

Proton-CT & Digital tracking calorimeter

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&
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- **Particle therapy** – a treatment of cancer
- **Bragg peak position** – the critical parameter in dose planning
- **Proton-CT** – a novel diagnostic tool for quasi-online dose plan verification
 - **Digital tracking calorimeter prototype**
 - **Results from simulations and beam tests**
 - **Towards a clinical prototype**

Particle therapy - the Bragg peak position

- **Key advantage of ions: Bragg peak**
 - Relatively low dose in the entrance channel
 - Sharp distal fall-off of dose deposition (<mm)!

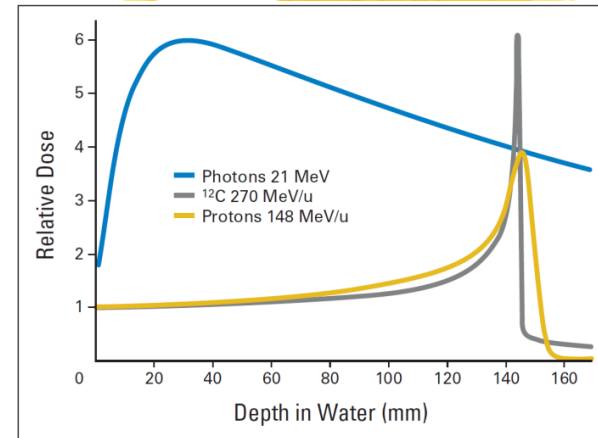
- **Challenge**

- Stopping power of tissue in front of the tumor has to be known – crucial input into the dose plan for the treatment
- Stopping power is described by Bethe-Bloch formula:

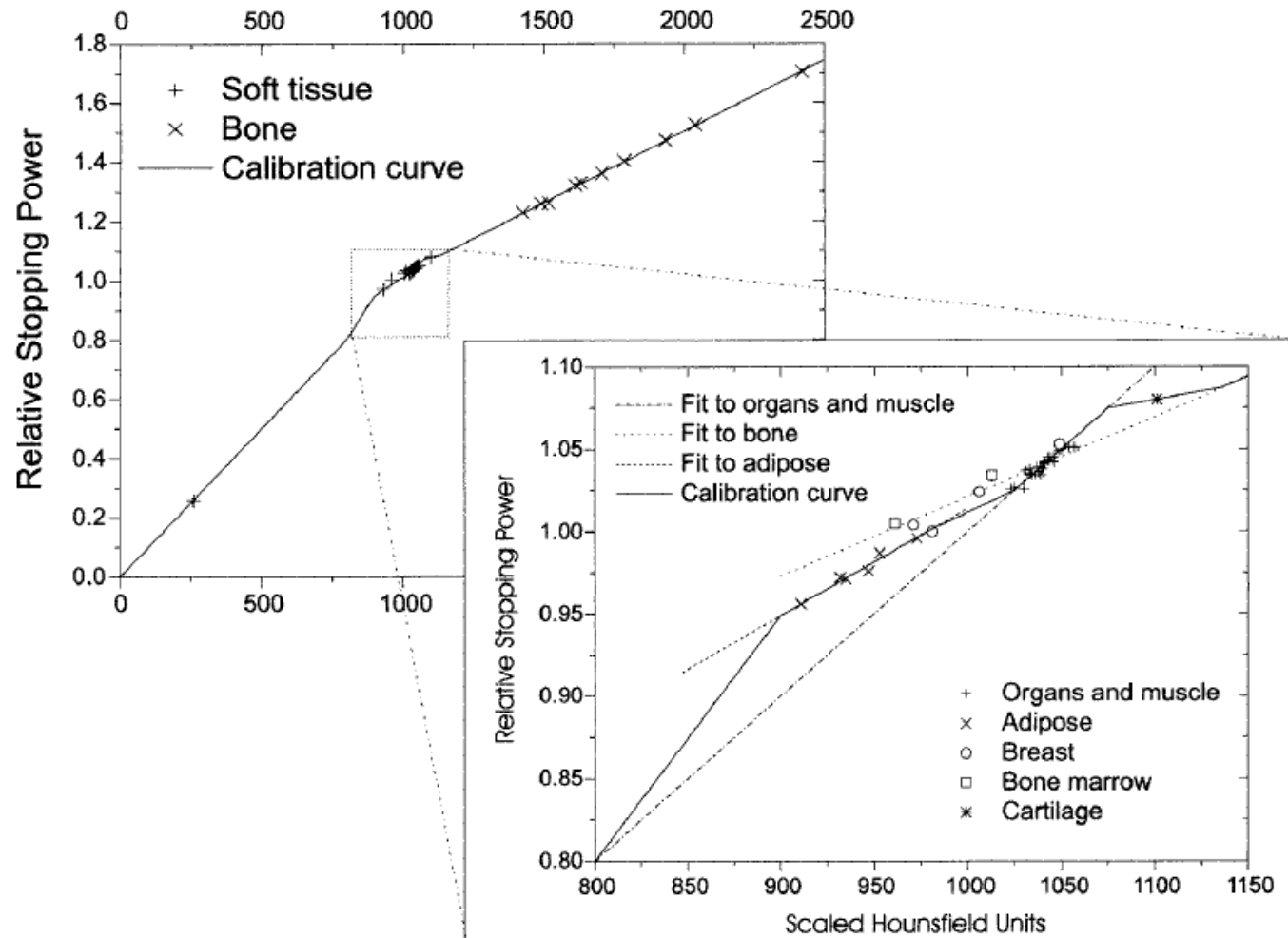
- $dE/dx \sim (\text{electron density}) \times \ln((\text{max. energy transfer in single collision})/(\text{effective ionization potential})^2)$

- **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



Schaffner, B. and E. Pedroni, *The precision of proton range calculations in proton radiotherapy treatment planning: experimental verification of the relation between CT-HU and proton stopping power*. Phys Med Biol, 1998. 43(6): p. 1579-92.

Range uncertainties

Clinical practice:

- Single energy CT: up to 7.4 % uncertainty

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

Unnecessary limitations -> reduce range uncertainties

Estimates for advanced dose planning:

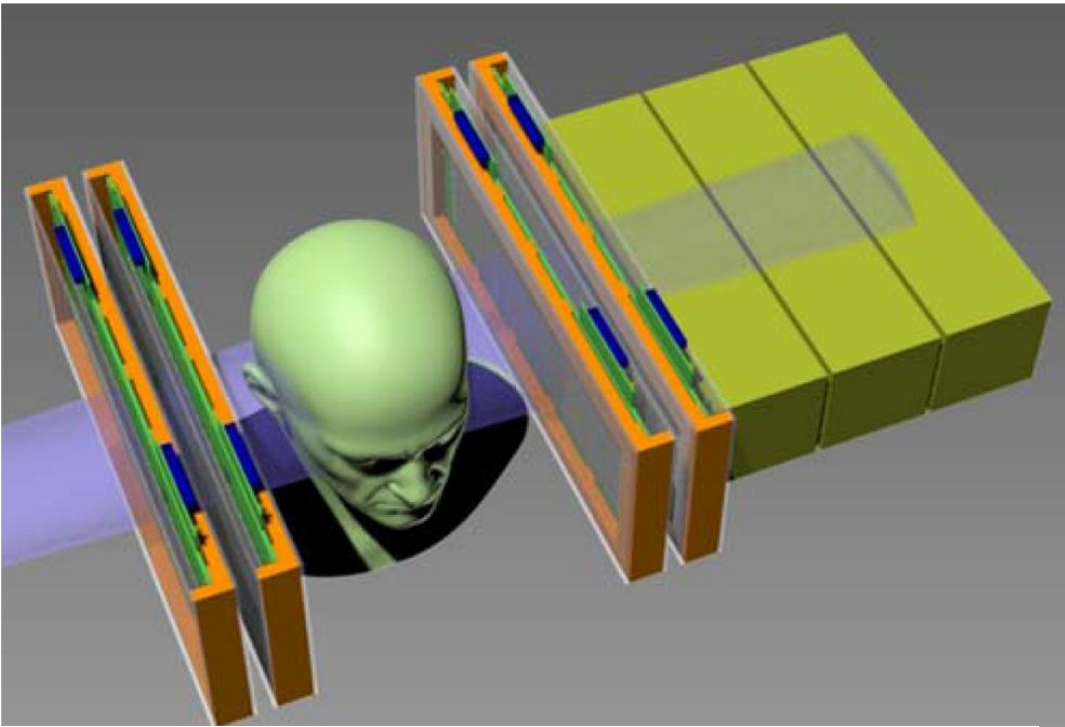
- Dual energy CT: up to 1.7 % uncertainty
- Proton CT: up to 0.3 % uncertainty

