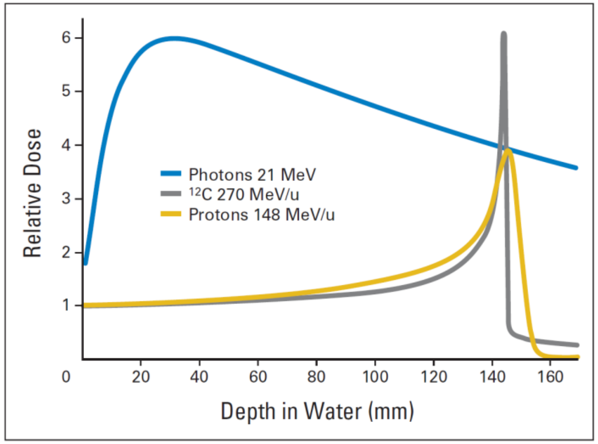
A DIGITAL TRACKING CALORIMETER FOR PROTON COMPUTED TOMOGRAPHY

D. Aadnevik[1], K. Austreim[1], H. Pettersen[1], D. Roehrich[1], T. Peitzmann[2], E. Rocco[2], H. Wang[2], C. Zhang[2], O.H. Odland[3]

[1] Institute of Physics and Technology, University of Bergen, Bergen, Norway
[2] Institute for Subatomic Physics, Utrecht University and Nikhef, Utrecht, The Netherlands
[3] Department of Radiation Oncology and Medical Physics, Haukeland University Hospital, Norway

- **Proton CT**
- **Digital tracking calorimeter prototype**
- **Results from simulations and beam tests**
- **Towards a clinical prototype**

Particle therapy - the Bragg peak position



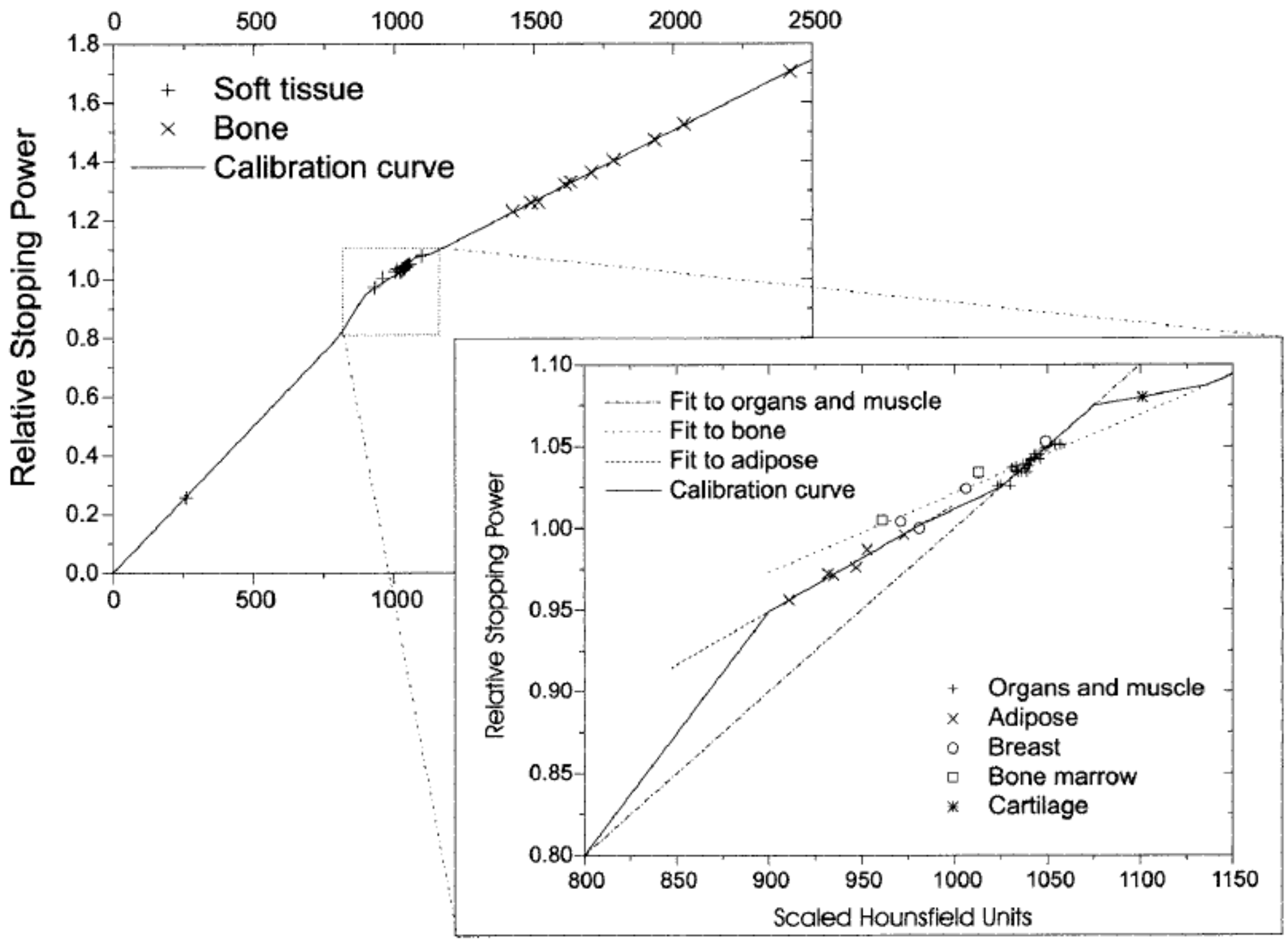
- **Key advantage of ions: Bragg peak**
  - **Relatively low dose in the entrance channel**
  - **Sharp distal fall-off of dose deposition (<mm)!**

- **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 ~ (electron density) x
    ln((max. energy transfer in single collision)/(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)

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 limitiations -> reduce range uncertainties

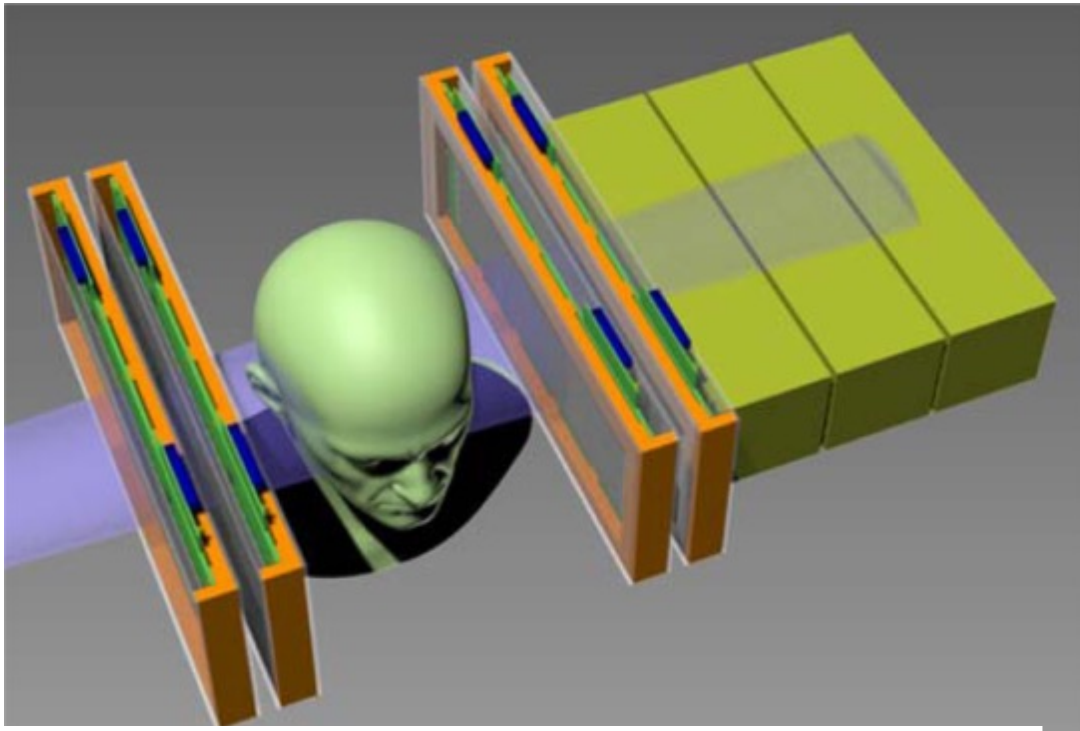
Estimates for advanced dose planning:

- **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 Sørensenn,[3] Jørgen Breede Baltzer Petersen,[4] Joachim E. Wildberger,[5] Frank Verhaegen,[6] and Guillaume Landry[7]
[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

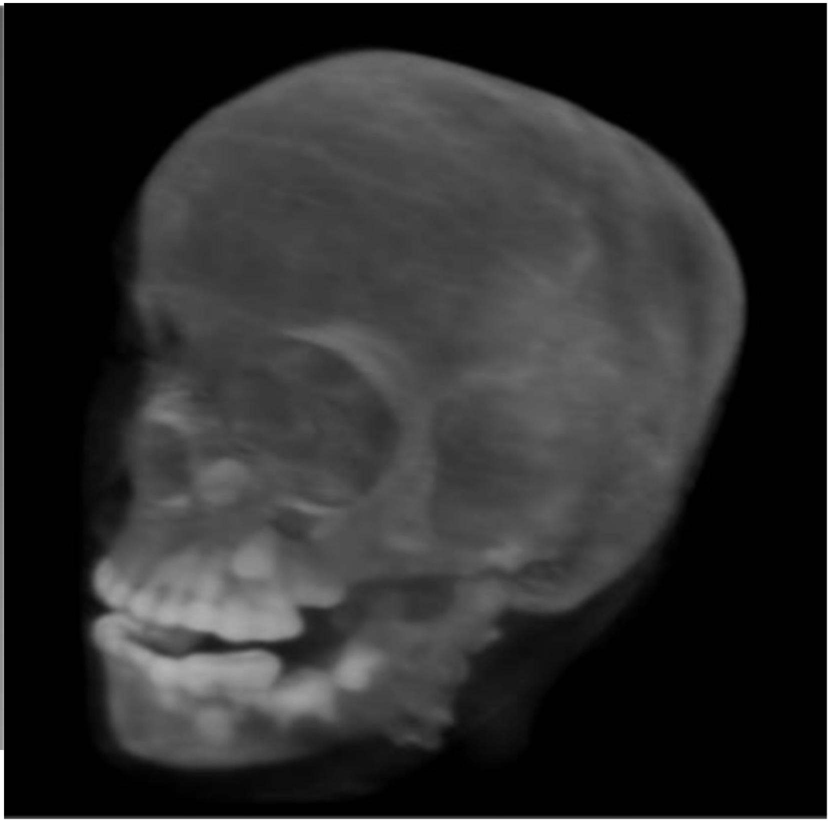
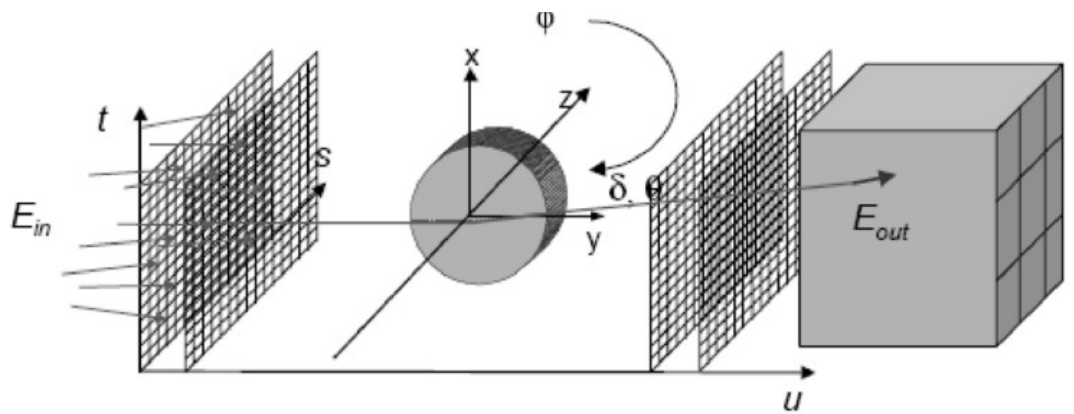


Fig. 14. 3D rendering of the pCT-reconstructed RSP map of a pediatric anthropomorphic head phantom.

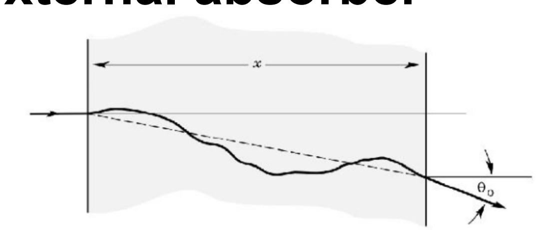
V.A. Bashkirov et al. / Nuclear Instruments and Methods in Physics Research A 809 (2016) 120–129

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
    - multiple Coulomb scattering (elastic collisions)
    - energy loss dE/dx (inelastic collisions)



- MS theory and Bethe-Bloch formula of average energy loss in turn depend on electron density in the target (and ionization potentials)

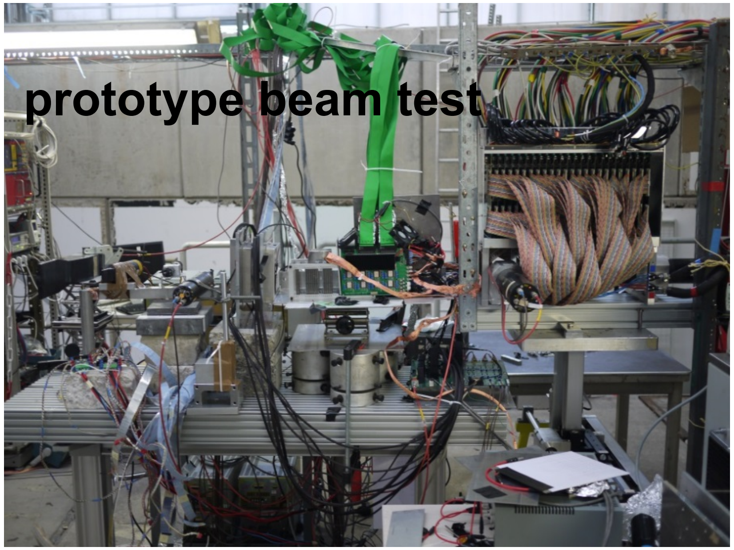
-> 3D map of electron density in target

-> online verification of dose plan

Proton-CT

High energetic proton beam traversing the target – intensity ~10^9 protons/sec

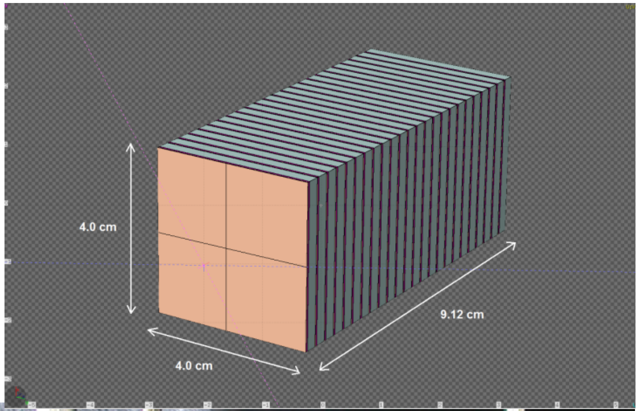
- **Detector requirements**
  - High position resolution (tens of μm)
  - Simultaneous tracking of large particle multiplicities
  - Fast readout
  - Radiation hardness
  - Front detector: low mass, thin sensors (50 μm)
  - Back detector: range resolution <1% of path-length
- **Conceptual design**
  - 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

