The Bergen proton CT project

ELMA Workshop on

Energy Loss Measurements with Monolithic Active Pixel Sensors

Trieste, Italy

10-11 09 2025

Gábor Bíró

biro.gabor@wigner.hun-ren.hu

HUN REN | wigner

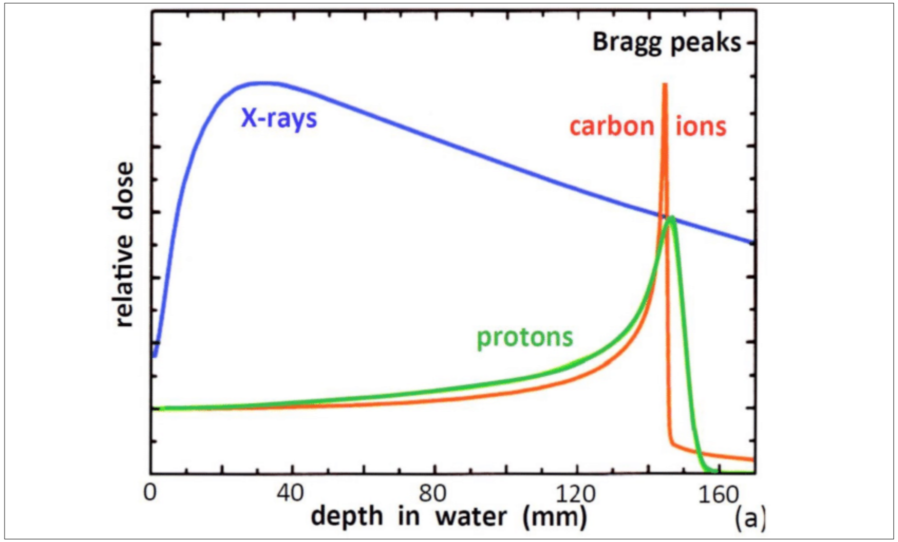
ELTE
EÖTVÖS LORÁND
TUDOMÁNYEGYETEM

The Bergen proton CT Collaboration and the SIVERT research group

- University of Bergen, Norway
- Helse Bergen, Norway
- Western Norway University of Applied Science, Bergen, Norway
- HUN-REN Wigner Research Center for Physics, Budapest, Hungary
- DKFZ, Heidelberg, Germany
- Saint Petersburg State University, Saint Petersburg, Russia
- Utrecht University, Netherlands
- Research and Production Enterprise “LTU”, Kharkiv, Ukraine
- Suranaree University of Technology, Nakhon Ratchasima, Thailand
- China Three Gorges University, Yichang, China
- University of Applied Sciences Worms, Germany
- University of Oslo, Norway
- Eötvös Loránd University, Budapest, Hungary
- Technical University TU Kaiserslautern, Germany

Particle therapy - the Bragg peak position

- Cancer treatment: surgery, chemotherapy, radiotherapy, immunotherapy
  - Effective eradication of all tumor cells vs. avoid injury to healthy tissue
- Key advantage of ions: Bragg peak
  - Relatively low dose in the entrance channel
  - Sharp distal fall-off of dose deposition (<mm)
- Challenge(s): Stopping power of tissue in front of the tumor has to be known
  - crucial input into the dose plan for the treatment
  - Bethe-Bloch formula:

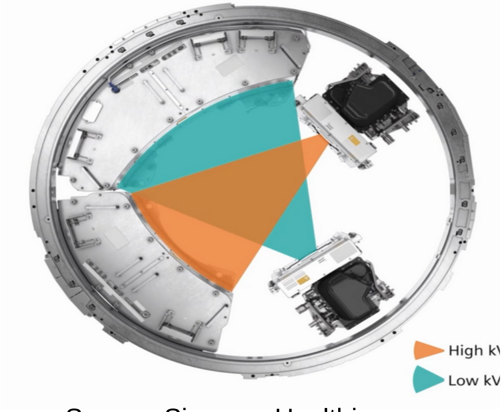


$$-\frac{\mathrm{d}E}{\mathrm{d}x} \propto (\text{electron density}) \times \ln \frac{\text{max. energy transfer in single collision}}{\text{effective ionization potential}}$$

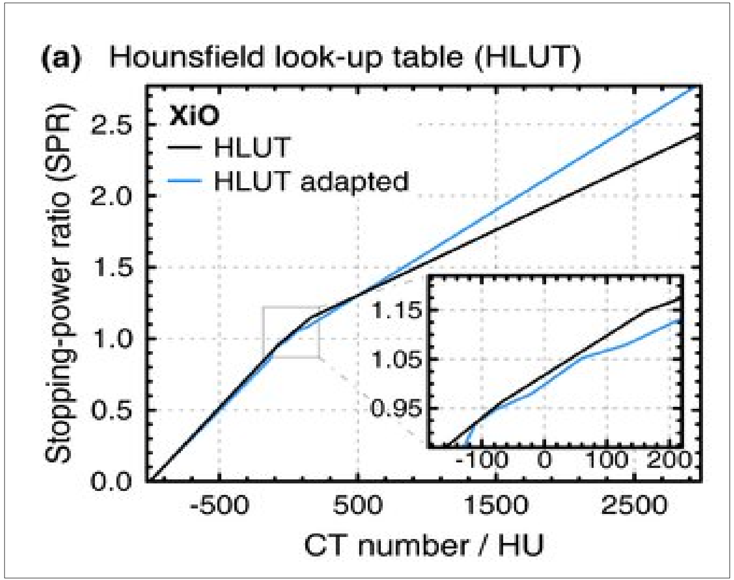
- Current practice: derive stopping power from X-ray CT
- Problem: X-ray attenuation in tissue depends not only on the density, but also strongly on Z (Z^5 for photoelectric effect) and X-ray energy

Stopping power calculation from X-ray CT

- How to deal with range uncertainties in the clinical routine?
  - Increase the target volume by up to 1 cm in the beam direction
  - Avoid beam directions with a critical organ behind the tumor
- Clinical practice: stopping power calculation derived from single energy CT: up to **7.4 %** uncertainty
- Estimates for advanced dose planning:
  - Dual energy CT: up to 1.7 % uncertainty
  - **Proton CT: up to 0.3 % uncertainty**
- Further advantages of proton CT:
  - no positioning/registration uncertainties
  - low dose → frequent imaging → adaptive treatment



