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 diagnostic tool for quasi-online dose plan verification**
- **Towards a clinical prototype**
  - **Digital tracking calorimeter prototype**
  - **Results from simulations and beam tests**

The Bergen proton CT collaboration

The Bergen pCT collaboration and the SIVERT research group

Institutions

University of Bergen, Norway

Helse Bergen, Norway

Western Norway University of Applied Science, Bergen, Norway

Wigner Research Center for Physics, Budapest, Hungary

DKFZ, Heidelberg, Germany

Saint Petersburg State University, Saint Petersburg, Russia

Utrecht University, Netherlands

RPE LTU, Kharkiv, Ukraine

Suranaree University of Technology, Nakhon Ratchasima, Thailand

China Three Gorges University, Yichang, China

University of Applied Sciences Worms, Germany

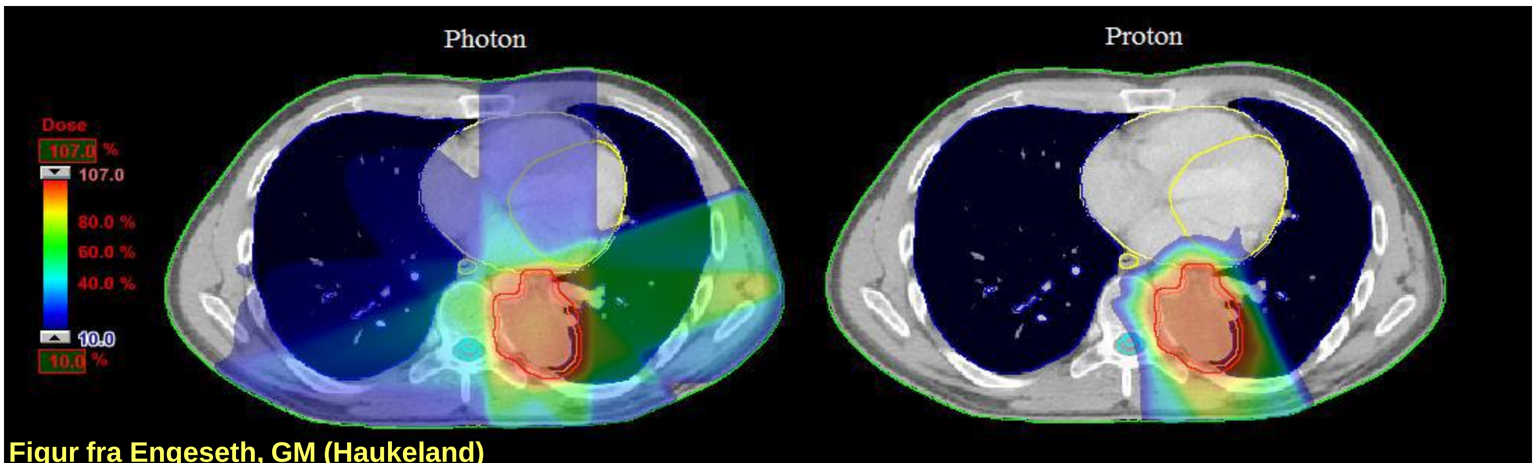
University of Oslo, Norway

Eötvös Loránd University, Budapest, Hungary

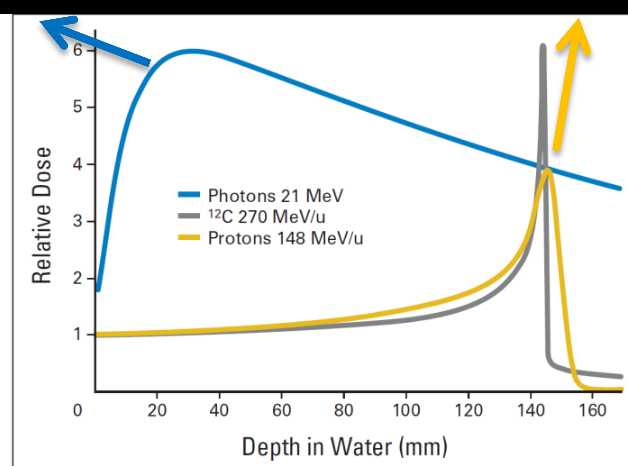
Technical University TU Kaiserslautern, Germany

Radiotherapy – photons vs hadrons

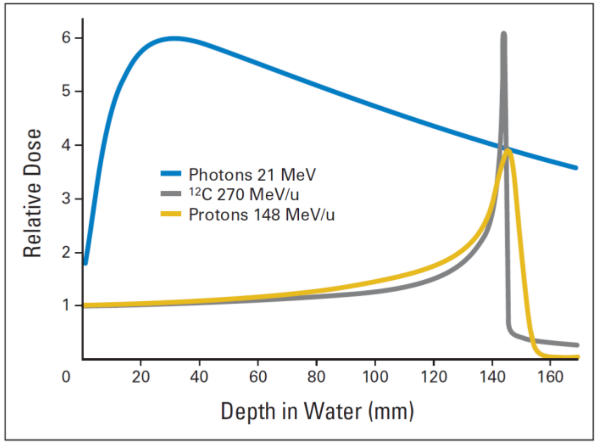
- **Treatment goal**
  - **Effective eradication of all tumor cells <-> avoid injury to healthy tissue**
  - **Radiotherapy is an important weapon in the battle against cancer**



  - **Contributions to successful treatment of cancer**
    - **45-50% surgery**
    - **40-50% radiotherapy**
    - **10-15% chemotherapy**



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 – range uncertainties

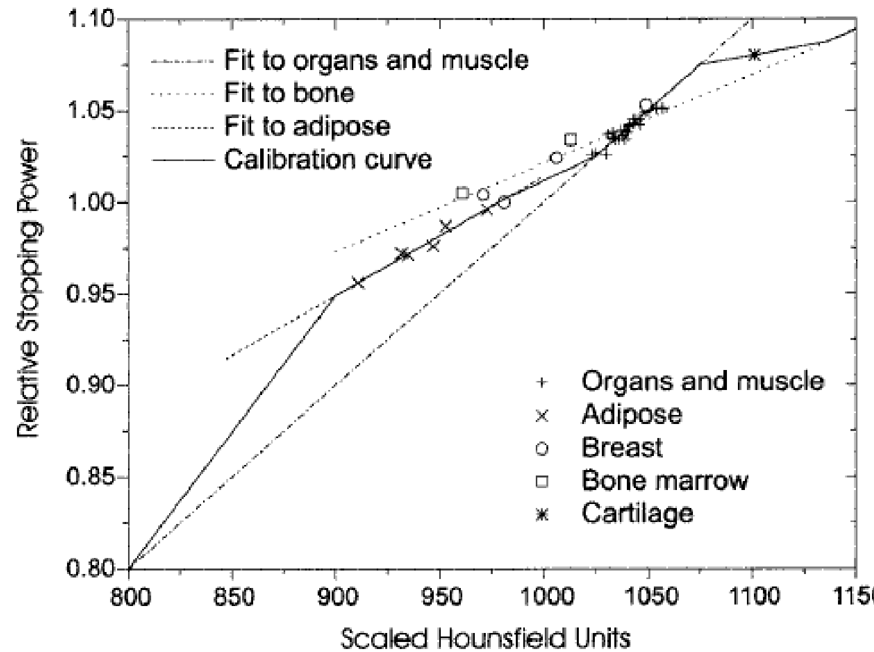
Clinical practice

- **Stopping power calculation derived from 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



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.

Estimates for advanced dose planning:

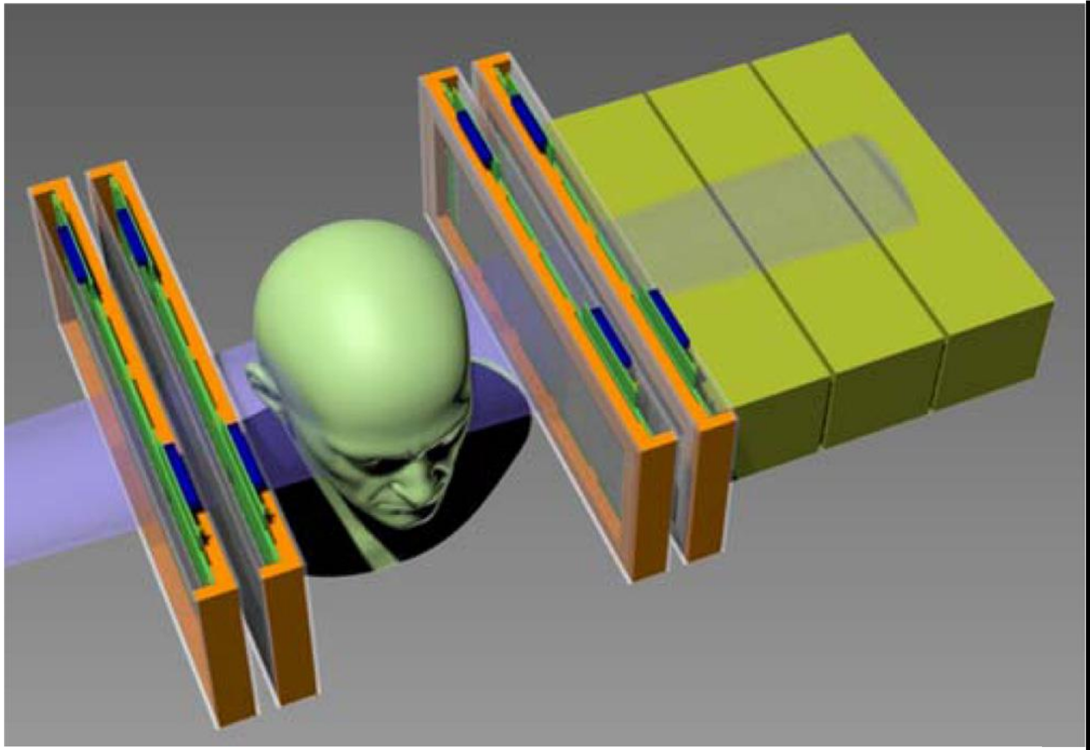
- **Dual energy CT: up to 1.7 % uncertainty**
- **Proton CT: up to 0.3 % uncertainty**

