Proposal for an upgraded Beam Gas Ionisation profile monitor

LHC Beam Size Measurement Review, 1st October 2019

James Storey
CERN BE-BI-BL

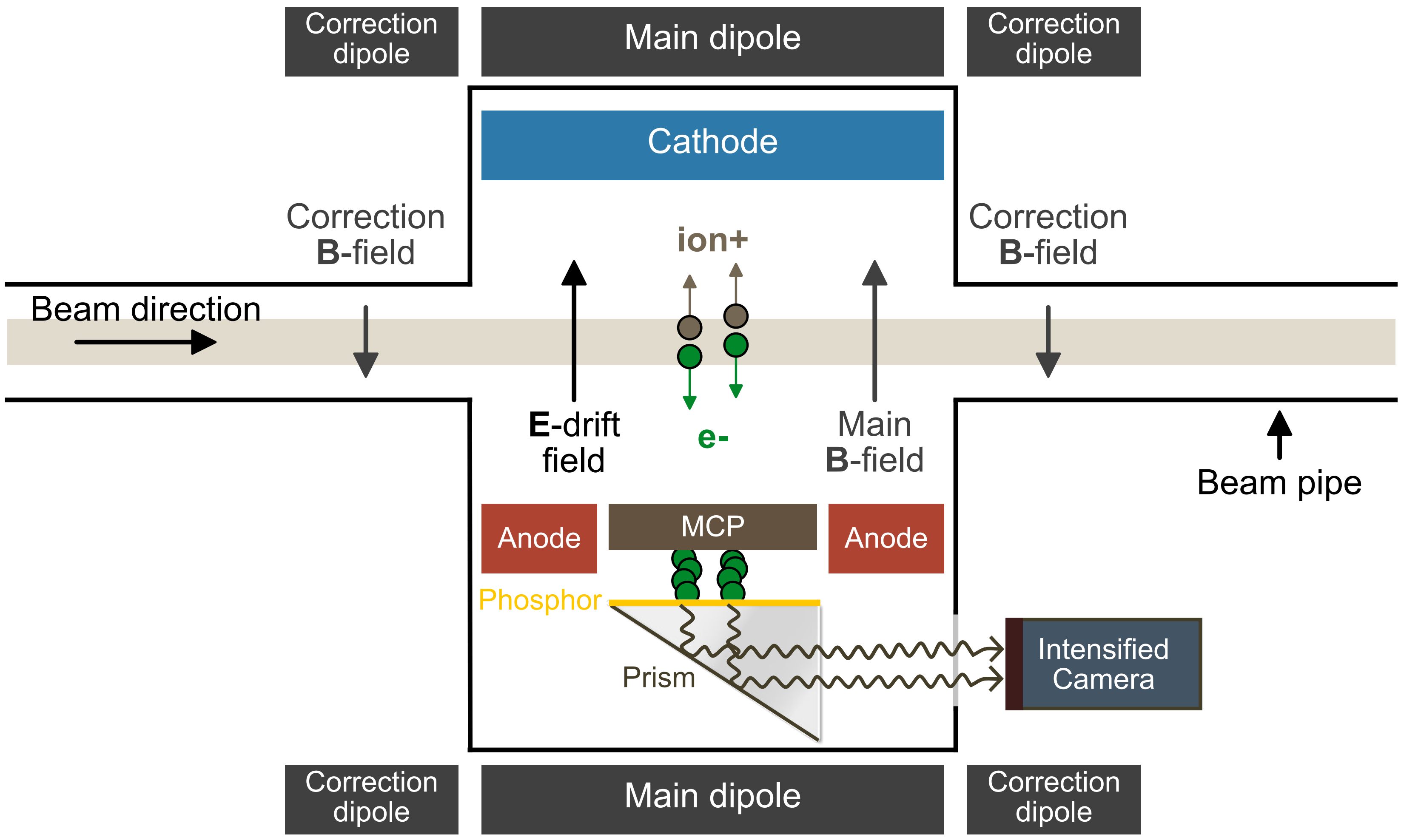
Acknowledgements:
S. Levasseur, H. Sandberg, W. Bertsche, A. Farricker, S. Gibson, R. Jones, F. Roncarolo, B. Salvachua, B. Salvant, G. Schneider, R. Veness, C. Vollinger, C. Zamantzas.

Contents

1. LHC MCP / optical based BGI profile monitors during Run 1 & 2 :
   - Technical problems ;
   - Performance limitations.
2. Significant BGI developments in the past few years :
   - IPMSim collaboration ;
   - Development of a Timepix3 based BGI profile monitor for the PS.
3. Proposal for a Timepix3 based BGI for HL-LHC.

1. LHC MCP / optical based profile monitors during Run 1 & 2

LHC MCP / optical based BGI profile monitor



Brief history

MCP / optical based BGI profile monitors with 0.2 T dipole magnets installed from the start of the LHC on both beams to measure both the horizontal & vertical beam profiles (4 instruments in total.)

Run 1 problems :

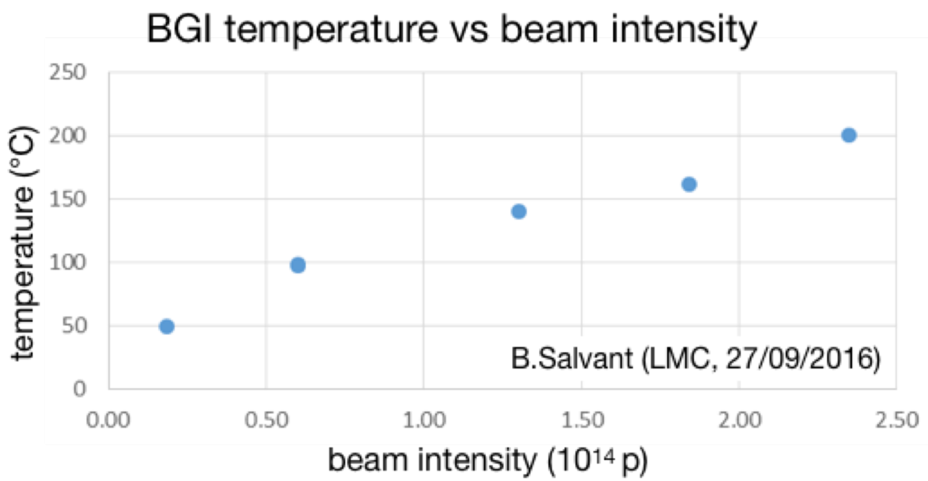
- **Proton beam profiles at E>4 TeV found to be distorted w.r.t. wire scanner measurement.** Simulations later identify problem – transport of ionisation electrons to imaging detector affected by transient beam electric fields.
- **Inhomogeneous ageing** of MCP, phosphor & intensified camera causes **distortion to beam profile** measurement and **high maintenance costs.**
- **Technical issues** (high voltage control, camera control) delayed progress.

