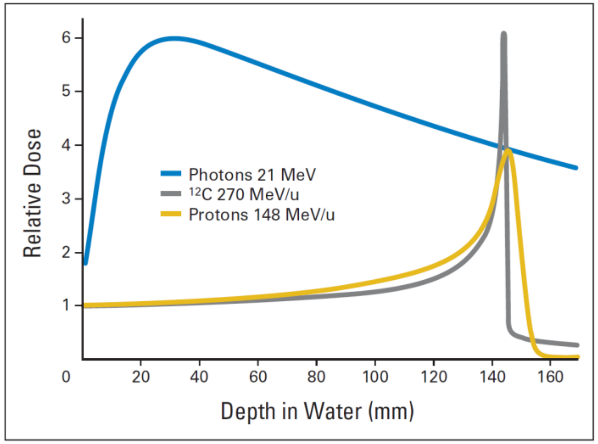
The Bergen proton CT project –

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



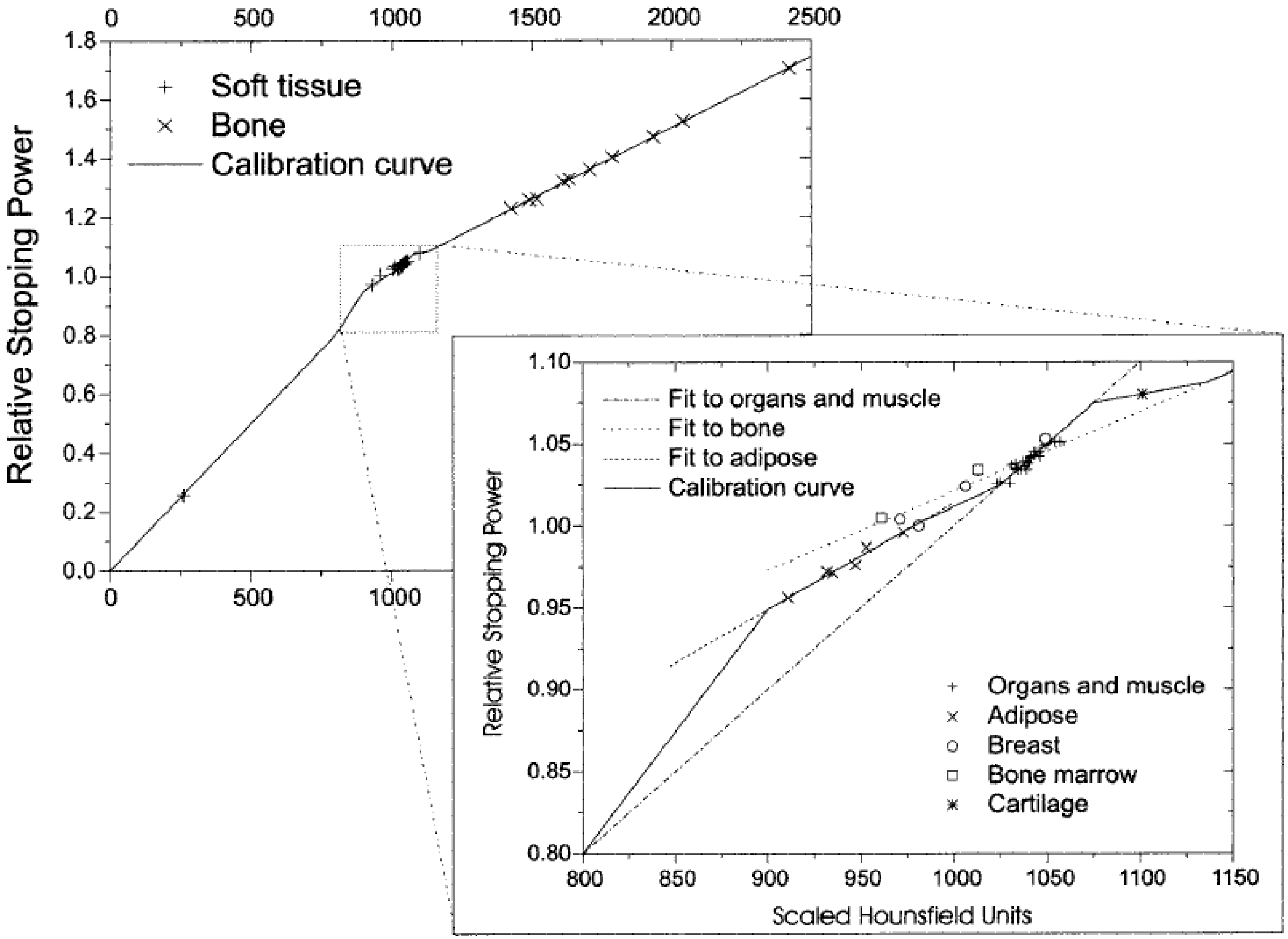
- **Key advantage of ions: Bragg peak**
  - **Relatively low dose in the entrance channel**
  - **Sharp distal fall-off of dose deposition (<mm)!**

- **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

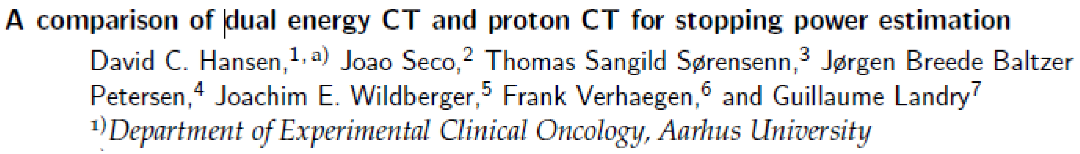
How to deal with range uncertainties in the clinical routine?

