ADVANCEMENTS IN THE SCINTILLATION FIBRE BEAM MONITOR FOR LOW-INTENSITY ION BEAMS AT HIT *

R. Hermann† [1,3,4,5], T. Haberer[1], O. Jäkel[1,2,6], A. Peters[1], B. Leverington[3] and T. Gehrke[2,5,6]
[1]Heidelberg Ion-Beam Therapy Center (HIT), Department of Radiation Oncology, Heidelberg University Hospital, Heidelberg, Germany
[2]German Cancer Research Centre (DKFZ), Department of Medical Physics in Radiation Oncology, Heidelberg, Germany
[3]Institute for Applied Physics, Goethe University Frankfurt, Frankfurt, Germany
[4]Physical Institute, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[5]Heidelberg University Hospital, Department of Radiation Oncology, Heidelberg, Germany
[6]National Center for Radiation Research in Oncology (NCRO), Heidelberg Institute for Radiation Oncology (HIRO), Heidelberg, Germany

Abstract

The scintillating fibre transverse ion-beam profile monitor developed at the Heidelberg Ion-Beam Therapy Center (HIT) for low-intensity ion beams is inexpensive and highly efficient. Further development allows for a standalone ion-beam position, profile and intensity monitoring in two dimensions, horizontal and vertical. Additionally, single ion measurement is possible, but for now limited to beam intensities below 5E4 ions/s. The beam monitor is based on scintillating fibres with enhanced radiation hardness. Silicon photomultipliers (SiPMs) convert the light output into an amplified electric signal, which is processed and recorded by a dedicated front-end readout system (FERS; A5200 by CAEN). The prototype has been tested successfully with proton-, helium-, carbon- and oxygen-ion beams. The ion energy varied from 50 – 430 MeV/u and intensities from single ions to 1E7 ions/s.

INTRODUCTION

The HIT facility offers pencil beams of protons, carbon, and helium ions for cancer treatment and research purposes, and oxygen ion beams for experiments. These beams come with varying energies, beam spot sizes, and intensities. HIT employs a technique called intensity-controlled raster scanning of pencil beams to deliver doses. Two multiwire proportional chambers (MWPC) constantly monitor the beam's position and width in both the horizontal and vertical planes, while three ionization chambers (IC) measure its intensity. The signals from these chambers are used to control the position and intensity of the beam through a feedback system. Since this setup is designed specifically for tumour treatments, it is not sensitive to beam intensities below 1E5 ions/s. The detector described in this article closes this gap.

Low-intensity ion beams are being used for experiments and, of particular interest, for a new imaging technique called helium ion-beam radiography [1], as the presented work is part of this project. The use of low intensities is necessary to limit radiation doses in patients and enable ion tracking required for single-ion imaging. Therefore, the low-intensity ion beam must be delivered in a controlled manner, especially concerning the desired raster scanning.

MATERIALS AND METHODS

HIT Accelerator Ion Beam

The ion species, beam energies and intensities at HIT are set for cancer treatment. A beam application and monitoring system (BAMS) controls the treatment beams in a feedback loop manner. Used are protons, helium, carbon and oxygen ions with energies from 48 – 430 MeV/u and intensities from 1E6 – 3.2E9 ions/s. The beam spot size ranges from 3 – 30 mm FWHM. Below the lowest treatment intensity setting the installed monitoring system is blind, which is where the scintillating fibre monitor becomes essential.

Prototype Setup and Working Principle

The setup here consists of three parts: Scintillating fibres: Kuraray SCSF-3HF, silicon photomultipliers (SiPMs): Hamamatsu S13360-1350PE, and a readout electronic: Caen FERS 5202.

The scintillating fibres are placed side by side with a 1x1 mm² cross-section. If an ion passes through part of its energy (→ Bethe Bloch formula) is absorbed and converted into photons. 5,3% of these photons are trapped via total internal reflection within the double-cladded fibres until they reach the fibre end and hit the SiPMs. The fibres were chosen due to their low cost, larger active area coverage, and no need for additional infrastructure like cooling, gas, or vacuum.

The SiPMs convert the photons into photoelectrons and amplify the electronic signal about 1E5 times. They were chosen for their low cost and magnetic field insensitivity. For the readout a commercial front-end readout electronic board [2] was chosen, eliminating the need for custom electronics or software development. This allows for a focus on specific data evaluation routines and enables scaling the the detector to the desired size with sub-millimetre resolution. More detail about the exact components and a more detailed working principle is found in [3].

---

* Work funded by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG), funding indicator JA 1687/11-1.

† richard.hermann@med.uni-heidelberg.de

Prototype Modification/Advancement

The main advancement to the prototype, first presented in [3], is the update from one dimension to two dimensions and a new scheme of light guidance from the fibre ends to the readout system.

The upgrade to 2D was done by adding a second layer of scintillating fibres orthogonal to the first one. A schematic is shown in Fig. 1, which also shows the final full-size detection area aimed at.

