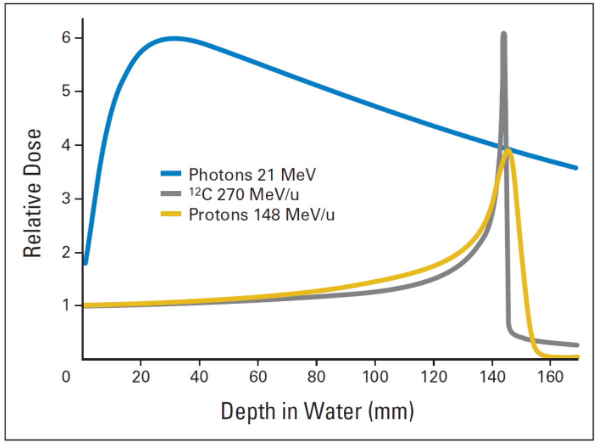
The Bergen proton CT project – proton tracking in a high-granularity digital tracking calorimeter

Dieter Roehrich
University of Bergen
for the
Bergen pCT collaboration

- **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)!**

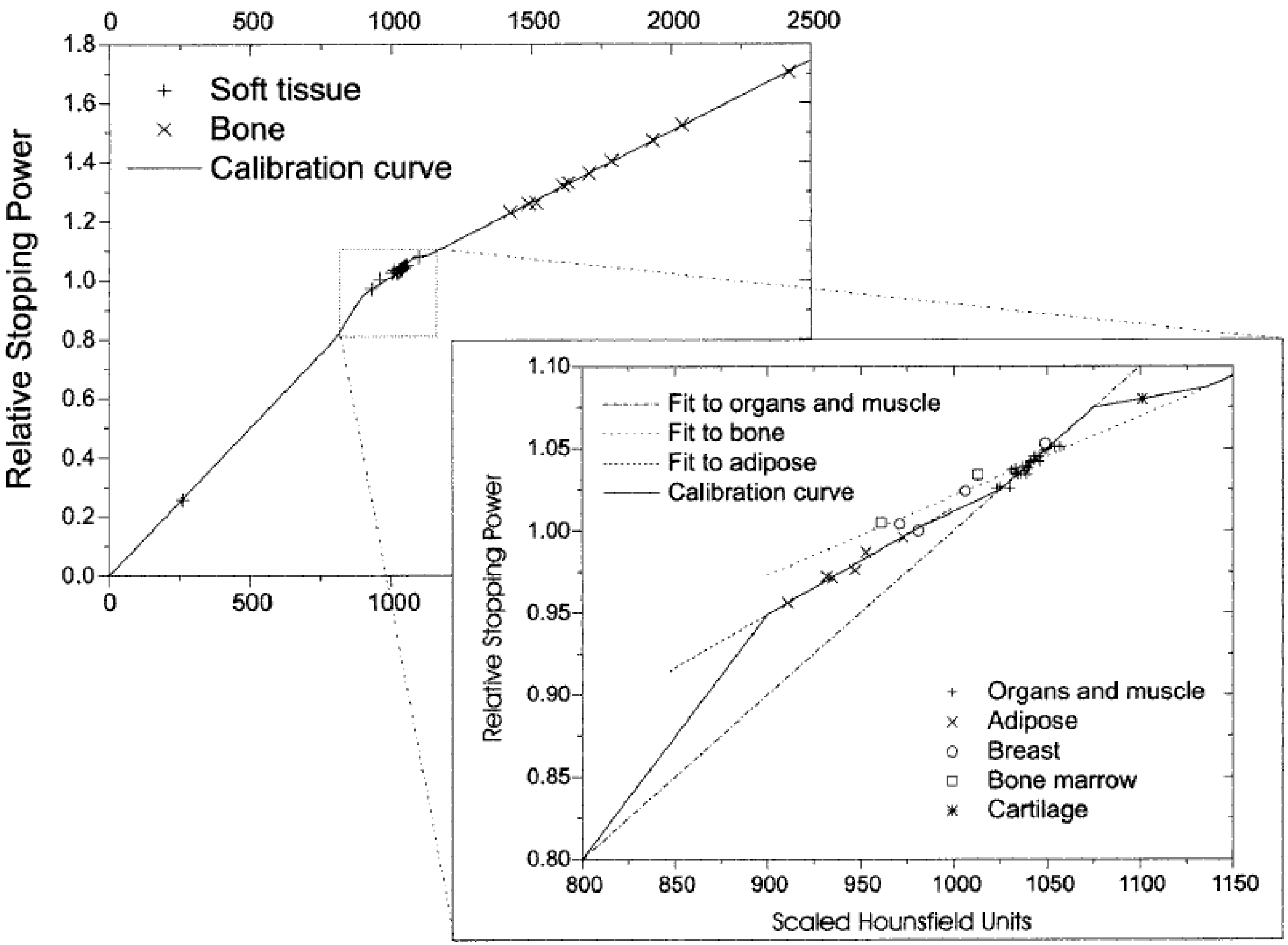


- **Challenge**
  - **Stopping power of tissue in front of the tumor has to be known – crucial input into the dose plan for the treatment**
  - **Stopping power is described by Bethe-Bloch formula:**

    - 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

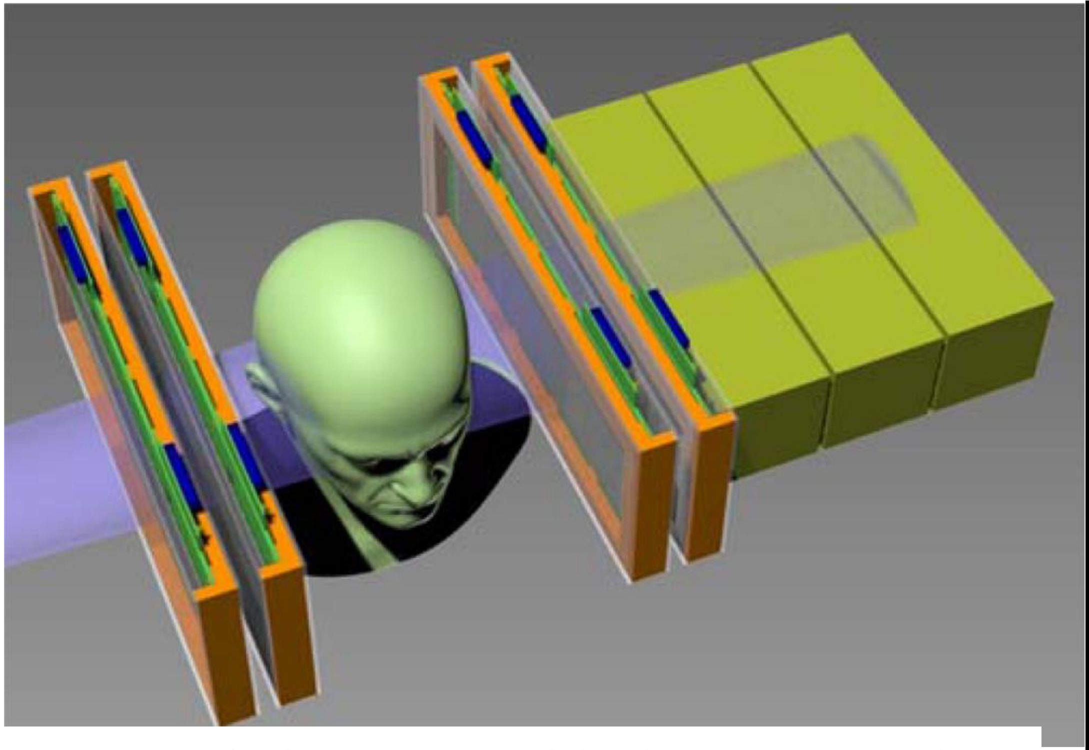
Unnecessary limitiations -> reduce range uncertainties

