ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-MOP17

DEVELOPMENT OF A SCINTILLATION FIBRE TRANSVERSE PROFILE MONITOR FOR LOW-INTENSITY ION BEAMS AT HIT*

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

Abstract

The Heidelberg Ion-Beam Therapy Center (HIT) provides proton, helium, and carbon-ion beams with different energies and intensities for cancer treatment and oxygen-ion beams for experimentation. The accelerator is able to provide ion beam intensities below the range used for therapies by manually degrading the beam. The beam monitoring system instrumentation currently installed is unable to measure the beam profile at these intensities. A secondary system that could cover this low intensity range is therefor of interest. The principle of operation is based on scintillating fibres, particularly those with enhanced radiation hardness. The fibres transform the deposited energy of a traversing ion into photons, which are then converted and amplified via silicon photomultipliers (SiPMs) into electric pulses. These pulses are recorded and processed by a novel and dedicated readout electronics: the front-end readout system (FERS) A5200 by CAEN. A prototype set-up consisting of all the above-mentioned parts was tested in beam and has proven to record the transverse beam profile successfully from intensities of 1E7 ions/s down to 1E2 ions/s.

INTRODUCTION

The HIT facility provides proton, carbon, and helium ion pencil beams for cancer treatment and research, and oxygen ion beams for experiments, all with various energies, beam spot sizes and intensities. HIT uses the method of intensity-controlled raster scanning of pencil beams as a dose delivery system.

The beam position and width (focus) in the horizontal and vertical plane are constantly monitored by two multi-wire proportional chambers (MWPC) and the intensity by three ionization chambers (IC). Their signals are used for position and intensity control via a feedback system. As this built-in setup is specifically designed for tumour treatments it does not need to be, and is not, sensitive to low-intensity ion beams, i.e. below 1E5 ions/s. This detector reported in this contribution closes this gap.

Low intensity beams are of interest for experiments, but also for a new imaging modality with potential of treatment verification: helium-beam radiography [1]. The presented work is part of this project. Only low intensities may be used as radiation dose in the patient has to be limited to the lowest amount possible and ion tracking based on sing ion imaging is desirable. For an optimized performance, the low-intensity ion beam needs to be provided in a controlled way.

Out of three possible detector technologies (gas, semiconductor, and scintillating fibre based) the scintillating fibre was chosen because of its advantages in terms of permanent use and placement within the beamline of an accelerator: the relatively low cost of the fibres while covering a larger active area, no need of attached subsystems like cooling, gas or vacuum and electronics remain in a safe distance from the beam. This idea follows techniques used in high energy physics, coupling scintillating fibres to silicon photomultipliers for single particle tracking [2]. The Super Proton Synchrotron has developed a similar system, although with different readout electronics and beam conditions [3].

A novel specialized commercial front-end readout electronic board came into use: the FERS A5202 by CAEN, which was for instance successfully implemented in a dual readout calorimeter by the team of R. Santoro [4]. Due to the commercial character, there was no need for an own development in electronics or software. Thus, one can concentrate on specific data evaluation routines. Also scaling up the detector to the desired size of 25 x 25 cm² with a sub-millimetre resolution is feasible to implement due to the scalability of the readout system.

MATERIALS AND METHODS

Ion Beam Characteristics

Adopted to the dose delivery system, the HIT accelerator provides ion beams for cancer treatment by a slow extraction scheme, i.e. the ions are extracted over several seconds (“Spill length”, here: 5 s). The energy/intensity range is given in Table 1. The beam spot sizes range from about 3 to 30 mm defined a s full -width half-maximum (FWHM), depending on the ion type and energy. For reaching low

---

* Work funded by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG), project number 426970603.

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

intensities, particle loss is forced by detuning the bending magnet right behind the ion sources.

