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Beam tests with FOCAL prototype

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PhD student at University of Bergen
Bergen pCT workshop, november 2016
Bergen, Norway

Proton CT in Bergen

The work started with FOCAL

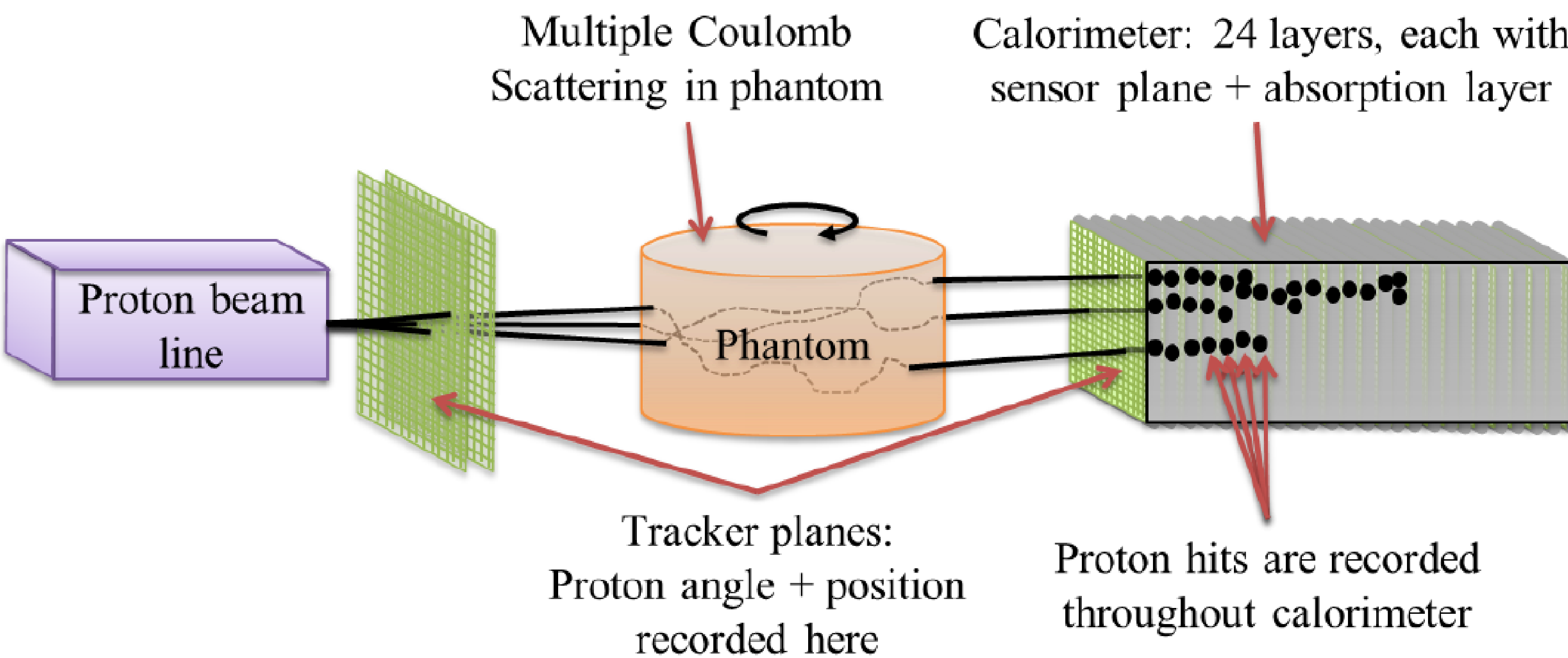
- Developed for HEP (ALICE experiment at CERN)
- University of Bergen and the University of Utrecht, NL

So far 3 MScs and 2 ongoing PhDs (me + Jarle) in Bergen to translate this effort into a fast pCT calorimeter

- MC and proton beam test data

My work: Develop analysis platform

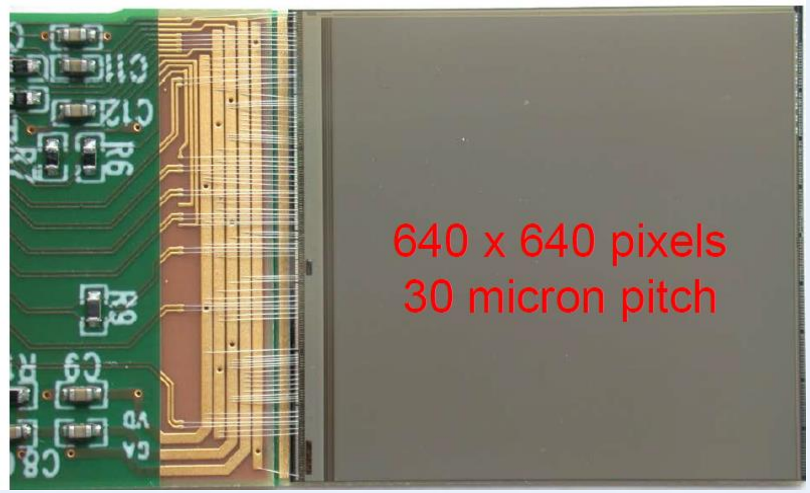
- Data processing
- Individual proton tracking
- Energy estimation

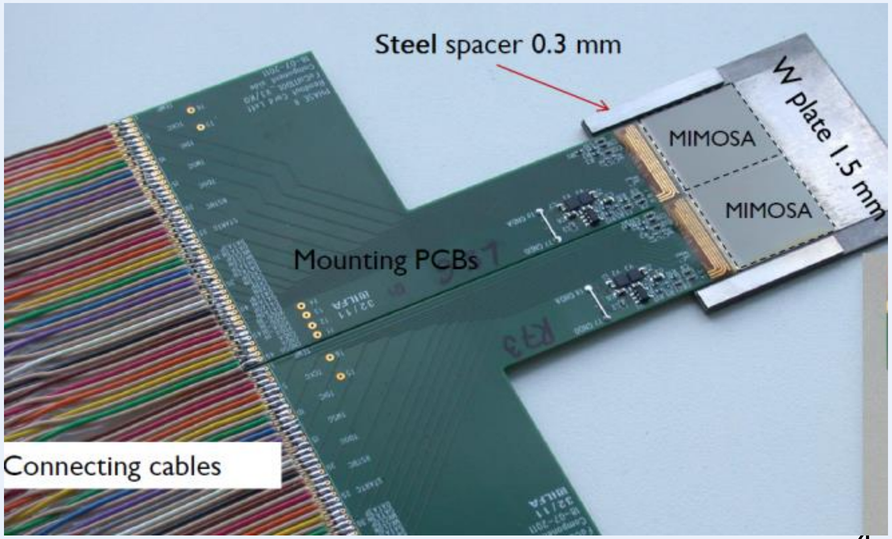

Multiple Coulomb Scattering in phantom
Calorimeter: 24 layers, each with sensor plane + absorption layer
Proton beam line
Phantom
Tracker planes: Proton angle + position recorded here
Proton hits are recorded throughout calorimeter

The FOCAL prototype

The detector is

- **Digital**: 1 bit readout per pixel, radiation hard, ~inexpensive
- **Fast**: 640 μs, rolling shutter readout
- **High-resolution**: 30 μm pitch
- **Small:** 4x4 cm^2 active area (4 chips x 2x2 cm^2)
- **Layered**: 24 sensor layers
- **Sampling calorimeter**: 3.3 mm Tungsten absorber for each sensor layer





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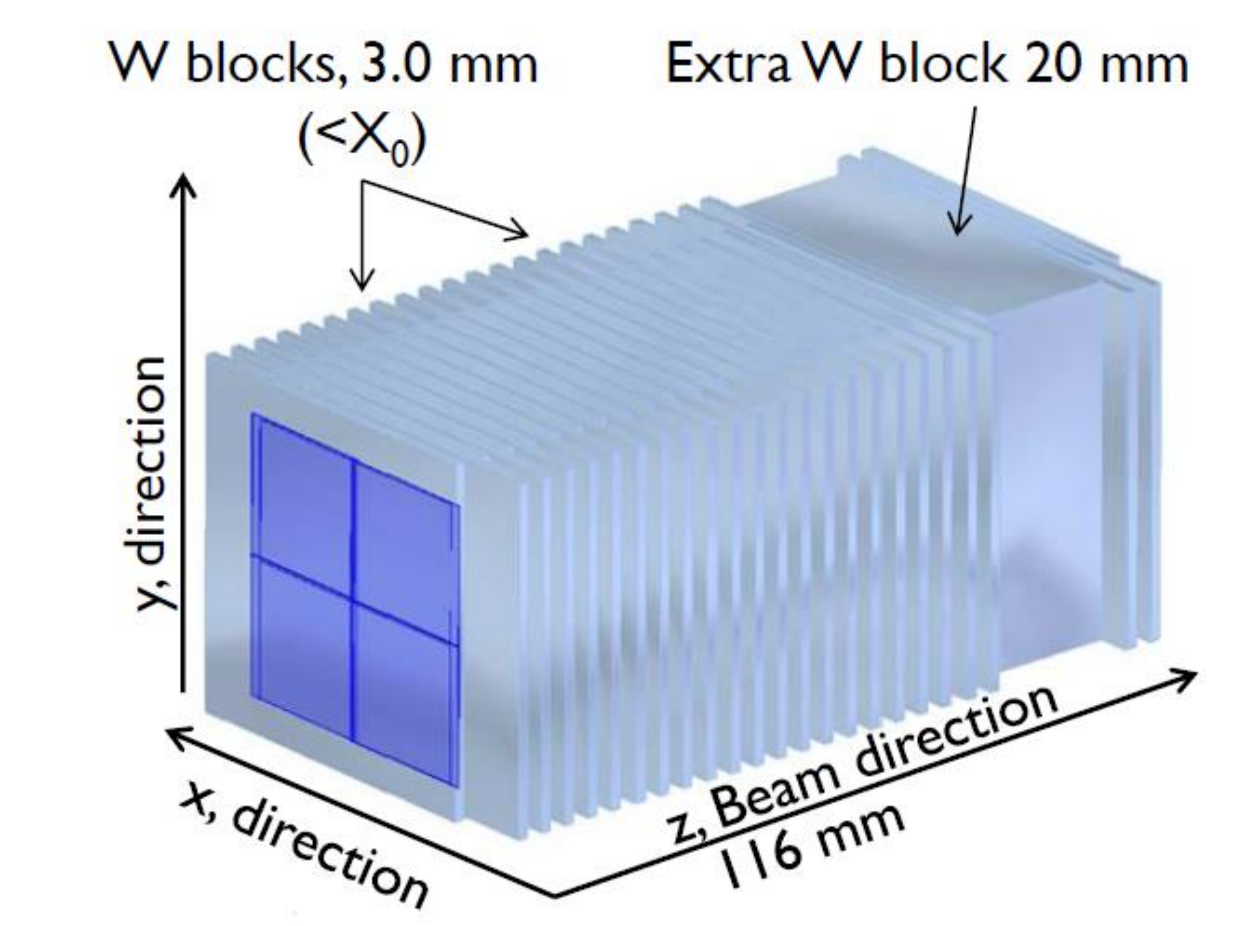
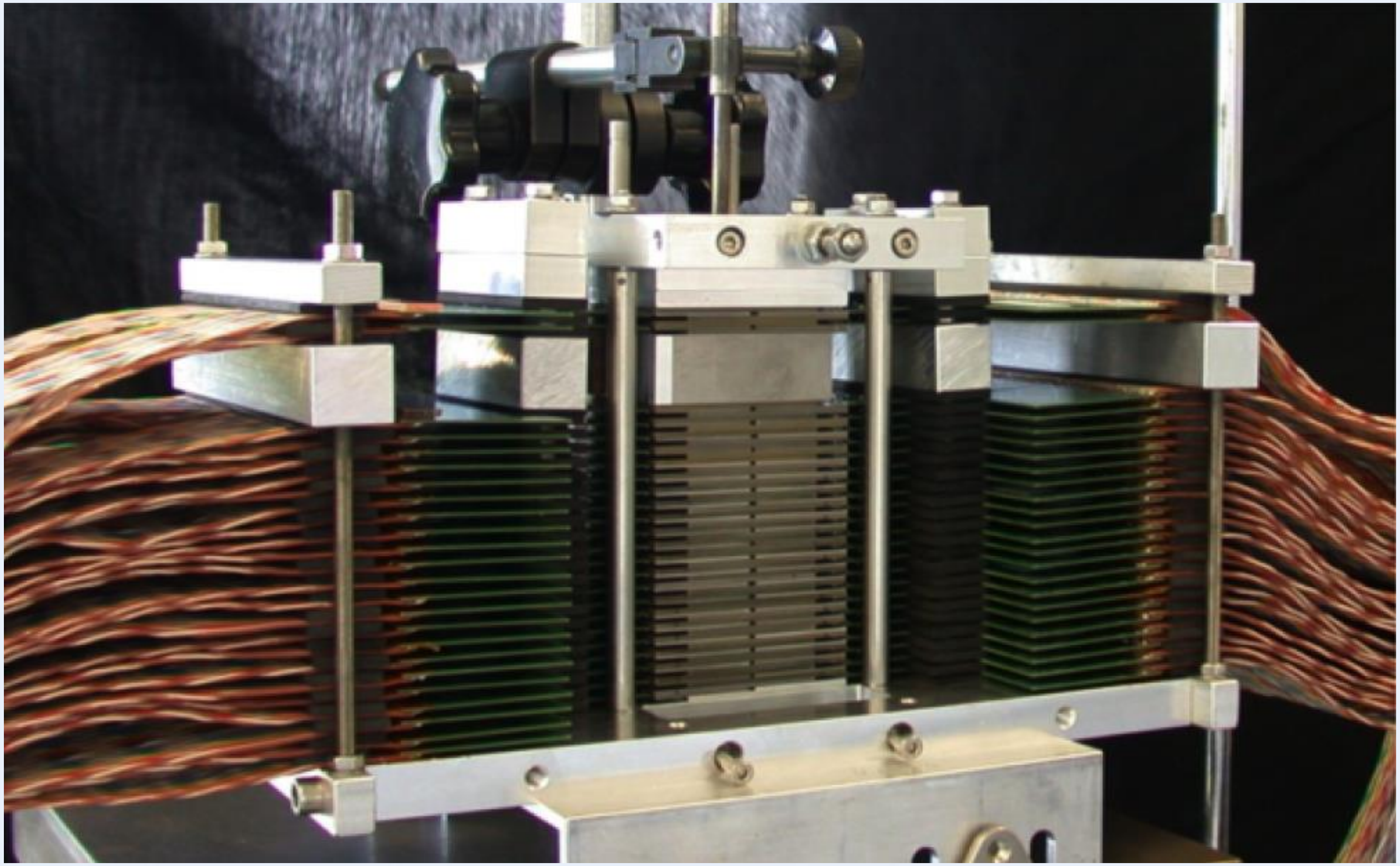
The FOCAL prototype



