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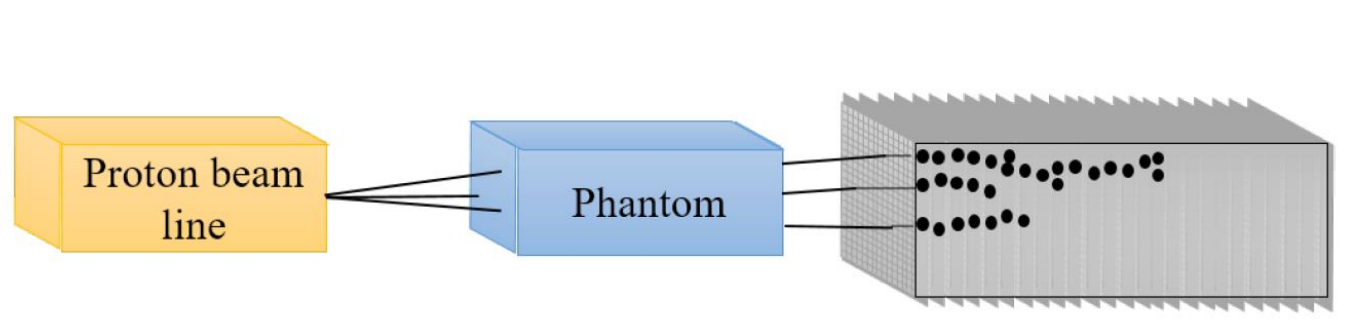
Proton CT in Bergen

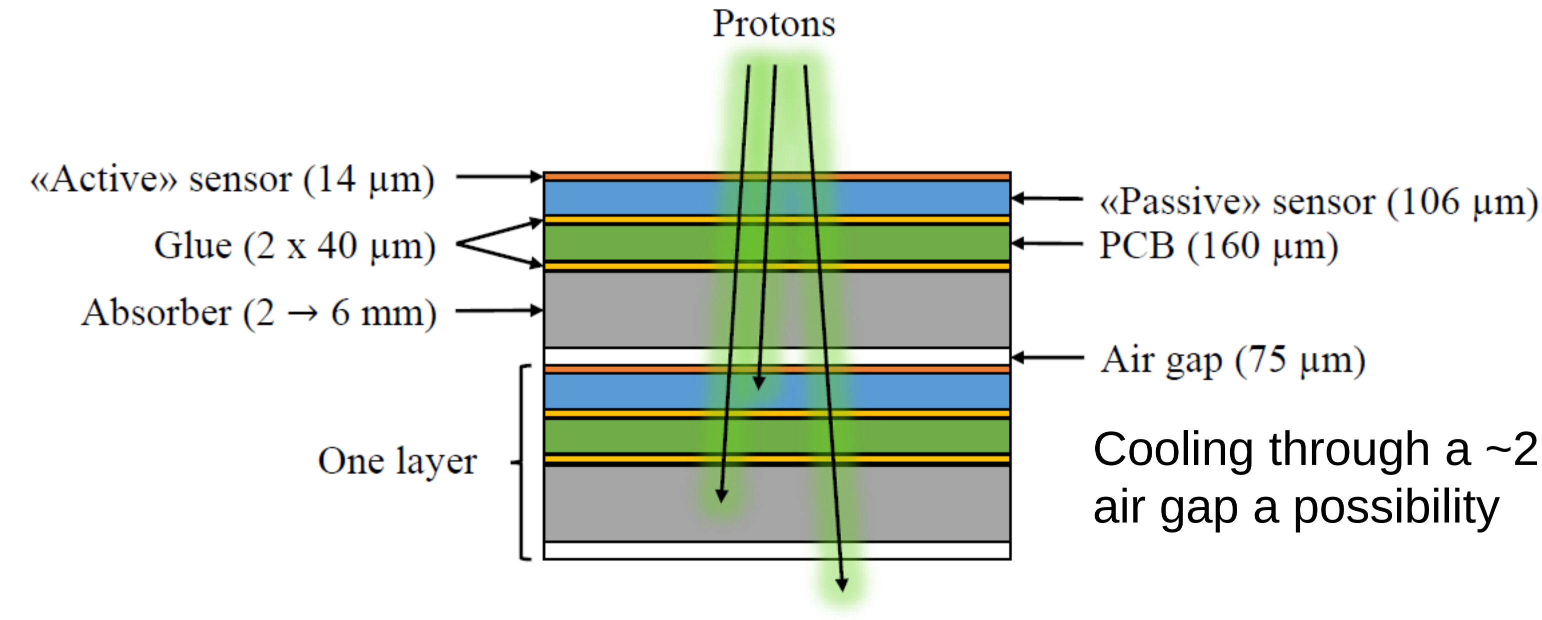
Helge Egil Seime Pettersen
PhD student
pCT workshop, august 2017
Loma Linda, CA

Overview

1. Overview of the design optimization project
2. Some feedback from the Loma Linda workshop
    1. Most Likely Path calculation
3. Postdoc application – What I'll be doing

Next prototype: Some simulation results – expected performance





Cooling through a ~2 mm air gap a possibility

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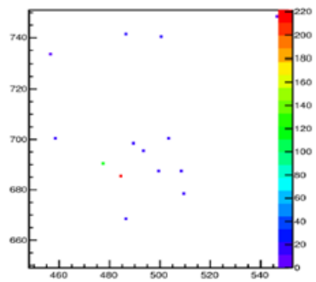
Analysis workflow

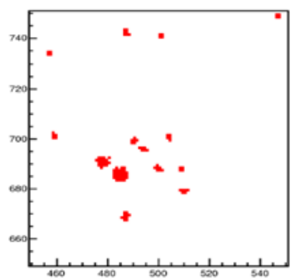
Data readout
MC, MC + truth, exp.

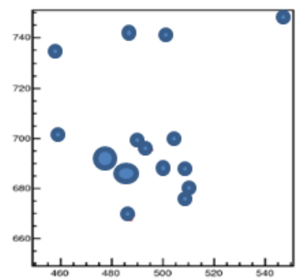
Pixel diffusion modelling (MC only)

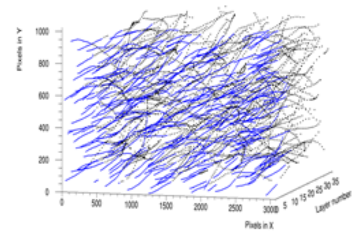
Cluster identification

Proton track reconstruction





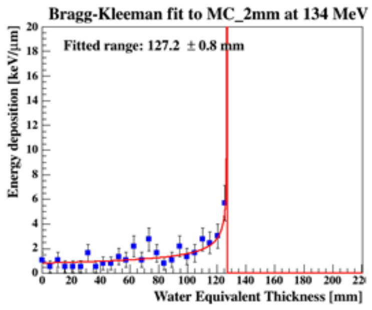


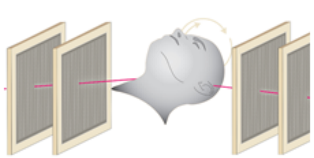


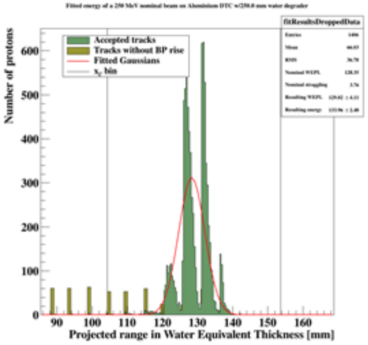
Individual track – energy loss fitting

If 3D reconstruction: MLP estimation

Residual range calculation







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Some simulation results

Individual proton tracks w/ Bragg Curve fit

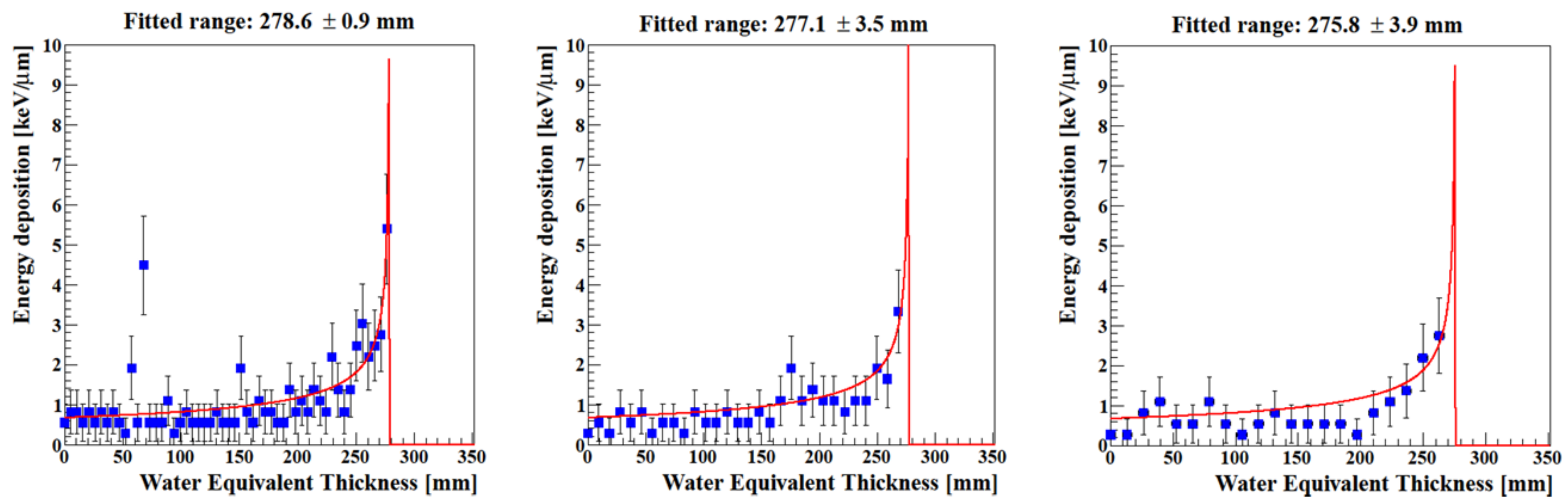
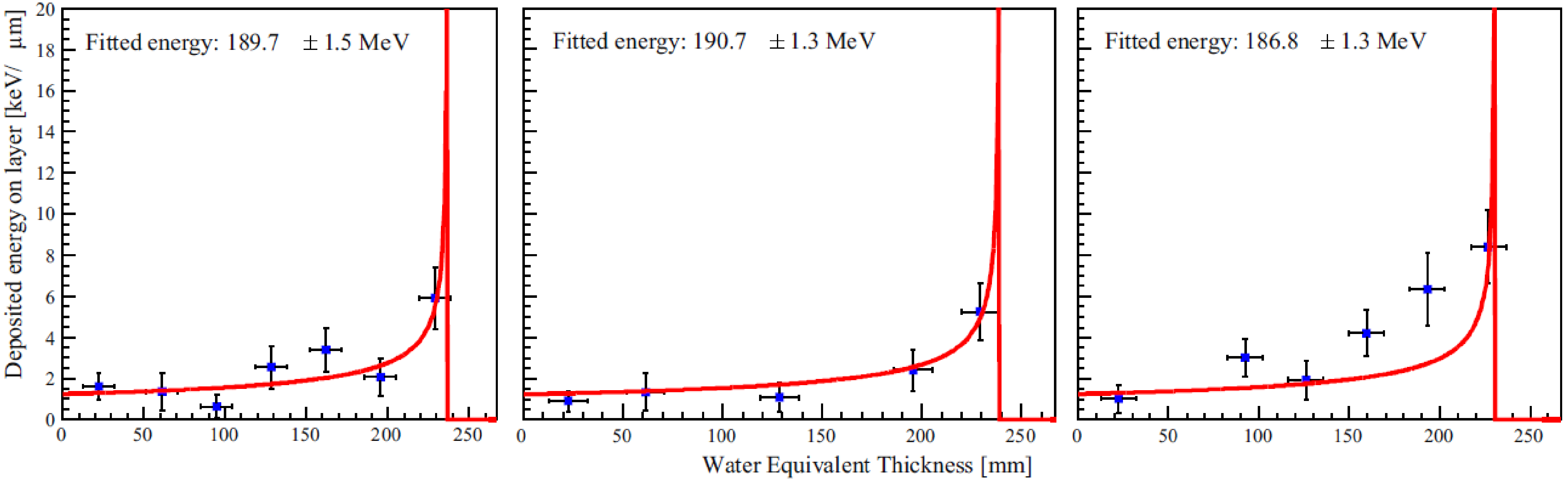


Figure 4: *Individual proton tracks with Bragg Curve fit. Note that the range found using thinner absorber designs yields higher range determination accuracy. The displayed accuracy is the output from the least-square method for an individual proton, and is not representative for an ensemble of protons. From a 250 MeV beam degraded using a 10 cm water phantom.*
Left: *2 mm Al absorber,* ***Middle***: *4 mm Al absorber,* ***Right***: *6 mm Al absorber.*

Data analysis

Some more examples



Bragg Curve fit to measurements from the 188 MeV experimental beam.

Range distribution per energy / voxel

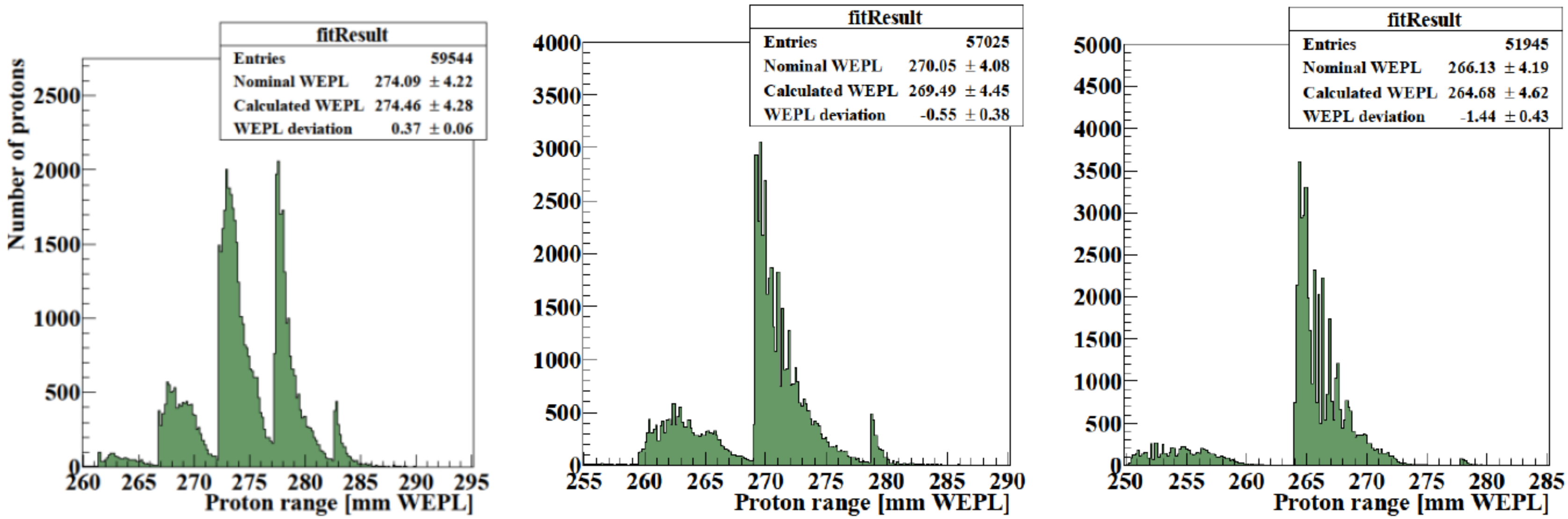


Figure 5: *The distribution of many individual fitted ranges. From this distribution the residual range $\langle \boldsymbol{R_0} \rangle$ and range straggling $\langle \boldsymbol{\sigma} \rangle$ of a proton ensemble is calculated, shown here as $\langle \boldsymbol{R_0} \rangle \pm \langle \boldsymbol{\sigma} \rangle$. Each rise in the distribution coincides with the beam reaching a new sensor layer. From a 250 MeV beam degraded using a 10 cm water phantom.* ***Left****: 2 mm Al absorber,* ***Middle****: 4 mm Al absorber,* ***Right****: 6 mm Al absorber.*

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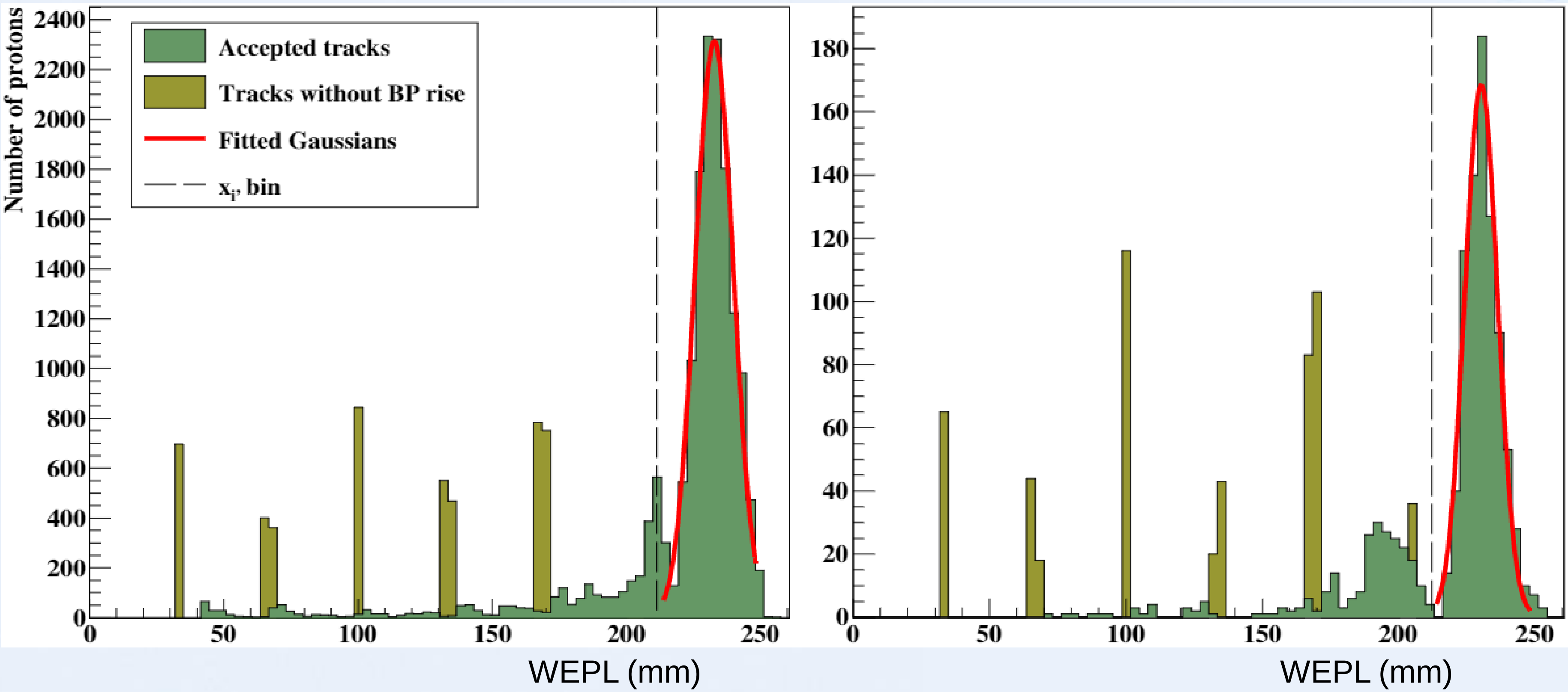
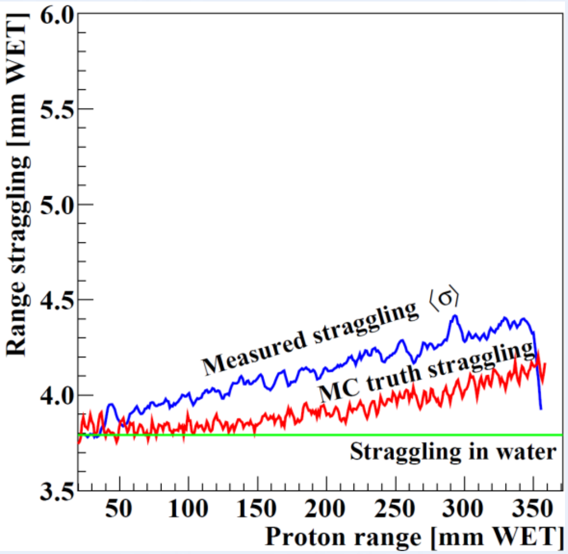
Compare this to FOCAL



