Prepared for submission to JINST

20$^{\text{TH}}$ International Workshops on Radiation Imaging Detectors
June 24-28, 2018
Sundsvall, Sweden

First Use of Timepix3 Hybrid Pixel Detectors in Ultra-High Vacuum for Beam Profile Measurements

---

H. Sandberg,[a,b,1] **W. Bertsche,**[b] **D. Bodart,**[a] **B. Dehning,**[a] **S. Gibson,**[c] **S. Levasseur,**[a,c] **M. Sapinski**[d] **K. Satou,**[e] **G. Schneider,**[a] **J.W. Storey,**[a] **and R. Veness**[a]

[a] *The European Organization for Nuclear Research (CERN), Geneva, Switzerland*
[b] *The University of Manchester, Cockcroft Institute, Manchester, United Kingdom*
[c] *Physics Department, Royal Holloway, University of London, Egham, Surrey, United Kingdom*
[d] *GSI Helmholtzcentre for Heavy Ion Research GmbH, Darmstadt, Germany*
[e] *Accelerator Laboratory, KEK, Oho, Tsukuba, Ibaaraki, Japan*

E-mail: `hampus.sandberg@cern.ch`

Abstract: A transverse beam gas ionization profile monitor is currently under development for the CERN Proton Synchrotron (PS) to provide non-destructive continuous measurements during a beam cycle. The implementation is exploring a new novel use of the Timepix3 hybrid pixel detector mounted inside the ultra-high vacuum of the accelerator beam pipe to provide direct detection of ionization electrons. In early 2017, a prototype monitor was installed and has been used successfully to measure the transverse beam profile. We have measured the evolution of the transverse beam profile throughout the beam cycle and also studied specific time windows within the cycle to measure, for example the transition crossing.

A radiation tolerant readout system for the Timepix3 detectors has been implemented which enables the connection of up to four detectors located in a highly radioactive environment. The first version of the readout was installed together with the prototype monitor in 2017 and a new version of the readout is currently under development which will enable the full speed data rate of the pixel detectors. We also envision potential use of the radiation tolerant readout system for beam instrumentation applications, which could provide new insight to beam diagnostics.

Keywords: Only keywords from JINST's keywords list please

---

[1] Corresponding author.

Contents

1 Introduction

During 2019 and 2020 a major upgrade of the Large Hadron Collider (LHC) injector chain will take place in order prepare the beams required to reach the goals of the High Luminosity LHC (HL-LHC). This includes upgrades to the Proton Synchrotron (PS) which is the accelerator of interest in this paper.

An instrument called a transverse beam profile monitor allow the operators of the accelerator to take measurements of the size of the beam and see in real time how tuning different parameters improves or worsens the beam. The currently available monitors are limited to taking one beam profile measurement per cycle in the PS. A different approach presented in this paper is based on the principle of beam gas ionization and the novel use of hybrid pixel detectors to achieve the required spatial and temporal resolution. The goal is to provide non-destructive and time-resolved beam profile measurements from injection to extraction at a rate of at least 1 kHz. Timepix3 hybrid pixel detectors have a precise time resolution of 1.5625 ns which is of particular interest since it enables time-resolved bunch-by-bunch measurement of the beam. The biggest constraint are the ultra-high vacuum (outgassing $<1 \times 10^{-7}$ mbar l/s), the high radiation (10 kGy/year at the beam pipe) and the presence of beam loss and electromagnetic interference. Because of the high radiation, the readout electronics mounted near the pixel detectors are designed to be radiation tolerant and each component in the system has been carefully selected for that purpose.

In the following pages, the basic principle of beam gas ionization profile monitors will first be introduced after which the specific use of hybrid pixel detectors for this implementation will be detailed. The data recorded by the Timepix3 will be discussed together with the processing of the data and the challenges it presents in terms of filtering and computation of a beam profile. In the final section, some example use cases of beam profile measurements will be presented.

2 Beam gas ionization profile monitor

Figure 1 shows the principle of operation for a beam gas ionization profile monitor (IPM). The beam is moving inside the beam pipe where a vacuum is maintained and passes through the volume of the monitor seen in the center of the figure. Residual gas molecules will interact with the highly energetic particles in the beam and through an ionization process, electrons and positively charged ions will be created. The spatial distribution of these ions and electrons is proportional to the distribution of particles in the beam and can therefore be used to infer the beam profile [3].

