Update on the pCT project in Bergen

Proton Imaging Workhop, Lyon

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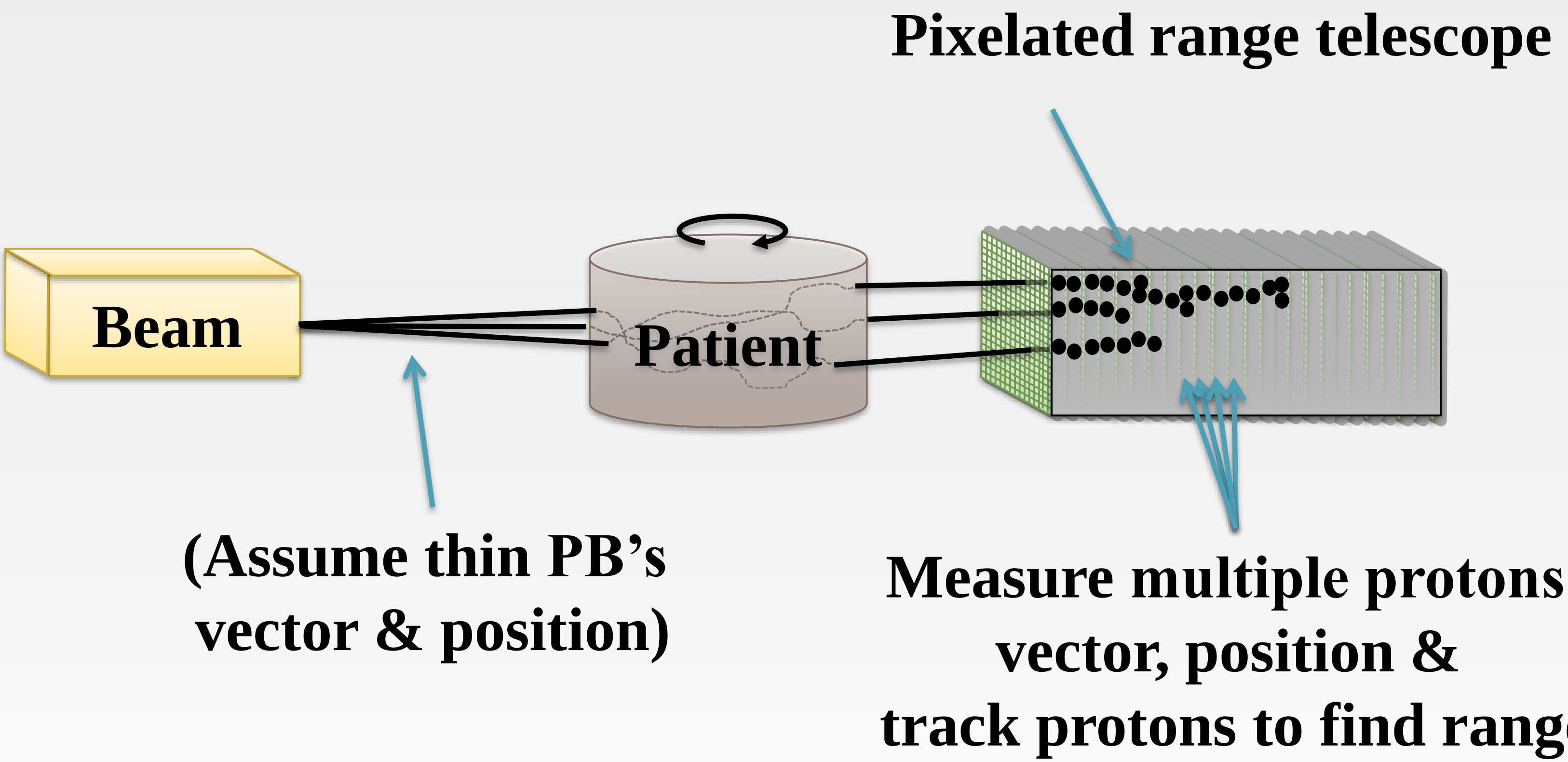
On behalf of the pCT project in Bergen

14 June 2018

Bergen, Norway
Pop. 280k, founded in 1070
Proton center in 2024

pCT – Digital Tracking Calorimeter

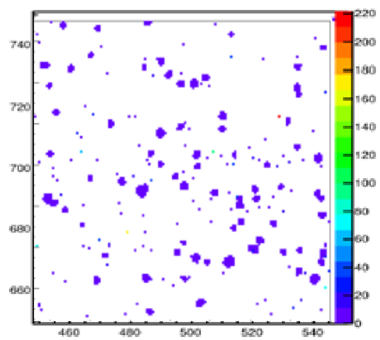


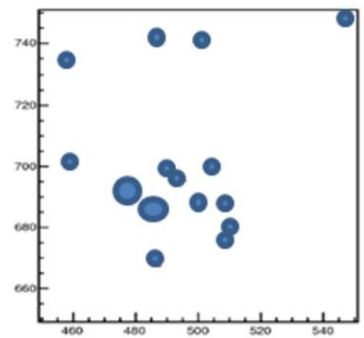
Data readout
Monte Carlo + exp.

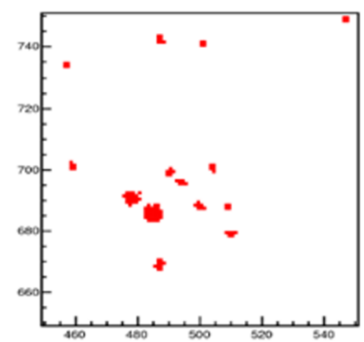
Proton hit identification

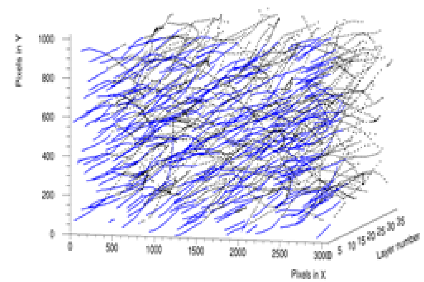
Charge diffusion modelling

Proton track reconstruction





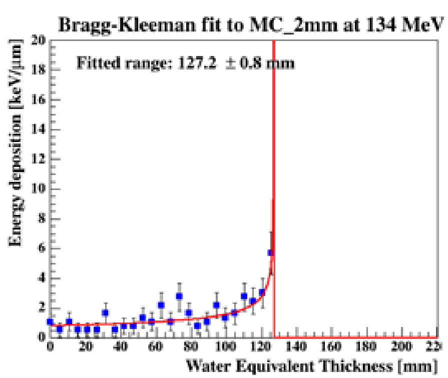


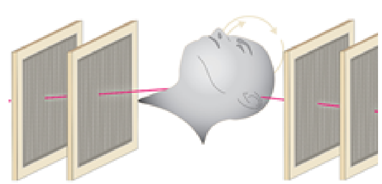


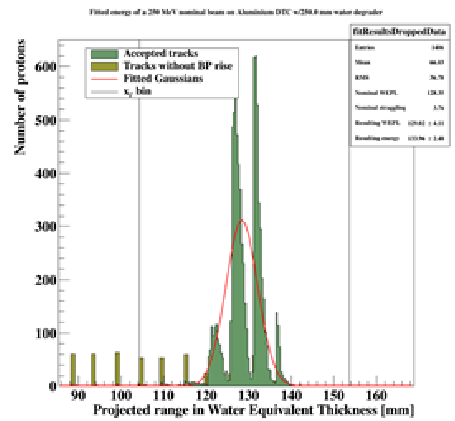
Individual track – energy loss fitting

If 3D reconstruction: MLP estimation

Residual range calculation

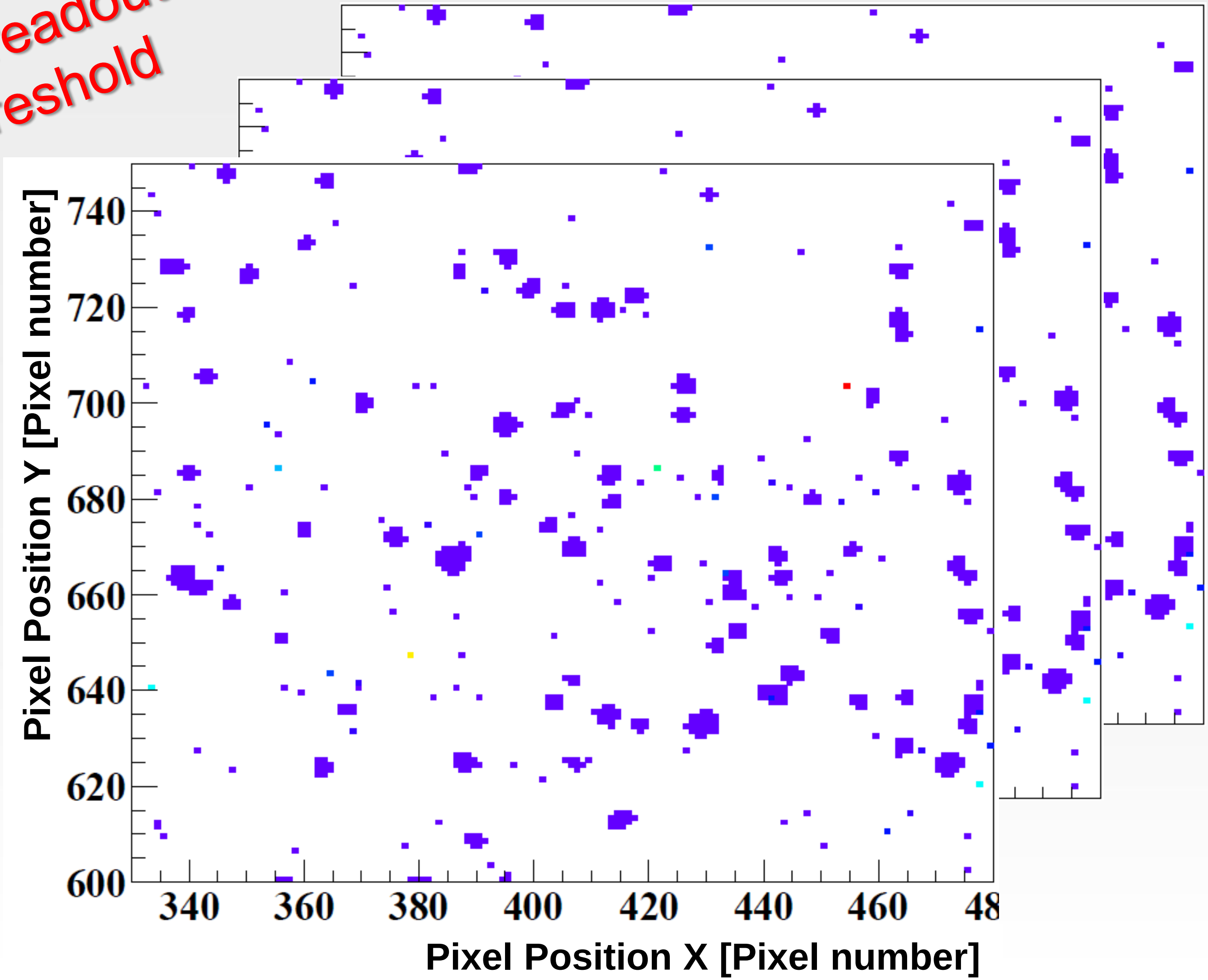




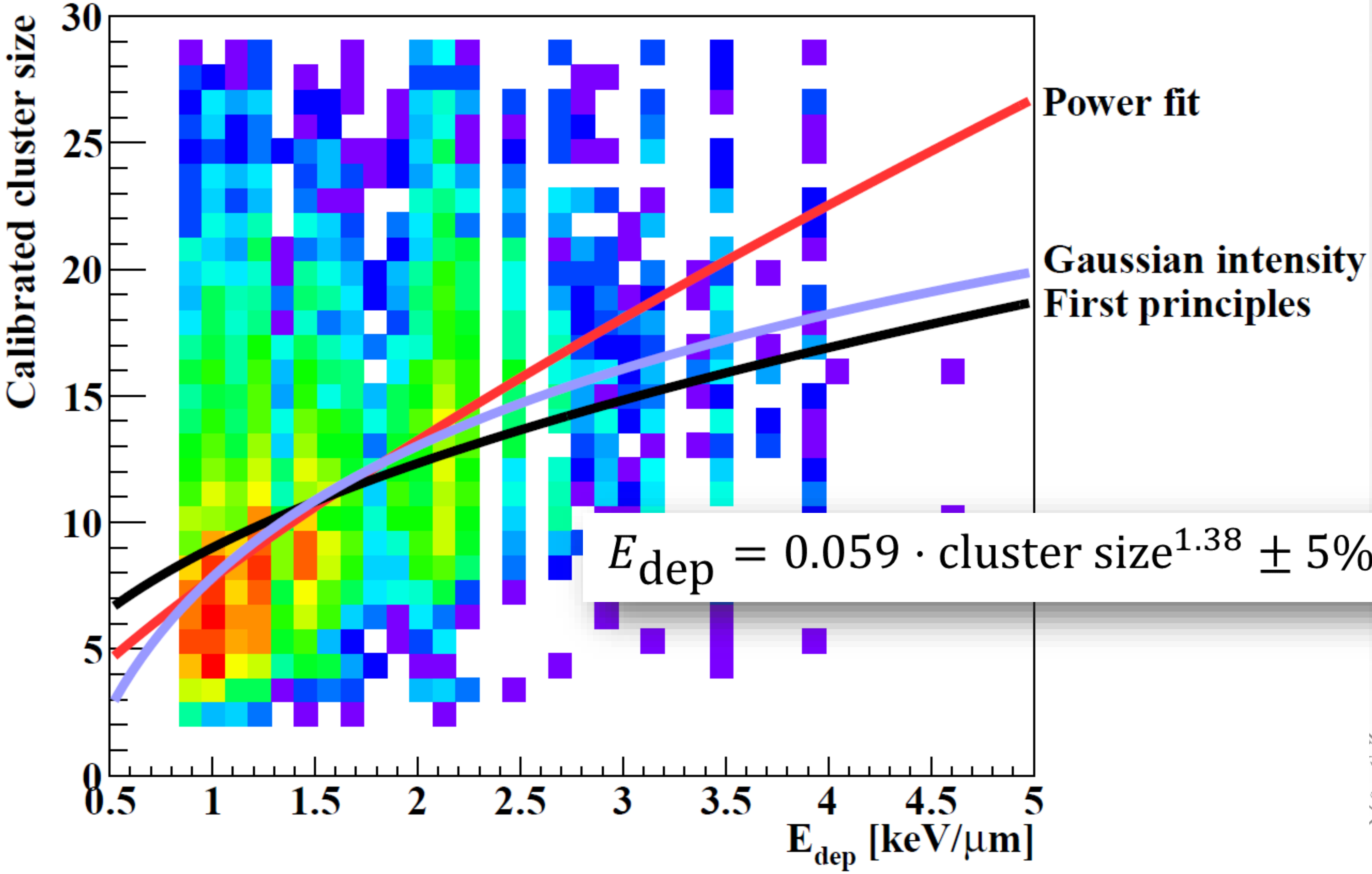


Protons hitting the pixel detectors

1-bit readout w/threshold



Charge diffusion model



$$E_{\text{dep}} = 0.059 \cdot \text{cluster size}^{1.38} \pm 5\%$$

Proton track reconstruction

- With a DTC-type detector:
  - It is possible to separate the signals from several protons in a single readout
  - All proton hits throughout the detector layers must be «de-spaghetti-fied» and reconstructed into tracks