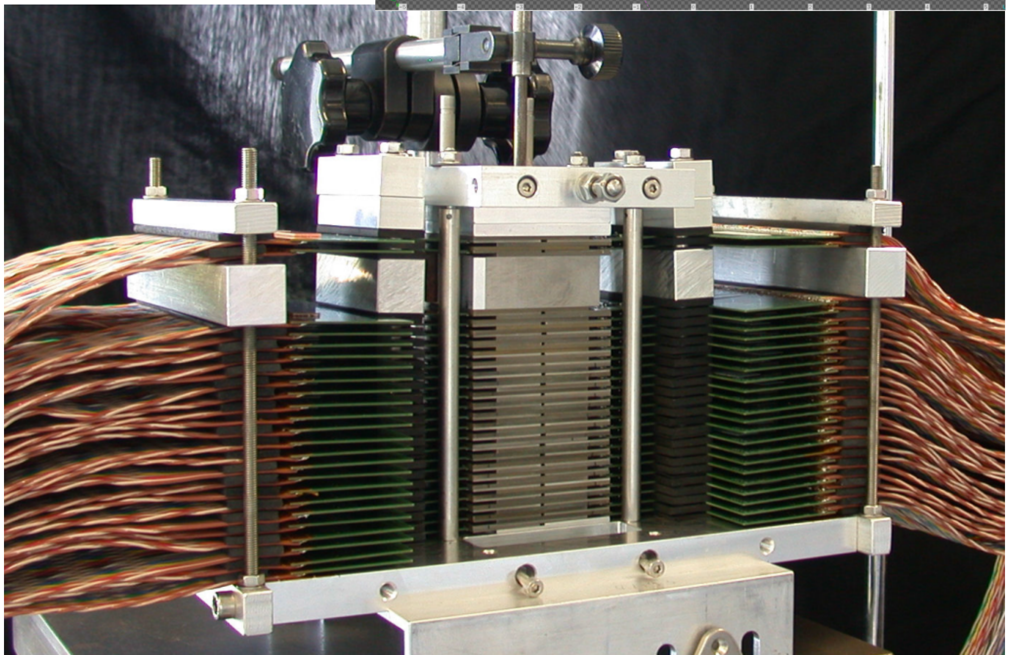


Digital tracking calorimeter prototype (I)

Silicon-tungsten sampling calorimeter

- optimised for electromagnetic showers
- compact design 4x4x11,6 cm^3
- 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



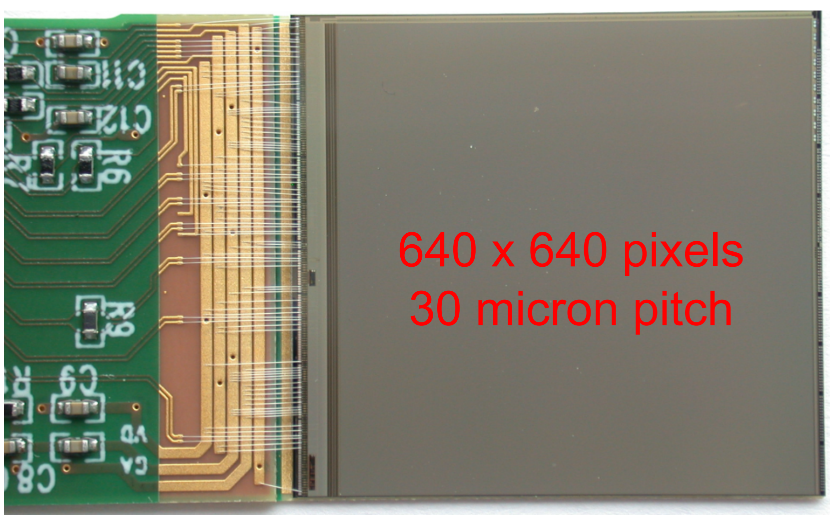


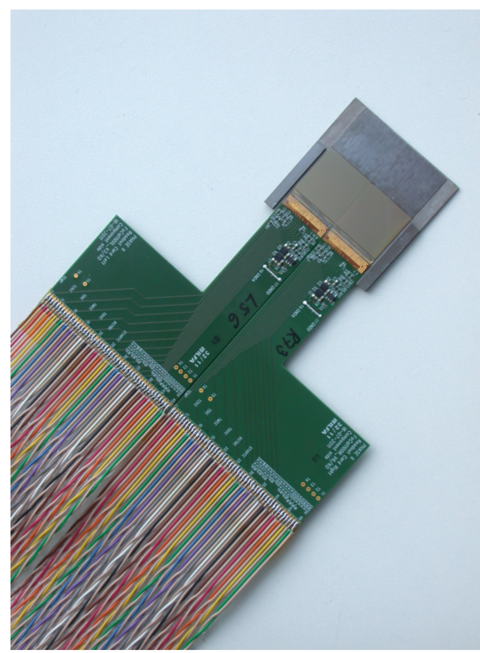
* IPHC Strasbourg

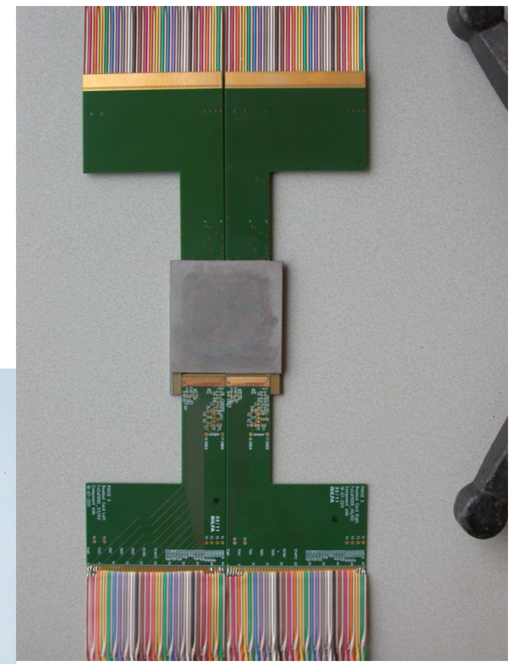
Digital tracking calorimeter prototype (II)

