Update on the pCT project in Bergen

Proton Imaging Workhop, Loma Linda

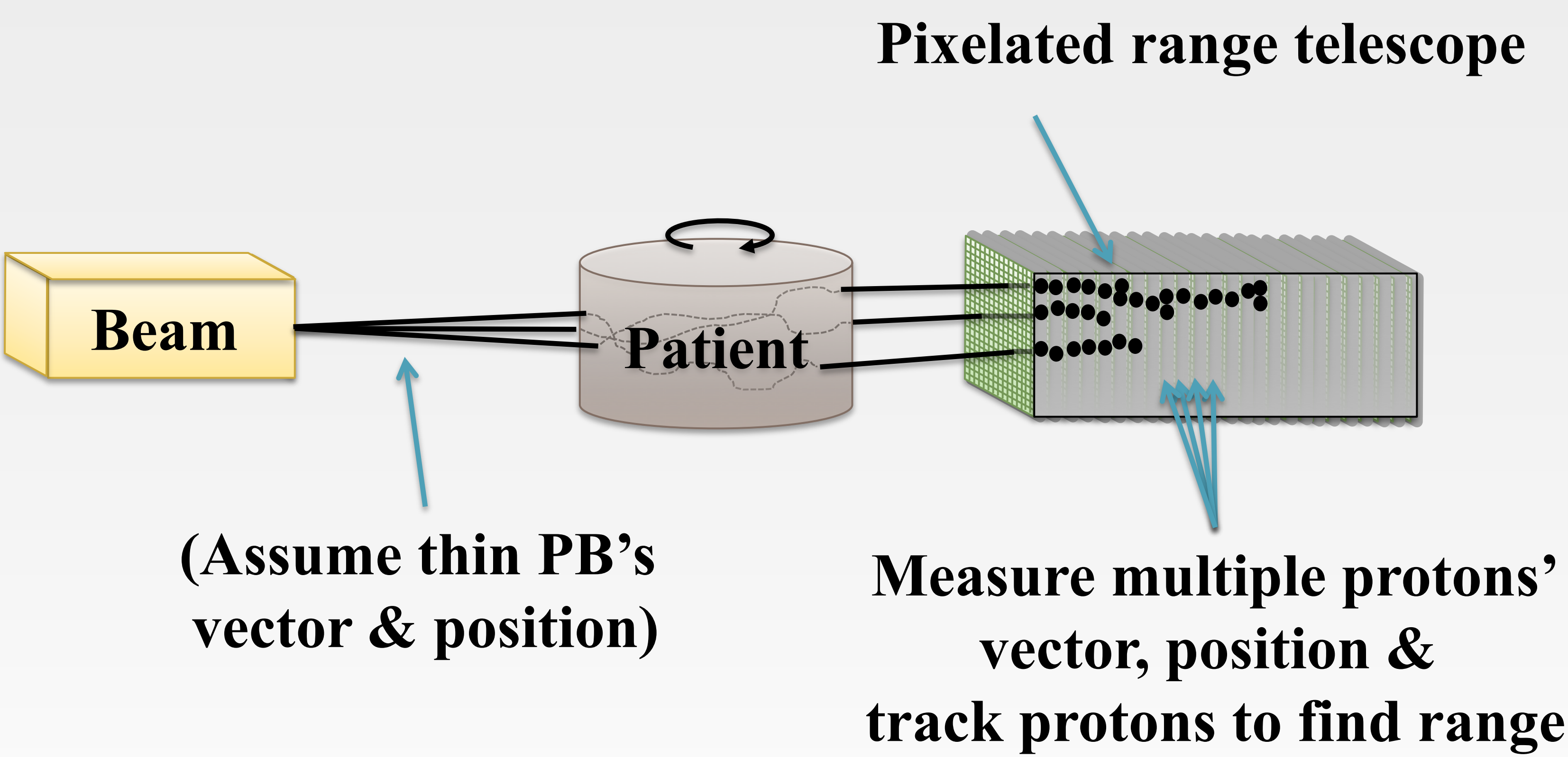
Helge E. S. Pettersen, PhD
On behalf of the pCT project in Bergen

6 — 8 August 2018

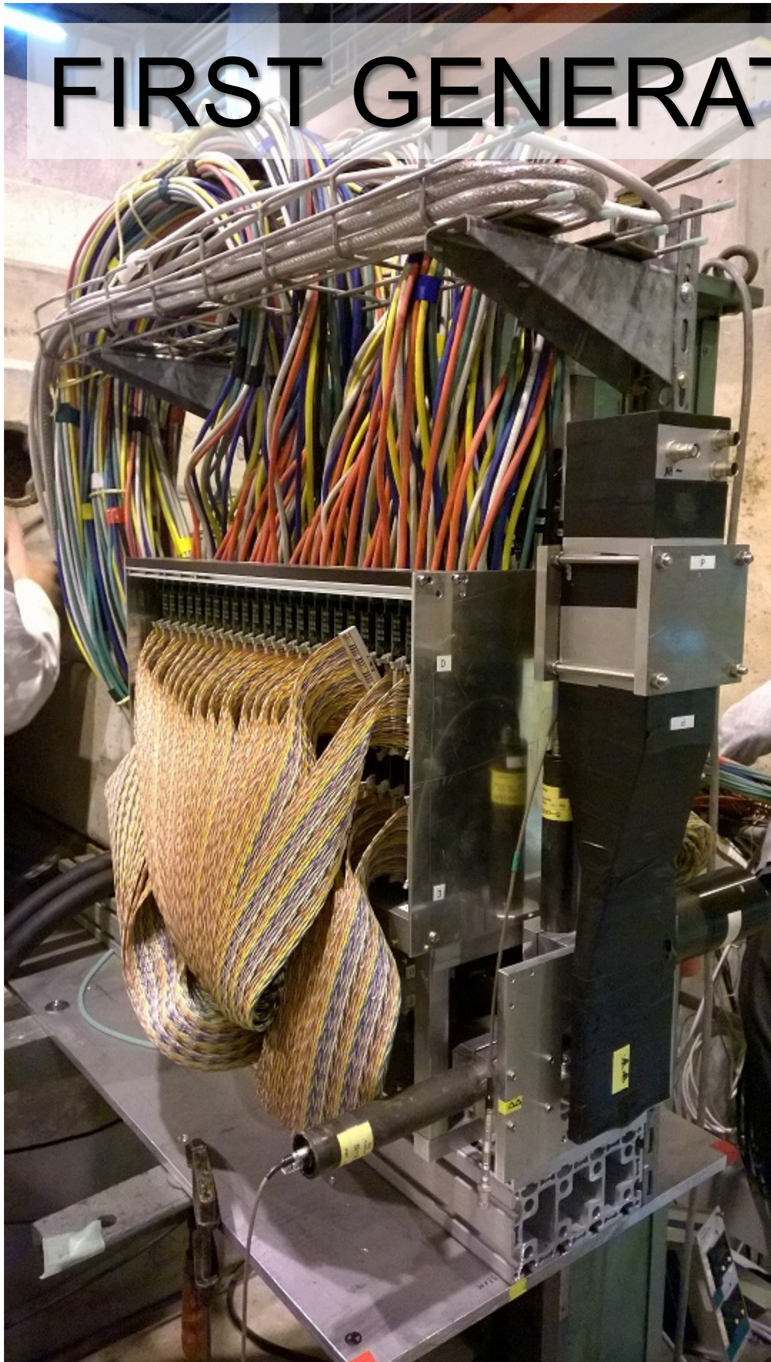
UNIVERSITY OF BERGEN

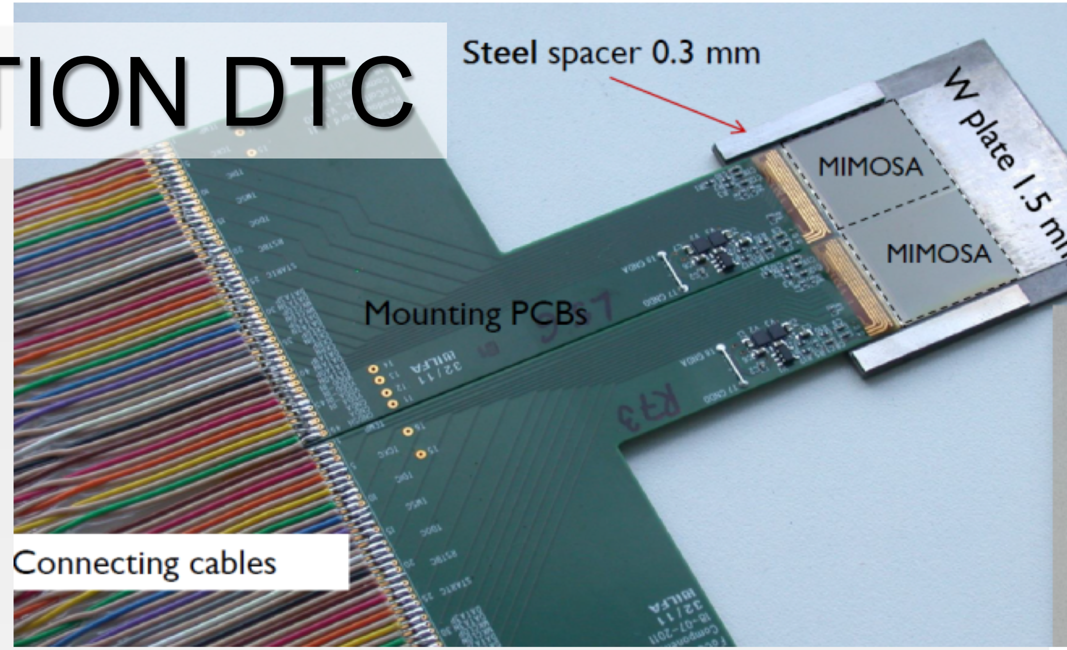
Bergen, Norway
Pop. 280k, founded in 1070
Proton center in 2022

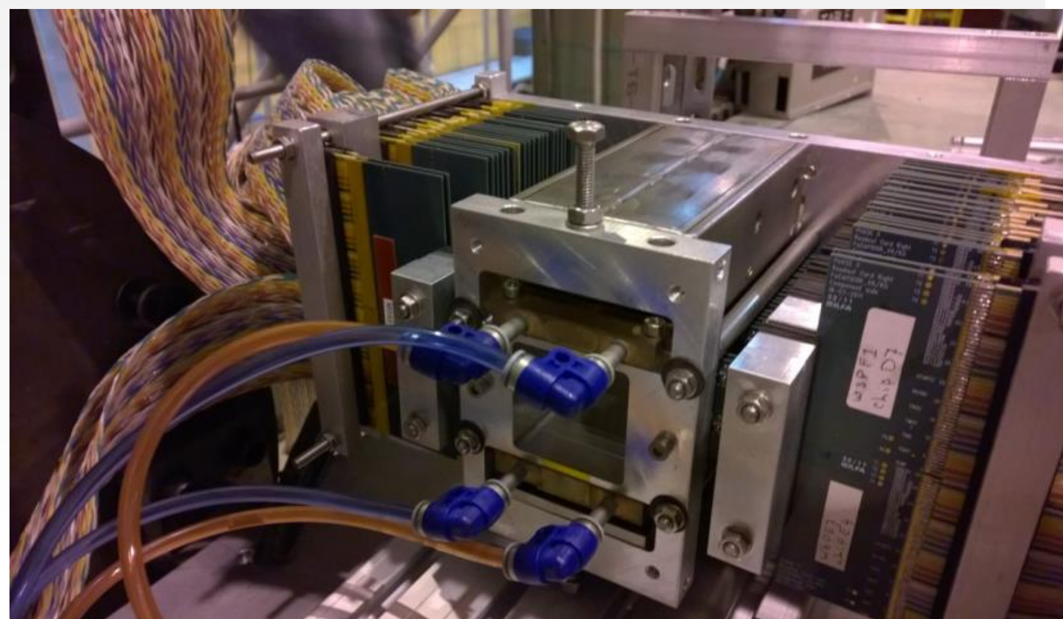
pCT – Digital Tracking Calorimeter



FIRST GENERATION DTC





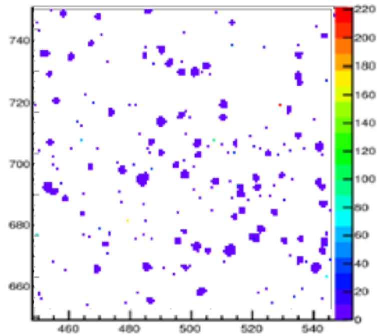


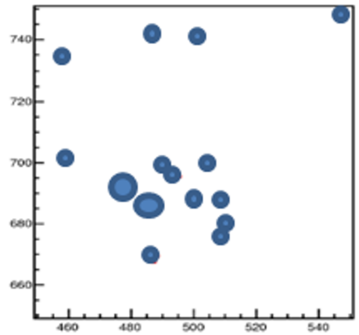
Data readout
Monte Carlo + exp.

