Demonstrator for a Proton CT System at MedAustron

F. Ulrich-Pur\textsuperscript{b}, T. Bergauer\textsuperscript{b}, A. Burker\textsuperscript{a}, A. Hirt\textsuperscript{a}, C. Irmler\textsuperscript{b}\textsuperscript{*}, S. Kaser\textsuperscript{b}, P. Paulitsch\textsuperscript{b}, F. Pitters\textsuperscript{b}, V. Teufelhart\textsuperscript{a,b}

\textsuperscript{a}Atominstitut, TU Wien, 1020 Vienna, Austria
\textsuperscript{b}Institute of High Energy Physics, Austrian Academy of Sciences, 1050 Vienna, Austria

Abstract

Ion beam therapy has become a frequently applied form of cancer therapy over the last years. The advantage of ion beam therapy over conventional radiotherapy using photons is the strongly localized dose deposition, leading to a reduction of dose applied to surrounding healthy tissue. Currently, treatment planning for proton therapy is based on X-ray computed tomography, which entails certain sources of inaccuracy in calculation of the stopping power (SP). A more precise method to acquire the SP is to directly use high energy protons (or other ions such as carbon) and perform proton computed tomography (pCT). With this method, the ions are tracked prior to entering and after leaving the patient and finally their residual energy is measured at the very end. Therefore, a pCT demonstrator, comprising a tracking telescope made from double-sided silicon strip detectors and a range telescope as a residual energy detector, was set up. First measurements with this pCT demonstrator were performed at beam tests at MedAustron, a center for ion therapy and research in Wiener Neustadt, Austria. The facility provides three rooms for cancer treatment with proton beams as well as one which is dedicated to non-clinical research.

This contribution describes the principle of ion imaging with proton beams in general as well as the design of the pCT demonstrator. Moreover, first results from recent beam tests and ideas for future developments will be presented.

Keywords: Proton CT, Ion Therapy, Double Sided Silicon Detectors, Multiple Coulomb Scattering Radiography

1. Introduction

Ion therapy is playing an increasingly important role in cancer treatment. The benefit of ion beams is, that ions have certain penetration lengths, depending on ion type, energy and target material, with a distinct maximum (Bragg peak) of their energy deposition at the last few millimeters of their range (Figure 1). Compared to radiotherapy with photons, this feature of ion beams allows for strongly localized energy deposition at the target depth, while the radiation dose to the surrounding tissues is reduced.

![Figure 1: Monte Carlo simulation of the energy deposition of photons, protons, carbon and helium ions as a function of the penetration depth.](image)

Prior to the therapy, a treatment plan has to be established. Currently, plans are based on X-ray computed tomography (CT), characterizing the tissue in terms of Hounsfield units (HU). For ion beam therapy an extrapolation from HU to stopping power (SP) \cite{1} is required. This conversion is a major source of uncertainty leading to inaccurate determination of SP and range \cite{2,3}. A more suitable approach is to use a high energy proton beam, which traverses the patient, to directly determine the SP distribution by performing a proton computed tomography (pCT) \cite{4}. In such a system, protons of known energy are tracked in front of and behind the patient and finally their residual energy is measured. From these data a three dimensional SP distribution can be computed.

Aiming to construct a demonstrator of a pCT setup, beam tests were performed at MedAustron, a cancer treatment facility located in Wiener Neustadt, Austria. MedAustron provides proton beams from 62.4 MeV to 252.7 MeV as well as carbon ion beams from 120 MeV/u to 402.8 MeV/u for radiation therapy. The facility features three rooms for treatment and one dedicated to non-clinical research room, where a proton beam with up to 800 MeV can be provided.

2. Proton CT Setup

A pCT setup as depicted in Figure 2 consists of two particle tracker elements in front of and behind the patient to determine the tracks of the passing protons as well as a residual energy detector. The SP is determined from the energy deposition of the particle along its path through the patient, given by the difference between initial and residual energies. The two trackers provide position and direction of the proton when it enters and
leaves the patient and thus allow to reconstruct the most likely path of the proton through the patient. Performing such a radiography for several incident angles and combining the data of tracker and residual energy detector is then used to determine a 3D distribution of the relative stopping power. A pCT demonstrator with three front and three rear tracker planes and a range telescope was built and subsequently tested in several beam tests with protons of various energies at MedAustron.

