Beam Gas Ionisation (BGI) Profile Monitor: Development

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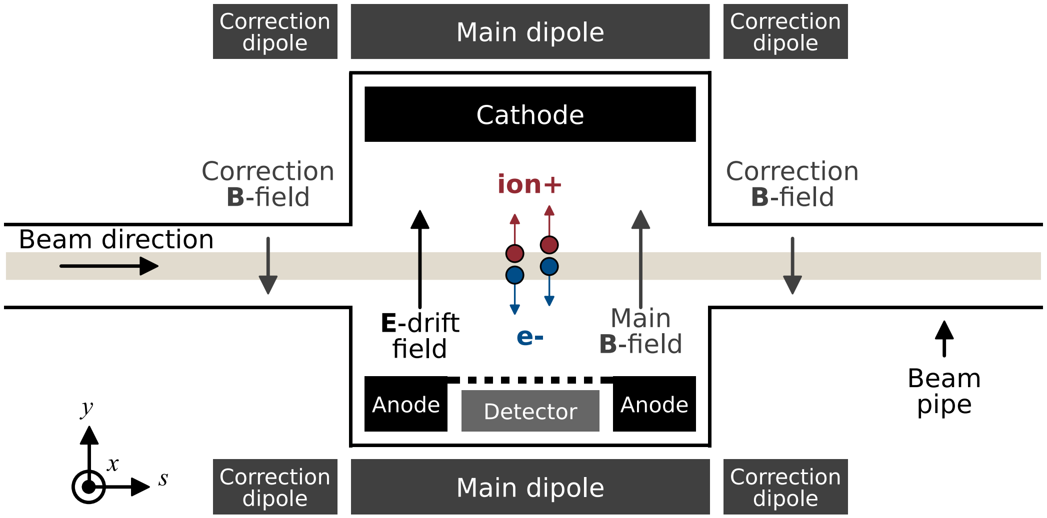
HL-LHC Beam Halo Review on 18th December 2024

Outline

- Technique
- Installations & Status
- Beam-Halo Signal Rates
- Technical Limits & Backgrounds
- Systematic Effects
- Template Questions & Summary Table

Beam Gas Ionisation (BGI) Profile Monitor



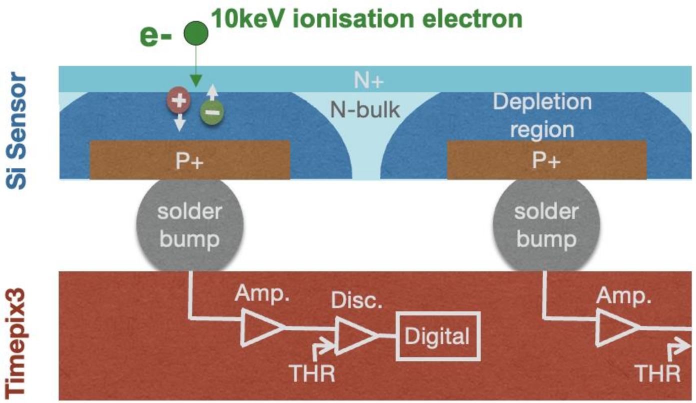
1. Beam ionises **residual gas**;
2. **Ionisation electron** accelerated & transported by electromagnetic fields onto detector;
3. Electron detector = **Timepix3(/4)** Hybrid Pixel Detector.