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

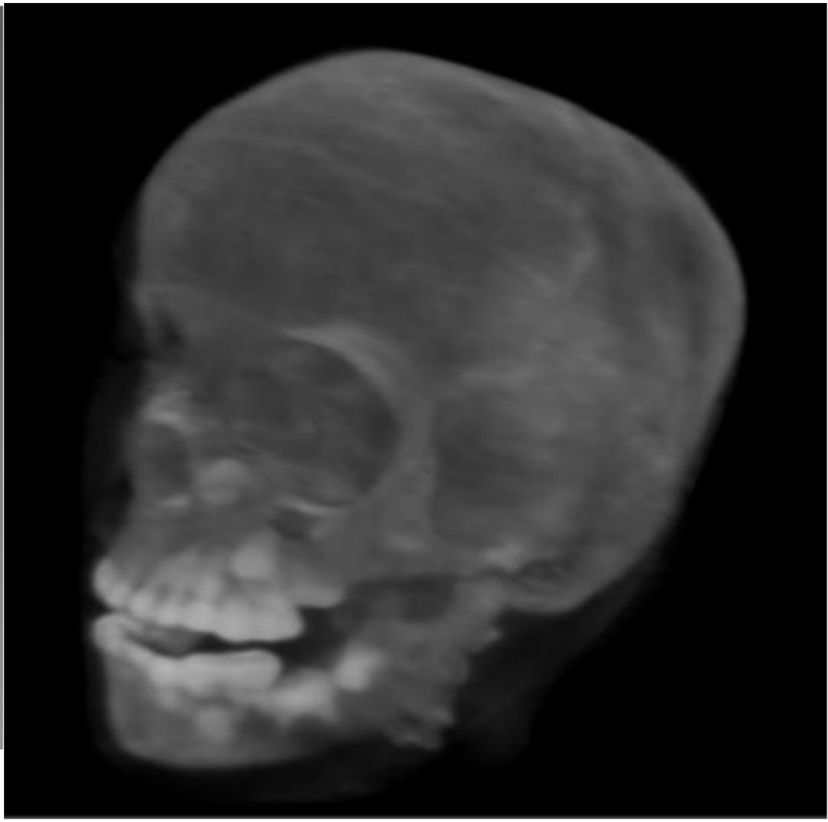


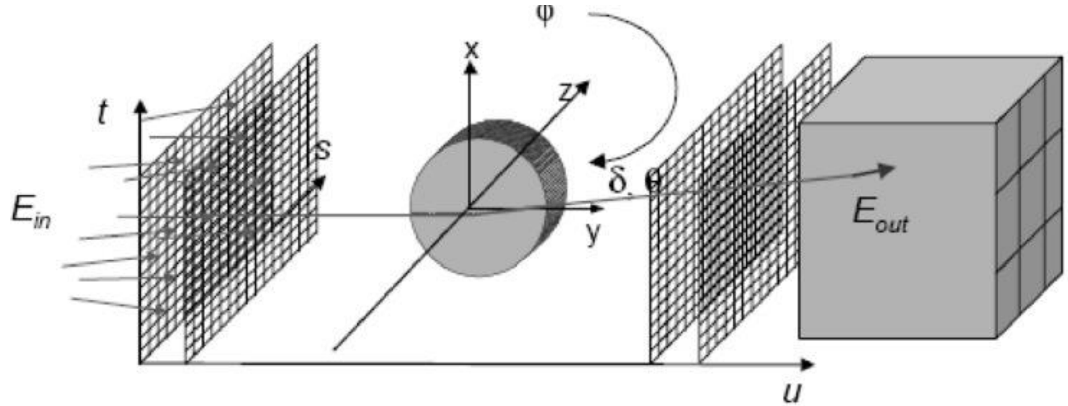
Fig. 14. 3D rendering of the pCT-reconstructed RSP map of a pediatric anthropomorphic head phantom.

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

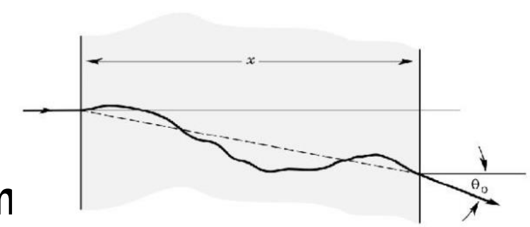
Proton-CT

- 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**



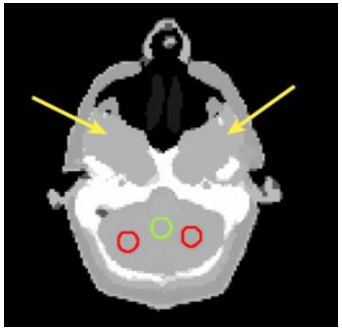
- **MS theory and Bethe-Bloch formula of average energy loss in turn depend on electron density in the target (and ionization potentials)**

-> 3D map of electron density in target

-> online verification of dose plan

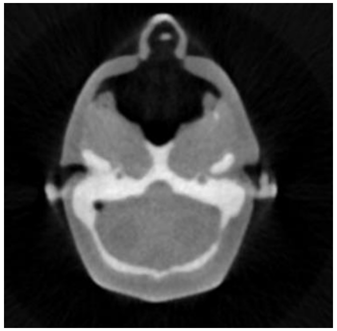
Proton-CT - images

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

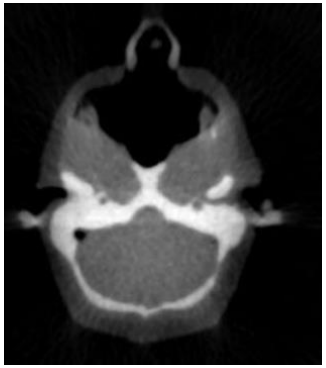


Phantom

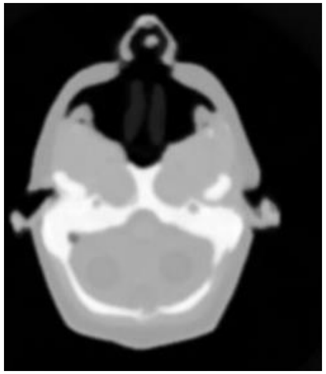
- Transmission map
  – records loss of protons
  due to nuclear reactions



- Scattering map
  – records scattering of protons off
  Coulomb potential



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

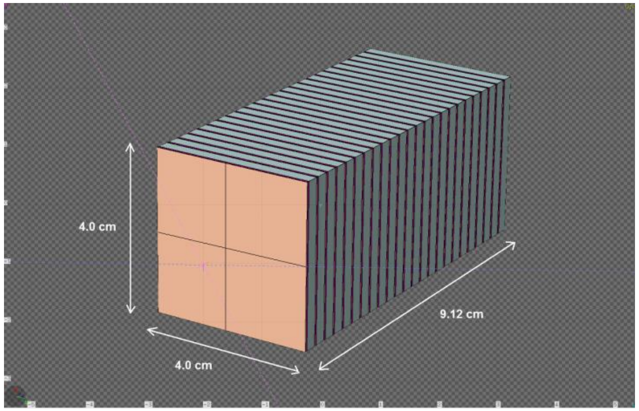


Cecile Bopp. PhD thesis, Strassbourg, 2013

Proton-CT

High energetic proton beam traversing the phantom – intensity ~ 10^7 – 10^9 protons/sec

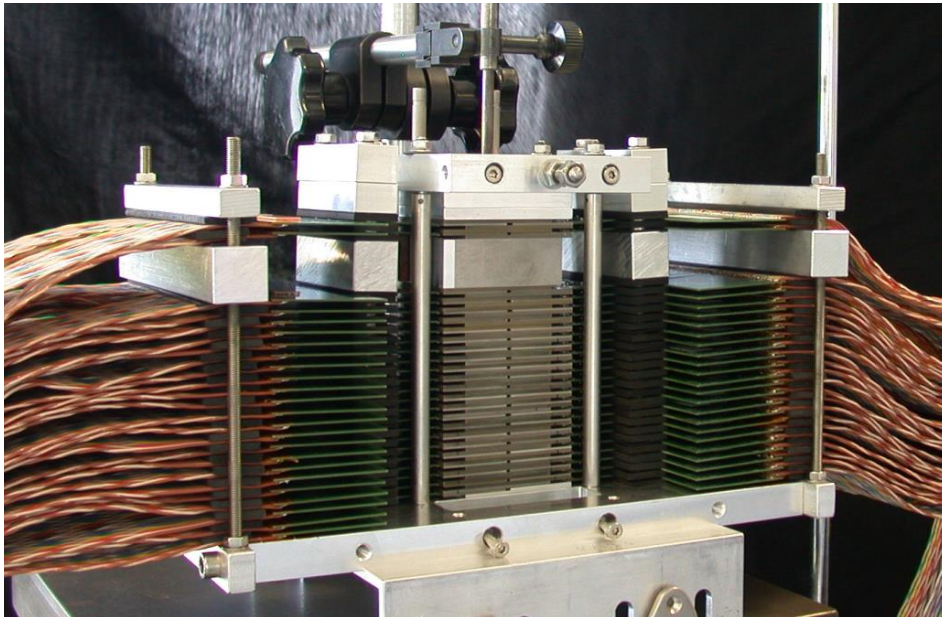
- **Detector requirements**
  - High position resolution (tens of μm)
  - Simultaneous tracking of large particle multiplicities
  - Fast readout
  - Radiation hardness
  - Front detector: low mass, thin sensors (50 μm)
  - Back detector: range resolution <1% of path-length
- **Conceptual design**
 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