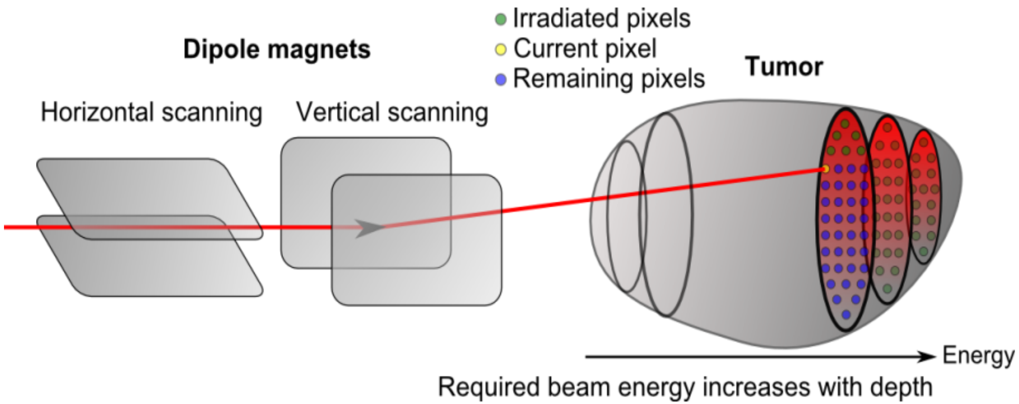
Source: Siemens Healthineers

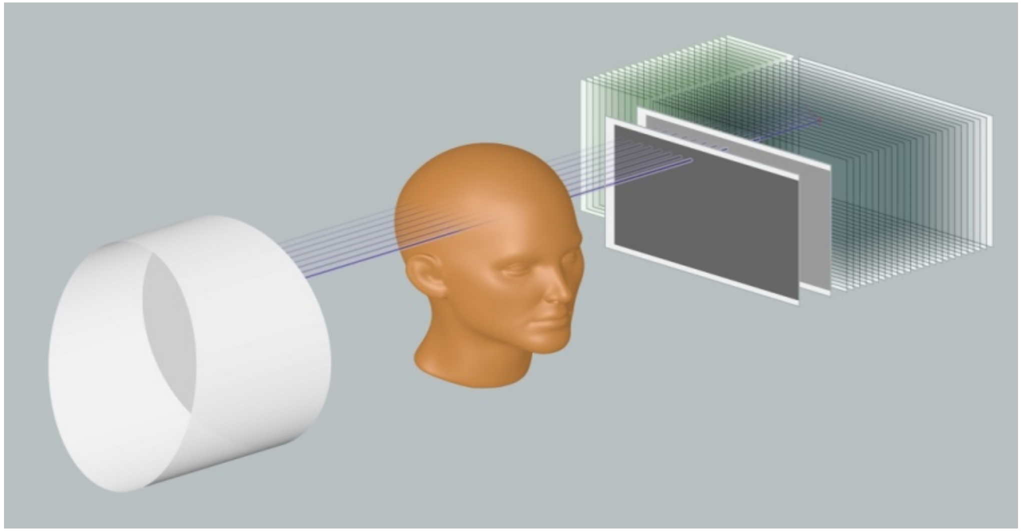


Wohlfahrt et al.(2020). Refinement of the Hounsfield look-up table by retrospective application of patient-specific direct proton stopping-power prediction from dual-energy CT. Medical Physics. 47. 10.1002/mp.14085.

Clinical proton CT - requirements

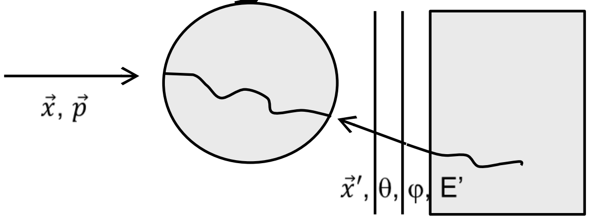
- Pencil beam scanning mode
  - Beam spot size, scanning speed, intensity
- Scanning time: seconds - minutes
- Detector:
  - Efficient simultaneous tracking of large particle multiplicities
  - Large area (~30 x 30 cm^2)
  - Radiation hardness
  - Front detector (first 2-3 layers):
    - high position resolution (~10 μm)
    - very low mass, thin sensors (~100 μm)
  - Back detector:
    - range resolution <1% of path-length
- System:
  - Compact
  - No gas, no HV
  - Simple air/water cooling

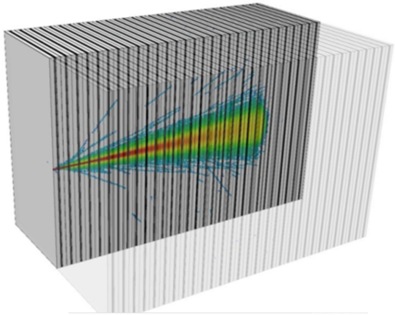


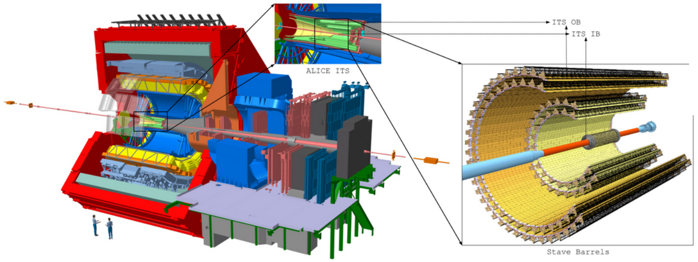


Bergen proton CT - Sensor layers with MAPS

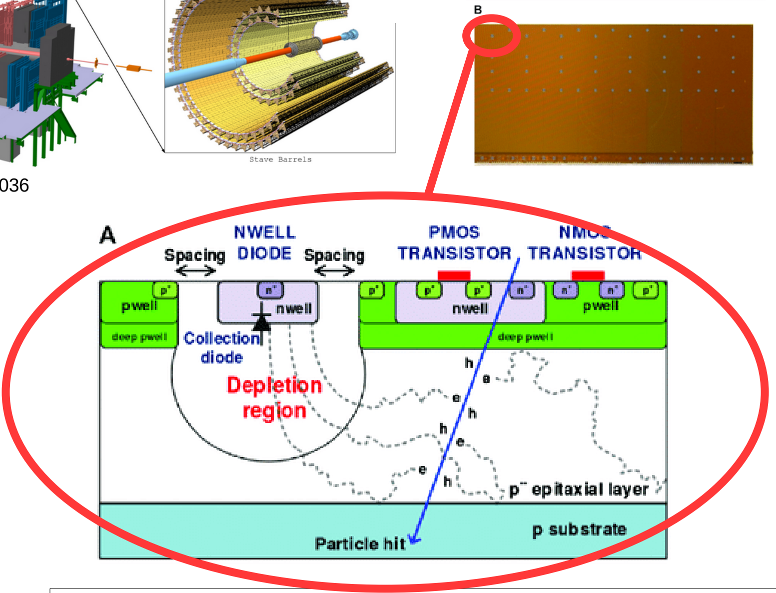
- Conceptual design: highly granular digital calorimeter for tracking, range and energy loss measurement
- Technical design: planes of CMOS sensors - Monolithic Active Pixel Sensors (MAPS) with digital readout - as active layers in a sampling calorimeter
- ALPIDE chip:
  - sensor for the upgrade of the inner tracking system of the ALICE experiment at CERN
  - chip size ≈ 3 × 1.5 cm^2
  - 1024 × 512 pixels
  - pixel size ≈ 29 × 27 μm^2
  - epitaxial layer = 25 μm
  - integration time ≈ 4 μs
  - pixel threshold: 92 e$^-$

