King Chulalongkorn Memorial Hospital
The Thai Red Cross Society

24th IEEE Real Time Conference

Development of the Proton Computed Tomography (pCT) prototype

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April 22 – 26, 2024

Proton Therapy

If you have *cancer*, what will you do?

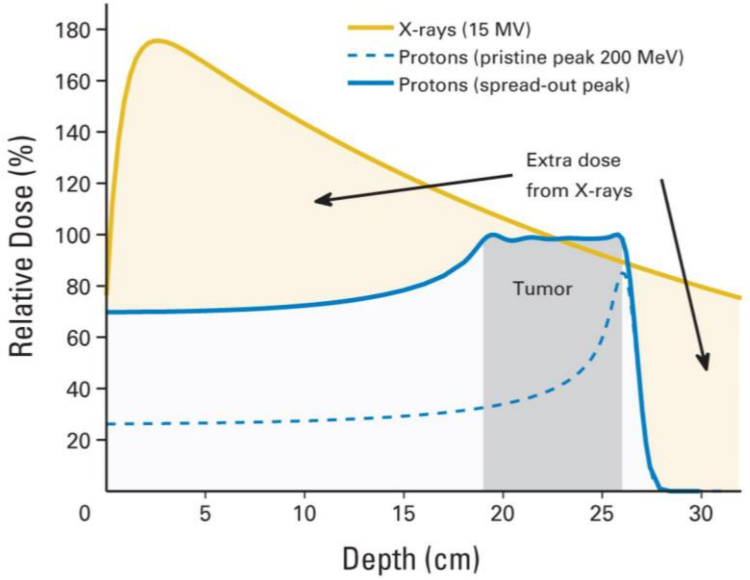
- Diagnostic : X-ray CT scan.
- Treatment : Chemotherapy? Radiation therapy?
- Disadvantages : destroy good tissues, side effects

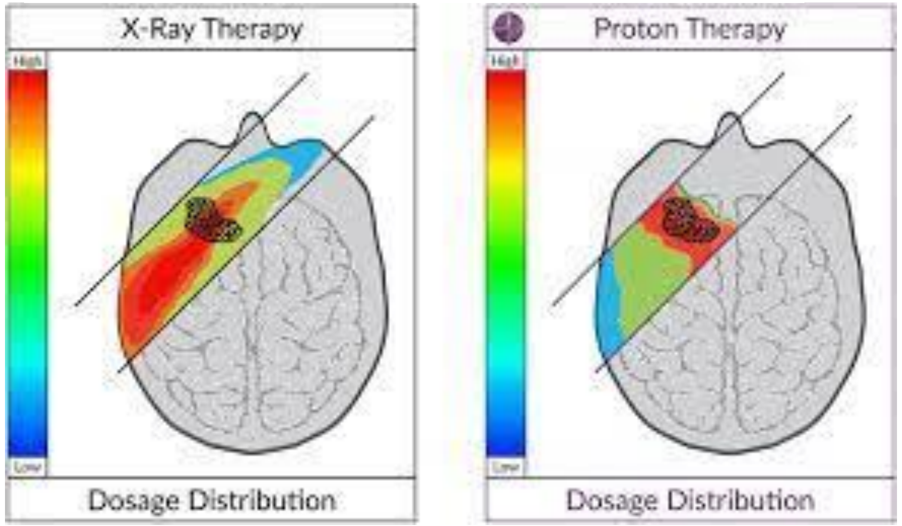
Proton therapy takes advantages

- Bragg peak at the targeted position
- Lower dose to normal tissues
- Higher dose to tumor tissues
- Higher efficiency
- Available now in Thailand -> KCMH

Disadvantages of proton therapy

- High operating cost
- Large facility : need accelerator





Pic: https://www.ilcn.org/proton-beam-therapy-versus-photon-beam-therapy-the-debate-continues/

Problems of X-ray CT Scan

- X-ray CT is not 100% compatible with proton therapy.
- Proton-CT could give a slightly better stopping power than the normal X-ray CT. The maximum error for proton CT and single energy CT are 0.51% and 7.4%, respectively. [D.C.Hansen et.al., Acts Oncologica, 2015, 54, 1638-1642]
- Relative electron density distribution can be measured directly with proton-CT. [R. W. Schulte et.al., Med. Phys., 32(4), 2005]
- X-ray CT delivers high dose to a patient. Repeat X-ray CT can cause dose accumulation.
- X-ray CT requires Iodinated contrast media, not good for allergies, asthma, thyroid, kidney disease, or suspected pregnant patients.
- X-ray CT is separated system from therapy, whereas, the proton-CT could be an integrated system (treatment immediately after imaging).
- Is proton-CT or X-ray better?

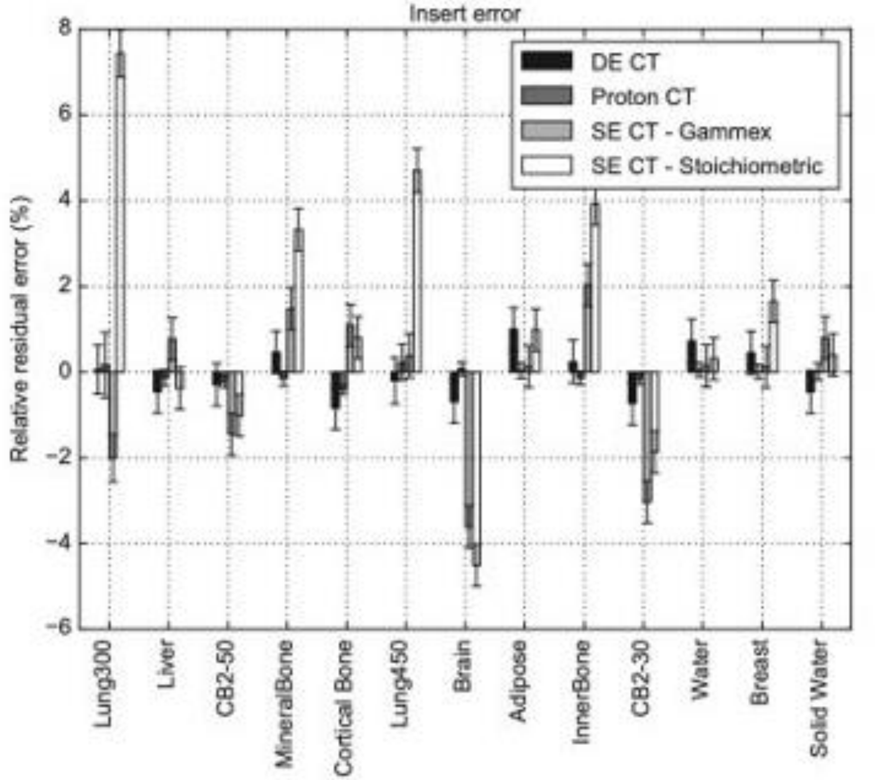


Figure 1. Residual errors in stopping power estimates based on DECT calibration, phantom SECT calibration (SECT – Gammex), stoichiometric SECT calibration (SECT – stoichiometric) and proton CT in each of the inserts of the Gammex phantom. Note that the DECT and the SECT data were fitted to the inserts in this phantom. Error bars show the 1σ confidence interval, as calculated from variance of the pixels in each insert. Additionally, for SECT and DECT, the error bars also include the uncertainties on ground truth stopping power.

D.C.Hansen et.al. A simulation study on proton computed tomography (CT) stopping power accuracy using dual energy CT scans as benchmark, Acts Oncologica, 2015, 54, 1638-1642

X-ray CT vs Proton CT

Topics	X-ray CT	Proton-CT
Better stopping power map for proton therapy	x	√
Low dose accumulation in patient	x	√
Require contrast media	x	√
Integrated system with proton therapy	x	√
Scanning time	√	x
Operating cost	√	x

Concept of our pCT prototype

Interactions of proton with matter

- Inelastic collisions with outer atomic electrons -> ionization/excitations
- Multiple Coulomb Scattering (MCS) from nuclei of the target materials.
- Protons loss their energy and deflection from original direction.
- Statistical distribution in : energy lost / angular displacement.
- Spatial resolution of pCT is limited by MCS processes.
- Density resolution of pCT is limited by energy-loss variation.

Proton energy requirement

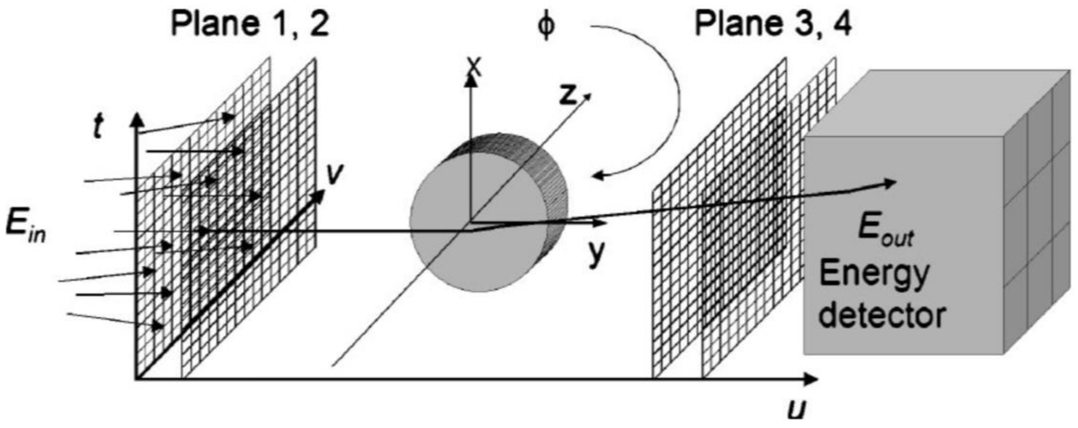
- 200 MeV protons can penetrate adult human skull (25.8 cm range in A 150 tissue-equivalent plastic).
- 250 MeV protons can penetrate adult tank (37.7 cm range).

