Comparing the BGI and BWS Transverse Profiles

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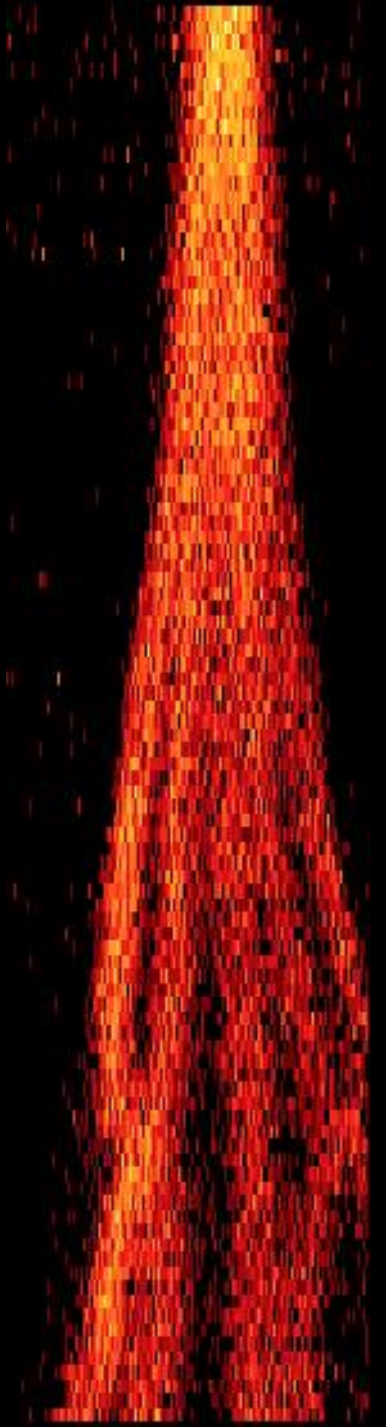
Joint Accelerator Performance Workshop



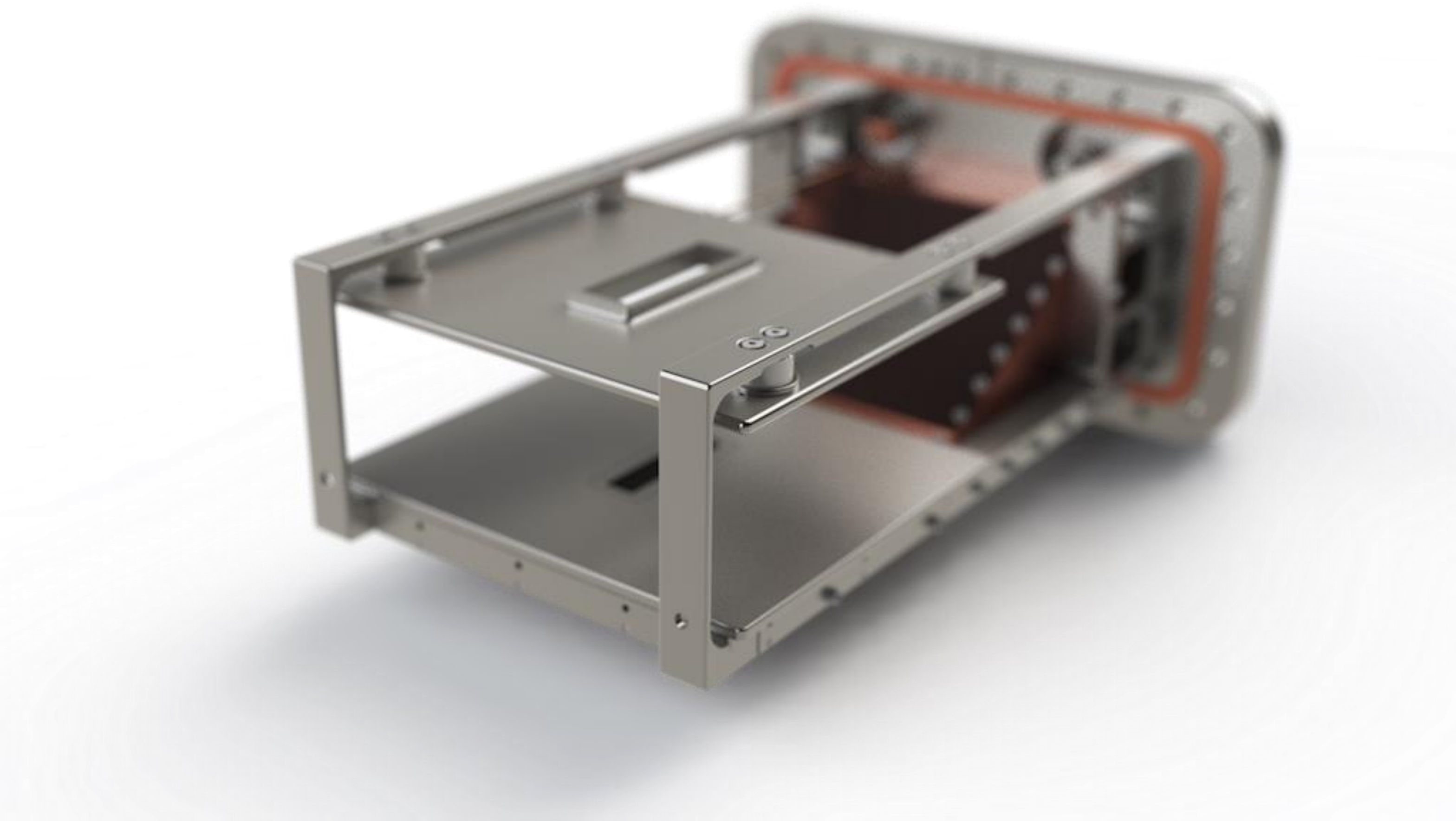
Presentation Outline

1. **BGI Overview**
   a. Measurement Capabilities

2. **Benchmarking with the BWS**
   a. Emittance Benchmarking
   b. Comparing Profile Distributions

3. **Feature Development**
   a. Measuring Beam Evolution
   b. Bunch-by-bunch measurements
   c. Measuring beam tails

4. **Future Directions**
   a. Making the BGI Fully Operational
   b. Scheduled Installations and Upgrades



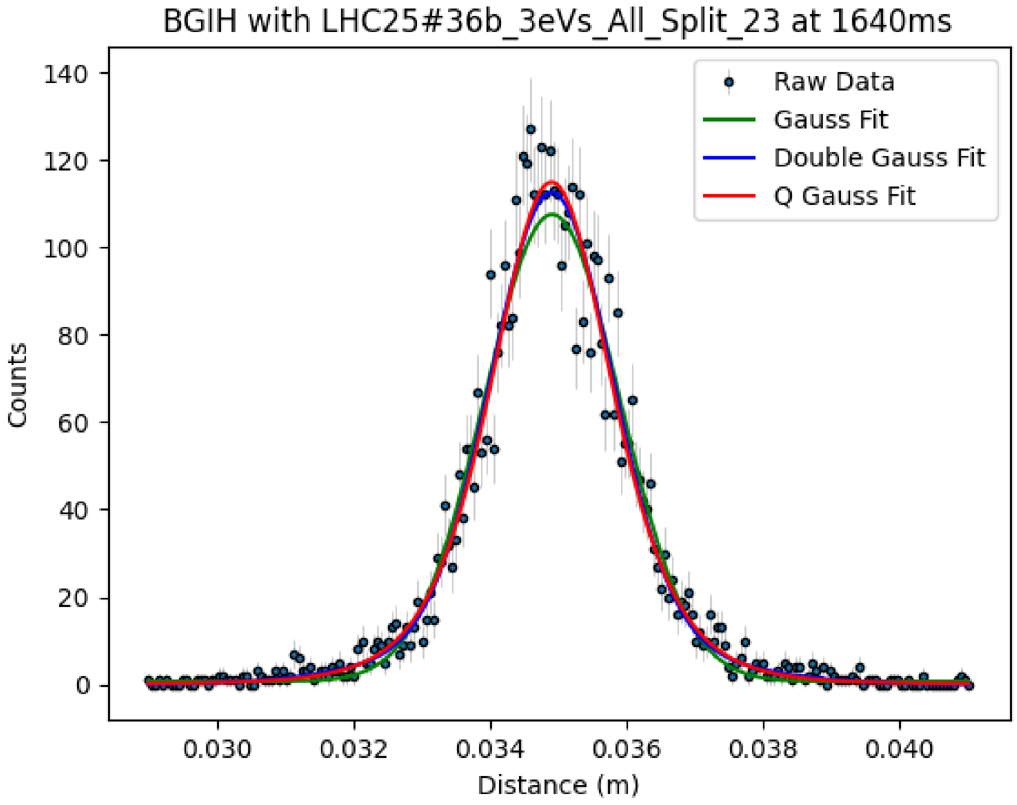
BGI Overview

The BGI in Brief

The **Beam Gas Ionisation Monitor (BGI)** is an Ionisation Profile Monitor (IPM) using **Timepix3** detectors, designed for **transverse profile measurements**.

