Latest developments of the Bergen pCT project

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On behalf of the **Bergen pCT collaboration** *and the* **SIVERT** research group

UNIVERSITY OF BERGEN

Overview

- The Bergen pCT collaboration
- The high granularity digital tracking calorimeter
- Monte Carlo simulation and image reconstruction
- Machine Learning methods applied to the data-flow chain
- Conclusions

The Bergen pCT collaboration

Status of the project

Financing

- 5 years (2017-2021)

Status

- Finishing the optimization of the mechanical design
- Testing of the cooling sytem
- Mass-production of the sensor chips
- Chips bonding to slabs
- MC simulations to investigate image reconstruction accuracy
- Machine learning methods applied to the data-flow chain

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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

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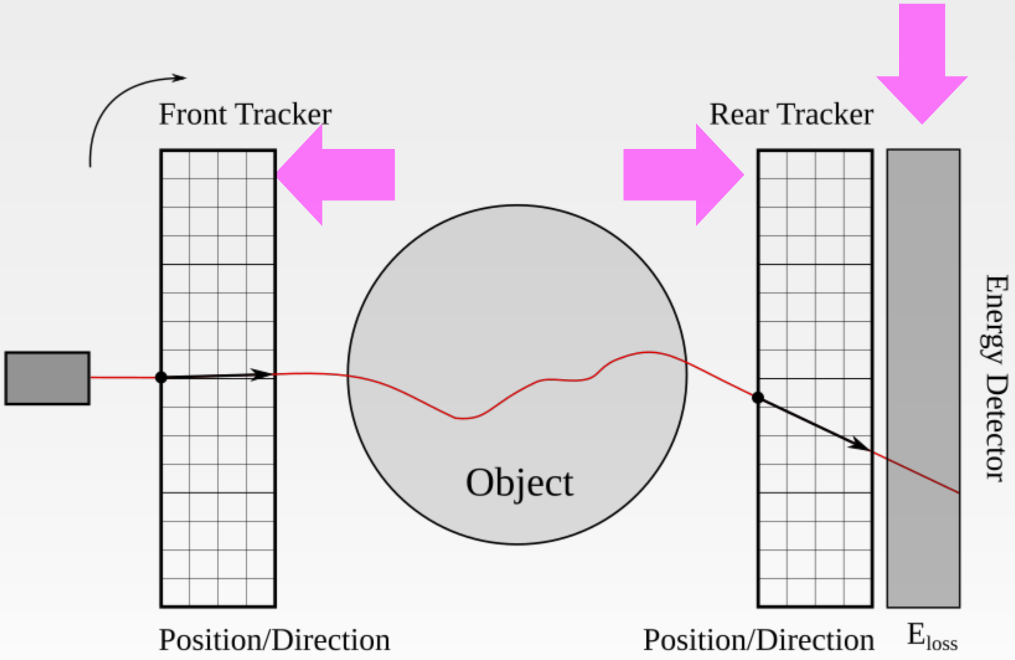
The high granularity digital tracking calorimeter

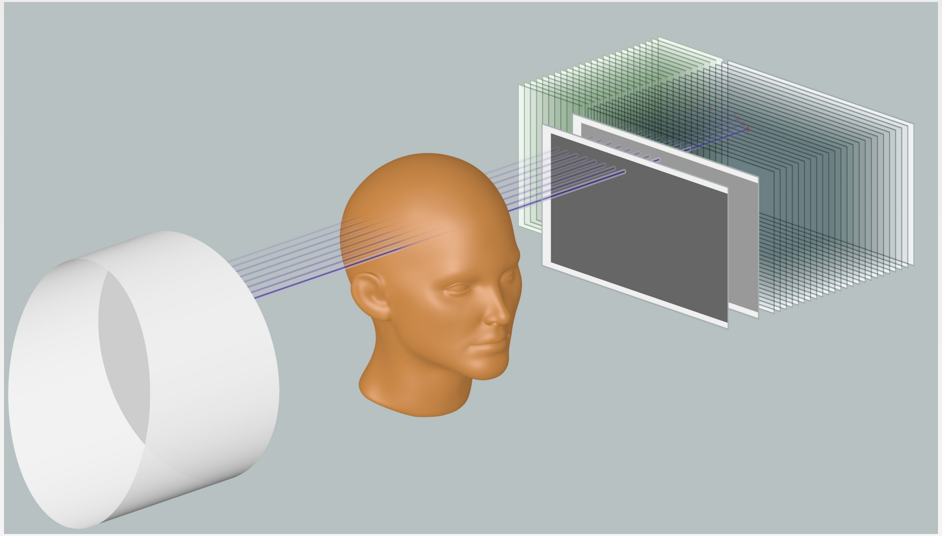
The pCT imaging concept

Trajectory and residual energy of each **single particle history** crossing an object from different directions

