Measuring the Beam Profile by Counting Ionization Electrons

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Hampus Sandberg (CERN, University of Manchester UK)

B. Dehning, D. Bodart, G. Schneider, J.W. Storey, R. Veness (CERN, Switzerland), W. Bertsche (University of Manchester, Cockcroft Institute, UK), S. Gibson, S. Levasseur (Royal Holloway, University of London, UK), K. Satou (J-PARC/KEK, Japan)

http://bgi-web.web.cern.ch
Ionization beam Profile Monitors (IPM’s) in a nutshell

Beam direction

E-drift field

ion+
e-

Cathode

Anode

Detector

Anode

Beam pipe
Example of Traditional IPM

Each step adds noise and disturbs the signal
IPM with Hybrid Pixel Detector\cite{1}

Direct detection of single ionization electrons

We can apply counting statistics
Hybrid pixel detector to binned profile

**Timepix3**[^2]
- 256 x 256 pixels
- 55 x 55 μm pixel size
- 14 x 14 mm
- Up to 40 million events/s

[^2]: Referenced as Timepix3 in the text.
Counting Statistics

Assumptions for each bin:

• Known average rate
• Discrete events occur independent of each other
• Time between two events is random
• Fixed window of time

Each bin can be modeled as a Poisson process
Poisson Distribution - Measured Data

\[ \lambda = 0.871 \pm 0.009 \]
Simulation

- Important tool to develop and validate the data analysis
- Gives an understanding of precision and accuracy
Step 1:
Take samples from a Gaussian distribution and put them in 55 µm wide bins

Step 2:
Distribute counts in each bin along rows to make a 2D pixel image
Simulation - making realistic data

Step 3:
Mark unresponsive pixels
(Ensure pixels in each bin have same average rate)

Step 4:
Use same number of responsive pixel in all columns
Beam profile - binned maximum likelihood fit

Pixel image to beam profile:
Sum the counts in each column to create a beam profile

True values:
\( \sigma: 2.0 \text{ mm} \)
\( \mu: 20.0 \text{ mm} \)

Residuals:
\( \sigma: 0.01 \text{ mm} \)
\( \mu: 0.02 \text{ mm} \)
Precision

- How much spread in the measured value?
- 10 000 Monte Carlo simulated profiles for each sample size

9% expected precision for 100 ionization electrons
Accuracy

- How far away from the true value?
- 500 simulated beam profiles for each combination of width & position
- Sample size of 100 ionization electrons per beam profile

1.2% expected accuracy for 100 ionization electrons
Beam profile measurements
Beam profile measurement

- @ CERN Proton Synchrotron
- Horizontal pixel IPM instrument
- Intensity: $60 \times 10^{10}$ protons
- Vacuum: $1 \times 10^{-10}$ mbar
- $5 \text{ ms} = 5500$ events
- On average: 2 ionization electrons per turn

![Graph showing beam profile measurement]
Turn-by-turn measurements at injection

• Single bunch operational beam with intensity: 70e10 protons

• Pressure bump from sublimation of ion pump
  • From nominal 2e-10 mbar to approx. 1e-8 mbar

• On average: 80 ionization electrons per turn
Turn-by-turn measurements at injection

- IPM: $0.184 \pm 0.008$ oscillations per turn
- SEM-grid measurement$^{[3]}$: 0.188 oscillations per turn
Conclusion

• Hybrid pixel detectors enables **detecting and counting** individual ionization electrons
  • Allows application of counting statistics to the data analysis
  • Assumptions for Poisson process in each bin are met
  • Binned maximum likelihood fit

• Monte Carlo simulation
  • Expected precision
  • Expected accuracy

• Beam profile measurement
  • Turn-by-turn at injection in good agreement with independent SEM-grid measurements

**A meaningful beam profile can be extracted from only 100 ionization electrons**
References


Extra information
How do we know if it’s a good fit?

• No simple analytical expression

• Run Toy Monte Carlo Simulations
  • Known beam width
  • Known sample size (i.e. number of ionization electrons)
  • Store calculated likelihood value for a range of width and sample size combinations
  • One simulation run seen on the right

• Fit to measured data
  • Is this likelihood value within the simulated range?
  • If not, calculate an RMS beam width instead