A comparison of dual energy CT and proton CT for stopping power estimation

David C. Hansen,^{1, a)} Joao Seco,² Thomas Sangild Sørensen,³ Jørgen Breede Baltzer Petersen,⁴ Joachim E. Wildberger,⁵ Frank Verhaegen,⁶ and Guillaume Landry⁷

¹⁾Department of Experimental Clinical Oncology, Aarhus University

Proton CT



H.F.-W. Sadrozinski / Nuclear Instruments and Methods in Physics Research A 732 (2013) 34–39

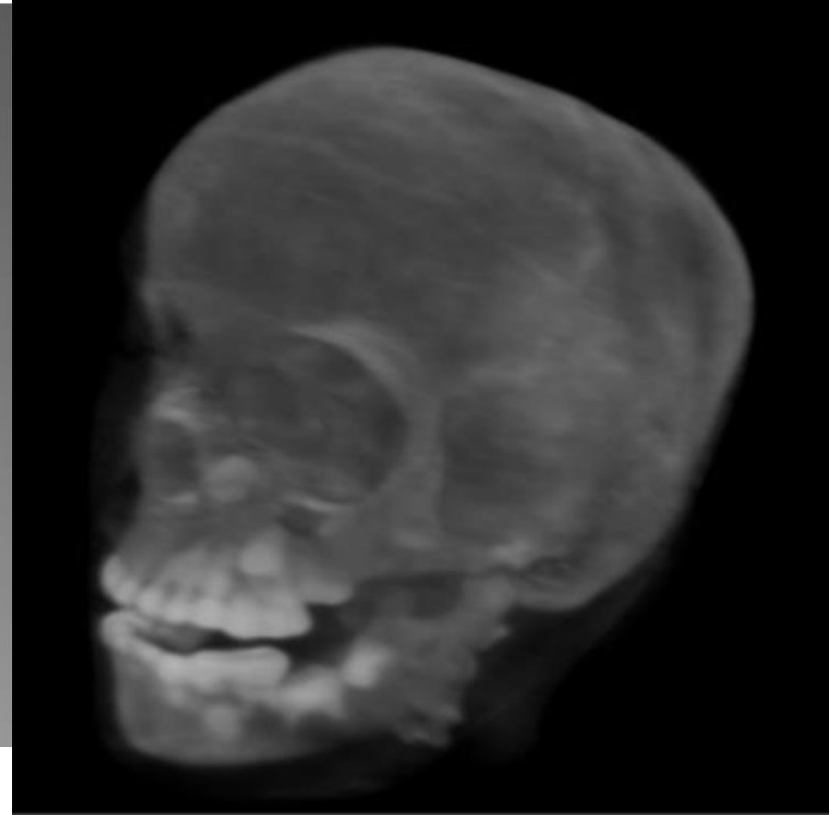


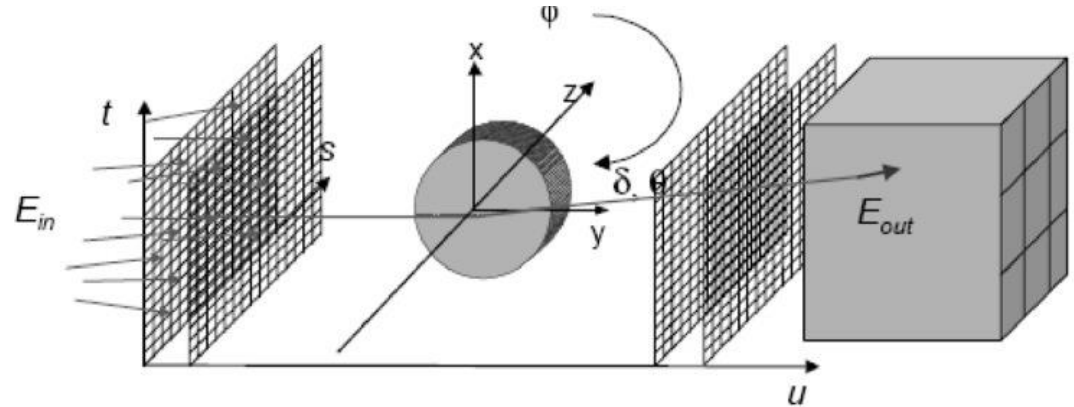
Fig. 14. 3D rendering of the pCT-reconstructed RSP map of a pediatric anthropomorphic head phantom.

V.A. Bashkurov et al. / Nuclear Instruments and Methods in Physics Research A 809 (2016) 120–129

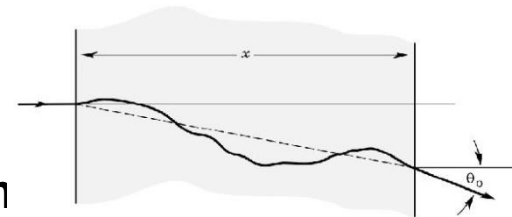
Proton-CT

- quasi-online dose plan verification

- high energetic proton beam quasi-simultaneously with therapeutic beam
- measurement of scattered protons
 - position, trajectory
 - energy/range



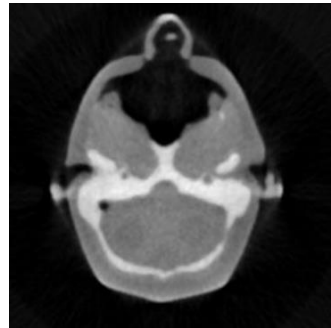
- reconstruction of trajectories in 3D and range in external absorber
 - trajectory, path-length and range depend on
 - nuclear interactions (inelastic collisions)
 - multiple Coulomb scattering (elastic collisions)
 - energy loss dE/dx (inelastic collisions with atom)
- MS theory and Bethe-Bloch formula of average energy loss in turn depend on electron density in the target (and ionization potentials)
 - > 3D map of electron density in target
 - > online verification of dose plan



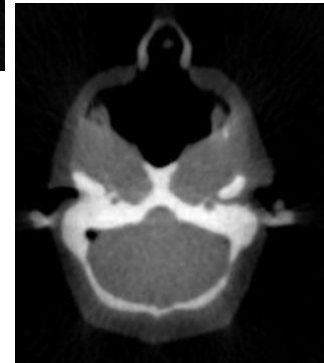
Proton-CT - images

- Traversing proton beam creates three different 2D maps
→ three imaging modalities

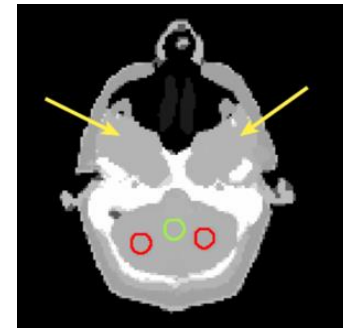
- **Transmission map**
 - records loss of protons due to nuclear reactions



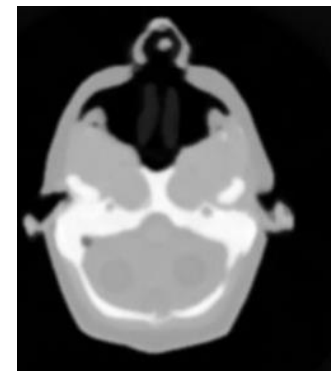
- **Scattering map**
 - records scattering of protons off Coulomb potential



- **Energy loss map**
 - records energy loss of protons (Bethe-Bloch)



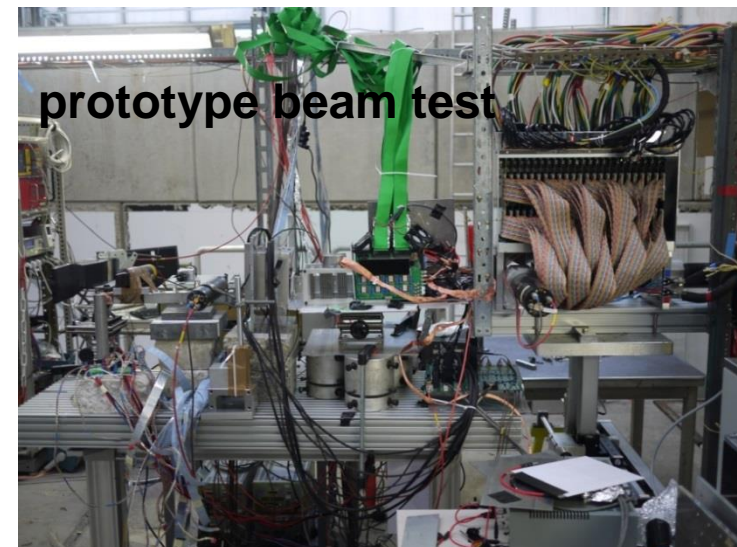
Phantom



Proton-CT

High energetic proton beam traversing the target –
intensity $\sim 10^9$ protons/sec