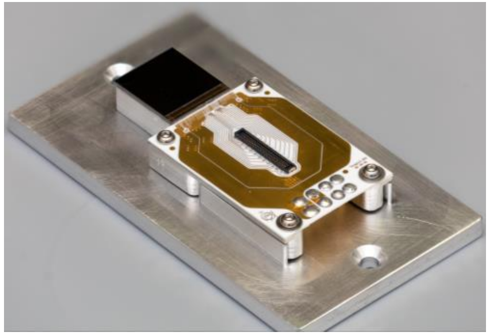
Ionisation Electron Detection

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**

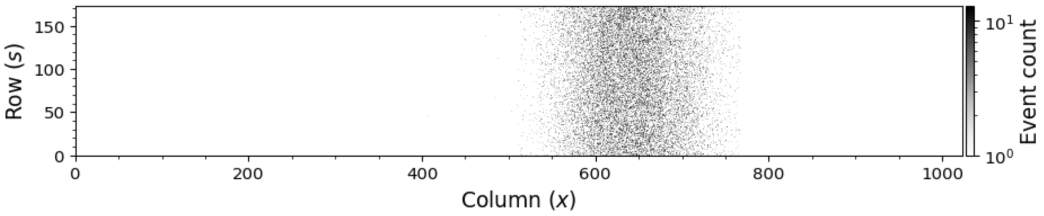


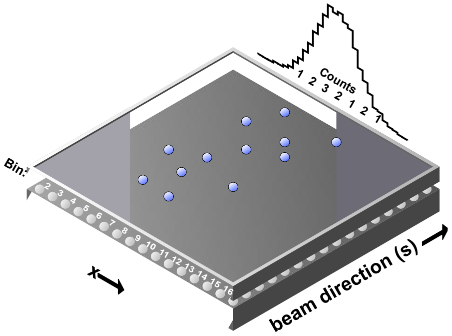


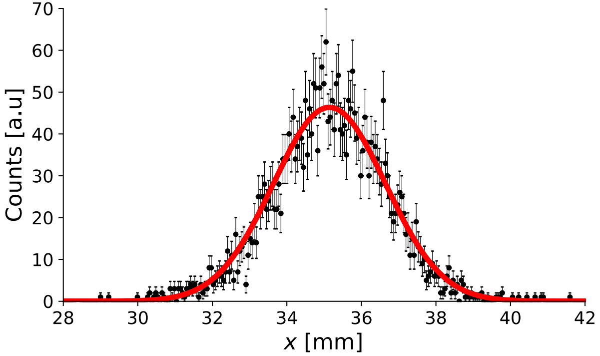
Single electron detection & **digitisation directly inside the beam pipe.**

Beam Profile Measurement

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



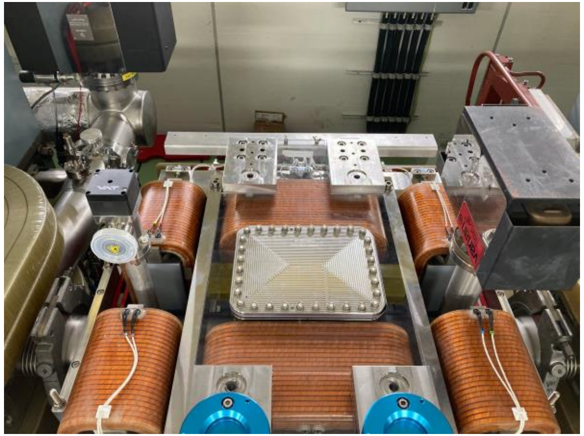




Refs. [IBIC 2017](), [IBIC 2019](), [IBIC 2021]()

