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:

\[ \frac{dE}{dx} \sim (\text{electron density}) \times \ln\left(\frac{\text{max. energy transfer in single collision}}{\text{effective ionization potential}}\right)^2 \]

• 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

Estimates for advanced dose planning:
- Dual energy CT: up to 1.7% uncertainty
- Proton CT: up to 0.3% uncertainty

Proton CT

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 cm²)
  - 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

\[ \vec{x}, \vec{p} \]

\[ \vec{x}', \theta, \varphi, E' \]

• \( x, p \) given by beam optics and scanning system

• \( x', \theta, \varphi, E' \) have to be measured with high precision
  • position resolution \( \sim 5 \, \mu m \) 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

Bragg-Kleeman fit to exp. data at 145 MeV
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 cm², 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
Mounting sensors on flexible cables

- ALPIDE mounted on thin flex cables
  (aluminium-polymide dielectrics: 30 μm Al, 20 μm plastic)
  ![ALPIDE chip](image1.png)  ![chip cable](image2.png)

- Flex with 9 ALPIDEs

- Module - flex on Al carrier
  flexible carrier board modules
  with 2x3 strings with 9 chips each

Design and production:
LTU, Kharkiv, Ukraine
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**

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

  Water cooling
  Dummy tracker layers
  Slit for air cooling
How to measure energy loss with a digital pixel sensor?

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

\[ \alpha \text{ particle} \quad \text{proton – } \alpha \quad \text{– C} \]
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

Radiographic image reconstruction - pRAD

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

* WET: Water Equivalent Thickness

pCT (3D) reconstruction

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

Algorithms: DROP, TVS, FDK;
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