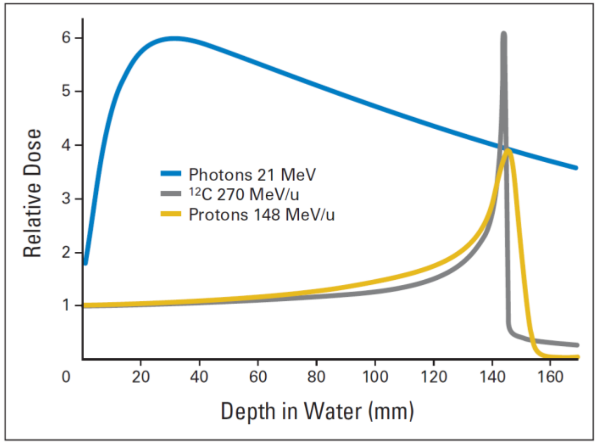
Proton-CT
&
Digital tracking calorimeter

Dieter Roehrich
University of Bergen
&
Bergen pCT group

- **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



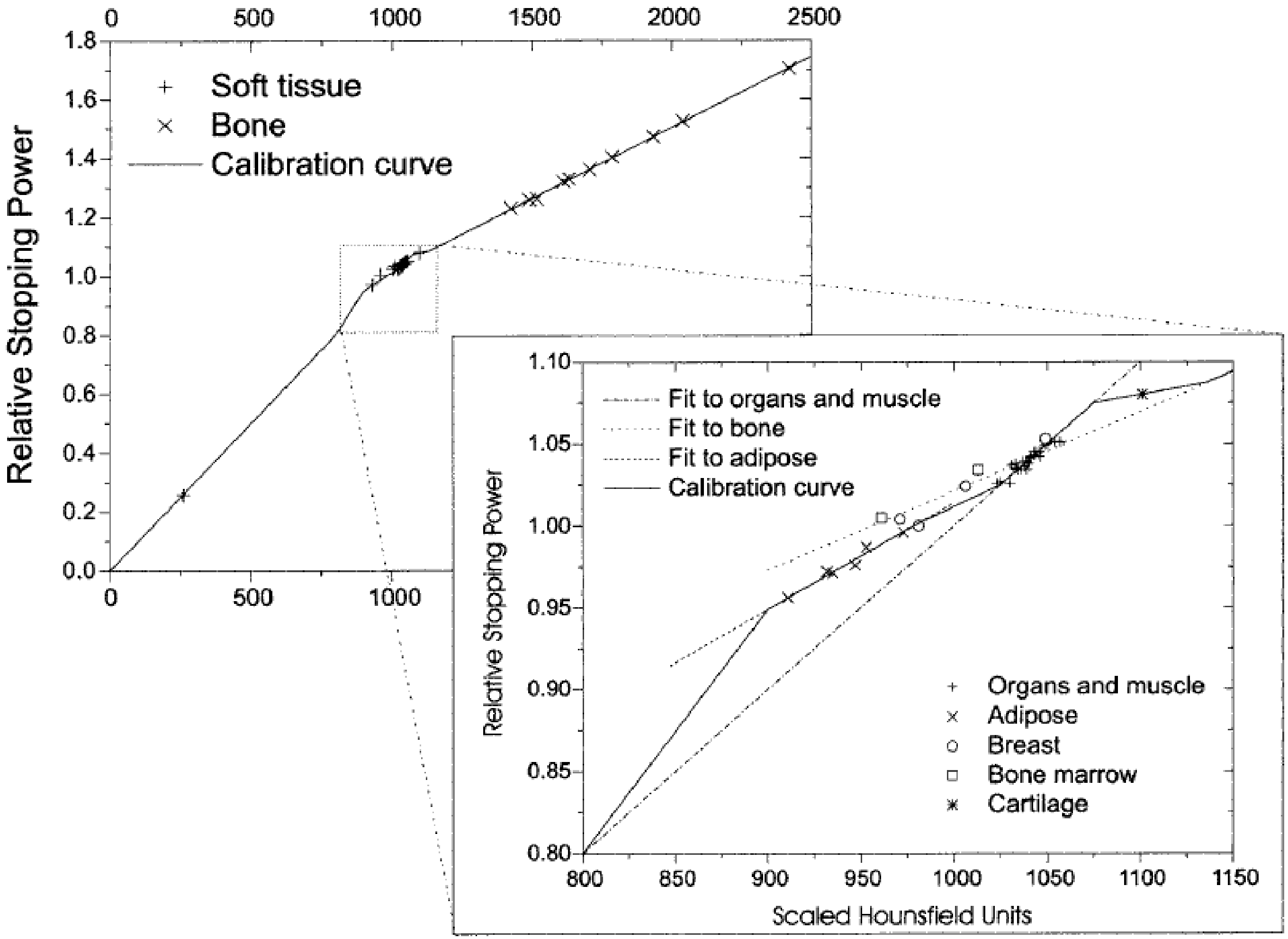
- **Key advantage of ions: Bragg peak**
  - **Relatively low dose in the entrance channel**
  - **Sharp distal fall-off of dose deposition (<mm)!**

- **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 ~ (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) 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

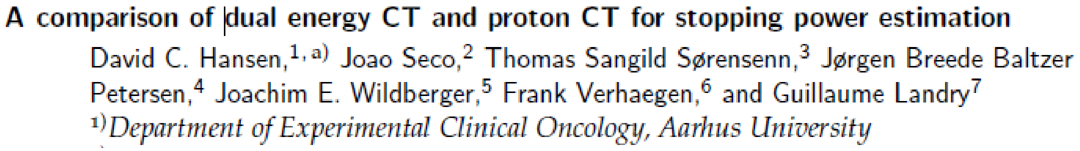
How to deal with range uncertainties in the clinical routine?

- Increase the target volume by up to 1 cm in the beam direction
- Avoid beam directions with a critical organ behind the tumor

Unnecessary limitiations -> reduce range uncertainties

Estimates for advanced dose planning:

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

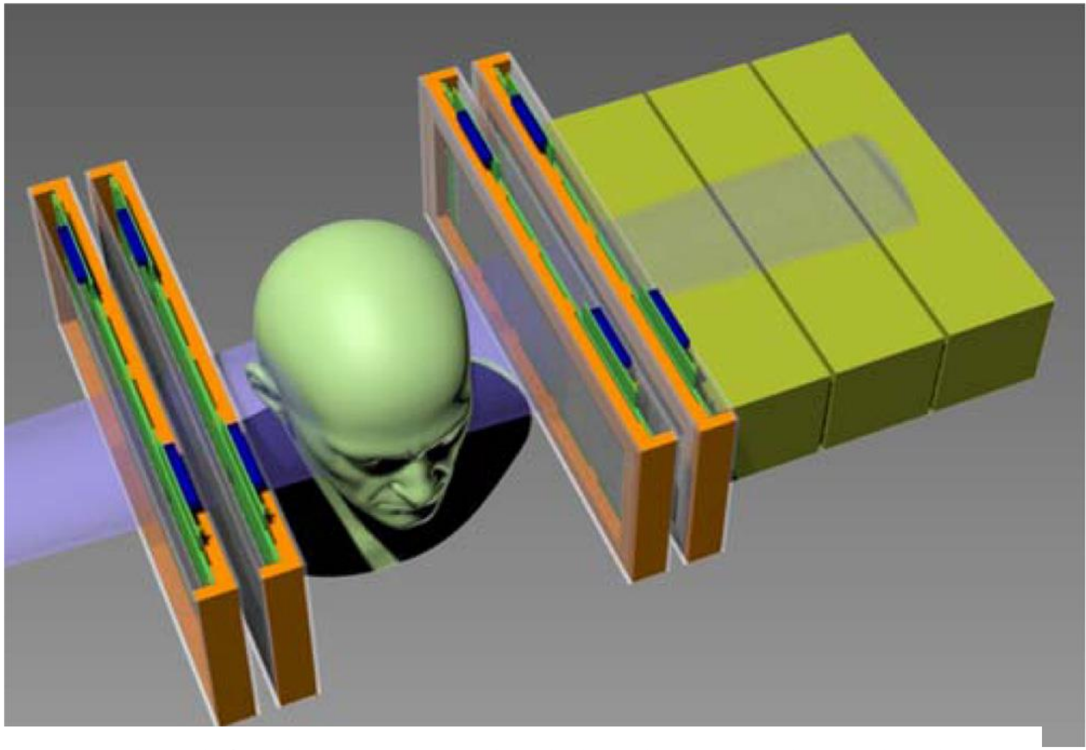


A comparison of dual energy CT and proton CT for stopping power estimation

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

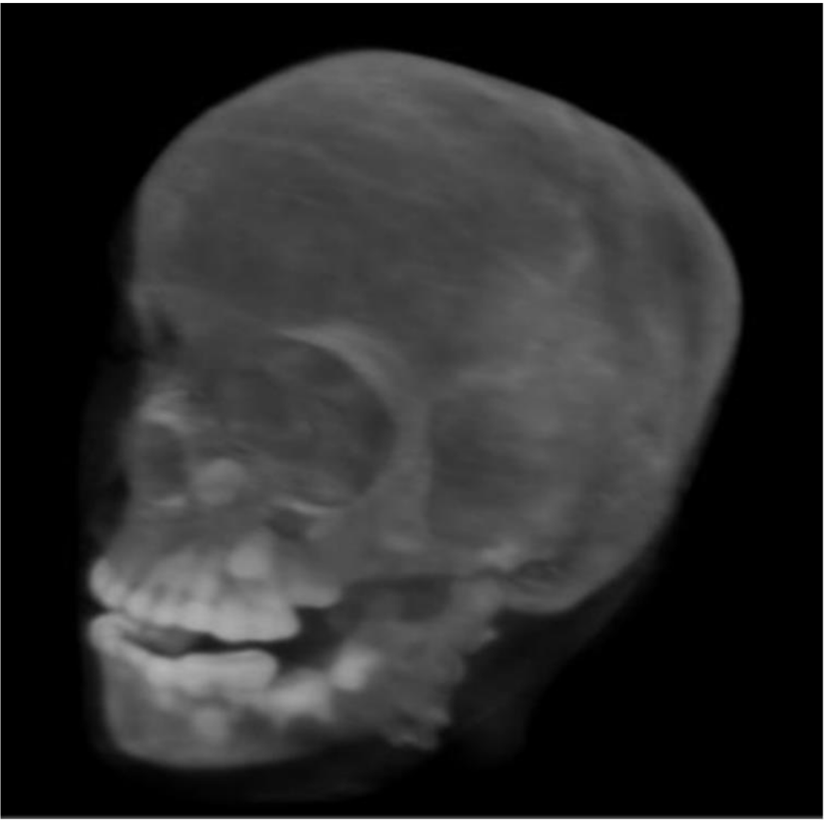
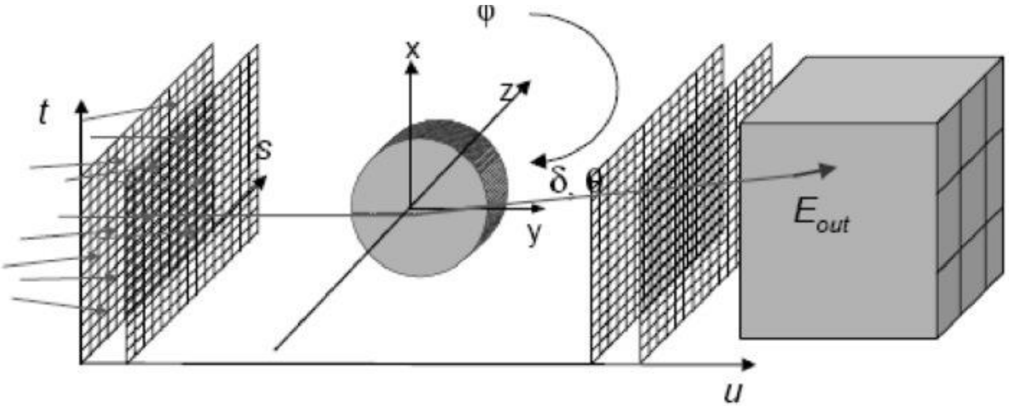


Fig. 14. 3D rendering of the pCT-reconstructed RSP map of a pediatric anthropomorphic head phantom.

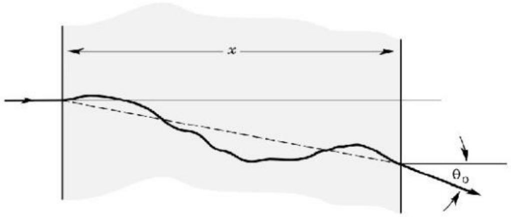
V.A. Bashkirov et al. / Nuclear Instruments and Methods in Physics Research A 809 (2016) 120–129

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
    - nuclear interactions (inelastic collisions)
    - multiple Coulomb scattering (elastic collisions)
    - energy loss dE/dx (inelastic collisions with atom



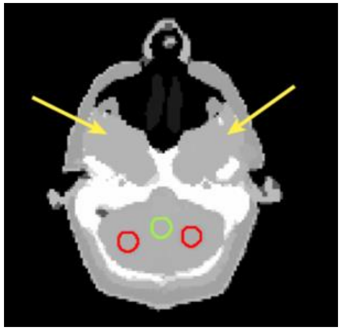
- MS theory and Bethe-Bloch formula of average energy loss in turn depend on electron density in the target (and ionization potentials)

  -> 3D map of electron density in target

  -> online verification of dose plan

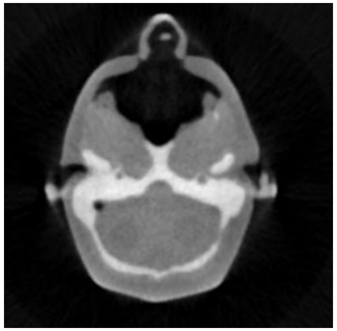
Proton-CT - images

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

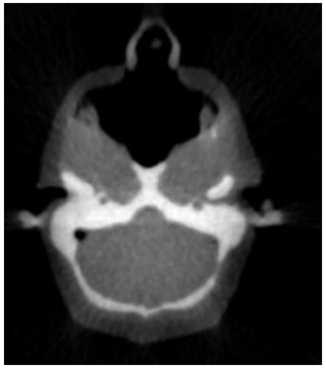


Phantom

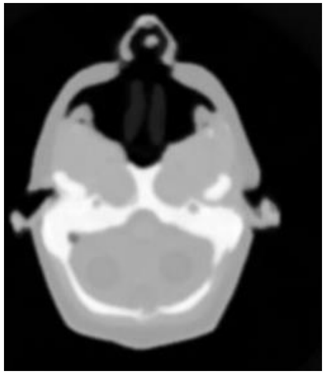
  - **Transmission map**
    – records loss of protons due to nuclear reactions