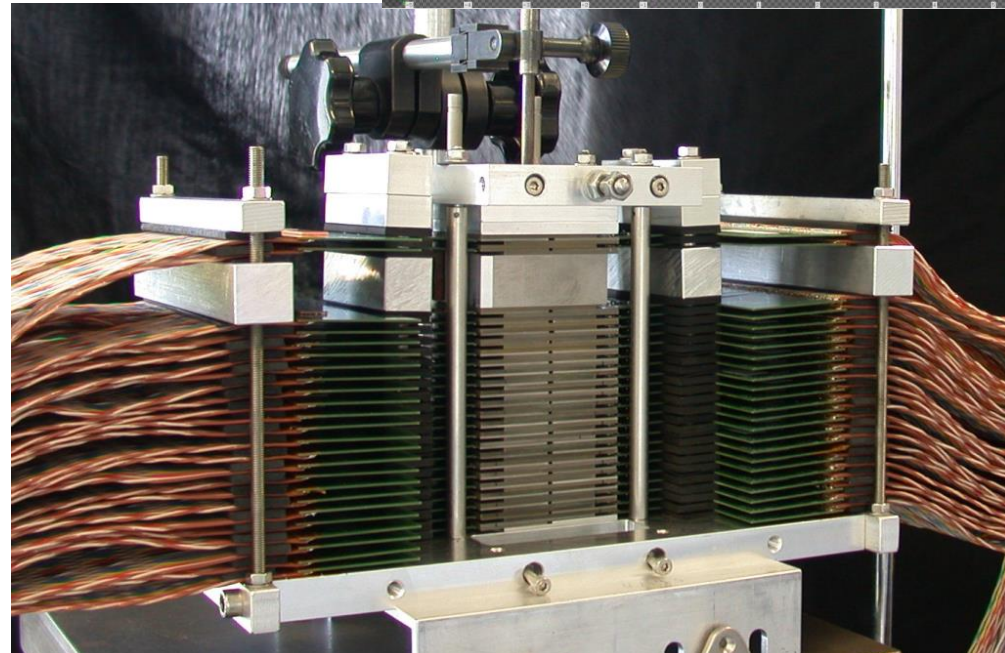
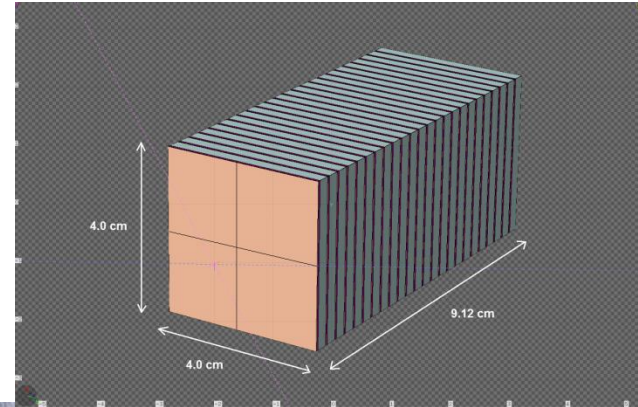
- **Detector requirements**
 - High position resolution (tens of μm)
 - Simultaneous tracking of large particle multiplicities
 - Fast readout
 - Radiation hardness
 - Front detector: low mass, thin sensors ($50 \mu\text{m}$)
 - Back detector: range resolution $< 1\%$ of path-length
- **Conceptual design**
 - Extremely high-granularity digital tracking calorimeter
- **Technical design**
 - Monolithic Active Pixel Sensors (MAPS)
 - Planes of CMOS sensors for tracking and as active layers in a sampling calorimeter



Digital tracking calorimeter prototype (I)

Silicon-tungsten sampling calorimeter

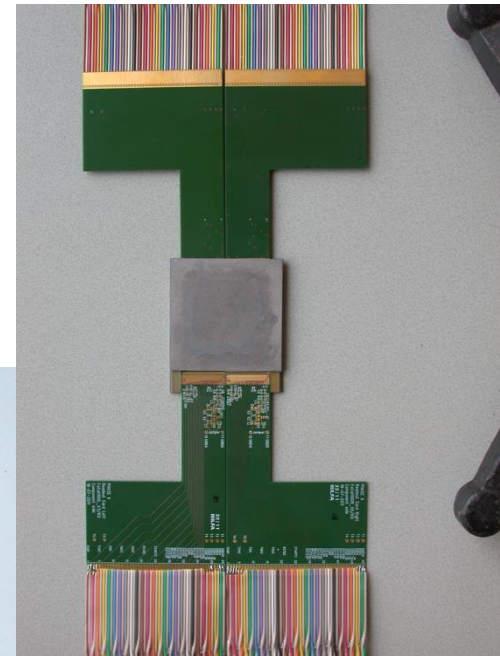
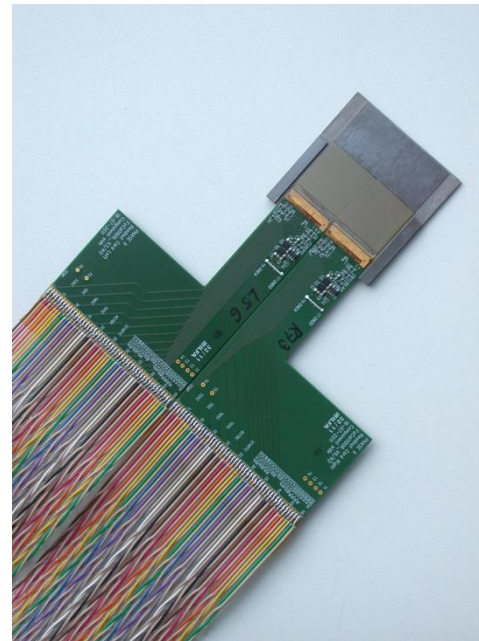
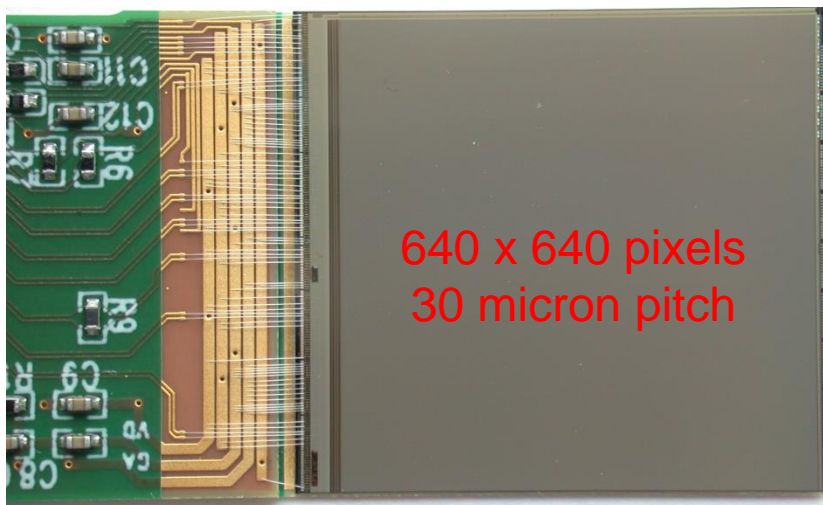
- optimised for electromagnetic showers
- compact design 4x4x11,6 cm³
- 24 layers
 - absorbers:
 - 3.5 mm of W ($\approx 1 X_0$)
 - Molière radius: 11 mm
 - active layers:
 - MAPS – MIMOSA 23*
 - 4 chips per layer
 - > 96 chips in total



Digital tracking calorimeter prototype (II)

MIMOSA 23

- on-chip digitisation
 - chip-level threshold setting
 - 1 bit per pixel
- sequential row readout (“rolling shutter”)
-> pixel integration time: 642 μ s
- continuous readout
- no zero-suppression

