14th HL-LHC Collaboration Meeting
Genoa - 9th October 2024

Update on the Beam Gas Ionisation (BGI) Profile Monitor

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Thanks to: M. Navarro Baeza, C. Fleisig, S. Gibson, M. Gonzalez Berges, S. Jackson,
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Outline

- **Introduction**
  - Functional Specification
  - Principle of Beam Gas Ionisation (BGI) Profile Monitor
- **BGI Design Studies**
  - Field Cage & Ionisation Electron Detector
  - Impedance Studies
  - Magnet
  - Integration
  - Expected Performance
- **PS & SPS BGI Experience & Implications for LHC BGI Design**
  - Performance of the PS & SPS BGI's
  - Technical Issues: Readout Architecture & EMI
- **Milestones & Timeline**

Functional Specification

Independent measurement of transverse **beam profile evolution** throughout the acceleration cycle.

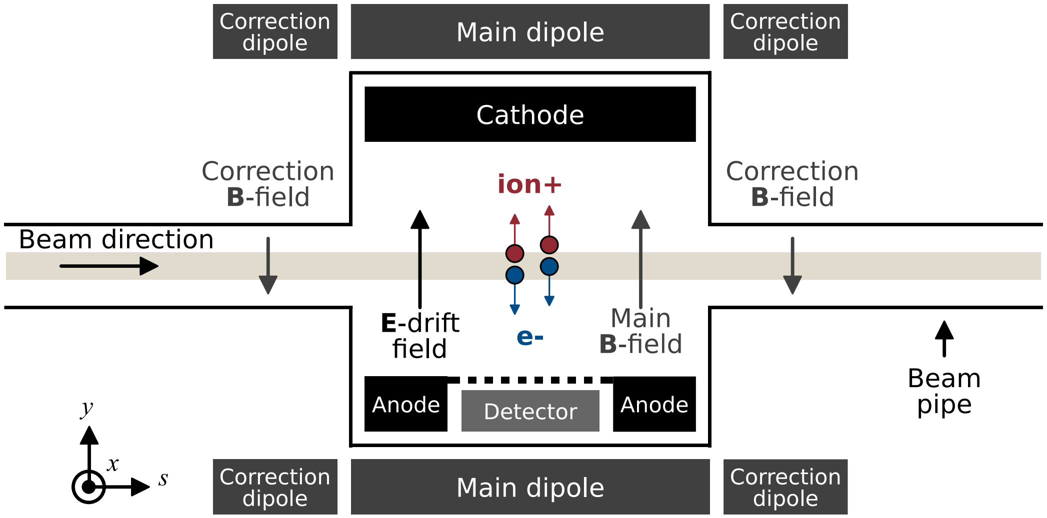
Original functional specification "Measurement of the Beam Transverse Distribution in the LHC Rings (LHC-B-ES-0006)", reviewed at "LHC Beam Size Measurement Review" (Oct. 2019.)

Specifications for HL-LHC:

Beam measurements (average over all bunches)
- Accuracy (systematic error) < 5%;
- Precision / reproducibility of about ~1%;
- Frequency > 10 Hz.

Bunch-by-Bunch measurements
- Precision / reproducibility of about ~1%;
- Frequency < 1 min. for all bunches.

Principle of Operation



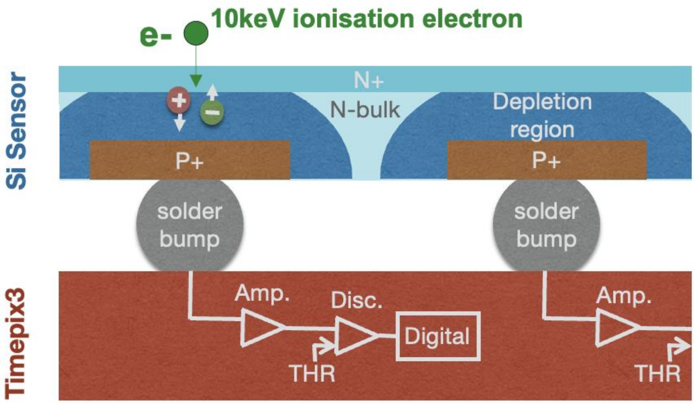
1. Beam ionises **residual gas**;
2. **Ionisation electron** accelerated & transported by electromagnetic fields onto detector;
3. Electron detector = **Timepix3(/4)** Hybrid Pixel Detector.

Ionisation Electron Detection with Timepix3/4

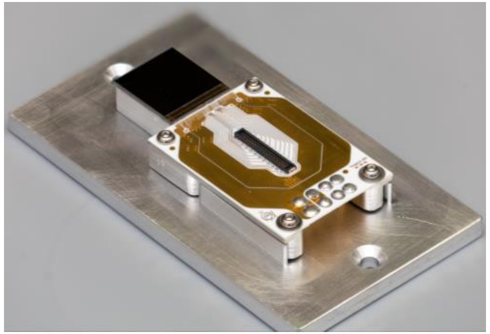
Timepix3(/4) Hybrid Pixel Detector optimized for **10 keV electron detection** inside the beam pipe

Charge > Threshold → Event, consisting of:

- Pixel position → **Where** ($\sigma_{position}$< 16 um)
- Time of Arrival (ToA) → **When** (σ_{time}=1.6 ns / 200 ps for TPX4)
- Time-Over-Threshold (ToT) → **~Energy**