MIMOSA 23

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





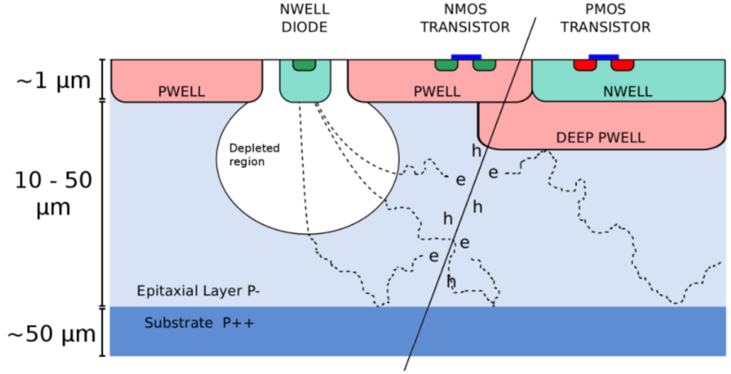


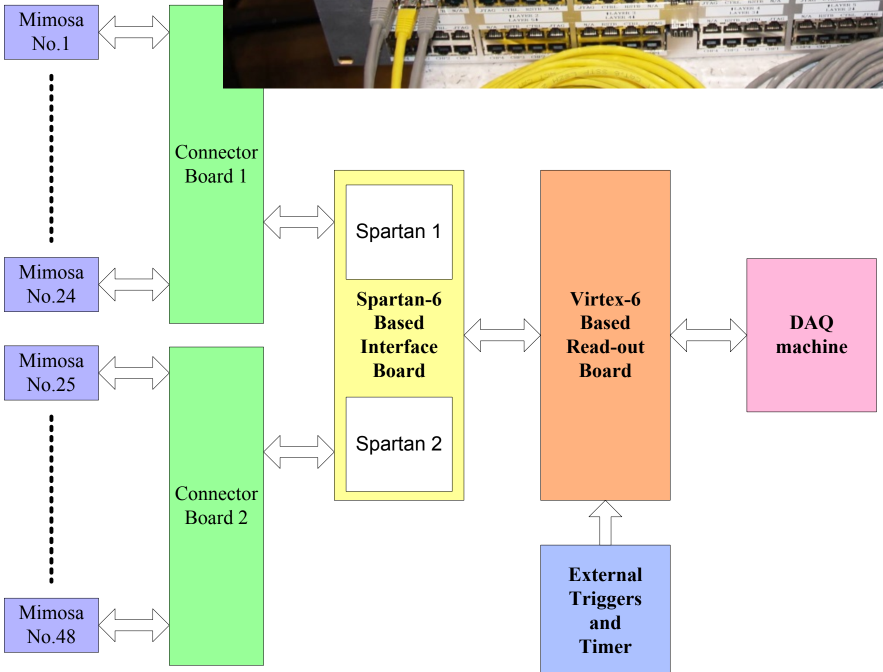
Integration of four sensors per layer

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)

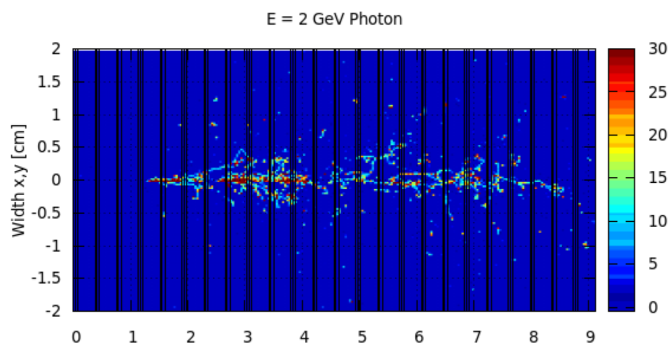


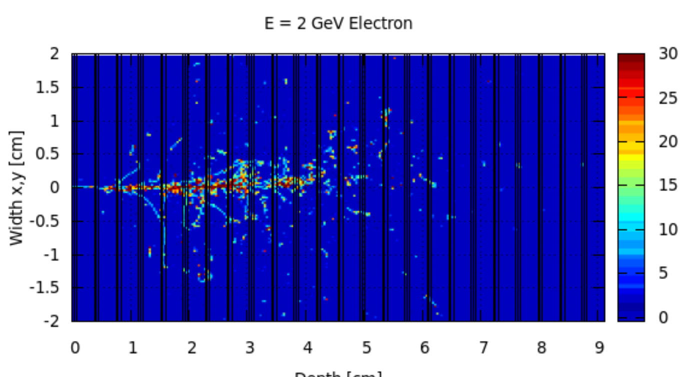


Simulation results

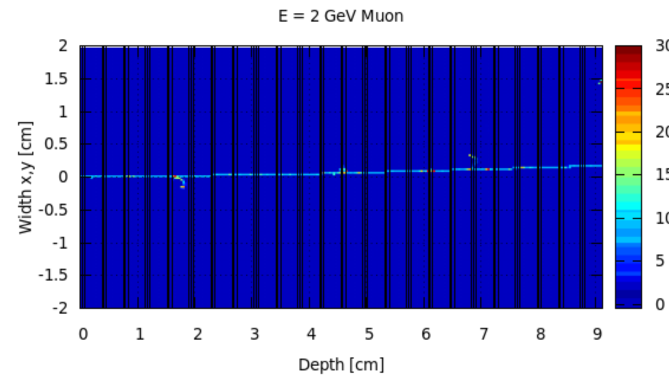
Detector response

Photons and electrons (e.m. shower)

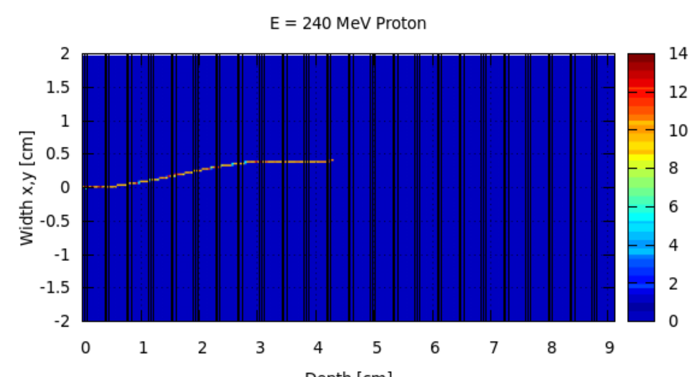




muons (MIP)



protons



Test beam results

Digital calorimeter

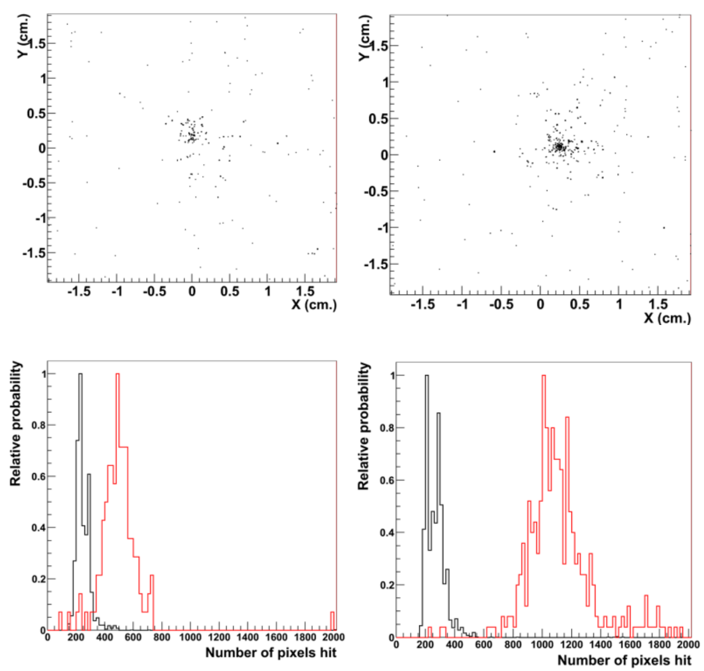
- particle counting method -
  number of hits should be proportional to the particle energy
- does it work for electromagnetic showers?