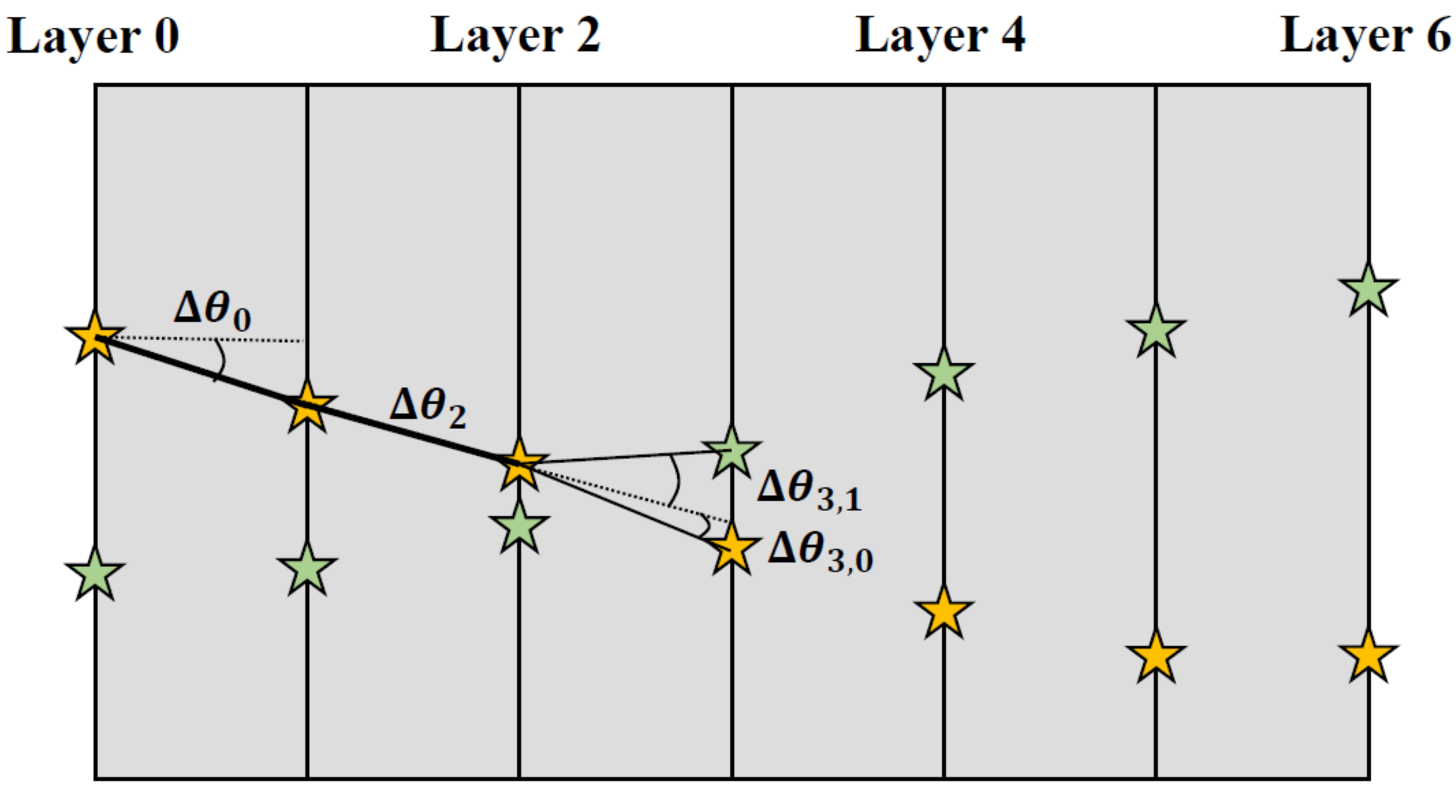
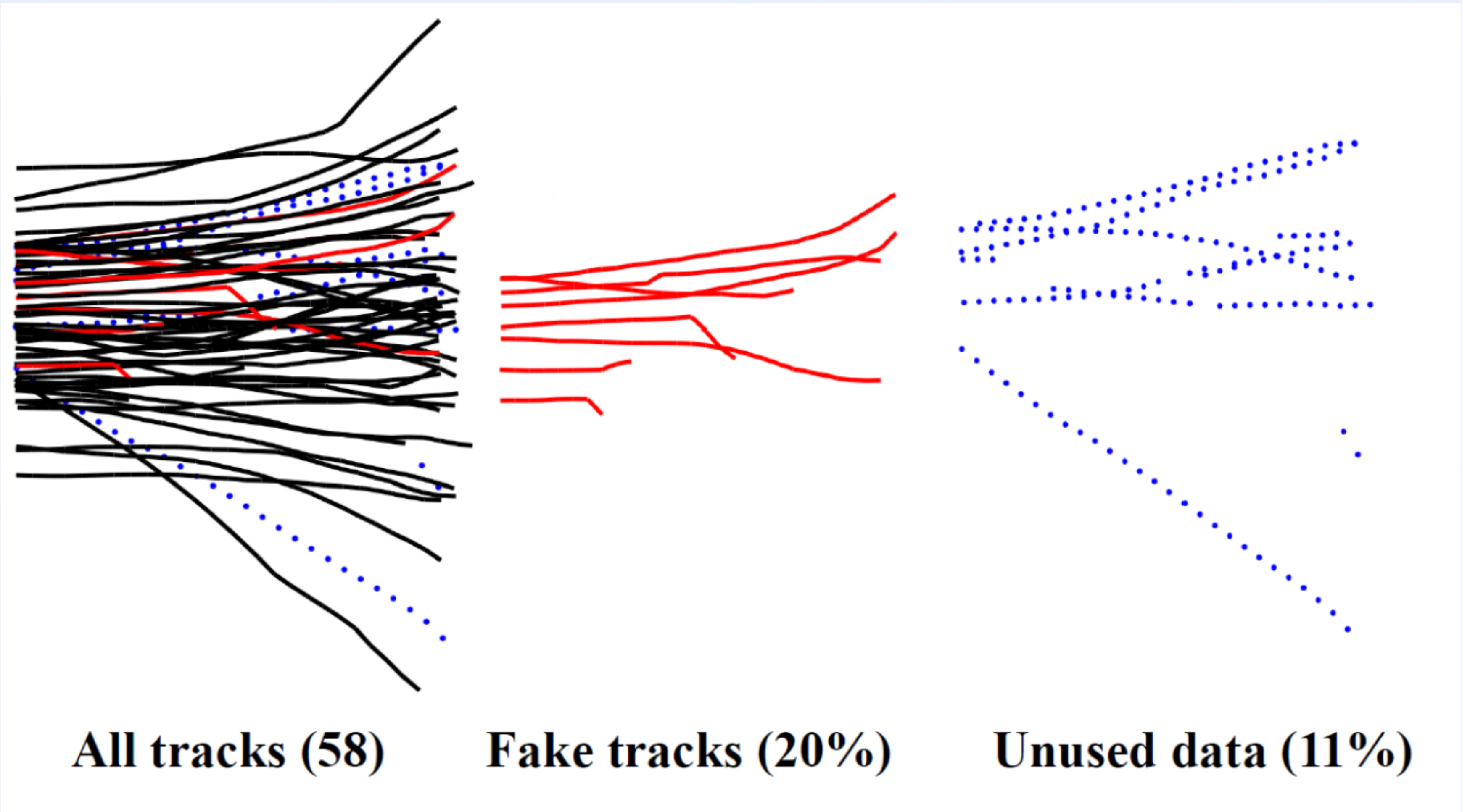
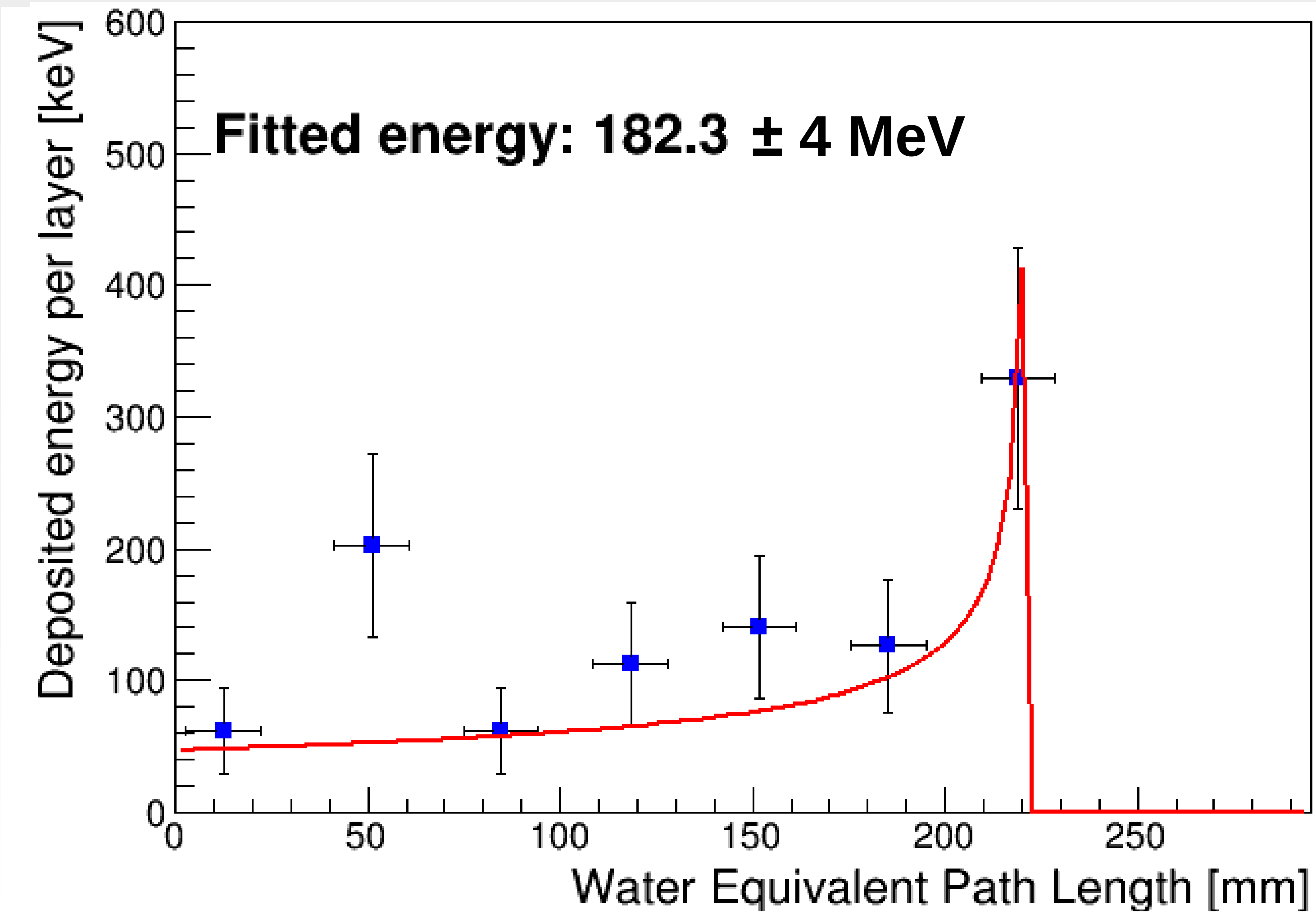


Figure 3. Example of the track reconstruction: In this case $\Delta\theta_{3,1} \gg \Delta\theta_{3,0}$ and the latter is chosen as the single next track segment.

Proton track reconstruction

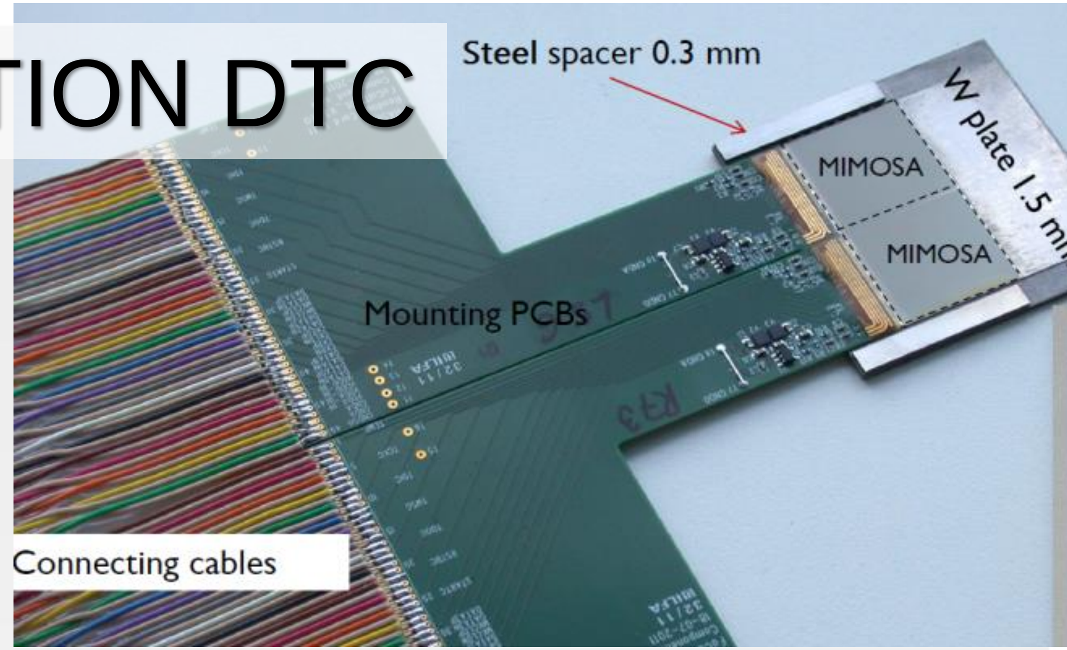


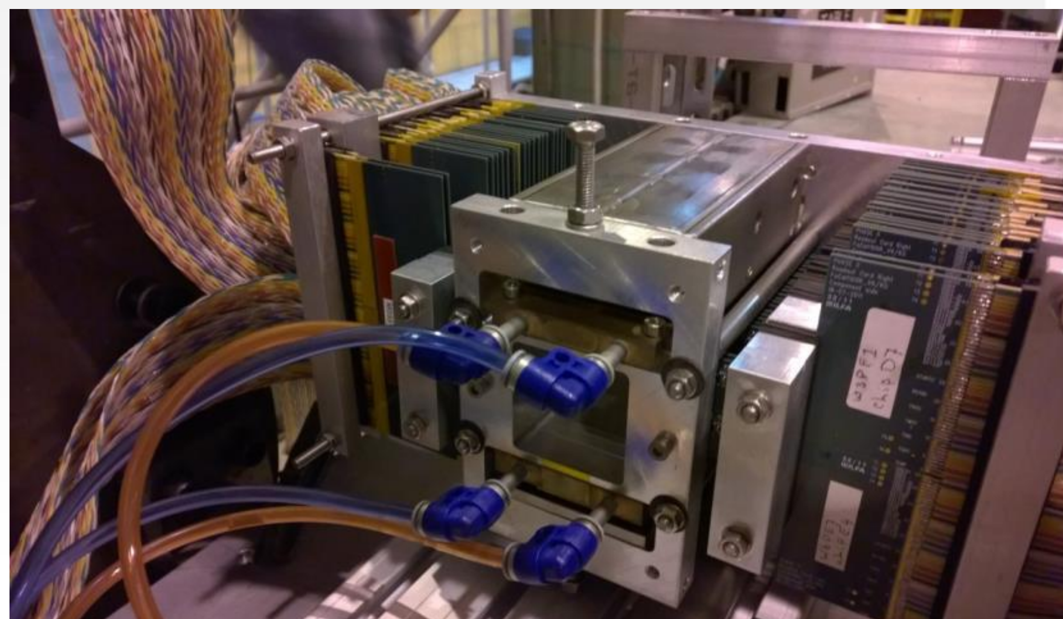
The individual proton range



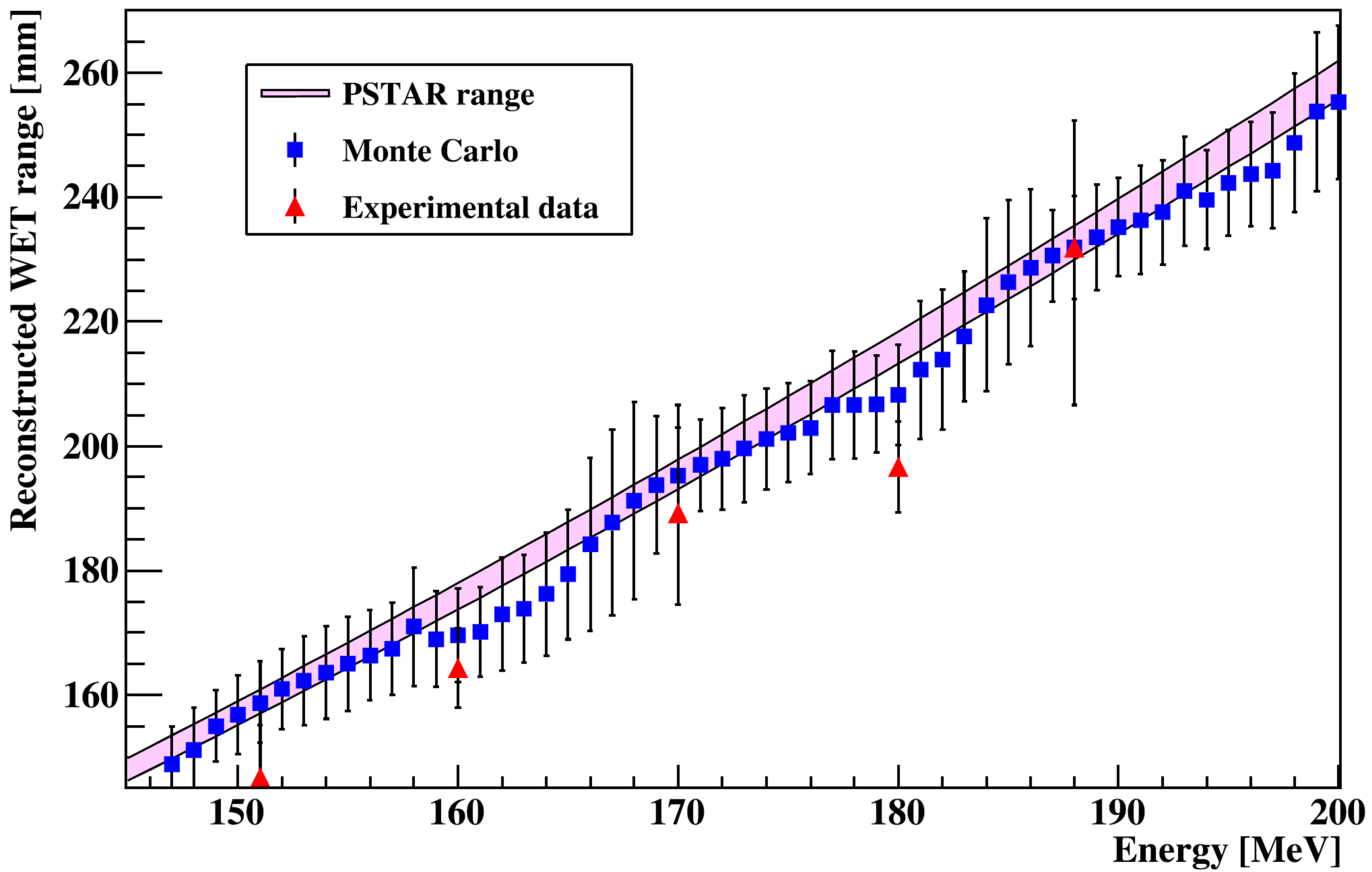
Bortfeld, T. *An Analytical approximation to the Bragg curve for therapeutic proton beams.* Med. Phys 24 2024-33 (1997)

FIRST GENERATION DTC





Proton Ranges with different energies



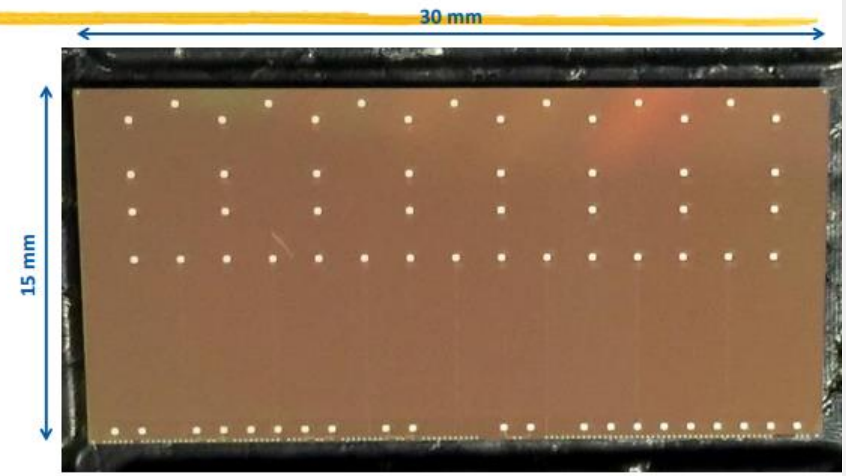
First gen DTC

- ALICE-FoCal prototype showed promise of DTC detector concept
  - Exp. beam data + Monte Carlo
  - Poor resolution, adequate intensity capacity
  - Compact design

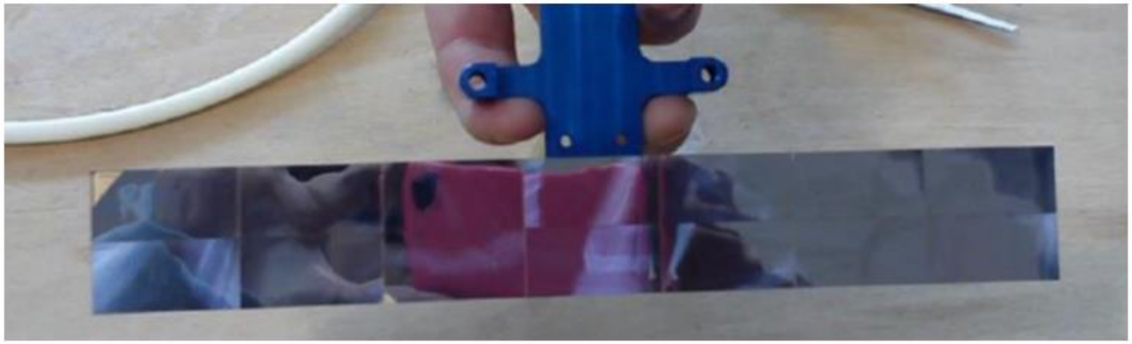
- See:
  - Pettersen, H. E. S. "*A Digital Tracking Calorimeter for Proton Computed Tomography.*" PhD, University of Bergen, 2018.
  - Pettersen, H. E. S., et al. "*Proton Tracking in a High-Granularity Digital Tracking Calorimeter for Proton CT Purposes.*" NIM A 860C (2017)

DTC design study

Pixel sensor – MAPS



- **ALPIDE chip**
  - **sensor for the upgrade of the inner tracking system of the ALICE experiment at CERN**
  - **chip size ≈ 3x1.5 cm^2, pixel size ≈ 28 µm, integration time ≈ 4 µs**
  - **on-chip data reduction (priority encoding per double column)**



M. Magner, IFEE 2014

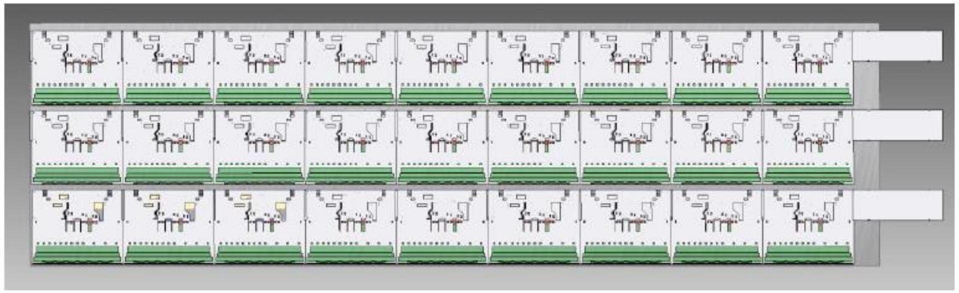
Design team:
CCNU Wuhan, CERN Geneva, YONSEI Seoul, INFN Cagliari, INFN Torino, IPHC Strasbourg, IRFU Saclay, NIKHEF Amsterdam

