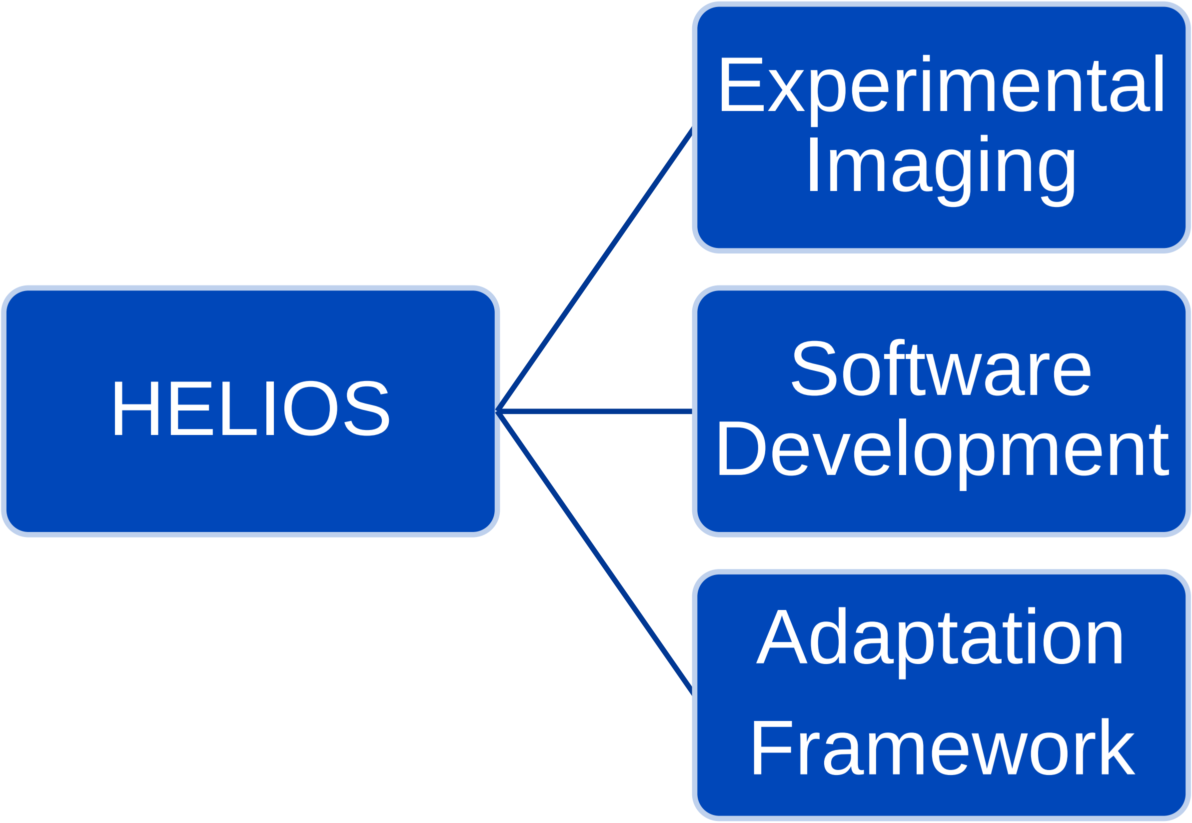
- Beam position detectors;
- Calorimeter for measuring of residual energy;
- Reconstruction algorithms.



HELIOS is based on the well-established technologies **HIT** multi-ion beam delivery (not in the same time) and **ProtonVDA** imaging detector (developed for specific proton beams).

HELIOS Project Structure

Developing a HELium Imaging Oncology Scanner for Range Guided Radiotherapy (RGRT) for Non-Small Cell Lung Cancer (NSCLC)



Development and customization of HELIOS prototype for ion imaging

Talk by Lukas Martin

Development of forward simulation and treatment planning framework

Talk by Jennifer Hardt

Testing treatment planning and reconstruction framework for adaptation purpose

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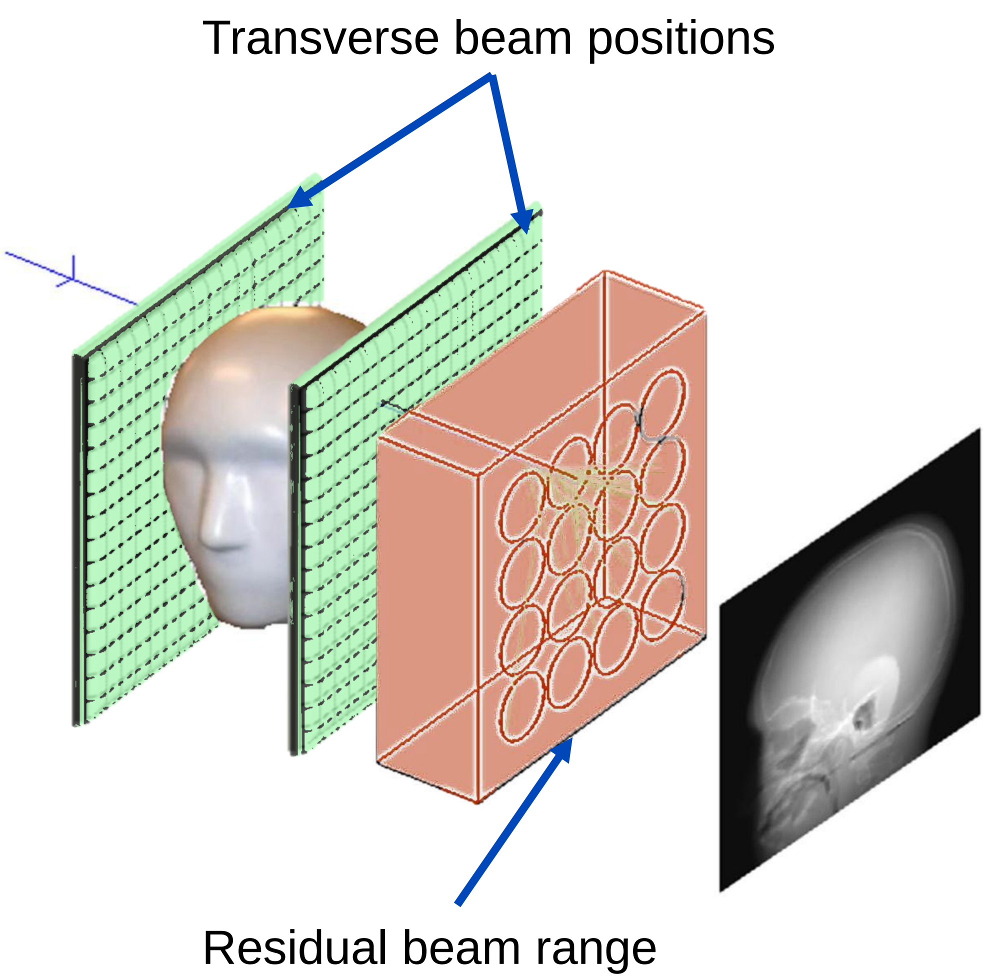
Imaging detector: principle of operation



Proton imaging detector system is optimized for:

- 40 cm × 40 cm field of view;
- 3 MHz readout rate;
- narrow scanning beam.

Detector consists of:

- Two (upstream / downstream) beam position trackers with two layers for horizontal and vertical readings, every layer - 384 scintillating fibers of 1 mm width;
- Residual range detector with monolithic scintillator and 16 PMTs;
- DAQ system with 4 ADC channels and 128 digital I/O channels.

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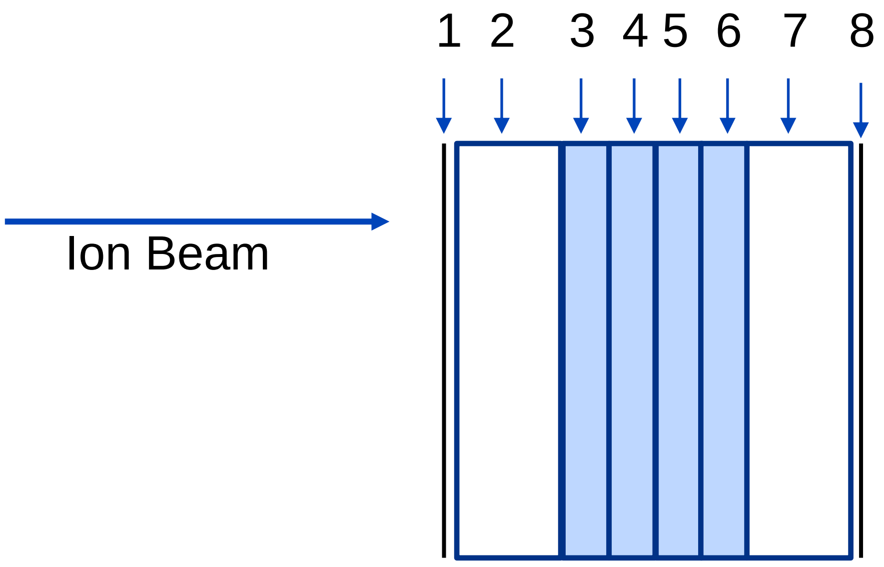
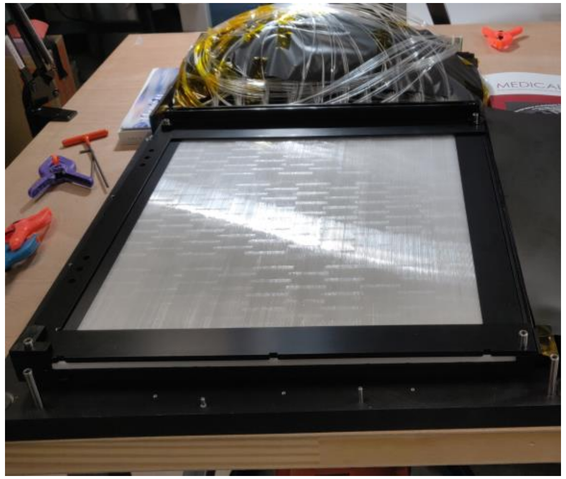
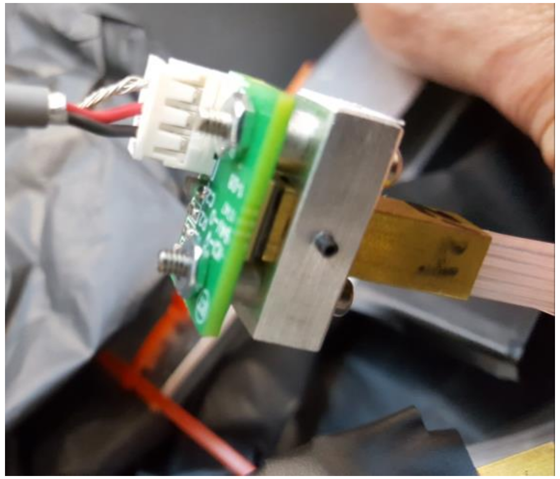
Imaging detector: beam position trackers



N, name	Thickness (cm)	Density(g/cm3)
1, Black Kapton film	0.0075	1.42
2, Rohacell HF 031	0.6	0.032
3, Scint. fibers Y1	0.1	1.05
4, Scint. fibers Y2	0.1	1.05
5, Scint. fibers X1	0.1	1.05
6, Scint. fibers X2	0.1	1.05
7, Rohacell 31	0.6	0.032
8, Black Kapton film	0.0075	1.42