T. Peitzmann, Utrecht University, for the ALICE-FoCal Collaboration
Prototype Studies for a Forward EM Calorimeter in ALICE

The FOCAL prototype



The FOCAL prototype

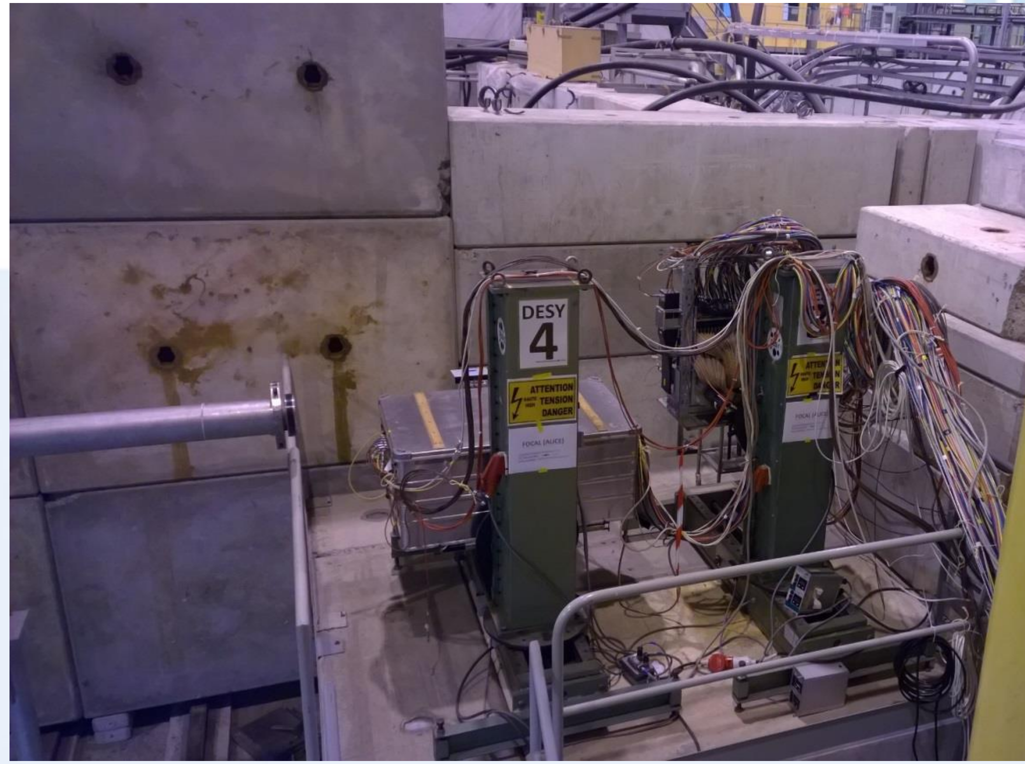
Material	Thickness [μm]	Radiation thickness	Density [g/cm³]
W absorber	1500	0.428 X_0	19.30
Silver glue	40	0.001 X_0	3.2
PCB	160	0.002 X_0	1.85
Silver glue	40	0.001 X_0	3.2
MIMOSA23	120	0.005 X_0	2.33
Air gap	170	6E-06 X_0	0.001
W absorber	300	0.086 X_0	19.30
Cyano-acrylate glue	70	0.0002 X_0	1.0
W absorber	1500	0.428 X_0	19.30
Air gap	75	3E-06 X_0	0.001

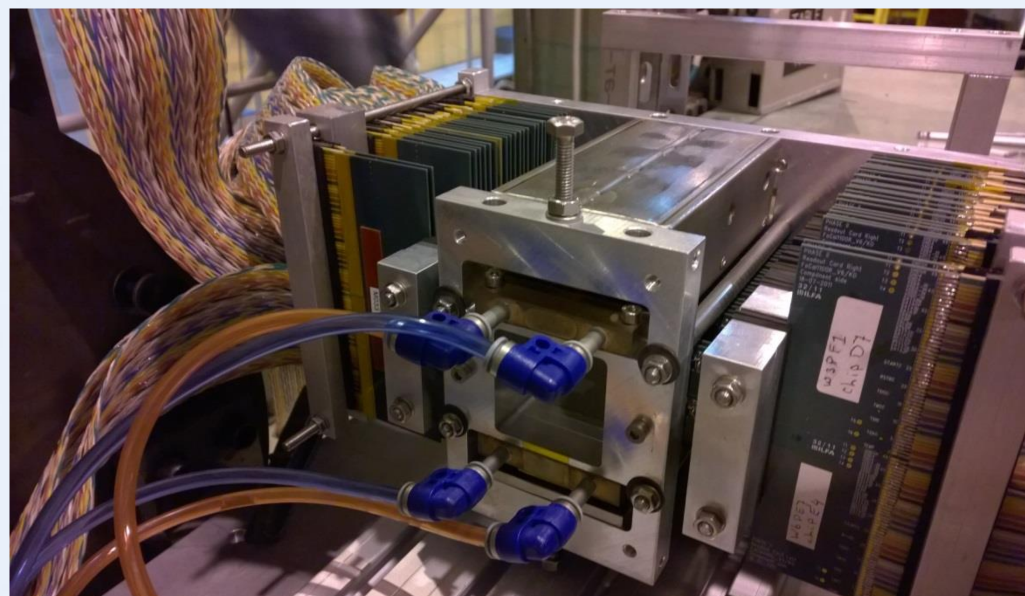
Table 1: *The materials and their key properties, as used in the MC setup. The thicknesses are displayed both in terms of geometric thickness and the corresponding radiation thickness in units of the radiation length* X_0.

Beam tests with FOCAL

Facility	Particle	Beam Energy (GeV)	Year
DESY	Electron	2, 5	2012
PS/SPS	Mixed beam (e^-, π)	$2 \div 8$ $30 \div 200$	2012
Laboratory	cosmic rays		2013
DESY	Electron	$2 \div 5$	2014
PS/SPS	Mixed beam (e^-, π)	2, 10 30 to 200+	2014

Table 1: Overview of the data taking including the beam test campaigns in 2012 and 2014.


DESY
4
ATTENTION
TENSION
DANGER



Beam tests with FOCAL

In addition, a group from Bergen + Utrecht took proton beams at KVI AGORFIRM i Groningen, the Netherlands

- December 2014

Key figures:

- Aluminum degraded pencil beams with energies 122, 140, 150, 160, 170, 180, 188 MeV
- Proton beam frequency of ~1.2 kHz
  - At most one proton per FOCAL readout (2 kHz)