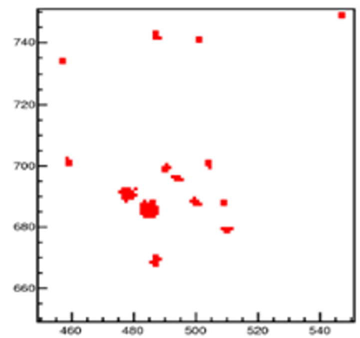
Proton hit identification

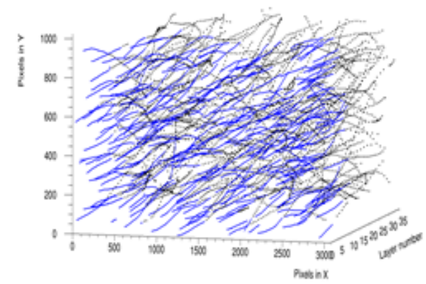
Charge diffusion modelling

Proton track reconstruction



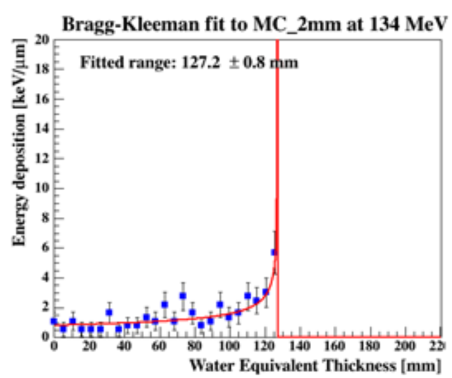


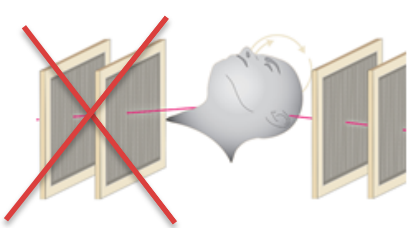




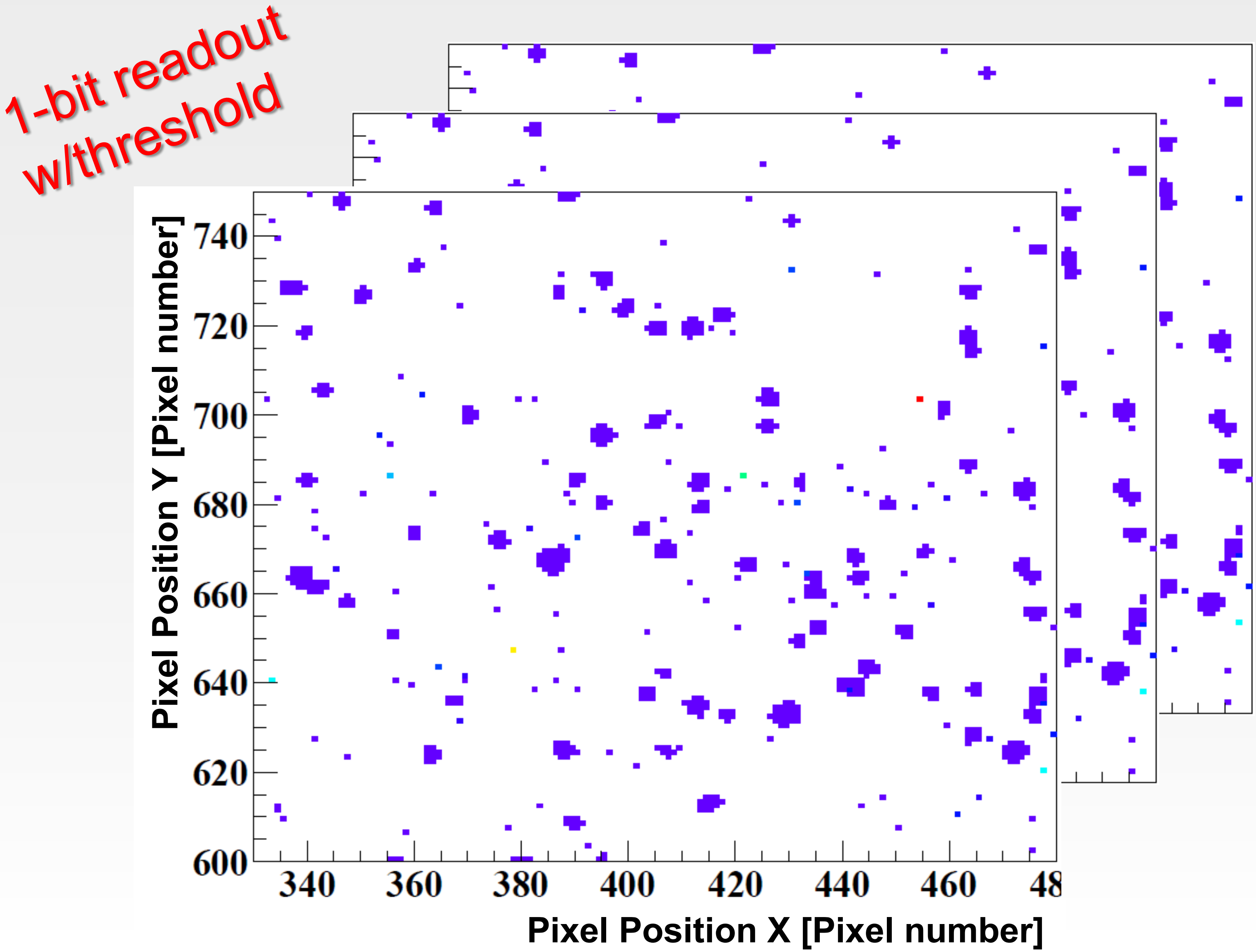
Individual track – energy loss fitting

If 3D reconstruction: MLP estimation

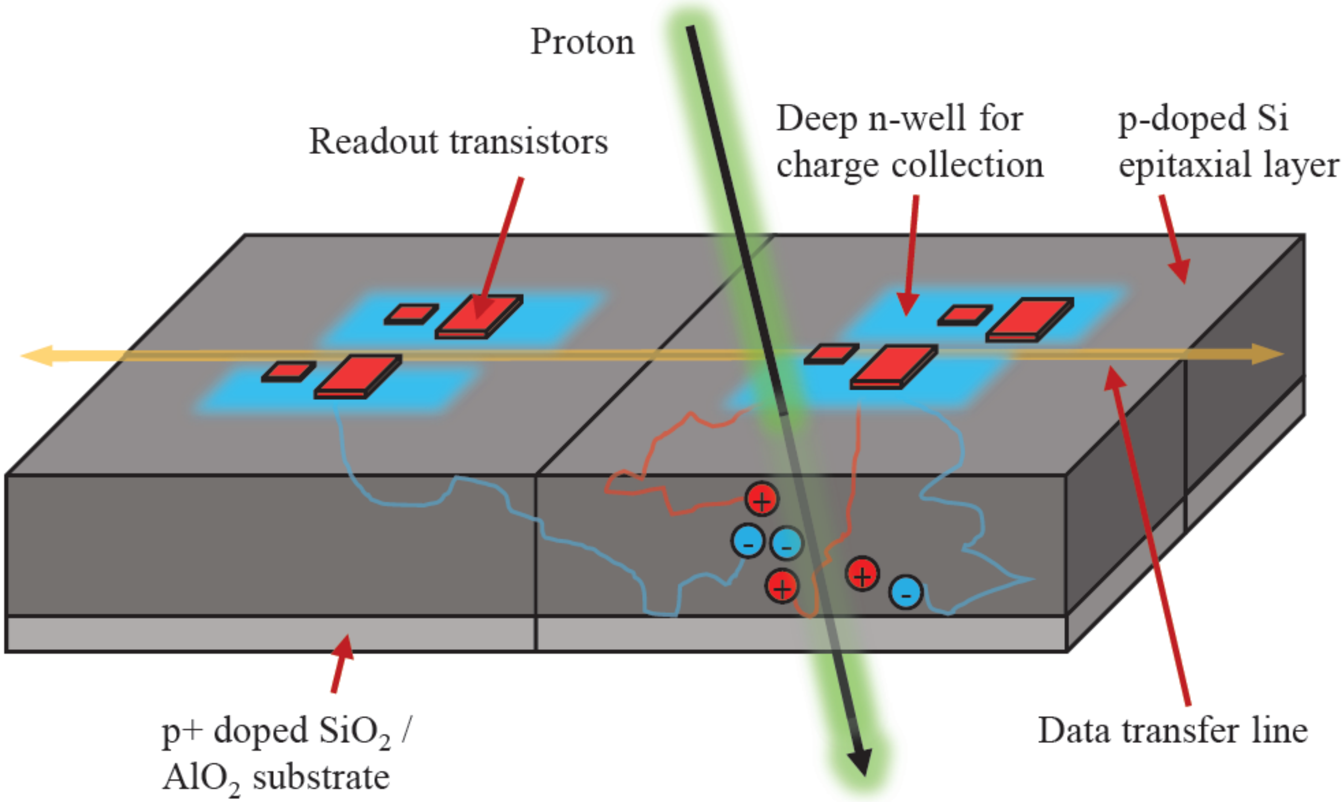




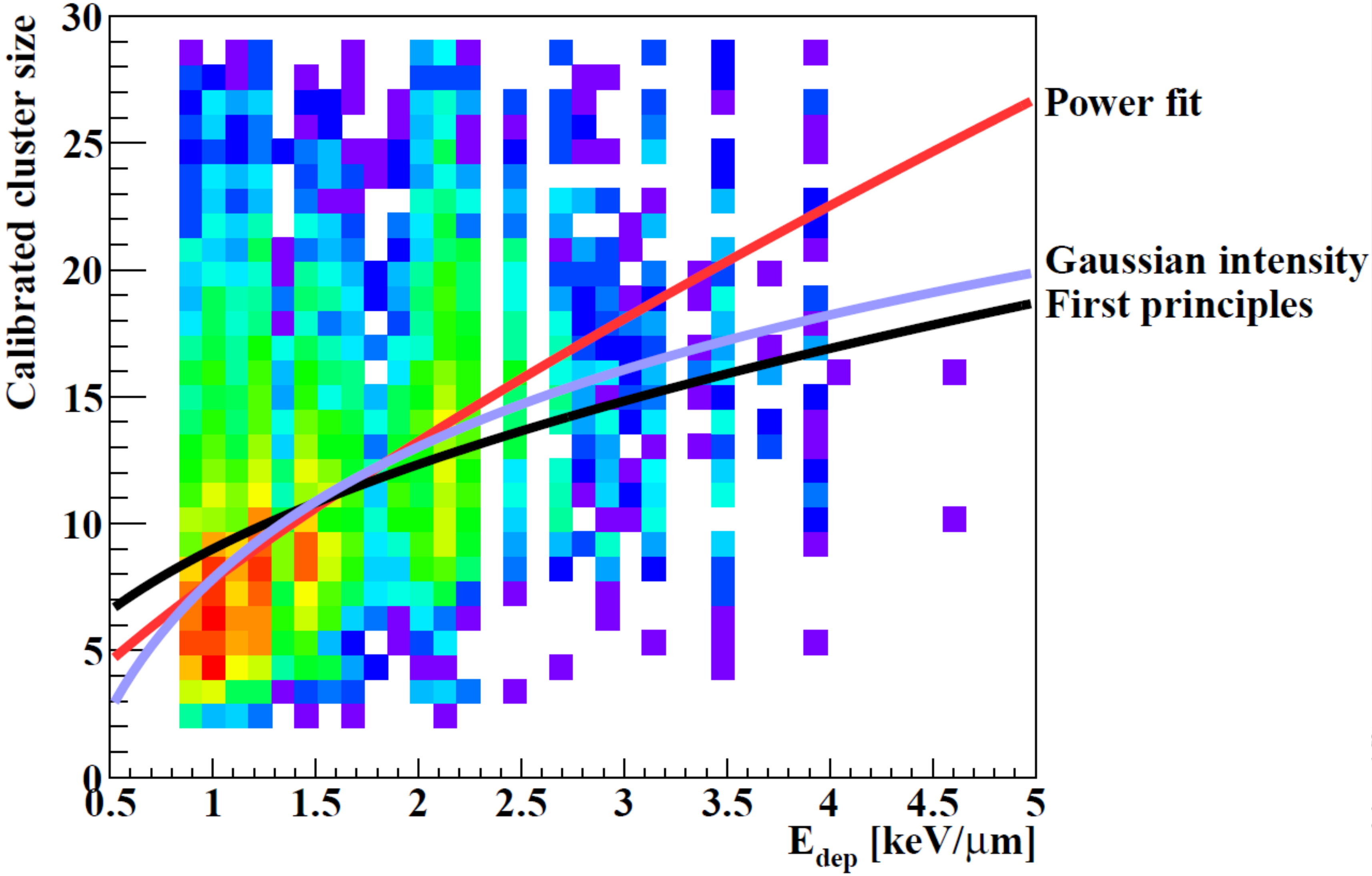
Protons hitting the pixel detectors



Charge diffusion in pixels



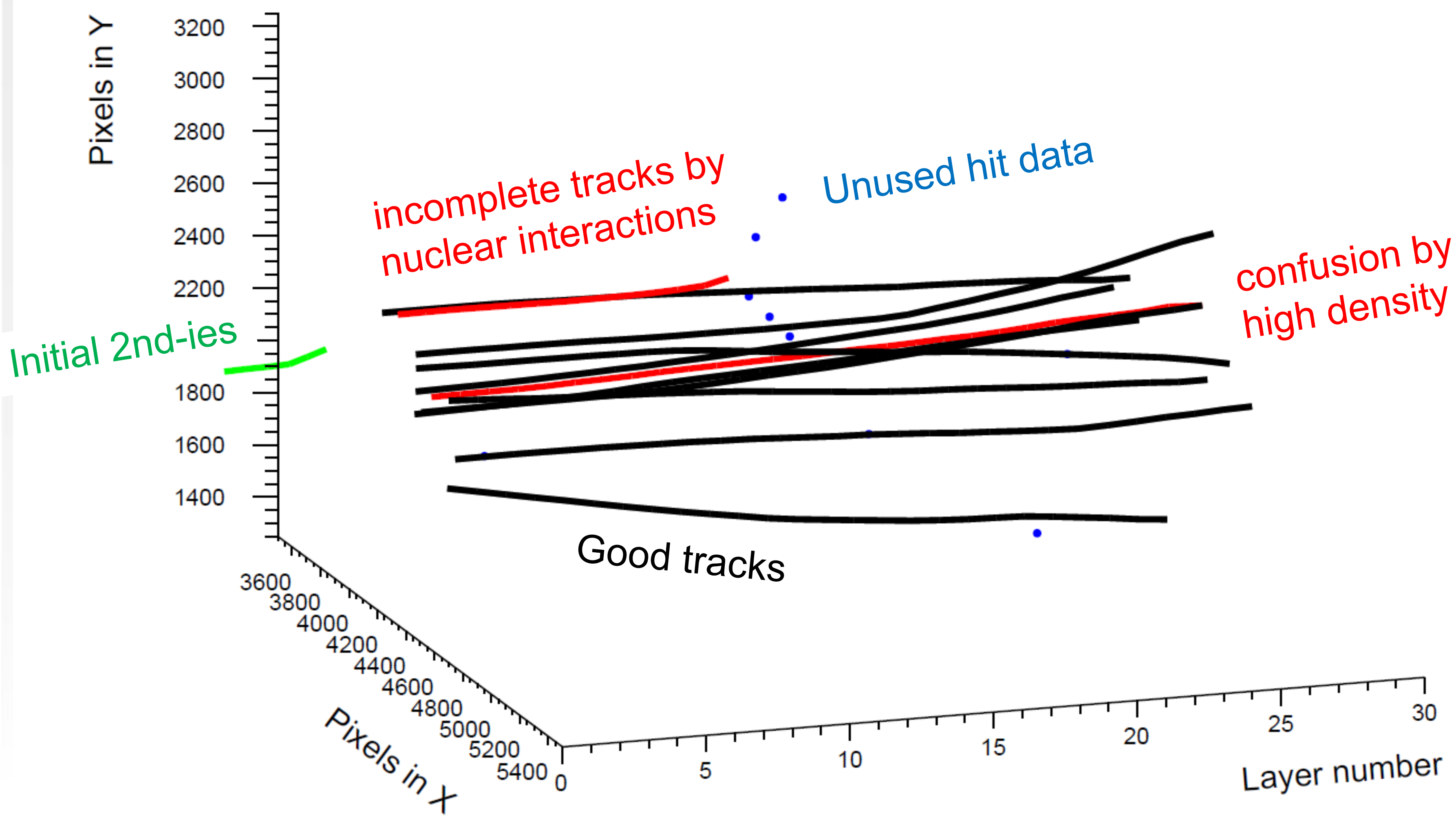
Charge diffusion model



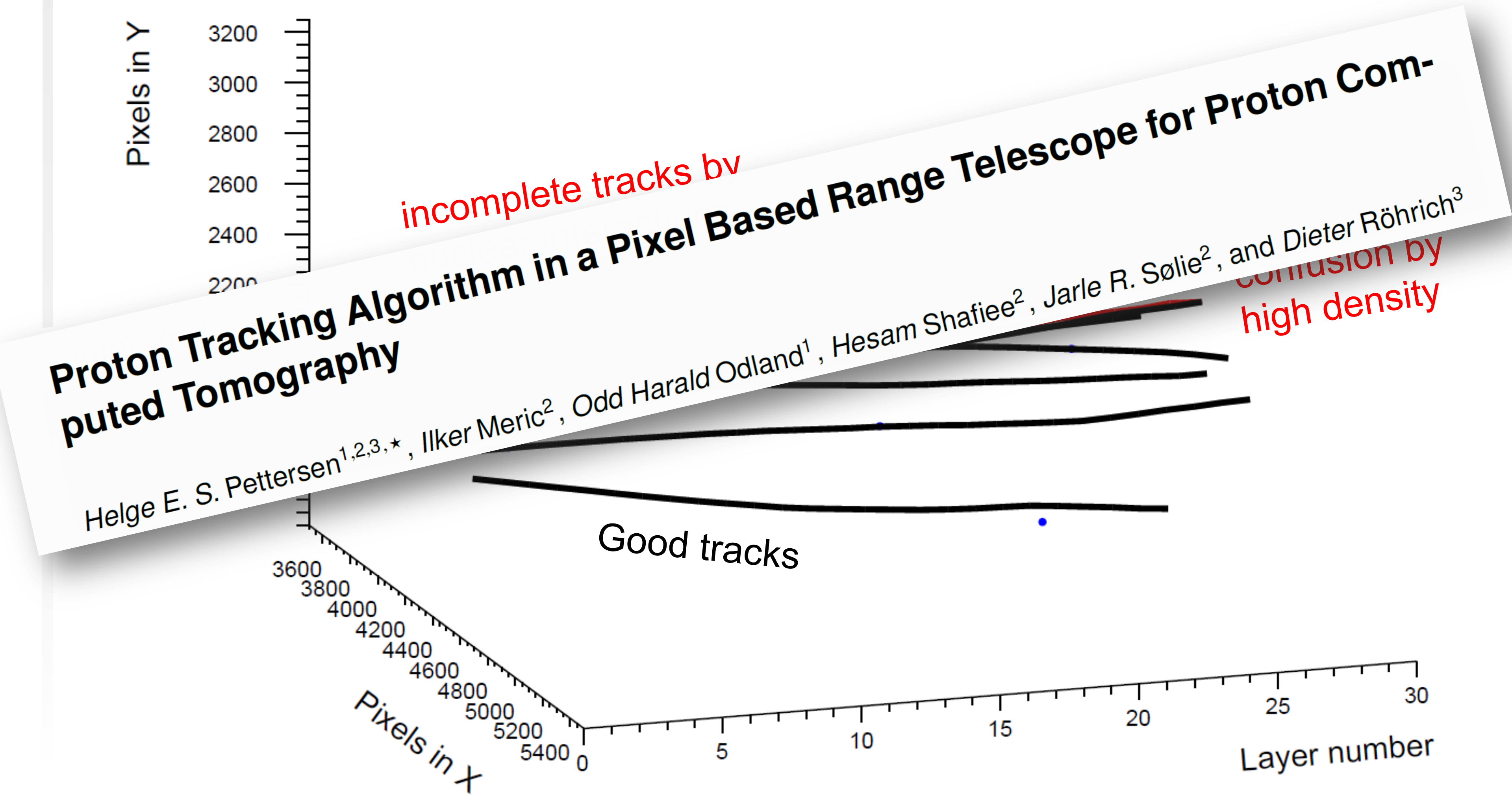
Proton track reconstruction

- 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

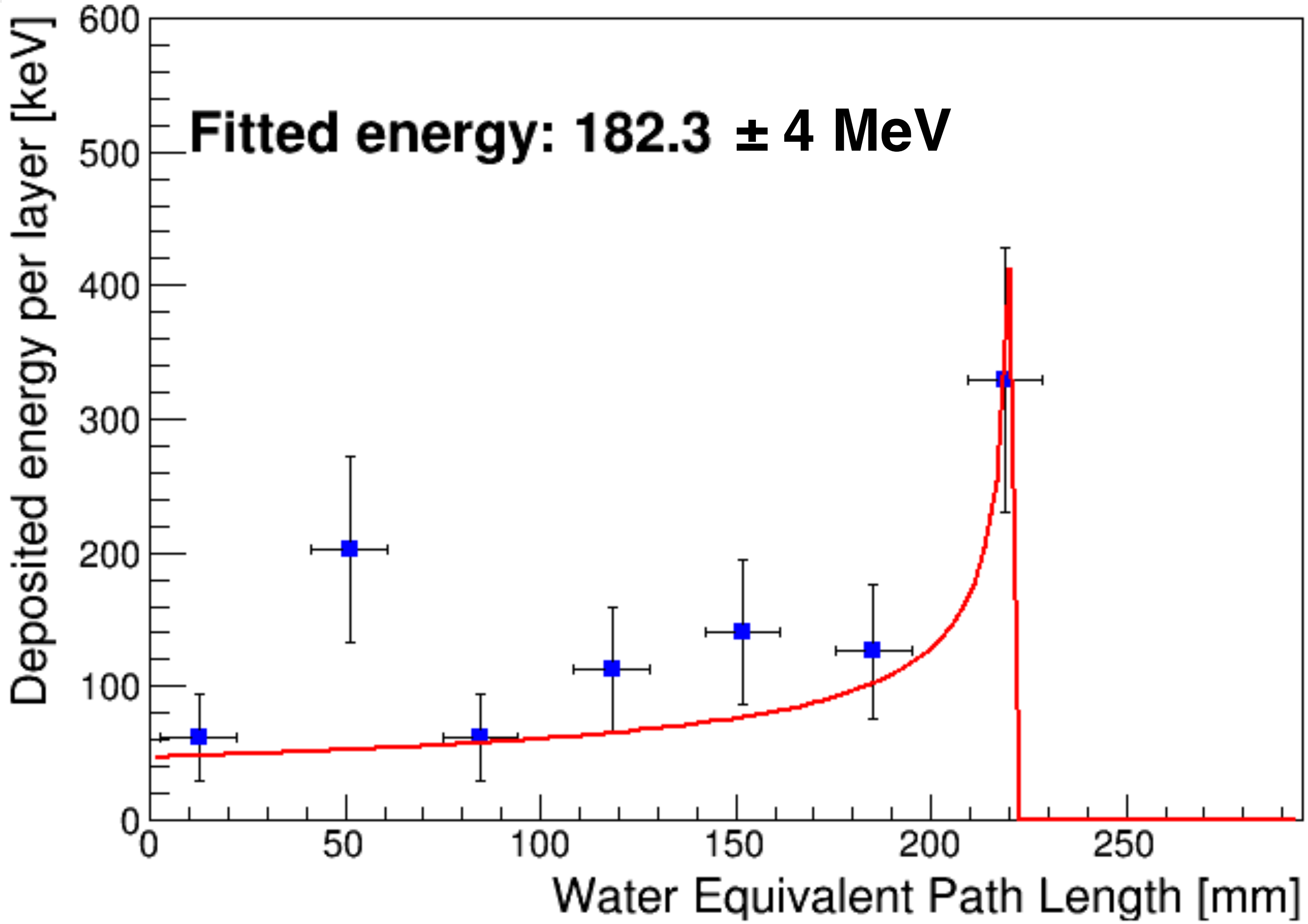
Proton track reconstruction



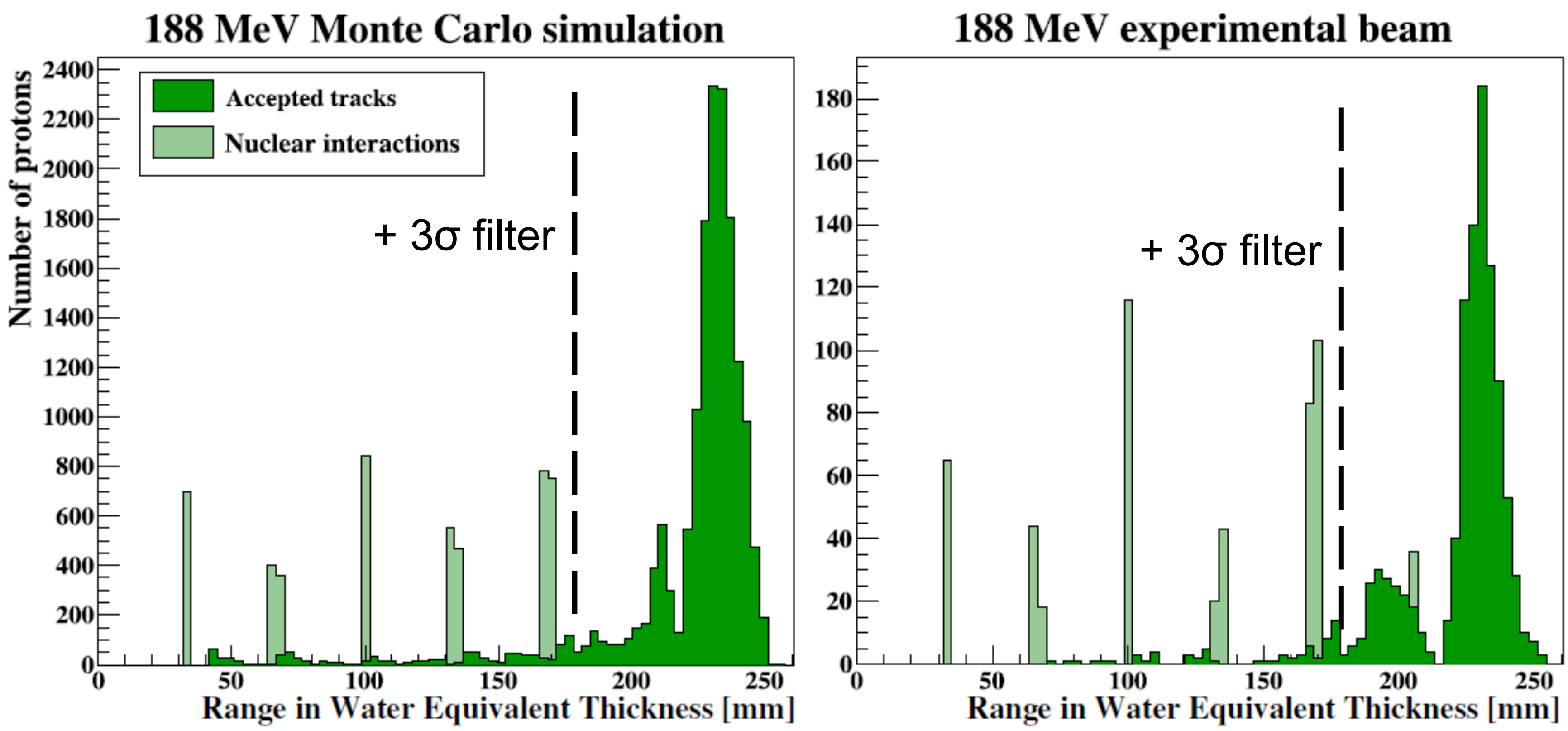
Proton track reconstruction



The individual proton range

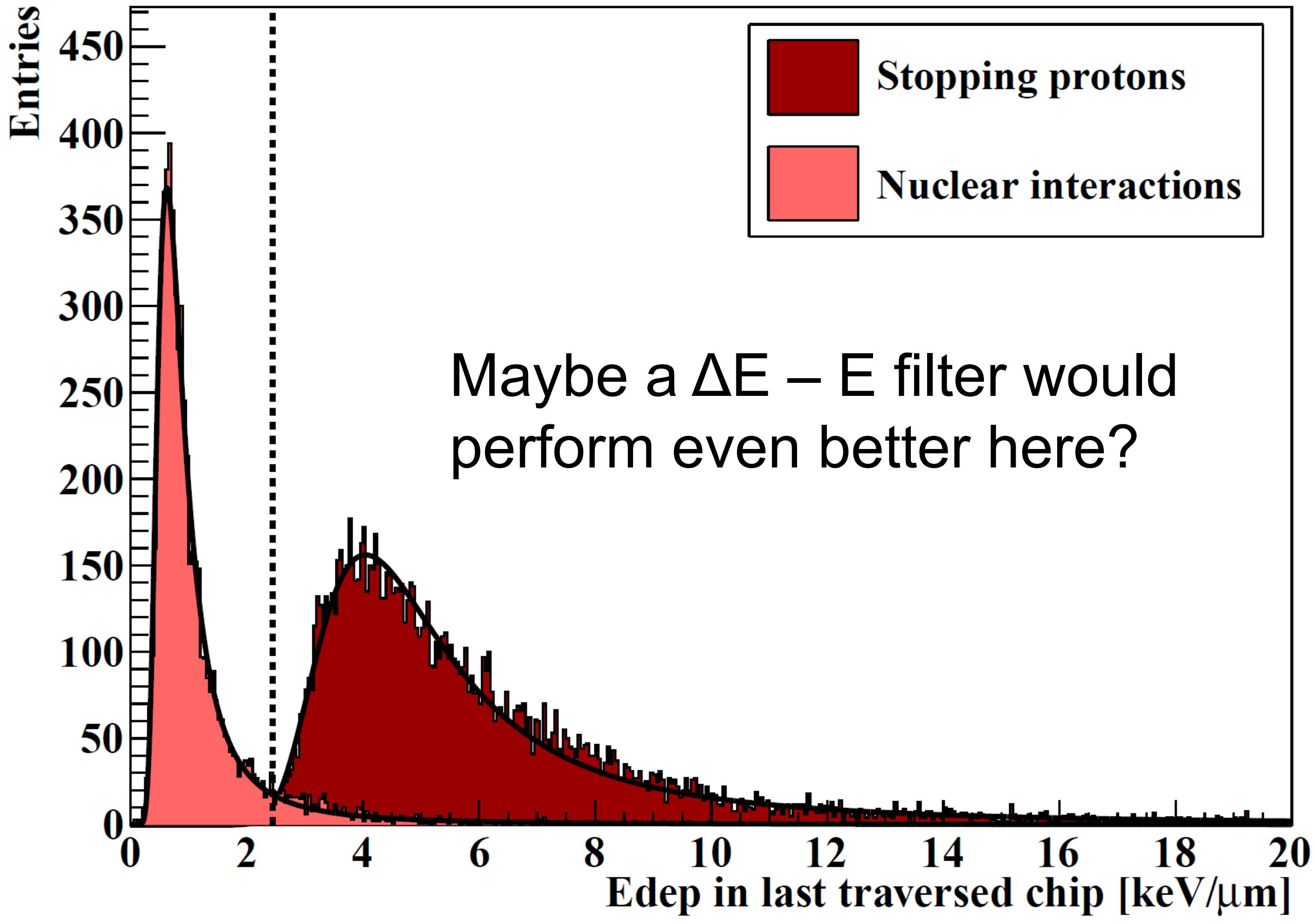


The ranges from many protons



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

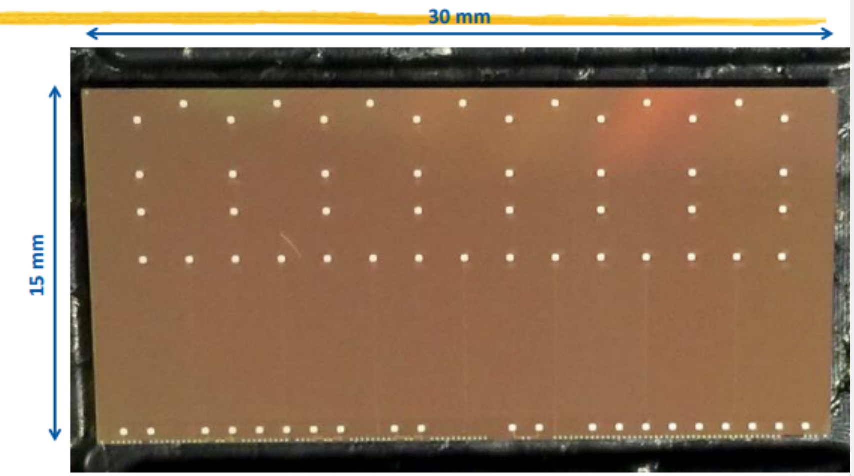
Filtering of nuclear events

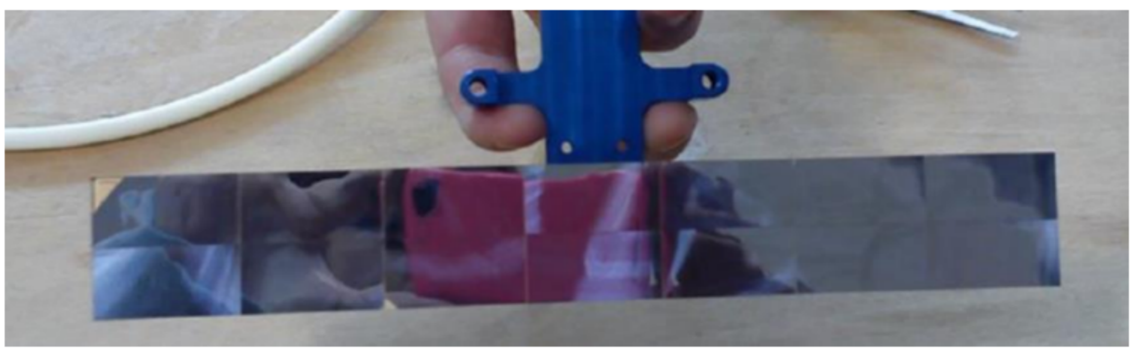


Next Generation DTC

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)**

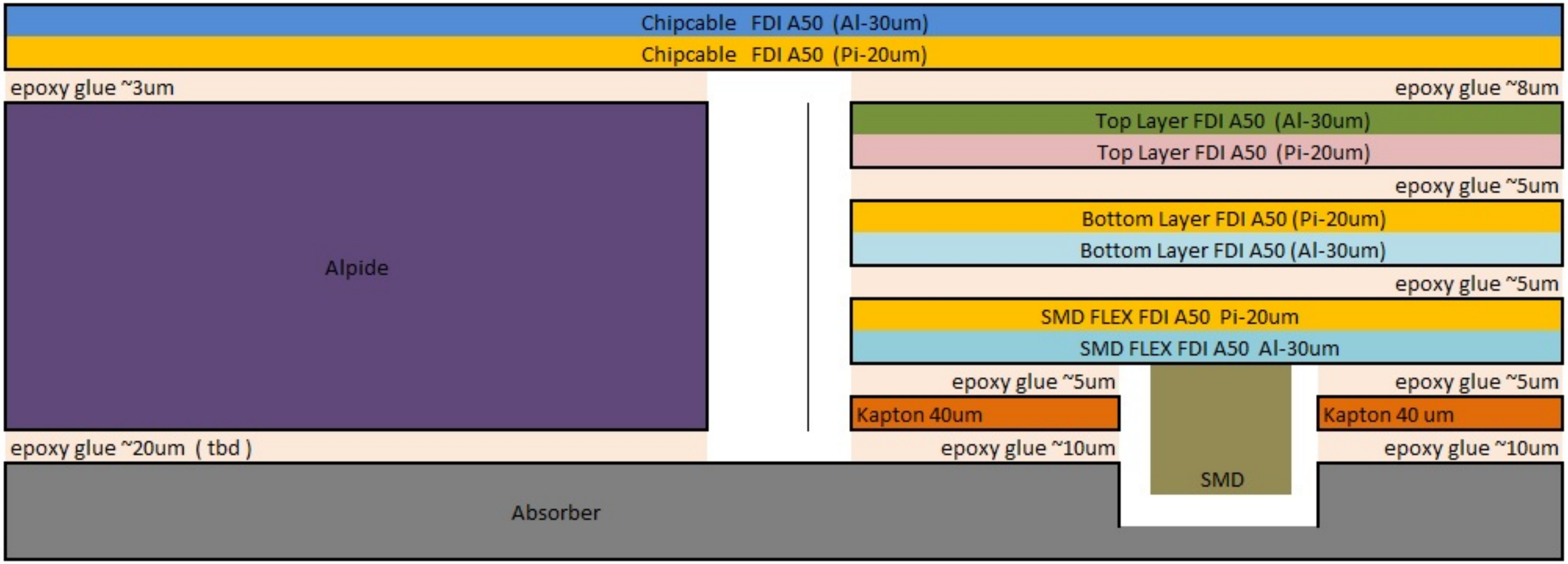




Design team:
CCNU Wuhan, CERN Geneva, YONSEI Seoul, INFN Cagliari, INFN Torino, IPHC Strasbourg, IRFU Saclay, NIKHEF Amsterdam

M. Magner, IFEE 2014

Digital Tracking Calorimeter(DTC)



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

Digital Tracking Calorimeter(DTC)

- **Bonding method**

Mechanical Connection → Ultrasound welding

Dielectric connection → Glue protection

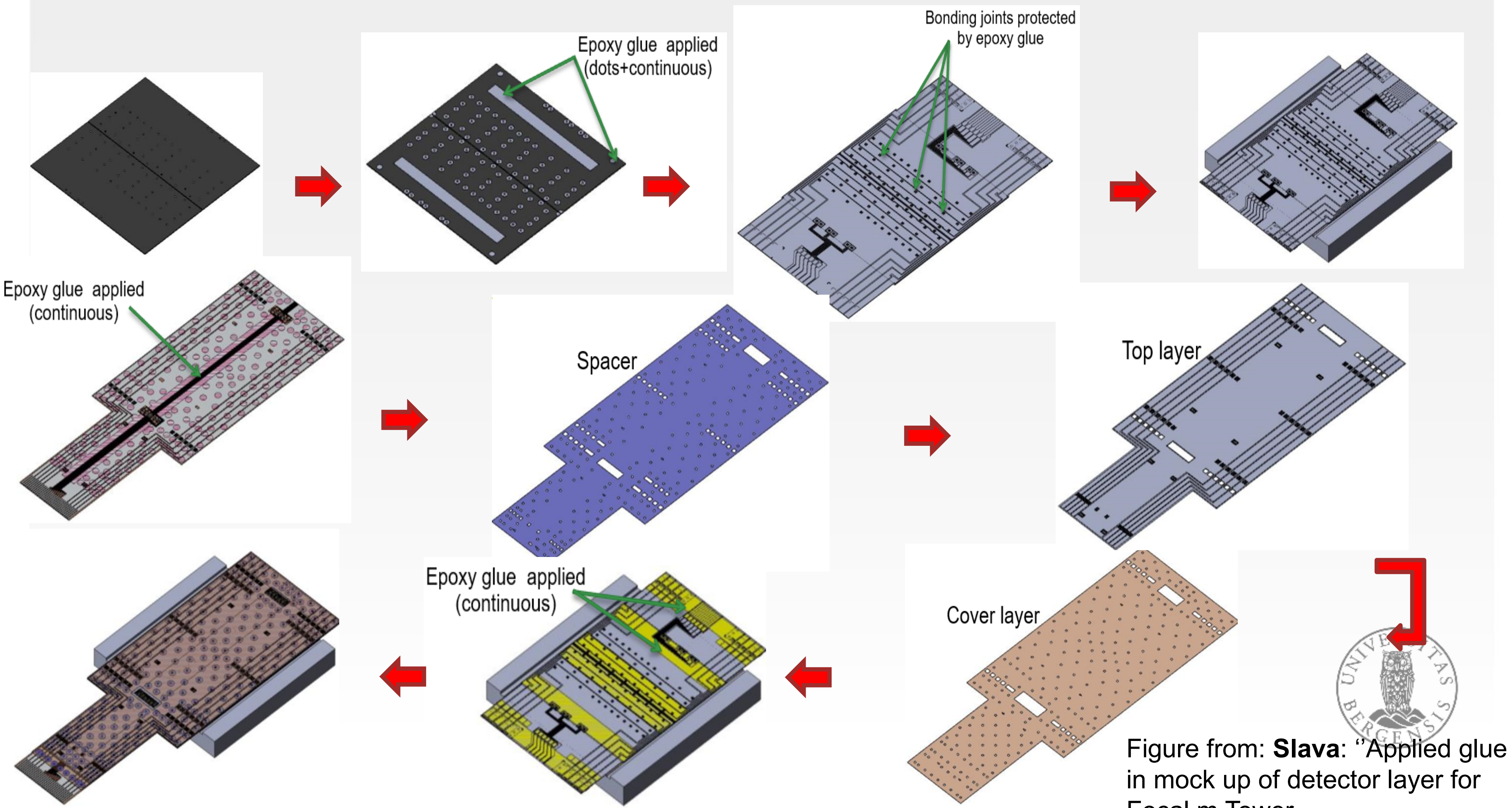


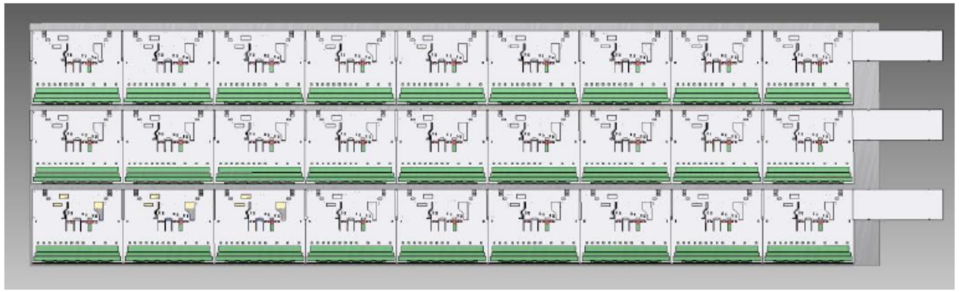
Figure from: **Slava**: "Applied glue in mock up of detector layer for Focal m Tower