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



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

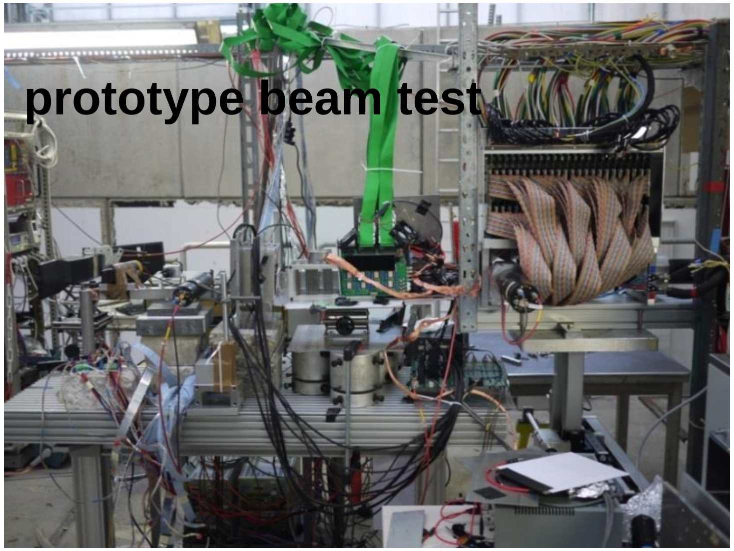


Cecile Bopp. PhD thesis, Strassbourg, 2013

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

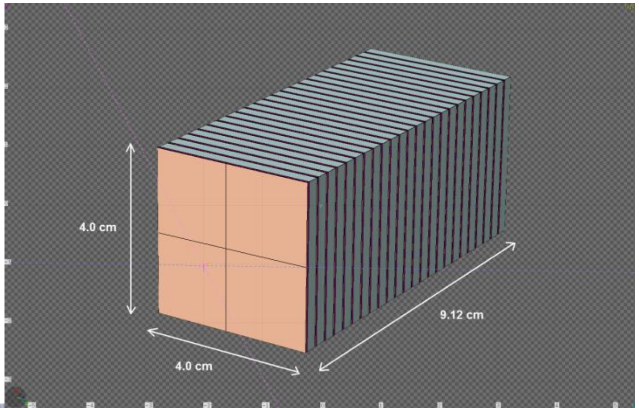


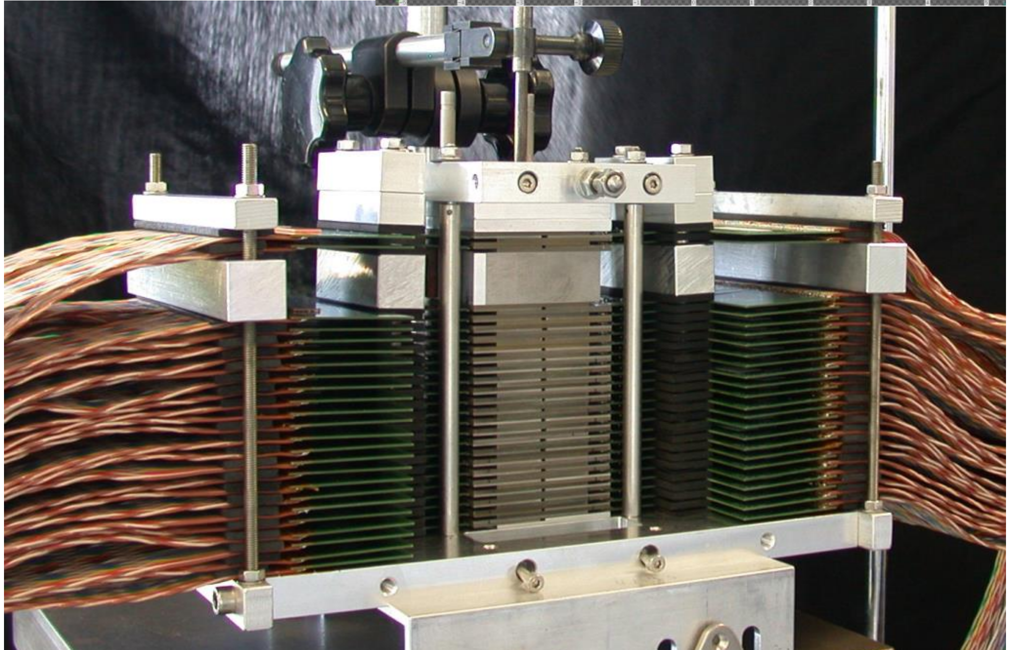
prototype beam test

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 (≈ 1 X_0)
    Molière radius: 11 mm
  - active layers:
    MAPS – MIMOSA 23*
    4 chips per layer
    -> 96 chips in total





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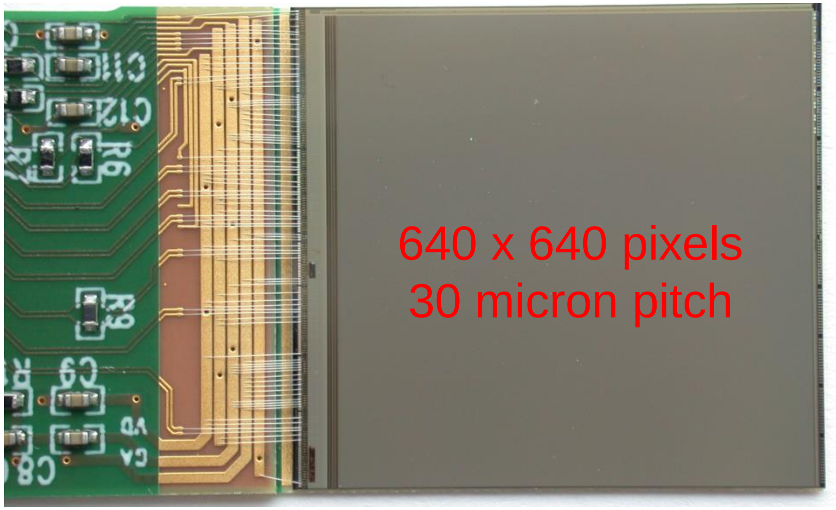
* IPHC Strasbourg

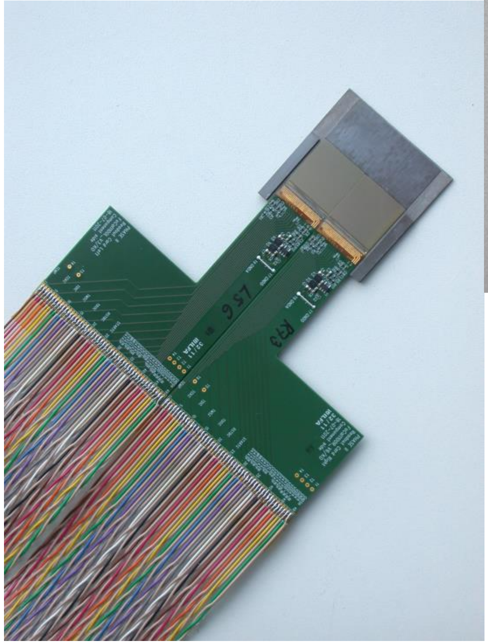
Digital tracking calorimeter prototype (II)