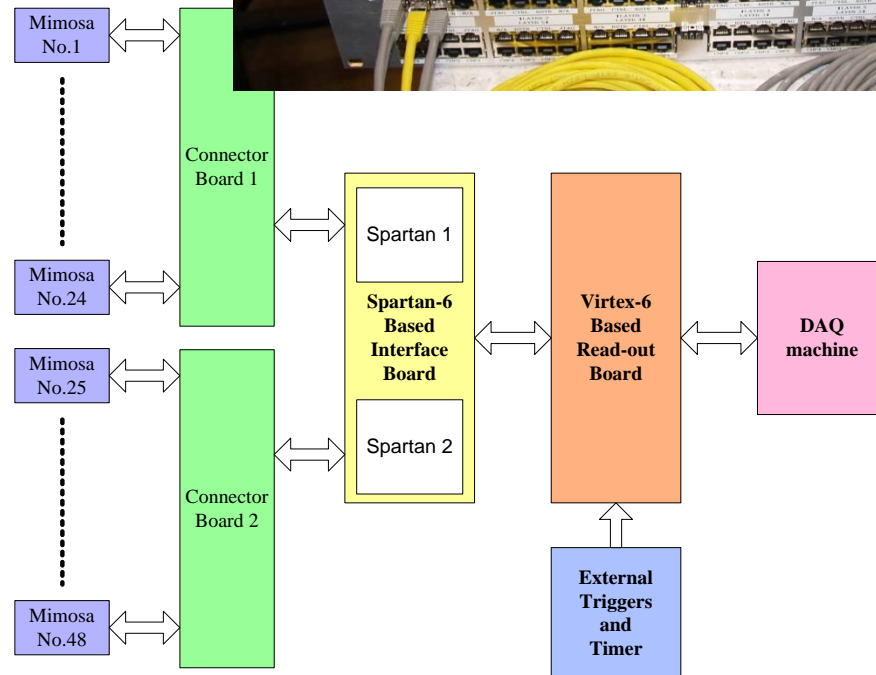
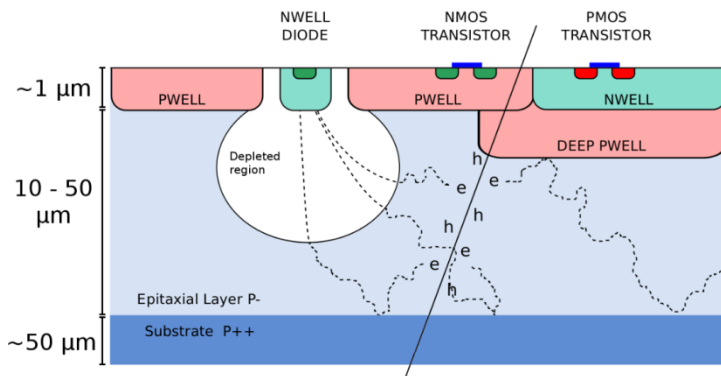
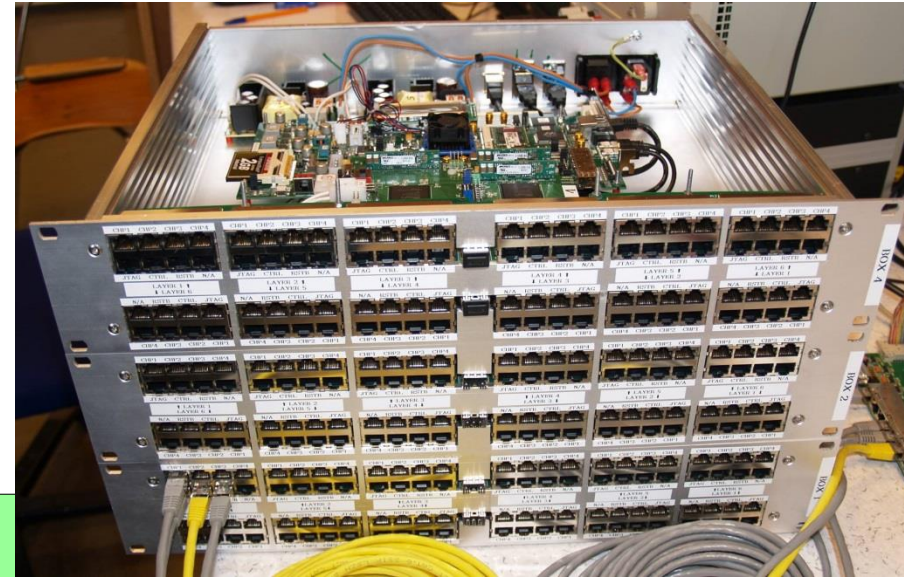


Integration of
four sensors
per layer

Digital tracking calorimeter prototype (III)

MIMOSA 23 readout

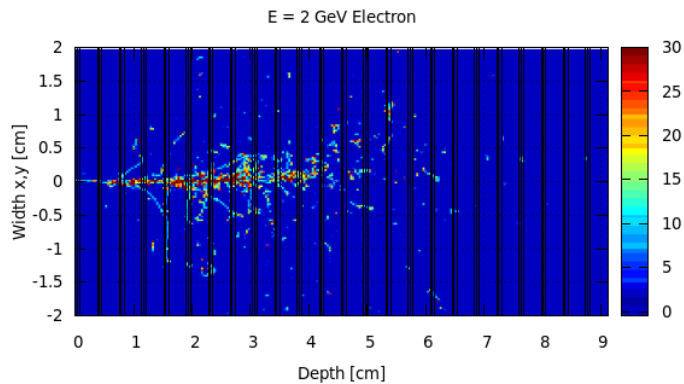
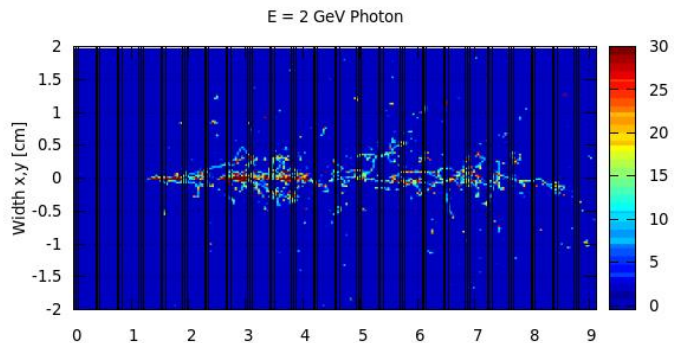
- 39 Mpixels
- raw data rate: 61 Gb/s
- FPGA based readout and DAQ
 - Spartan 6 FPGAs interfacing the MIMOSA chips
 - Virtex 6 based DAQ (2 GB DDR3 RAM, ethernet)



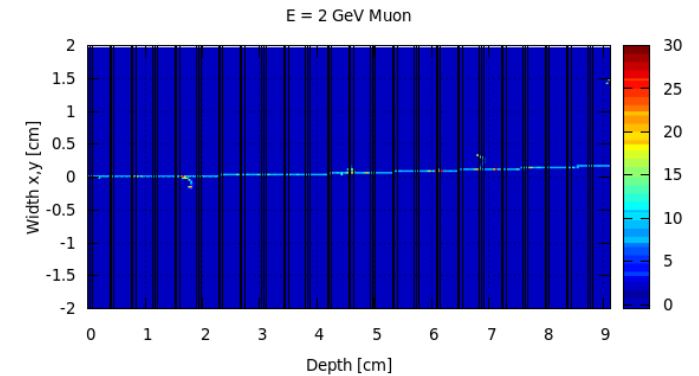
Simulation results

Detector response

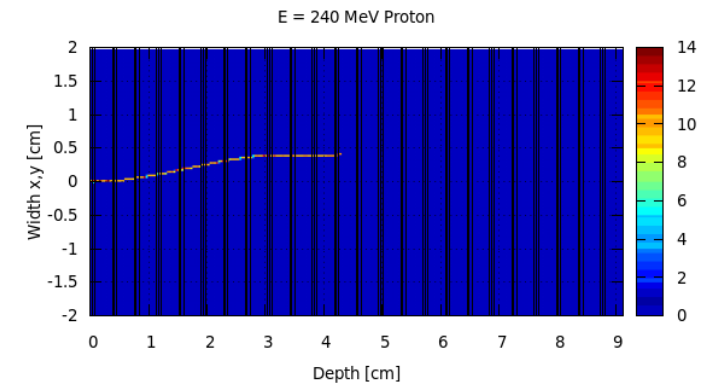
Photons and electrons (e.m. shower)



muons (MIP)



protons



Test beam results

Digital calorimeter

- particle counting method – number of hits should be proportional to the particle energy
- does it work for electromagnetic showers?

