A High-granularity Digital Tracking Calorimeter developed for proton CT

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on behalf of the Bergen pCT collaboration

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Outline

- Proton Computed Tomography
- Mechanical Design of the Bergen pCT
- Results from various beam tests
- Image Reconstruction
- Outlook and other uses

Proton Computed Tomography

- Treatment with charged particles reduces dose delivery to healthy tissue
- Uncertainty of Bragg-peak placement when image is acquired with conventional CT
- Particle imaging allows for the direct measure of particle range within target

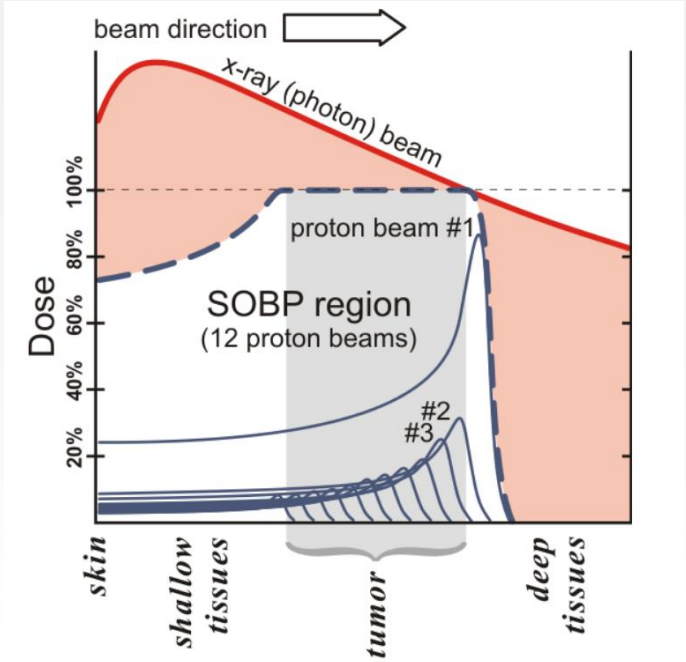


Figure 1:The different depth dose distributions from photons and protons, as a function of depth in water [1]

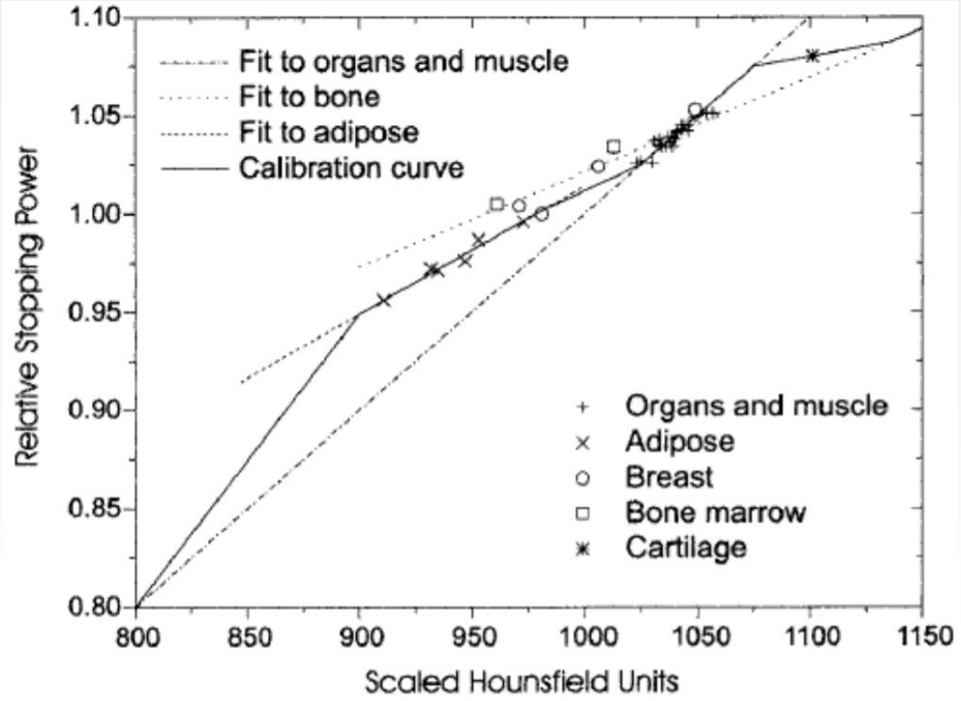
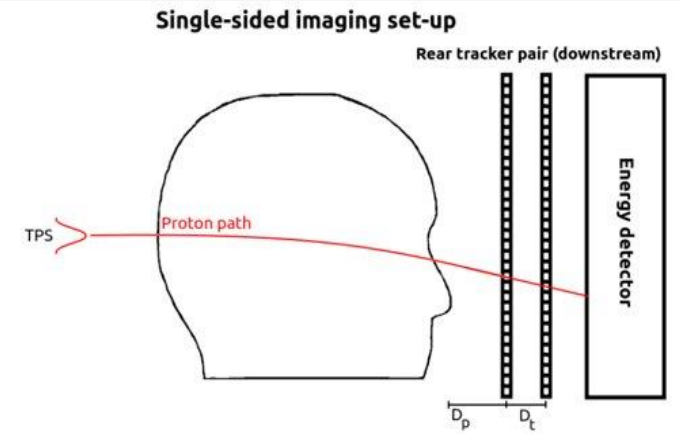


Figure 2: RSP as a function of HU [2]