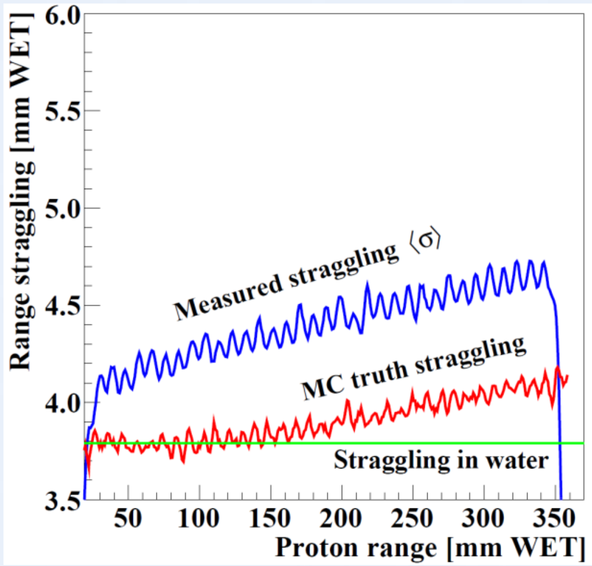
Left: *188 ± 3 MeV from a 188 MeV MC simulated mono-energetic beam.*
Right: *187 ± 3 MeV from the 188 MeV beam taken during the KVI Groningen beam test.*

Some simulation results

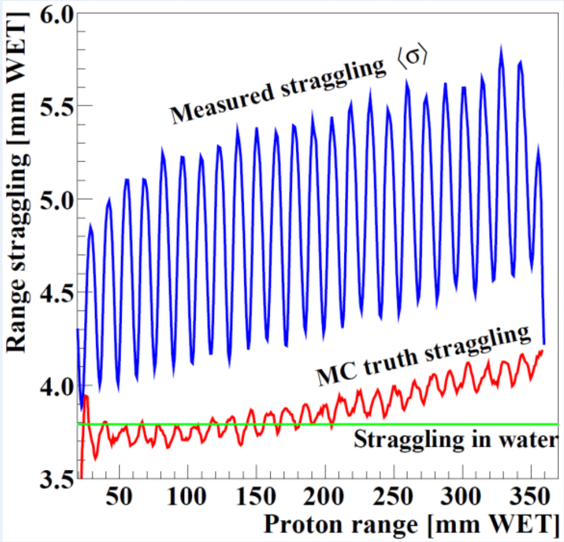
Range resolution cf. to range straggling



2 mm



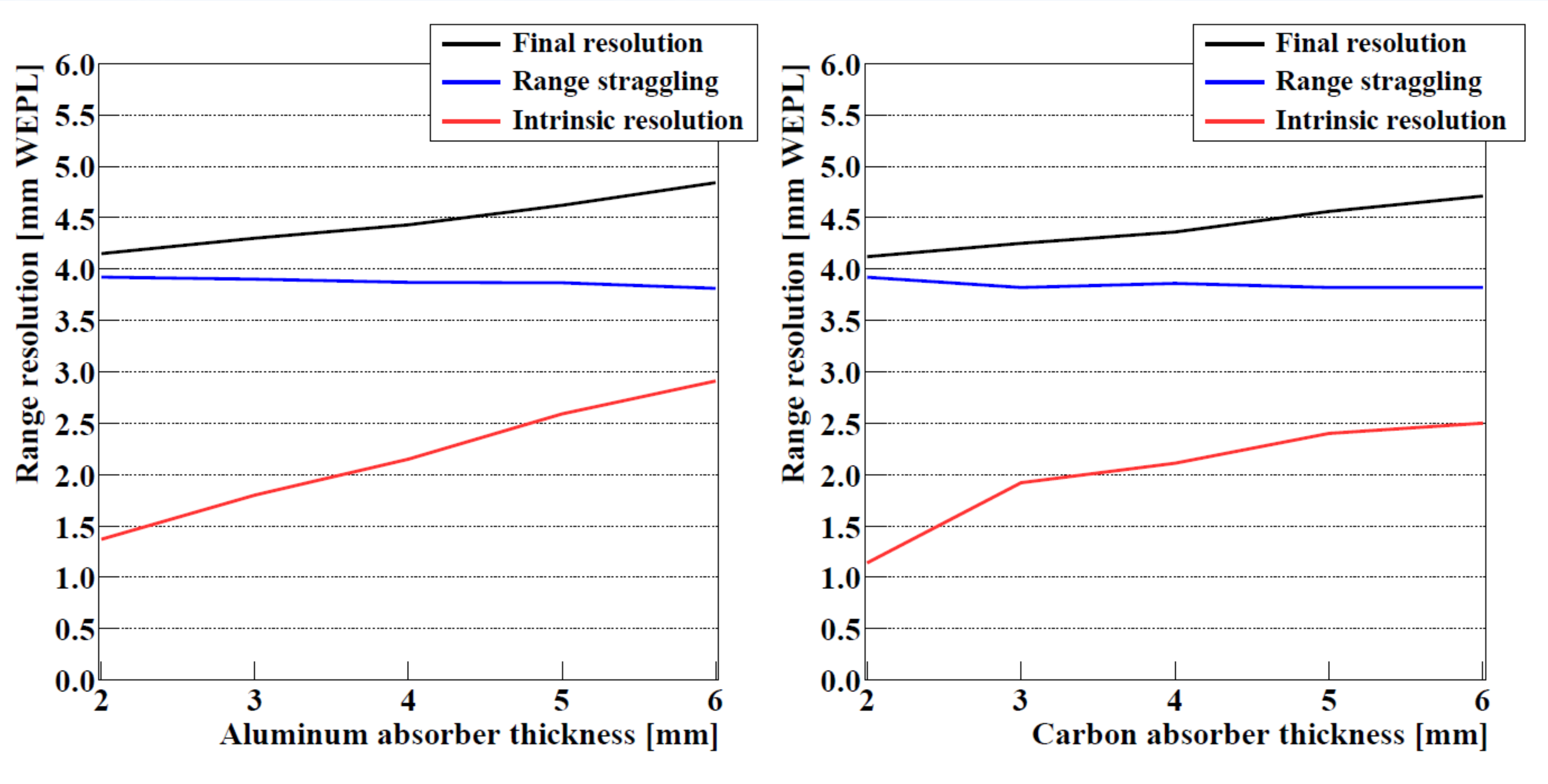
4 mm



6 mm

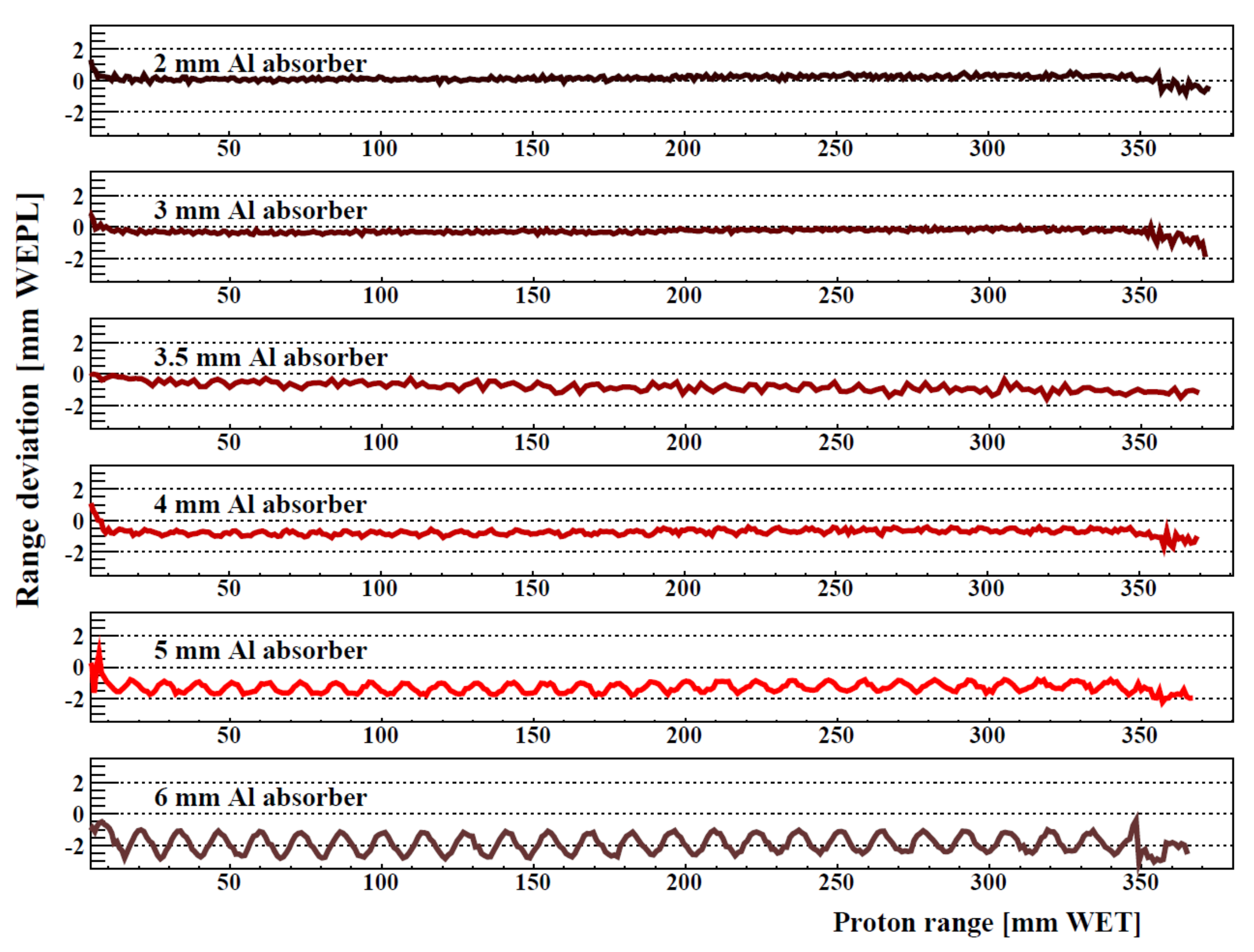
Some simulation results

Range resolution cf. to range straggling



Some simulation results

Range *accuracy* and linearity (in MC…)



Some simulation results

Range *accuracy* and linearity (in MC…)

Material	Thickness	$t/\sqrt{12}$ WEPL	Resolution	Excess straggling	Pre-straggling resolution	Layers for 230 MeV + 5σ
Al	2 mm	1.5 mm	4.16 mm	6.1%	1.38 mm	67
Al	3 mm	2.1 mm	4.26 mm	9.2%	1.69 mm	48
Al	4 mm	2.7 mm	4.35 mm	12.4%	1.97 mm	39
Al	5 mm	3.3 mm	4.50 mm	16.4%	2.28 mm	32
Al	6 mm	3.9 mm	4.70 mm	23.3%	2.73 mm	27
Al	7 mm	4.5 mm	4.76 mm	26.0%	2.78 mm	23
Loma Linda	N/A	N/A	4.1 mm*	N/A	N/A	N/A
FOCAL	32 mm	9.2 mm	15.6 mm**	N/A	N/A	11