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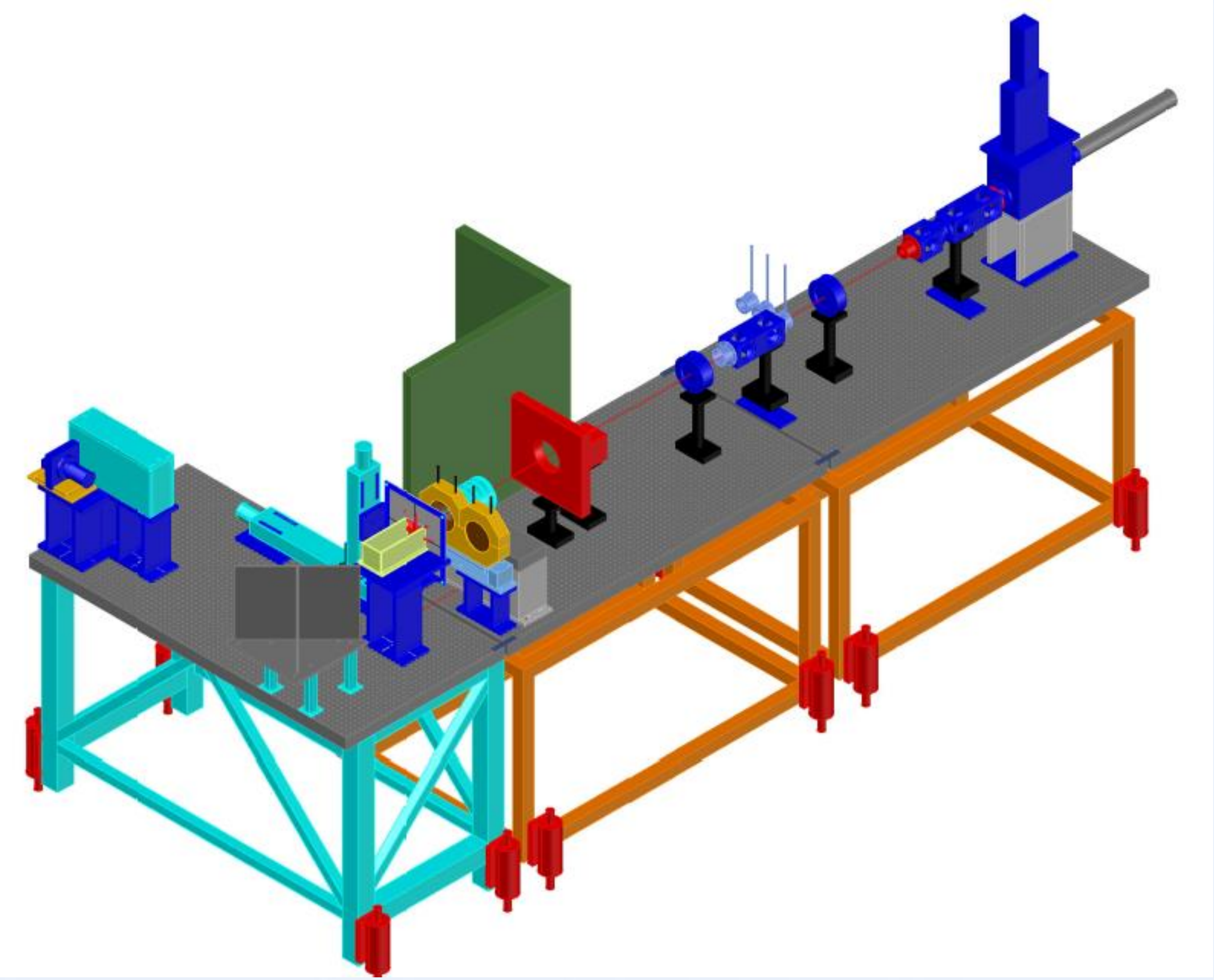
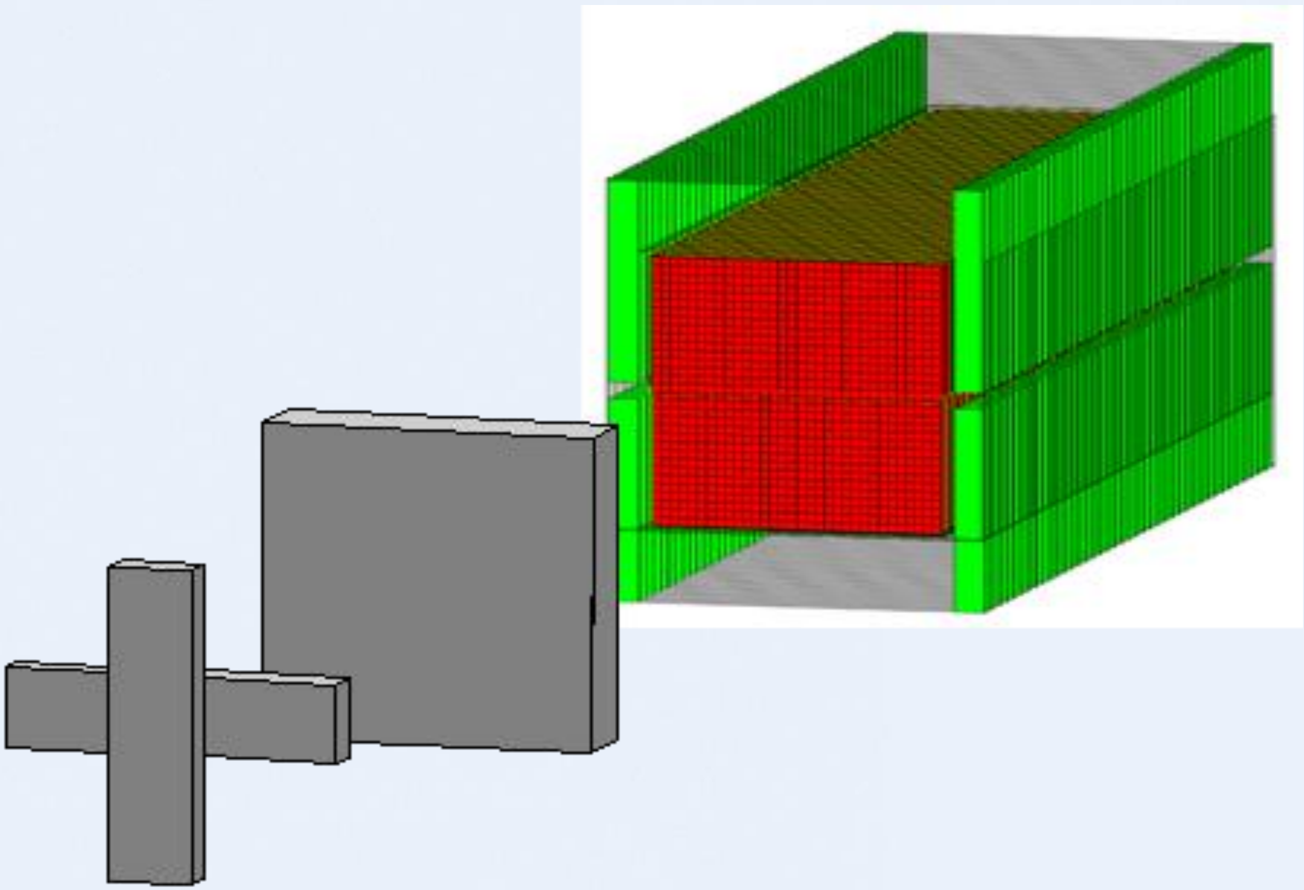
Beam tests with FOCAL



Beam optics

3 Scintillators were used for triggering

- Horizontal, Vertical, Front



Readout

Final energy	150 MeV	160 MeV	170 MeV	180 MeV	188 MeV
Al degrader thickness	35 mm	27 mm	17 mm	8 mm	0 mm
Number of readout frames	819	762	4944	1334	2739
Number of reconstructed tracks	363	358	3098	803	1813

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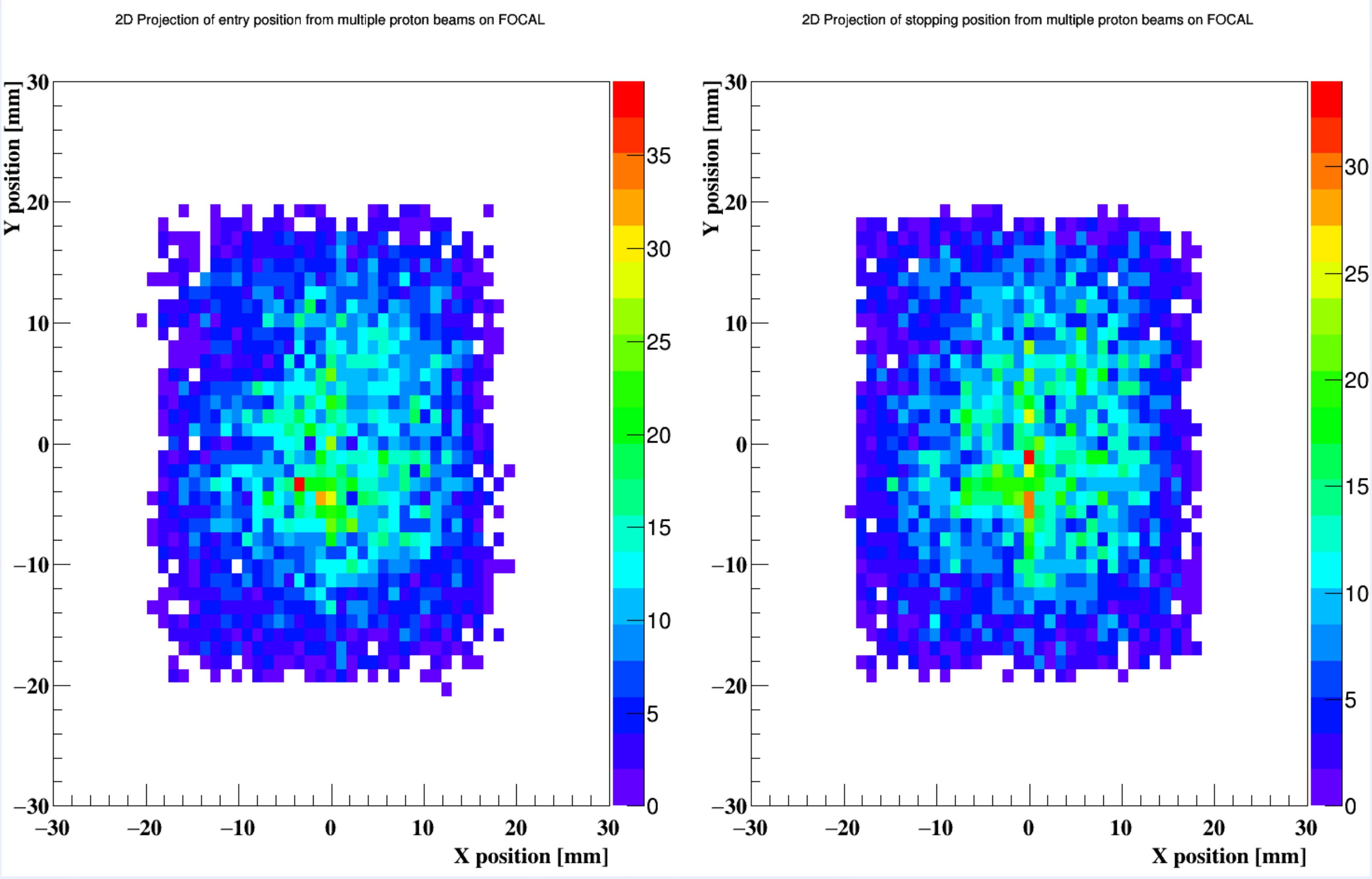
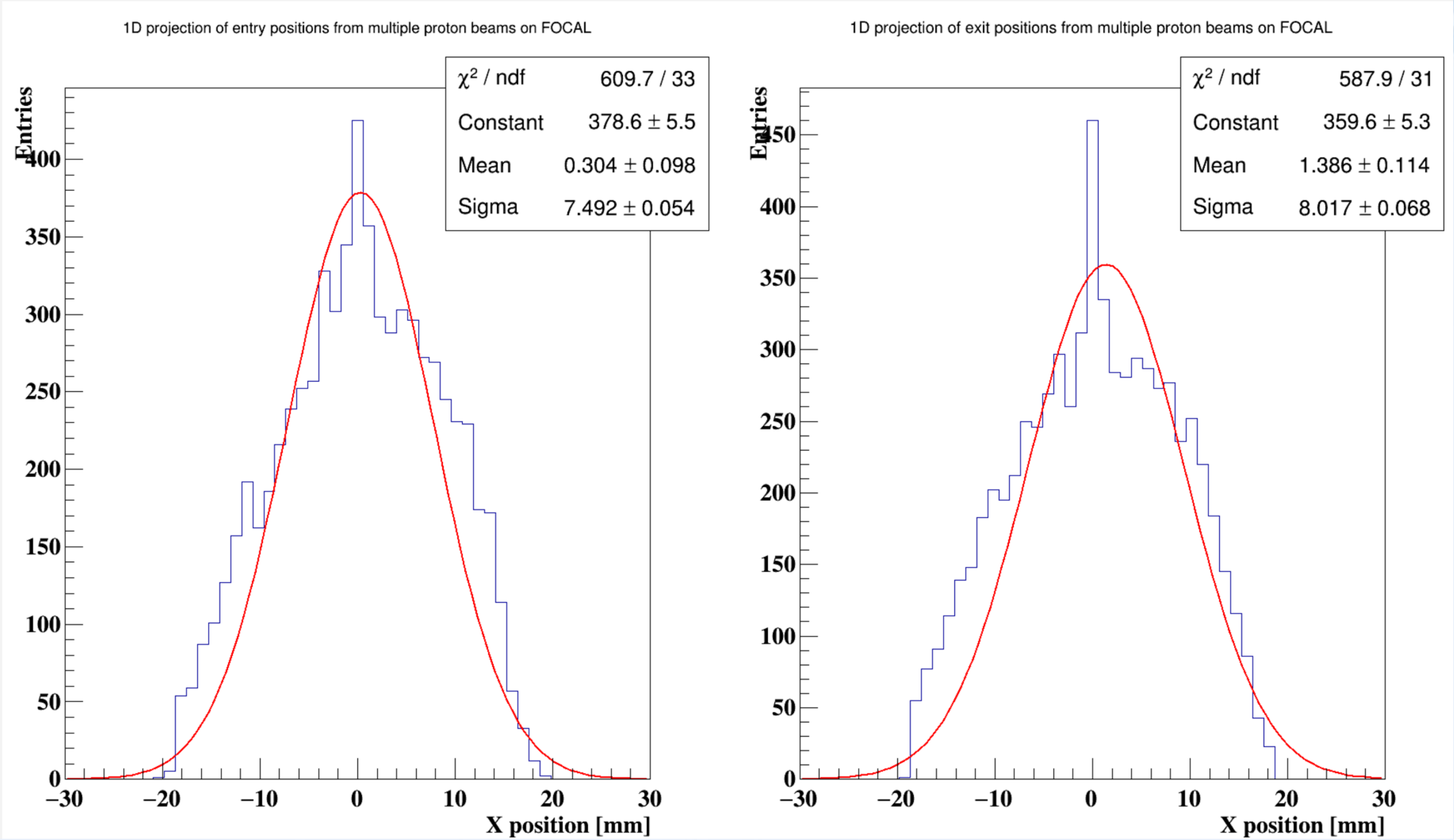
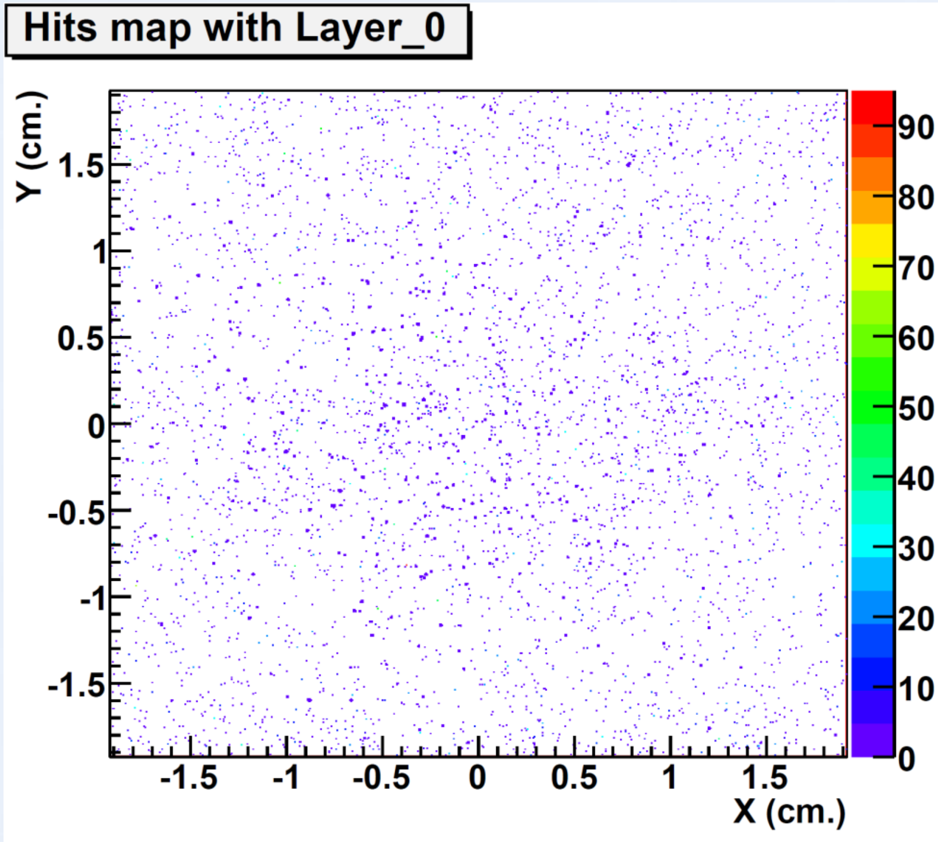
Measured proton positions: Entry and stopping position