Requirements and design choices

- Requirements:
  - Fast readout speed
  - High-granularity
- Single-sided Imaging setup
- Digital Tracking Calorimeter
  - Layer-by-layer
  - Silicon pixel sensors used as both tracking and energy detectors



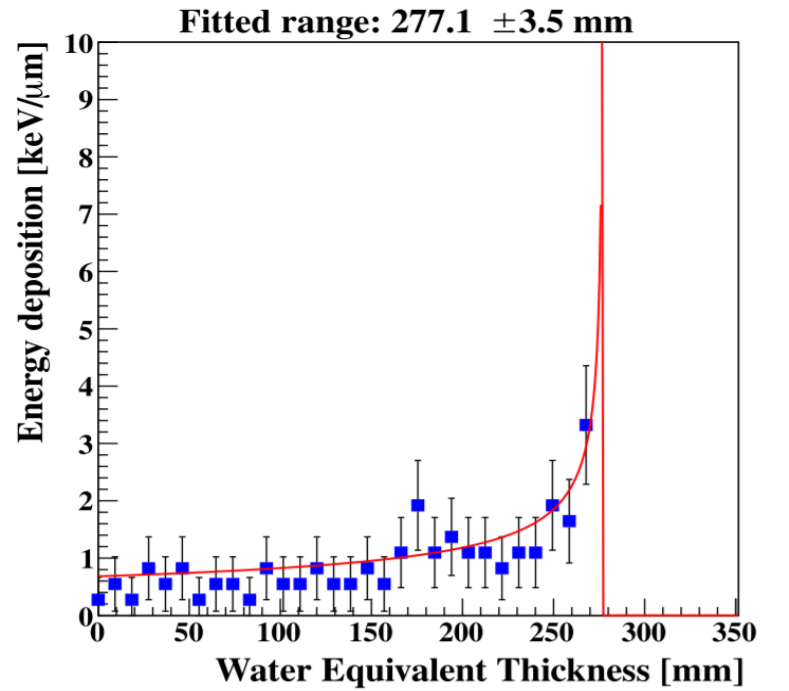


Figure 3 (bottom left): Single sided proton computed tomography [3]

Figure 4 (Top right): Energy deposition as a function of depth, fit by Bragg-Kleeman equation [4]

Digital Tracking Calorimeter

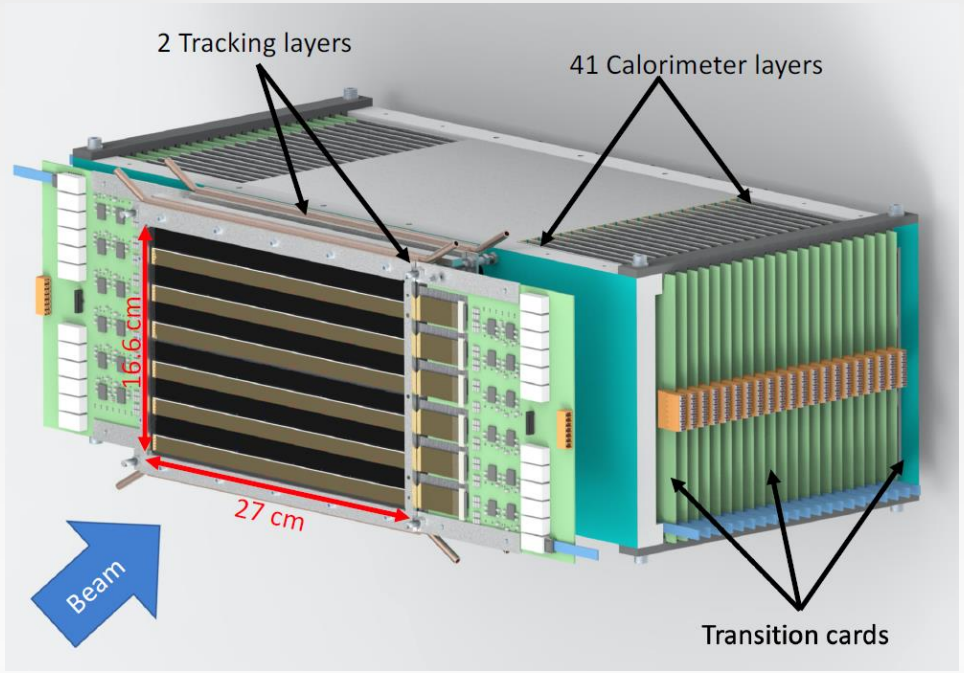
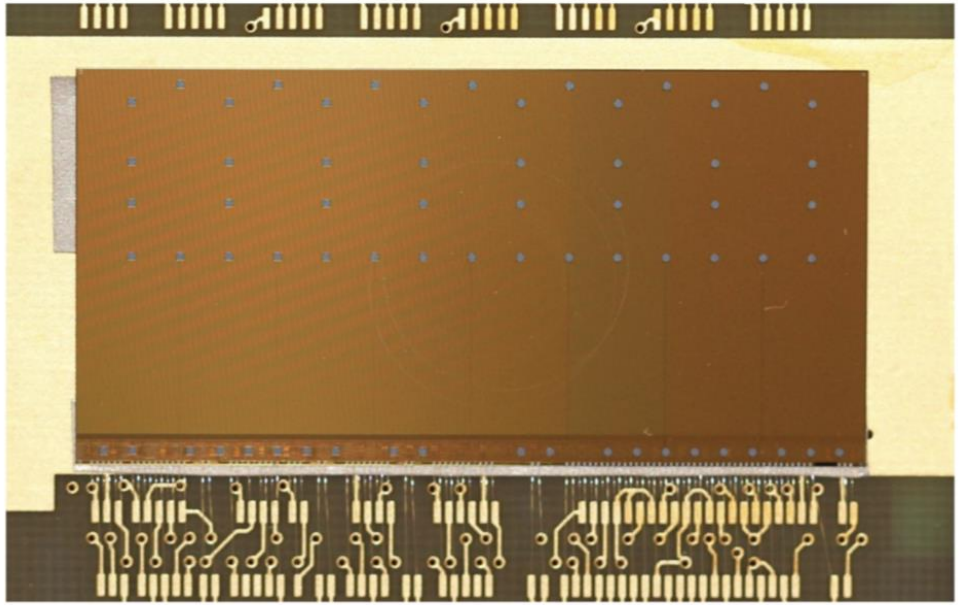


