The Bergen proton CT project

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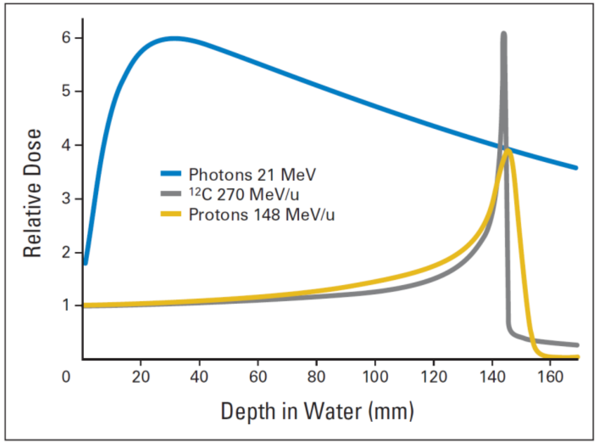
for the Bergen pCT collaboration

- **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**

Norway: University of Bergen - Helse Bergen - Western Norway University of App. Sci. - University of Oslo; The Netherlands: Utrecht University; Hungary: Wigner Research Center for Physics, Budapest – Eötvös Loránd University, Budapest; Germany: DKFZ Heidelberg - University of Applied Sciences Worms – Technical University TU Kaiserslautern; Russia: St. Petersburg State University; Thailand: Suranaree University of Technology, Nakhon Ratchasima; China: China Three Gorges University, Yichang; Ukraine: RPE LTU, Kharkiv

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

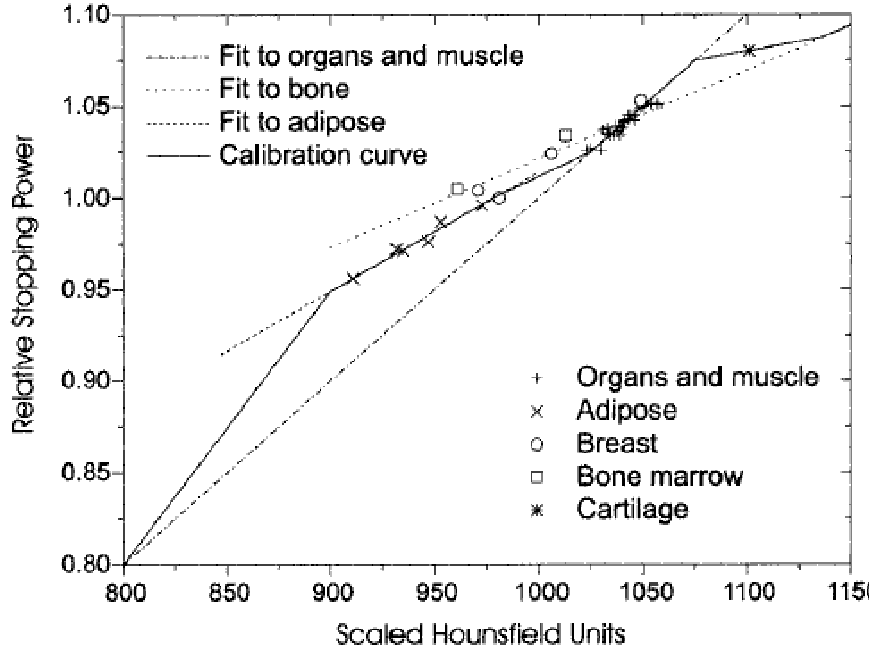
Clinical practice

- **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:

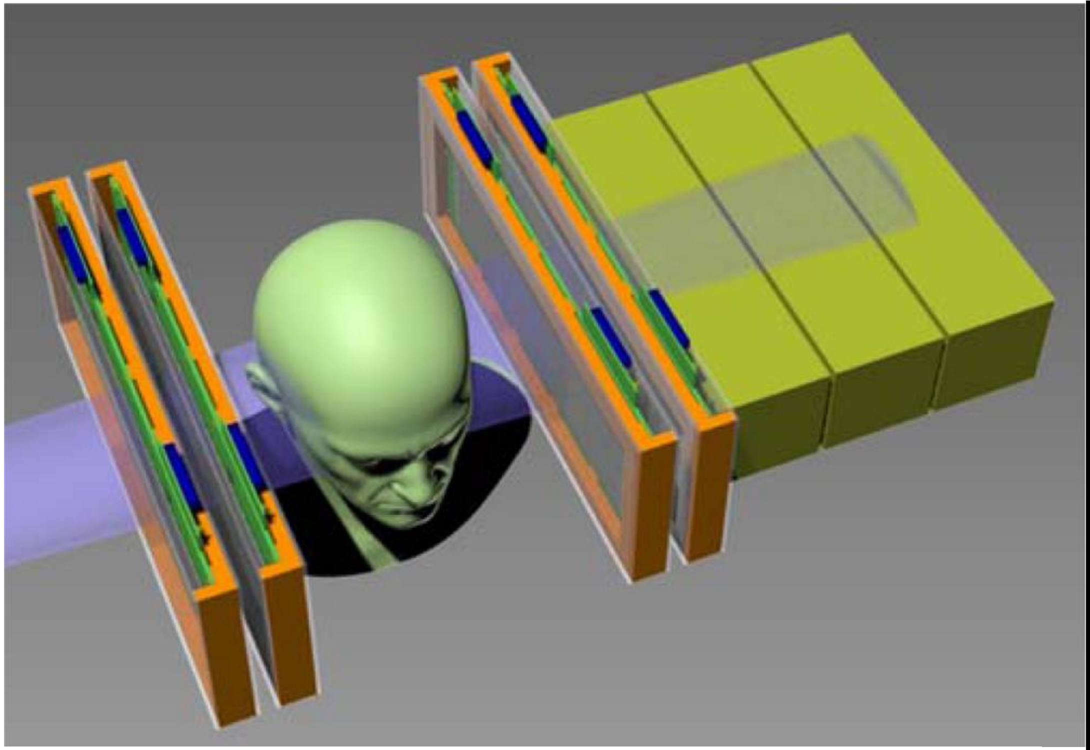
- **Dual energy CT: up to 1.7 % uncertainty**
- **Proton CT: up to 0.3 % uncertainty**