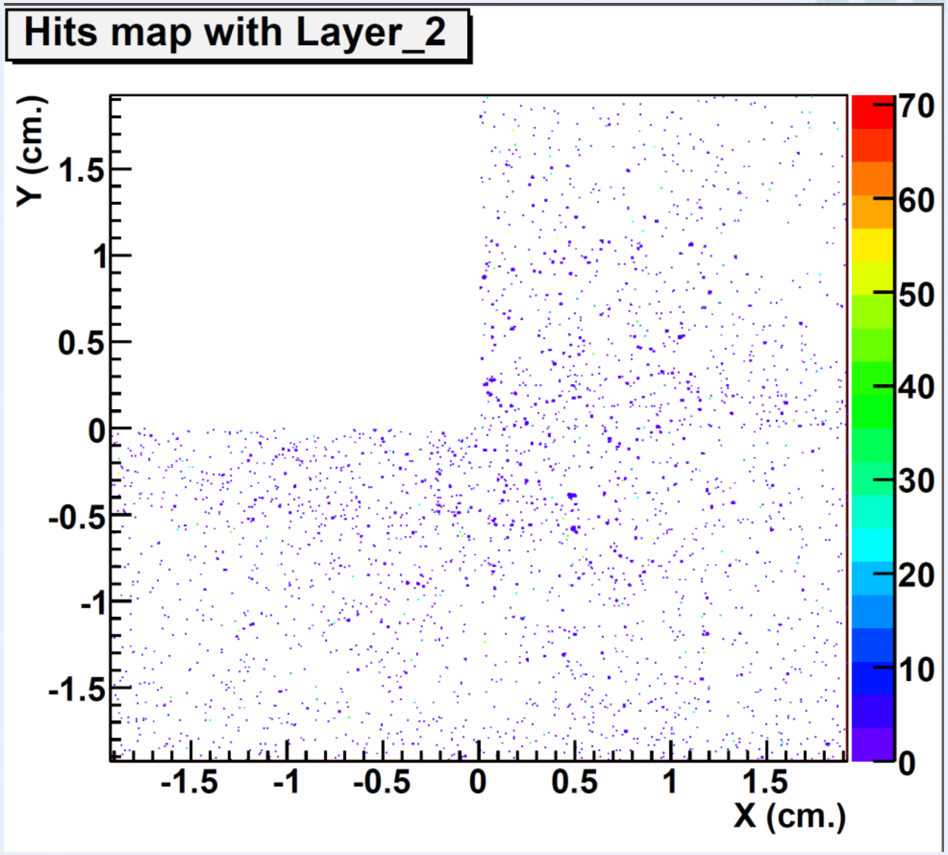


Measured proton positions: Entry and stopping position



Good & bad layers





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Analysis

The data is analysed in «summed readout frames»

- 500 protons/analysis → 1 MHz
  - Depending on target reconstruction accuracy
- With improved tracking algorithms, larger sensor areas and a readout speedup of 20x – 100x (from 640 µs): Fast!

Tools:

- C++, ROOT
- GATE v7.0 + Geant4 v9.6.4
  - emstandard_opt3 and 80 µm step / threshold

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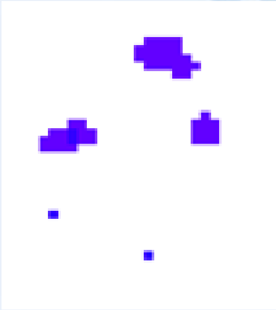
Analysis workflow



1. Identify all hits in detector
2. Find all connected neighbor hits in a layer
    1. Cluster size is proportional to deposited energy
3. Do tracking on all clusters – find proton tracks. Gives:
    1. Track lengths / ranges
    2. Angular distributions
    3. Nuclear interactions
    4. Development of cluster sizes → shows a bragg peak
4. Use depth dose model to find most probable range for each proton
5. Do this for all protons in system – can handle about 500 protons concurrently (33 protons cm^{-2} or 67 000 protons $\mathrm{cm}^{-2}\mathrm{s}^{-1}$)

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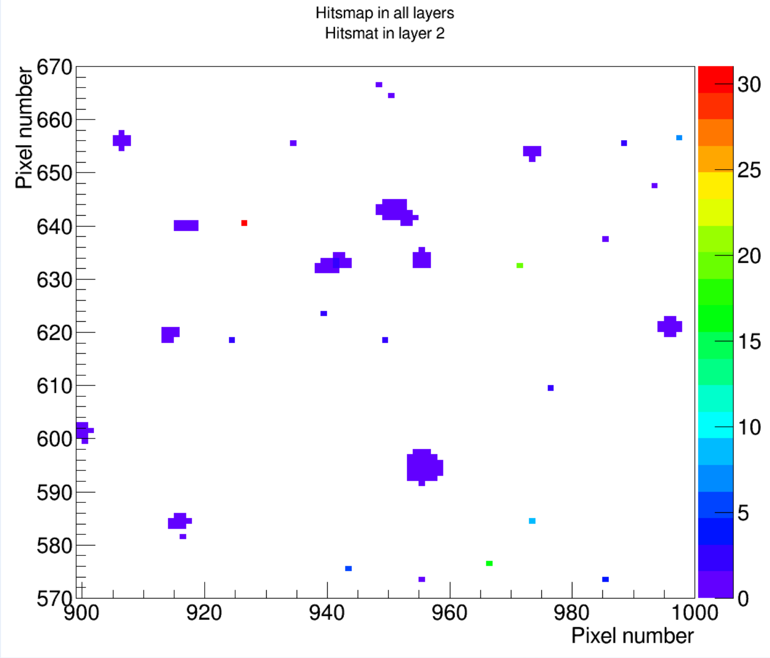
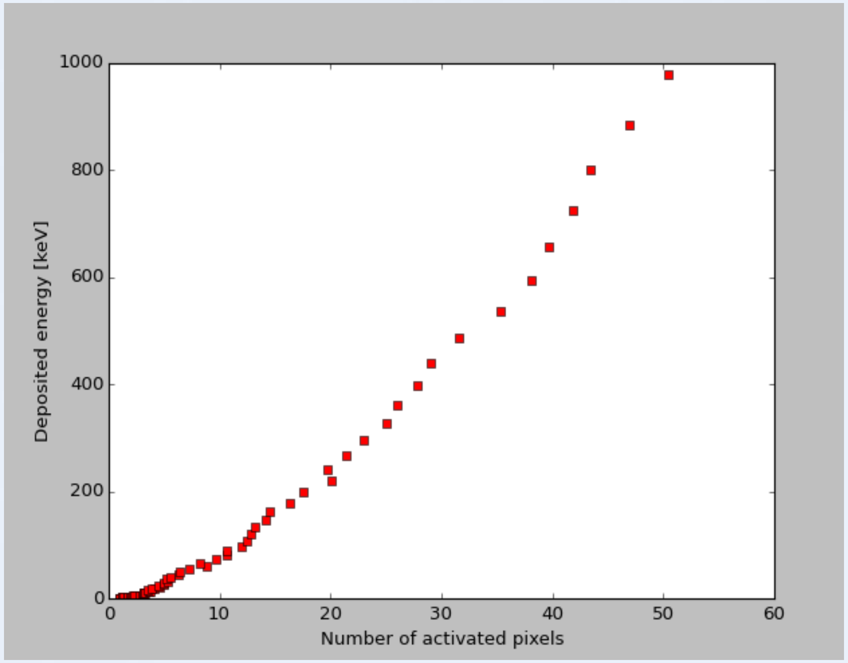
Charge clustering model

Each proton track creates charge diffused pixel clusters

- The cluster size is proportional to the deposited energy
- Use MC+data to estimate E_{dep} in each cluster



Data



Charge Diffusion Model

How to calculate edep from cluster size

Different models for cluster size calculation

- Phenomenological Gaussian model w/ variable sigma (used in NIMA paper)
- Model based on expected diffusion in epitaxial layer (ongoing work with MSc student)

• L. Maczewski, Measurements and simulations of MAPS (Monolithic Active Pixel Sensors) response to charged particles - a study towards a vertex detector at the ILC, PhD, 2010. http://arxiv.org/abs/1005.3710 (accessed January 12, 2015).