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

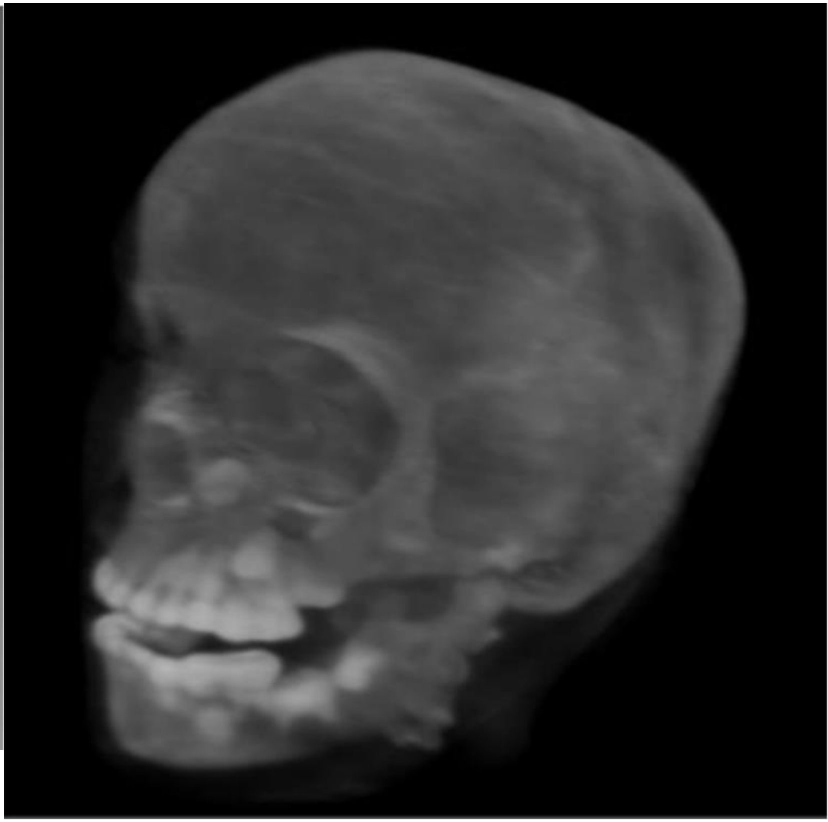


Fig. 14. 3D rendering of the pCT-reconstructed RSP map of a pediatric anthropomorphic head phantom.

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

Imaging with protons – nothing new

- **Proton radiography**

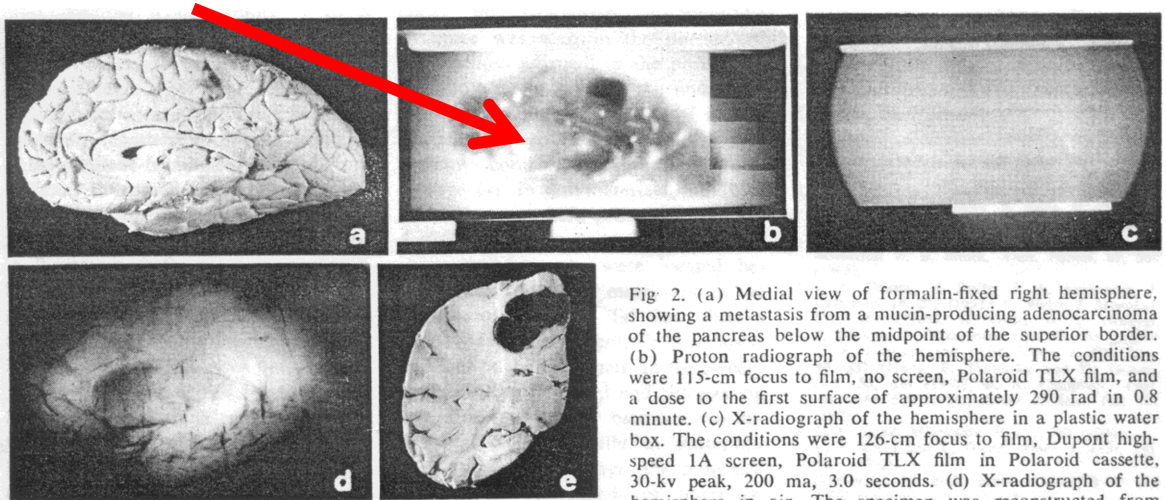
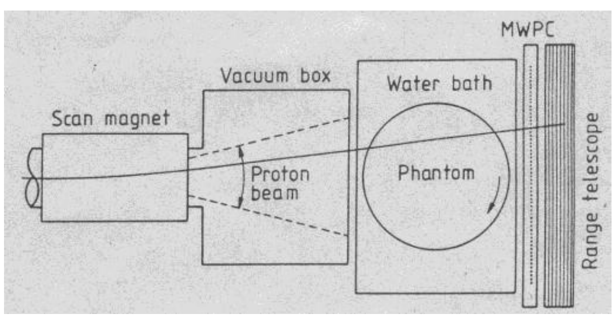


Fig. 2. (a) Medial view of formalin-fixed right hemisphere, showing a metastasis from a mucin-producing adenocarcinoma of the pancreas below the midpoint of the superior border. (b) Proton radiograph of the hemisphere. The conditions were 115-cm focus to film, no screen, Polaroid TLX film, and a dose to the first surface of approximately 290 rad in 0.8 minute. (c) X-radiograph of the hemisphere in a plastic water box. The conditions were 126-cm focus to film, Dupont high-speed 1A screen, Polaroid TLX film in Polaroid cassette, 30-kv peak, 200 ma, 3.0 seconds. (d) X-radiograph of the hemisphere in air. The specimen was reconstructed from serial coronal sections. Note that the tumor is just visible. The conditions (optimal) were 92-cm focus to Kodak mammography film, 27-kv constant potential, 20 ma, 2 minutes. (e) Photograph of a slice taken through the tumor.

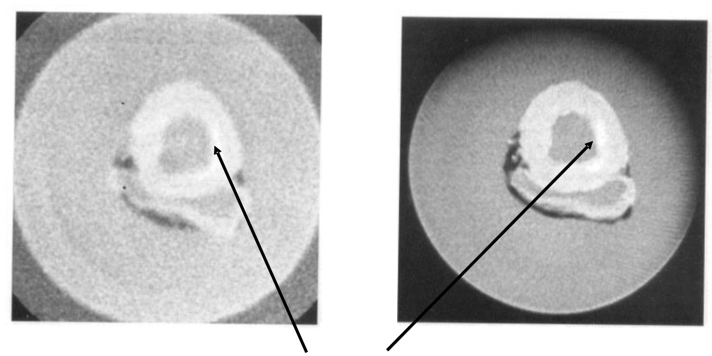
Steward and Kohler (1973)

- **Proton CT**



Hanson et al (1982)

Protons (Dose=2.7 mGy) **X-rays (Dose 21 mGy)**



Myokardinfarkt

Imaging with protons – many prototypes

… still no clinical system

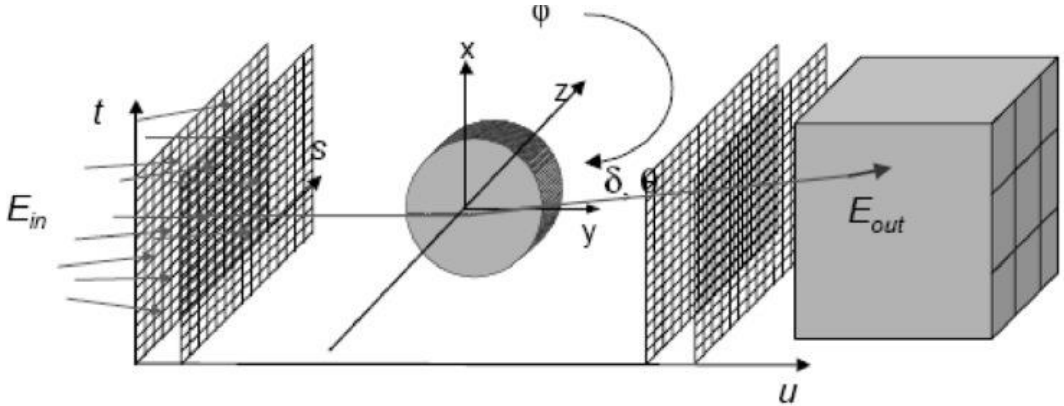
Table 3. A summary of current and recent proton radiography (pRG)/proton CT (pCT) prototypes

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

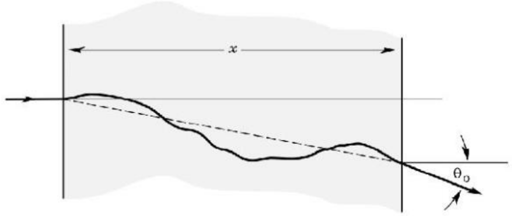
G. Poludniowski, N. M. Allinson, and P. M. Evans, “Proton radiography and tomography with application to proton therapy”, *Br. J. Radiol.*, vol. 88, no. 1053, pp. 1–14, 2015

Proton-CT
- quasi-online dose plan verification

- **high energetic proton beam quasi-simultaneous 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)**



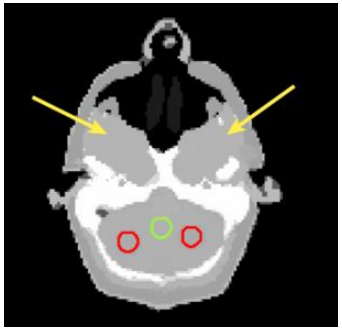
- **MS theory and Bethe-Bloch formula of average energy loss in turn depend on electron density in the target (and ionization potentials)**