Towards the clinical prototype

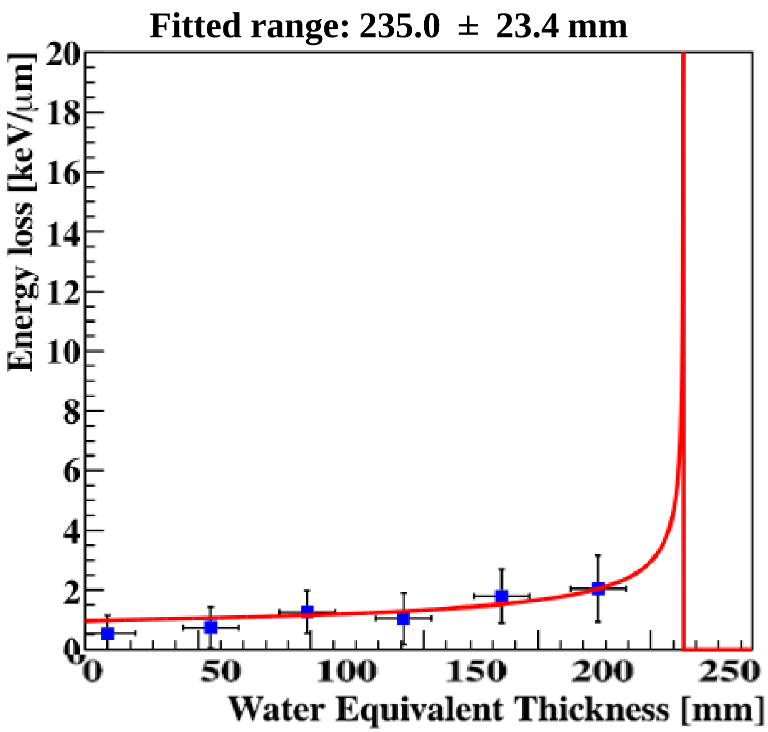
Implementation – final system

- Modular structure – exchangeable front layers
- Dimension
  - Front area: 27 cm x 15(18) cm
  - 41 layers of absorbers/sensors
  - Two tracking stations - 2 thin sensor layers (total thickness < 0.4 mm), 2 cm apart front face of calorimeter and - if neccessary - in front of phantom
- Sensitive layers - ALPIDE chips bonded to flexible PCBs

flexible carrier board modules (9 x 3 chips) (design and production: LTU, Kharkiv)



Idea: More sensor layers, less material



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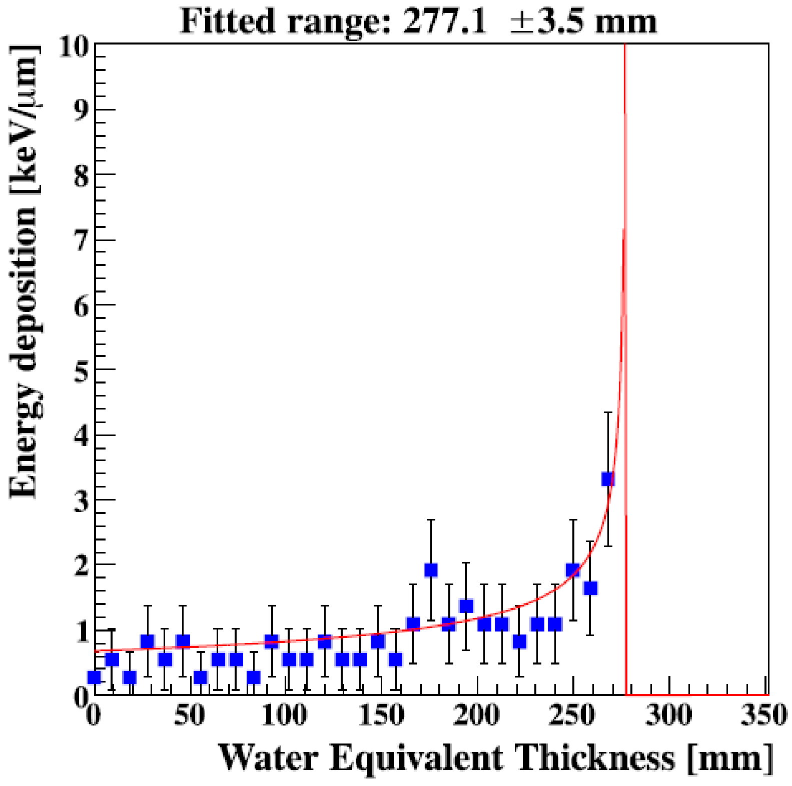
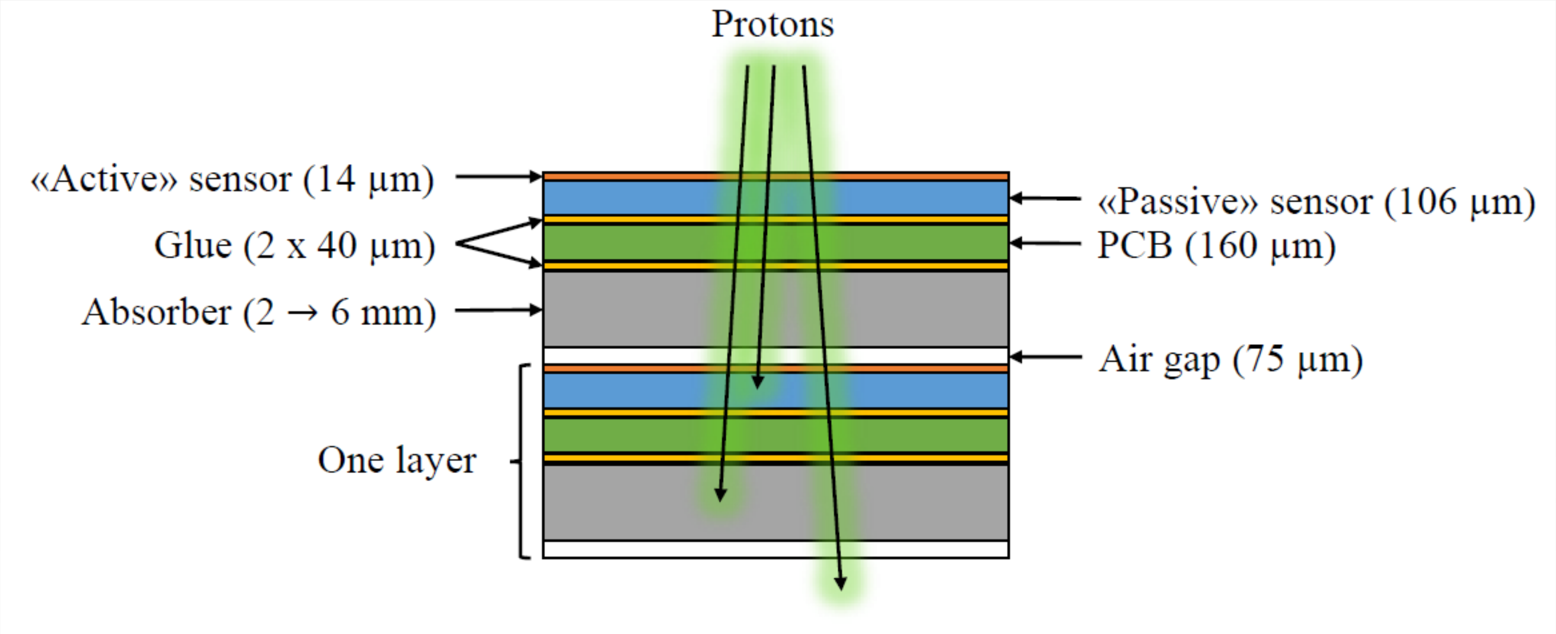
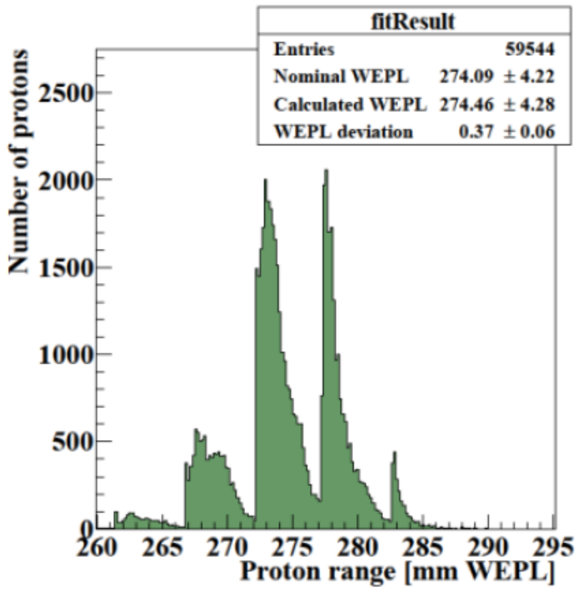


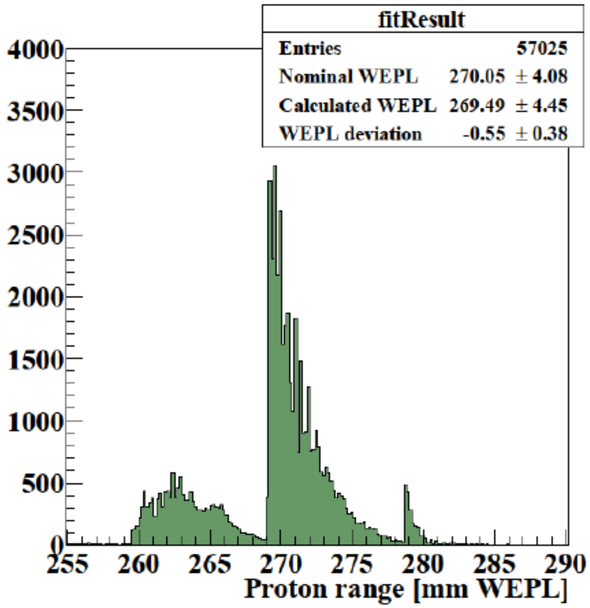
Design optimization: Absorber thickness



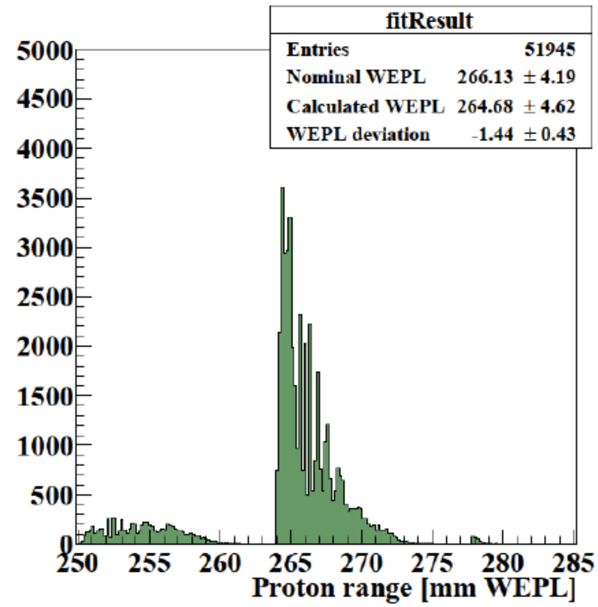
Range distribution per beam



2 mm Al



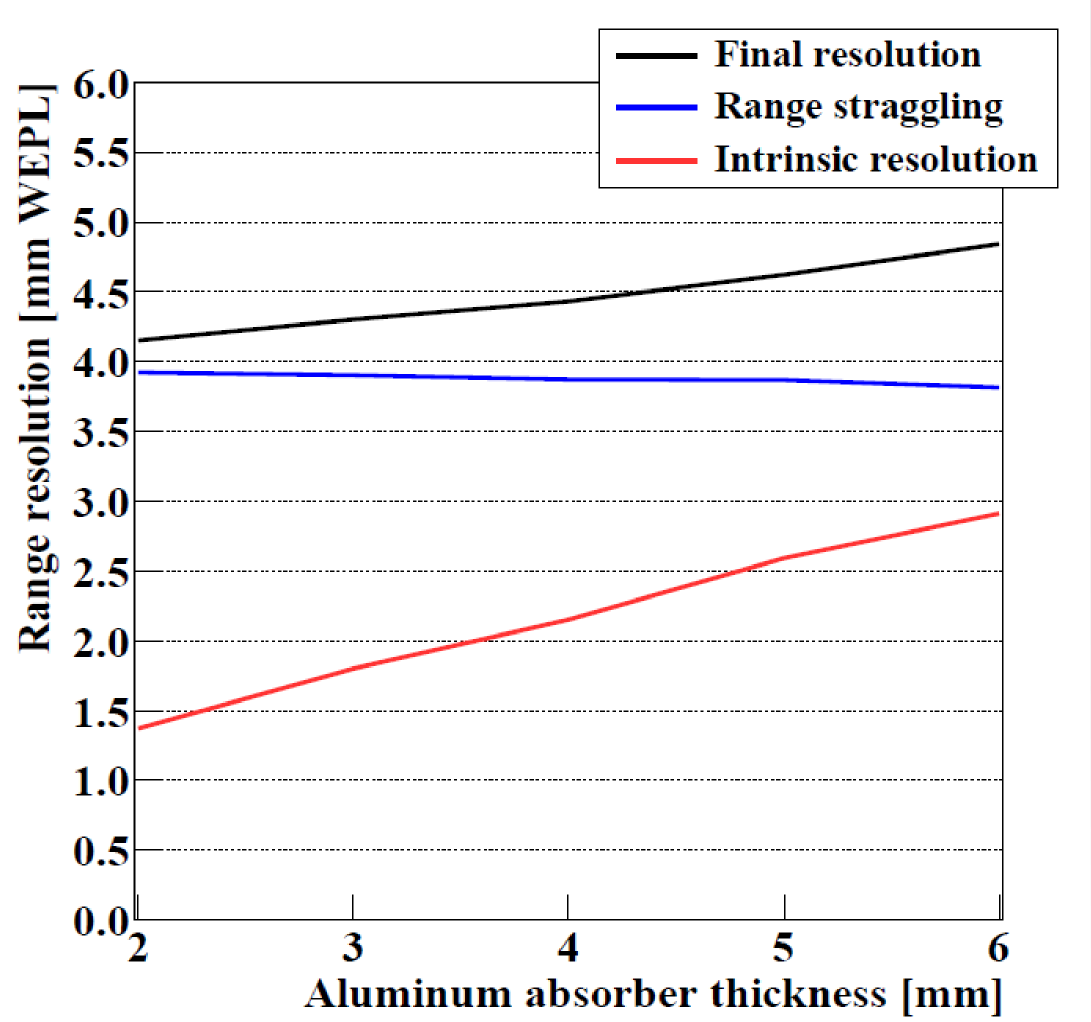
4 mm Al



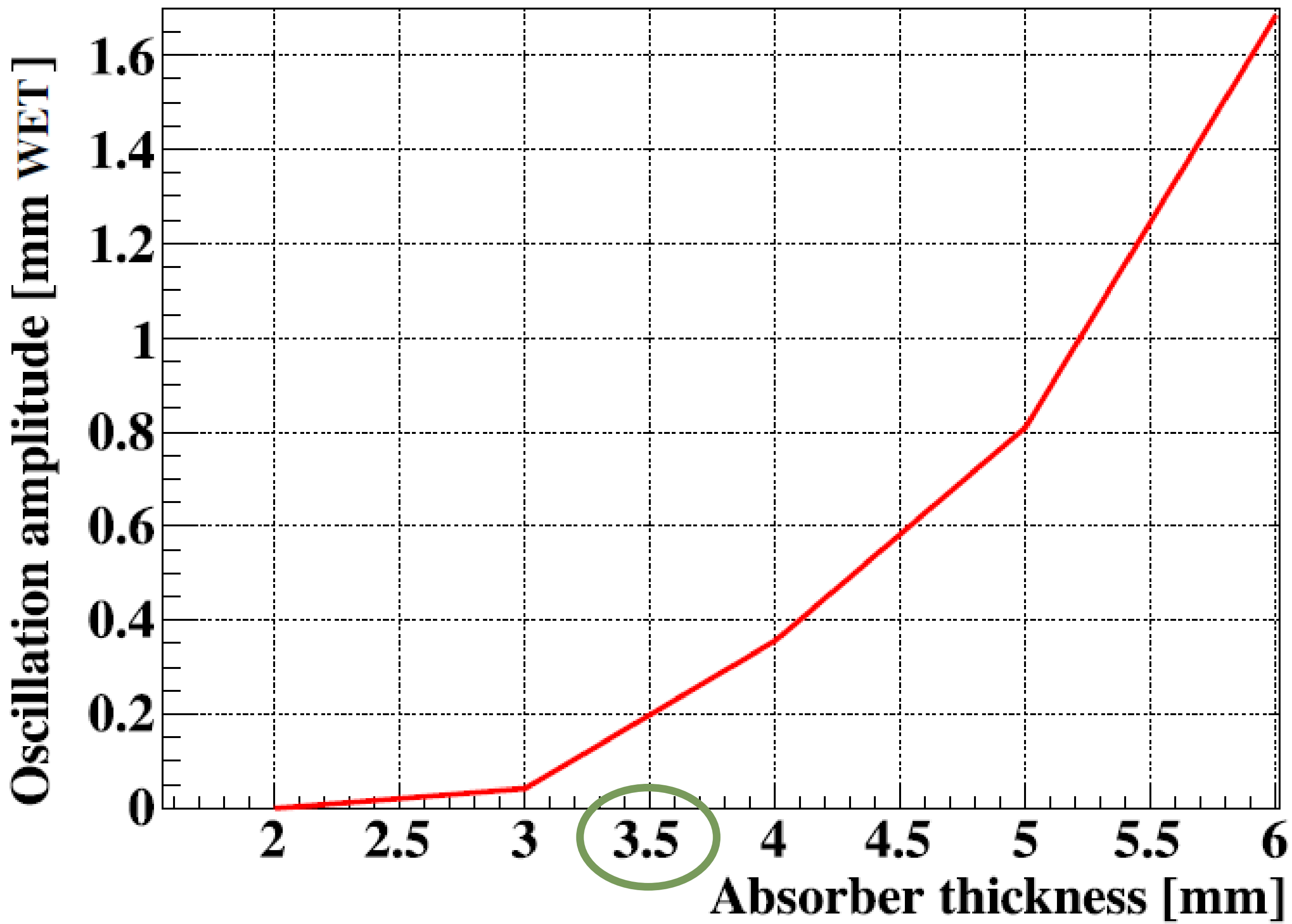
6 mm Al

Range uncertainty: MC design study

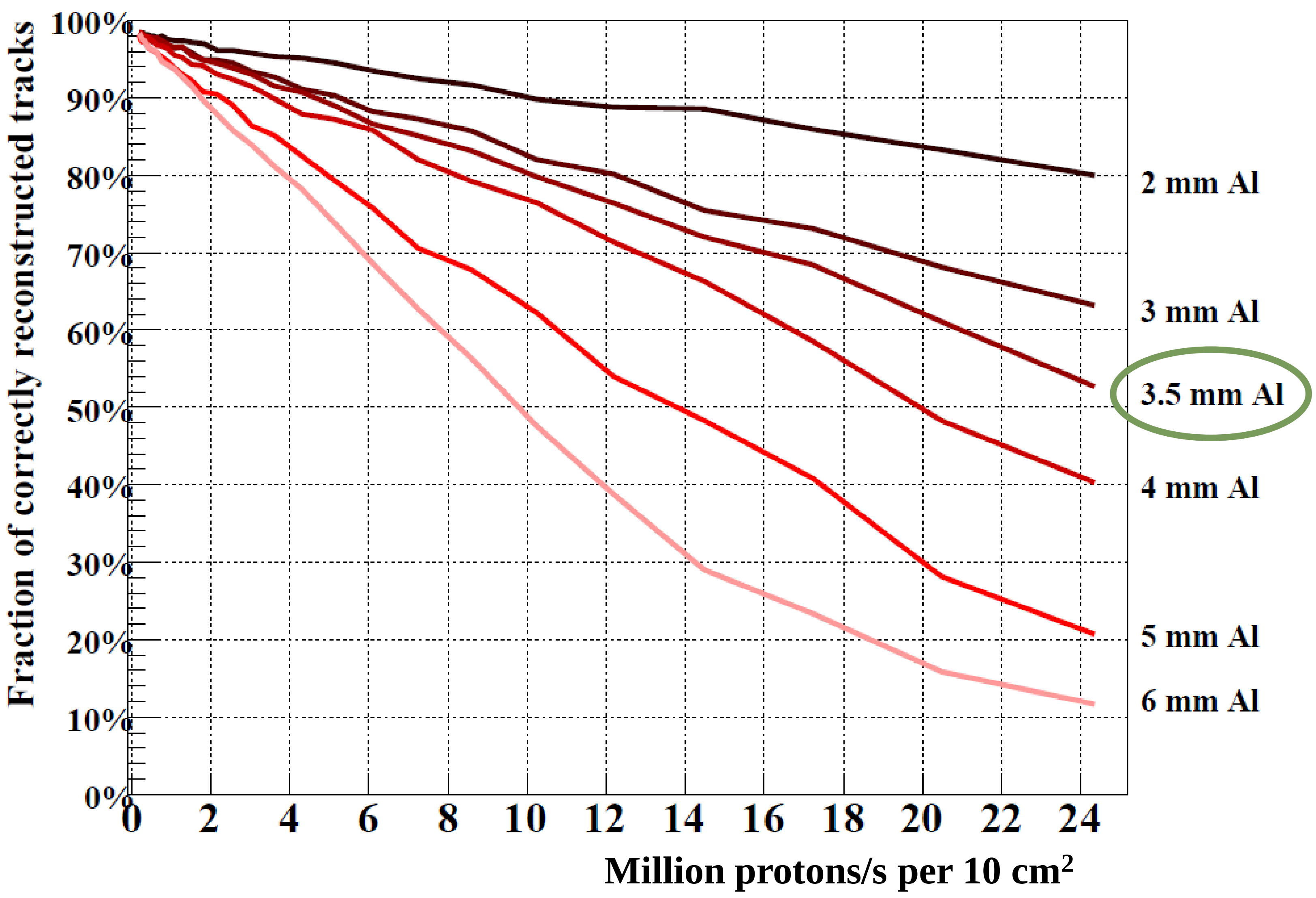
$$\langle \sigma_R \rangle = \frac{\sigma_R}{\sqrt{n_p}}$$