- 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

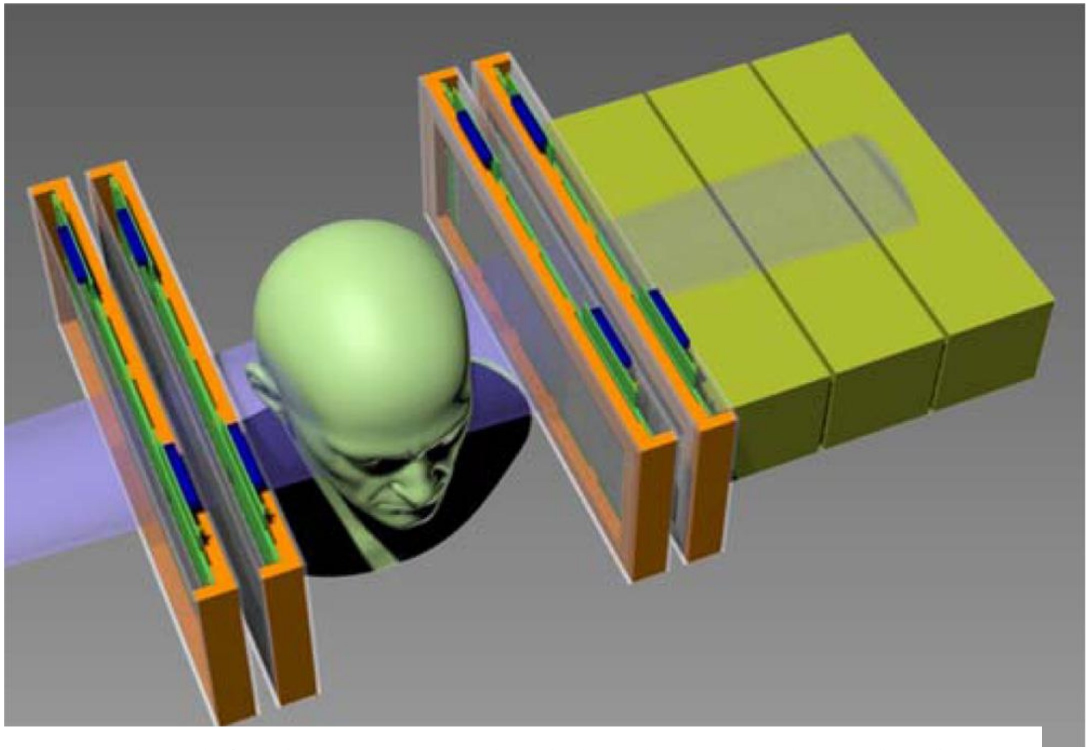


A comparison of dual energy CT and proton CT for stopping power estimation

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

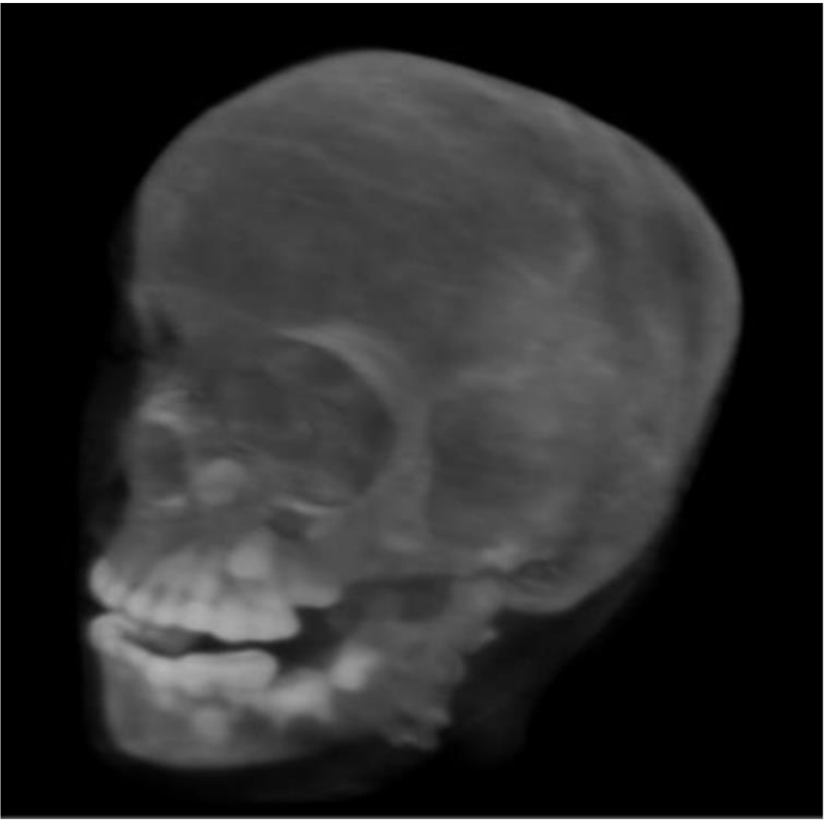


Fig. 14. 3D rendering of the pCT-reconstructed RSP map of a pediatric anthropomorphic head phantom.

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

Imaging with protons – many prototypes

… still no clinical system

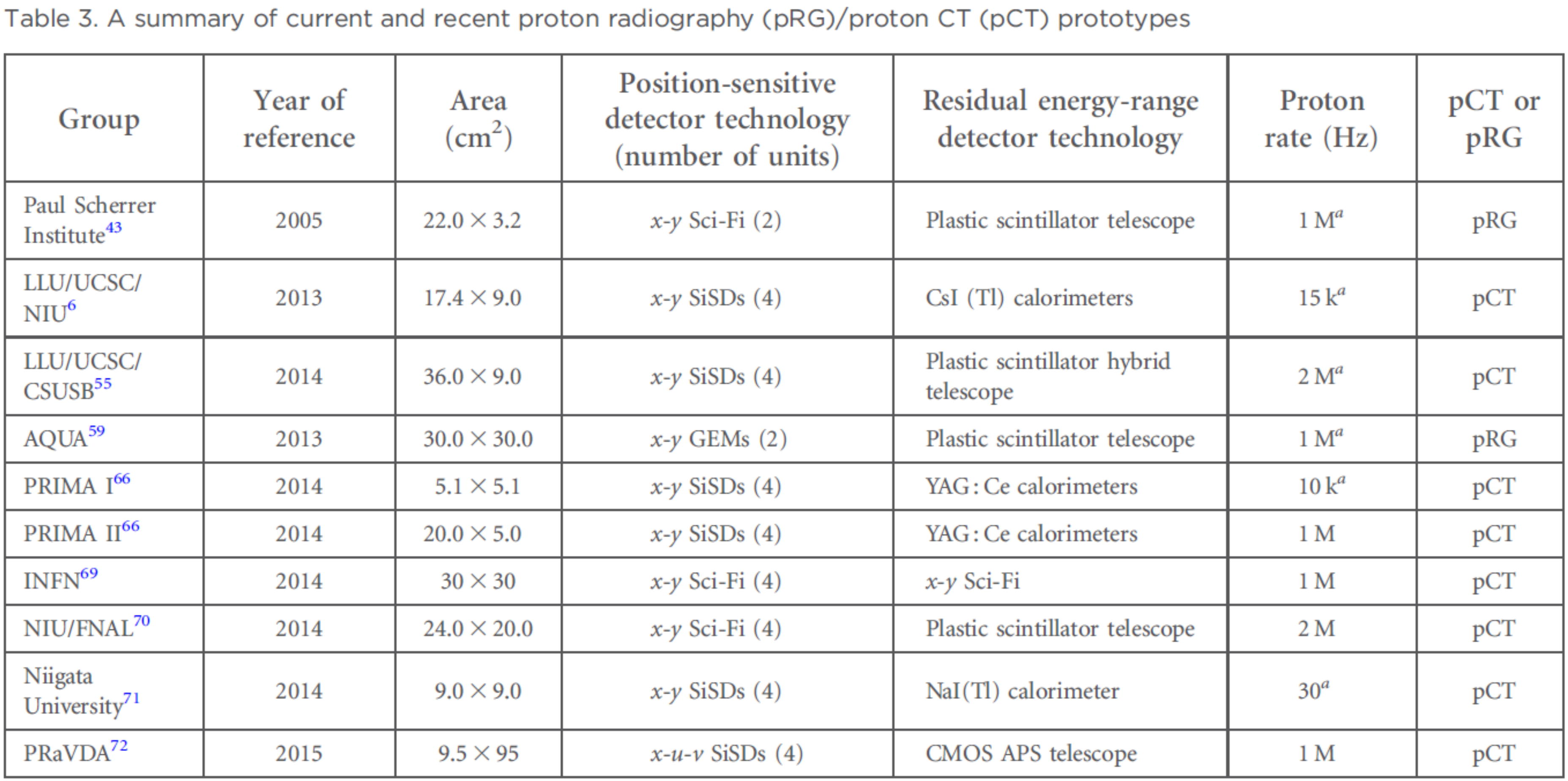


Table 3. A summary of current and recent proton radiography (pRG)/proton CT (pCT) prototypes

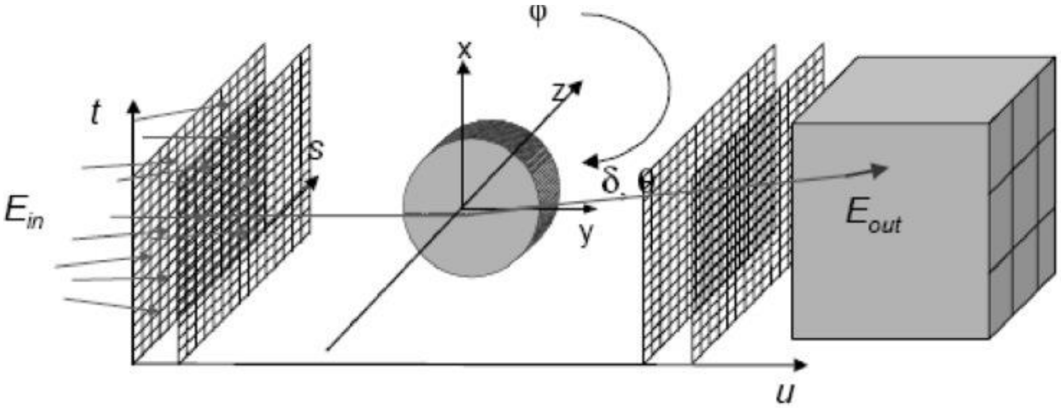
Group	Year of reference	Area (cm^2)	Position-sensitive detector technology (number of units)	Residual energy-range detector technology	Proton rate (Hz)	pCT or pRG
Paul Scherrer Institute[43]	2005	22.0 × 3.2	*x-y* Sci-Fi (2)	Plastic scintillator telescope	1 M[a]	pRG
LLU/UCSC/ NIU[6]	2013	17.4 × 9.0	*x-y* SiSDs (4)	CsI (Tl) calorimeters	15 k[a]	pCT
LLU/UCSC/ CSUSB[55]	2014	36.0 × 9.0	*x-y* SiSDs (4)	Plastic scintillator hybrid telescope	2 M[a]	pCT
AQUA[59]	2013	30.0 × 30.0	*x-y* GEMs (2)	Plastic scintillator telescope	1 M[a]	pRG
PRIMA I[66]	2014	5.1 × 5.1	*x-y* SiSDs (4)	YAG : Ce calorimeters	10 k[a]	pCT
PRIMA II[66]	2014	20.0 × 5.0	*x-y* SiSDs (4)	YAG : Ce calorimeters	1 M	pCT
INFN[69]	2014	30 × 30	*x-y* Sci-Fi (4)	*x-y* Sci-Fi	1 M	pCT
NIU/FNAL[70]	2014	24.0 × 20.0	*x-y* Sci-Fi (4)	Plastic scintillator telescope	2 M	pCT
Niigata University[71]	2014	9.0 × 9.0	*x-y* SiSDs (4)	NaI(Tl) calorimeter	30[a]	pCT
PRaVDA[72]	2015	9.5 × 95	*x-u-v* SiSDs (4)	CMOS APS telescope	1 M	pCT

