MEASURING THE BEAM PROFILE BY COUNTING IONIZATION ELECTRONS

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Abstract

The principle of non-destructive beam profile measurement with rest gas ionization electrons has remained largely unchanged since the technique was first proposed in the late 1960's. Ionization electrons (or ions) are transported by an electrostatic field onto an imaging detector, where the spatial distribution of detected electrons is a direct measure of the transverse beam profile. The detector typically consists of one or more Micro-Channel Plates (MCP's) to amplify the signal, followed by either a phosphor screen and camera, or pickup electrodes. A long-standing problem is the ageing of the MCP's, which limits the accuracy of the beam profile measurement.

A new technique to detect ionization electrons has been developed at CERN, which uses a hybrid pixel detector to detect single ionization electrons. This allows the application of counting statistics to the beam profile measurement. It will be shown that a meaningful beam profile can be extracted from only 100 electrons. Results from the new instrument will be presented, which demonstrate the ability to measure the beam profile of single bunches turn-by-turn, which offers new opportunities for beam diagnostic insights.

IONIZATION PROFILE MONITORS

Ionization beam Profile Monitors (IPM's) have several strengths, the most important being the non-destructive nature of the measurement. This enables studies of the evolution of the beam profile throughout a full cycle. Many different techniques to detect ionization electrons have been studied over the years, but common to all is the need to amplify the ionization electron signal. To increase the signal strength it is usual to integrate over many turns and to add Micro-Channel Plates (MCPs) to amplify the original signal. The final detection of the amplified signal is done either optically - with a phosphor converter and intensified camera - or with analog pickup electrodes and amplifiers. A problem with these amplifications is that each conversion of the signal will provide distortion and add noise, making it more difficult to understand the relationship between the detected signal and the original signal coming from the ionization process. In addition, during the integration window, the beam width and position must remain constant otherwise the measured beam profile will be convoluted with any changes in these parameters.

To overcome these limitations, a new type of IPM has been implemented where the detection is performed using hybrid pixel detectors. The pixel detector enables direct detection of single ionization electrons with the added ability to filter out background particles. A more detailed description of the instrument, the so-called PS-BGI, can be found in [1].

BENEFITS OF COUNTING

Direct detection allows the use of counting statistics in the analysis of the recorded data. The basic idea is that discrete events occur independently of each other at a known average rate within a fixed window of time, with the time between two events considered as random. For the PS-BGI, the events are the detected ionization electrons from the pixel detector and the known rate comes from the ionization process. The time window is set by how long the detector is enabled which, for example, could be one turn or a number of turns. If the ionization electrons are spatially separated and limited in number, they can be considered independent given the large detection area of 14 mm × 56 mm. These arguments fit well to a Poisson distribution.

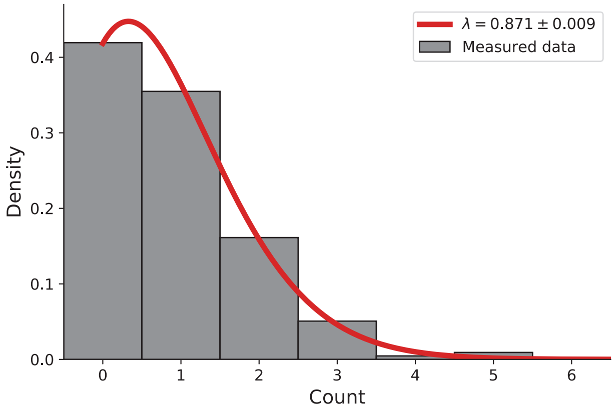

Figure 1: Measured counts from a single pixel column fitted with a Poisson distribution.

The Poisson distribution can be used to model the count of ionization electrons for a given transverse position. In the beam direction s, the count rate at a given transverse position is considered to be over the 14 mm length of the detector.

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The count of ionization electrons in a specific pixel detector column (i.e. at a fixed transverse position) should therefore follow a Poisson distribution. Figure 1 shows one column from measured data fitted with a Poisson distribution. The distribution can be seen to represent the measured data rather well, confirming that counting statistics is a good choice for the processing of the PS-BGI data.

Monte Carlo Simulation

An added benefit of this counting model is that it is easily simulated. This can be used to validate the data processing and to extract the expected instrument accuracy and precision. The first step is to randomly draw a fixed number of samples from a normal (Gaussian) distribution. This represent a perfectly Gaussian beam profile where the samples can be thought of as the number of ionization electrons produced at specific transverse positions. As illustrated in Fig. 2, in the PS-BGI four independent detectors are used with the gaps between detectors in the order of 100 µm. If an ionization electron falls in a gap it will not be detected and therefore any drawn samples in a gap from the simulation are also removed. Next, the samples are put into 55 µm wide bins which is the size of a square pixel in the detector. The binned samples are converted to a two-dimensional pixel image by distributing the total count in each bin along 256 rows in the s-direction. After this step, simulated data can be processed and analyzed the same way as measured data.