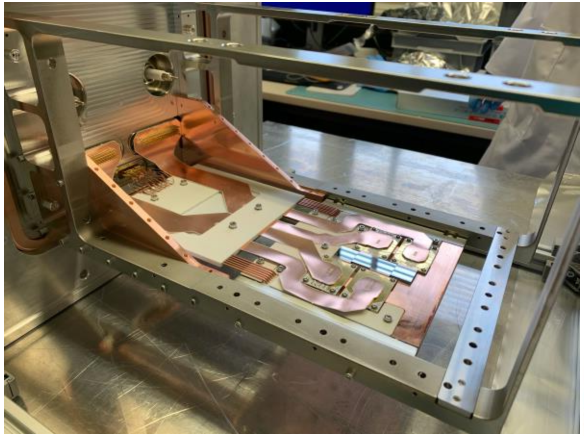
Existing BGI's based on Timepix3

- **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

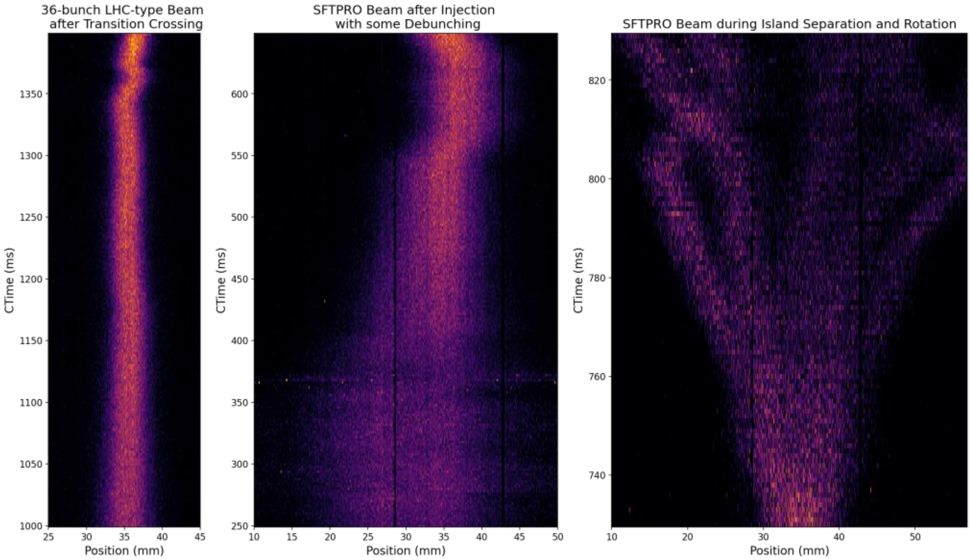


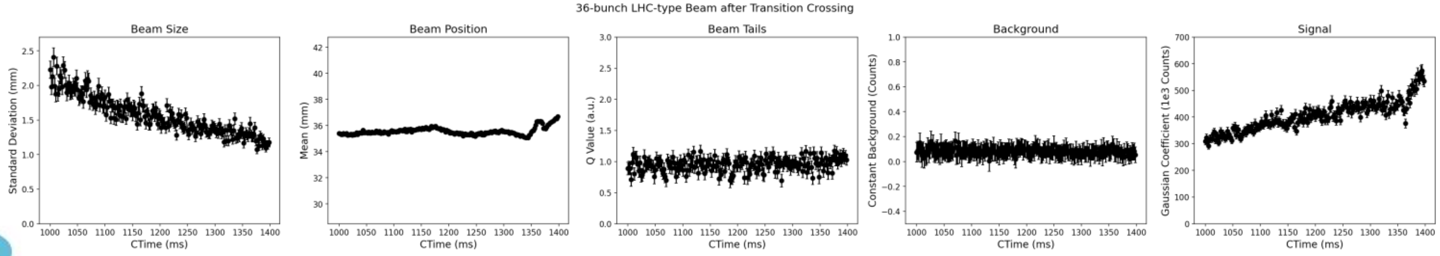
UHV compatible Timepix3 electronics

Example: Beam Evolution Measurments

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





Status of PS & SPS BGI's

Current Status

- Despite promising results (*), PS & SPS BGI's are not yet fully operational.
- Review held 3rd September 2024 → outcome EDMS 3161142
- Follow-up at BI-Technical Board on 28th November

Main Outcomes

1. Move immediately to FESA-on-SoC platform.
    - In progress.
2. Highest priority is to solve SPS BGI communication problem with Timepix3 during AWAKE & LHC25 cycles:
    - Investigations made at ATS EMC lab in November 2024, symptoms reproduced, issues identified & potential solutions to be implemented during EYETS 24/25 & validated during 2025 run.
    - Important to solve this with a view to the LHC BGI & to validate the operation of Timepix4 in the LHC in 2026.