Gaussian Model

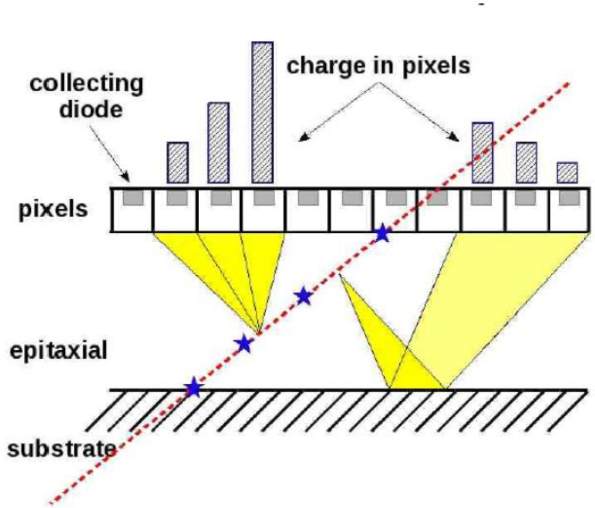
1. Assume the charge diffusion is Gaussian in *shape*
2. Sigma dependent on edep → $\sigma = \left(\alpha E_{\text{dep}}\right)^{\beta}$
3. Sample Gaussian N times ($N = \gamma E_{\text{dep}}$) and paint in histogram around original hit $\vec{x}$
4. Compare MC+model with data to find α, β, γ
5. From n *unique* pixel hits, we find

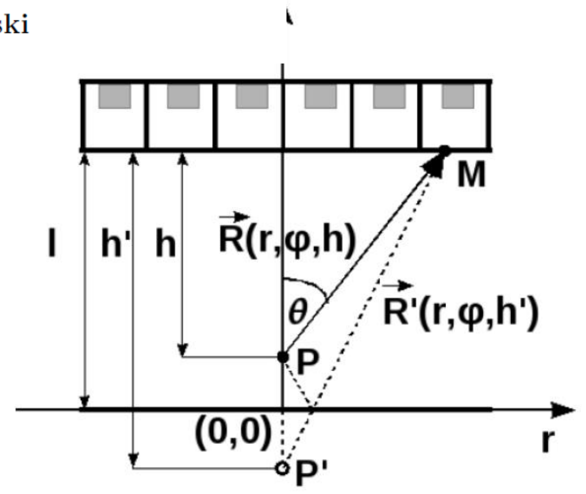
$$E_{\text{dep}} = -4 + 3.9\,n + 1.2 \cdot 10^{-2} n^2 - 1.1 \cdot 10^{-3} n^3 - 1.4 \cdot 10^{-6} n^4$$

Analytical model

Measurements and simulations of MAPS (Monolithic Active Pixel Sensors) response to charged particles - a study towards a vertex detector at the ILC

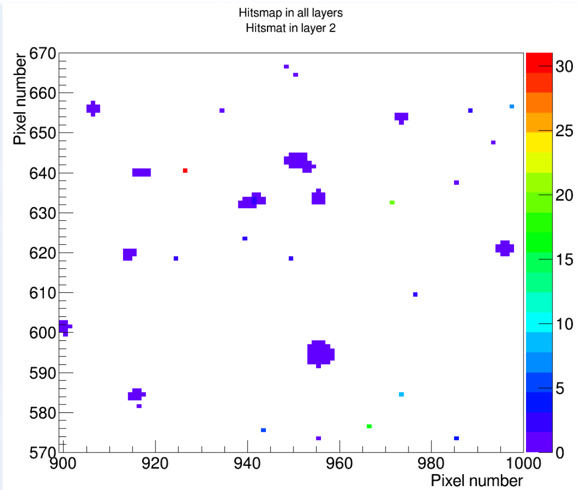
Łukasz Janusz Mączewski



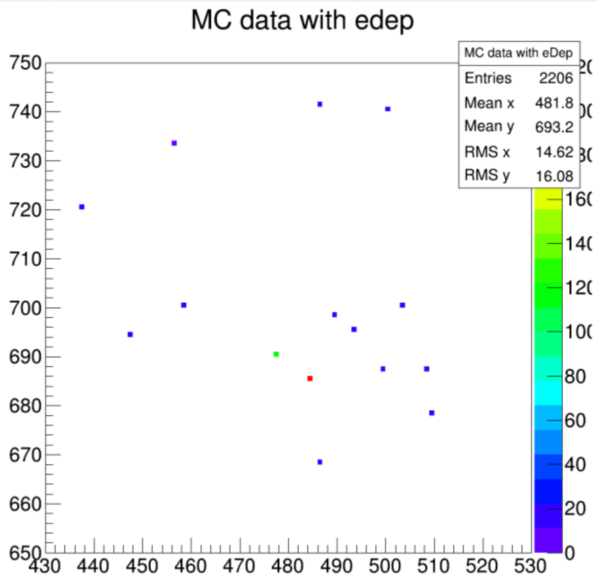


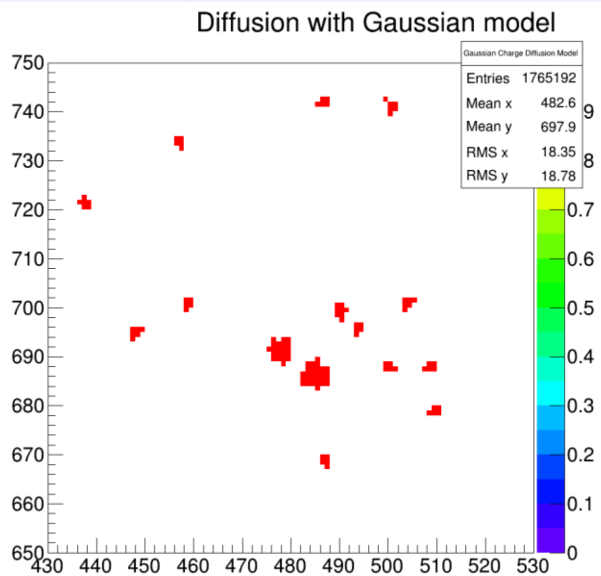
$$\rho(\vec{R})\mathrm{d}r\mathrm{d}\phi = \frac{\mathrm{d}\Omega}{4\pi} \cdot \exp\left(-\frac{|\vec{R}|}{\lambda}\right) = \frac{hr}{4\pi|\vec{R}|^3} \cdot \exp\left(-\frac{|\vec{R}|}{\lambda}\right)\mathrm{d}r\mathrm{d}\phi,$$

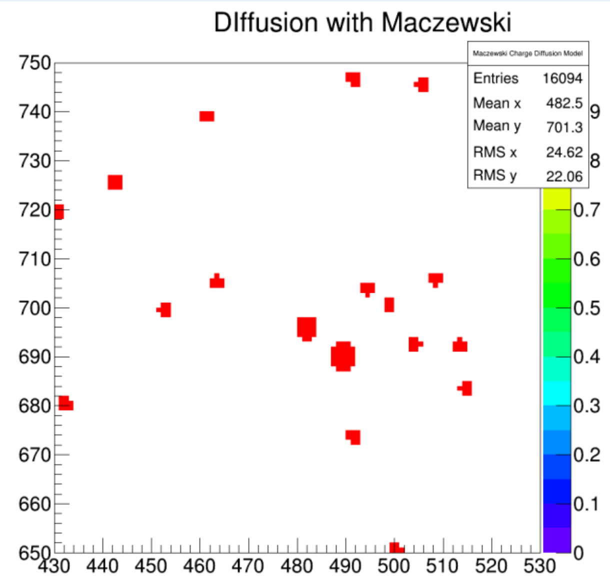
How to calculate edep from cluster size



Data







2015).

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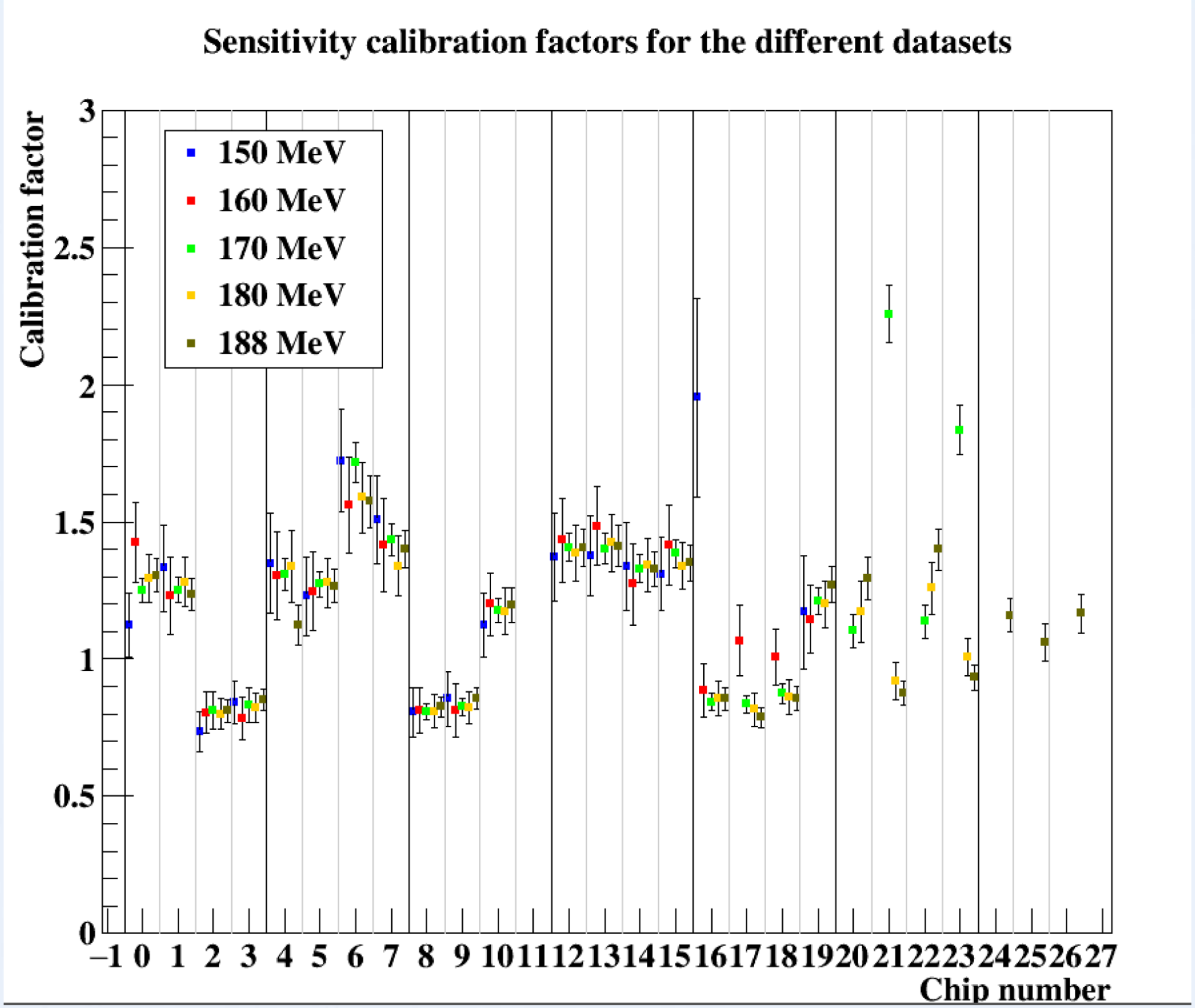
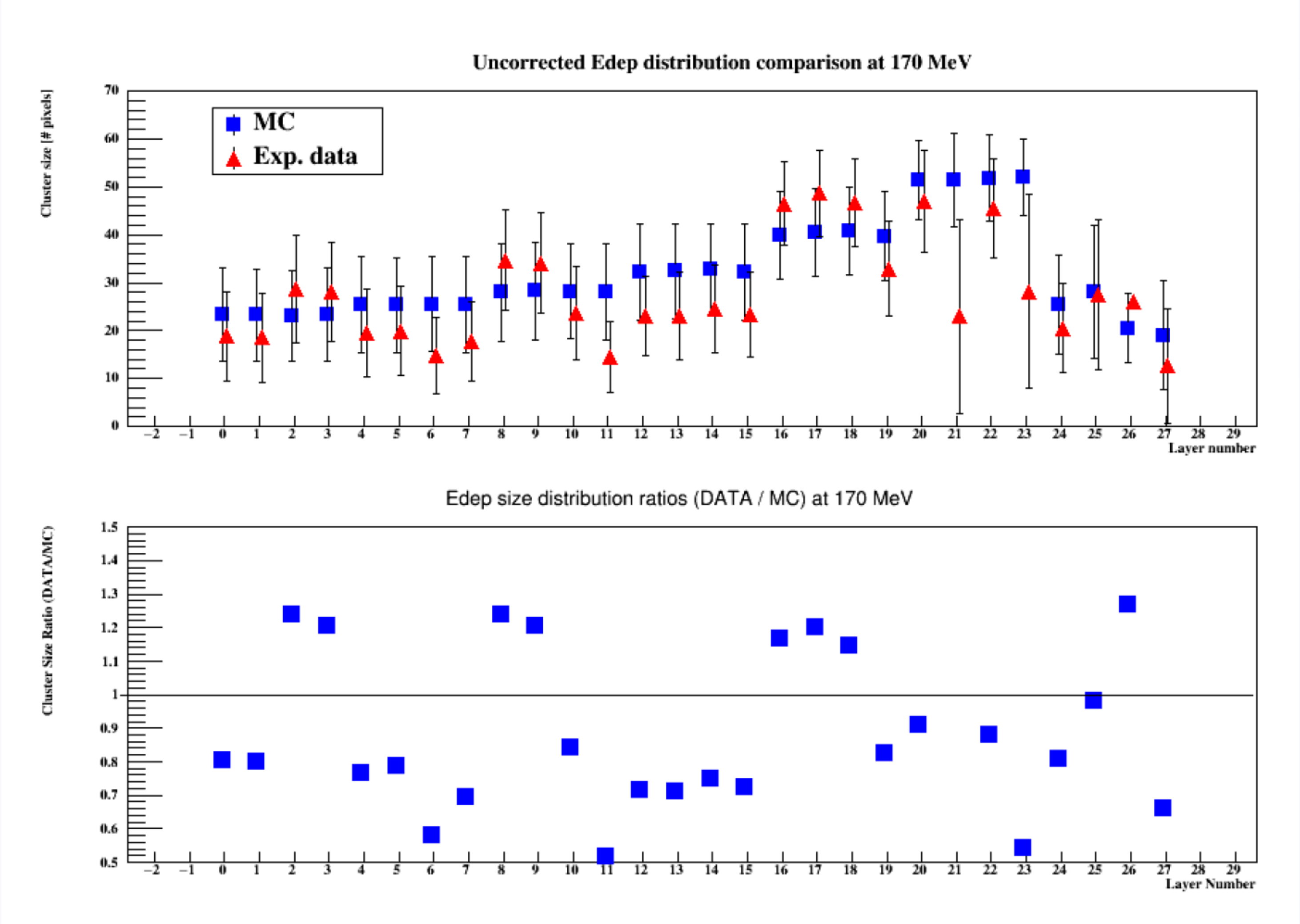
Individual chip calibration