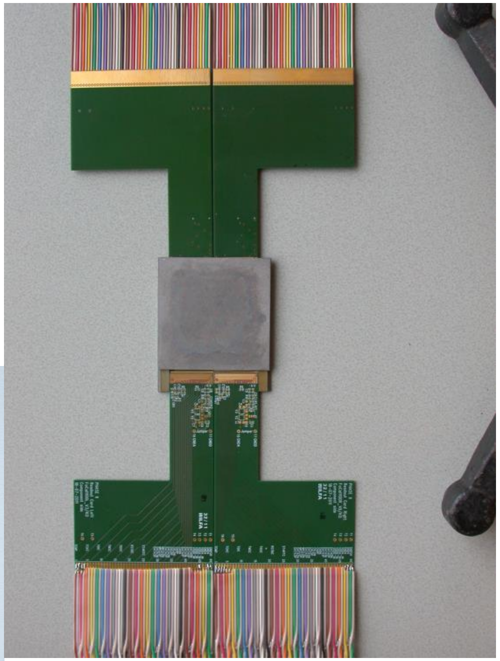
MIMOSA 23

- 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



640 x 640 pixels
30 micron pitch



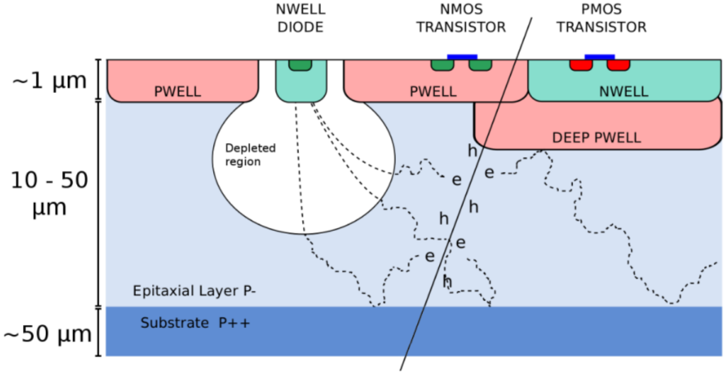


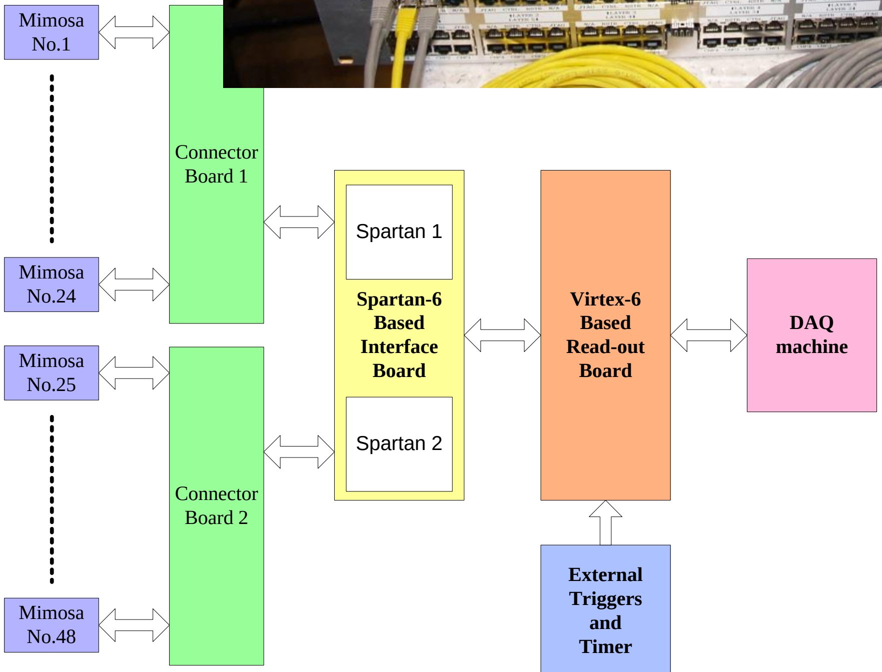
Integration of four sensors per layer

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)





Mimosa No.1

Mimosa No.24

Mimosa No.25

Mimosa No.48

Connector Board 1

Connector Board 2

Spartan 1

Spartan-6 Based Interface Board

Spartan 2

Virtex-6 Based Read-out Board

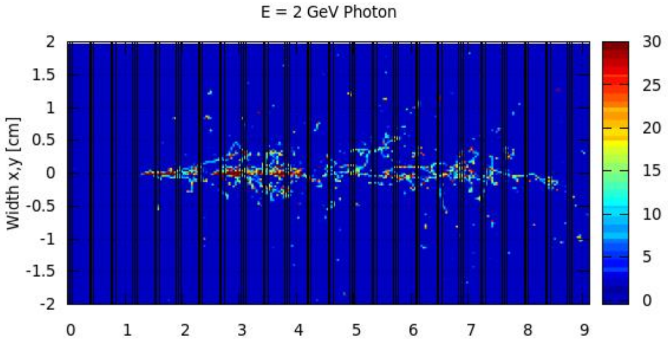
DAQ machine

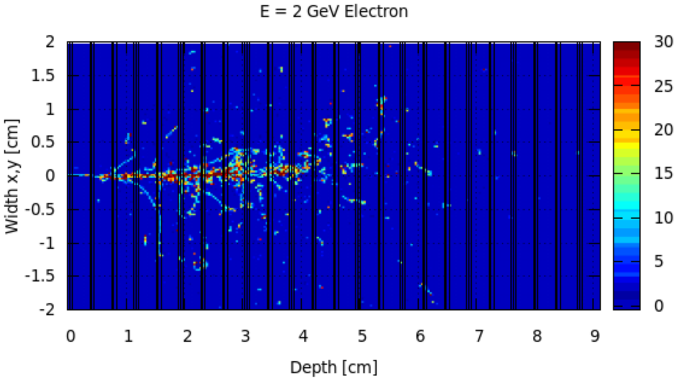
External Triggers and Timer

Simulation results

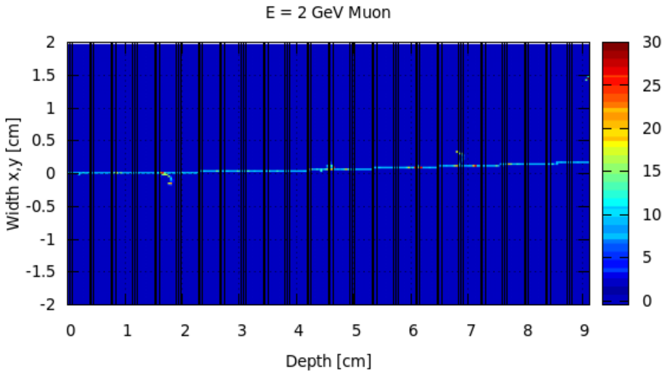
Detector response

Photons and electrons (e.m. shower)

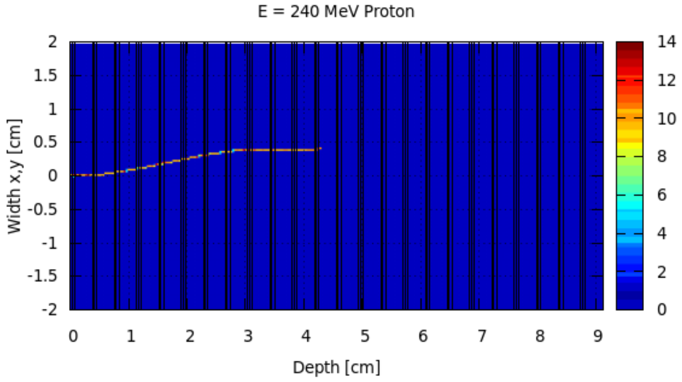




muons (MIP)