-> 3D map of stopping power

-> online verification of dose plan

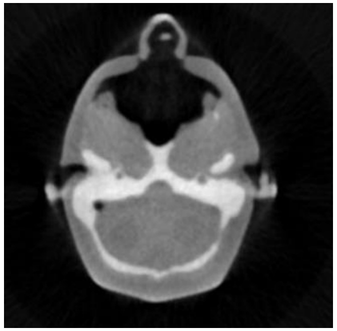
Proton-CT - images

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

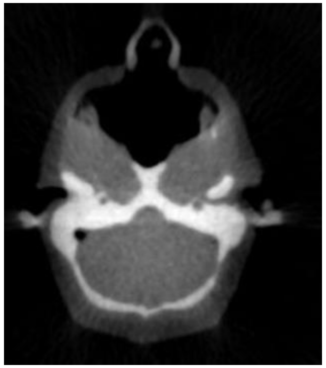


Phantom

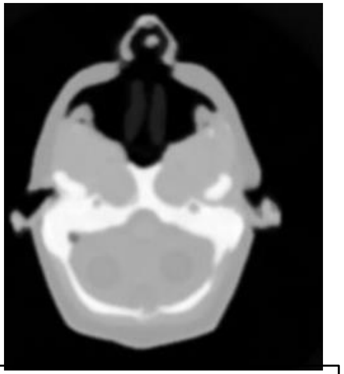
- Transmission map
  – records loss of protons
  due to nuclear reactions



- Scattering map
  – records scattering of protons off
  Coulomb potential



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

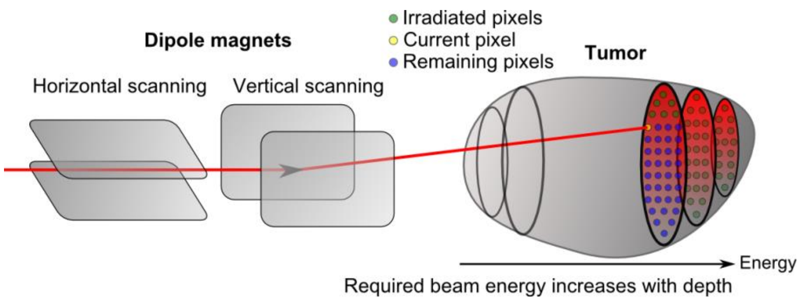


Cecile Bopp. PhD thesis, Strasbourg, 2013

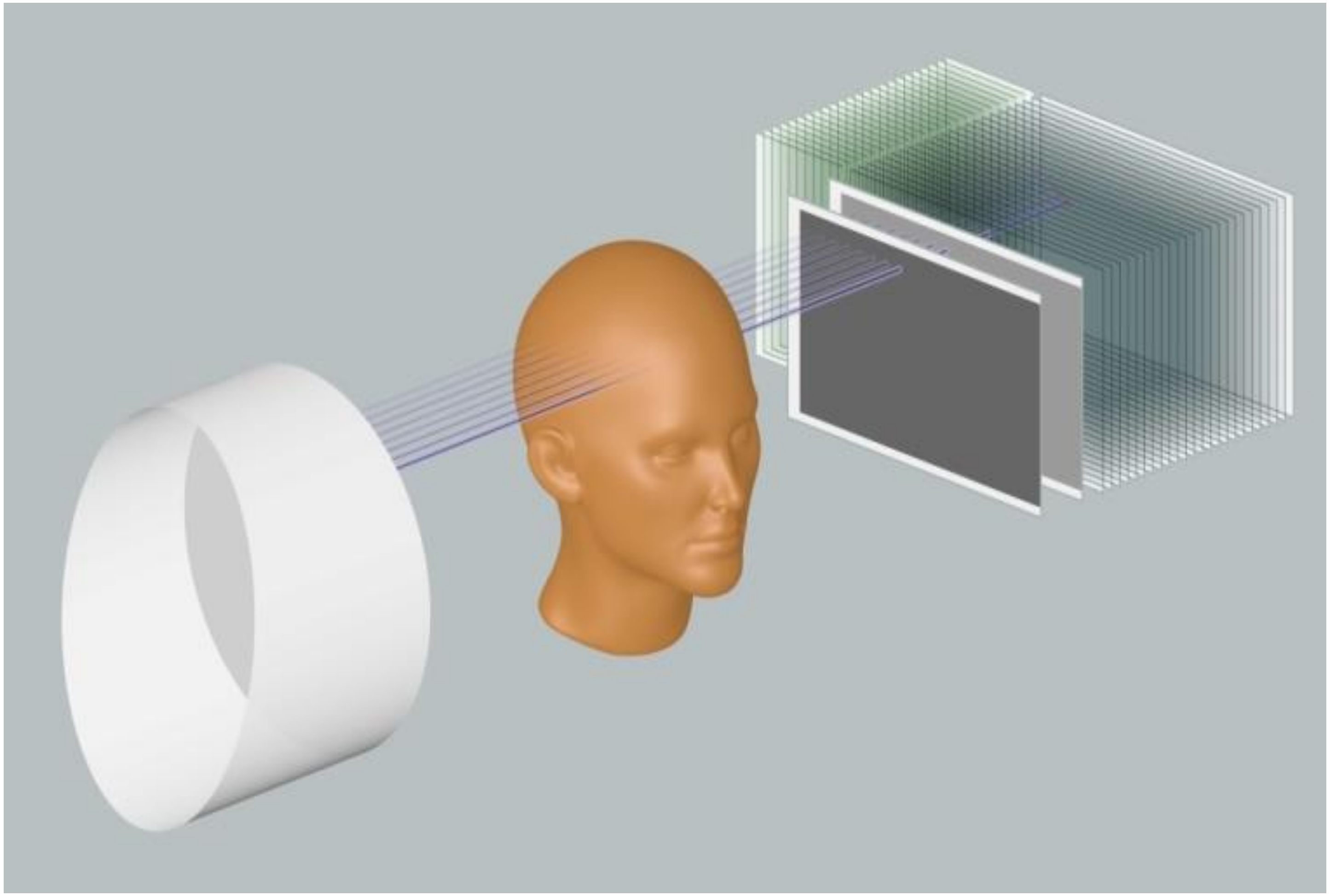
Clinical pCT - requirements

Operate with clinical beam settings

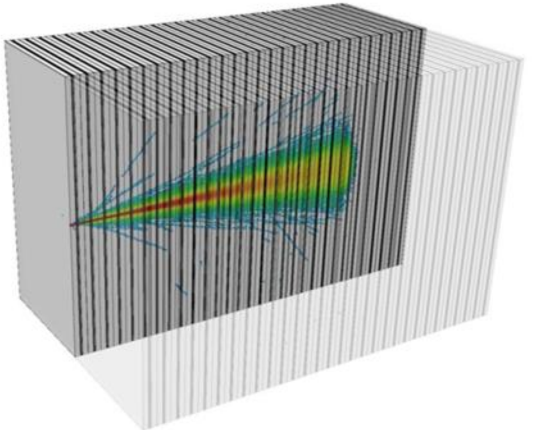
- Pencil beam scanning mode
  - Beam spot size, scanning speed, intensity
- Scanning time
  - Seconds … minutes
- Detector
  - Efficient simultaneous tracking of large particle multiplicities
  - Large area (~30 x 30 cm^2)
  - Radiation hardness
  - High position resolution (~10 μm)
  - Front detector (first 2-3 layers): very low mass, thin sensors (~100 μm)
  - Back detector: range resolution <1% of path-length
- System
  - Compact
  - No gas, no HV
  - Simple air/water cooling

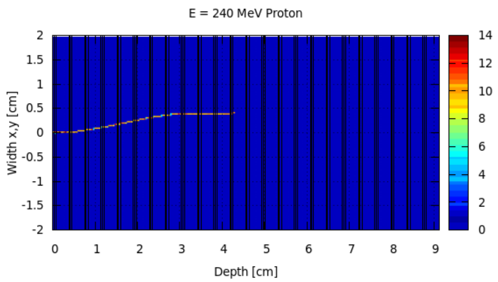


Clinical pCT - design

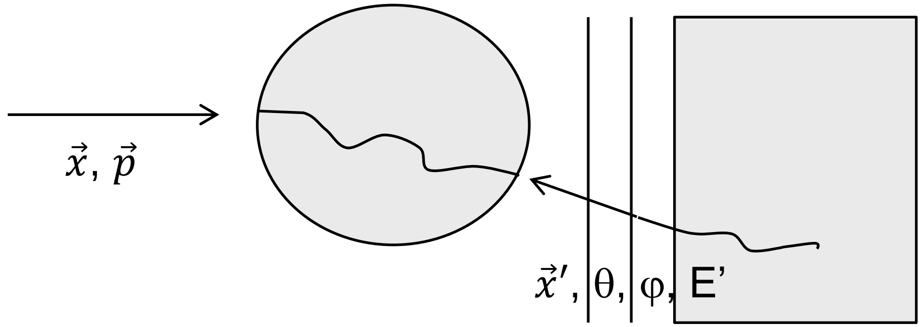


Clinical pCT - design





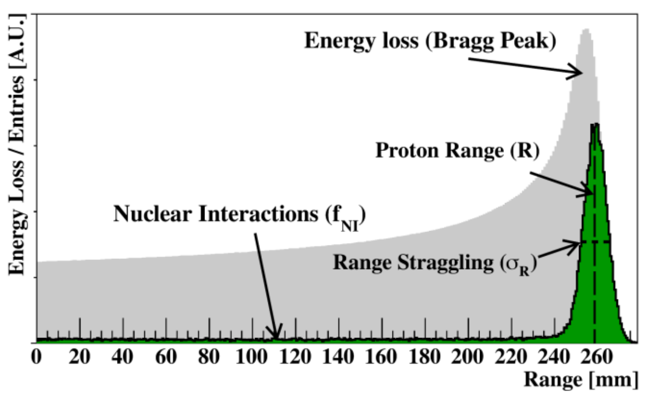
- **Conceptual design**



  - x, p **given by beam optics and scanning system**
  - x', θ, φ, E' **have to be measured with high precision**
    - **position resolution ~5 μm with minimal MS, i.e. first two tracking layers very thin**