Individual chip calibration



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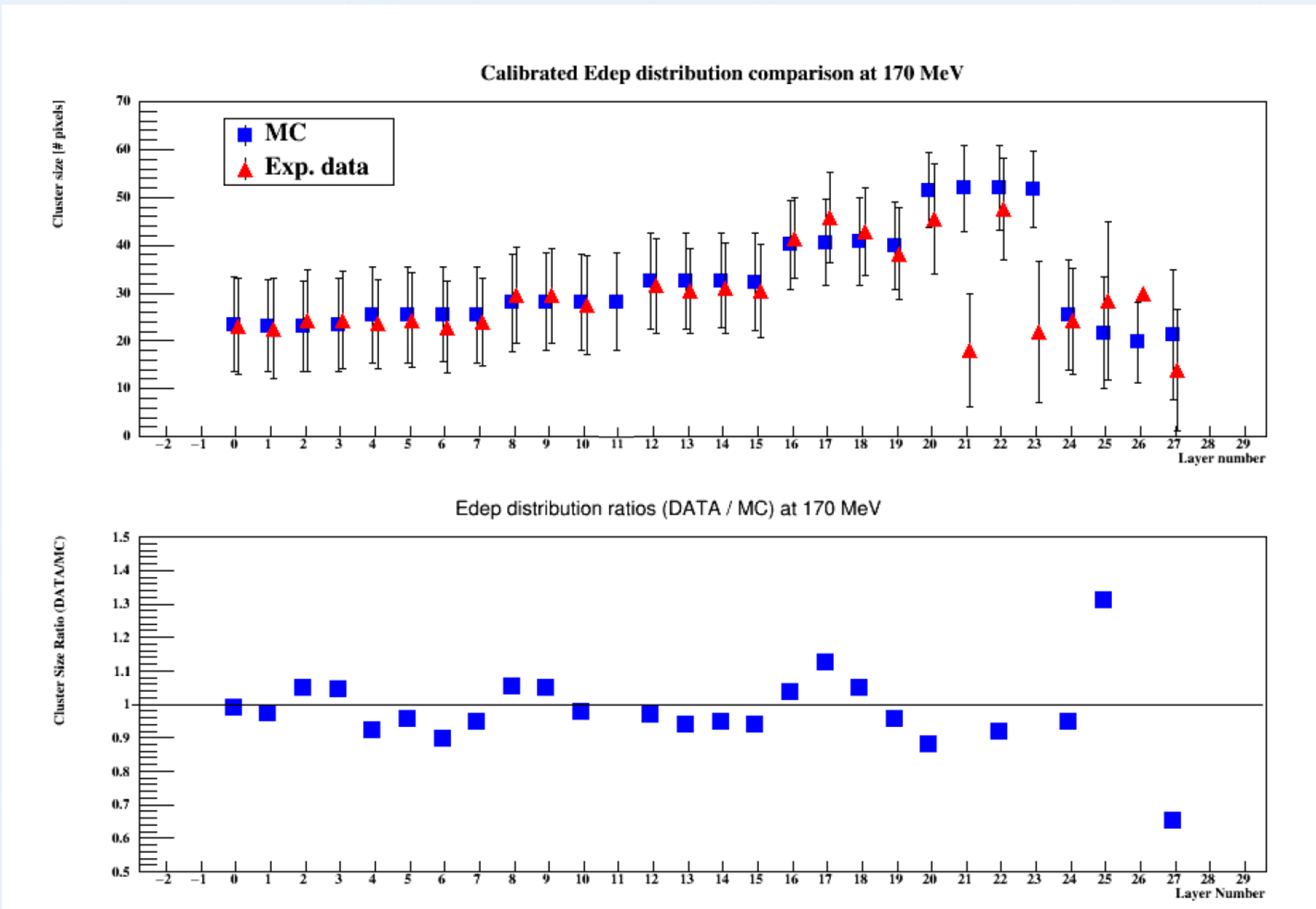
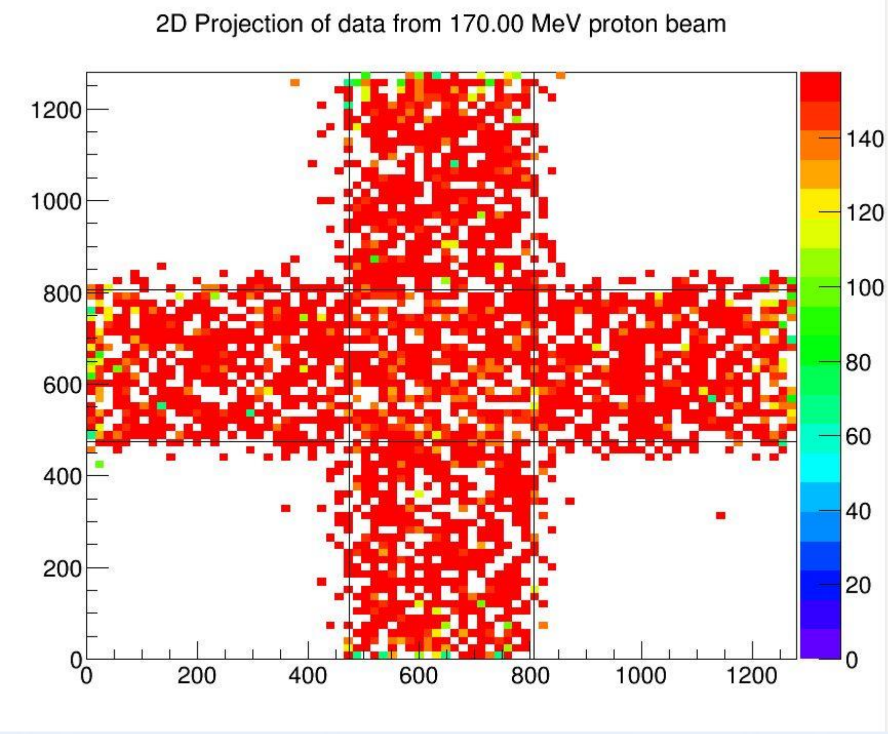
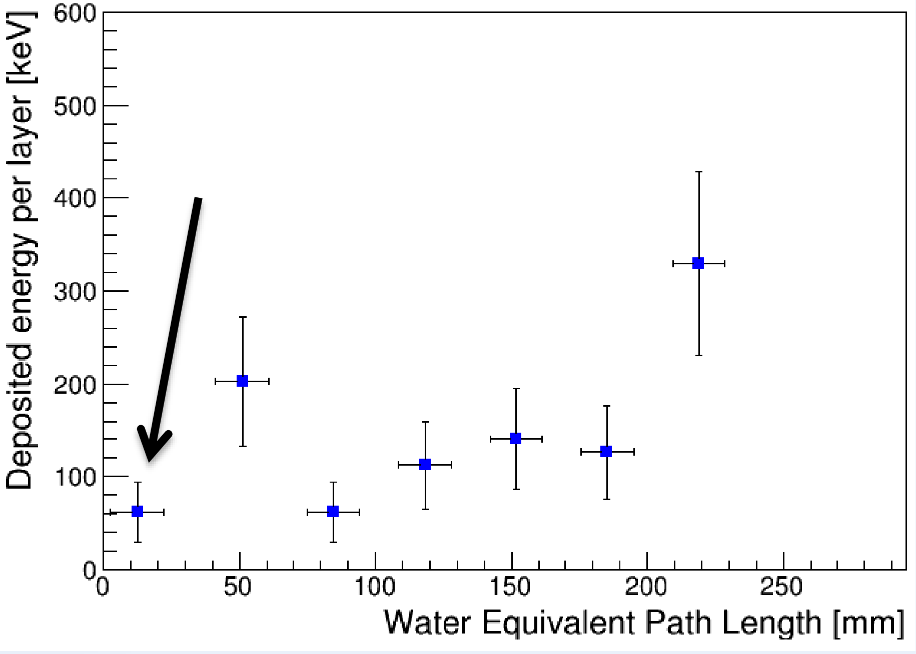
Individual chip calibration



Other corrections performed

- Alignment corrections using cosmic muon data from Utrecht
- Initial energy correction for protons traversing 1-3 scintillators (WEPL > 0 at first sensor layer)





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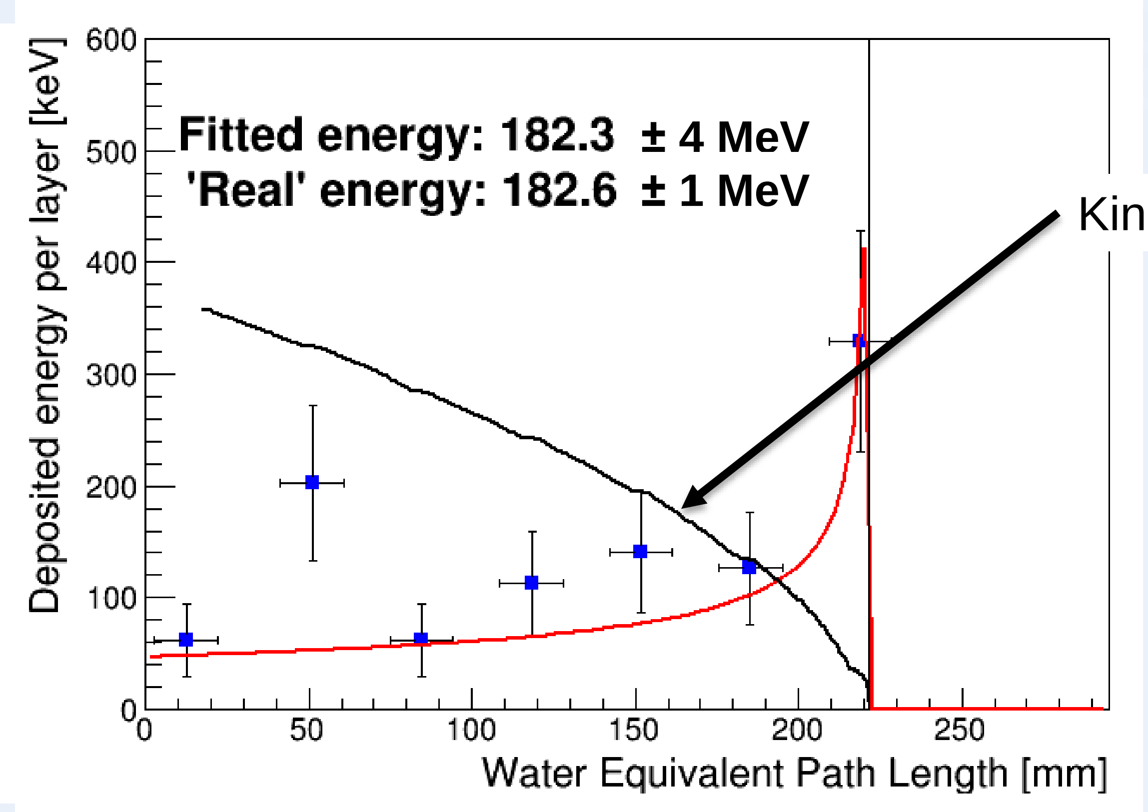
Data analysis

- A simple tracking algorithm finds clusters from the same proton
  - Possible to plot Range vs E_{dep} $(R = \alpha\, E^p)$