protons



Test beam results

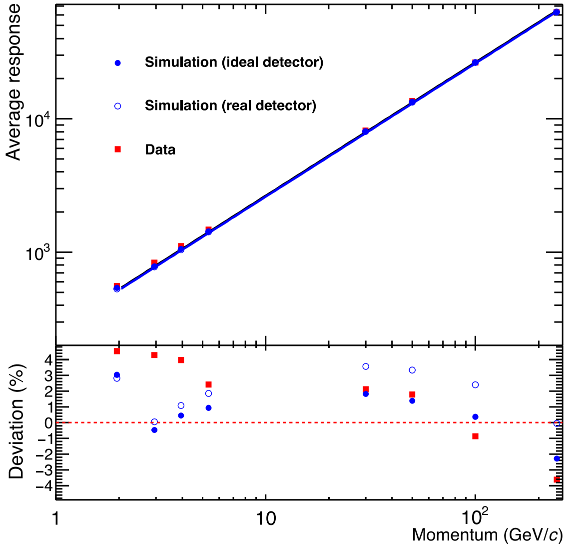
Digital calorimeter

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

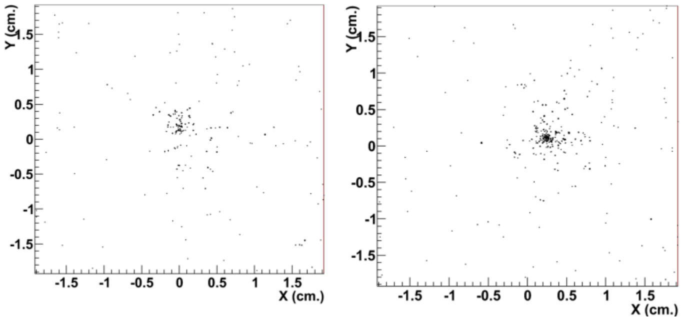
electrons

2 GeV **5 GeV**

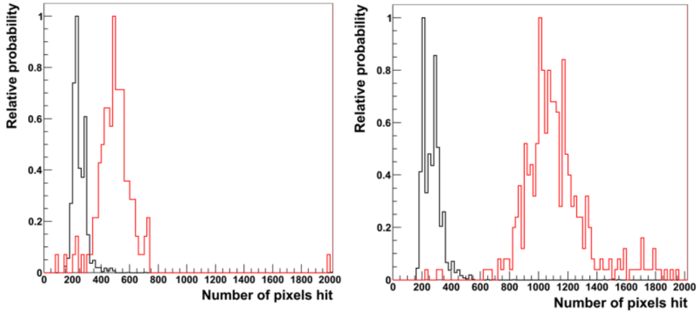
linearity



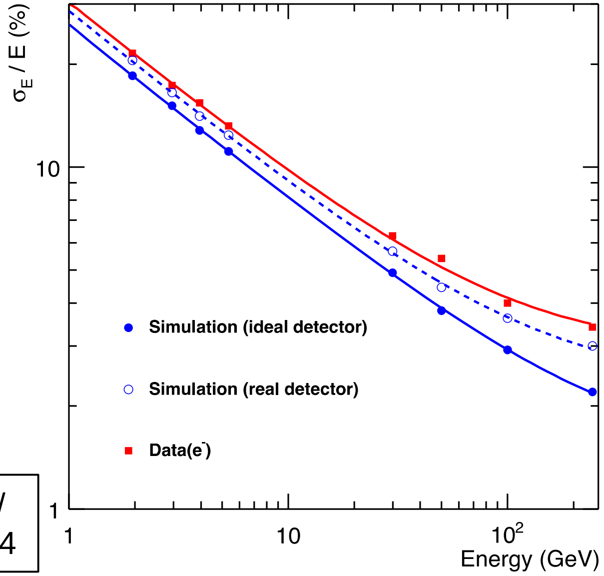
shower pattern



hit distribution



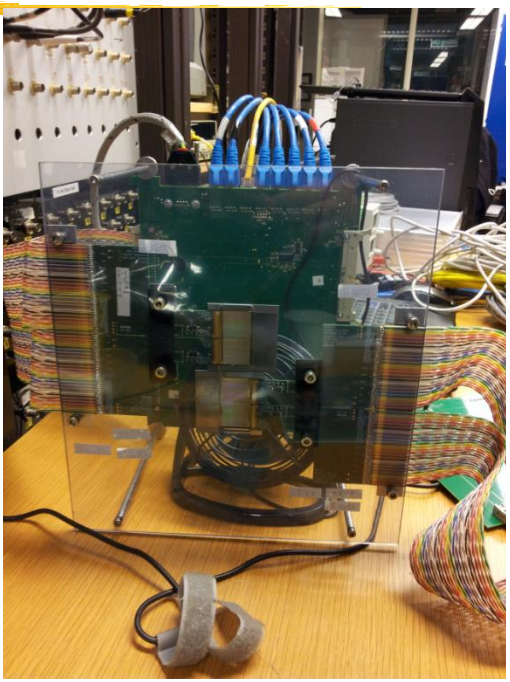
energy resolution



E. Rocca,
ICHEP 2014

http://arxiv.org/abs/1708.05164

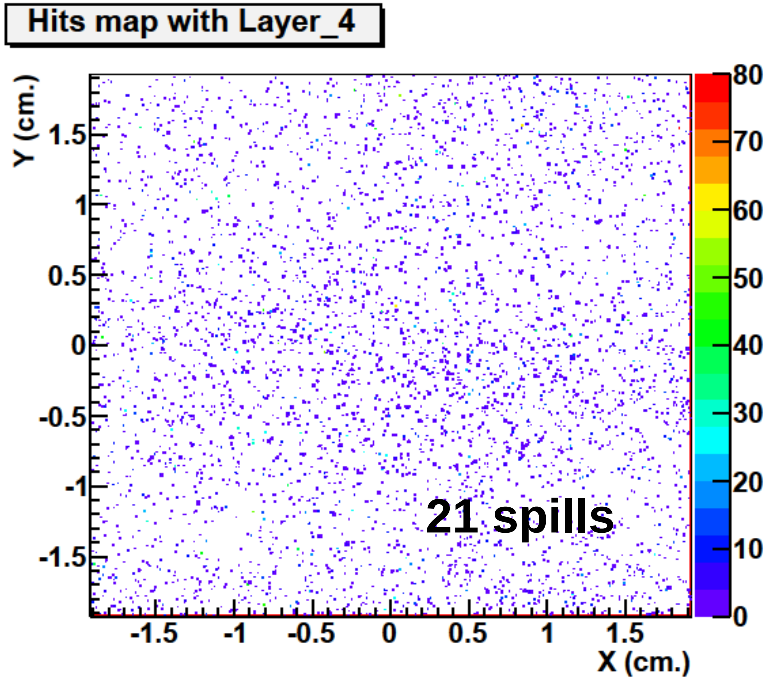
Digital tracking calorimeter – rangemeter (I)

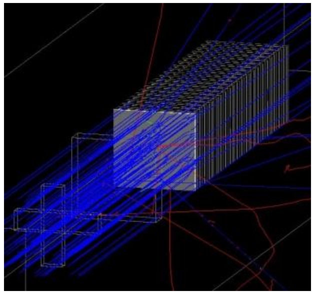


Range measuring resolution

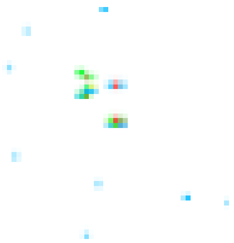
- **Stopping: proton beam tests at KVI (Groningen)**
  - **Full prototype (24 layers, tungsten absorber)**
    -> validation of simulations
  - **Energy: from 122 to 190 MeV**
  - **Intensity:**