BGI Features

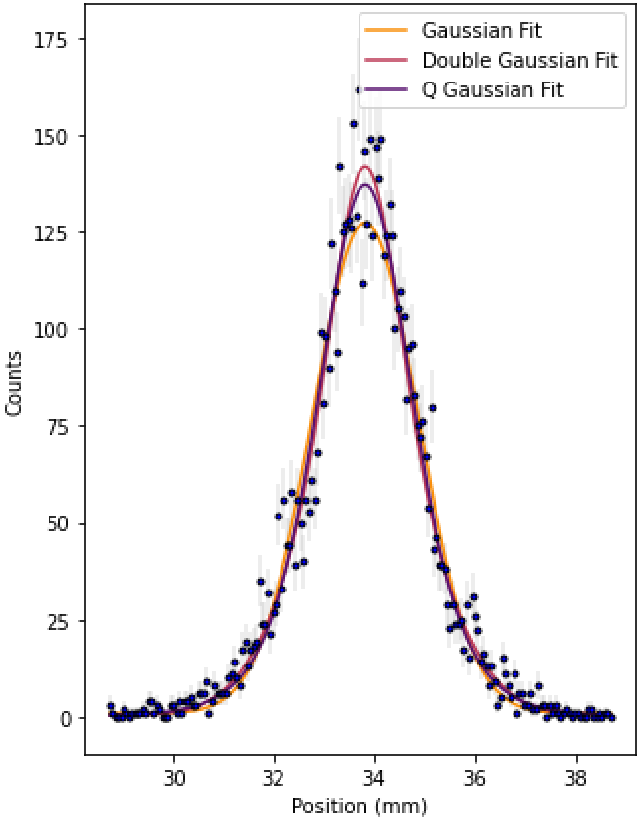
- **Non-destructive** measurement
- Beam profile is measured by counting individual ionisation electrons
- Simple uncertainty quantification with Poisson statistics
- Regular operating mode with ≥ 100 ns integration time, integrating over all bunches
- **Bunch-by-bunch** measurements using 1.56 ns time resolution per ionisation event
- Monitor **beam evolution** throughout the cycle with up to 1024 profiles / cycle
- Highly sensitive **beam loss monitor**
- Can **boost signal** using gas injection



BGI Profile Examples

The following profiles are taken with a 36-bunch LHC-type beam at flat-top, with a 1.9 ms integration time, without gas injection.

BGIH Profile



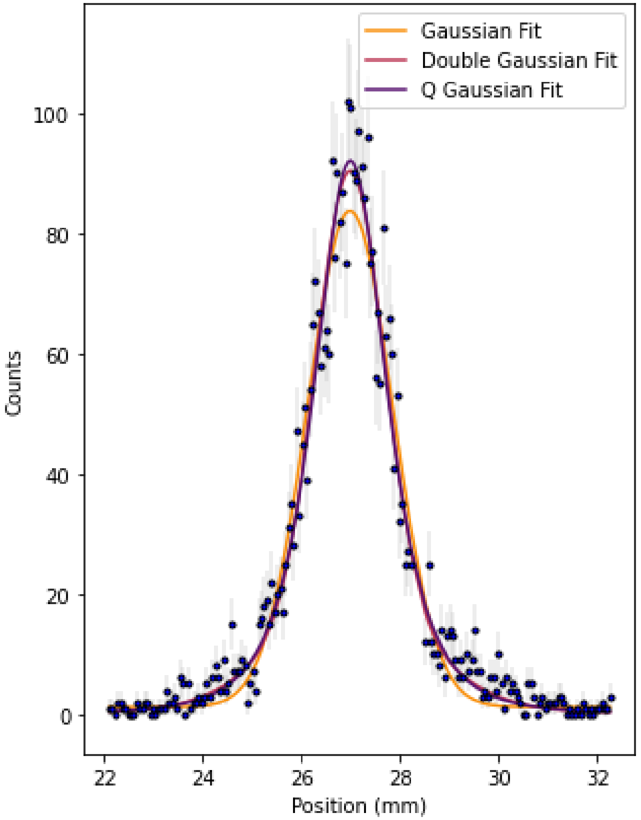
Total Counts:
6603 counts

σ:
0.90 ± 0.03 mm

Background:
0.0 ± 0.3 counts

q:
1.27 ± 0.05

BGIV Profile



Total Counts:
3703 counts

σ:
0.67 ± 0.03 mm

Background:
0.0 ± 0.3 counts

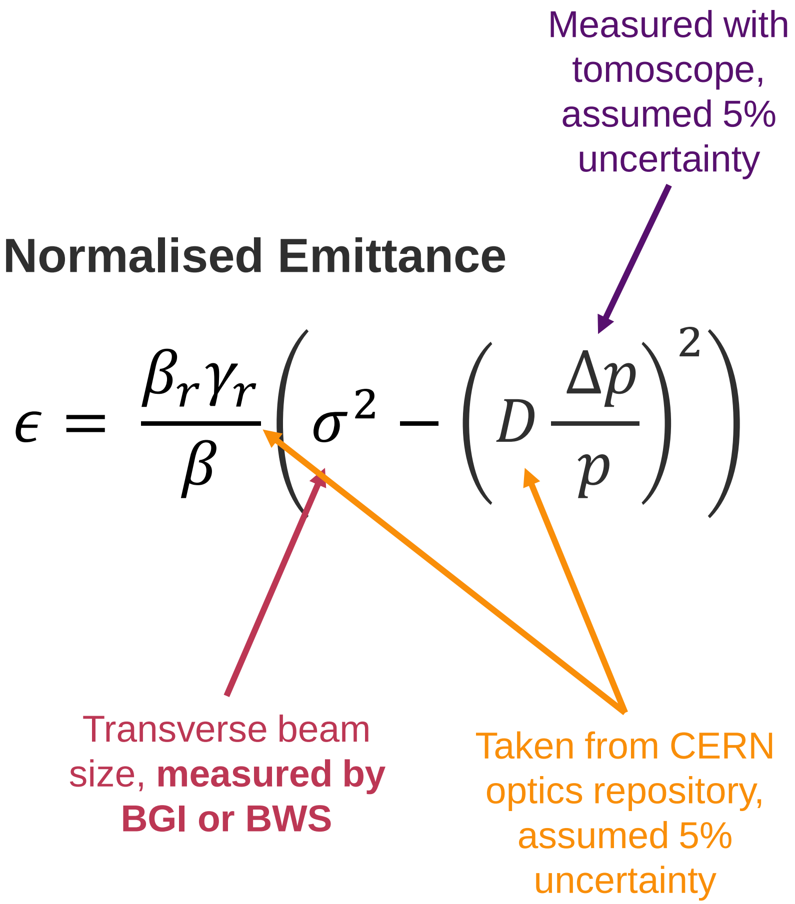
q:
1.51 ± 0.05

BGI-BWS Benchmarking

Using the PS-BGIs and PS-BWSs

Emittance Benchmarking

Normalised Emittance

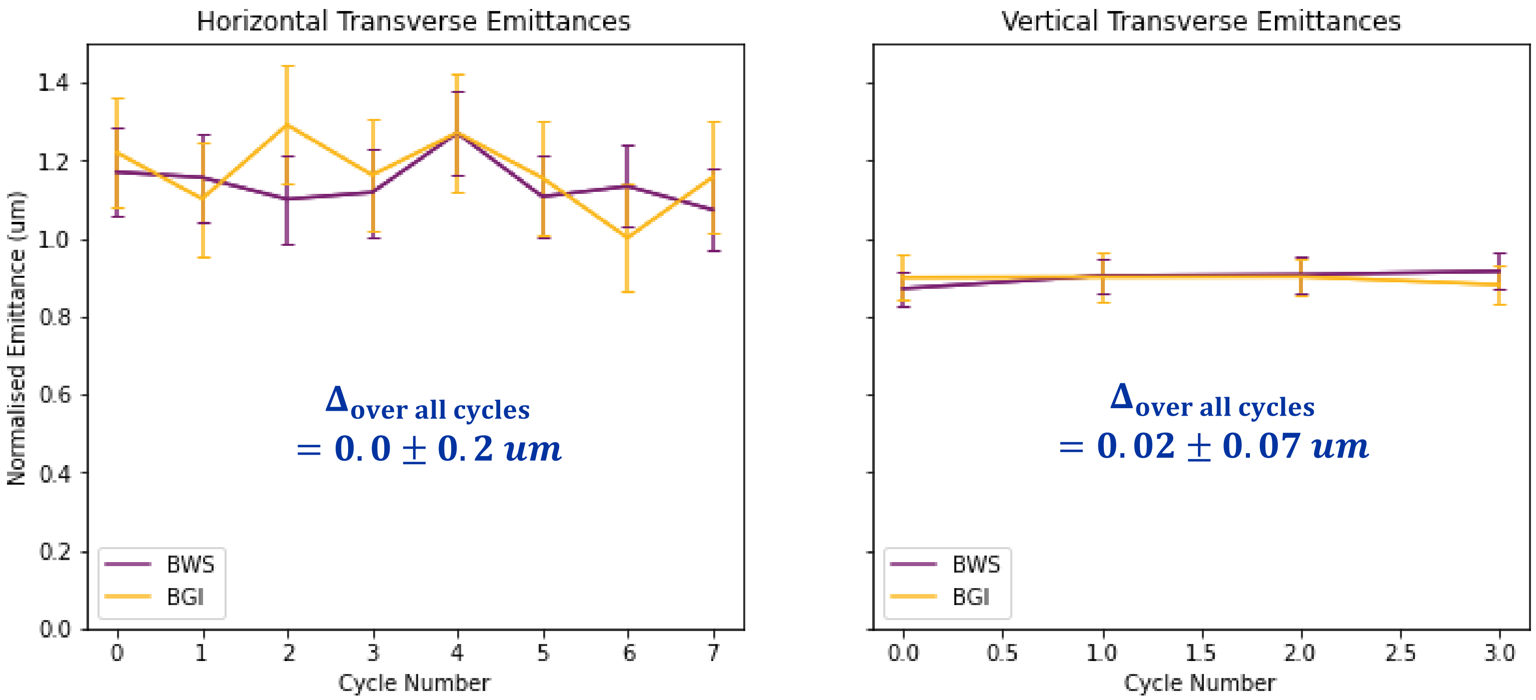


$$\epsilon = \frac{\beta_r \gamma_r}{\beta}\left(\sigma^2 - \left(D\frac{\Delta p}{p}\right)^2\right)$$

