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COMMISSIONING OF TIMEPIX3 BASED BEAM GAS IONISATION PROFILE MONITORS FOR THE CERN PROTON SYNCHROTON

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Abstract

A pair of operational Beam Gas Ionisation (BGI) profile monitors was installed in the CERN Proton Synchrotron (PS) at the beginning of 2021. These instruments use Timepix3 hybrid pixel detectors to continuously measure the beam profile throughout the cycle in the horizontal and vertical planes. In the weeks following their installation, both BGI's were commissioned in situ by equalizing and tuning the thresholds of the Timepix3 detectors.

First measurements were taken during the beam commissioning period, demonstrating the operational readiness of the instruments. Sextupolar components originating from the magnetic shield in the vertical BGI magnet were later discovered and required compensation to reduce their effect on the PS beams. With the compensation in place, operational measurements could be started and provided new insights into the dynamics of the PS beam cycles.

INTRODUCTION

A novel BGI profile monitor design aims at providing continuous, bunch-by-bunch and turn-by-turn measurement of the transverse beam profile in the CERN PS [1]. This instrument design uses electric and magnetic fields to transport electrons from rest-gas ionisation to a Timepix3 [2] based detection system installed directly inside the beam vacuum. The beam profile is inferred from the transverse distribution of the detected electrons. In 2017 a prototype was successively installed in the CERN PS and was updated in 2018 with new detectors. It provided the first measurements of transverse horizontal beam profiles using this novel design and demonstrated the feasibility of the in-vacuum Timepix3 use [3, 4].

During the long shutdown 2 of the CERN accelerator complex, the prototype was replaced by an operational instrument and a second instrument was installed to measure the transverse beam profile in the vertical plane. The horizontal BGI reused the vacuum chamber, magnet and infrastructure from the prototype instrument, while the vertical BGI required the installation of a new vacuum chamber and a new 0.2 T triplet dipole magnet. Both instruments were ready for the first beam in the PS on March 2021.

DETECTOR SETUP AND EQUALISATION

A new generation of in-vacuum detector electronics was designed and manufactured for the operational vertical and horizontal instruments. This new design consist of an array of four modules each with one Timepix3 chip. This solves production yield issues discovered with the prototypes and improves the manufacturability and reliability of the detector. To ensure that the detectors were working as expected, each of them was tested twice, once in the lab prior to installation and once in the CERN PS after installation. The testing procedure consists of; measurements of the detector and sensor bias currents, temperature measurements, internal digital-to-analog converter (DAC) response scans, equalisation, threshold tuning and detection tests using radioactive sources. Equalisation and threshold tuning are the two most important step of the commissioning.

The equalisation process aims to create a uniform response of all pixels in the matrix by tuning 4-bit DACs that shifts the response of each pixel relative to a global threshold. All pixels have a slightly different response due to manufacturing process variations and for a fixed input signal some pixels are therefore below the threshold while others are above. The response is measured at the maximum and minimum range of the pixel DACs to find the ideal value for each pixel. Figure 1 presents the Timepix3 matrix response measurement before (two large distributions) and after equalisation (narrow central distribution). Equalisation

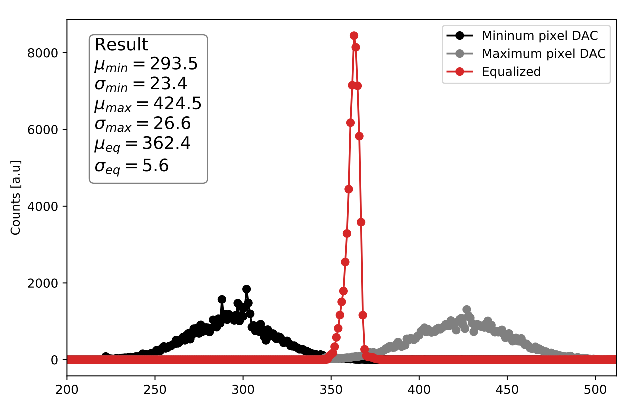

Figure 1: Equalisation result from a Timepix3 detector in the operational horizontal BGI instrument.

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also allows to locate dead and noisy pixels as they fail to reach their equalisation target.

Threshold tuning consists of adjusting the detection threshold of each Timepix3 against a common signal source. This maximises the efficiency of ionisation electrons detection and eliminates differences in efficiency between the four detectors. A ^{55}Fe radiation source is used in the lab, while in the CERN PS, the remnant radiation background is used. A more detailed description of the detector setup and testing is given in [5]. After installation the detectors successfully passed the testing procedure and no significant difference was found when compared to the results of the lab tests.