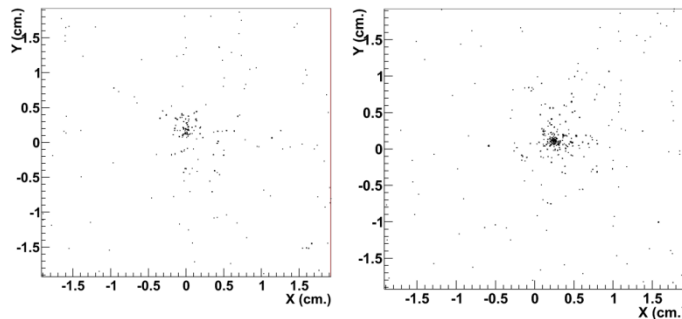
electrons

linearity

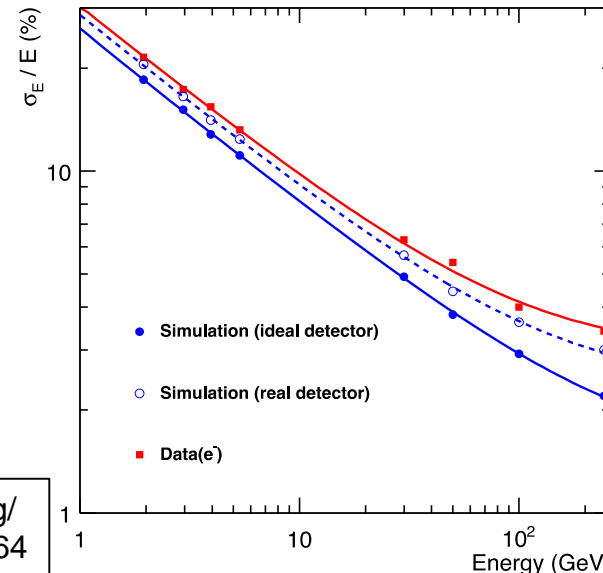
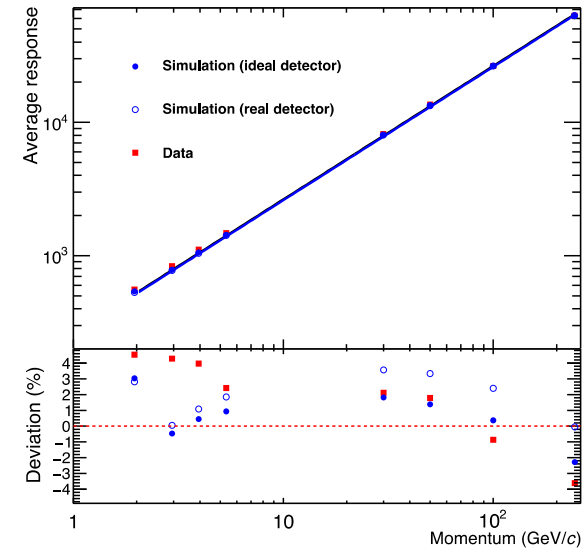
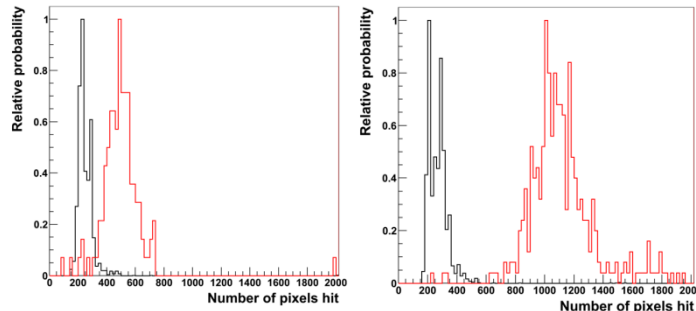
2 GeV

5 GeV

shower pattern



hit distribution



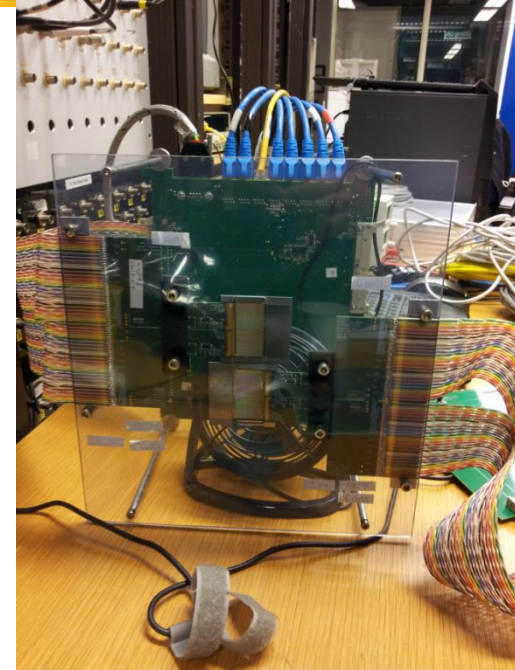
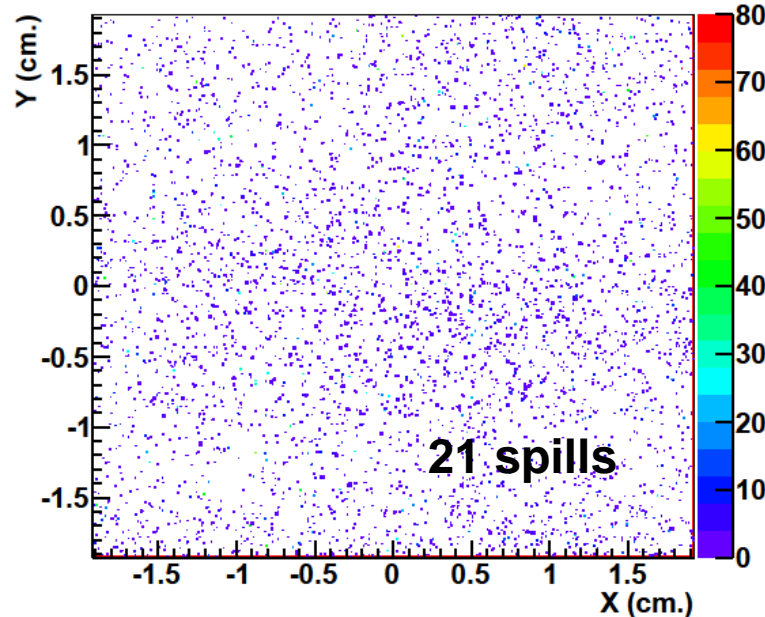
energy resolution

Digital tracking calorimeter – rangemeter (I)

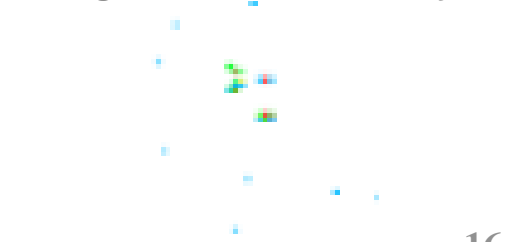
Range measuring resolution

- **Stopping: proton beam tests at KVI (Groningen)**
 - Full prototype (24 layers, tungsten absorber)
-> validation of simulations
 - Energy: from 122 to 190 MeV
 - Intensity:
 ≈ 1 proton per frame (640 μ sec),
800 protons per spill