12 fibers per 1 SiPM
Readings only every 32 mm



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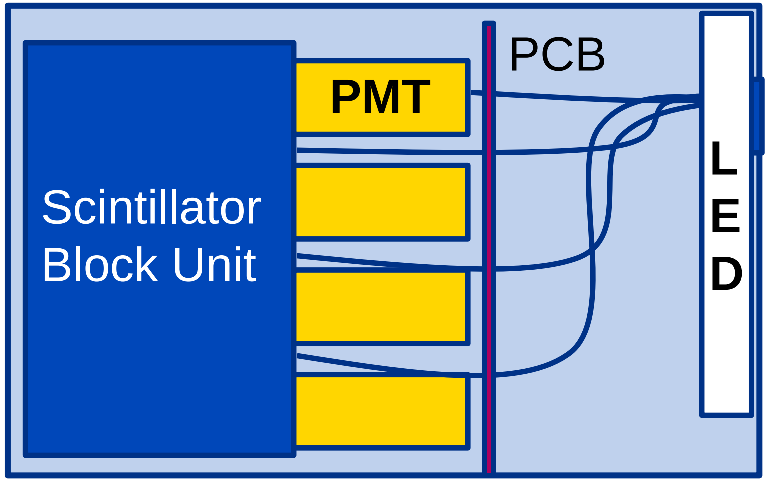
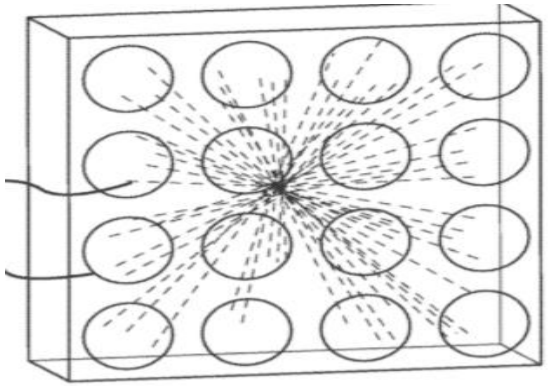
Imaging detector: range detector





Range detector:

- PCB base to provide high voltage
- PMT to detect light
- Scintillator Block Unit, produces light when proton crosses the scintillating material
- 4 ADC channels:
  - E, the sum of the sixteen PMT signals
  - U, Diagonal sum with different weights
  - V, Diagonal sum with different weights
  - C, the sum of the central PMTs.

E

+1	+1	+1	+1
+1	+1	+1	+1
+1	+1	+1	+1
+1	+1	+1	+1

U

	+1	+2	+3
-1		+1	+2
-2	-1		+1
-3	-2	-1	

V

-3	-2	-1	
-2	-1		+1
-1		+1	+2
	+1	+2	+3

C

+1			+1
	-1	-1	
	-1	-1	
+1			+1

Imaging detector: operation process

- Event = Trigger (Energy detector) && Upstream Tracker (4 hits) && Downstream Tracker (4 hits);

- Calibration of the energy detector to obtain covariance matrix for each spot (X, Y, Residual Range):

$$K_{EUV} = \begin{bmatrix} cov(EE) & cov(EU) & cov(VE) \\ cov(UE) & cov(UU) & cov(UV) \\ cov(VE) & cov(VU) & cov(VV) \end{bmatrix}$$

$$\chi^2 = \Delta^T {K_{euv}}^{-1} \begin{bmatrix} E - \bar{E} \\ U - \bar{U} \\ V - \bar{V} \end{bmatrix}$$

- Low energy cut to filter our fragments;

- χ^2 filter in the data preprocessing stages;

- 3 sigma filter during image reconstruction.

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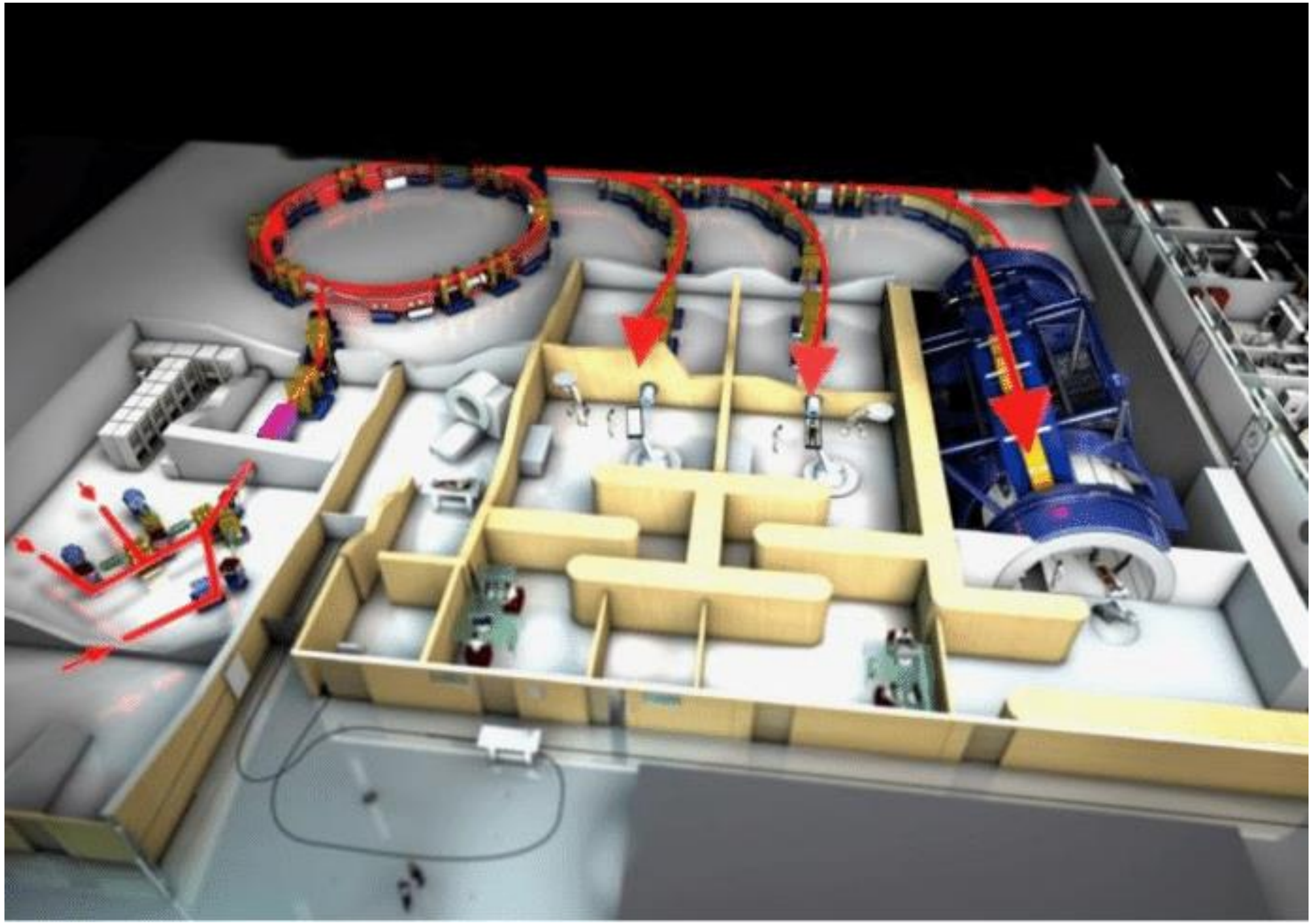
Heidelberg Ion Therapy Center (HIT) – beam source



- Synchrotron based facility
- 2 Treatment + 1 **Experimental room** with fixed beam, 1 Gantry

- Multi ions: **p, He**, C, O
- Beam energy: 50 - 430 Mev/u

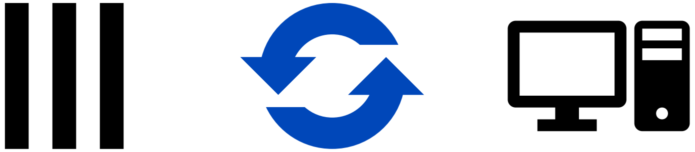
- Pulsed mode
- Continuous scanning

- Beam intensity for protons: $1.2 \times 10^8 - 2 \times 10^{10}$
- Beam intensity for helium ions: $2 \times 10^7 - 5 \times 10^9$
- Beam intensity for carbon ions: $2 \times 10^6 - 5 \times 10^8$

Standard slow multi-turn extraction @ HIT

Ion chambers &
Wire chambers

Intensity
modulation

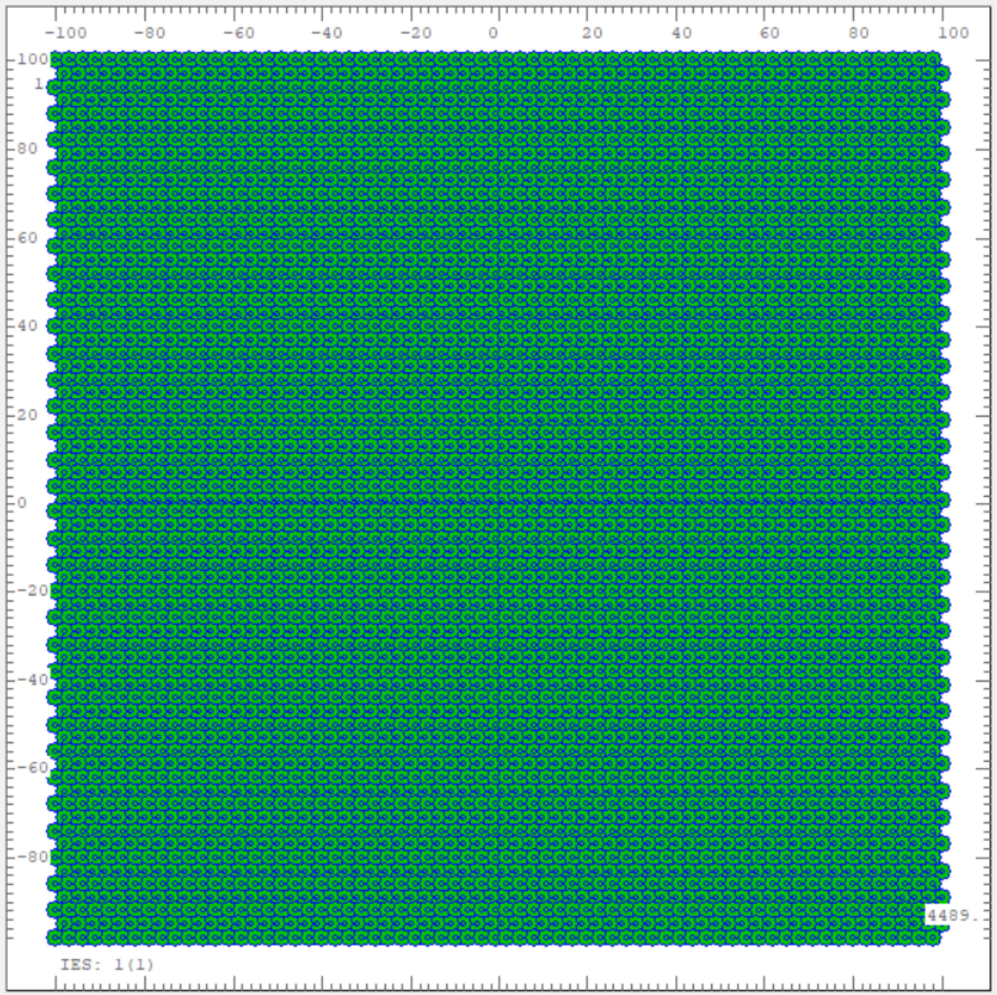


Real time feedback system

Beam is stable and repeatable

Key HIT beam parameters:

- Proton and helium beam @ 50 – 220 MeV/u;
- 20 cm × 20 cm active scanning field;
- σx , σy from 4.9 to 20 mm.