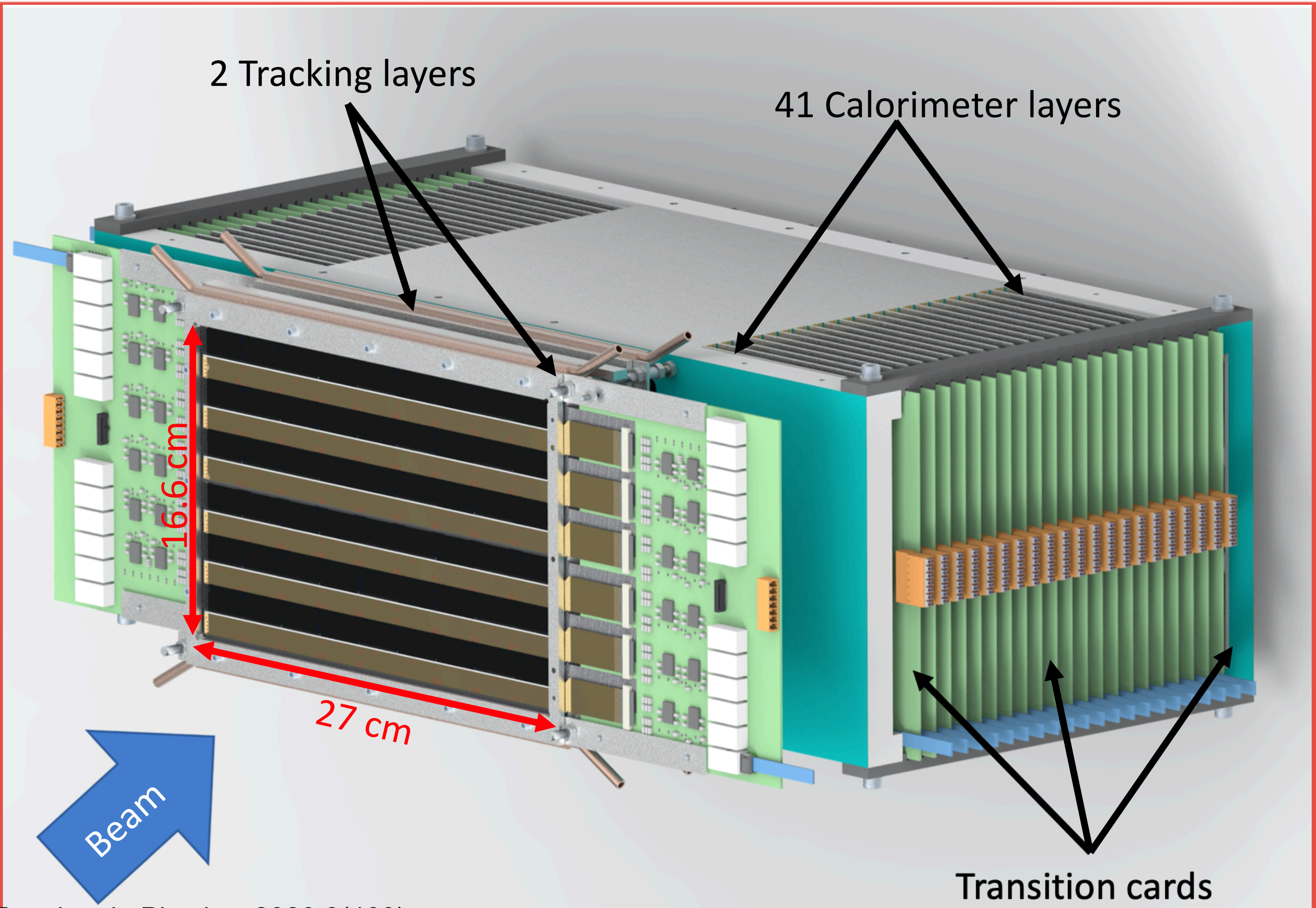
- **Tracker system:**
  entrance and exit points
- **Energy detector:**
  residual energy
- Residual Energy into water equivalent path length (**WEPL**)
- WEPL and path information are used to reconstruct the relative stopping power (**RSP**) of each voxel in the target through reconstruction algorithms



The project



- The Bergen (Norway) pCT collaboration novel pCT scanner is completely based and the ALPIDE pixel sensor
- Segmented high-granularity digital tracking calorimeter (DTC) used both as tracker system and energy/range detector
- Optimized for pCT, it can handle pencil beams with high particle rate and localized dose depositions
- No Front Tracker assuming direction and position from TPS information
- Thanks to its segmented structure, the device is able to track single proton histories crossing the object at the same times