Mean energy loss

- Mean energy of proton after passing though a thickness can be determined.

Image reconstruction

- Relative electron density can be obtained by integrating the reciprocal stopping power.



$$\int_{E_{\text{in}}}^{E_{\text{out}}} \frac{dE}{S(I_{\text{water}},E)} = \int_L \eta_e(\mathbf{r})\,dl\,.$$

R.W. Schule et. al., Density resolution of proton computed tomography, Med. Phys. 32(4), 2005.

KCMH proton treatment center

varian
A Siemens Healthineers Company

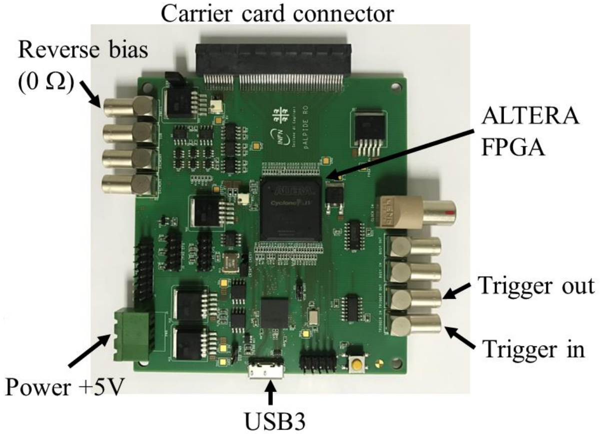
King Chulalongkorn Memorial Hospital
The Thai Red Cross Society

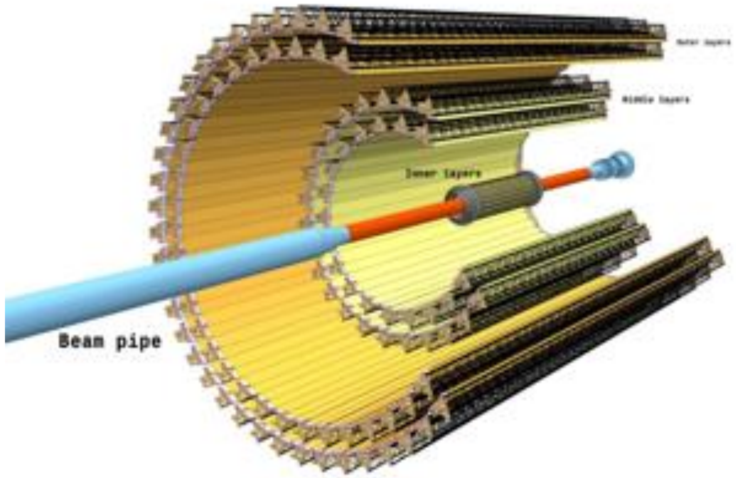
- The first proton therapy center in Southeast Asia.
- HRH Princess Maha Chakri Sirindhorn Proton Center.
- Located at King Chulalongkorn Memorial Hospital (KCMH) in Bangkok.
- Constructed in 2019 and start treatment from 2020.
- Cyclotron based accelerator by Varian.
- Energy 70-220 MeV.
- Pencil gaussian beam with 5-7 mm one sigma.
- Operate in patient and QA mode.
- SUT signed an MoU with KCMH for joining research regarding proton therapy and applications.
- SUT signed non disclosure agreement with Varian to access some electronic instrument to control the proton beam.

https://www.bangkokbiznews.com/news/royal/1024965

ALICE Pixel Detector (ALPIDE)

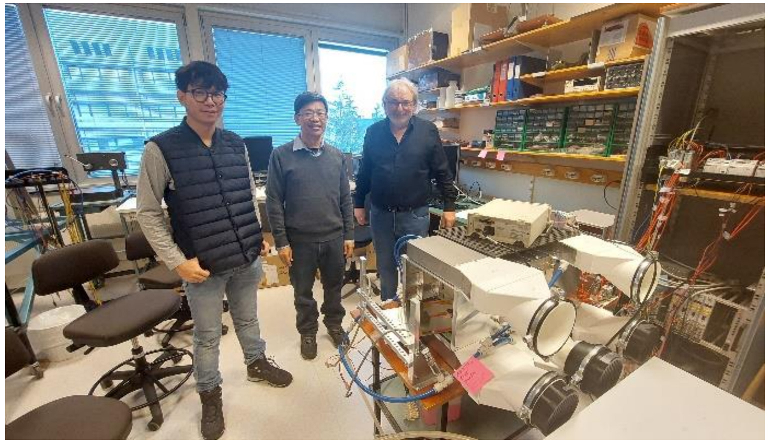
- ALPIDE sensor developed by ALICE (A Large Ion Collider Experiment) collaboration at CERN (The European Organization for Nuclear Research).
- ALPIDE sensor is the silicon-based monolithic active pixel sensor for position sensitive particle detectors.
- ALPIDE has been used in the ITS (Inner Tracking System) of ALICE detector to measure particles from hadron-hadron collisions.
- SUT is ALICE member since 2012 working in ITS1 upgrade project.
- ALPIDE sensors were characterized their properties at SLRI (Synchrotron Light Research Institute, Thailand) at the beam test facility before storage ring.

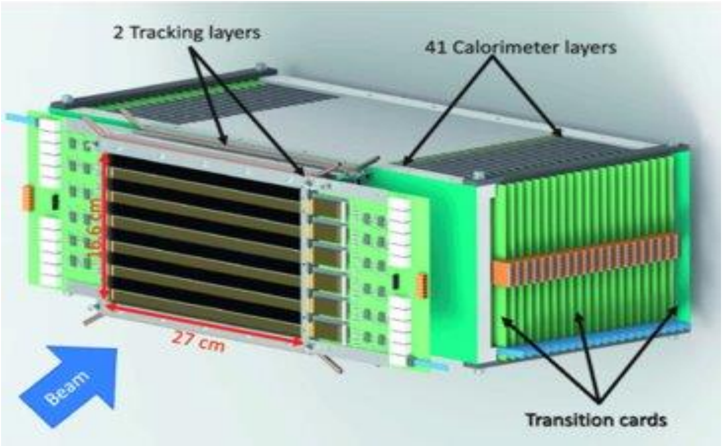


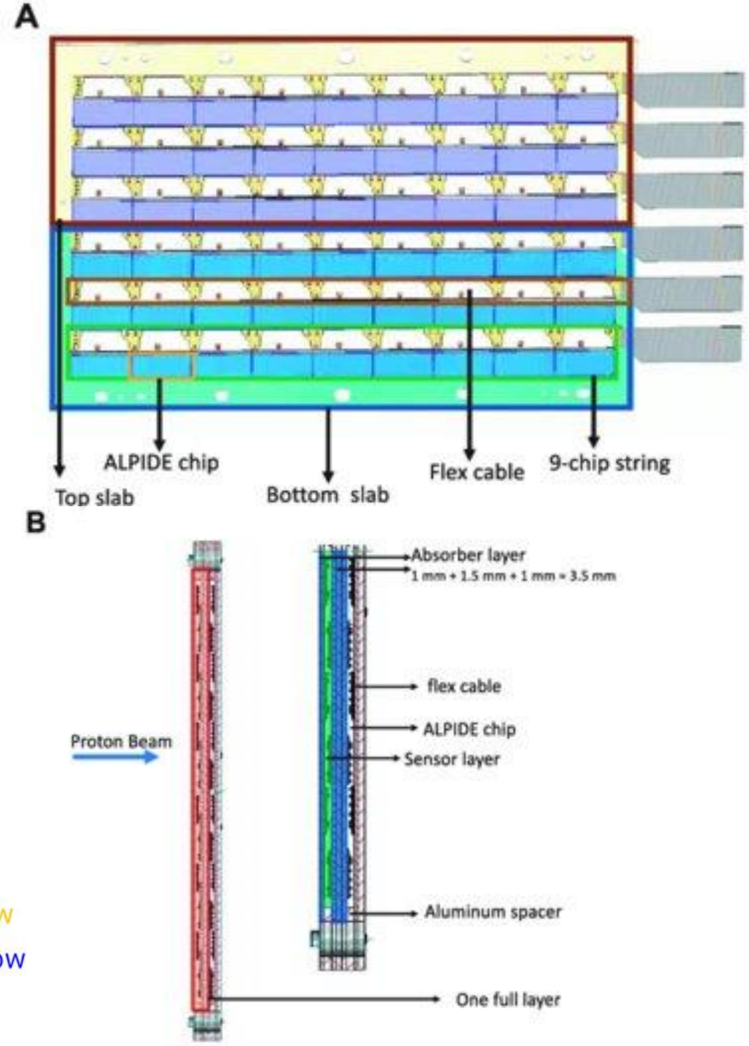


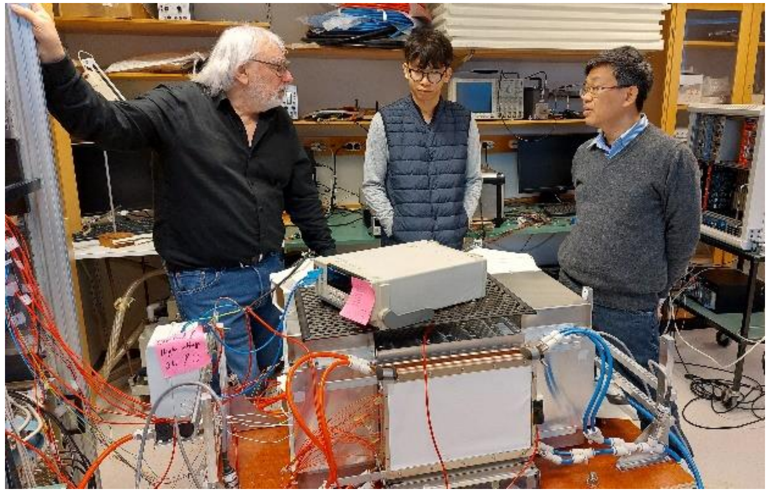
M. Mager, ALPIDE, the Monolithic Active Pixel Sensor for the ALICE ITS upgrade, NIM-A, 824, 2016, 434-438