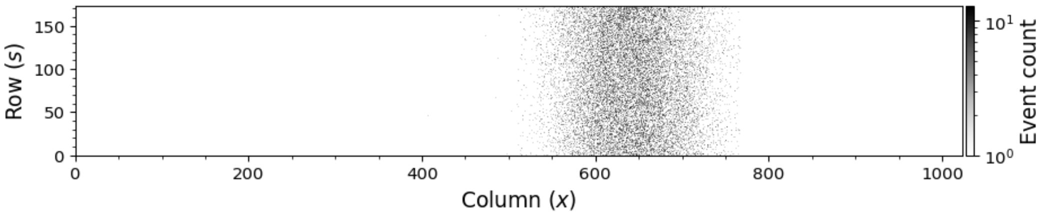
Single electron detection & **digitisation directly inside the beam pipe.**

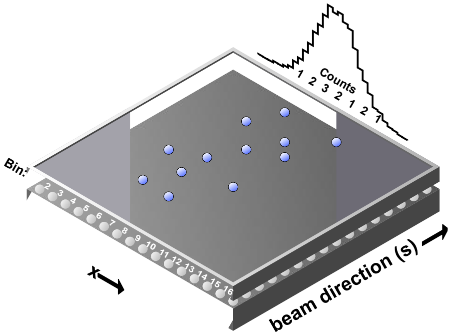


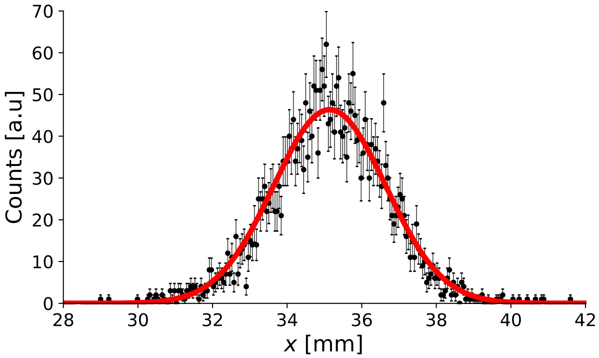
Ref. Medipix Collaboration

Beam Profile Measurement

Measure beam profile by **counting** the number of **ionisation electrons** detected in each column.



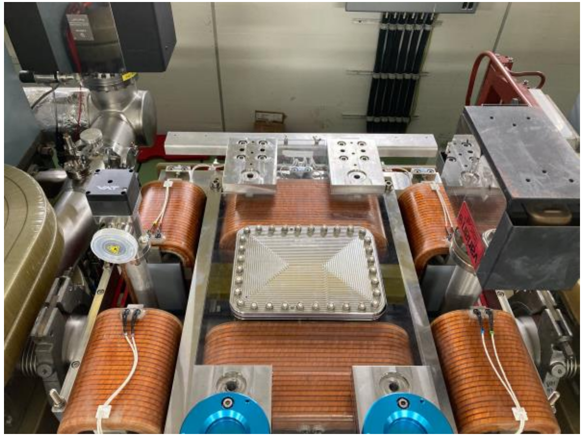




Refs. IBIC 2017, IBIC 2019, IBIC 2021

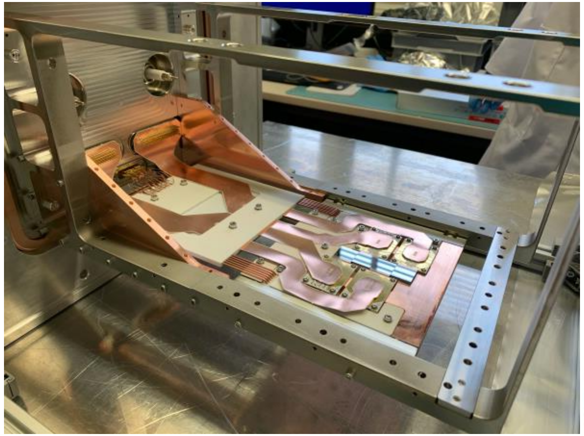
Existing BGI’s based on Timepix3

- **PS BGI-Horizontal & BGI-Vertical** profile monitors installed in LS2
- **SPS BGI-Horizontal** installed during YETS 23/24, **SPS BGI-Vertical** to be installed YETS 24/25



PS BGI-Vertical

Field cage + Faraday cage



UHV compatible Timepix3 electronics

LHC BGI (2007-2018): MCP/Optical Based

BGI’s were originally installed in the LHC, but removed in 2017/18 due to damage to the instruments caused by **beam induced heating**.

Original design based on detection of ionisation electrons with a Microchannel Plate (MCP) + Phosphor Screen + Optics + Intensified Camera.

Technical Limitations:

- **Impedance** no problem for beam, but 260W power into instrument;
- **Inhomogeuous ageing** of MCP / Phosphor / Intensitifed camera

Performance Limitations:

- **Distortion** to measured profile at E>4 TeV;
- **Not an independent measurement**, due to need to cross-calibrate with BWS to remove optical aberations (PSF of optics).