    ≈ 1 proton per frame (640 μsec), 800 protons per spill





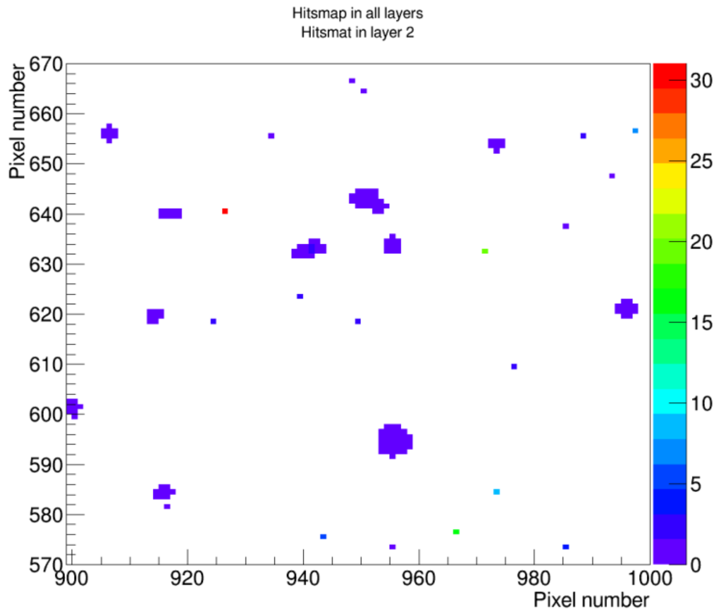
broad beam spot



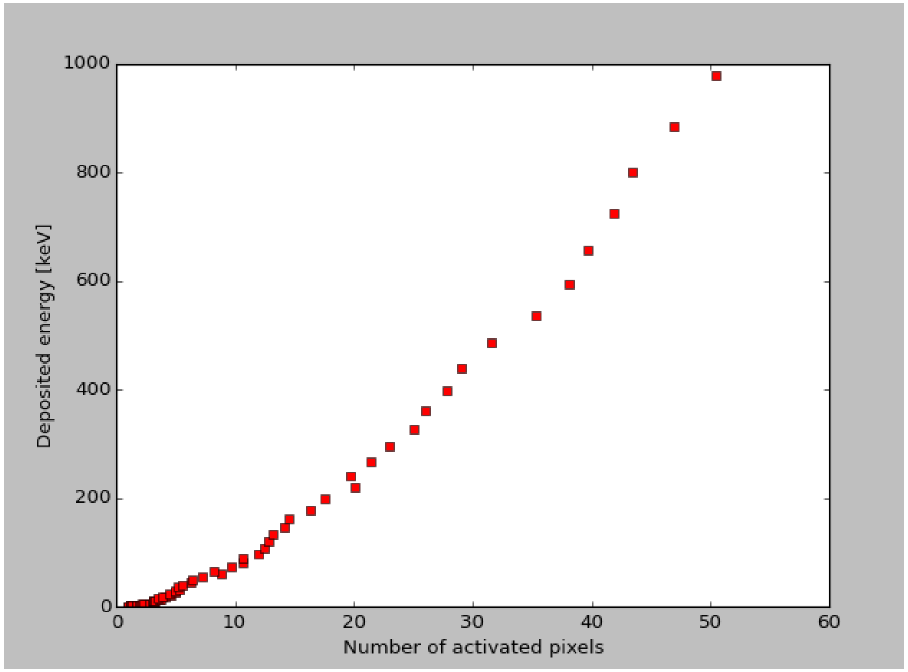
single track in 4 layers

Digital tracking calorimeter – rangemeter (II)

Range measuring resolution



H. Pettersen

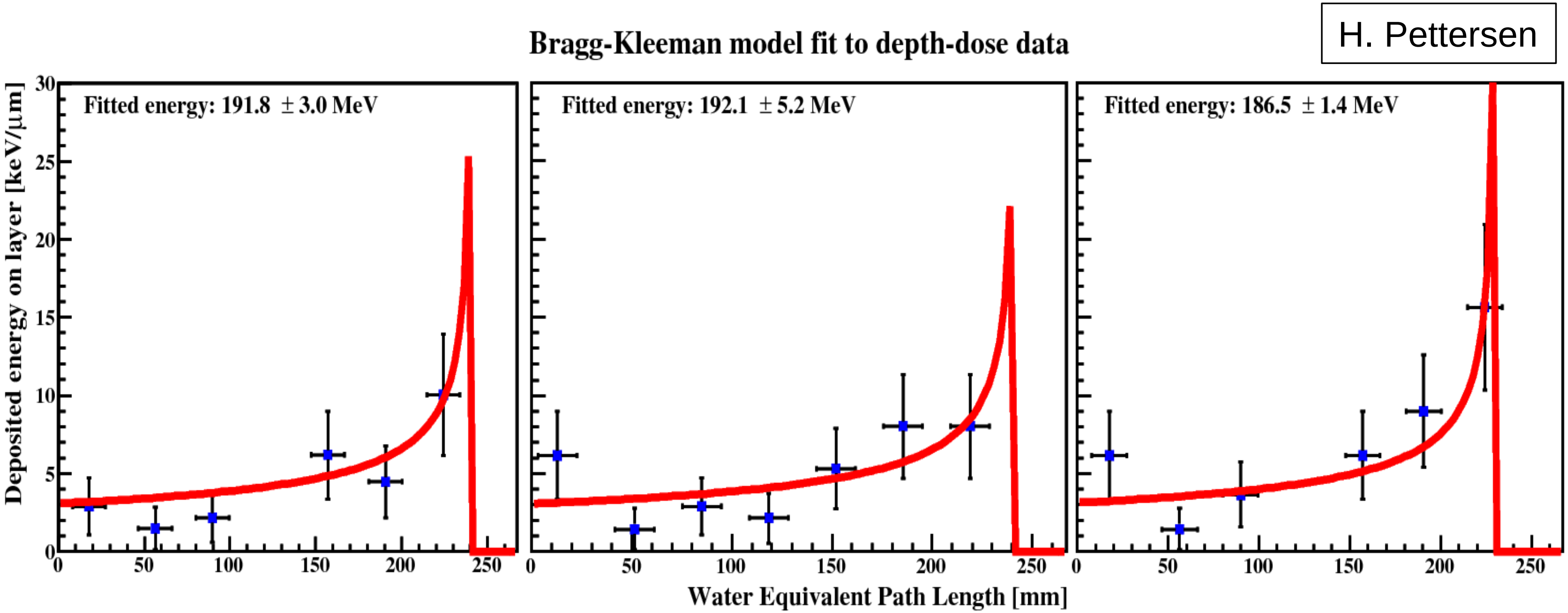


- **Energy loss measurement**
  - **hadron tracks:**
    number of hits in a sensitive layer along the particle trajectory ("cluster size") depends (weakly) on the energy loss

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

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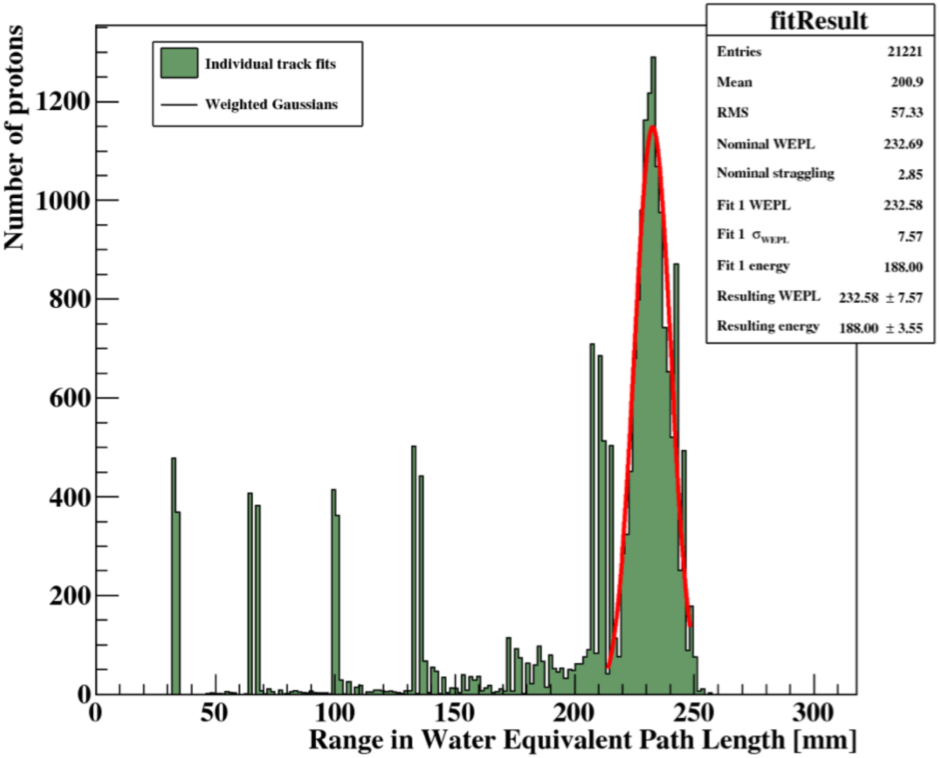
* Bortfeld, T. *An Analytical approximation to the Bragg curve for therapeutic proton beams.* Med. Phys 24 2024-33 (1997)