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

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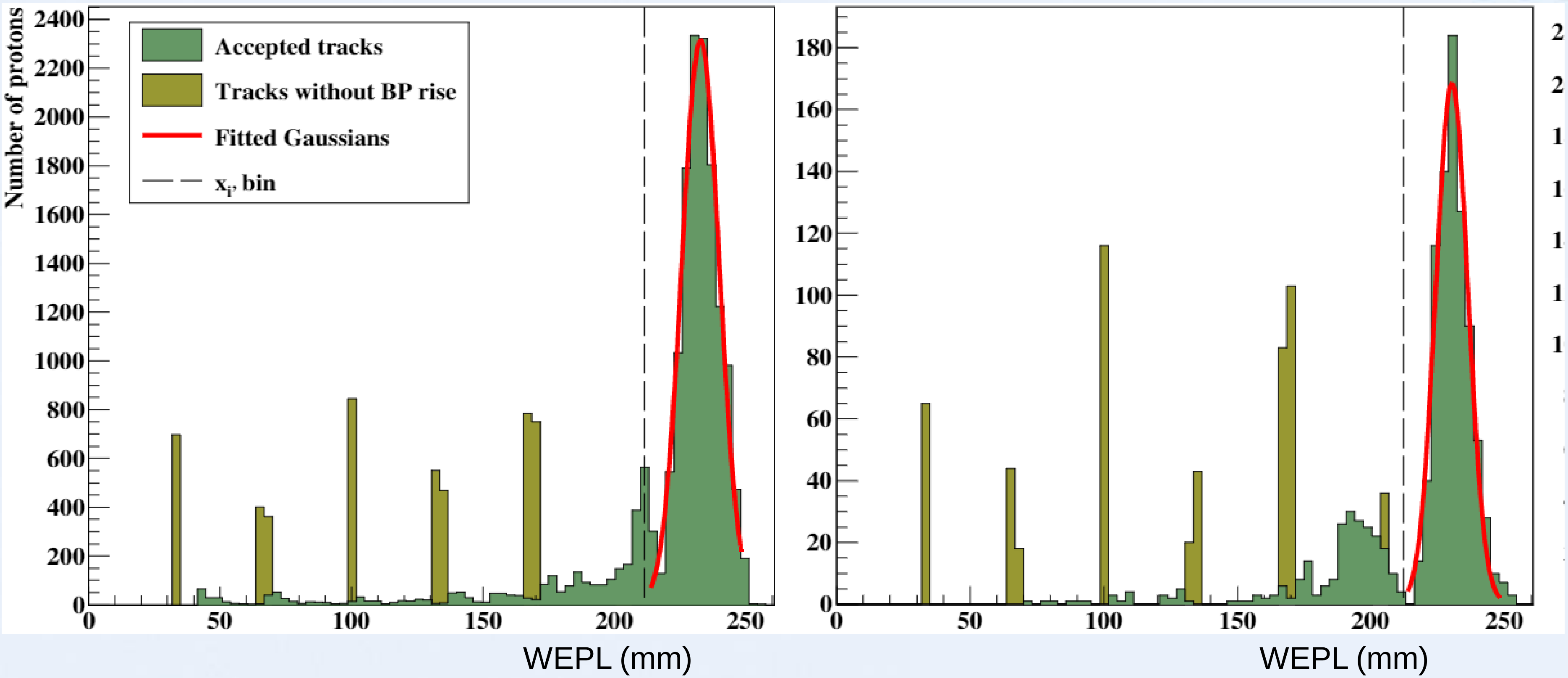
Finding average energy from many protons



Left: *188 ± 3 MeV from a 188 MeV MC simulated mono-energetic beam.*
Right: *187 ± 3 MeV from the 188 MeV beam taken during the KVI Groningen beam test.*

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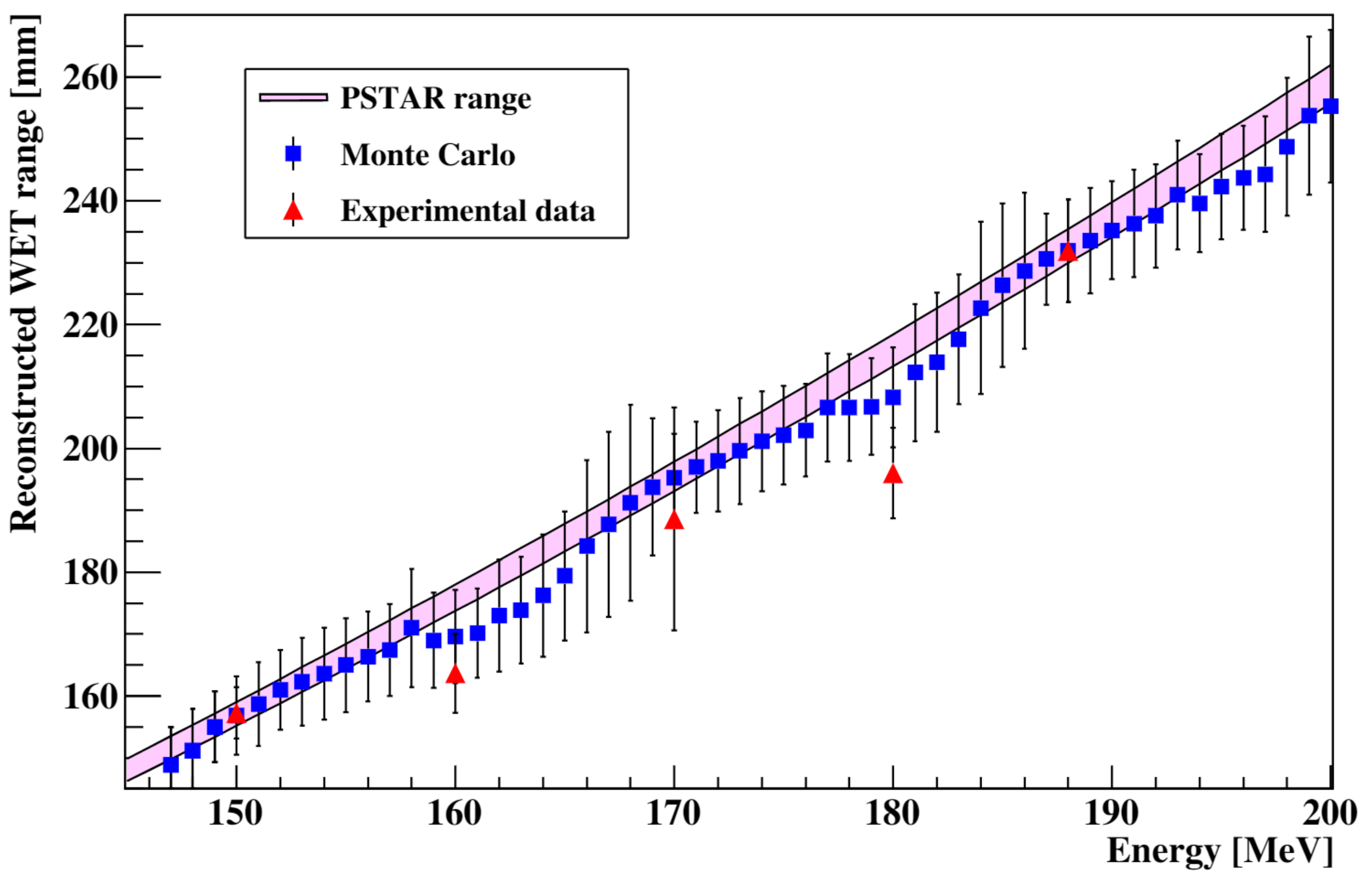
Finding average energy from many protons



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Conclusion

- The Tracking Detector works as a proton CT calorimeter
  - Optimized for HEP, not low-energy protons
  - Limited range resolution due to the Tungsten absorber
  - Fast readout speed (~1 MHz)

Next prototype: Good range resolution, very fast readout

More information

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

H. E. S. Pettersen*[a, b], J. Alme[b], 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]

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Abstract

Radiation therapy with protons as of today utilizes information from x-ray CT in order to estimate the proton stopping power of the traversed tissue in a patient. The conversion from x-ray attenuation to proton stopping power in tissue introduces range uncertainties of the order of 2-3% of the range, uncertainties that are contributing to an increase of the necessary planning margins added to the target volume in a patient. Imaging methods and modalities, such as Dual Energy CT and proton CT, have come into consideration in the pursuit of obtaining an as good as possible estimate of the proton stopping power. In this study, a Digital Tracking Calorimeter is benchmarked for proof-of-concept for proton CT purposes. The Digital Tracking Calorimeter is applied for reconstruction of the tracks and energies of individual high energy protons. The presented prototype forms the basis for a proton CT system using a single technology for tracking and calorimetry. This advantage simplifies the setup and reduces the cost of a proton CT system assembly, and it is a unique feature of the Digital Tracking Calorimeter concept. Data from the AGORFIRM beamline at KVI Groningen in the Netherlands and Monte Carlo simulation results are used to in order to develop a tracking algorithm for the estimation of the residual ranges of a high number of concurrent proton tracks. High energy protons traversing the detector leave a track through the sensor layers. These tracks are spread out though charge diffusion processes. A charge diffusion model is applied for acquisition of estimates of the deposited energy of the protons in each sensor layer by using the size of the charge diffused area. A model fit of the Bragg Curve is applied to each reconstructed track and through this, estimating the residual range of each proton. The range of the individual protons can at present be estimated with a resolution of 4%. The readout system for this prototype is able to handle an effective proton frequency of 1 MHz by using 500 concurrent proton tracks in each readout frame, which is at the high end range of present similar prototypes. A future further optimized prototype will enable a high-speed and more accurate determination of the ranges of individual protons in a therapeutic beam.

Keywords: proton therapy, proton CT, GEANT4 simulations, tracking calorimeter.

1 Introduction

There has been a significant increase in the number of cancer patients treated with proton radiation therapy in the recent decades worldwide. As of January 2015, more than 137 000 patients have been treated with charged particle therapy [1]. The motivations for application of proton therapy during cancer treatment are the prospects of reducing the irradiated volume of the patient during radiation treatment. Short term and long term treatment-induced side effects, such as the probability for radiation-induced secondary cancers, are then reduced due to the finite range of protons in tissue.

Proton therapy as of today is performed with the delivery of pre-calculated dose plans for each patient: The applied dose plans are based on x-ray computed tomography (CT) images. The x-ray CT images reflect the patient's anatomy, however they provide limited resolution for calculating how the protons traverse and deposit dose in the patient's body during proton therapy. The Relative Stopping Power (RSP) for protons in tissue is needed in order to calculate the proton range during dose calculations in

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arXiv.org > physics > arXiv:1611.02031

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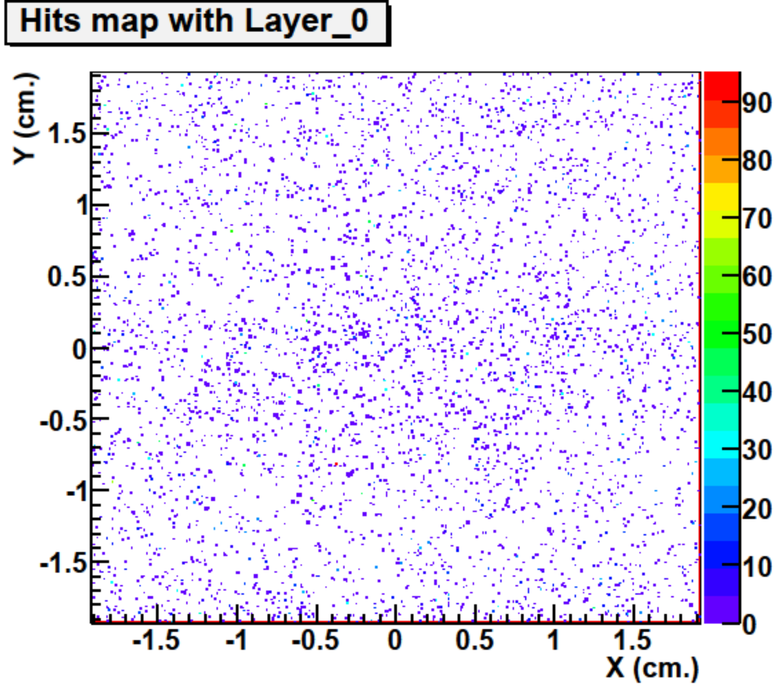
Helge Egil Seime Pettersen, Johan Alme, Anthony van den Brink, Mamdouh Chaar, Dominik Fehlker, Ilker Meric, Odd Harald Odland, Thomas Peitzmann, Elena Rocco, Hongkai Wang, Shiming Yang, Chunhui Zhang, Dieter Röhrich