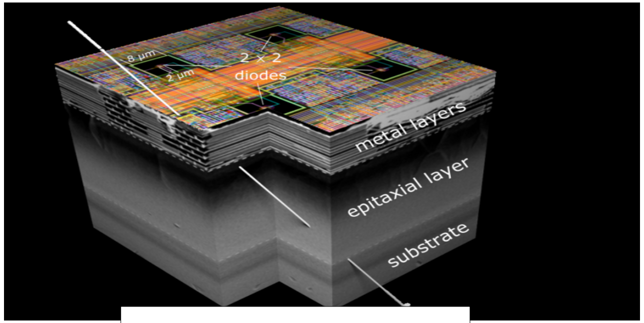






JINST 17, 04 (2022) pp.C04036



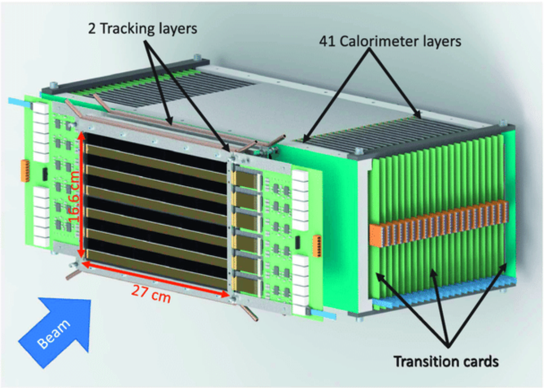


M. Mager, IFEE 2014

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

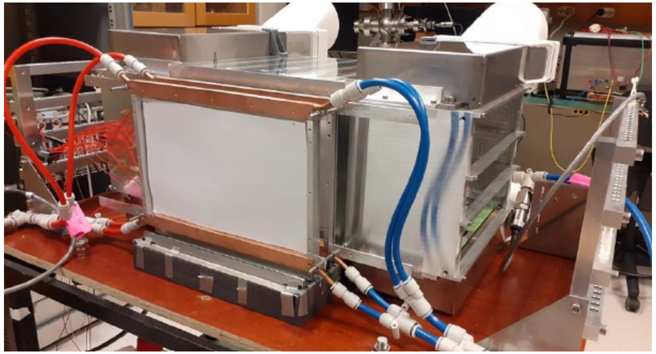
Bergen proton CT - Sensor layers with MAPS

- Geometry:
  - front area: 27 cm × 18 cm (108 ALPIDE/layer)
- ”sandwich” calorimeter
  - alternating layers of absorbers and sensors
  - longitudinal segmentation: 41+2 sensor+absorber layers
  - ~5µm track position resolution
  - ~100 tracks per readout frame
- aluminium absorbers
  - energy degrader, mechanical carrier, cooling medium
  - thickness: 3.5 mm



J Alme, et al. (2020) Frontiers in Physics. 8(460)

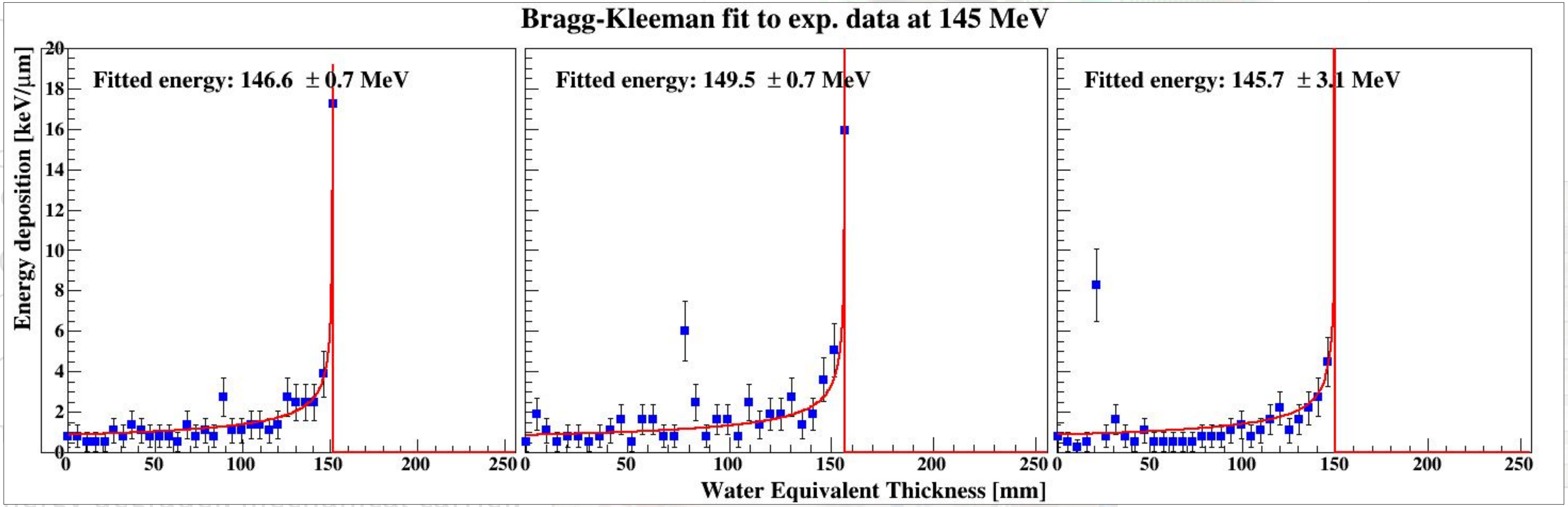
Design and production: LTU, Kharkiv, Ukraine



Mechanical integration and cooling, Utrecht University & University of Bergen

Bergen proton CT - Sensor layers with MAPS

- Geometry:
  - front area: 27 cm × 18 cm (108 ALPIDE/layer)
- ”sa
  - a
  - lo
    s
  - 1
    i
  - ~
- alu
  - energy degrader, mechanical carrier, cooling medium
  - thickness: 3.5 mm