FIRST BEAM MEASUREMENTS

As soon as the beam arrived in the PS in March 2021 the BGI instruments were switched on to start measuring the beam profile. The readout software had been integrated with the operational control system of the CERN accelerator complex during the long shutdown. Computers with dedicated software, called Front-End Software Architecture (FESA) device, control the BGI instruments and allow beam profiles to be read out and published to operational software applications, user created scripts and to the logging database. To synchronize the instruments with the accelerator there are hardware triggers connected to the readout electronics and the FESA devices. The readout has been designed to acquire up to 1024 beam profiles for any beam cycle in the PS with configurable integration time and repetition rate. The settings of the instrument are specific for each cycle, and this allows to measure each of them individually even when played one after the other in a programmed sequence called super cycle.

Figure 2 shows a pixel image from the four Timepix3 detectors in the horizontal BGI instrument acquired during the first week of March 2021 when the first beams were circulating in the PS. The image looks as expected with a uniform response along the direction of the beam (s) and a gradient along the transverse horizontal direction (x). The honeycomb shaped shadow is from an RF shield mounted above the detectors, which blocks the ionisation electrons, creating areas with lower count rate in the detector. A method to correct and ensure a uniform detection efficiency is discussed in [6] and was applied to the operational readout during the first weeks of the instrument commissioning period.

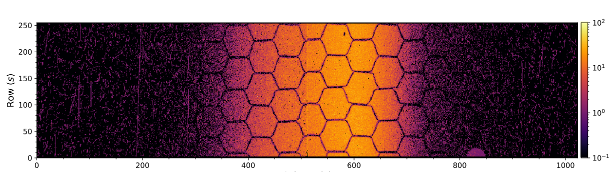

Figure 2: Pixel image of a single bunch beam cycle in the PS.

The pixel image in Fig. 2 is a 1.2 s integration of a full single bunch beam cycle. For beam profile measurements integration times in the order of 2 ms or less are used to capture the details of the beam dynamics within the cycle. An integration time of 2 ms for each beam profile results in a total of 600 profiles for this single bunch beam. In Fig. 3 all these beam profiles are shown in a waterfall plot with the first profile at the bottom and the last at the top. This shows the strength of the BGI instruments in that they can resolve the dynamic behavior of the beam from a single capture of a cycle. Single shot instruments, such as wire scanners, would require measurements of 600 cycles where the start trigger is stepped throughout the cycle.

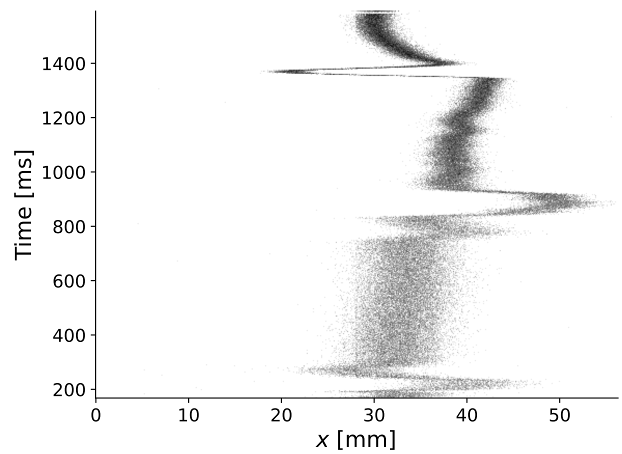

Figure 3: Waterfall plot of a single bunch LHC beam cycle.

The time evolution of the beam size and position throughout a cycle can be determined by fitting a Gaussian distribution to each beam profile, an example of this type of measurement is shown in Fig. 4. This is the intended operational mode of the BGI instruments as it facilitates quantification of the beam dynamics and performance.

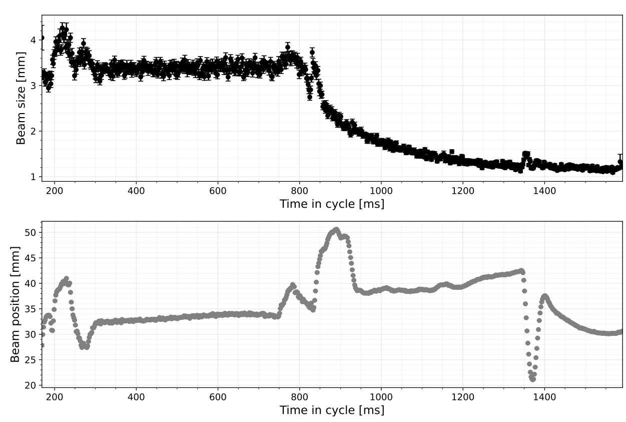

Figure 4: Evolution of the beam size (top) and position (bottom) of a single cycle.