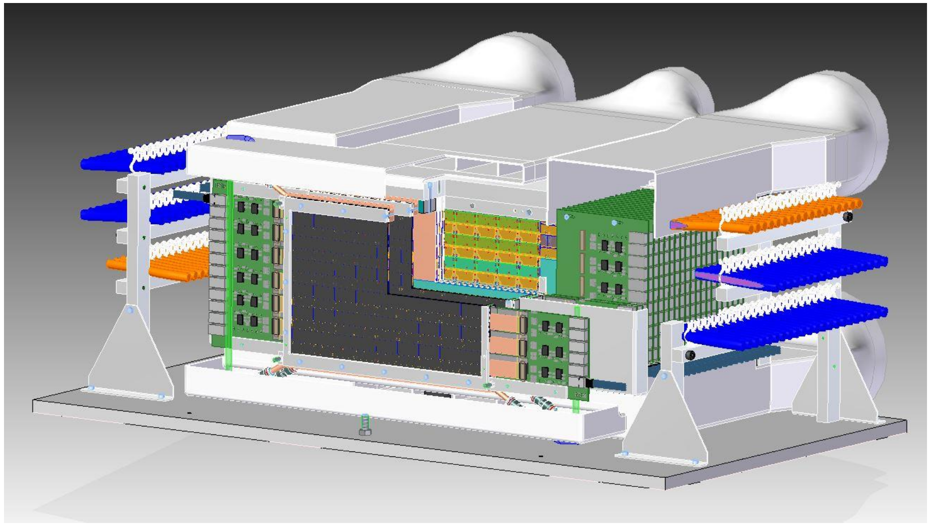
→ **Extremely high-granularity digital calorimeter for tracking, range and energy loss measurement**

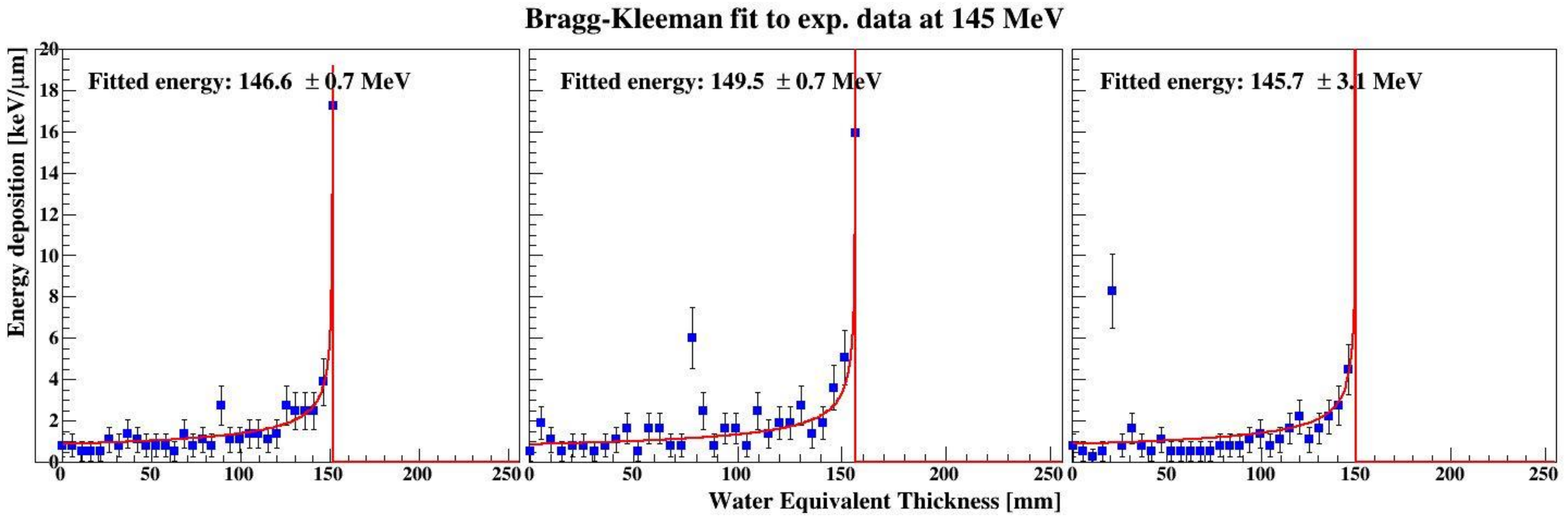
- **Technical design**
  - **Planes of CMOS sensors – Monolithic Active Pixel Sensors (MAPS) with digital readout– as active layers in a sampling calorimeter**



The Bergen pCT (clinical) prototype

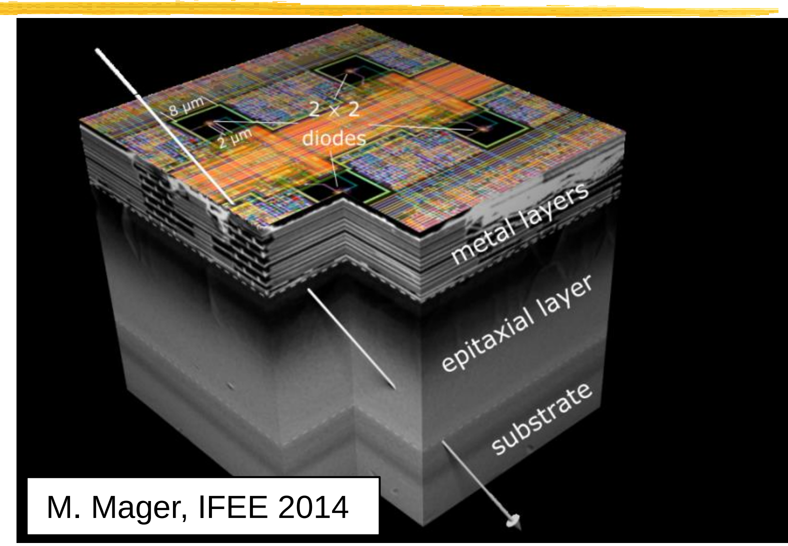
- **geometry**
  - **front area: 27 cm x 18 cm**
- **"sandwich" calorimeter**
  - **alternating layers of absorbers and sensors**
  - **longitudinal segmentation: 41 layers**
- **aluminium absorbers**
  - **energy degrader, mechanical carrier, cooling medium**
  - **thickness: 3.5 mm**



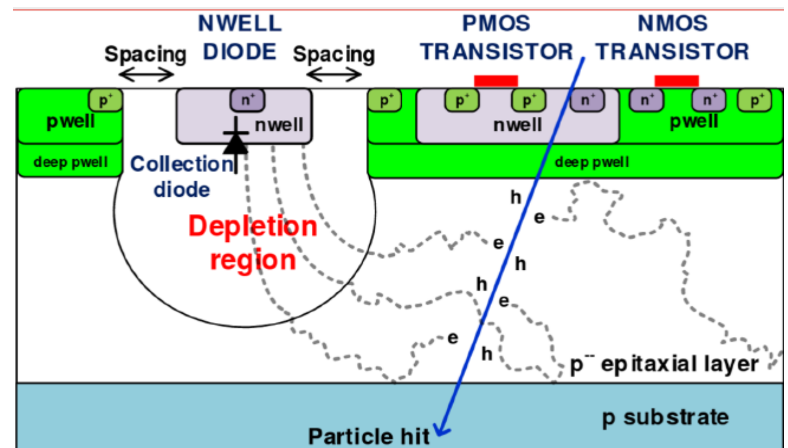


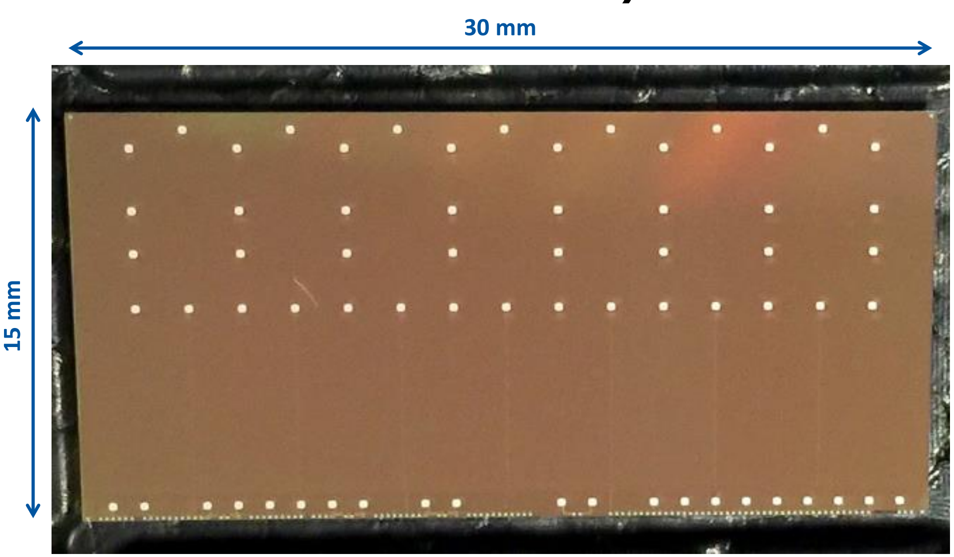
Sensor layers – Monolithic Active Pixel Sensors (MAPS)

- **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. Mager, IFEE 2014





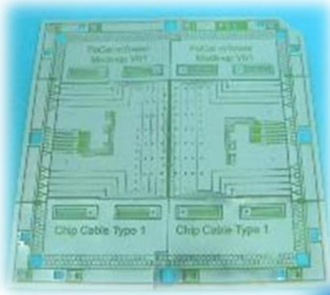
Design team:
CCNU Wuhan, CERN Geneva, YONSEI Seoul, INFN Cagliari, INFN Torino, IPHC Strasbourg, IRFU Saclay, NIKHEF Amsterdam