Table 1: Therapeutically Ion Beam Specifications Provided by the HIT Accelerator

Ion	Energy [MeV/u]	Intensity [ions/s]
Proton	48.12 – 221.06	8.0e+7 – 3.2e+9
Helium	50.57 – 220.51	2.0e+7 – 8.0e+8
Carbon	88.83 – 430.10	2.0e+6 – 8.0e+7
Oxygen	103.77 – 430.32	1.0e+6 – 4.0e+7

Prototype Setup and Working Principle

The detection method of the prototype setup is as follows: The ions from the ion beam pass through the scintillating fibres, where part of their energy is lost through ionisation and re-emitted as photons through fluorescence. A small percentage (< 5.3%) of them is trapped in the fibres via total internal reflection at the core-cladding interfaces and guided to silicon photomultipliers (SiPMs), which create an electronic signal for every detected photon. These signals are processed by a front-end readout system (FERS) and transmitted to a computer via USB or Ethernet.

A 3D printed structure composed of black polyacid (PLA) is used to arrange and mount the fibres in a single plane, and then couple them to the SiPMs. A schema of the complete arrangement is shown in Fig. 1. This whole arrangement is covered with a box blocking external light, which may superimpose the signal, create unwanted noise and could lead to destructive currents. For the latter, the electronics have an overcurrent security turn off.

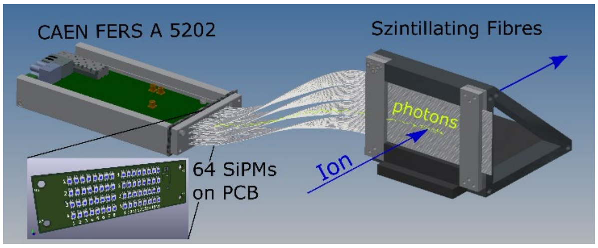

Figure 1: Experimental setup: scintillating fibres in frame, 64x SiPMs soldered on a printed circuit board (PCB), electric signal processing in FERS A5202.

Scintillating Fibres

The scintillation process describes the conversion of energy absorbed (e.g. deposited by ions which pass through the scintillating material, described by the Bethe-Bloch-formula) into photons in or close to the visible range. In the described setup organic plastic fibre scintillators with a 1 mm diameter are used. These fibres absorb and emit the energy via weakly bound orbital electrons, typically in benzene rings. A wavelength shifter (Stokes shift) is added to the scintillator to prevent the re-absorption of photons within the material and for tuning the output wavelength to the desired one.

To figure out if the more radiation hard green emitting fibres have a significantly lower light output or signal-to-noise ratio compared to the more common blue ones the two fibre types have been installed next to each other in this first test setup, as shown in Fig. 2.

Radiation damage is unavoidable when interfering with the ion beam. In scintillating fibres, the damage shows as losses in short wavelengths, i.e. the blue parts of the spectrum. The two fibres tested in the prototype setup were: (a) Kuraray SCSF-78 with the blue colour output (peak at $\lambda = 450$ nm), a fast decay time of 2.8 ns, and a long attenuation length of over 4 m and (b) Kuraray SCSF-3HF (3-hydroxyflavone) with a green output (peak at $\lambda = 530$ nm) and therefore higher radiation hardness, with a similar attenuation length, but a slower decay of 7 ns [5].

One additional advantage of scintillating fibres, in general, is their insensitivity to the magnetic field. This is of interest in the upcoming project of beamline integrated Magnet Resonance Imagers (MRIs).

Figure 2: The two fibre types glued into 3D prints. The scintillating fibre area consists of (a) 32 blue fibres (channel 0 – 31) and (b) 32 green fibres (channel 32 – 63).

The fibres have single or multi-cladding, which describes one or two thin layers around the fibres (thickness of a layer is 2% of the fibre diameter) with lower refractive indices. This increases the fraction of light, which is trapped inside the fibre. The scintillating core is polystyrene with a refractive index of n0 = 1.59. A single layer of Polymethylmethacrylate (PMMA, n0 = 1.49) raises the trapping efficiency to at least 3.1 %, and with a second layer of the fluorinated polymer (FP, n0 = 1.42) it reaches 5.4 % [5].