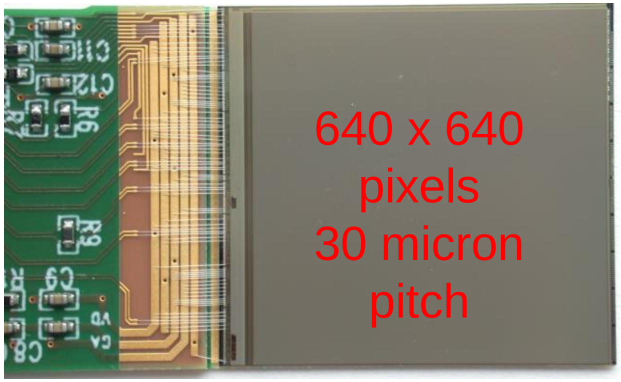


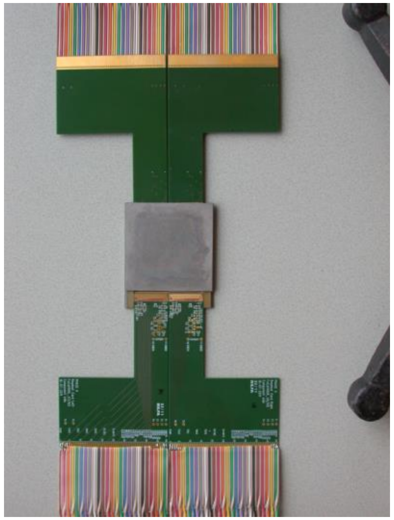
Digital tracking calorimeter prototype (I)

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
    - **on-chip digitisation**
    - **chip-level threshold setting**
    - **1 bit per pixel**







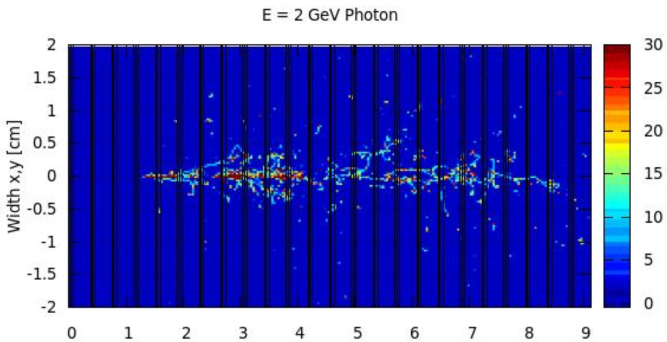
---

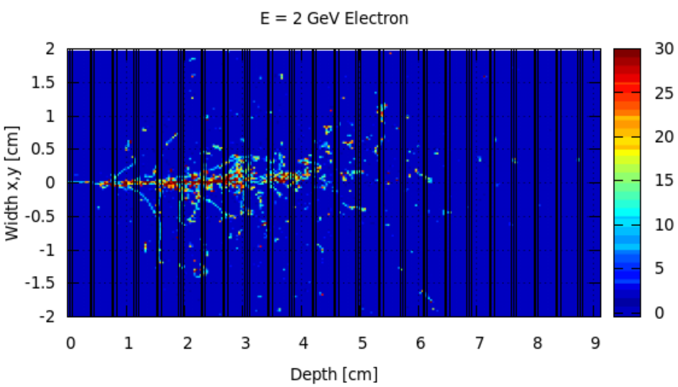
* IPHC Strasbourg

Simulation results

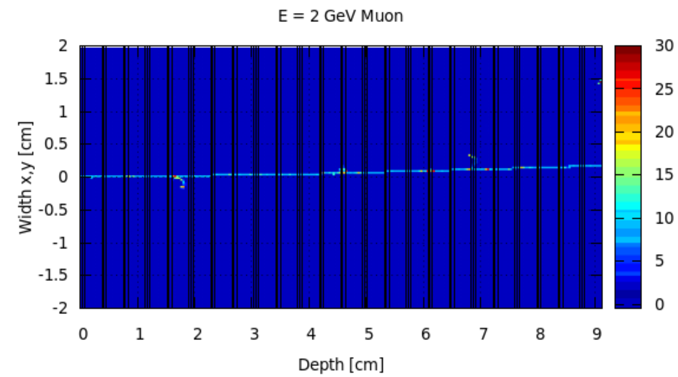
Detector response

Photons and electrons (e.m. shower)

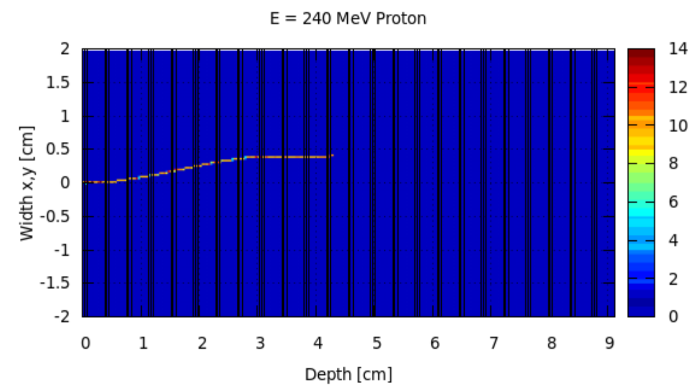




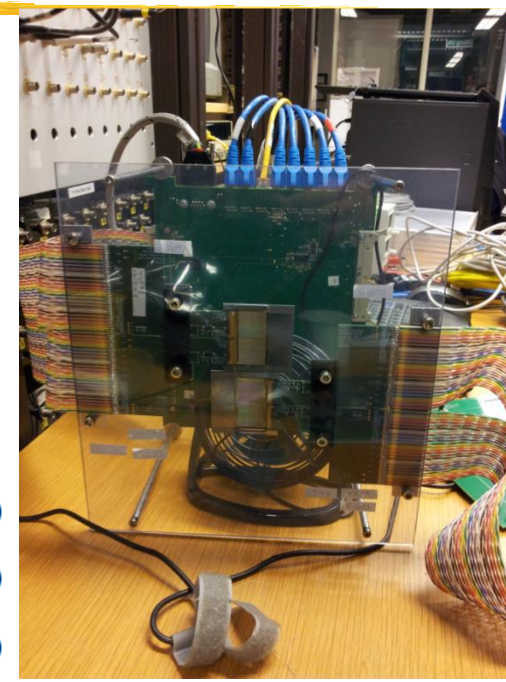
muons (MIP)



protons



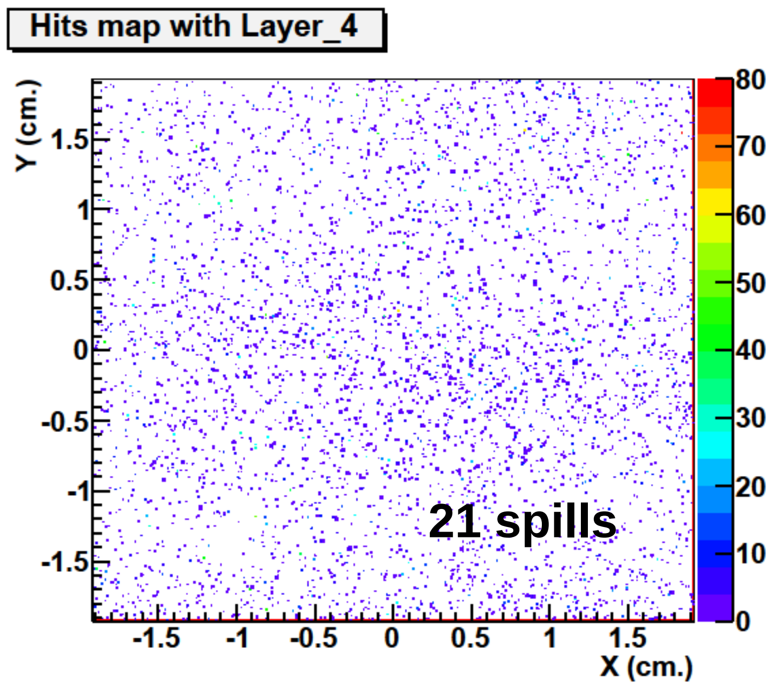
Digital tracking calorimeter – rangemeter (I)