electrons

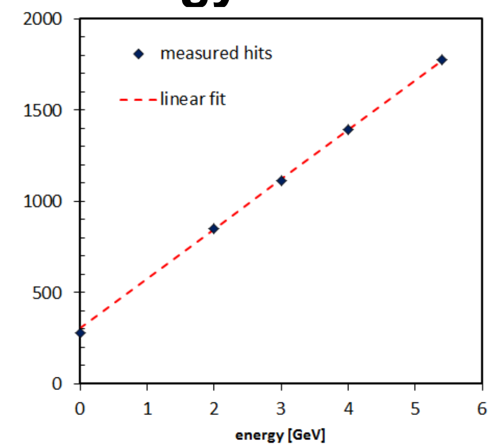
2 GeV 5 GeV

shower pattern

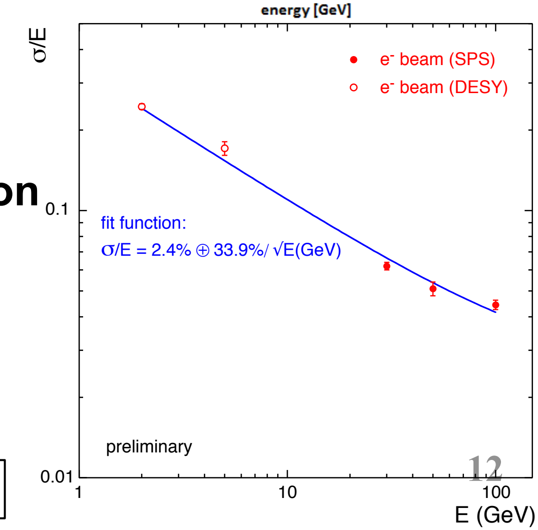
hit distribution



linearity

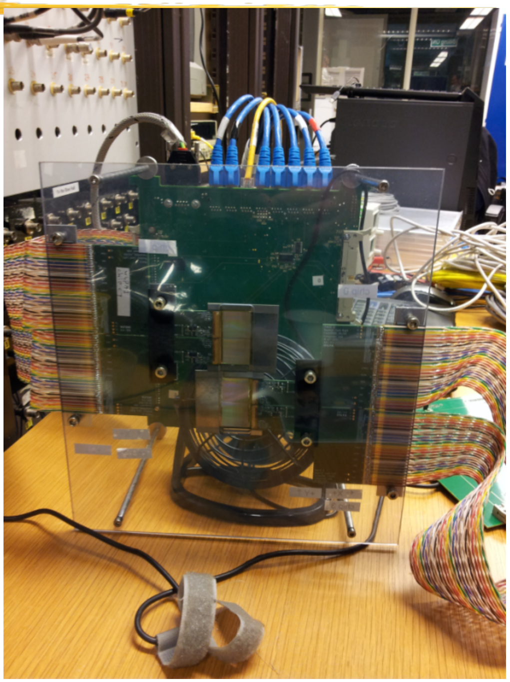


energy resolution (preliminary)



E. Rocca, ICHEP 2014

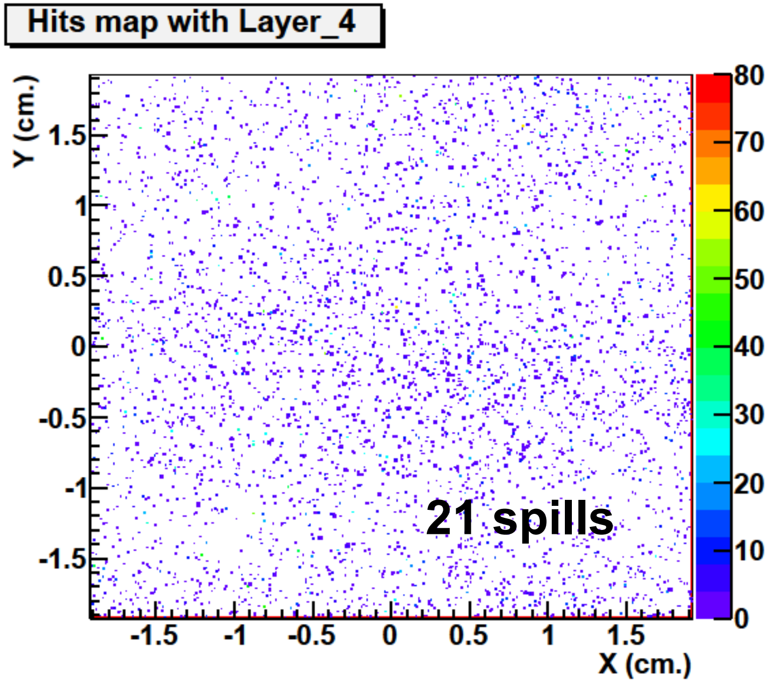
Digital tracking calorimeter – rangemeter (I)



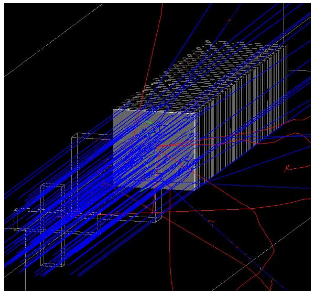
Range measuring resolution

- **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 μsec), 800 protons per spill