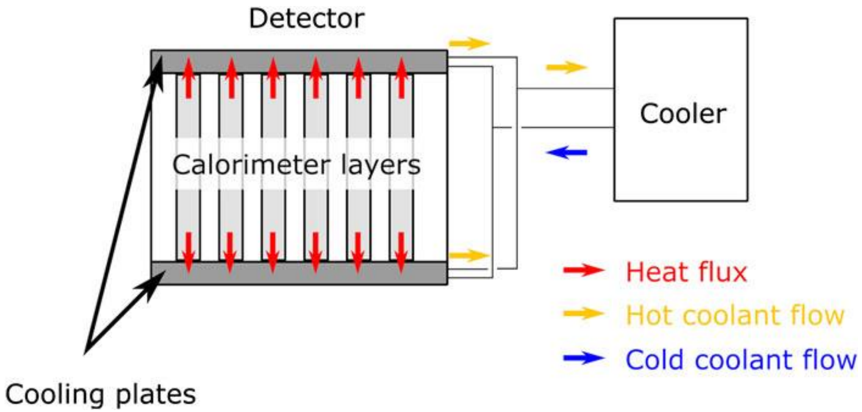
Bergen pCT prototype









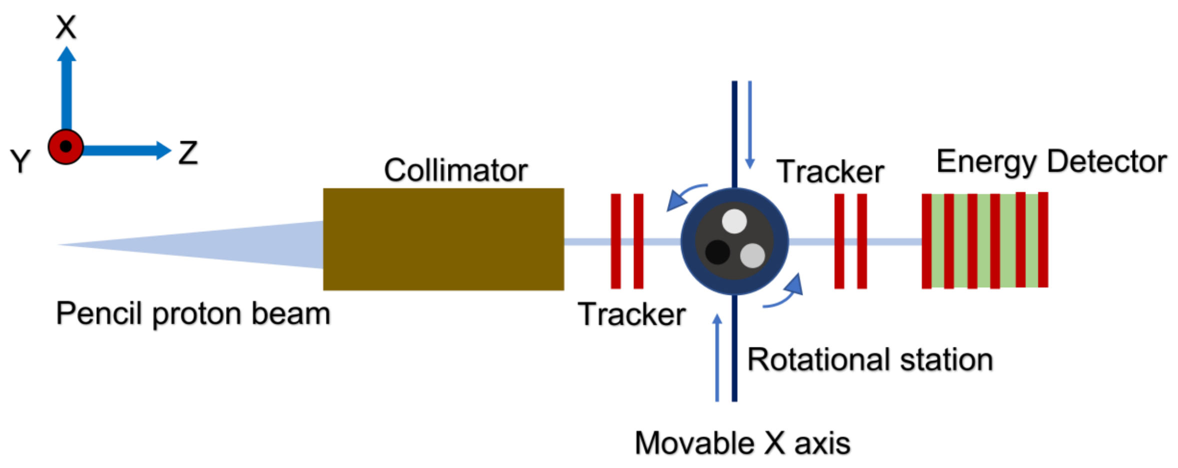


pCT-SUT has been collaborated with pCT-Bergen since 2019.

J. Alme et.al., A High-Granularity Digital Tracking Calorimeter Optimized for Proton CT, Front. Phys. Sec. Medical Physics and Imaging, 8, 2020