An electric field of 285 kV/m is applied between the cathode and the anode [1]. Ionization particles created at the center of the field will therefore be at a potential of 10 kV. With the direction of the electric field as outlined in figure 1, the electrons will accelerate down and the ions up. A magnetic field parallel to the electric, created using a dipole magnet outside of the beam pipe with a maximum field strength of 0.2 T, helps maintain the transverse position of the electrons [2]. Two smaller correction dipole magnets, located either side of the main dipole magnet, ensure that the integrated B-field experience by the beam is zero. When the electrons have moved to the bottom of the instrument they have an energy of around 10 keV and will be recorded using a detector.

Traditionally the first stage of the detector for an IPM has been a micro-channel plate (MCP) which acts as a charge amplifier [4]. After it is used, each channel in the plate require some time to recover and more importantly the lifetime of each channel is limited. The center of the beam has higher density which will create a strong signal and therefore degrade the channels in the MCP located in this region more compared to the rest of the plate. This is problematic since it causes a non-uniform gain that gets worse with time and eventually the MCP will need to be replaced. An alternative detector without MCPs is therefore of interest for IPM's.

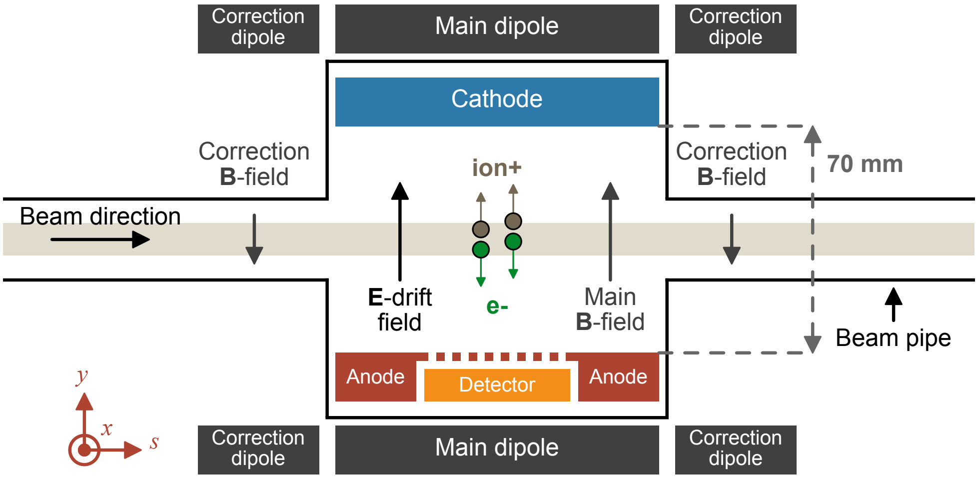

Figure 1. Block diagram of a beam gas ionization profile monitor.

3 Timepix3 hybrid pixel detector

Hybrid pixel detectors (HPD) have several features that make them interesting for IPM's. The separated sensor allows the use of different dimensions, materials and properties that can be optimized for the specific application. Silicon sensors with a thickness in the order of 300 µm with a metal layer on the top is common. For the IPM HPD the metal layer is removed in order to detect the 10 keV electrons since otherwise they would be absorbed before reaching the sensitive region in the silicon. For the first detector assembly all the metalization was removed which required the bias connection to be glued to the sensor. In the second version, small metal strips were left on two sides of the sensors where a wire could be attached using a wire bonding machine. To increase the radiation hardness of the sensor it was changed from using 100 µm thick P-on-N silicon to 100 µm thick N-on-P silicon.

Timepix3 readout chip consists of a 256 x 256 matrix of 55 µm x 55 µm pixels [5]. Each detector is 14 mm x 14 mm and to cover all possible beam sizes in the PS four of these detectors are mounted side by side perpendicular to the beam direction, giving a total detection area of 56 mm x 14 mm. Timepix3 provides an excellent time resolution of 1.5625 ns and together with a fast readout rate of 80 Mevents/s it enables bunch-by-bunch measurements of the beam profile. The minimum threshold of the chip is around 500 electrons which means that charged particles hitting the silicon sensor with an energy greater than 1.8 keV can be detected. Each event detected by the Timepix3 will produce an event consisting of: the row and column where the event occurred; the time of arrival and the time over threshold.