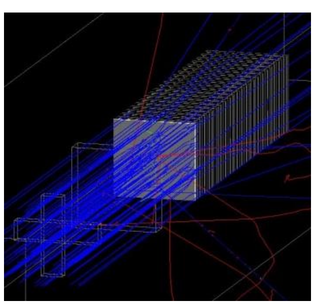


Range measuring resolution

- **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





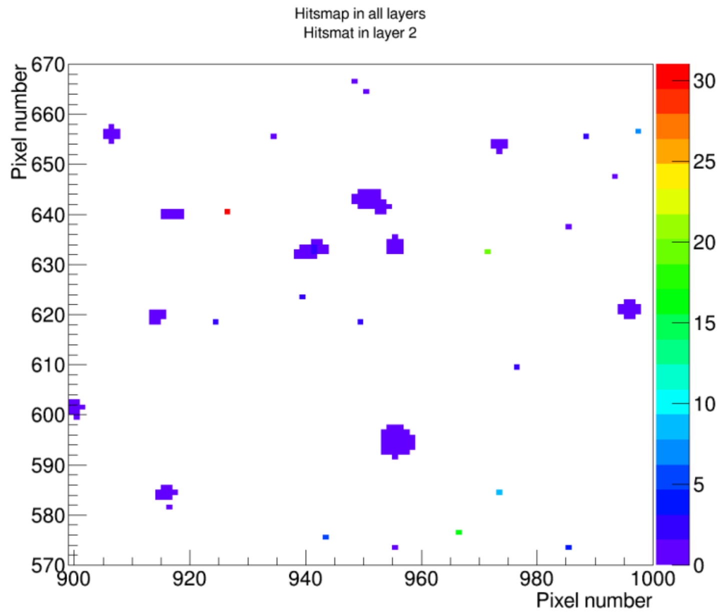
broad beam spot

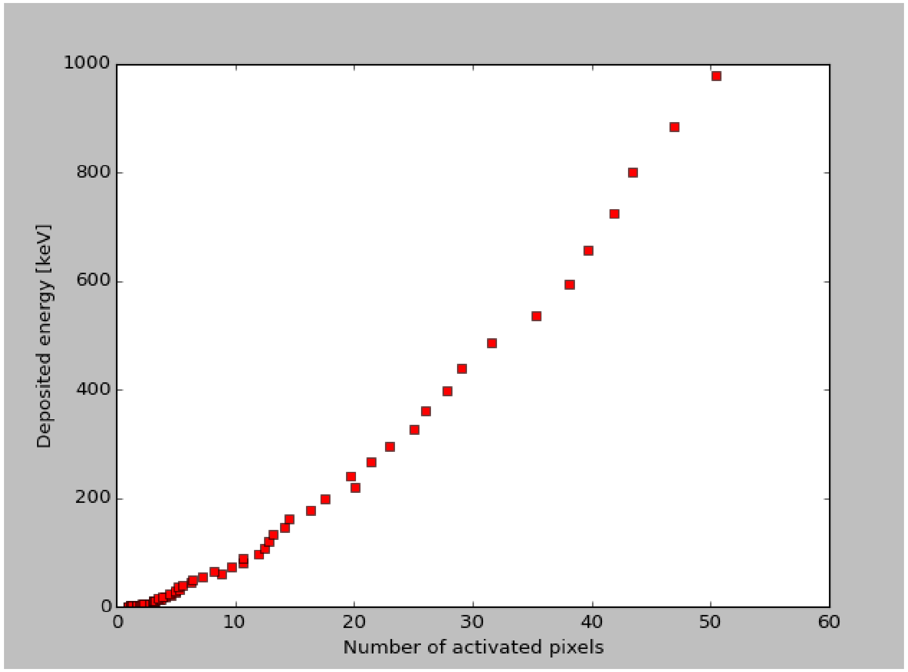
single track in 4 layers

Digital tracking calorimeter – rangemeter (II)

Range measuring resolution

H. Pettersen



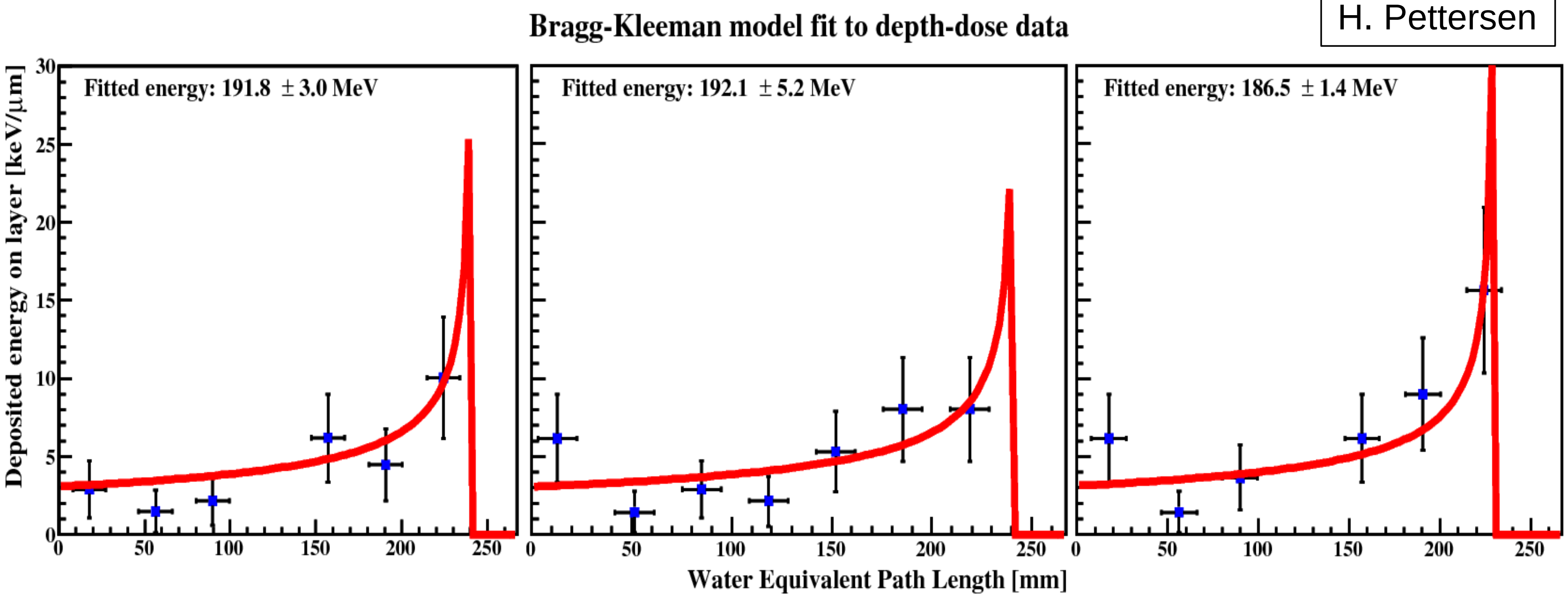


- **Energy loss measurement**
  - **hadron tracks:**
    number of hits in a sensitive layer along the particle trajectory ("cluster size") depends on the energy loss

Digital tracking calorimeter – rangemeter (IV)