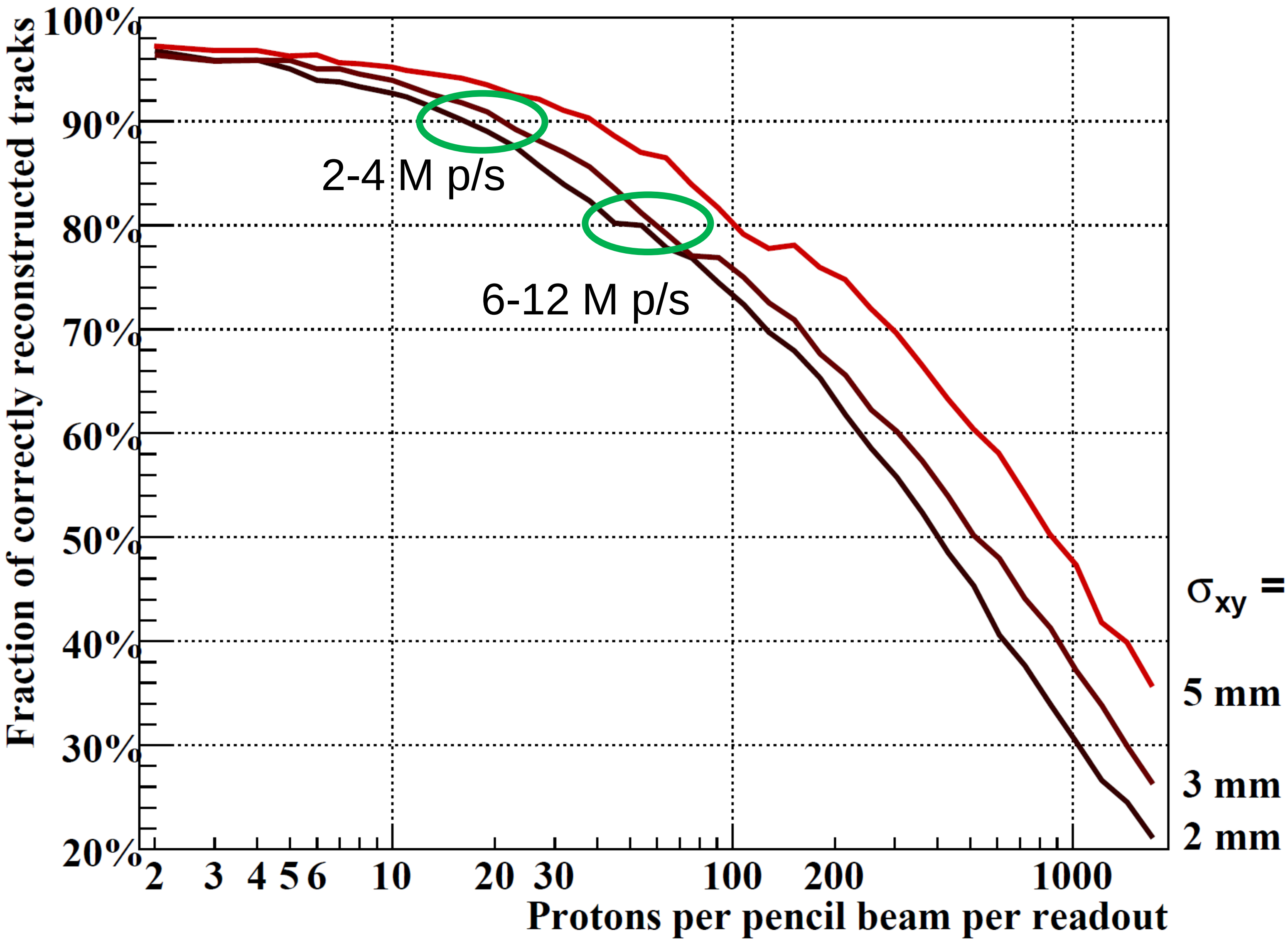
Systematic range error



Tracking quality: Uniform field

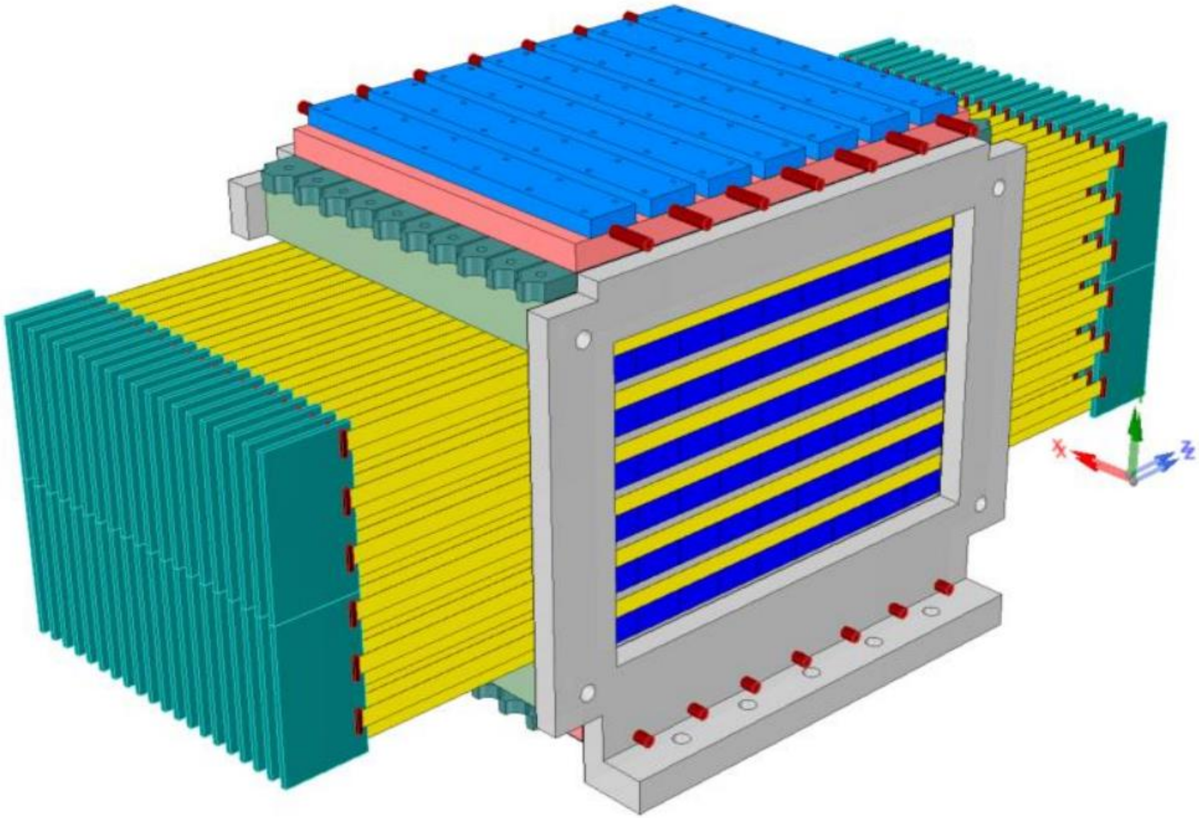


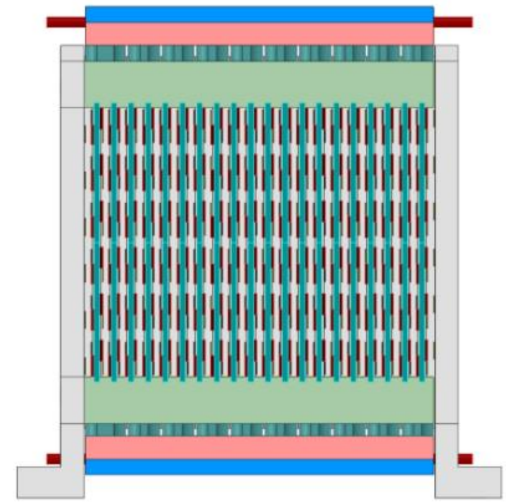
Tracking quality: pencil beam

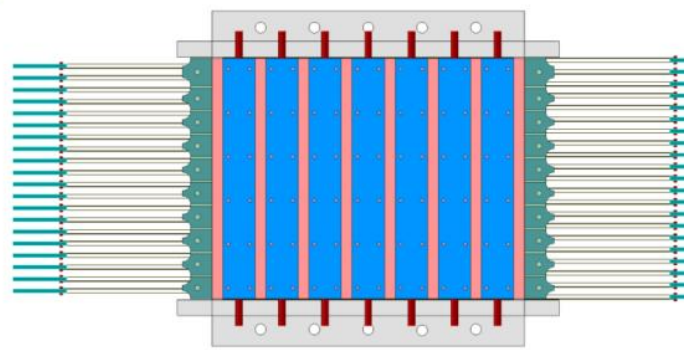


Digital Tracking Calorimeter(DTC)

- **Third(latest) version of proton CT calorimeter design**

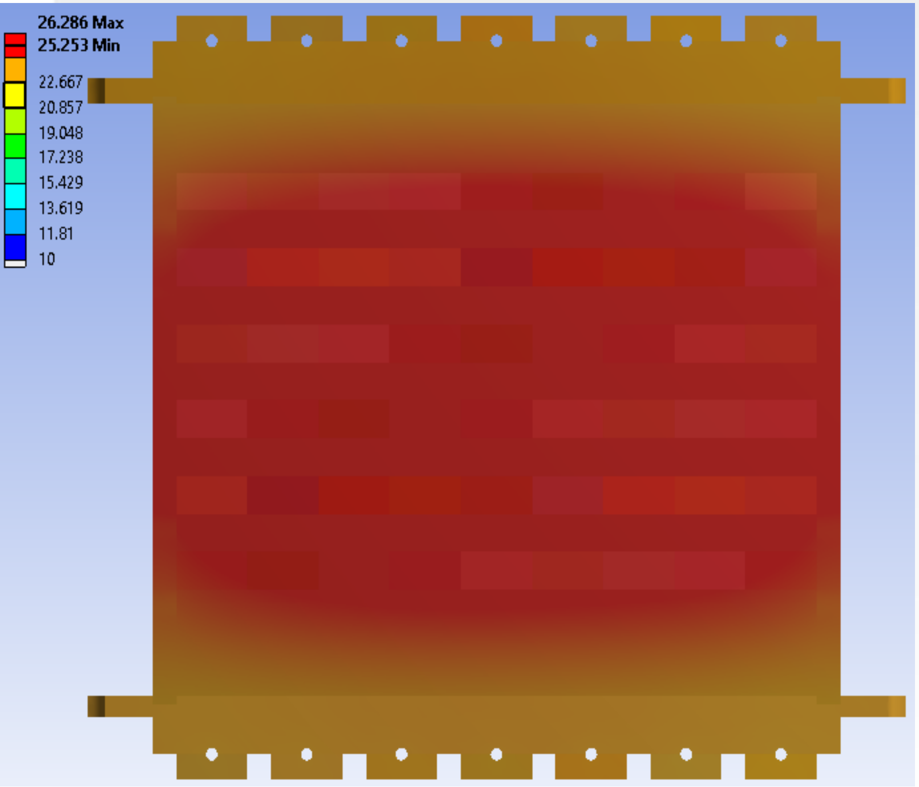




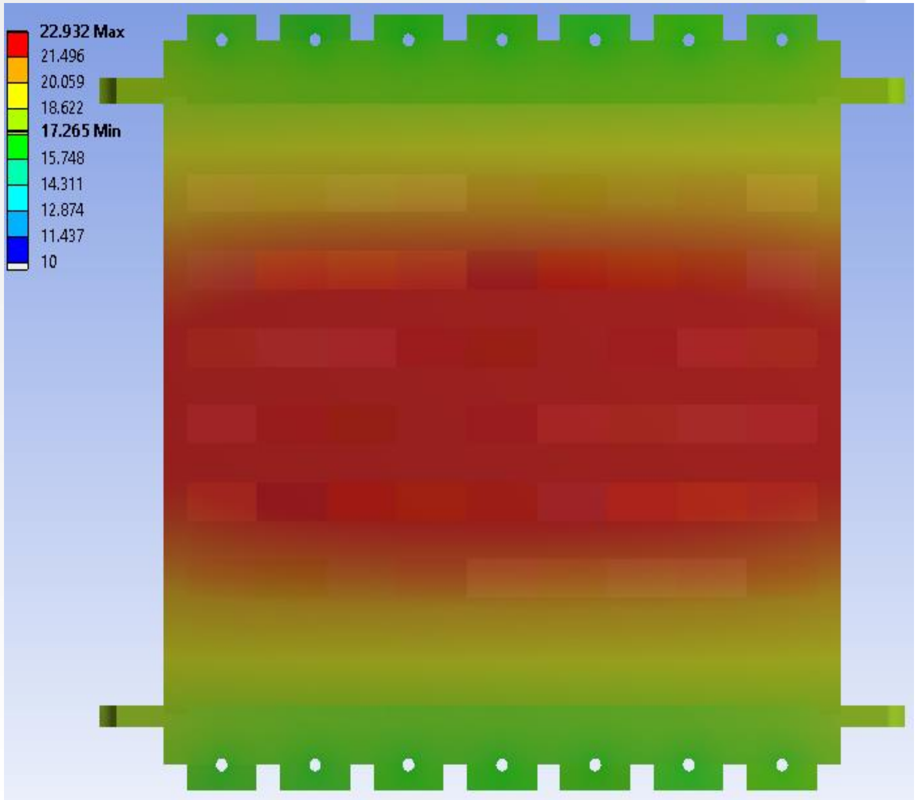


Heat sink design

Air cooled design, max ~26 degrees C



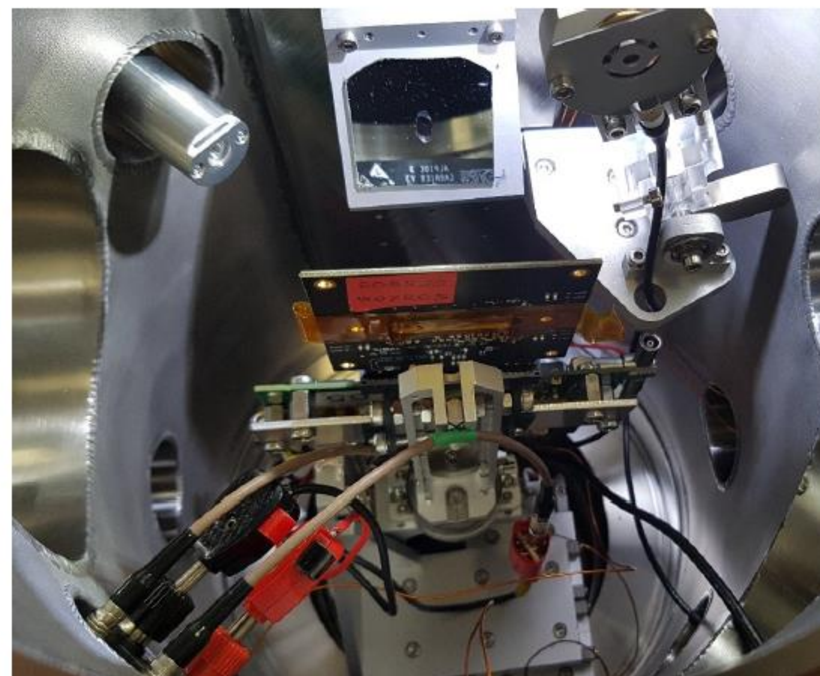
Water cooled design, max ~23 degrees C



Experimental measurements with ALPIDE

Experimental setup

- Beam
  - Ion: Helium-4
  - Energy: 10 MeV (+/- 100 keV)
  - Rate: ~ 2k to 10k ions/sec
  - Trigger rate: 100 kHz (10μs period)

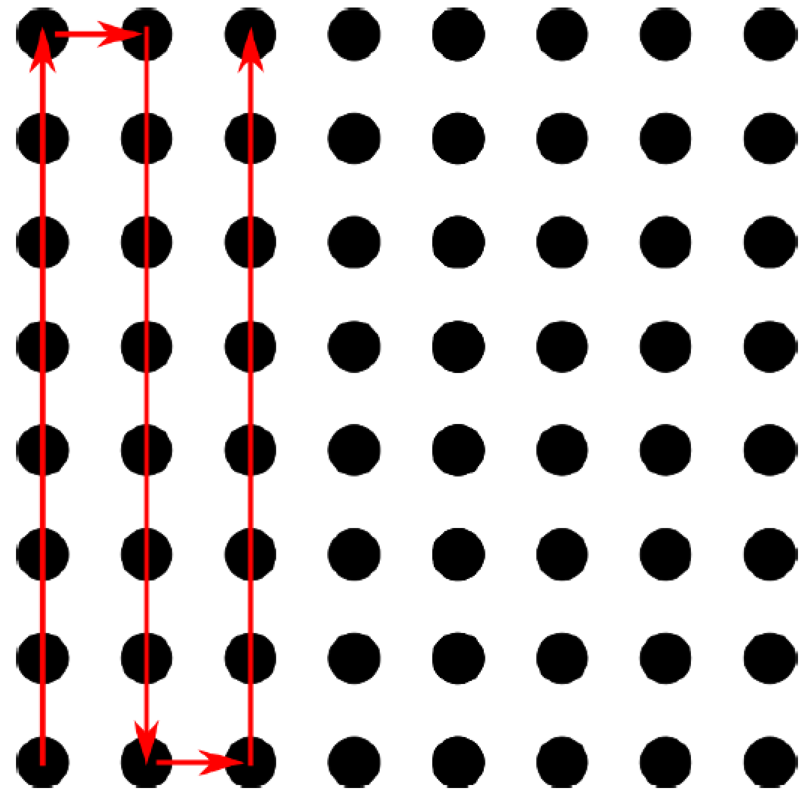


Scan procedure

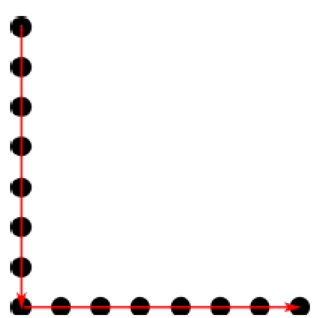
Dataset 180124_192025

- ALPIDE surface was raster scanned
  - Spot size: < 1 µm
  - Spot pitch: 1 µm
  - Spots: 128 x 128
  - Dwell time: 100 ms