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 interleaved with 3.5 mm Al
  - 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)



Prototype mounting

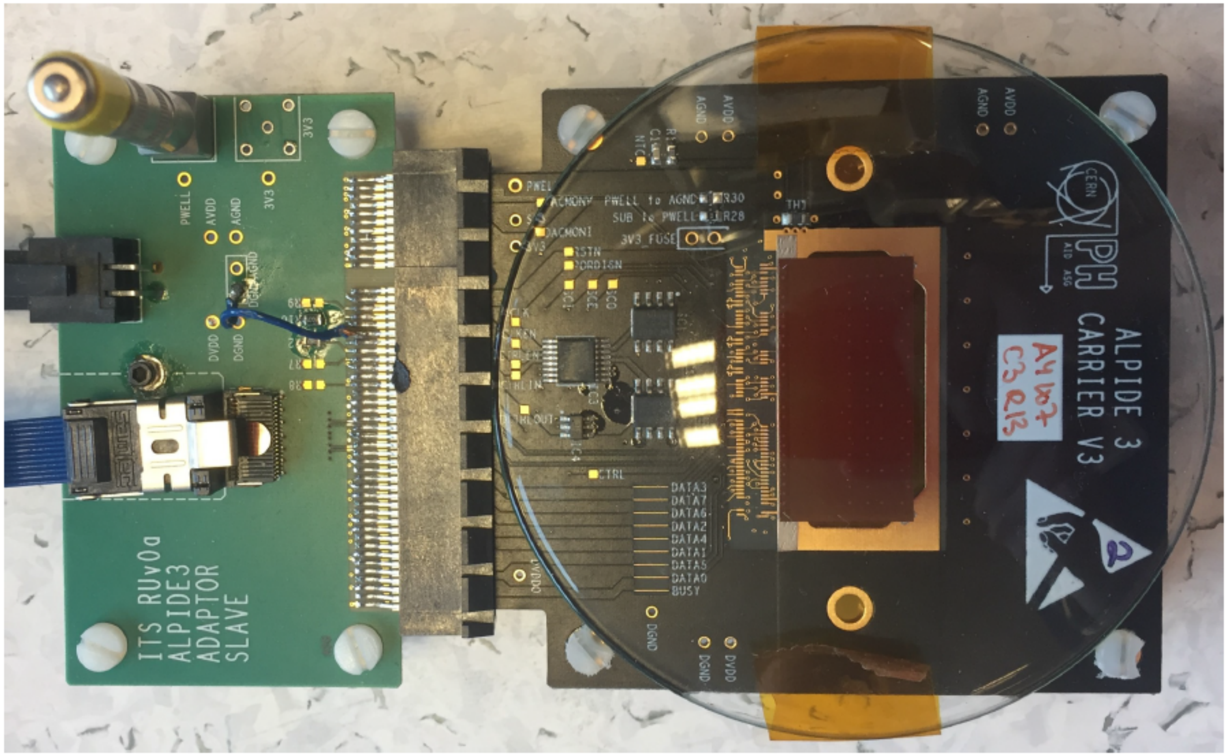
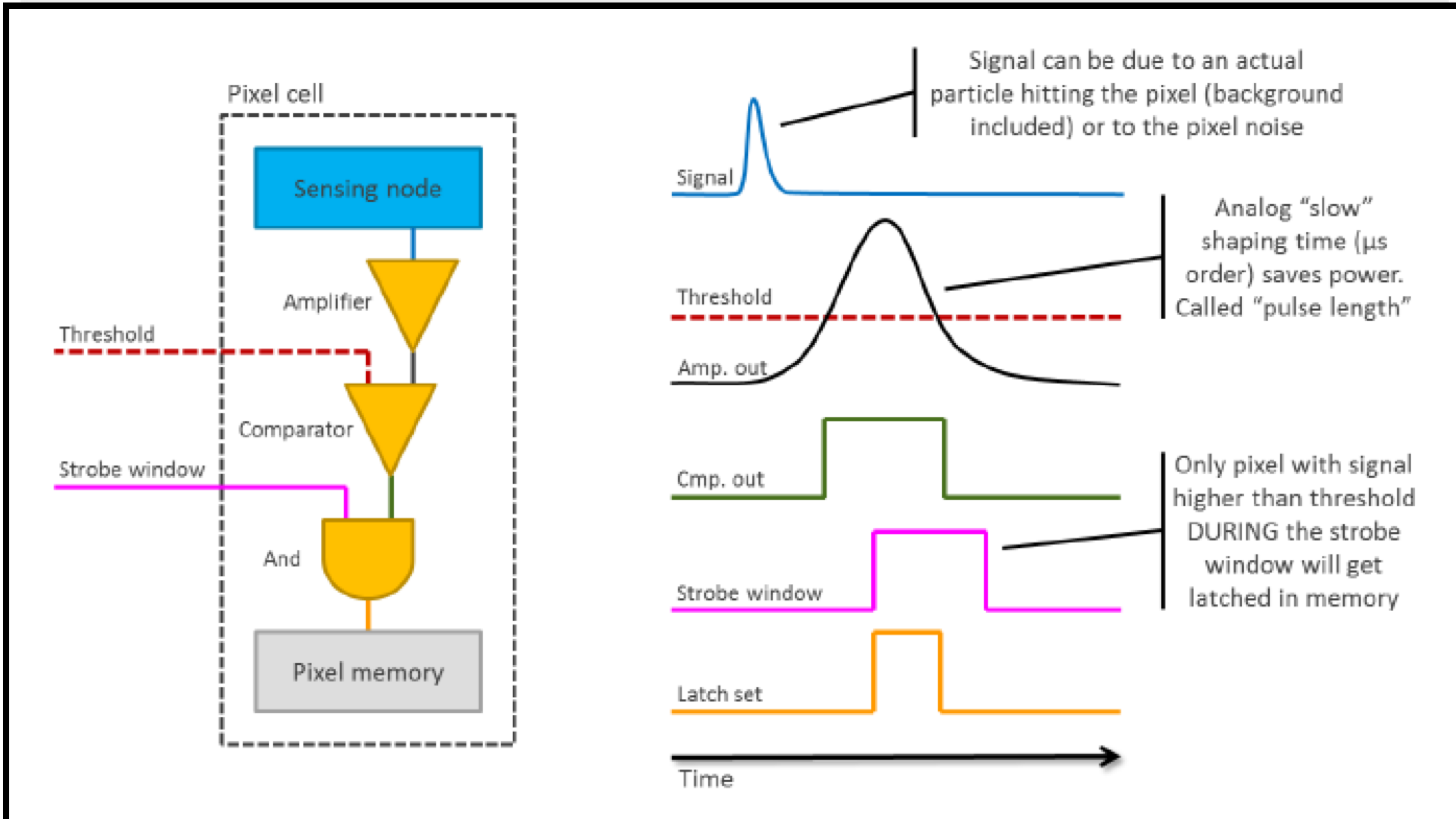


Figure 4.6: On the right: The ALPIDE carrier card. On the left: the ALPIDE adaptor slave.

http://bora.uib.no/handle/1956/16041: **Design of High-Speed Digital Readout System for Use in Proton Computed Tomography**


Pixel cell
Sensing node
Amplifier
Threshold
Comparator
Strobe window
And
Pixel memory
Signal can be due to an actual particle hitting the pixel (background included) or to the pixel noise
Signal
Threshold
Amp. out
Analog "slow" shaping time (μs order) saves power. Called "pulse length"
Cmp. out
Strobe window
Only pixel with signal higher than threshold DURING the strobe window will get latched in memory
Latch set
Time

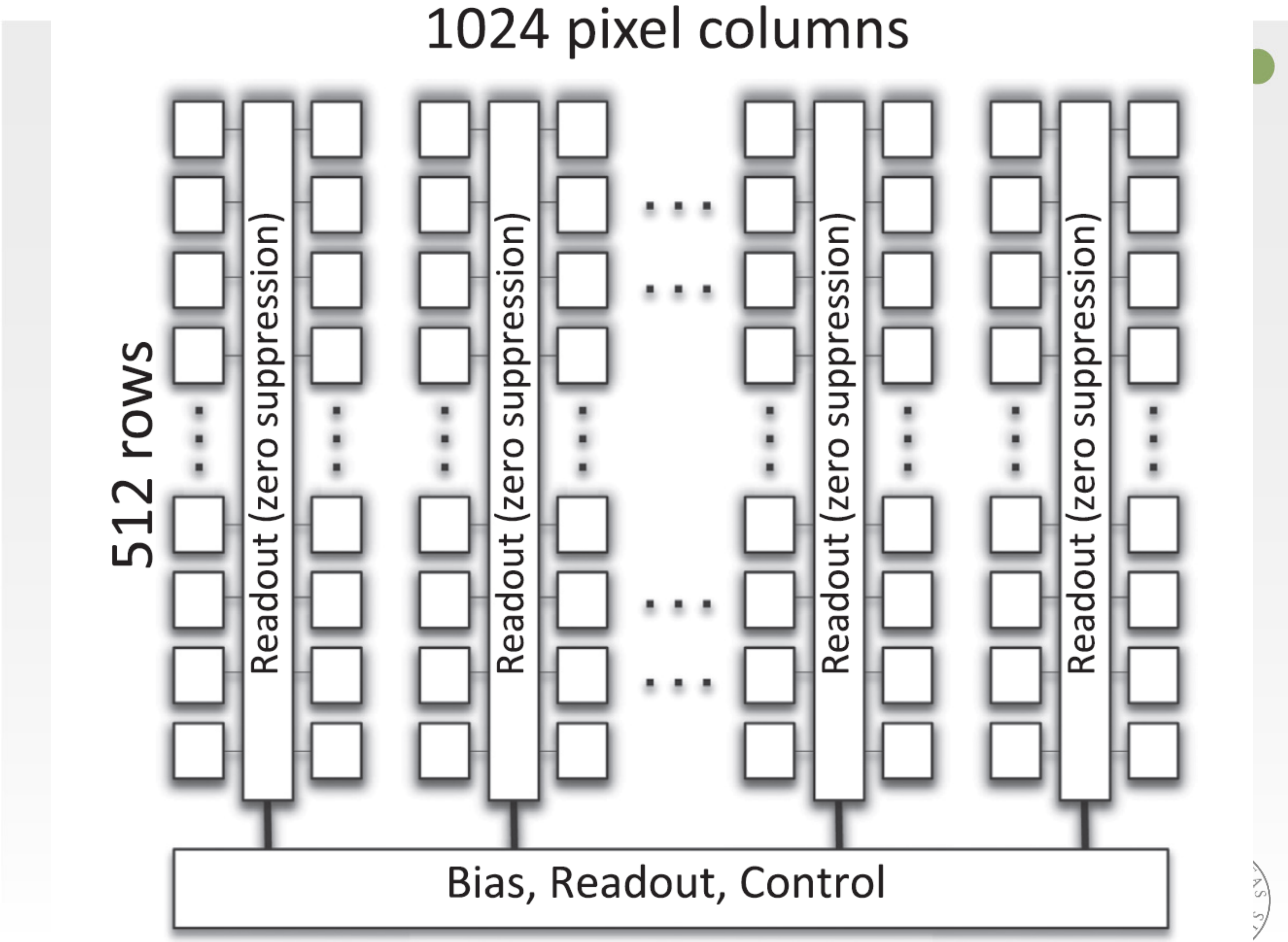
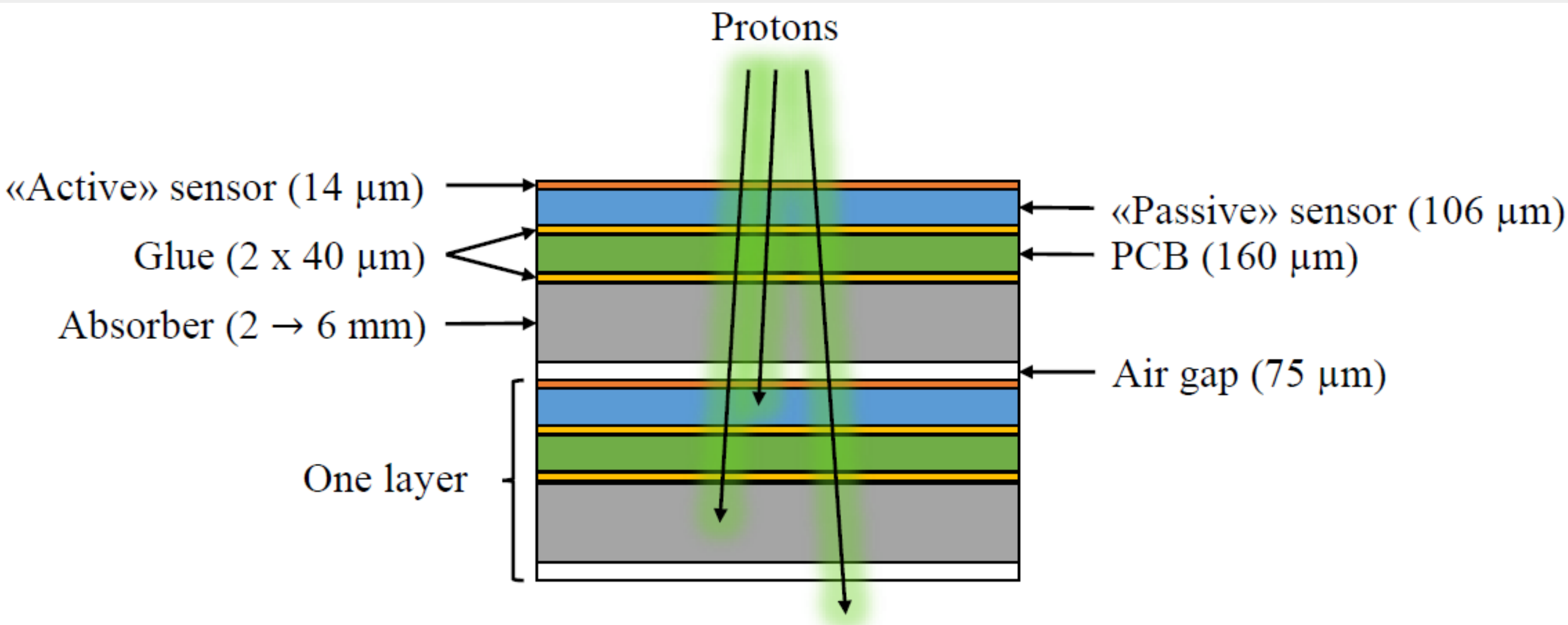
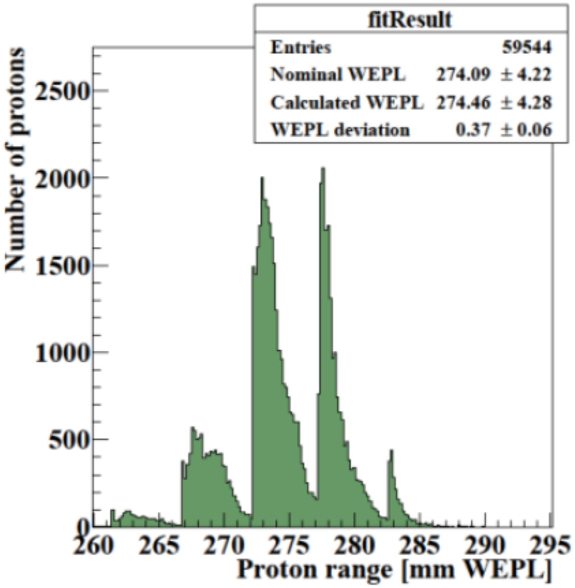


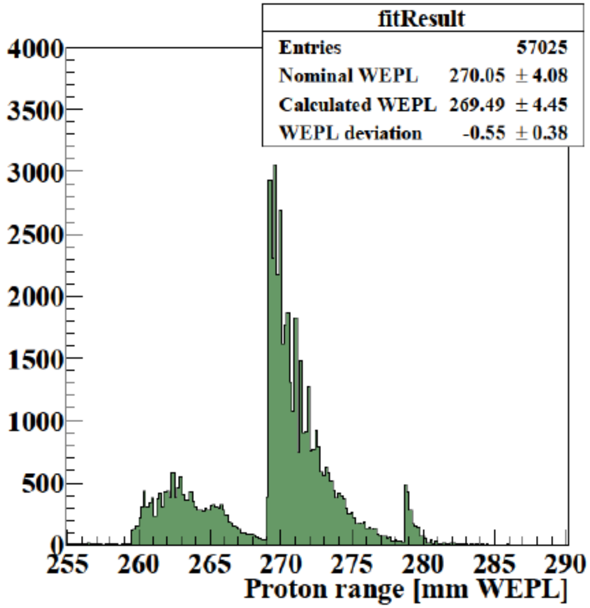
Fig. 1. Architecture of the ALPIDE chip.

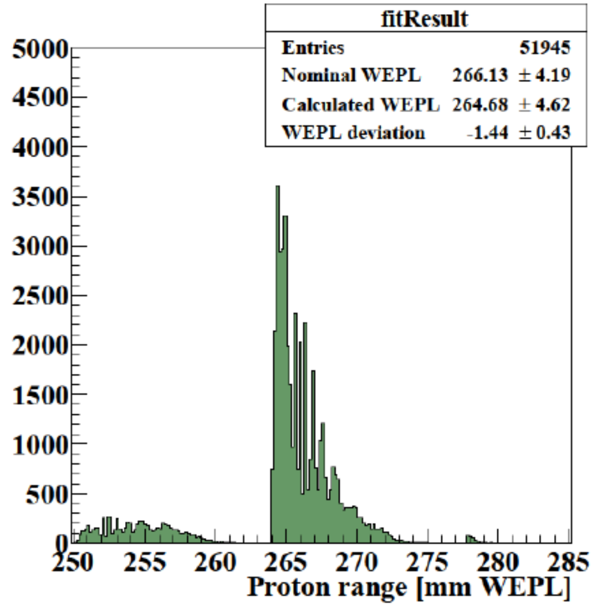
Design optimization: Absorber thickness



Range distribution per beam





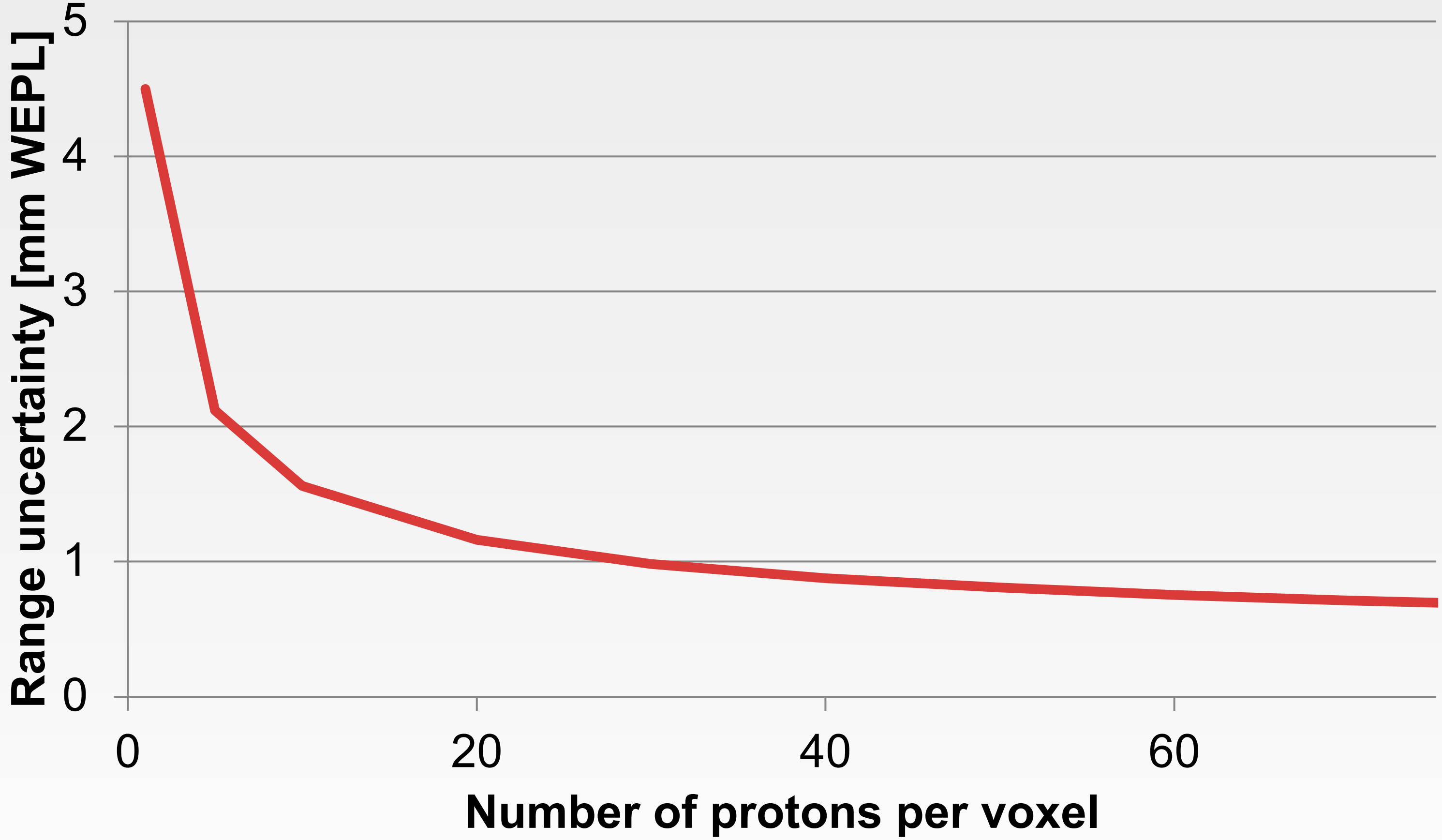


2 mm Al

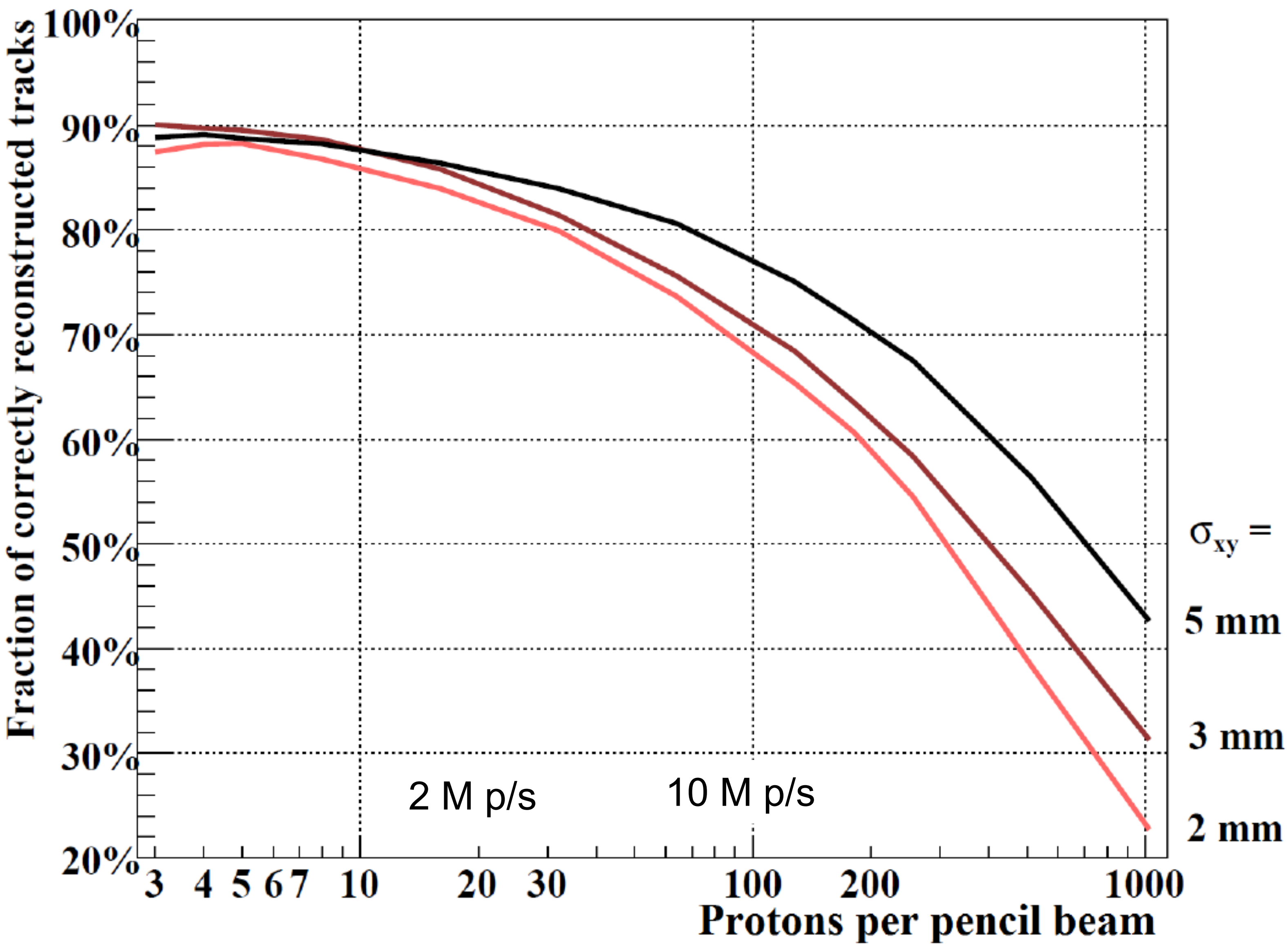
4 mm Al

6 mm Al

MC - Range resolution (sys ⊕ stoch)