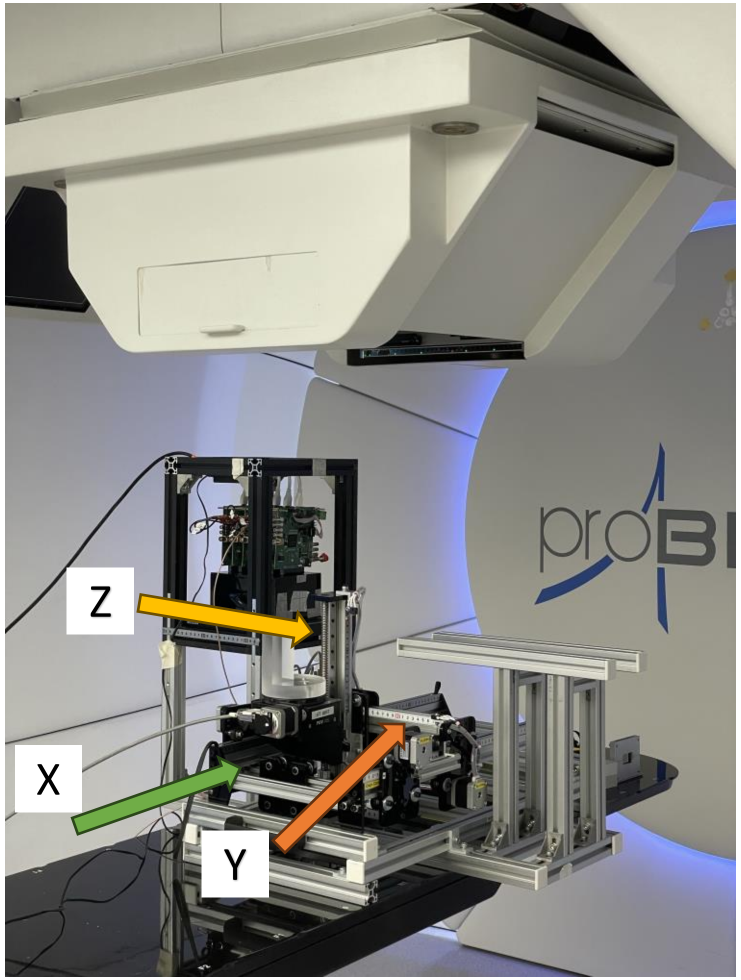
pCT 3-axis translator

2nd CT generation

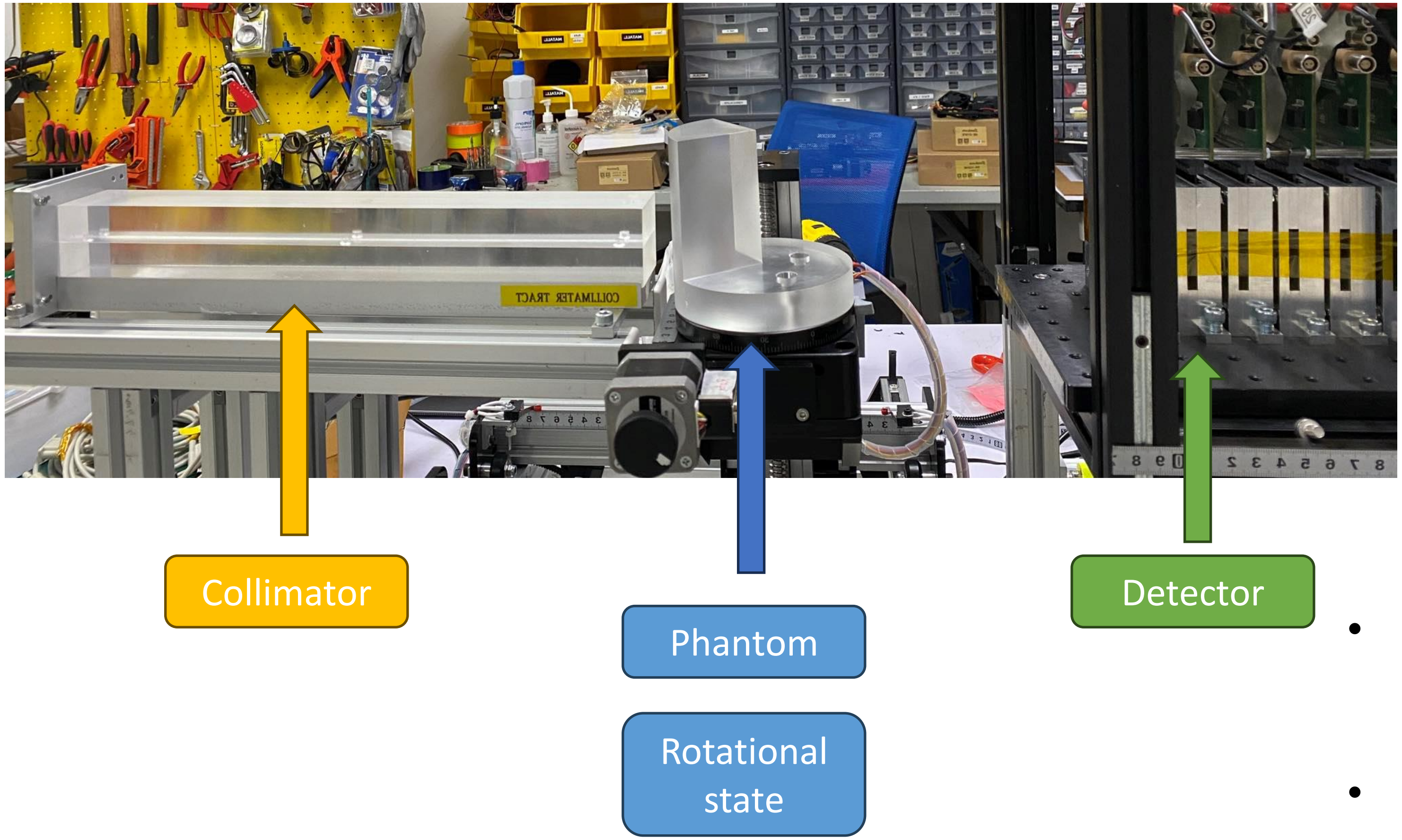


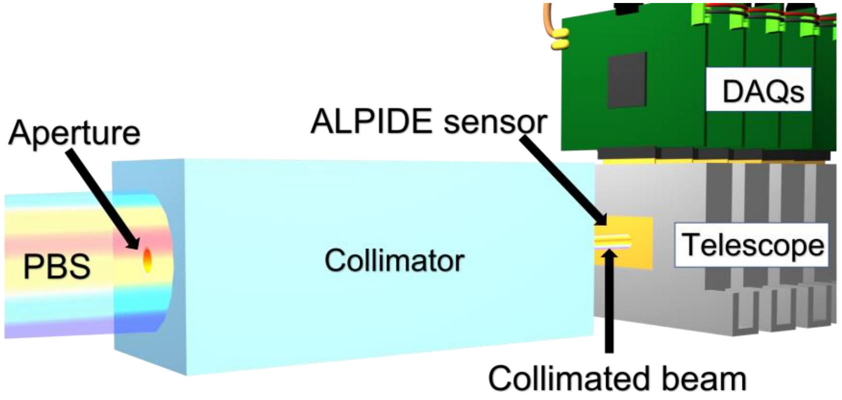
- XYZ translators.
- Rotating the phantom to a specific angle.
- Collimate the pencil beam in front of the phantom.
- Measuring the residual energy behind the tracker.

pCT 3-axis translator constructed at pCT workshop, SUT



pCT with phantom

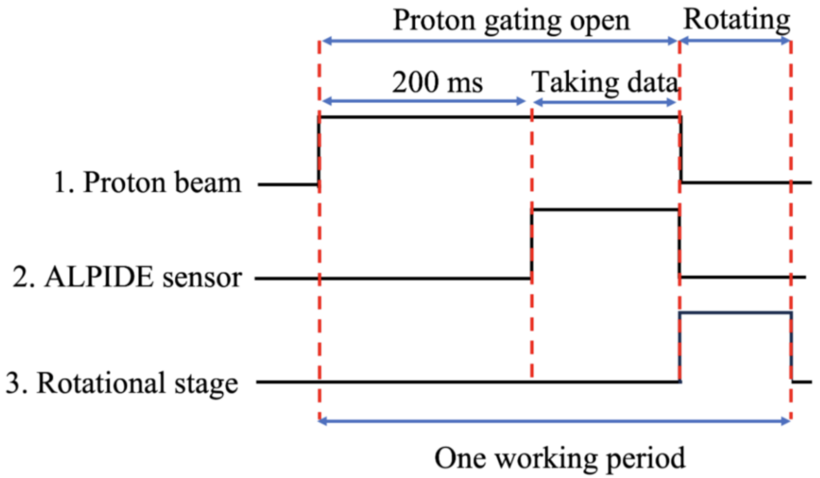


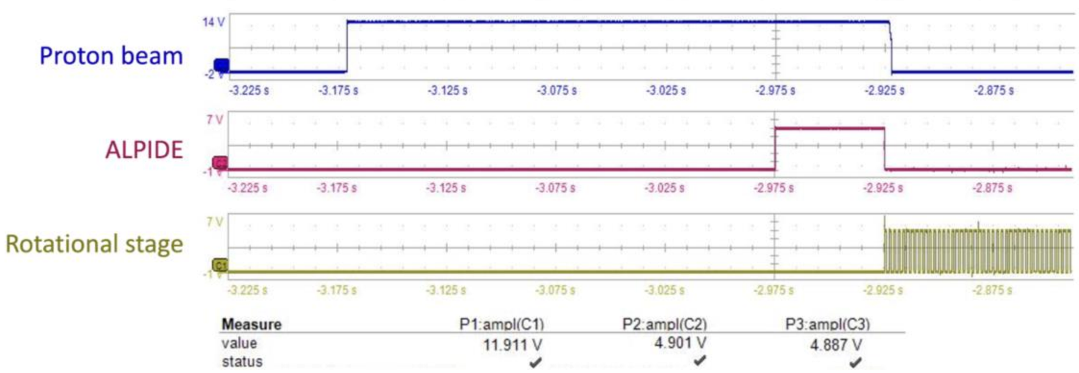


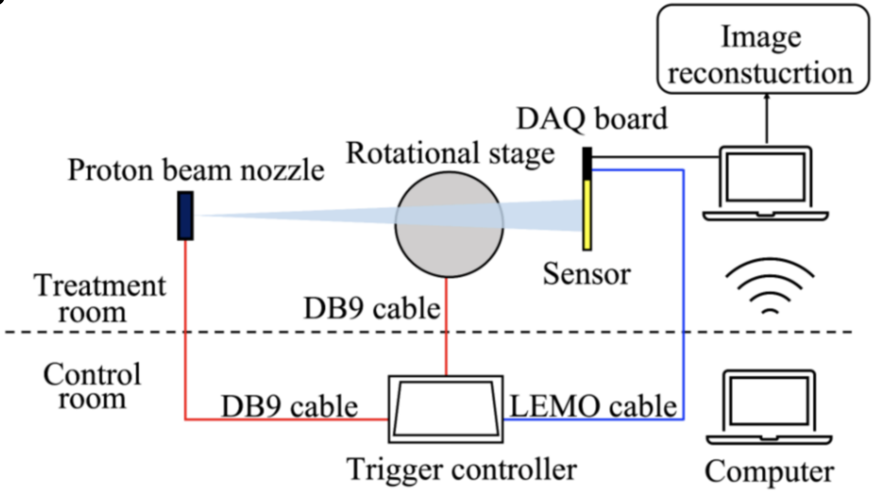
- Reducing the number of proton hits by PMMA collimator.
- Rotating phantom to get multiple projections needed for pCT data.

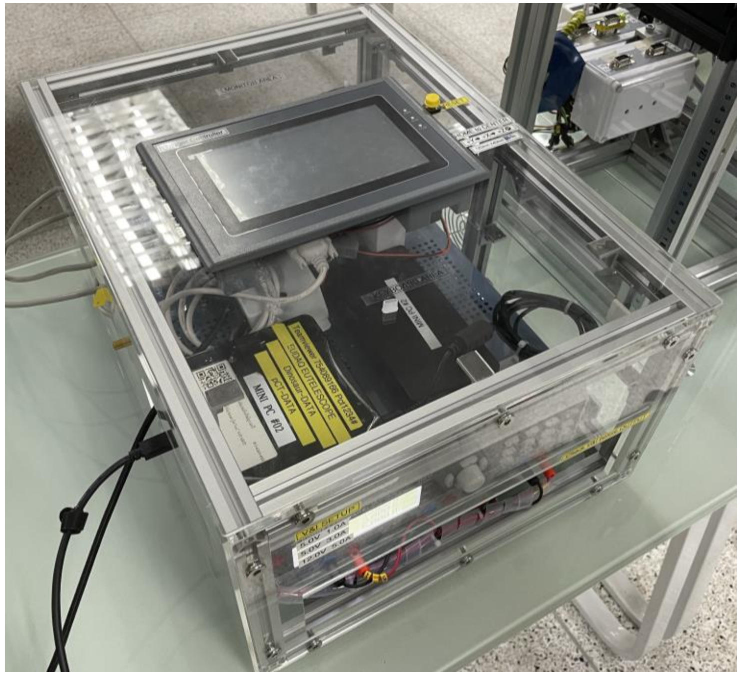
The trigger controller

- Trigger controlling system behaves as a central instrument to synchronize the pCT components working in consequent.
- First, 12V pulse signal is sent to TSS box of the proton .
- Second, 5V pulse is sent to ALPIDE sensors.
- Third, 5V pulse is sent to a rotational stage.