Digital tracking calorimeter – rangemeter (V)

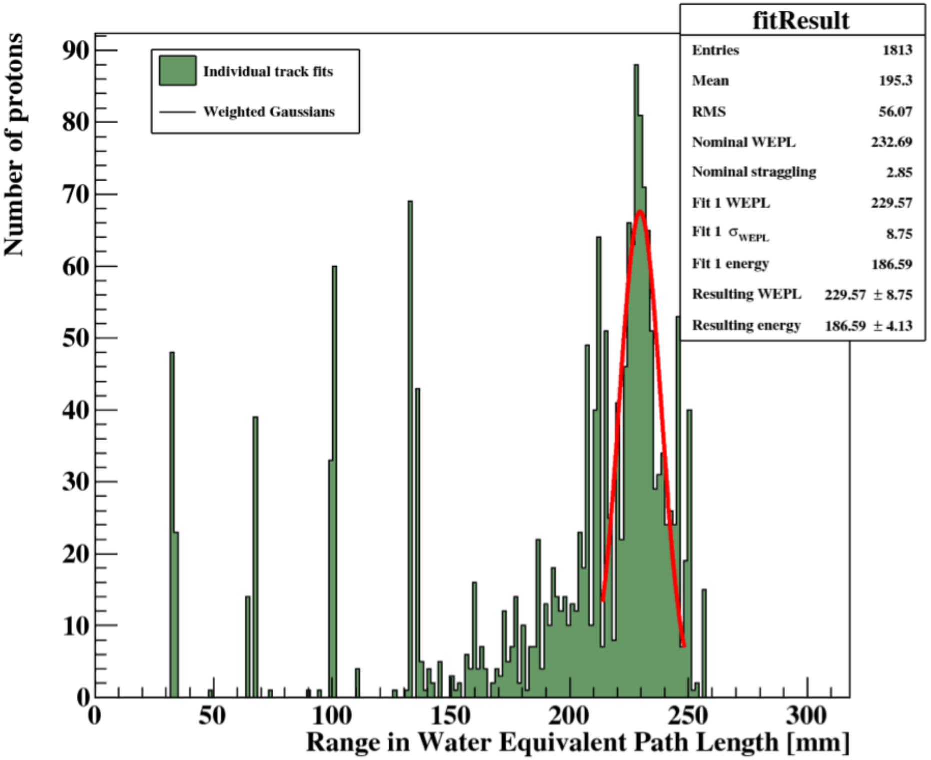
- **Energy/range resolution for 188 MeV protons**

H. Pettersen

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

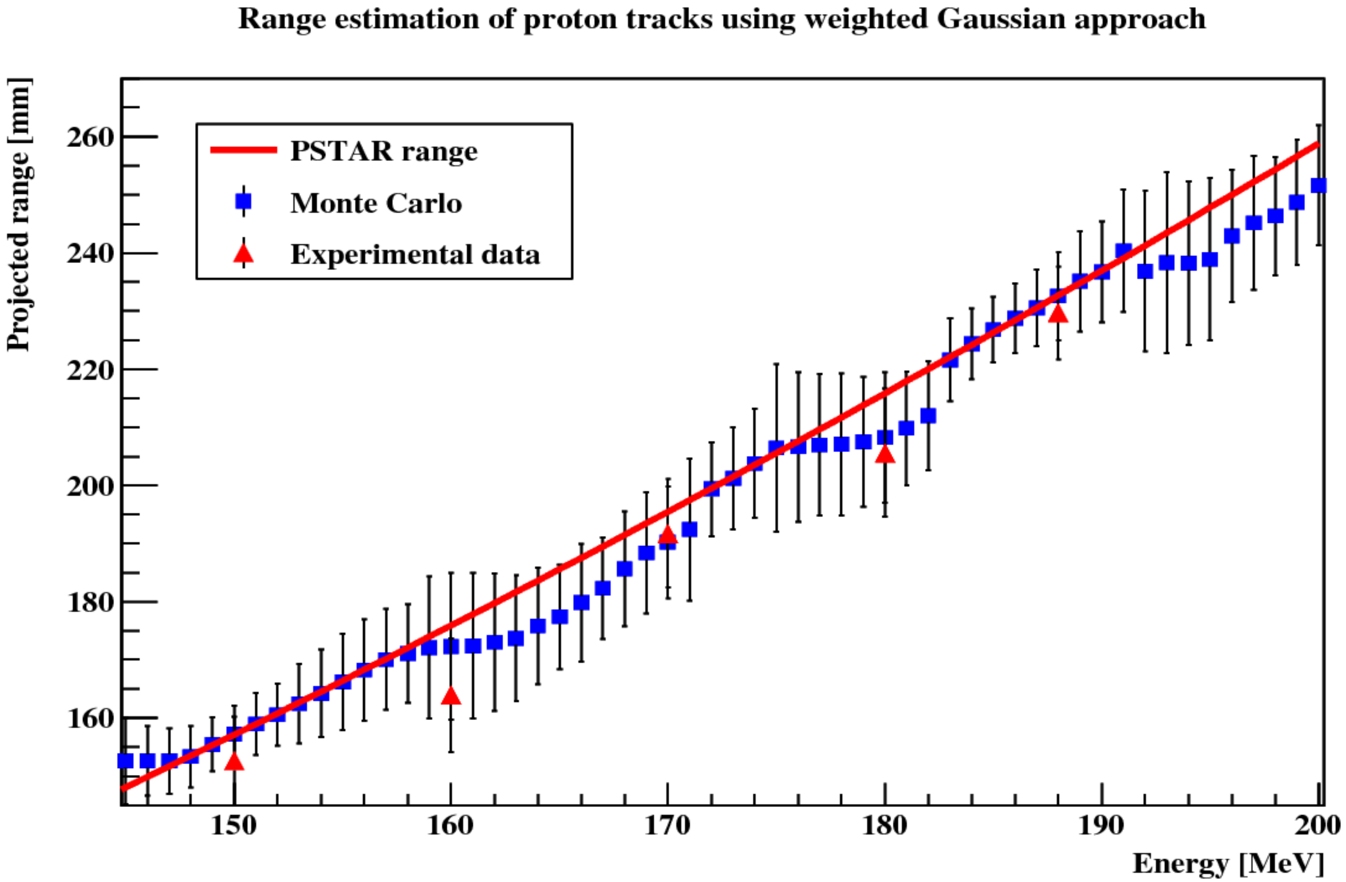


Fitted energy of a 188.00 MeV beam in Tungsten (Exp. data)



Digital tracking calorimeter – rangemeter (VI)

- **Range vs proton beam energy**



-> 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**
  - 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