G. Poludniowski, N. M. Allinson, and P. M. Evans, “Proton radiography and tomography with application to proton therapy”, *Br. J. Radiol.*, vol. 88, no. 1053, pp. 1–14, 2015

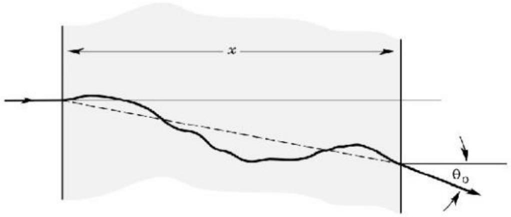
Proton-CT

- quasi-online dose plan verification

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



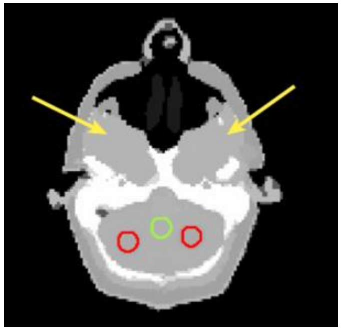
- **reconstruction of trajectories in 3D and range in external absorber**
  - **trajectory, path-length and range depend on**
    - **nuclear interactions (inelastic collisions)**
    - **multiple Coulomb scattering (elastic collisions)**
    - **energy loss dE/dx (inelastic collisions with atomic electrons)**



- **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 stopping power
  -> online verification of dose plan

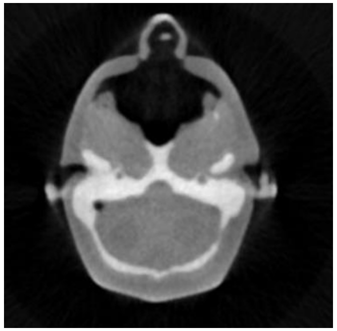
Proton-CT - images

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

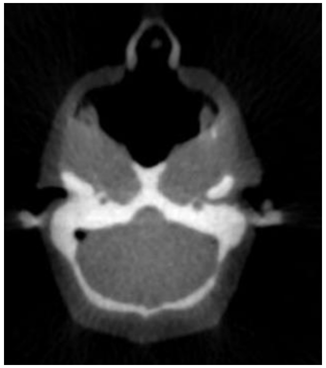


Phantom

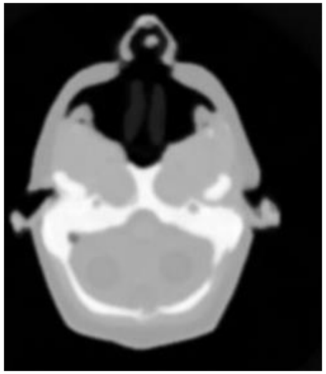
  - **Transmission map**
    – records loss of protons due to nuclear reactions



  - **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

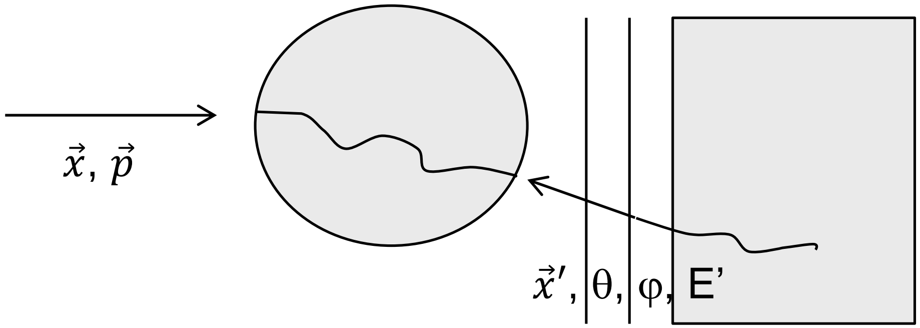
Clinical pCT - requirements

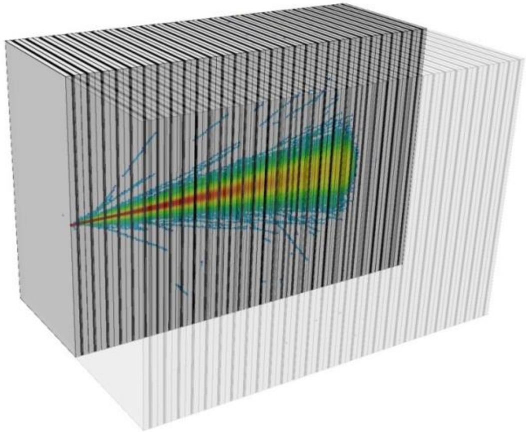
High energetic proton beam traversing the phantom

- **Beam**
  - **Intensity ~ 10^7 – 10^9 protons/sec**
  - **Pencil beam scanning mode**
- **Detector**
  - **High position resolution (~10 μm)**
  - **Simultaneous tracking of large particle multiplicities**
  - **Large area (> 30 x 30 cm^2)**
  - **High reconstruction efficiency**
  - **Fast readout**
  - **Radiation hardness**
  - **Front detector (first 2-3 layers): low mass, thin sensors (~100 μm)**
  - **Back detector: range resolution <1% of path-length**
- **System**
  - **Compact**
  - **No gas, no HV**
  - **Simple air/water cooling**

Clinical pCT - design

- **Conceptual design**

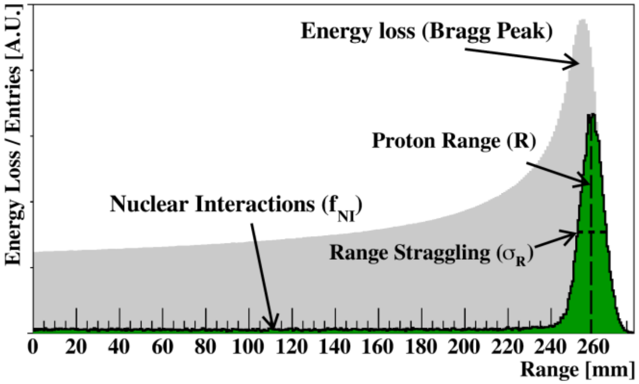




  - $\vec{x}, \vec{p}$ **given by beam optics and scanning system**
  - $\vec{x}', \theta, \varphi$ **have to be measured with high precision**
    - **position resolution ~5 μm with minimal MS i.e. very thin first two tracking layers**

→ **Extremely high-granularity digital calorimeter for tracking, range and energy loss measurement**

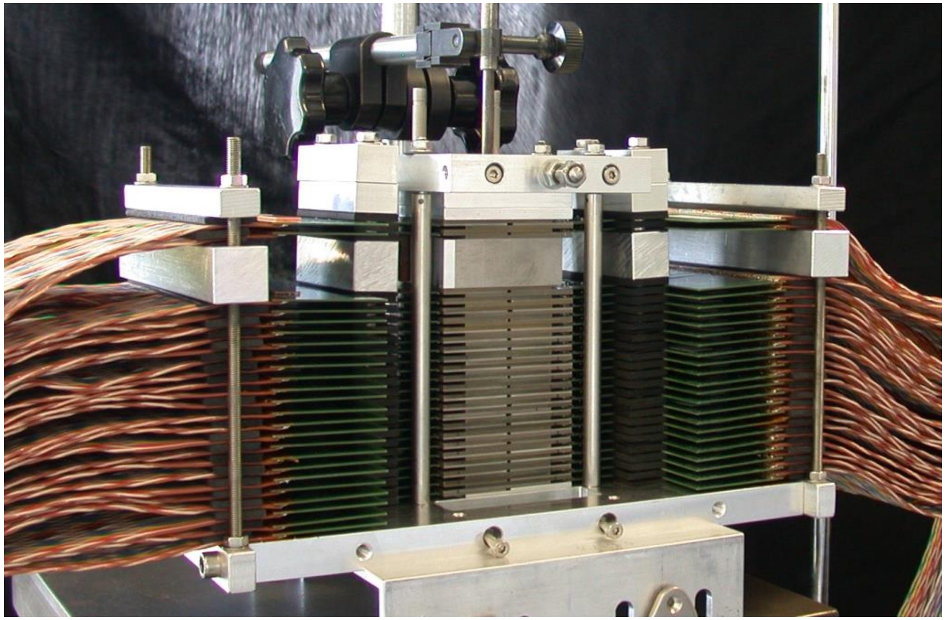
- **Technical design**
  - **Planes of CMOS sensors – Monolithic Active Pixel Sensors (MAPS) – as active layers in a sampling calorimeter**