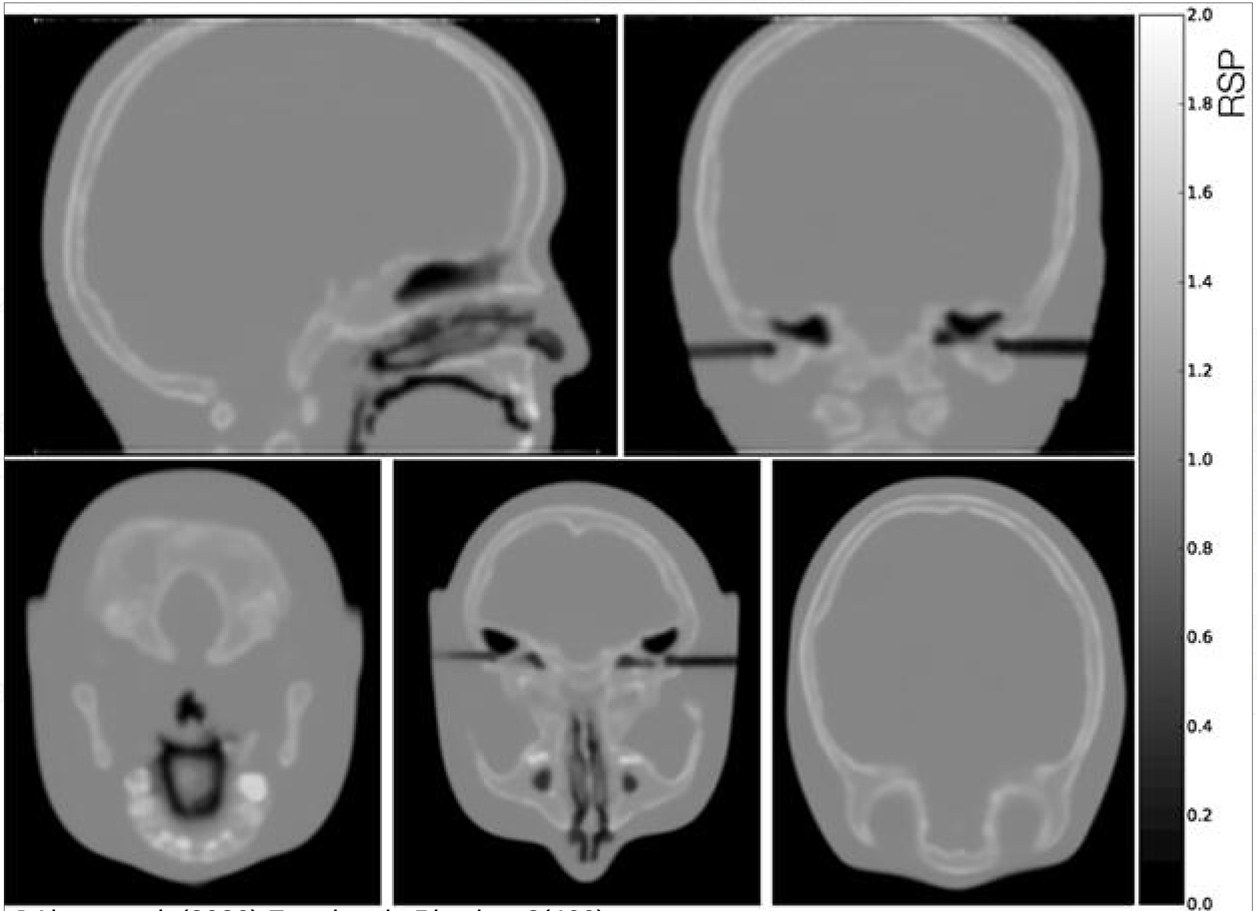


Design and production: LTU, Kharkiv, Ukraine

Mechanical integration and cooling, Utrecht University & University of Bergen

Bergen proton CT - Sensor layers with MAPS

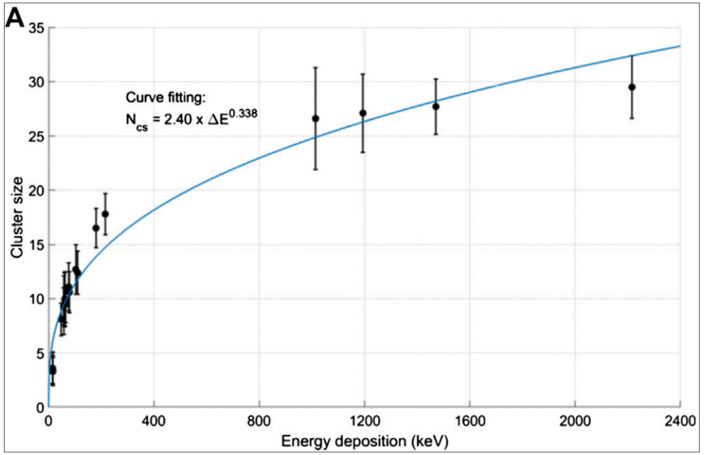
- 230 MeV
- 360 projections, 1° steps
- 3.5 x 10^6 protons per projection
- 7.9 x 10^8 protons for 3D reconstruction