Measured with tomoscope, assumed 5% uncertainty

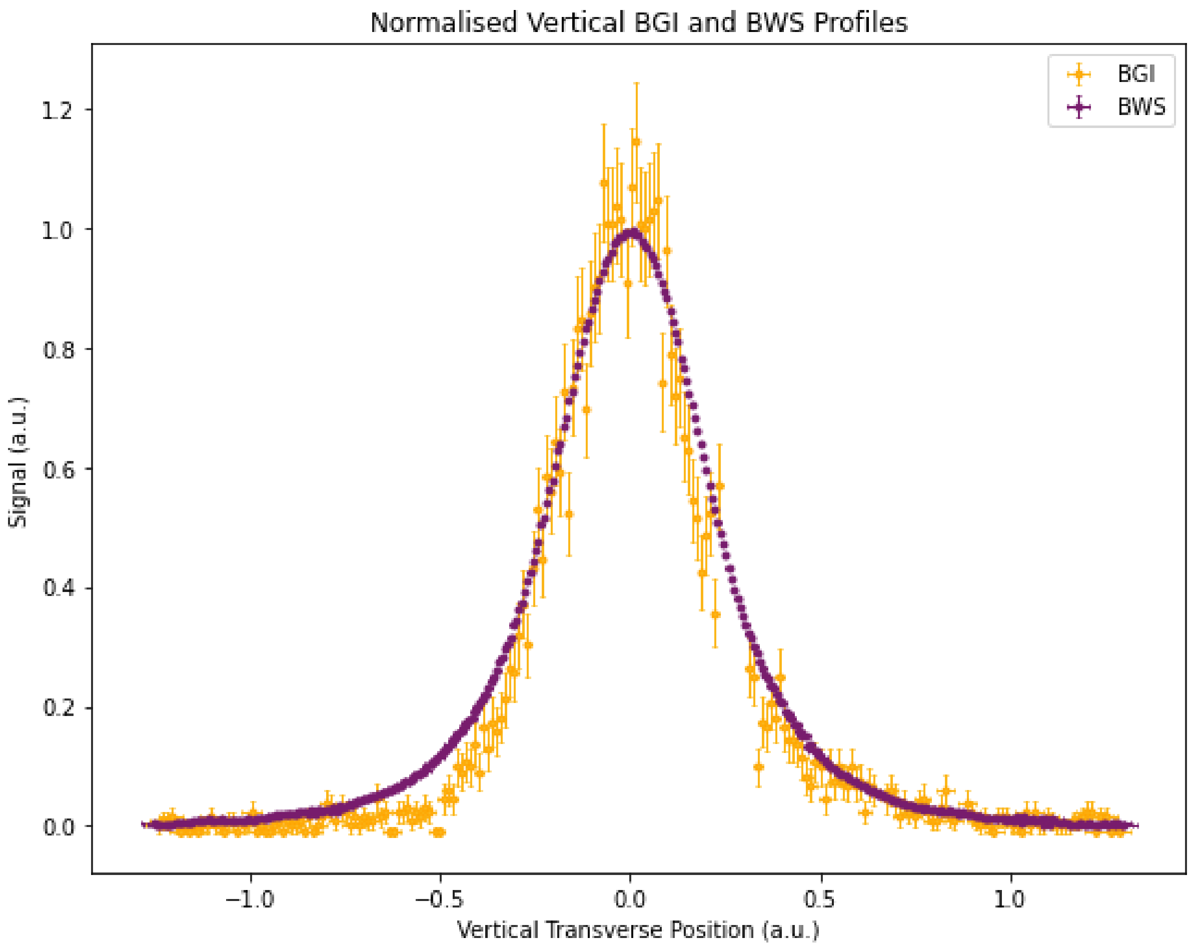
Transverse beam size, **measured by BGI or BWS**

Taken from CERN optics repository, assumed 5% uncertainty



- Data collected with LHC-type beam at flat top with both PS-BGIs (1.9 ms integration), BWS.64.V and BWS.65.H, without gas injection
- Error of the transverse beam size is taken to be one sigma from the covariance matrix
- **Emittances of BGI and BWS agree within less than one sigma**

Profile Distribution Comparison



- Measurement taken with 36-bunch LHC-type beam a flat top with BGIV and BWS.64.V
- BGI used 1.9 ms integration time, without gas-injection
- Zero dispersion optics in the vertical plane allows **linear scaling of the x-axis by $1/\sqrt{\boldsymbol{\beta}}$** for comparison of BGI and BWS profiles

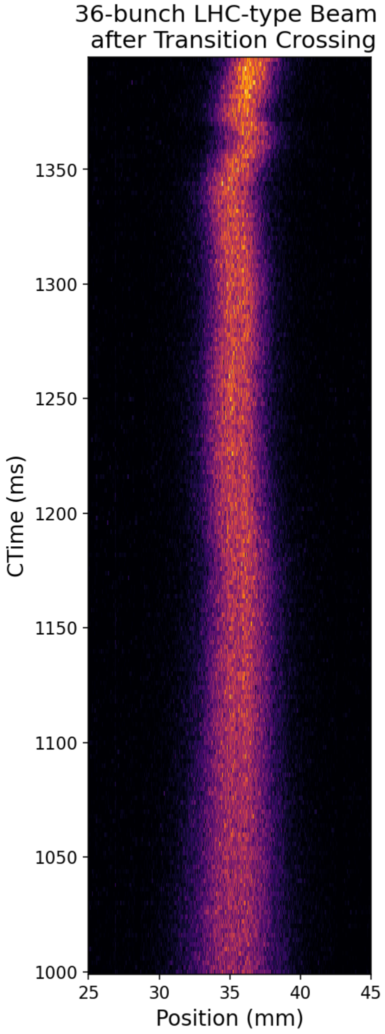
$$\sigma = \sqrt{\beta\epsilon + \cancel{\left(D\frac{\Delta p}{p}\right)^2}}$$