2.1. Tracker

Six modules equipped with double-sided silicon strip detectors (DSSDs) were used for the tracker. The sensors are made from n-substrate silicon of a thickness of 300 µm and an active area of 25 × 50 mm². They feature 512 AC coupled strips on each side, which are arranged orthogonally at a pitch of 50 µm on the p-side (y coordinate) and 100 µm on the n-side (x coordinate), respectively. The usage of DSSDs as tracker in a pCT system is motivated in their resolution and radiation hardness as well as the availability of large-area sensors.

2.2. Range telescope

A proton range telescope, formerly developed by the TERA foundation [9] was used as a residual energy detector. It consists of 42 plastic scintillator slices with an active area of 300 × 300 mm² and thickness of 3 mm. The plastic scintillators are coupled to 1 mm² silicon photomultipliers (SiPM). The digitized signals of the SiPMs are then processed by a custom DAQ board and read out via a LabView based software [9]. This range telescope allows to measure protons with energies up to ≈ 140 MeV at a data acquisition rate of ≤ 1 MHz.

2.3. pCT demonstrator

In order to synchronize the data obtained by the tracker and the range telescope, the AIDA2020 trigger and logic unit (TLU) [10], implemented in the EUDAQ2 framework [11], was used. The coincident signal of two 50 × 50 × 10 mm³ plastic scintillators, located between the rear tracker and the range telescope and connected to the TLU was used as a trigger.

A schematic overview of the full pCT demonstrator is depicted in Figure 2. The object to be imaged (phantom) is placed upon a rotating table between the front and rear trackers and irradiated from various angles. The phantom itself (Figure 5) is a 1 cm³ aluminum cube with 2 mm steps and cutouts with 0.5 mm and 1 mm width. An image of the pCT demonstrator setup is shown in Figure 6.

3. Reconstruction Methods

3.1. Proton computed tomography

In a pCT, 3D information on the spatial structure and stopping power within a phantom can be obtained by irradiation digitized and zero suppressed. Finally, the data are read out by the EPICS based run and slow control software [8], which in addition controls the CAEN power supply. The data transfer from the FADC boards to the data acquisition PC is currently implemented via a VME bus interface, which allows a data acquisition (DAQ) rate of up to 500 Hz.

Figure 2: Sketch of a pCT setup

Figure 3: View of n-side and p-side of a tracker module showing the DSSD and the front-end electronics with the APV25 chips.

Figure 4: Readout chain of the DSSD tracker.

Figure 5: View of the pCT demonstrator setup.
from several angles. For this purpose, 2D forward projections are recorded by assigning the energy loss of each proton, which is obtained from residual energy measurements, to a certain position (pixel) on a plane perpendicular to the beam direction by using the tracker measurements. A Geant4 Monte Carlo model was used to simulate this process by generating 180 projections of the aluminum cube shown in Figure 5 using $5 \times 10^5$ protons per projection in steps of 1°. Ideal spatial and energy resolutions of the detectors prior to and after the object were assumed and the initial beam energy was set to 100.4 MeV. Resulting projections simulated at 0° and 90° can be seen in Figure 7.

The MATLAB/CUDA based framework TIGRE (Tomographic Iterative GPU-based REconstruction toolbox) was chosen to reconstruct the 3D image. This framework already offers a set of reconstruction algorithms for CT from four main algorithms families: filtered back projection, simultaneous algebraic reconstruction technique (SART), type, the Krylov subspace method and the total variation regularization. In order to use this code without modification, straight-line proton paths inside the phantom have been assumed in the reconstruction. This first-order approximation ignores the multiple Coulomb scattering (MCS) of the protons inside the phantom. The most accurate path estimates for pCT have been shown to be cubic spline and most likely path.