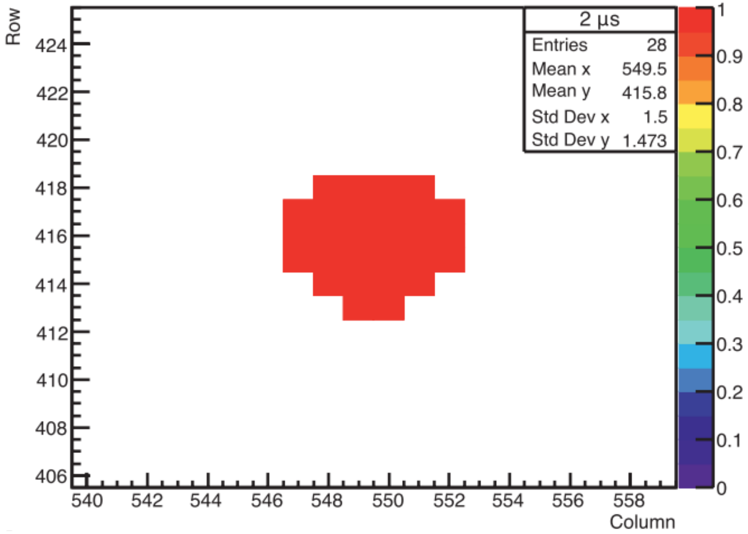


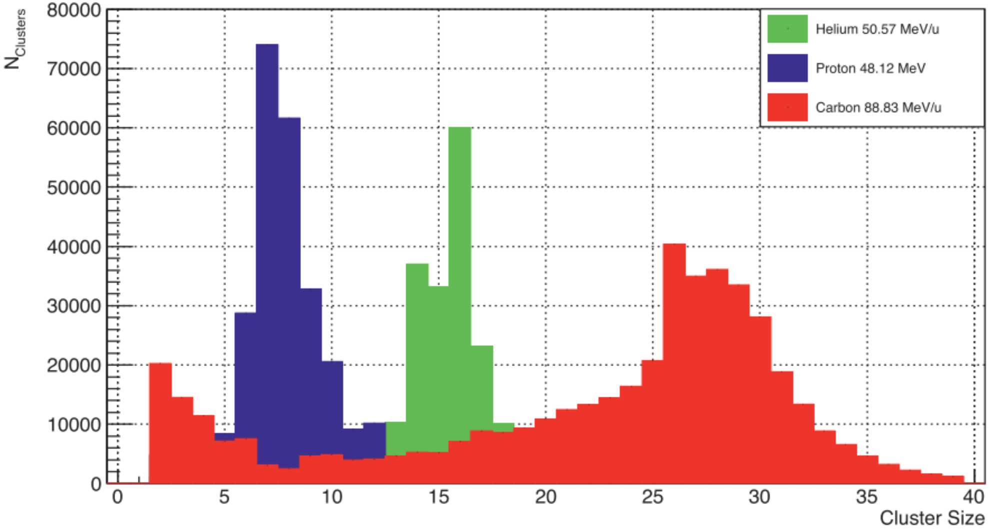
J Alme, et al. (2020) Frontiers in Physics. 8(460)

Energy loss measurements with a digital pixel sensor

- DTC: a sampling calorimeter, designed to estimate the residual range (WEPL) of protons up to 230 MeV by sampling the energy deposition along its path until it is completely stopped by the absorbers between the sensitive layers
    - Operate ALPIDE in ”charge collection by diffusion mode”
- Measure size of charge cluster
    - Cluster size increases with energy loss



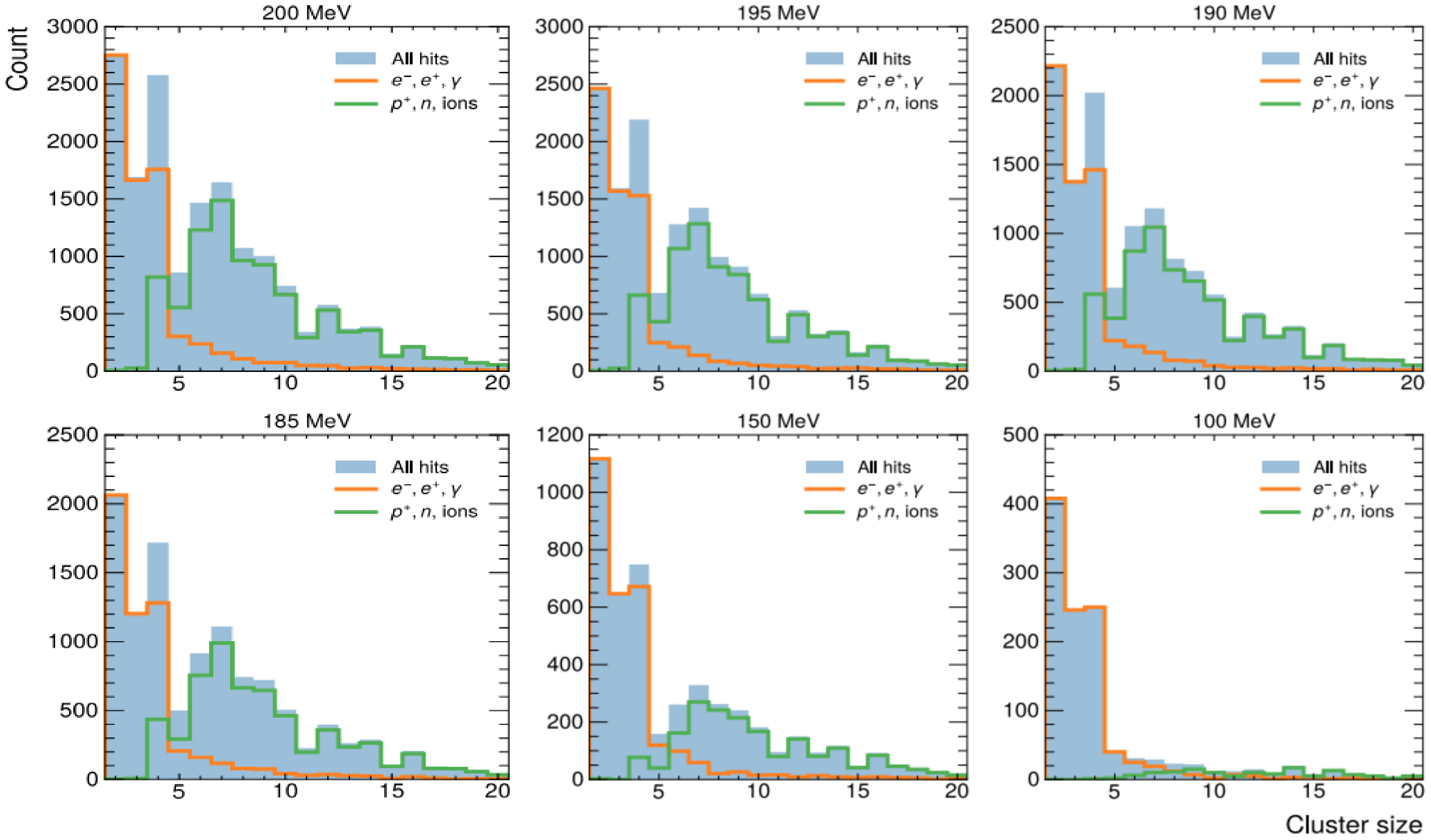




J Alme, et al. (2020). Frontiers in Physics, 8 (460)

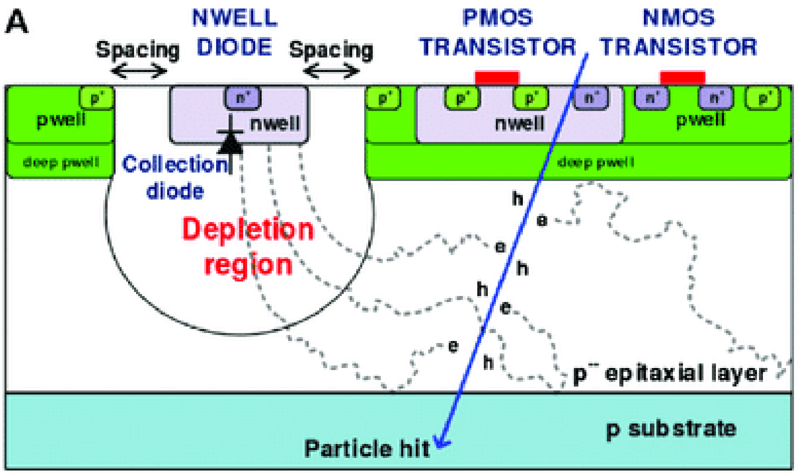
Online dose delivery monitoring - secondaries