Figure 5: Schematic of the Bergen pCT detector [6]

- 108 ALPIDEs on each layer
- Two tracking layers
  - 50 µm ALPIDE mounted on ~300 µm carbon sheets
- 41 Calorimeter layers
  - 100 µm ALPIDE
  - 3 mm aluminium absorber

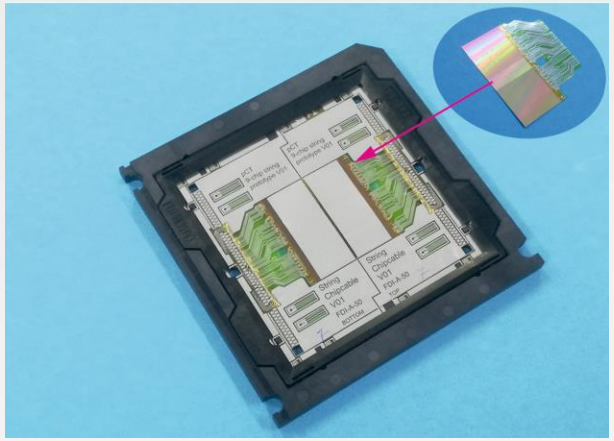
ALPIDE sensor

- Monolithic Active Pixel Sensor
- Pixel size: 29.24 µm x 26.88 µm
- Pixel matrix: 1024 x 512
- Peaking time ~2µs
- 3 in-pixel memories

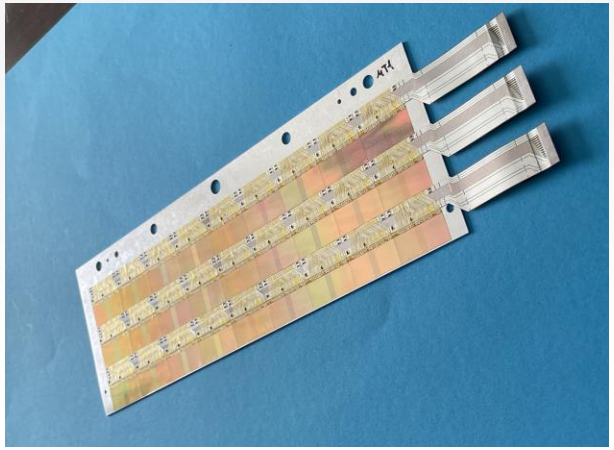


- Figure 6: Photograph of the ALPIDE. Interface pads used for bonding to the printed circuit board are visible (gray squares). [6]

Mounting process of a layer

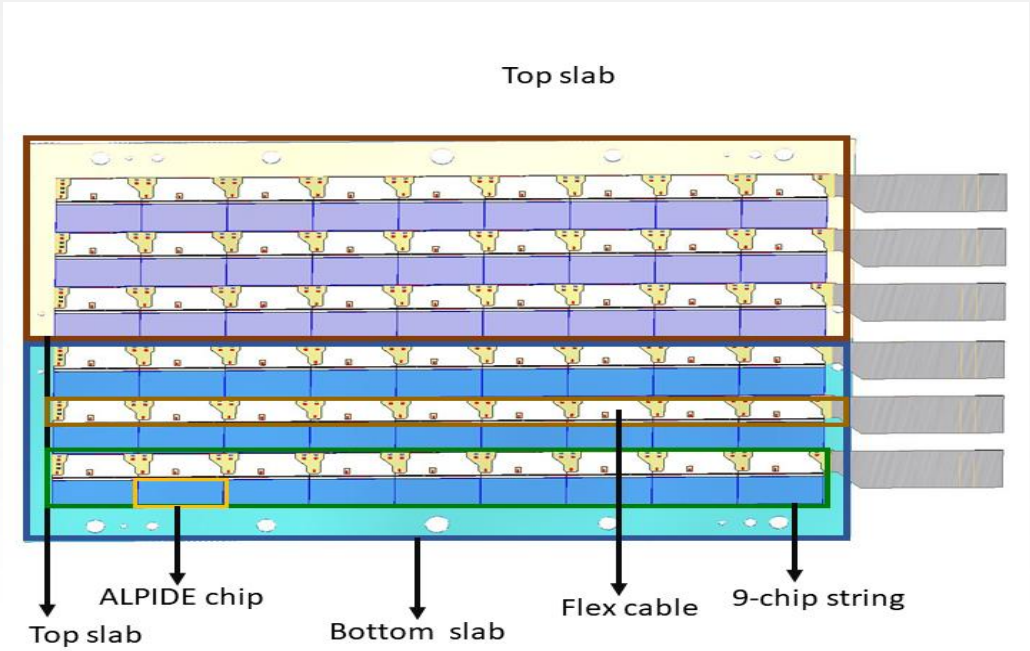


- Figure 7: Photograph of the ALPIDE chips bonded to a flex-cable [6]