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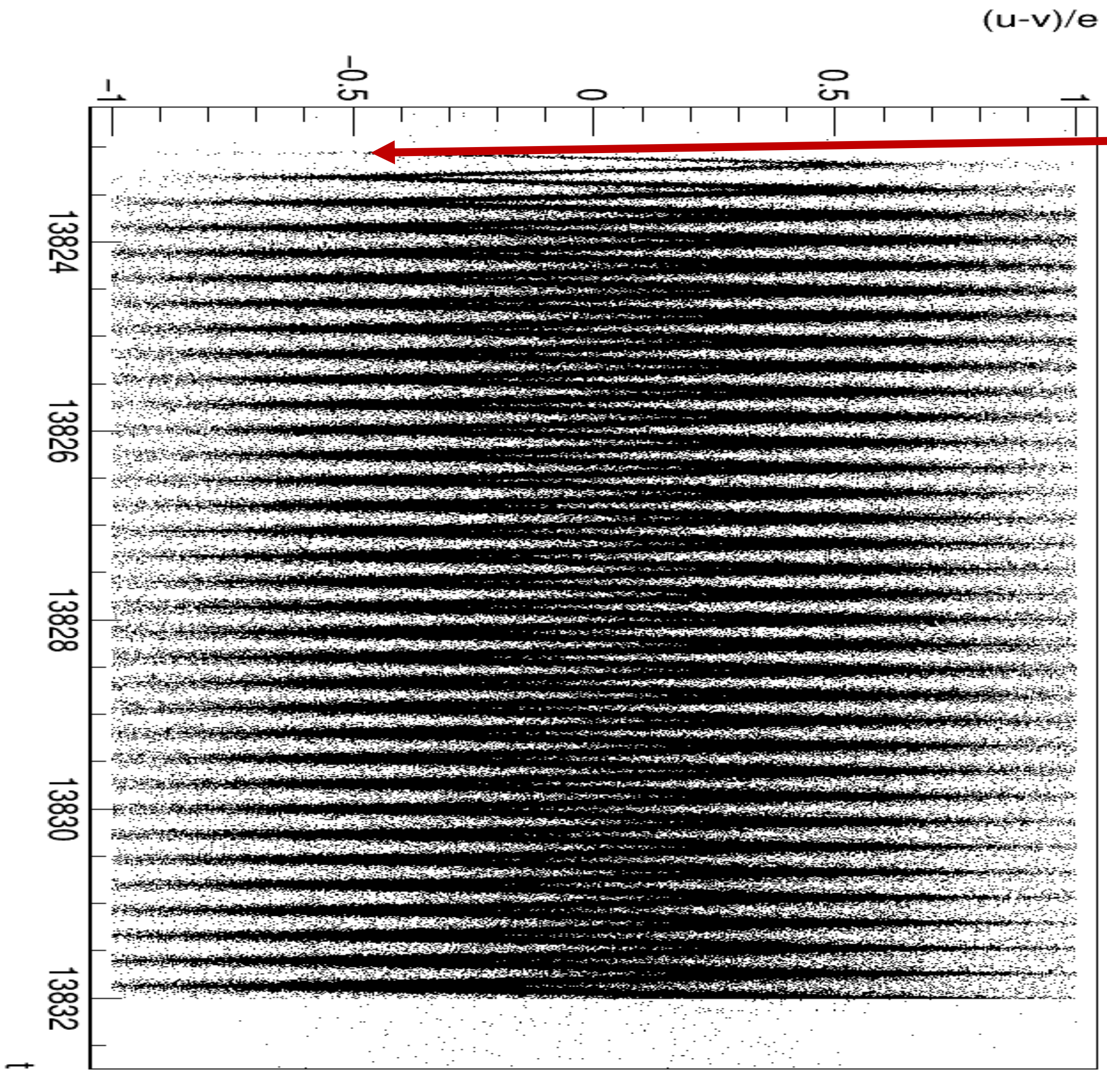
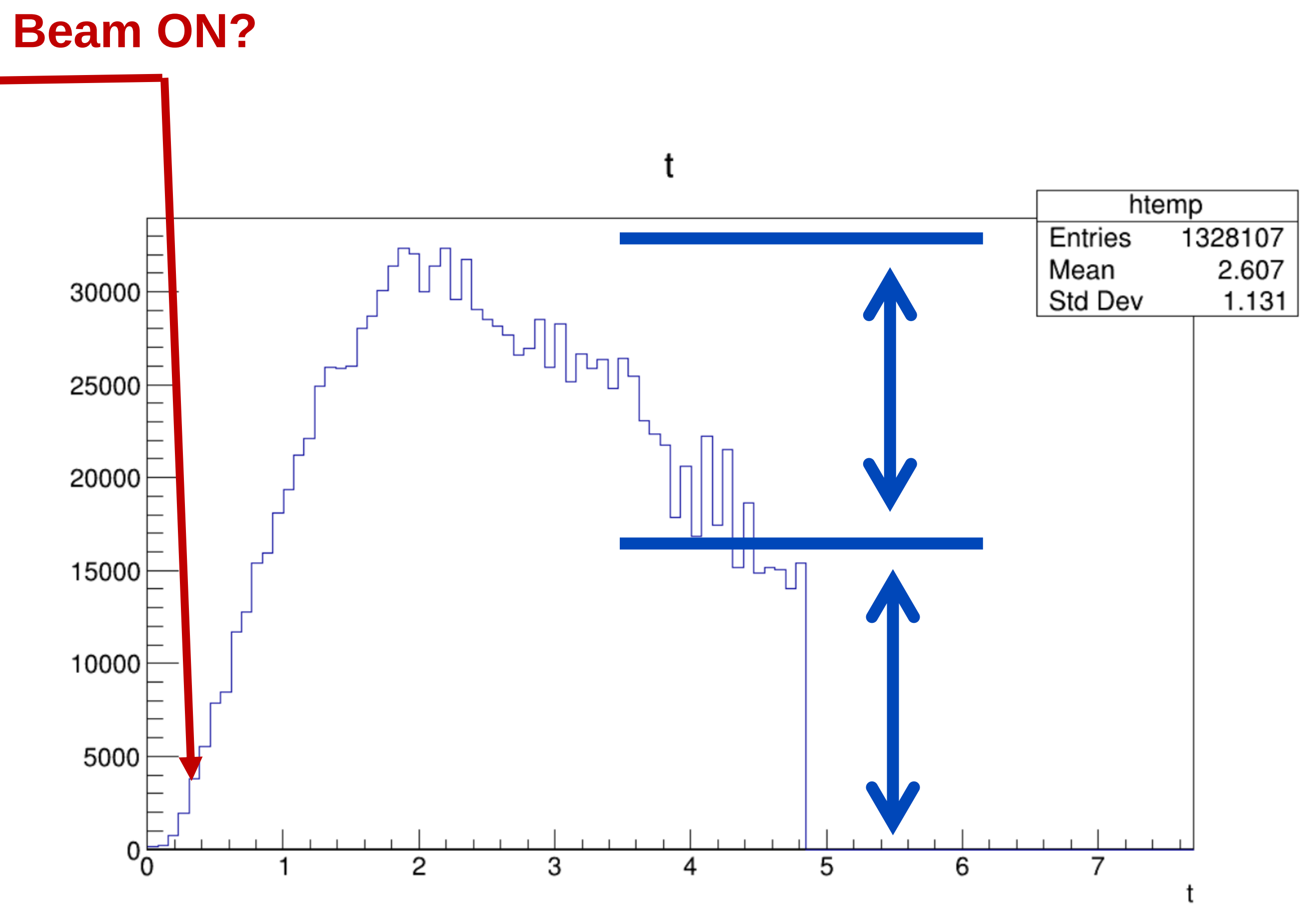
Manual low intensity extraction @ HIT