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* At 200 MeV. Scintillator measurements, res. does not scale linearly with depth.
** Resolution scaled to 230 MeV from 188 MeV
```

Some simulation results

Range *accuracy* and linearity (in MC…)

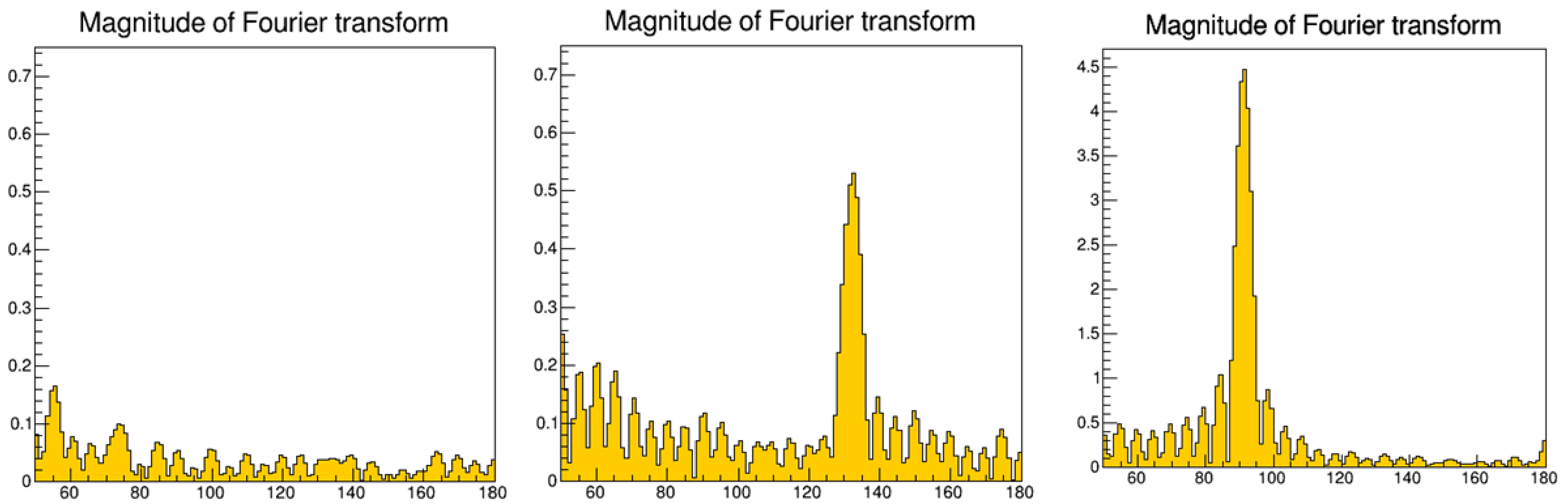

Figure 9: *The Fourier transform of 2 mm (**left**), 4 mm (**middle**) and 6 mm (**right**) absorber geometries. Compare this to* **Figure 6**, *where the wobbles are discernible: Here they are measurable.*

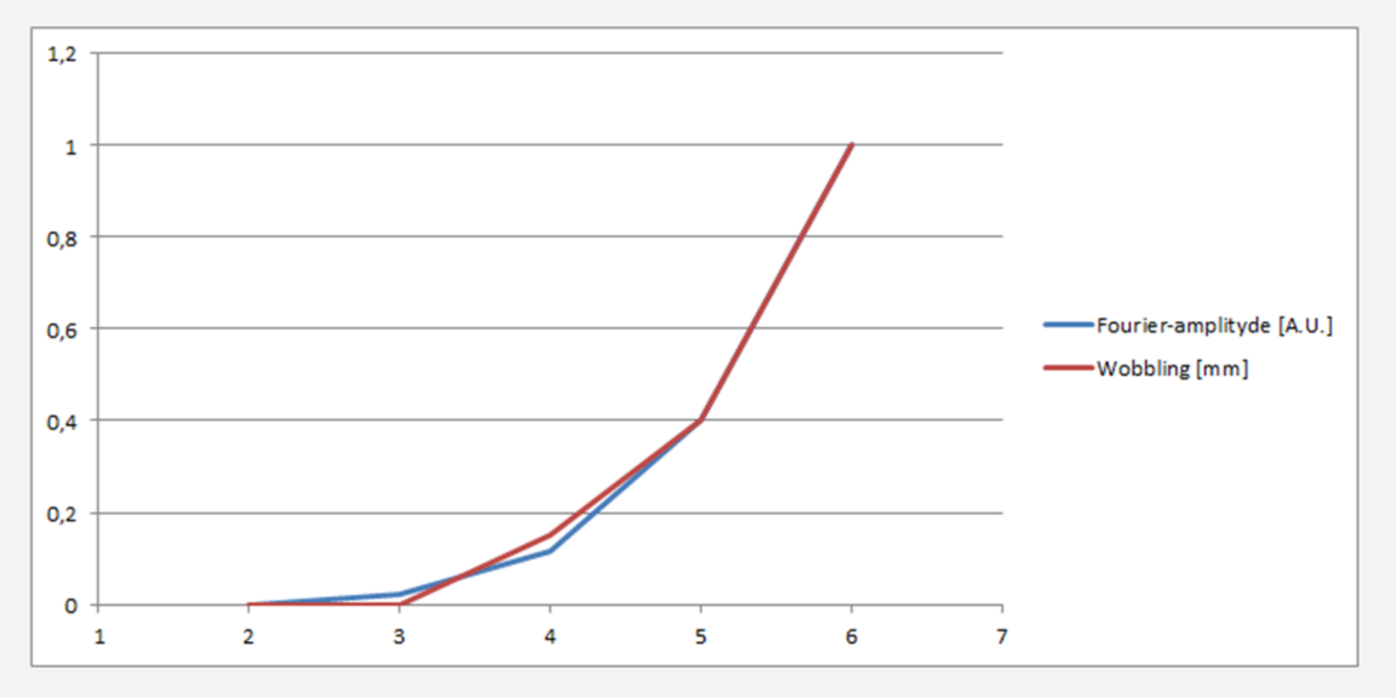

Figure 10 *Measurements of the peak-to-peak amplitude of the wobbles and the (artificially scaled) Fourier amplitude. X-axis is absorber thickness, Y-axis mm peak-to-peak. The measurements agree, and so it is trivial to quantify the amplitude of the oscillation artefacts.*

Compare this to FOCAL …

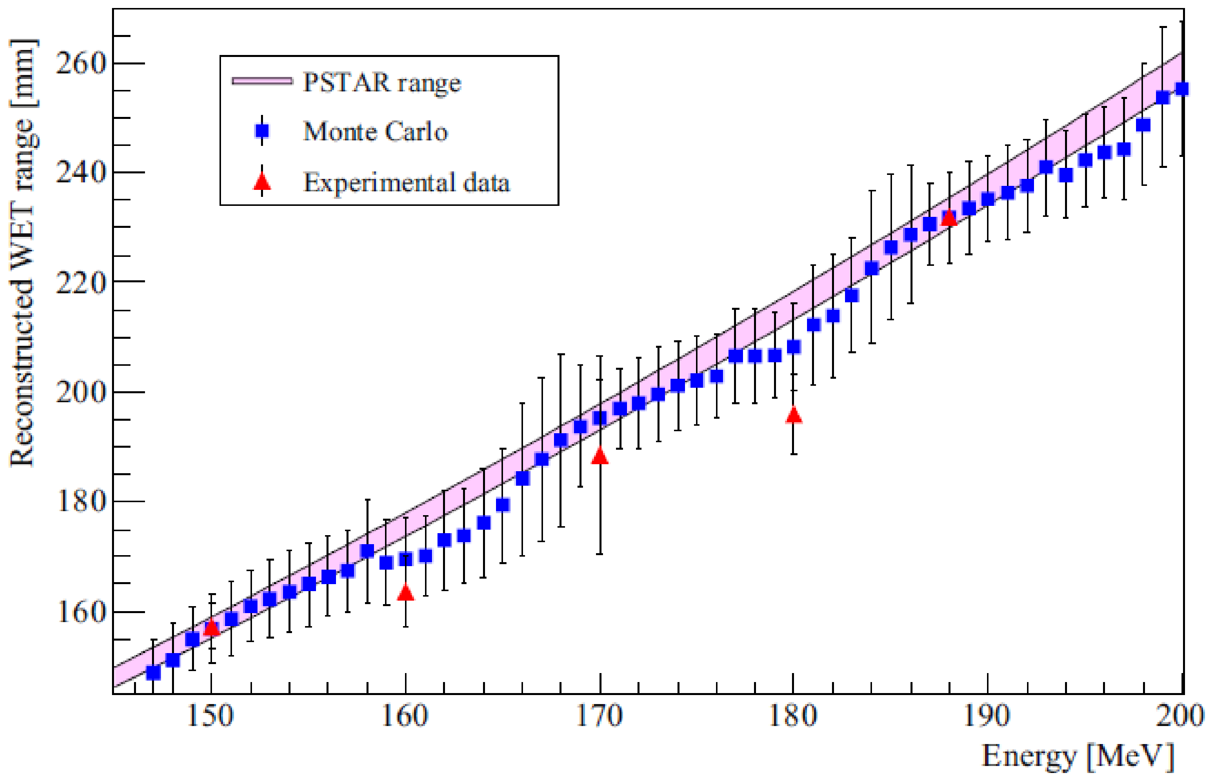

Fig. 7. Reconstructed ranges $\langle \hat{R_0} \rangle$ of proton beams with different energies. Results from both the MC simulations and from the experimental measurements are displayed on the plot. The PSTAR range is displayed using a band representing the expected range straggling. Average numbers for the deviations between R_0 and $\langle \hat{R_0} \rangle$ as well as the corresponding resolution $\langle \hat{\sigma} \rangle$ are presented in Section 6.3.

Particle tracking

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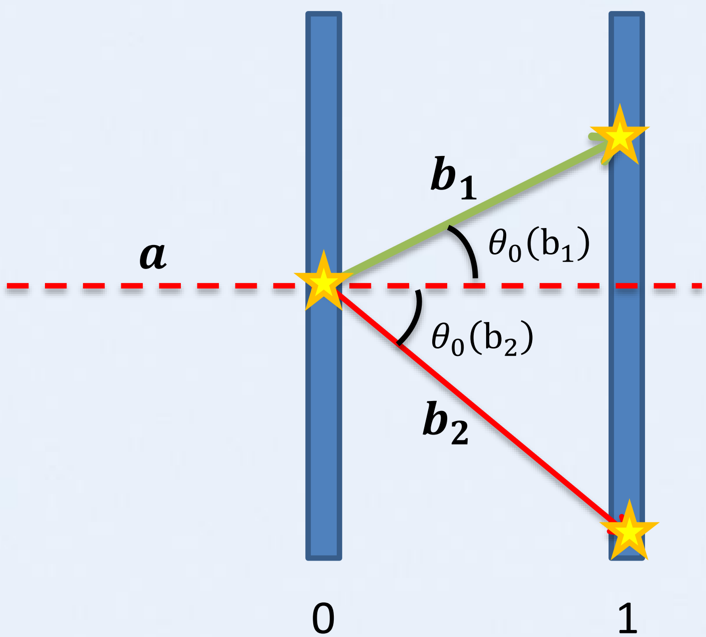
Tracking algorithm

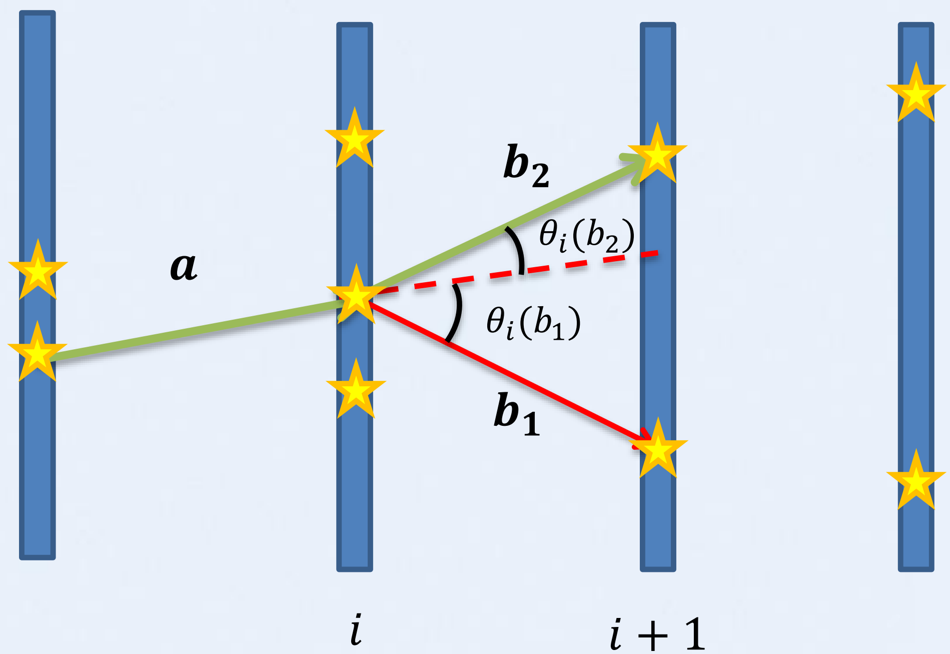
1. Use all hits in first layer as seeds
2. Test all seeds against hits in next layer:
   1. Evaluate: Find change in direction θ_0 in first sensor layer (assume parallel beam here) against all hits in next layer
   2. Compare θ_0 against a threshold value: If below, keep the hit in next layergiving rise to lowest θ_0: Here it's $\boldsymbol{b_1}$.



$$\theta_0(\boldsymbol{x}) = \cos^{-1}\left[\frac{\boldsymbol{a}\cdot\boldsymbol{x}}{|\boldsymbol{a}|\cdot|\boldsymbol{x}|}\right]$$

Tracking algorithm

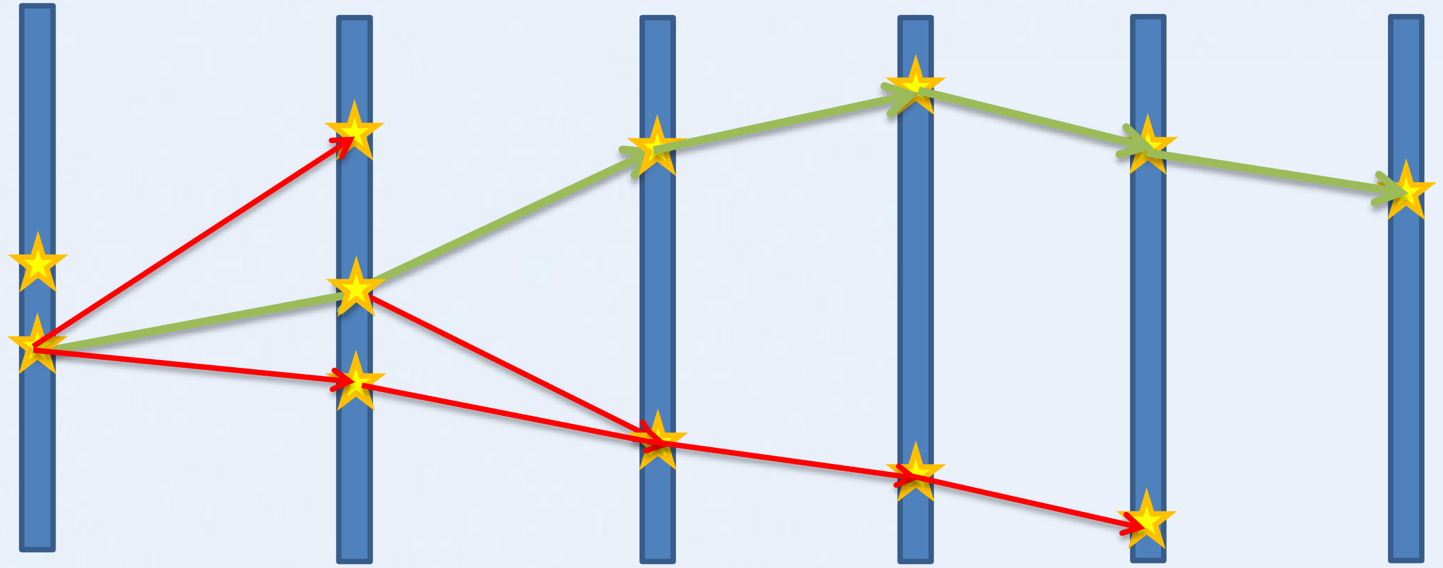
1. For all next layers, find angular change θ_i and append the hit with «lowest-scattering» cluster.



$\boldsymbol{\theta_i(b_1) > \theta_i(b_2) \rightarrow}$ **Use** $\mathbf{b_2}$

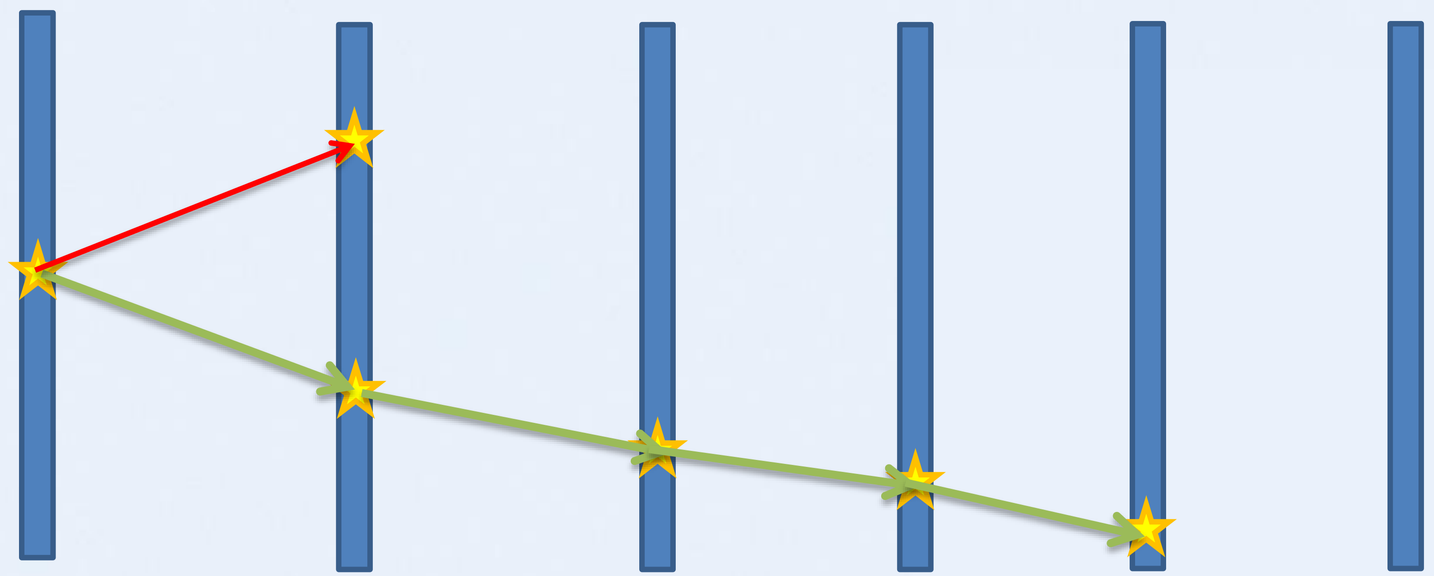
Tracking algorithm

1. When a few tracks are made from the same seed pair, find the best one using different scoring criteria (total angular change, length, existence of Bragg Peak, etc.)
2. Keep the track (green) and remove all hits connected to it



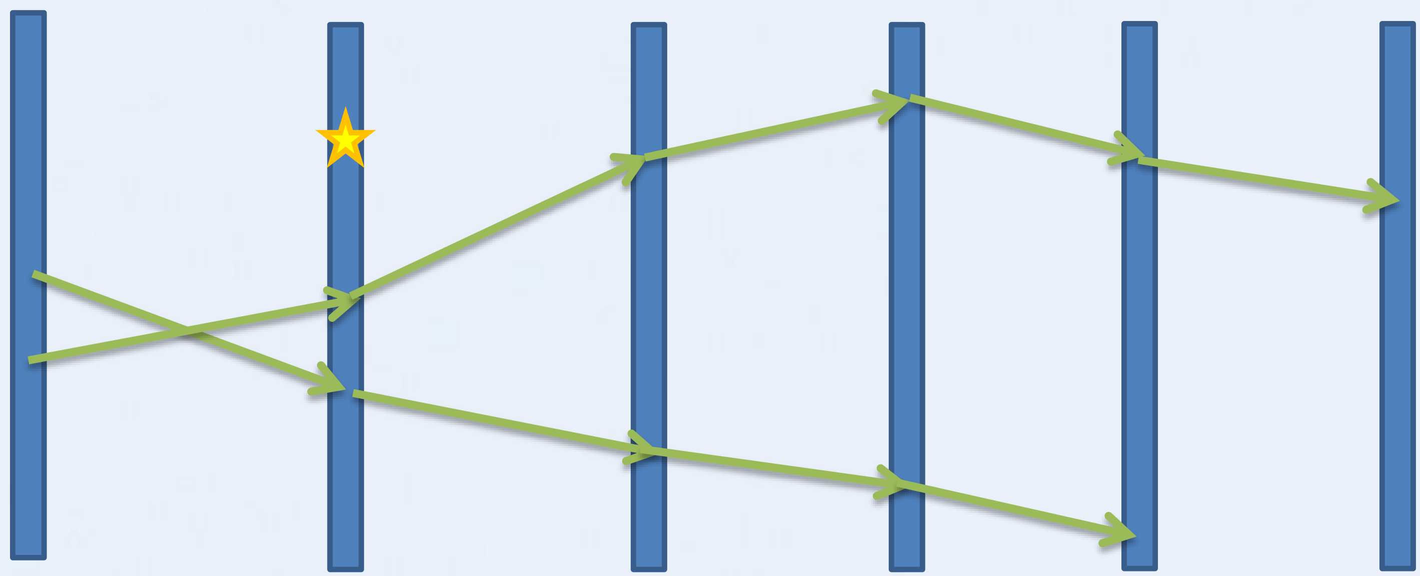
Tracking algorithm

1. Redo the tracking on the reduced data



Tracking algorithm