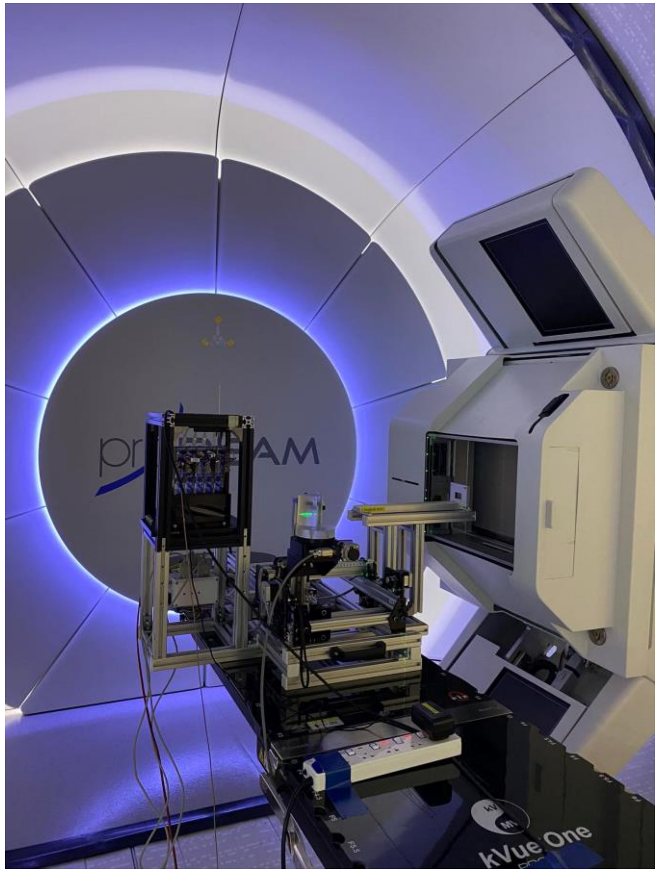






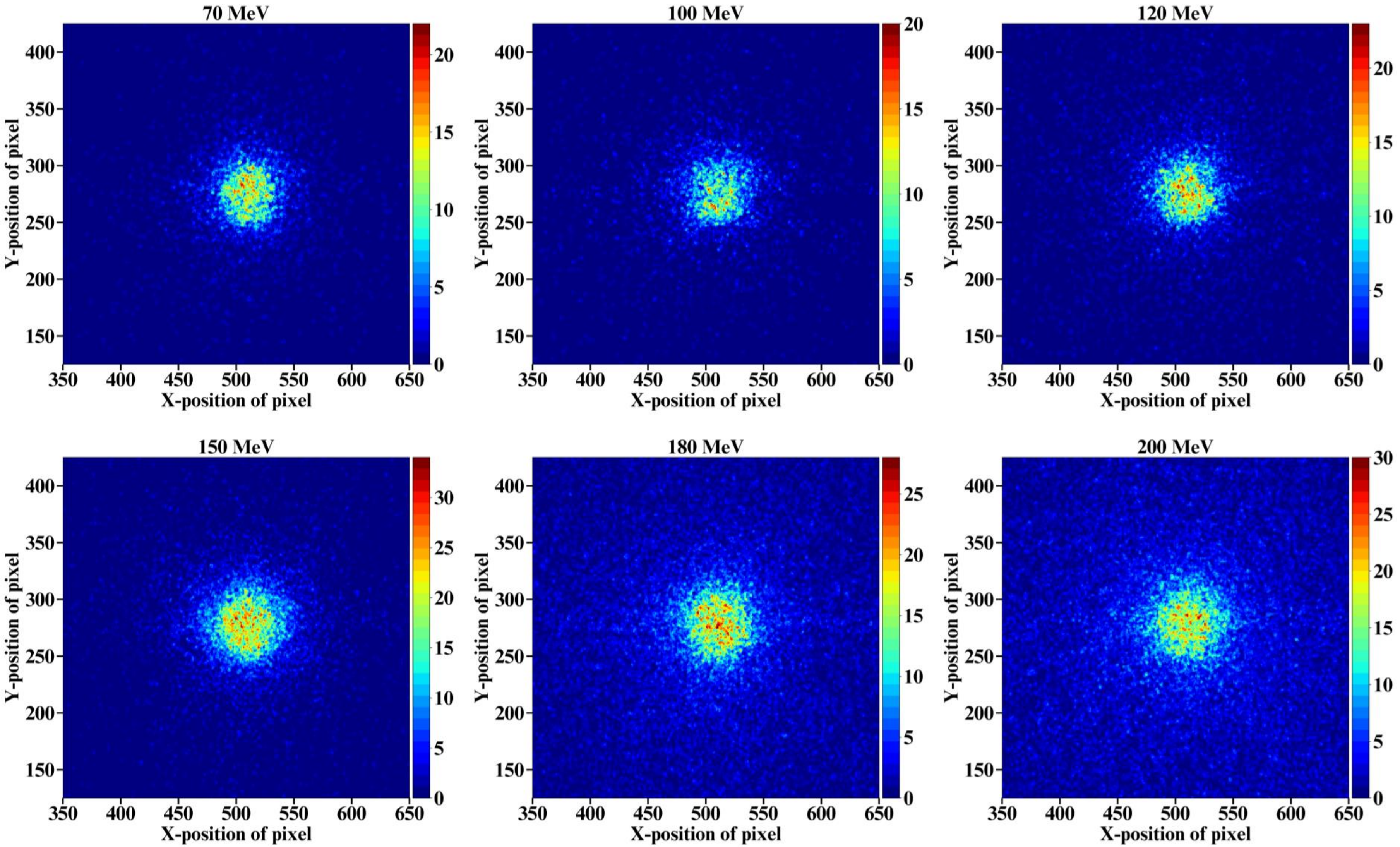


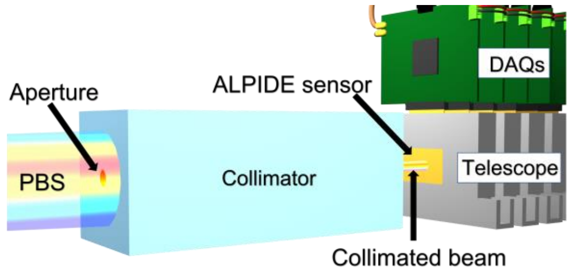
Experimental operations



Setup and testing the pCT 3-axis controller (mobile cart) at Proton center, KCMH on 19 August 2023.

Collimated beam profile



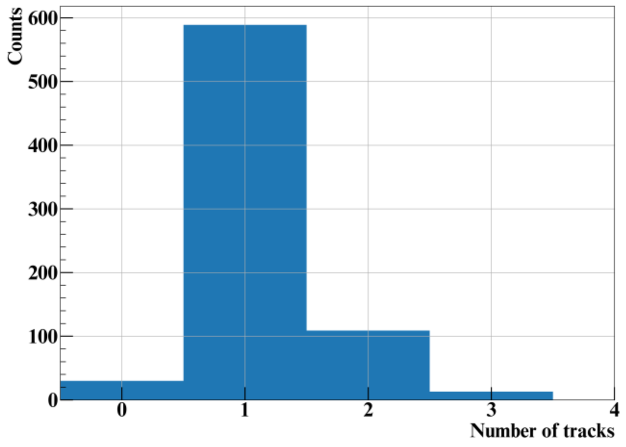


- The beam profile of 70, 100, 120, 150, 180, 200 MeV
- Lateral beam is reduced by using PMMA collimator.
- Gaussian model fitting.
- Single Gaussian fit in 70 and 100 MeV.
- Double Gaussian fit for 120 – 200 MeV.
- Selecting 2-sigma area.

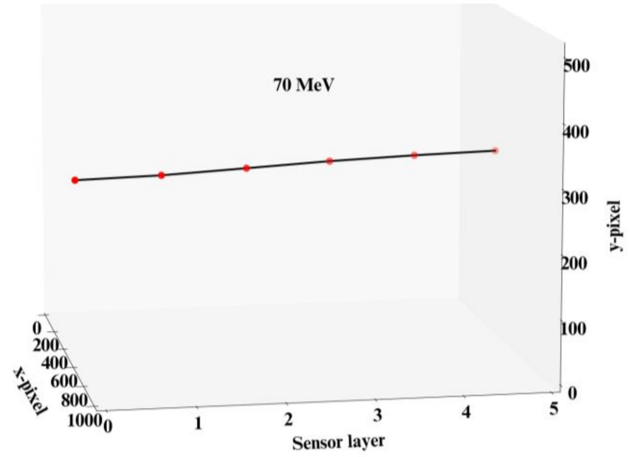
Tracks result

70 MeV

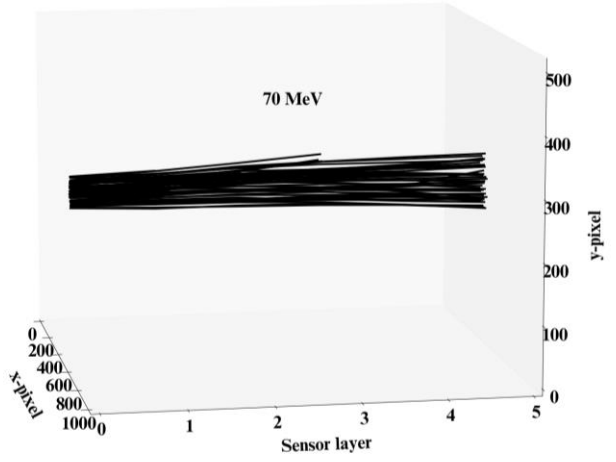
Number of tracks distribution



Single frame

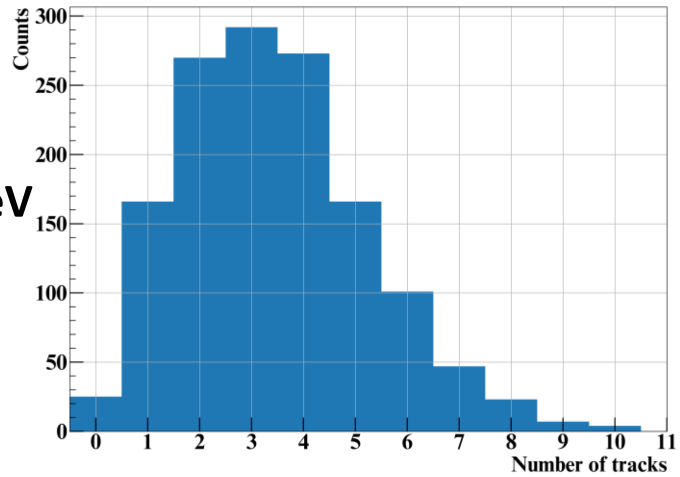


Multiple frames (50)