(*) Refs.: https://bgi.web.cern.ch/papers/

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).

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HL-LHC BGI: Timepix4 Based

Compact design based on **direct detection of ionisation electrons inside the beam pipe** with a **Timepix4 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.)

Baseline HL-LHC WP13 instrument to provide independent bunch-by-bunch beam profile measurment throughout the acceleration cycle.

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Beam Halo Measurement with HL-LHC BGI?

Expected Ionisation Electron Yields

	Injection	Collision
E_k [GeV]	450	7000
N_b [10^{10} p/b]	22	22
n_b	2748	2748
Residual gas (H_2, 1x10^{-10} mbar)		
$\sigma_{ion,H2}$ [Mb]	0.300	0.371
$n_{electrons}$ [/turn]	630	770
$n_{electrons}$ [/s]	7.0x10^6	8.7x10^6
Gas injection (Ar, 1x10^{-8} mbar)		
$\sigma_{ion,Ar}$ [Mb]	1.61	2.04
$n_{electrons}$ [/turn]	3.4x10^5	4.2x10^5
$n_{electrons}$ [/s]	3.8x10^9	4.8x10^9

Refs.: CERN-Thesis-2020-236, Beam-Gas Ionsiation Cross Sections at 7TeV

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Expected Ionisation Electron Yields

	Injection	Collision
Residual gas (H_2, $1x10^{-10}$ mbar)		
$n_{electrons}$ [/s]	$7.0x10^6$	$8.7x10^6$
$n_{electrons}$ [/s] * RI($3\sigma \rightarrow \infty$)	$2.2x10^5$	$2.8x10^5$
$n_{electrons}$ [/s] * RI($3.5\sigma \rightarrow \infty$)	9700	12000
$n_{electrons}$ [/s] * RI($5\sigma \rightarrow \infty$)	20	25
Gas injection (Ar, 1x10-8 mbar)		
$n_{electrons}$ [/s]	$3.8x10^9$	$4.8x10^9$
$n_{electrons}$ [/s] * RI($3\sigma \rightarrow \infty$)	$1.2x10^8$	$1.5x10^8$
$n_{electrons}$ [/s] * RI($3.5\sigma \rightarrow \infty$)	$5.3x10^6$	$6.7x10^6$
$n_{electrons}$ [/s] * RI($5\sigma \rightarrow \infty$)	$1.1x10^4$	$1.4x10^4$

Assuming Gaussian beam profile

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Readout Limitations

1 x ionisation electron creates ~1 x Timepix4 event

Limitations of Timepix4

- Technical limit of 2.5 GEvents/s (16 links @ 10.24 Gbps.)
- Demonstrated links @640 Mbps through vacuum feedthrough → **155 MEvents/s.**
- Maximum pixel event rate = **10.8 kHz / pixel** (512 x 448 pixel array = ¼ M pixels.)

Limitations of Timepix4 Readout System (BIPXL)

- Current FPGA limited to event processing at maximum rate of **125 MEvents/s.**

Key Limits

- **Maximum event rate per Timepix4 = 125 MEvents/s**
- **Maximum event rate per pixel = 10.8 kHz / pixel**

Expected Ionisation Electron Yields

	Injection	Collision
Residual gas (H_2, $1x10^{-10}$ mbar)		
$n_{electrons}$ [/s]	$7.0x10^6$	$8.7x10^6$
$n_{electrons}$ [/s] * RI(3σ→∞)	$2.2x10^5$	$2.8x10^5$
$n_{electrons}$ [/s] * RI(3.5σ→∞)	9700	12000
$n_{electrons}$ [/s] * RI(5σ→∞)	20	25
Gas injection (Ar, 1x10-8 mbar)		
$n_{electrons}$ [/s]	~~$3.8x10^9$~~	~~$4.8x10^9$~~
$n_{electrons}$ [/s] * RI(3σ→∞)	$1.2x10^8$	~~$1.5x10^8$~~
$n_{electrons}$ [/s] * RI(3.5σ→∞)	$5.3x10^6$	$6.7x10^6$
$n_{electrons}$ [/s] * RI(5σ→∞)	$1.1x10^4$	$1.4x10^4$