1. Voilà, all tracks are reconstructed



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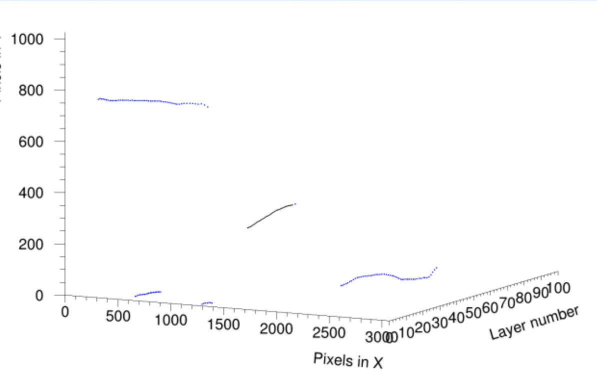
Proton tracking – Accuracy

The more protons to be reconstructed at the same, the smaller the probability of finding the correct track



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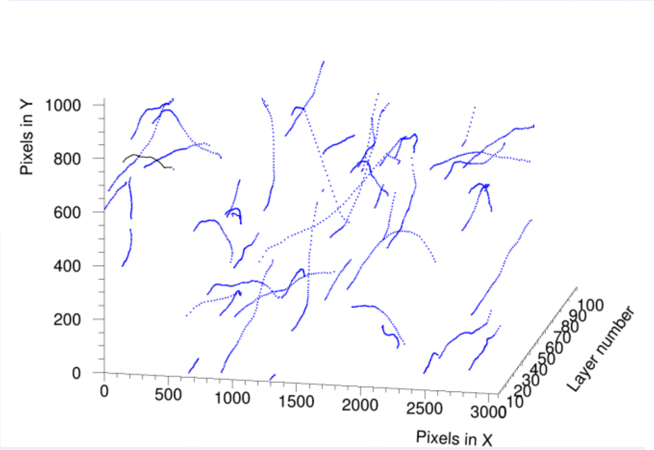

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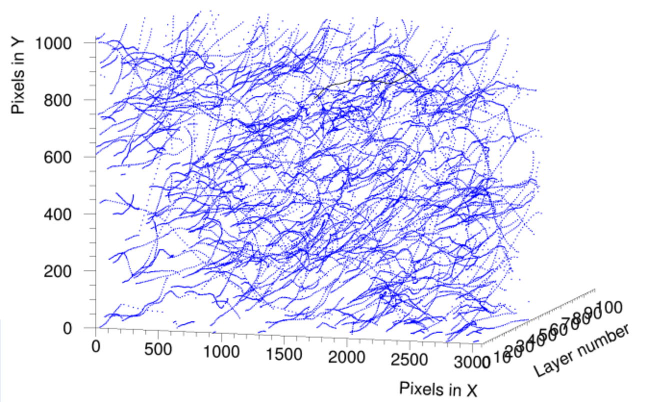

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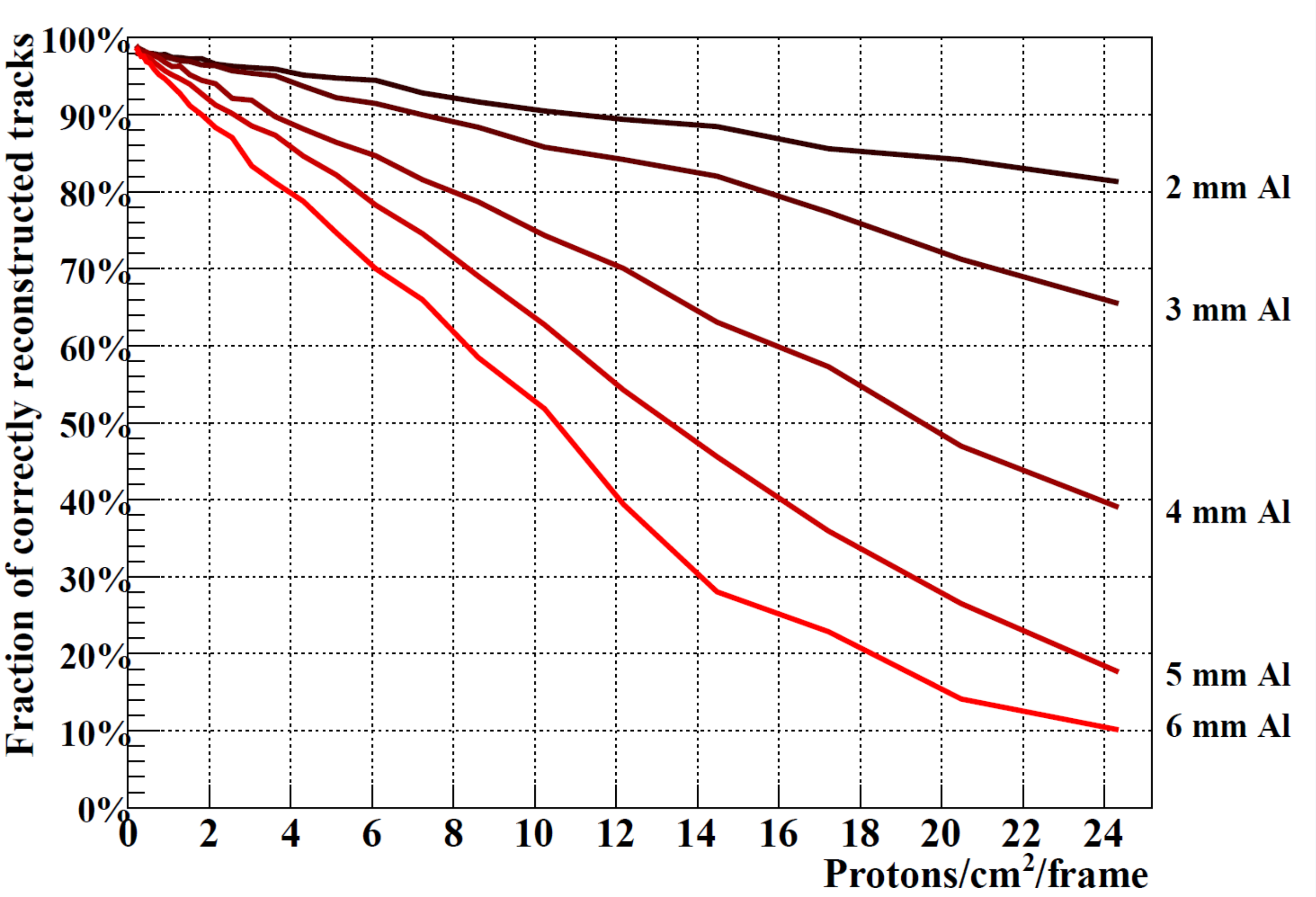
Some simulation results

Track reconstruction efficiency



Expected beam density

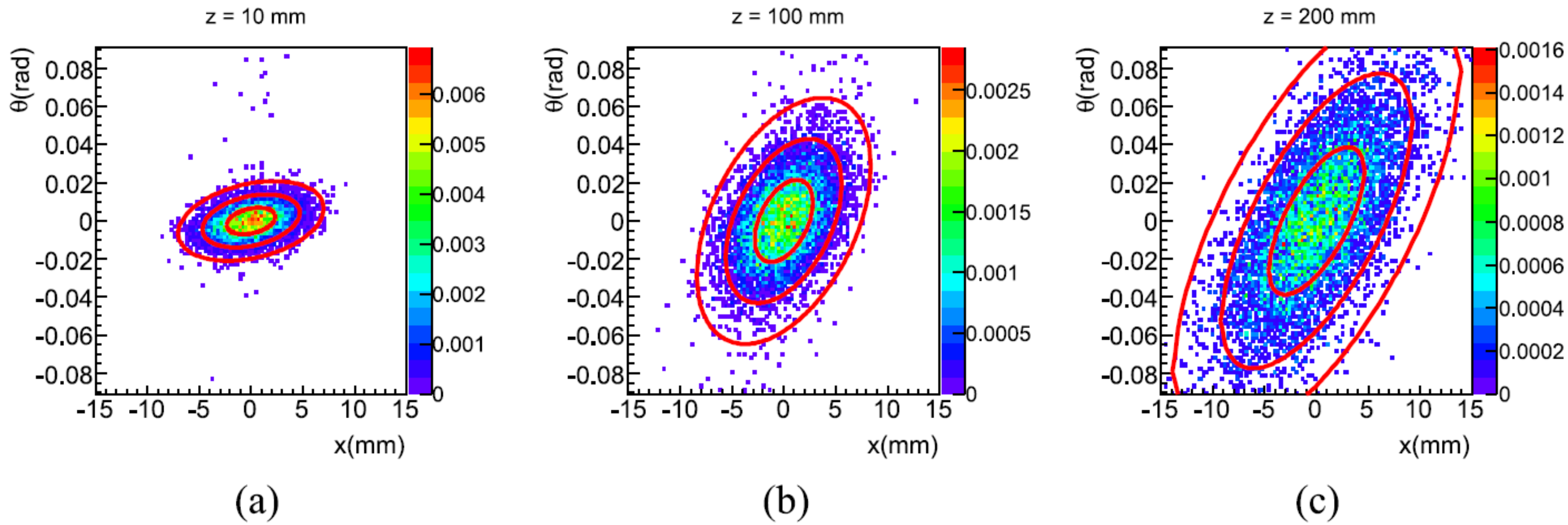


FIG. 3. Beam ellipse area in the phase space for three different water depths (a) $z = 10$ mm, (b) $z = 100$ mm, and (c) $z = 200$ mm. The colored scale refers to the normalized proton probability density function from the Monte Carlo sample. The contour lines represent the 1-, 2-, and 3-σ of the normalized bivariate Gaussian distribution predicted analytically.

A pencil beam approach to proton computed tomography

Regina Rescigno,[a] Cécile Bopp, Marc Rousseau, and David Brasse
Université de Strasbourg, IPHC, 23 rue du Loess, Strasbourg 67037, France and CNRS, UMR7178, Strasbourg 67037, France

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Conclusion next prototype

- Track 5M protons/s/cm^2 with 90% reconstruction efficiency -
- Range uncertainty per proton = 10 % above range straggling
- <0.5 mm systematic error from 20 mm WET to full detector length (containing a 230 MeV beam)

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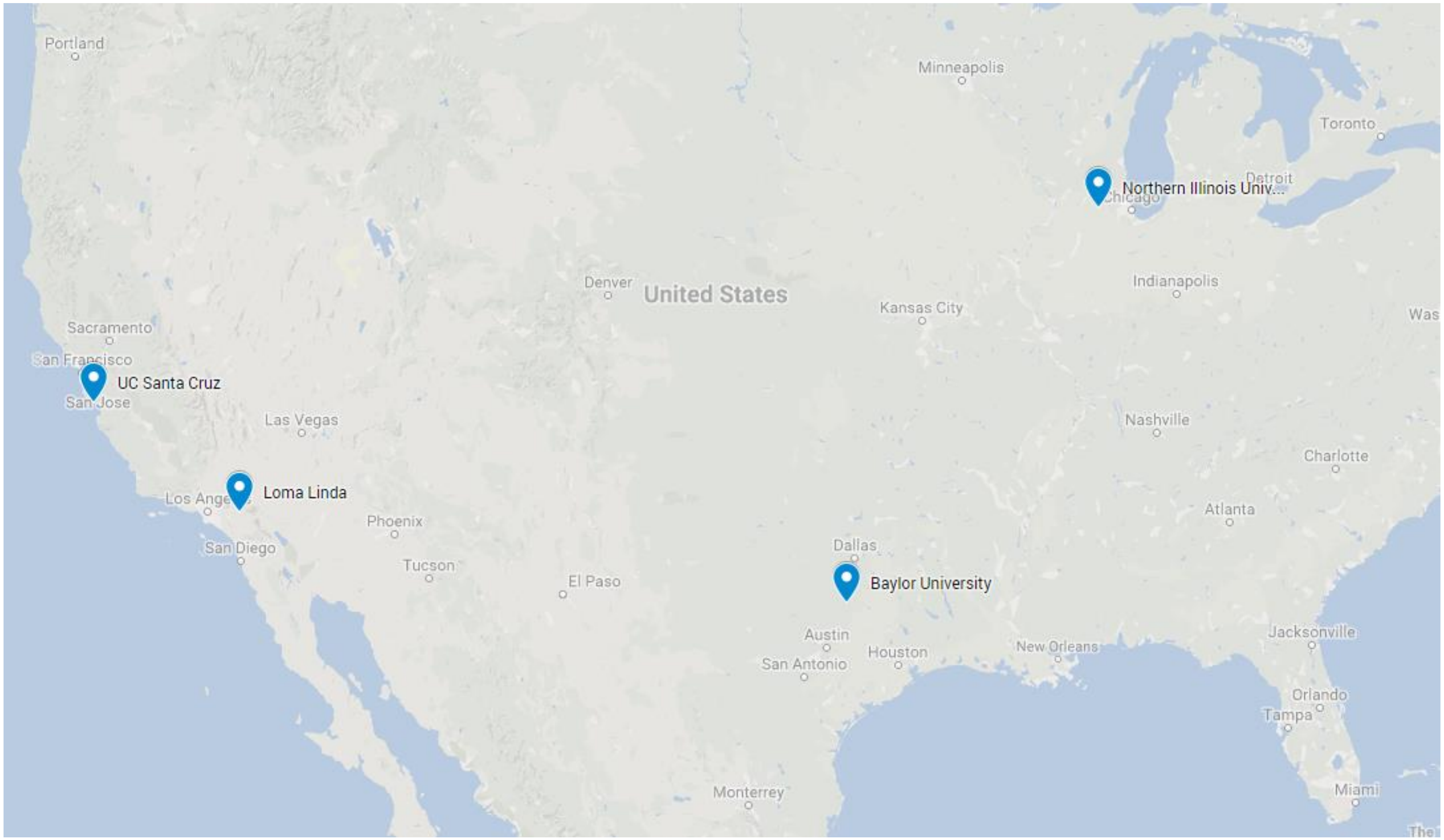
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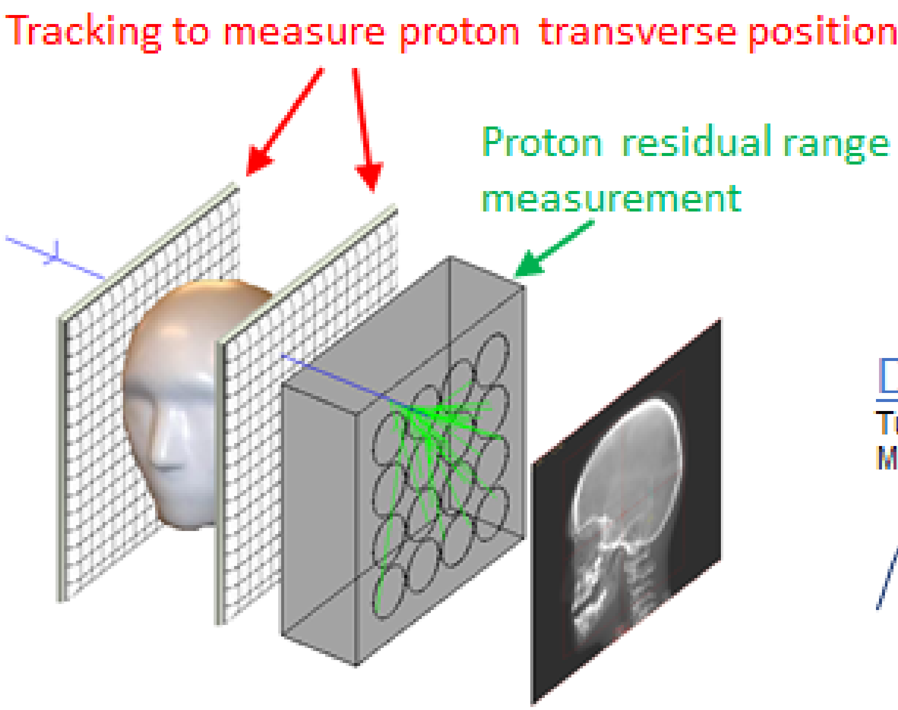
Tucson
El Paso
Austin
Houston
New Orleans
Jacksonville
San Antonio
Orlando
Tampa
Monterrey
Miami

Some feedback on the project

- I recently went to a pCT workshop in Loma Linda, CA
- They're working towards a clinical prototype within 2-3 yrs, using the FNAL fiber optics calorimeter prototype
  - Need to build an isocentric rotating chair, not trivial
- After some discussion, it's very hard to use a front tracker and corrolate hits with > 1 protons / frame
  - No-go on using spreading foils for ~uniform fields
- Luckily, already some research on pencil beam CT

Principle of Proton Imaging (CT or radiography)

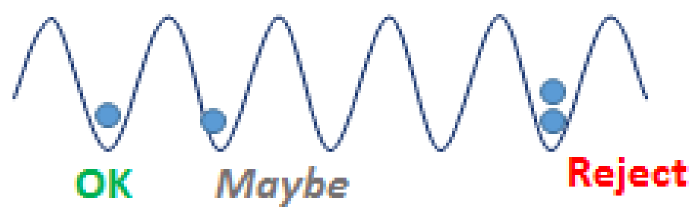


<u>Proton Imaging *immediately* before treatment:</u>
Use protons with enough energy to traverse patient.
Use ultra-low intensity beam (~0.01% of treatment intensity)
- Lower dose than equivalent x-ray image.

<u>Subsequent treatment beam uses:</u>
- Lower energy, protons stop in tumor