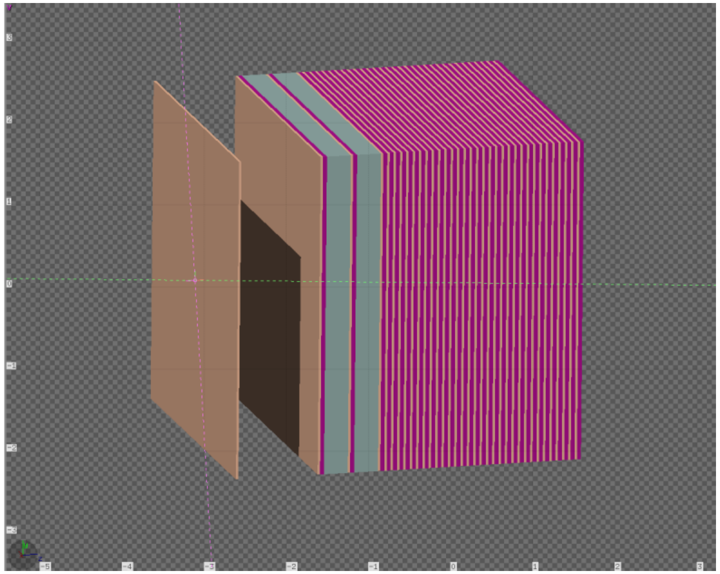
WP7: Reconstruction software

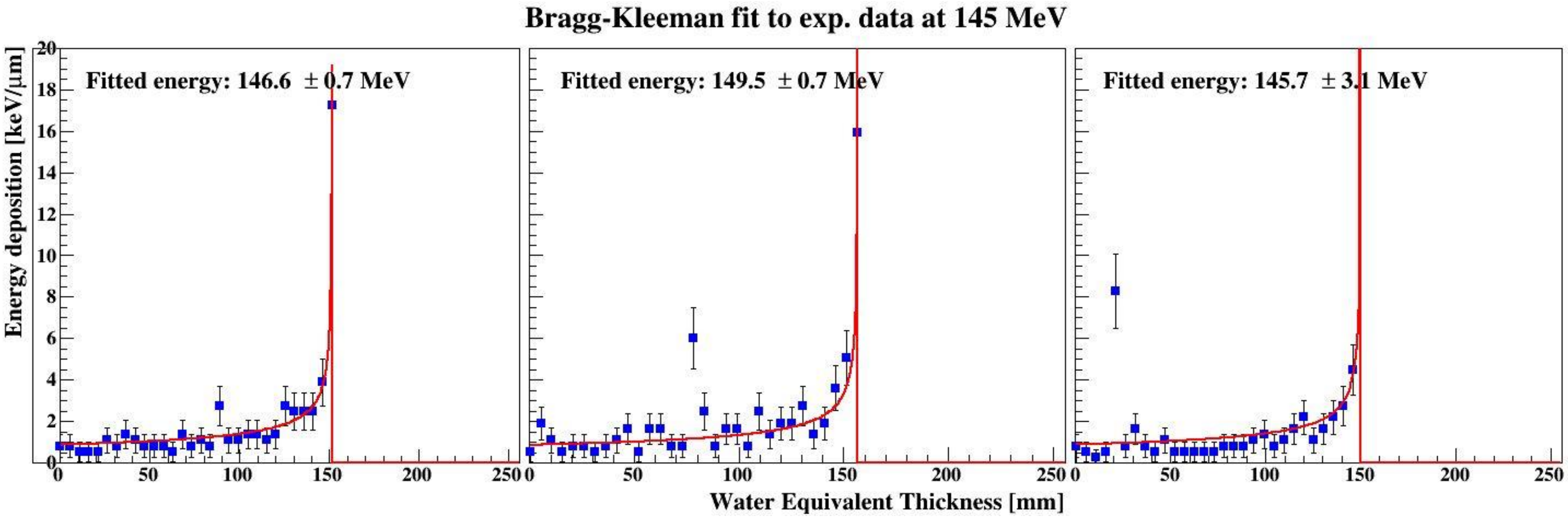
- Calorimeter response
- Calorimeter track reconstruction
- Reconstruction of 3D trajectory – track vector matching
- 3D stopping power map

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)

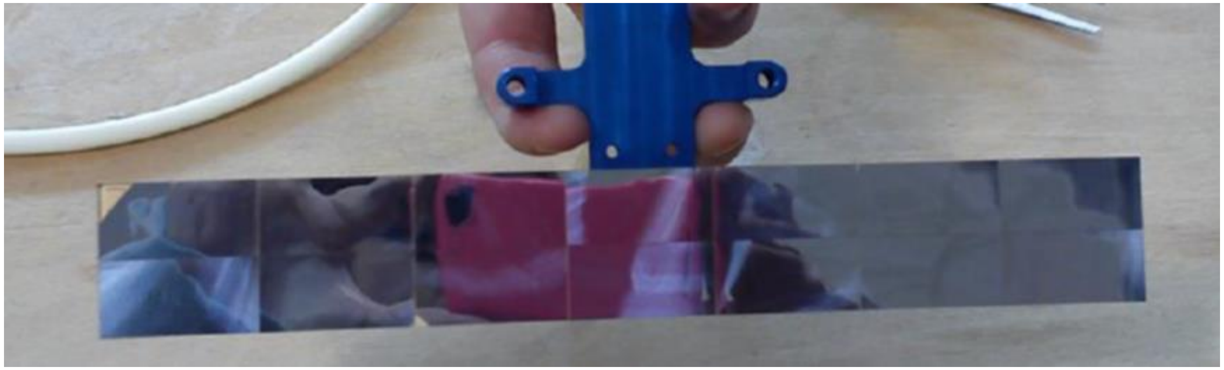




Towards a clinical prototype (II)

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 ≈ 3x1.5 cm^2, pixel size ≈ 28 µm, integration time ≈ 4 µs
    - on-chip data reduction (priority encoding per double column)

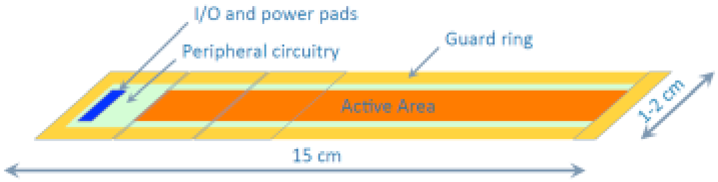


M. Magner, IFEE 2014

Towards a clinical prototype (III)

Strategy

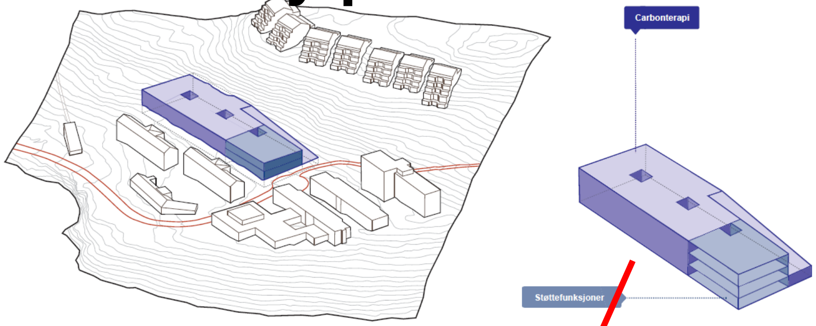
- Modular structure – exchangeable front layers (tracking and absorber layers)
- Use the existing ALPIDE chips as sensitive layers
- R&D project to tailure ALPIDE design to medical applications
  - Faster charge collection and readout: 4 μs -> < 1 ns
  - Larger sensors - wafer-scale integration by stitching



  - 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