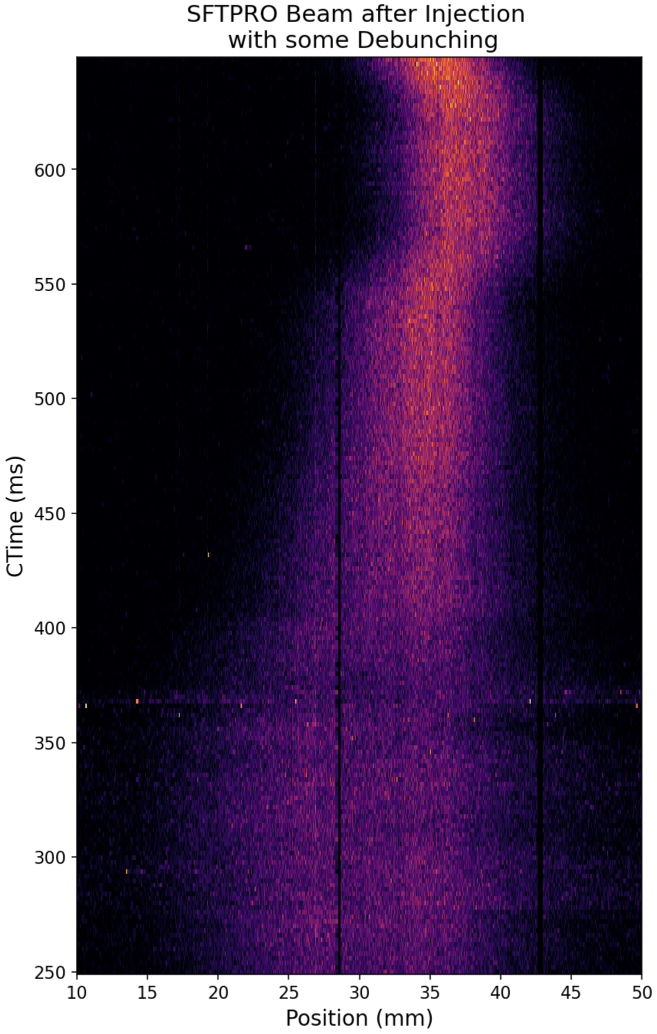
Feature Development

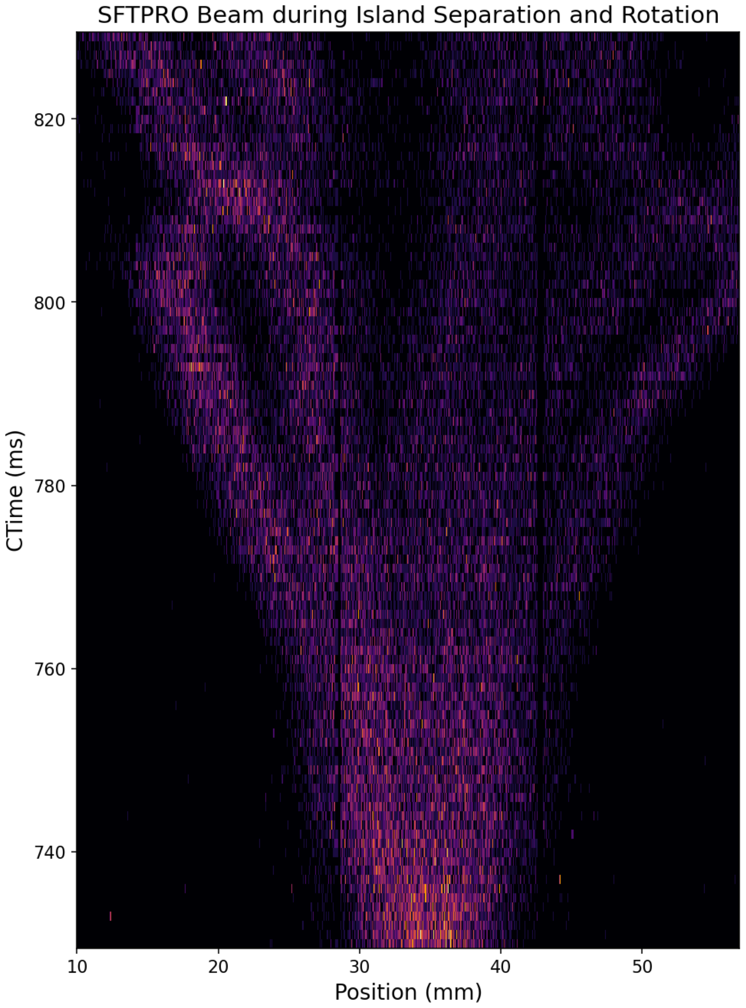
Measuring Beam Evolution

Measuring many profiles over the course of one cycle, provides information on the evolution of:

i. Profile distribution
ii. Transverse emittance
iii. Beam position
iv. Relative intensity

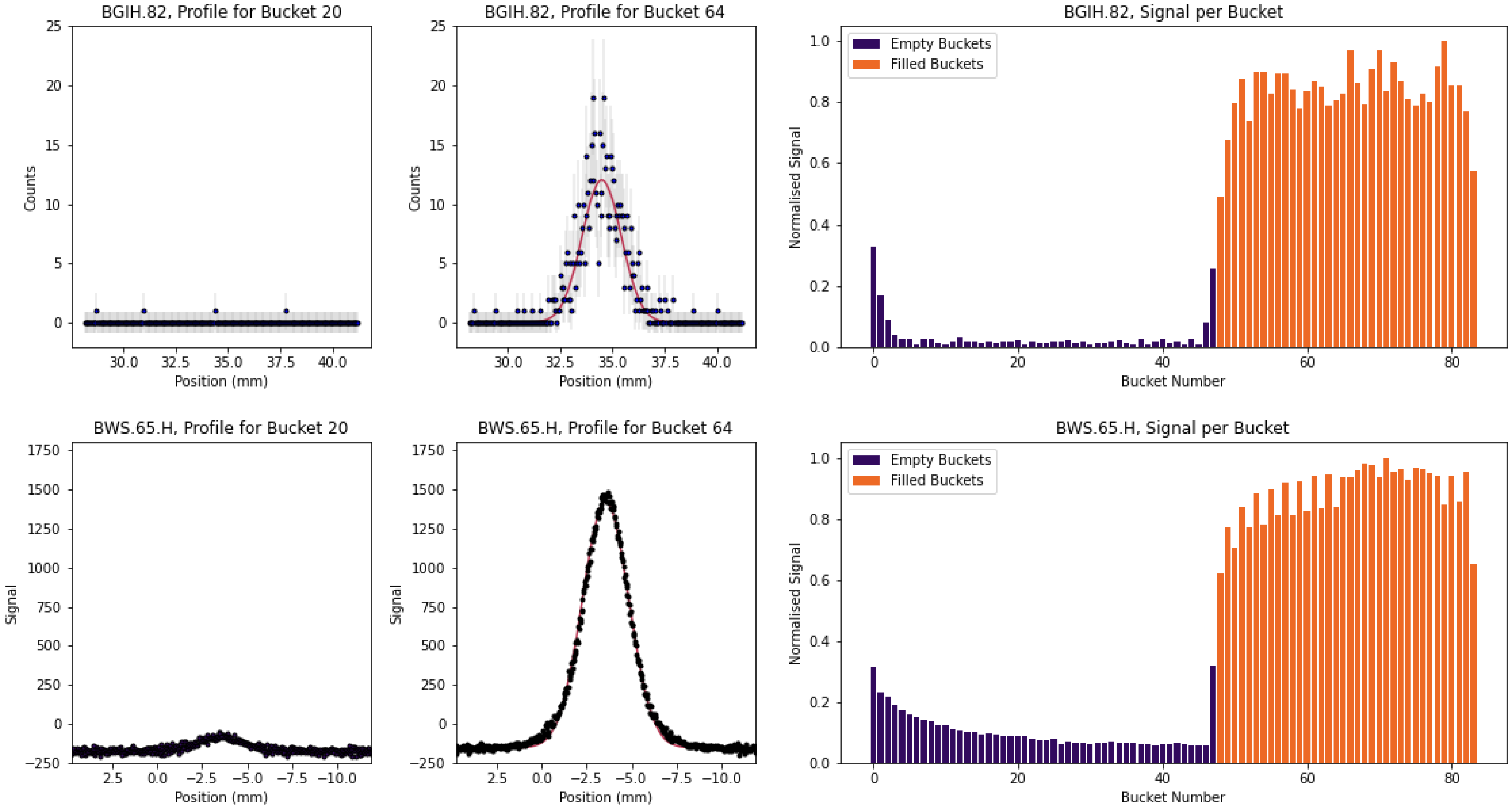

36-bunch LHC-type Beam after Transition Crossing


SFTPRO Beam after Injection with some Debunching


SFTPRO Beam during Island Separation and Rotation

First-Steps Towards Bunch-by-Bunch Validation

- Used 36-bunch LHC-type beam at flat top with harmonic 84, without gas injection
- BGI operated in “RF mode”, integrating over 2000 turns
- **Results validate BGI bunch-by-bunch time structure**
- BGI signal could be increased to improve profile quality


BGIH.82, Profile for Bucket 20

BGIH.82, Profile for Bucket 64

BGIH.82, Signal per Bucket

BWS.65.H, Profile for Bucket 20

BWS.65.H, Profile for Bucket 64

BWS.65.H, Signal per Bucket

Tail/Halo Measurements

Metrics for Good Tail Measurements:

1. High **signal to noise ratio**
2. High **count rate**

Enhancing BGI Performance for Tail Measurements:

- Factors such as intensity, energy, rest gas composition and vacuum pressure affect signal

$$n \propto \overbrace{\sigma(Z, \beta)}^{\text{Ionisation Cross-section}} \times \underbrace{I}_{\text{Beam Intensity}} \times \overbrace{P}^{\text{Rest gas pressure}}$$

- Use **gas injection** to boost signal
- Apply cluster finding algorithm to **remove any noise/beam loss** (previously demonstrated)

An Example of BGI Performance for Tail Measurements:

Using a 36-bunch LHC-type beam at flat-top in the PS, assuming tails are events outside 3.5 σ

- **~1e3 counts / second in the tails** without gas injection
- **~5e5 counts / second in the tails** with argon gas injection and a pressure increase of 10^2 mbar

Future Directions

Vision for PS-BGI Operation

Default Configurations

- Expert-chosen configurations for each beam type
- Operators could choose to leave the BGI **ON at all times**, set to a configuration of interest

Ex. 72-bunch LHC-type beam, BGI-configurations:

- Beam evolution (injection to extraction) without gas-injection
- Beam evolution (injection to extraction) with gas-injection
- Bunch-by-bunch at flat-top with gas injection
- Turn-by-turn at flat-top with gas injection

Custom Setup Options for Studies

- Modifiable settings (integration times, number of profiles per cycle etc.) of default BGI-configurations
- Collect in **raw-data mode**, so the beam-loss removal algorithm may be applied

Ex. For tail studies, an operator simultaneously:

- Uses gas injection
- Operates in bunch-by-bunch mode
- Collects in raw-data mode and remove beam-loss in post-processing