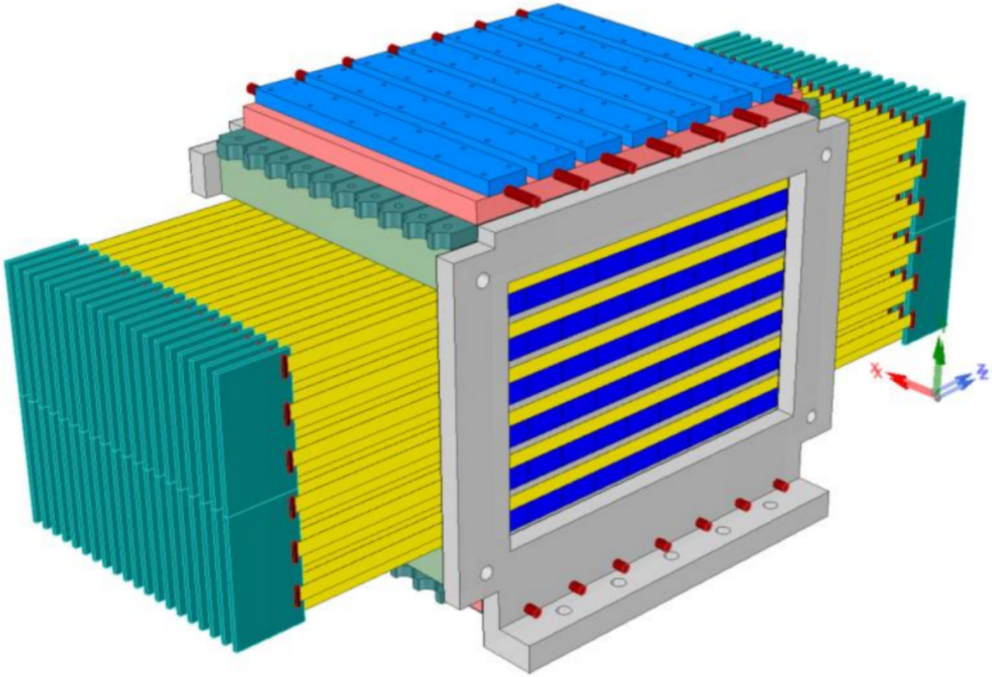


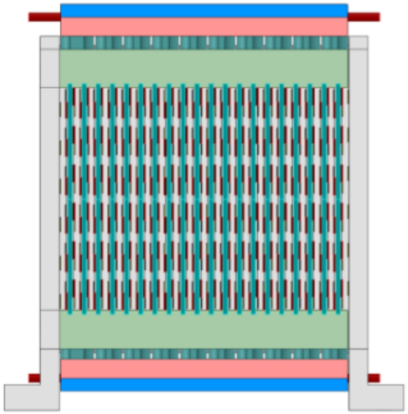
MC - Tracking quality, pencil beam

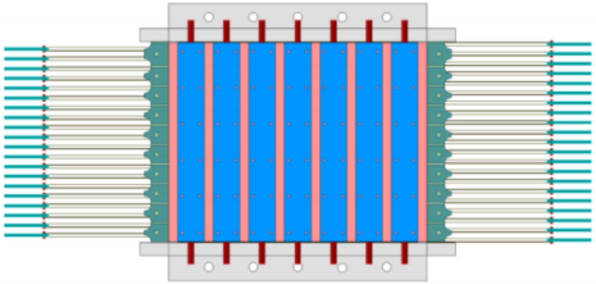


Digital Tracking Calorimeter(DTC)

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

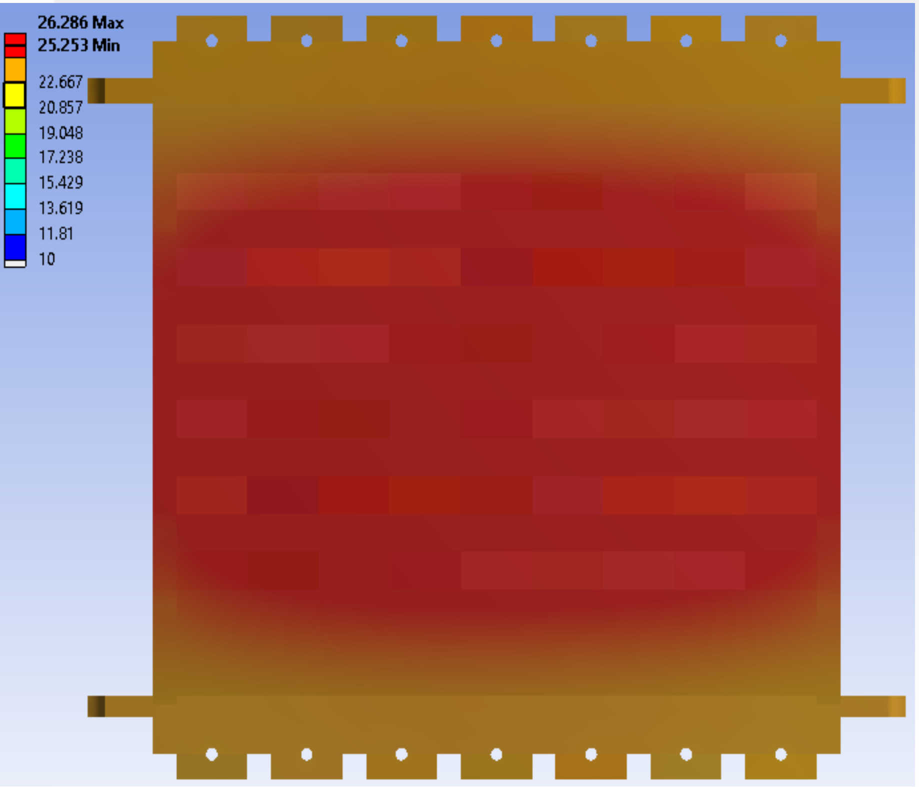




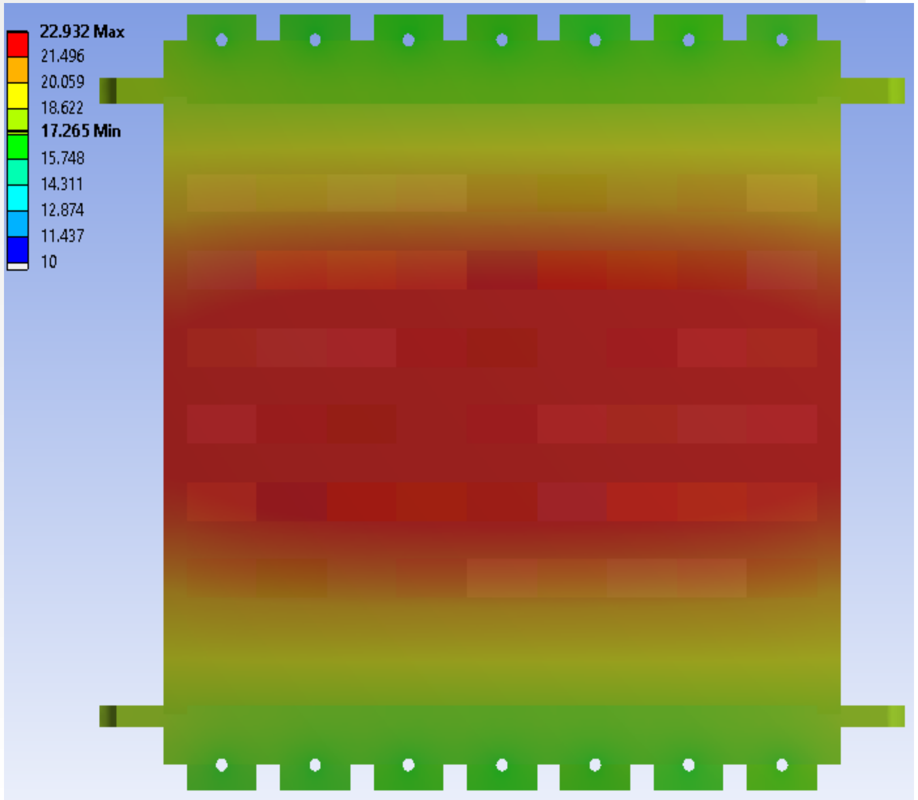


CAD/sim - Heat sink design

Air cooled design, max ~26 degrees C



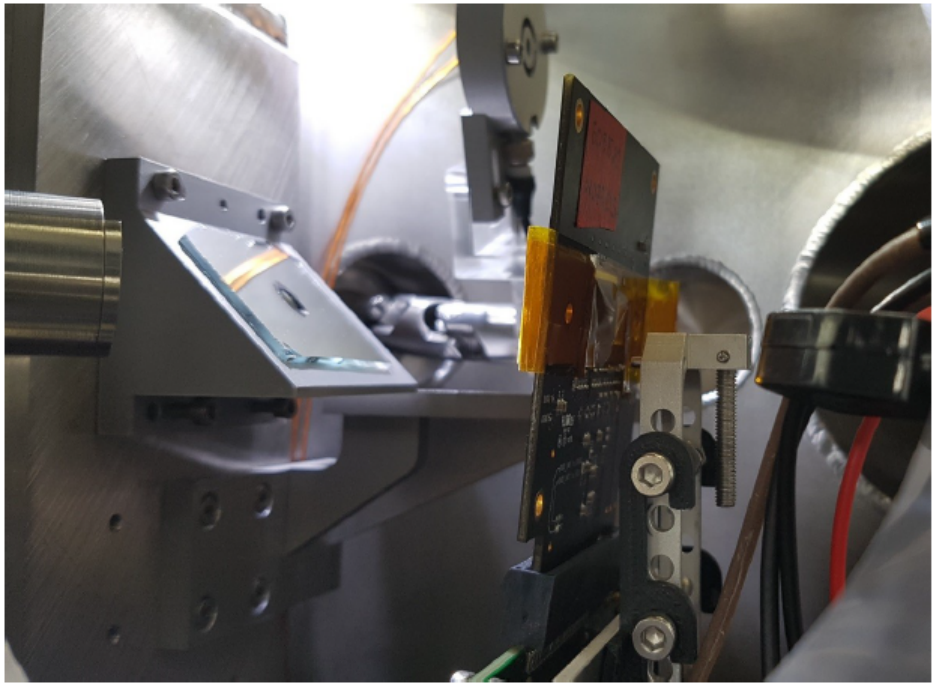
Water cooled design, max ~23 degrees C

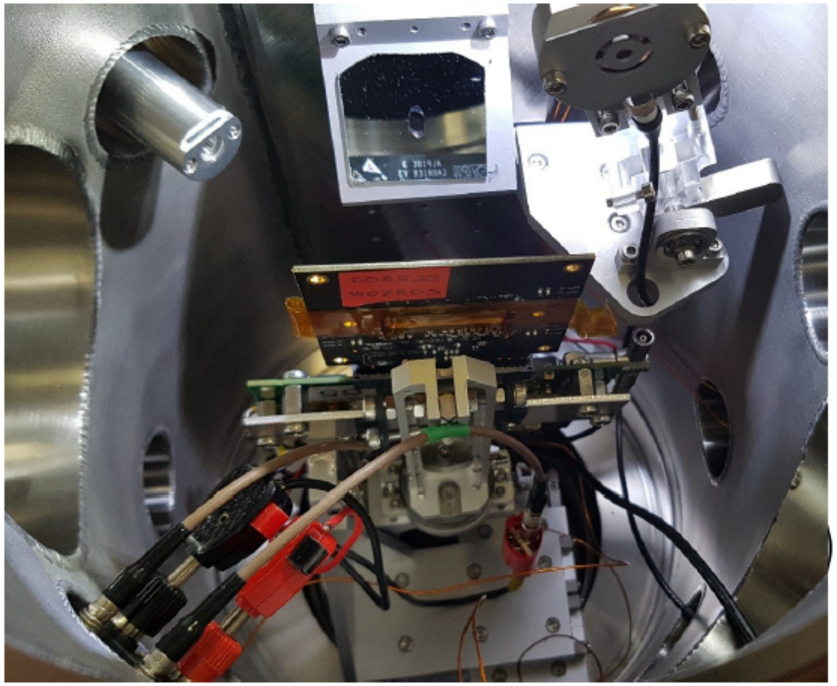


Experimental measurements with ALPIDE: Sydney 2018

Experimental setup

- Beam
  - Ion: Helium-4
  - Energy: 10 MeV (+/- 100 keV)
  - Rate: ~ 2k to 10k ions/sec
  - Trigger rate: 100 kHz (10μs period)
  - Bias Voltage: 0 V, -3 V, -6 V

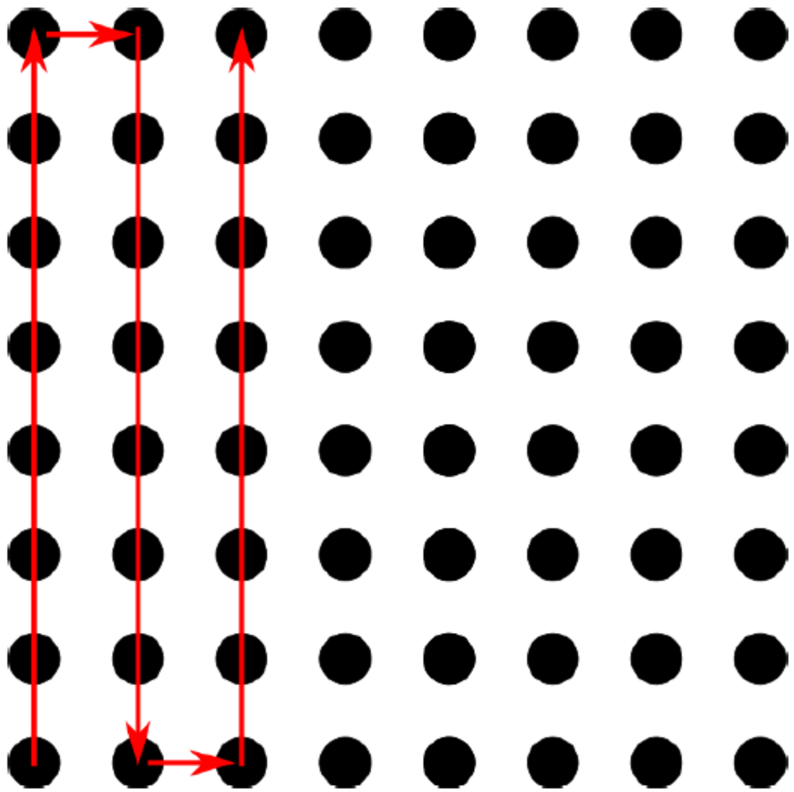




Experimental setup #2

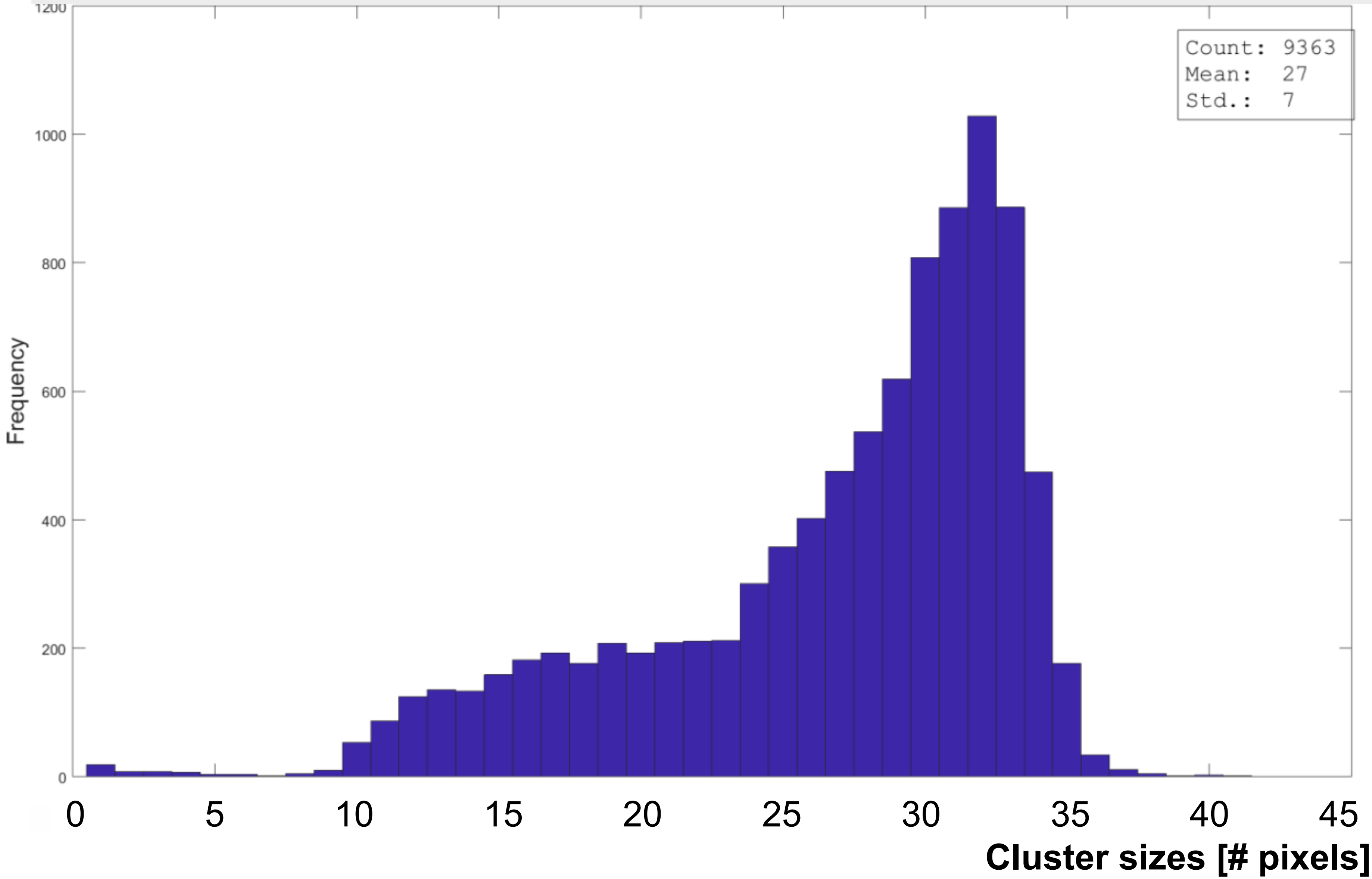
- ALPIDE surface was raster scanned
  - Spot size: < 1 µm
  - Spot pitch: 1 µm
  - Spots: 128 x 128
  - Dwell time: 100 ms

  Single Pixel: 28 x 28 spots

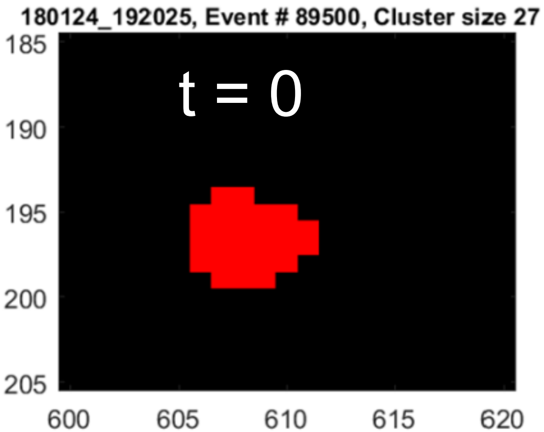


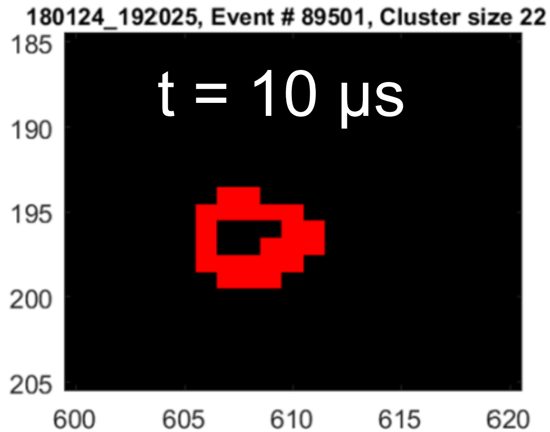
uib.no

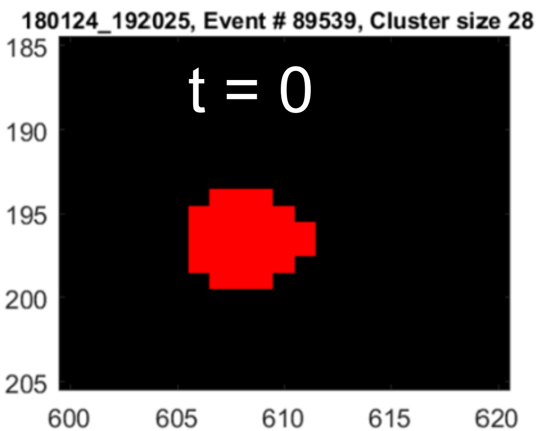
Cluster Sizes from high LET micro beam

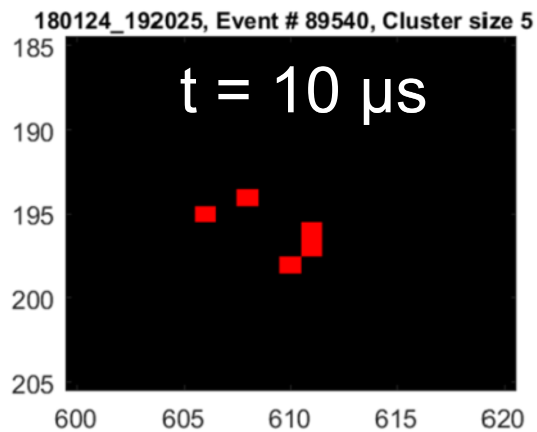


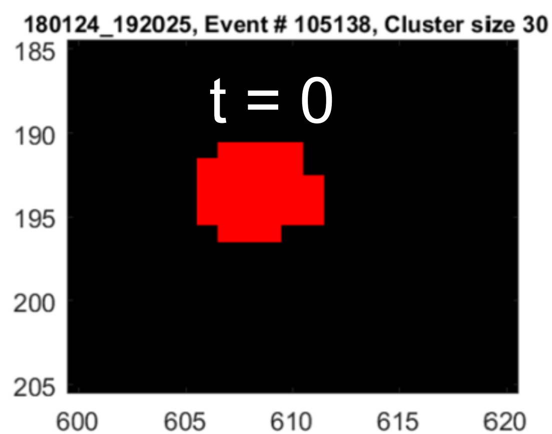
Time structure of charge diffusion

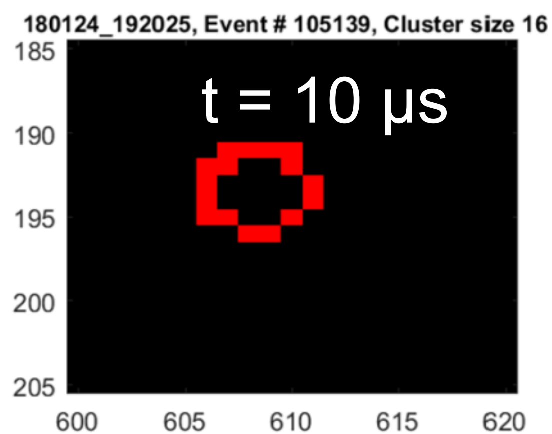










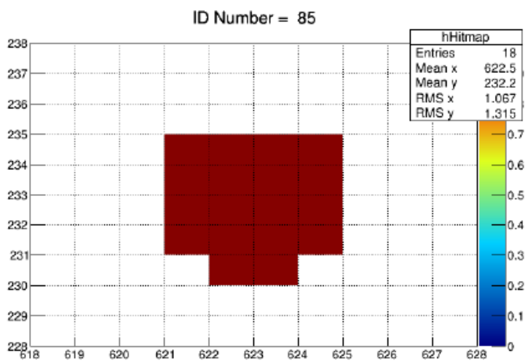


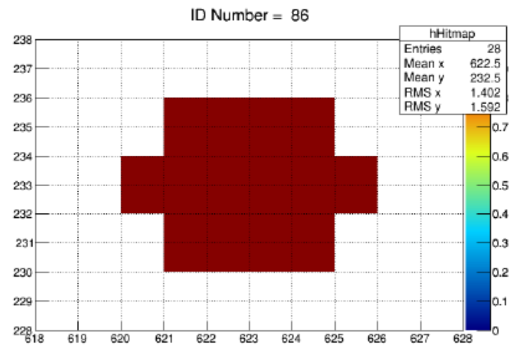
…. using an 4He source and 1 μs integration time