Scanning pattern in the manual mode



Beam is unstable and not repeatable

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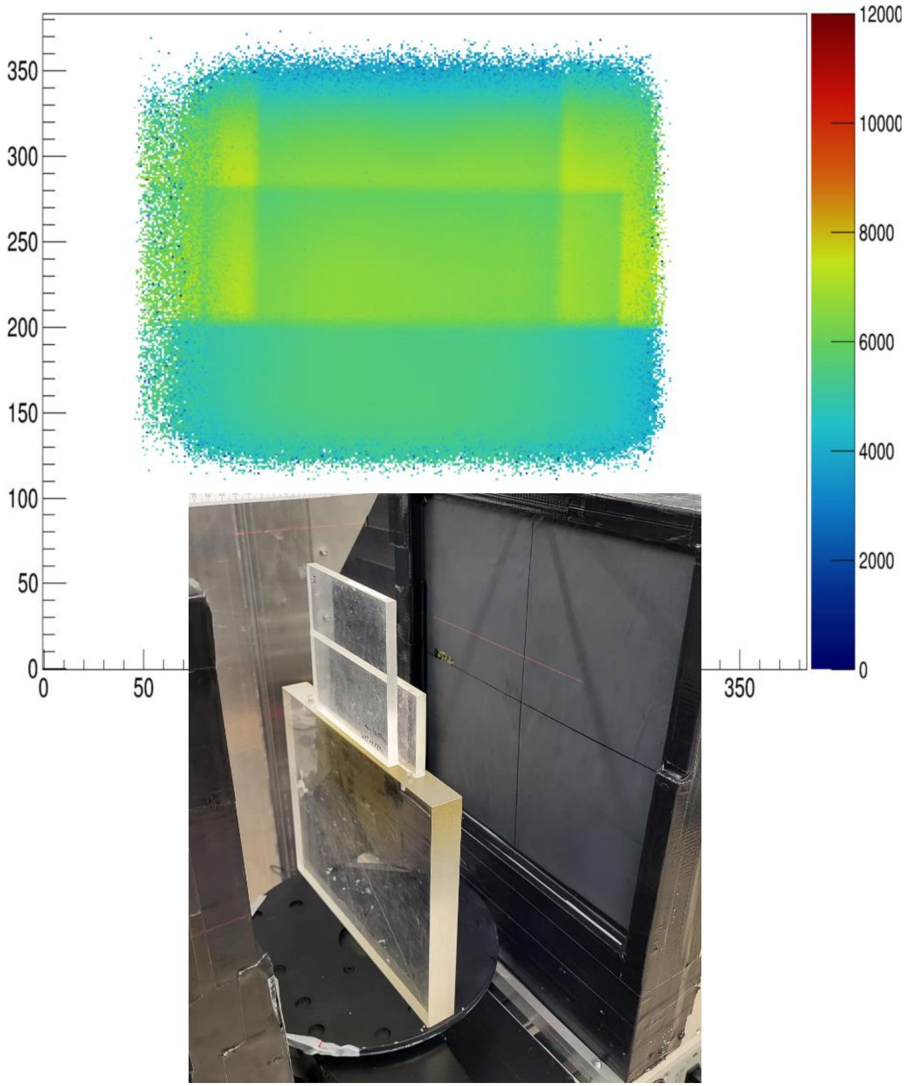
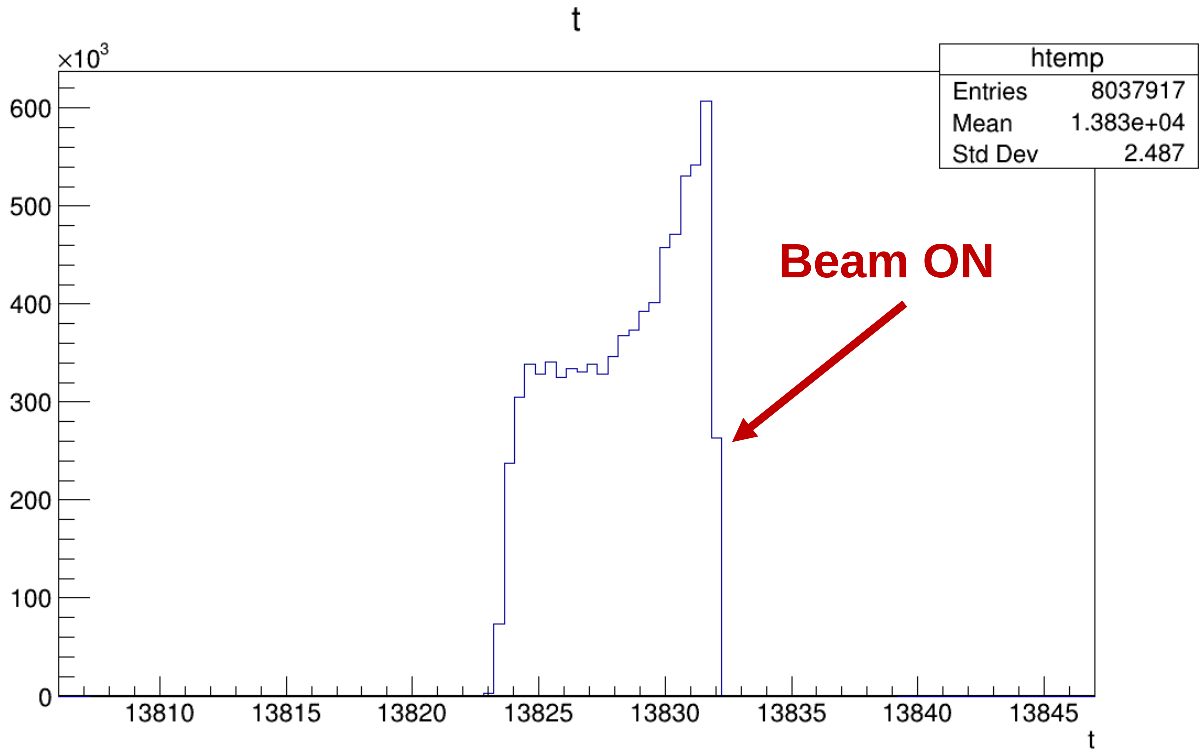
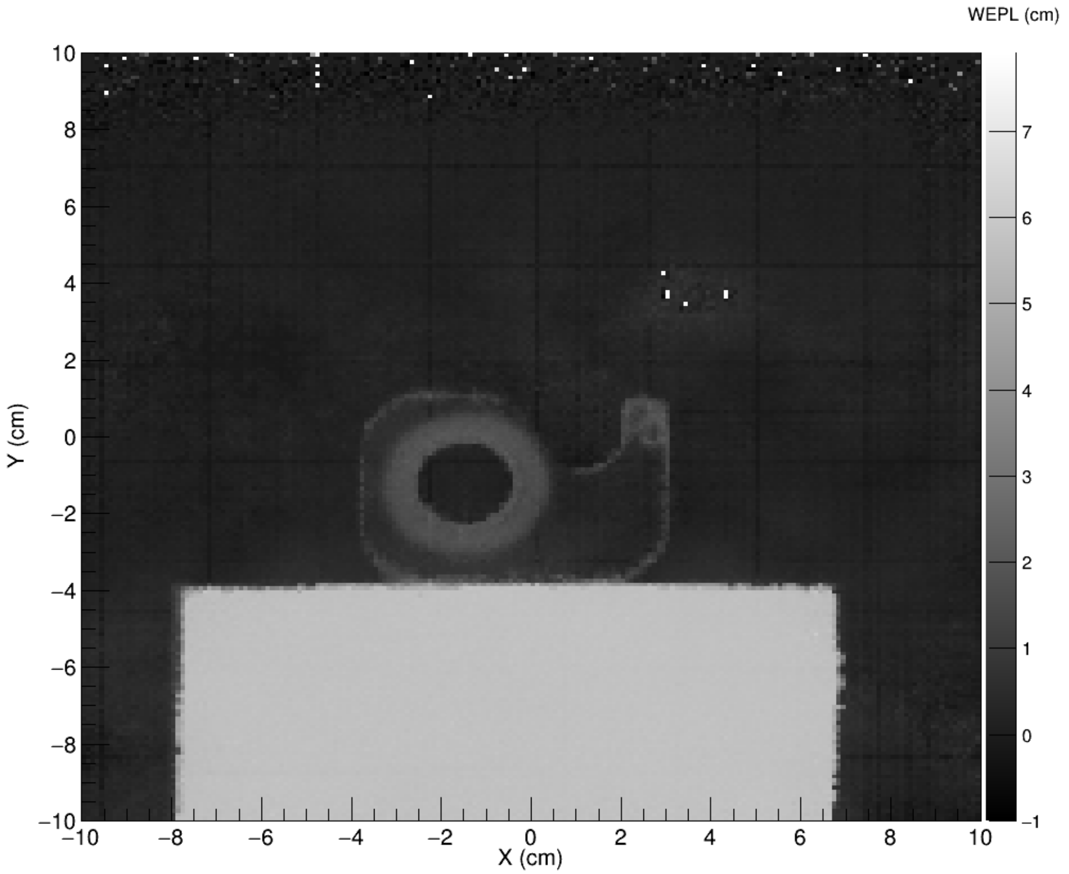
Beam position synchronization



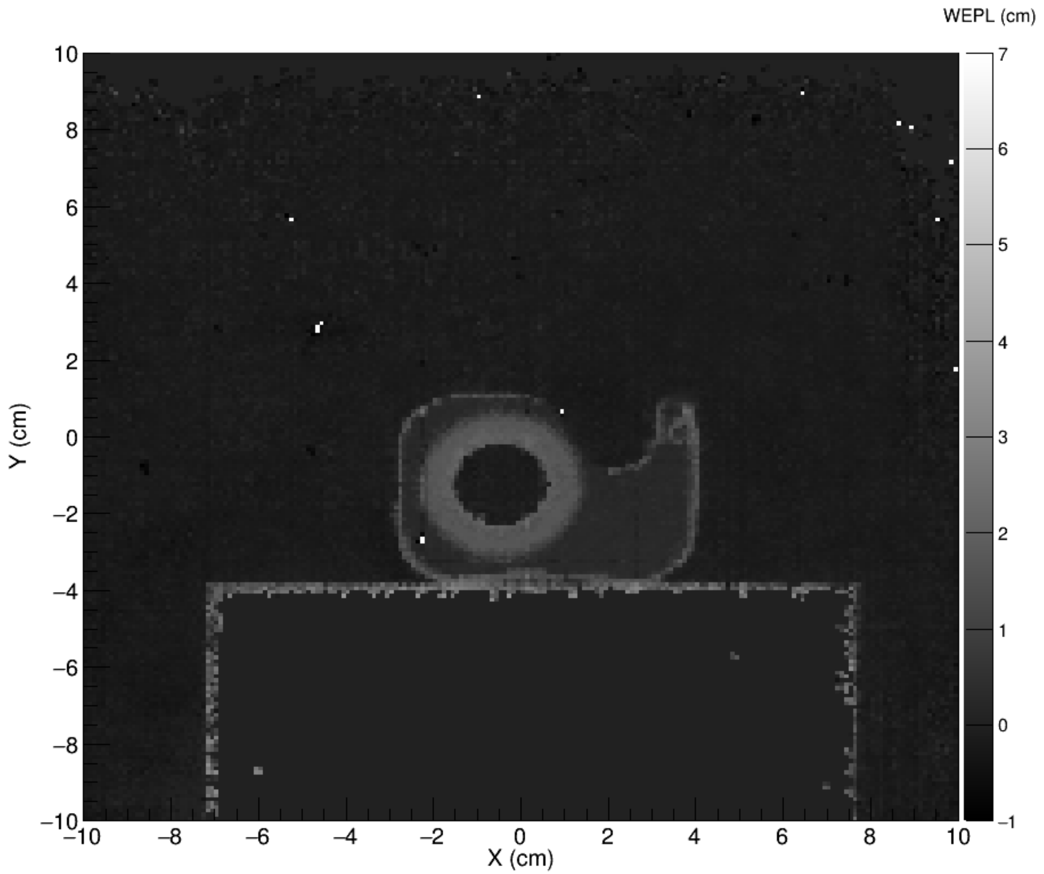


- Initial idea was to reverse the time during the data processing
- It worked, but made the data processing more complicated
- Reverse synchronization only and binary search

Experimental data: first proton and helium images



Proton radiograph, 120 MeV, around 3000 protons per spot



Helium radiograph, 80 MeV/u, around 1000 helium ions per spot

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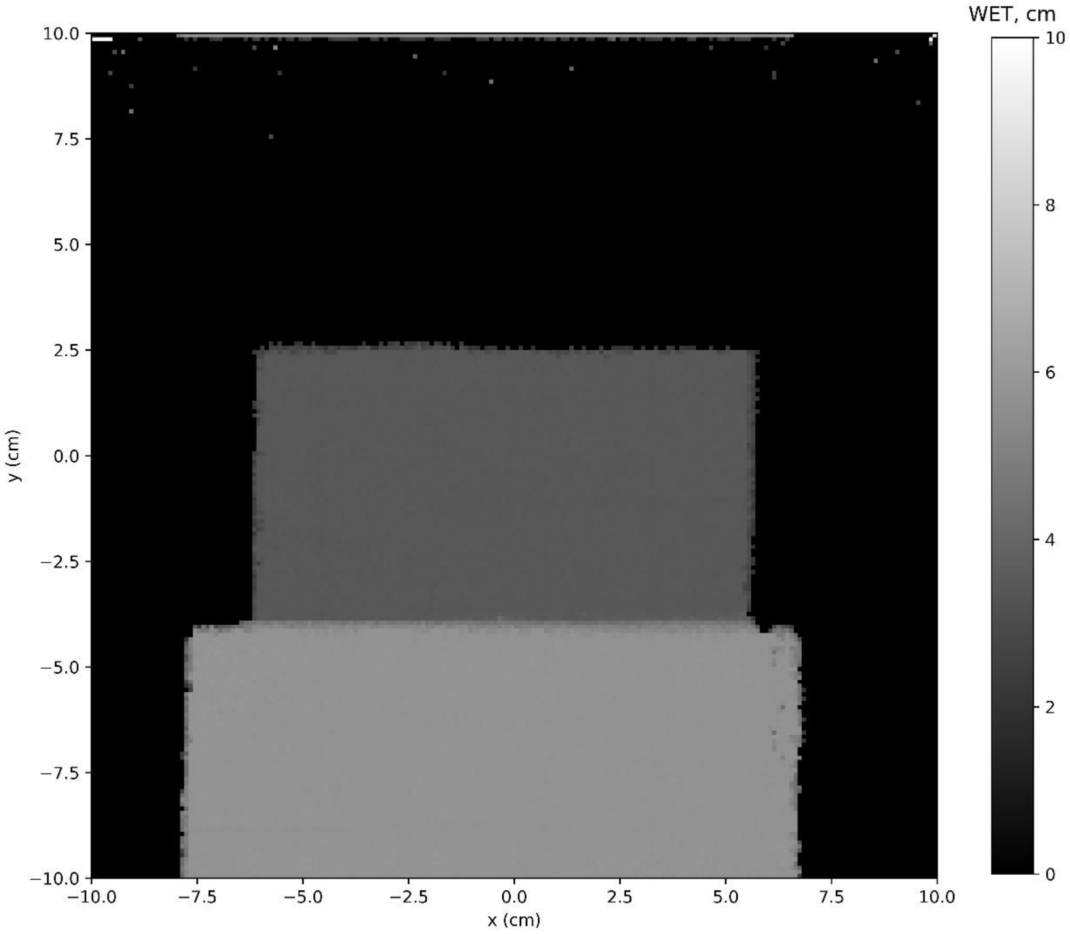
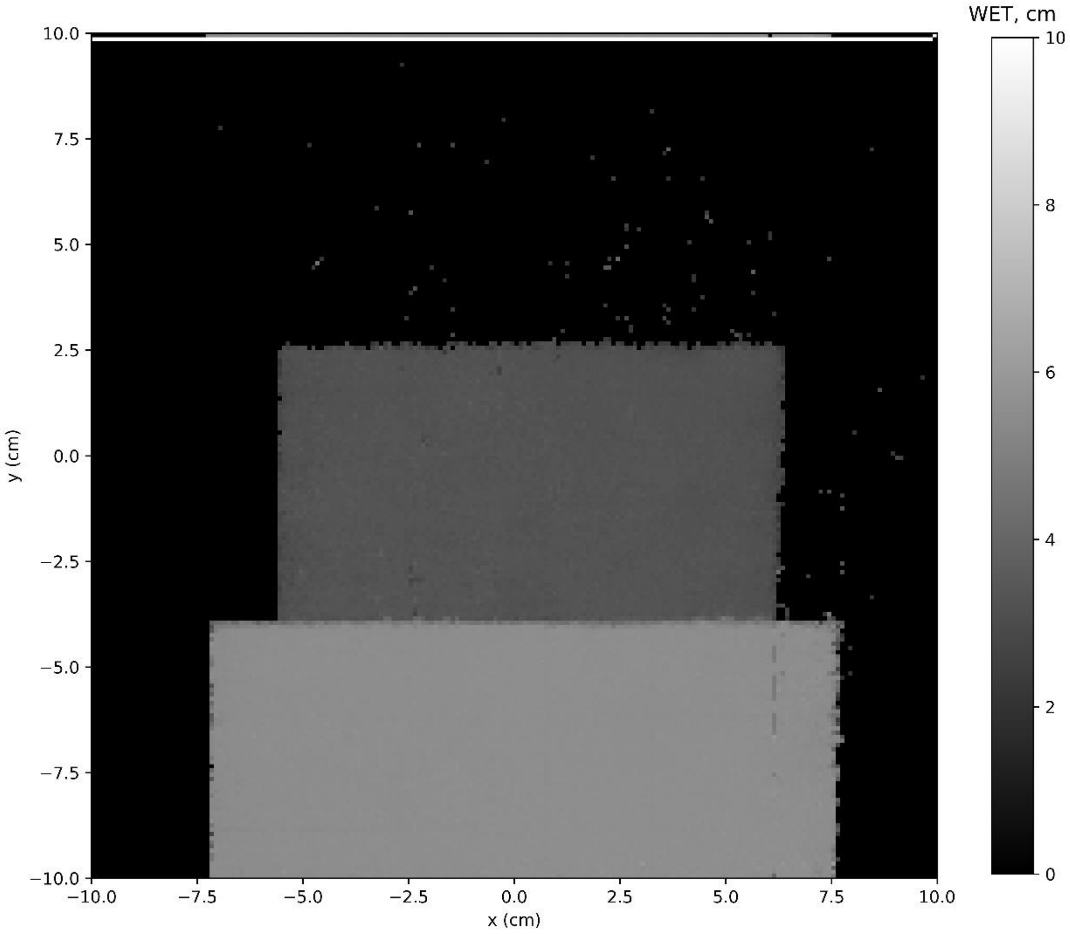
Experimental data: alignment and WET check