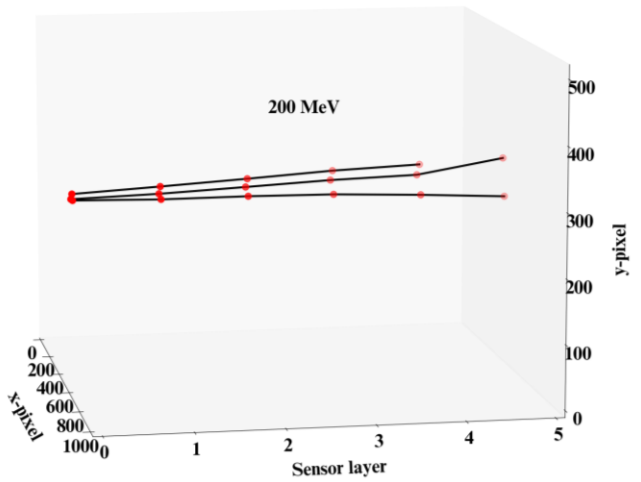


200 MeV

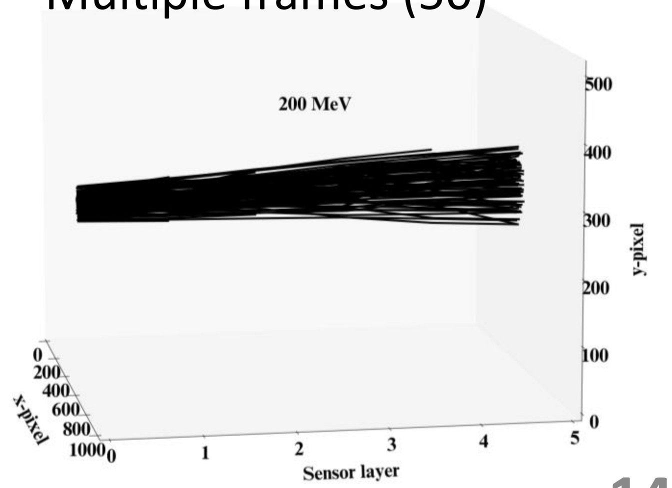
Number of tracks distribution



Single frame



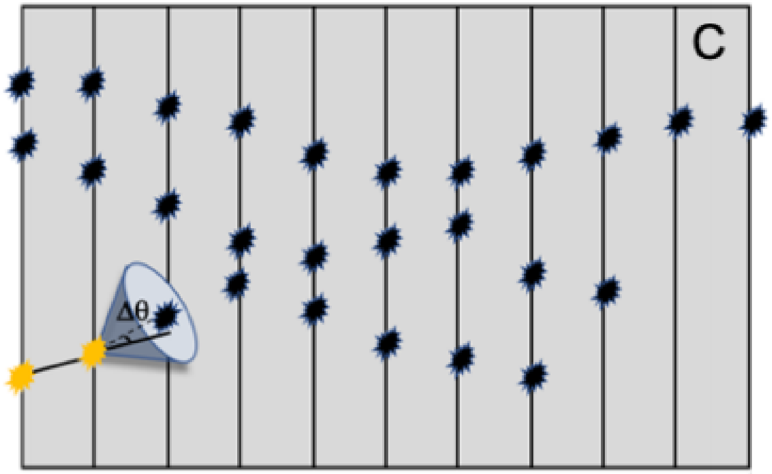
Multiple frames (50)



Track efficiency

- The angle of the search cone is determined by S_{max} and its value determines the amount of deflection that is allowed during track reconstruction.
- Too small values of S_{max} lead to prematurely discarded track candidates, and too large values cause confusion by including the wrong candidates where there should be none.
- Find the angular change for each candidate in the next layer and calculate

$S_n = \sqrt{\sum_{layer}^{n}(\Delta\theta_{layer})^2}$, where n indicates the proton density.



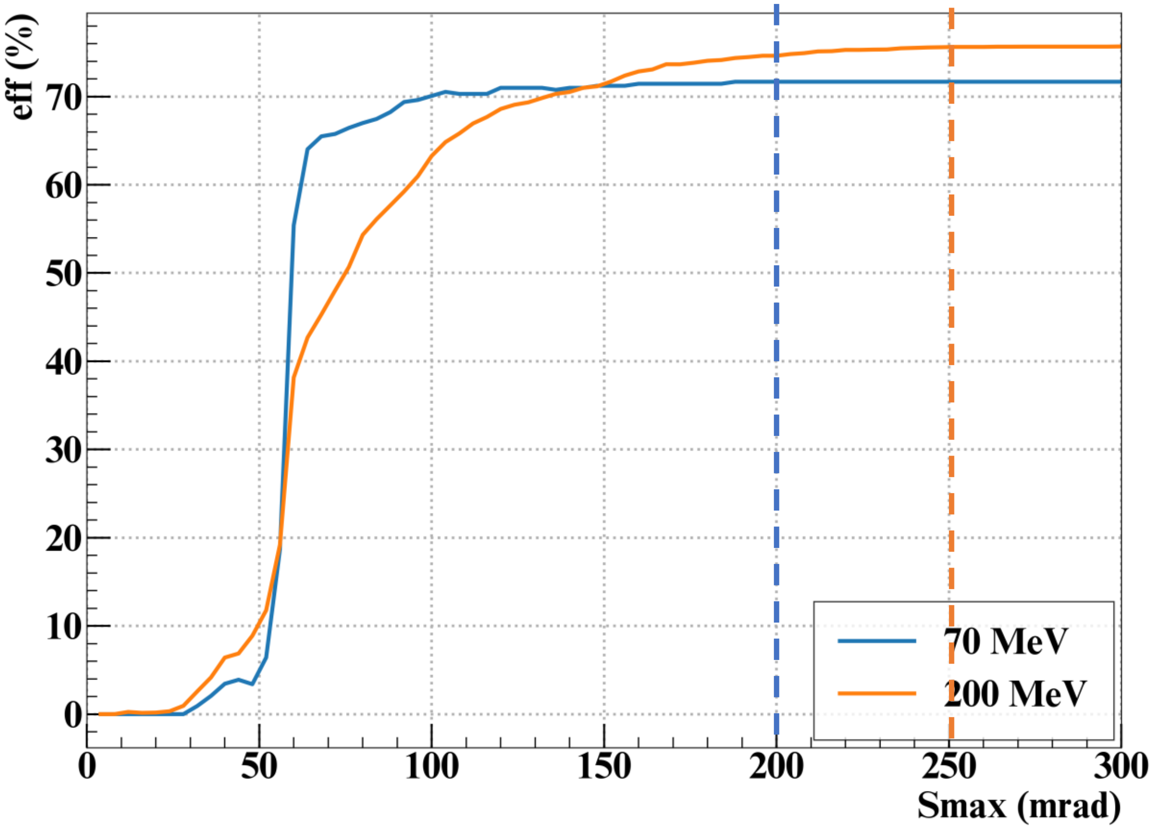
https://dx.doi.org/10.1088/1361-6560/abca03