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

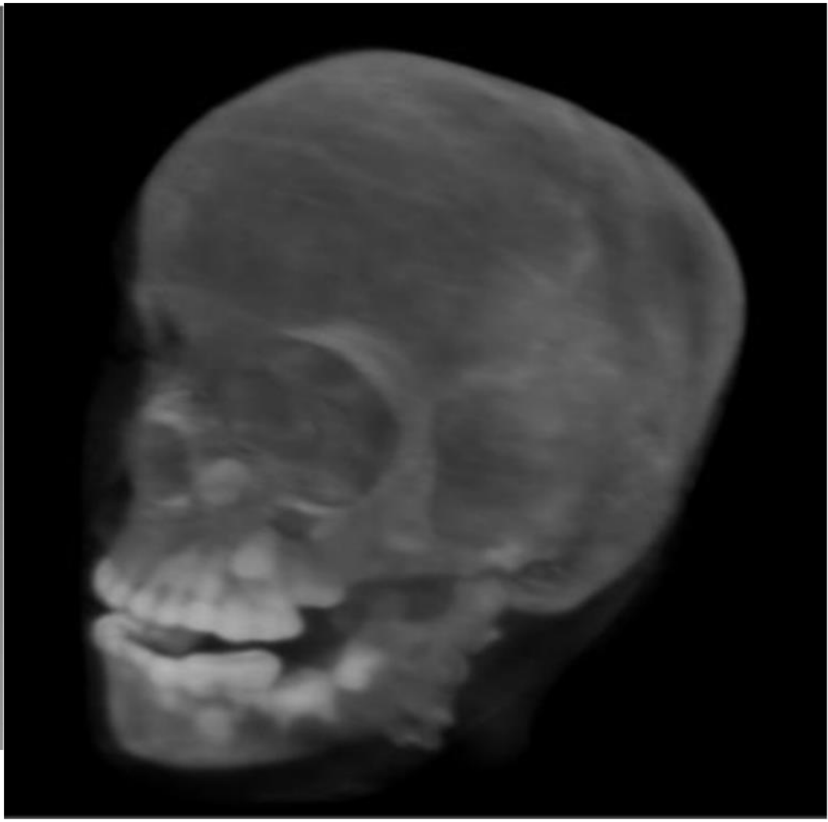
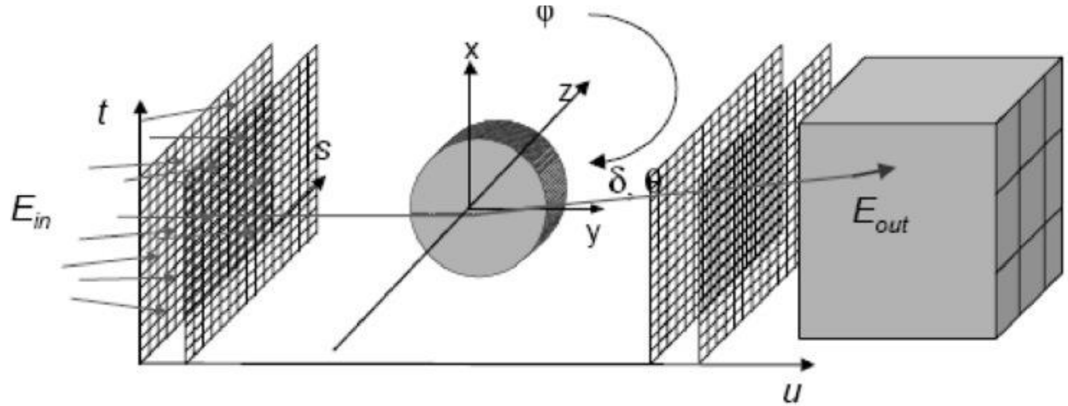


Fig. 14. 3D rendering of the pCT-reconstructed RSP map of a pediatric anthropomorphic head phantom.

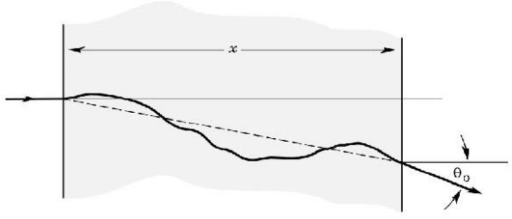
V.A. Bashkirov et al. / Nuclear Instruments and Methods in Physics Research A 809 (2016) 120–129

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)**

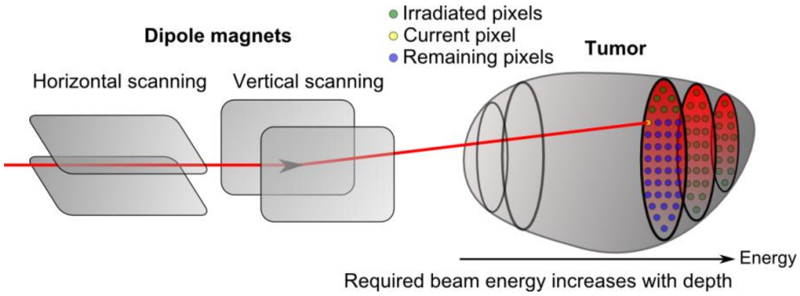


- **MS theory and Bethe-Bloch formula of average energy loss in turn depend on electron density in the target (and ionization potentials)**
  -> 3D map of stopping power
  -> online verification of dose plan

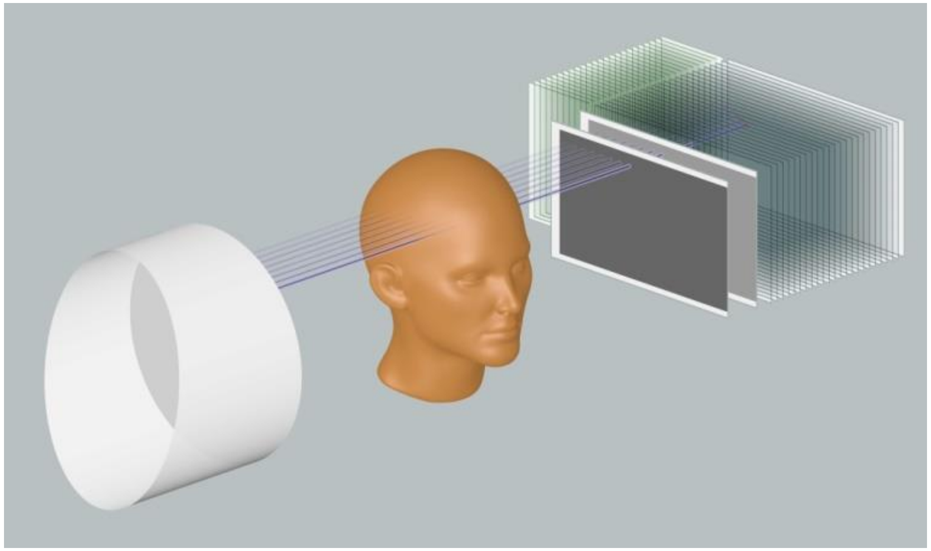
Clinical pCT - requirements

Operate with clinical beam settings

- Pencil beam scanning mode
  - Beam spot size, scanning speed, intensity
- Scanning time
  - Seconds … minutes