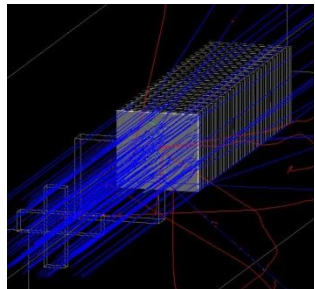
Hits map with Layer_4



single track in 4 layers

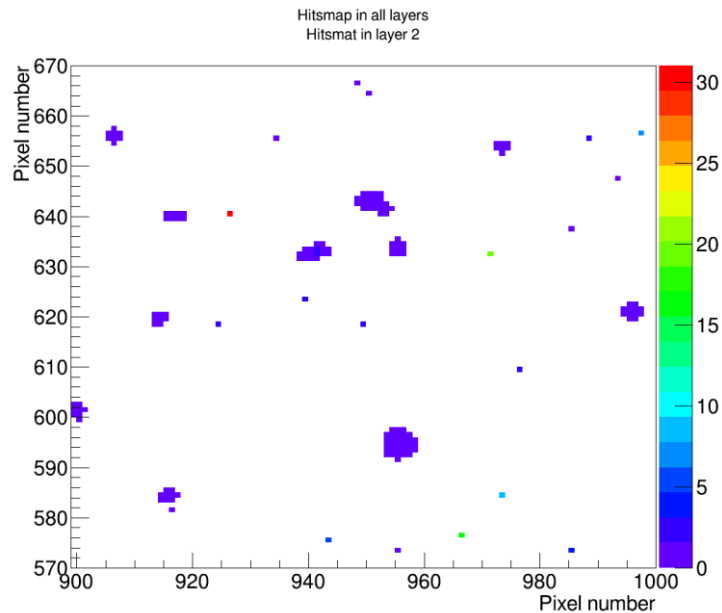


broad beam spot

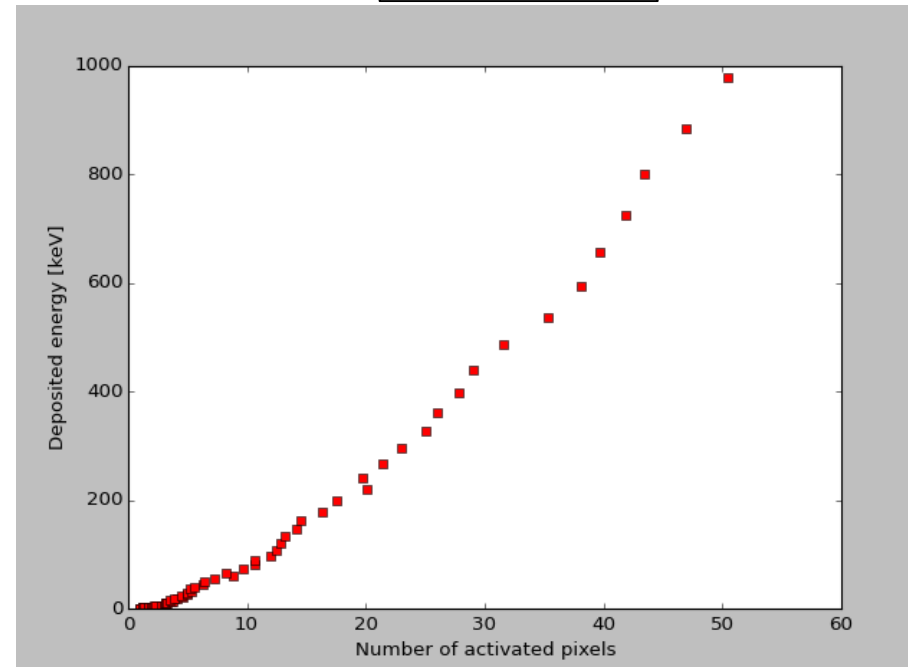


Digital tracking calorimeter – rangemeter (II)

Range measuring resolution



H. Pettersen



- **Energy loss measurement**

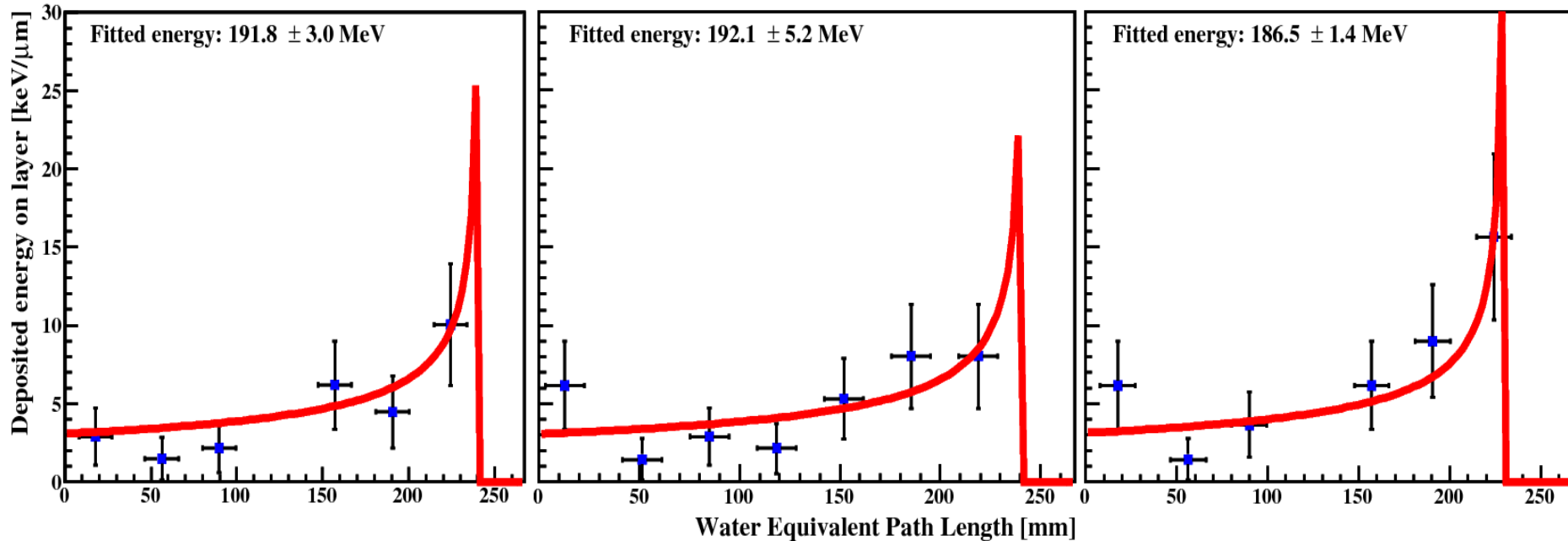
- **hadron tracks:**
 - **number of hits in a sensitive layer along the particle trajectory ("cluster size") depends (weakly) on the energy loss**

Digital tracking calorimeter – rangemeter (IV)

- Tracking of a single proton, collecting clusters along the trajectory and fitting a Bragg curve*

H. Pettersen

Bragg-Kleeman model fit to depth-dose data



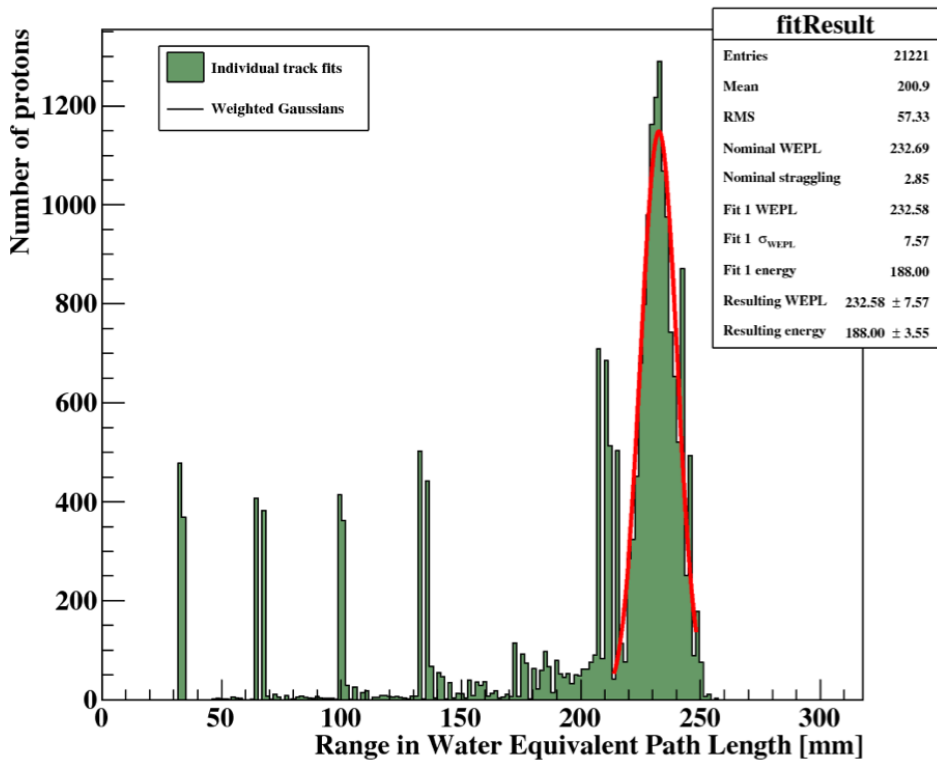
* Bortfeld, T. *An Analytical approximation to the Bragg curve for therapeutic proton beams.* Med. Phys 24 2024-33 (1997)