Alme J, et al., Frontiers in Physics. 2020;8(460)

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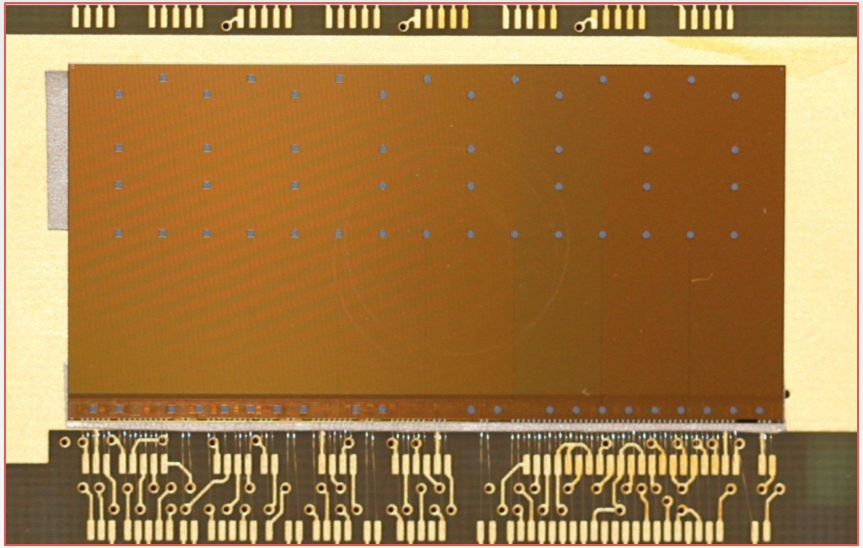
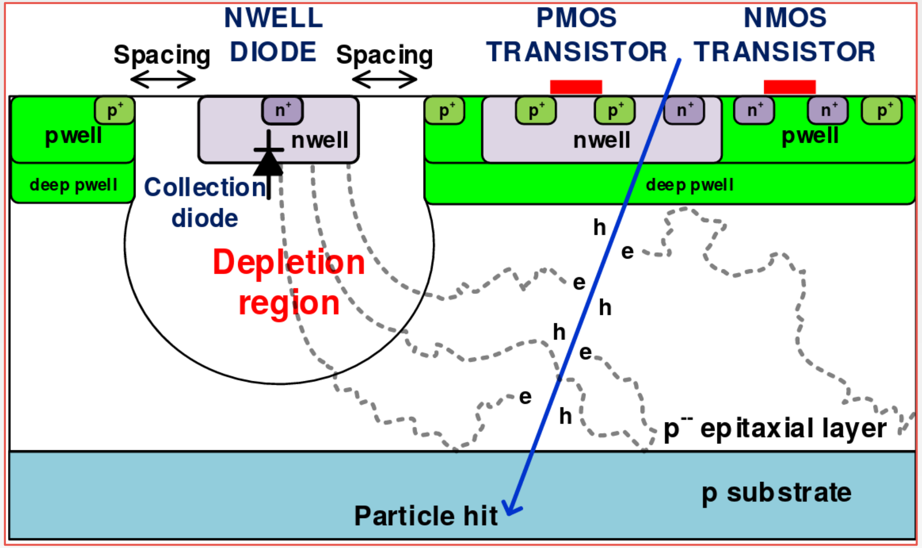
The ALPIDE chip





- The ALPIDE pixel sensor is a CMOS Monolithic Active Pixel Sensor (MAPS)
- Chip size: 30 mm x 15 mm
- Pixel size: ~28 μm²
- Integration time: ~4 μs
- On-chip data reduction

Aglieri Rinella G.,NIM A. 2016; 845: 583-587

General structure

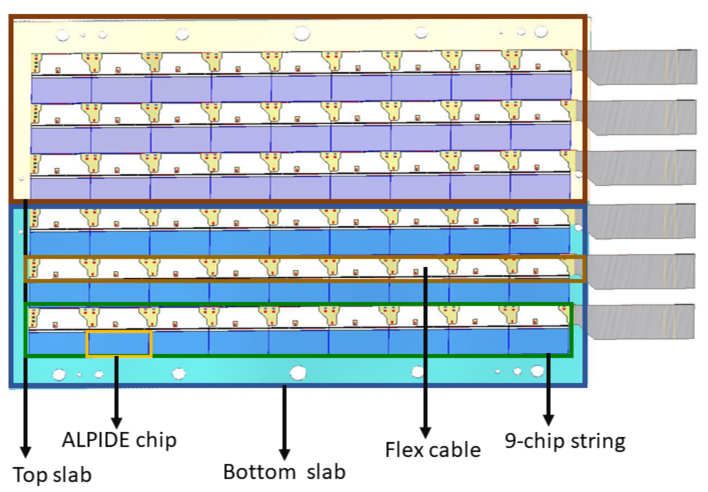
Tracking layers:

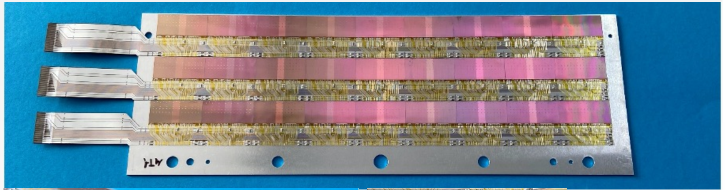
- <200 µm thick carbon-epoxy carrier to minimize the material budget
- Single slab containing 9 x 6 ALPIDE chips

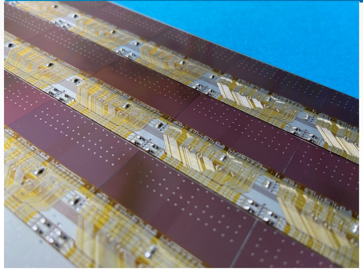
Calorimeter layers

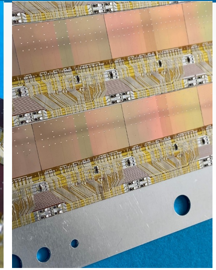
- 3.5 mm (1 + 1.5 + 1 mm) thick Al degrader, functioning also as carrier
- Top- and bottom-slab containing each 9 x 3 ALPIDE chips

ALPIDE chips ultrasonically bonded onto thin traces of pure aluminum on a polyimide flex and subsequently bonded to a larger flexible printed circuit board





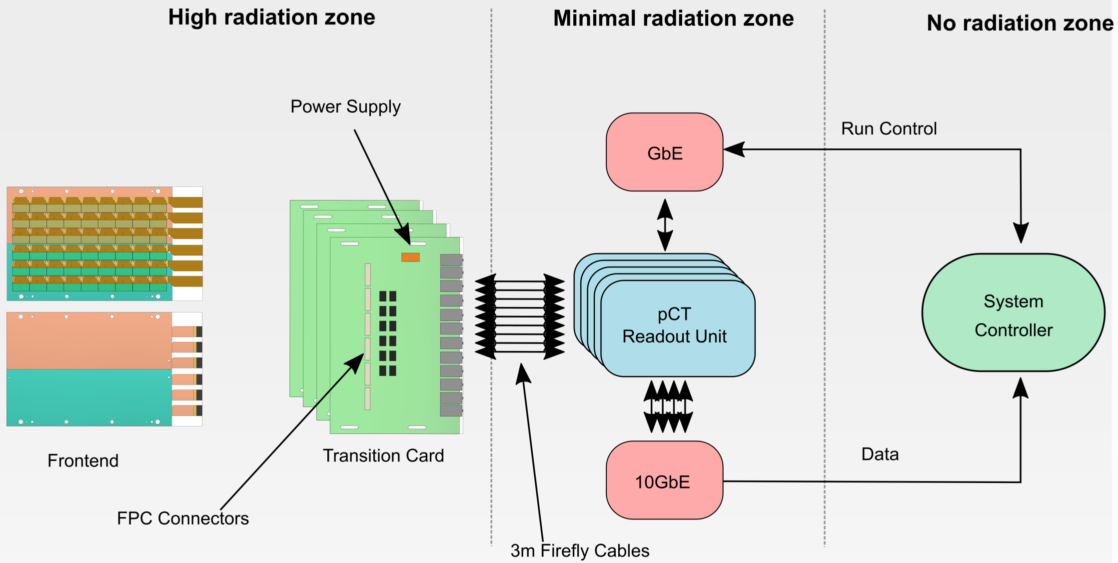




Alme J, et al., Frontiers in Physics. 2020;8(460)
Borshchov VM, et al., Met. Funct. Mater (2017) 23(4):143–53

Electronics

- 108 ALPIDE chips for each sensor layer
- Possibility of ALPIDE functional testing after Single-point Tape-Automated Bonding to exclude mounting defective chips in the strings → increase of reliability and production yield at assembling string and DTC as a whole



- Trigger-less readout architecture: no external nor any high-level trigger system implemented.
- The read-out electronics is fast enough to acquire 2D images in few seconds

Alme J, et al., Frontiers in Physics. 2020;8(460)

Applications

- Fast proton radiographs full pCT scan for treatment planning
- With a carbon-helium mixed beam, where carbon ions would be used for treatment and helium ions would be used for verification*
- Placing the detector beside the treated patient at an opportune angle, secondary radiation (e.g., charged nuclear fragments, neutron) originating from the Bragg peak area could be tracked for *in situ* range verification