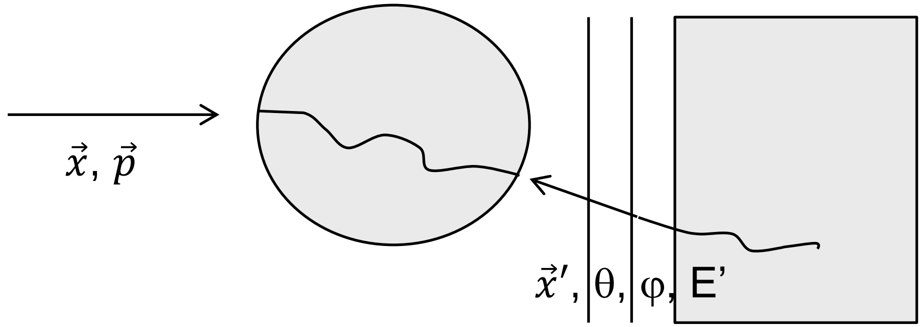


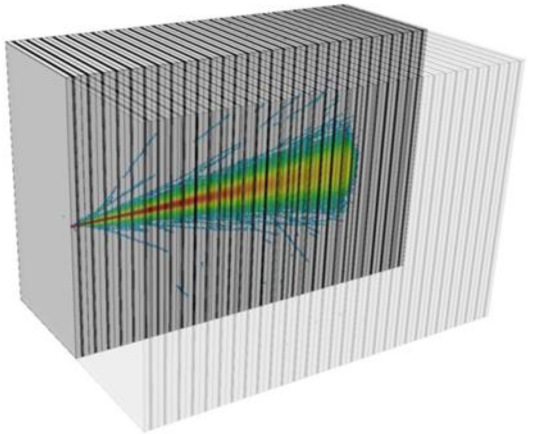
- Detector
  - Efficient simultaneous tracking of large particle multiplicities
  - Large area (~30 x 30 cm^2)
  - Radiation hardness
  - High position resolution (~10 μm)
  - Front detector (first 2-3 layers):
    very low mass, thin sensors (~100 μm)
  - Back detector:
    range resolution <1% of path-length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

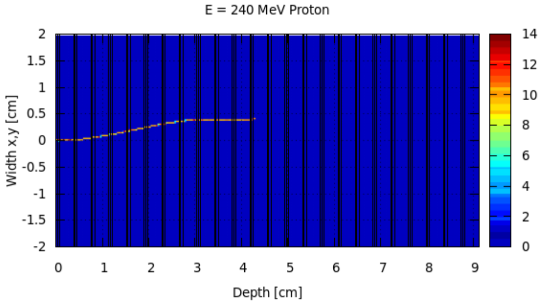


Clinical pCT - design

- Conceptual design



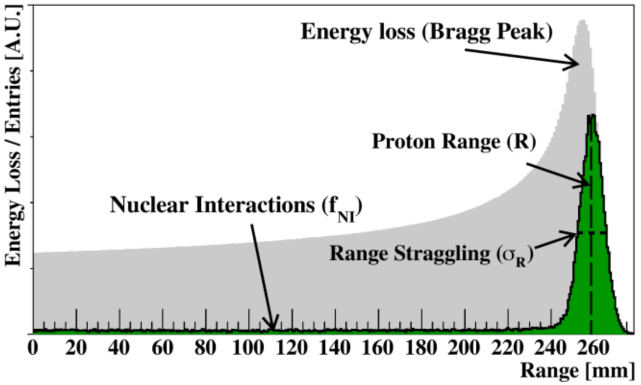




  - ***x,p*** given by beam optics and scanning system
  - ***x'**, θ, φ, E'* have to be measured with high precision
    - position resolution ~5 μm with minimal MS, i.e. first two tracking layers very thin

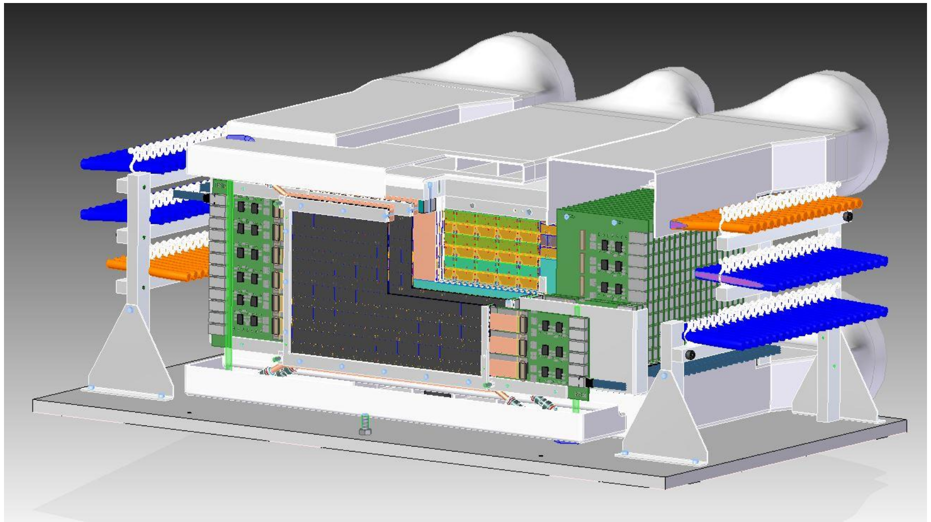
→ **Extremely high-granularity digital calorimeter for tracking, range and energy loss measurement**