The four detectors are mounted on a ceramic board inside the ultra-high vacuum of the PS [6]. Two flexible cables made with a liquid-crystal polymer (LCP) substrate connects the ceramic board to electrical vacuum feedthroughs. The ceramic board is mounted on a second ceramic board which is attached to a copper plate to which a stainless steel pipe has been brazed where cold demineralized water is flowing to provide cooling for the detectors.

4 Data readout and processing

Since the digitization of the ionization electron signal is done inside the Timepix3 pixel detector, a stream of digital data is sent from the chip. This early step to a digital signal is advantageous in many ways and in strong contrast to other ionization profile monitors where the signal is kept analog longer in the signal path.

4.1 Radiation tolerant readout architecture

Each Timepix3 detector provide eight serial data links at rates of up to 640 Mbit/s. With the system of four detectors running at the highest readout rate, a maximum of 20.48 Gbit/s of data can be expected. To add to the complexity, the readout electronics need to be located in the vicinity of the instrument which implies high radiation and presence of electromagnetic interference. In figure 2 the full readout chain is presented as a block diagram. The back-end on the left is located in an environment with no radiation or vacuum requirements which means that normal commercial components are used here. Approximately 150 m of two optical fibers for duplex data transmission and copper cables for power and various sensors connect the back-end to the front-end which is located inside the accelerator tunnel.

Below the beam pipe, a common front-end readout board designed at CERN called GEFE is mounted in a rack [7]. The board contains a field-programmable gate array (FPGA) called ProASIC3E from Microsemi that has been tested to withstand a total ionizing dose of up to 750 Gy. The optical fiber connection to the back-end is done using the GBTx chip and a VTRx optical transceiver, which are components from the GBT project that have been designed to be radiation hardened [8]. A significant limitation of this first version of the system is the single optical GBT link which is limited to a 3.2 Gbit/s data rate. The detectors are therefore run at a slower readout rate of 80 Mbit/s for each link which gives a total of 2.56 Gbit/s of data for all detectors. A new system is currently under development that will enable the full readout speed.

The Timepix3 detectors can each process up to 80 Mevents/s with the highest readout rate enabled. For the first version of the readout this is limited to 5 Mevents/s per detector. The back-end has a buffer that can store 8 Mevents in total, which means that data can be recorded for 400 ms if all detectors would send the maximum amount of data. Fortunately, not all detectors will be running at the maximum rate all the time because the beam does not cover the full detector area.

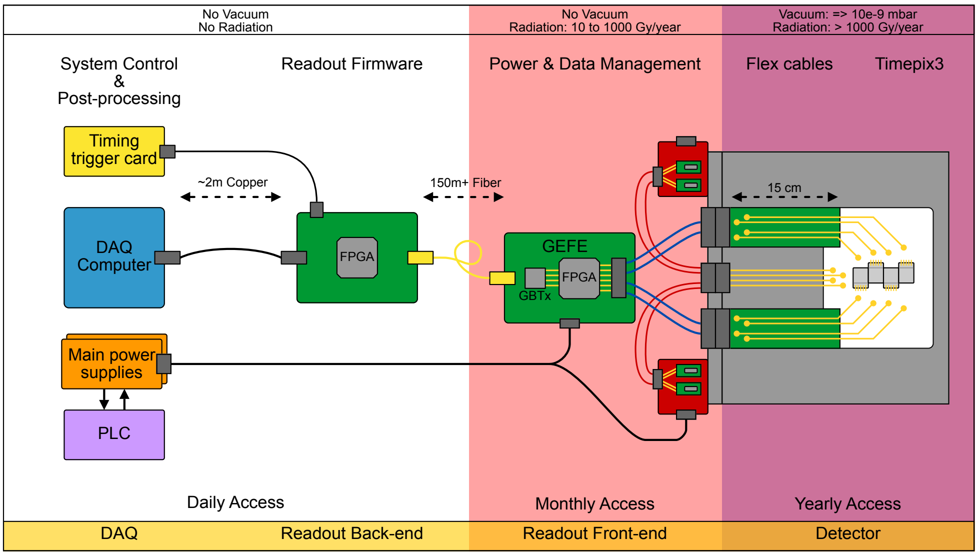

Figure 2. Schematic overview of the radiation tolerant readout architecture.