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

H. Pettersen

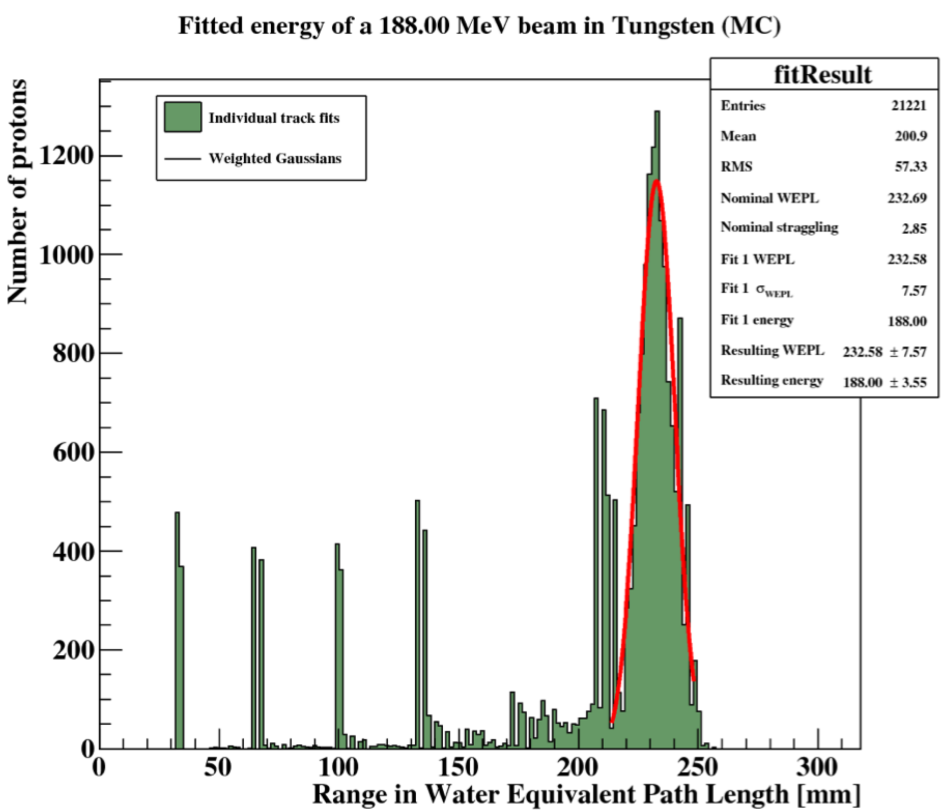


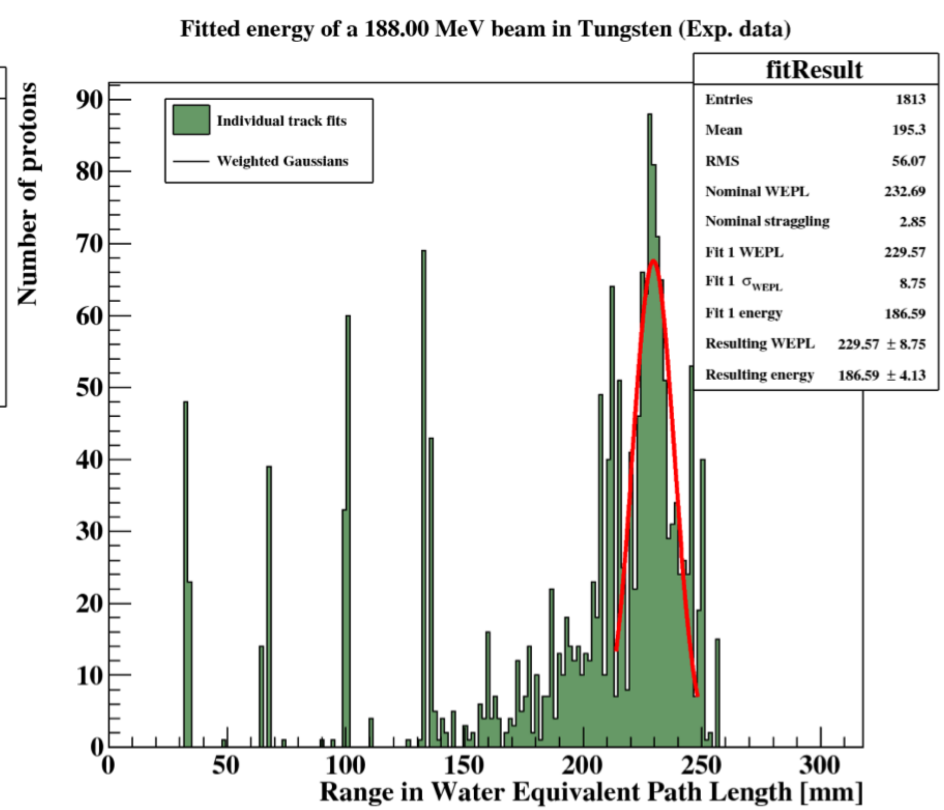
*** Bortfeld, T. *An Analytical approximation to the Bragg curve for therapeutic proton beams.* Med. Phys 24 2024-33 (1997)**

Digital tracking calorimeter – rangemeter (V)

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

H. Pettersen





Towards a clinical prototype – Bergen pCT Collaboration

- **Organisation**
  - UiB, HiB, HUS
  - Utrecht University
  - DKFZ Heidelberg
  - …
- **Financing**
  - 44 MNOK, 5 years (2017-2021)
- **Status**
  - Finishing the optimisation of the design
  - Start massproduction of ALPIDE chips
  - Sensor characterisation

UNIVERSITY OF BERGEN

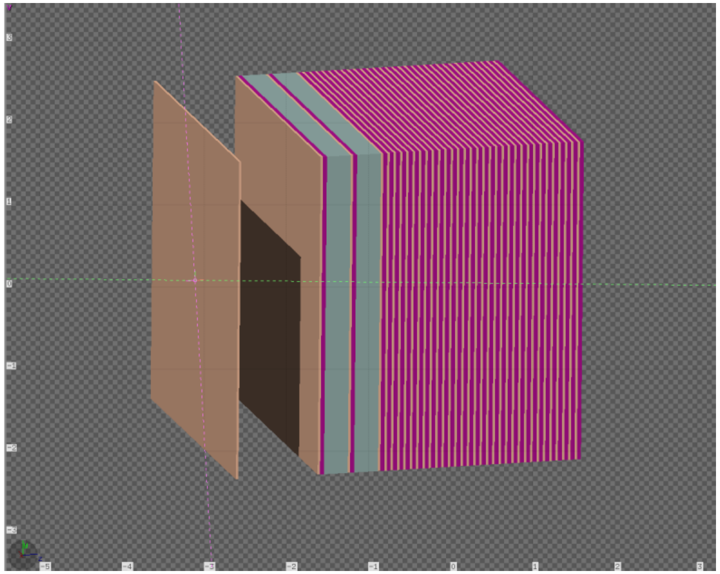
HØGSKOLEN I BERGEN
BERGEN UNIVERSITY COLLEGE

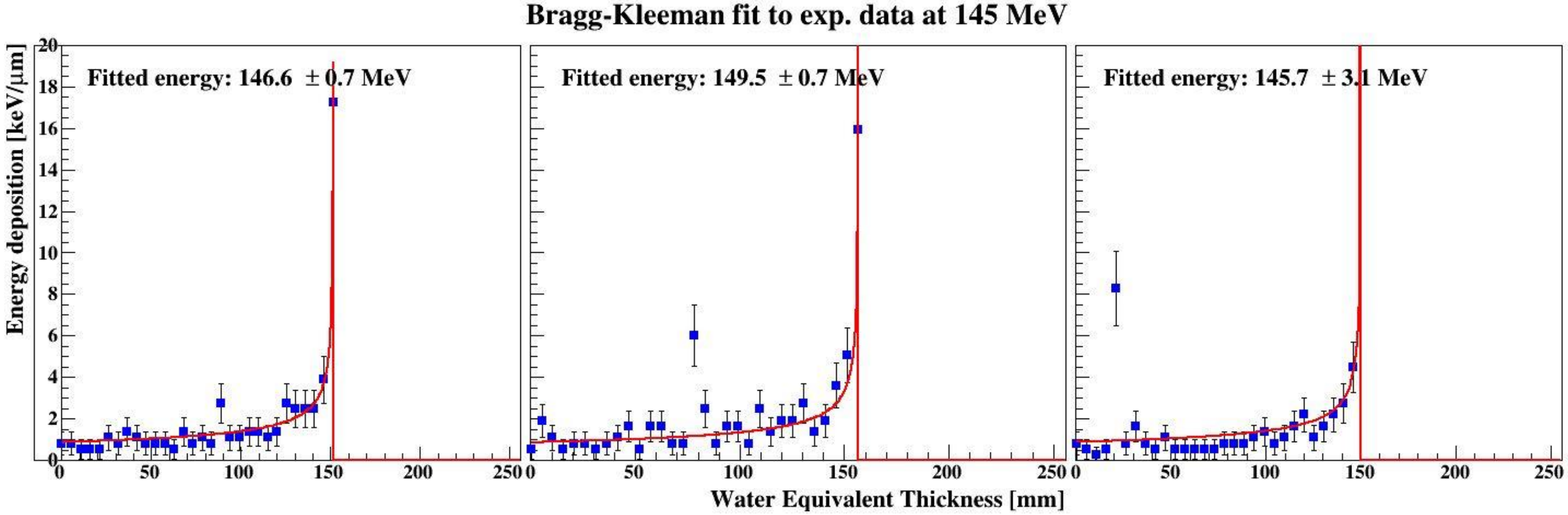
HELSE BERGEN
Haukeland University Hospital