Maximum event rate per Timepix4 = $1.25x10^8$ events / s

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Maximum Rates Per Pixel

	Injection	Collision
Residual gas (H_2, $1x10^{-10}$ mbar)		
Max $n_{electrons}$ [/pixel/s]	$5.2x10^2$	$2.3x10^3$
Gas injection (Ar, 1x10-8 mbar)		
$n_{electrons}$ [/pixel/s]	~~$2.8x10^5$~~	~~$1.3x10^6$~~
$n_{electrons}$ [/pixel/s] * RI($3\sigma \rightarrow \infty$)	~~$2.5x10^4$~~	~~$1.1x10^5$~~
$n_{electrons}$ [/pixel/s] * RI($3.5\sigma \rightarrow \infty$)	$1.1x10^3$	$5.2x10^3$

Maximum event rate per pixel = $10.8x10^3$ events / pixel / s

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Beam Halo "Signal"

Assuming Gaussian distrubtion.

With only residual gas ionisation (H_2, $1x10^{-10}$ mbar):

- **~10,000 samples / second** in the range [3.5σ → inf.]
- No readout limitations.
- Measure core & halo simulataneuously.

With gas injection (Ar, $1x10^{-8}$ mbar):

- **~5M samples / second** in the range [3.5σ → inf.]
- Signal rate in the core is too high → Mask out (almost) all pixels (next slide).
- **Bunch-by-bunch halo measurments** possible at rate of **1800 samples / bunch / second.**

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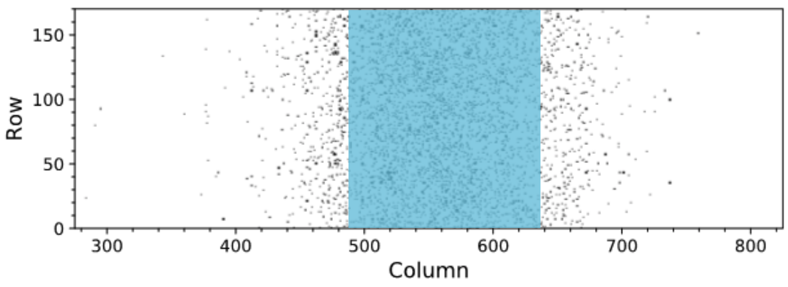
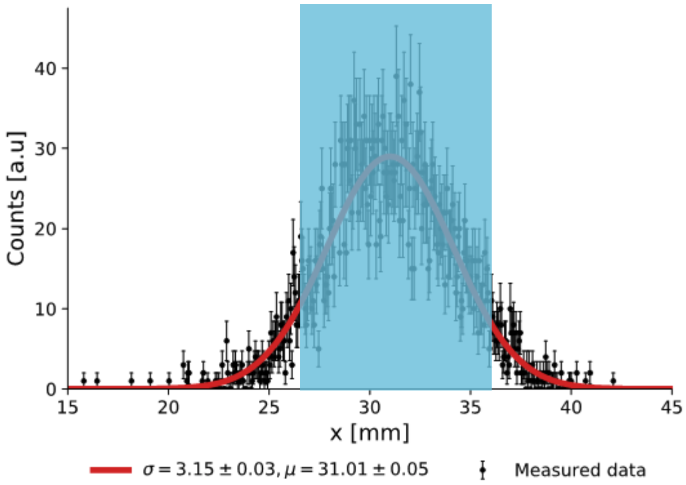
Avoiding Saturation with Gas Injection

Timepix4 allows the **masking of individual pixels**, whereby enabling to **mask the "core"** (i.e., functioning as a ~"digital coronagraph.")