*Volz L, et al. Physics in Medicine & Biology. 2020;65(5):055002. 10.1088/1361-6560/ab6e52

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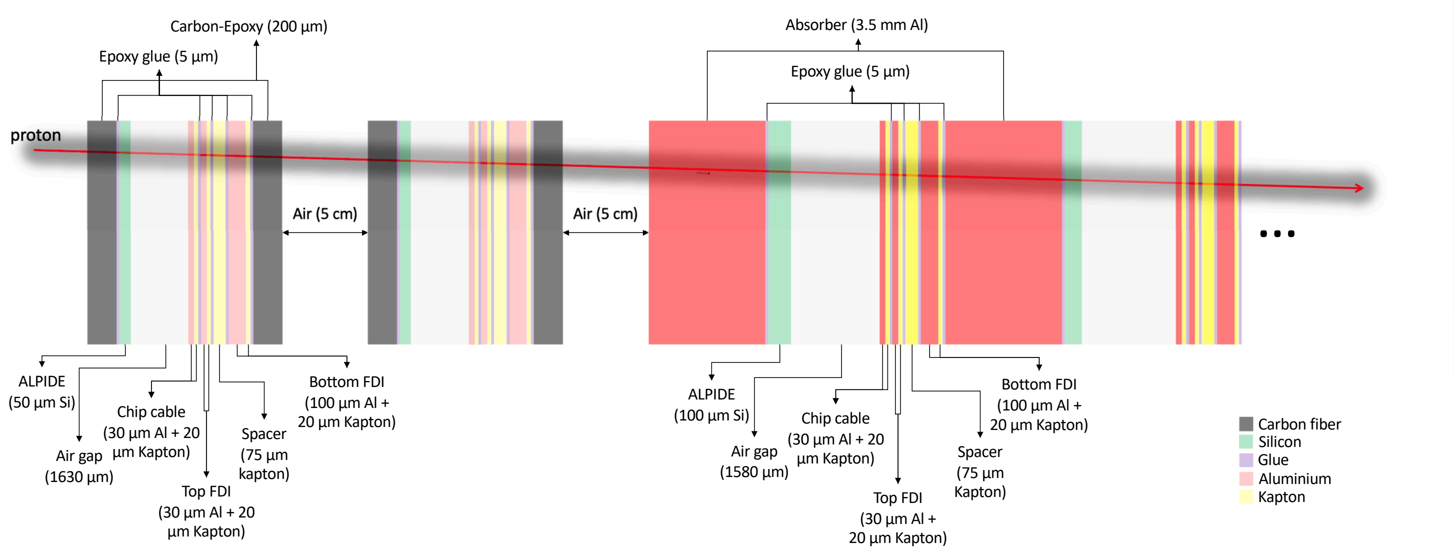
Monte Carlo simulation and image reconstruction

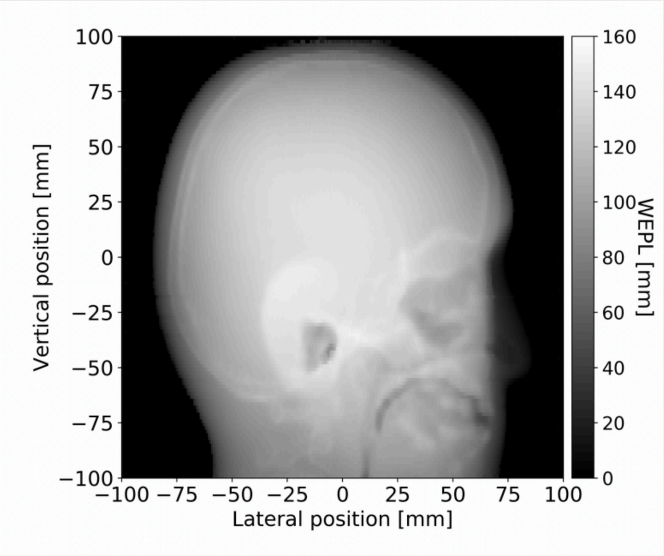
The Monte Carlo simulation

- GATE version 8.2 with Geant4 version 10.5.1
- Full material budget of the DTC accounted for
- Proton radiographs (pRad) and full pCT scans with different phantoms
- Physics builder list QBBC_EMZ recommended by the GATE collaboration
- Water mean ionization energy: 78 eV