- pCT as an imaging calorimeter detects all secondaries
  - charged particles, photons and neutrons
- Correlation: number of detected secondaries (charge clusters) <-> proton range inside the phantom
- gamma/neutron ratio depends on target/absorber ratio (i.e. Bragg peak position)



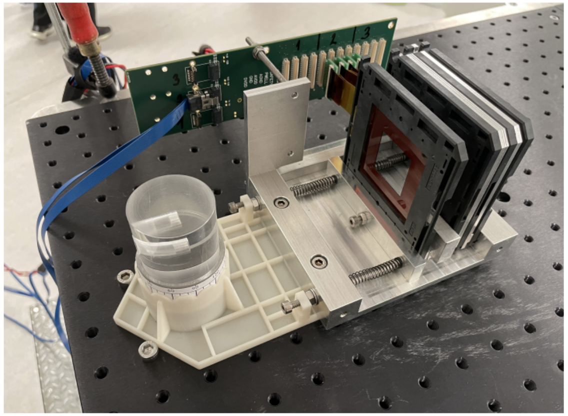
Charge Diffusion Models

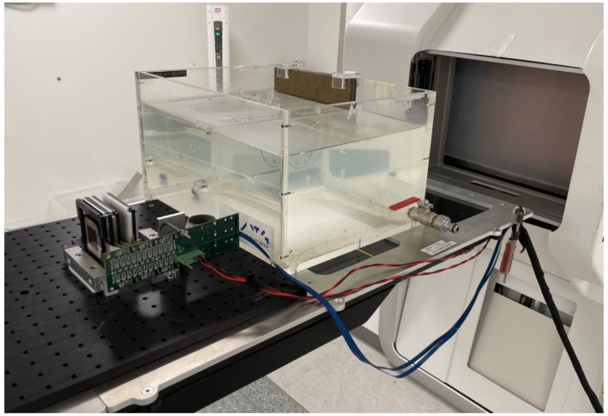
- Energy deposition = electron-hole pairs, which diffuse in the epitaxial layer to neighboring pixels
- Diodes collect electrons and turn on when reaching the charge threshold
- How do we model this in the simulation to turn the energy deposition into pixel clusters (and back)?



- Experiments @ Danish Centre for Particle Therapy (DCPT) in Arhus University Hospital
  - 4 layers, 2 ALPIDEs per layer

- **Proton CT**
  - Cylindrical PMMA phantom with Al disk insert
  - Absorbers: 4/4 mm Al or 6/2 mm Al
  - Beam energy: 93–95 MeV
    - → p+ stop in detector (layer 3 or 4)
- **Treatment (in-situ range verification, RV)**
  - Water phantom
  - Absorbers: 5 mm PMMA + 4/4 mm Al
  - Beam energy: 100–200 MeV
    - → p+ stop in phantom


pCT


Treatment

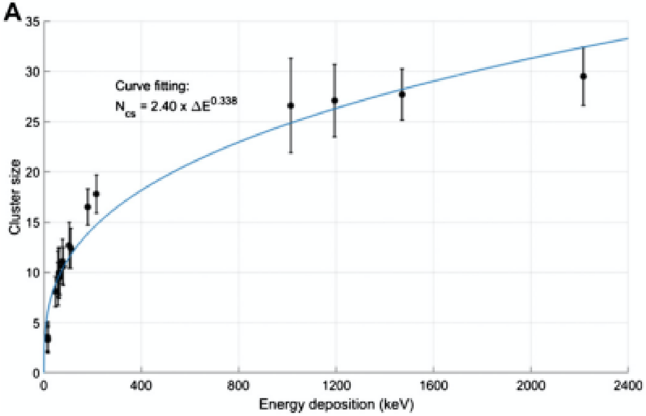
A Schilling, et al. (2025). Biomed. Phys. Eng. Express, 11 035005
J Alme, et al. (2020). Frontiers in Physics. 8(460)

Charge Diffusion Models

- Optimization procedure: Grid search
- Objective: Maximize histogram intersection

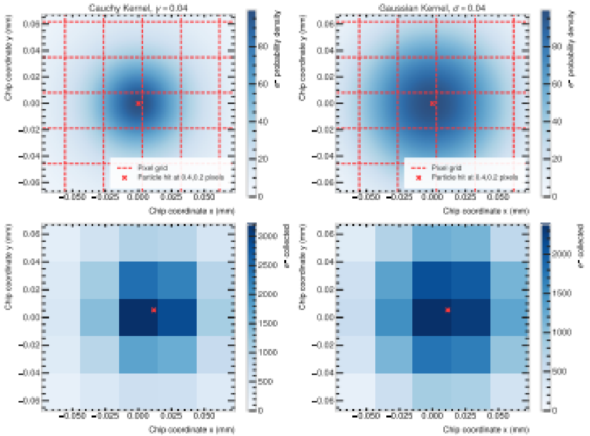
Power Fit (Pettersen et al. 2019)

$$n = a \cdot E_{dep}^{b}$$



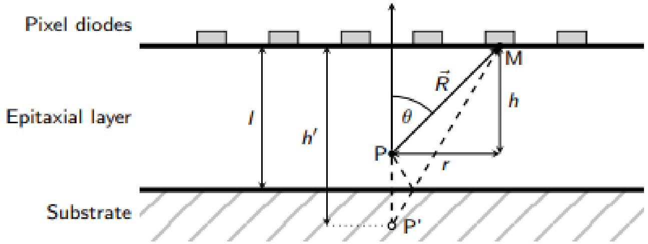
Cauchy-Lorentz Kernel (Dritsa 2011)

$$\mathcal{K}_{Cauchy}(x, y) = \frac{\gamma}{2\pi\left(\sqrt{x^2 + y^2 + \gamma^2}\right)^3}$$