Norwegian government has decided to build two particle therapy facilities (Oslo, Bergen), to be operational by 2022

Optimisation of the design

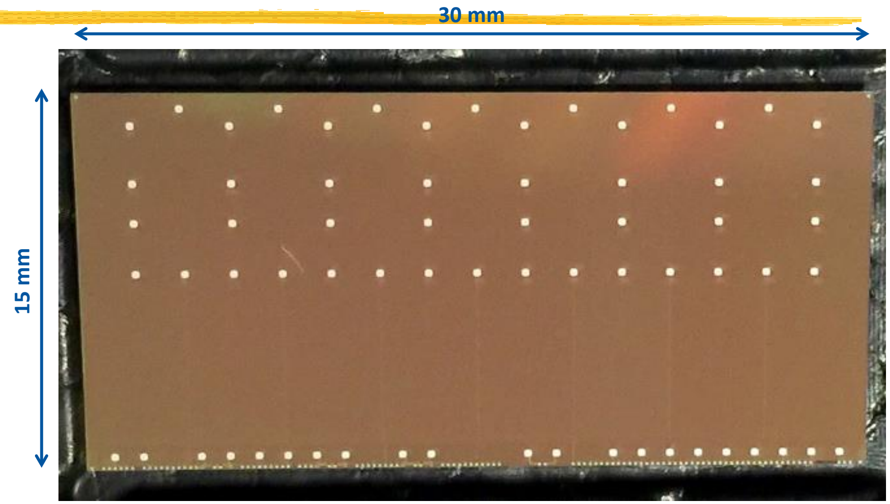
- **geometry**
- **longitudinal segmentation**
  - **number of sensitive resp. absorber layers**
- **absorber**
  - **energy degrader, mechanical carrier, cooling medium**
  - **material choice: Al**
  - **thickness (3.5 mm)**

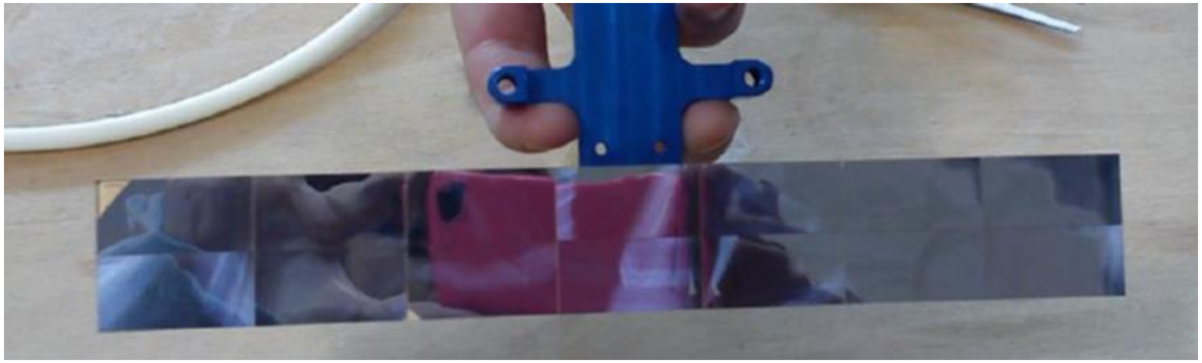




Pixel sensor – MAPS

- **ALPIDE chip**
  - **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)**

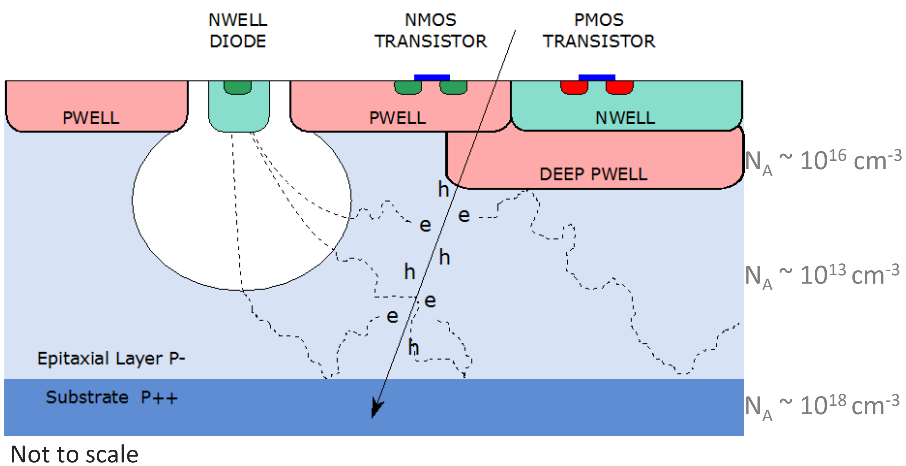


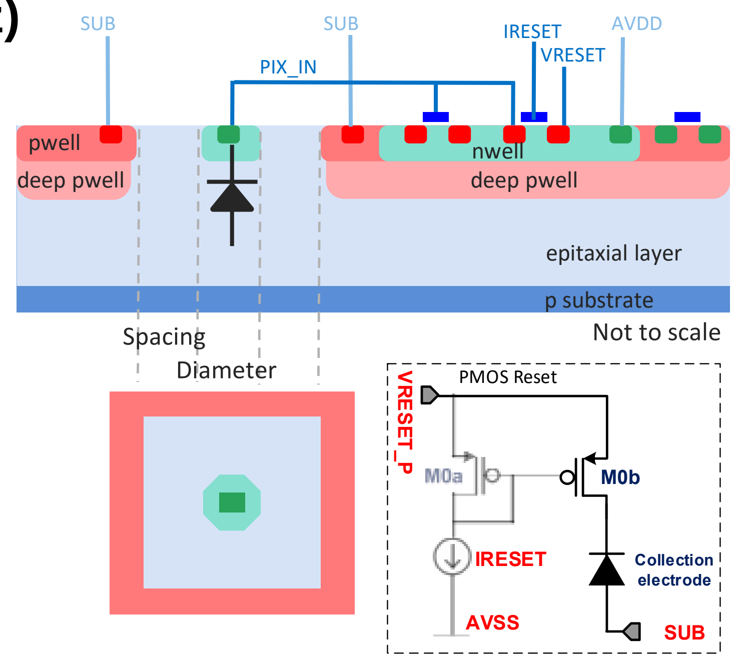


Design team:
CCNU Wuhan, CERN Geneva, YONSEI Seoul, INFN Cagliari, INFN Torino, IPHC Strasbourg, IRFU Saclay, NIKHEF Amsterdam

ALPIDE – pixel cell

- **CMOS 180 nm Imaging Process (TowerJazz)**
  - 3nm thin gate oxide, 6 metal layers

