Journal of Instrumentation

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To cite this article: M. Aehle *et al* 2023 *JINST* **18** C02051

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This content was downloaded from IP address 143.93.247.119 on 20/03/2023 at 13:13

Published by IOP Publishing for Sissa Medialab

Received: *November 28, 2021*
Accepted: *July 13, 2022*
Published: *February 23, 2023*

12th International Conference on Position Sensitive Detectors
12–17 September, 2021
Birmingham, U.K.

The Bergen proton CT system

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https://doi.org/10.1088/1748-0221/18/02/C02051

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Abstract: The Bergen proton Computed Tomography (pCT) is a prototype detector under construction. It aims to have the capability to track and measure ions' energy deposition to minimize uncertainty in proton treatment planning. It is a high granularity digital tracking calorimeter, where the first two layers will act as tracking layers to obtain positional information of the incoming particle. The remainder of the detector will act as a calorimeter. Beam tests have been performed with multiple beams. These tests have shown that the ALPIDE chip sensor can measure the deposited energy, making it possible for the sensors to distinguish between the tracks in the Digital Tracking Calorimeter (DTC).

Keywords: Image reconstruction in medical imaging; Computerized Tomography (CT) and Computed Radiography (CR); Instrumentation for hadron therapy

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Contents

1 Introduction

Hadron therapy has become a widely accepted treatment form for malignant tumours in the last 30 years. It is a method that takes advantage of the concentrated dose delivery to a confined area for charged particles. Proton Computed Tomography (pCT) is an imaging technique used in diagnostics to directly reconstruct a charged particle's relative stopping power (RSP) as it traverses the object of interest. This allows for a reduction in uncertainty, which in turn reduces the dose delivered to healthy tissue during the treatment phase. The Bergen pCT collaboration is constructing a Digital Tracking Calorimeter (DTC) to accurately track and determine individually charged particles' range and inherent energy. As a particle traverses the detector, it will deposit energy in the sensitive layers and thus produce a 3D digital hit map along its path. Most pCT scanners utilize both a front-tracker and a rear-tracker in the imaging process. The Bergen pCT, however, is designed as a multilayered sandwich structure without a front tracker. Positional information about the incoming particles will be obtained from beam optics. Thus the Bergen pCT can be classified as a single-sided tracker system [1].

2 Design

The pCT is composed of 43 layers in total, where each detector layer is electrically identical with 108 ALPIDE chip sensors per layer. The first two layers will act as tracking layers to obtain positional information about the incoming particle. The 41 subsequent layers will act as a digital calorimeter composed of CMOS pixel sensors. Each Digital Tracking Calorimeter (DTC) layer is constructed similarly, albeit with minor differences between the tracking and calorimeter layers. The ALPIDE chip sensor is a monolithic active pixel sensor. It is manufactured utilizing the 180 nm CMOS Imaging Sensor process by TowerJazz Semiconductor. The ALPIDE chip (30×15 mm^2) contains a matrix of 1024×512 pixels. Each pixel can amplify, discriminate, and shape the incoming signal, and they measure $\approx 27 \times 29$ μm^2 in size. The high granularity provided by the ALPIDE chip allows for simultaneous tracking of multiple particles [2].

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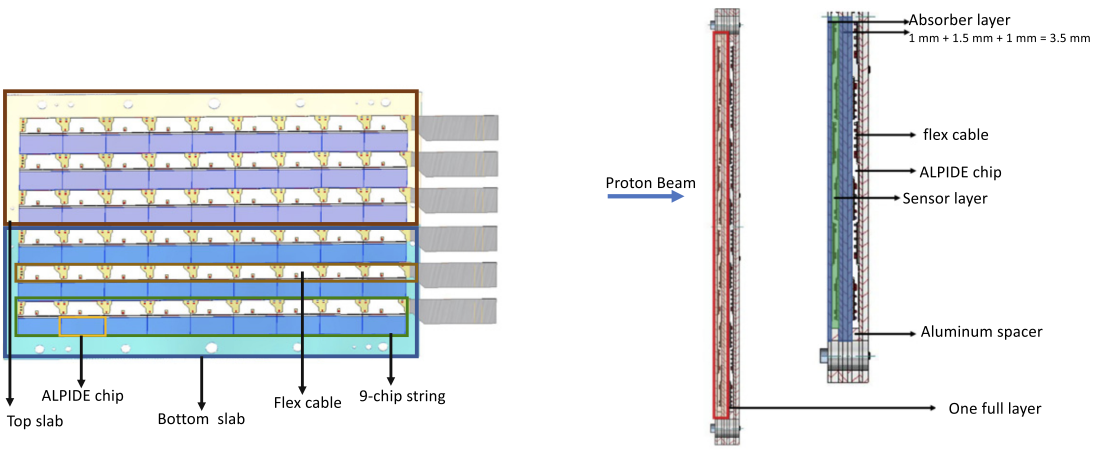
Nine ALPIDE sensor chips are single-point tape-automated bonded to a flex cable known as a *string*. Three strings together on a 1 mm thick aluminium plate constitute a slab. A slab can either be top or bottom. A top and a bottom slab together create a half layer, shown in figure 1(a). A half layer is not capable of covering the entire area because of the non-sensitive part of the flex cables. A complete layer is constructed by utilizing two half layers facing each other with alternating chip positioning to cover the entire area. The two half layers facing each other are illustrated in figure 1(b). The layout of the calorimeter layers of the pCT is as described above. They will be mounted with 100 µm thick ALPIDE chips, and 3.5 mm aluminium plates will be used as absorber material between the layers. For the tracking layers, it is desirable to minimize the non-sensor material. To achieve this, 50 µm thick ALPIDE chips will be mounted on ≈300 µm thick carbon-epoxy sandwich sheets, covering an area of $200 \times 290\,\text{mm}^2$. Each sheet is composed of three layers of carbon paper and two layers of carbon fleece. The final prototype will have a size of $27 \times 16.6\,\text{cm}^2$, large enough to image a human head.