Run 2 problems :

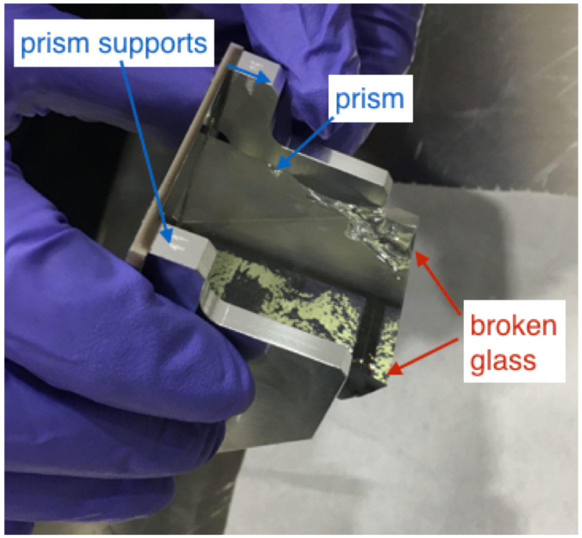
- **Damage to instruments due to beam induced heating – all instruments removed during EYETS 16/17.**
- Consensus that instruments should only be re-installed if solution found to remove the heating. Solution requires re-design of electric field cage → **new instrument design.**

Technical problem 1: Damage to instrument due to beam induced heating

Beam induced heating



Consequence for the instrument

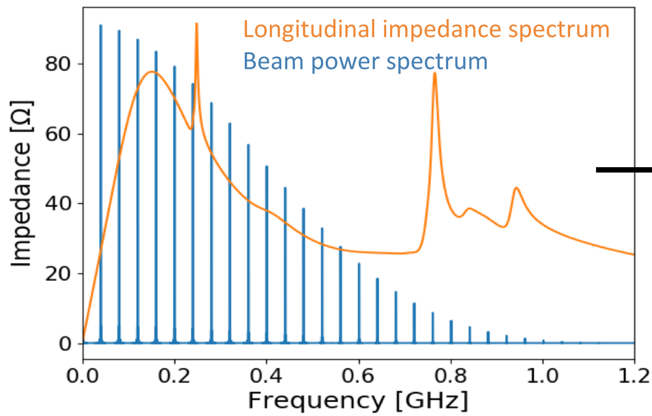


Prism broken at the contact locations with the aluminum support.

Aaron Farricker (BE-RF)

BGI impedance simulations

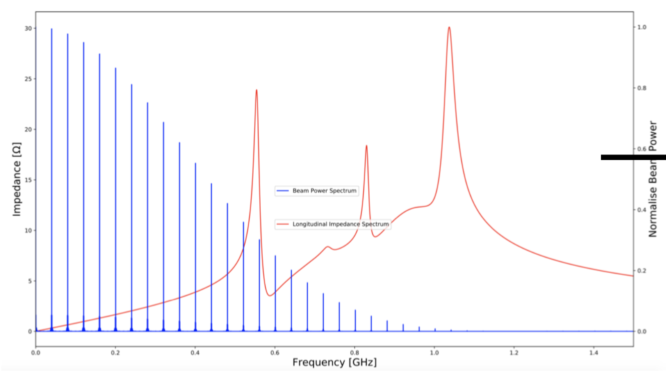
Simulation of LHC BGI



Power loss in the BGI = 90 – 260 W

However, impact of impedance on the beam in both transverse & longitudinal planes is minimal.

Simulation with design changes



11 W power loss in the BGI

Design change = surface of support arms non-conductive + smaller electrodes → **new instrument design.**

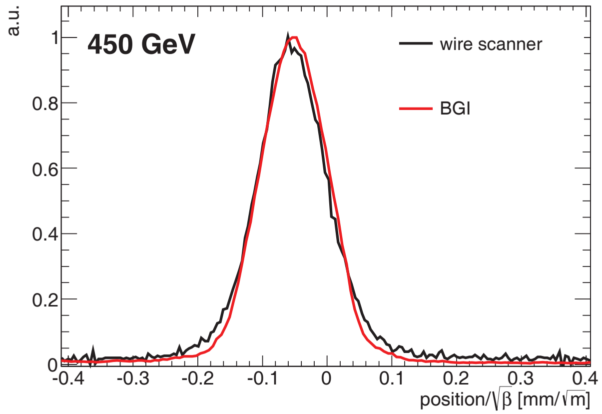
Technical problem 2: Ageing of MCP & phosphor screen & intensified cameras

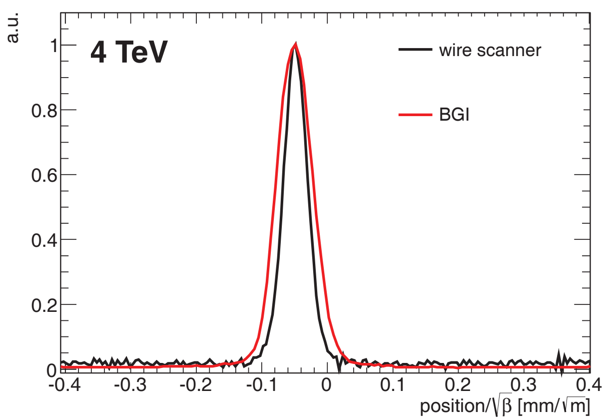
MCP ageing

- Micro-Channel Plates (MCP) age due to bombardment by the ionisation electrons ;
- Since ageing is mainly where the ionisation electrons impact the MCP this leads to a **time varying inhomogeneous gain and distortion to the beam profile measurement** ;
- **Common problem**, with different solutions under development -
  - Limit MCP exposure time (J-PARC, Fermilab) ;
  - Physically change location of MCP exposure (Fermilab) ;
  - Calibrate MCP gain either with UV lamp (GSI) or Electron Glass Plate (CERN) ;
  - Long lifetime MCP's (Manufacturers) ;
  - Remove the MCP (CERN Timepix3-BGI).