Proton radiograph, 101.90 MeV

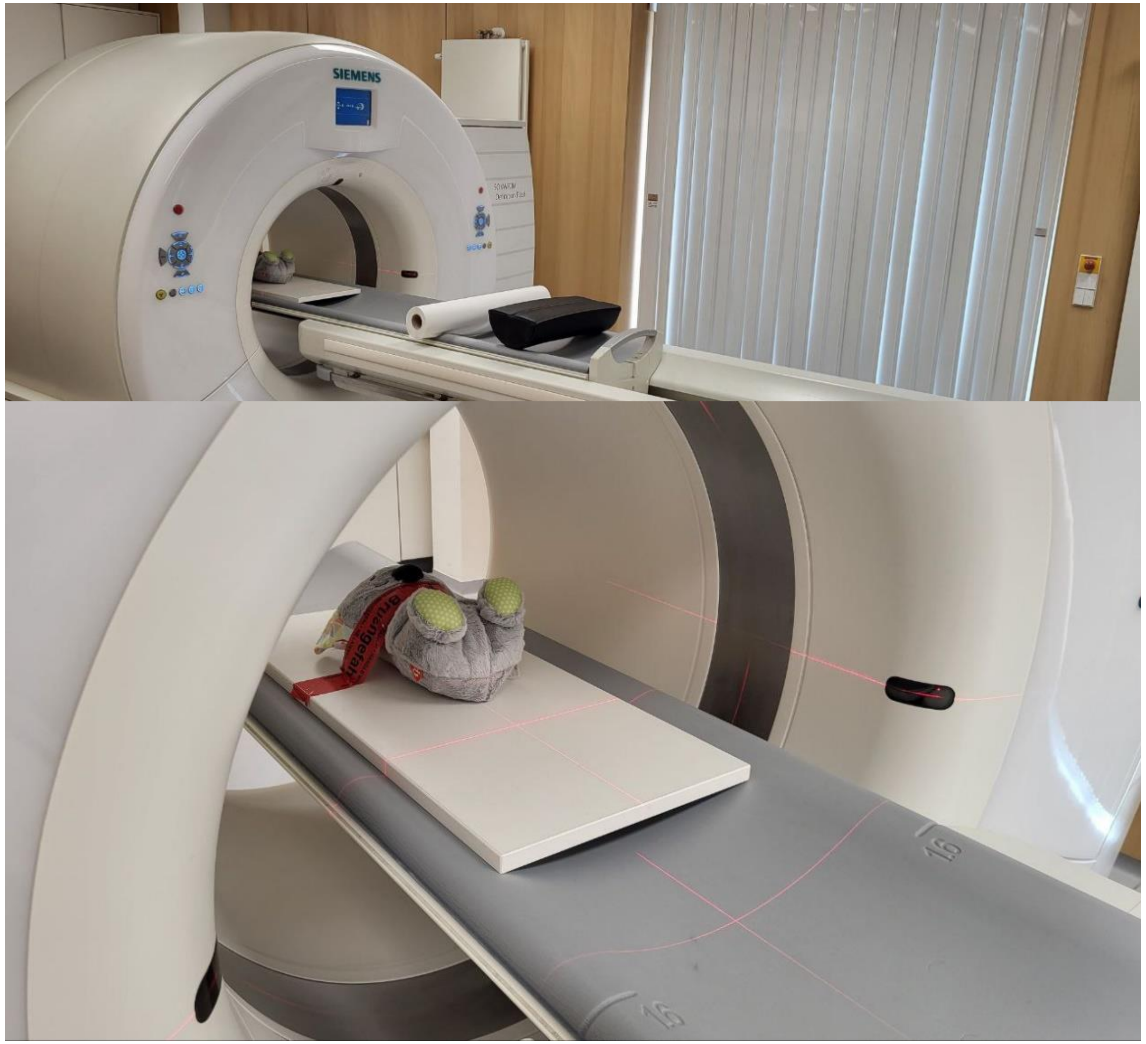
WET_{up} = 3.48 ± 0.02 cm; WET_{up} = 5.86 ± 0.03 cm

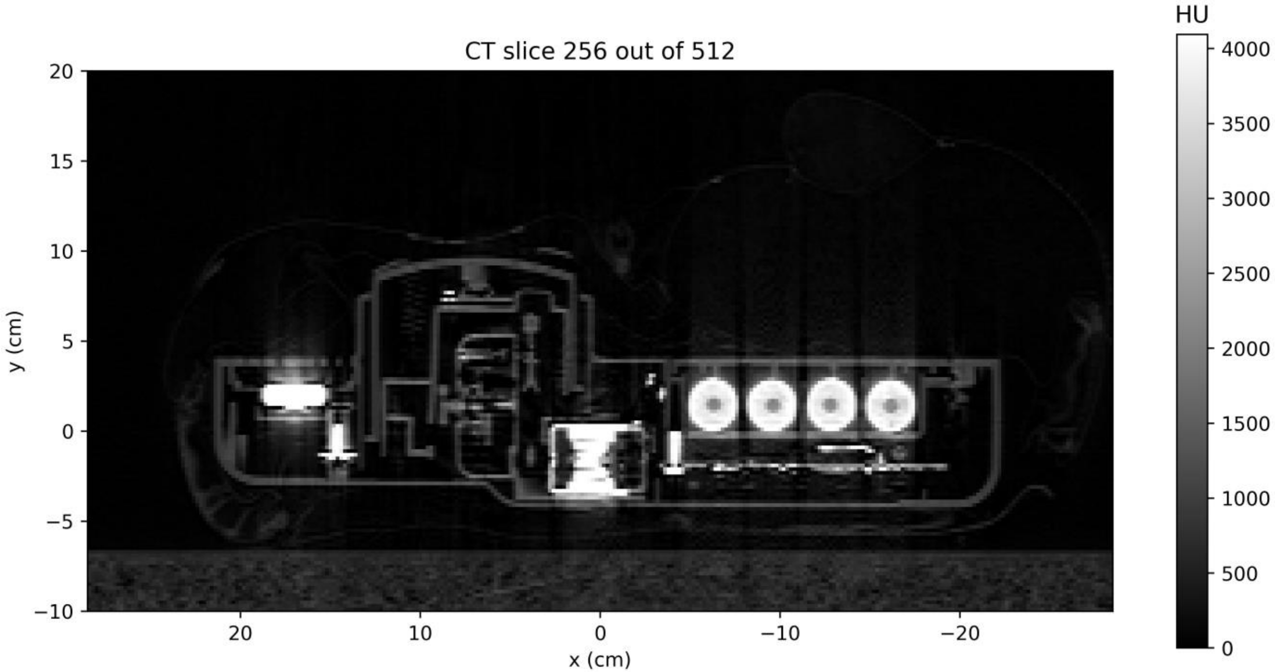


Helium radiograph, 104.46 MeV/u

WET_{up} = 3.47 ± 0.06 cm; WET_{up} = 5.84 ± 0.03 cm

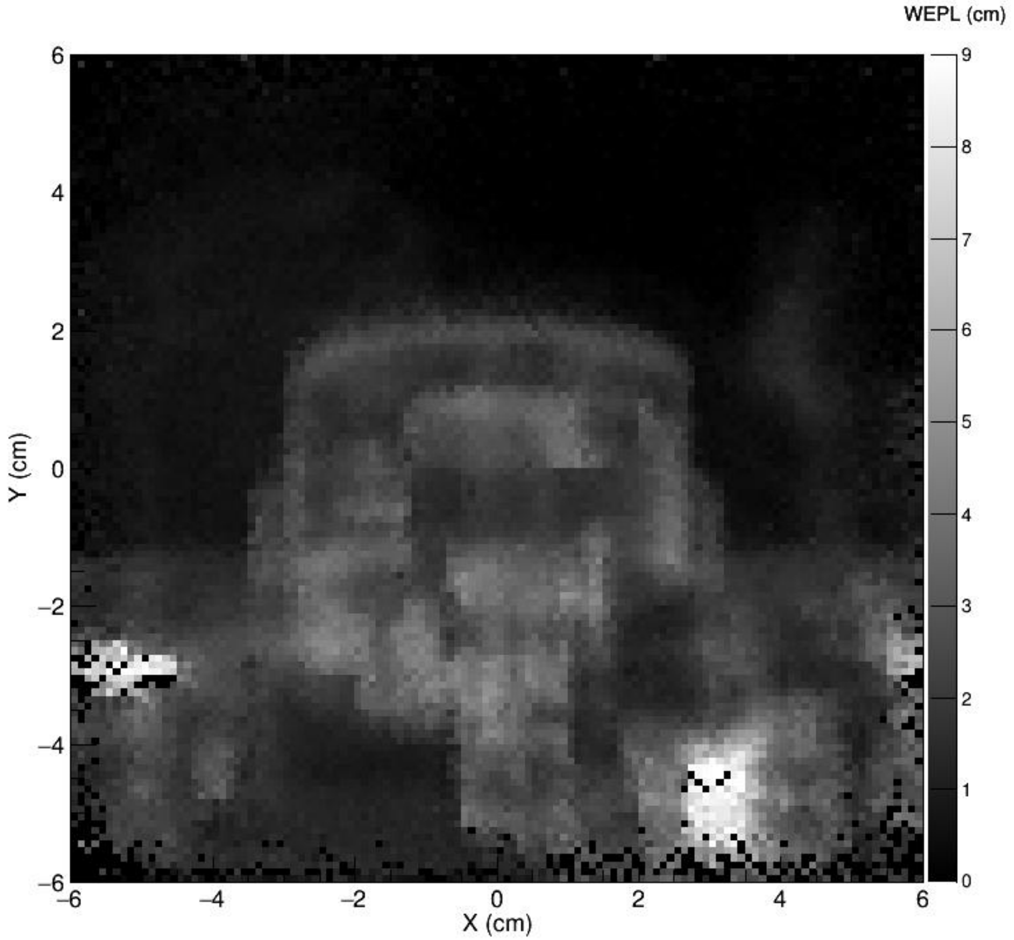
Experimental data (motion phantom): single energy 4DCT