Example: Mask pixels in range -3.5σ < x < 3.5σ reduces the date from **$5x10^9$ to $7x10^6$ events / s.**

Could still leave unmasked some pixels under the "core" distribution to allow for a concurrent complete profile measurement.



Backgrounds

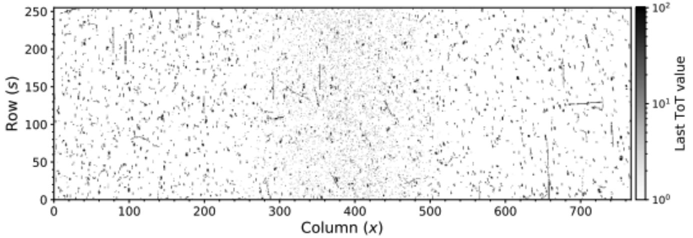
Background(s)

- Timepix4 Hybrid Pixel Detector is **sensitive to any charged particle crossing the sensor**.
- Possible sources of charged particle backgrounds include:
  - Secondary particles from inelastic beam gas interactions;
  - Particles from the decay of surrounding activated material;
- Other possible backgrounds = synchrotron light, florescence of injected gases, etc.

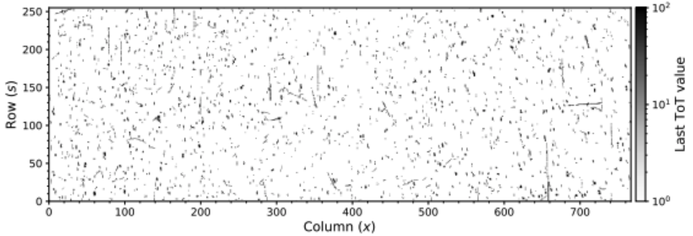
Mitigation

- Use **cluster finding methods** (e.g. DBSCAN) to transform Timepix4 events into particle events and then apply selection criteria (e.g. cluster size, cluster energy) to select only ionisation electrons.
- **Method already demonstrated with the PS BGI.**