HL-LHC BGI: Timepix Based

Compact design based on **direct detection of ionisation electrons inside the beam pipe** with a **Timepix HPD**. Electrons guided to detector with **0.6T magnetic field.**

Technical Limitations (HL BGI solution):

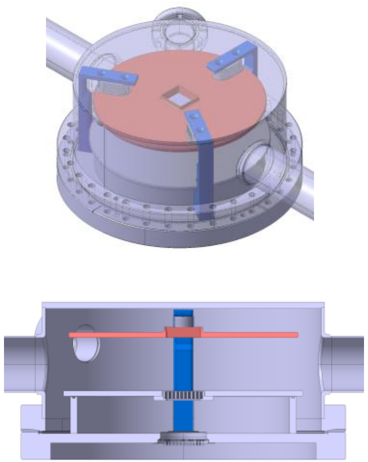
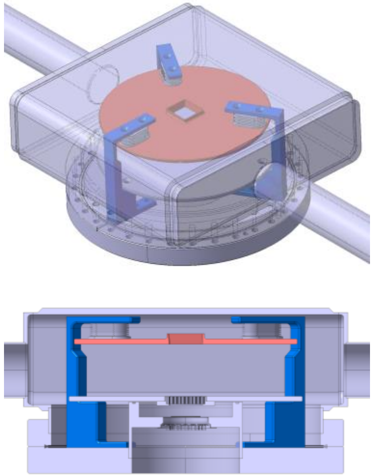
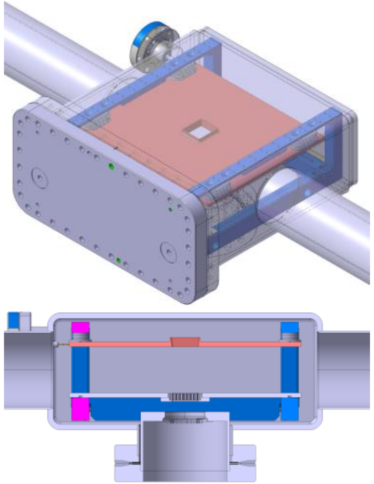
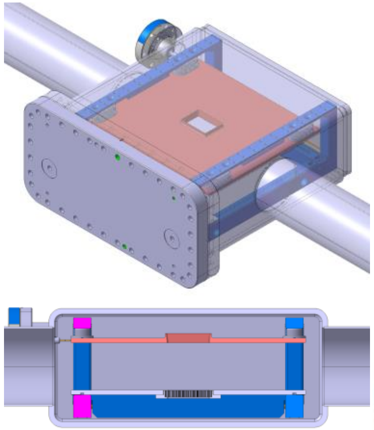
- **Impedance** no problem for beam, but 260W power into instrument; → Compact low impedance design with active cooling.
- **Inhomogeuous ageing** of MCP / Phosphor / Intensitifed camera. → Replaced with Timepix3/4 HPD.

Performance Limitations (HL BGI solution):

- **Distortion** to measured profile at E>4 TeV; → Higher strength guiding magnetic field.
- **Not an independent measurement**, due to need to cross-calibrate with BWS to remove optical aberations (PSF of optics).→ Direct detection inside beam beam pipe (no optics.)

HL-LHC BGI Design Studies

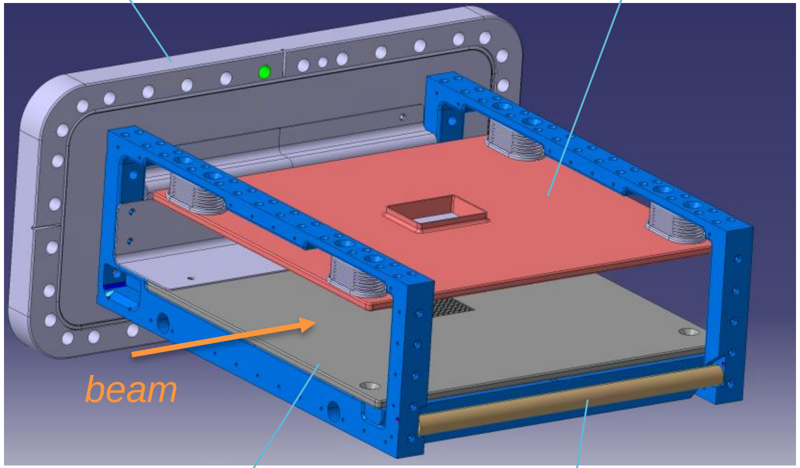
Circular Flange		Rectangular Flange	
Circular chamber	Rectangular chamber	Rectangular chamber	Rectangular chamber
Timepix4	Timepix4	Timepix4	Timepix3 or 4
1	2	3	4

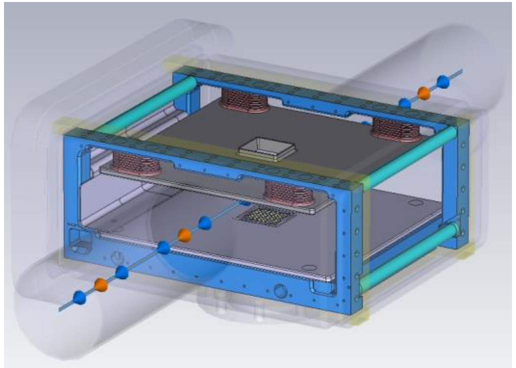
Ref. M. Teresa Ramos Garcia, HL-LHC BGI Design Review