- Figure 8: Photograph of the ALPIDE chips on slab

- Bonded to Chip Cable by Single-Point Tape Automated Bonding
- Nine sensors bonded on flex is known as a 9-chip string
- Three 9-chip strings consittutes a slab
- Two half layers face to face cover the full area

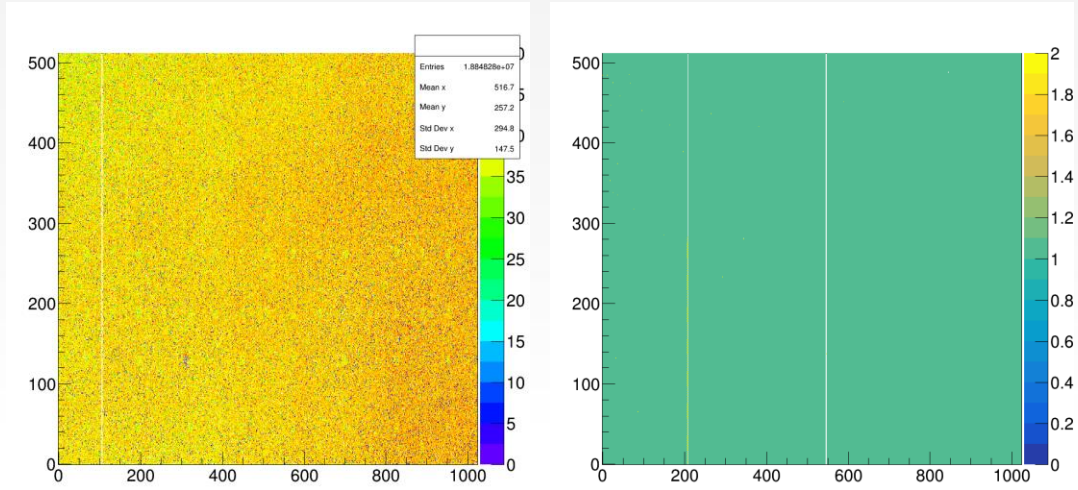


- Figure 9: Half a layer consists of ALPIDEs on aluminum carrier [6]

Verification during mounting process

- Figure 10: Photograph of the production test box used for verification of the ALPIDE sensors after bonding.

- ALPIDE is tested multiple times during the mounting process.
  - Power Test to look for shorts in the pixel-matrix
  - Digital scans to validate the communication with the sensor
  - Matrix scans to evaluate the response of the front-end electronics



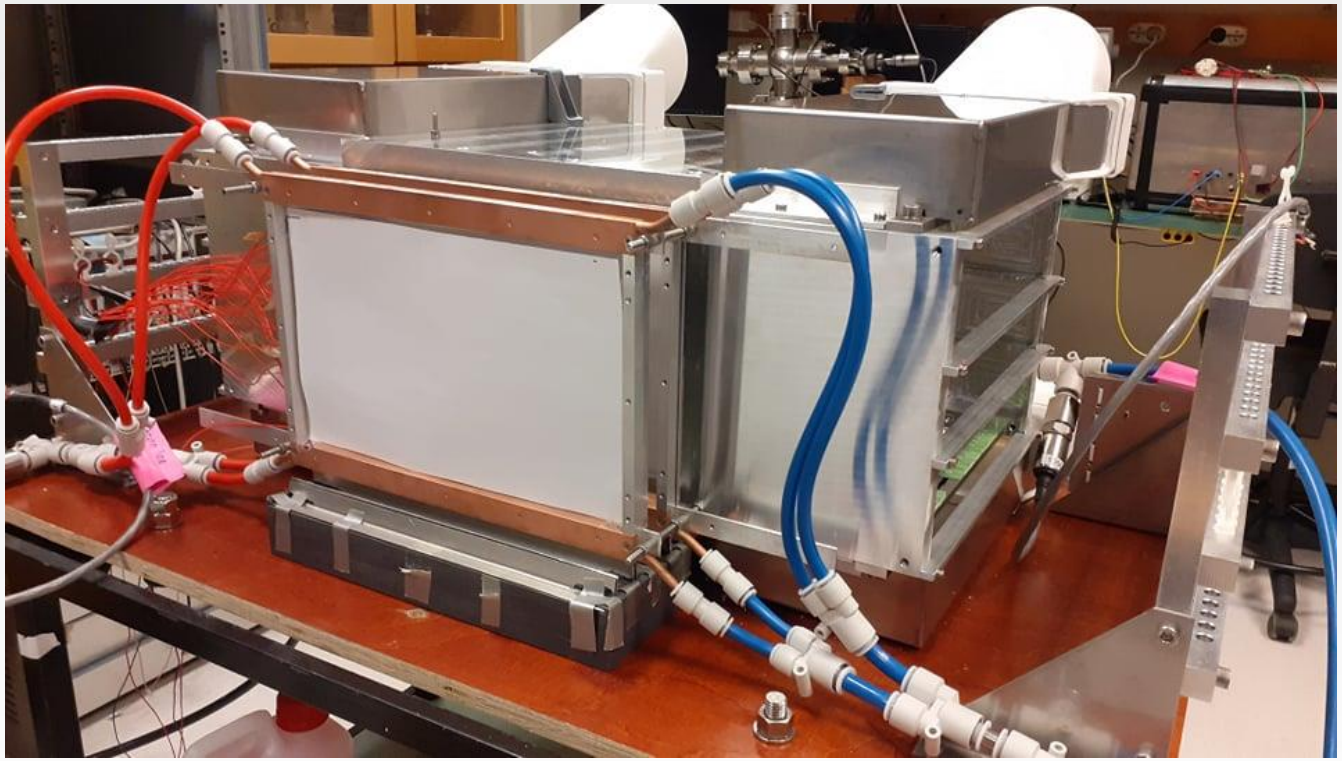
- Figure 11: (left) Threshold scan (right) Analog scan