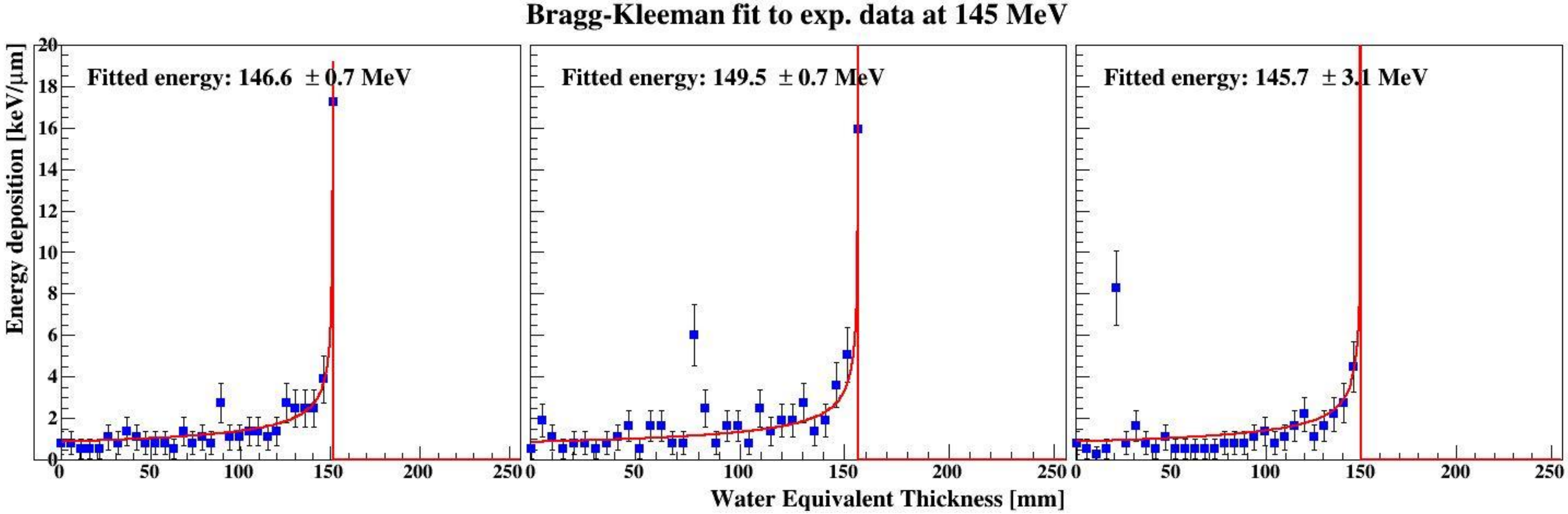
- Technical design
  - Planes of CMOS sensors – Monolithic Active Pixel Sensors (MAPS) with digital readout– as active layers in a sampling calorimeter



The Bergen pCT (clinical) prototype

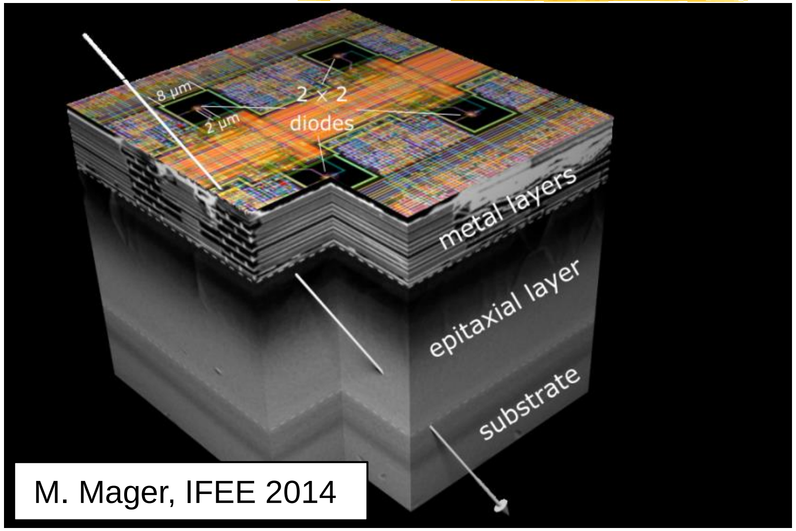
- **geometry**
  - **front area: 27 cm x 18 cm**
- **”sandwich” calorimeter**
  - **alternating layers of absorbers and sensors**
  - **longitudinal segmentation: 41 layers**
- **aluminium absorbers**
  - **energy degrader, mechanical carrier, cooling medium**
  - **thickness: 3.5 mm**



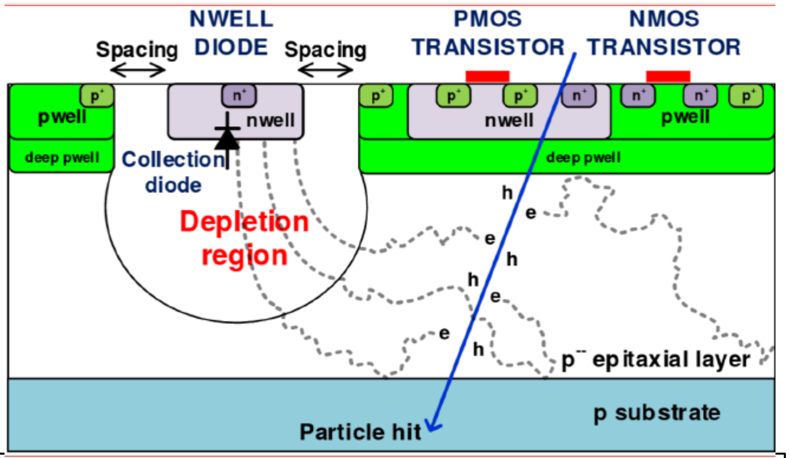


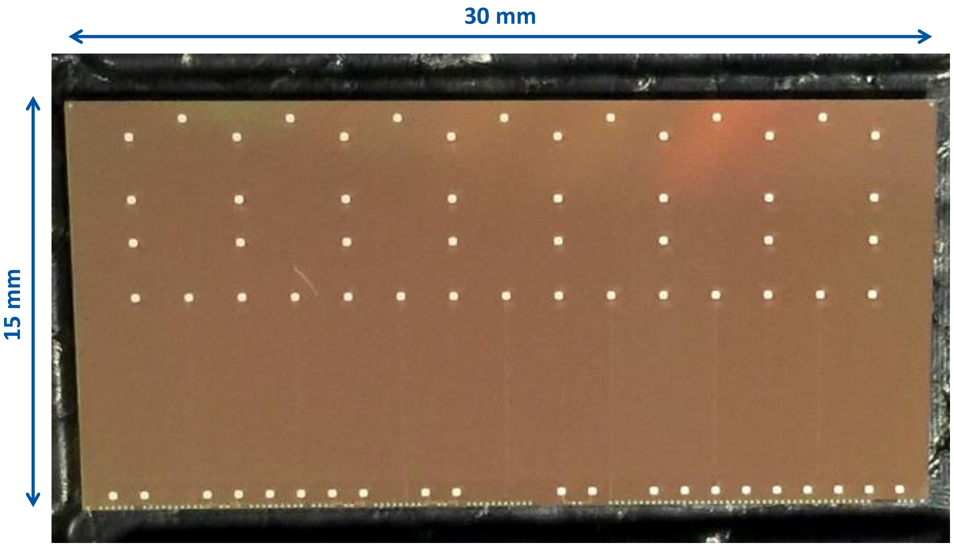
Sensor layers – Monolithic Active Pixel Sensors (MAPS)