  Single Pixel: 28 x 28 spots



- L scan



2.4.1 0V bias

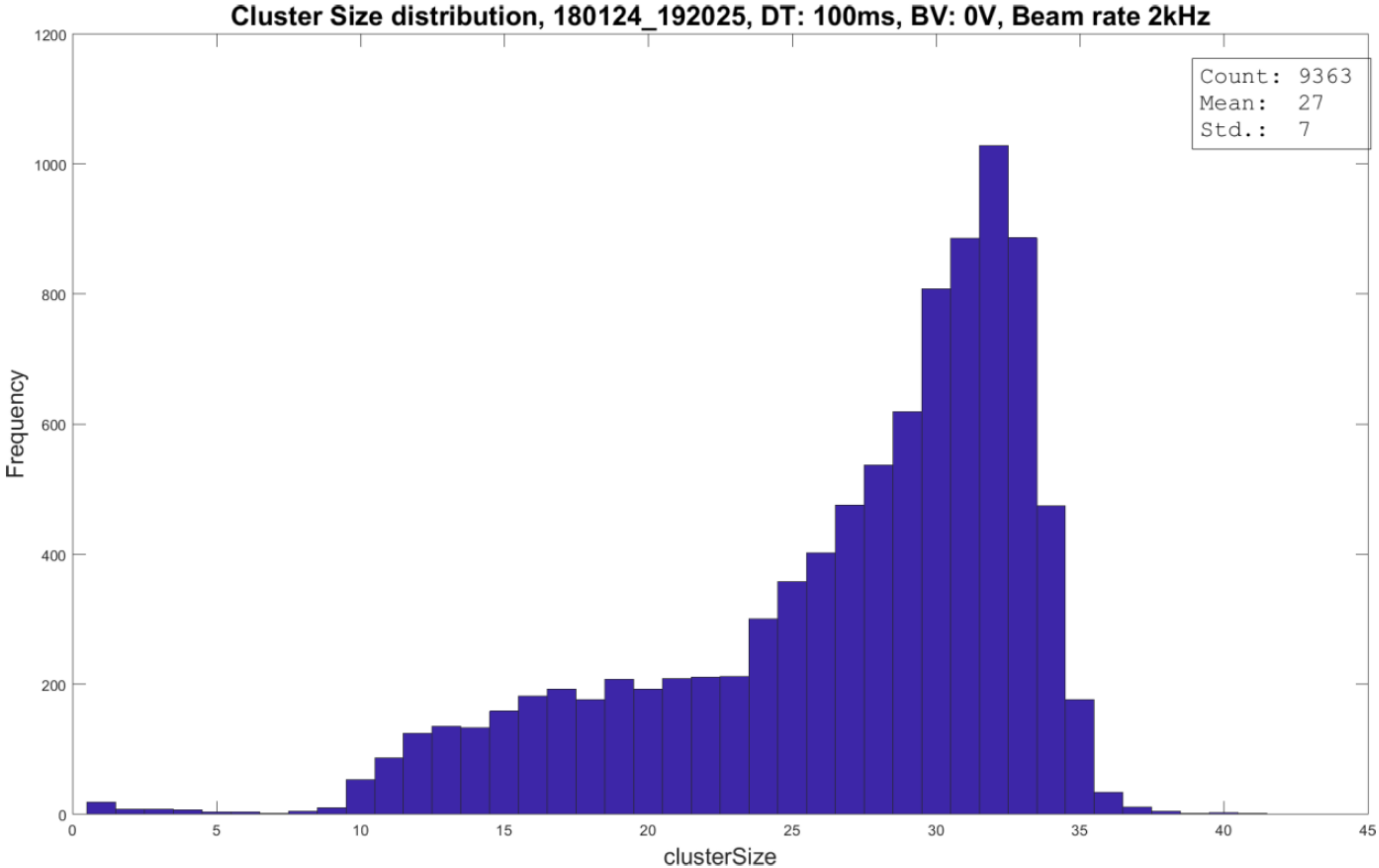
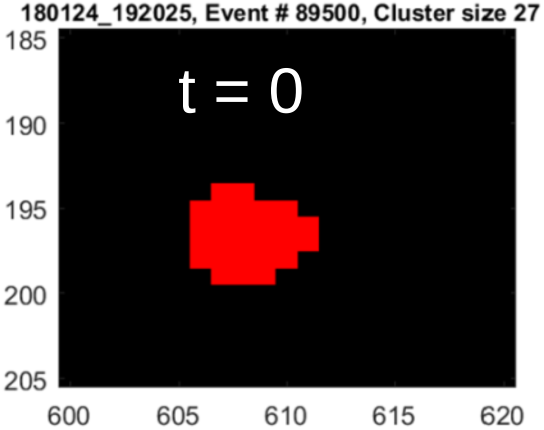
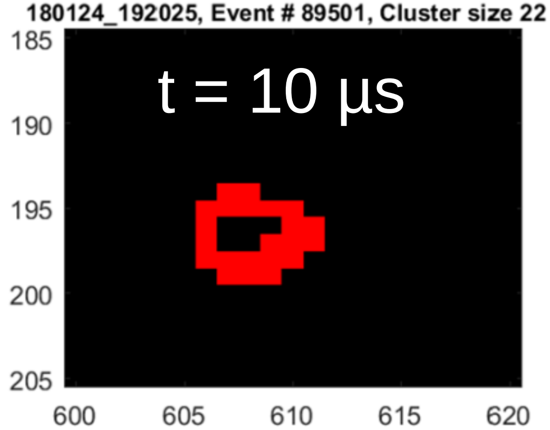
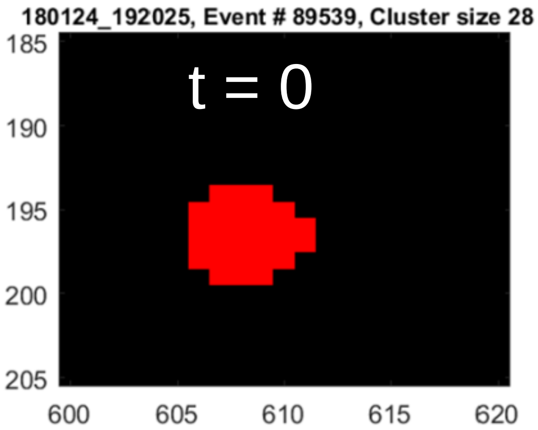
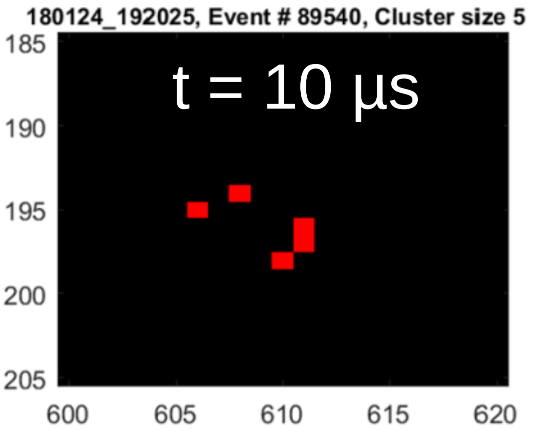


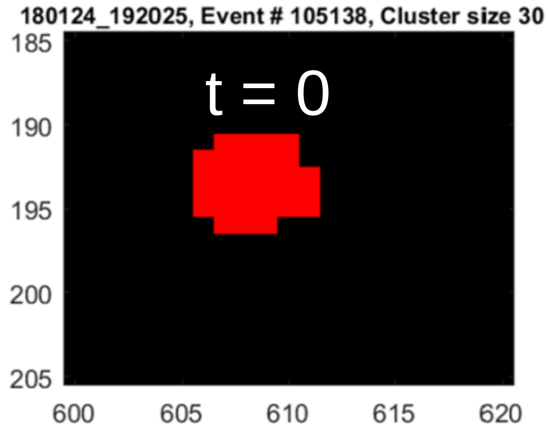
Figure 16: Cluster size distribution after the removal of the smaller clusters in consecutive events with 0 bias voltage.

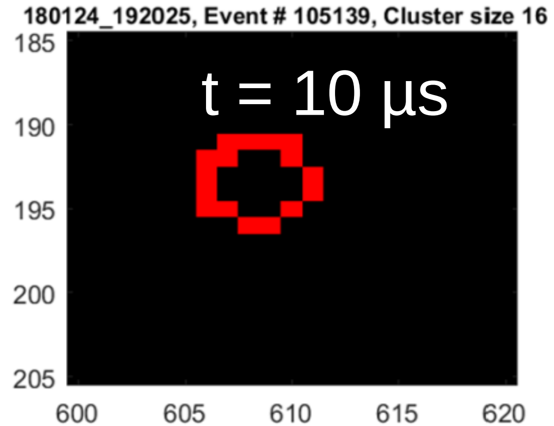

180124_192025, Event # 89500, Cluster size 27
t = 0
185
190
195
200
205
600
605
610
615
620


180124_192025, Event # 89501, Cluster size 22
t = 10 μs
185
190
195
200
205
600
605
610
615
620

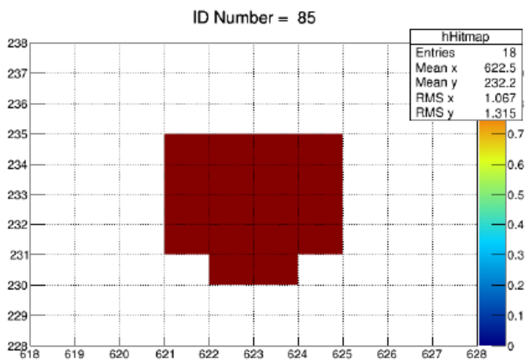

180124_192025, Event # 89539, Cluster size 28
t = 0
185
190
195
200
205
600
605
610
615
620

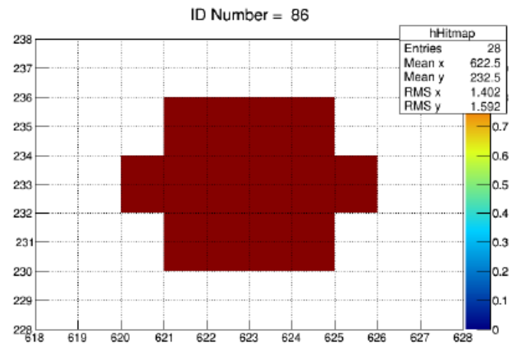

180124_192025, Event # 89540, Cluster size 5
t = 10 μs
185
190
195
200
205
600
605
610
615
620

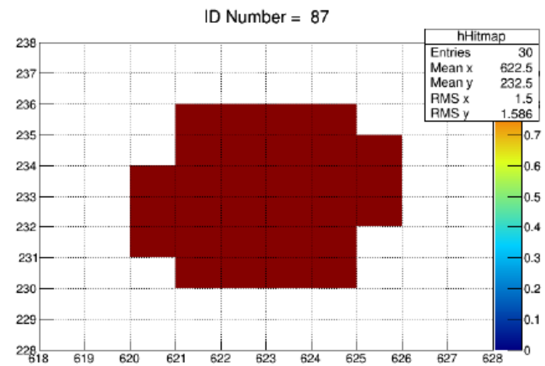

180124_192025, Event # 105138, Cluster size 30
t = 0
185
190
195
200
205
600
605
610
615
620

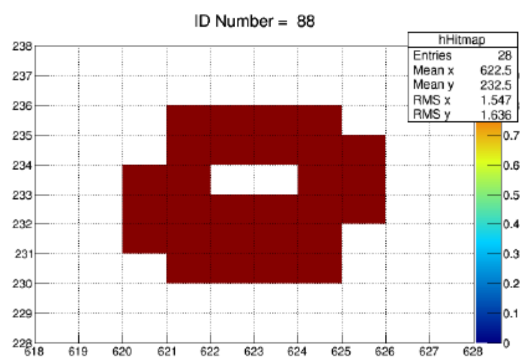

180124_192025, Event # 105139, Cluster size 16
t = 10 μs
185
190
195
200
205
600
605
610
615
620