Mounting sensors on flexible cables

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

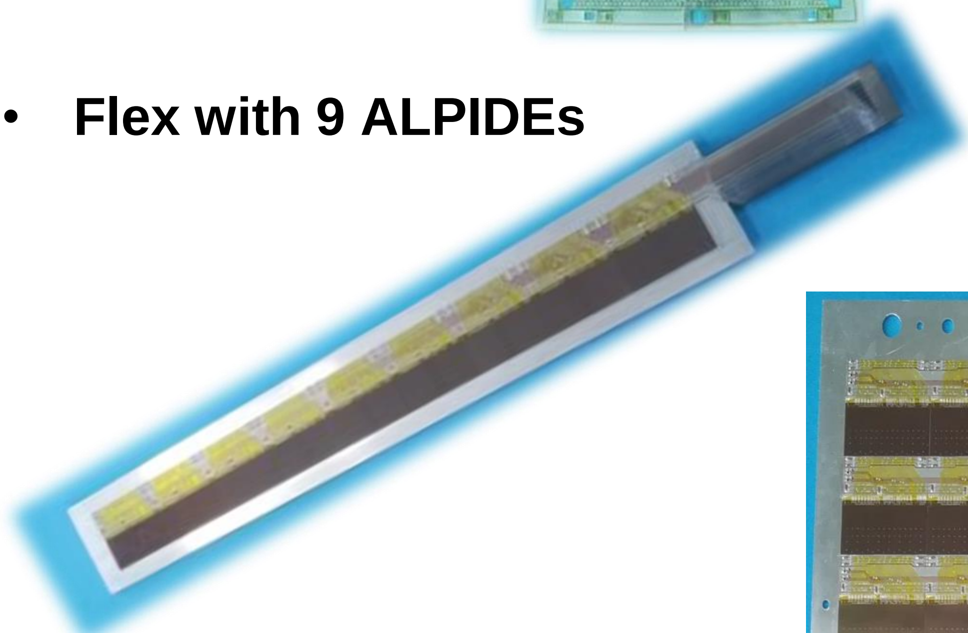
ALPIDE chip

chip cable



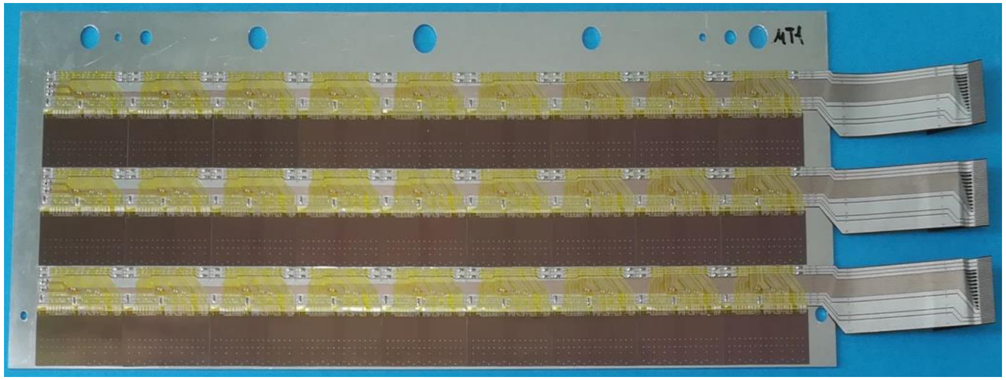
Design and production:
LTU, Kharkiv, Ukraine

- **Flex with 9 ALPIDEs**



- **Module - flex on Al carrier**

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

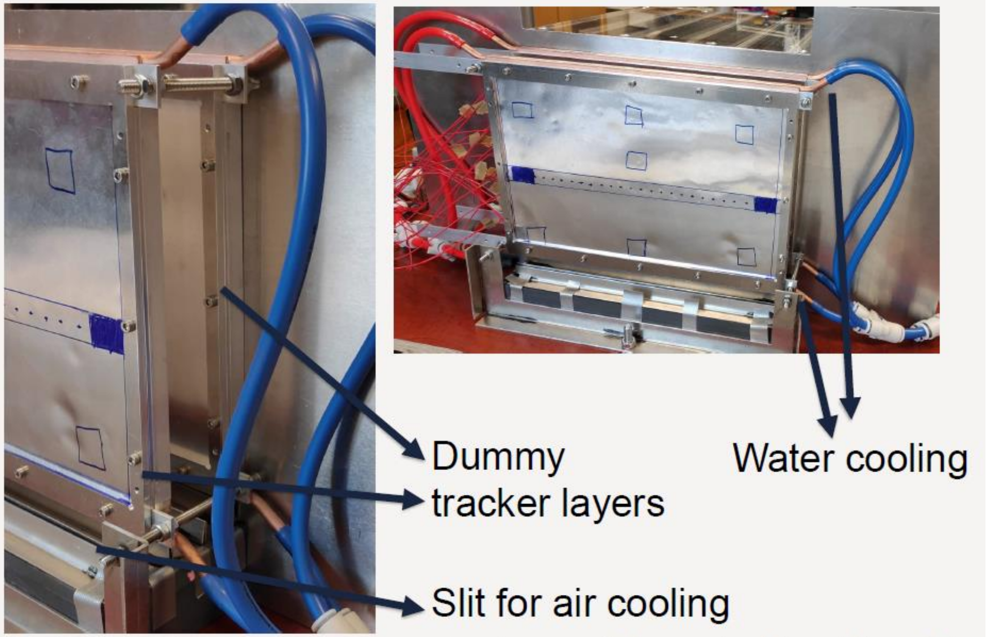


Ultra-thin tracking layers

- **Thinned ALPIDEs (50 μm) mounted on a thin flex and glued to a large sandwiched carbon fiber sheet (pyrolitic graphite paper + carbon fleece + epoxy resin)**

Sandwiched carbon fiber sheet, fabricated at St Petersburg State University (G. Feofilov, S. Igolkin)

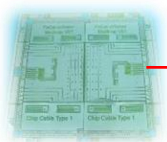
mechanical integration and cooling



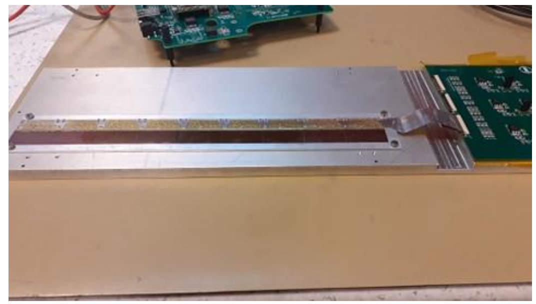
Prototype tracking layers designed fabricated by Utrecht University, tested at University of Bergen

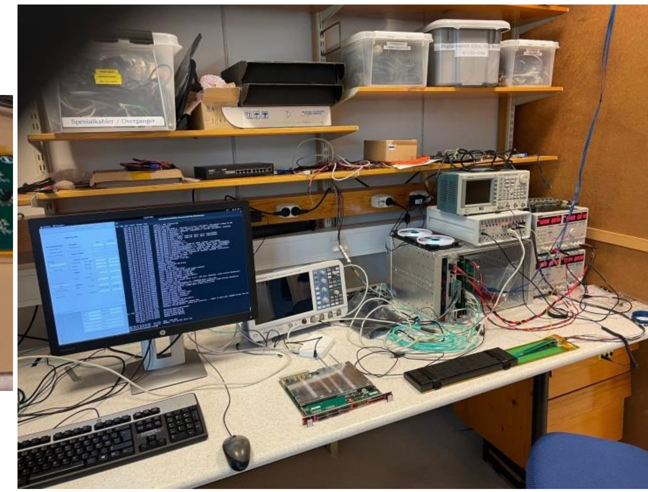
Readout electronics

- **Test station for ALPIDE sensor mounted on chip cable**

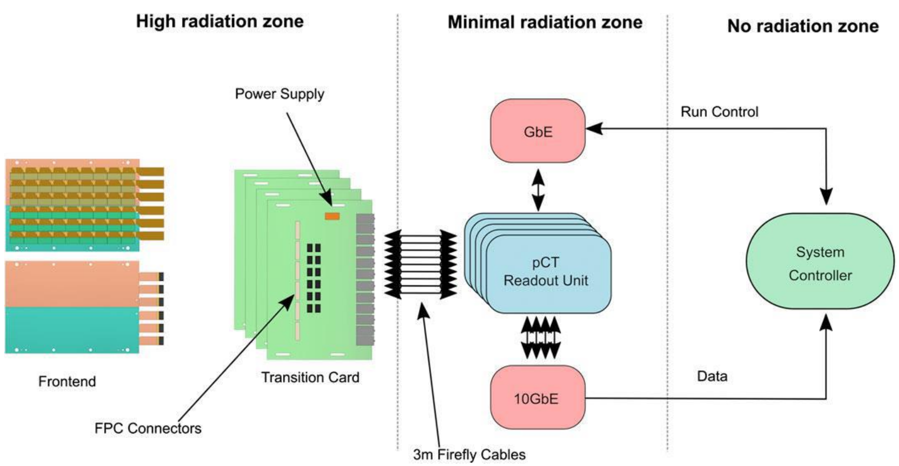


- **Test station for full 9-chip string**





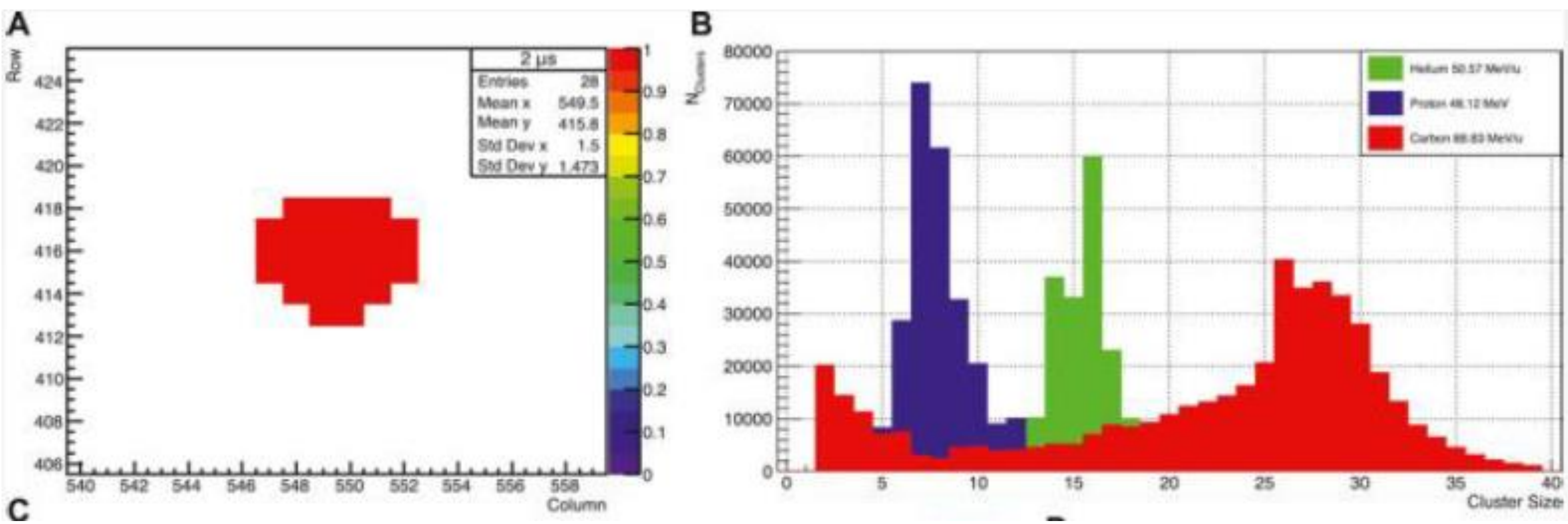
- **pCT readout unit – FPGA based design**



How to measure energy loss with a digital pixel sensor?