OPERATIONAL ISSUES

During the beam commissioning period the operators had issues with beam losses and conducted a study to find the cause of it. After some time, it was discovered that the

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magnetic shield of the dipole magnet for the vertical BGI instrument, which was installed and had not been used in the accelerator yet, caused some unwanted sextupolar components and resonances in the beam. This was later confirmed by the magnet group through rigorous simulations and a permanent solution was found which requires adjustment to the shielding plates in the magnet. The fix has been scheduled for the next winter shutdown. In the meantime, the magnet activation is controlled by the operators and enabled only for selected cycles where its effect is compensated using the other magnets in the PS. The horizontal magnet does not have this issue and has been installed in the PS since 2017.

EXAMPLES OF OPERATIONAL MEASUREMENTS

In the following section examples of operational measurements will be shown that were kindly provided by M. Coly, M. Fraser and A. Huschauer from the CERN operational, accelerator beam transfer and physics groups. The discussion will be limited to the measurement setup and how the BGI instruments were used. Beam performance will not be analyzed or discussed.

Beamlets in Multi-turn Extraction Beam

The PS accelerator is producing beams with different properties for experimental areas and for further acceleration in the Super Proton Synchrotron (SPS). One of these beams going to the SPS is using a multi-turn extraction (MTE) technique, where the beam is split in the transverse phase space into several beamlets to be extracted individually [7]. After splitting, the beamlets can be observed with the BGI instrument as shown in Fig. 5, where five lines can be seen at different transverse positions. One of the beamlets, called the core, has a higher intensity and is identified by the more intense color in the figure. This difference in intensity can be detected by the BGI because the number of ionisation electrons is proportional to the number of particles in the beam. The dynamic behavior of the beamlets as a function of the time in the cycle is also visible and give insight to how they behave.

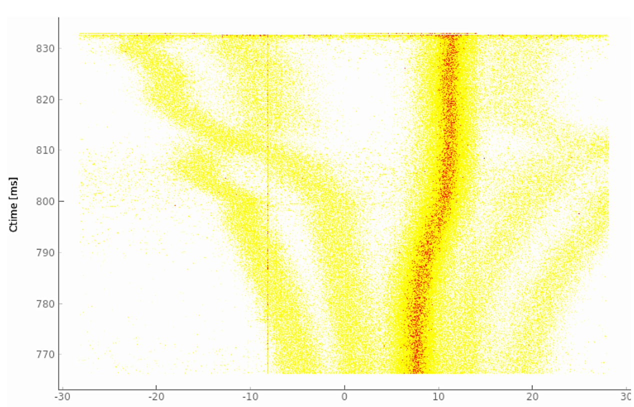

Figure 5: Beamlets of the MTE beam measured with the BGI.

Second Injection Beam Losses

The Timepix3 pixel detectors used in the BGI instruments detects not only ionisation electrons, but also particles originating from beam losses and activated material. The detectors are mounted in the primary vacuum of the accelerator, about 7 cm from the beam. During normal operation with stable beams in the PS the amount of beam loss is negligible and can be seen as an occasional track on the pixel image. In some specific cases the amount of losses can be greater and is usually distributed over the full detector sensor area. The cause of such losses detected by the BGI can then be investigated further.

Figure 6 is an example of a measurement where higher losses can be observed. At 1320 ms there is a wide band that extends outside the uniform beam profile at the center of the waterfall plot. At this time in the cycle a second injection of particles usually occurs, triggered by the injection kicker magnet kicking the beam from the transfer line into the PS, where particles are already circulating. During this specific measurement the kicker magnet was active but no particles were injected. The beam loss detected by the BGI is therefore correlated to a disturbance to the particles already in the PS beam pipe. Beam loss measurements with the BGI only show it at one location in the accelerator, in contrast to the beam loss monitoring (BLM) system that measure the losses around the whole accelerator.

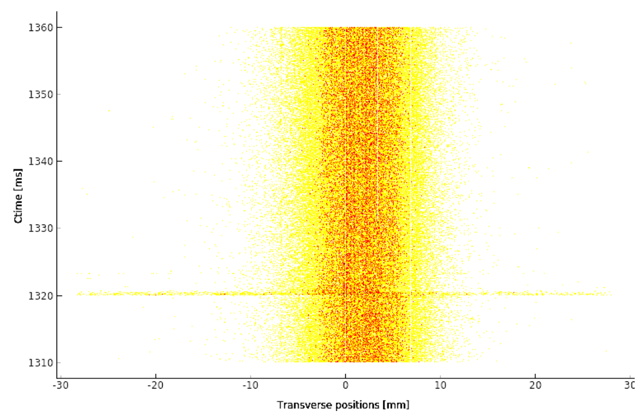

Figure 6: Second injection beam losses seen with the BGI.