- **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





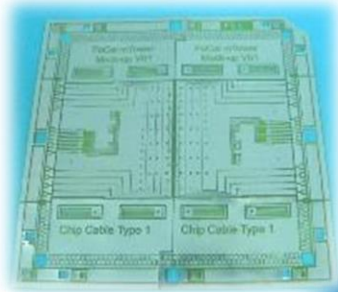
Design team:
CCNU Wuhan, CERN Geneva, YONSEI Seoul, INFN Cagliari, INFN Torino, IPHC Strasbourg, IRFU Saclay, NIKHEF Amsterdam

Mounting sensors on flexible cables

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

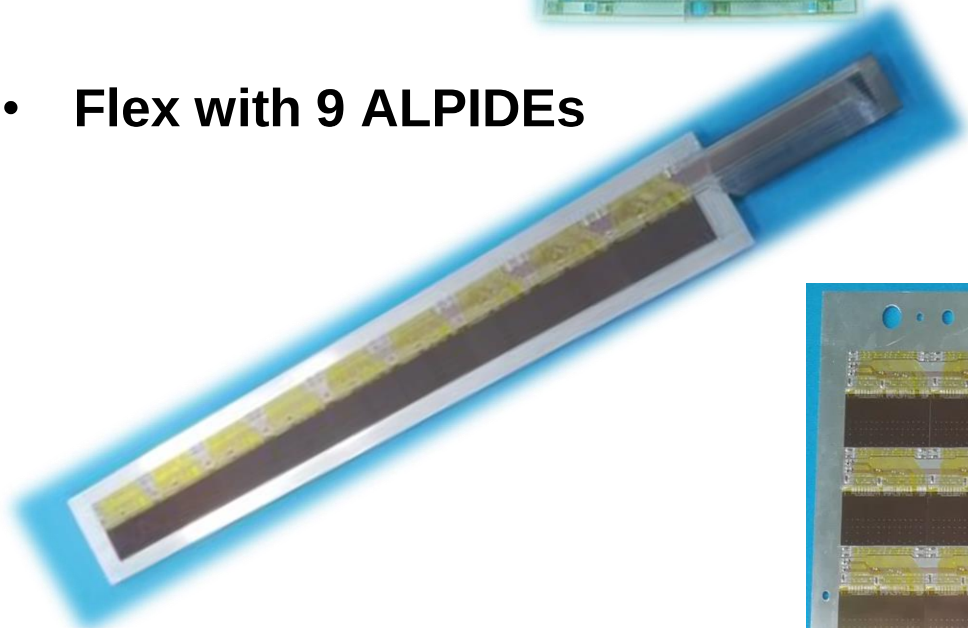
ALPIDE chip

chip cable



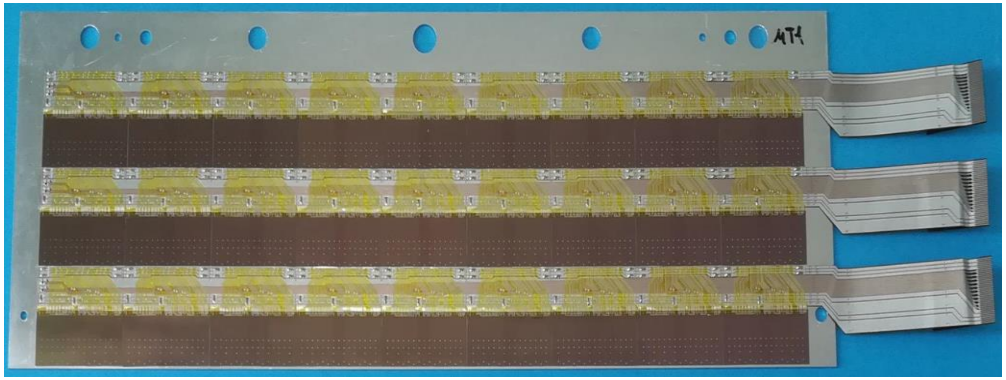
Design and production:
LTU, Kharkiv, Ukraine