For All Setups

- Live monitoring and automatic logging of data

Next Steps for the PS-BGI
Overcoming Technical Challenges

Goal #1: No expert required

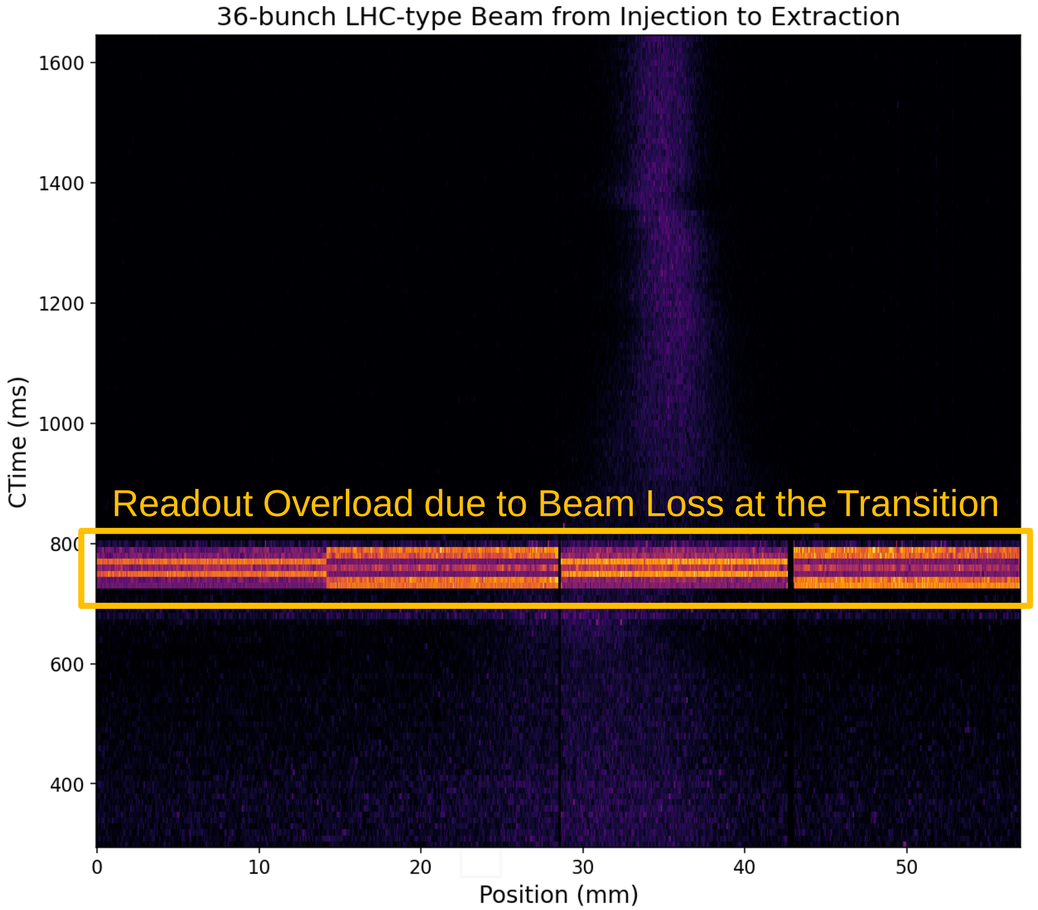
- Automate noisy pixel masking
- Determine and implement systematic calibration protocols (in progress)
- Increase robustness of Timepix3 readout electronics with front-end upgrade (in progress)

Goal #2: Measuring from Injection to Extraction

- Prevent data overload by allowing integration settings to vary over a cycle
- Have an expert determine an optimal default configuration for each beam-type

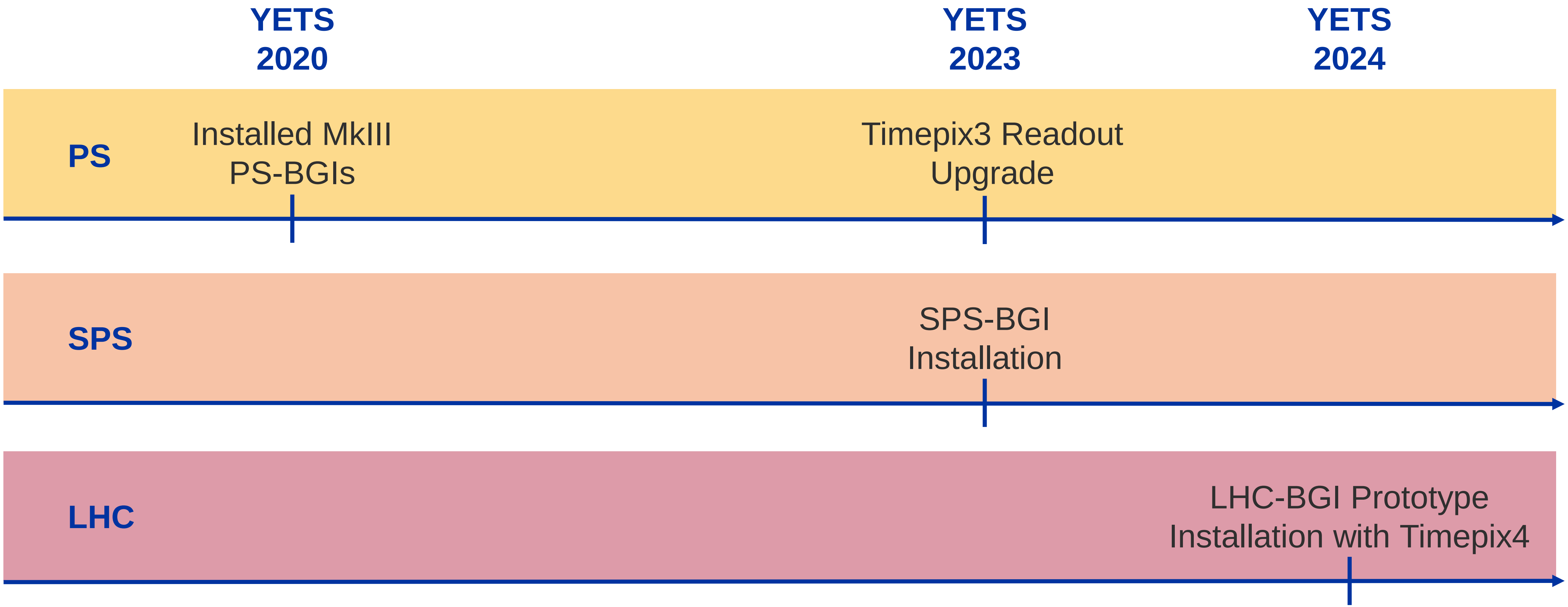
Goal #3: Bunch-by-Bunch

- Enable offset tuning with step sizes < 5 ns



Readout Overload due to Beam Loss at the Transition

Future Developments for the BGI
Installations Along the Accelerator Chain



YETS 2020

YETS 2023

YETS 2024

PS

Installed MkIII PS-BGIs

Timepix3 Readout Upgrade

SPS

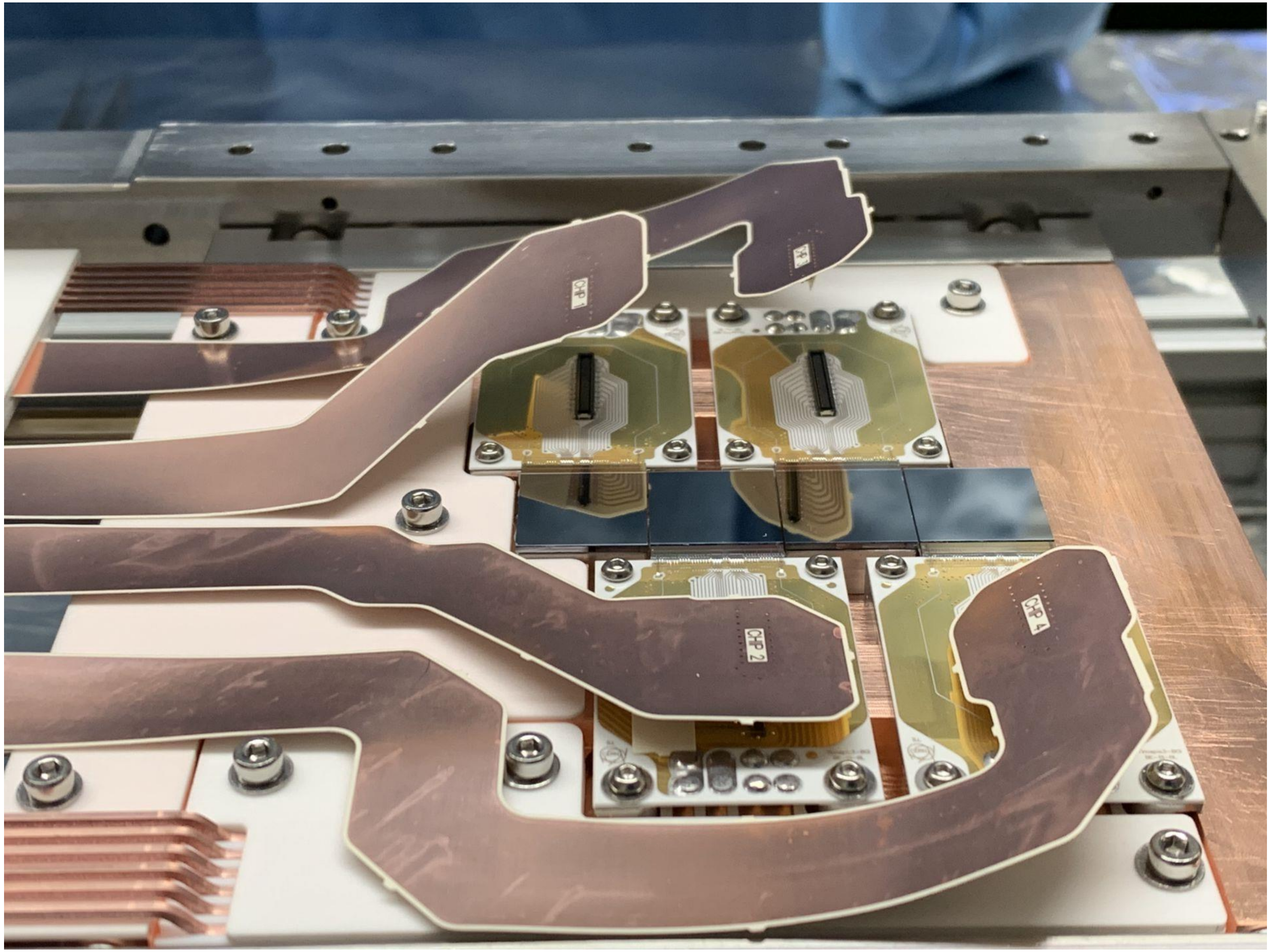
SPS-BGI Installation

LHC

LHC-BGI Prototype Installation with Timepix4

Summary

- The BGI has promising features for emittance, tails/halo and transverse profile studies
- Successfully validated BGI beam profiles with BWS for LHC-type beam at flat-top
- Further development in progress for the instrument to be fully operational
- Future installations of the BGI in the SPS and LHC in the coming years