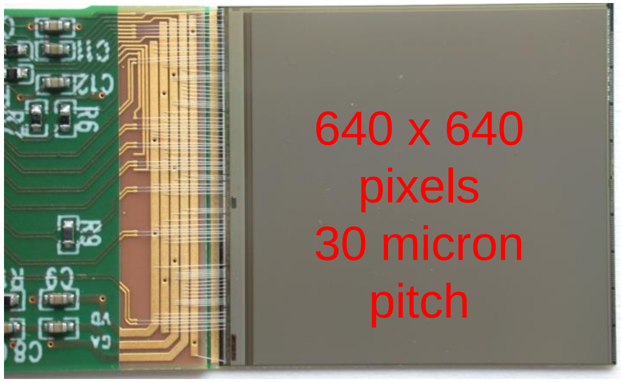


Digital tracking calorimeter prototype (I)

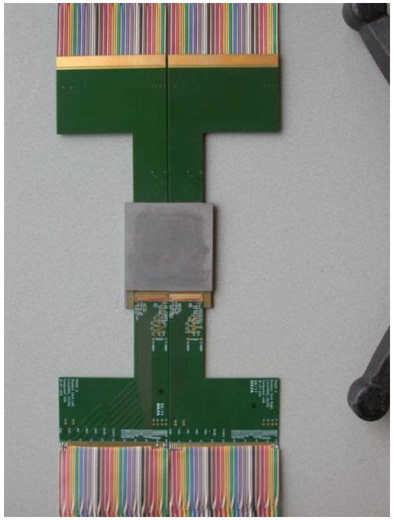
Silicon-tungsten sampling calorimeter

- optimised for electromagnetic showers
- compact design 4x4x11,6 cm^3
- 24 layers
  - absorbers:
3.5 mm of W (≈ 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





640 x 640 pixels
30 micron pitch



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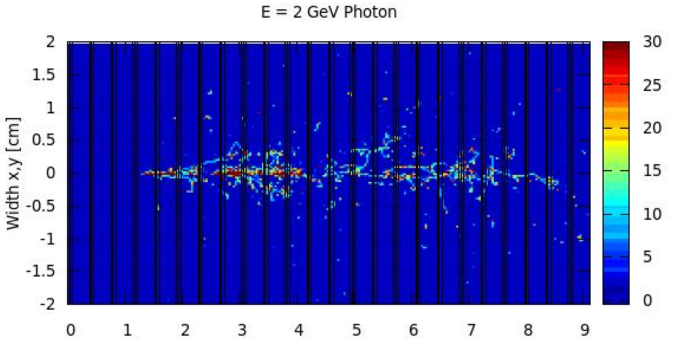
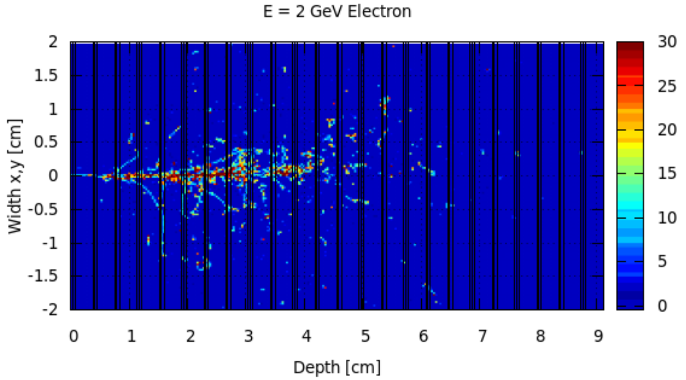
* IPHC Strasbourg

Simulation results

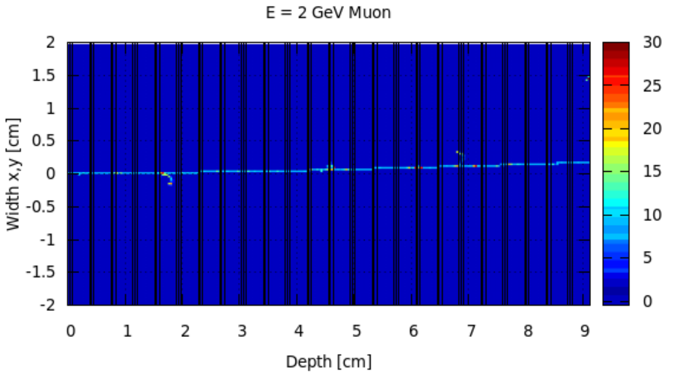
Detector response

Photons and electrons (e.m. shower)

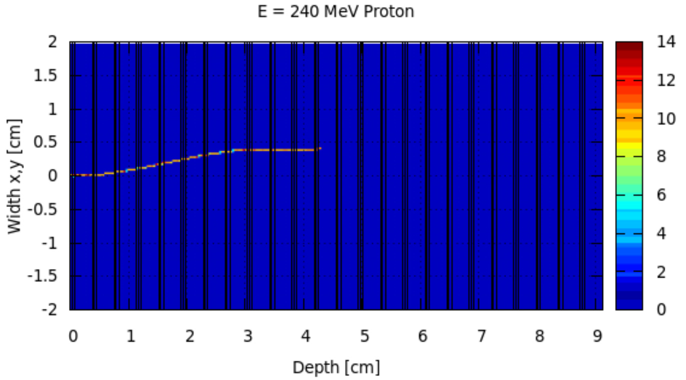




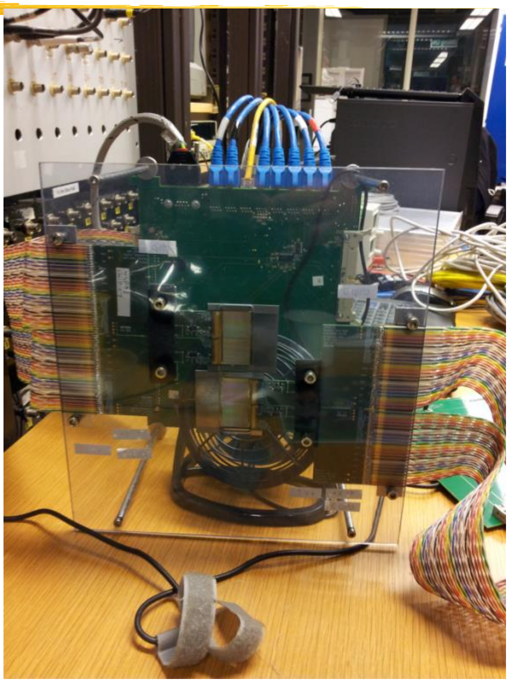
muons (MIP)



protons



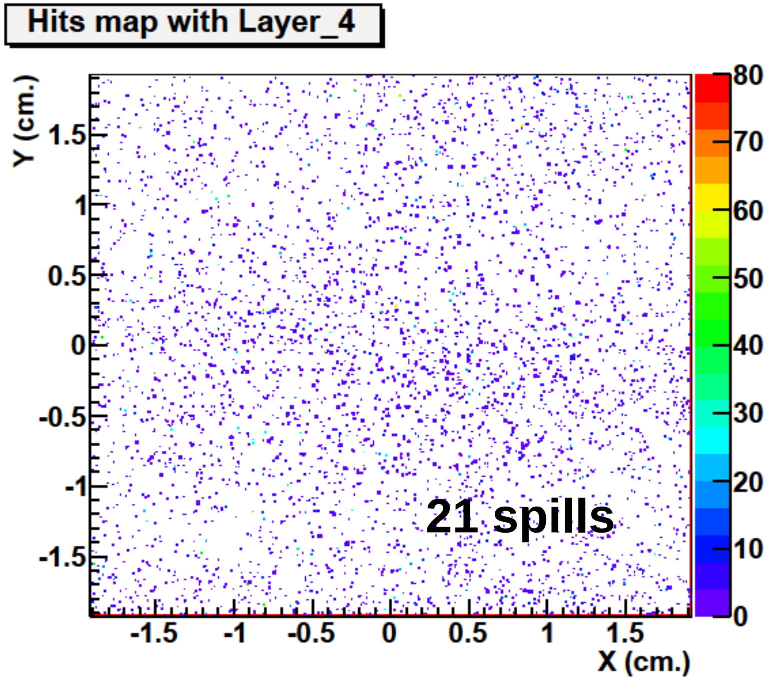
Digital tracking calorimeter – rangemeter (I)