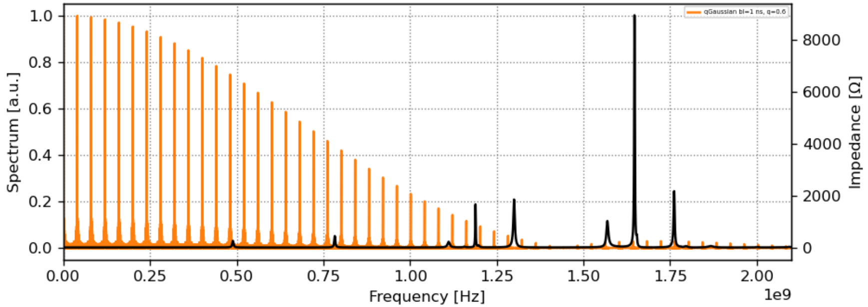
HL-LHC BGI Instrument Design

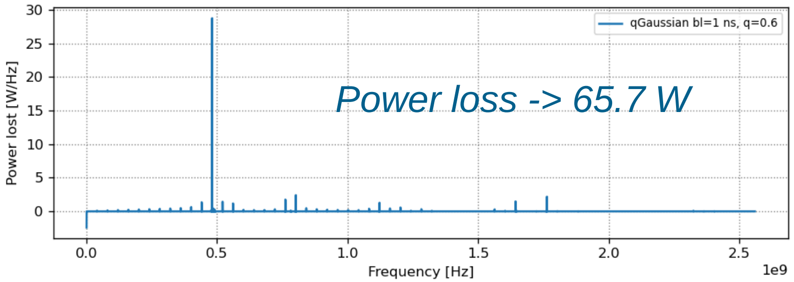
- **Baseline** evolution of **PS & SPS BGI design.**
- **Familar design** with known, but hopefully improvable, limitations.
- Beam aperture restriction = 50 mm.
- Compatible with both Timepix3 & Timepix4.



Impedance Studies







Best design so far:

- Stainless steel cathode;
- Damping rods;
- Cathode 200 x 200 mm.

Longitudinal impedance & power loss okay.
Optimisation ongoing.

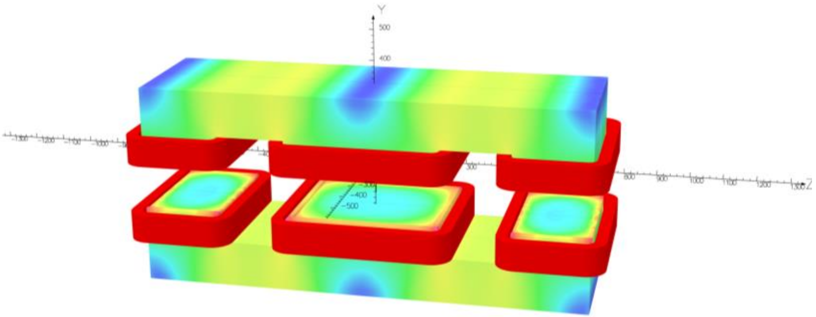
Ref. Hikmet Bursali, HL-LHC BGI Impedance Study

0.6T Magnet - New Triplet Dipole

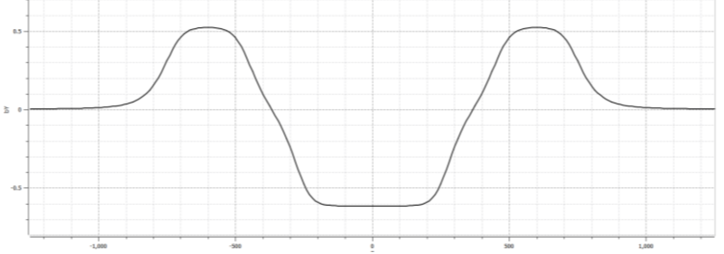
BGI design presented at [HL BGV/BGI Review in Oct. 2022]() based on new **self-compensating triplet dipole magnet**.

Separate power convertors (Polaris 2P) for Main & Corrector fields.

Recommendation of reviewers to investigate:
- Permanent magnet solution;
- Reducing number of (costly) power convertors.