Appendix

Calculating the Expected Number of Ionised Electrons

Number of Ionised Electrons:

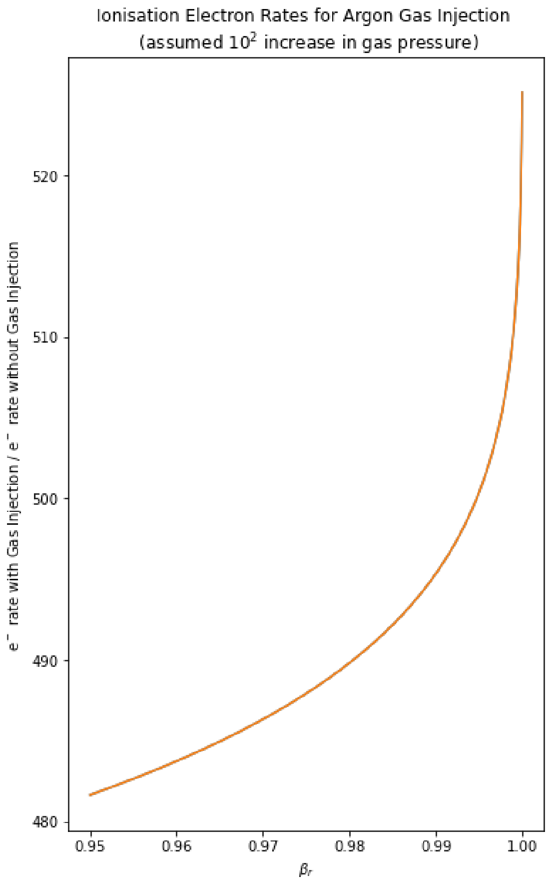
$$n = L\sigma N \times \frac{P}{kT}$$

L: detector length
N: number of protons passing over the BGI
P: pressure in the beam-pipe
k: Boltzmann constant
T: temperature

Ionisation Cross-section:

$$\sigma = 4\pi Z^2 \frac{\hbar^2}{(mc\beta)^2}(M^2\chi + C), \qquad \chi = \ln\frac{\beta}{\sqrt{1-\beta^2}} - \beta^2$$

Z: atomic number of beam particle
m: mass of the electron
c: speed of light
β : beam speed over the speed of light
M^2 : constant dependent on rest gas composition
C: constant dependent on rest gas composition



See this document from the vacuum group discussing correction factors for the ionisation cross-section equation at high energies

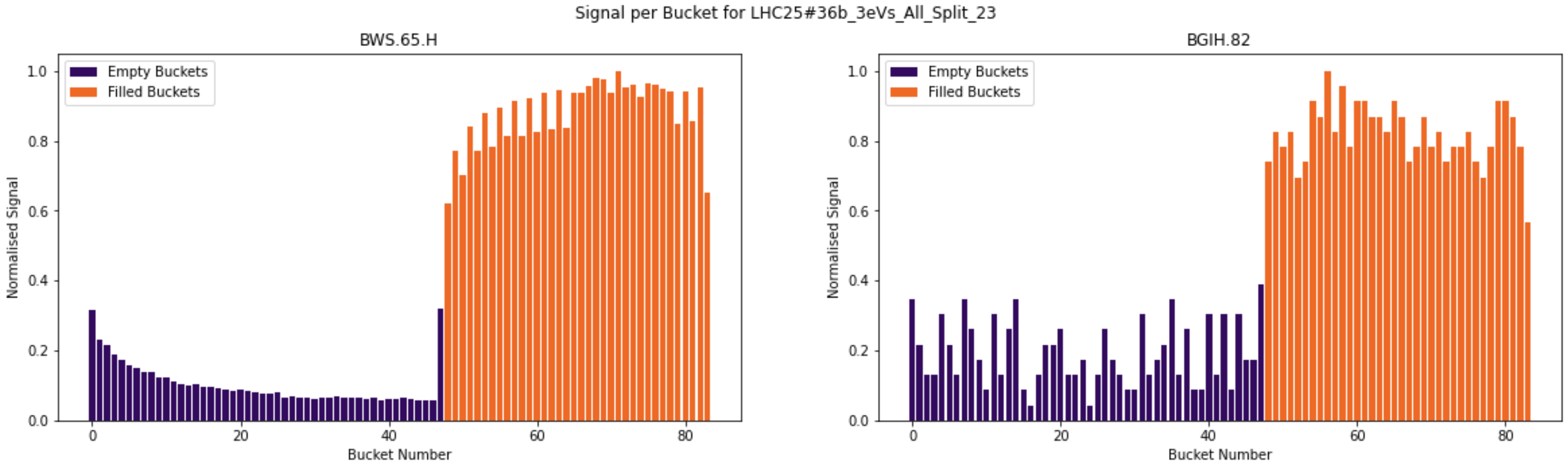
Note: These equations do not account for factors that affect signal such as detector efficiency and noise

Bunch-by-Bunch Signal Metrics

- Different metrics for signal give us slightly different results
- Difference can be attributed to **BWS** linear background with a slope
- Difference can be attributed to noise picked up by **BGI** pixel detectors, which result in **outliers** in the profile

*Note: **y** in the equations on the right denotes the array of y-values that forms the transverse profile associated with each bucket*