- **Flex with 9 ALPIDEs**



- **Module - flex on Al carrier**

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

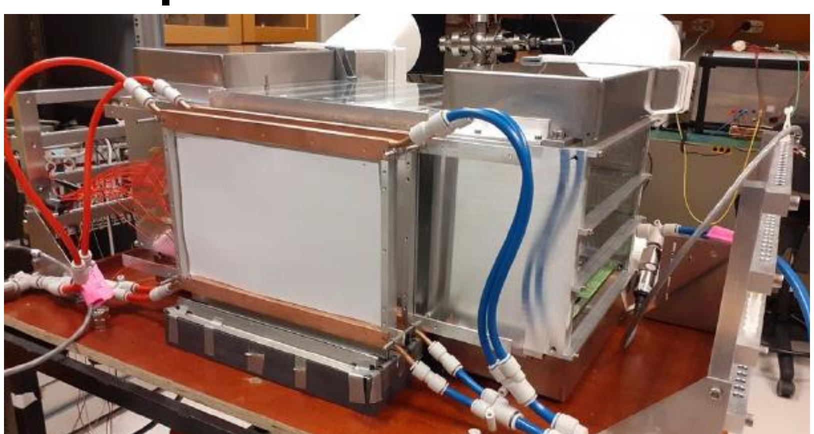


Assembly at IFT/UiB

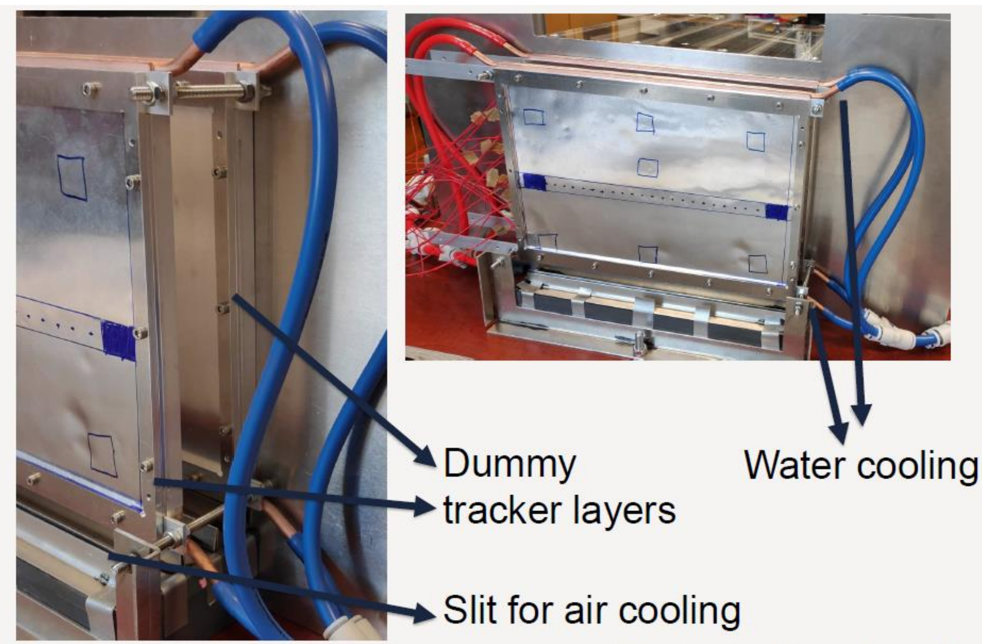
- **Ultra-thin tracking layers**
  - **thinned ALPIDEs (50 μm) mounted on a thin flex and glued to a large sandwiched carbon fiber sheet (pyrolitic graphite paper + carbon fleece + epoxy resin)**

Sandwiched carbon fiber sheet, fabricated at St Petersburg State University

- **Setup in the lab**



mechanical integration and cooling

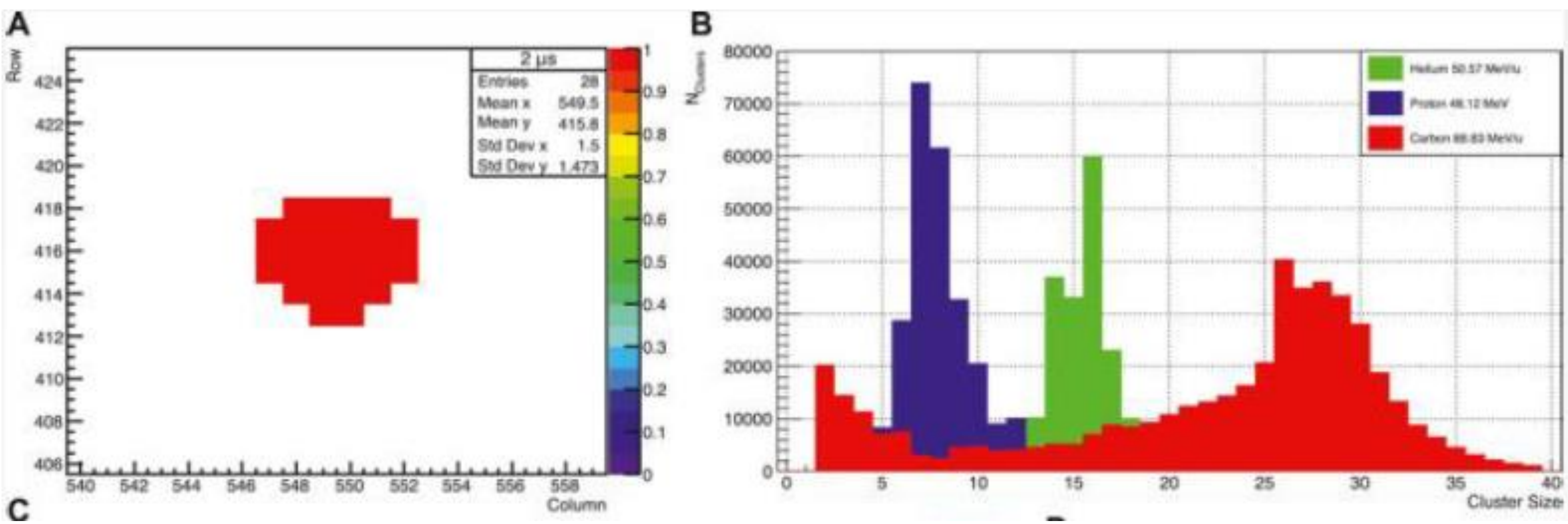


Prototype tracking layers designed fabricated by Utrecht University, tested at University of Bergen

How to measure energy loss with a digital pixel sensor?

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

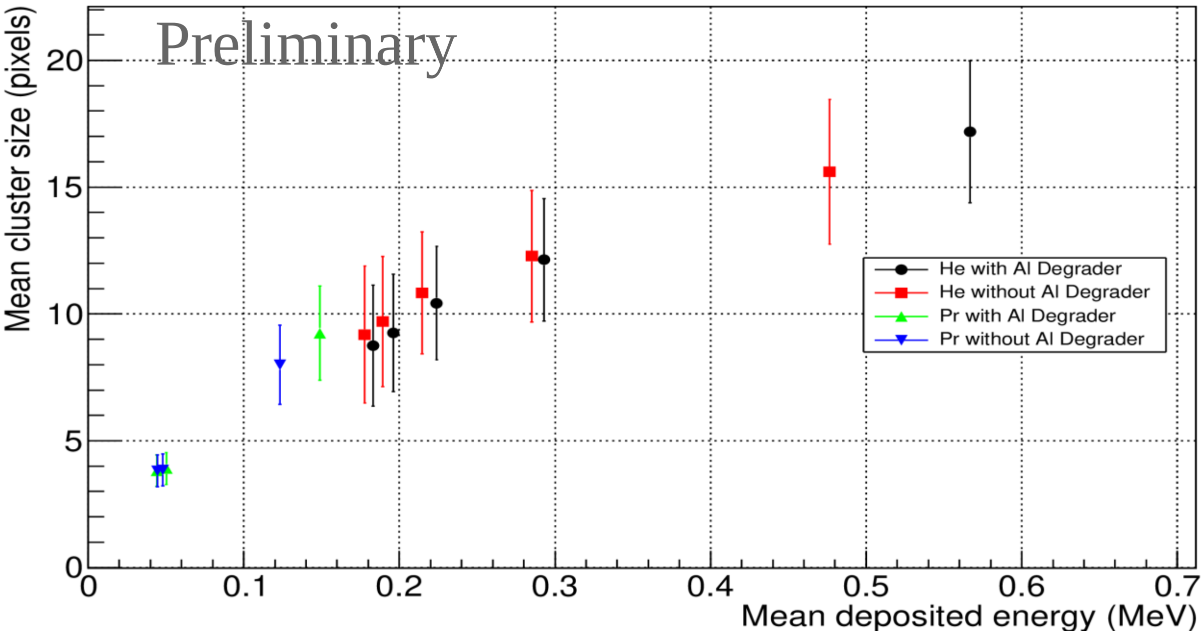
α particle **proton – α – C**



How to measure energy loss with a digital pixel sensor?