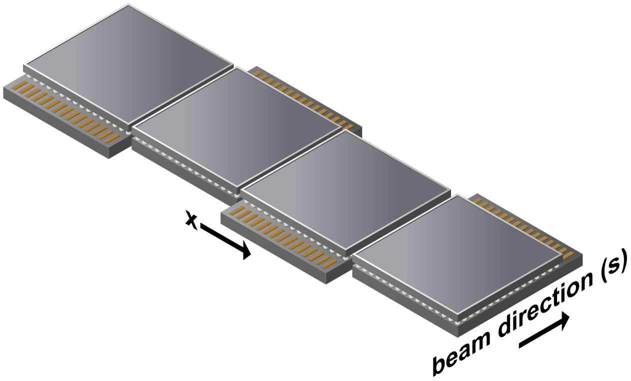

Figure 2: Four hybrid pixel detectors used in the PS-BGI instrument with gaps between.

Unresponsive Pixels

Some of the 65536 pixels per detector are unresponsive or have a different response than normal, e.g. are in the shadow of an EMI screen that shields the detector from electromagnetic effects of the beam. These pixels must be removed from the data analysis because they will invalidate the argument of a uniform average rate in each bin. Removing a pixel in one column implies removing one pixel from all other columns to keep the statistics for each column comparable. This can be another unresponsive pixel or a good pixel in the case where a column no longer contains unresponsive pixels. With this manipulation the statistical nature across columns is maintained while the effective number of rows is reduced. An example of the final image is seen at the top in Fig. 3. The image still contains all 1024 columns but the number of effective rows is reduced from the maximum 256 depending on how many unresponsive pixels there are. From this pixel image the beam profile can be extracted by taking the sum of counts per column, which gives the simulated beam profile data seen at the bottom in Fig. 3.

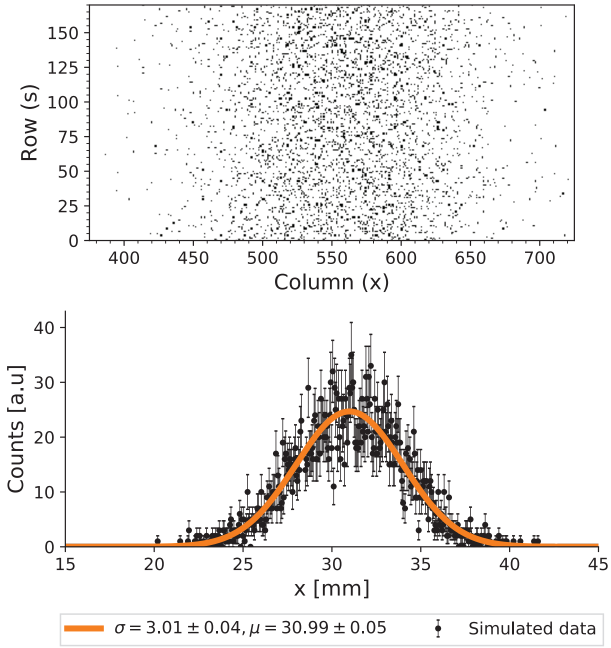

Figure 3: Pixel image (top) and beam profile with a fitted Gaussian distribution (bottom) from simulated data of 5500 events.

Binned Maximum Likelihood Fit

As the simulation assumes a Gaussian profile it is now possible to find the best estimate of the Gaussian parameters and to quantify the goodness of fit. The argument made earlier that each bin follows a Poisson distribution can be used together with the maximum likelihood estimation method to fit a Gaussian distribution to the data. The likelihood function is:

$$L = \prod_i \frac{e^{-\lambda_i} \lambda_i^{k_i}}{k_i!}, \tag{1}$$

where k_i is the number of observed events in bin i and λ_i is the event rate in bin i. Using this method it is possible to have a count of 0 in a bin and no re-binning is necessary. A fit to the simulated data is shown at the bottom in Fig. 3 where the original Gaussian distribution has a width of $\sigma = 3.0$ mm and a mean position of $\mu = 31.0$ mm.

Unfortunately, there is no general analytical expression that can be used to determine if the fit is good or not from the likelihood value. It is therefore necessary to run many Monte Carlo simulations where the Gaussian distributions are known to determine the expected likelihood value distribution. The likelihood value calculated for a fit to measured data can then be compared to the simulated likelihood distribution to determine if the fit is good or not, i.e. if the measured profile is Gaussian. If the fit is not good, an RMS beam width can be calculated instead using the weighted standard deviation.