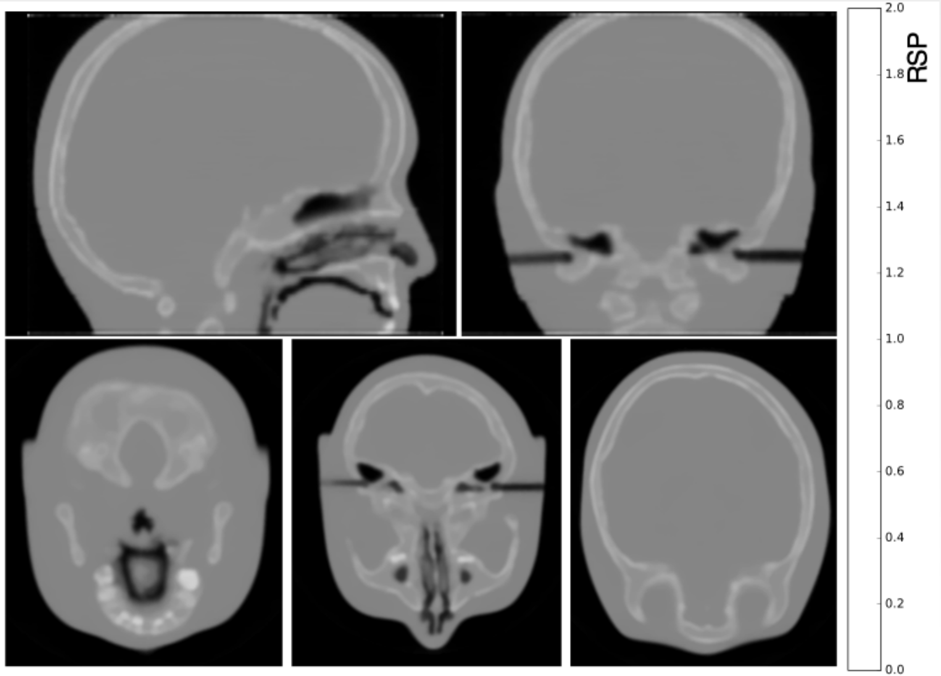
Alme J, et al., Frontiers in Physics. 2020;8(460)
Jan S, et al., Phys Med Biol (2011) 56(4):881–901
Jan S, et al., Phys Med Biol (2004) 49(19):4543–61
Agostinelli S, et al., NIM A (2003) 506(3): 250–303
Allison J, et al., IEEE Trans Nucl Sci (2006) 53(1): 270–8

Image reconstruction for simulated scans



pRad

- 230 MeV
- 10^7 primary protons
- ~ 15 μSv deposited dose



pCT

- 230MeV
- 360 projections, 1° step
- 3.5×10^6 protons per projection
- 7.9×10^8 protons for reconstruction

Alme J, et al., Frontiers in Physics. 2020; 8(460)

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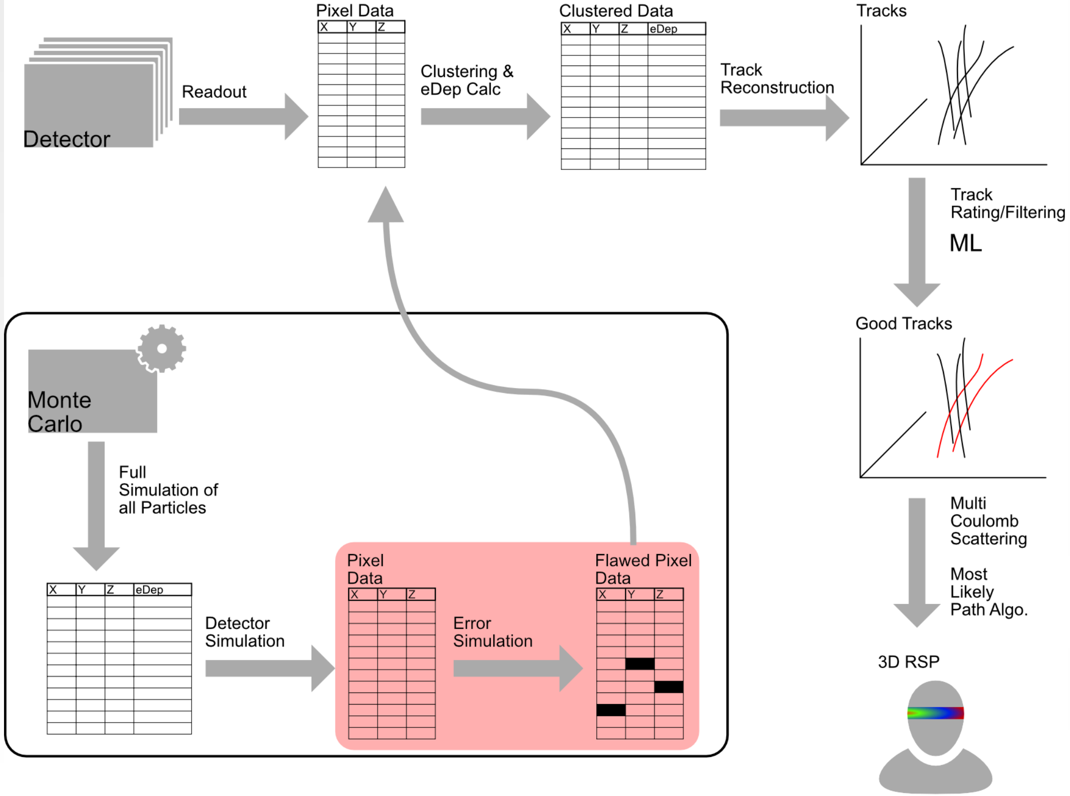
Machine Learning methods applied to the data-flow chain

