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TIME-RESOLVED TRANSVERSE BEAM PROFILE MEASUREMENTS WITH A REST GAS IONISATION PROFILE MONITOR BASED ON HYBRID PIXEL DETECTORS

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Abstract

A novel rest gas ionisation profile monitor which aims to provide continuous, bunch-by-bunch and turn-by-turn measurement of the transverse beam profile has recently been installed in the CERN Proton Synchrotron (PS) as part of the LHC Injector Upgrade (LIU) project. The instrument consists of an electric drift field to transport ionisation electrons produced by beam-gas interaction onto a measurement plane, and a magnetic field to maintain the transverse position of the ionisation electrons. The electron detector located at the measurement plane is based on four in-vacuum hybrid pixel detectors. The detectors record the position, time and energy of single ionisation electrons with unprecedented precision compared to traditional MCP based techniques. Continuous transverse beam profile measurements for LHC-type beams in the PS will be presented, demonstrating the unique capabilities of the instrument to provide new insights into beam dynamics throughout the acceleration cycle.

INSTRUMENT OVERVIEW

The LHC Injector Upgrade (LIU) sets tight limits on emittance growth in the LHC injector chain. Accurate time-resolved measurement of the transverse beam profile is required in order to identify the causes of the emittance blowup. To this end a new generation of rest gas Ionisation Profile Monitors (IPM) is under development for the Proton Synchrotron (PS) that will facilitate continuous bunch-by-bunch measurement of the transverse beam profile. An overview of the instrument is presented in Fig. 1. The principal of the instrument is as follows: ionisation electrons produced by the beam / rest-gas interaction are accelerated towards an electron detector by an electric drift field formed by a cathode at −20 kV. The electrons are detected by a silicon hybrid pixel detector which is installed - for the first time at CERN - directly inside the ultra-high vacuum environment of the beam pipe. The corresponding ionisation ions are transported by the electric drift field through a hole in the cathode - called the ion trap - in order to suppress the creation of secondary electrons that would otherwise create a background to the main ionisation electron signal [1]. A 0.2 T self-compensating magnetic field parallel to the electric drift field ensures that the transverse positions of the electrons are maintained from the point of creation to the electron detector, mitigating the effects of electron drift caused by the electric field imperfections, the ionisation process and the beam space-charge. A complete description of the instrument design is presented in [2–4].

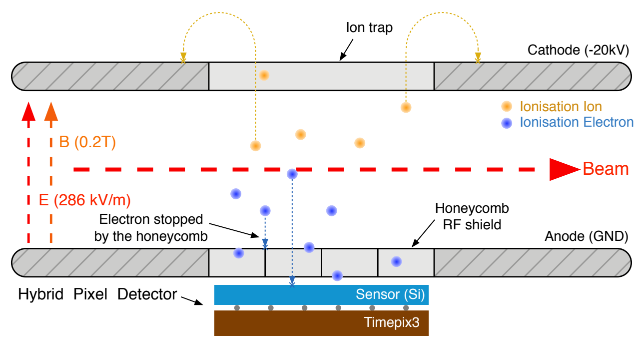

Figure 1: PS-BGI schematic overview. The Hybrid Pixel Detector records the charge deposited in the sensor, time of arrival and location of an ionisation electron hit.

Detection of Ionisation Electrons

Rest gas ionisation electrons are typically detected in this type of instrument by means of one or more Micro-Channel Plates (MCPs) to amplify the electron signal, followed by either a phosphor screen and camera or anode strips. In practice, however, it has been shown that the MCPs limit the spatial resolution of the detected electrons and suffer from inhomogeneous ageing and lifetime issues. To address both issues the new IPM for the PS dispenses with MCPs by detecting electrons directly by means of a Hybrid Pixel Detector (HPD) consisting of a pixelated 100 μm deep n-on-p silicon sensor bonded to a pixelated Timepix3 readout chip [5]. The complete electron detector is composed of four 14 mm x 14 mm HPDs placed side by side in a row perpendicular to the beam direction. Each HPD consists of a 256 x 256 matrix of 55 μm x 55 μm pixels. Each pixel measures the charge deposited in the sensor, the location in terms of pixel coordinates and the time at which it is deposited with a resolution of 1.56 ns. An event is created in the Timepix3 chip when the charge deposited crosses a user-defined threshold. The chips are used in the so-called "data-driven" readout mode, where each event is directly read-out with a maximum rate of 80 Mevent/s. This fine time

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resolution and high detection rate enable the measurement of the beam profile continuously throughout a PS cycle.

BEAM PROFILE RECONSTRUCTION

In order to measure the transverse beam profile a series of data processing steps are required, namely: cluster finding, energy filtering, honeycomb correction and, finally integration of events to form the beam profile. Each of these steps will be described in detail below.