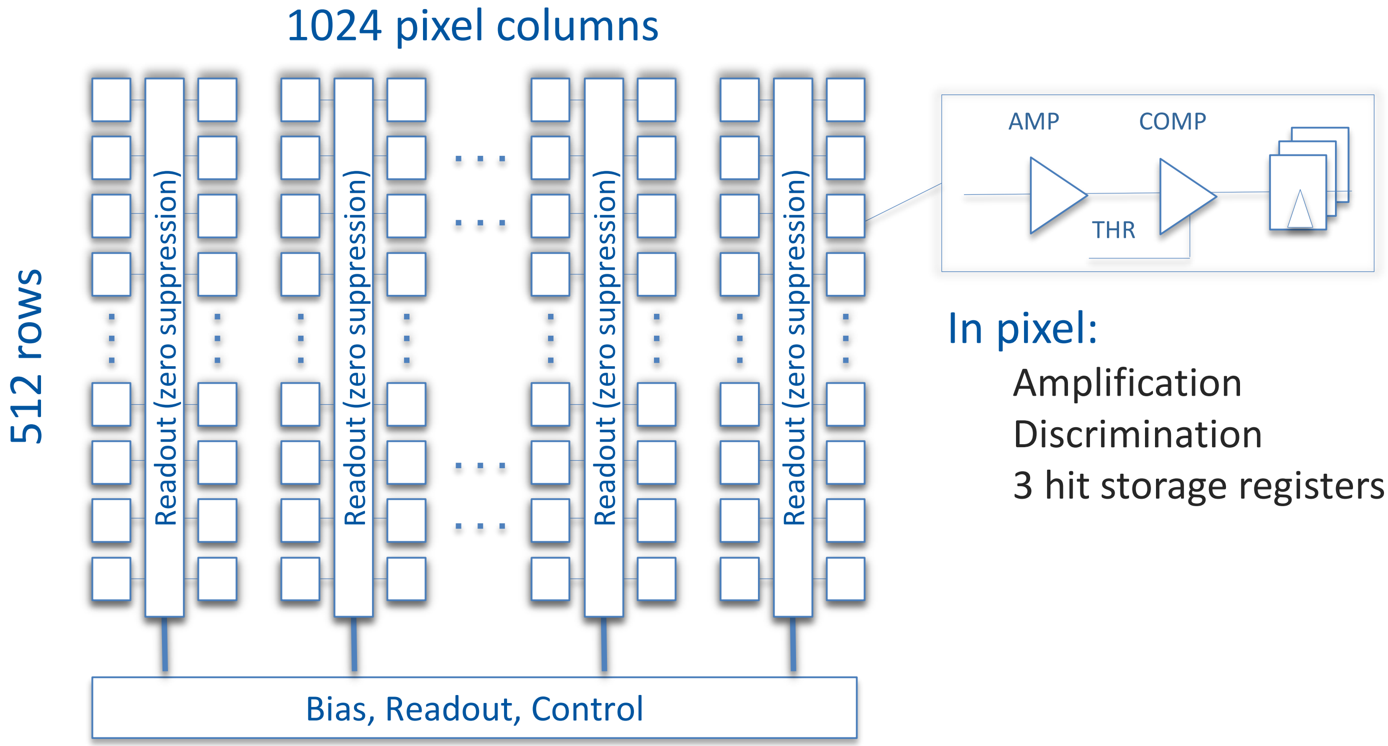




- **29 µm x 27 µm pixel pitch, 25 µm thick epitaxial layer**
- **Substrate thinned to 100 µm or 50 µm**
- **1024 x 512 pixels**
- **Small n-well diode -> low capacitance -> large S/N**
- **Reverse bias to substrate -> increased depletion volume**
  -> charge collection by drift

ALPIDE – architecture

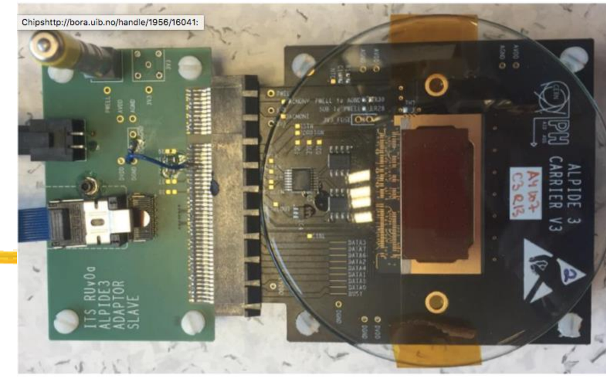
- 29 μm x 27 μm pixel pitch
- Deadtime-free frond
- Zero-suppressed matrix readout
- Triggered or continuous readout



In pixel:

Amplification
Discrimination
3 hit storage registers (MEB)

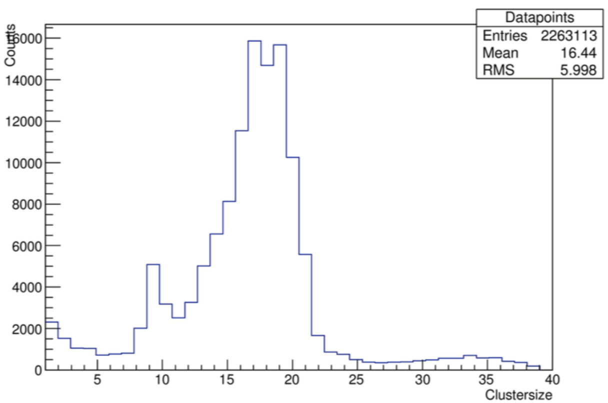
First beam test results



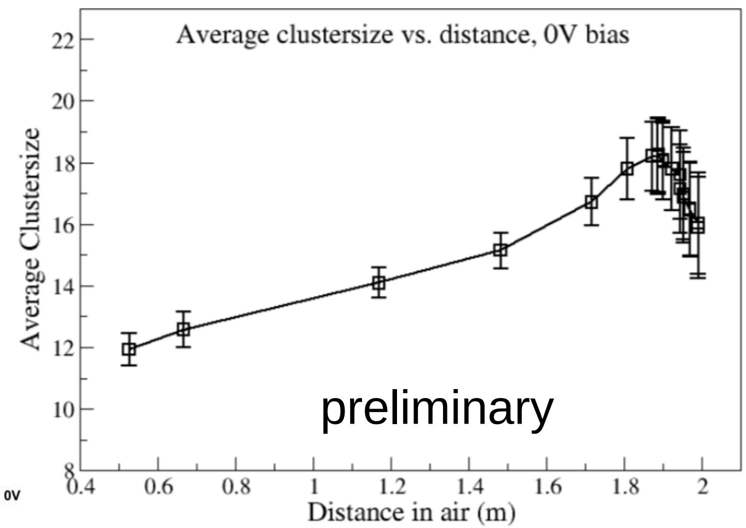
Cluster size vs dE/dx

- 16 MeV external proton beam in air
- Cluster size of a MIP: about 2-4 pixels

cluster size distribution

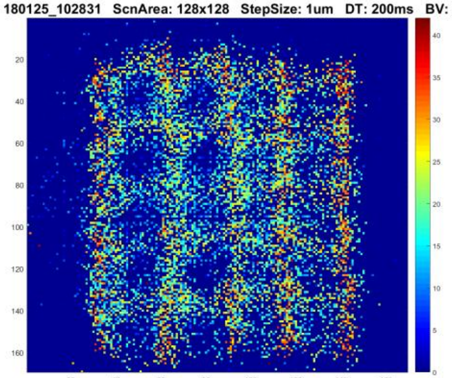


average cluster size vs dE/dx



Uniformity of cluster size

- He microbeam
  @ ANSTO



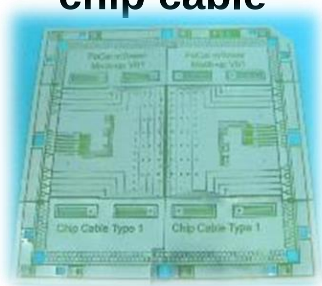
raw cluster sizes,
no bias voltage

Mounting sensors on flexible cables

- **ALPIDE mounted on thin flex cables (aluminium-polymide dielectrics: 30um Al, 20um plastic)**