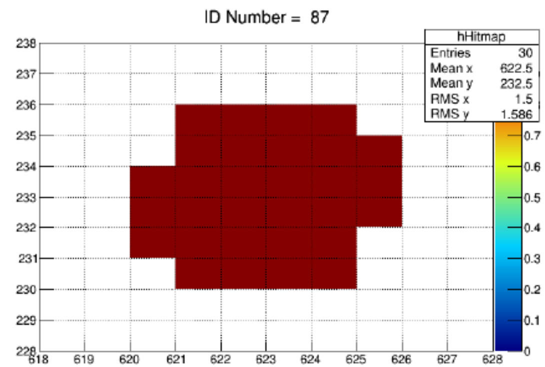
t = 0

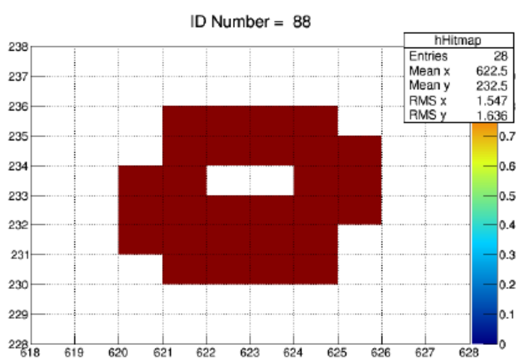
t = 1 μs

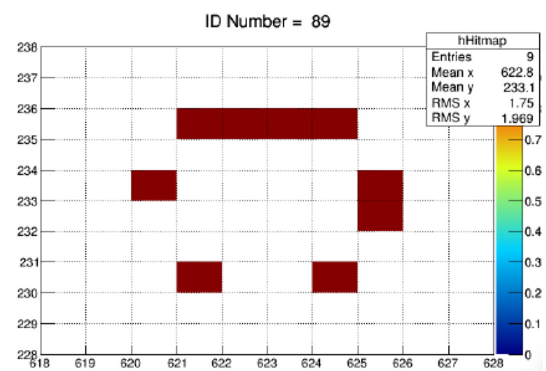
t = 2 μs







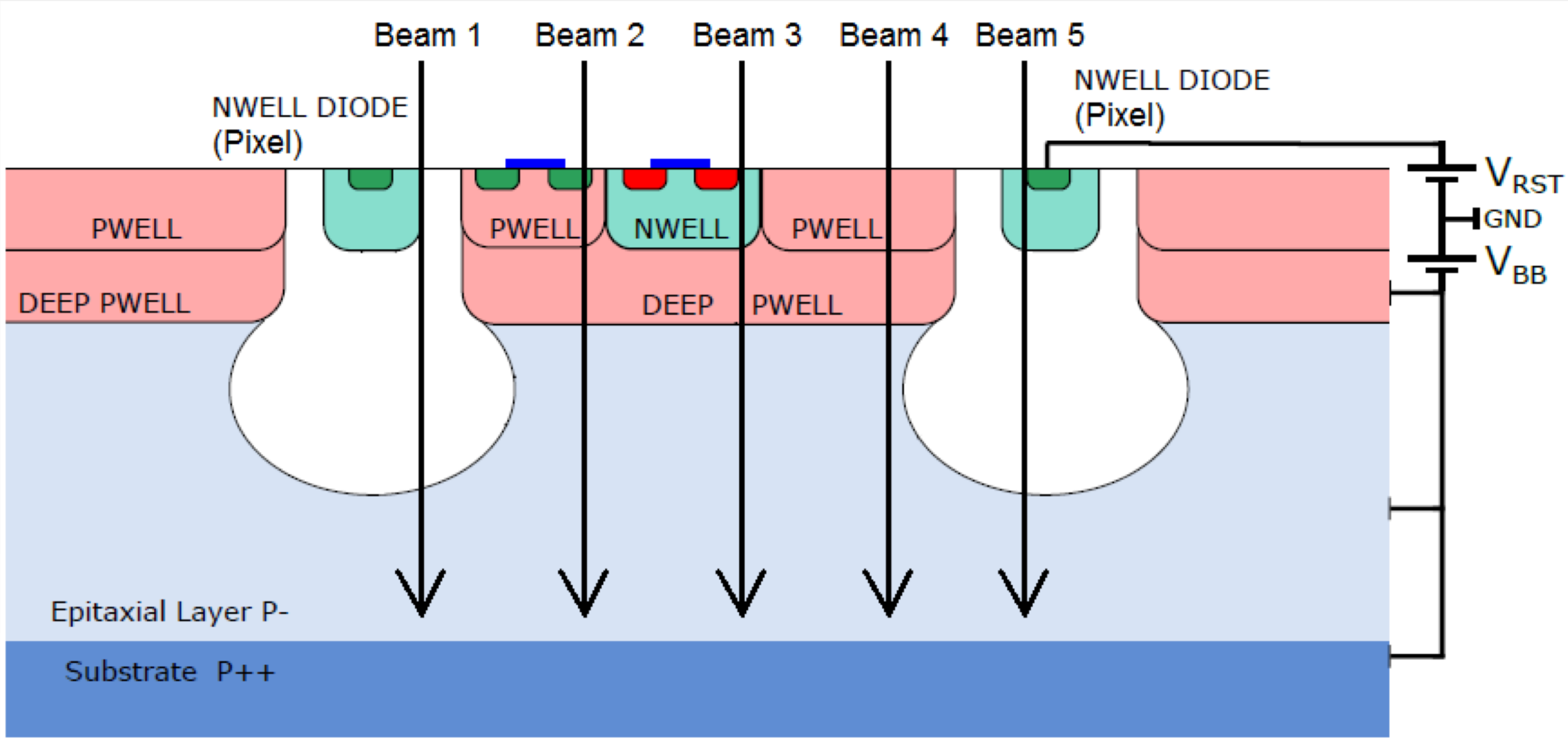


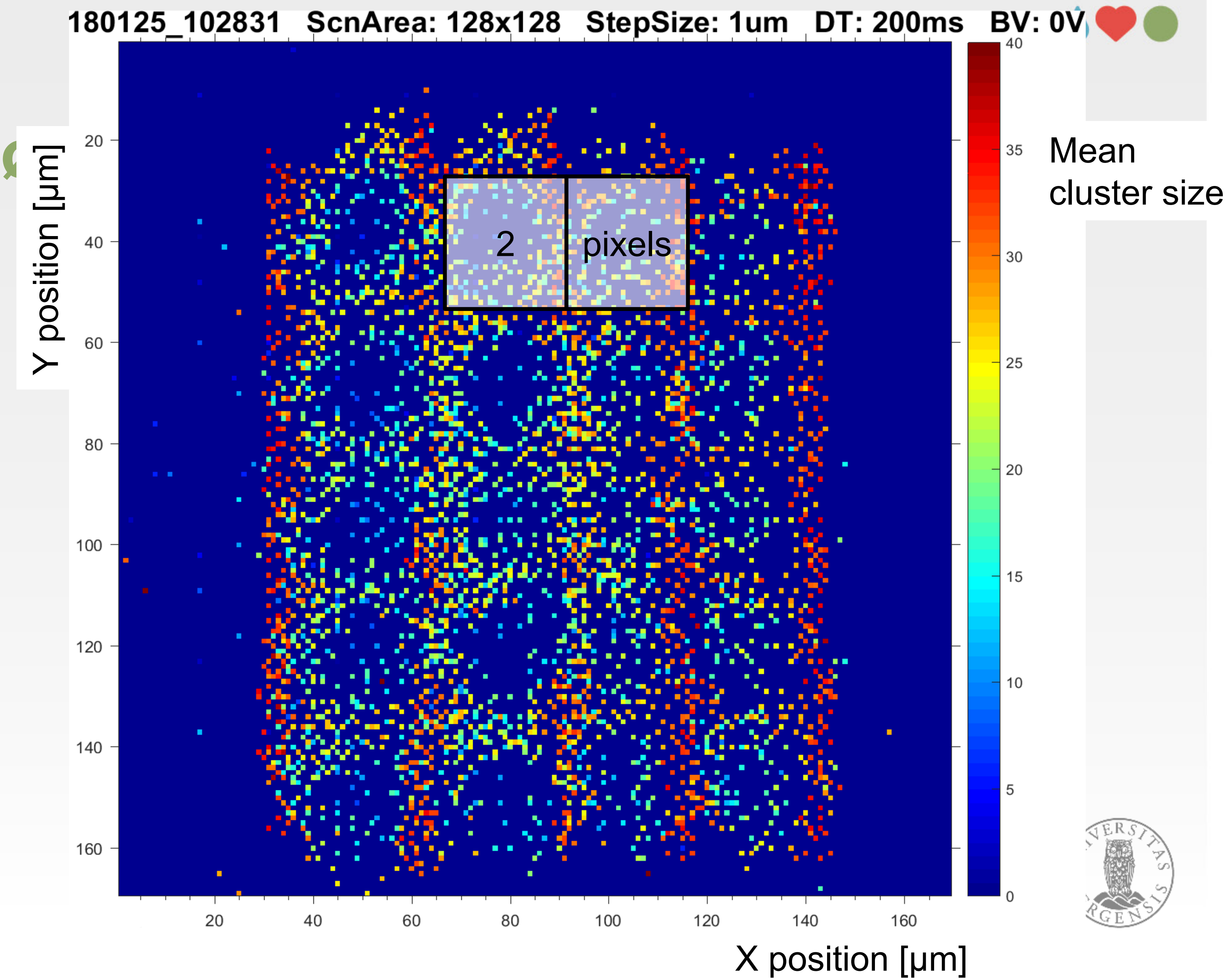


t = 3 μs

t = 4 μs

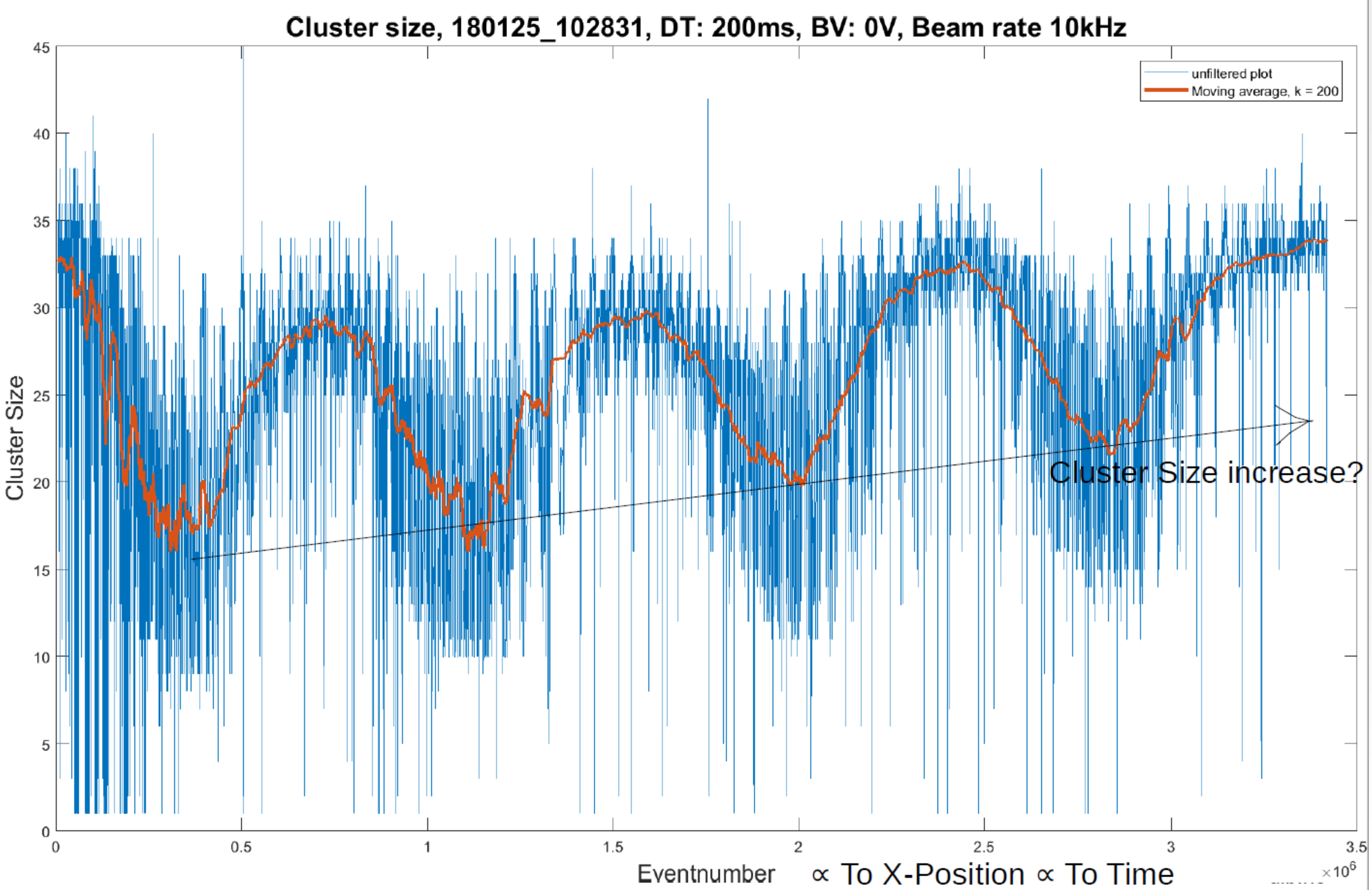
Incident position vs cluster sizes



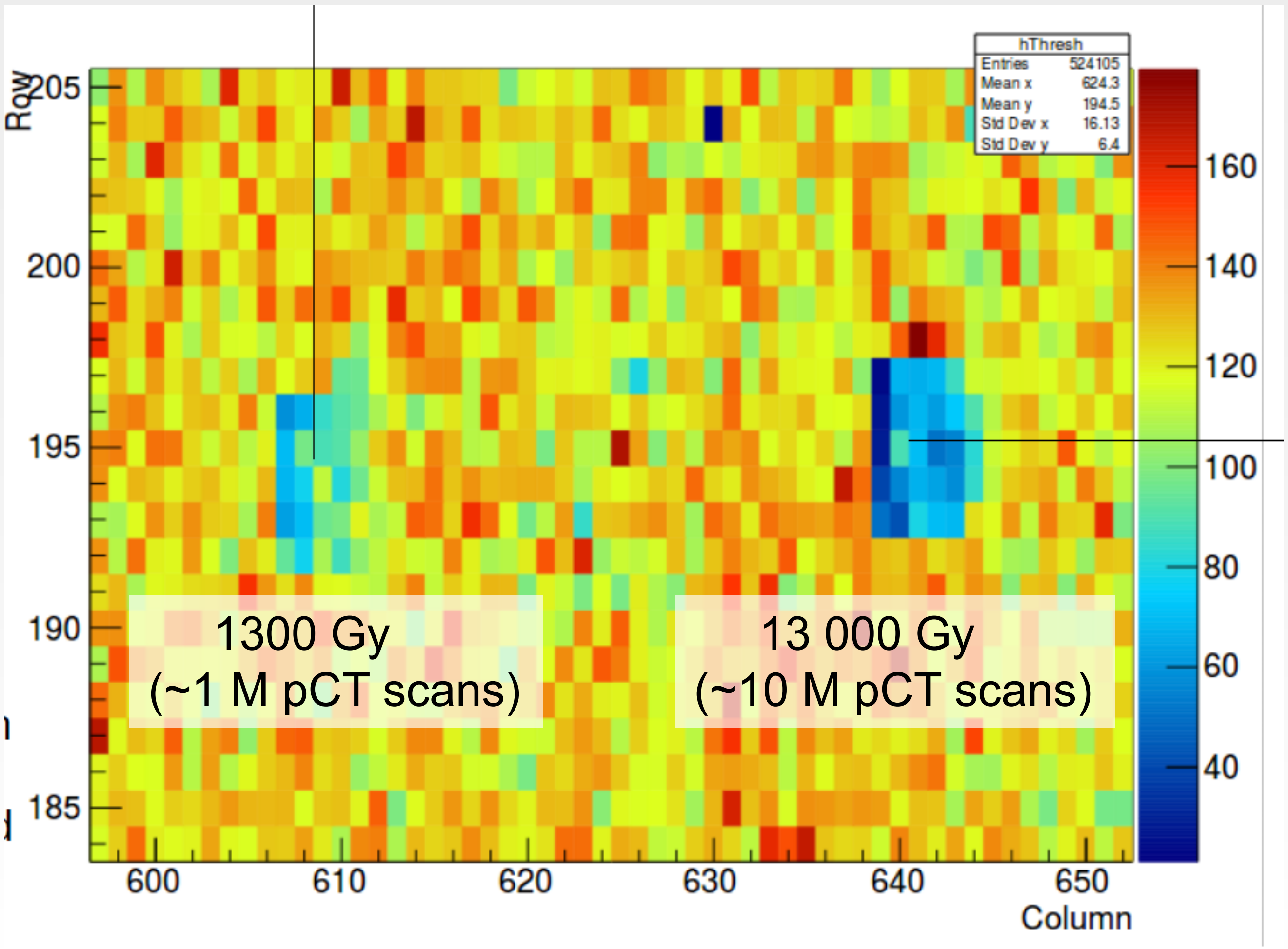


180125_102831 ScnArea: 128x128 StepSize: 1um DT: 200ms BV: 0V
Y position [μm]
X position [μm]
2 pixels
Mean cluster size
20
40
60
80
100
120
140
160
0
5
10
15
20
25
30
35
40

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



Radiation damage (TID) – threshold values



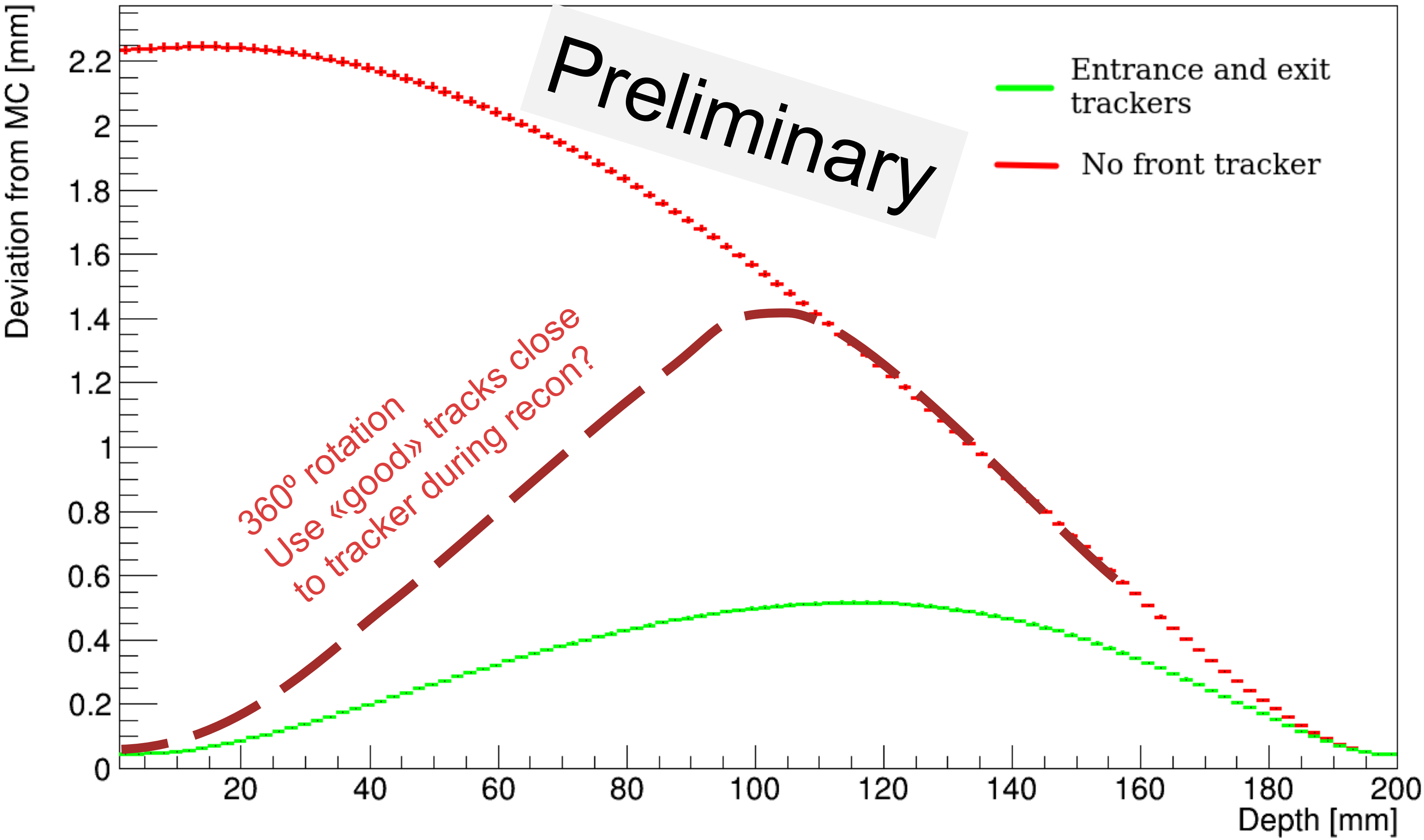
One-sided tracker geometry

Design simplification

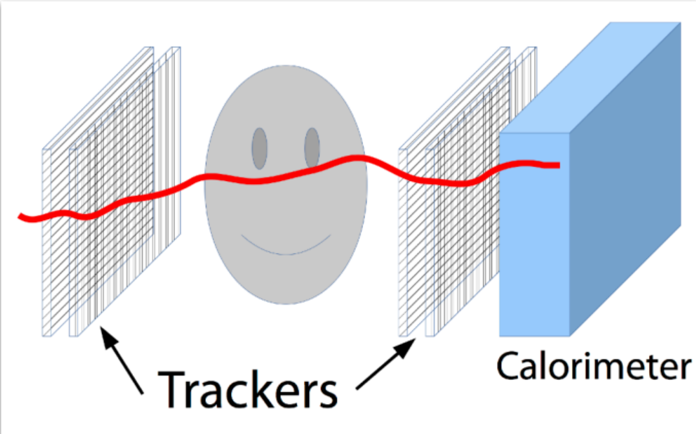
- No front tracker + thin pencil beam
  - What's the resolution degradation?
  - How thin beam to expect?

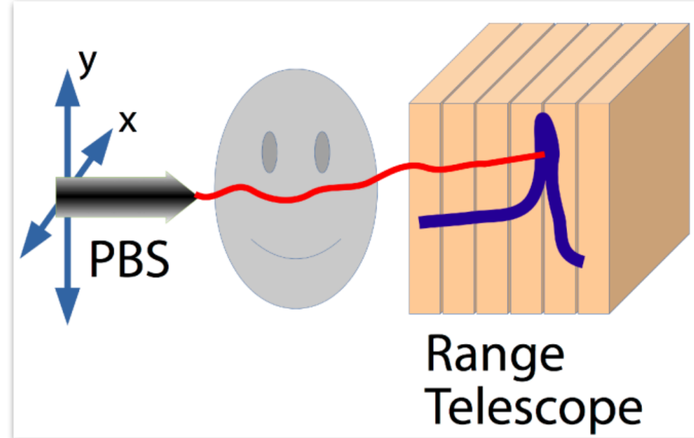
- Currently undergoing MLP + image reconstruction studies with these constraints
  - Collaboration with Heidelberg

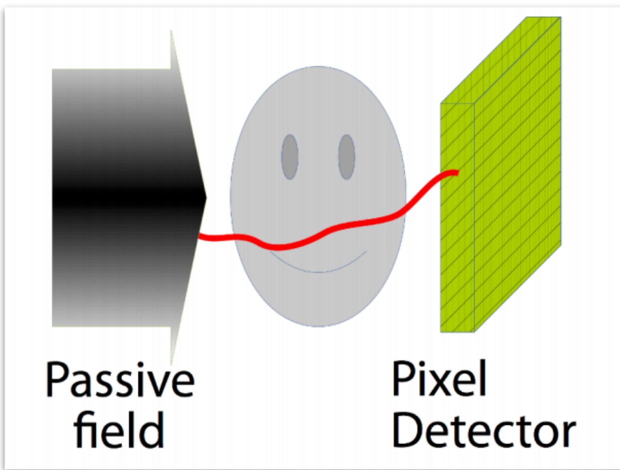
Deviation from MC - Trackers vs. No Front Tracker

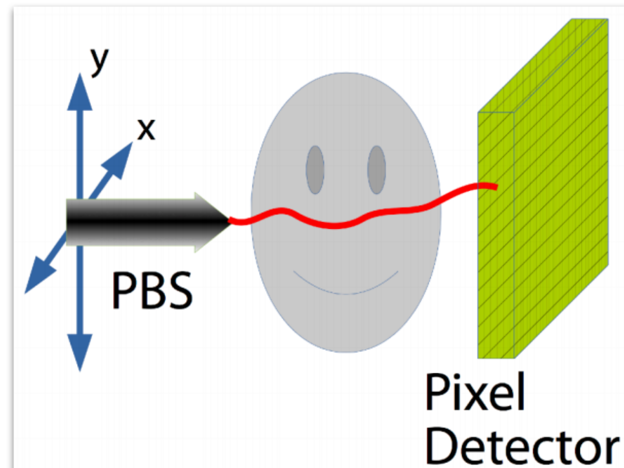


200 MeV @ 6 mm FWHM, 20 cm water phantom





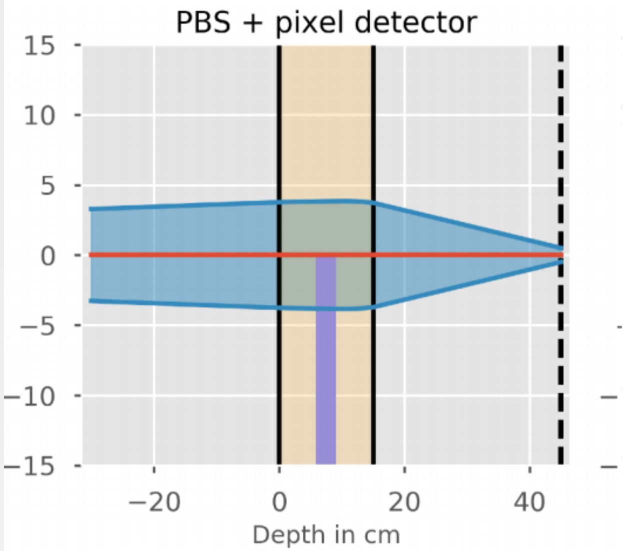




A comprehensive theoretical comparison of proton imaging set-ups in terms of spatial resolution

PAG

N. Krah[1]

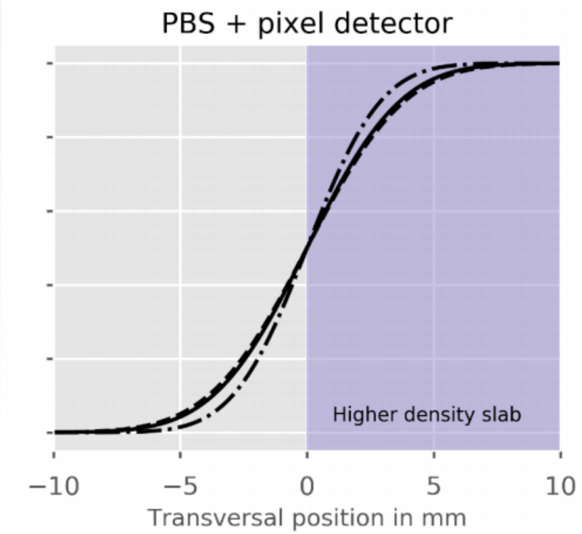


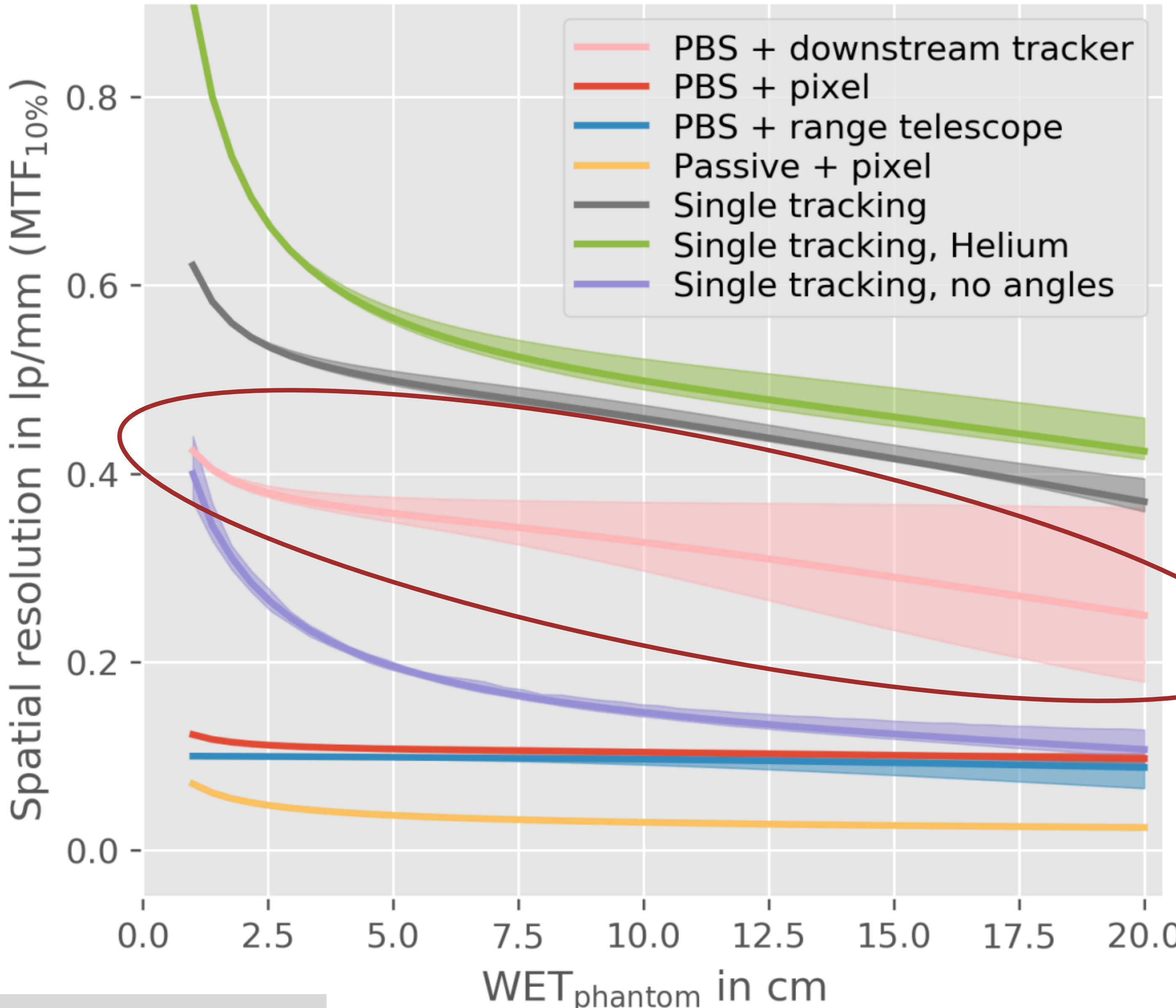
(Preliminary) plots courtesy of Nils Krah
Presented at Lyon workshop june 2018

iopscience.iop.org/article/10.1088/1361-6560/aaca1f

Edge spread distribution

Spatial resolution in lp/mm





(Preliminary) plots courtesy of Nils Krah
Presented at Lyon workshop june 2018

iopscience.iop.org/article/10.1088/1361-6560/aaca1f

***interpret with care**

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. 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): 51–61