Similar problem for the phosphor screen and intensified camera (includes MCP).

Performance limitation 1: Distortion to **proton** beam profile for E > ~4 TeV





At E = 450 GeV – effect of bunch electric field on the trajectories of ionisation electrons mitigated by 0.2 T magnetic field.

At E > 4 TeV – the 0.2 T magnetic field is insufficient to mitigate this effect → **distortion to the measured beam profile.**

M. Sapinski et al., 2012, "The first experience with LHC Beam Gas Ionization Monitor", Proc. IBIC2012

Performance limitation 2: Optical aberration errors

Ionisation electron imaging detector "chain" consists of: MCP → Phosphor → Prism → Optics → Intensified camera.

Due to **optical aberrations** a point incident on the MCP becomes smeared; the total response of the imaging chain to the point is described by a **Point Spread Function (PSF).**

Detected image is the **convolution of the true beam image and the PSF**. Therefore to recover true beam image need to know the PSF.

Run1 approach**: use wire scanner as the reference** (i.e. true) measurement with which to determine PSF.

Consequence - BGI measurement dependent on another device and beta functions at two locations → **not an independent beam size measurement.**

Summary of problems & limitations

Technical problems :

1. Damage to instrument due to beam induced heating.
2. Inhomogeneous gain due to ageing of imaging detector components.

Performance limitations :

1. Distortion to proton beam profiles for E > 4 TeV.
2. Not an independent measurement due to optical point spread.

2. Significant BGI developments in the past few years

Simulation of rest gas ionisation profile monitors : IPMSim collaboration

Inter-laboratory effort (CERN, J-PARC, GSI, Fermilab, BNL, ESS, ISIS) formed in 2016 to create a **common tool for the design & understanding of rest gas Ionisation Profile Monitors** (“IPM” == “BGI” at CERN).

1st IPMSim collaboration meeting at CERN (March 2016)

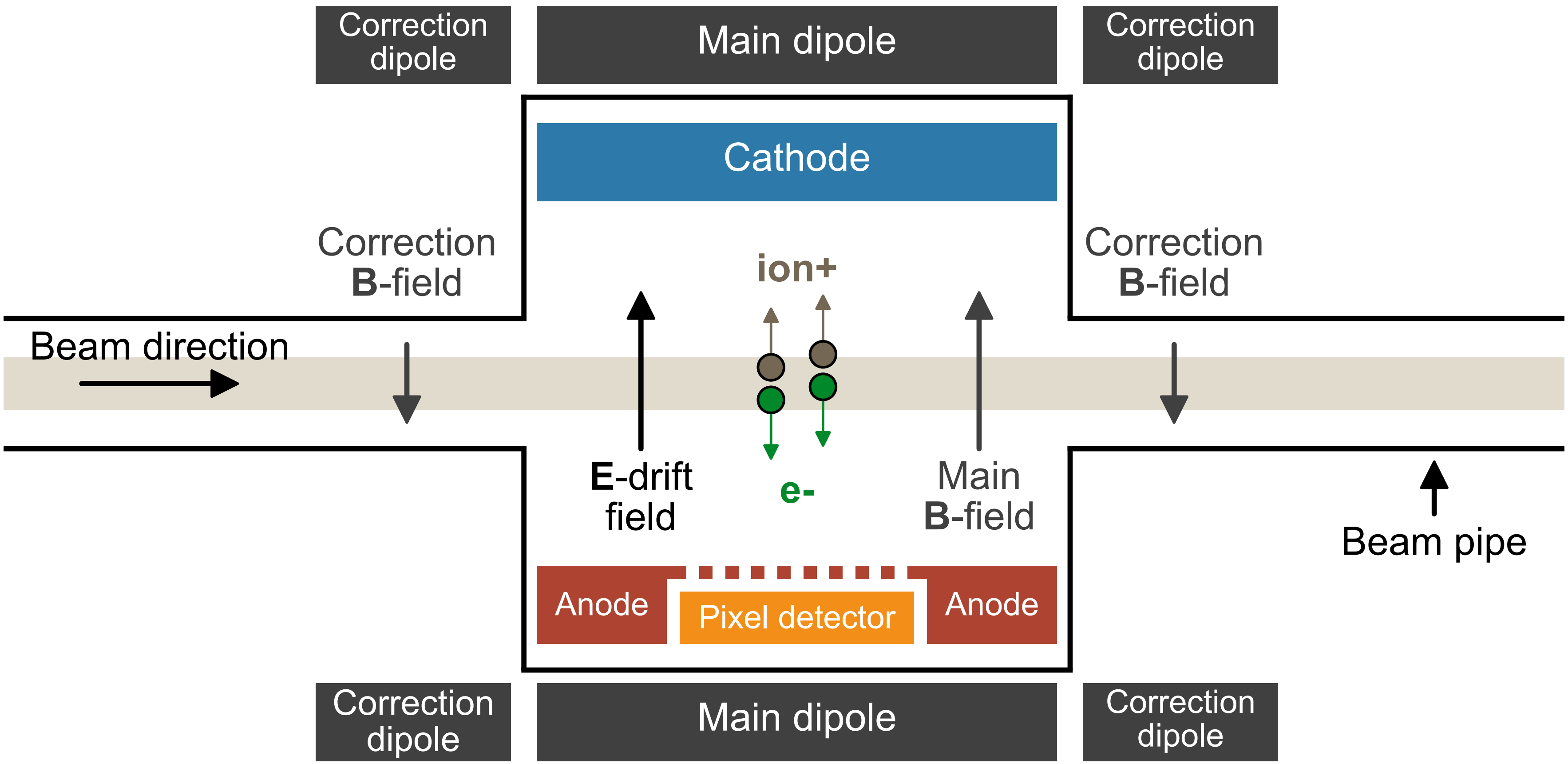
IPMSim is a **complete simulation of rest gas ionisation profile monitors**, including:

- Initial ionisation electron velocities ;
- Guiding electric & magnetic fields ;
- Beam fields ;
- & Particle tracking.

Now a **well established tool,** used to study in particular :

- **Beam profile distortion** ;
- **Field cage design**.

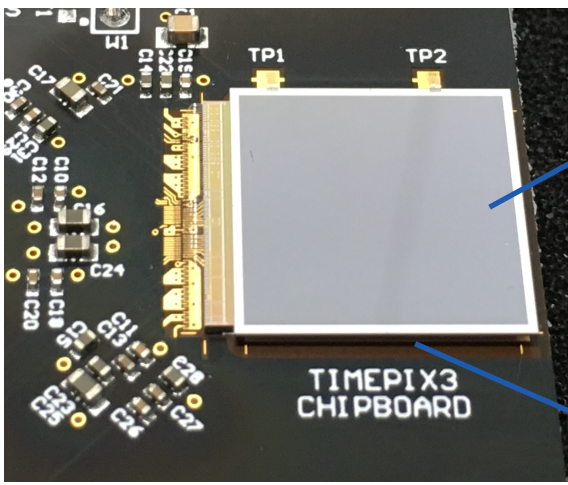
New BGI profile monitors for LIU-PS

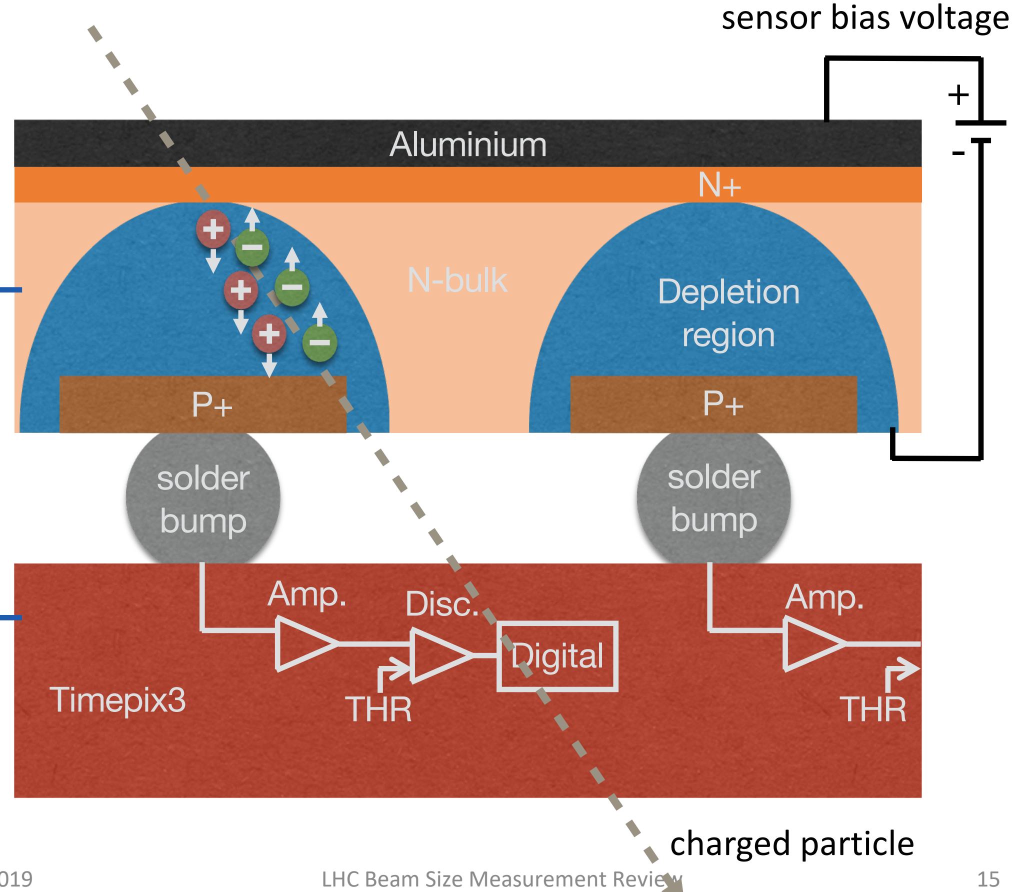


Timepix3 hybrid pixel detector

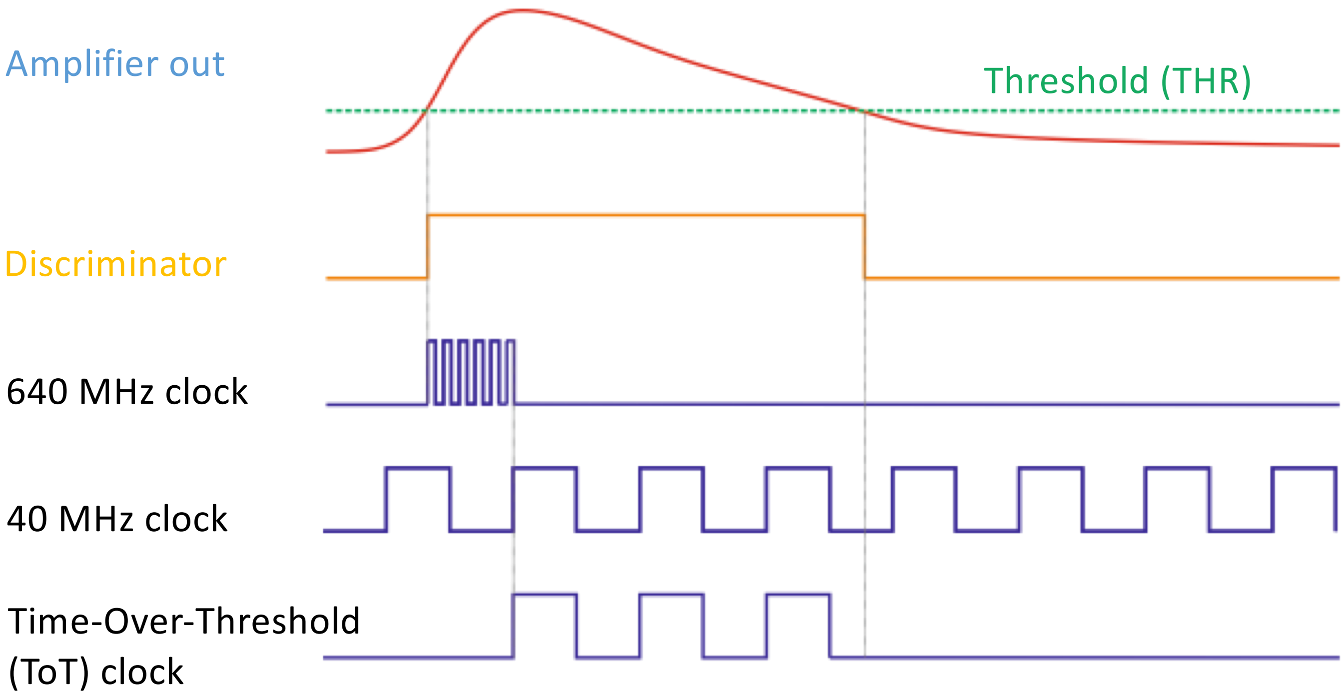