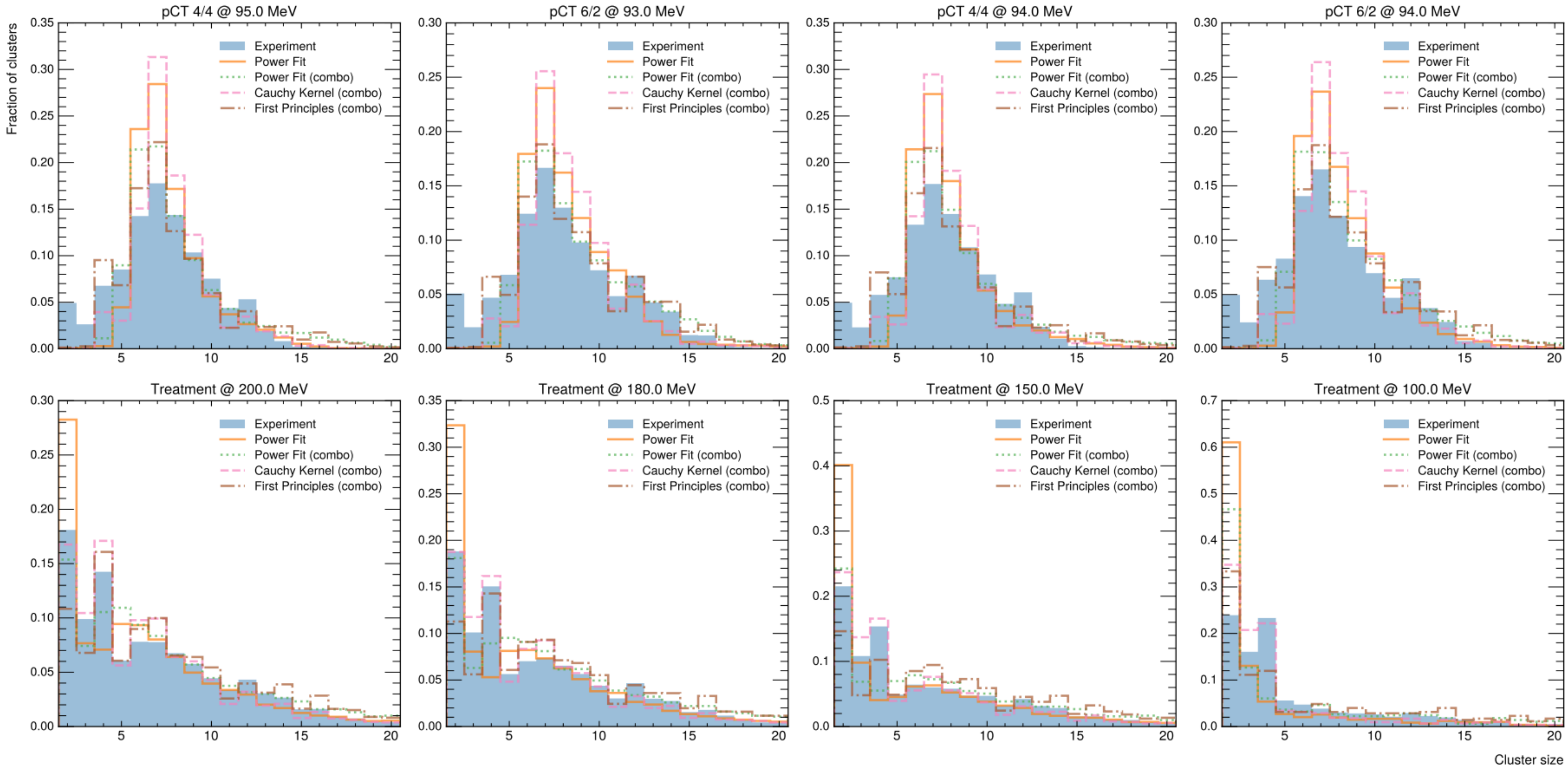
First Principles (Maczewski 2010)

$$\rho(\vec{R}) = \frac{hr}{4\pi|\vec{R}|^3} \cdot \exp\left(-\frac{|\vec{R}|}{\lambda}\right)$$



A Schilling, et al. (2025). “Modeling charge collection in silicon pixel detectors for proton therapy applications” Biomed. Phys. Eng. Express 11 035005
H E S Pettersen, et al. (2019). “Design optimization of a pixel-based range telescope for proton computed tomography”. In: Physica Medica 63, pp. 87–97
C A Dritsa (2011). “Design of the micro vertex detector of the CBM experiment. Development of a detector response model and feasibility studies of open charm measurement”. PhD thesis. Goethe University Frankfurt/Main
L Maczewski (2010). “Measurements and simulations of MAPS (Monolithic Active Pixel Sensors) response to charged particles-a study towards a vertex detector at the ILC”. In: PhD thesis, Warsaw University

Charge Diffusion Models - Cluster Size Distributions



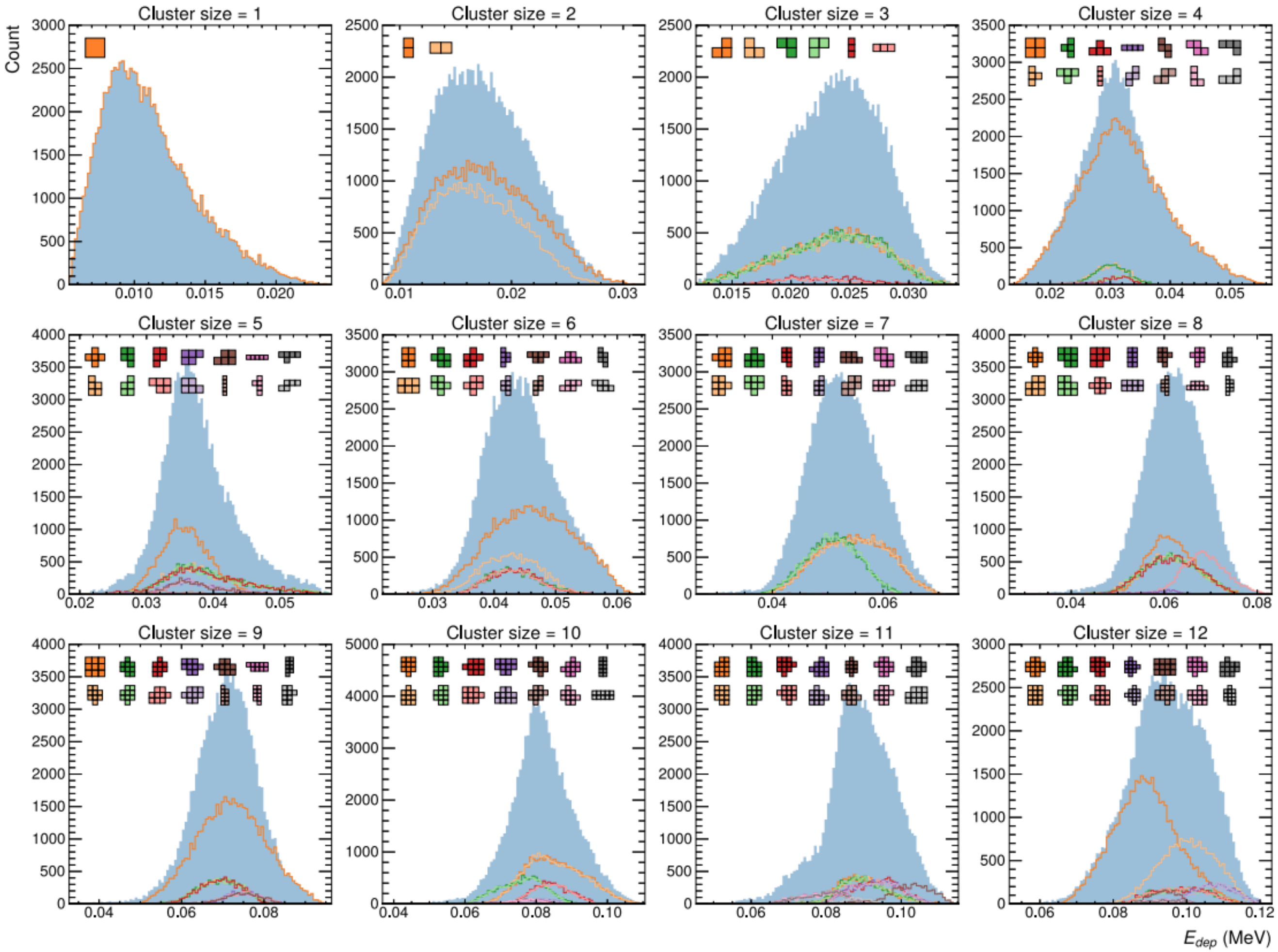
Charge Diffusion Models - Cluster Size Distributions