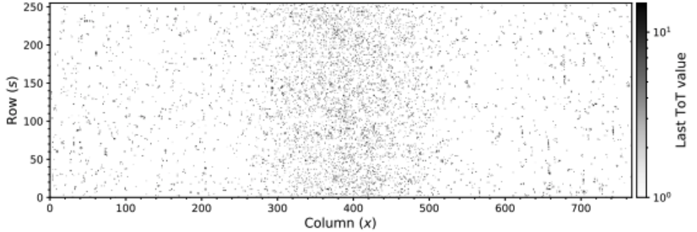
Raw data = Signal + Background



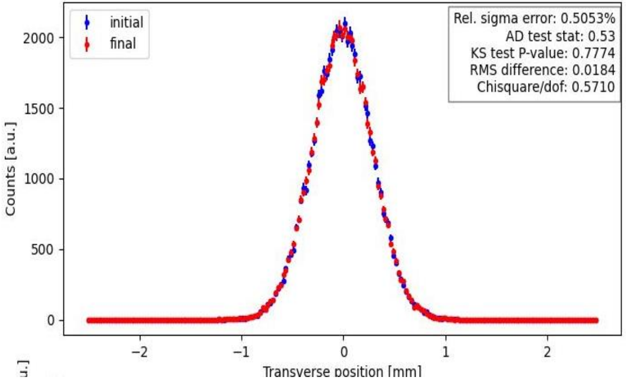
Clusters passing Background selection



Clusters passing Signal selection



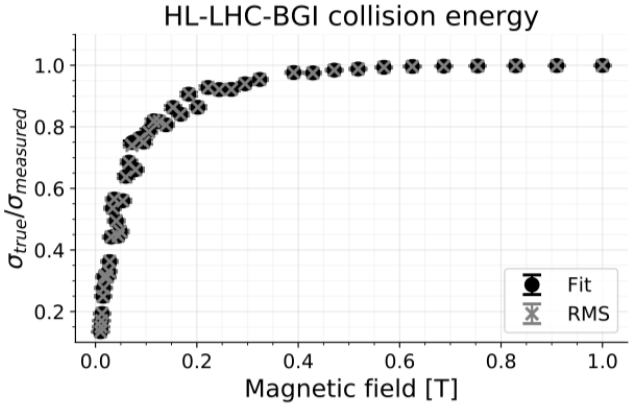
Systematics (I)



Ideal instrument preserves the ionisation electron transverse position during transport from creation to the detection (Timepix4) plane.

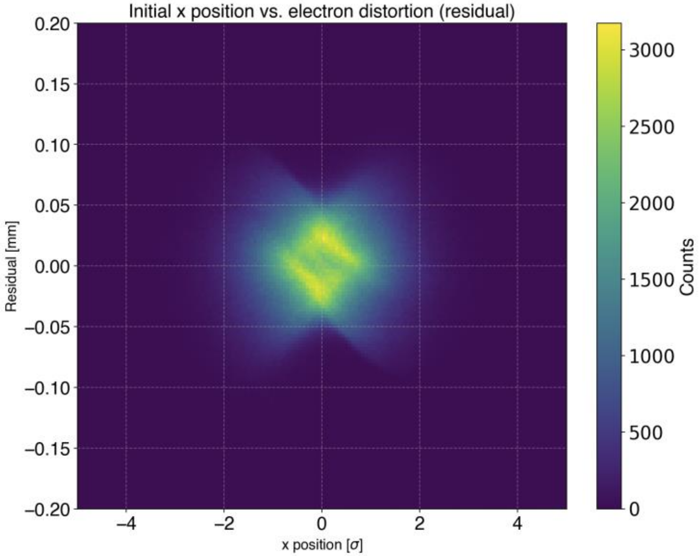
Transport of ionisation electron from formation to the electron detector studied with CST-Studio (Static EM-fields) & IPMSim (tracking of ionisation electron in dynamic and static EM-fields.)

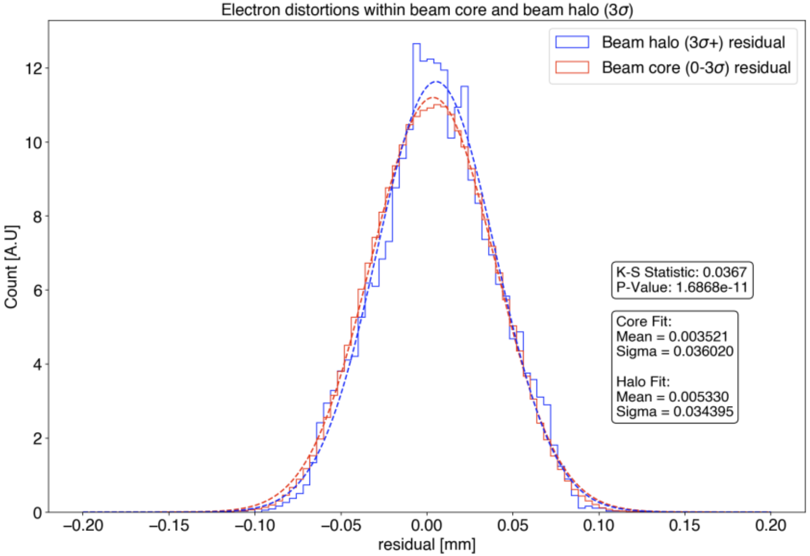
Magnetic strength specified to ensure beam size measured with a systematic error < 2%.