(Submitted on 7 Nov 2016)

arXiv:1611.02031 [physics.med-ph]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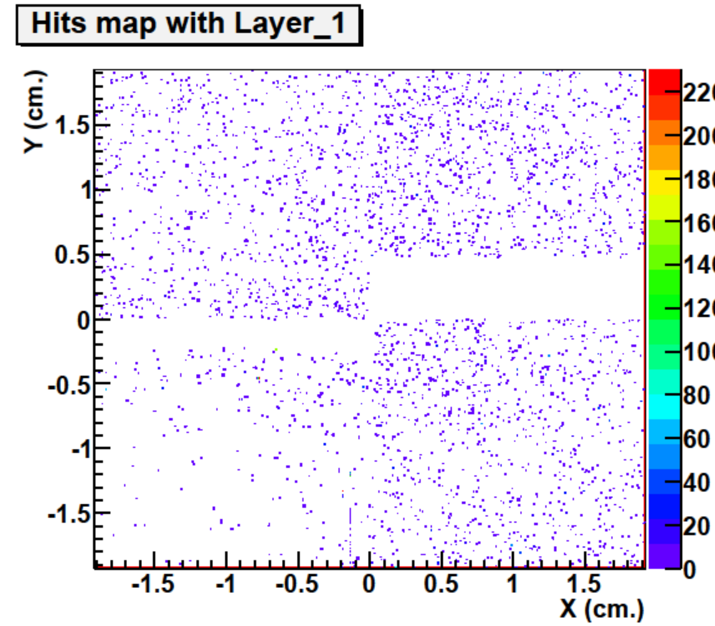
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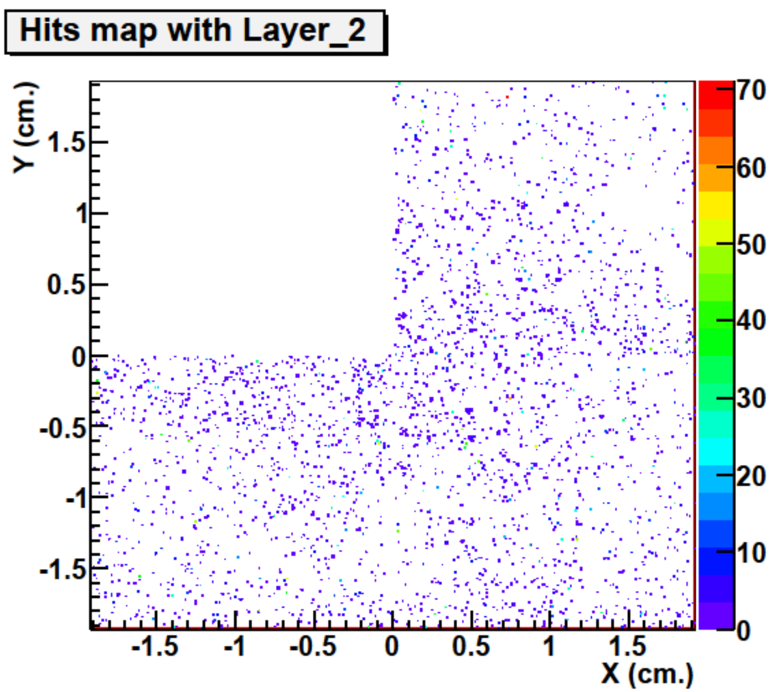
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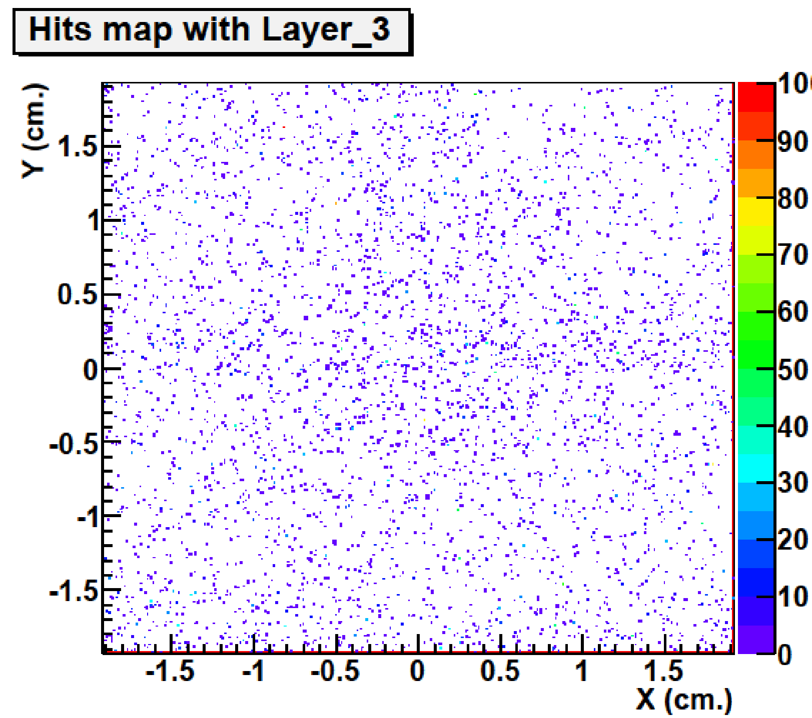
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X (cm.)
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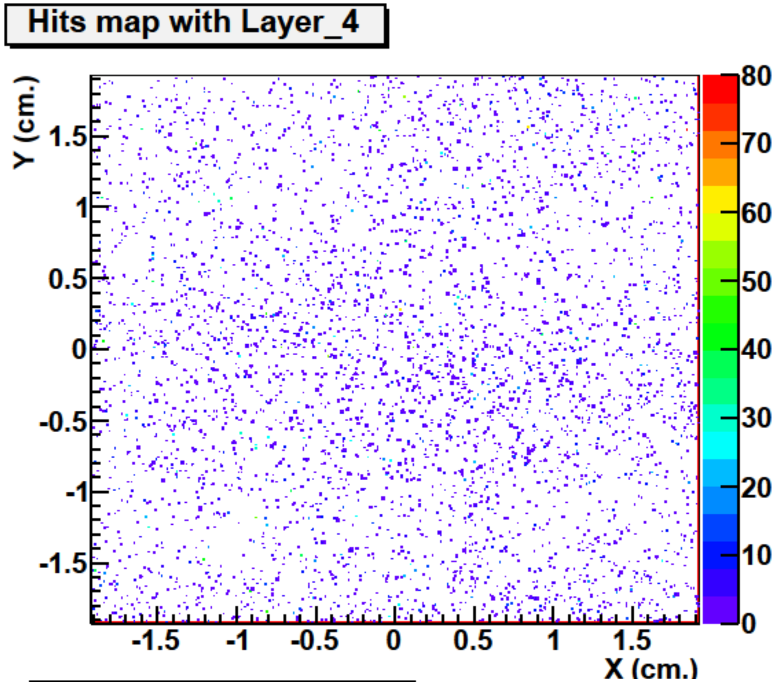

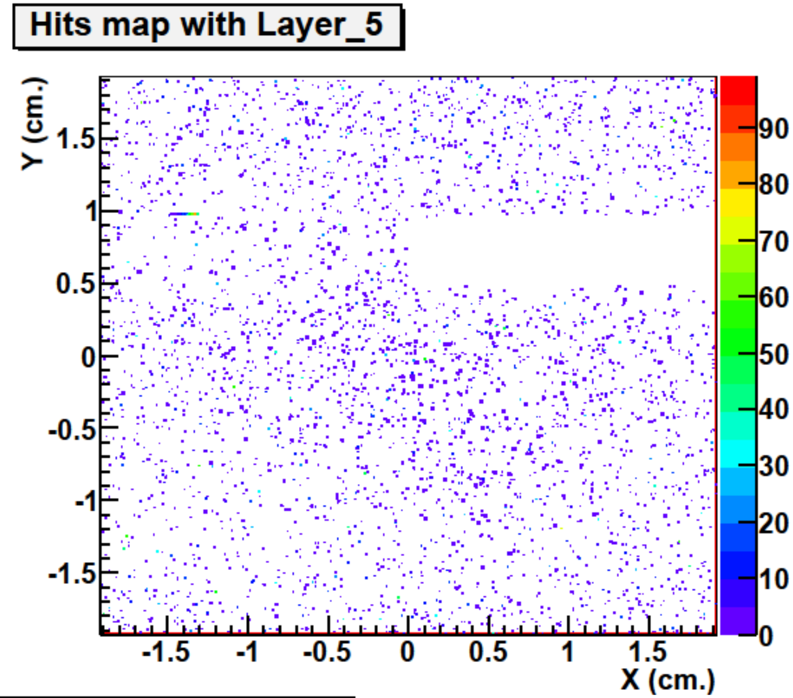

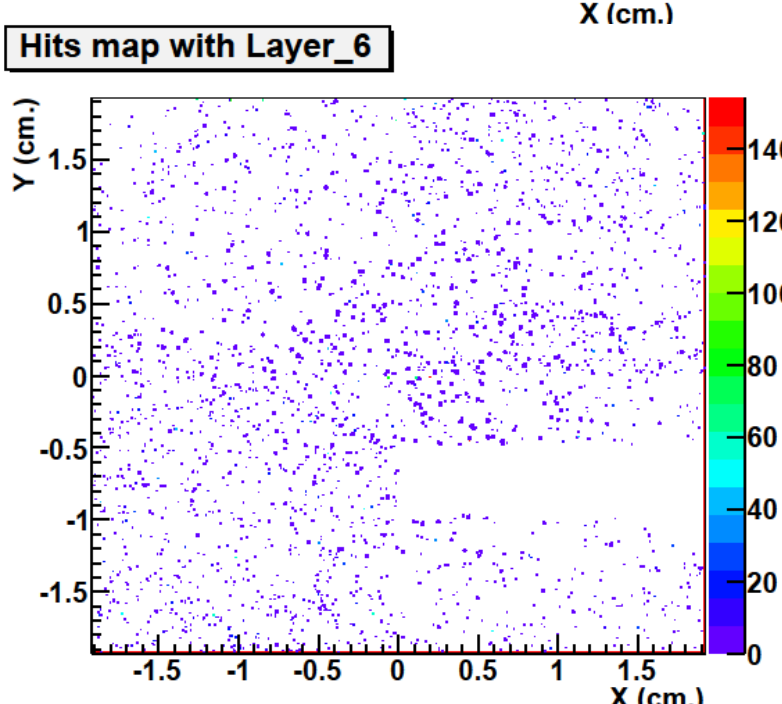

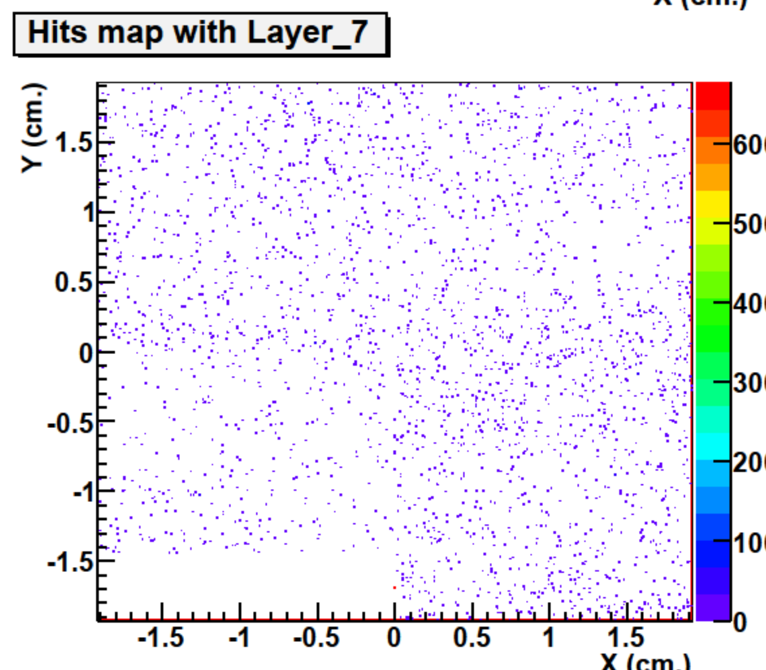

- Last layer with large hit clusters
- After Bragg peak