Digital tracking calorimeter – rangemeter (V)

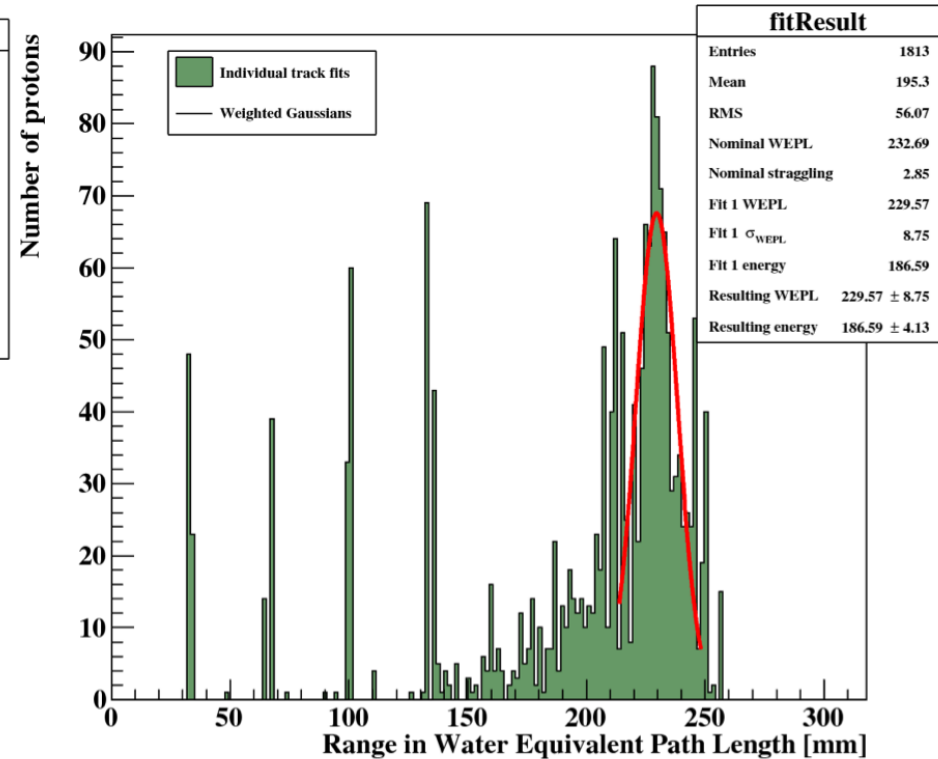
- Energy/range resolution for 188 MeV protons

H. Pettersen

Fitted energy of a 188.00 MeV beam in Tungsten (MC)



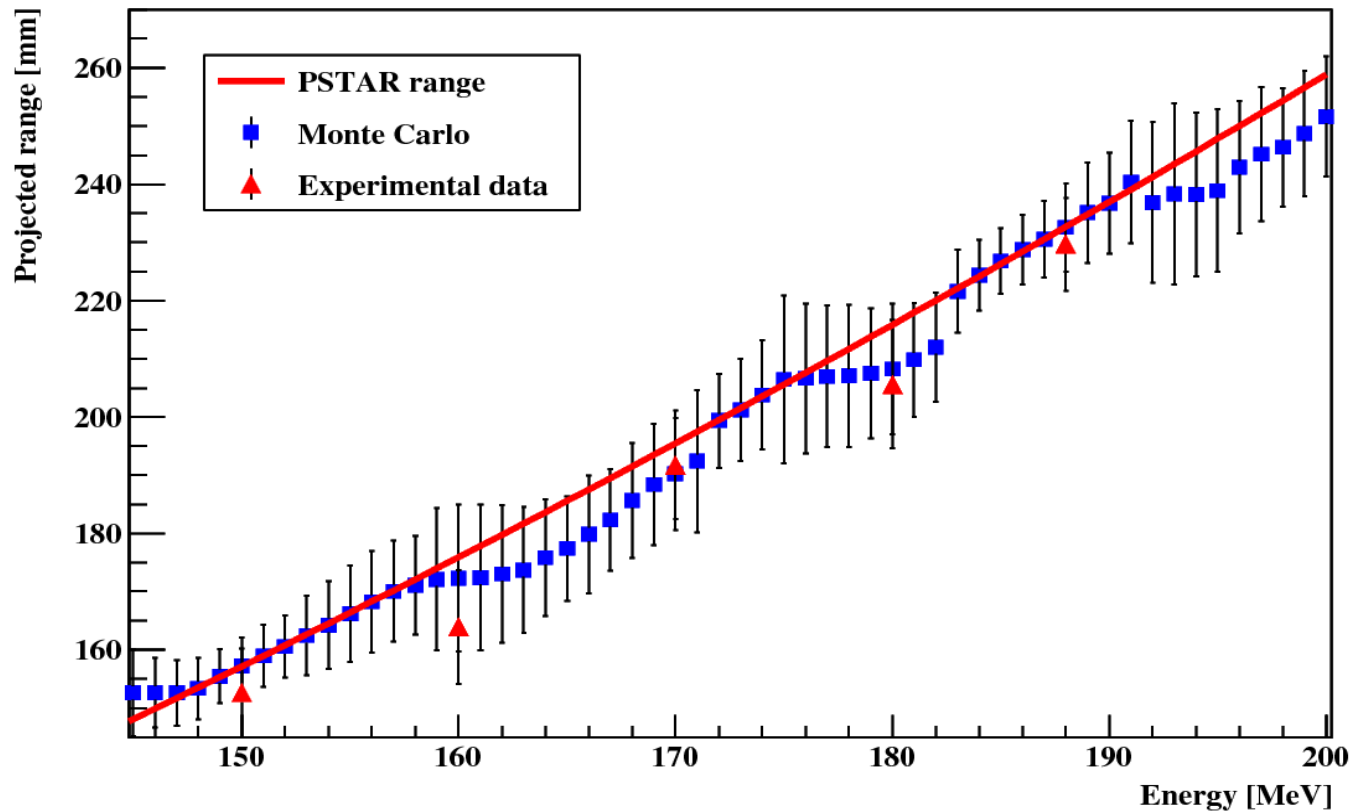
Fitted energy of a 188.00 MeV beam in Tungsten (Exp. data)



Digital tracking calorimeter – rangemeter (VI)

- Range vs proton beam energy

Range estimation of proton tracks using weighted Gaussian approach



-> good agreement between data and MC

Towards a clinical prototype

– Bergen pCT Collaboration

- **Organisation**

- UiB, HiB, HUS

UNIVERSITY OF BERGEN



- International collaboration

- Utrecht
- ...

- Joining forces with another pCT project
(Padova - Piero Giubilato, ERC grant iMPACT - 1.8 MEUR) – under discussion



- **Financing**

- Toppforsk (26 MNOK, 5 years)
- BFS (18 MNOK, 4 years)
- Helse Vest

- **Next steps**

- Finishing the optimisation of the design
- Production of ALPIDE chips

Towards a clinical prototype

– Bergen pCT Collaboration

Work packages

WP1: Simulation and design optimization

- Detector specifications: Optimization of geometry and segmentation
- Evaluation of rate capabilities of the digital backend of the sensor
- Optimisation of the readout electronics architecture

WP2: Chip submission and sensor characterization

- Improved sensor and data encoding design
- Chip submission
- Testing of prototypes

WP3: Data readout

- Development and testing of readout electronics
- Setting up a full readout chain
- Development of firmware and software

WP4: Assembly

- Assembly of chips into HICs/staves
- Assembly of staves into layers

WP5: System integration

- Integration of layers into a compact detector
- Mechanical and electrical integration, cooling

WP6: Commissioning

- Commissioning of the PRM in beams
- Performance evaluation in a pre-clinical environment, i.e. with phantoms