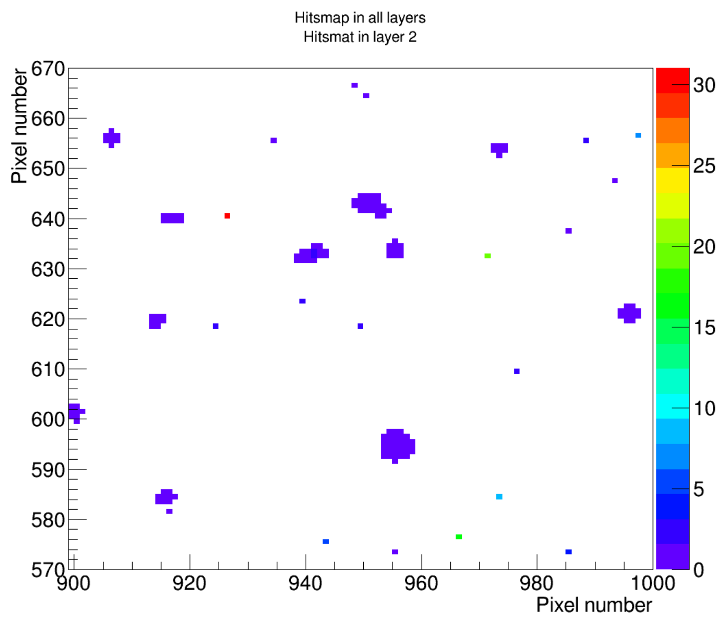
single track in 4 layers



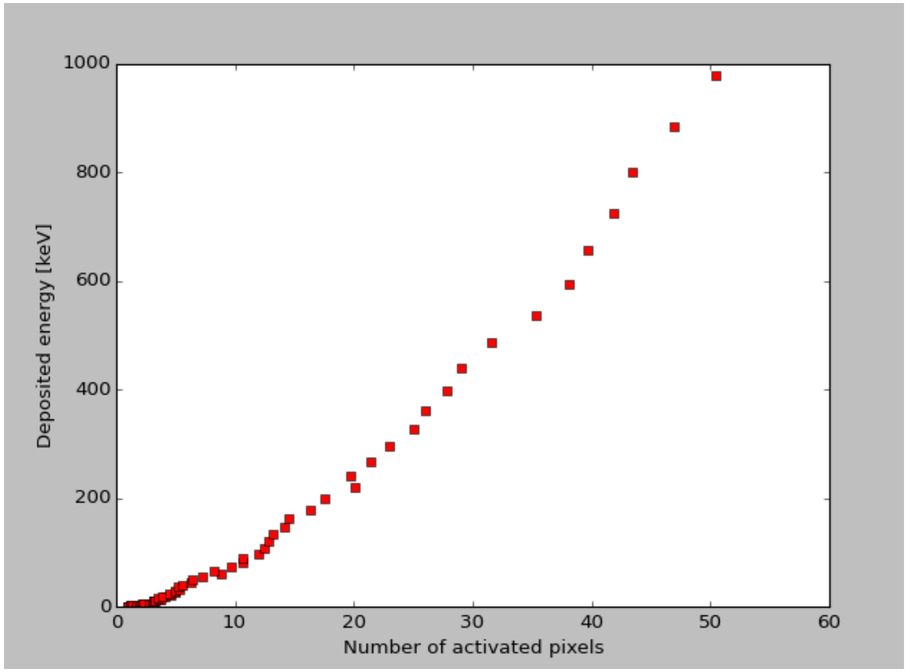
broad beam spot

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

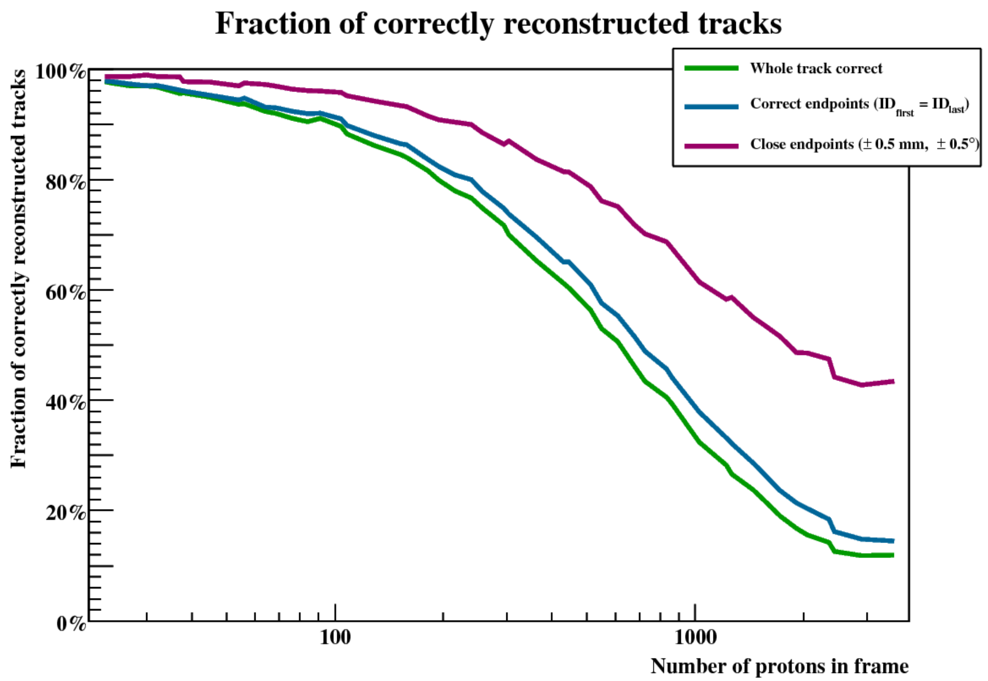
Digital tracking calorimeter – rangemeter (III)

Tracking in high occupancy environment

H. Pettersen

- **Data taking**
  - **1 proton per read-out frame (640 μsec)**

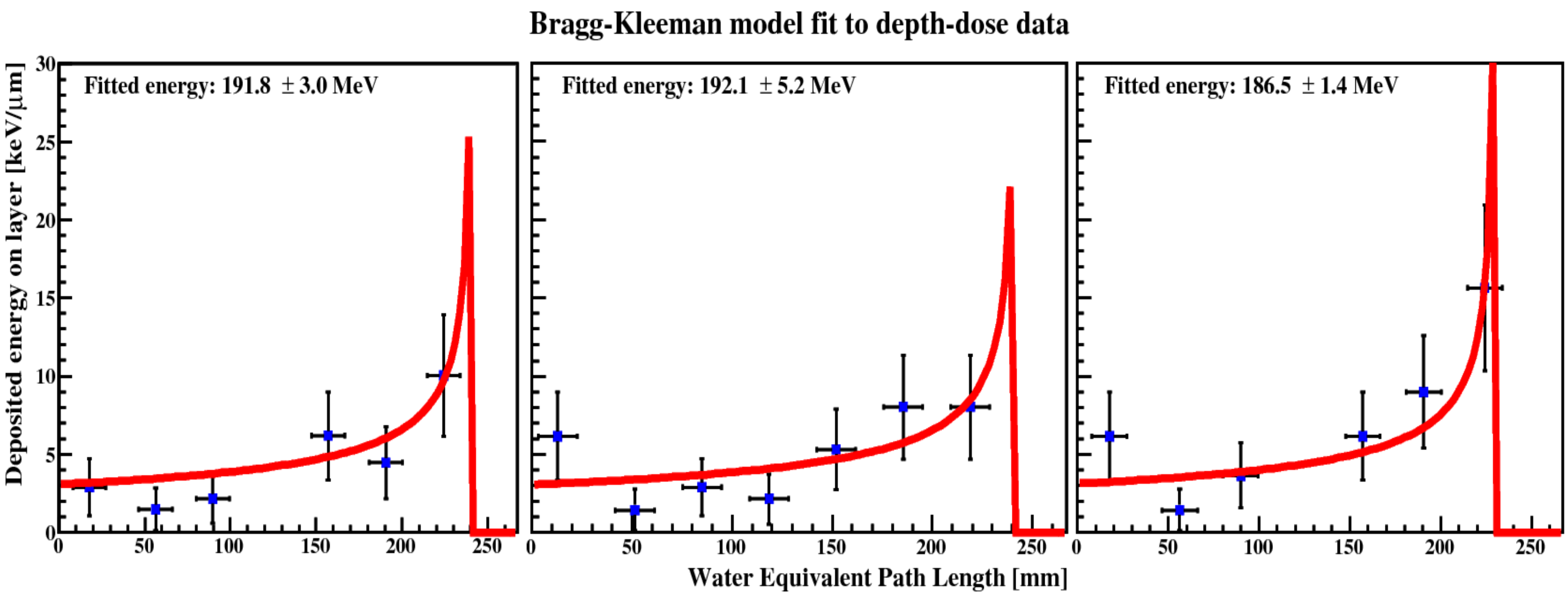
- **Occupancy simulation**
  - **Add several raw data frames and repeat tracking**



-> capable of tracking about 10^4 protons/cm^2/sec

Digital tracking calorimeter – rangemeter (IV)

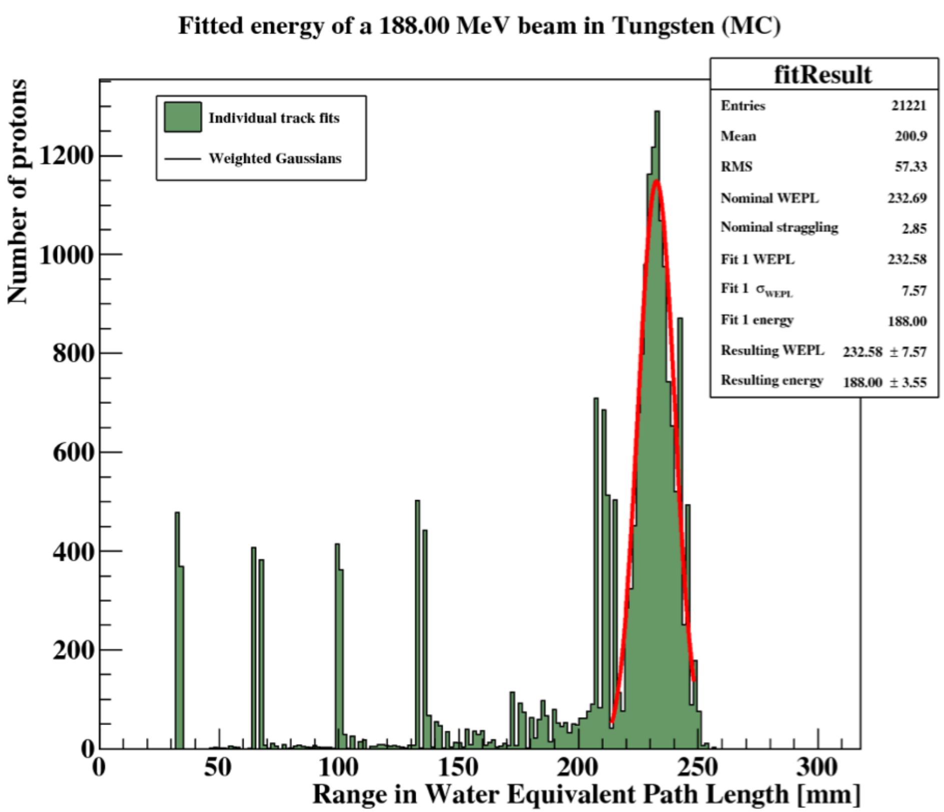
- **Tracking of a single proton, collecting clusters along the trajectory and fitting a Bragg curve***