Silicon Photomultipliers (SiPMs)

The silicon photomultiplier S13360-1350PE by Hamamatsu is a set of 667 single avalanche photodiodes (APDs) which together form an active area of 1.3 x 1.3 mm^2. The APDs are operated in Geiger mode, which means their output is independent of the number of photons [6].

These SiPMs were chosen for their fitting photon detection efficiency (PDE) spectrum shown in Fig. 3. The refractive index of 1.55 in the window material fits the one of the scintillating fibres so that no photons are reflected at the interface.

Even in the case of an airgap, still small enough that all non-reflected photons hit the SiPM, an upper limit estimation of the loss would only be 11.8%. (Calculated with Fresnel equations and based on the worst condition which still transmits light: an incidence angle of 26.7° [5] at the interface from the fibre (n0 = 1.59) to air (n0 = 1) and subsequently from air to the SiPM window (n0 = 1.55).

The signal amplification (gain) of the SiPMs creates 1.7E6 electrons for each detected photon. The pulse of a 1 mm^2 pixel pitch, consisting of 50 µm pixels (APDs), recovers within 50 ns (20 MHz) [6]. If several photons hit within the recharging phase the recovery may not be completed. This may lead to uncounted hits.

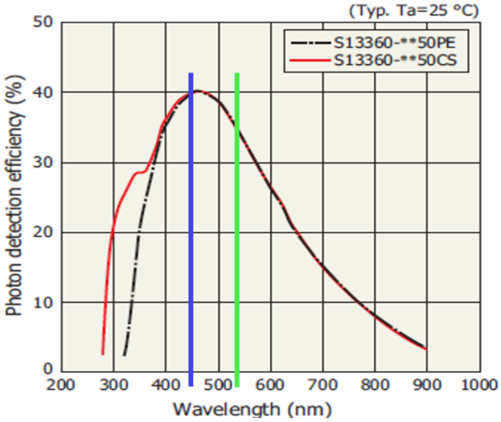

Figure 3: PDE of the Hamamatsu S13360-130PE. The blue (λ = 450 nm) and green (λ = 530 nm) lines indicate the output wavelength of the SCSF-78 and the SCSF-3HF scintillating fibres.

Front End Readout System (FERS)A5202

The FERS A5202 is specifically designed to read out SiPMs in large detector arrays [7]. The standalone boards are capable of reading out 64 channels and can be connected in series (daisy chain) via a concentrator board to up to 8192 channels. Different acquisition modes are available of which the Counting and Timing Mode are the ones of interest here. In Counting mode, a time window is set in which the counts per channel are summed up. The count caps at 20 Mcps, which is exactly the limit for pulse level recovery of the used SiPMs (20 MHz). In Timing mode, the exact timestamp of each firing SiPM is saved. Due to more detailed information, the timing mode is limited by how data is packed and transmitted in the links to a lower number of ions per second (~5E4 ions/s) compared to the Counting mode (~1E7 ions/s). The estimations were evaluated in experiments at HIT and could be improved via adjustments. Detailed information about the data structure, the description of the different measure modes (Counting, Timing, timestamped spectroscopy and pulse height analysis) and the used built-in electronics (e.g. Citiroc, FPGA) are found in the associated manuals CAEN provides [7].

EXPERIMENTAL RESULTS

The purpose of the detector is to measure the position, beam width, and the intensity of the beam at low intensities (<1E5 ions/s). This was successfully tested in the range of 1E2 – 1E7 ions/s.

The low end of the intensity spectrum (1E2 pps) is set due to lacking data for reliable position measurement. Purely by statistical probability, the beam position determined by a fit could vary with these few counts in the order of millimetres, which is worse than the position accuracy of the detector of at least 1 mm. A measurement close to this lower limit in intensity has been successfully achieved with a helium ion beam with the maximal available energy of 220 MeV/u, shown in Fig. 4.