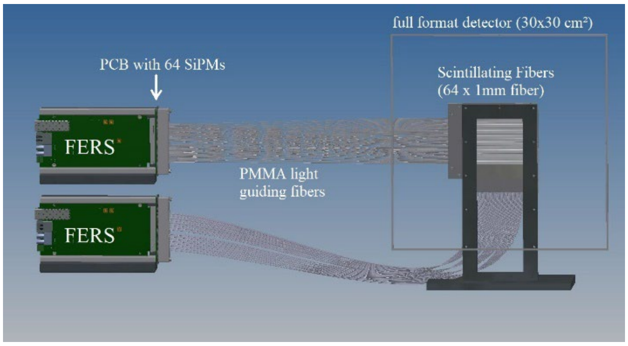

Figure 1: Schematic setup of the 2D prototype with for x and y direction: 64 scintillating fibres, a printed circuit board (PCB) with 64 silicon photomultipliers (SiPMs) on it and a front-end readout system (FERS) attached.

Concerning the light guidance, here the scintillating fibres are not directly connected to the SiPMs but end at the edge of the central detection window. There, via an adapter, inexpensive PMMA light guiding fibres (TRUcomponents) are attached. This was done due to two reasons: First, a setup with light guiding fibres starting at the edge of the detection area would allow for an easy manufacturing and exchange mechanic of the active scintillating fibre mat in the detection area. Second, light-guiding fibres are inactive and do not produce additional photons if for example muons or neutrons stemming from inelastic interactions are creating fake hits outside of the detection area.

An exchange of the fibre mats is unavoidable, as radiation damage will cause lower light output of the scintillating fibres after high-dose application. In comparison to the refurbishing of gas detectors or the replacement of semiconductor detectors scintillating fibres are here financially preferable.

EXPERIMENTAL RESULTS

Interface Scintillation to PMMA Fibre

The change in light-guiding system did decrease the quality of measurements. In the first implementation of the clear fibre coupling, the alignment wasn't as precise as desired. This resulted in a misalignment of the fibres leading to loss of light and crosstalk into neighbouring channels. Figure 2 shows how the same measurement looked before and after the change.

The interface between the scintillating fibres and the light-guiding ones is shown in Fig. 3.

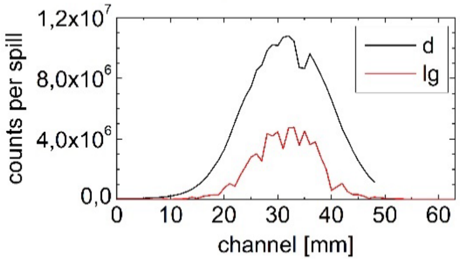

Figure 2: Comparison of the direct (d) to the new light guide (lg) Version with the same proton beam (energy, focus, intensity). A nearly three times lower intensity and non-smooth Gaussian profile are visible.

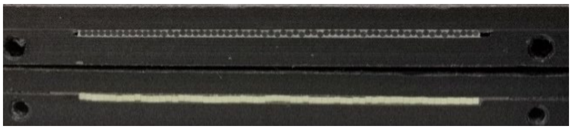

Figure 3: Interface from scintillating fibres (square, yellow, bottom) to light guiding PMMA fibres (round, clear, top).

This intersection affects the measurement in three ways: First, the cross-section of the scintillating fibre is a 1x1mm^2 square and the light-guiding fibres are 1mm diameter round fibres. This leads to a loss of photons as the round cross-section area is only 79% of the square. Second, an even more relevant factor is the additional air gap and therefore losses to reflection due to refractive index changes. And third, as the fibres are all next to each other and installed by hand the alignment is hardly always one-to-one, which leads to strong crosstalk effects. For protons, the produced number of photons is barely above the threshold, so when some photons crosstalk into a different channel hits are below the threshold and are missed, which explains the lower intensity shown in Fig. 2. For heavier ions on the other hand there are even enough photons created to generate fake hits in neighbouring fibres due to crosstalk, leading to double or triple counts and a intensity higher than expected.

Countermeasure: Correction Factor

To counteract the problem of non-gaussian measurements due to crosstalk double counts and missed hits on the other side, a correction factor for each channel is needed. This factor is derived from a line scan measurement, where every fibre is hit by the same number of ions. Therefore, the measurement should be a perfect line. From the deviations to the average value, a correction factor is calculated for each channel individually, visually shown in Fig. 4.

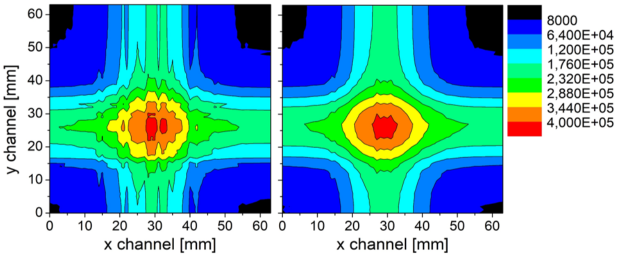

Figure 4: 2D projection of two 1D beam profile measurements. (b) shows the correction applied on (a).