- Higher intensity, delivers prescribed dose

Detector measures individual protons.

Turn down beam intensity to obtain single-proton bunches:
Most bunches will be empty, ~10% will contain one proton.



ProtonVDA

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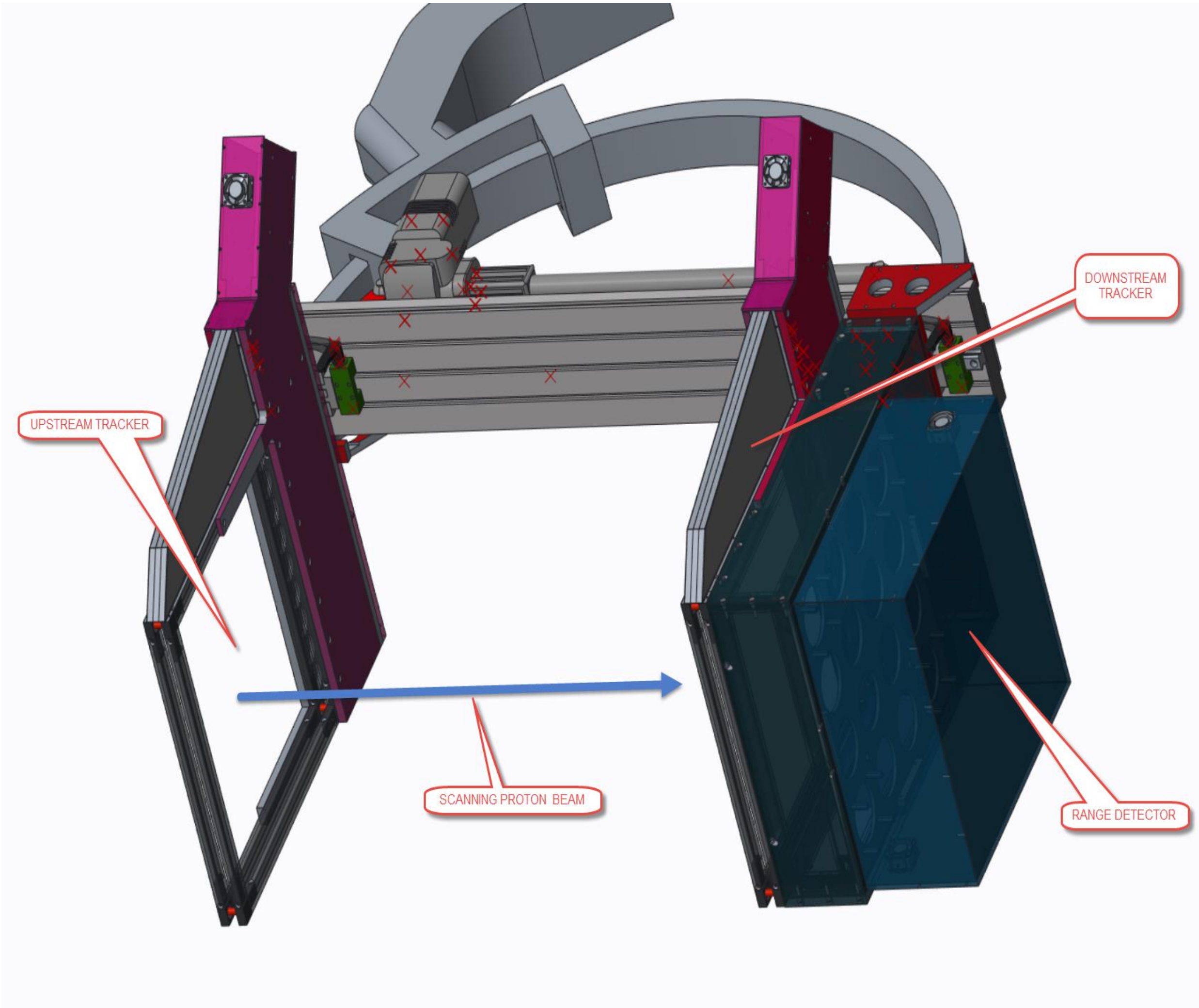
•3D drawing

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Postdoc application

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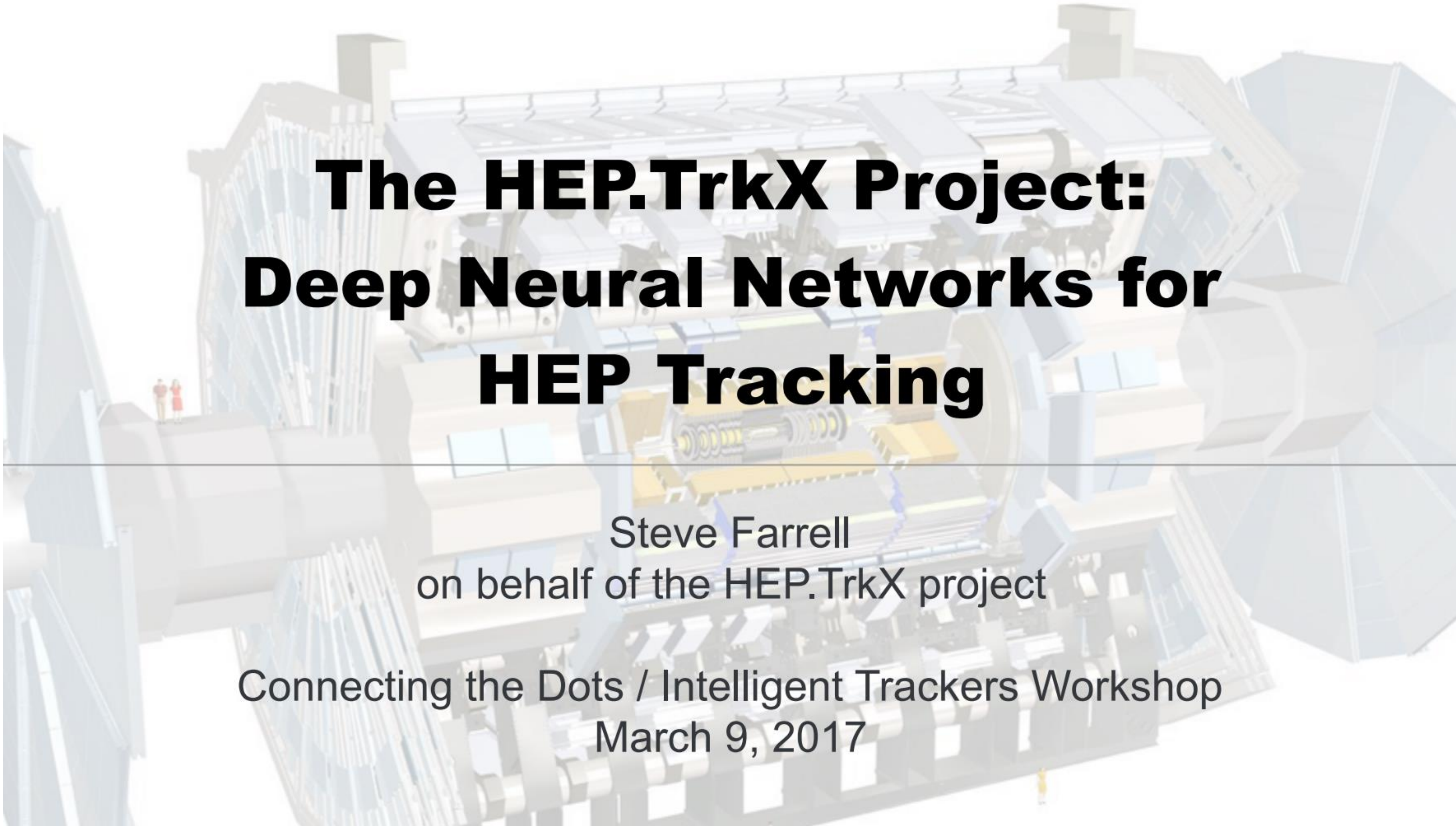
Overview

- I have applied for a Helse Vest postdoctoral fellowship
- 2.5 years duration after my defense in ~feb - apr
- + 6m Stay with the US groups?

Project goals:

1. Implement, test, compare, develop, adapt, … different schemes for image reconstruction: RTK, Baylor’s code, simple IR algorithms
2. Most Likely Path and different beam types. Pencil beam w/o trackers – what’s the resolution degradation?
3. Continue to be part of this project, software development, +++


The HEP.TrkX Project:
Deep Neural Networks for
HEP Tracking
Steve Farrell
on behalf of the HEP.TrkX project
Connecting the Dots / Intelligent Trackers Workshop
March 9, 2017

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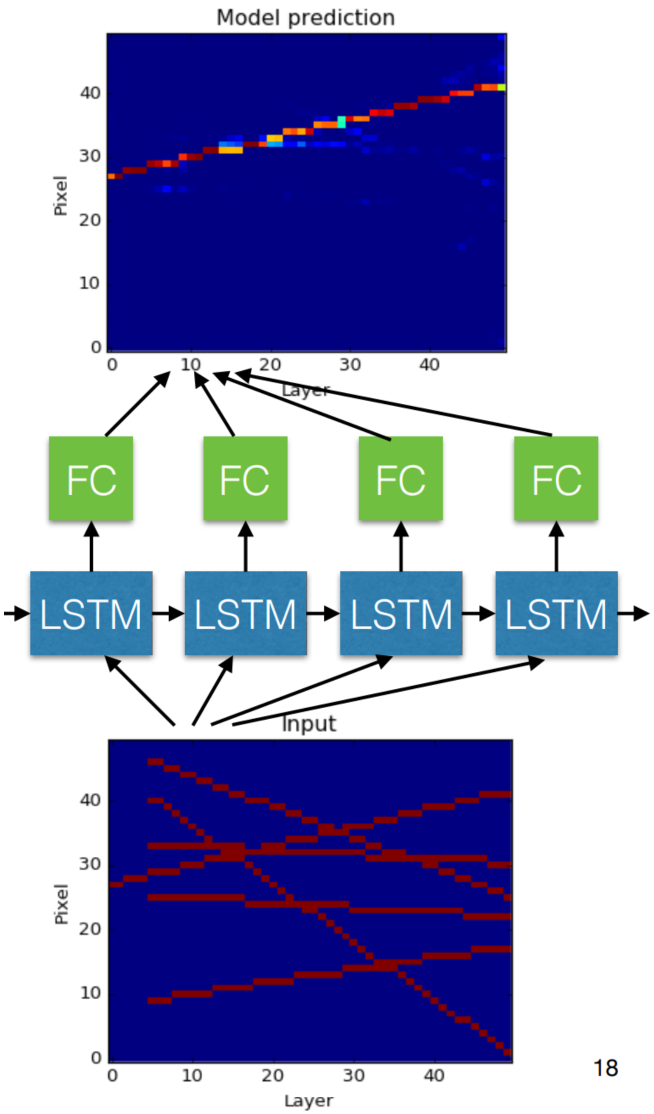
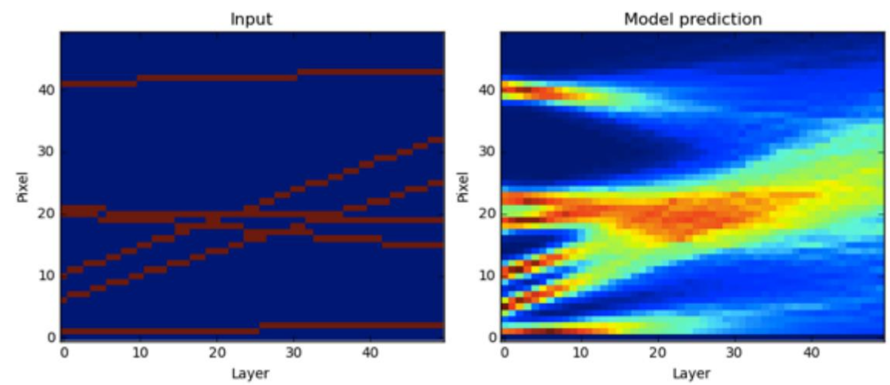


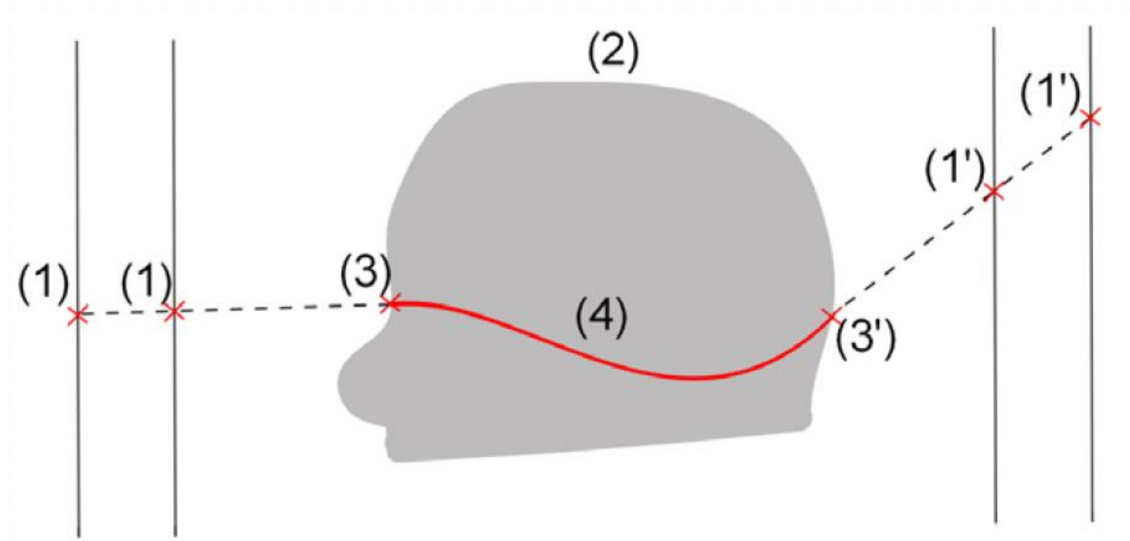
- However, it does get unstable with large numbers of tracks



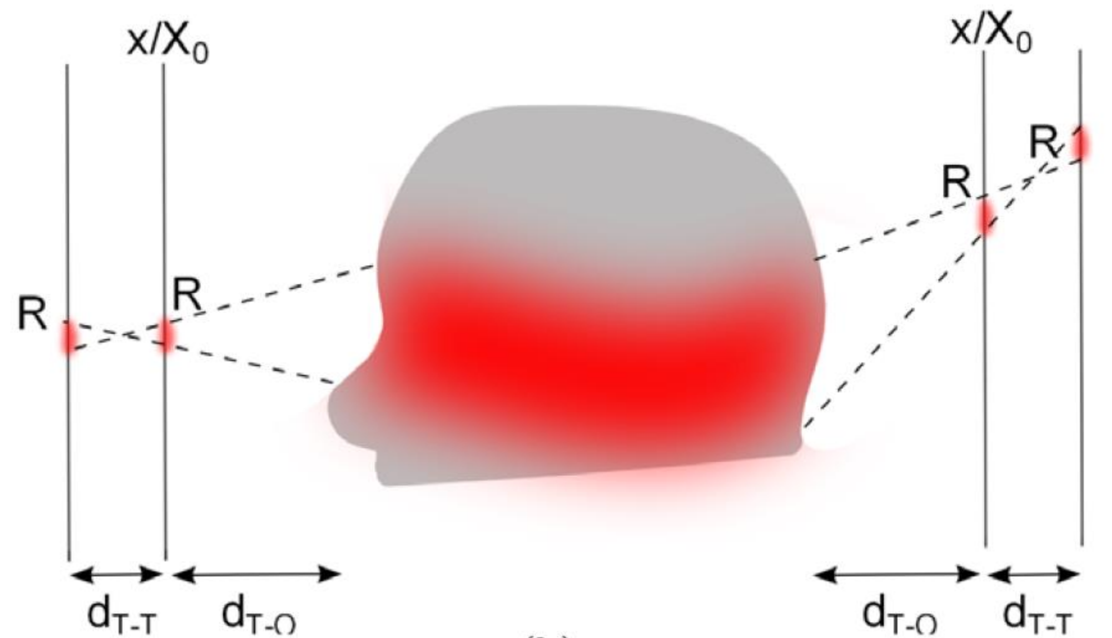
Inhomogeneous Most Likely Path

Inhomogeneous Most Likely Path - Spline Hybrid Algorithm

- The MLP is calculated only at the material boundaries.
- A spline is fitted between the lateral positions at the boundaries, given the angles at which the proton enters and exits the phantom.
- Empirical observation: computational effort is reduced significantly.



(a)



(b)

Charge diffusion

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).

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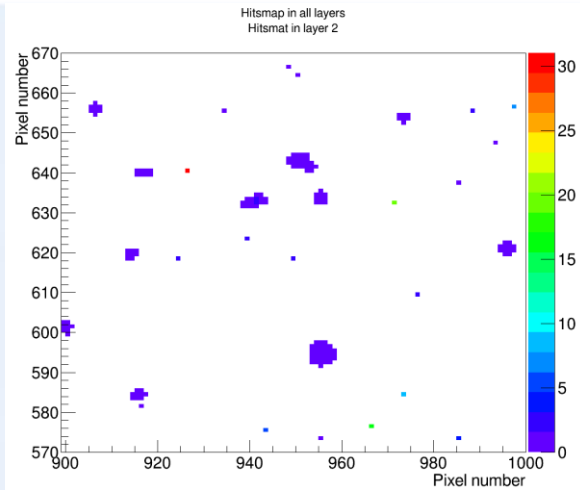
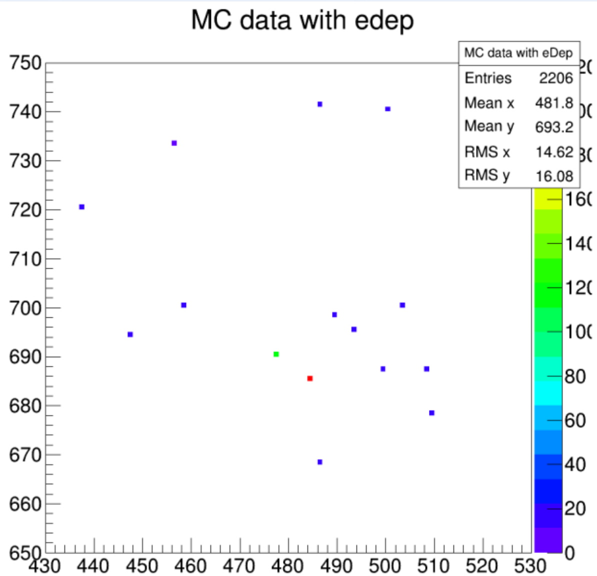
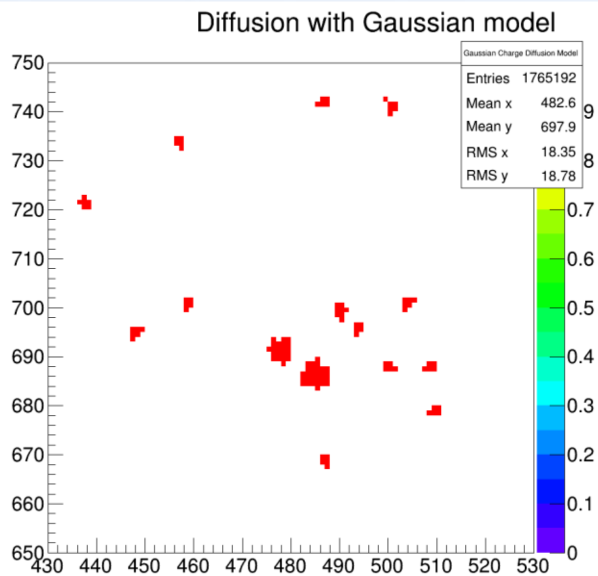
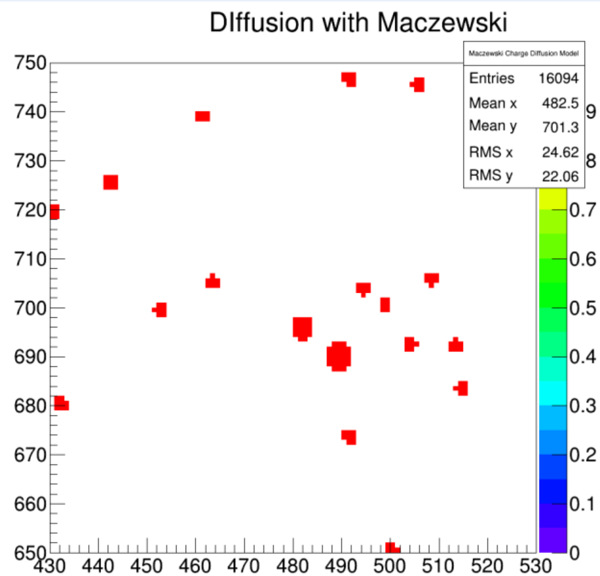
How to calculate edep from cluster size



Data







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

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

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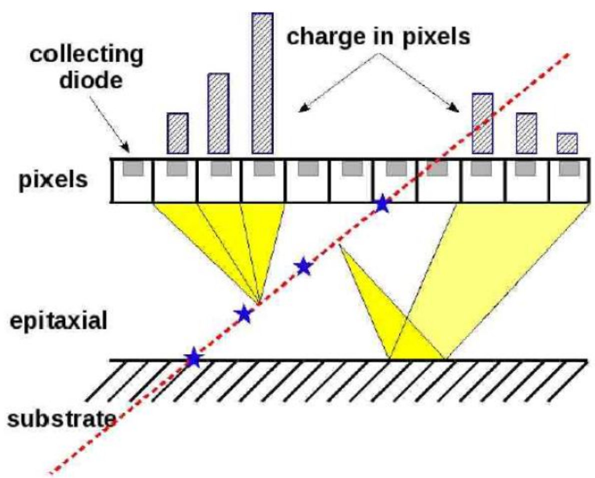
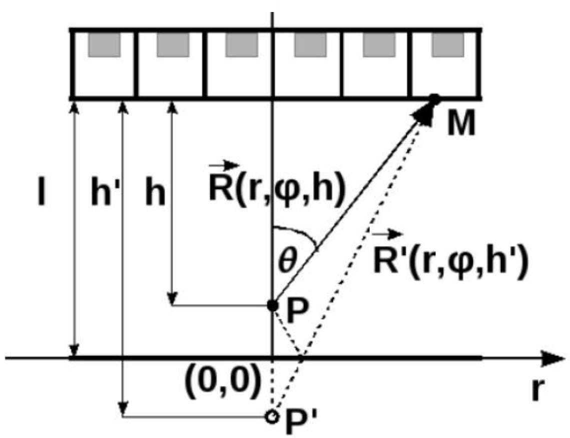
Analytical model

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

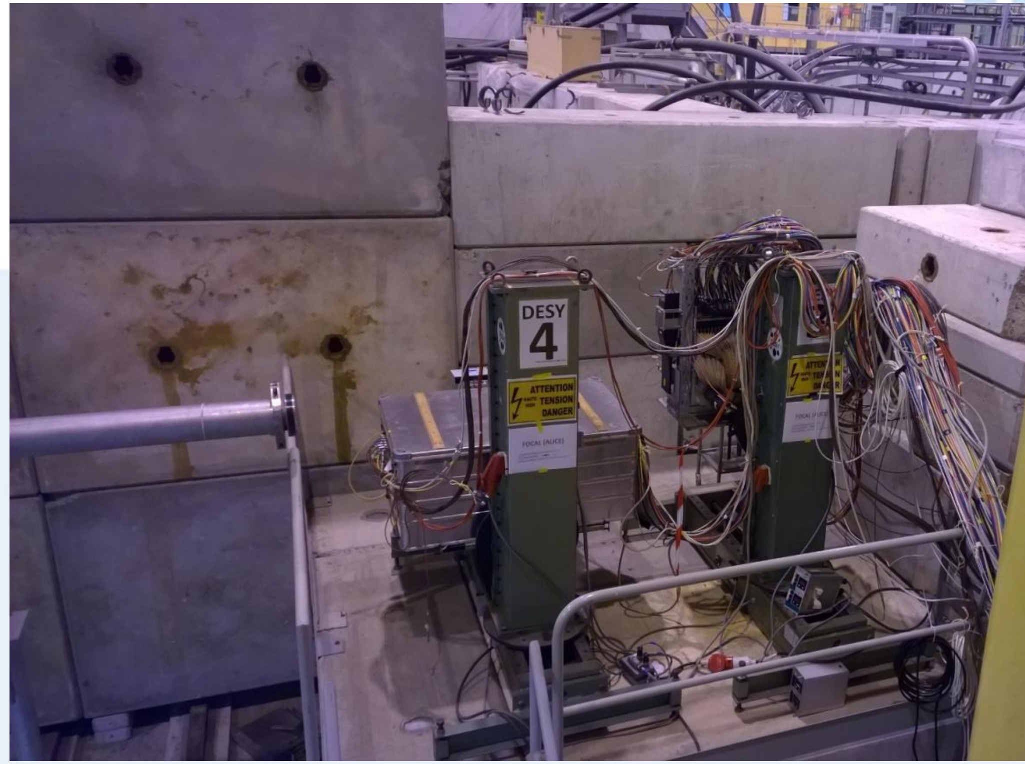
Łukasz Janusz Mączewski

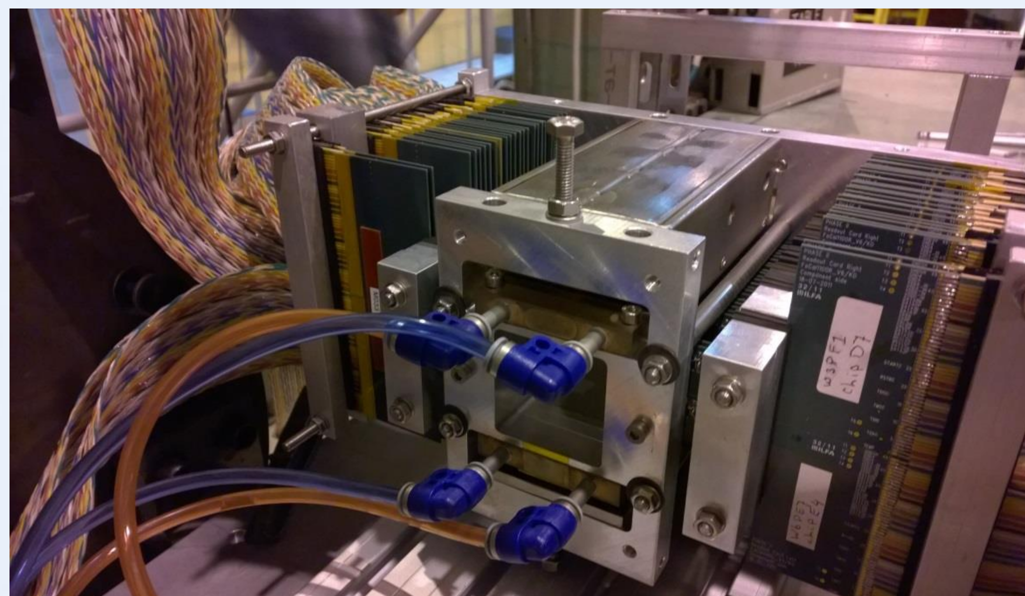