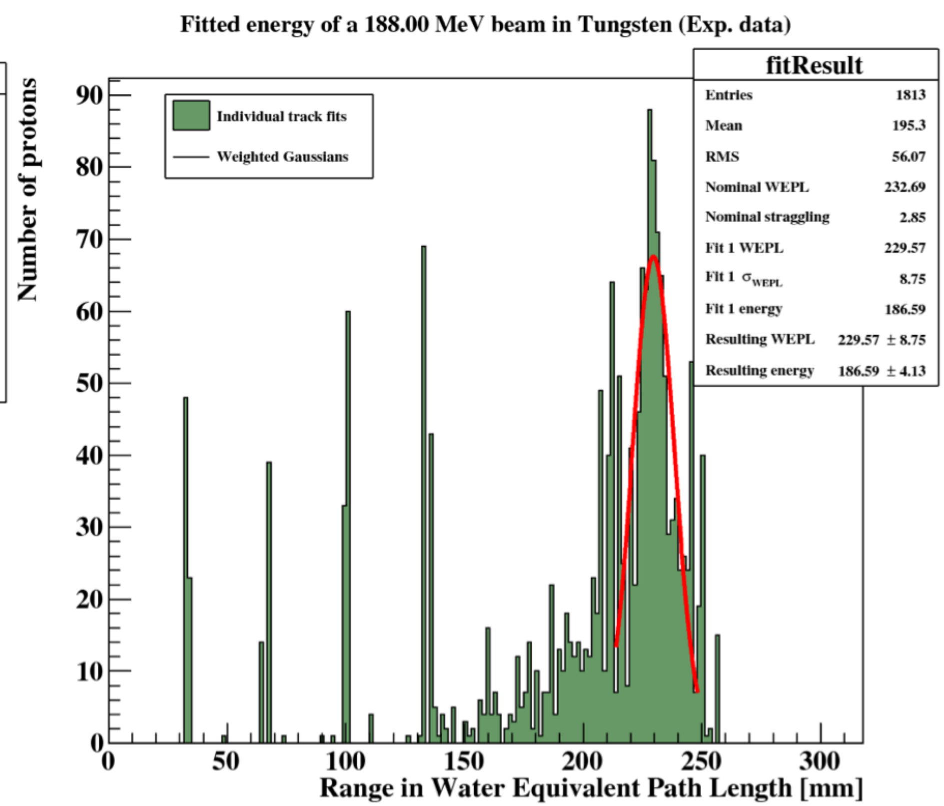


* Bortfeld, T. *An Analytical approximation to the Bragg curve for therapeutic proton beams.* Med. Phys 24 2024-33 (1997)

Digital tracking calorimeter – rangemeter (V)

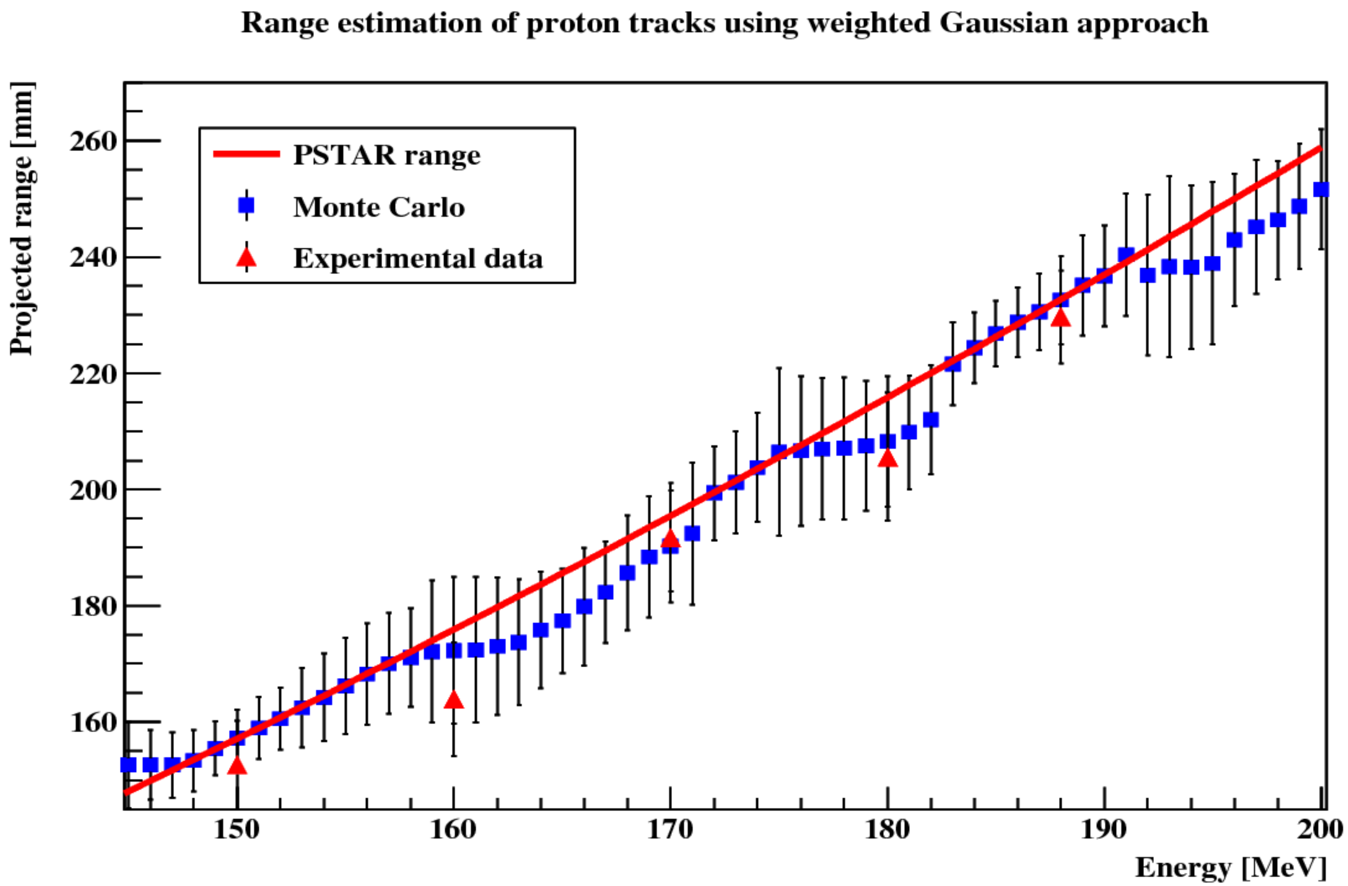
- **Energy/range resolution for 188 MeV protons**





Digital tracking calorimeter – rangemeter (VI)

- **Range vs proton beam energy**



-> good agreement between data and MC

Towards a clinical prototype – Bergen pCT Collaboration

- **Organisation**
  - UiB, HiB, HUS
  - 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**
  - Optimisation of the design
  - Submission of next generation 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