- **Operate ALPIDE in ”charge collection by diffusion mode”**
- **Measure size of charge cluster**

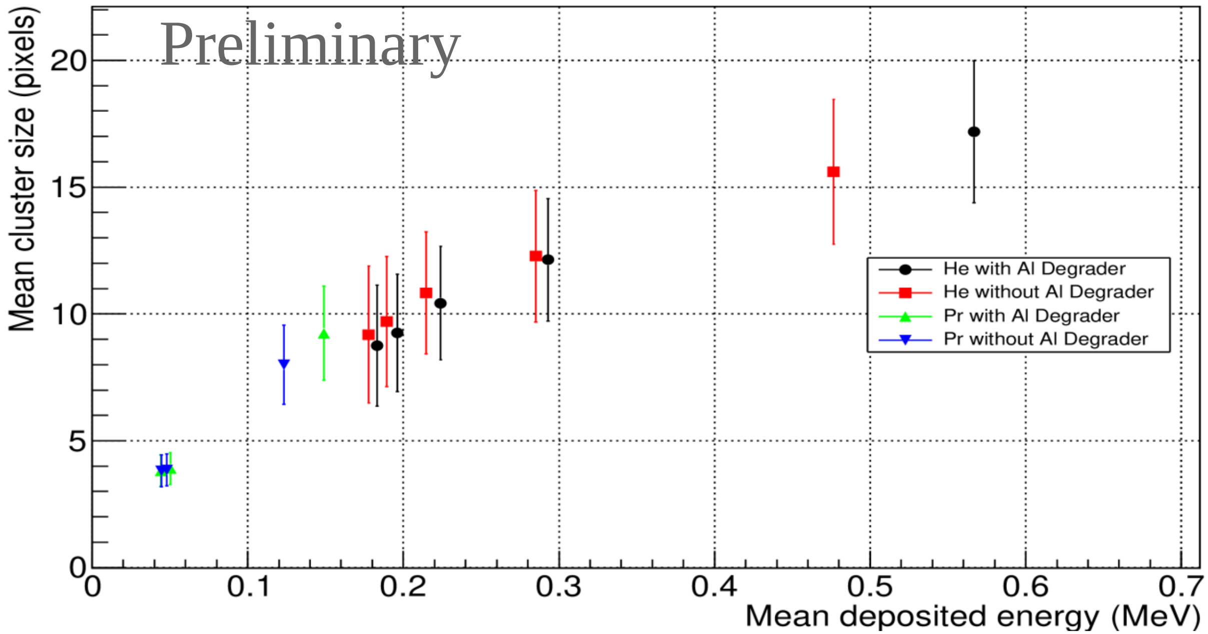
α particle **proton – α – C**



How to measure energy loss with a digital pixel sensor?

- Operate ALPIDE in ”charge collection by diffusion mode”
- Measure size of charge cluster

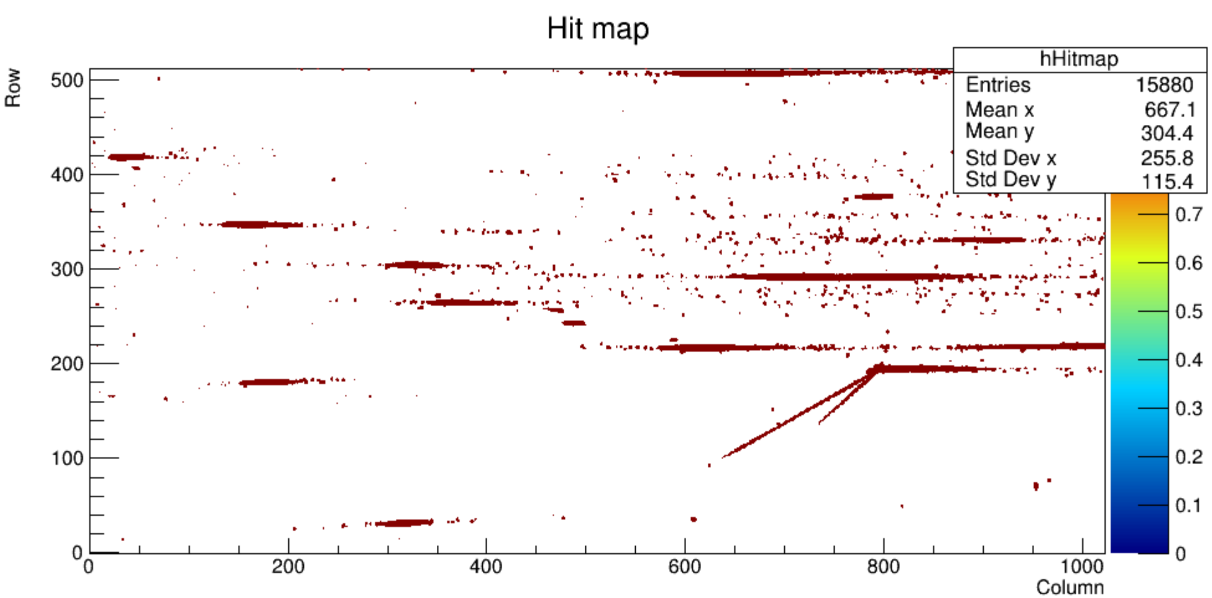
- Results from proton and He-beams at different energies (HIT)



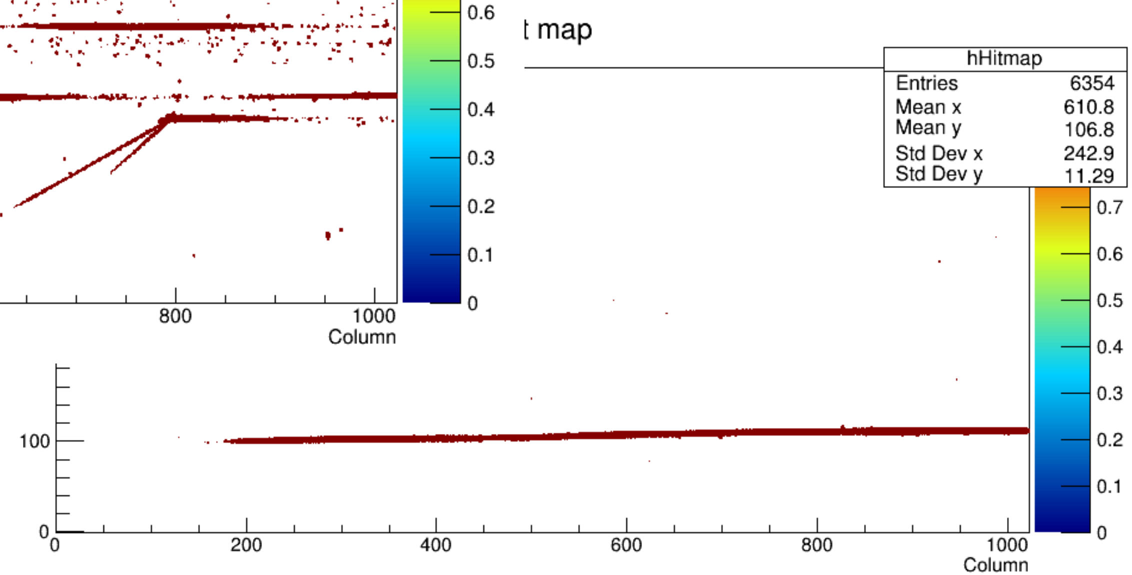
- Cluster size increases with simulated energy loss

Can ALPIDE cope with highly ionising particles?