$$\rho(\vec{R})\mathrm{d}r\mathrm{d}\phi = \frac{\mathrm{d}\Omega}{4\pi} \cdot \exp\left(-\frac{|\vec{R}|}{\lambda}\right) = \frac{hr}{4\pi|\vec{R}|^3} \cdot \exp\left(-\frac{|\vec{R}|}{\lambda}\right)\mathrm{d}r\mathrm{d}\phi,$$

Beam tests


DESY
4
ATTENTION
TENSION
DANGER
FOCAL (ALICE)



Beam tests with FoCal

Proton beam tests in December 2014

- At KVI-CART in Groningen, Netherlands
- Aluminum degraded pencil beams with energies 122, 140, 150, 160, 170, 180, 188 MeV
- Proton beam frequency of ~1.35 kHz
  - At most one proton per FOCAL readout (2 kHz)
  - In total 7000 reconstructed proton from 10500 readout frames
  - 5 MB/readout = 24 layers * 4 chips/layer * 640 * 640 pixels
- Raw data demuxed & de-pedestalled on site
- Data converted to (x,y,layer) hitmaps in Utrecht

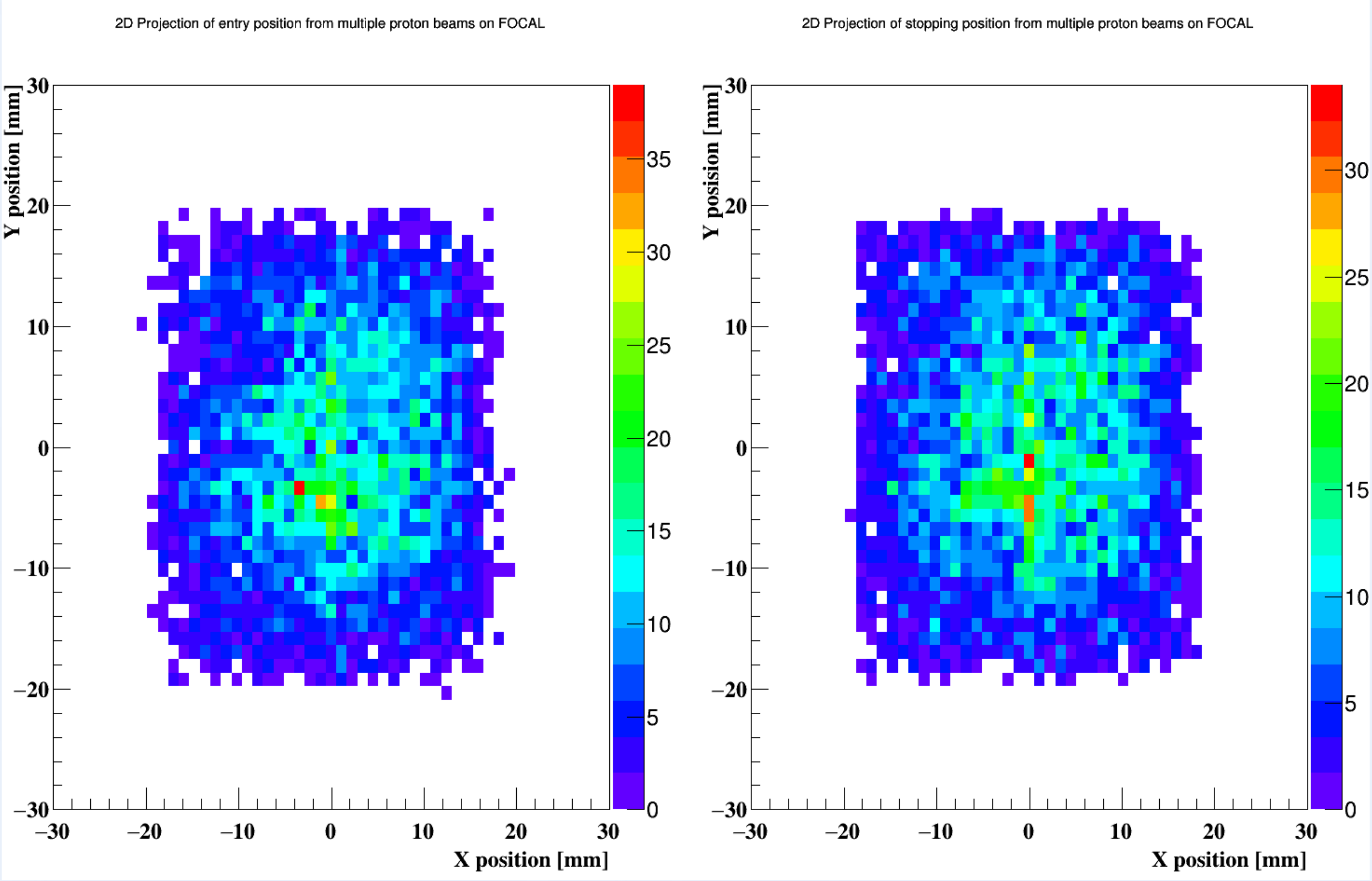
Beam tests with FOCAL

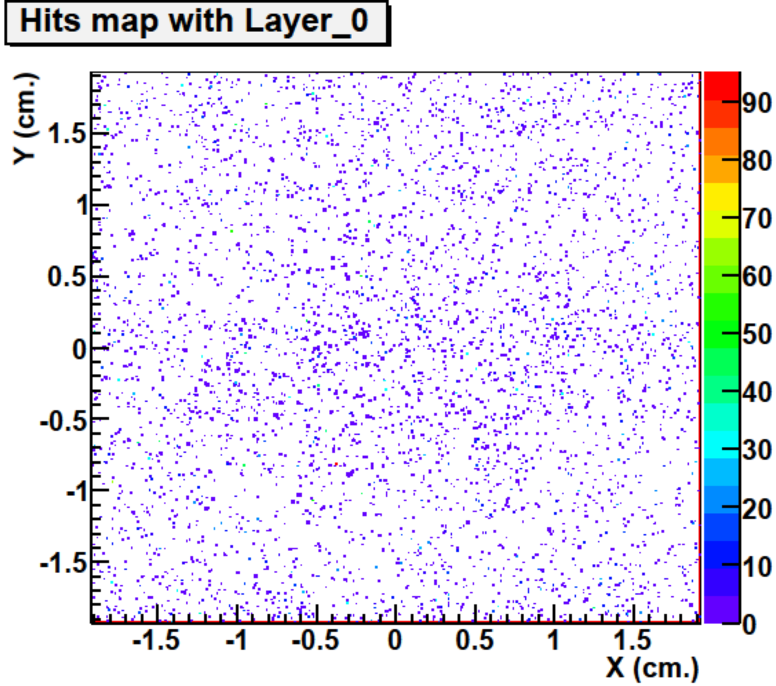
Facility	Particle	Beam Energy (GeV)	Year
DESY	Electron	2, 5	2012
PS/SPS	Mixed beam (e^-, π)	$2 \div 8$ $30 \div 200$	2012
Laboratory	cosmic rays		2013
DESY	Electron	$2 \div 5$	2014
PS/SPS	Mixed beam (e^-, π)	2, 10 30 to 200+	2014

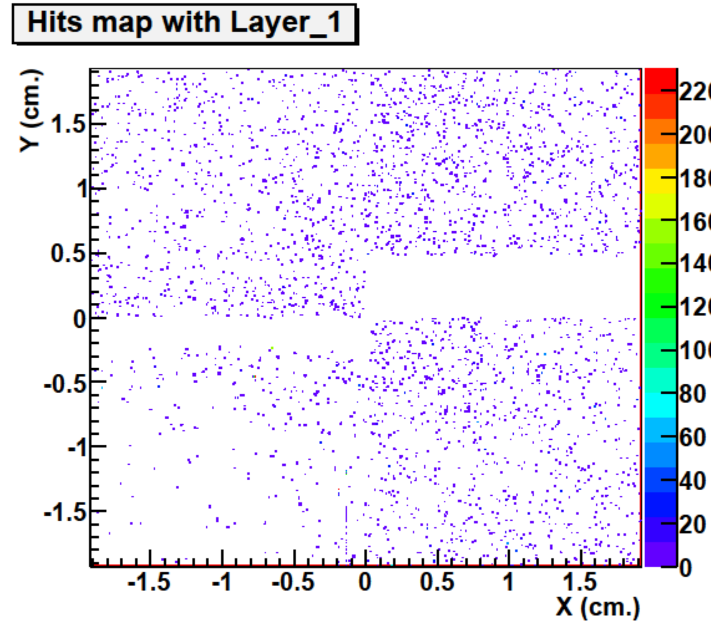
Table 1: Overview of the data taking including the beam test campaigns in 2012 and 2014.

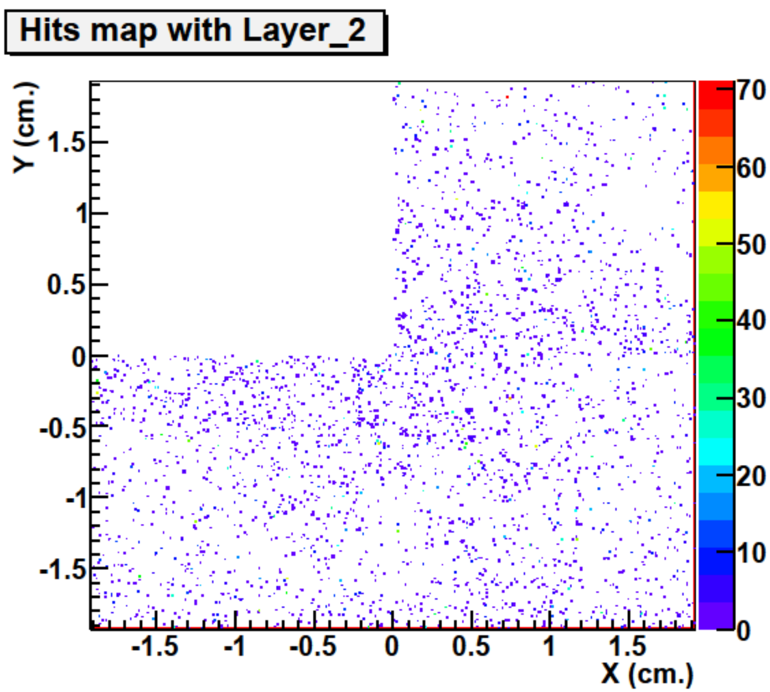
+ Proton beam in Groningen, NL

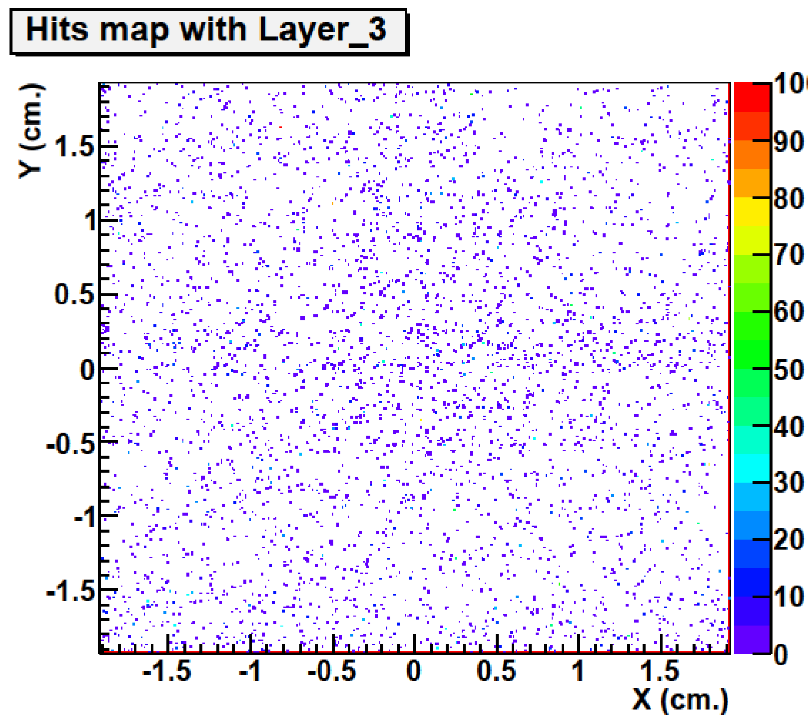
Measured proton positions: Entry and stopping position




Hits map with Layer_0
Y (cm.)
X (cm.)
-1.5 -1 -0.5 0 0.5 1 1.5
0 10 20 30 40 50 60 70 80 90


Hits map with Layer_1
Y (cm.)
X (cm.)
-1.5 -1 -0.5 0 0.5 1 1.5
0 20 40 60 80


Hits map with Layer_2
Y (cm.)
X (cm.)
-1.5 -1 -0.5 0 0.5 1 1.5
0 10 20 30 40 50 60 70


Hits map with Layer_3
Y (cm.)
X (cm.)
-1.5 -1 -0.5 0 0.5 1 1.5
0 10 20 30 40 50 60 70 80 90

Data analysis

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Data analysis

This process is thorougly explained in my 2017 NIMA paper

Nuclear Instruments and Methods in Physics Research A 860 (2017) 51–61

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

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

CrossMark

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Data analysis overview

My thesis work:

- Develop analysis platform
- Benchmark FOCAL detector for pCT
- Optimize design for next prototype

Details:

- GATE / ROOT / C++ / Python
- Monte Carlo + experimental data postprocessing
- Proton track reconstruction INSIDE detector
- Per-pixel energy loss (diffusion and clustering)
- Per-proton energy estimation
- So far: No 3D recon

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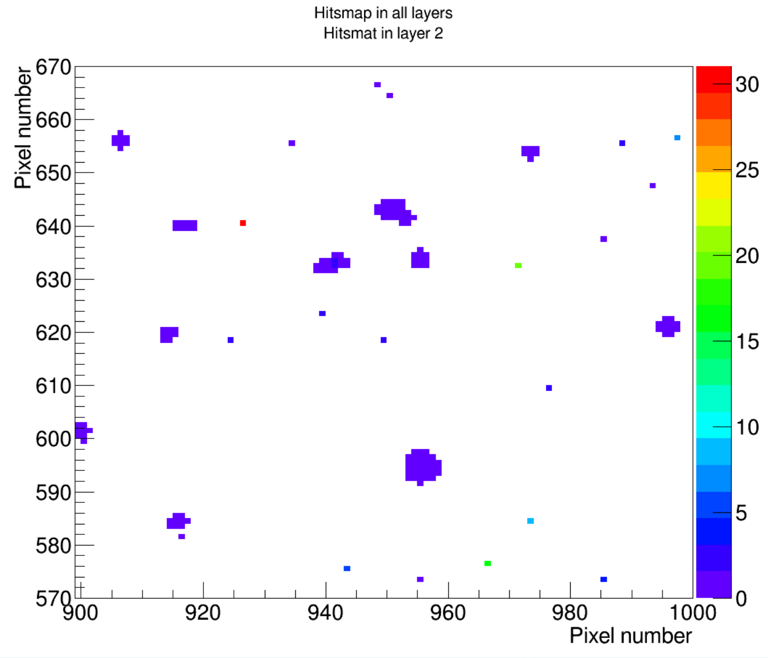
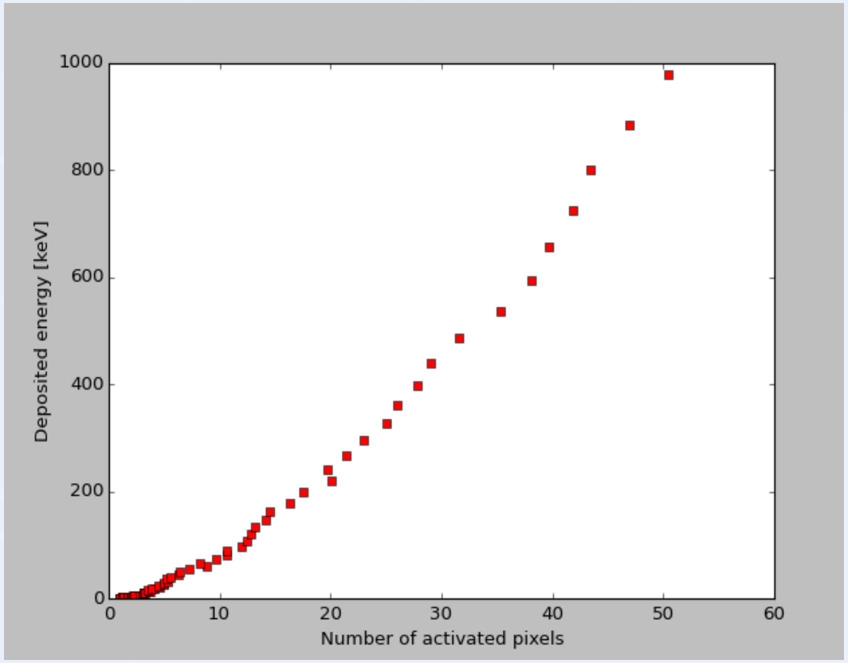
Charge clustering model

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

Proton tracking – Accuracy