Tracking Layers

- Figure 12: Sandwiched Carbon Fiber sheet
  200 mm x 290 mm x 0.3 mm

- Thinned ALPIDE sensors mounted on carbon sheet
  - Thickness 50 µm
- Carbon sheet with total thickness ~300 µm
- Carbon sheet is mounted in aluminium frame
- Materials used in carbon sheet:
  - Pyrolitic graphite paper
  - Carbon Fleece
  - Epoxy Resin

Mechanical Structure and Cooling



- Support structure for carbon sheets
- Water cooling of sensor layers
- Air cooling of transition cards

- Figure 13: Photograph of the mechanical structure

Readout

- Transition Card to act as intermediate between front-end and readout unit
- Custom readout unit based on Xilinx Kintex Ultrascale FPGA
- One readout unit per layer (108 ALPIDEs)
- Motherboard to synchronize triggering signal
- Can support up to four Independent 10 Gbit links

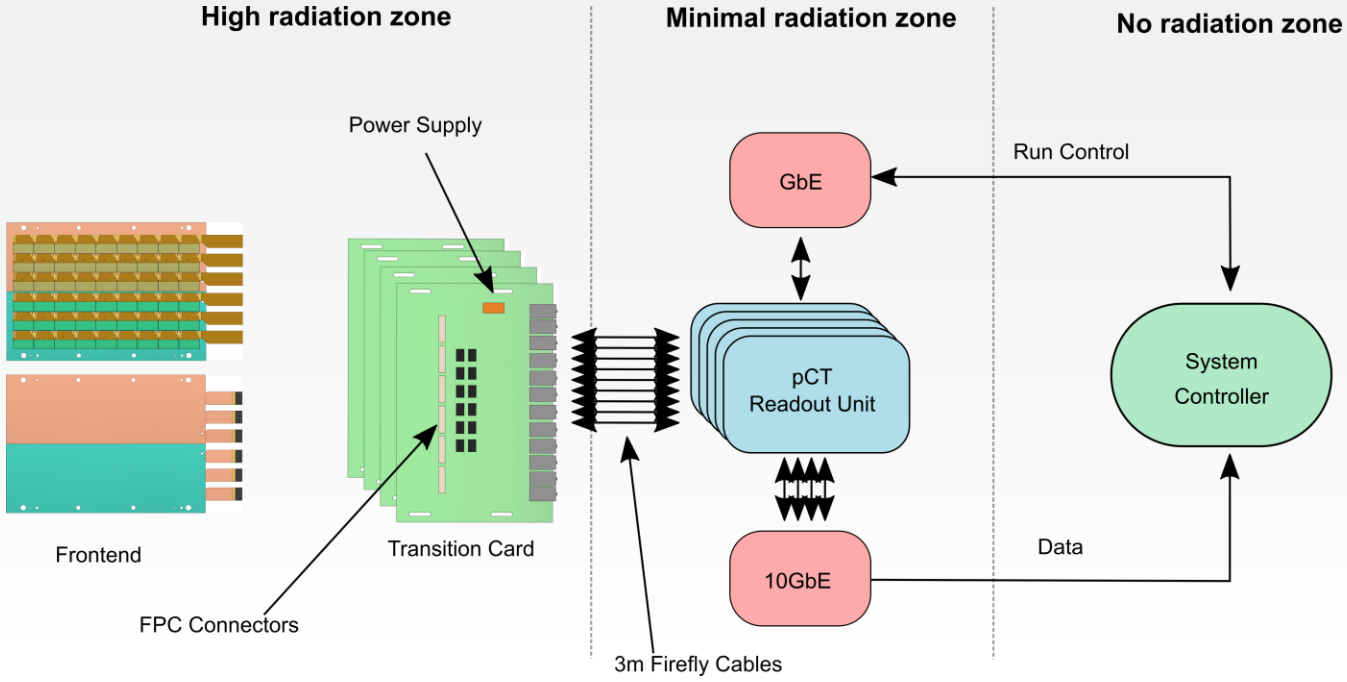


Figure 14: The pCT system electronics architecture. [6]