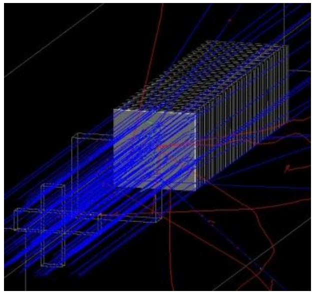


Range measuring resolution

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

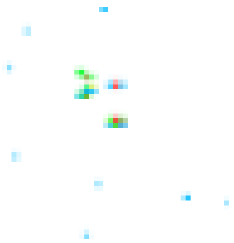
    ≈ 1 proton per frame (640 μsec), 800 protons per spill





broad beam spot

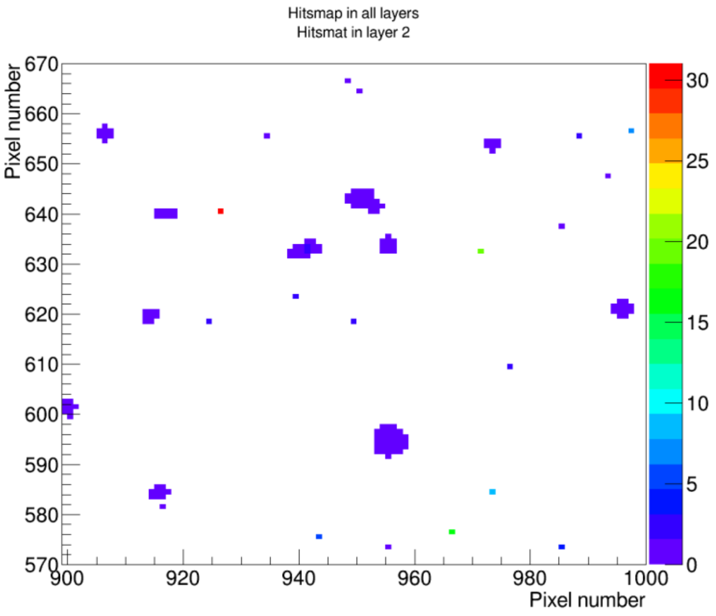
single track in 4 layers

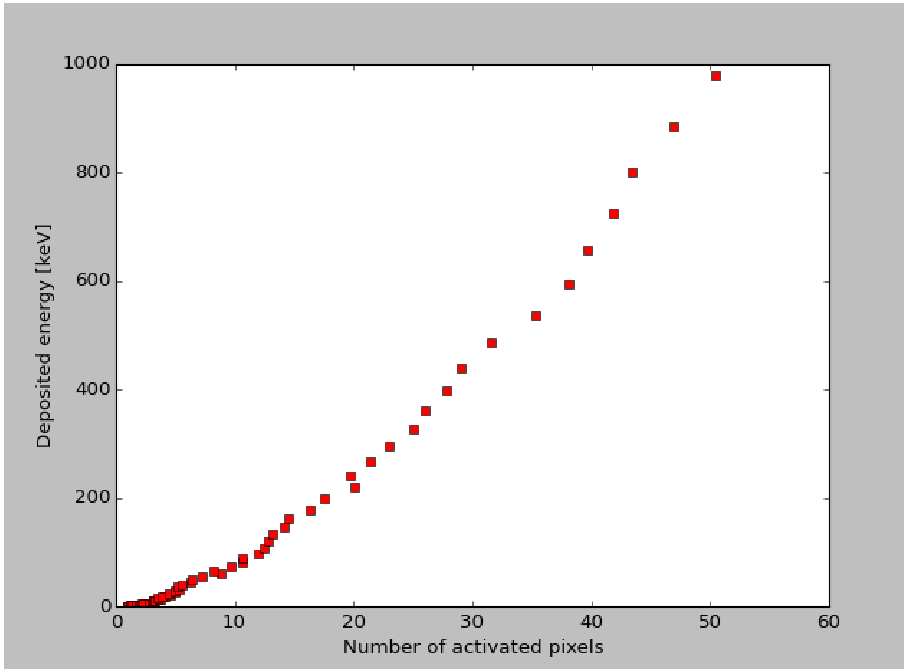


Digital tracking calorimeter – rangemeter (II)

Range measuring resolution

H. Pettersen



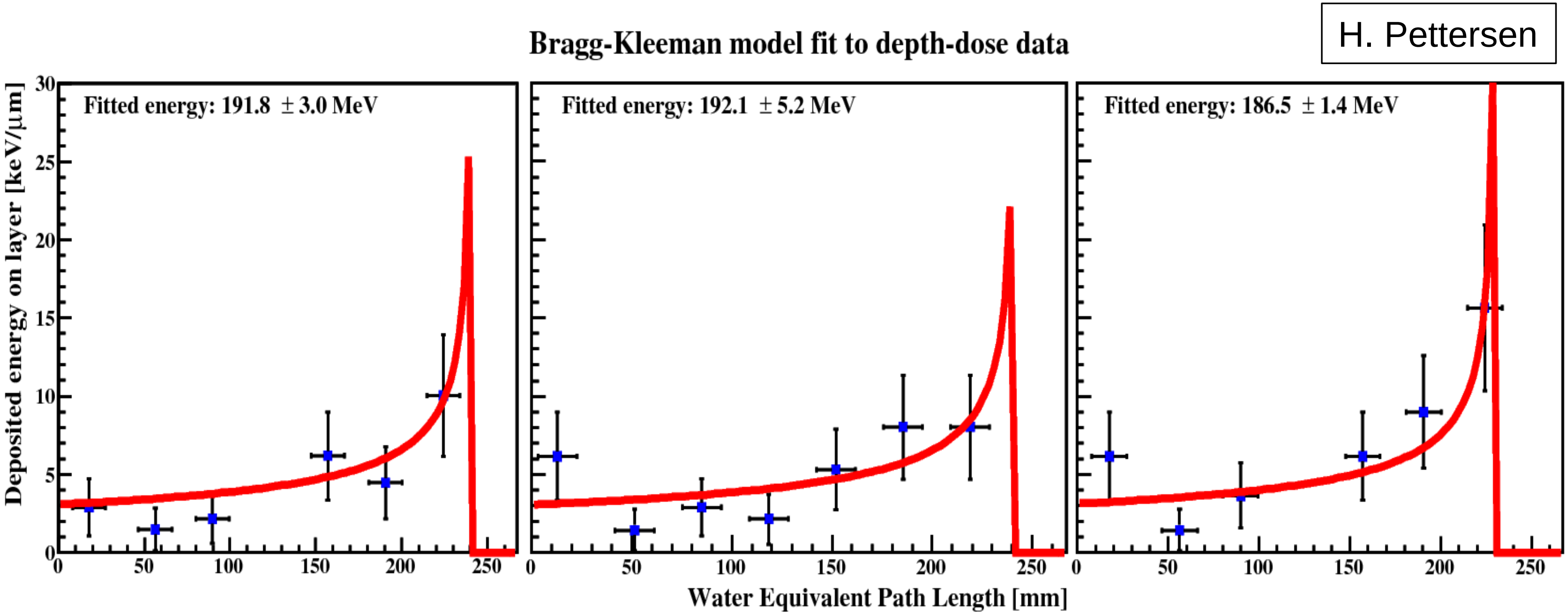


- **Energy loss measurement**
    - **hadron tracks:**
      number of hits in a sensitive layer along the particle trajectory (”cluster size”) depends on the energy loss

Digital tracking calorimeter – rangemeter (IV)