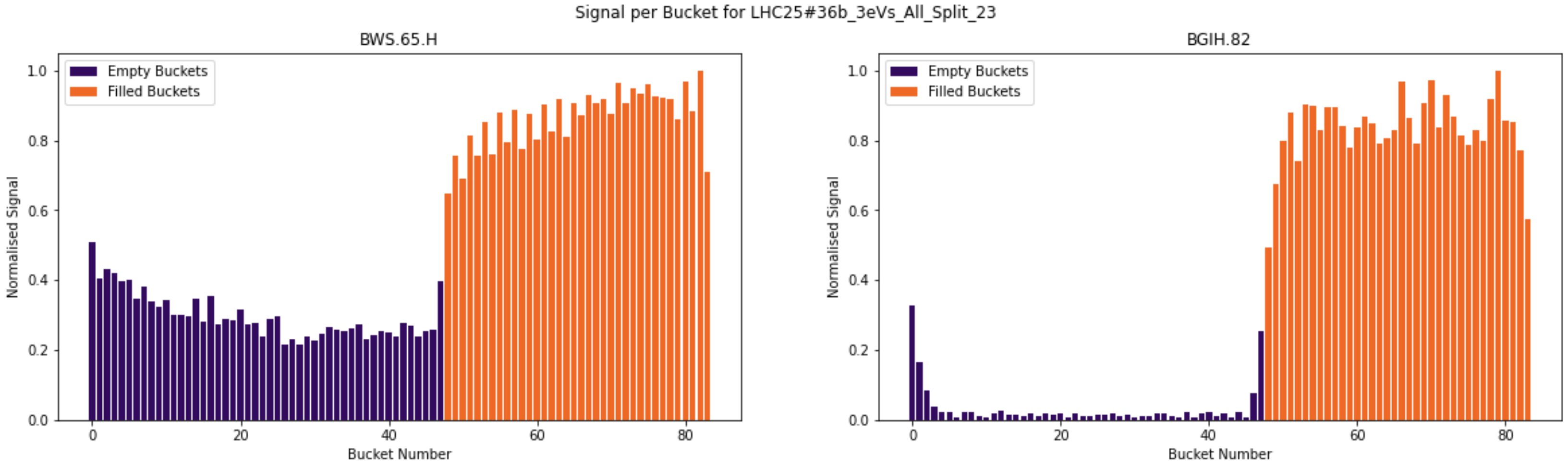
$$Signal = \max\{y\} - \min\{y\}$$


Signal per Bucket for LHC25#36b_3eVs_All_Split_23

BWS.65.H

BGIH.82

$$Signal = \sum(y_i - min\{y\})$$


Signal per Bucket for LHC25#36b_3eVs_All_Split_23

BWS.65.H

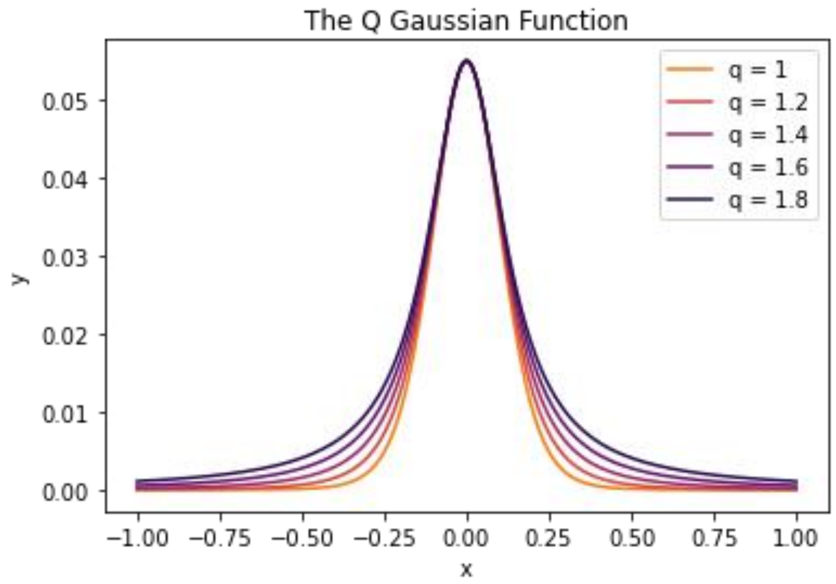
BGIH.82

The Q Gaussian

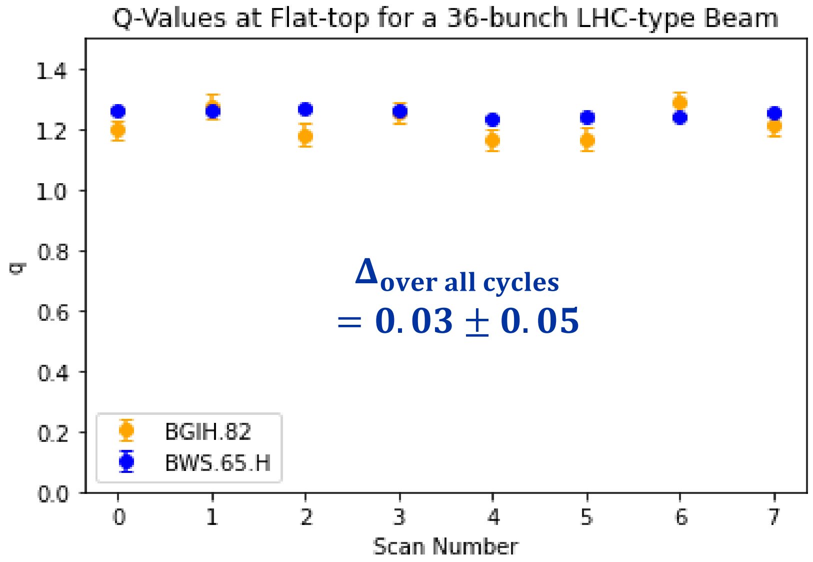
Q Gaussian Function:

$$f(x) = |1 - \frac{1}{2}(1-q)\frac{(x-\mu)^2}{\sigma^2}|^{\frac{1}{1-q}}$$

- Provides a more accurate model of the data
- Q value can be used to quantify the tail population



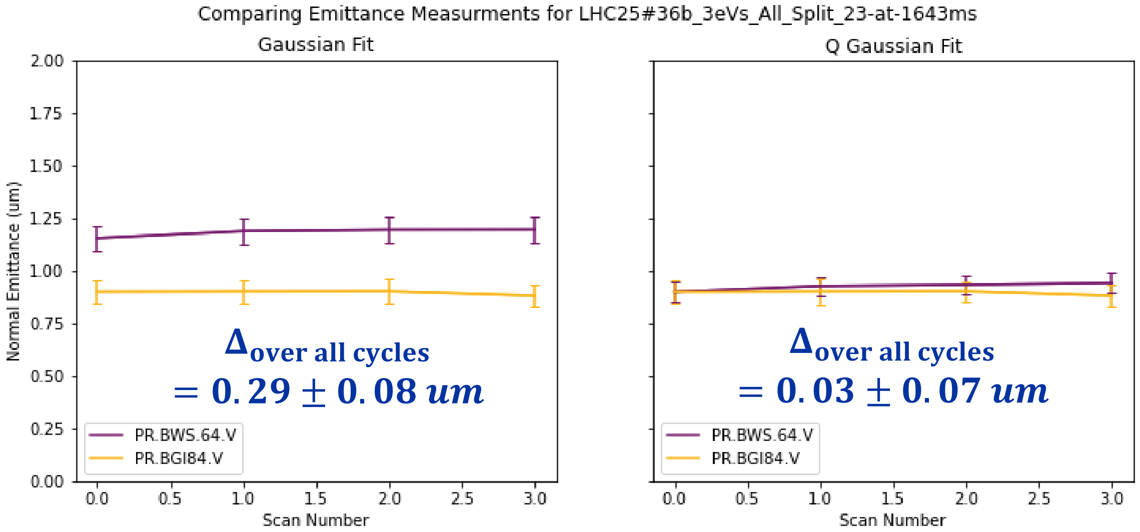
The Q Gaussian Function



Q-Values at Flat-top for a 36-bunch LHC-type Beam

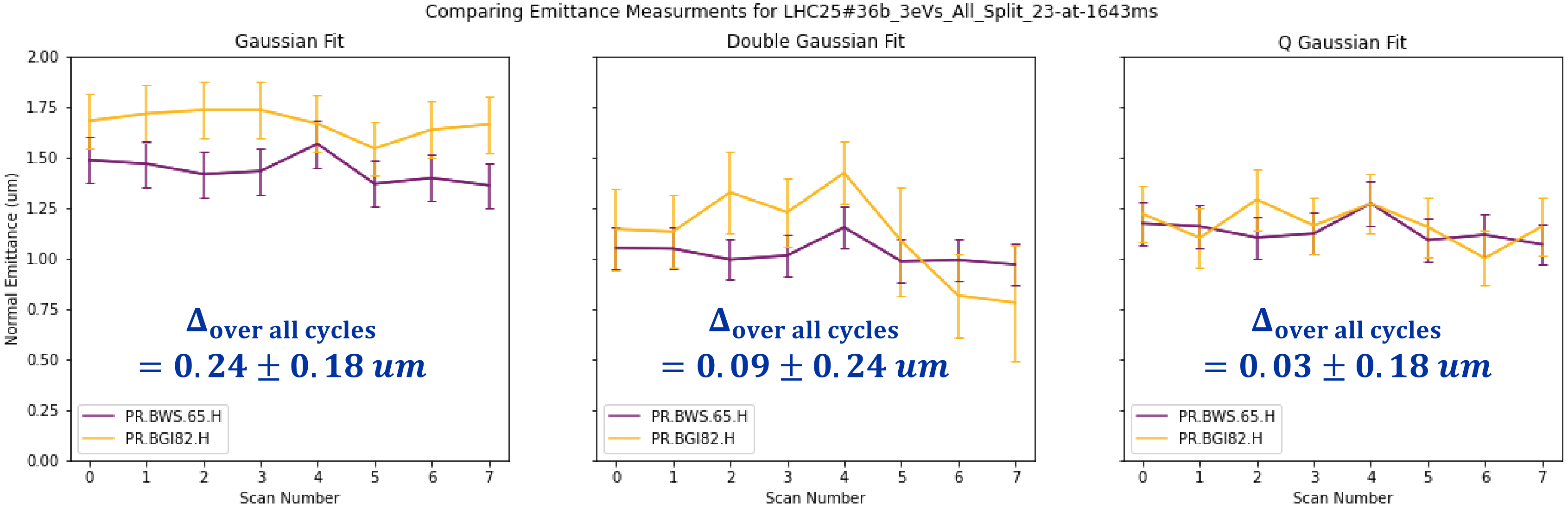
$\Delta_{\text{over all cycles}} = 0.03 \pm 0.05$