4.2 From pixel image to beam profile

Each event recorded by the Timepix3 includes information about the location, time of arrival and time over threshold. By counting the number of events for each location, a pixel image as seen in figure 3 can be created. The brighter a pixel is, the more events occurred in that location. Along the s-direction of the image a uniform signal is seen, while in the x-direction the signal fades out from the middle. This is the expected image of ionization electrons from a beam passing over the detector. The beam profile along the x-direction is obtained by summing the number of counts along the s-direction of the pixel image to create a histogram as seen at the bottom of the figure. The image also contains a clear honeycomb structure which looks like a shadow. This is caused by a metallic radio frequency shield mounted directly above the detector in order to suppress any electromagnetic interference that might affect the Timepix3. The low energy ionization electrons do not have enough energy to penetrate this shield. During the analysis, a correction factor for each column is applied which corrects for this honeycomb shadow. In many cases the beam profile is expected to have a Gaussian shape which means a function can be fitted to the histogram data as seen in the figure. From the Gaussian function fit, the mean and variance can be extracted. In other cases, the shape of the beam profile might not follow any known distribution and therefore requires calculation of the first (mean) and second (variance) statistical moment.

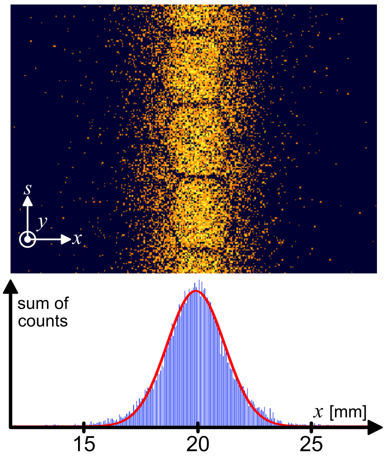

Figure 3. Pixel image at the top used to produce the beam profile histogram at the bottom with a Gaussian function fitted to it.

4.3 Filtering

It is important that the recorded events are actually coming from ionization electrons. This is not always the case as there is also beam loss and other background particles hitting the detectors. Some filtering of the data is therefore required. At the top of figure 4 an unfiltered pixel image is shown. The signal from the beam is clearly visible but there are also tracks and clusters which in this application can be considered as background noise and needs to be filtered out. These background signals are easily identifiable using the information provided by the Timepix3 for each event. Events that form a track or cluster will be close together in time and located near each other and the time over threshold for these events will be higher compared to the ionization electrons. This is because these events come from highly energetic beam loss and background particles. In contrast, events that are from ionization electrons will mostly be single pixel events with a lower time over threshold value. By applying these criteria to the original pixel image at the top of figure 4 it is possible to filter out the background noise and obtain a clean pixel image as seen at bottom of the figure.

5 Beam profile measurements

5.1 Beam profile evolution

An important requirement for this new beam profile monitor is the ability to take time resolved measurements continuously throughout a single beam cycle. The measurement shown in figure 5

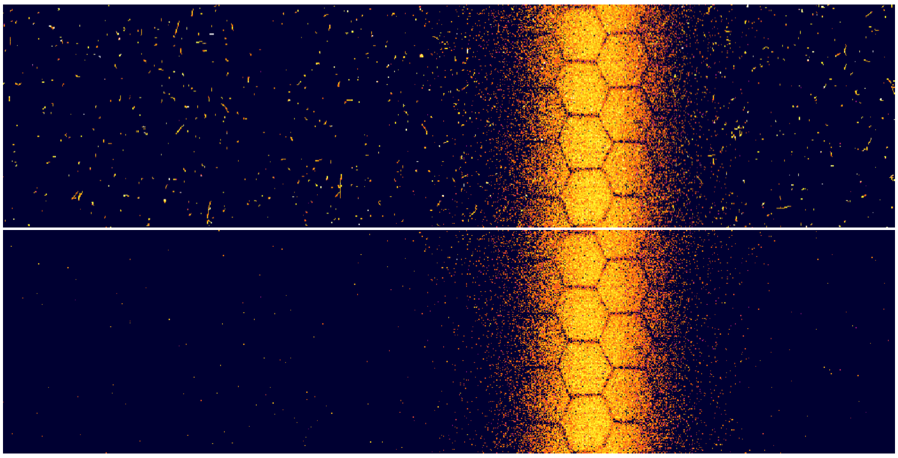

Figure 4. Top: pixel image before filtering. Bottom: pixel image after filtering.

was taken for a proton beam with an intensity of 1×10^{11} charges with a 10 ms integration window throughout the cycle. An electric drift field of 285 kV/m and a magnetic field of 0.08 T was used. The data seen in figure 5 has not been filtered in order to demonstrate the importance of the filtering when recording data. At the top of the figure is a pixel image of the beam immediately after injection to the PS where the momentum is approximately 2 GeV/c. The bottom pixel image in the figure shows the beam just before extraction where the momentum is close to 26 GeV/c. As can be seen in the figure, the beam gets narrower as the momentum increases which is expected. The beam also moves in the x-direction throughout the cycle.