Figure 4 also shows noise. This noise is mainly thermal, which shows up as so-called dark counts. The dark count rate (DCR) while having no beam can be brought below the value of 50 Hz by correct settings. One is the threshold setting of the SiPMs, where a signal is only counted if at least 5 APDs (“pixels”) of a SiPM fire simultaneously. This takes out crosstalk events within the SiPMs. In between the SiPMs a light shielding blocks this crosstalk.

Having beam there is crosstalk, which happens in between the fibres and limits the SNR to a factor of 50 – 100. More details about the crosstalk between the fibres can be found in [3].

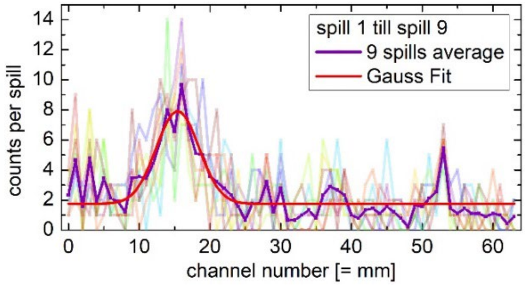

Figure 4: Proof of concept measurement of a low-intensity helium beam with ca. 8 ions/s (recorded by TimePix [1]). An average over several spills is needed as the non-feedbacked low-intensity spills vary in intensity.

The upper end of the possible spectrum is 1E7 ions/s, shown in Fig. 5. It also shows 1D beam profiles of the four different ion types provided at HIT. As the intensity range is different for each ion type a setting at the low end of the therapeutic range was chosen. Noticeable are the non-smooth profiles of helium and proton, where the intensities are above 1E7 pps. At this point, some counts are missed and the gaussian form gets lost. The reason for the missed counts is the SiPM recharge duration of 50ns, as photons incoming within that time will not be detected.

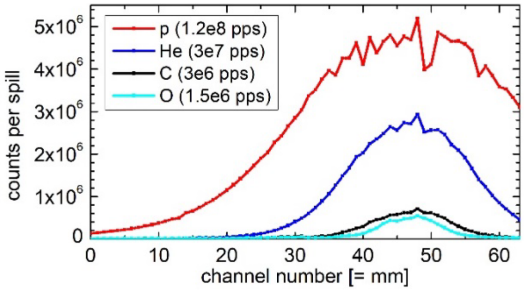

Figure 5: 1D beam profiles of all 4 ion types at HIT with different intensities. The beam energy is irrelevant, as a count is independent of the number of photons created.

In a context like a therapy accelerator, radiation damage to in-beam-line detectors is a major issue. Over time a high amount of dose (ions depositing energy) is delivered, damaging the detector. This means a regular refurbishing or replacement of the scintillating fibres.

There are more radiation hard scintillating fibres, but SiPMs have a higher PDE for the blue spectra, see Fig. 3. Therefore, the 3HF green and the “standard” blue fibres have been set up for comparison. Contradicting the expectation set by the better PDE for the blue spectra, measurements at HIT show that the green 3HF have a higher output and SNR, as Fig. 6 indicates.

Besides beam position and beam width also intensity can be measured with the presented setup. Two 5 s long low-intensity carbon ion spills with 430 MeV/u have been compared, and are shown in Fig. 7. A comparison with the internal in-beamline integrated and calibrated scintillator shows that the spill shapes are matching (intensity variation due to non-feedbacked beam). Also, a comparison of two feedback-controlled spills with different energy levels but the same intensity showed a difference in intensity of only 1%.

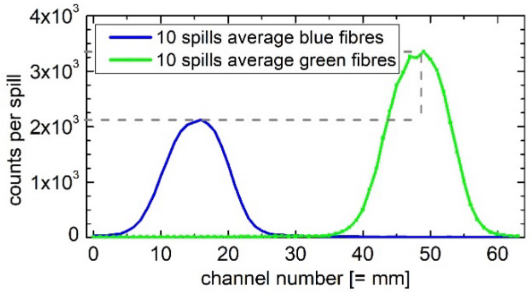

Figure 6: Ion counts averaged over 10 spills: Kuraray SCSF-78 (blue, 450 nm) and Kuraray SCSF-3HF (green, 530 nm).