Energy deposition in ALPIDE

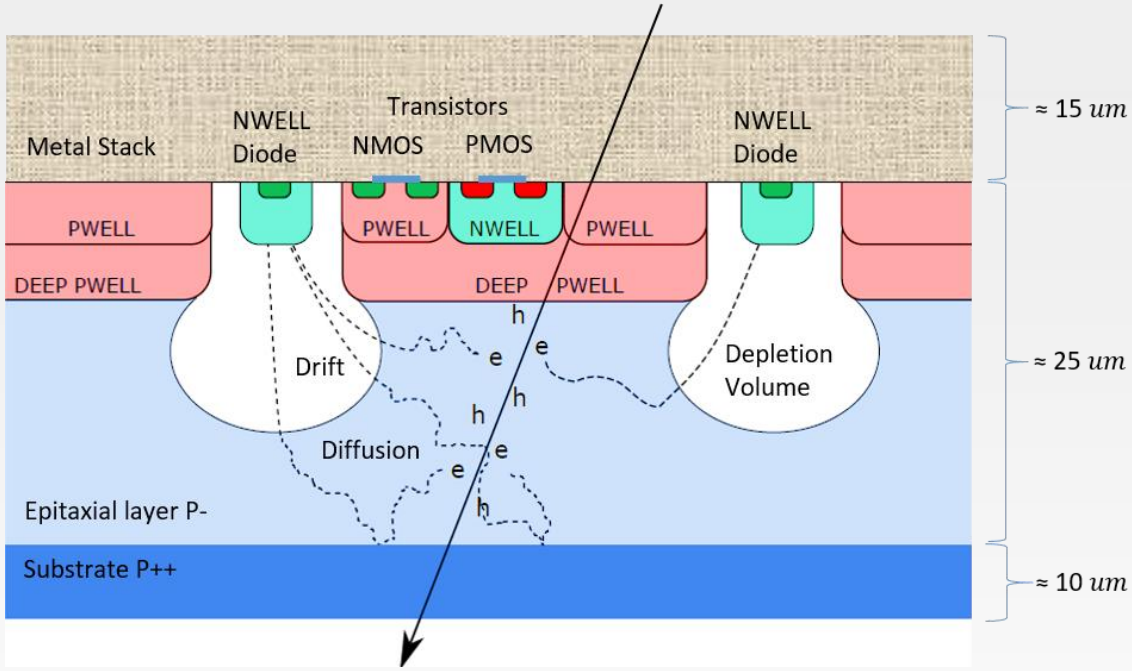


Figure 15: ALPIDE front-end [7]

- Incoming particle deposits energy in the epitaxial layer
- The signal may spread to multiple collection diodes
- Possibilty of back-biasing the collection diodes up to –6V
  - -3V to be applied in tracking layers

Energy measurements

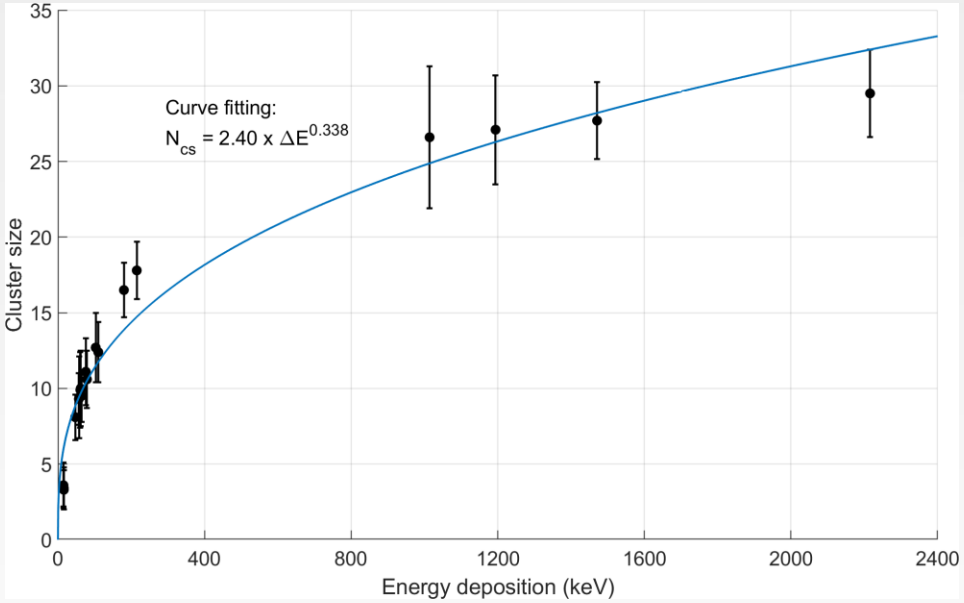


Figure 16: Measured Cluster Size vs energy deposition. [6]

- Correlation between cluster size and deposited energy
- Penetration depth in DTC will provide information about the initial energy of the particle

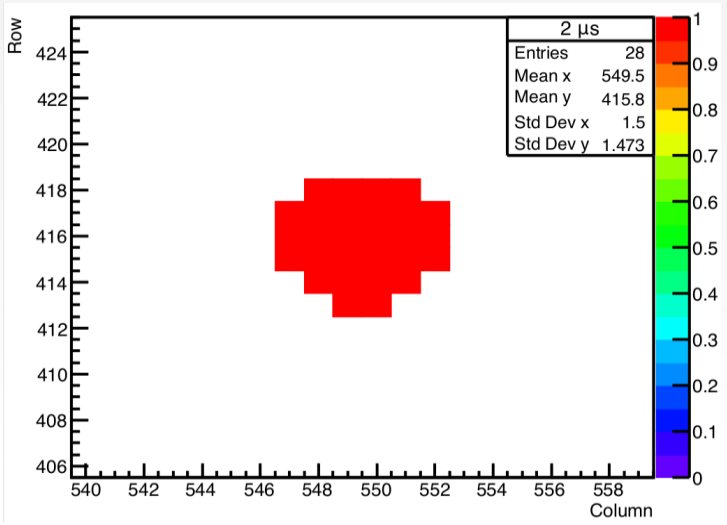


Figure 17: Single Cluster from an alpha source. [6]