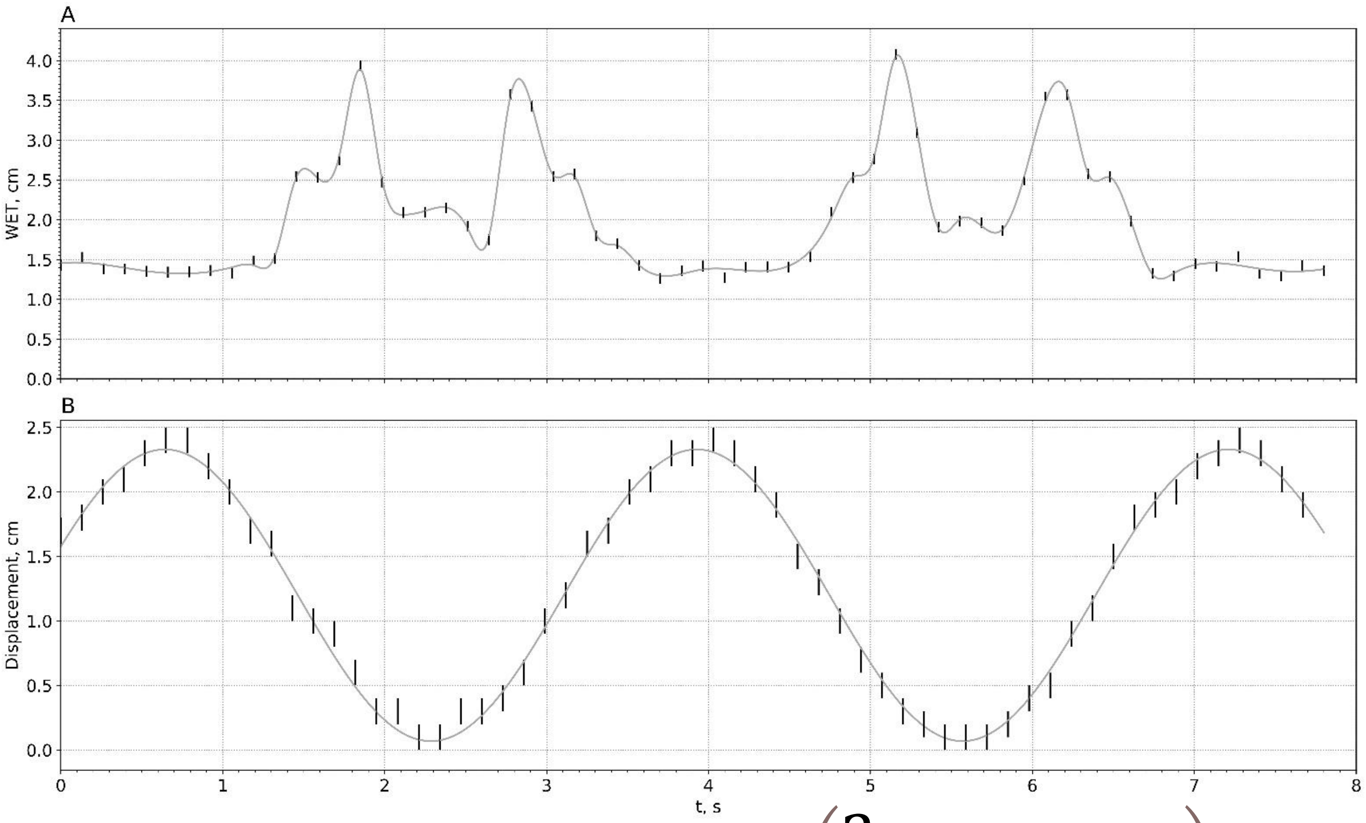


CT data from Siemens SOMATOM system, 120 kV.

Experimental data (motion phantom): pRad(t) @ NMCPC



Proton radiograph, 120 MeV, 10 cm x 10 cm field, beams were spaced every 5 mm, around 125 ms per frame, around 500 protons per spot



$$f(t) = f_0 + A \times \sin\left(\frac{2\pi}{T} \times t + p_0\right)$$

$A = 1.130 \pm 0.014$ cm, $A_{meas} = 1.10 \pm 0.05$ cm

$T = 3.28 \pm 0.01$ s, $T_{meas} = 3.3 \pm 0.1$ s

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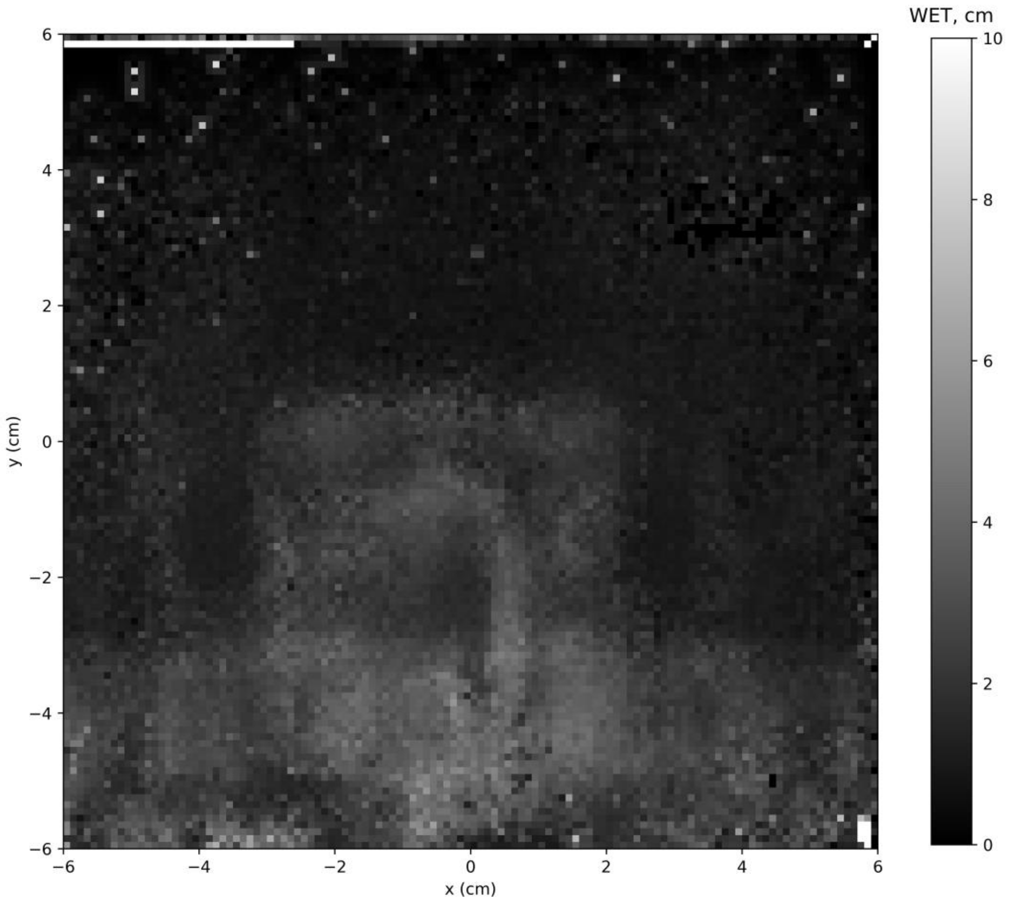
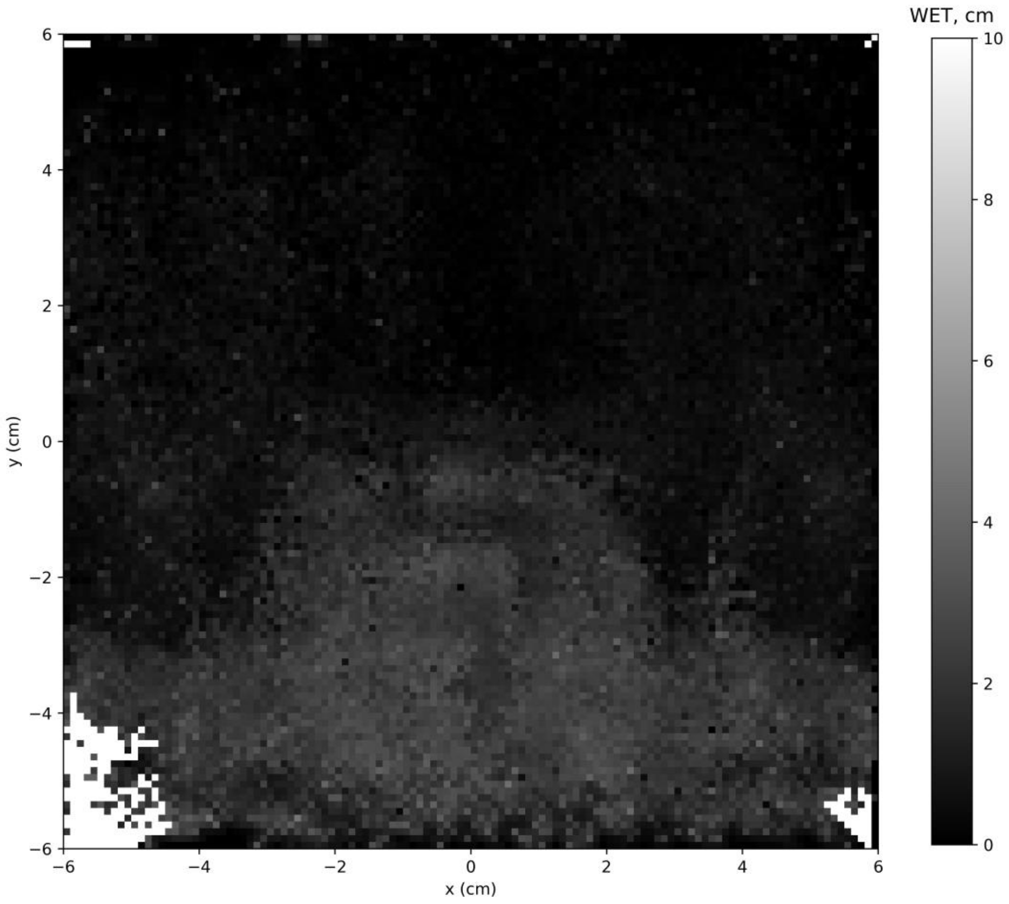
Experimental data (motion phantom): p/HeRad(t) @ HIT