PRECISION & ACCURACY

Using the simulation it is possible to determine the expected precision and accuracy of the instrument.

Precision

The precision of the beam width measurement (the variation in multiple measurements) depends on the sample size i.e. the number of detected ionization electrons. A simulation was performed where the sample size was varied from 50 to 10,000 ionization electrons. For each value, a total of 10,000 profiles were generated with different beam widths and positions. The beam profiles were fitted and an RMS value was calculated for the measured beam width σ_x. Because it is a simulation, the true beam width σ_{true} is known and a residual for each profile can therefore be calculated as:

$$r = \frac{\sigma_{\text{true}} - \sigma_x}{\sigma_{\text{true}}}. \tag{2}$$

For a given sample size, the residuals of all 10,000 profiles has a standard deviation σ_{residual} which defines the precision of the measurement. Figure 4 shows the expected precision for the different sample sizes. The precision for the fit- and RMS-values are in good agreement. It can be seen that for a sample size of 100 ionization electrons a precision better than 10% is expected, while achieving 1% precision requires over 5000 ionization electrons.

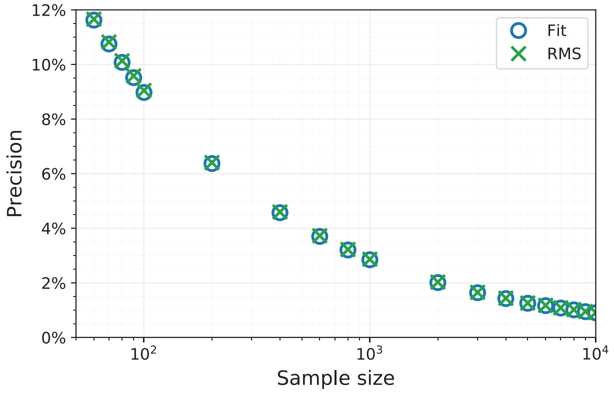

Figure 4: Expected precision of beam width measurements as a function of sample size for a Gaussian fit- and RMS-values.

Accuracy

To investigate the expected accuracy of the beam width measurement it is interesting to look at any systematic errors caused by specific combinations of beam position and width. This was studied in a simulation where the true beam width σ_{true} was varied between 1.0 mm and 3.0 mm and the true beam position μ_{true} was varied ±7.0 mm from the center of the vacuum chamber. These values were chosen to make sure the beam will cross over the gaps between the detectors which could reduce the accuracy of the measurement. For each combination of width and position, 1000 beam profiles - each with a sample size of 100 ionization electrons - were generated and the residual for each was calculated using Eq. (2). The mean μ_{residual} of all 1000 residual values was calculated which defines the accuracy.

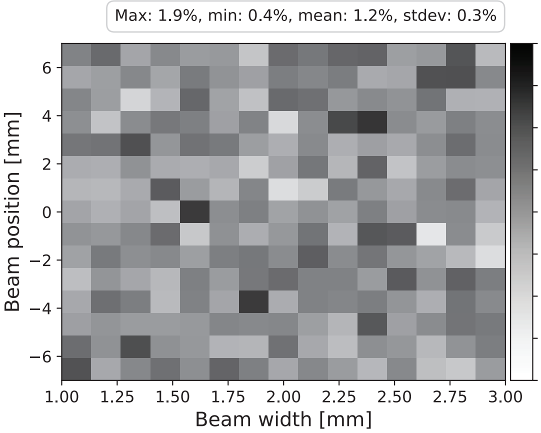

Figure 5: Expected accuracy of beam width measurements as a function of the true beam width and position with a sample size of 100.

Figure 5 shows the expected accuracy of the beam width measurement for fit values for all studied cases. The mean accuracy is 1.2% with a standard deviation of 0.3% and a maximum value of 1.9%.

Therefore, for a sample size of 100 ionization electrons, an accuracy better than 2% and precision better than 10% is expected.

VALIDATION MEASUREMENTS

The following measurements were taken using the horizontal PS-BGI instrument which is installed in the Proton Synchrotron at CERN (CPS).

Beam Profile Measurement

This data was acquired on November 1st 2018 for a LHC type beam with an intensity of 60×10^{10} protons and a residual vacuum pressure of 1×10^{-10} mbar. An integration window of 5 ms was chosen which resulted in a total of 5500 recorded events. The pixel image from the acquisition can be seen in Fig. 6, which can be seen to closely resemble the image for the same number of events simulated in Fig. 3.

A Gaussian distribution is fitted to the measured beam profile data at the bottom in Fig. 6, which gives a beam width of 3.15 ± 0.03 mm. The likelihood value for this distribution is 241. From the simulated data, the expected likelihood value for this specific case is 199 ± 43, which means that the measured data is consistent with a Gaussian beam profile model with the parameters found from the fit.