LHC BGI magnet



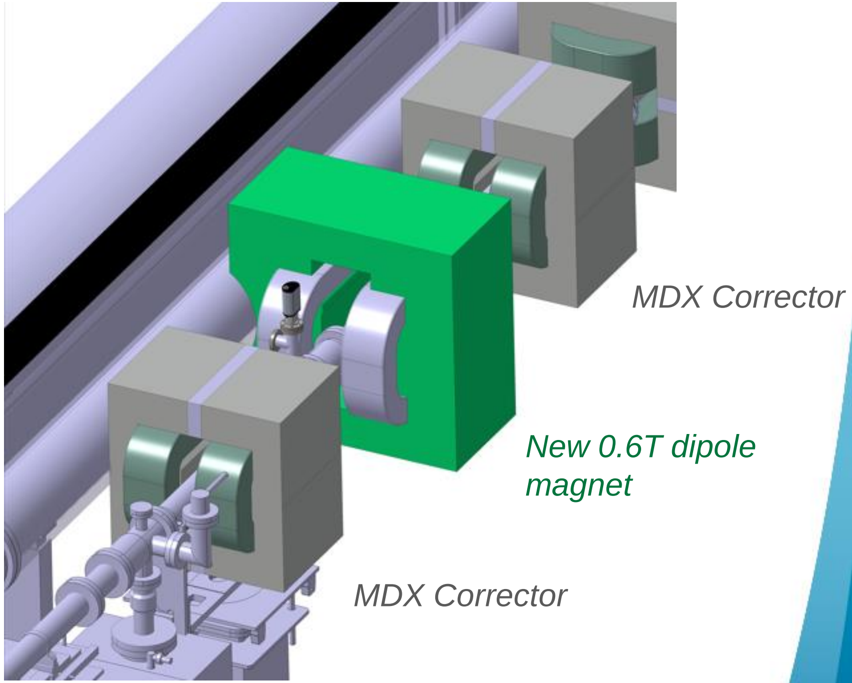
B field along the beam axis

Ref. HL-LHC BGI Magnet Review, Dominique Bodart

0.6T Magnet - New Dipole + MDX Correctors

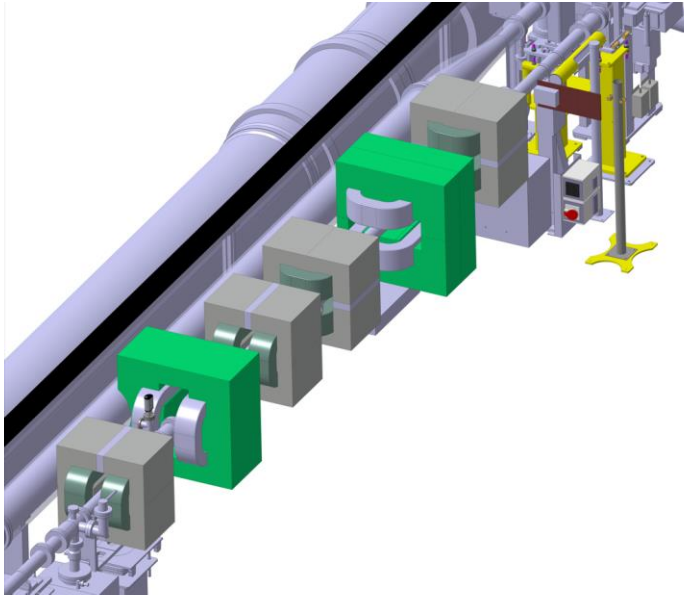
Permanent Magnet
- Designs studied by TE-MSC;
- Instrument integration very challenging;
- Not pursued.

Current Solution: New Dipole + MDX Correctors
- New 0.6T main dipole magnet for instrument;
- Correction with exisiting MDX magnets;
- Possibility to re-use existing power convetors;
- Significant potential budget saving.

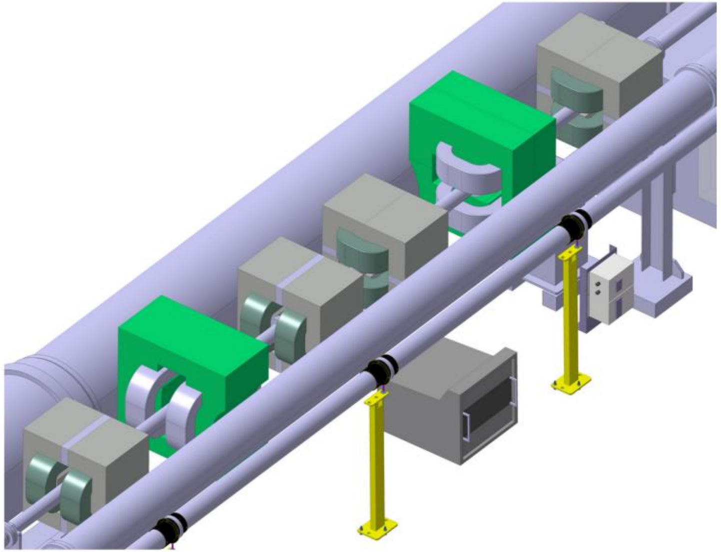


Ref. HL-LHC BGI Magnet Review, Dominique Bodart

Integration at Pt.4



5L4 - BGI-Horizontal & Vertical on B1

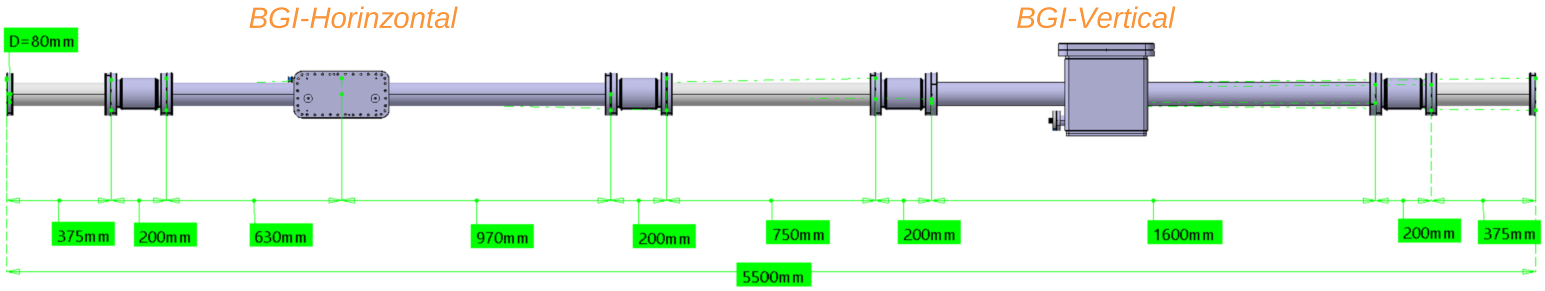


5R4 - BGI-Horizontal & Vertical on B2

Ref. Miguel Navarro Baeza, Integration Study of the BGI in the HL-LHC machine IP4