	Histogram intersection	Wasserstein distance	χ^2
Power Fit	0.772	0.767	266.659
Power Fit (combo)	0.836	0.844	618.627
Cauchy Kernel (combo)	**0.849**	**0.627**	**209.434**
First Principles (combo)	**0.849**	1.030	482.784
Power Fit	0.766	0.761	**451.190**
Power Fit (pCT)	0.845	1.101	1838.388
Cauchy Kernel (pCT)	**0.869**	0.515	509.260
First Principles (pCT)	0.858	**0.502**	714.570
Power Fit	0.808	0.634	95.657
Power Fit (RV)	0.867	0.491	54.138
Cauchy Kernel (RV)	**0.932**	**0.285**	**13.520**
First Principles (RV)	0.820	1.444	239.818

- Mean metrics for different diffusers across multiple datasets
  - Computed over cluster sizes 2–20
  - Different models have the best agreement with data, depending on the metric and the application

Charge Diffusion Models - Cluster Shape Distributions

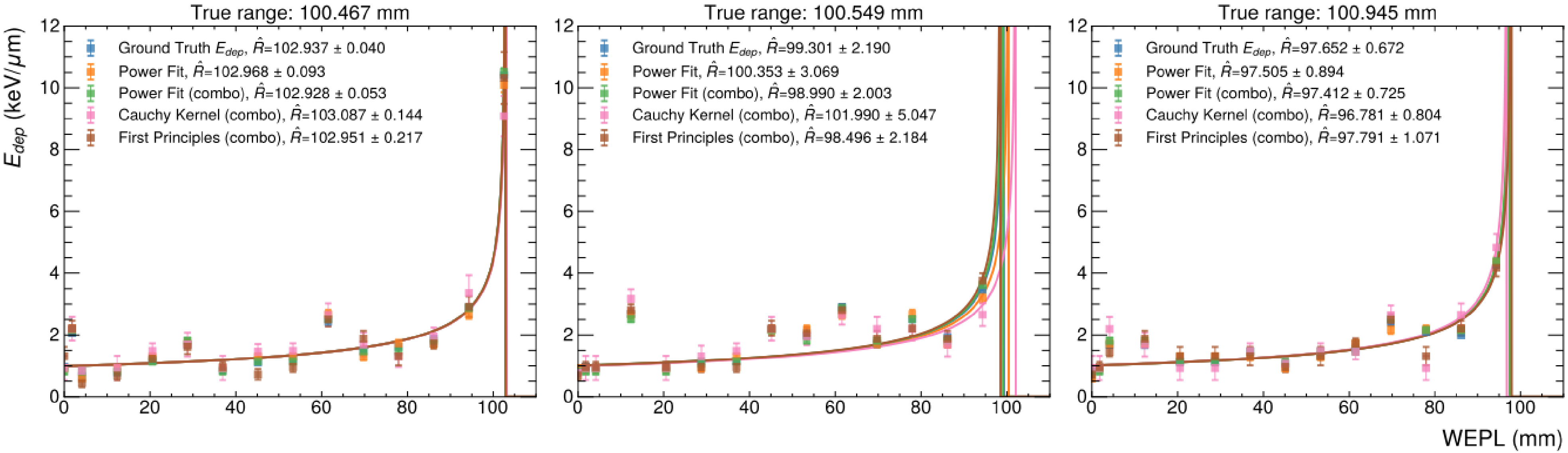
- The estimated energy deposition of a given cluster shape will change based on which charge diffusion model is used
- The same energy deposition can lead to clusters of different sizes, depending on where in the pixel the hit arrived
- E_{dep} look-up-table (LUT) for each cluster size **and shape**
- Analyzing the shape instead of the cluster size alone can improve the energy resolution of the chip



Charge Diffusion Models - E_{dep} resolution and WEPL fits

	MAE (keV)		RMSE (keV)	
	size	shape	size	shape
Power Fit	2.76		3.27	
Power Fit (combo)	2.13		2.47	
Power Fit (pCT)	1.98		2.29	
Cauchy Kernel (combo)	7.48	6.93	10.17	9.36
Cauchy Kernel (pCT)	4.86	4.59	6.92	6.46
First Principles (combo)	4.95	4.73	6.80	6.45
First Principles (pCT)	5.11	4.90	6.99	6.65

- The choice of diffusion model has a tangible impact on critical downstream applications like dose estimation and range verification
  - Task-specific models: power law for pCT, and a Cauchy Kernel for range verification
- The WEPL resolution for the DTC is strongly correlated with the resulting E_{dep} resolution from a charge diffusion model (though the difference in WEPL resolution is within 5%)



Summary

- Proton CT to aid precise dose planning for hadron therapies
- Quasi-online dose plan verification
  - Spatial resolution of 1-2 mm
  - Water-Equivalent-Thickness (WET) precision of 1-2 mm
  - Low dose → daily adaptive treatment
- Online dose delivery monitoring
  - Sub-mm position resolution of the Bragg peak position in real-time
- Construction of the pCT system
  - Mounting of sensors to flex cables in Kharkiv – in progress
  - Assembly and integration into services (power, cooling, readout)
- Commissioning with proton beams at the Bergen proton therapy facility

Thank you for your attention!

A Schilling, et al. (2025). "Modeling charge collection in silicon pixel detectors for proton therapy applications" Biomed. Phys. Eng. Express 2025 11 035005
J Alme, et al. (2020). "A High-Granularity Digital Tracking Calorimeter Optimized for Proton CT" Frontiers in Physics. 8(460)
H E S Pettersen, et al. (2019). "Design optimization of a pixel-based range telescope for proton computed tomography". Physica Medica 63, 87-97