Application of Machine Learning

- Training data created from GATE simulations
- ML models are employed to improve the reliability and the robustness of the pCT imaging reconstruction data-flow chain
- Additional types of simulated errors added to continue shrinking the gap between simulated and experimental data



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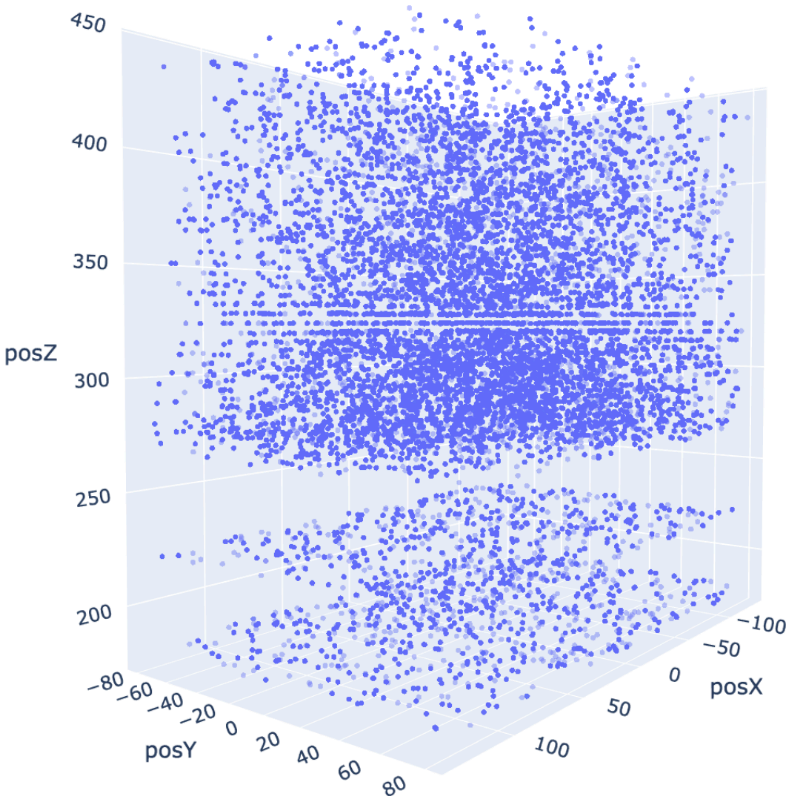
Application of Machine Learning

- Training data created from GATE simulations
- Beam energy and direction are tuned so that the Bragg peak arises inside a water cube
- A variety of supervised ML methods, including both parametric and nonparametric regression models, introduced to predict the Bragg peak position by analyzing the secondary particles produced by the proton beam
- A plastic layer inserted between the tracking layers is used to convert uncharged secondary particles (e.g., neutrons) not visible for the DTC into charged particles