Discard

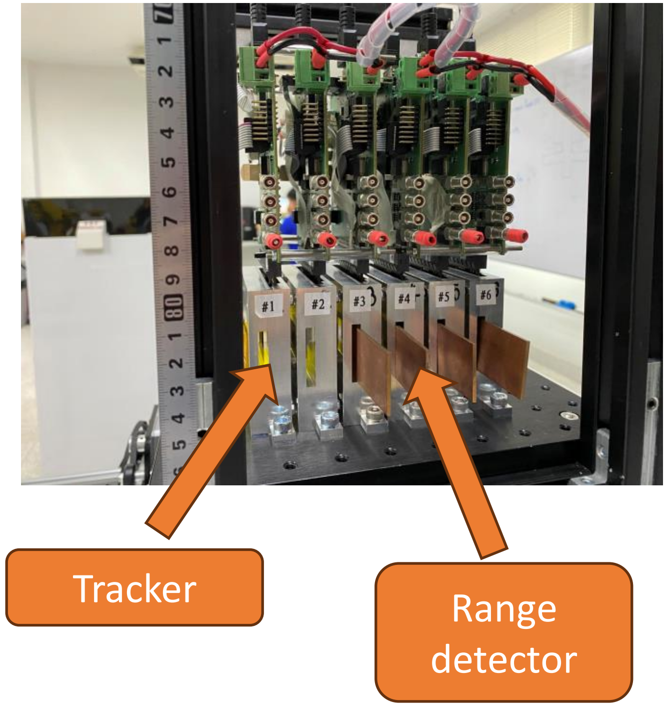
$S_n > S_{max}$

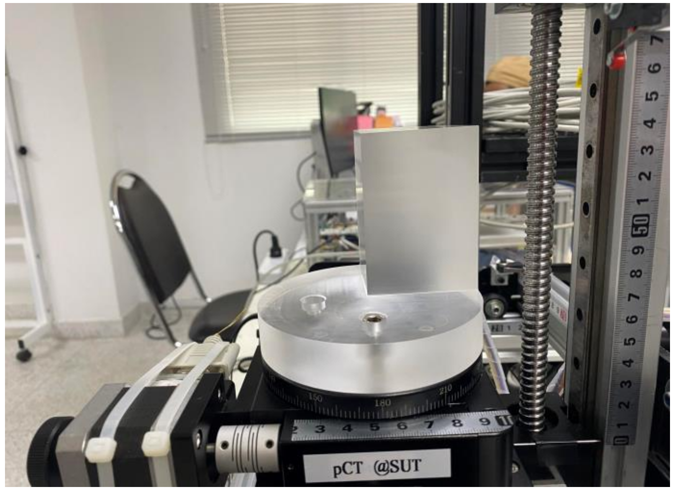
Accept

$S_n \leq S_{max}$

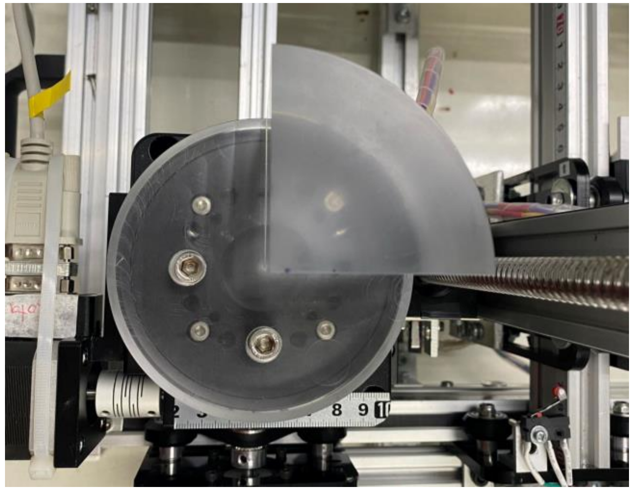


Collecting pCT data





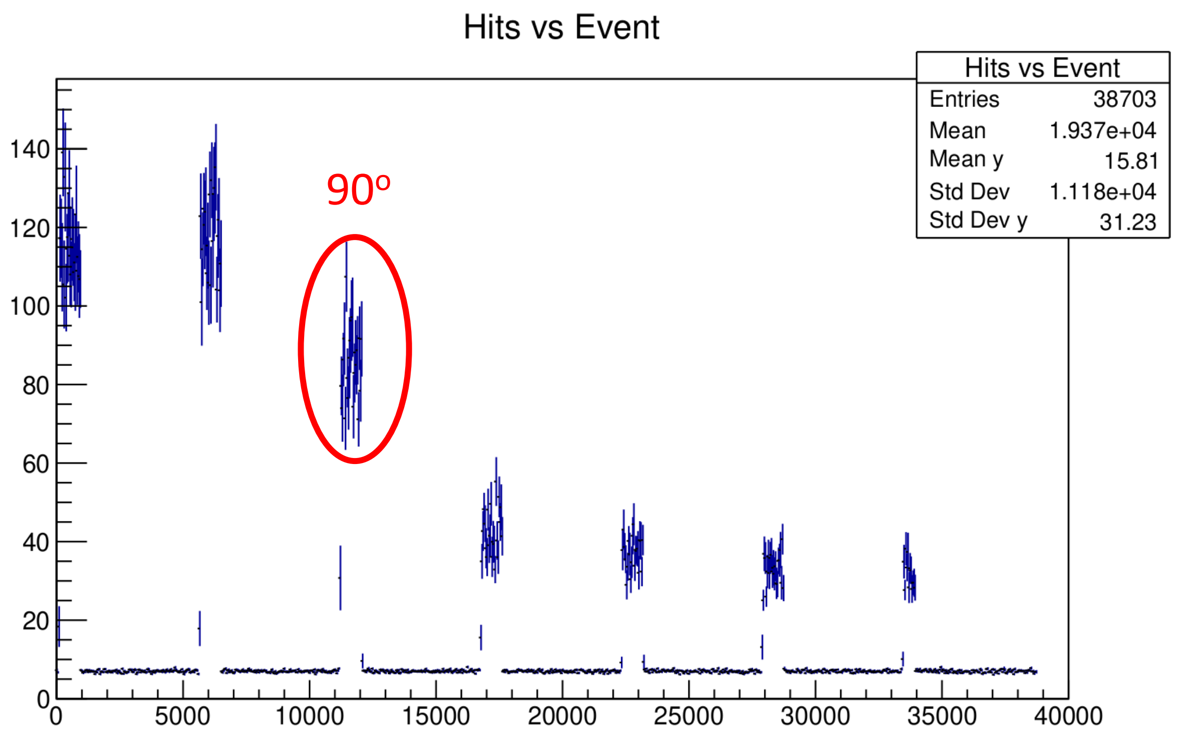
Side view

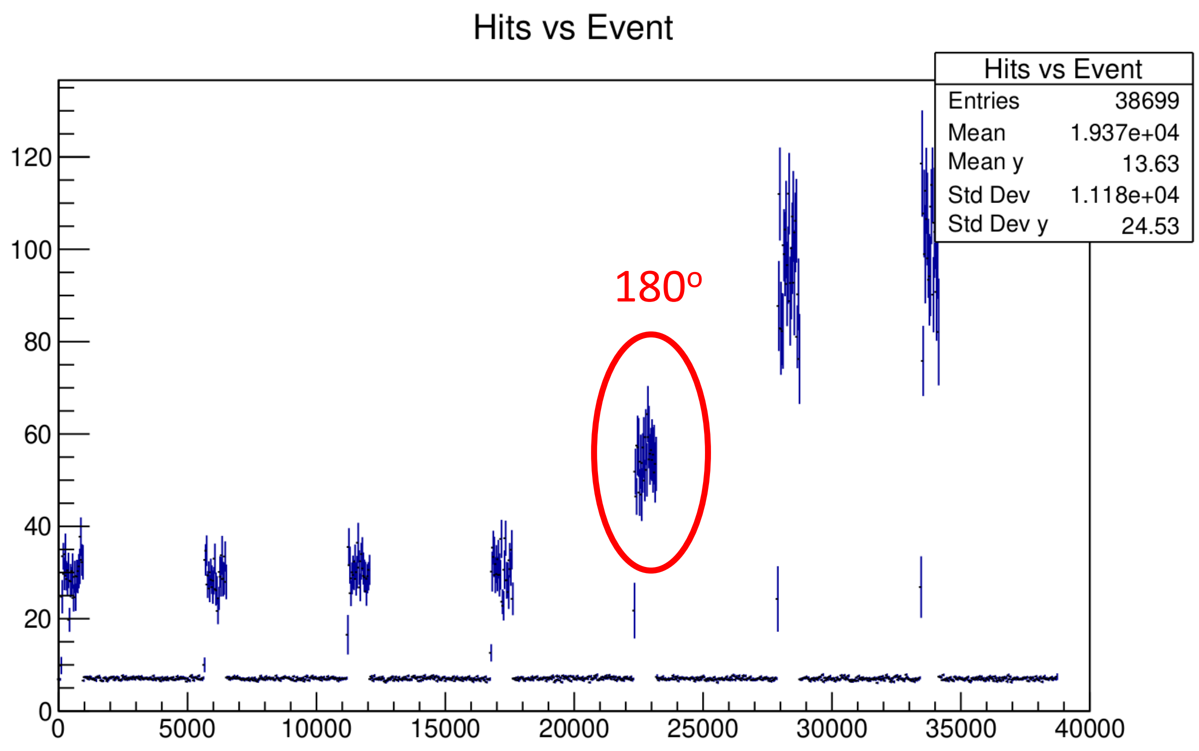


Top view

- The proton tracker uses two ALPIDE sensors.
- Cu (2mm) absorbers are inserted between two sensors to be a range detector.
- A 1/4-cylinder phantom is rotated for multiple projections of the radiation.

Collecting pCT data





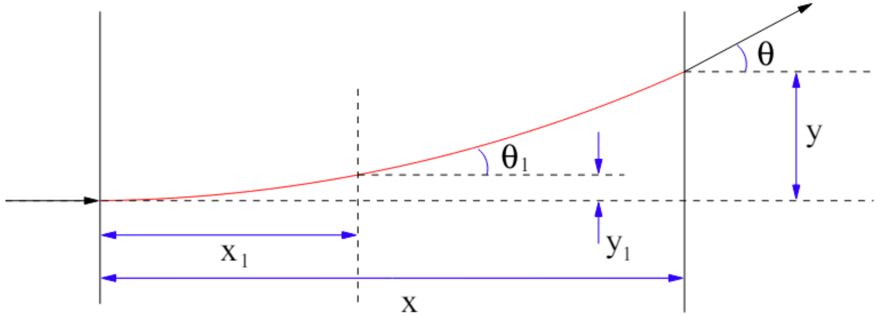
- The results show hit entries for radiation from all sensors.
- The 1/4-cylinder phantom is rotated 10 degrees for each projection.
- The number of entries decreases when we change the angle.