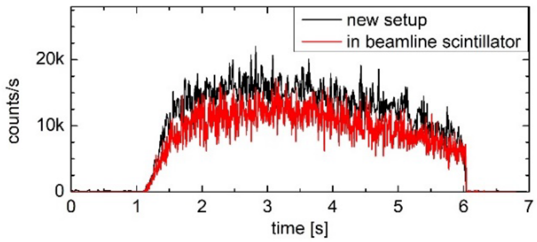

Figure 7: Intensity vs. time measurement of a 5 s spill (time bin 5 ms): presented detector (black), in-beamline integrated and calibrated detector (red).

CONCLUSION

The scintillating fibre profile monitor has been successfully tested with the proton, helium, carbon and oxygen ion beams provided at the HIT facility. The energies varied from 50 – 430 MeV/u with intensities from 1E2 up to 1E7 pps. The lower limit is only due to too low signals for fitting, while the upper limit is due to the speed of the electronics (SiPMs and FERS A5202). Testing two different fibre types showed that the general-purpose fibres with a 450 nm output are inferior in terms of SNR compared to the desired more radiation hard 3HF fibres with a 530 nm output.

In conclusion, the described setup is a reliable and fully functional beam position, width, and intensity monitor for the yet unmonitored low-intensity ion beams at HIT. With that applications based on controlled low-intensity beams, like ion radiography, become feasible.

OUTLOOK

For a controlled low-intensity ion beam at HIT, the measurement data of the presented setup needs to be transferred in real-time to the intensity control system. The integration into the feedback system is one main future development.

A simpler and closer next step will be the second fibre layer orthogonal to the first one to make a simultaneous horizontal and vertical measurement possible, preferably done with square instead of round fibres for a more evenly distributed in-beam material.

Provided that a perfect synchronization to other detectors can be established this monitor could work as a single ion front tracker, which is a highly desired option for the purpose of the underlying DFG project, the ion radiography detector.

As a final step, this setup will either be itself extended to a full 256 x 256 mm² plane or more likely combined with the scintillating fibre planes of [2]. This would allow monitoring of single ions up to the highest intensities (proton, 3.2E9 ions/s) with one set of scintillating fibre mats, greatly decreasing the necessary in-beam material.

ACKNOWLEDGEMENTS

Many thanks to the HIT team to be always helpful and providing such a great experimental environment. Special thanks to Patrick Busch, Stephan Brons, Eike Feldmeier, Christian Schömers and Andreas Gaffron.

To Romualdo Santoro and his team from INFN working on a Dual Readout Calorimeter with the same front-end readout [4]: thanks for the helpful discussions and also for the design of the SiPM-PCB.

REFERENCES

1] T. Gehrke, M. Martišíková, *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] B.D. Leverington *et al.*, “A prototype scintillating fibre beam profile monitor for Ion Therapy beams”, *J. Instrum.,* vol. 13, p. 05030, 2018. `doi:10.1088/1748-0221/13/05/P05030`

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

[4] M. Antonello *et al.*, “Dual-readout calorimetry: Present status and perspective”, *Int. J. Mod. Phys. A,* vol. 36, p. 2142017, 2021. `doi:10.1142/S0217751X21420173`

[5] Kuraray Co., Ltd., “Plastic Scintillating Fibres”, `https://www.kuraray.com/uploads/5a717515df6f5/PR0150_psf01.pdf` (checked last 03.08.2022)

[6] Hamamatsu Photonics K.K., “MPPC Technical note”, `https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/ssd/mppc_kapd9008e.pdf` (checked last 03.08.2022)

[7] CAEN S.p.A., “FERS-5200 Front-End Readout System Datasheet DS7218”, `https://www.caen.it/products/a5202/` (checked last 03.08.2022)