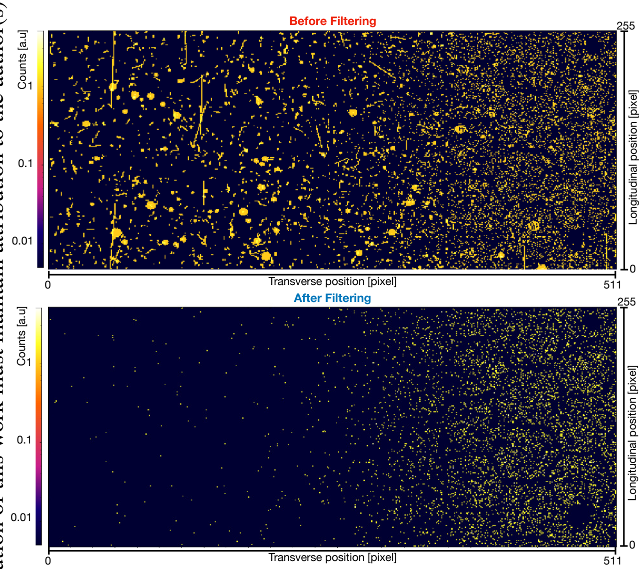

Figure 2: Top: Detector image before filtering. Bottom: Detector image after filtering. For clarity only half of the detector surface is shown with the beam ionisation electron events located on the right of the image.

Cluster Finding and Filtering

Due to the high sensitivity of the HPDs a significant number of background particles originating from primary and secondary beam losses are detected at the same time as the ionisation electrons. The background particles traverse the HPD sensor depositing charge in several pixels in a pattern referred to as a cluster. In contrast the ionisation electrons impact the HPD perpendicular to the sensor surface and deposit charge in typically one or two pixels. It is therefore possible to remove background particles by identifying events belonging to a common cluster. A recursive algorithm is used to find neighbouring pixel events that occur within a common time window. Each cluster is then summed into a single event where the center of mass is used to define its position. Background particles are then removed by selecting only events where the cluster size is below or equal to that expected from ionisation electrons.

Energy Filtering

It was established in [2] that the ionisation electron signal has a narrow energy spectrum compared with with the energy spectra of minimum ionising background particles. After cluster filtering an energy filter is applied to remove events inconsistent with the energy expected for the ionisation electrons. Figure 2 shows the HPD events before and after cluster and energy filtering, demonstrating the effectiveness of the filtering methods.

Honeycomb Correction

The HPD detectors are located inside a Faraday cage to protect the sensitive electronics from the beam wake field. A stainless-steel honeycomb provides an opening in the Faraday cage to allow the ionisation electrons to reach the surface of the HPD sensor. Electrons which impact the honeycomb itself have insufficient kinetic energy to pass through the material; this leads to dead regions on the detector surface which, if left uncorrected, would distort the beam profile measurement. To correct for this effect the location of the dead regions are identified by illuminating the honeycomb with ionisation electrons from a beam that is scanned over the electron detector surface by means of a beam orbit bump. Weighting factors are then determined for each HPD column parallel to the beam direction to ensure a homogeneous sensitivity over the detector surface.

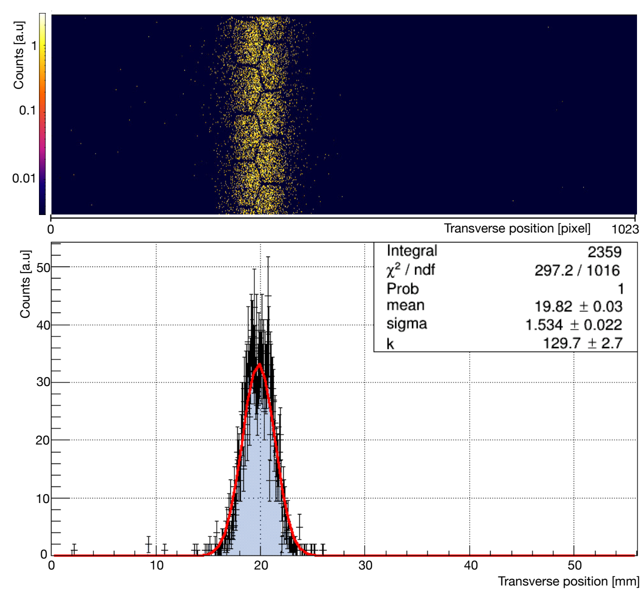

Figure 3: Top: Detector image of a LHC type beam before extraction in the PS after cluster and energy filtering. Bottom: Horizontal beam profile with honeycomb correction and Gaussian fit to the transverse beam profile.

Beam Profile Measurement

The transverse beam profile is constructed by summing the events per HPD column that pass the cluster and energy filter criteria for the time window of interest, and weighting each column with the honeycomb correction factors. The position of each column within a HPD is known to nanometer precision and the spacing between chips to micrometer precision. The beam size is determined by a Gaussian fit to the beam profile. An example is shown in Fig. 3 for an LHC type beam at PS top energy (26 GeV/c).

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TIME-RESOLVED MEASUREMENTS

The results presented in this section were acquired during the 2017 run using the first prototype IPM installed in the PS during the 2016 / 2017 winter shutdown. Measurements over two different time scales are shown: the first taken over 30 ms at top energy and the second over a 10 μs period which illustrates the exquisite time resolution of the instrument.