- Every ALPIDE sensor has to cope with tens to hundreds of slow protons per μsec
- Stress test: irradiation along the chip with 140 MeV/u carbon beams (HIT)



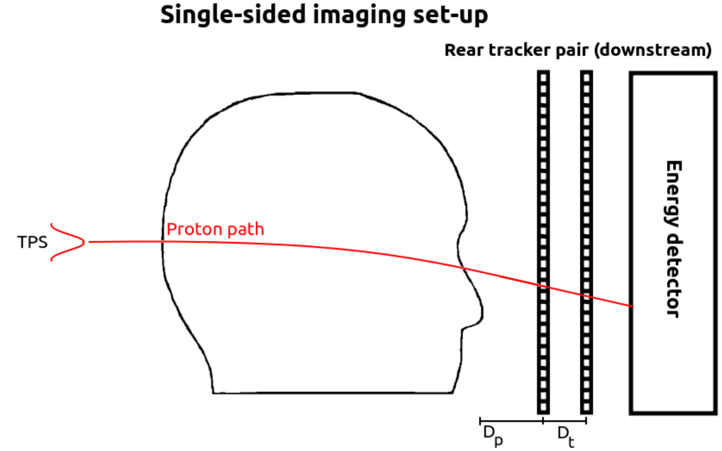
beams from the right



- Successful recording of stopping carbon beams

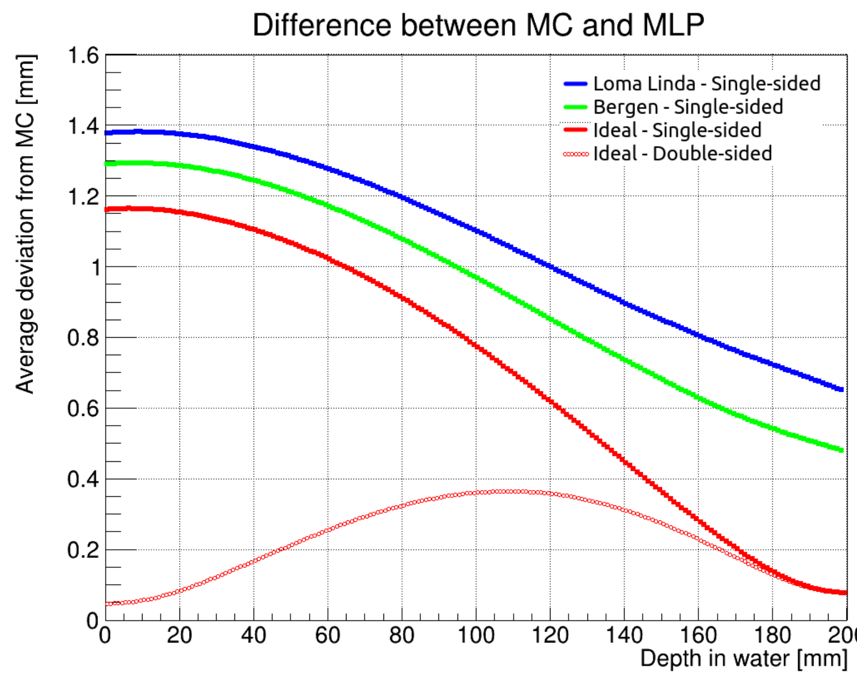
Does 3D reconstruction work with trackers only behind the phantom?

- **Single-sided imaging**
  - **Most Likely Path estimate**
    - **Entrance – beam optics**
    - **Exit – pCT front trackers**



  - **Difference between MC truth and estimated proton path**
    - **Beam spot size: 7 mm**

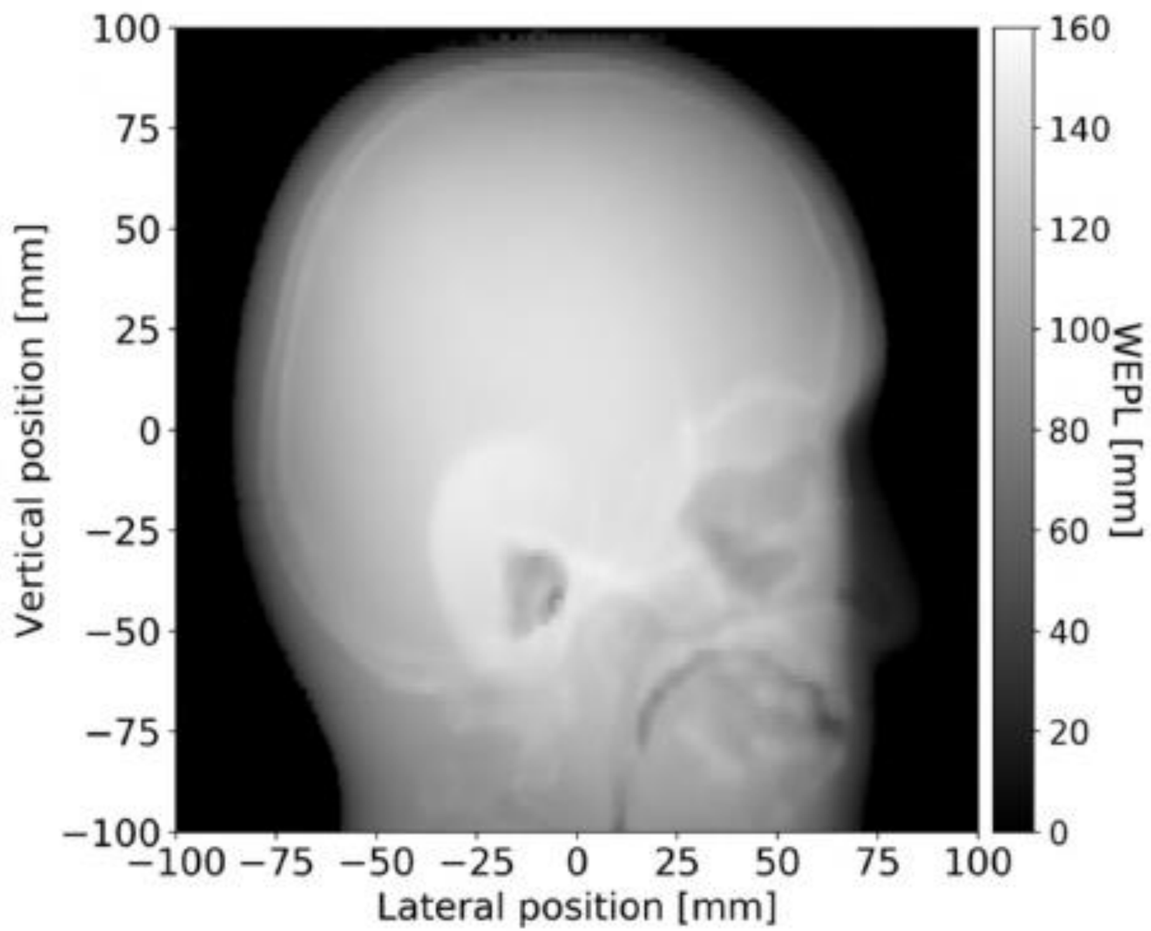
-> deviations ≤ 1.2 mm



Krah, N., et.al., (2018). A comprehensive theoretical comparison of proton imaging set-ups in terms of spatial resolution, Physics in Medicine & Biology 63 (13): 135013.

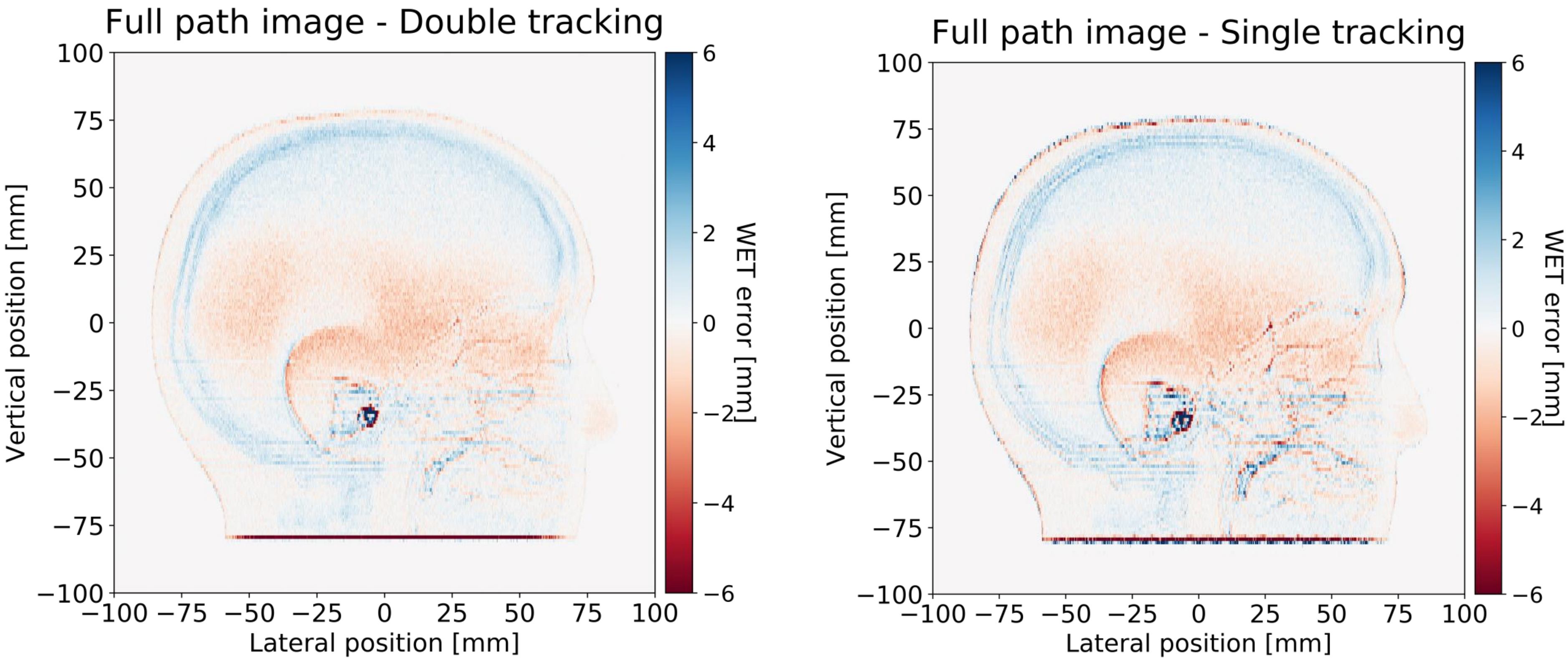
Radiographic image reconstruction - pRAD

- **Head phantom radiograph (simulation)**
  - **230 MeV**
  - **10^7 protons**
  - **~ 15 μSv deposited dose**