Integration at Pt.4

Proposed integration layout



Installation planning with TE-VSC:

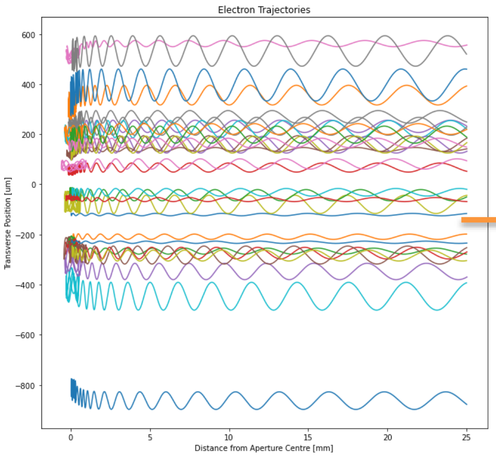
- Reconfiguration of vacuum components to take place at beginning of LS3, initially with drift tubes in place of the BGI instruments;
- Installation of BGI instruments later in LS3.

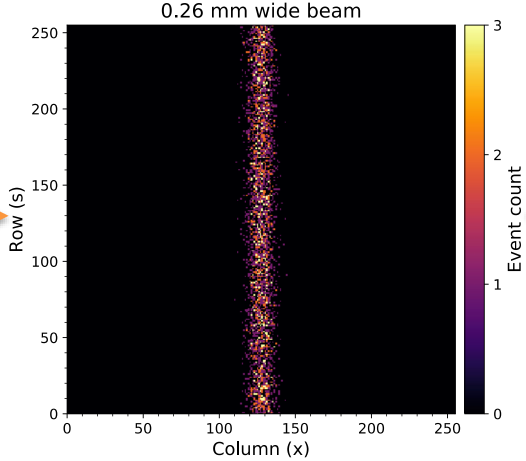
Ref. Chiara Pasquino, HL-LHC WP15 Integration Meeting

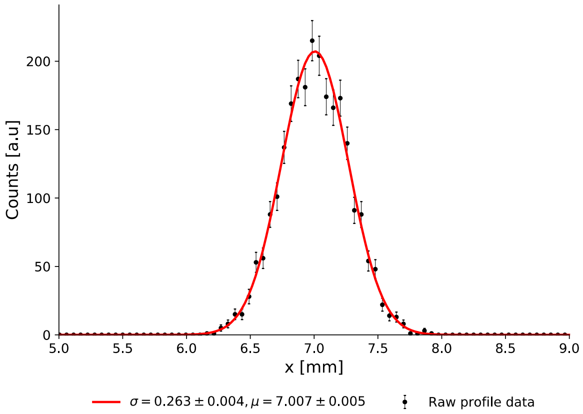
Expected Performance: Precision & Accuracy

Simulation Workflow:

- Electrostatic simulation of field cage with CST Studio;
- Simulation of ionisation electron formation & transport to electron detector with Virtual-IPM.



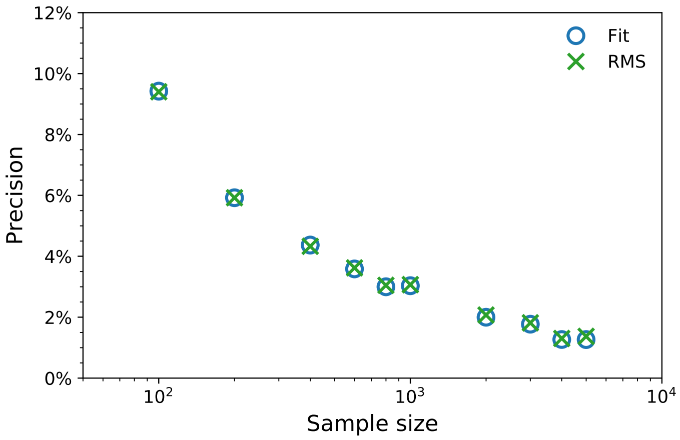




- For each simulation calculate residual = true beam size – measured beam size.

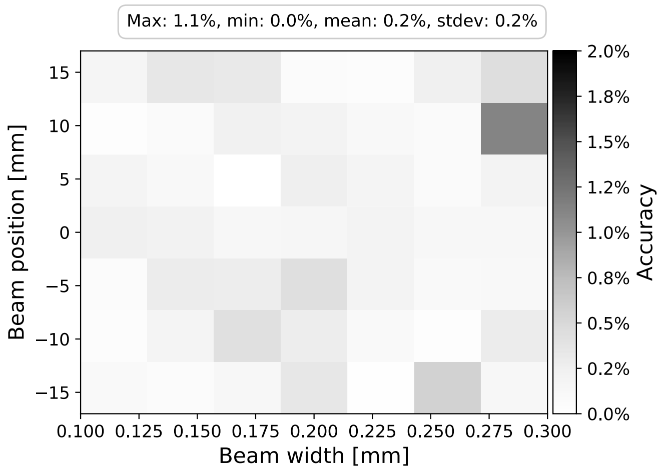
Expected Performance: Precision & Accuracy

Statistical error (precision)
= standard deviation of residual distribution



e.g. single measurement with 2000 ionisation electrons → 2 % statistical error.

Systematic error (accuracy)
= mean of residual distribution



Negligeable systematic error due to field cage, space charge, Timepix3 pixel pitch.