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

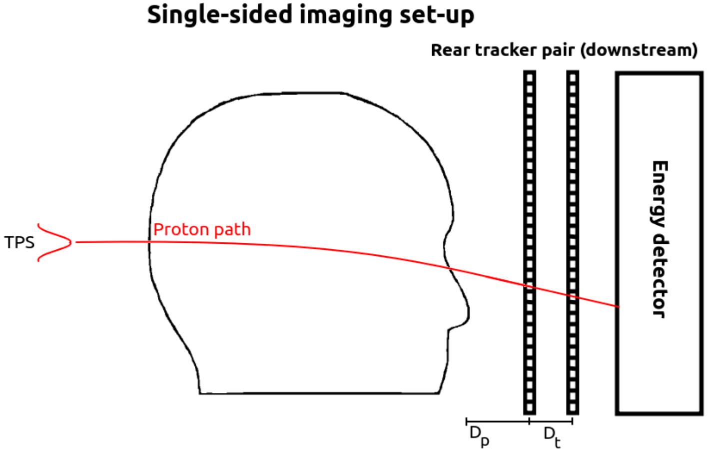
- **Results from proton and He-beams at different energies (HIT)**



- **Cluster size increases with simulated energy loss**

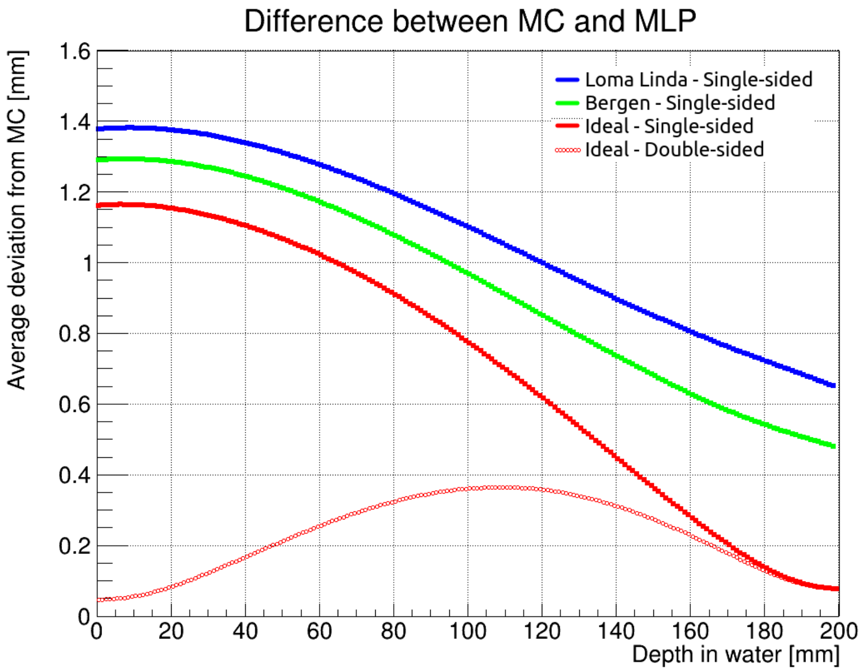
Does 3D reconstruction work with trackers only behind the phantom?