Radiographic image reconstruction - pRAD

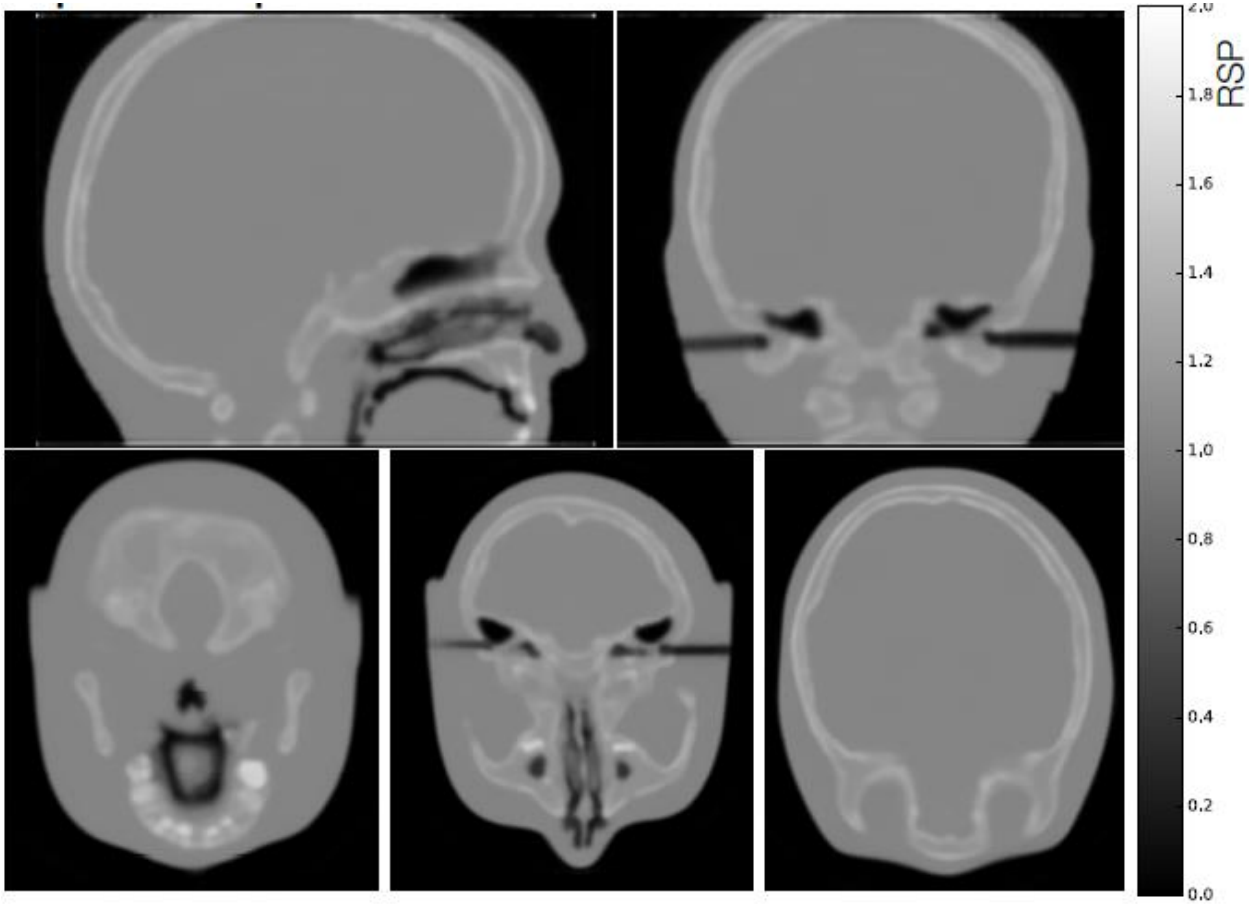
- **Quality of head phantom radiographs - WET errors (simulation)**



Collins-Fekete, C.-A., et al., (2016). A maximum likelihood method for high resolution proton radiography/proton CT, Physics in Medicine and Biology 61 (23): 8232.

pCT (3D) reconstruction

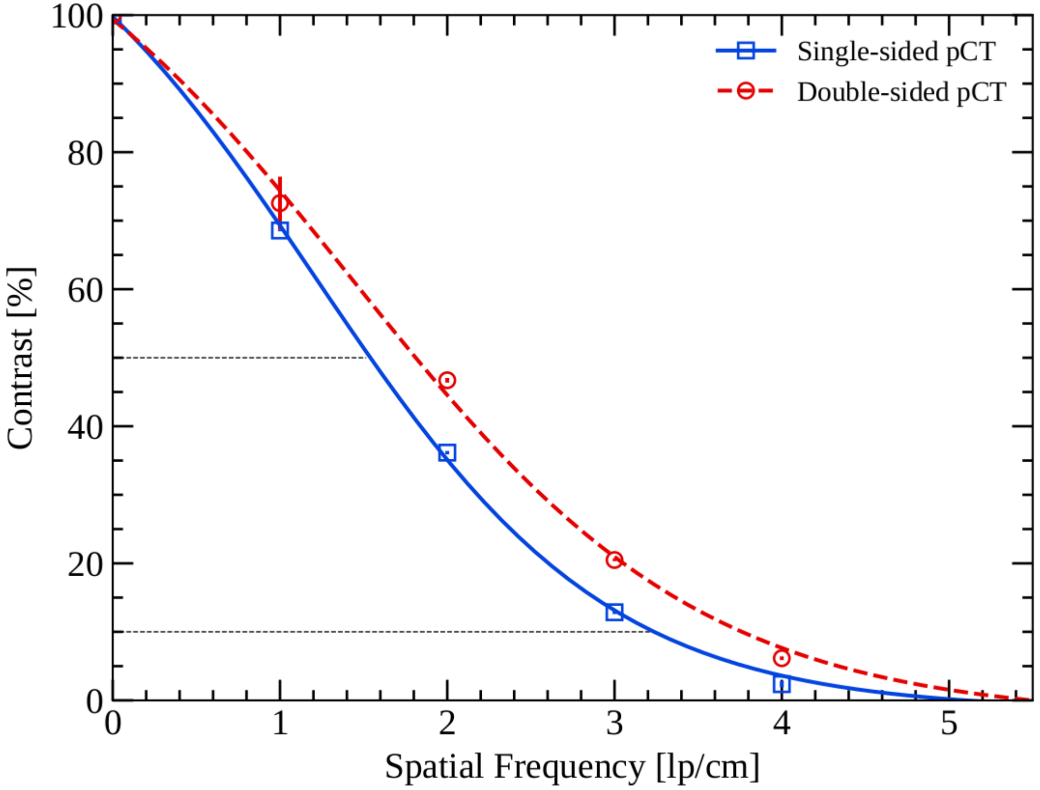
- **Head phantom pCT (simulation)**
  - **230 MeV**
  - **360 projections, 1° steps**
  - **3.5 x 10^6 protons per projection**
  - **7.9 x 10^8 protons for 3D reconstruction**

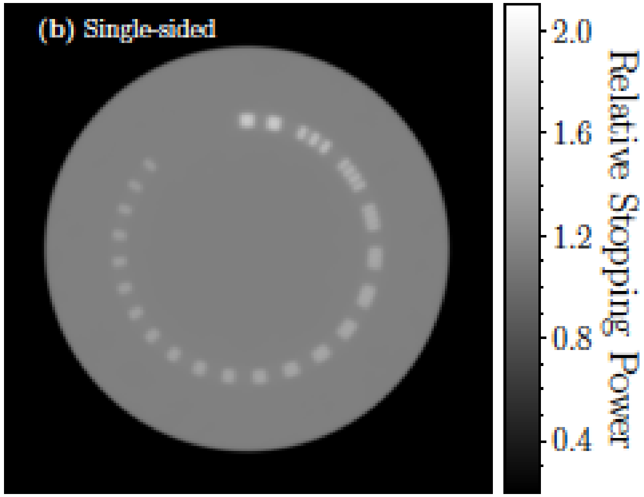


Algorithms:
DROP, TVS, FDK;
Penfold, S. N., et al., (2010). Total variation superiorization schemes in proton computed tomography image reconstruction, Medical Physics 37 (11): 5887–5895.

pCT (3D) reconstruction

- **Reconstruction of the Catphan® CTP528 line pair module (simulation)**





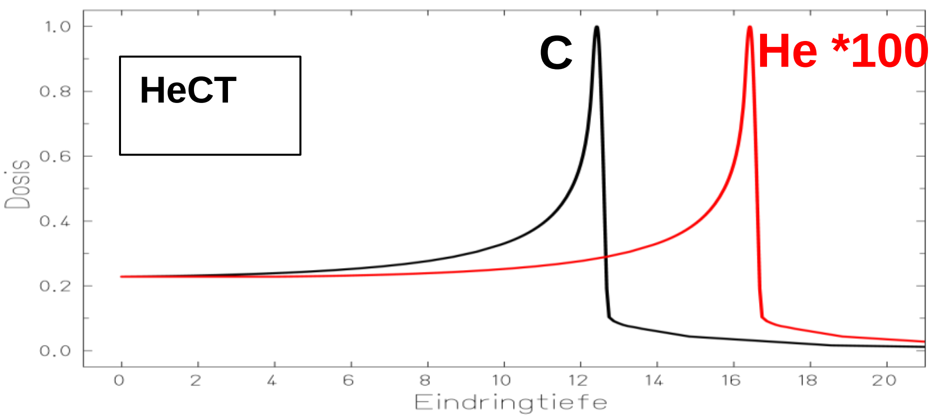
Algorithms:
DROP, TVS, FDK;
Penfold, S. N., et al., (2010). Total variation superiorization schemes in proton computed tomography image reconstruction, Medical Physics 37 (11): 5887–5895.

What’s next?

- **Construction of pCT system**
  - **Sensors have been produced, mounting of sensors to flex cables has started**
  - **Assembly and integration into services (power, cooling, readout)**
- **Commissioning with p and He beams @ HIT and MedAustron**
- **Phantom and patient studies at the Bergen proton facility (operational in 2024)**

What's next?

- **Online Bragg peak monitoring during treatment**
  - **Carbon beam with 1% Helium (as proposed by GSI/HIT and CNAO)**
    -> pCT as He pilot-beam monitor



  - **Proton beam:**
    pCT detects (and tracks) all secondaries – charged particles, photons (via showers), neutrons (via recoil protons)
    -> pCT as particle/energy flow monitor

* HeCT – less MS, better resolution, PhD thesis C. Collins Fekete, Univ. Laval, Quebec, 2017

This is the end