The Bragg-Kleeman rule

$$-\frac{dE}{dx} = -\frac{E^{1-p}}{p\alpha},$$

was used to approximate the stopping power within the phantom since it contains the energy-independent material parameter \(\alpha\) which can be extracted from the reconstructed image. \(E\) is the proton energy and \(p\) is set to 1.7 for protons at the considered energy in aluminum. In order to obtain \(\alpha\), the value for \(p\) is inserted in Equation (2) which then transforms to

$$1.7 \cdot E^{0.7} dE = \frac{1}{\alpha(x,y,z)} dz,$$

where \(dz\) is an infinitesimal path element along the assumed proton path in \(z\)-direction. Equation (2) is integrated over proton energy and path,

$$1.7 \cdot \int_{E_{\text{in}}}^{E_{\text{res}}} E^{0.7} dE = \int_{z_{\text{in}}}^{z_{\text{res}}} \frac{1}{\alpha(x,y,z)} dz,$$

where \(E_{\text{in}}\) is the initial proton beam energy, \(E_{\text{res}}\) is the residual proton energy and \(z_{\text{in}}\) and \(z_{\text{res}}\) are the proton entry and exit position to the phantom. Solving the left side of Equation (3) and approximating the path integral by a sum, the forward projection can finally be defined as the left side of

$$E_{\text{in}}^{1.7} - E_{\text{res}}^{1.7} \approx \sum \frac{1}{\alpha(x,y,z)} \Delta z,$$

to obtain the reciprocal of the unknown parameter \(\alpha\). This step is analogous to the projection definition in X-ray CT, where the unknown function is the absorption coefficient of a material.

### 3.2. Multiple scattering radiography

In order to have an image reconstruction for material estimation without depending on residual energy measurement, a second reconstruction workflow was applied. Clusters from hits...
on the tracking planes were used to create track based multiple scattering radiographies [17], using beam test data from a proton beam at MedAustron with an initial kinetic energy of 100.4 MeV [13]. Two projections of the phantom were acquired with approximately $3.5 \times 10^5$ tracks per projection, with a large enough spot size to completely cover the phantom.

The clusters were grouped by the front and rear trackers to create two linear track segments which meet at a point of closest approach. A plane normal to the beam direction was partitioned into $500 \times 500 \mu m^2$ pixels in the $x$- and $y$-direction and located at the $z$-position of the phantom. Each track was associated with a pixel in this plane. Thus, each of the pixels was linked to a distribution of kink angles. For each individual particle the kink angle is defined as the change in angle between the front and rear track segments, projected onto the $x$- and $y$-directions. Both of these projected angles were then combined to obtain

$$\theta = \sqrt{(\theta_{\text{rear}} - \theta_{\text{front}})^2 + (\theta_{\text{rear}} - \theta_{\text{front}})^2}. \quad (5)$$

For each pixel, the median of this distribution of combined angles was used as gray scale value in the forward projection image.

4. Results

4.1. Calibration of the range telescope

After calibrating the gain of the SiPMs with 800 MeV protons at MedAustron, the range for different proton energies was measured, using $5 \times 10^5$ events per energy (Figure 8). Due to instabilities and hardware failures of the SiPM voltage supply, a proton beam at MedAustron with an initial kinetic energy of 3 MeV was used to investigate the accuracy of the scattering estimates. These regions with a known material thickness were selected to investigate the accuracy of the scattering estimates. These regions are indicated in Figure 11 as white rectangles, annotated with the corresponding thickness of aluminum in the $z$-direction. A thickness of 0 mm corresponds to no phantom and defines the

$$R = aE^p. \quad (6)$$

For this measurement, a systematic difference of $\approx 1$ cm in range as well as an efficiency loss of $\approx 95\%$ was observed. The reason for this is still unknown and has to be investigated further.

Because of this low efficiency and the instabilities of the SiPM voltage supply, a full pCT reconstruction was only applied on simulated data of this pCT setup.

\begin{figure}[h]
\centering
\includegraphics[width=\columnwidth]{figure8.png}
\caption{Range measurement for different energies. A high efficiency loss due to a missing signal at the Bragg peak position is shown.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\columnwidth]{figure9.png}
\caption{Geant4 simulation of the range calibration curve of the TERA range telescope compared to the measured range for different energies, using a 1.5 MeV threshold.}
\end{figure}

4.2. Proton computed tomography

The full pCT image reconstruction chain is still work in progress. However, with the presented frameworks and assumptions made in Section 3, preliminary results can be obtained using simulated data. The iterative algorithm OS-SART [19] (member of the iterative SART-type algorithm family) of the TIGRE toolkit performed best regarding reconstruction time (less than 10 s for 5 iterations on a Nvidia GeForce GTX 1080 Ti) and stopping power accuracy. A volume of $15 \times 15 \times 15$ voxels with a voxel size of $0.2 \times 0.2 \times 0.2 \ mm^3$ has been used to determine the SP in a region of interest (ROI) within the reconstructed phantom. Compared to a SP literature value of aluminum [20] of 15.28 MeV cm$^{-1}$ at 100.4 MeV, the observed value of 15.13 MeV cm$^{-1}$ results in a relative error of approximately 1\%.