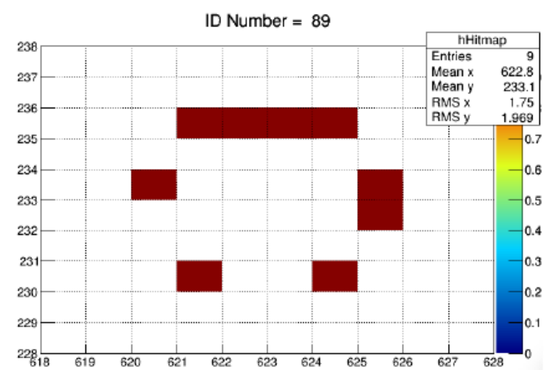
t = 0 | t = 1 µs | t = 2 µs





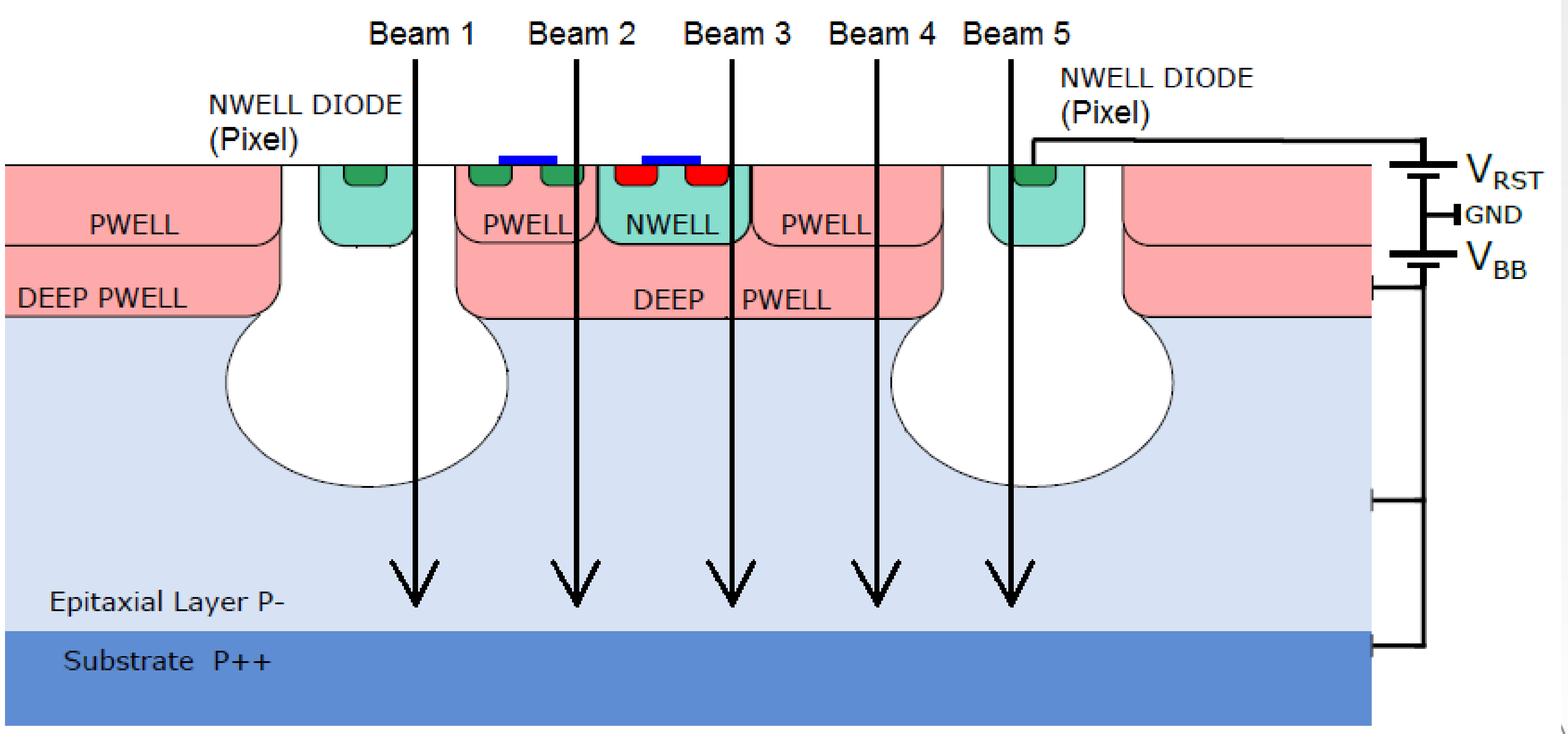


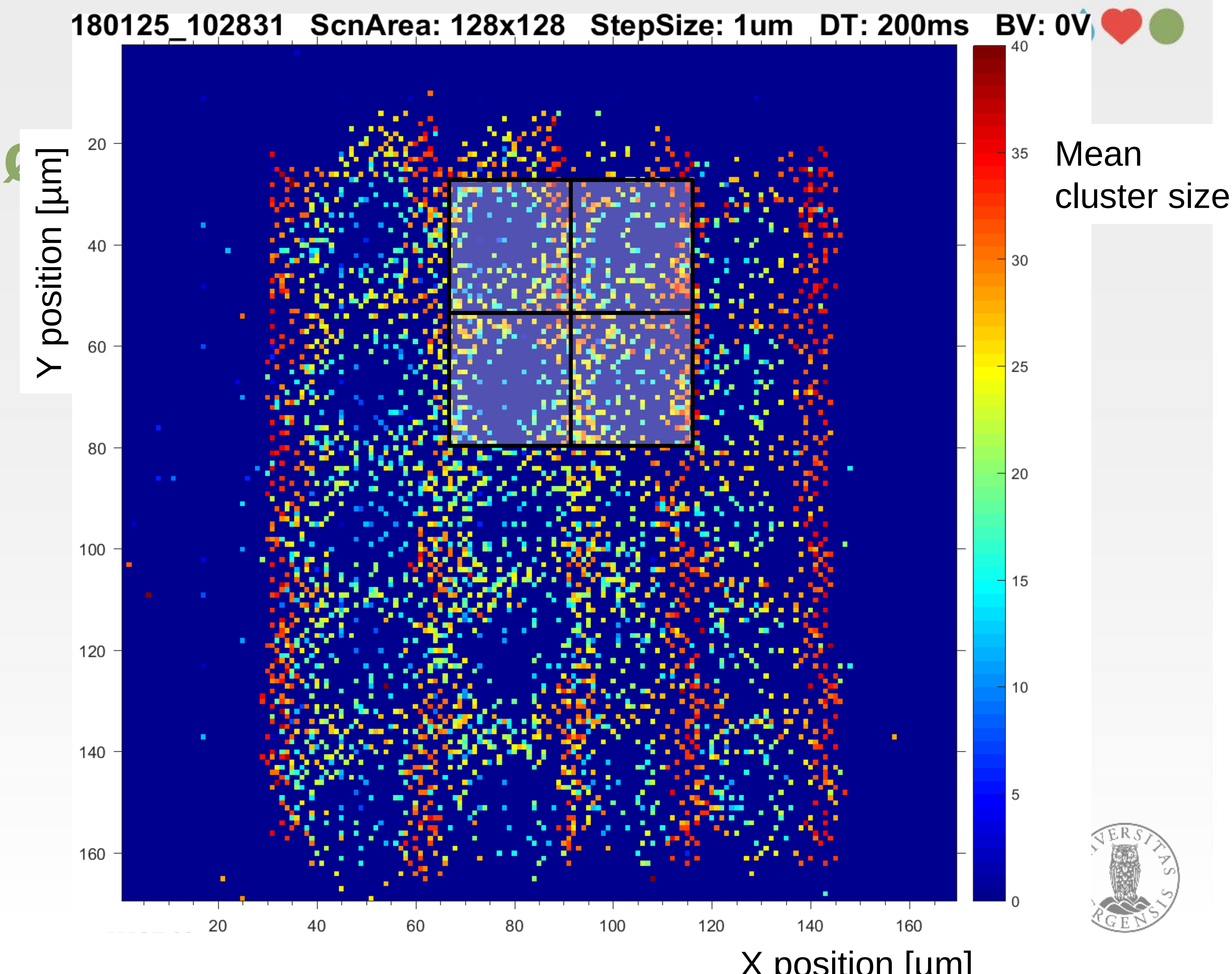




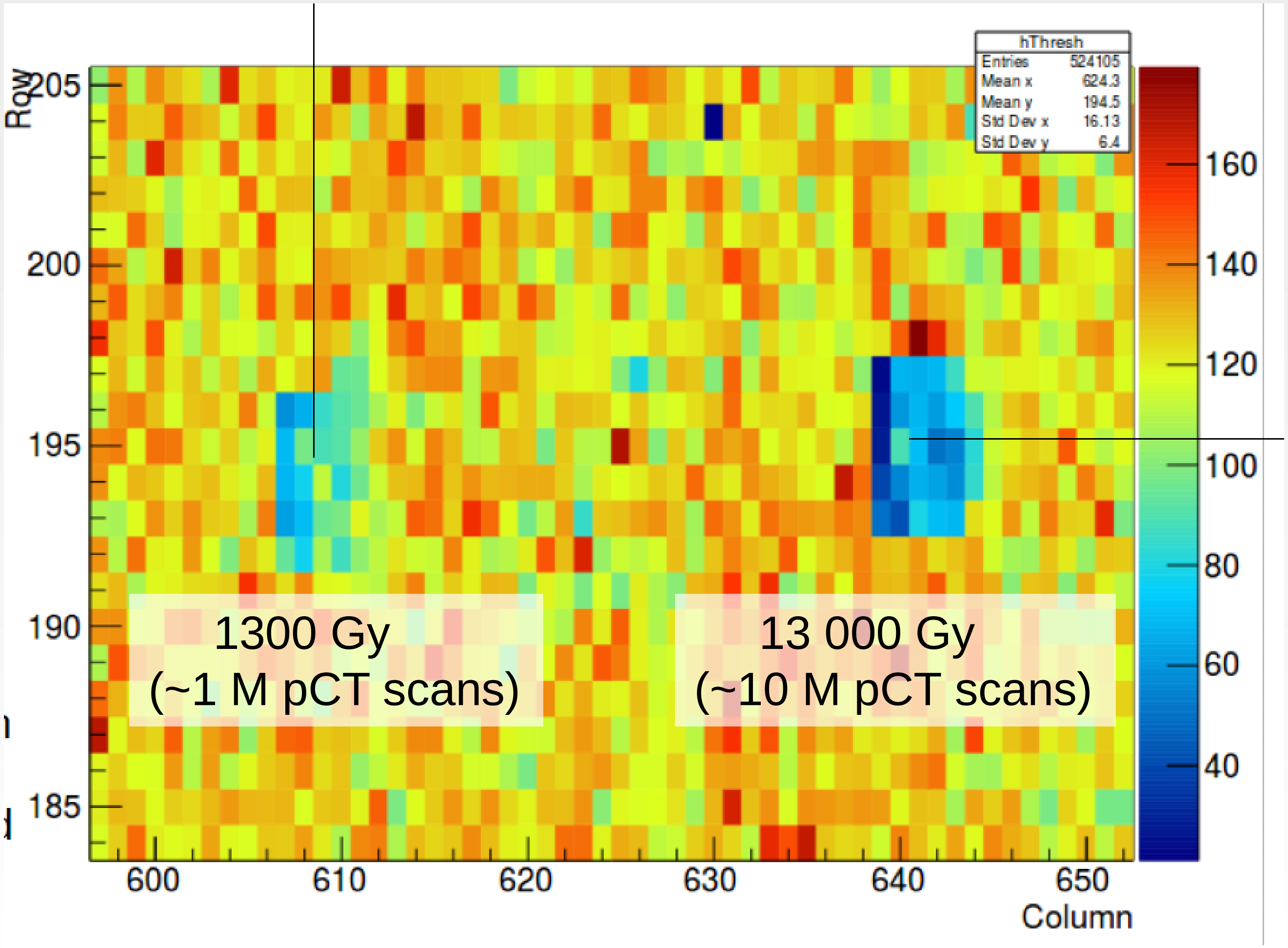
t = 3 µs | t = 4 µs

Incident position vs cluster sizes

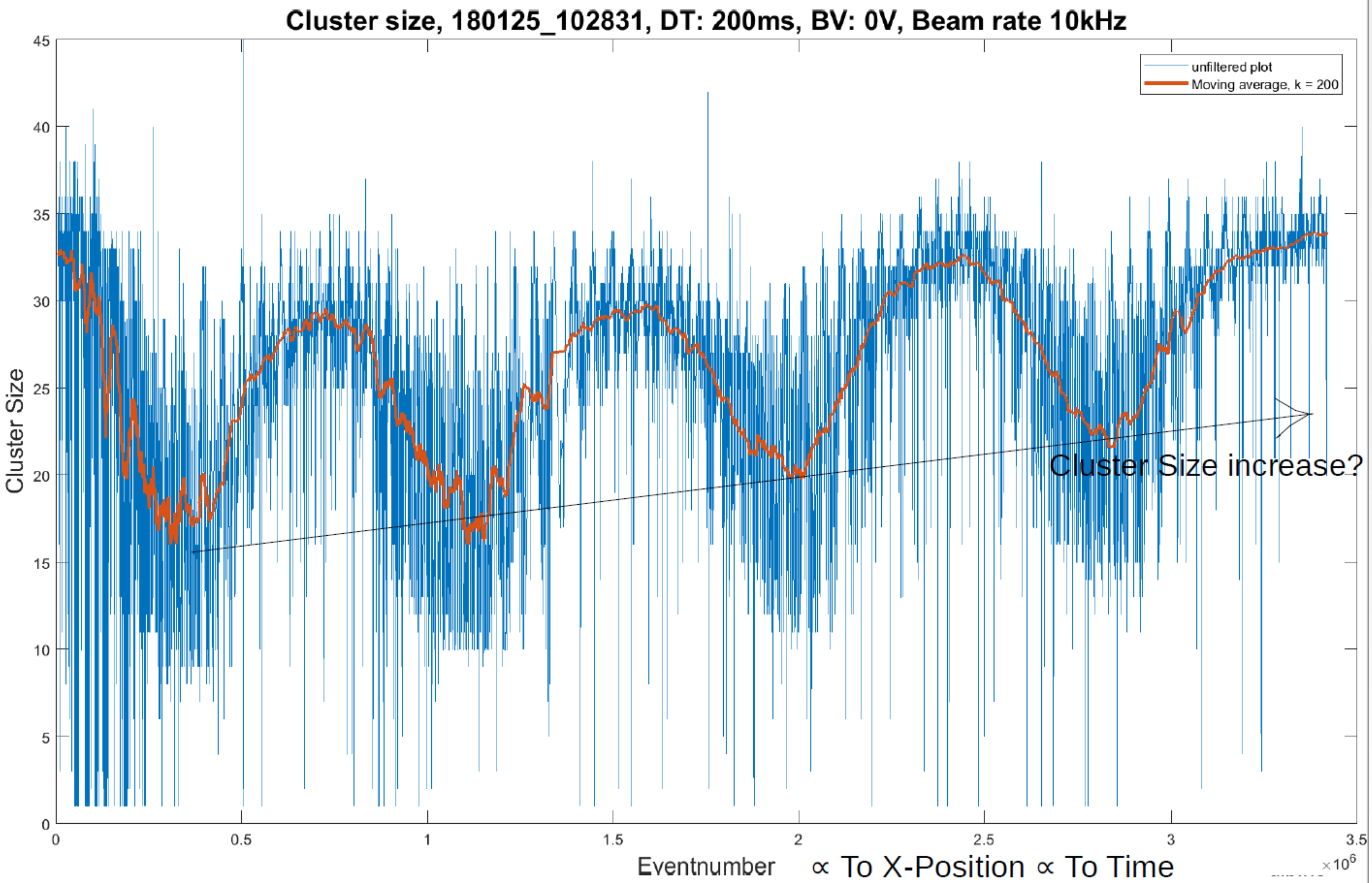



180125_102831 ScnArea: 128x128 StepSize: 1um DT: 200ms BV: 0V
Mean cluster size
Y position [µm]
X position [µm]
20
40
60
80
100
120
140
160
0
5
10
15
20
25
30
35
40

Radiation damage (TID) – threshold values



Radiation damage increases and Threshold goes down -> Increase in Cluster Size?



Conclusions

- Monte Carlo design optimization of 2nd gen DTC
  - Expect high resolution & intensity capacity
  - Under construction: Mounting, DAQ, ...

- What's next:
  - Find resolution of MLP w/one-sided trackers
  - When built: beam test w/phantom
  - (Improve in-detector tracking)

Further reading

- Pettersen, H. "*A Digital Tracking Calorimeter for Proton Computed Tomography.*" PhD, University of Bergen, 2018.
- Pettersen, H. E. S., et al. "*Proton Tracking in a High-Granularity Digital Tracking Calorimeter for Proton CT Purposes.*" NIM A 860C (2017): 51–61
- Pettersen, H. E. S., et al, *Proton Tracking Algorithm in a Pixel Based Range Telescope for Proton Computed Tomography*, submitted to Web of Conferences
- Aglieri Rinella, G. "*The ALPIDE Pixel Sensor Chip for the Upgrade of the ALICE Inner Tracking System*." NIM A 845 (2016): 583–87.

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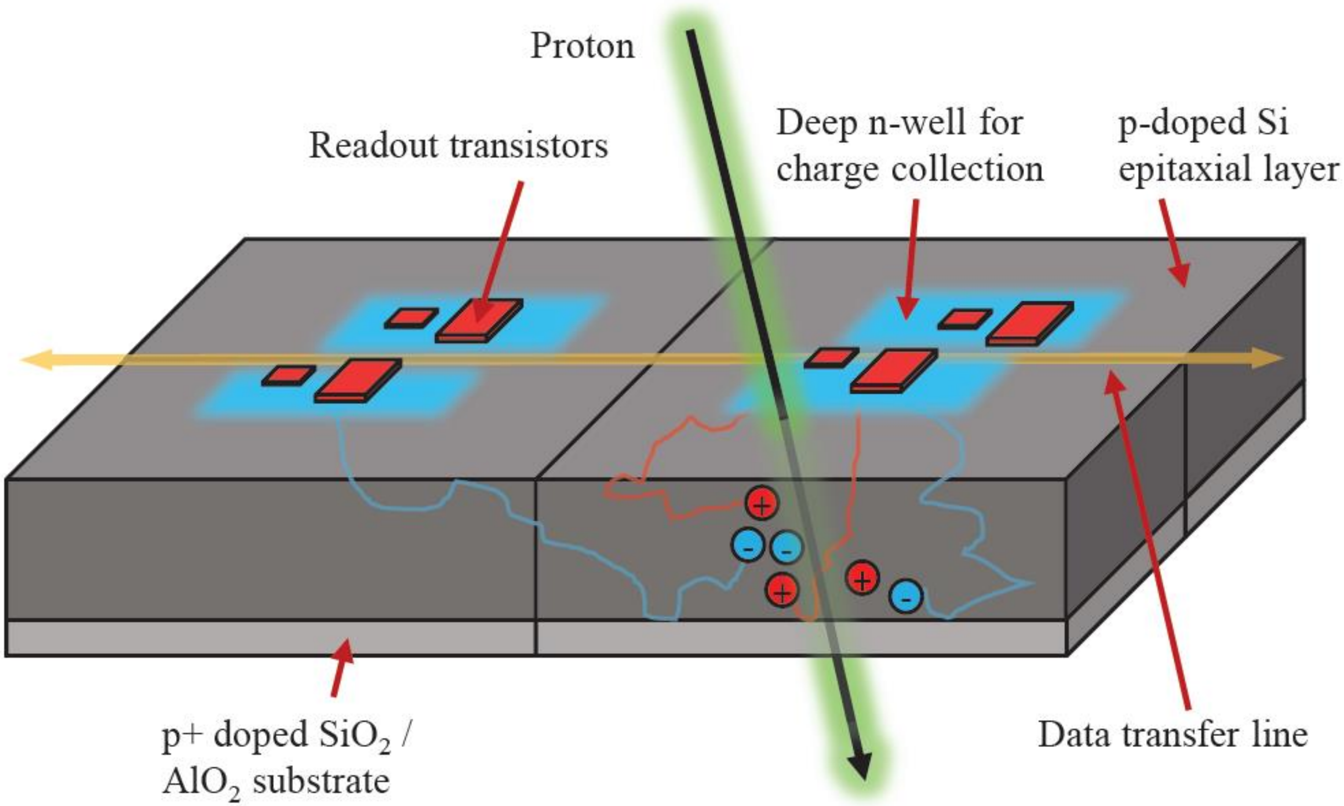
Backup slides

Charge diffusion in pixels



Next prototype: Chips

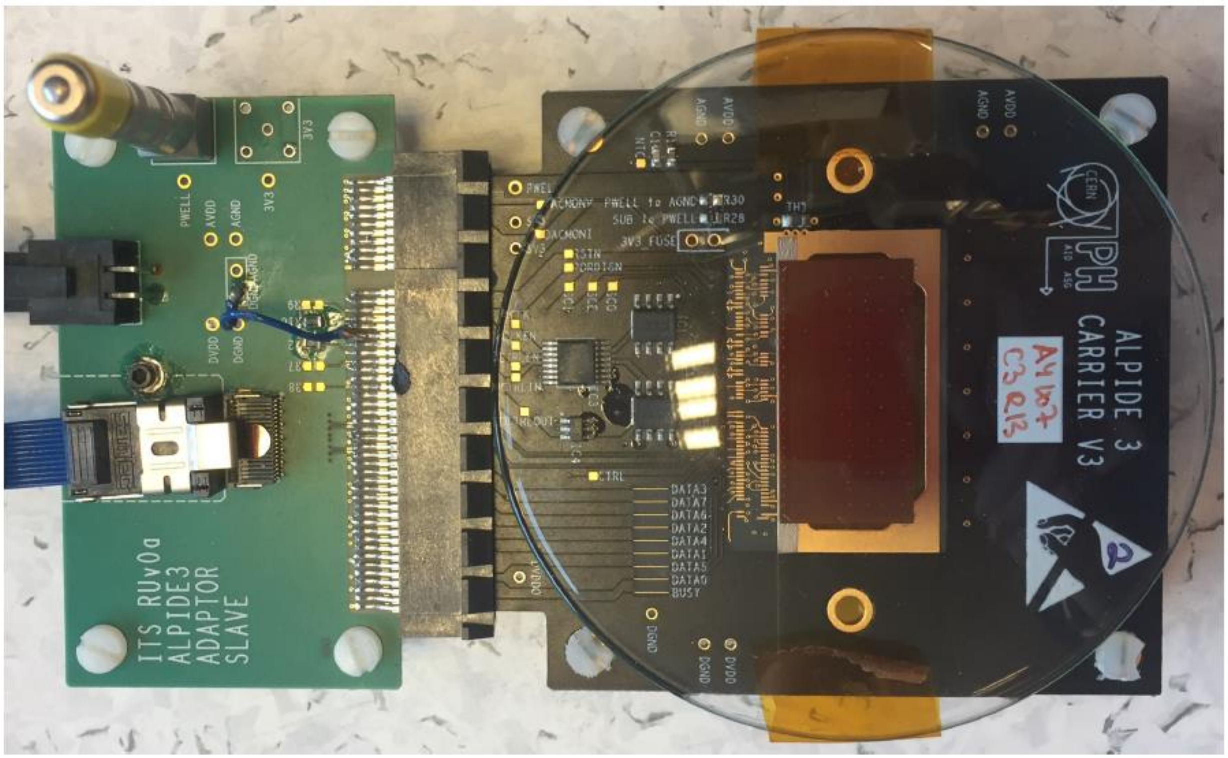


Figure 4.6: On the right: The ALPIDE carrier card. On the left: the ALPIDE adaptor slave.

Digital Tracking Calorimeter(DTC)

- **Chip & read-out electronics**

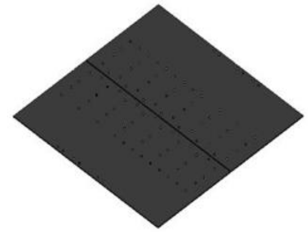
  Chip size = 1.5cm x 3cm

  Demanded sensitive area = 18cm x 27cm

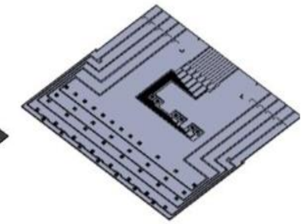
  Space for data readout strip

  Cooling methods & coolant channel

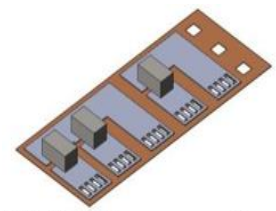
  Uniformity



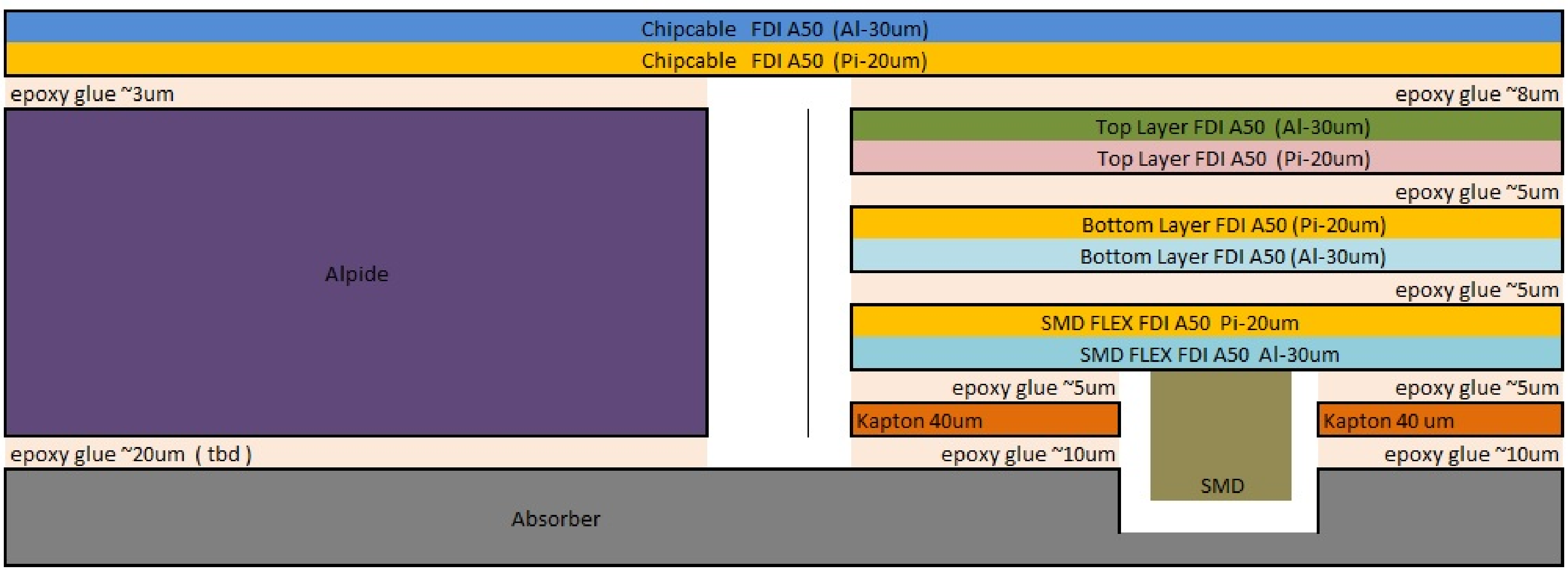
Alpide chip



Chip Cable Type 1



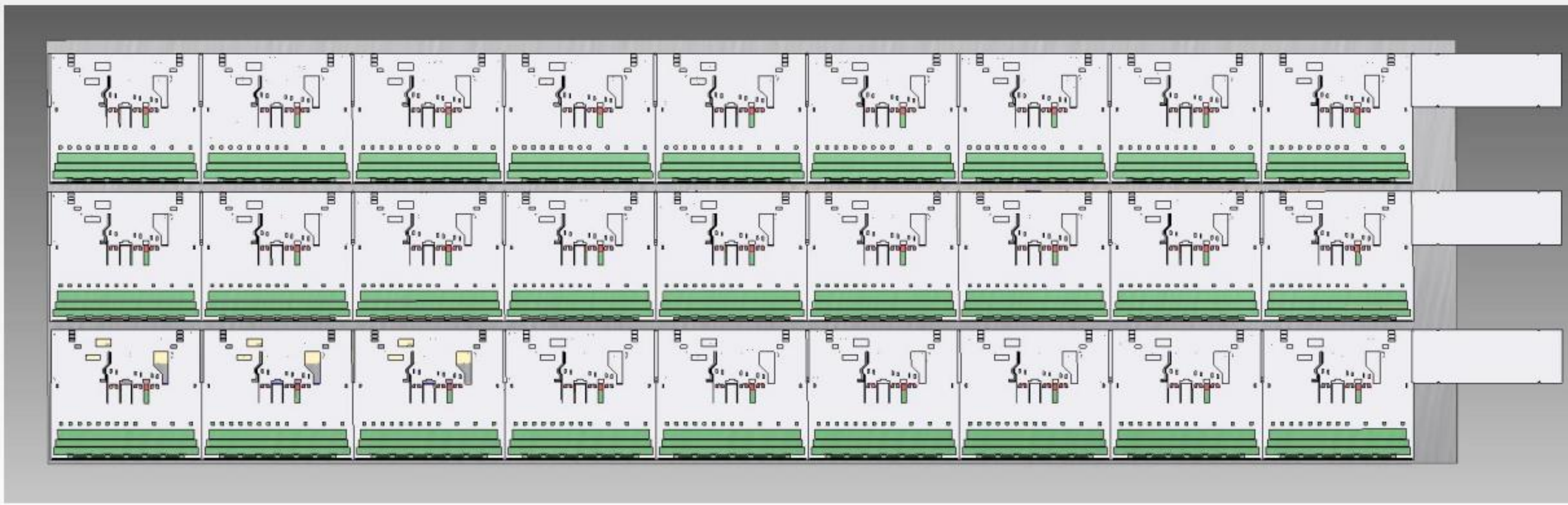
SMD Flexmount



Figures from Slava: ''9 Alpide string'' & Nikhef '' Mock up of Focal slab''

COOP with Utrecth/Kharkiv

- 3-string structure
- Detector layer base (x4 -> 36 chips)



Digital Tracking Calorimeter(DTC)