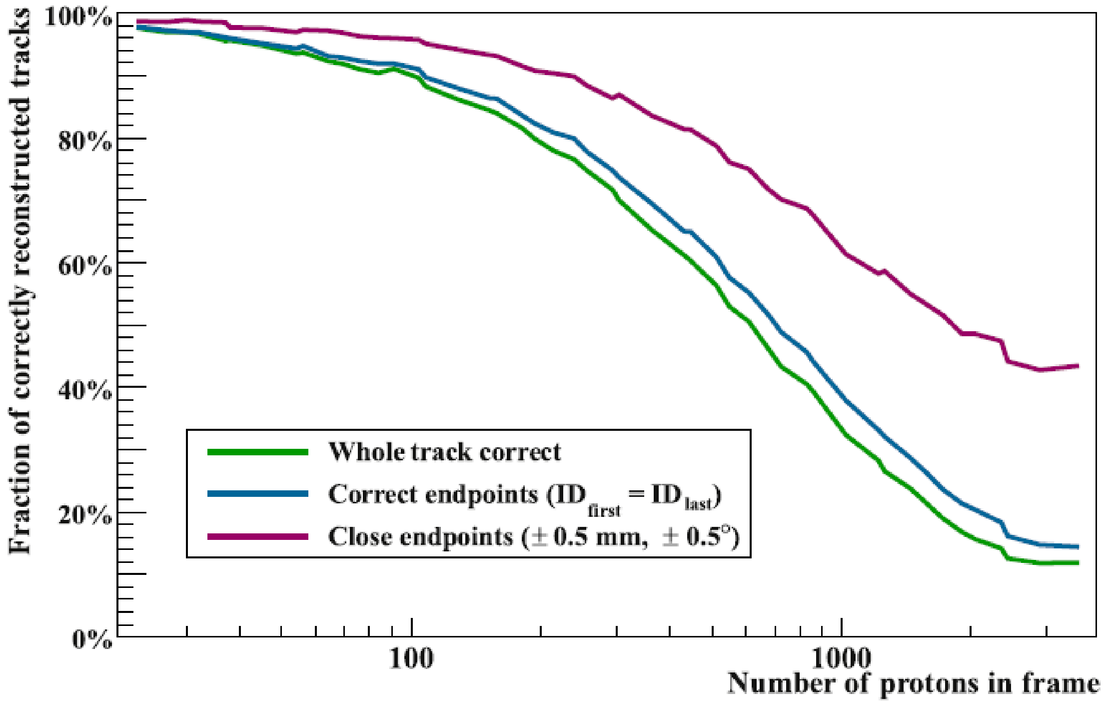
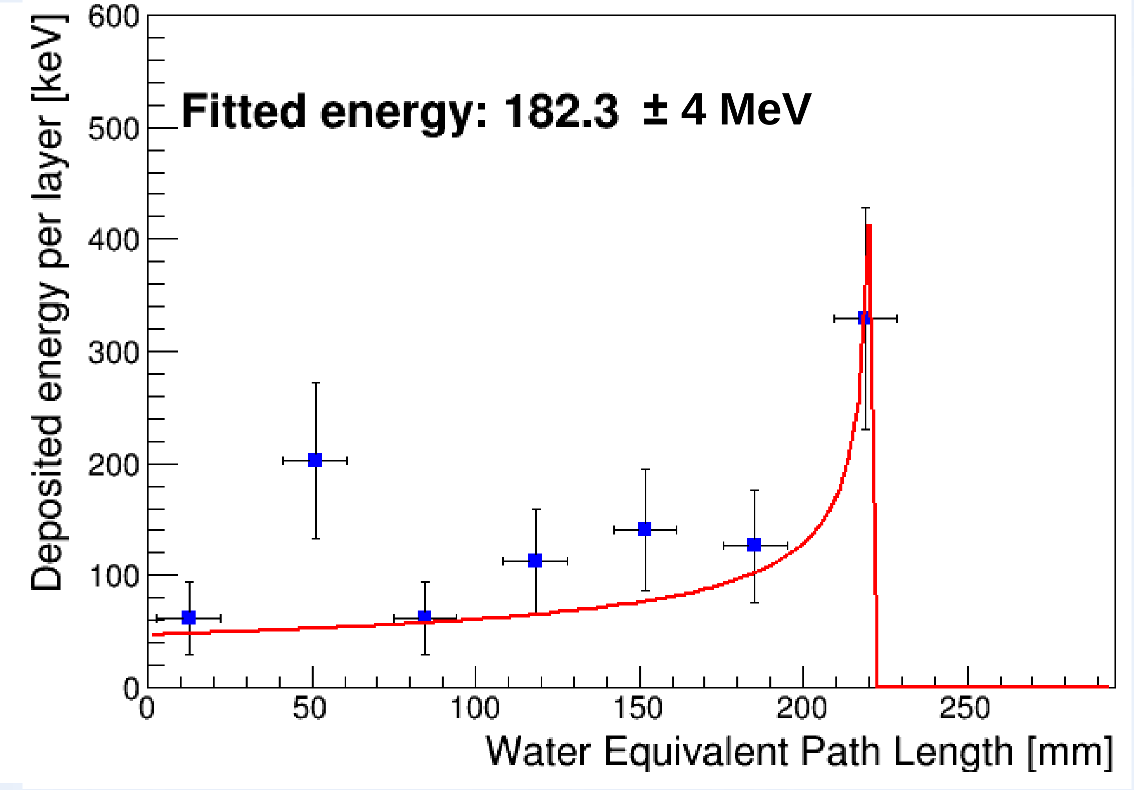


Fig. 8. The fraction of correctly reconstructed tracks, benchmarked using MC simulations. The track consists of one cluster in each layer, each cluster is tagged with an event ID in GATE. The figure shows the portion of tracks which are identified as correctly reconstructed, viz. they originate from the same primary particle. Three curves are shown according to different definitions of a correct track reconstruction, see Section 6.5 for details.

Data analysis

For each proton it's possible to plot proton depth vs E_{dep}

And do model fitting with Bortfeld's Bragg Curve $R = \alpha\, E^{p}$



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

Conclusion

- The Tracking Detector is feasible as a pCT calorimeter
  - Optimized for HEP, not low-energy protons
  - Limited range resolution due to the Tungsten absorber
    - 4% systematic error, 4% stochastic error (cf. 1% range straggling)
    - Systematic error partly due to lack of experimental data and modelling, and to the undersampling of the Bragg Curve
  - Fast readout speed (~1 MHz)
- So how about the next protoype optimized for pCT?

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Next prototype

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Next prototype

- Bergen Proton CT group is a ~6M USD project to build the next-gen tracking detector for pCT
- Based on the ALICE Inner Tracking System's ALPIDE chip:
  - 2D Stackable 3x1.5 cm^2 chips
  - 5-20 µs 1-bit readout w/zero suppression and 3-bit buffer depth
  - ALICE-provided readout electronics + stave geometry stacked to ~13.5x27 cm^2
  - Enough $$ for ~40 layers??
  - Tracker + calorimeter of same design

Next prototype: Chips

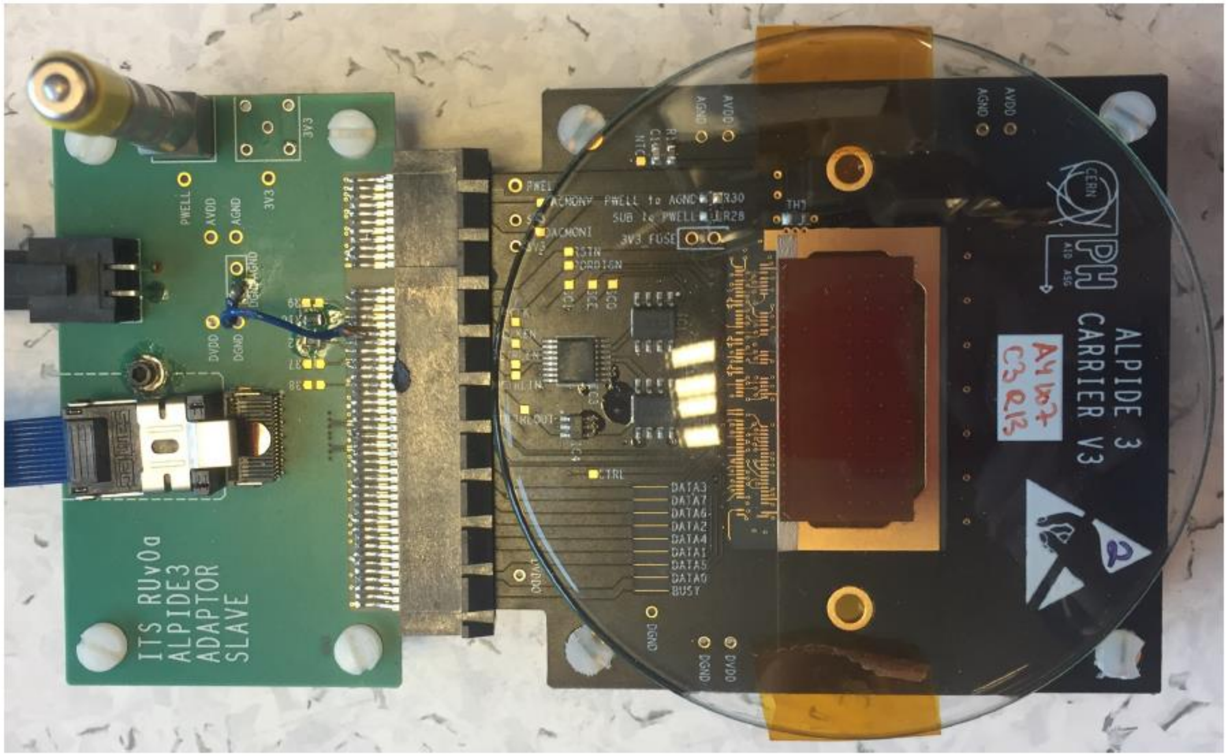
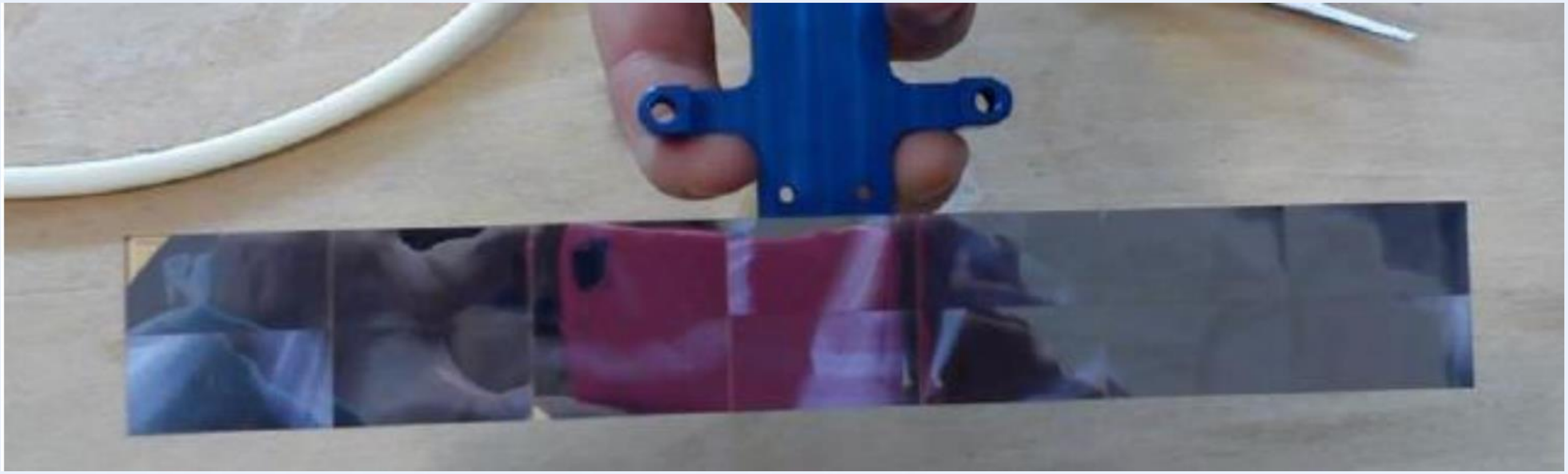


Figure 4.6: On the right: The ALPIDE carrier card. On the left: the ALPIDE adaptor slave.

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

Next prototype: Chips



7x2 chip array -> 3 x 21 cm^2

Next prototype: Electronics

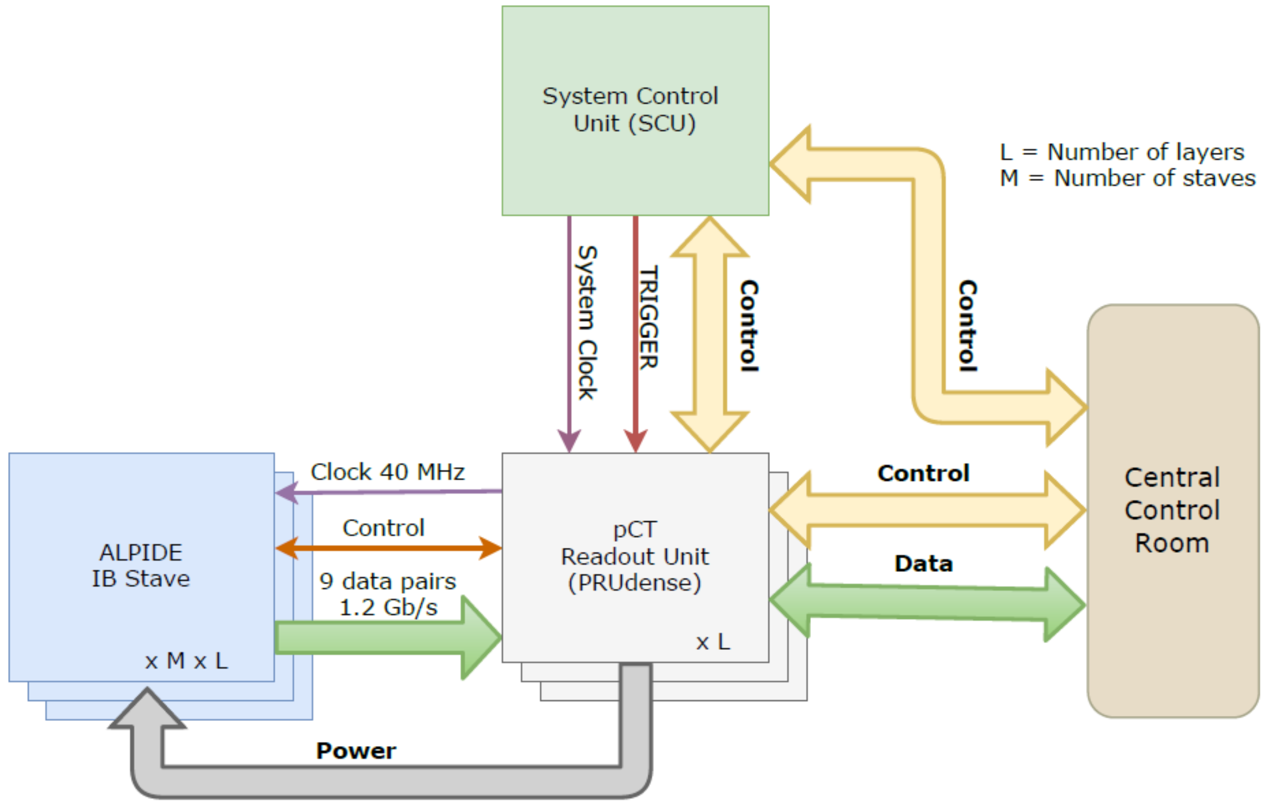
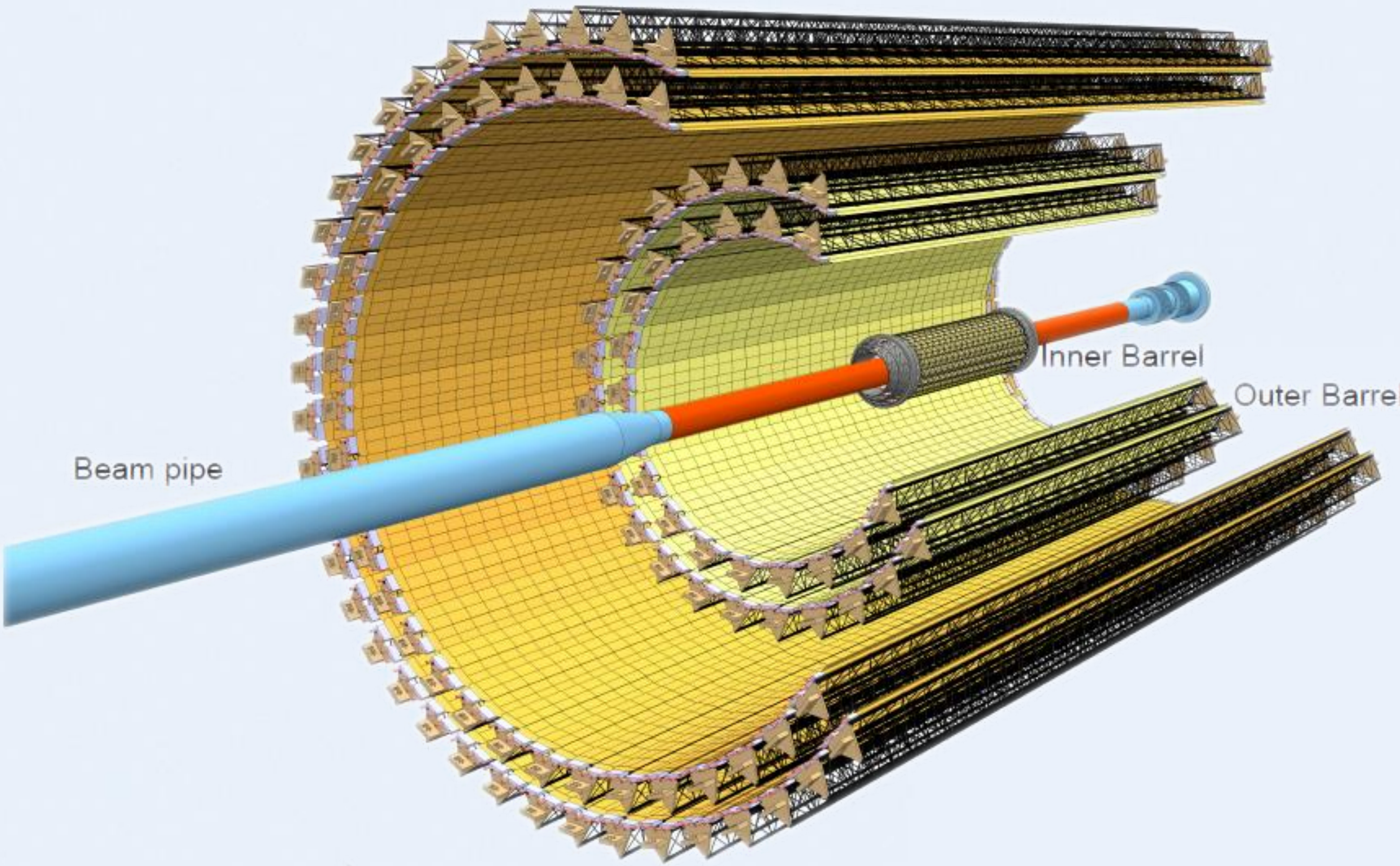


Figure 4.2: Block diagram of the proposed pCT Readout System.

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

Next prototype: Stave design



The ALICE Collaboration, "Technical Design Report for the Upgrade of the Inner Tracking System"

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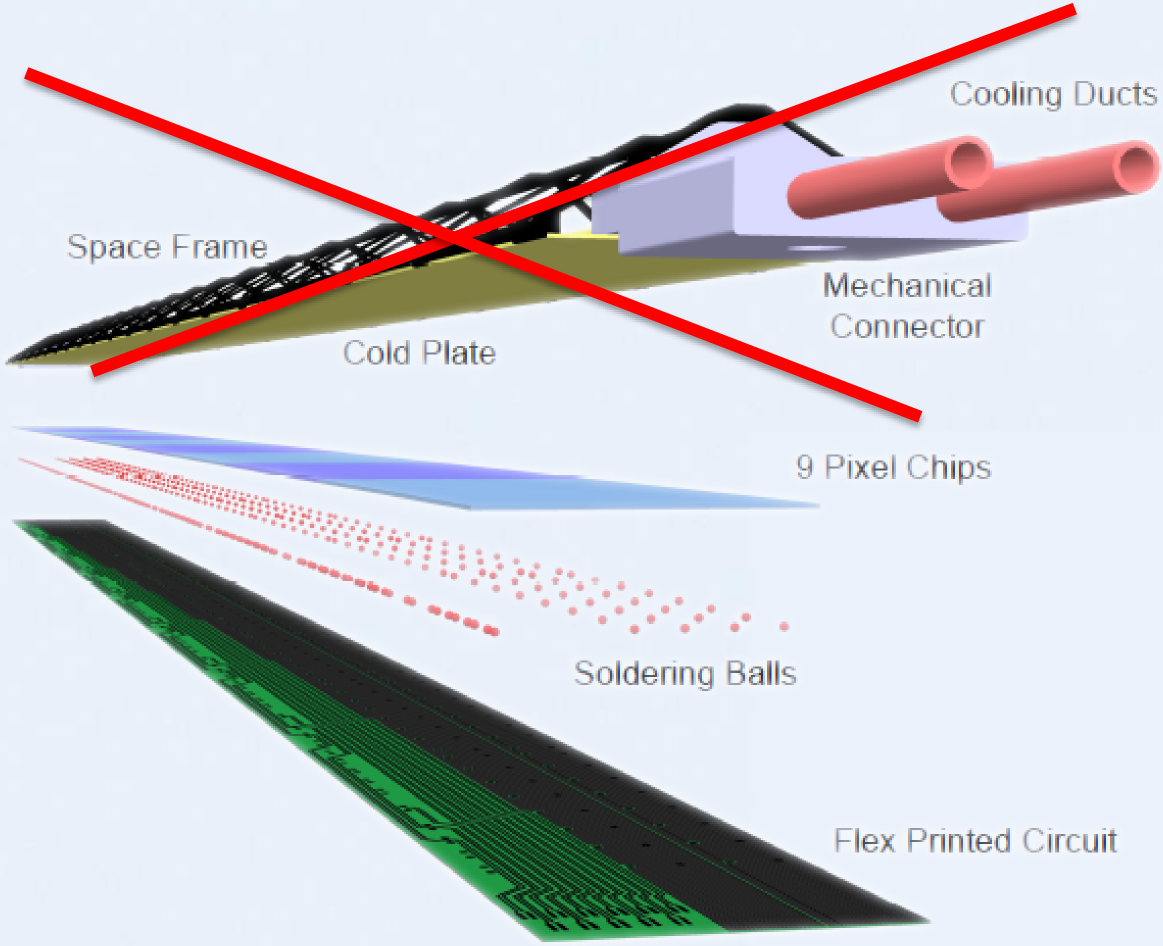
Next prototype: Stave design



[7] L. Musa, “ITS & ITS Upgrade. Pixel Sensor and Detector Module”

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Back-up slides