Expected Performance

Performance estimates for beam profile measurements with **residual gas pressure** of $1x10^{-10}$ mbar (**no gas injection**) & assuming same ionisation electron detection efficiency as PS BGI instrument:

HL-LHC protons

- Average beam size: Integration window = 0.5 ms → 5000 e^- → Precision = 1%
- Bunch-by-bunch beam size: Integration window = 1 s → 5000 e^- → Precision = 1%
- Accuracy < 2 %

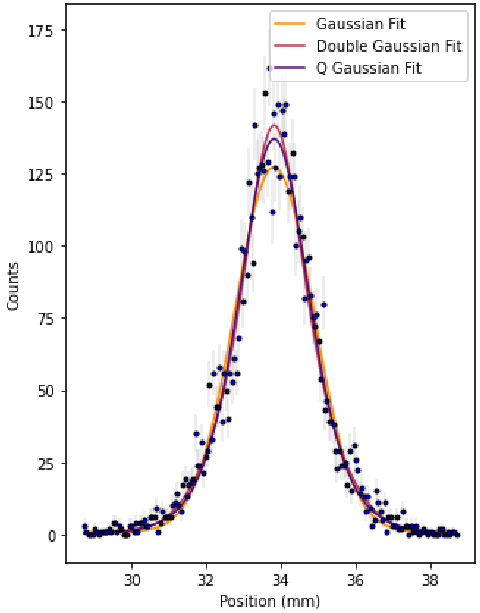
HL-LHC Pb82+

- Average beam size: Integration window = 0.05 ms → 5000 e^- → Precision = 1%
- Bunch-by-bunch size: Integration window = 100 ms → 5000 e^- → Precision = 1%
- Accuracy < 2 %

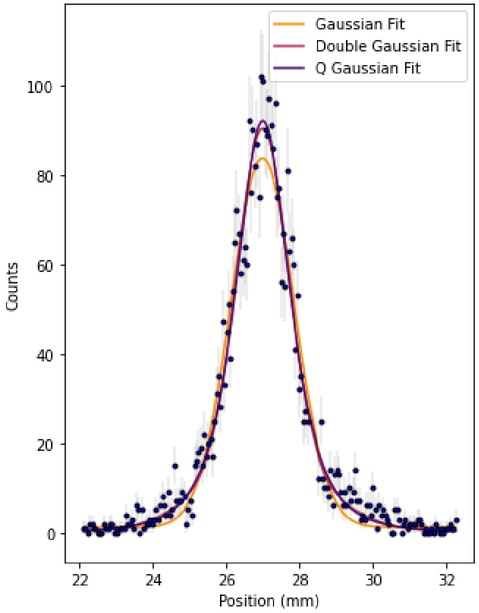
Expected performance meets functional specificition.

Accuracy of PS BGI Measurments

In practice - how well does performance meet expectation?
Example: Measurment of **LHC-type beam at flat top** with both **PS BGIs** (1.9 ms int.), **without gas injection.**



PS BGI-Horizontal

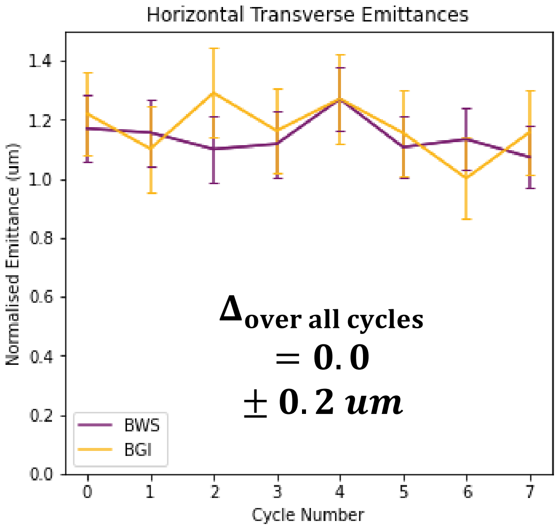


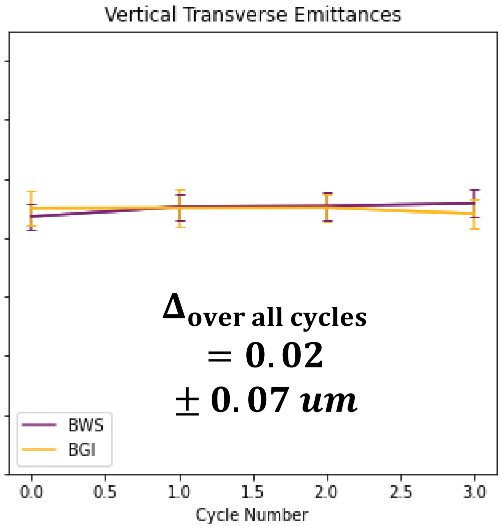
PS BGI-Vertical

[Ref. Clara Fleisig, JAPW23]

Accuracy of PS BGI Measurments

- Measure at same moment in the cycle with the Beam Wire Scanners (BWS)’s & then compare the emittance measured by the BGI and BWS:





- Emittances measured by the BGI and BWS are in agreement, as expected from the Virtual-IPM simulation.

Ref. Clara Fleisig, JAPW23

Technical Issues

Timepix3 based BGI instruments are not yet operational.

Two main issues: 1) Processing of Timepix3 data; 2) **EMI of SPS BGI Timepix3**.

Recent CERN internal review - "PS & SPS BGI Review".