- **Bonding method**

Mechanical Connection → Ultrasound welding

Dielectric connection → Glue protection

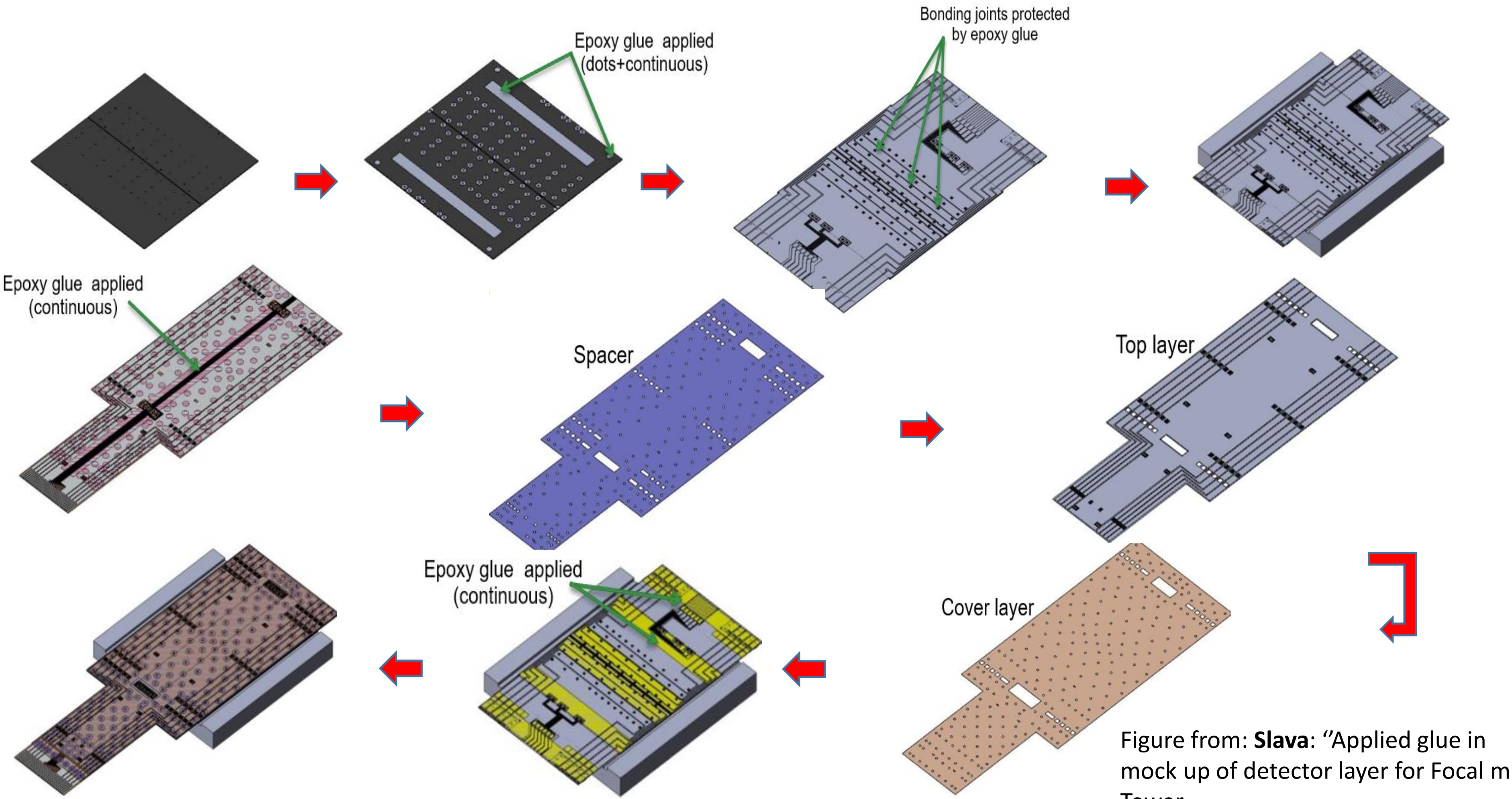


Figure from: **Slava**: ''Applied glue in mock up of detector layer for Focal m Tower

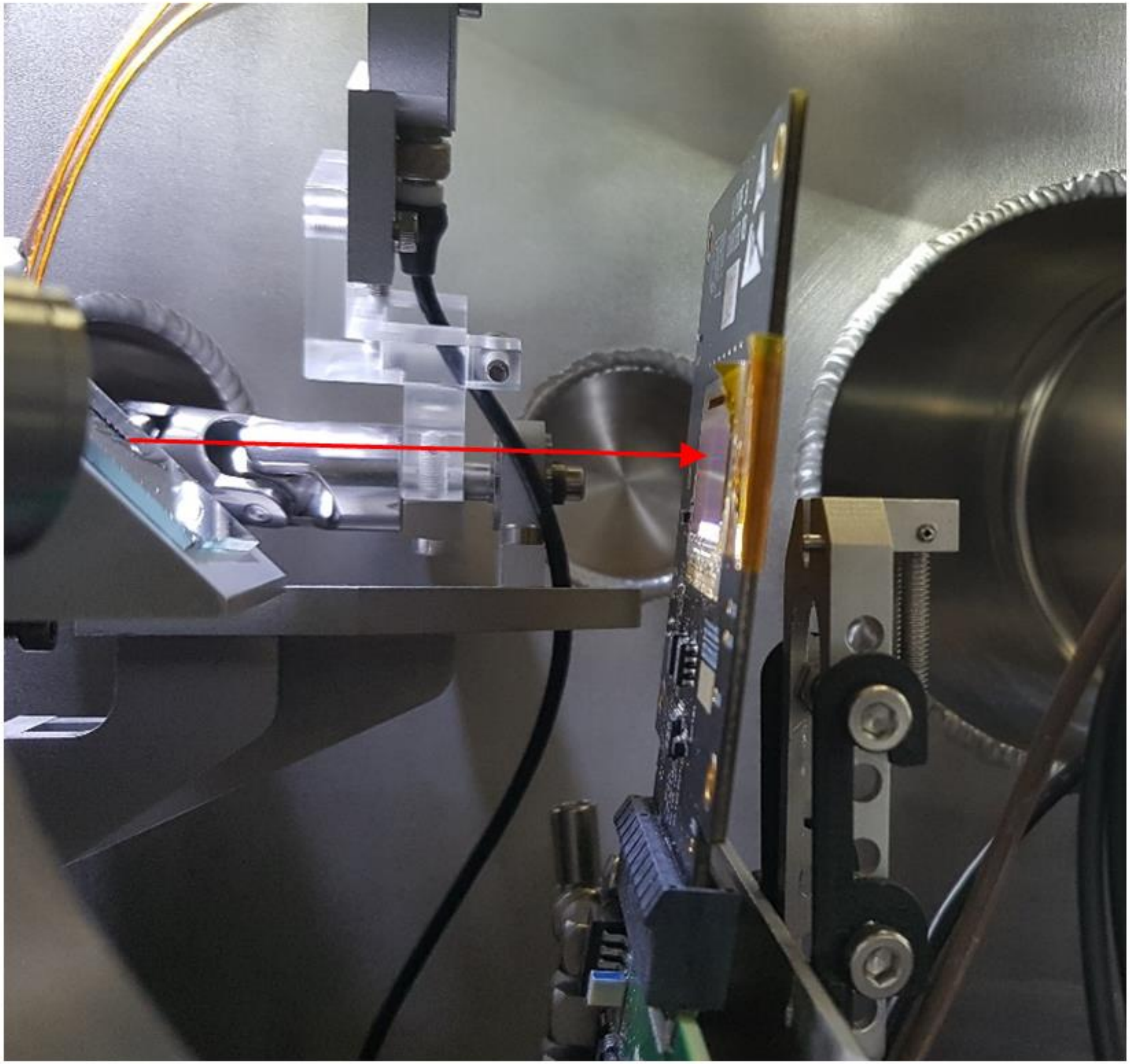
One RU for all systems?

- Interface 24 ALPIDE chips

- Current baseline:
  - Trenz TE820, MPSoC Module with Xilinx Zynq UltraScale+ ZU4CG-1E
  - Affordable
    - Multiple systems can be produced
  - Reuse of firmware/software from VCU118 development

Photo Shows Similar Product

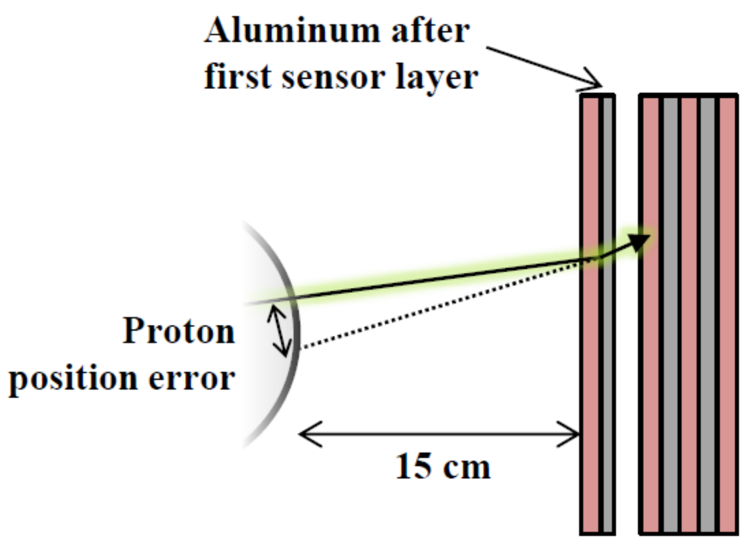
Photo Shows Similar Product

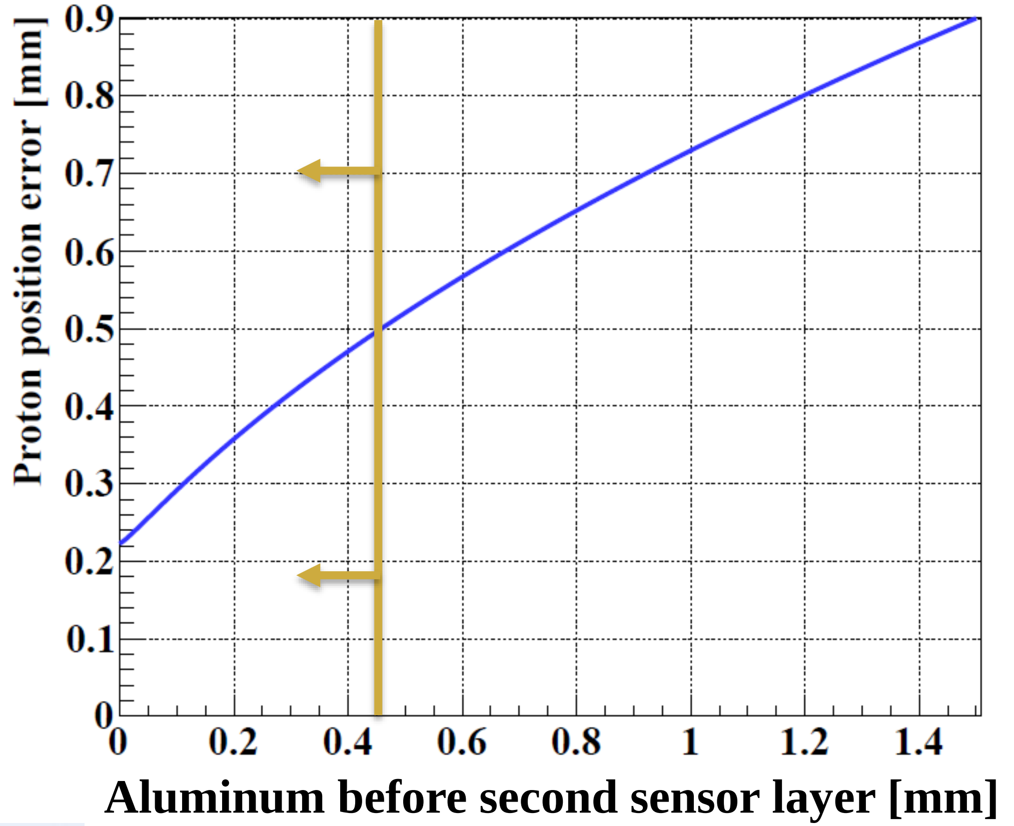


ALPIDE detector inside the vacuum chamber. The red arrow illustrates the beam direction. The ALPIDE is tilted approximately 5° so that it would fit inside the vacuum chamber.

HELSE BERGEN
Haukeland University Hospital

Scattering in first layers





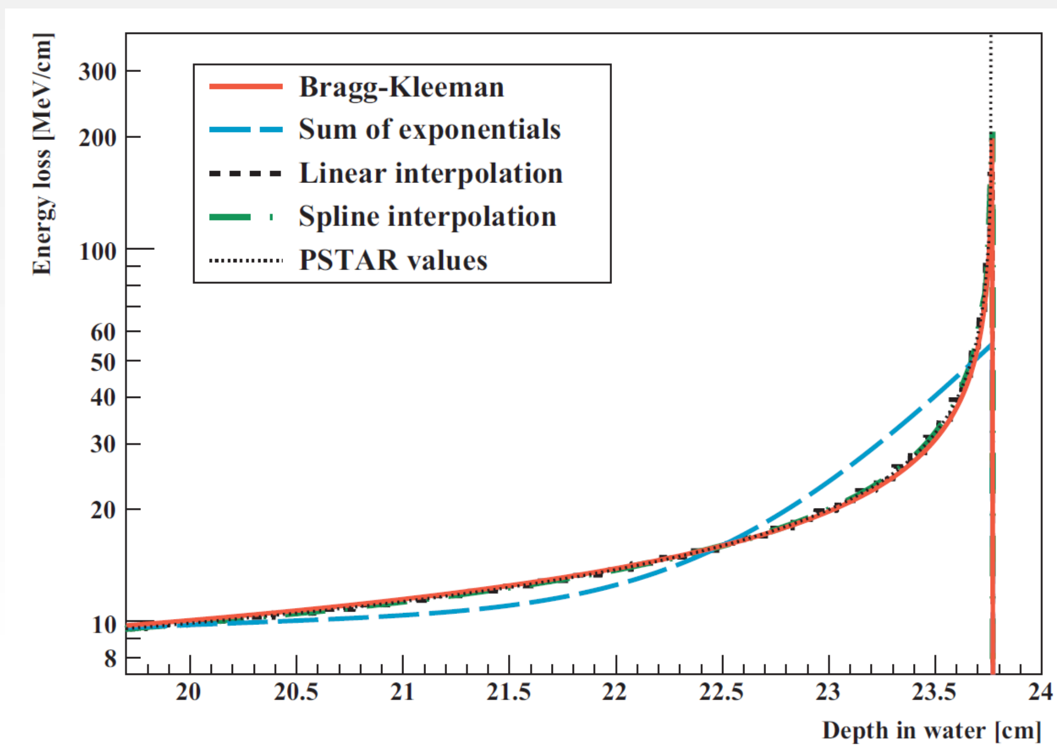
$$\theta_0 \simeq \frac{14.1 \text{ MeV}}{p_1 v_1} \sqrt{\frac{x}{X_0}} \left(1 + \frac{1}{9} \log_{10} \frac{x}{X_0}\right)$$

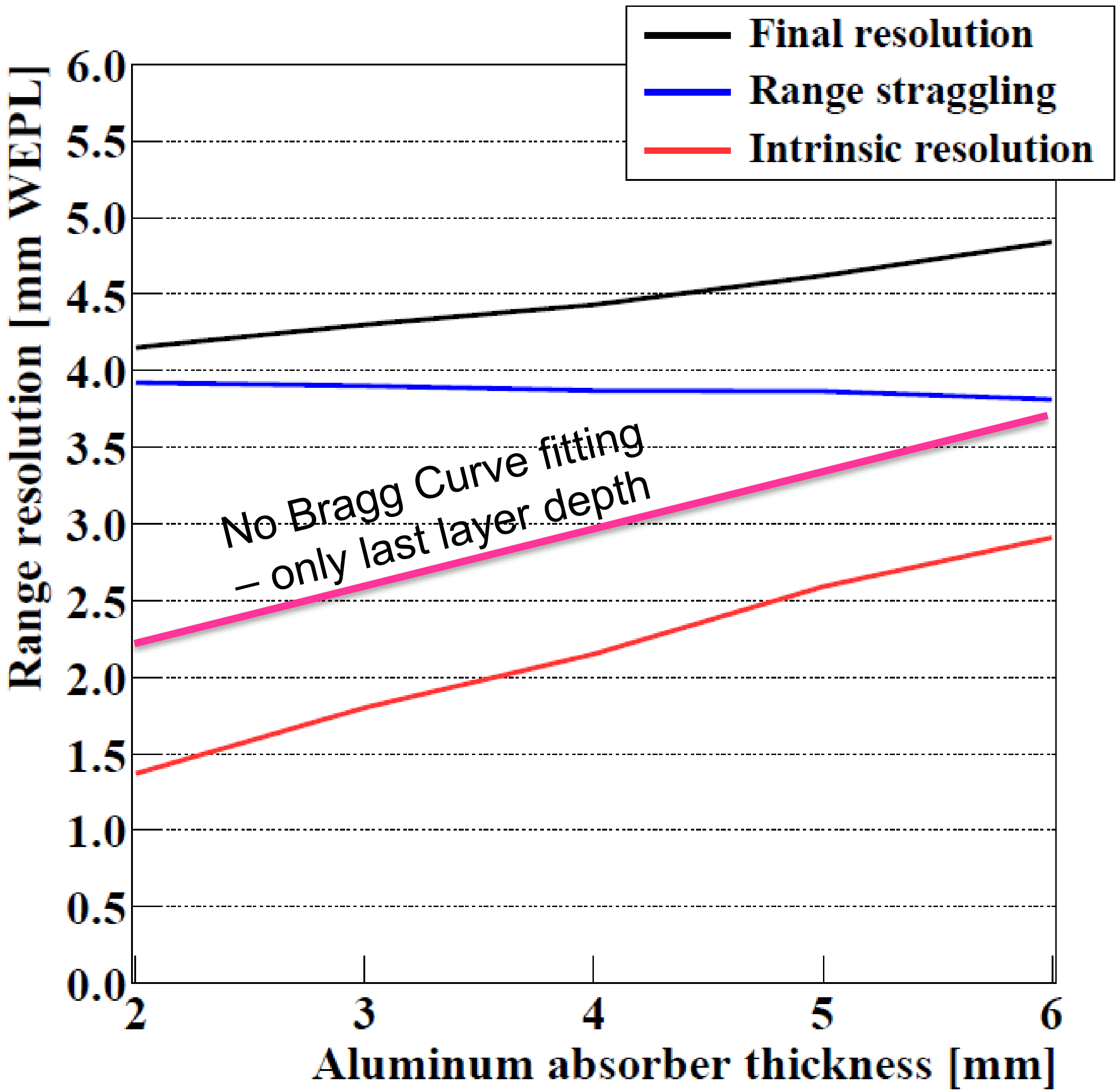
Dose to detector

- 200 M protons for pCT image
- 40 layers * ~300 keV/layer = 12 MeV / proton
- Weight of pixel sensors = 700 g
- 200 M * 12 MeV / 700 g ~ 1 mGy