Hybrid Pixel Detector (HPD): Pixelated sensor bump bonded to a pixelated readout chip.

Sensor: 256 x 256 matrix of **55µm x 55µm** PN-diodes (**pixels**), with total area of 2 cm^2.
Readout chip: 256 x 256 matrix of readout channels (CMOS 130nm).





Timepix3 response to charge



minimum threshold = 500 e$^-$ (1.8 keV)

time resolution = 1.5625 ns

Amplifier out > threshold

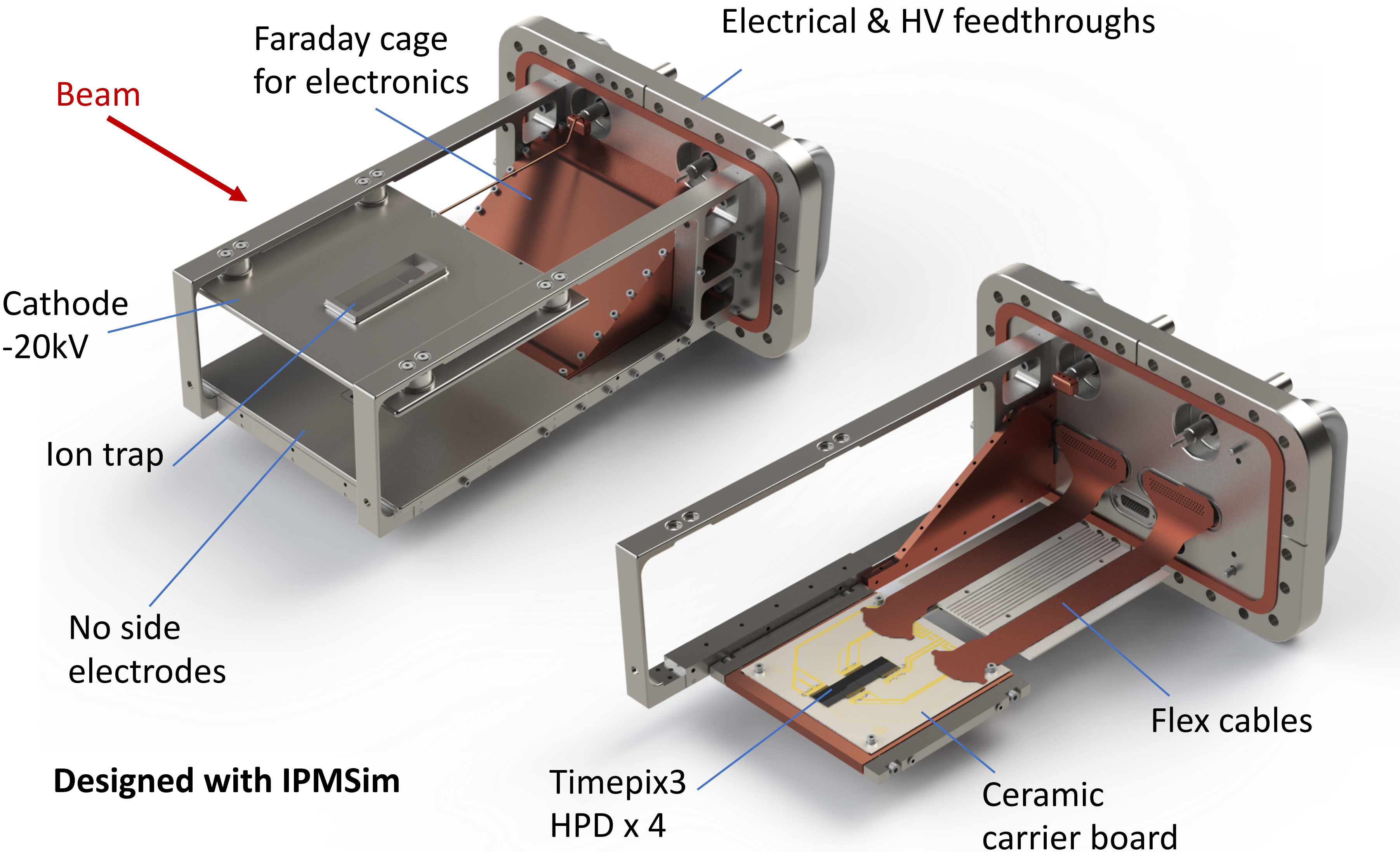
→ **Event**

Each **event** consist of:

- Pixel position → **Where**
- Time of Arrival (ToA) → **When**
- Time-Over-Threshold (ToT) → **Energy**

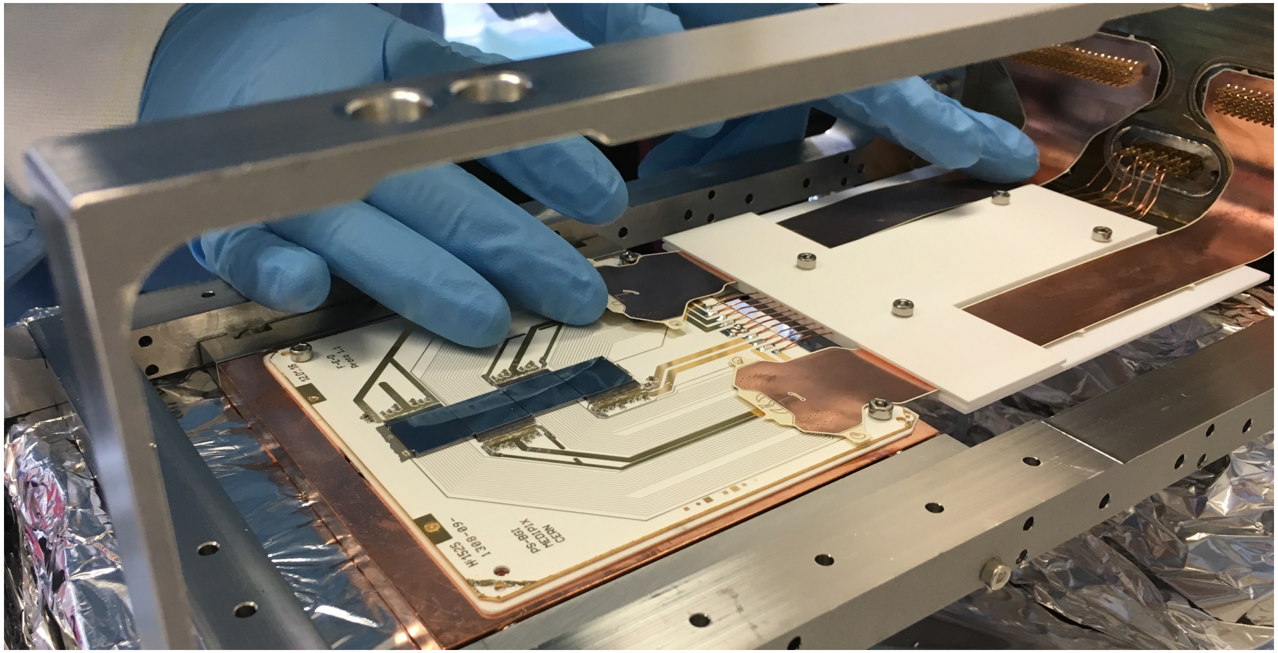
Max.
80M events / s

Timepix3-BGI design for the PS



Designed with IPMSim

Realisation of UHV compatible detector

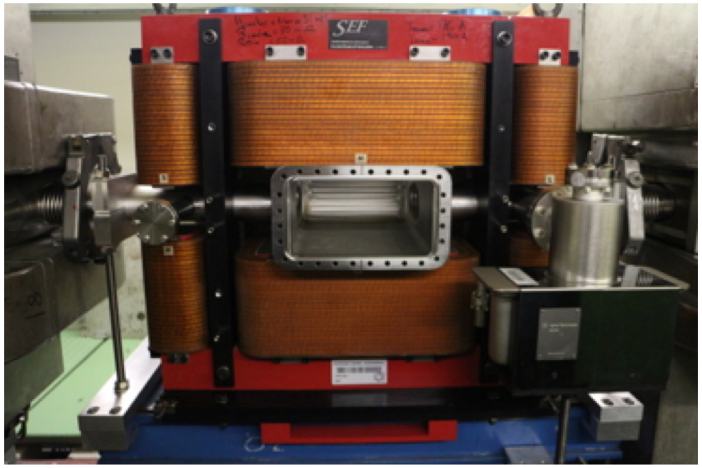


Ceramic carrier board
- 2 metal layers, Al_2O_3 substrate.
- 4 x Timepix3 with 100um n-on-p sensors.

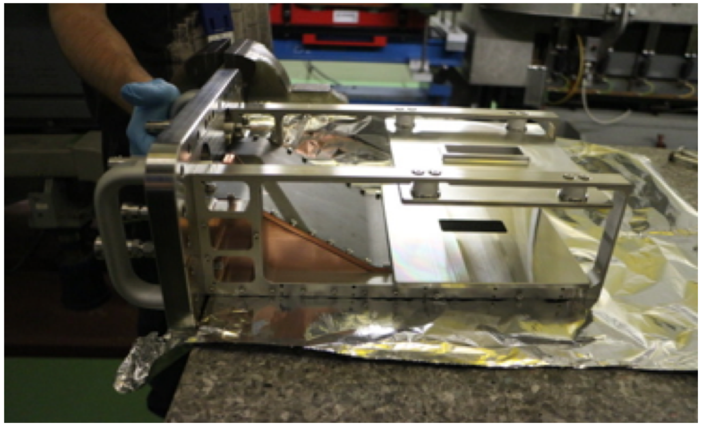
Flexible cables
- Connect ceramic board to vacuum electrical feedthroughs.
- Two metals layers with a Liquid Crystal Polymer (LCP) substrate.

All components qualified by vacuum group for operation in PS primary vacuum.