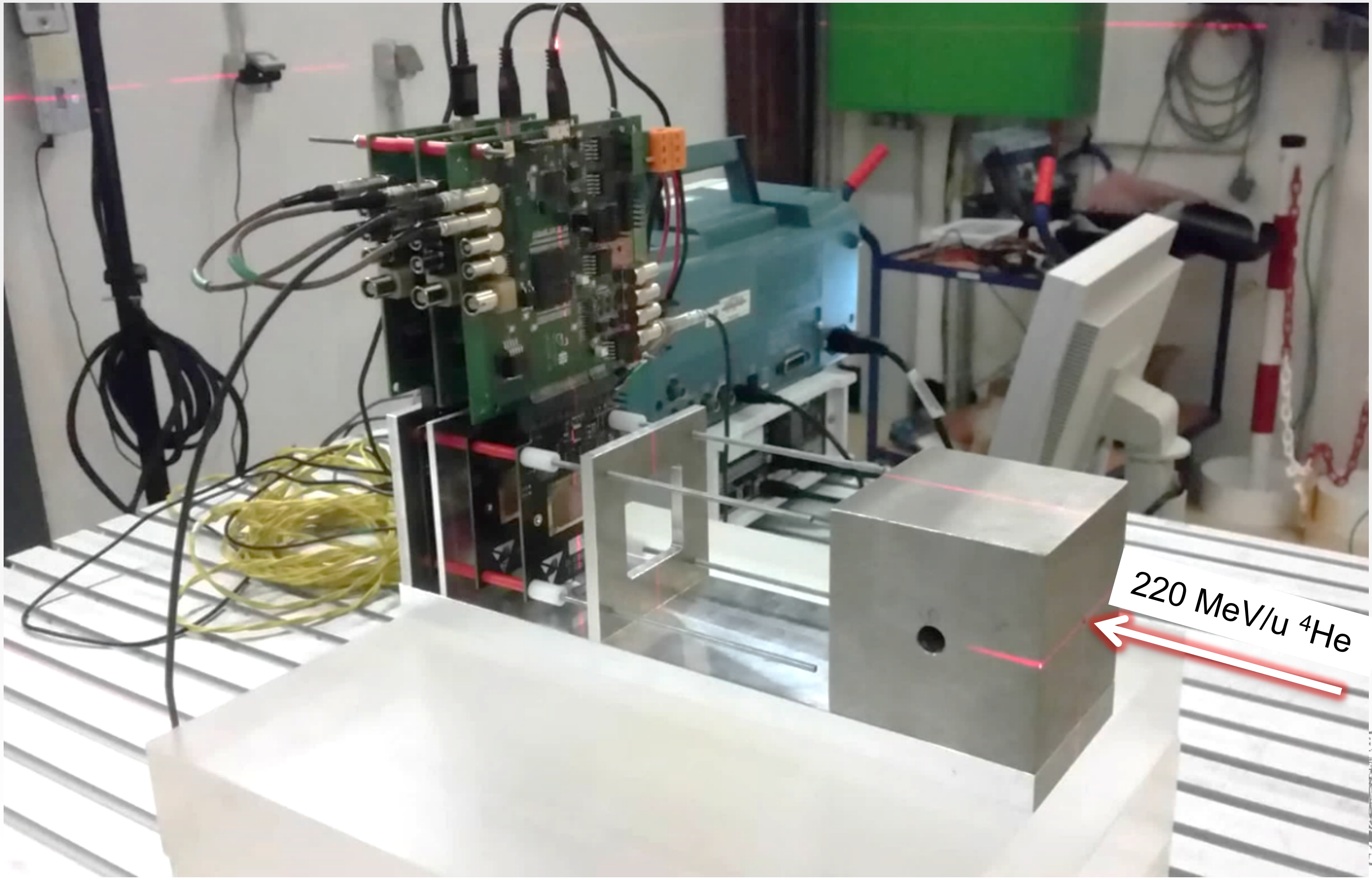
- **Pettersen, H. E. S., et al. «*Proton Tracking Algorithm in a Pixel Based Range Telescope for Proton Computed Tomography*»,** recently submitted to Web of Conferences after HEP-organized track reconstruction workshop

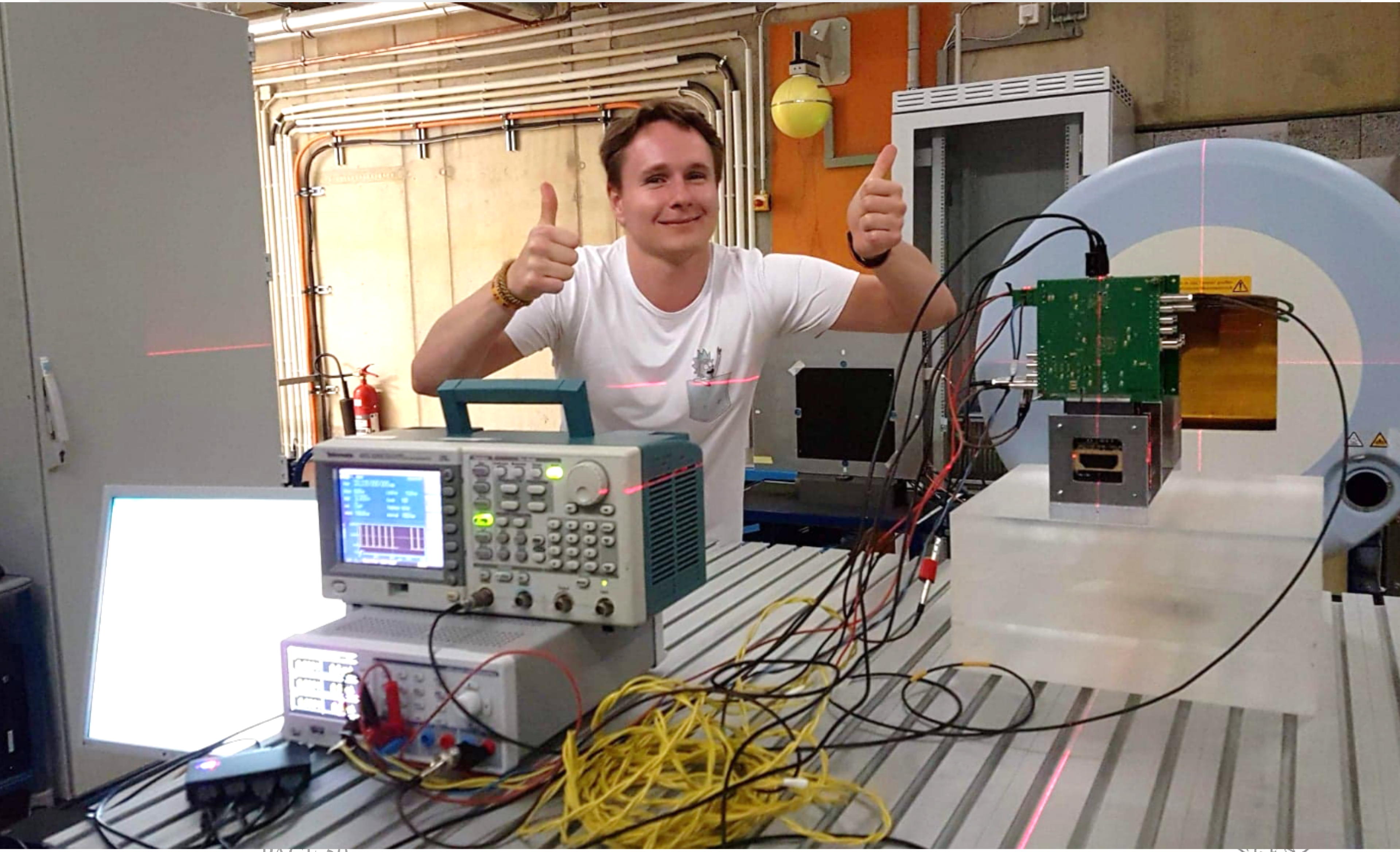
- Aglieri Rinella, G. "*The ALPIDE Pixel Sensor Chip for the Upgrade of the ALICE Inner Tracking System*." NIM A 845 (2016): 583–87.

UNIVERSITY OF BERGEN // HAUKELAND UNIVERSITY HOSPITAL

Backup slides

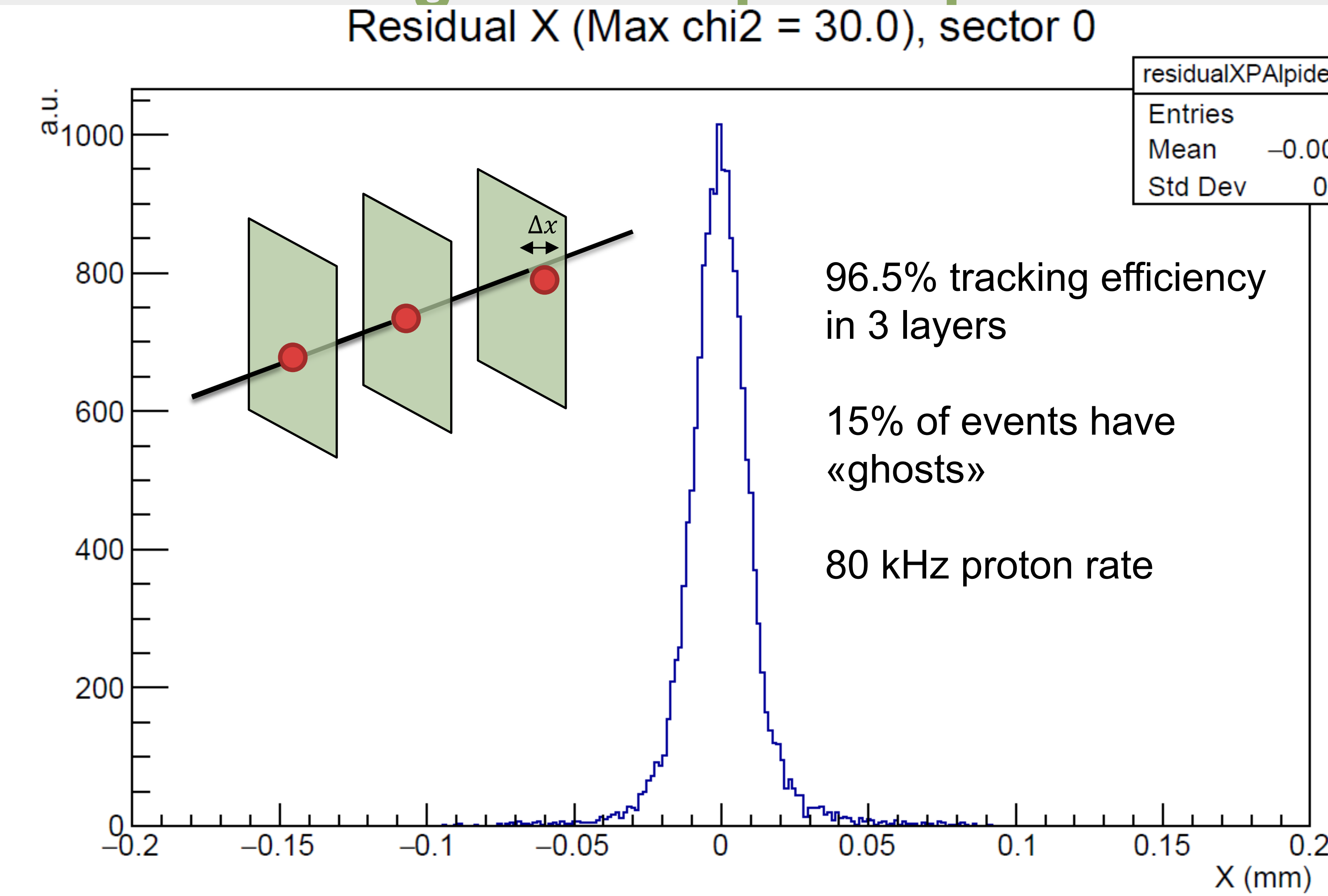
Heidelberg Telescopic Experiment





MSc student Simon Huiberts in Heidelberg

Heidelberg Telescopic Experiment

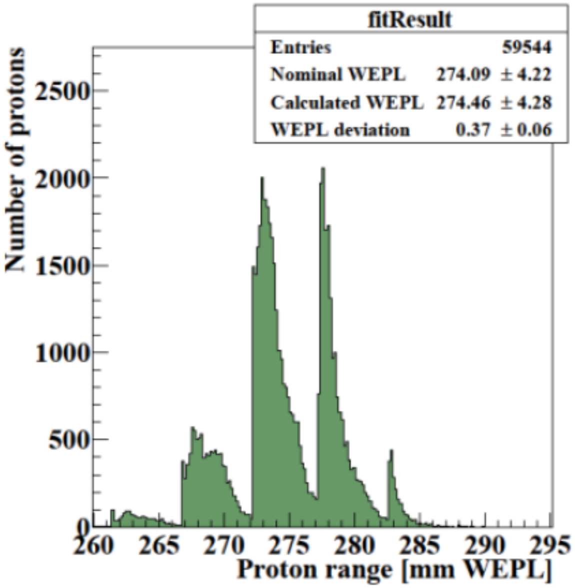


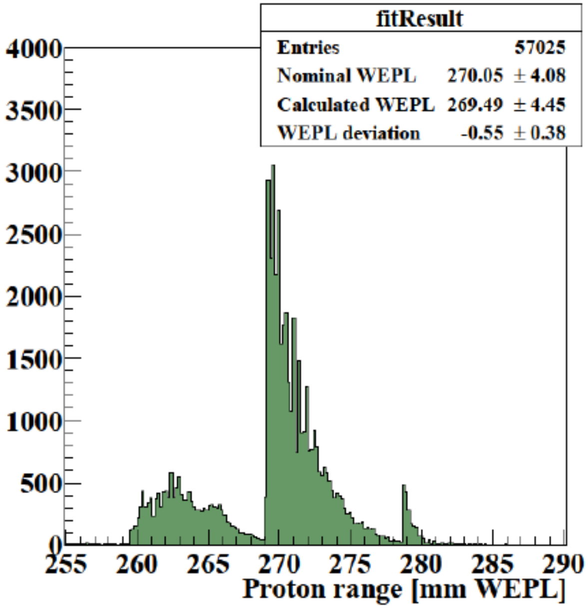
96.5% tracking efficiency in 3 layers

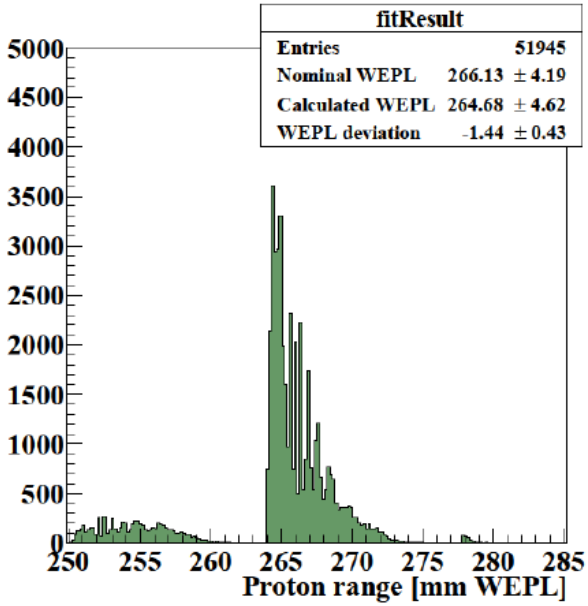
15% of events have «ghosts»