Systematics (II)

What happens to ionisation electrons in the **beam halo** during transport from creation to the detection plane? Simulation of 3.5M ionisation electrons with IPMSim.





Point spread for ionisation electrons created in the beam halo is approximately the same as for those created in the beam core.

‘Template questions’

1. What is the maximum contrast your technique can achieve? At which sigma value?
   - Signal [3.5σ→inf.] = 10 kHz (residual gas) or 5 MHz (injected gas)
   - Particle backgrounds = ~0 (with cluster finding + selection)
   - Electrical backgrounds = 0
2. What fraction of the total beam can you measure in the ROI (relative integral)?
   - With residual gas → no limit in the ROI
   - With gas injection → x > 3.5σ
3. What is the absolute number of particles you can detect in the ROI?
   - Signal [3.5σ→inf.] = 10 kHz (residual gas) or 5 MHz (injected gas)
4. Can your technique provide:
   - 1D beam profiles? Yes
   - 2D beam images? No
5. What is the fastest acquisition rate you can achieve for a full machine measurement?
   - 5 MHz (with injected gas)

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‘Template questions’

6. Does your technique support bunch-by-bunch measurements? Yes
   - How many turns are needed for a measurement?
     - 1800 samples / bunch / second
   - What is the minimum number of particles needed per bunch?
     - Linear scaling between number electrons (samples) and particles per bunch
7. Can your technique be connected to an interlock system? Possibly, but requires further study
   - What would be the response time?
     - Need to study number of electrons needed for an interlock.
   - What reliability level can be achieved?
     - Needs further study.
8. Is your technique expected to perform all along the LHC cycle? Yes
9. Assuming it will be possible to increase beam size at the location of your detectors, would your technique gain or lose performance reach? Gain - since larger beam reduces the effects of space charge on the distortion to the transverse position of the ionisation electrons. Aperture of new dipole magnetic fixed, so would be difficult to increase instrument aperture beyond 50mm.

Summary Table

Performance Metric	Required Range	Use Case(s)	Your Technique
Contrast	10^-4 to 10^-6	Collimation: 10^-4 at upper bound	Signal = 10 kHz (residual gas) or 5 MHz (injected gas) Background = tbd. (~0)
		MP: 10^-6 at 6.7σ	
Relative Integral	0.2% to 5%	Collimation: 5% to 0.5%	See table on slide #14.
		MP: 1.4% to 0.2%	
Absolute Integral	10^10 to few 10^12	Collimation: 1.5×10^12	See table on slide #14.
		MP: (1-4)×10^10	
1D Profile Capability	Yes/No	Required for Beam-Beam	Yes.
2D Image Capability	Yes/No	Required for Beam-Beam	No.
Max. Acquisition Rate	10-60 seconds	MP: ~10s	5 MHz with injected gas → 1800 electron / bunch / s.
		Others: ~60s	
Bunch-by-Bunch Gating	Yes/No	Required for Beam-Beam	No gating required for Bunch-by-Bunch (use timestamp of electrons), but gating is possible.
Number of Turns Needed	-	All cases accept multi-turn	With gas injection 5 MHz → 440 samples / turn.
Interlock Capability	Yes/No	Required for MP	Needs further study.

Conclusion

- New generation of Beam Gas Ionisation (BGI) profile monitors have been developed for the PS & SPS, based on direct detection of individual ionisation electron inside the beam pipe.
- Long development, which is still to be completed, but offers the potential for **independent continuous non-invasive bunch-by-bunch beam profile measurements throughout the acceleration cycle.**
- Common technique for PS, SPS & LHC.
- Beam halo measurement with residual gas ionisation at 10 kHz (core + halo) and gas injection at 5 MHz (halo only.)

- Additional costs (w.r.t.. current EVM) - possible consolidation of gas injection system(s).
- Main risk - electromagnetic interference between beam & Timepix4 - not specific to beam halo measurement. Solutions to be validated in 2025.