Occupancy Studies

- Pencil beam to be used for pCT
  - ~3 mm beamspot
  - ~10^6 protons per beam spot
- ALPIDE
  - 3 in-pixel memories
  - 50 ns to read and clear pixel
  - Integration time ~4µs
- Busy Flag
  - Indicates that last available memory is used for writing current frame
- Busy Violation
  - No available memory for current frame
- Limiting factor is number of hits in region as hits are read out sequentially

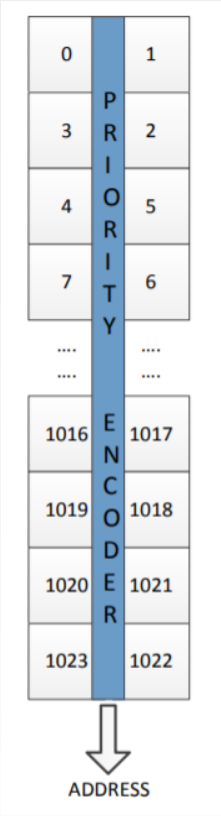


Figure 19: Priority Encoder [7]

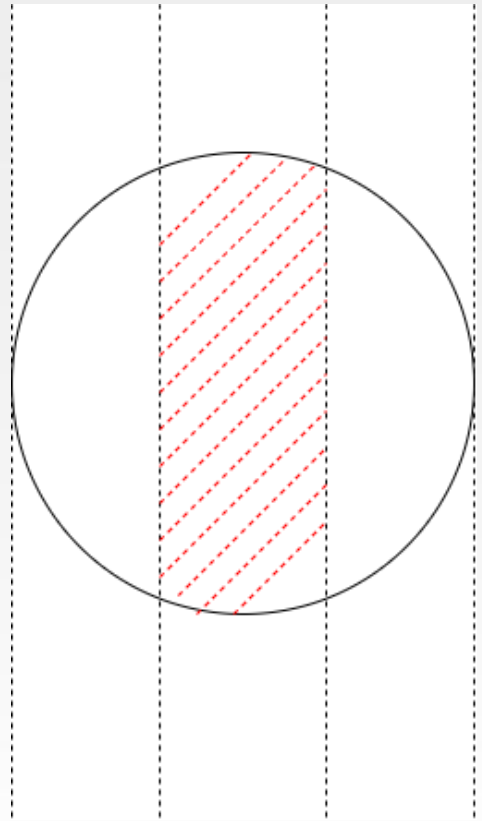


Figure 20: Pencil beam over ALPIDE region. Only illustrativte purpose.