80 kHz proton rate

Range distribution per beam





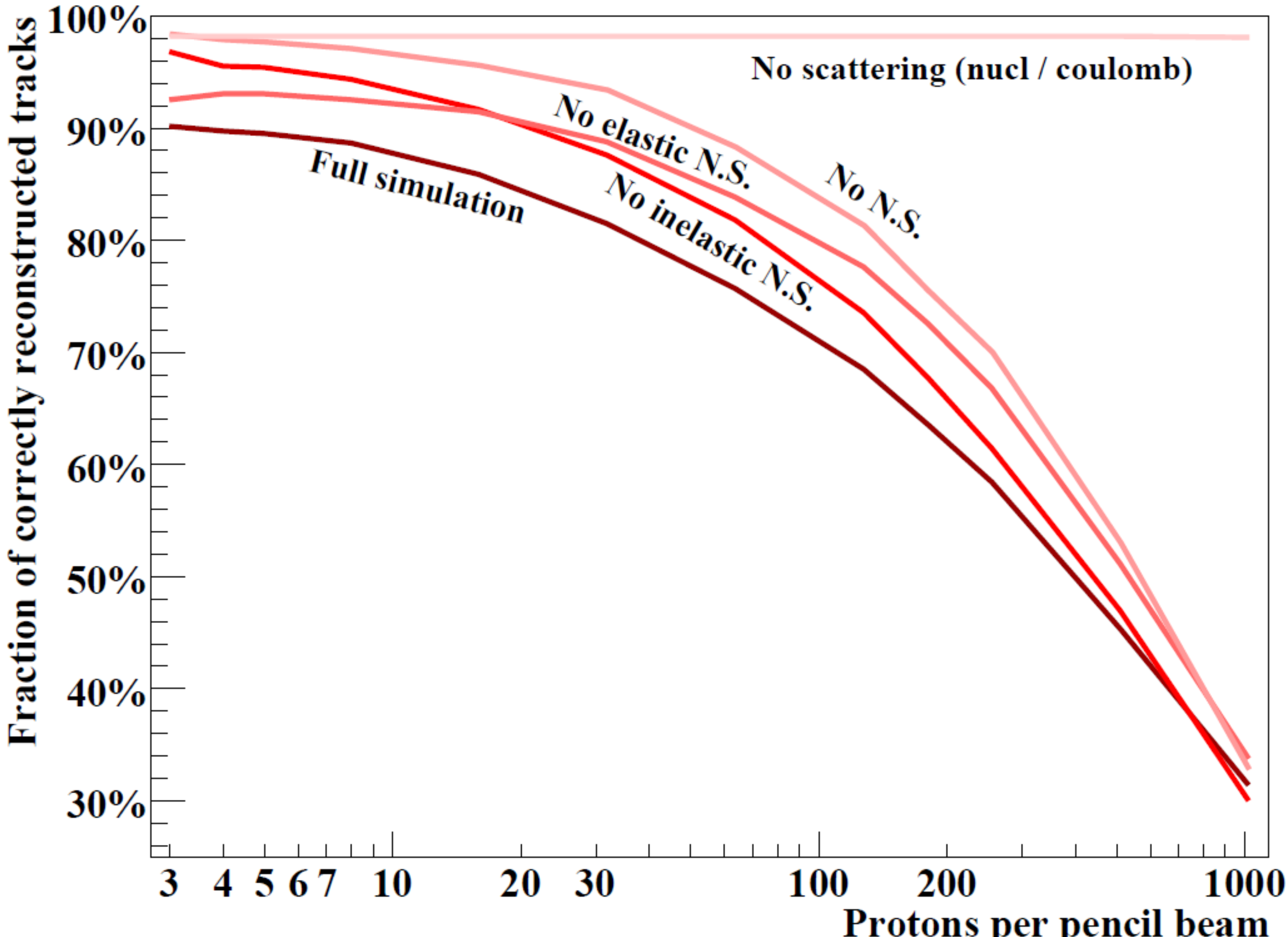


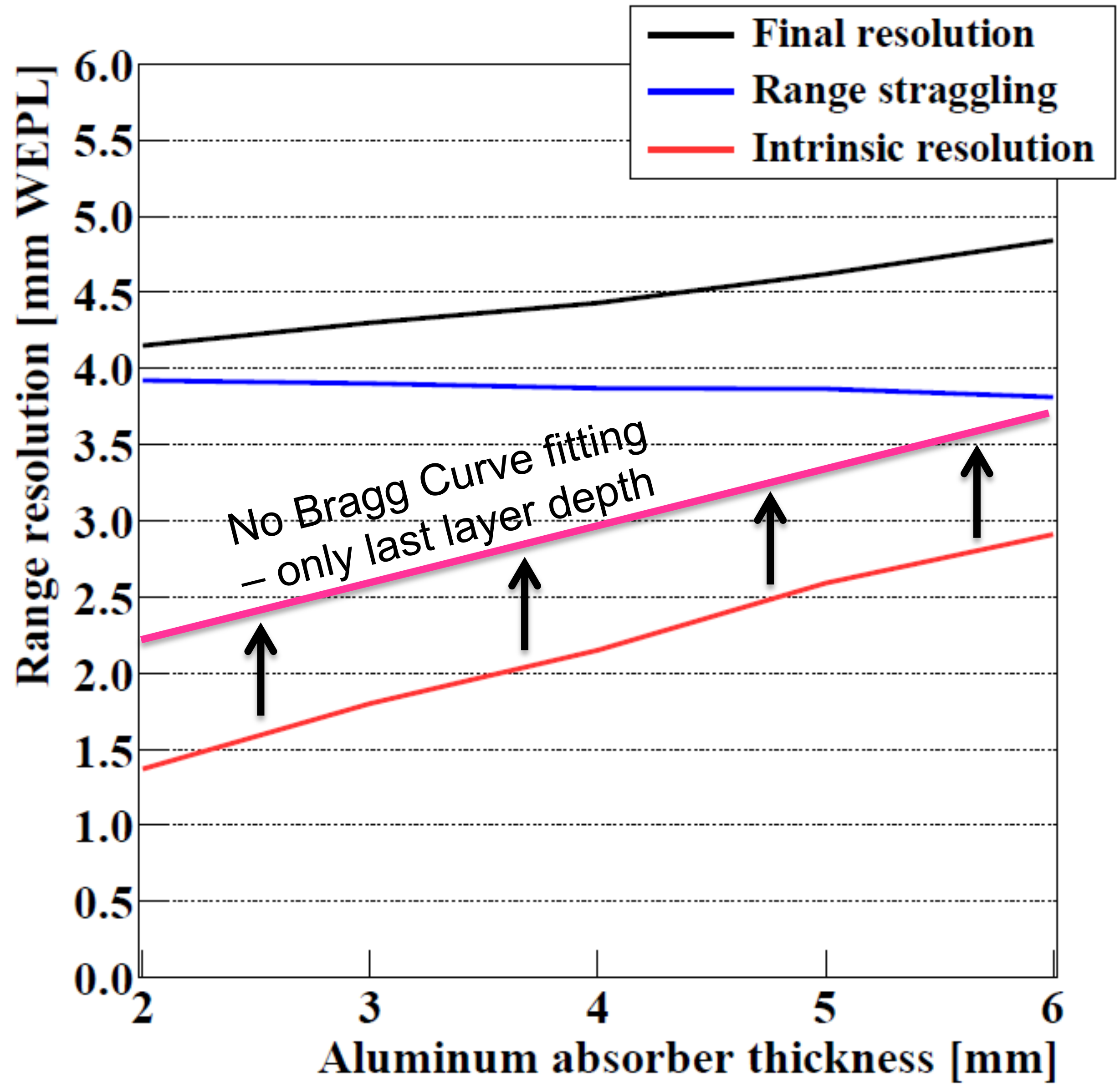
2 mm Al

4 mm Al

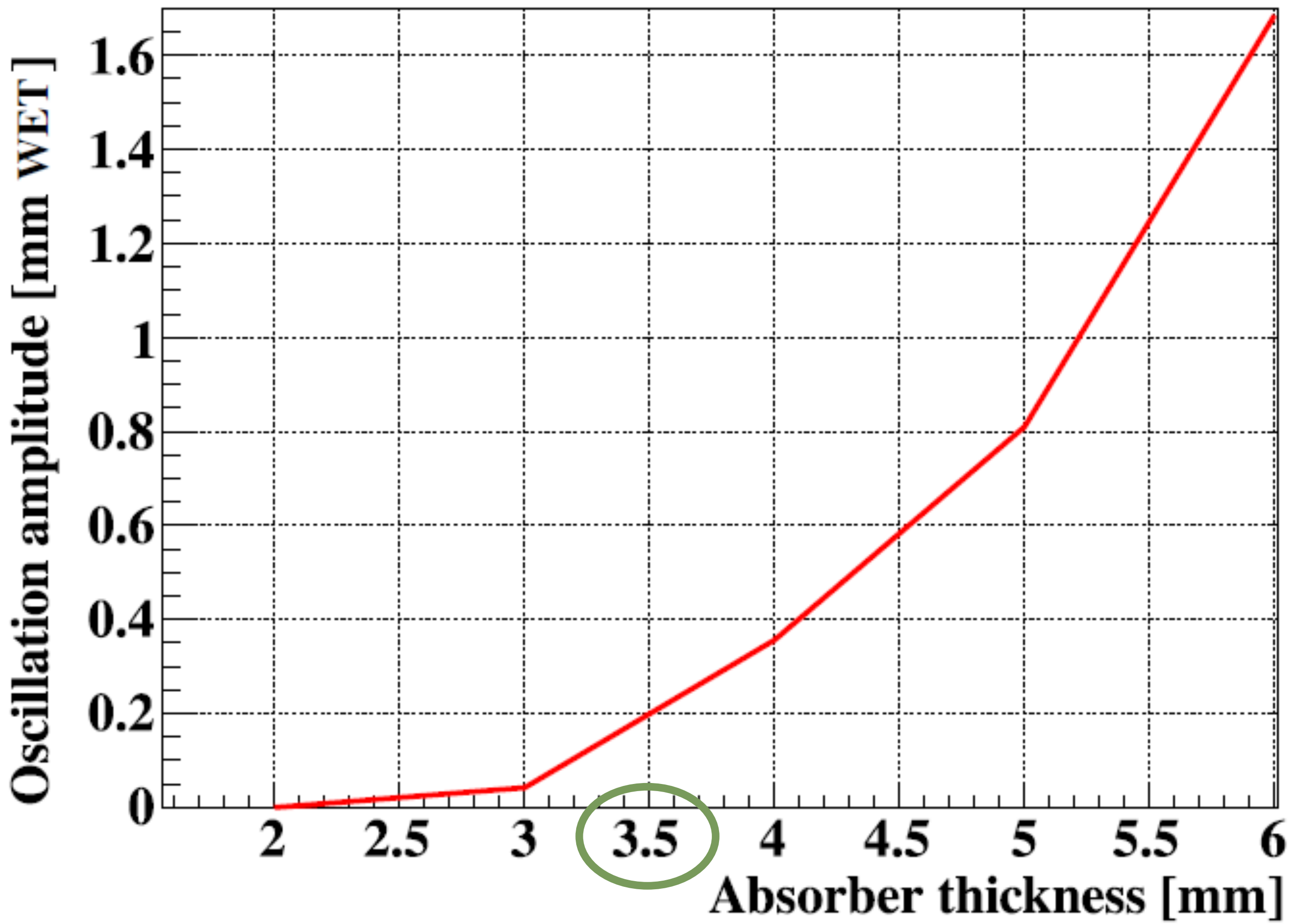
6 mm Al

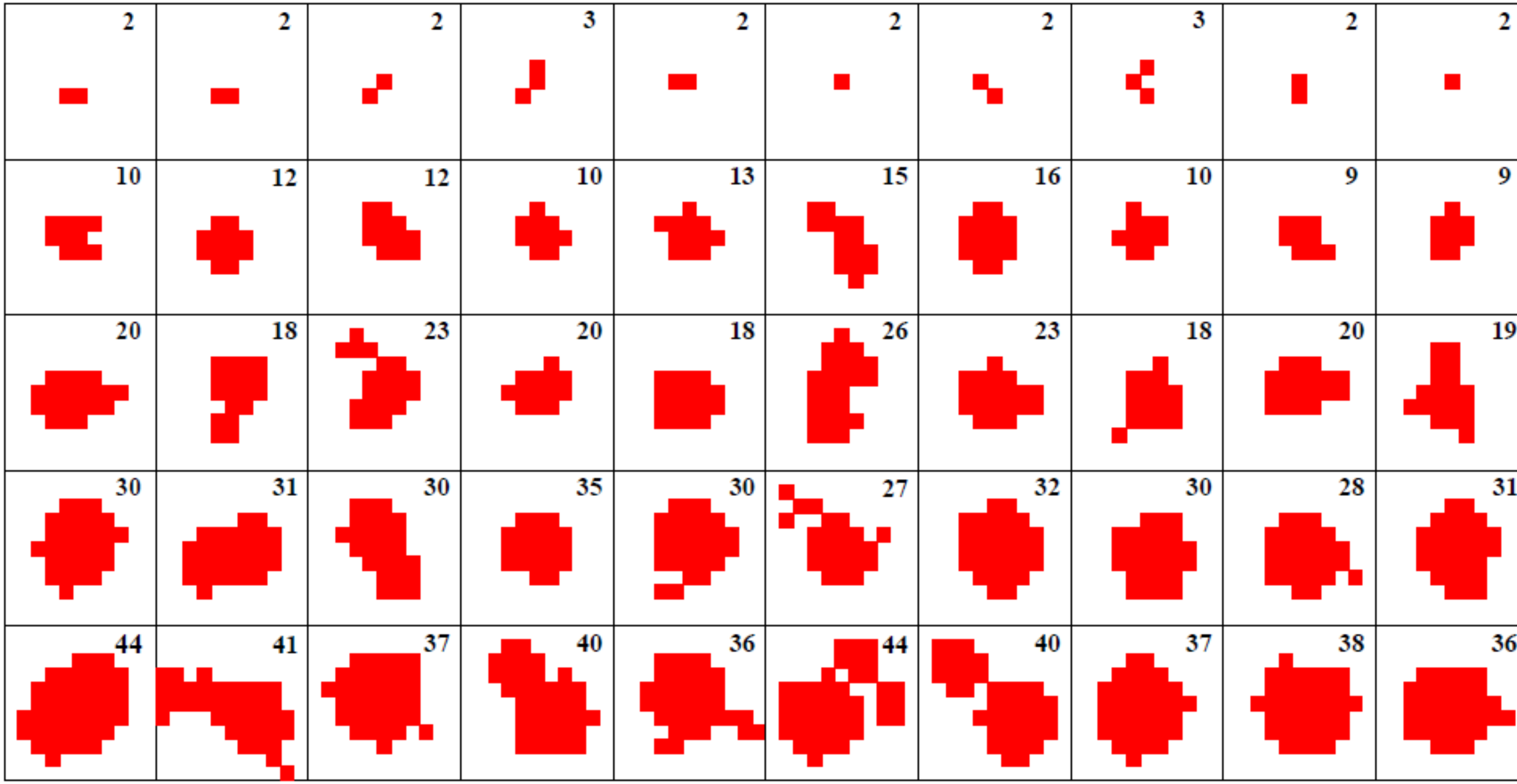
Degradation effects to tracking

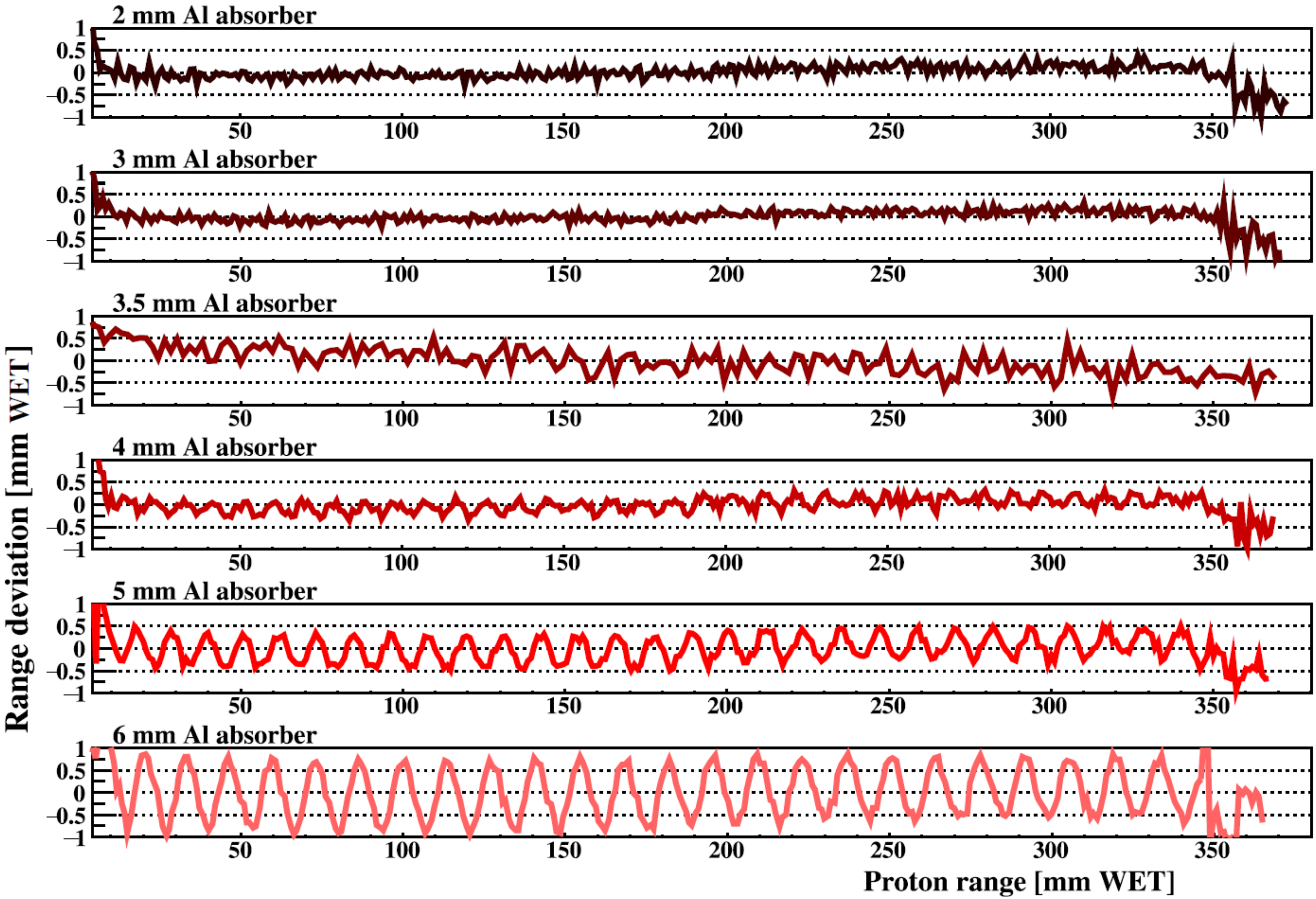



Final resolution
Range straggling
Intrinsic resolution
Range resolution [mm WEPL]
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
2
3
4
5
6
Aluminum absorber thickness [mm]
No Bragg Curve fitting
– only last layer depth

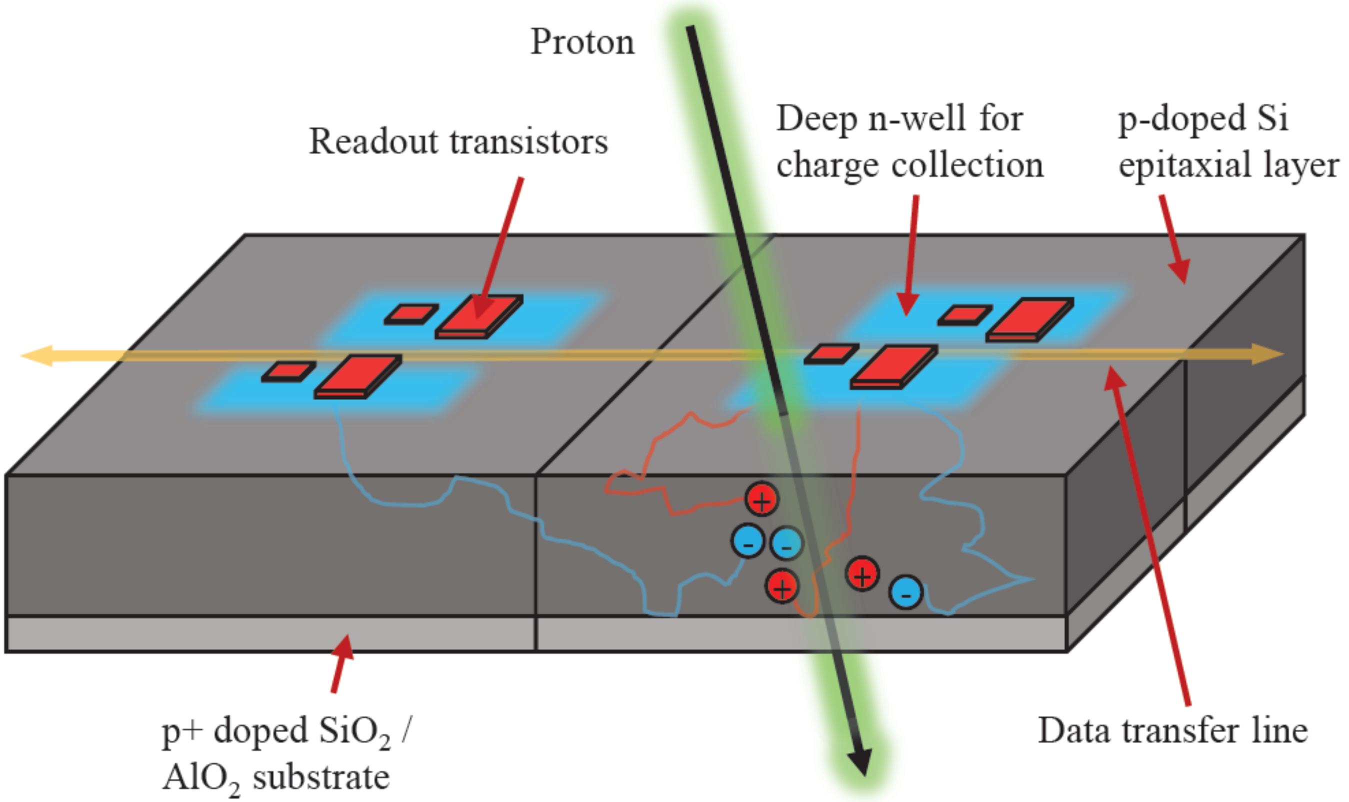
Systematic range error




2 2 2 3 2 2 2 3 2 2
10 12 12 10 13 15 16 10 9 9
20 18 23 20 18 26 23 18 20 19
30 31 30 35 30 27 32 30 28 31
44 41 37 40 36 44 40 37 38 36

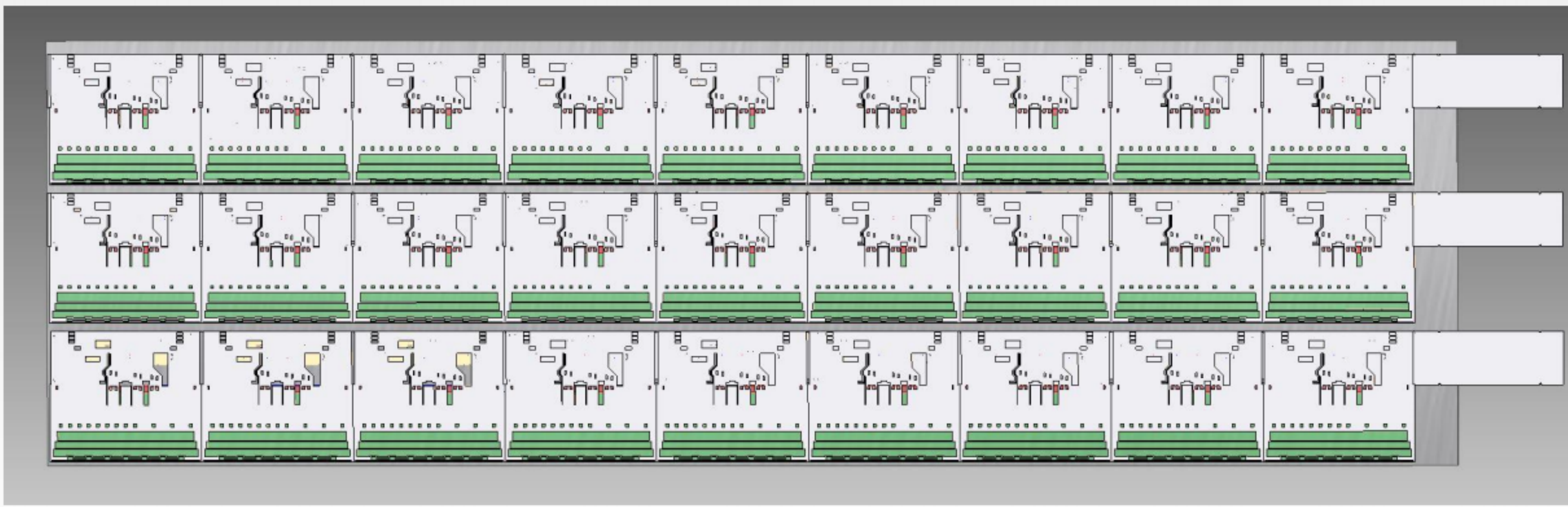

2 mm Al absorber
3 mm Al absorber
3.5 mm Al absorber
4 mm Al absorber
5 mm Al absorber
6 mm Al absorber
1
0.5
0
−0.5
−1
50
100
150
200
250
300
350
Range deviation [mm WET]
Proton range [mm WET]

Charge diffusion in pixels



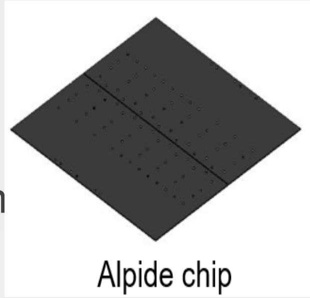
COOP with Utrecth/Kharkiv

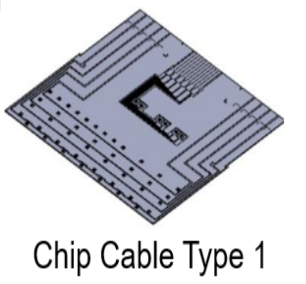
- 3-string structure
- Detector layer base (x4 -> 36 chips)

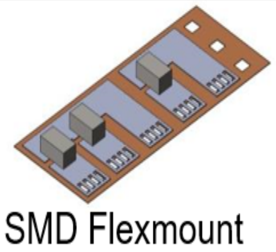


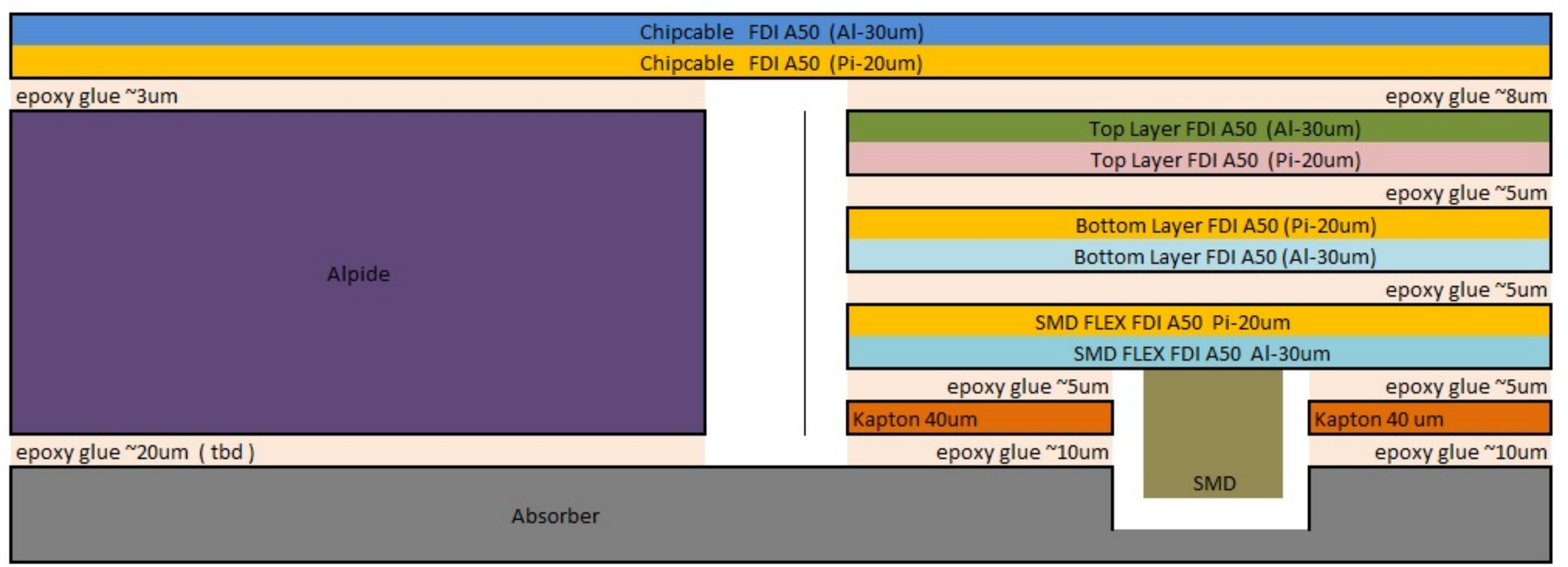
Digital Tracking Calorimeter(DTC)

- **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









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

Digital Tracking Calorimeter(DTC)

- **Bonding method**

Mechanical Connection → Ultrasound welding

Dielectric connection → Glue protection

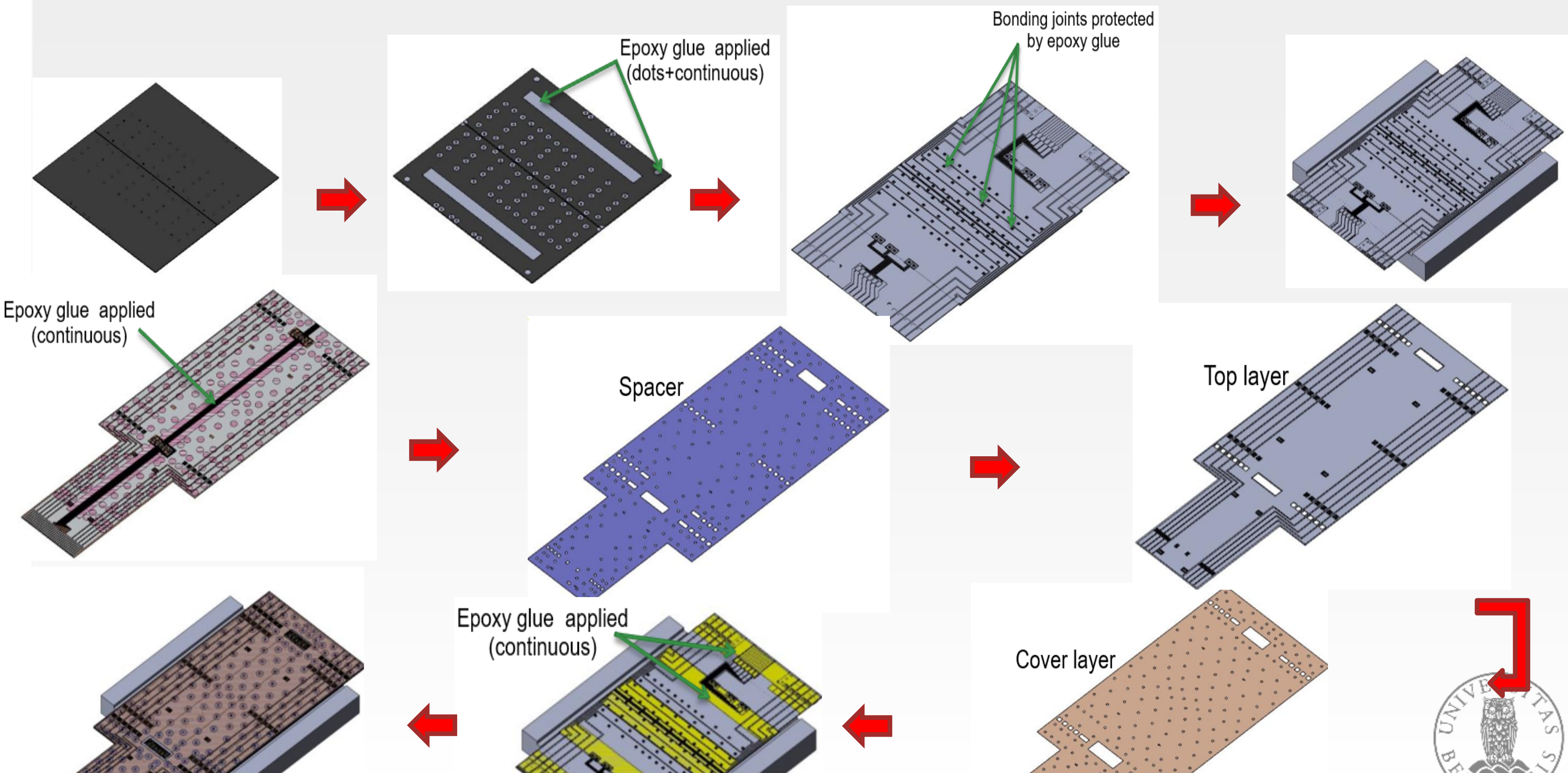


Figure from: **Slava**: ''Applied glue in mock up of detector layer for Focal m Tower

Conclusions on ALICE-FoCal prototype

ELSEVIER

Contents lists available at ScienceDirect

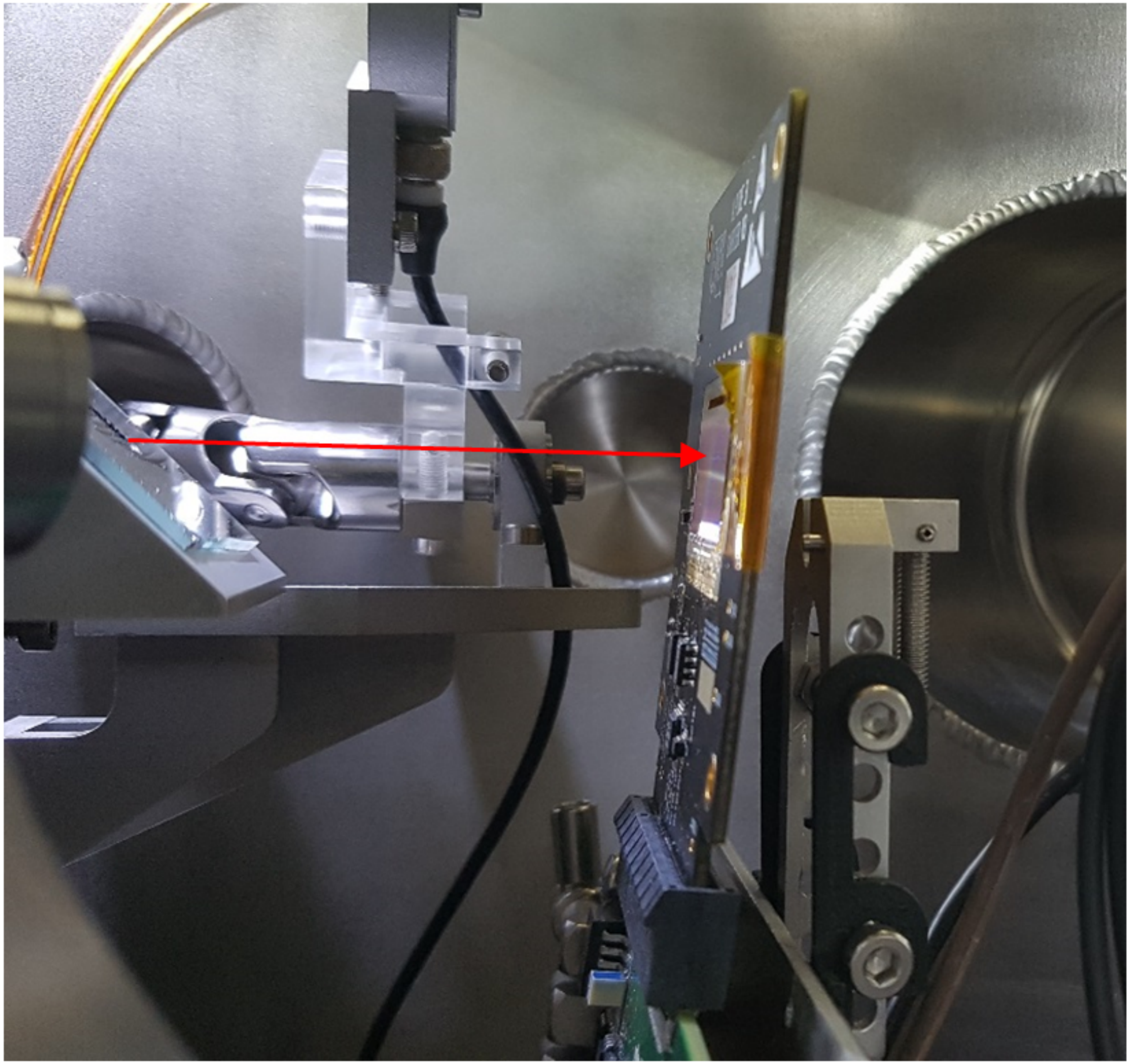
Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Proton tracking in a high-granularity Digital Tracking Calorimeter for proton CT purposes

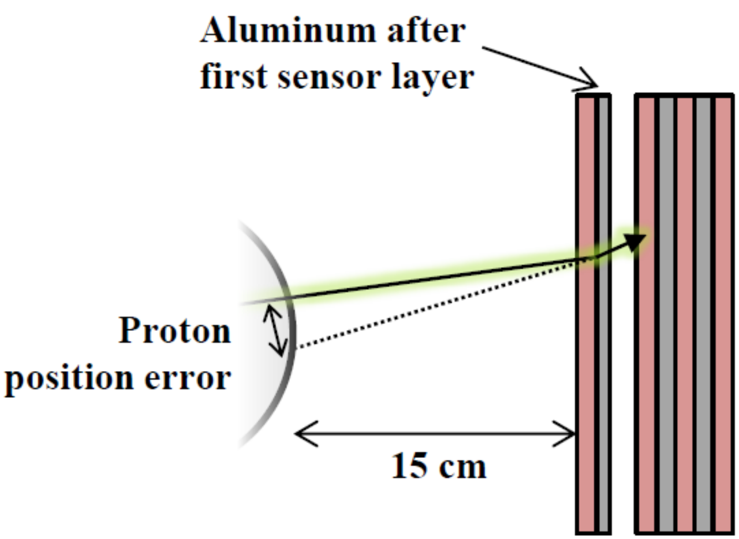
H.E.S. Pettersen[a,b,*], J. Alme[b], A. Biegun[e], A. van den Brink[c], M. Chaar[b], D. Fehlker[b], I. Meric[d], O.H. Odland[a], T. Peitzmann[c], E. Rocco[c], K. Ullaland[b], H. Wang[c], S. Yang[b], C. Zhang[c], D. Röhrich[b]

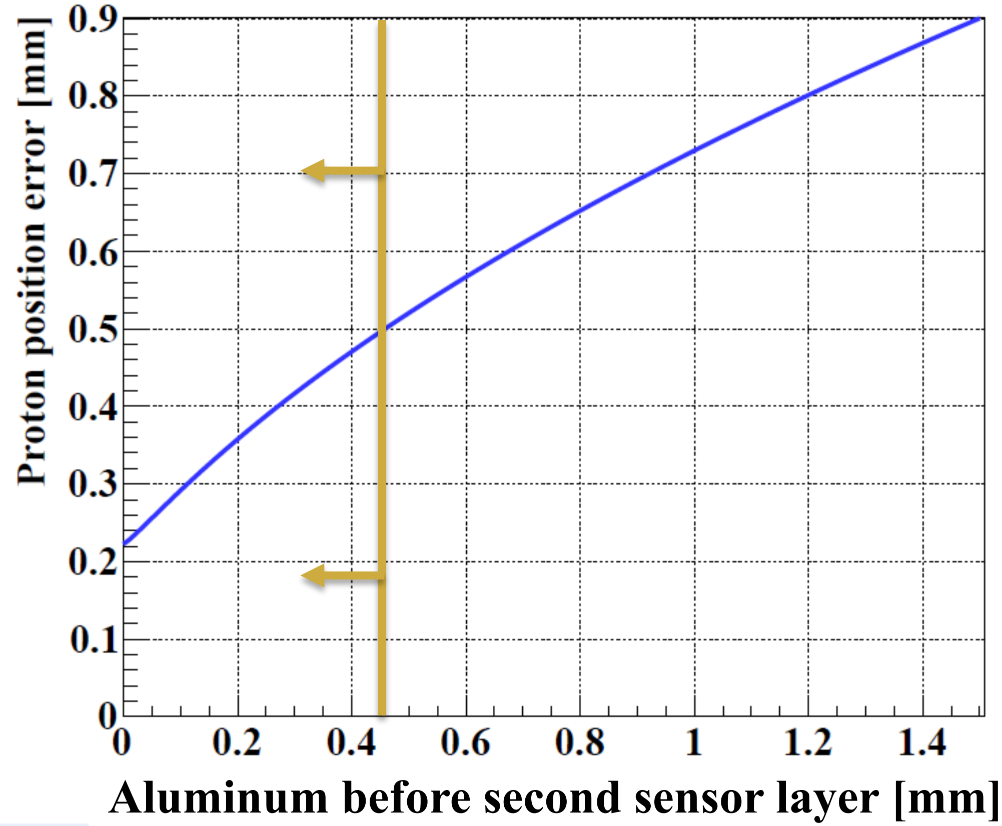
- Intensity capacity: 1 million protons/s when 80% are reconstructed «correctly»
  - Similar numbers as other prototypes



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.