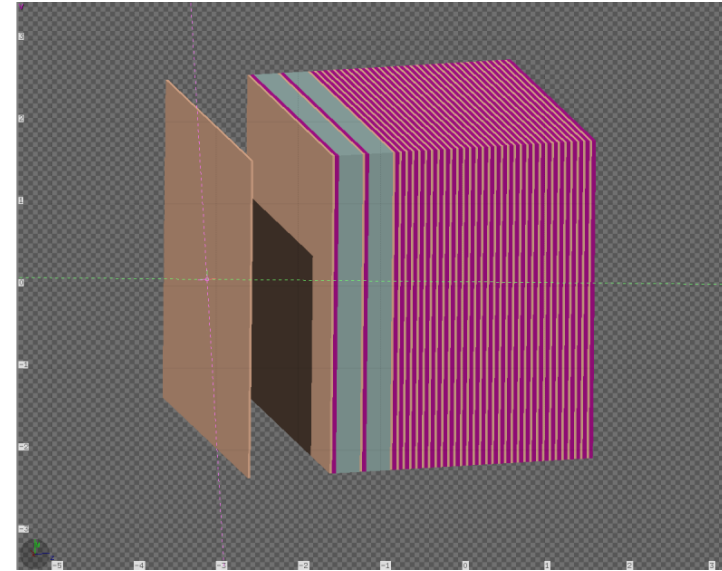
WP7: Reconstruction software

- Calorimeter response
- Calorimeter track reconstruction
- Reconstruction of 3D trajectory – track vector matching
- 3D stopping power map

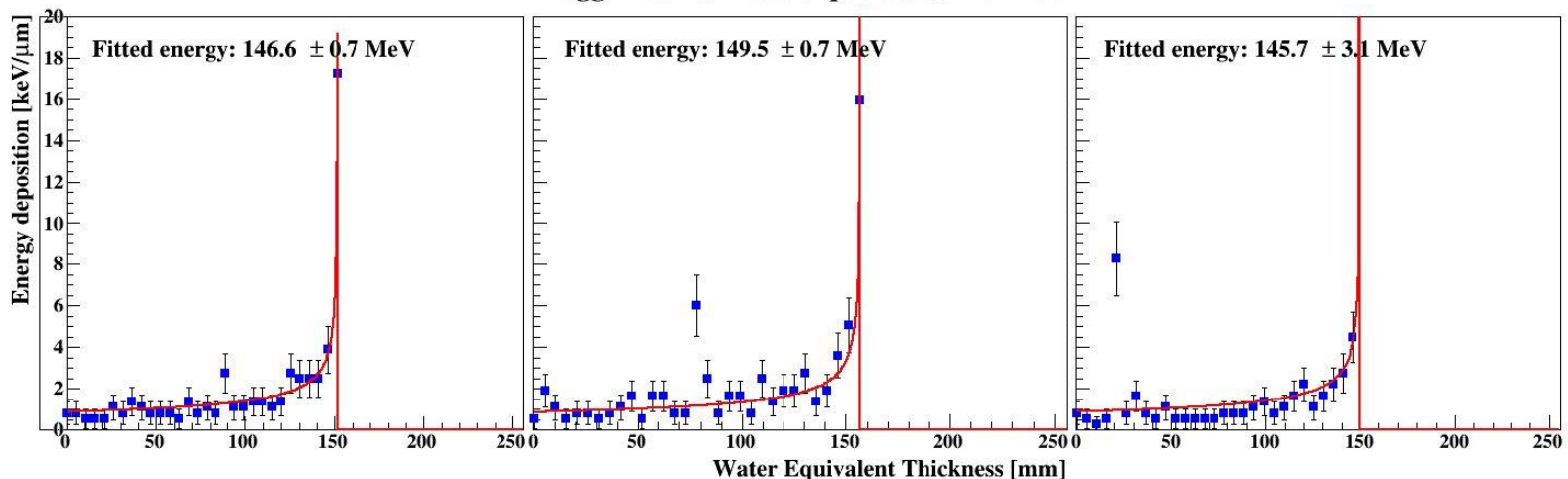
Towards a clinical prototype (I)

Optimisation of the design

- geometry
- longitudinal segmentation
 - number of sensitive resp. absorber layers
- absorber
 - energy degrader, mechanical carrier, cooling medium
 - material choice: Al
 - thickness (2-4 mm)



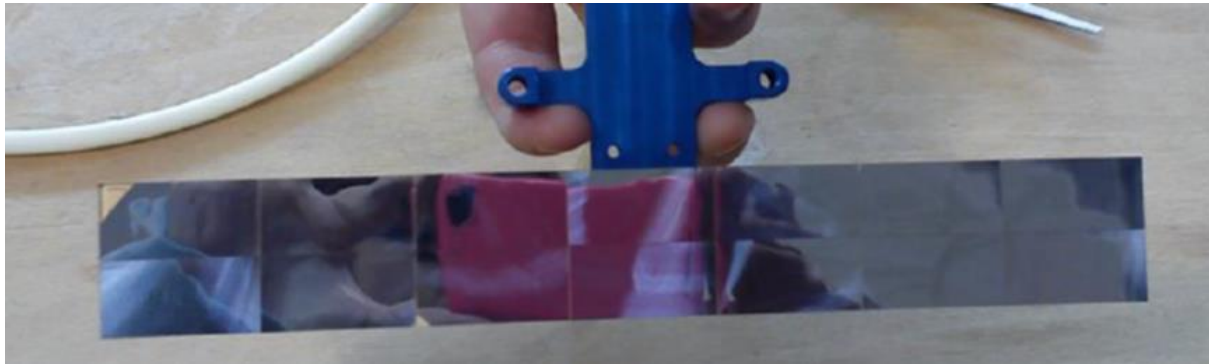
Bragg-Kleeman fit to exp. data at 145 MeV



Towards a clinical prototype (II)

Optimisation of the design

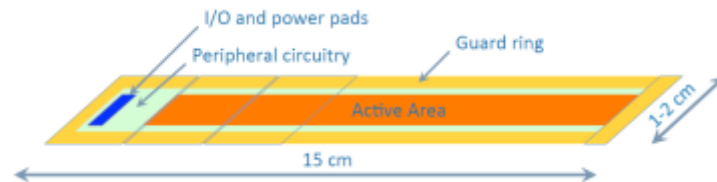
- **sensors – MAPS**
 - **ALPIDE chip**
 - **Design team: CCNU Wuhan, CERN Geneva, YONSEI Seoul, INFN Cagliari, INFN Torino, IPHC Strasbourg, IRFU Saclay, NIKHEF Amsterdam**
 - **sensor for the upgrade of the inner tracking system of the ALICE experiment at CERN**
 - **chip size $\approx 3 \times 1.5 \text{ cm}^2$, pixel size $\approx 28 \mu\text{m}$, integration time $\approx 4 \mu\text{s}$**
 - **on-chip data reduction (priority encoding per double column)**



Towards a clinical prototype (III)

Strategy

- **Modular structure – exchangeable front layers (tracking and absorber layers)**
- **Use the existing ALPIDE chips as sensitive layers**
- **R&D project to tailure ALPIDE design to medical applications**
 - **Faster charge collection and readout: $4\ \mu\text{s}$ \rightarrow $< 1\ \text{ns}$**
 - **Larger sensors - wafer-scale integration by stitching**



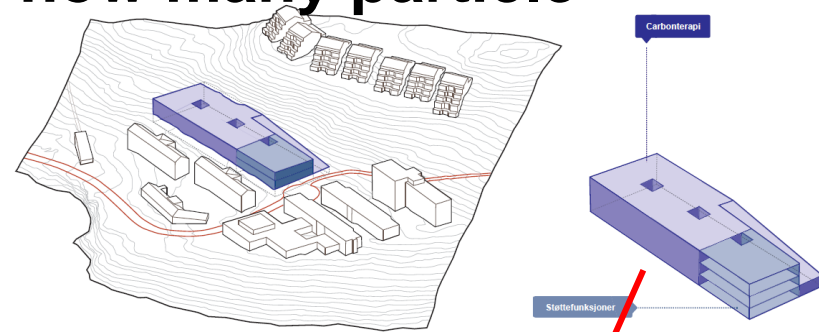
- **Thinner sensors (in case of tracking station between nozzle and patient)**

Hadron therapy in Norway

Ongoing discussion in Norway on how many particle therapy facilities are to be build

What can we hope for in Bergen?

- Combined proton and carbon facility
- State-of-the-art technology
 - fast scanning/repainting system
 - active energy modulation
 - beam gating system
 - several treatment rooms
 - superconducting gantry for carbon ions



University Hospital

This is the end