ALPIDE chip

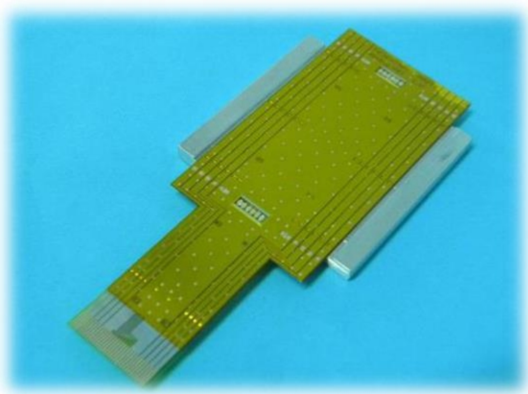
chip cable



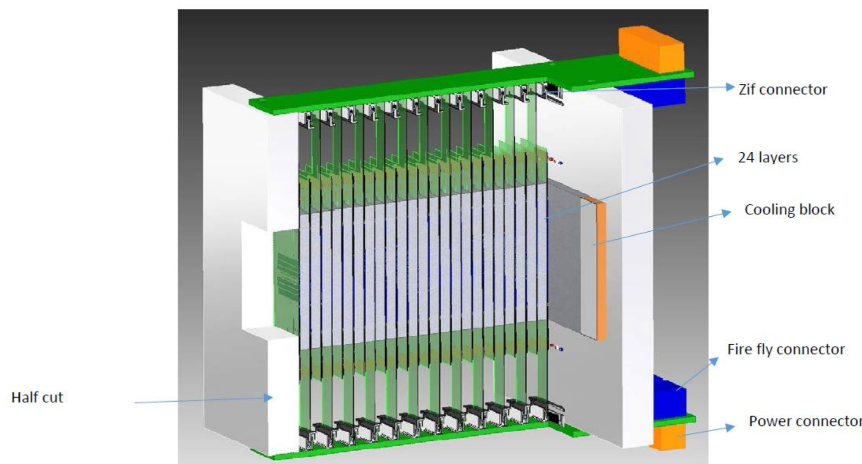
design and production:
LTU, Kharkiv, Ukraine

- **Intermediate prototype**

chip cable with two ALPIDEs



stack of sensor layers

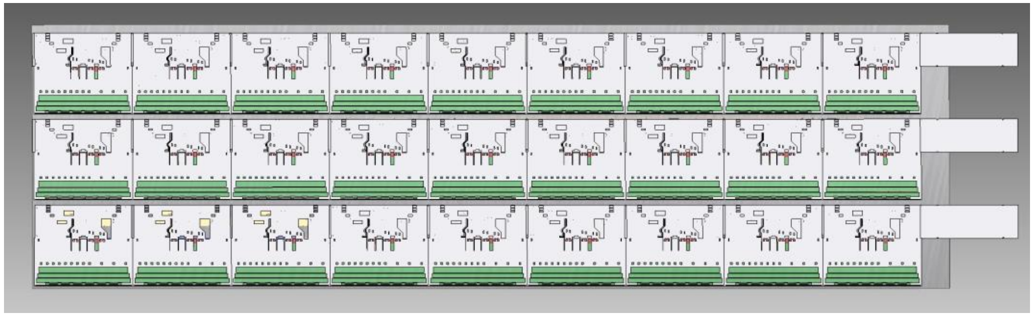


Towards the clinical prototype

Implementation – final system

- Modular structure – exchangeable front layers
- Dimension
  - Front area: 27 cm x 15(18) cm
  - 41 layers of absorbers/sensors
  - Two tracking stations - 2 thin sensor layers (total thickness < 0.4 mm), 2 cm apart front face of calorimeter and - if neccessary - in front of phantom
- Sensitive layers - ALPIDE chips bonded to flexible PCBs

flexible carrier board modules (9 x 3 chips)
(design and production: LTU, Kharkiv)



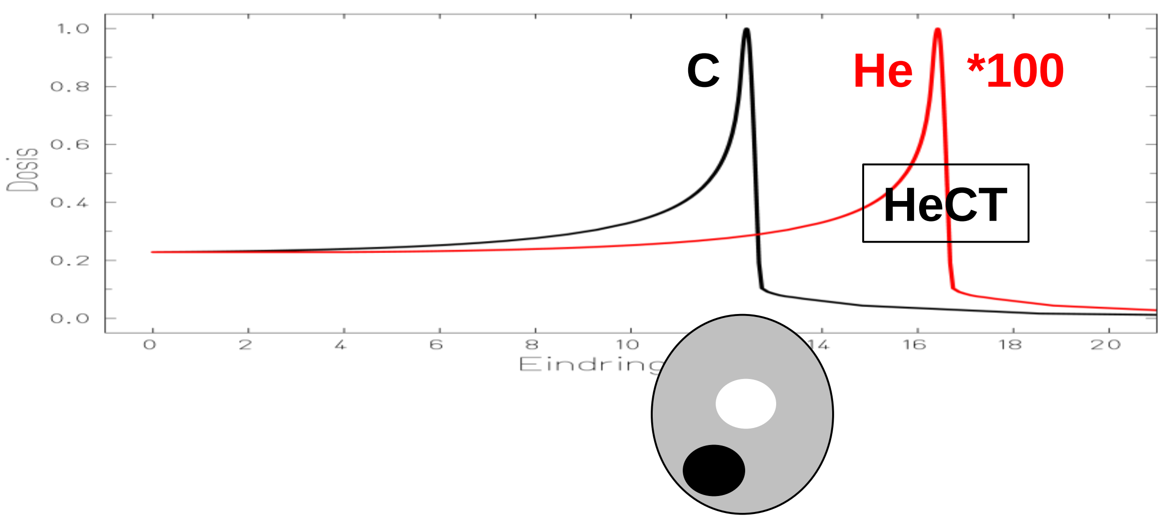
- Expected performance (simulation)
  - Range accuracy: < 0.5 mm WET
  - Flux: > 2.5 x 10^6 particles/(cm^2sec)

Next steps

- **Construction of prototype**
  - **First chip cables with mounted chips will be available in March**
  - **First sensor module: September**

- **Extensive commissioning with proton beams**

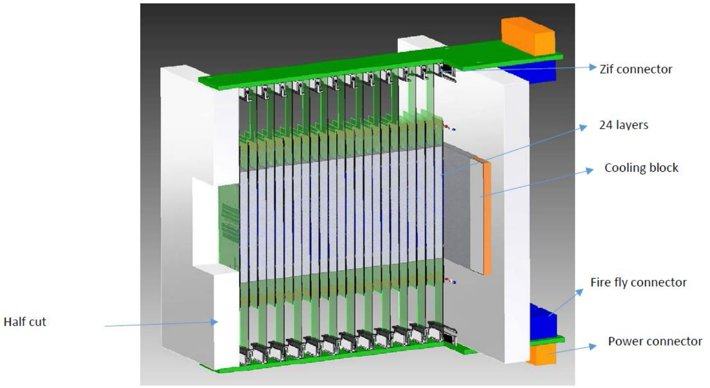
- **Commissioning with He beams**
  - **HeCT – less MS, better resolution***
  - **Carbon beam with 1% Helium (as proposed by HIT and CNAO):**



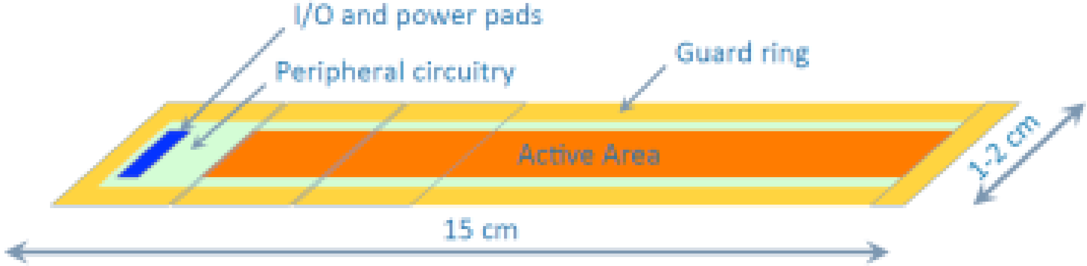
* PhD thesis C. Collins Fekete, Univ. Laval, 2017

Outlook

- **Applications of a stack of ALPIDEs**
  - **Two layers back-to-back: w/ and w/o bias voltage -> charge collection by diffusion (dE/dx) and by drift (counting)**
  - **Ga and plastic foils: thermal and fast neutrons**
  - **Tungsten converter: gamma (tracker)**
  - **No absorber: tracking telescope (< 100 µm thickness)**
  - **….**



- **R&D project to tailure ALPIDE design to medical applications**
  - **Faster charge collection and readout: 4 µs -> < 1 ns**
  - **Thinner and larger sensors (wafer-scale integration by stitching) -> no need for carrier board (especially helpful in case of tracking station between nozzle and patient)**



This is the end