Intermediate Plateau Beam Size Squeeze

When a full cycle is measured the BGI instrument provides the operator with an overview of how the beam evolves throughout the cycle in the transverse plane as shown earlier in Fig. 4. If the measurement shows an unexpected beam size or position evolution, the operator can further investigate it by programming a trigger for a more detailed measurement in that specific area of the cycle for the following cycles.

One such measurement is shown in Fig. 7 where there is a dip at 1450 ms in the beam size (σ) evolution. This happens in the so called intermediate plateau, a part of the cycle where the beam has been accelerated to an intermediate energy before the second injection. The longitudinal momentum spread was observed to decrease and increase

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during the acceleration, which couples to the horizontal beam size through dispersion, explaining what is observed with the BGI instrument. With up to 1024 beam profiles measured per cycle the BGI can detect rapid changes in the beam size as demonstrated here.

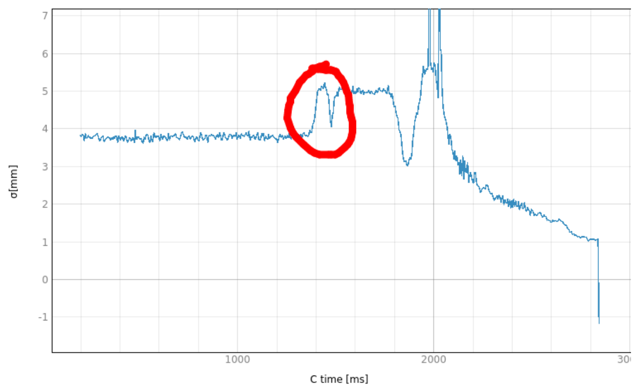

Figure 7: Beam size changes measured with the BGI due to rapid changes in the longitudinal momentum spread.

Injection Mismatch Oscillations

In [4] it was shown that the prototype BGI instrument was capable of resolving turn-by-turn beam profiles, but the period of a turn in the PS is 2.2 µs and with only residual gas in the BGI instrument there is not enough ionisation electrons detected to resolve the profile. For the prototype instrument a nearby vacuum pump was sublimated to create a localised pressure bump which was enough to create around 80 electrons per turn. Based on this measurement it was decided to equip the operational BGI instruments with dedicated argon gas injection systems, making it possible to increase the ionisation electron rate on demand.

An initial test of the gas injection system and turn-by-turn measurements using the operational horizontal instrument is shown in Fig. 8. This is currently a work-in-progress, but the first test shows that the expected beam size oscillations induced by an injection mismatch can be observed with the BGI. The operational processing of the Timepix3 events needs further development to ensure that each is assigned to the correct turn in the cycle.

CONCLUSION

Beam gas ionisation profile monitors have successfully been commissioned in the CERN PS for operational measurements of the transverse beam profiles in the horizontal and the vertical plane. The Timepix3 hybrid pixel detectors used in the instrument were tested and equalized in the lab prior to installation in the primary vacuum of the accelerator and the same process was repeated after installation. No significant discrepancies were found between the results

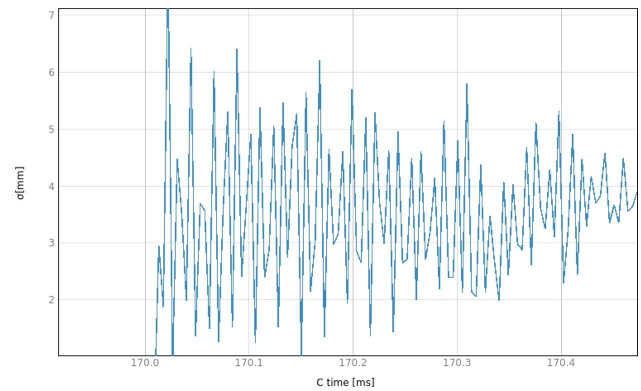

Figure 8: Forced injection mismatch induces beam size oscillations.

obtained in lab and those obtained after installation for the same instrument. Both instruments were ready before the restart of the PS in March 2021 and could successfully measure the profile of the beam since the beginning of the run. Operational software was prepared and integrated with the CERN control system and accelerator timing signals and has been used by the operators and beam physicists. Examples of operational measurements have been shown where the non-invasive and continuous measurement technique of the Timepix3 based BGI instrument is highlighted.

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