Beam Profile Measurement at Top Energy

The measurement was performed on a modified LHC beam consisting of 4 bunches from the PS Booster (PSB) injected into the PS. The beam intensity was 15.5×10^{11} protons. The beam size measurement is shown in Fig. 4 over a 30 ms period at the PS top energy of 26 GeV/c. The wire-scanner measurement taken at the same time measured a beam size of 1.60 mm, which when adjusted for the different lattice functions at the location the location of the IPM gives an expected value of 1.55 mm in very good agreement with the IPM measurement. Intriguingly the beam size oscillates between 1.57 mm and 1.42 mm, while the beam position oscillates between 20.15 mm and 19.6 mm; the origin of these oscillations is still under investigation.

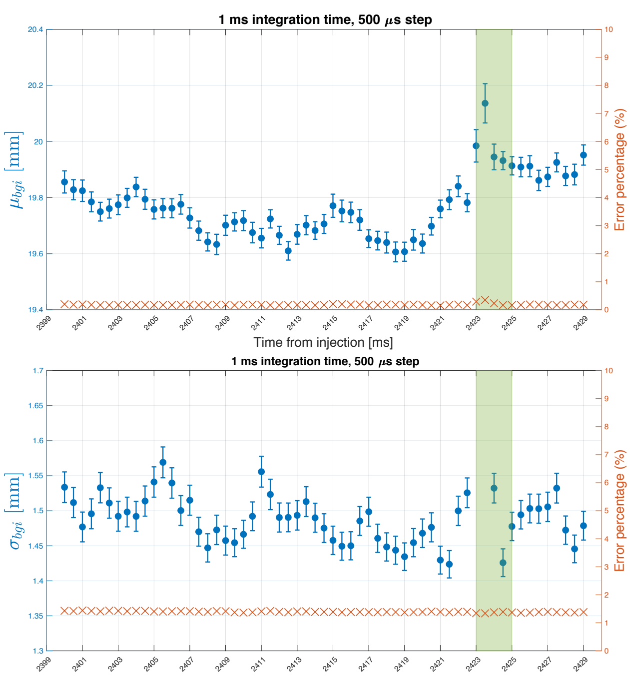

Figure 4: Profile measurement for 30 ms at PS top energy. The top figure shows the beam position, while the bottom one shows the beam width. The region highlighted in green represents the time period of the wire-scanner measurement.

Bunch-by-Bunch Time Structure

The ionisation-electron count-rate measurement was performed on a modified LHC-BCMS beam consisting of 3 bunches spaced by 254 ns with an intensity of 7×10^{11} protons per bunch. The ionisation count rate over a 10 μs and 1 μs time window are shown in Fig. 5. In the 10 μs window the time structure of the counts follow a 2.3 μs period which corresponds to the PS revolution period. In the 1 μs window the time structure of each of the 3 bunches is visible. Each bunch yields an average of 5 ionisation electrons per turn which is insufficient for a meaningful beam profile measurement. Integrating the ionisation signal over 10 turns yields sufficient signal for a profile measurement with a 5 % statistical error. It is planned to install an upgraded instrument and readout electronics in 2018 to further reduce the number of turns required for a useful beam profile measurement.

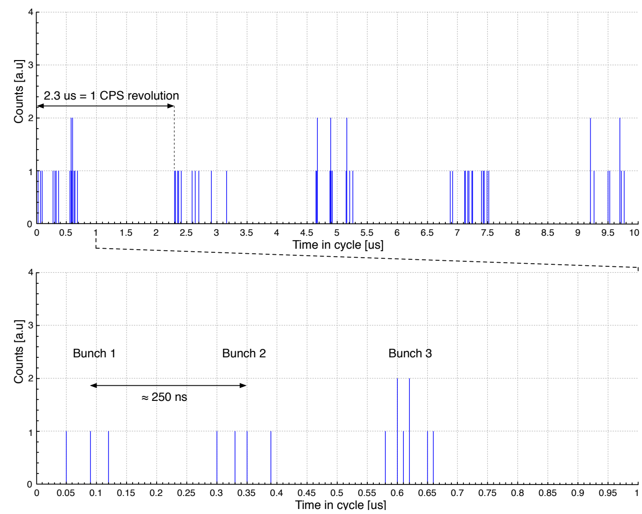

Figure 5: Ionisation electron counts as a function of time for a 10 μs (top) and 1 μs (bottom) window. The signal for each PS revolution is clearly visible in the top plot, while the signal for each individual bunch is visible in the bottom plot.

SUMMARY

A new IPM has been installed in the CERN PS to provide continuous time-resolved measurements of the transverse beam profile. Methods used to filter and reconstruct the beam profile from its novel imaging detector have been presented. Time resolved beam profile measurements were performed and the high temporal-resolution of the instrument was demonstrated by detecting individual bunches within LHC type beams.

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