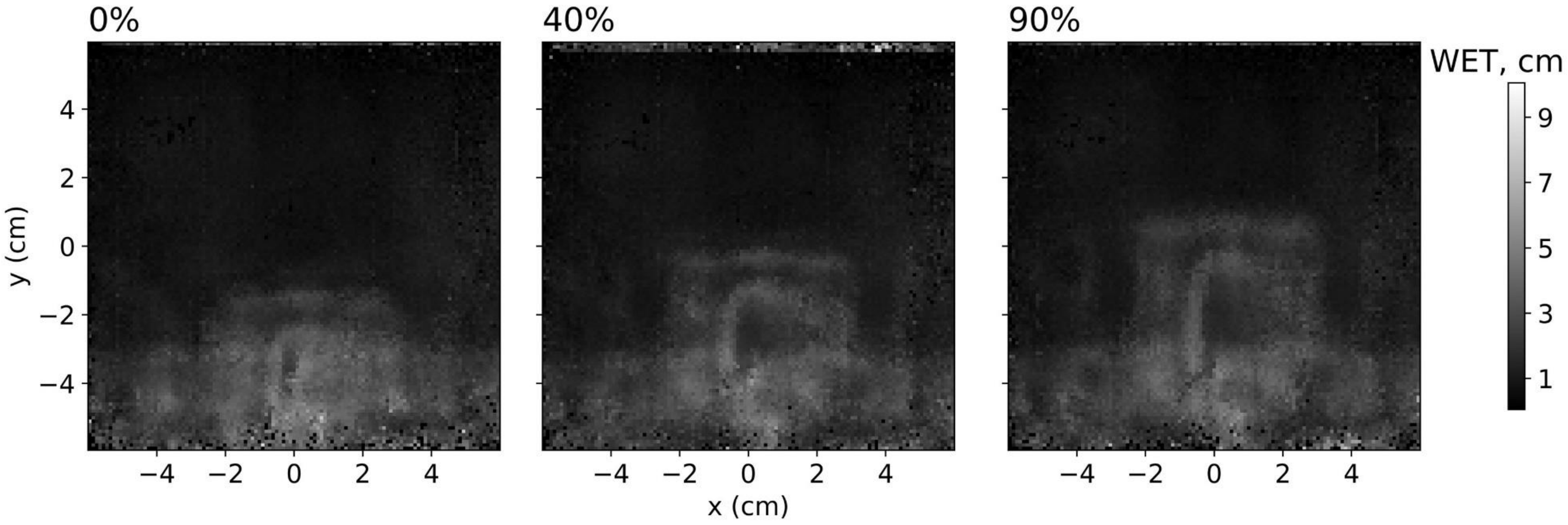


Proton radiograph, 121.95 MeV, 10 cm x 10 cm field, beams were spaced every 5 mm, around 560 ms per frame, around 1000-1200 protons per spot



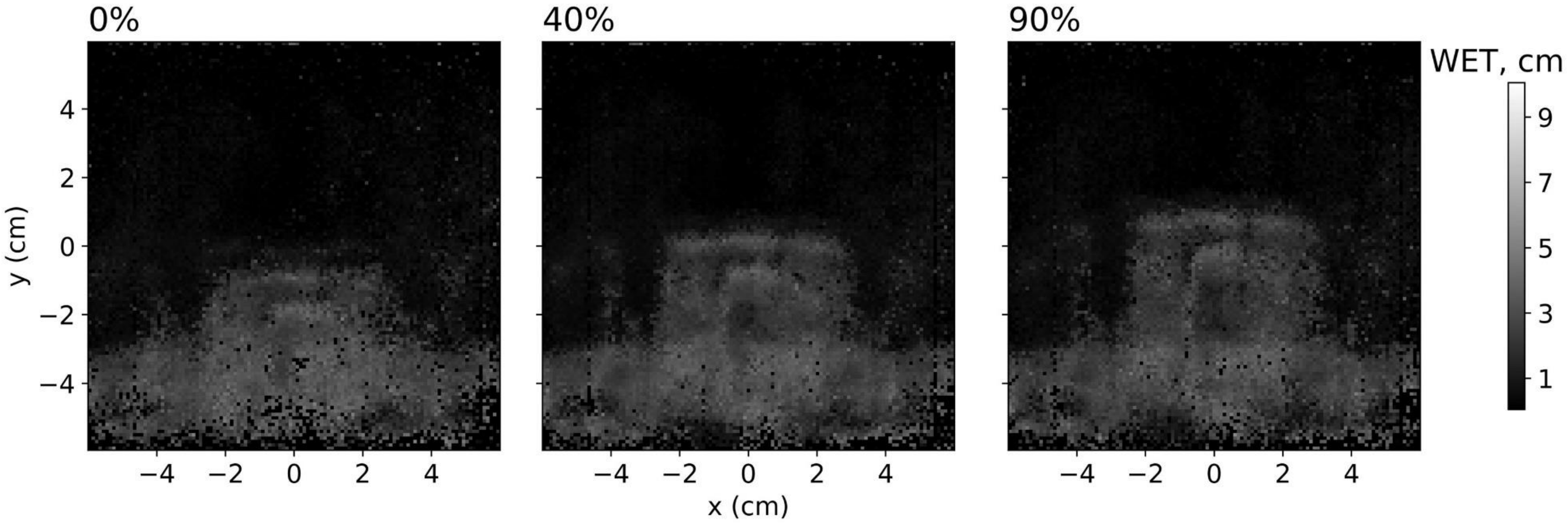
Helium radiograph, 80.64 MeV, 10 cm x 10 cm field, beams were spaced every 5 mm, around 450 ms per frame, around 150-600 ions per spot