Occupancy studies

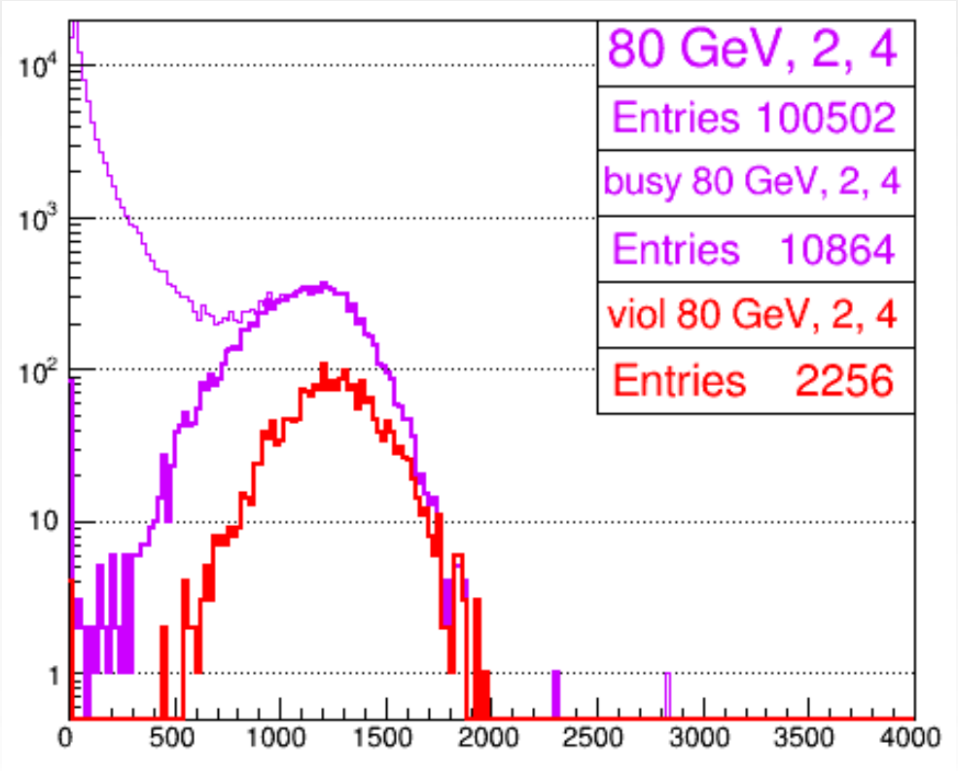


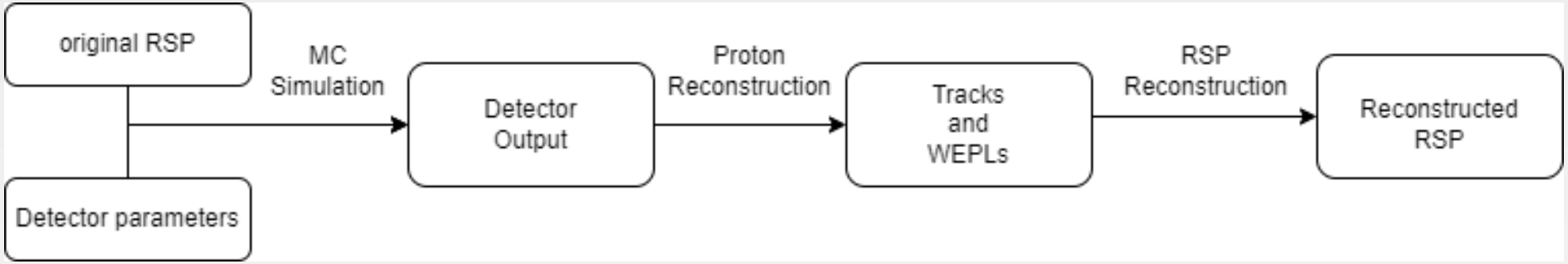
Figure 21: Busy Violations as a function of hits in ALPIDE

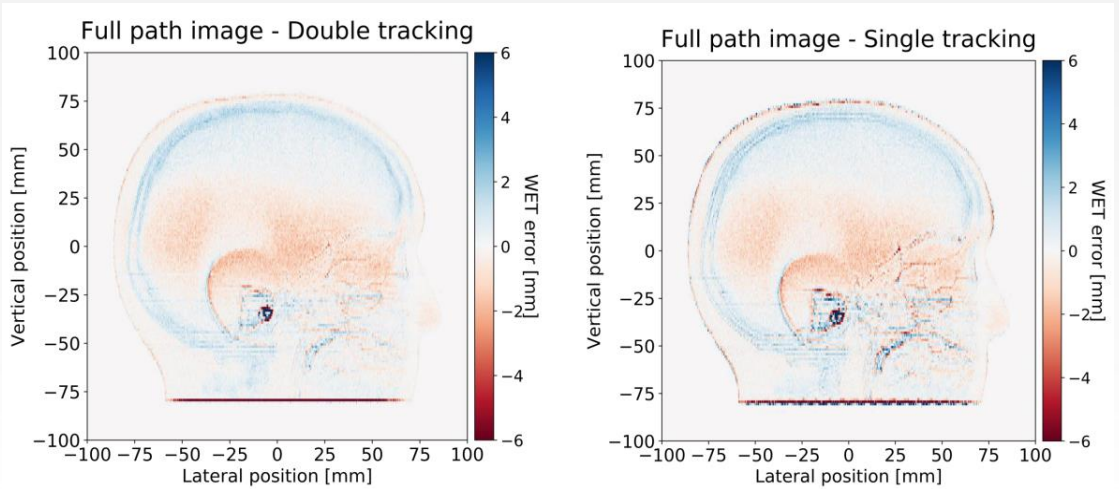
- ALPIDE placed in 80 GeV beam (mixed)
- ALPIDE placed behind 5 and10 layers of tungsten
  - Thickness 3.5 mm
- Continuous trigger rate of 100 kHz, (same trigger system as in final DTC)
- ALPIDE should be able to handle a rate of ~5*10⁶ [protons/s] in pencil beam with 3 mm beamspot, assuming no scattering in patient/phantom

Image Reconstruction

- The energy of the incoming proton is estimated by a fit of the Bragg-Kleeman equation, and converted to water-equivalent path length (WEPL)
- Track reconstruction in DTC
- Most Likely Path (MPL) to estimate proton trajectory
- To reconstruct the relative stopping power (RSP) in the phantom/patient from the tracks and WEPLs, solve a linear system A*RSP=WEPL. The matrix A depends on the tracks and geometry.

Reconstruction based on simulation





- Figure 22:WET errors for different tracking setups [8]

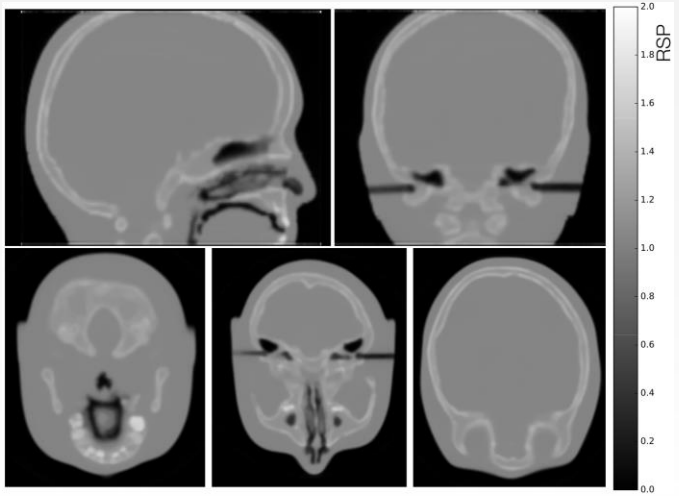


Figure 23: pCT reconstruction of the simulated head phantom in the modeled setup. [6]

Outlook and other uses

- Mechanical design is complete
- Mass production of sensor layers
- Expected to be installed in medical facilities in 2024
- Online applications during treatment

Thank you for your attention

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References

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- [2] B Schaffner and E Pedroni 1998 *Phys. Med. Biol.* 43 1579
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