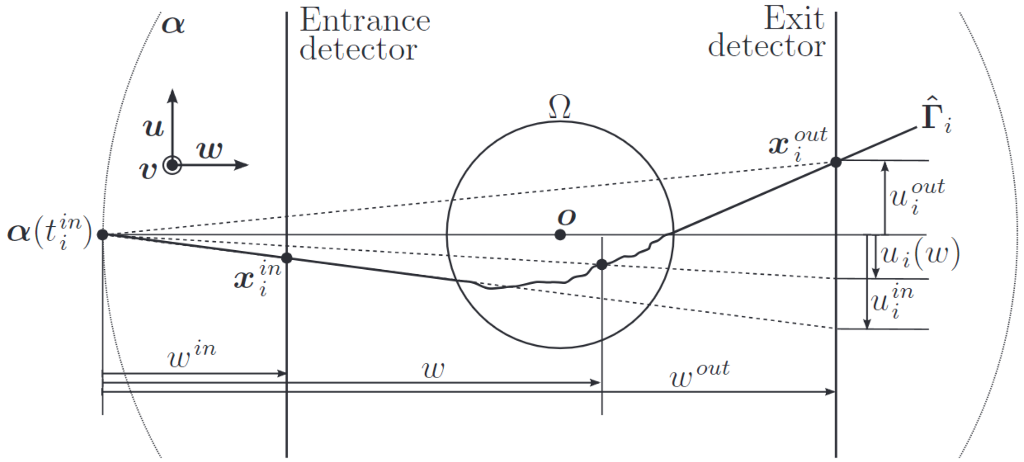
Image reconstruction algorithm

$$g_{j,p}^{in} = \frac{\sum_{i \in \mathbf{I}_p} h_j\left(u_i^{in}, v_i^{in}\right) G\left(E_i^{in}, E_i^{out}\right)}{\sum_{i \in \mathbf{I}_p} h_j\left(u_i^{in}, v_i^{in}\right)}$$

<u>Filtered back projection (FBP)</u>

- Back projecting from the residual energies of multiple projections of proton paths inside a phantom to image space.
- Filtering the projections to perform better reconstructed image.





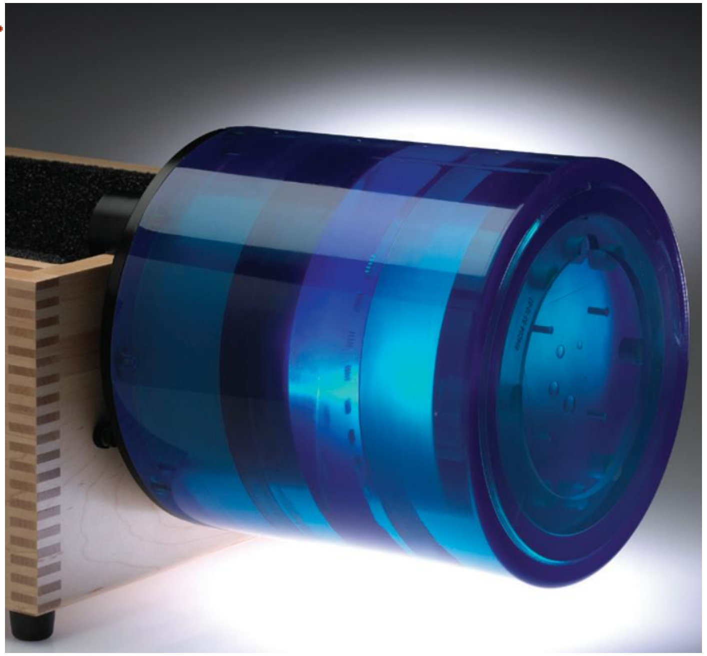
<u>Most likely path (MLP)</u>

- Estimate the proton path inside a phantom because of MCS.
- The most important factor affecting the image quality of the reconstruction.

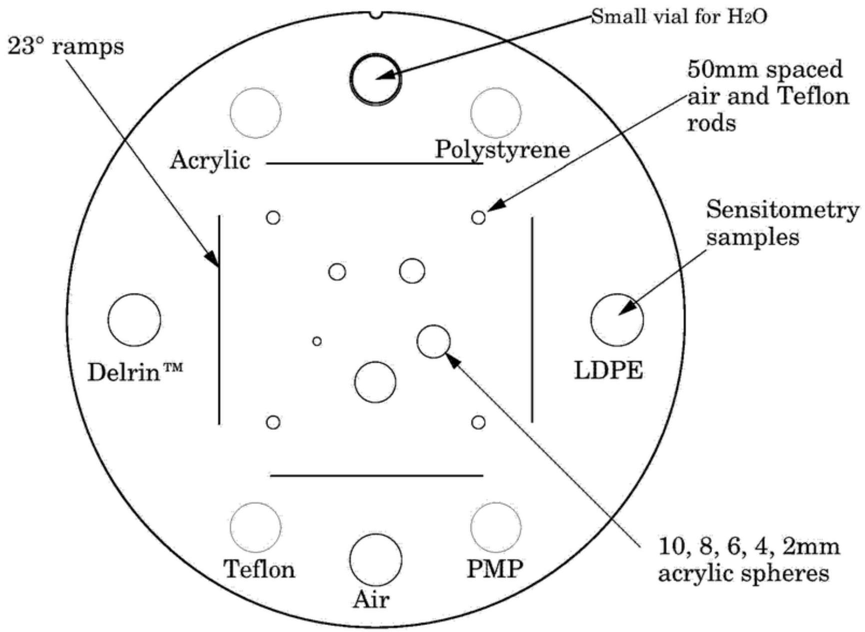
https://aapm.onlinelibrary.wiley.com/doi/10.1118/1.4789589

https://iopscience.iop.org/article/10.1088/0031-9155/49/13/010

Image reconstruction with CTP404



Catphan® 600



Material properties of CTP404

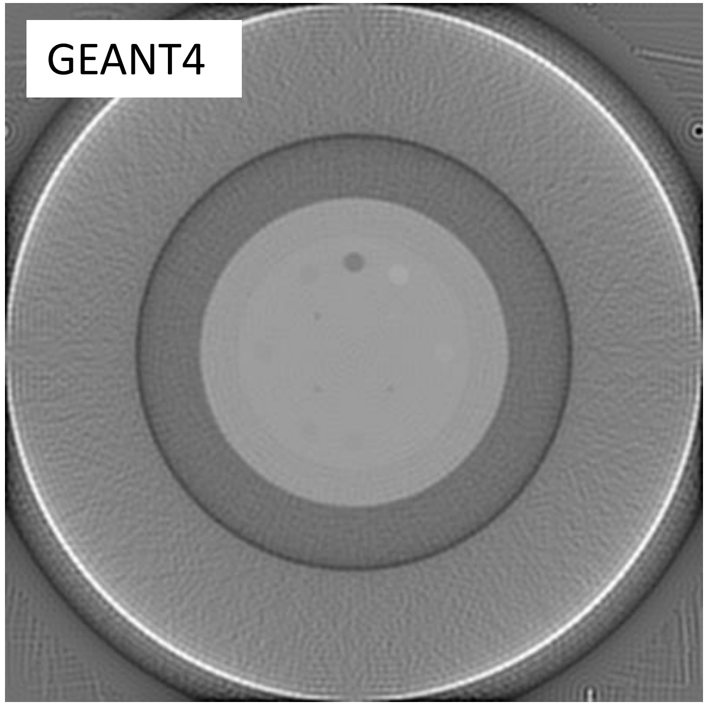


Image reconstruction with FBP + MLP

- Simulate CTP404 phantom in GEANT4.
- 450x450 of Image resolution.
- Nvidia Tesla A100.

Catphan® 500 and 600 Product Guide

Summary

- We use the acrylic collimator to eliminate lateral dose fall-off in the beam.
- With the collimated beam, the activated signals found in six ALPIDEs can be reconstructed as proton trajectories.
- The pCT 3-axis translator synchronizes the XYZ axis, rotational state, and ALPIDEs for multiple projections in the experiment.
- The range detector is constructed by inserting absorber plates between sensors, and the first couple ALPIDEs are left as a position-sensitive detector.
- The filtered back projection (FBP) that is usually applied to conventional CT is combined with the most likely path (MLP) to reconstruct the image in this pCT data.

Bergen pCT collaboration

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

Acknowledgement

Nuclear and plasma sciences society

Suranaree University of Technology

Development of Promotion for Talent Science and Technology

University of Bergen

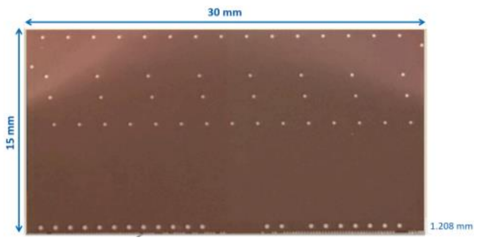
King Chulalongkorn Memorial Hospital

A Large Ion Collider Experiment

Future work

Open to collaboration!

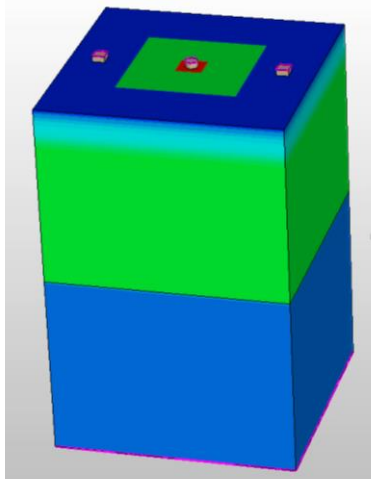
pCT sensor design



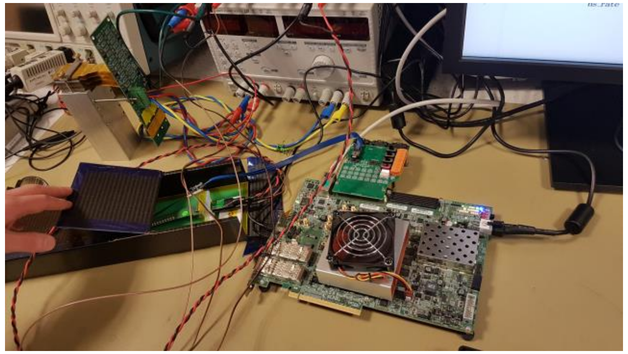
ALPIDE sensor can be designed in technology aid design (TCAD)

Sentaurus TCAD

SYNOPSYS



New FPGA (Xilinx VCU118) for DAQ



Bergen setup

SUT Xilinx

Thank you

Q&A