Experimental data (motion phantom): p/HeRad(t) @ HIT



$A_{pRad,HIT} = 1.24 \pm 0.10$ cm

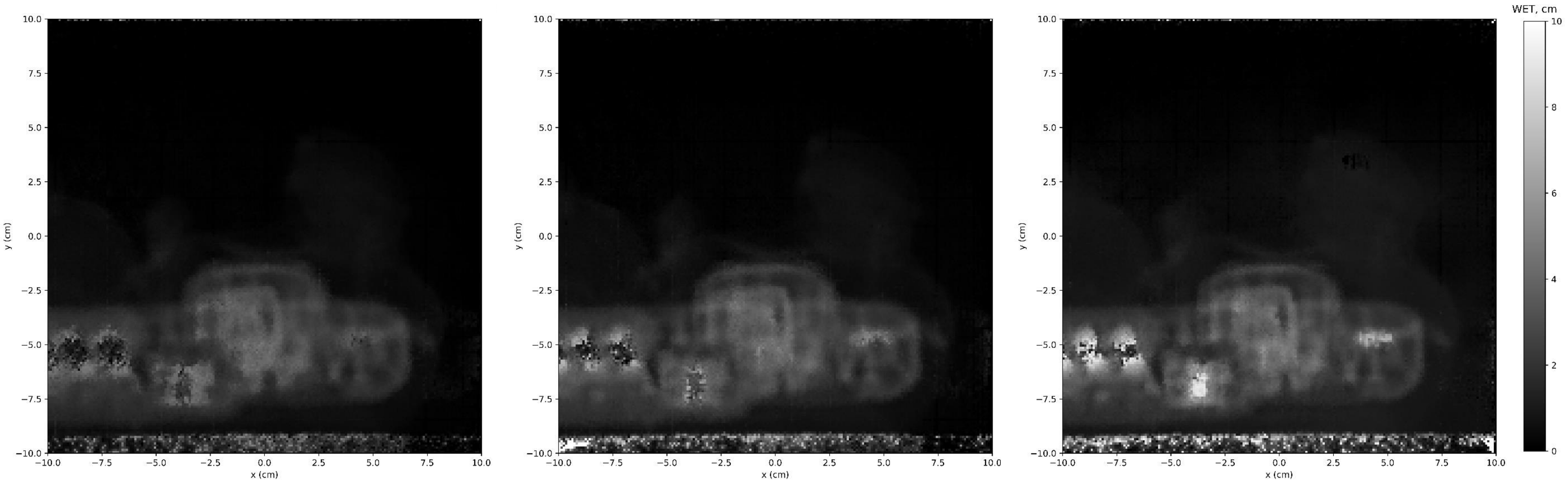
$T_{pRad,HIT} = 3.4 \pm 0.1$ s



$A_{HeRad,HIT} = 1.28 \pm 0.14$ cm

$T_{HeRad,HIT} = 3.5 \pm 0.2$ s

Experimental data: single energy pRads

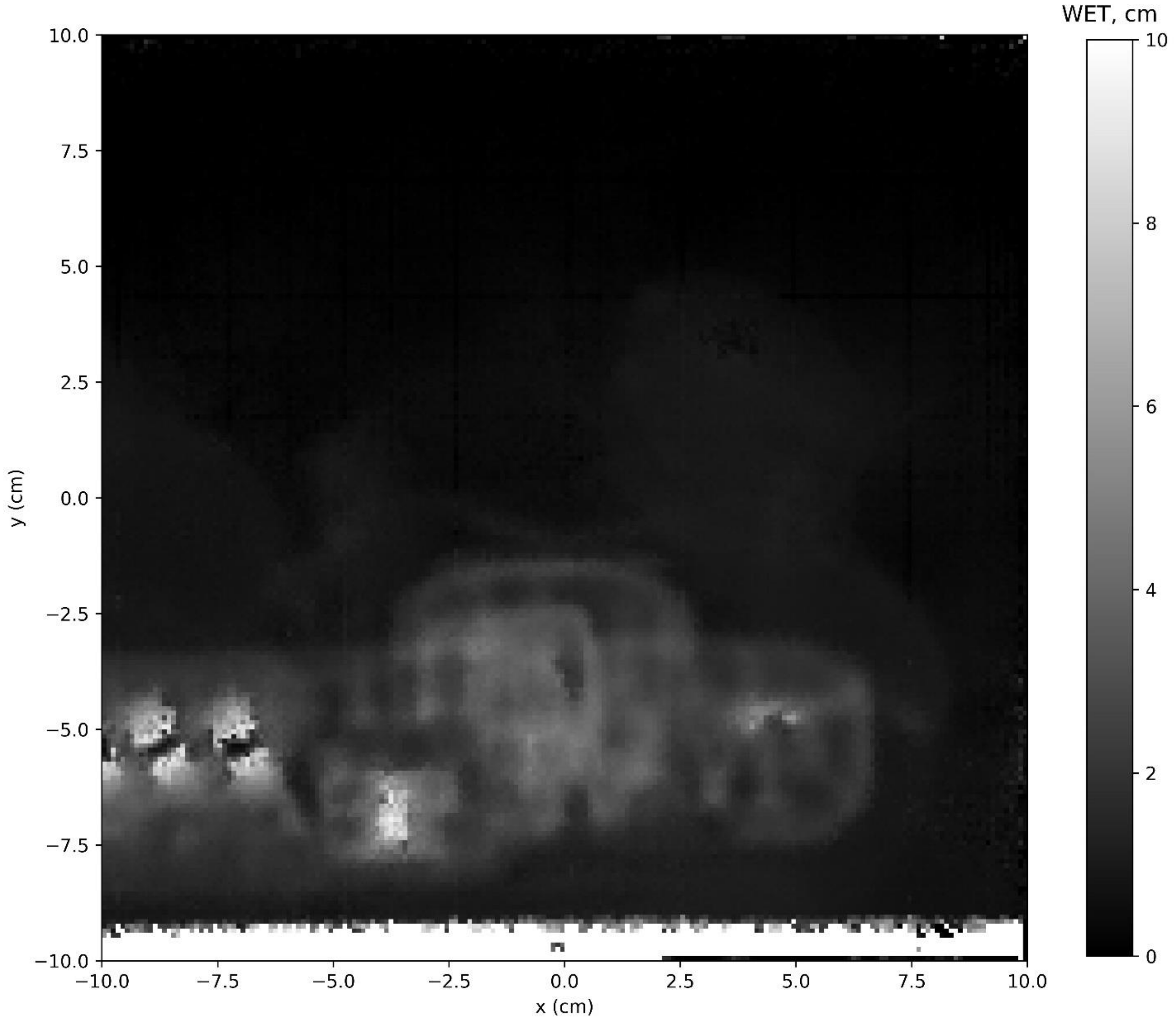


Proton radiograph, 93.79 MeV

Proton radiograph, 108.88 MeV

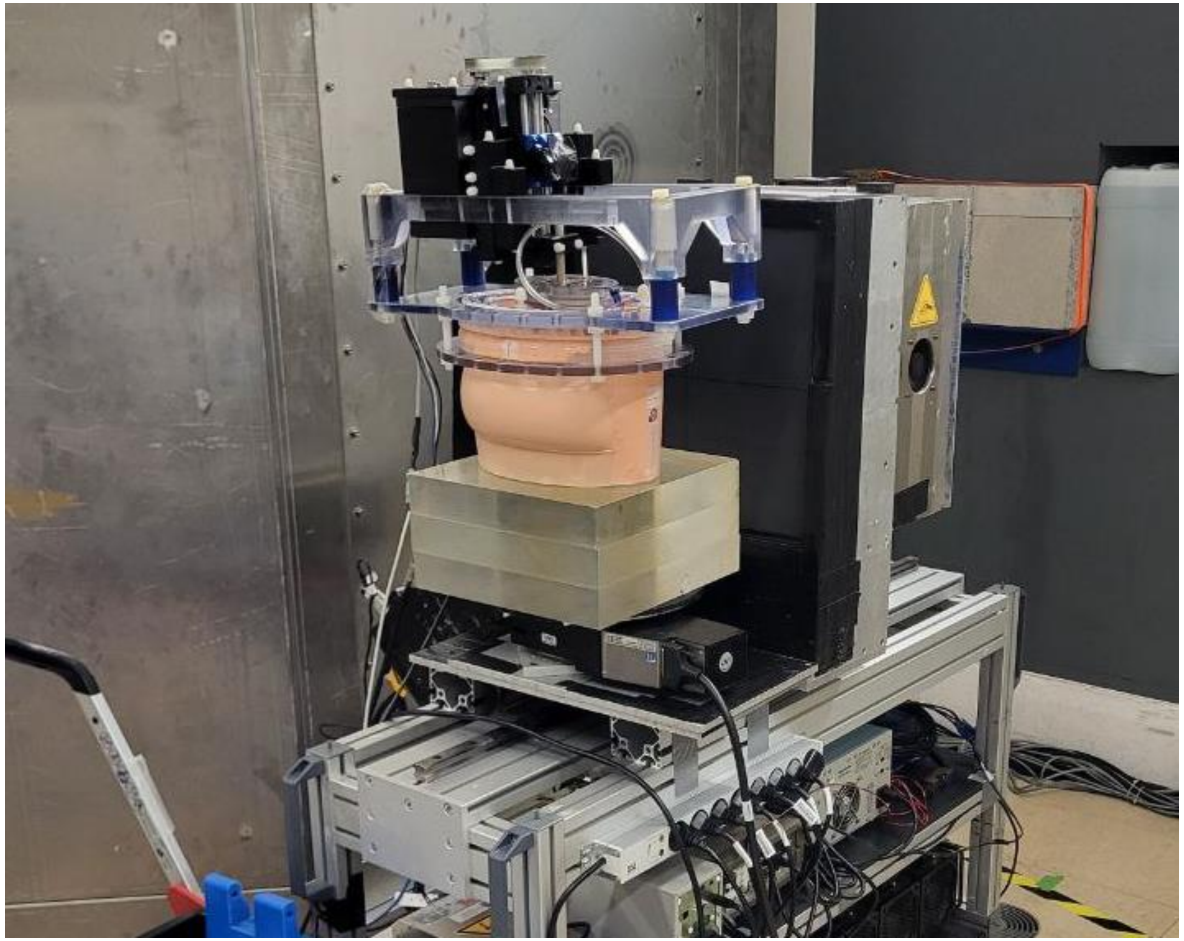
Proton radiograph, 121.95 MeV

Experimental data: multi energy pRad

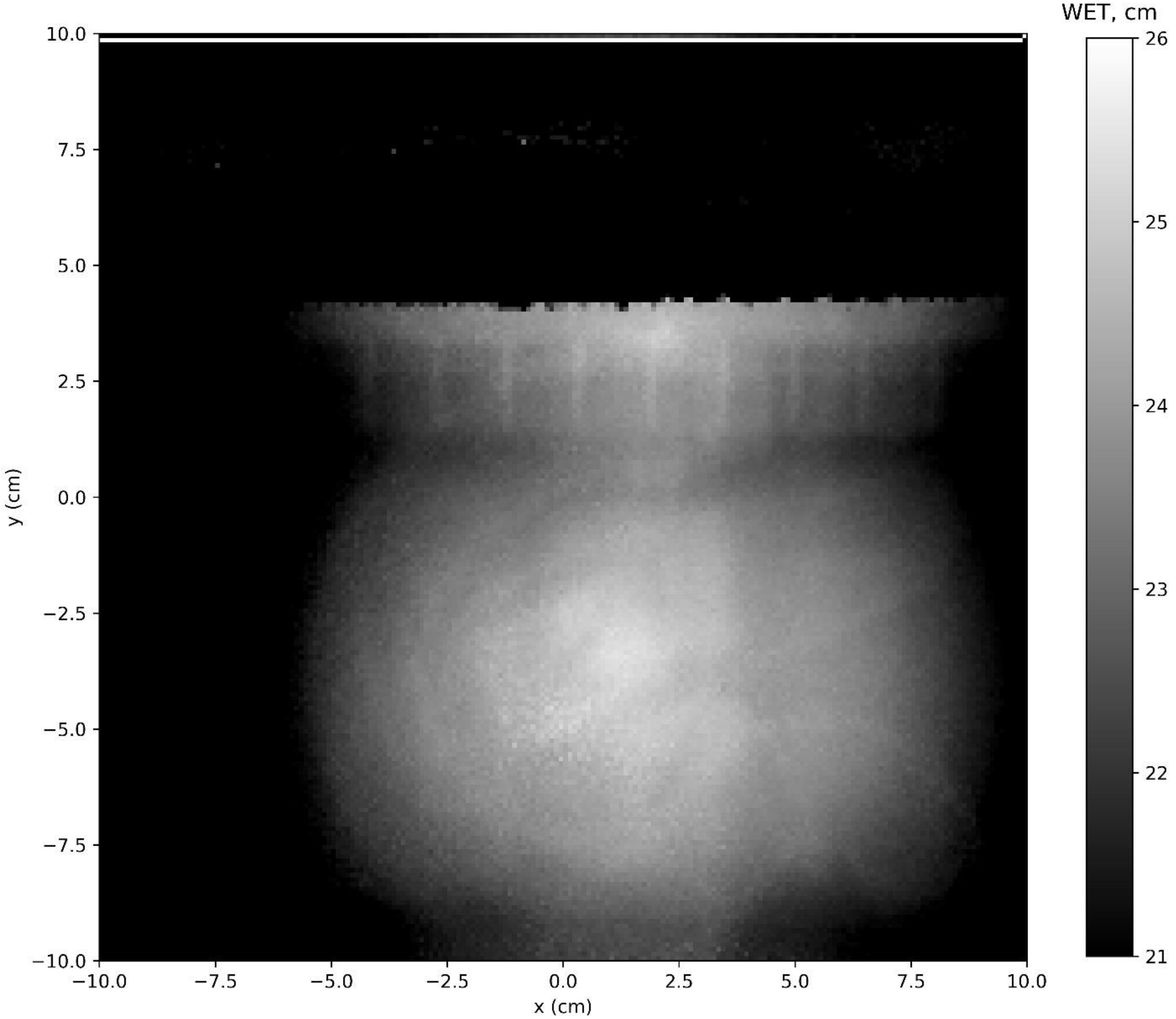


Proton radiograph, combined 93.79, 108.88 and 121.95 MeV

Experimental data: abdominal phantom



Proton radiograph, single energy, 210 MeV



Proton radiograph, single energy, 210 MeV

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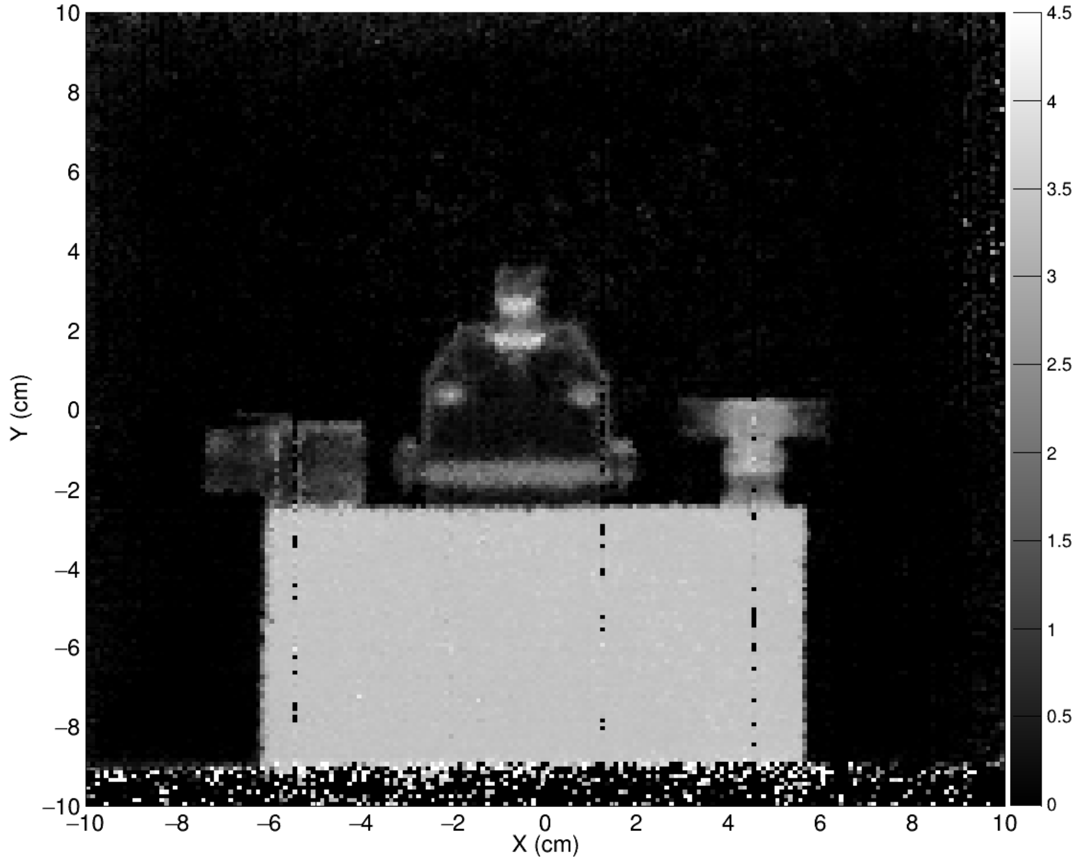
Conclusions

1. Adapted the beam delivery mode to the detector parameters;
2. Achieved working mode with both positioning trackers, allowing to obtain high quality, low noise static proton and helium radiographs;
3. Demonstrated the ability to obtain fast (so far noisy) moving proton and helium radiographs;
4. Demonstrated the ability to work with a single positioning tracker for helium ion radiography (*Talk by Lukas Martin*).
5. Tested pCT and HeCT mode, need to obtain and process more data.



Helium radiograph, 95 MeV/u, around 1000 ions per spot

Thank you for your attention!

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FLASH WORKSHOP 2025

THE ROLE OF OXYGEN IN FLASH RADIATION THERAPY

HEIDELBERG (GERMANY), JULY 1^{ST} – JULY 3^{RD}, 2025

MORE INFORMATION ON: WWW.DKFZ.DE/FLASH_WORKSHOP2025

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