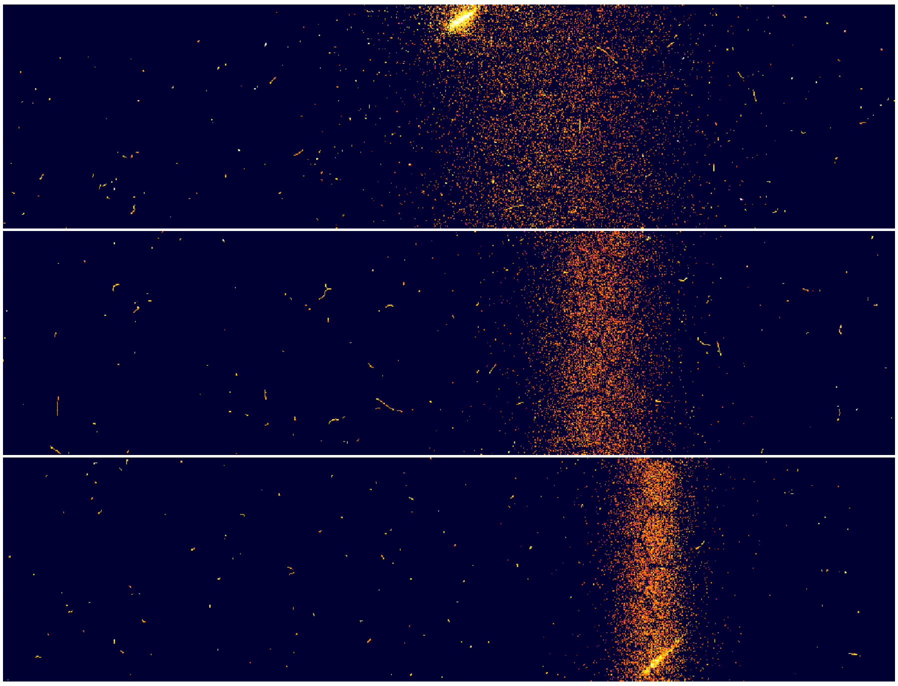

Figure 5. Beam profile evolution from injection momentum of around 2 GeV/c (top) to extraction momentum of 26 GeV/c (bottom).

5.2 Transition crossing example

Another use case is to look at specific parts of the cycle in detail with the highest possible time resolution. This is illustrated by the measurement shown in figure 6. Five cycles of a lead ion beam with intensities ranging from 4.3×10^{10} charges to 5.1×10^{10} charges were recorded for a 200 ms time window where each data point is an integration over 500 µs. An electric drift field of 285 kV/m and a magnetic field of 0.2 T was used. The pixel detector image for each data point was processed and filtered as described earlier and the resulting histogram was fitted with a Gaussian function. From the fit, a beam width (sigma) and beam position (mean) can be extracted and this is what is shown in figure 6. The first observation to be made is that all five cycles are consistent with each other which demonstrates the repeatability of the measurements taken with this instrument. Looking at both the sigma and the mean, it is clear that something is happening with the beam at around 970 ms. The mean position of the beam jumps by almost 3 mm and the beam width (sigma) starts to oscillate. Further investigation and discussion with the accelerator physicists lead to the conclusion that this point in time in the cycle is the transition crossing. This is a critical point in the beam cycle where the beam might become unstable.

As a comparison, a similar measurements done using a wire scanner, which is limited to a single beam profile measurement per cycle, would be impractical because of the time it would require. A total of 2000 data points were taken for this measurement with the IPM which means that 2000 cycles needs to be measured with a wire scanner to obtain similiar data.