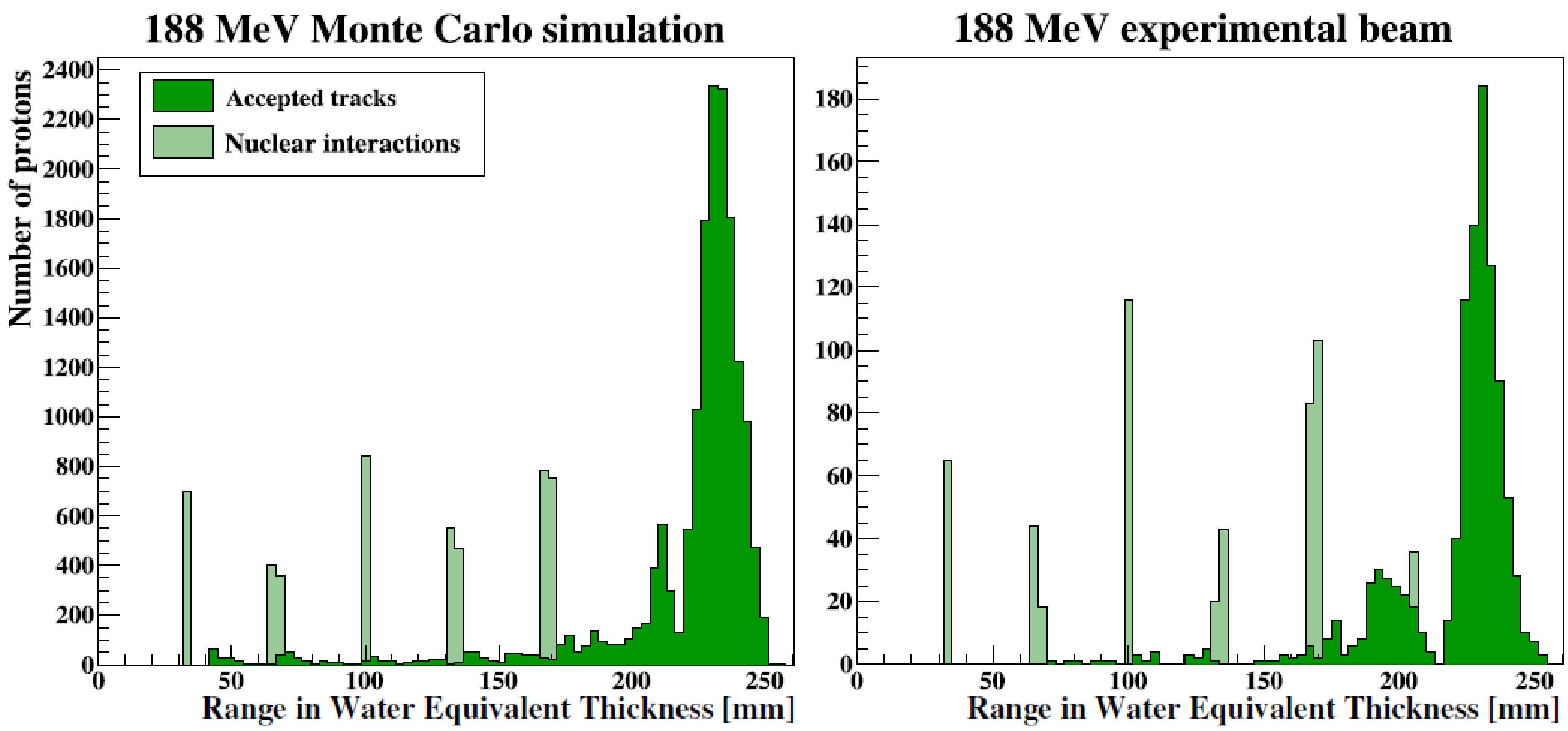
- The Bragg-Kleeman range-energy relationship, $R = \alpha E^p$, can be rewritten to give an accurate depth-dose curve for a *single* proton:

$$\frac{\mathrm{d}E}{\mathrm{d}z} = \frac{(R-z)^{1/\mathrm{p}-1}}{p\alpha^{1/\mathrm{p}}}$$



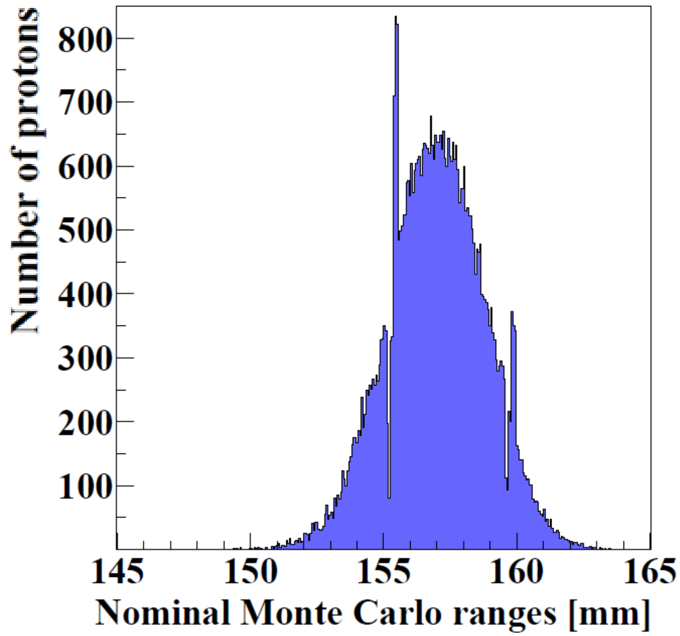

Final resolution
Range straggling
Intrinsic resolution
No Bragg Curve fitting
– only last layer depth
Range resolution [mm WEPL]
Aluminum absorber thickness [mm]
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
2
3
4
5
6

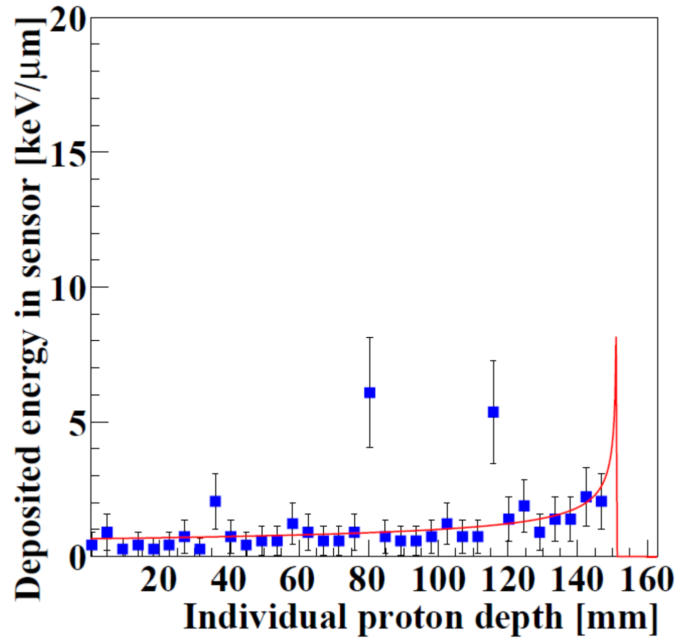
The ranges from many protons

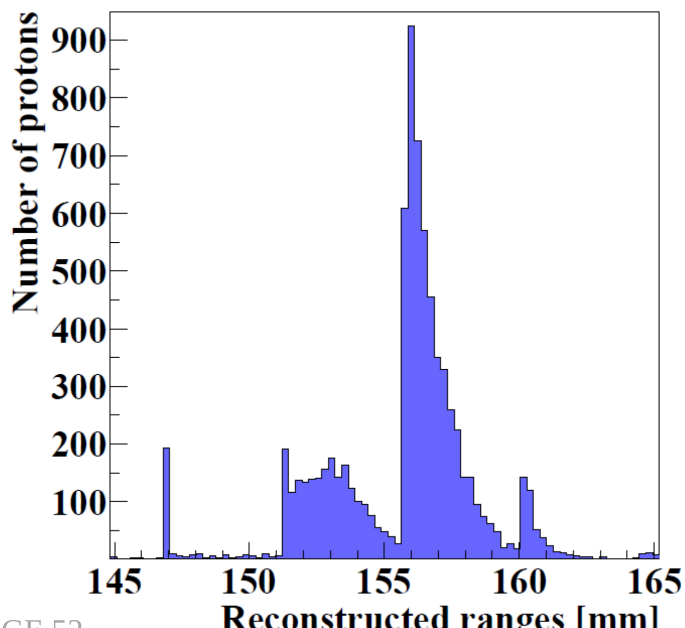


$$\langle\hat{R}\rangle = \frac{\sum_{i=i'}^{\infty} w_i x_i}{\sum_{i=i'}^{\infty} w_i},$$

$$\langle\hat{\sigma}_R\rangle = \sqrt{\frac{\sum_{i=i'}^{\infty} w_i(x_i - \langle\hat{R}\rangle)^2}{[\sum_{i=i'}^{\infty} w_i] - 1}}$$







$$\langle \hat{R} \rangle = \frac{\sum_{i=i'}^{\infty} w_i x_i}{\sum_{i=i'}^{\infty} w_i},$$

$$\langle \hat{\sigma}_R \rangle = \sqrt{\frac{\sum_{i=i'}^{\infty} w_i (x_i - \langle \hat{R} \rangle)^2}{[\sum_{i=i'}^{\infty} w_i] - 1}}$$

Material	PMMA	Graphite	Aluminum	Copper	Tungsten
4 mm WET equivalent [mm]	3.46	2.24	1.9	0.66	0.4
Scattering angle [mrad]	3.25	4.7	6.0	9.2	15.3
Neutron yield [10^{-4}]	69.2	71.9	80.9	74.1	26.9
Thermal conductivity [W/mK]	0.25	25–240	205	401	174
Thermal Expansion [10^{-6} K^{-1}]	70	4–8	21–24	16	4.5

Table 5.1: *Properties of the potential absorber materials (Particle Data Group, 2015; Touloukian et al., 1971; Goodfellow Inc., 2018).*

Absorber thickness [mm]	2	2.5	3	3.5	4	4.5	5	5.5	6
Layers needed (230 MeV)	66.6	55.2	47.1	41.1	36.5	32.8	29.7	27.2	24.4
Layers needed (200 MeV)	52.8	43.8	37.4	32.6	29	26	23.6	21.6	20

Table 5.2: *The number of layers needed to contain a 230 MeV and a 200 MeV beam, respectively, in the different geometries, when a necessary extra margin corresponding to a distance of three times the range straggling is added.*

Beam energy [MeV]	120	160	180	139	170	188	151
Layers covered	1	1	1	2	2	2	3
Nominal range R [mm]	105.9	175.7	215.9	137.5	195.7	232.7	158.8
Reconstructed range $\langle \hat{R} \rangle$ [mm]	97.0	164.0	196.2	132.2	188.5	231.1	137.8
Range error $\langle \langle \hat{R} \rangle - R \rangle$ [mm]	-8.9	-11.7	-19.6	-5.2	-7.2	-1.6	-21.0
Rel. range error [%]	-8.4	-6.7	-9.1	-3.9	-3.7	-0.7	-13.2
Nom. range straggling σ_R [mm]	2.6	2.8	2.8	2.6	2.8	2.8	2.7
Range uncertainty $\langle \hat{\sigma}_R \rangle$ [mm]	6.5	6.3	7.5	19.1	16.3	25.1	17.4
Rel. range uncertainty [%]	6.1	3.6	3.5	13.9	8.3	10.8	11.0

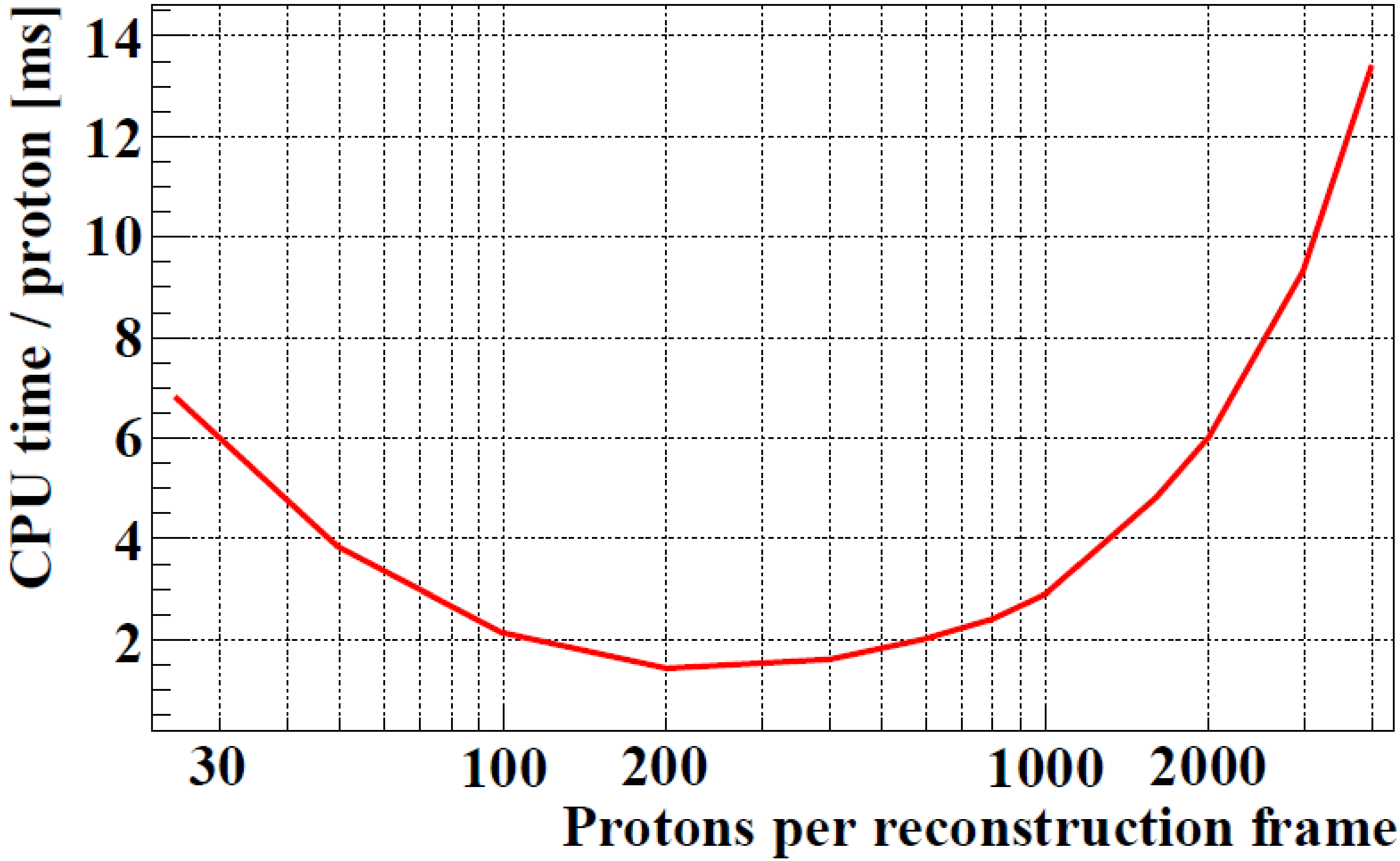
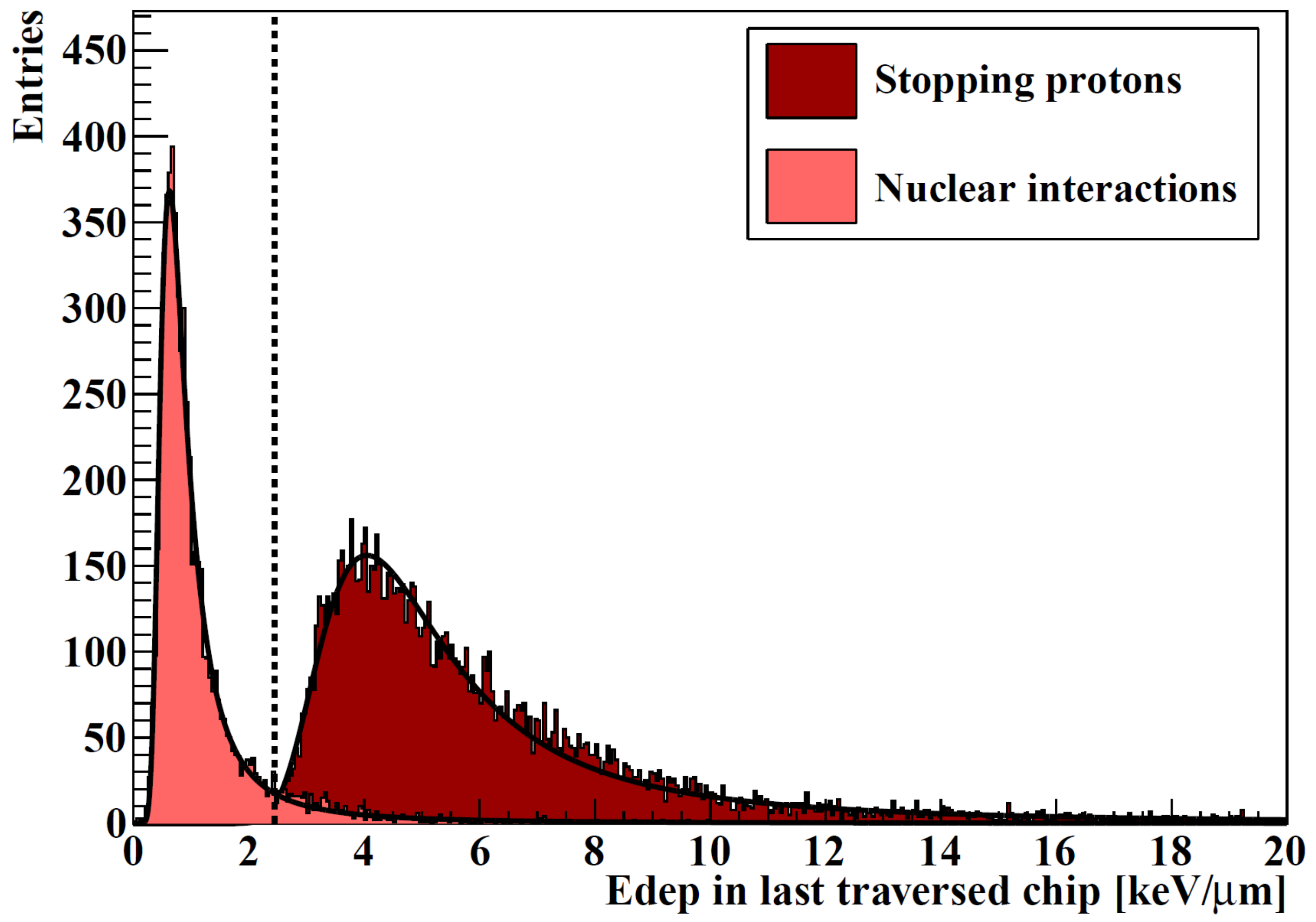
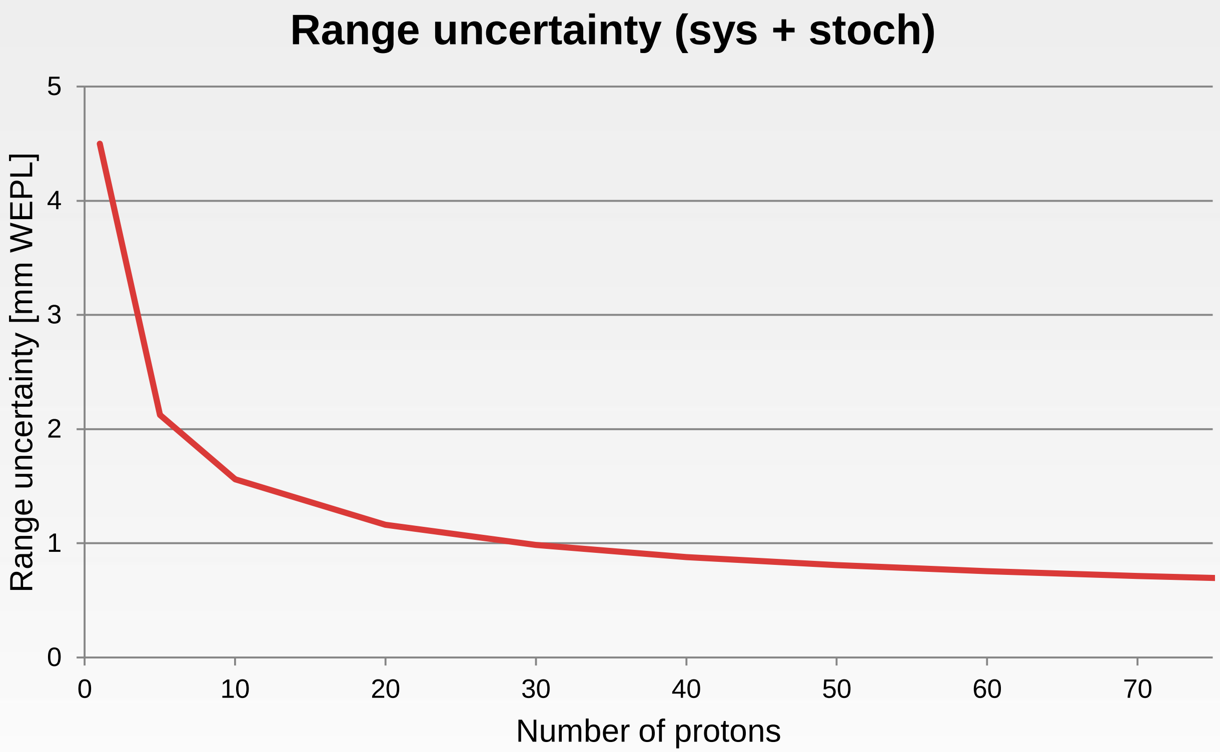


Figure 6: *The CPU time spent on proton track reconstruction. Below 100 protons per reconstruction-frame, the (constant) time spent on reconstruction overhead becomes a large fraction of the total time.*

Charge clustering model




Range uncertainty (sys + stoch)
Range uncertainty [mm WEPL]
0
1
2
3
4
5
0
10
20
30
40
50
60
70
Number of protons