- **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**

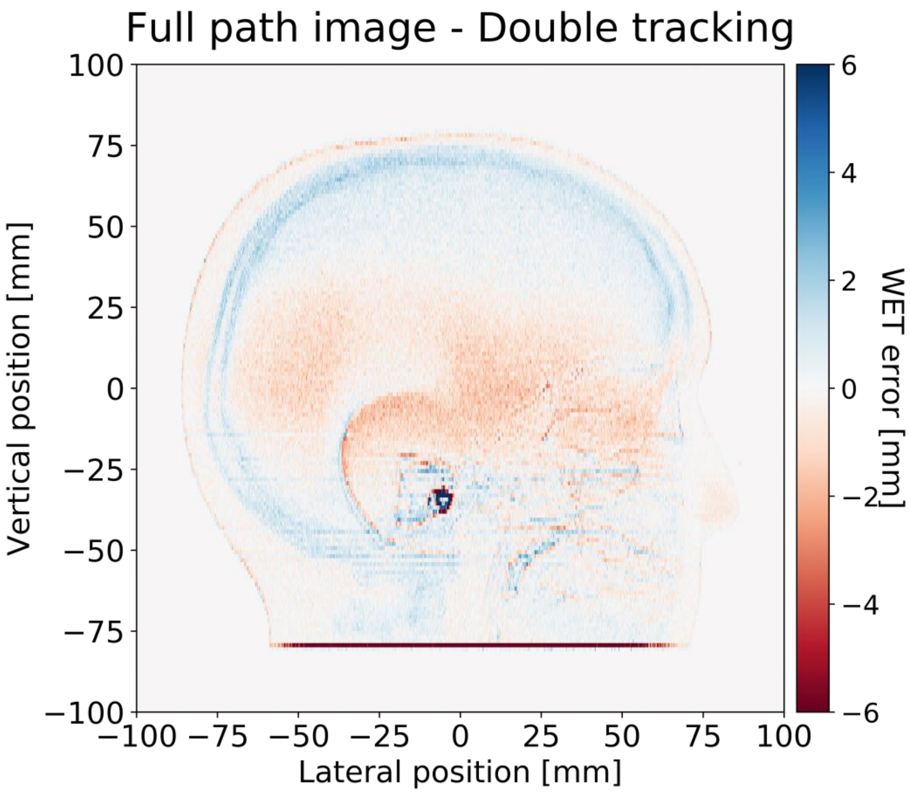
-> deviations ≤ 1.2 mm

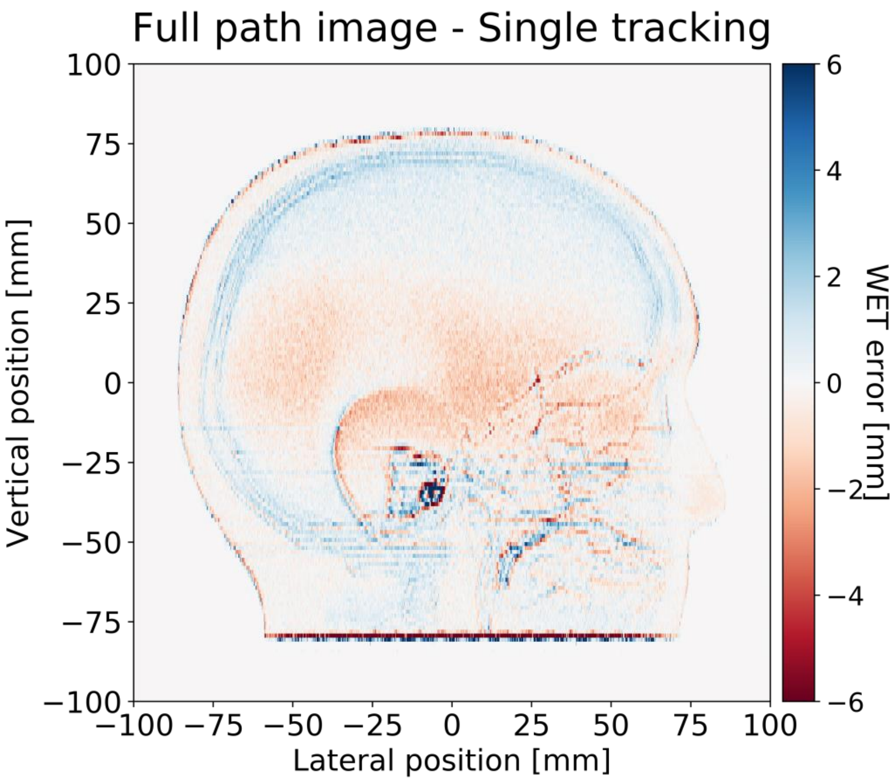


Krah, N., et.al., (2018). A comprehensive theoretical comparison of proton imaging set-ups in terms of spatial resolution, Physics in Medicine & Biology 63 (13): 135013.

Radiographic image reconstruction - pRAD

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



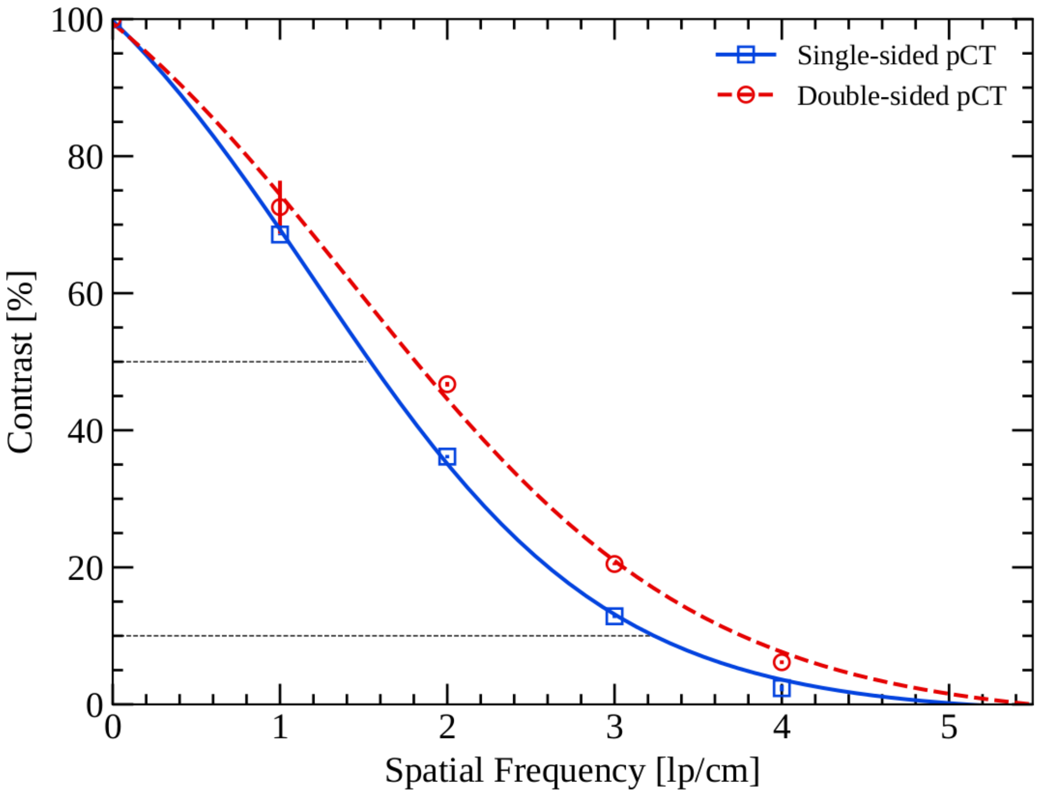


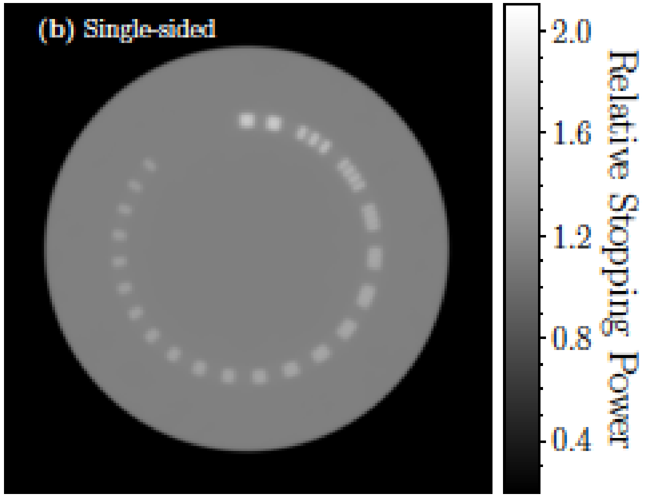
* WET: Water Equivalent Thickness

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

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



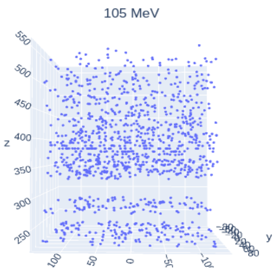


Algorithms:
DROP, TVS, FDK;
Penfold, S. N., et al., (2010). Total variation superiorization schemes in proton computed tomography image reconstruction, Medical Physics 37 (11): 5887–5895.

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 proton beams at the Bergen proton therapy facility in 2024**

- **Online Bragg peak monitoring during treatment**
  - **pCT as an imaging calorimeter detects all secondaries – charged particles, photons and neutrons**
    -> pCT as particle/energy flow monitor
  - **Matching the 3D-position of the Bragg-peak inside the patient to the shower shape of emitted particles**
    -> Machine Learning methods like CNN



  - **First studies (simple water phantom, supervised learning):**
    - **Precision of beam energy reconstruction: ~2 MeV**
    - **position resolution of the Bragg-peak: ~1-2 mm (tbc)**

This is the end