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

H. Pettersen



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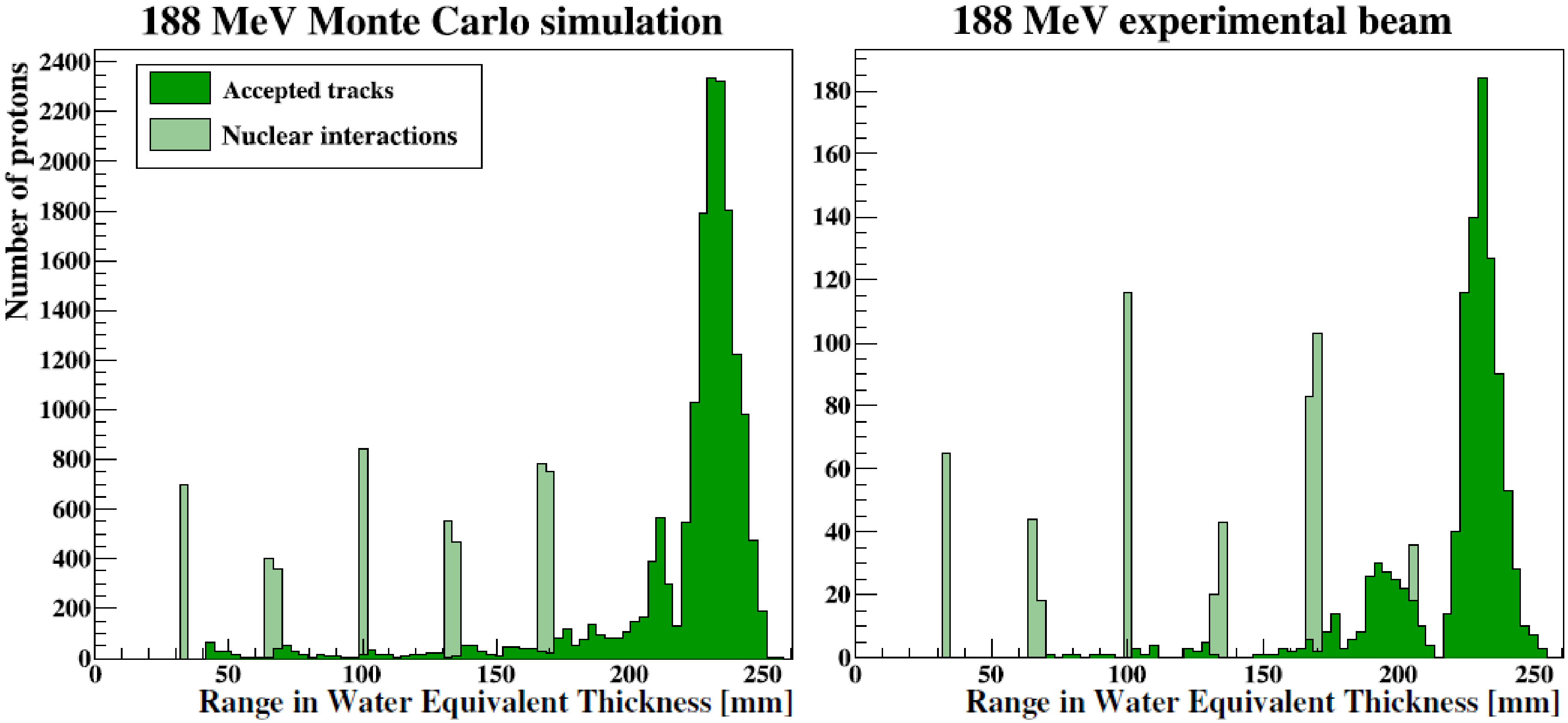
* Bortfeld, T. *An Analytical approximation to the Bragg curve for therapeutic proton beams.* Med. Phys 24 2024-33 (1997)

Digital tracking calorimeter – rangemeter (V)

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

H. Pettersen, PhD thesis,
UiB, 2018



$$\langle\hat{R}\rangle = \frac{\sum_{i=i'}^{\infty} w_i x_i}{\sum_{i=i'}^{\infty} w_i},$$

$$\langle\hat{\sigma}_R\rangle = \sqrt{\frac{\sum_{i=i'}^{\infty} w_i (x_i - \langle\hat{R}\rangle)^2}{[\sum_{i=i'}^{\infty} w_i] - 1}}$$

Towards a clinical prototype – Bergen pCT Collaboration

UNIVERSITY OF BERGEN

HØGSKOLEN I BERGEN
BERGEN UNIVERSITY COLLEGE

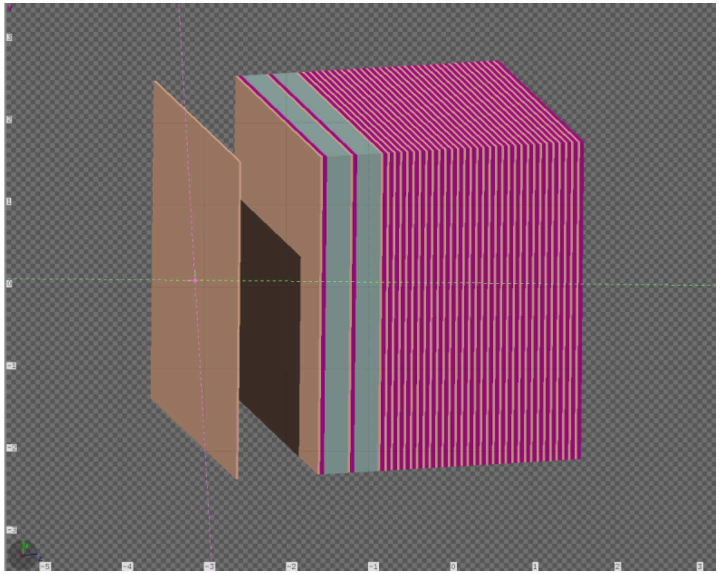
HELSE BERGEN
Haukeland University Hospital

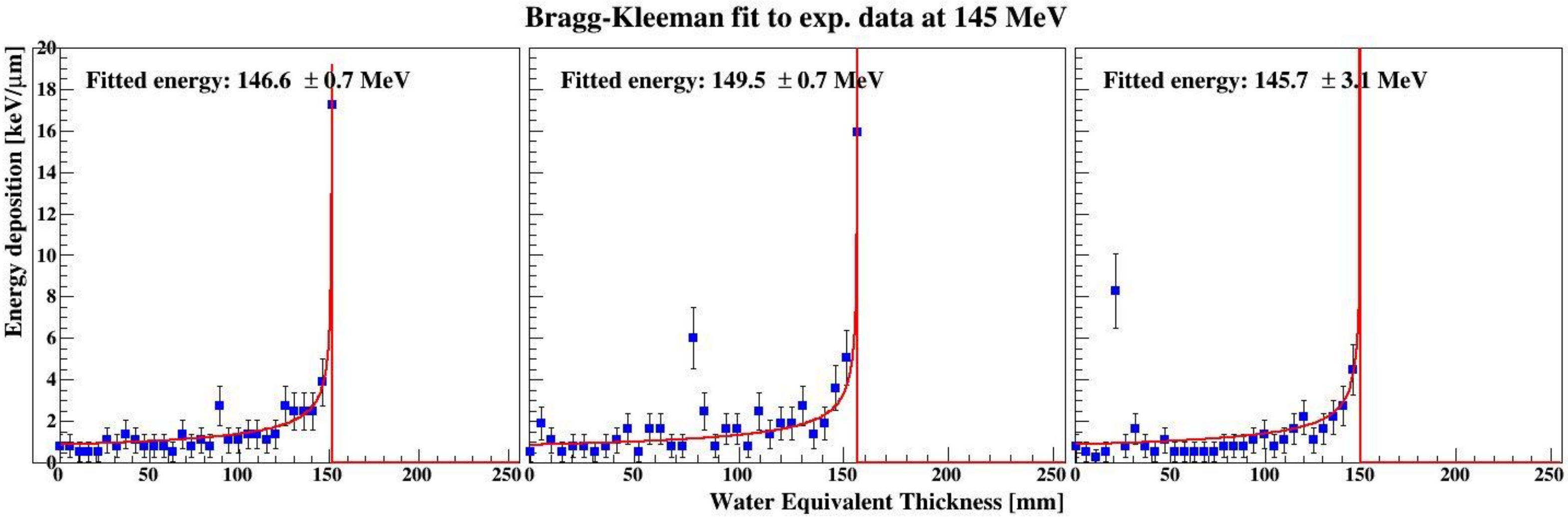
- **Organisation**
  - UiB, HiB, HUS
  - Utrecht University
  - DKFZ Heidelberg
  - Wigner, Budapest
- **Financing**
  - 44 MNOK, 5 years (2017-2021)
- **Status**
  - Finishing the optimisation of the design
  - Sensor characterisation
  - Start massproduction of ALPIDE chips soon