Scattering in first layers





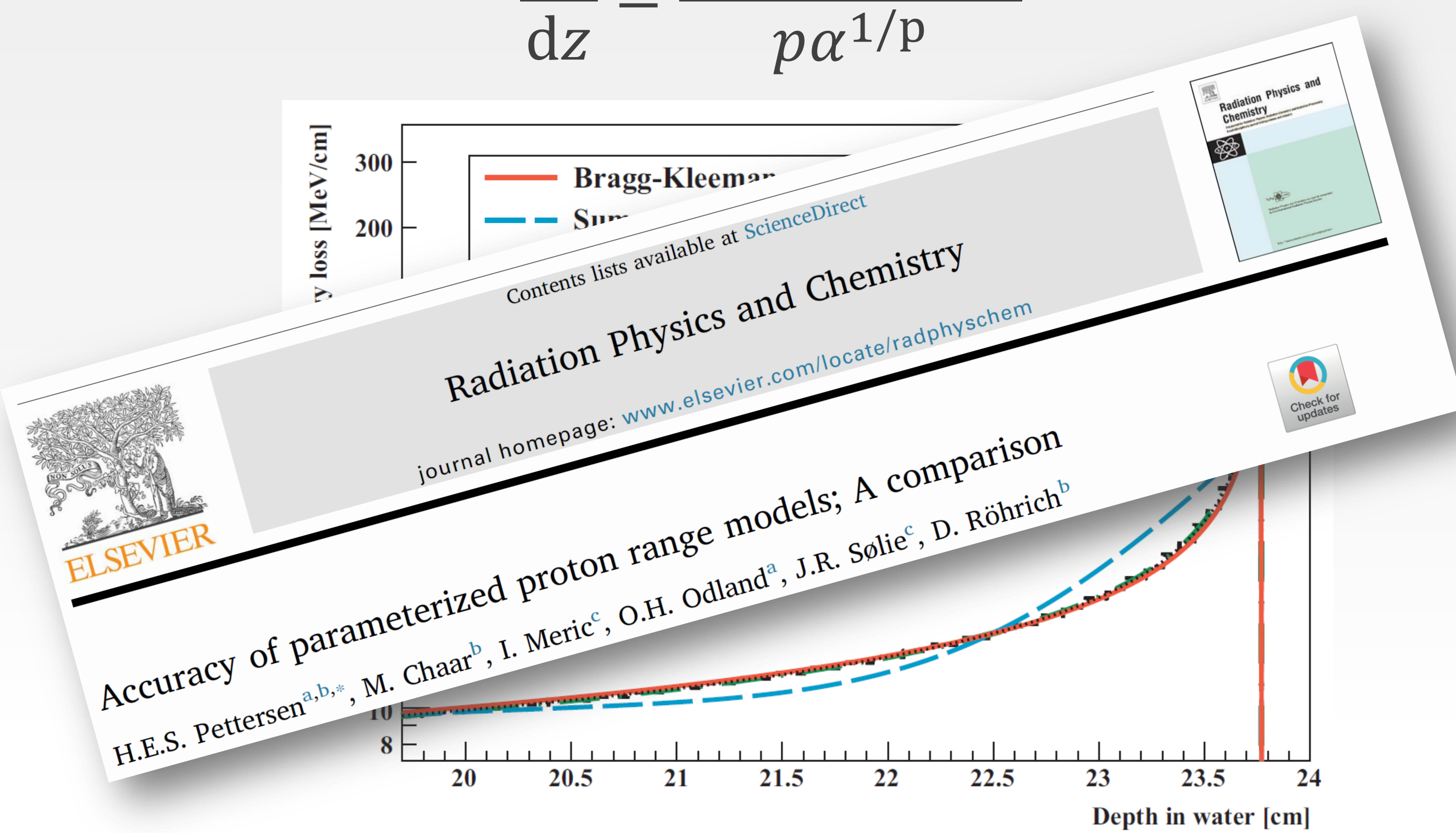
$$\theta_0 \simeq \frac{14.1\ \text{MeV}}{p_1 v_1}\sqrt{\frac{x}{X_0}}\left(1 + \frac{1}{9}\log_{10}\frac{x}{X_0}\right)$$

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 ~ <u>1 mGy</u>

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

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



Conclusions next prototype

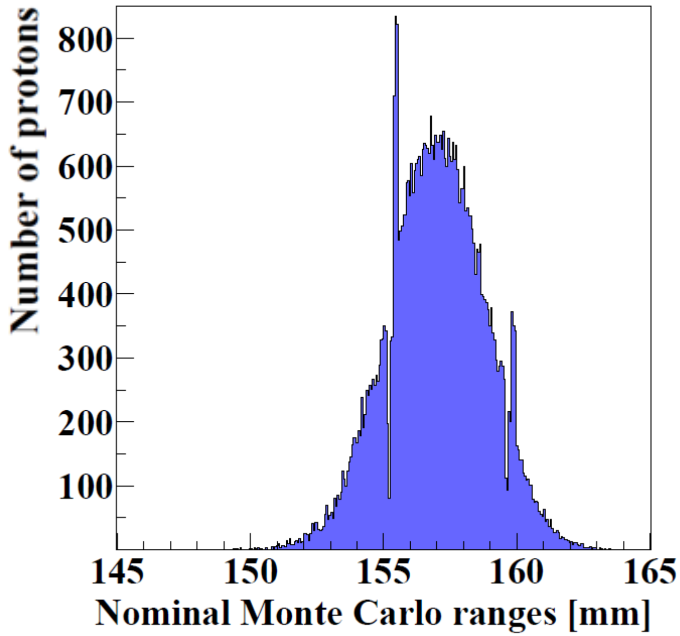
	Constraint	LLUMC#2	ALICE-FoCal DTC	Next-gen DTC
Number of trackers	$N = 4$	4	1	2
Pixel pitch	$P/\sqrt{12} < 1$ mm	0.1 mm	8.7 μm	8.1 μm
Tracker pitch	$PL/\sqrt{6}D < 1$ mm	0.5 mm	0.06 mm	0.25 mm
Tracker offset	$0.1L\sqrt{T/X_0} < 1$ mm	1.4 mm	2.1 mm	0.9 mm (300 μm tracker design)
Resolution	R < 3 mm	2.7 mm*	20 mm	2 mm (3.5 mm design
Proton intensity (over 10 cm^2 detector area)	$f \geq 2$ Mp/s	1 Mp/s	0.6 Mp/s**	~10 Mp/s**

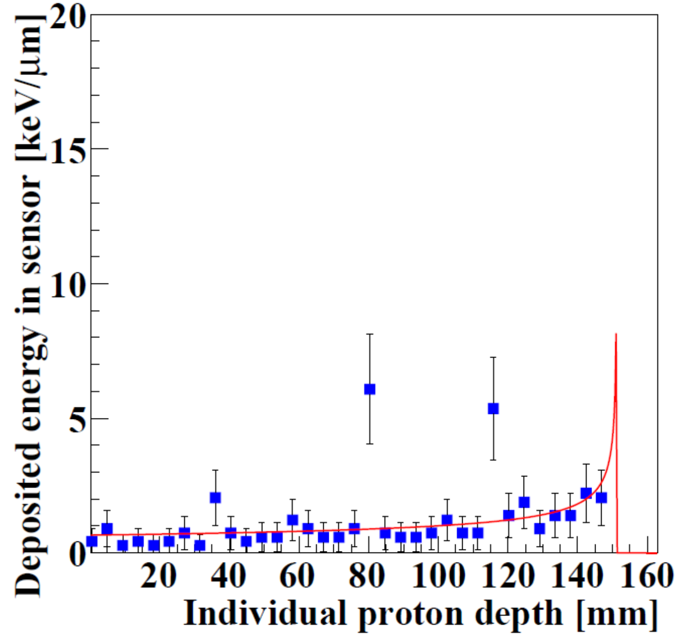
*Scaled from 200 MeV scintillator energy resolution
**At 80 % reconstruction efficiency

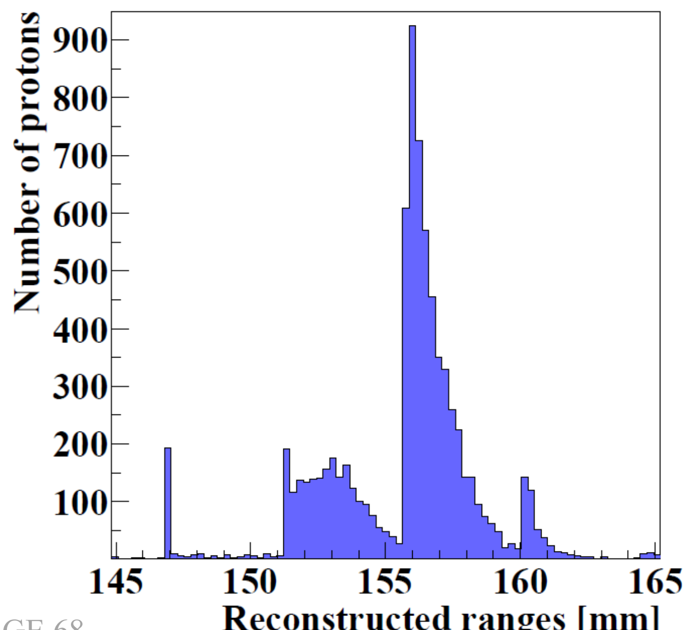
REVIEW ARTICLE

Proton radiography and tomography with application to proton therapy

[1,2]G POLUDNIOWSKI, PhD, [3]N M ALLINSON, ScD and [1]P M EVANS, DPhil







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

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

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

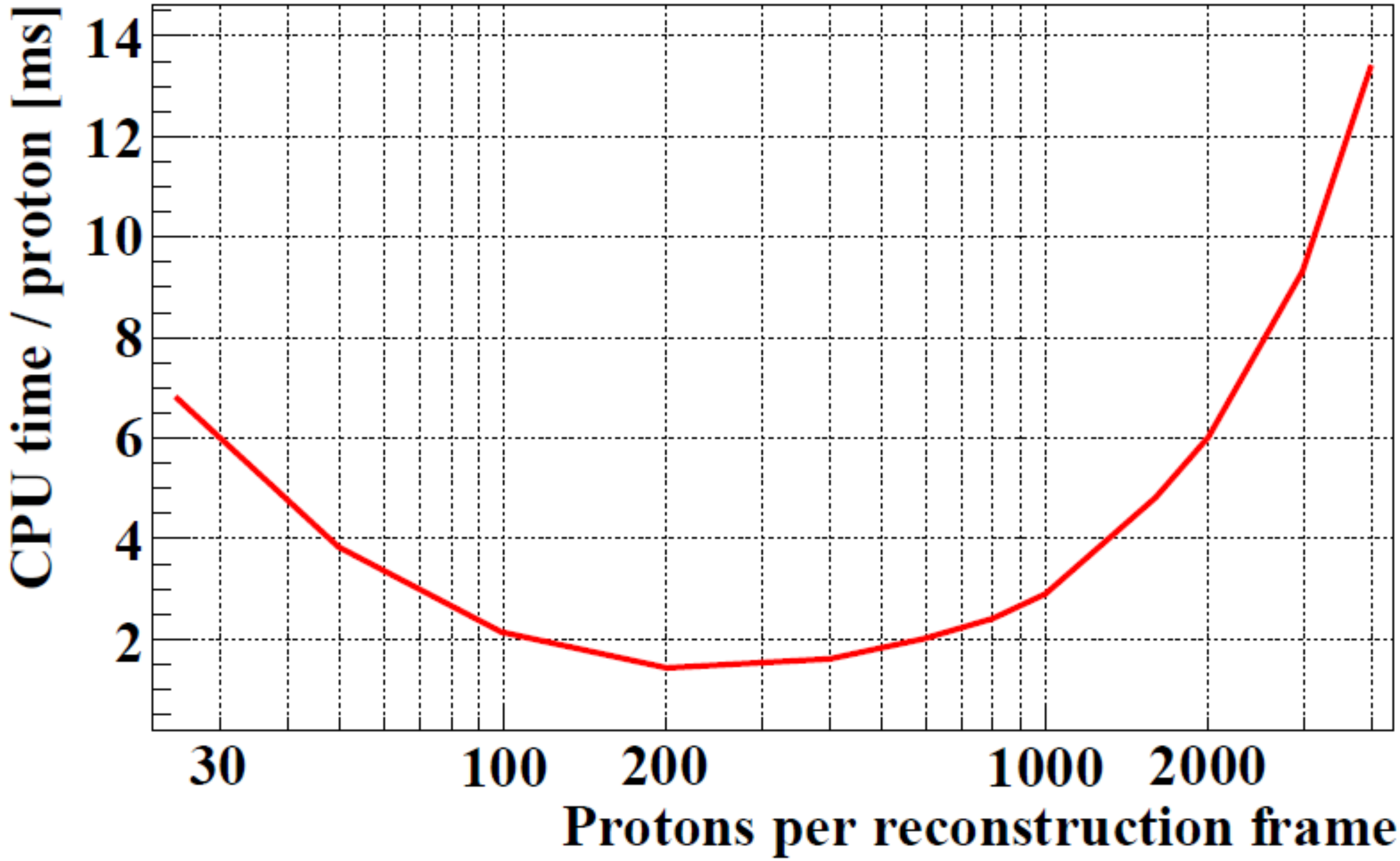
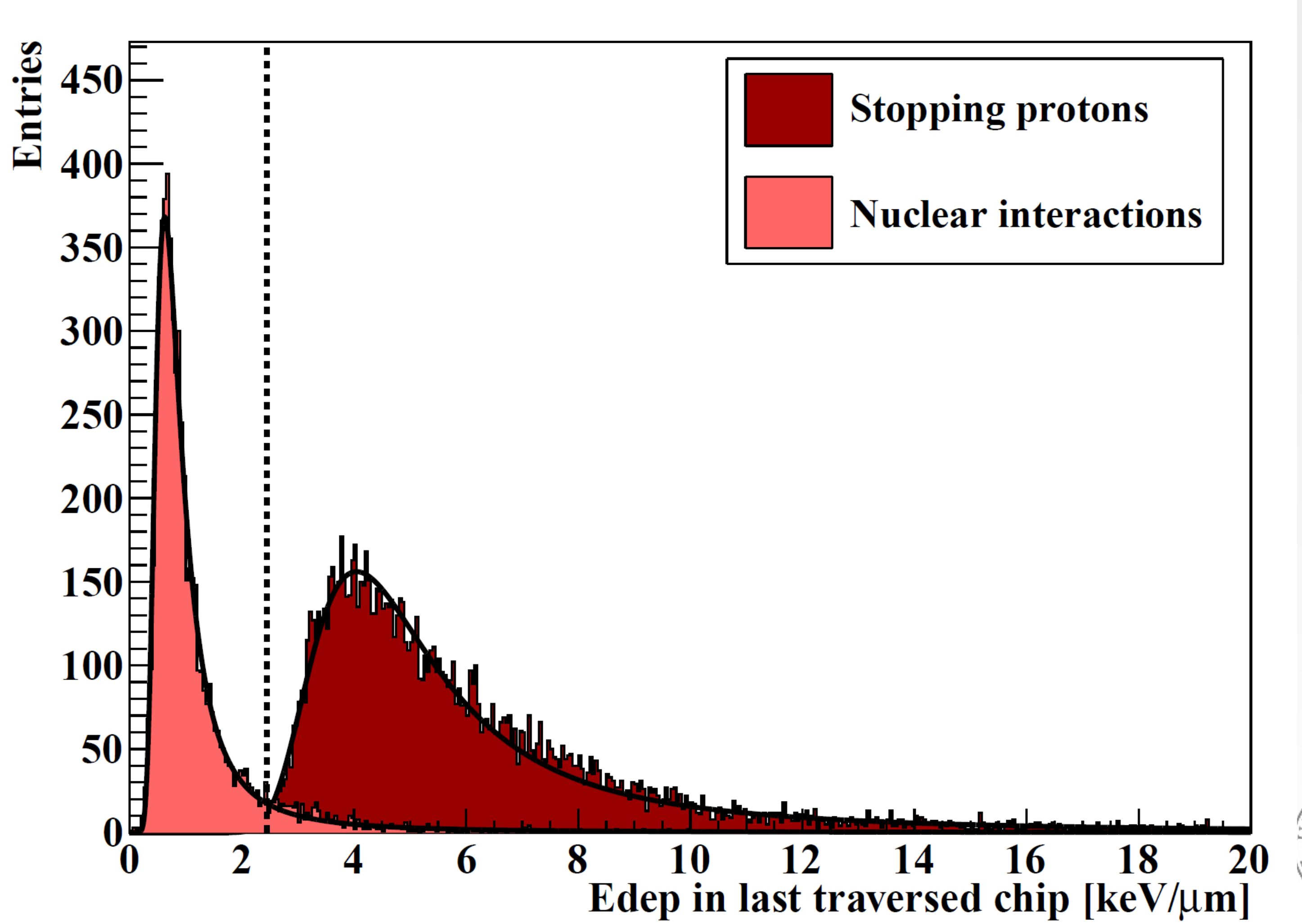
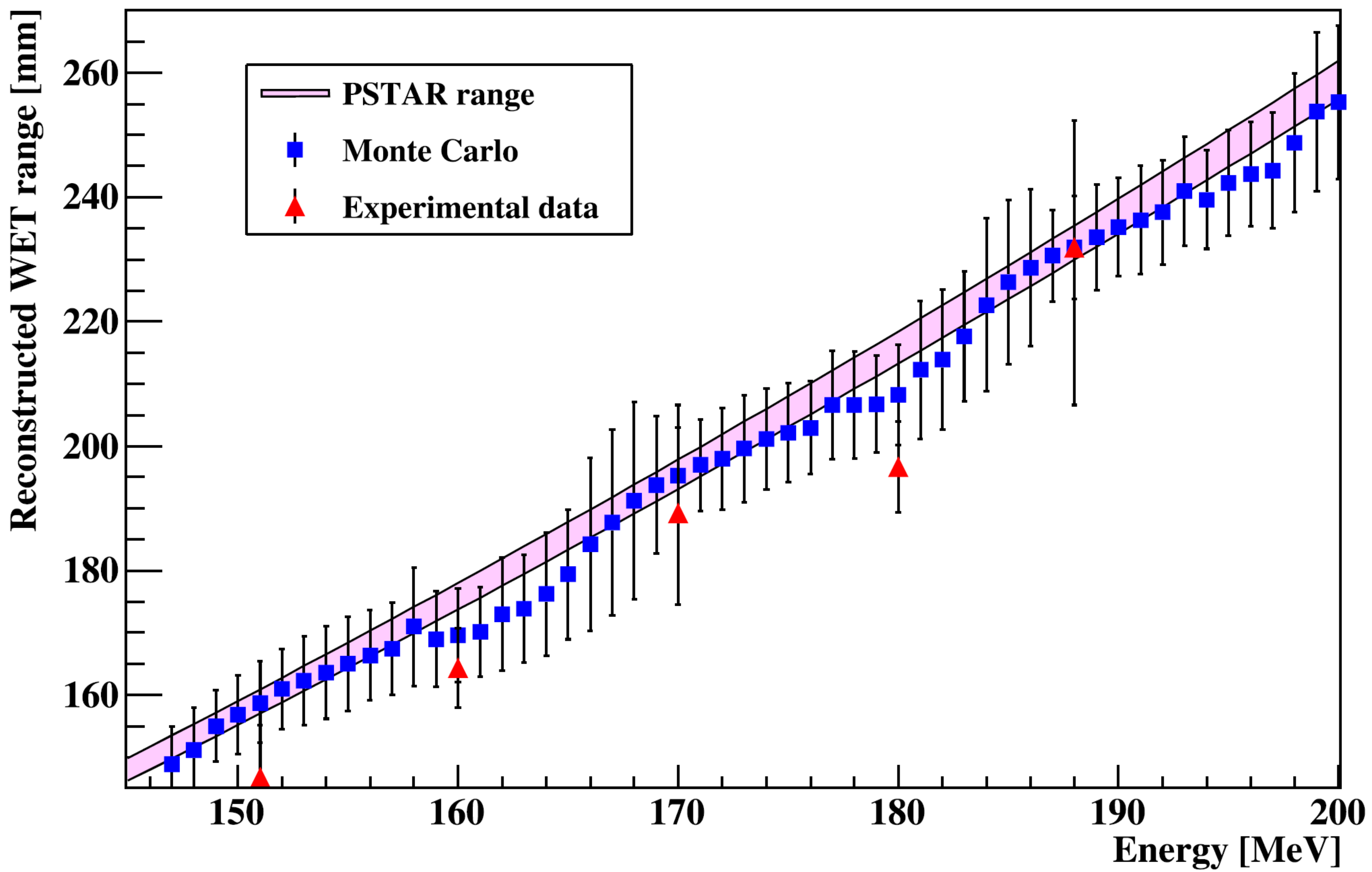


Figure 6: *The CPU time spent on proton track reconstruction. Below 100 protons per reconstruction-frame, the (constant) time spent on reconstruction overhead becomes a large fraction of the total time.*

Charge clustering model



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
    - 5 mm WET systematic error (from low # sensor layers)
    - 20 mm WET range uncertainty
    - ~ 60k protons/cm^2 / s (20% fake rate)
  – Compact design

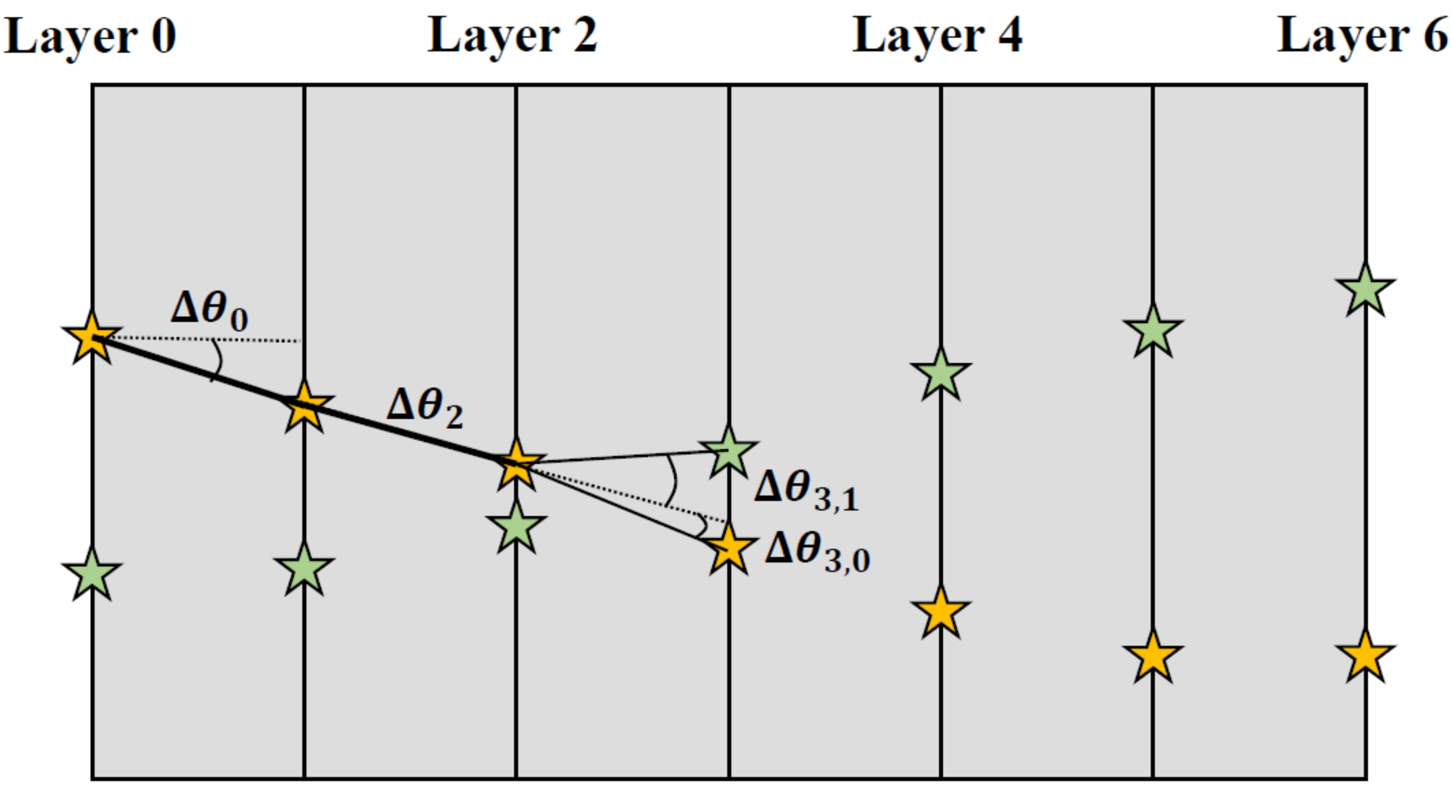


Figure 3. Example of the track reconstruction: In this case $\Delta\theta_{3,1} \gg \Delta\theta_{3,0}$ and the latter is chosen as the single next track segment.

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