Comparing Emittances with Different Fit Types



$\Delta_{\text{over all cycles}} = \mathbf{0.29 \pm 0.08}\ um$

$\Delta_{\text{over all cycles}} = \mathbf{0.03 \pm 0.07}\ um$

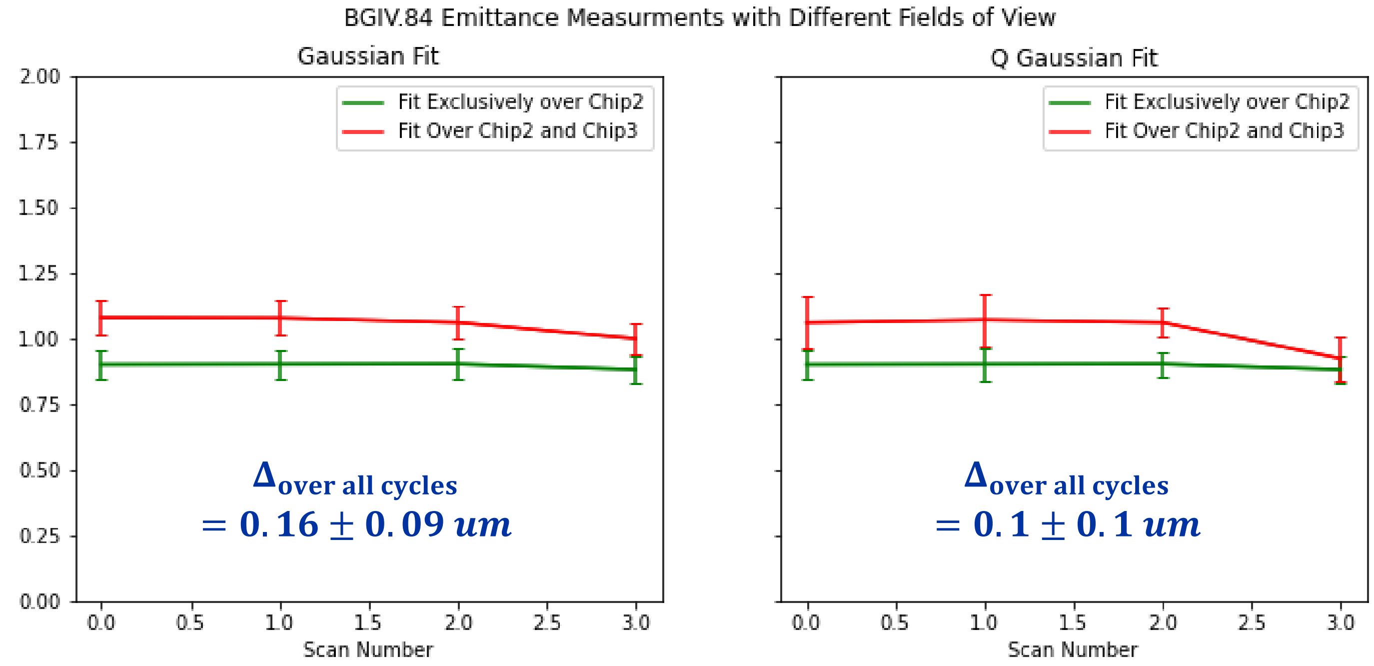


$\Delta_{\text{over all cycles}} = \mathbf{0.24 \pm 0.18}\ um$

$\Delta_{\text{over all cycles}} = \mathbf{0.09 \pm 0.24}\ um$

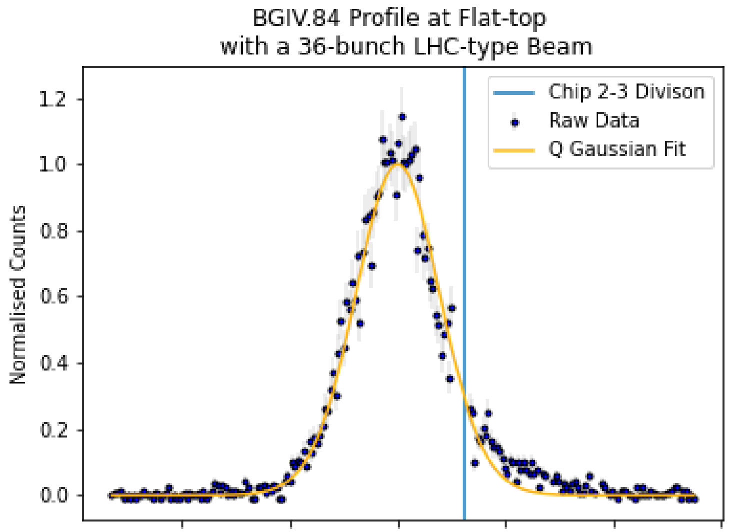
$\Delta_{\text{over all cycles}} = \mathbf{0.03 \pm 0.18}\ um$

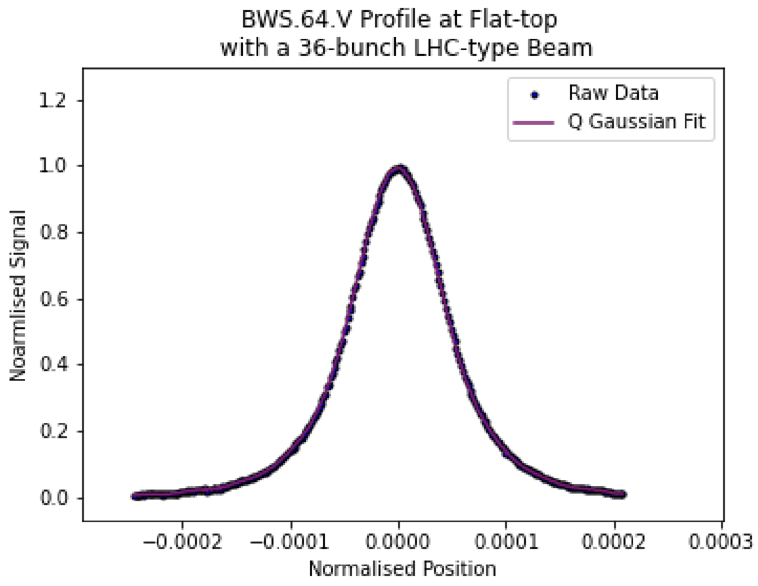
Investigating the Asymmetry on the BGIV



$$\Delta_{\text{over all cycles}} = 0.16 \pm 0.09\ um$$

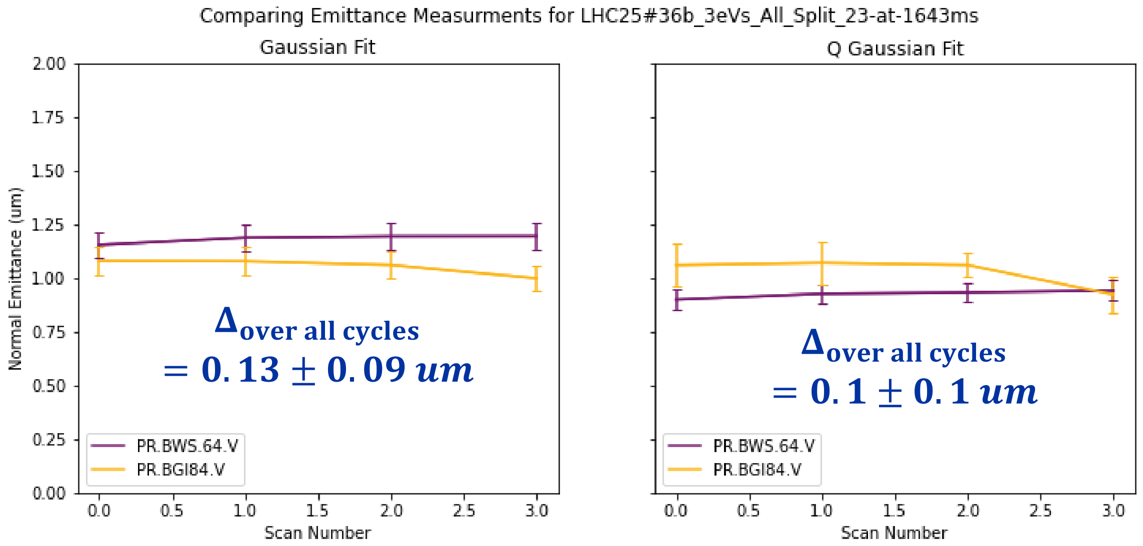
$$\Delta_{\text{over all cycles}} = 0.1 \pm 0.1\ um$$





Investigating the Asymmetry in the Vertical BGI

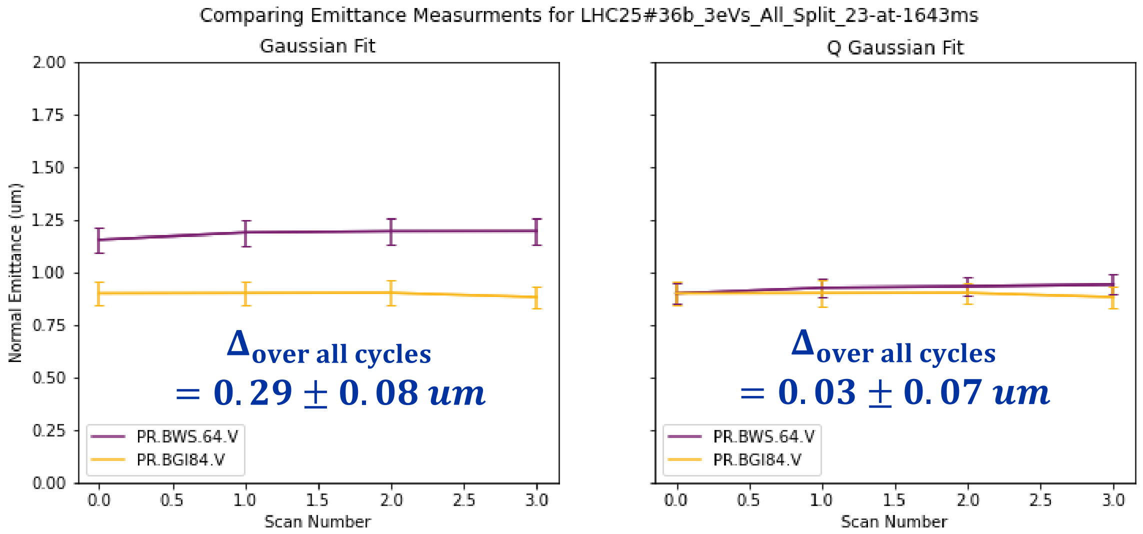
Fitting over Both Chip2 and Chip3



$\Delta_{\text{over all cycles}} = 0.13 \pm 0.09\ um$

$\Delta_{\text{over all cycles}} = 0.1 \pm 0.1\ um$

Fitting Exclusively Over Chip2



$\Delta_{\text{over all cycles}} = 0.29 \pm 0.08\ um$

$\Delta_{\text{over all cycles}} = 0.03 \pm 0.07\ um$