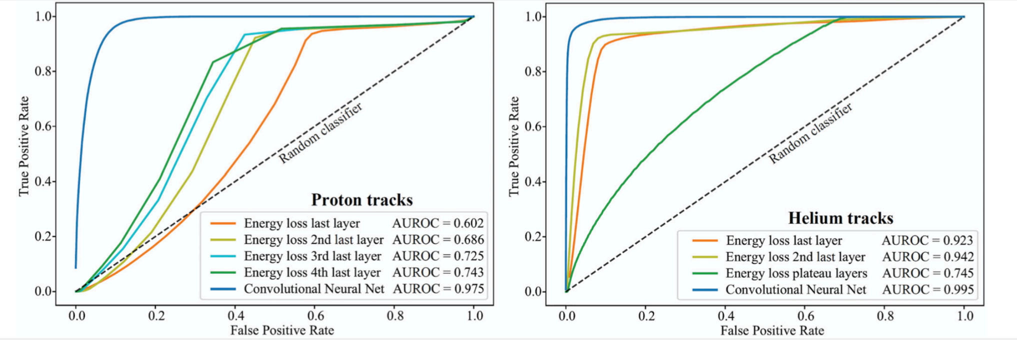


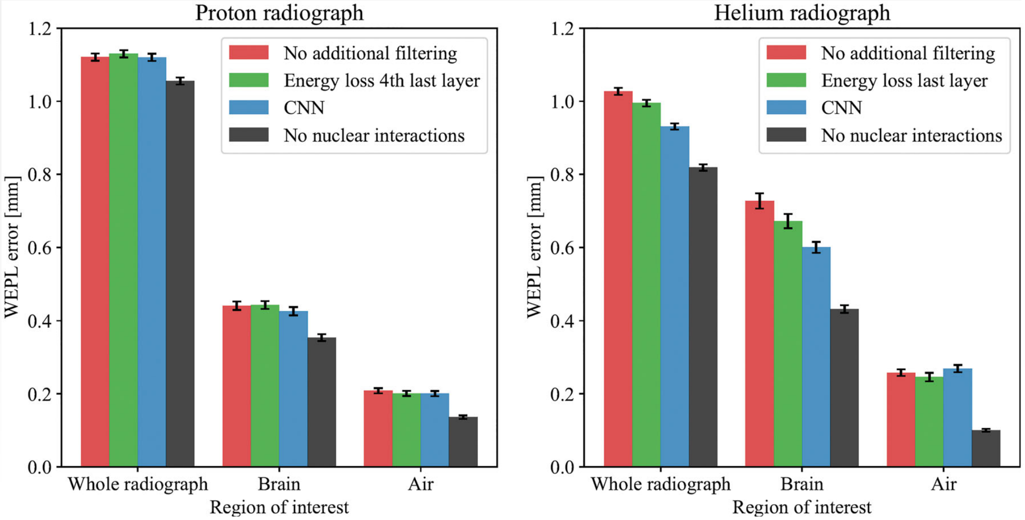
Application of ML methods

Pettersen HES, et al., IONC. 2021;10.1080/0284186X.2021.1949037

- Training data created from GATE
- Convolutional neural network employed for filtering wrongly reconstructed tracks during imaging
- The CNN was trained by simulation and reconstruction of tens of millions of proton and helium tracks
- CNN filter compared to simple energy loss threshold methods using the Area Under the Receiver Operating Characteristics curve (AUROC)
- Image quality and WEPL error of proton and helium radiographs compared

➡ Improved the filtering of proton and helium tracks but only in the helium radiograph this lead to improved image quality.





Conclusions

- Thanks to the high-granularity and high-speed readout, high intensity beams can be handled by the DTC
- The final version of the ALPIDE slabs are being bonded and will be ready to be tested soon
- The full DTC should be finished presumably in one year
- Machine learning models being applied to:
  - ➢ Improve robustness of the data-flow chain
  - ➢ Improve track filtering during reconstruction
  - ➢ in situ range verification analyzing secondary particles originating from the Bragg peak area

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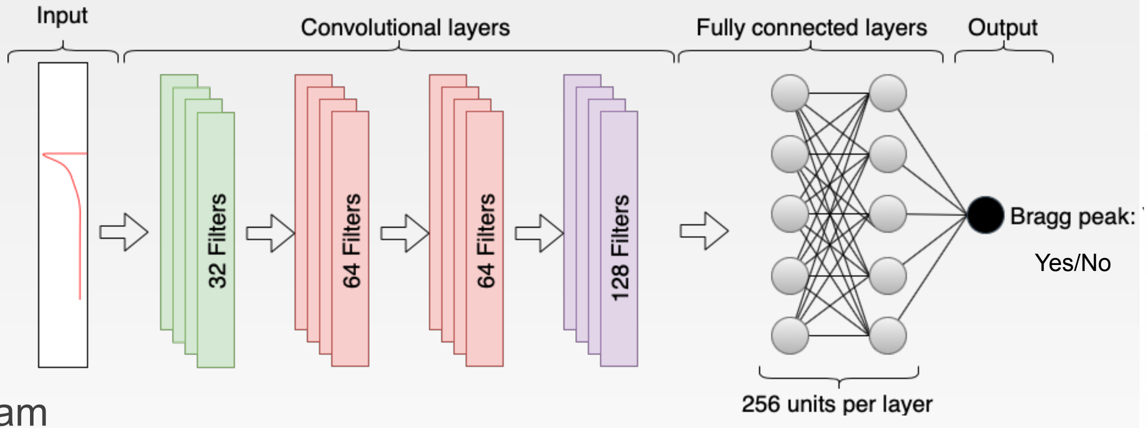

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