Norwegian government has decided to build two particle therapy facilities (Oslo, Bergen), to be operational by 2022 rep. 2025

Optimisation of the design

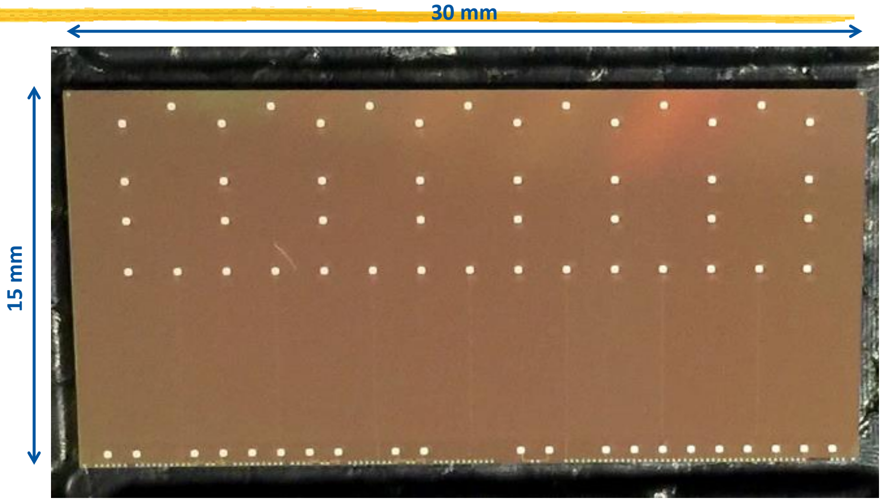
- **geometry**
  - front area: 27 cm x 15(18) cm
- **longitudinal segmentation**
  - number of sensitive resp. absorber layers: 41
- **absorber**
  - energy degrader, mechanical carrier, cooling medium
  - material choice: Al
  - thickness: 3.5 mm

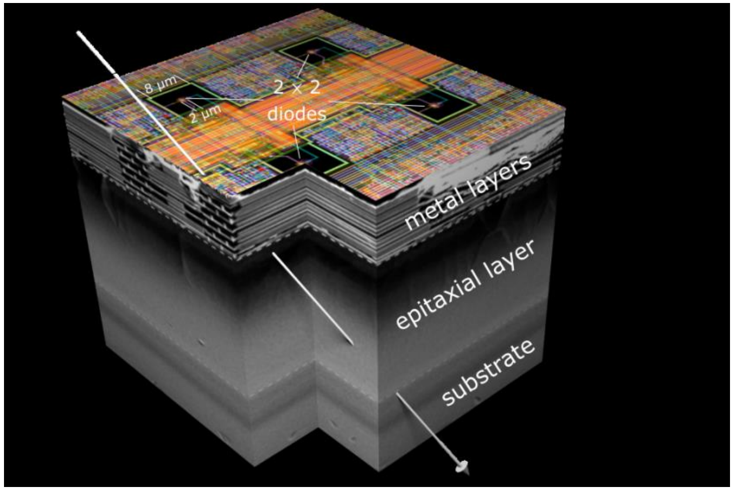




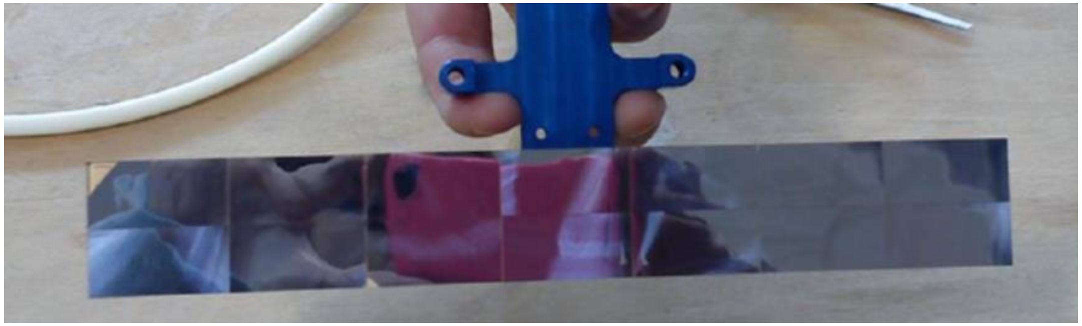
Pixel sensor – MAPS

- **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)**



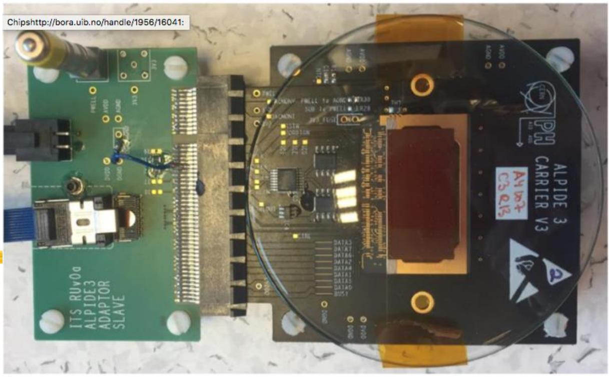


M. Magner, IFEE 2014



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

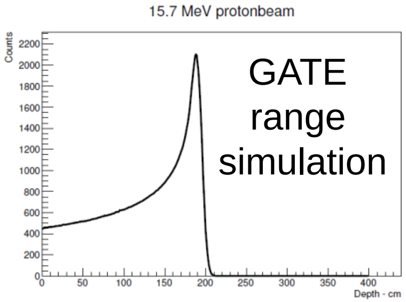
Characterisation of ALPIDE with proton and Helium beams



Cluster size vs dE/dx

- **16 MeV external proton beam in air @ OCL**

(cluster size of a MIP: about 4 pixels)