The correction factor varies more strongly for protons compared to the heavier ions as missed hits due to not enough photons to exceed the noise threshold are only a problem for the lighter ions. Therefore, for every ion sort and energy a line-scan has to be done once. To ensure that the correction based on a line-scan is sufficient, it first has been successfully checked to be repeatable and secondly, a comparison with a full area scan has been done, which showed a small average difference of 3.5%. As visually seen in Fig 4. applying the correction factor is a helpful measure to regain the Gaussian beam profile.

As seen in measurements with very low intensity applying the correction factor is also beneficial to correct noise. This means that a line scan standardisation for each ion after any change to the detector (e.g. position) is in general a beneficial measure, even without the interface intersection.

New Measurement Mode

The classic mode is the Counting mode. In this mode, the hits per channel within a certain time window are counted. This results in a time resolution as good as the set time window, where the lowest possible is around 300µs.

In Timing mode, every hit gets its timestamp with a 0.5ns least significant bit resolution [2]. This mode has the highest amount of information and therefore, beam position, width, intensity and spill form can be derived from this measurement, as seen in Fig. 5.

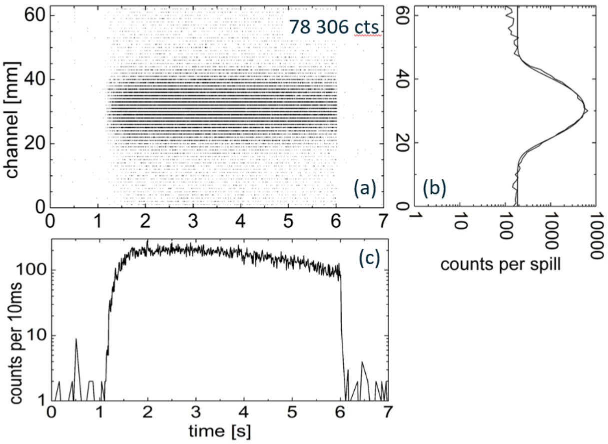

Figure 5: The Timing measurement mode plus its potentially derived plots: (a) time of arrival, (b) beam profile and (c) spill form.

If the time-of-arrival (ToA) data is summed over all channels within a defined time window (here 10ms) a spill form is acquired. If instead every channel is summed over an again defined time window (here the full 5s spill) a beam profile, position and intensity can be obtained.

However, a lot of information means a lot of data. The current data processing and writing speed limits the use of this mode to a very low intensity of below 5E4 ions/s. This limit will be increased with an update in the readout electronics, as described in the Outlook section.

CONCLUSION

In conclusion, the scintillating fibre transverse ion-beam profile monitor developed at the Heidelberg Ion-Beam Therapy Center (HIT) provides a highly efficient and inexpensive solution for monitoring low-intensity ion beams. The prototype has been tested successfully within proton, helium, carbon, and oxygen-ion beams, and has been updated to allow for a standalone ion-beam position, profile, and intensity monitoring in two dimensions, horizontal and vertical. The addition of PMMA light-guiding fibres allows for an easy manufacturing and exchange mechanics of the active scintillating fibre mat in the detection area. This is a significant advancement that can enable ion tracking based on single-ion imaging, making low-intensity ion beams useful for experiments and imaging techniques like helium-beam radiography.

OUTLOOK

To integrate measurement data into the feedback system and enable single ion front tracking for the helium ion radiography detector at HIT, real-time transfer of data must be set up. To suppress noise during single ion tracking, a second 2D monitor may need to be added, ideally with time-of-flight measurement [4]. Additionally, the intersection in the light guiding system will be updated in a way to separate neighbouring fibres and reduce crosstalk. Finally, the setup shall be extended to a full 256 x 256 mm² plane and get integrated into the feedback system. To achieve these goals, new electronics (Caen concentrator board DT5215) and program updates for existing systems are necessary and will be implemented.

REFERENCES

[1] C. Knobloch *et al.*, “Experimental helium-beam radiography with a high-energy beam: Water-equivalent thickness calibration and first image-quality results”, Med. Phys., vol. 49, pp. 5347–5362, 2022. `doi:10.1002/mp.15795`

[2] CAEN S.p.A., FERS-5200 Front-End Readout System. Datasheet DS7218, `https://www.caen.it/products/a5202`

[3] R. L. Hermann, M. Galonska, T. Gehrke, Th. Haberer, B. Leverington, and A. Peters, “Development of a Scintillation Fibre Transverse Profile Monitor for Low-Intensity Ion Beams at HIT”, in *Proc. IBIC'22*, Kraków, Poland, Sep. 2022, pp. 67-70. `doi:10.18429/JACoW-IBIC2022-MOP17`

[4] I. Ortega Ruiz *et al.*, “A Multipurpose Scintillating Fibre Beam Monitor for the Measurement of Secondary Beams at CERN”, in *Proc. IBIC'18*, Shanghai, China, Sep. 2018, pp. 468-471. `doi:10.18429/JACoW-IBIC2018-WEPB15`