(Selected) Review Panel Recommendations:

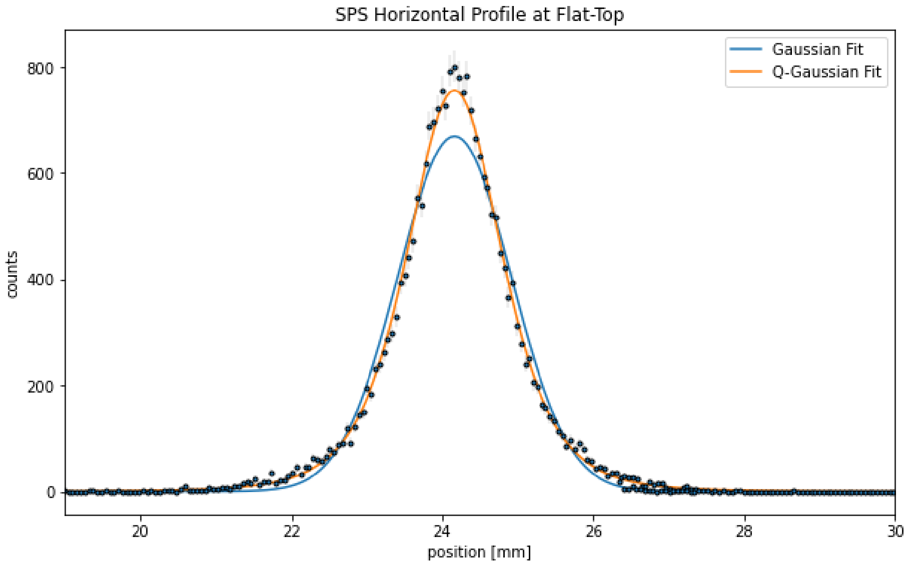
1. *"Fully support proposal to move [Timepix data] processing from SoC towards a powerful server computer."* → This is the architecture originally planned for the LHC BGI.

2. *"EMI issues are a significant problem, and we note that the project is taking this seriously and requesting outside expertise from the EMC forum."* → *Highly relevant to the LHC BGI and needs to be solved.*

SPS BGI: Results after YETS 23/24

Measurment of single LHC bunch (LHC4) at flat-top

- Integration window = 2 ms;
- Recorded 24,000 electrons in this integration window.



Fit results

Gaussian:

- sigma: 0.751 +/- 0.006 mm
- reduced chi^2 = 15.6

q-gaussian:

- sigma = 0.589 +/- 0.004 mm
- q = 1.374 +/- 0.008
- reduced chi^2 = 5.8

Looks promising...

Loss of Communication with Timepix3 during LHC25 & AWAKE Cycles

Background - Timepix3 data readout

- Data from Timepix3 is readout on 8 x differential pairs (“*dataouts*”) @640 MHz.
- Header (“comma”) sent periodically by Timepix3 on each *dataout* link.

Problem

- During LHC25 & AWAKE cycles synronisation with the dataout links is lost (i.e. comma is not recovered) → can’t readout the data.
- Communication is recovered after reconfiguring the Timepix3’s.

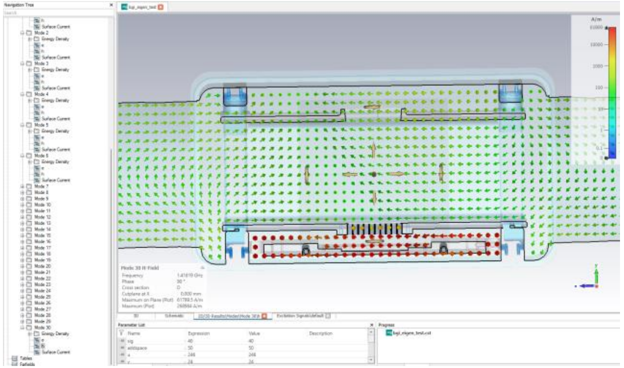
Cause

- Suspect EMI problem is causing the Timepix3 to reset.

SPS BGI EMI Studies

Current Investigations:
1. Beam based measurments (what cycles perturb Timepix3 & when.)
2. Measurments at the **ATS EMC lab**.
3. **Improve Faraday cage** design for the SPS BGI-Vertical, which will be installed during YETS 24/25.

Clue = Communication lost during AWAKE cycle immediately **after bunch rotation**, at which time:
- Bunch length reduced to 0.9ps → Higher frequencies in the power spectrum enhanced;
- Higher frequencies pass through Faraday cage & perturb electronics(?)



CST Simulation of SPS BGI eignemodes. Strong mode at 1.4 GHz inside Faraday cage (Study by Hikmet Bursali)

Milestones & Timeline upto LS3

Milestone	Date
Engineering specification for BGI readout system	End of 25
Installation of SPS BGI-Vertical with improved Faraday cage	YETS 24/25
Installation of new infrastrure at Pt.4 & Timepix3 BLM	YETS 24/25
Global emittance monitoring review	Mid-2025
Installation of prototype HL-LHC BGI instrument	YETS 25/26

Summary & Outlook

The HL-LHC BGI has the potential to provide **independent**, **non-destructive bunch-by-bunch transverse beam profile measurements throughout the accleration cycle.**

Building on experience of PS and SPS BGI developments.

Design status:

- Mechanical design & integration well advanced;
- Impedance & beam induced heating under control;
- Magnet design optimised to reduce cost.

Top priority is to solve EMI issue in the SPS.

Thanks!