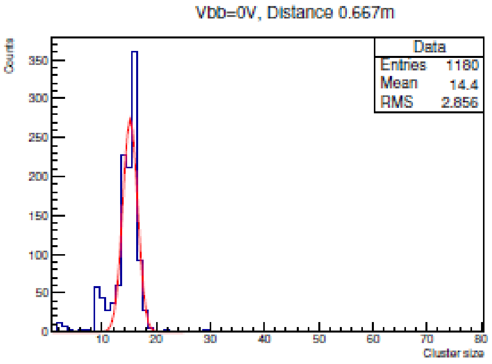


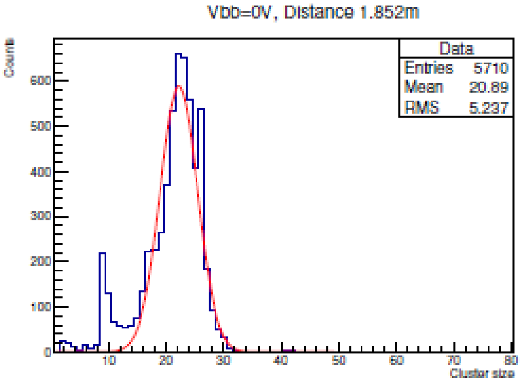
GATE range simulation

cluster size distribution

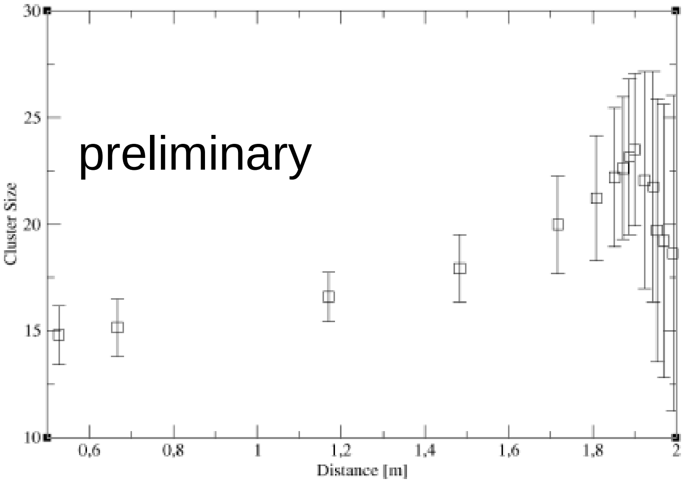
LET: 10 keV/μm

15 keV/μm





average cluster size vs range



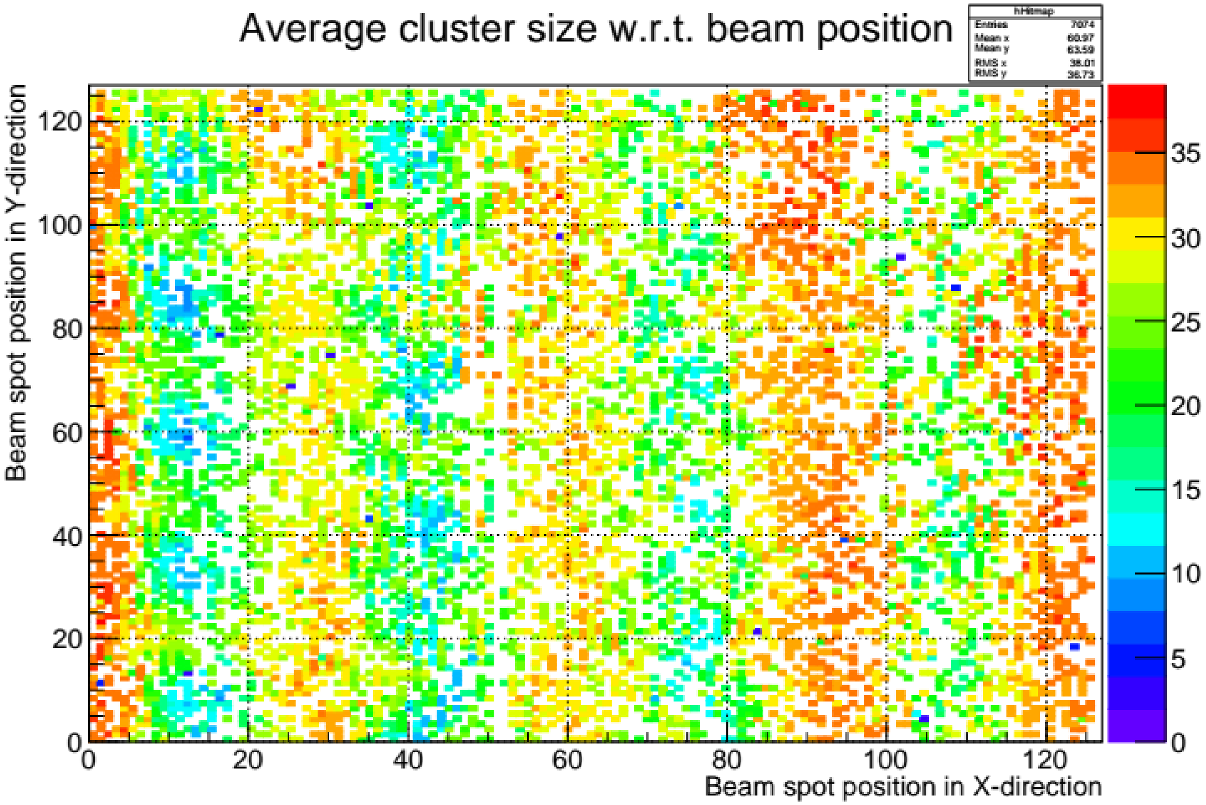
preliminary

V. Eikeland, Master thesis, UiB, 2018

Characterisation of ALPIDE with proton and Helium beams

Uniformity of cluster size

- **He microbeam @ ANSTO**
  - **Scan area: 4.5 x 4.5 pixels**
  - **Beam spot: 1 μm**
  - **Energy: 10 MeV**



preliminary

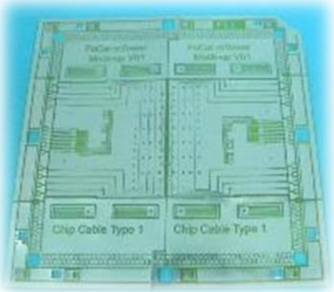
S. Huiberts, Master thesis, UiB, 2018

Mounting sensors on flexible cables

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

ALPIDE chip

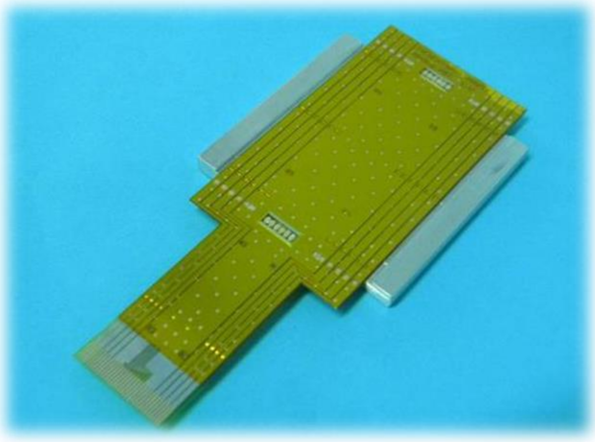
chip cable



design and production:
LTU, Kharkiv, Ukraine

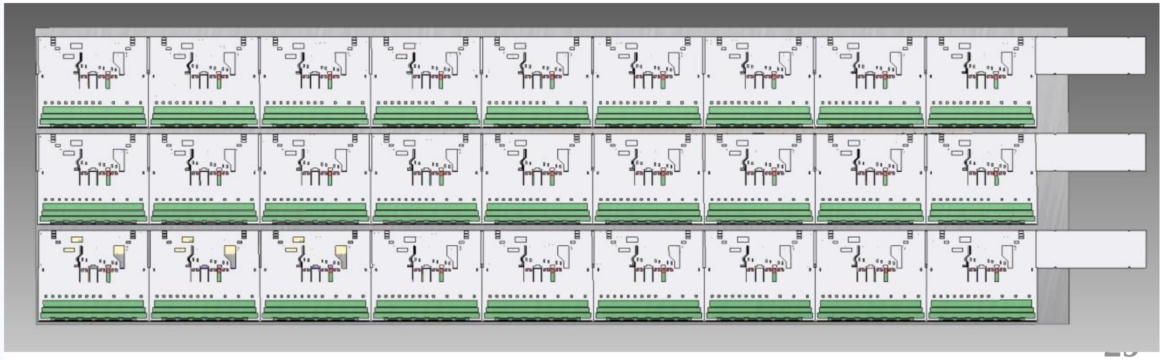
- **Intermediate prototype**

  chip cable with two ALPIDEs



- **Final system**

  flexible carrier board modules
  with 2x3 strings with 9 chips each



Towards the clinical prototype

- **Challenges**
  - **Two tracking layers at the front face - total thickness < 0.4 mm, 2 cm apart**
    - **Sensors: thinned down to 50 μm**
    - **Flex: ~100 μm**
    - **Carrier: Al or carbon foam/prepreg ~200 μm**

- **Readout system and DAQ**
  - **PCBs with Xilinx Virtex Ultrascale+ FPGAs (one per layer)**

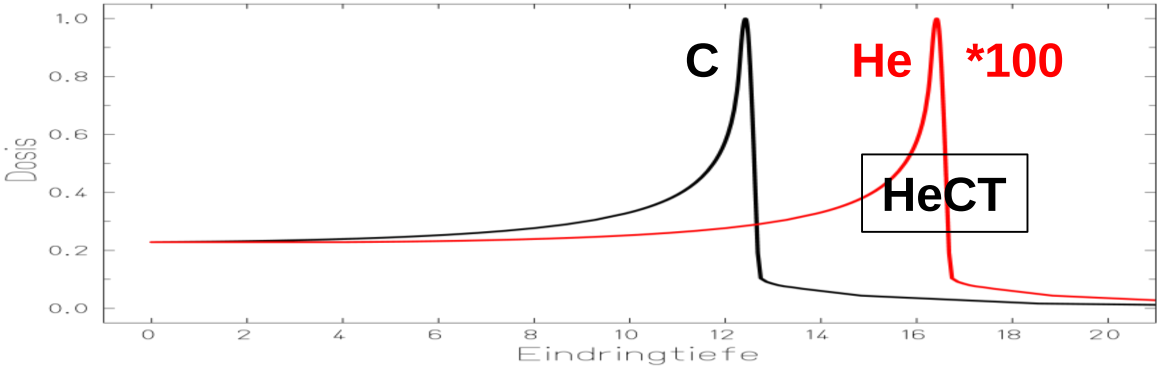
- **Expected performance (simulation and beam tests)**
  - **Range accuracy: < 0.5 mm WET**
  - **Position resolution: 5 μm**
  - **Radiation hardness > 5 kGy resp. 1.7x10^{13} 1 MeV neq/cm^2**
  - **Flux: > 1...8 x 10^6 particles/cm^2/s**

Next steps - Outlook

- **Construction of prototype**
  - **First chip cables with mounted chips are being tested**
  - **First sensor module: December**

- **Extensive commissioning with proton beams**

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



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

This is the end