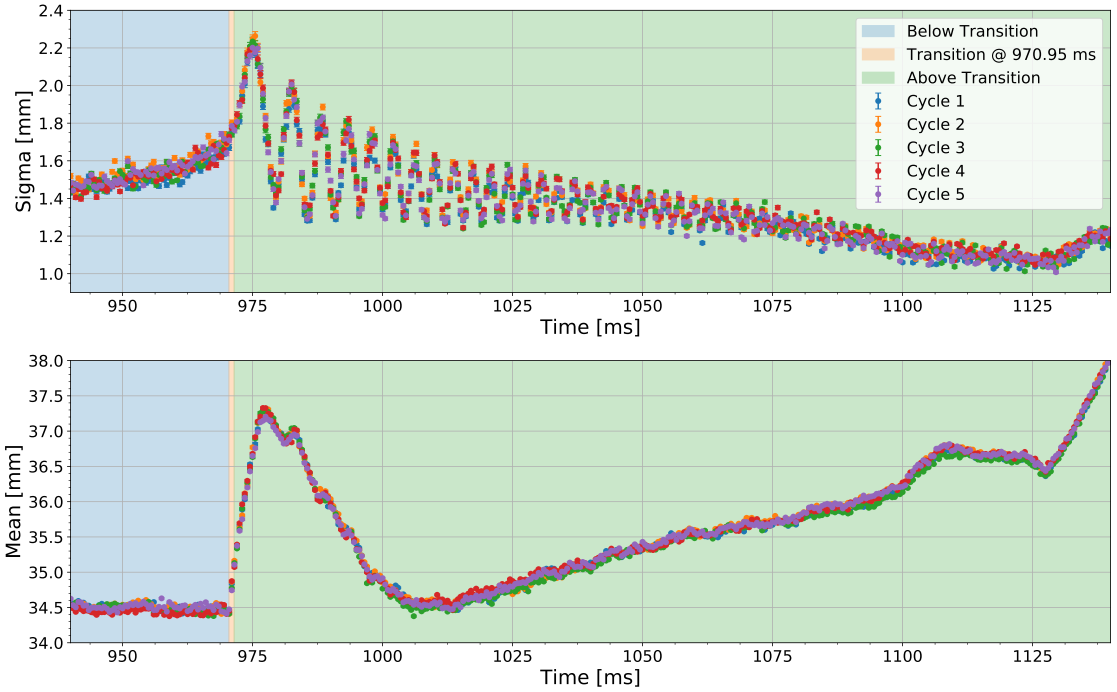

Figure 6. Beam width (sigma) at the top and beam position (mean) at the bottom for a 200 ms time window with the transition crossing at 970.95 ms.

6 Conclusion and future work

A transverse beam profile monitor using hybrid pixel detectors has been implemented that meets the operational requirements of ultra high vacuum (outgassing $<1 \times 10^{-7}$ mbar l/s), high radiation (10 kGy/year at the beam pipe) and presence of beam with losses and electromagnetic interference. The prototype instrument has been in use since the beginning of 2017 and data has been recorded throughout 2017 and 2018. Beam gas ionization profile monitors based on pixel detectors show great promise as it enables continuous non-destructive measurements at >1 kHz with direct detection of ionization electrons, which means that no MCP is needed. The available time resolution from the Timepix3 readout chip allows time resolving of individual bunches in the beam and the time over threshold information has proven useful for filtering the data. The radiation tolerant readout system developed for this instrument also enables the use of pixel detectors at accelerators for other applications. Bunch-by-bunch beam loss monitoring using pixel detectors is one example of a potential use case which could give new insights for beam diagnostics.

References

[1] O.Keller et al., *Feasibility Study of a Novel, Fast Read-out System for an Ionization Profile Monitor Based on a Hybrid Pixel Detector*, proceedings of HB2014, MOPAB41.

[2] J.W. Storey et al., *Development of an Ionization Profile Monitor Based on a Pixel Detector for the CERN Proton Synchrotron*, In: (2016), TUPB059. 4 p.

[3] W.H. DeLuca, *Beam detection using residual gas ionization*, IEEE Transactions on Nuclear science 16.3 (1969): 813-822.

[4] J. Krider, *Residual gas beam profile monitor*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 278.3 (1989): 660-663.

[5] T. Poikela et al., Timepix3: *a 65K channel hybrid pixel readout chip with simultaneous ToA/ToT and sparse readout*, 2014 JINST 9 C05013.

[6] S. Levasseur et al., *Development of a rest gas ionisation profile monitor for the CERN Proton Synchrotron based on a Timepix3 pixel detector* 2017 JINST 12 C02050

[7] M. Barros Marin et al., *The Giga Bit Transceiver based Expandable Front-End (GEFE) – a new radiation tolerant acquisition system for beam instrumentation*, 2016 JINST 11 C02062.

[8] P. Moreira et al., *The GBT Project*, TWEPP09, Paris, France, Sep 2009.