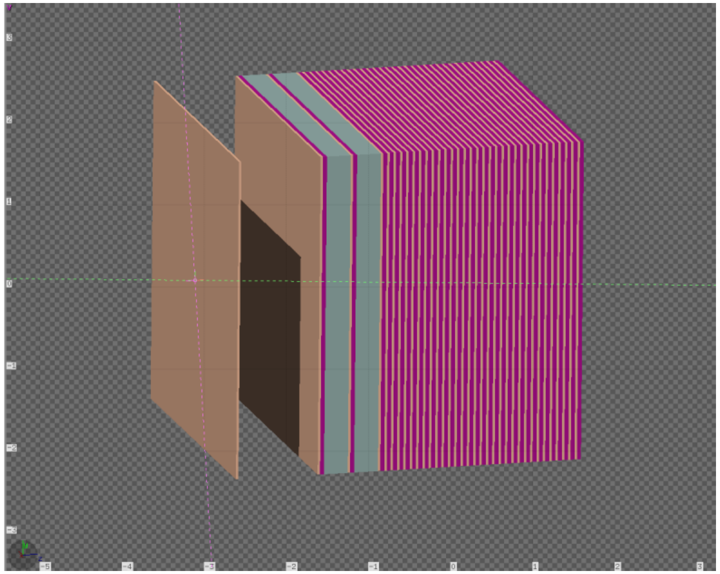
WP4: Assembly
- Assembly of chips into HICs/staves
- Assembly of staves into layers

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

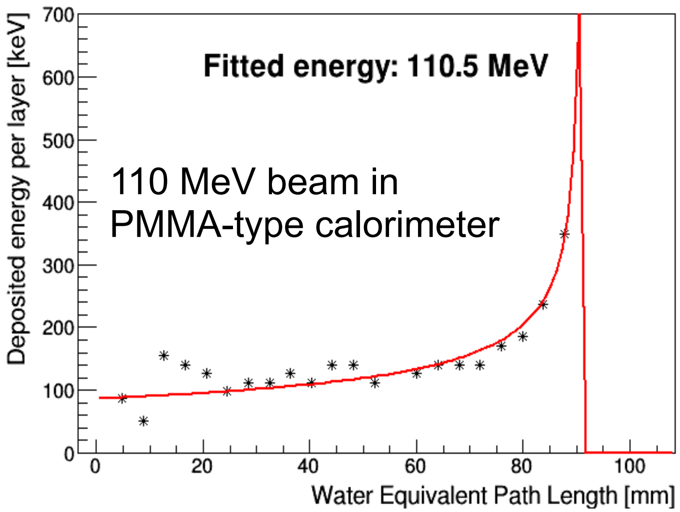
WP7: Reconstruction software
- Calorimeter response
- Calorimeter track reconstruction
- Reconstruction of 3D trajectory – track vector matching
- 3D stopping power map

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, carbon fiber
  - thickness (3 mm at the moment)

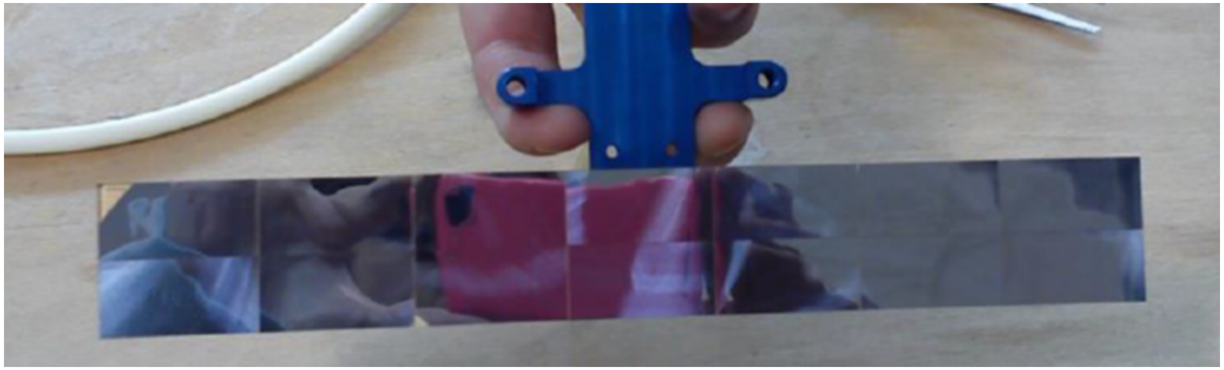


Towards a clinical prototype (II)

Optimisation of the design

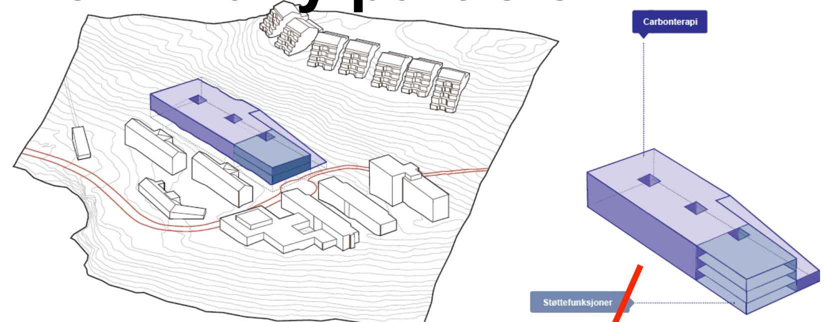
- **sensors – MAPS**
  - **ALPIDE (CERN, INFN, CCNU, Yonsei)**
    - **sensor for the upgrade of the inner tracking system of the ALICE experiment at CERN**
    - **chip size ≈ 3x1.5 cm^2, pixel size ≈ 28 μm, integration time ≈ 4 μs**
    - **on-chip data reduction (priority encoding per double column)**

M. Magner, IFEE 2014



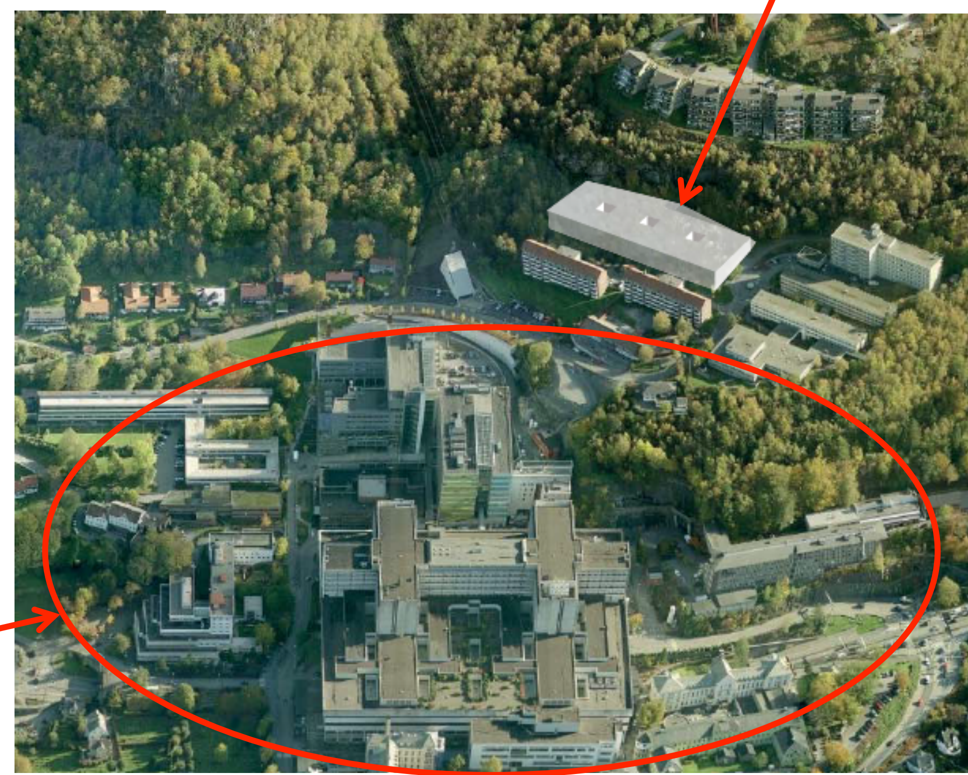
Hadron therapy in Norway

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