4.3. Multiple scattering radiography

Using the track-based multiple scattering method [17], images of the position resolved widening of a proton beam due to multiple Coulomb scattering were obtained. Figure 11 illustrates this for two different rotations of the stair profile phantom. Six regions with a known material thickness were selected to investigate the accuracy of the scattering estimates. These regions are indicated in Figure 11 as white rectangles, annotated with the corresponding thickness of aluminum in the $z$-direction. A thickness of 0 mm corresponds to no phantom and defines the
background due to scattering in the silicon sensors. Kink angles within these regions were compared to the expectation given by the Highland approximation according to [21]

\[ \theta_0 = \frac{13.6 \text{MeV}}{\beta c} z \sqrt{\frac{x}{X_0}} \left[ 1 + 0.038 \ln \left( \frac{x}{X_0} \right) \right], \quad (7) \]

where \( \beta c \), \( p \) and \( z \) are the proton’s velocity, momentum and charge number, respectively, \( x \) is the thickness of the phantom and \( X_0 = 88.97 \text{mm} \) the radiation length of aluminum [22].

Proton energy loss in aluminum was numerically evaluated. For the background, the Highland model was evaluated with different depths the mean background, while the standard deviations were added together.

Table 1: Expected and observed scatter distribution widths and relative error, sorted by the material thickness. Mean measurement angles were reduced by the mean background, while the standard deviations were added together.

| Thickness   | Expectation [mm] | Observation [mrad] | Relative error [%] |
|-------------|------------------|--------------------|--------------------|
| background  | 8.48             | 8.54 ± 0.57        | 0.69               |
| 2           | 9.27             | 9.42 ± 2.26        | 1.58               |
| 4           | 13.73            | 14.05 ± 2.60       | 2.36               |
| 5           | 15.62            | 16.26 ± 2.92       | 4.07               |
| 6           | 17.40            | 17.54 ± 2.07       | 0.82               |
| 10          | 23.81            | 25.21 ± 2.92       | 5.86               |

\[ \epsilon = \frac{|\theta_{\text{observed}} - \theta_{\text{expected}}|}{\theta_{\text{expected}}}, \quad (9) \]

They were found to be less than 6 % and increased for larger material thicknesses.

5. Summary and Outlook

A demonstrator for proton computed tomography is being built, using six tracker planes made of double-sided silicon strip detectors and 42 plastic scintillators to be used as a range telescope. Efforts are being made to synchronize these otherwise independent systems, using a trigger logic unit, in order to correlate proton path and energy loss data. Since the tracker modules are read out via VME bus interface, the DAQ rate is currently limited to 500 Hz. In order to achieve higher DAQ rates
a data transfer based on user datagram protocol (UDP) via Gigabit Ethernet interface is currently being implemented. The constructed demonstrator has been used at beam tests in July and November 2019. Due to hardware instabilities and high efficiency loss of the range telescope, only the tracking data are currently available in a useful quality. Hardware upgrades for stabilizing and monitoring of the SiPM voltages of the range telescope, as well as other calorimeter technologies are currently under investigation.

The obtained tracking data were used to create track-based multiple scattering radiographies of an aluminum stair phantom with cutouts. Measured beam widening due to multiple Coulomb scattering was compared to estimates with the Highland formula and a simple energy loss computation. Kink angles were overestimated for a few percent, with an increasing discrepancy for larger phantom thicknesses. These errors were likely caused by the simplistic treatment of energy loss as a geometric mean instead of an integral.

A replica of the physical setup was modelled in the Geant4 [12] simulation framework to generate auxiliary data. These are being used to explore available toolkits for data analysis, with respect to image reconstruction, and to prepare a common reconstruction workflow for relative stopping power and scattering power imaging with nonlinear path models taken into account.

Acknowledgements

The authors would like to thank A. Bauer, W. Brandner, S. Schultschik, B. Seiler, R. Stark, H. Steininger, R. Thalmeier and H. Yin for their contributions to the construction of the pCT demonstrator. This project received funding from the Austrian Research Promotion Agency (FFG), grant numbers 875854 and 869878.

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