(a) (b)

Figure 1. (a) Half layer consisting of a top slab and a bottom slab [1]. (b) Schematic side view of two layers in the calorimeter (left), and half layer with details (right) [1]. Reproduced from [1]. CC BY 4.0.

The ALPIDEs mounted on a string share the same clock and slow control signals. Each ALPIDE sensor has its individual 1.2 Gbit/s LVDS data line. Each layer is connected to a custom-made transition card (TC), an intermediate between the ALPIDE chip sensors and the readout electronics. Each layer has a dedicated pCT readout Unit (pRU) based on a Xilinx Kintex Ultrascale FPGA, and the communication between the pRU and the TC is via twelve Samtec FireFly connectors [1].

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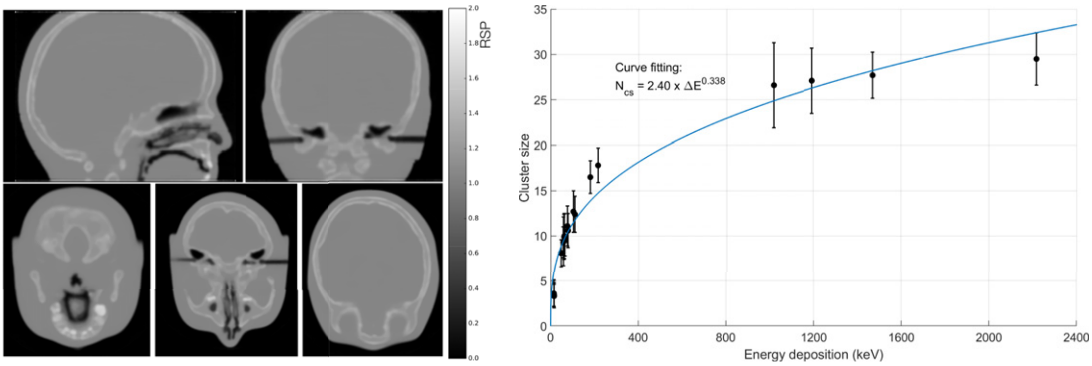
3 Simulation

Different views of a head phantom reconstructed with the modelled setup can be observed in figure 2(a). The image shows that the different salient structures in the head are well distinguishable. A detailed description of the simulation for the Bergen pCT scanner can be found in [1].



(a) (b)

Figure 2. (a) From top left to bottom left clockwise: Sagittal, coronal, and three axial views of a full pCT reconstruction of the simulated head phantom in the modeled setup [1]. (b) Cluster size (the number of adjacent pixel hits) as a function of the energy deposition in the epitaxial layer of the ALICE pixel detector (ALPIDE) chip. The energy deposition was evaluated through MC simulation, the cluster sizes are obtained from multiple beam experiments [1]. Reproduced from [1]. CC BY 4.0.

4 Experimental results

The ALPIDE chip sensor has been tested in multiple beam environments allowing for the characterization of the ALPIDE chip to understand the behaviour of the final pCT system. In figure 2(b) the cluster size (the number of adjacent pixel hits) measured by the ALPIDE as a function of the deposited energy in the epitaxial layer of the ALPIDE is presented. It can be observed that there is a clear correlation between the deposited energy and the cluster size which will be used to give a more accurate description of the range of an incoming particle in the DTC. The capability of the ALPIDE to distinguish between the deposited energies of the incoming particles also allows for the identification of different particle species. This will allow the DTC to function as a continuous tracking device capable of identifying interactions, such as hadronic processes or Coulomb scattering, as these will produce different cluster distributions in the DTC. In turn, this identification of particles will provide a filter allowing for the possibility to distinguish between a primary and a secondary particle, which will be helpful for the reconstruction [1].

5 Conclusion

The Bergen pCT scanner has shown a capability of acting as a high granularity DTC, functioning both as a tracking device and an energy/range detector. Designing the system as a single-sided

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tracker system allows it to be operated with a higher particle rate during the imaging process. The design reduces both the complexity and the cost of the system compared to a two-sided detector system. The prototype is built with scalability in mind, allowing for the possibility of future system upgrades. The final prototype is expected to be installed in medical facilities by 2024 [1].

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