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Beam test

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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

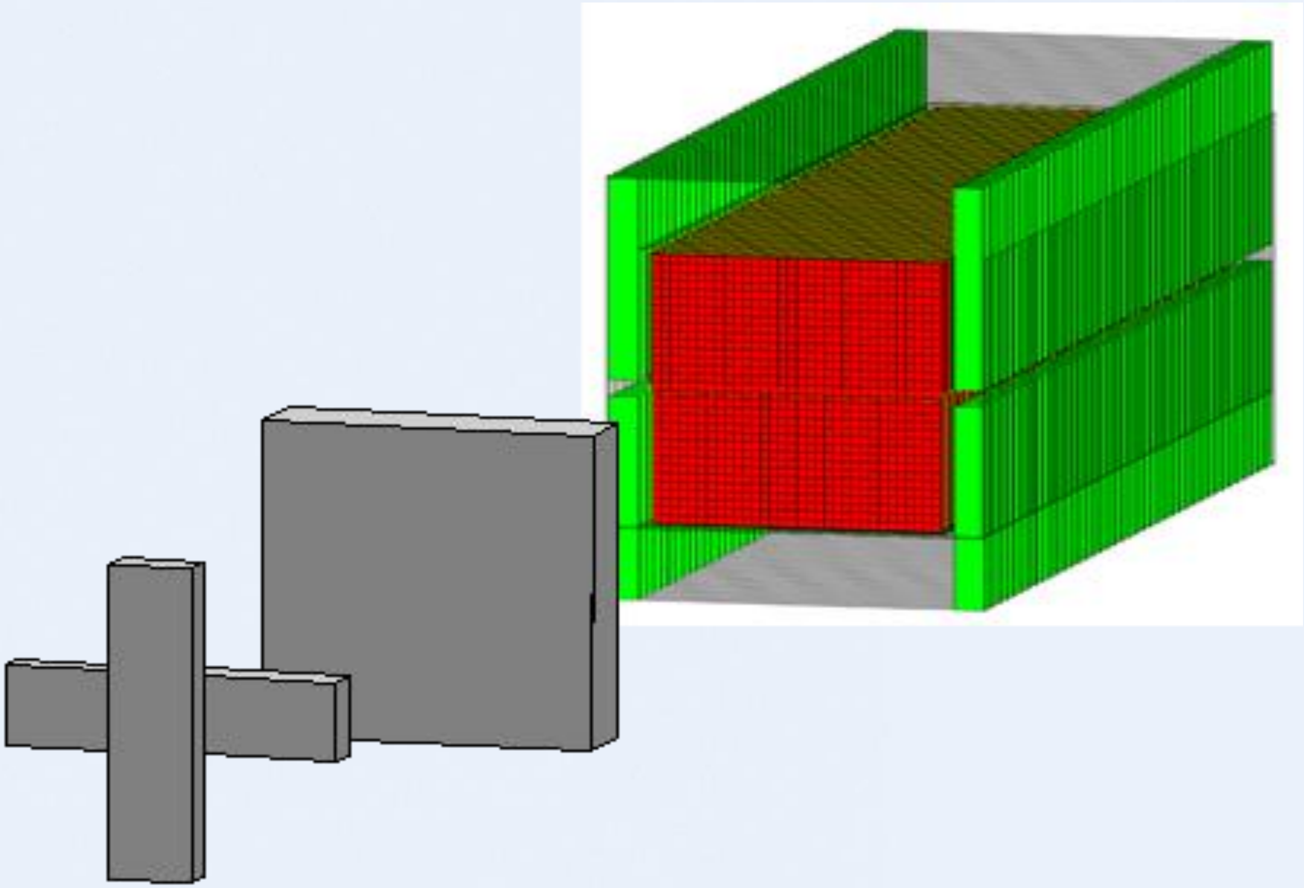
Table 1: *The materials and their key properties, as used in the MC setup. The thicknesses are displayed both in terms of geometric thickness and the corresponding radiation thickness in units of the radiation length* X_0.

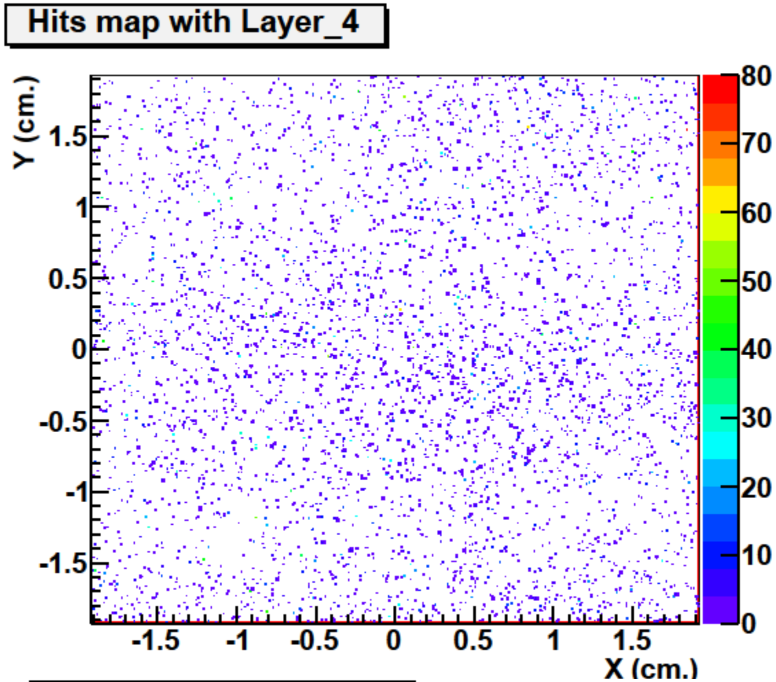
Pettersen, H.E.S. et al. (2017). “Proton Tracking in a High-Granularity Digital Tracking Calorimeter for Proton CT Purposes.” *Nucl. Instrum. And Meth. in Phys. Res.* 860C: 51–61.

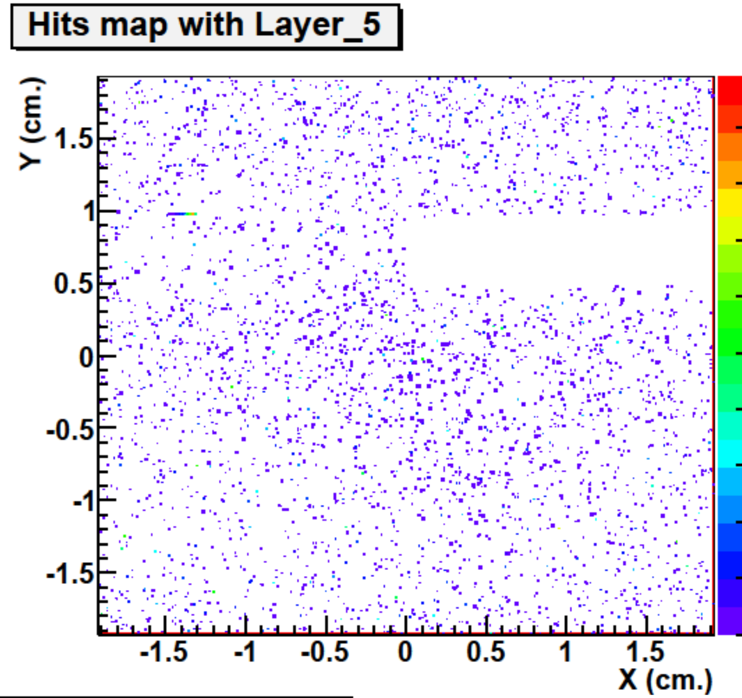
Beam optics

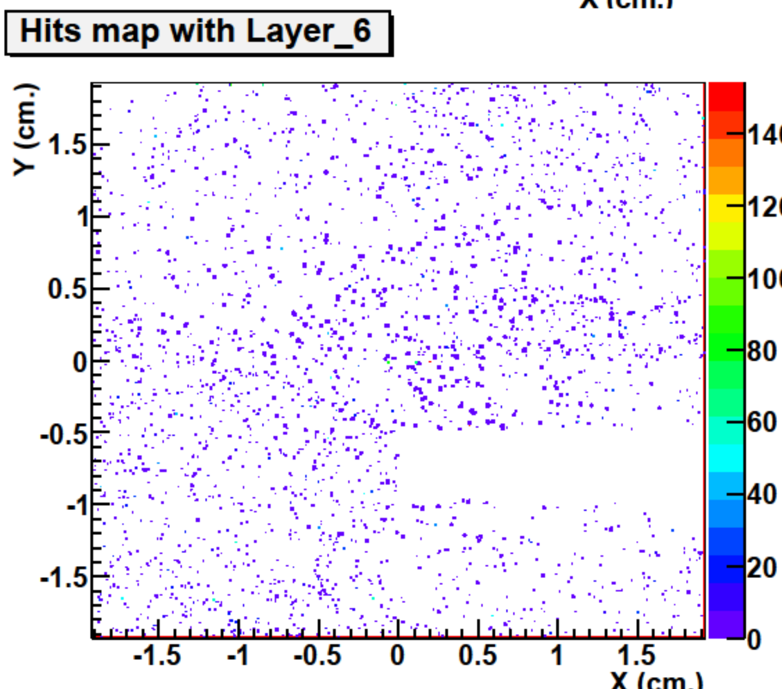
3 Scintillators were used for triggering

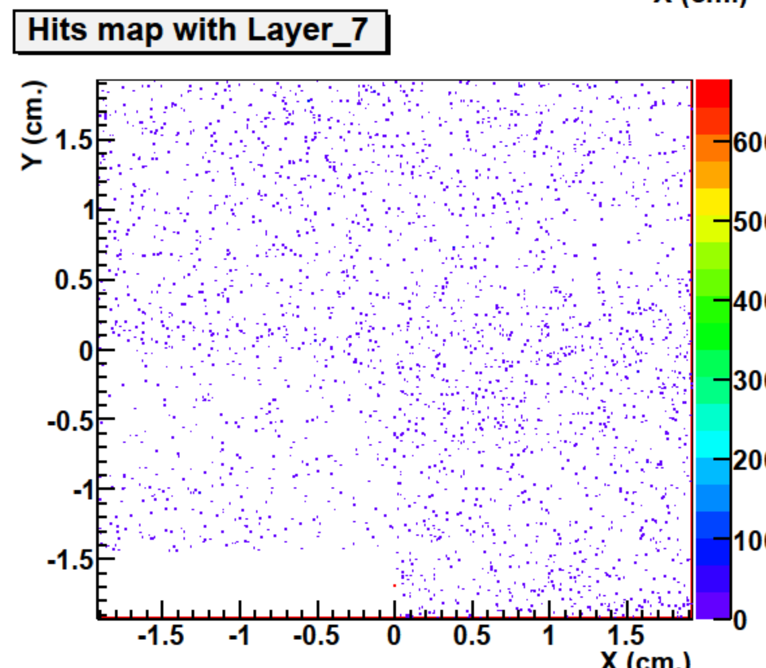
- Horizontal, Vertical, Front











- Last layer with large hit clusters
- After Bragg peak

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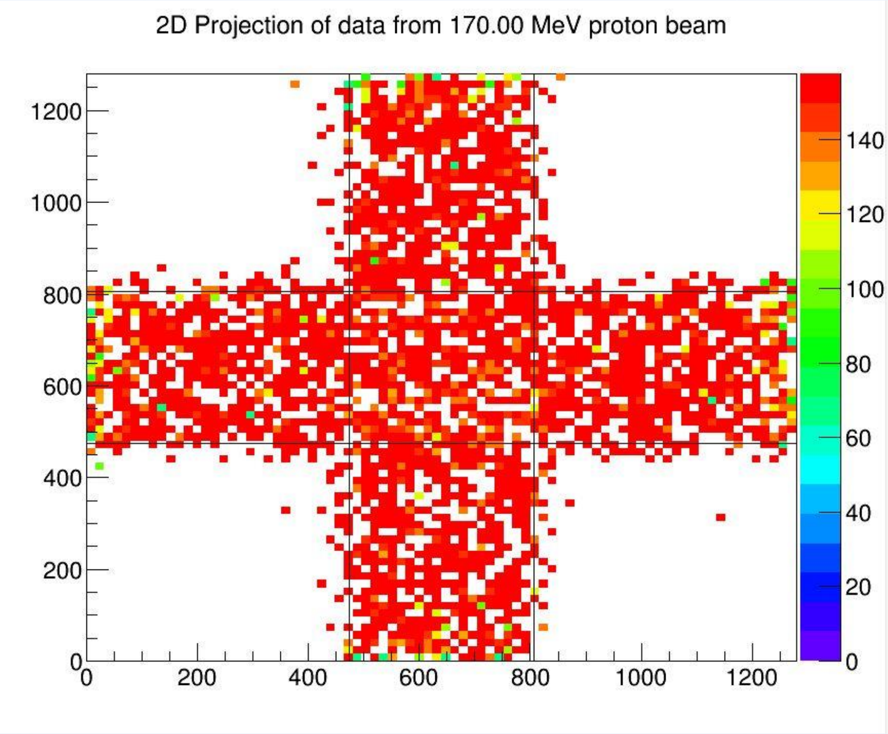
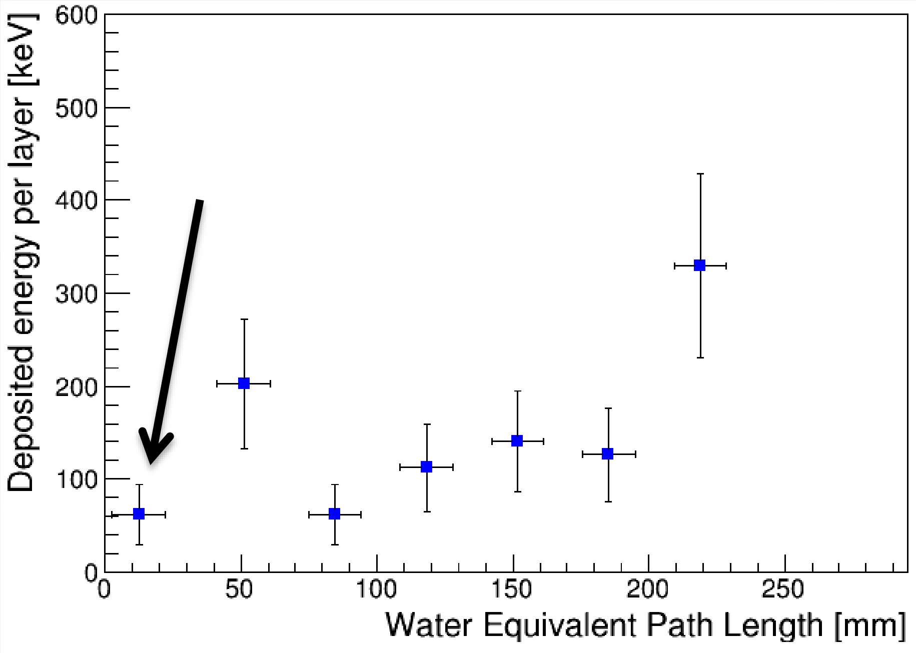
Other corrections performed

- 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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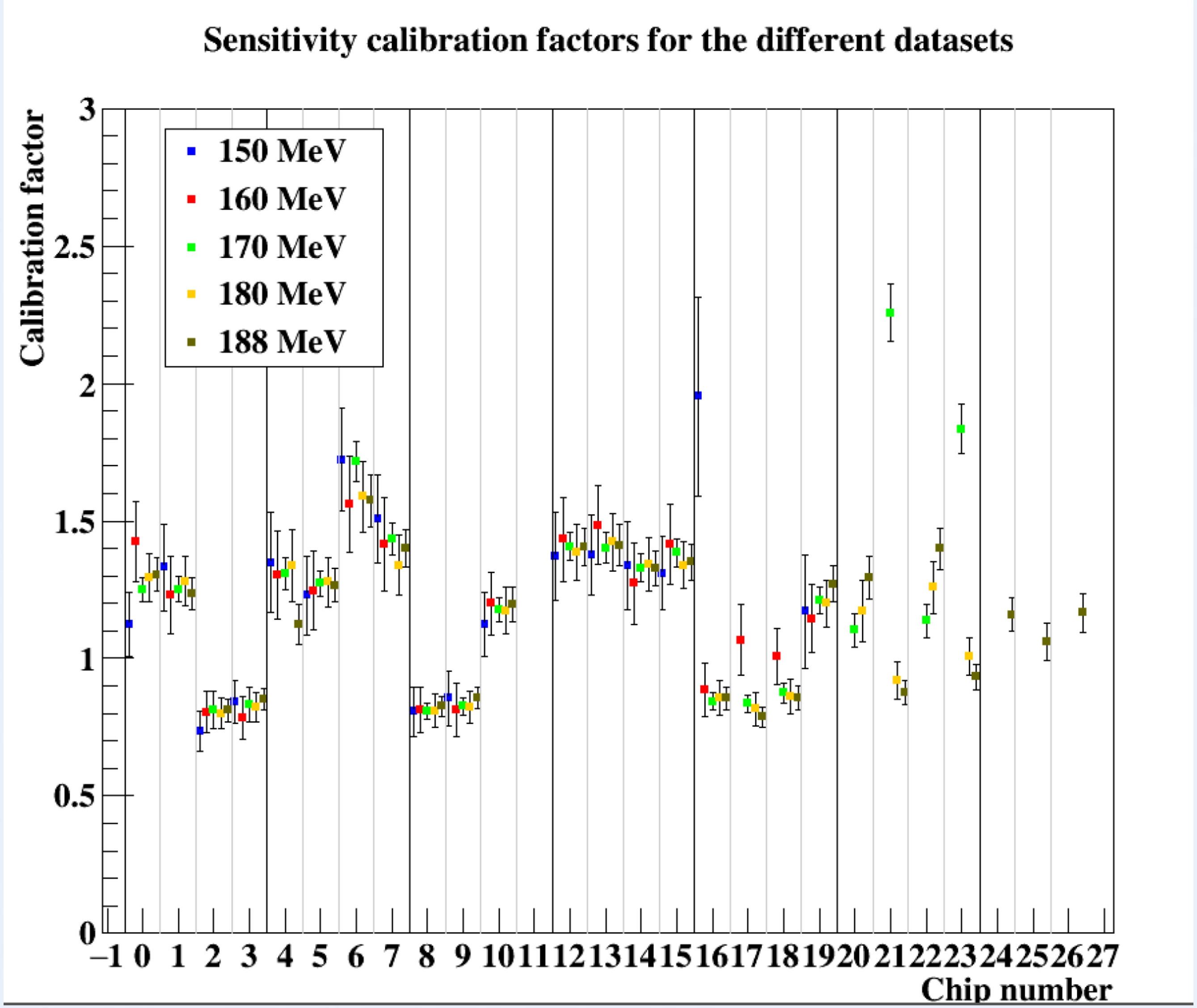
Individual chip calibration



Ongoing projects

Results 2

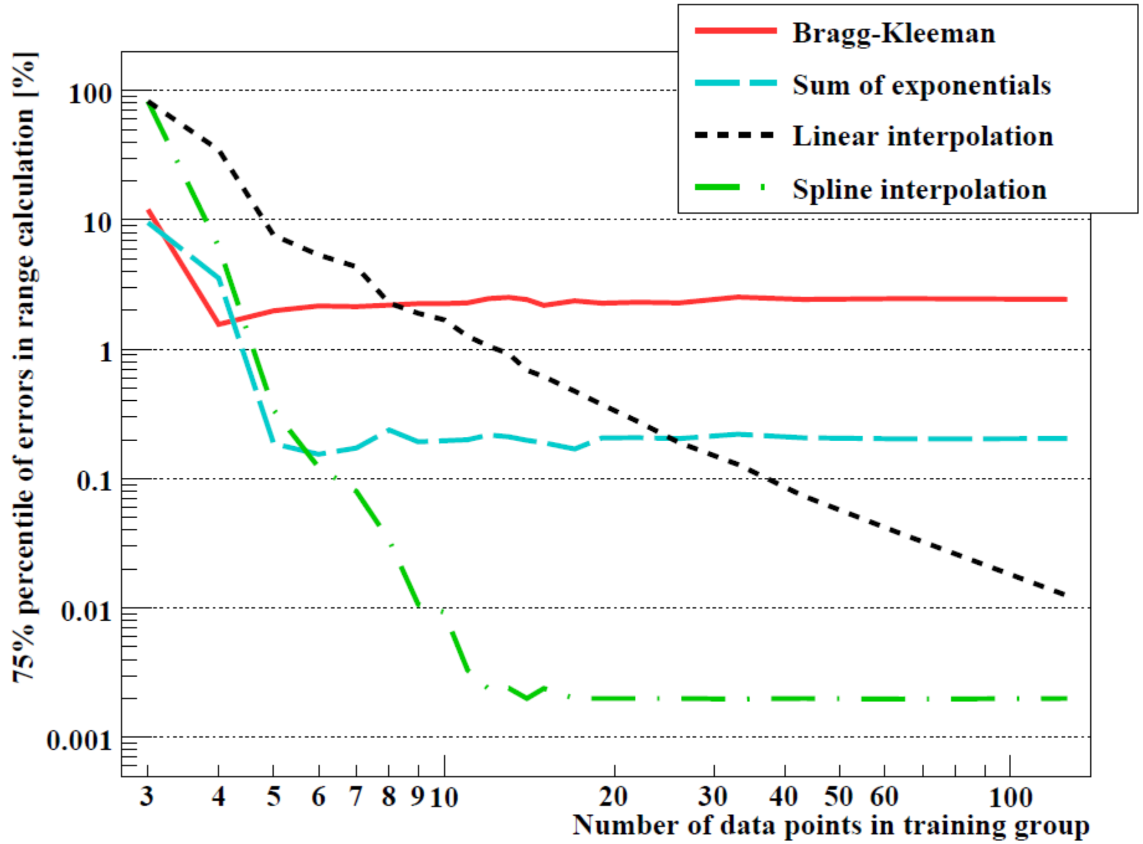


Figure 3: The training stability of the models, as a function of the number of datapoints in the training dataset. The error shown here is the 75% percentile of all the relative errors as shown to the left.

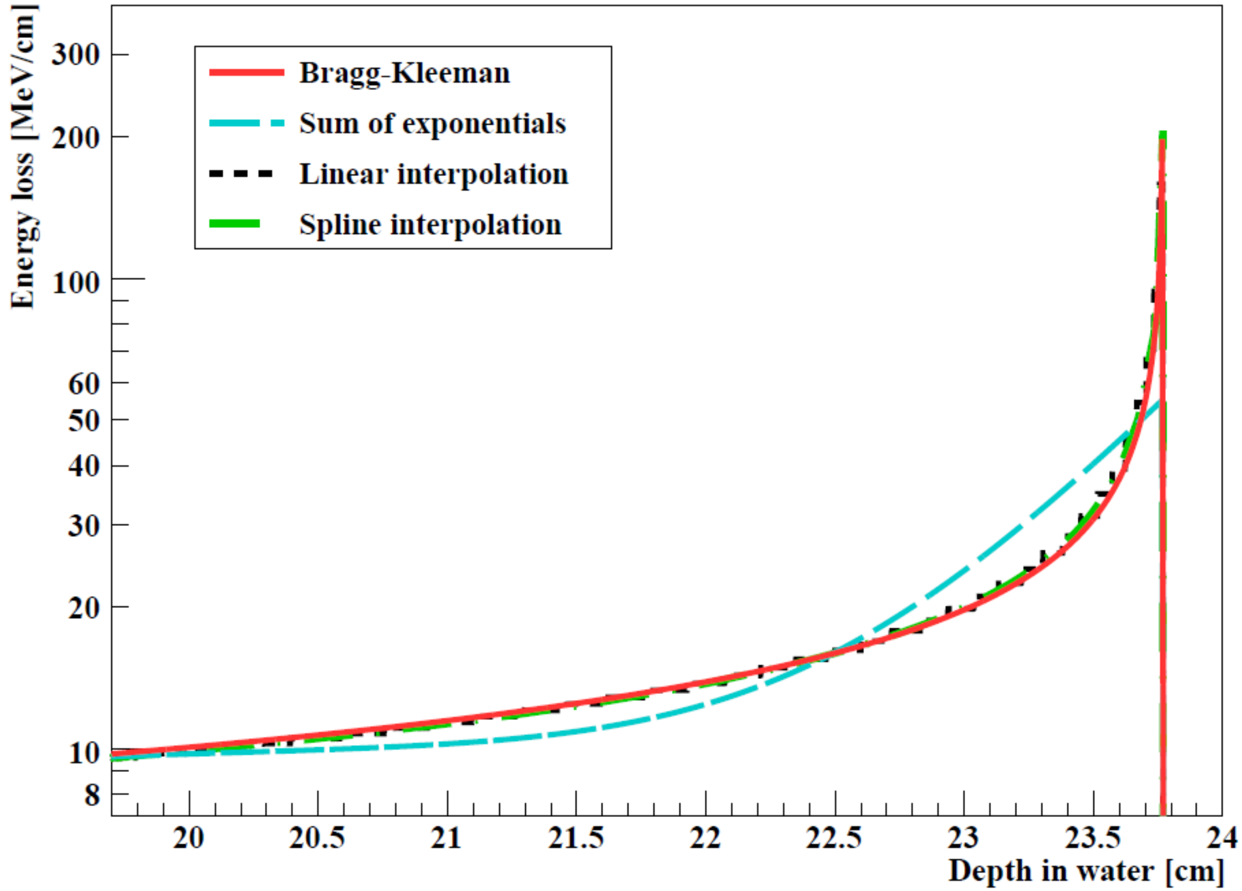


Figure 4: Pristine Bragg curves for individual 190 MeV protons, obtained by differentiating the models made from the cross-validation dataset. The R_0 value is kept constant to simplify the comparison.

Conclusion

The spline interpolation model yields the highest accuracy. A sub-percent range calculation accuracy is obtained for all models above 90 MeV, and for the spline interpolation model above 10 MeV.

A larger number of datapoints are required for an interpolation-based range calculation scheme: 4 measurements is sufficient for the Bragg-Kleeman model, 5 for the sum of exponentials, the spline interpolation converges to a stable error at 12 datapoints, and the linear interpolation does not converge even after 125 data points.

The shape of the Bragg curve and stopping position of individual protons are best represented by using the differentiated Bragg-Kleeman rule in conjunction with spline interpolation.

This work has been submitted to Radiation Physics and Chemistry [4]. Furthermore, the results presented in this work have been applied to the analysis of data from a proton range telescope [5].