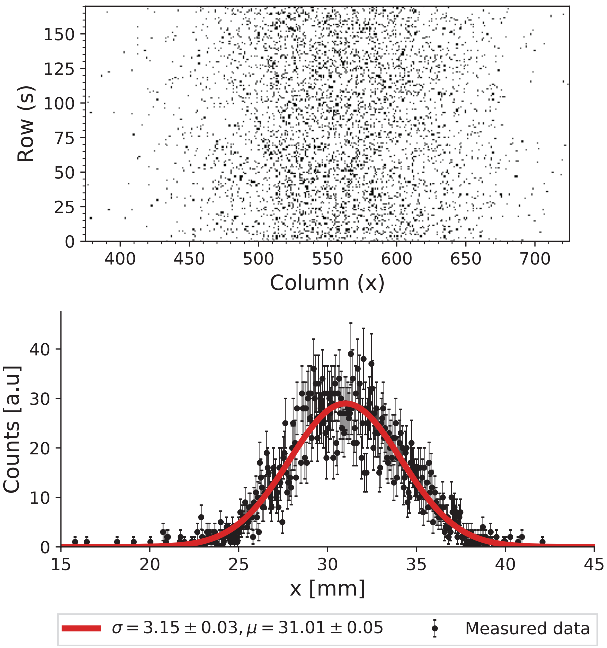

Figure 6: Pixel image (top) and beam profile with a fitted Gaussian distribution (bottom) from measured data. The beam is travelling from top to bottom in the image.

Turn-by-turn Measurements at Injection

In [2] turn-by-turn beam profile measurements are presented which were acquired using a wire grid that was permanently inserted into the beamline during the measurements. To prevent damage to the wires, the beam was only allowed to circulate for 30 turns before being kicked out. The goal of the measurement campaign was to study mismatch from the transfer line to injection in the CPS. For a normal operational beam the horizontal beam width was observed to be oscillating turn-by-turn with a frequency of 0.182 oscillations per turn.

The horizontal PS-BGI instrument typically measures in the order of 1 to 2 ionization electrons per bunch per turn. As shown earlier, around 100 electrons are needed to measure a meaningful beam profile with better than 10% precision. One way to increase the ionization rate is to create a local pressure bump in the region where the ionization occurs. This can be achieved by sublimating an ion pump located next to the PS-BGI instrument.

On September 12th 2018 data was recorded for an operational single bunch beam with an intensity of 70×10^{10} protons, similar to the beam used for the wire-grid measurements in [2]. Before the measurement the nominal vacuum pressure was 2×10^{-10} mbar while during the measurement it was increased to approximately 1×10^{-8} mbar. The signal was boosted to around 80 ionization electrons per bunch per turn, which is sufficient for a meaningful beam profile measurement. Figure 7 shows the beam width measured in this way for each of the first 30 turns. A sinusoidal function with a 1st order polynomial fitted to the data gives a frequency value of 0.184 ± 0.008 oscillations per turn. This is in good agreement with the measured frequency from the wire grids in [2] of 0.182 oscillations per turn. The positive slope of the fitted function is as expected, indicating a growth in the beam emittance as the particles within the bunch filament to fill the mismatched phase space.

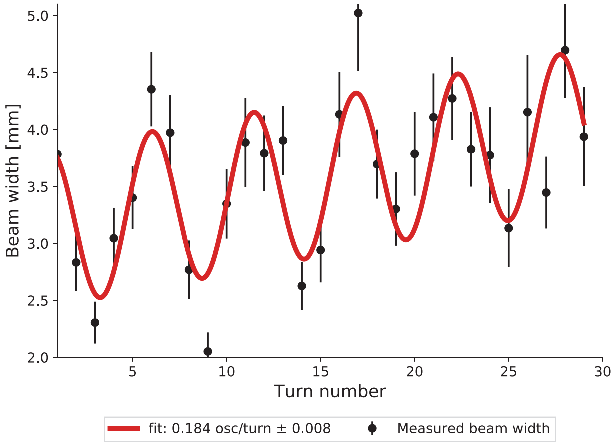

Figure 7: Measured beam width for a single bunch after each turn.

CONCLUSION

The application and data analysis of an ionization beam profile monitor using hybrid pixel detectors has been presented. In contrast to traditional IPMs, no conversion or amplification after the ionization process is needed which allows the beam profile to be measured by directly counting ionization electrons. It has been shown that the response of each detector pixel can be described by a Poisson distribution which enables the use of a global binned maximum likelihood fit. Using this technique, data from Monte Carlo simulations were presented from which the expected accuracy and precision of the instrument could be determined, with turn-by-turn beam profile measurements of a single bunch at injection confirming that less than 100 ionization electrons per profile are required for a meaningful fit.

REFERENCES

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