Installation in the CERN PS



0.2T self-compensating triplet dipole magnet & instrument vacuum chamber



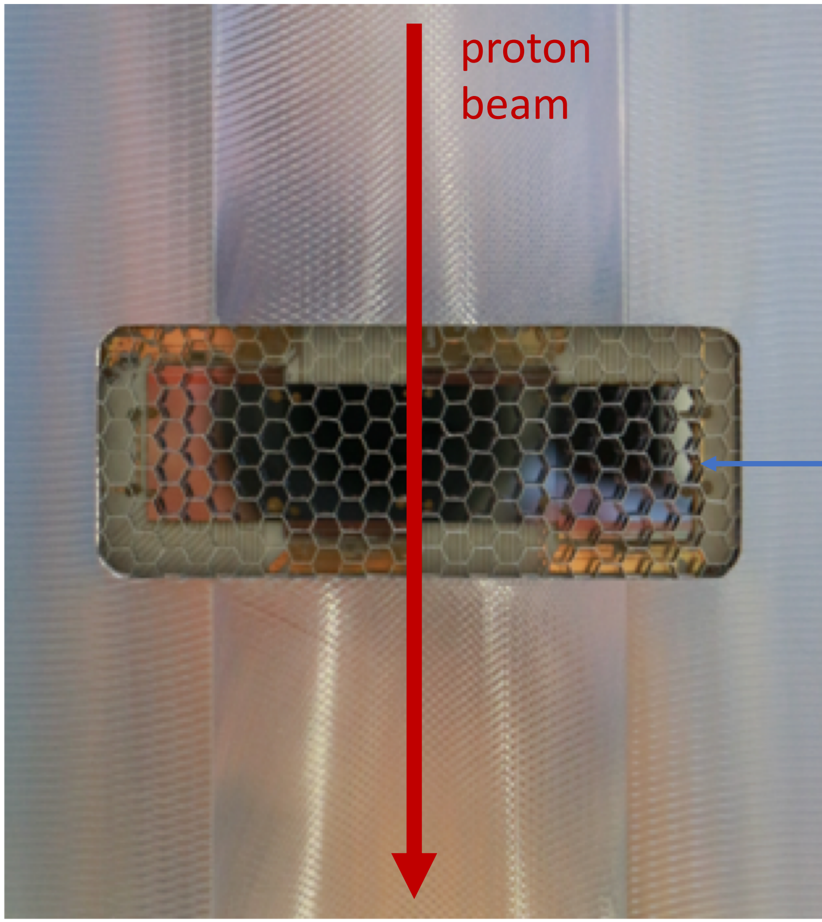
Timepix3-BGI before installation

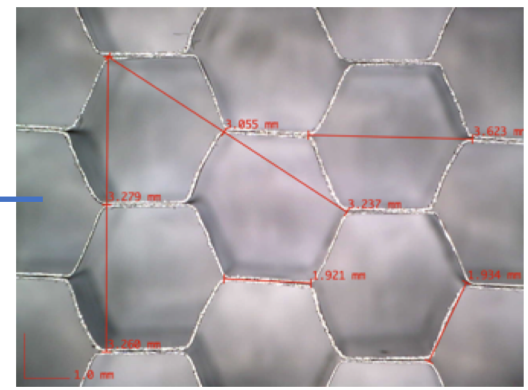
Installation in the CERN PS

Vacuum pump down:

- 1 x 10-8 mbar after 24 hours,
- **2 x 10-10 mbar steady state.**

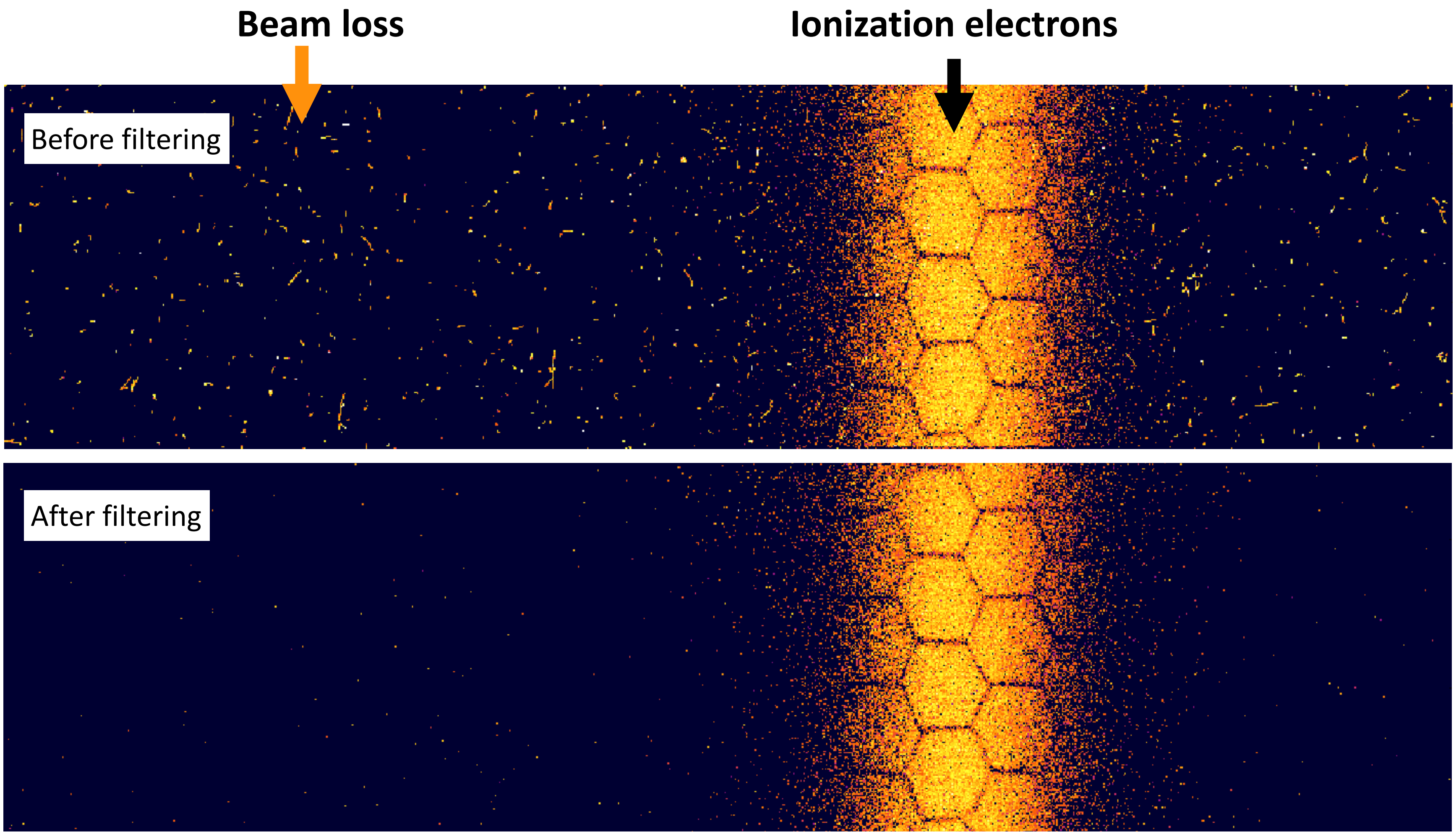
Faraday cage for Timepix3 & cables





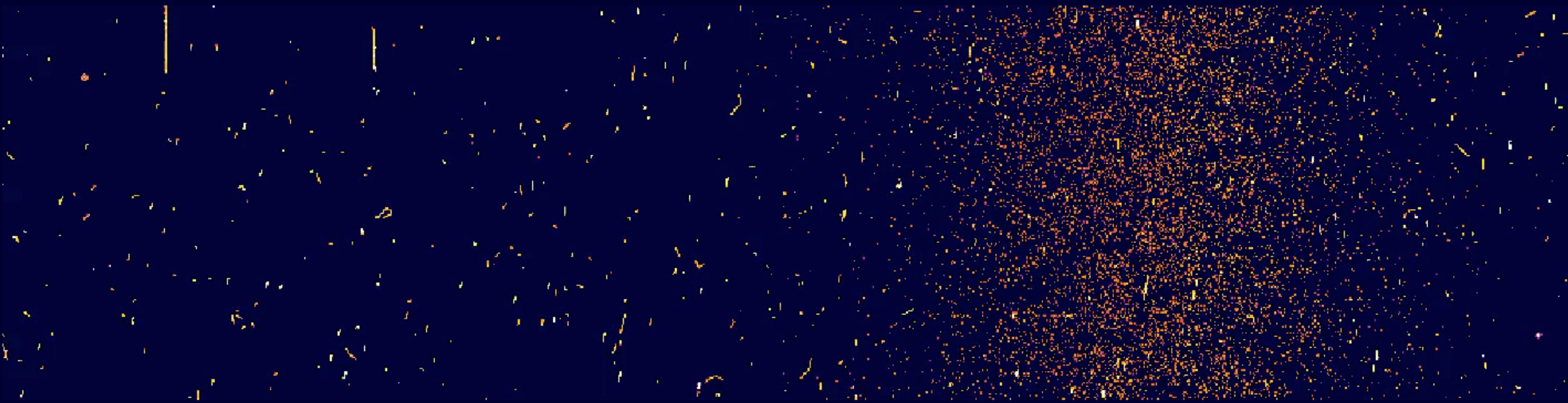
honeycomb structured
RF shield

Example beam images



- **Signal:** Ionization electrons - single-pixel events with low ToT.
- **Background**: beam loss particles - multi-pixel events close in time with higher ToT.

Video of complete LHC cycle in the PS

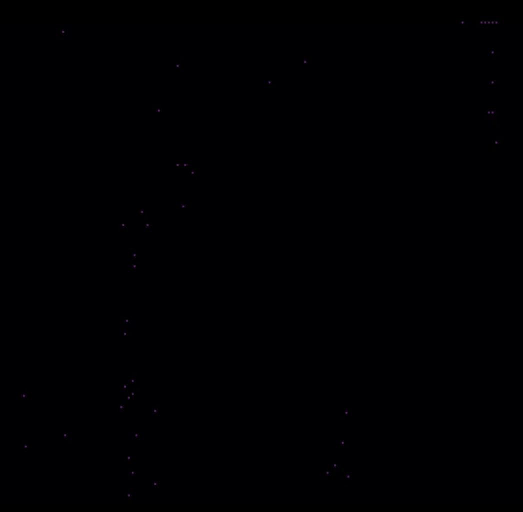


- Video shows LHC type beam from injection, through acceleration and finally extraction.
- 1.5 seconds in real time: slowed down here for viewing purpose.
- Each frame is 10 ms of data
- Not filtered to show background particles.

http://bgi-web.web.cern.ch/bgi-web/images/iworid-2018-video.gif

Video of partially stripped lead ion beam

Raw data



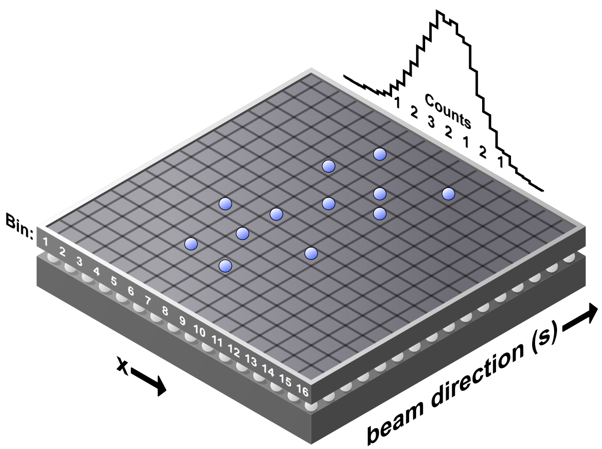
Beam parameters:

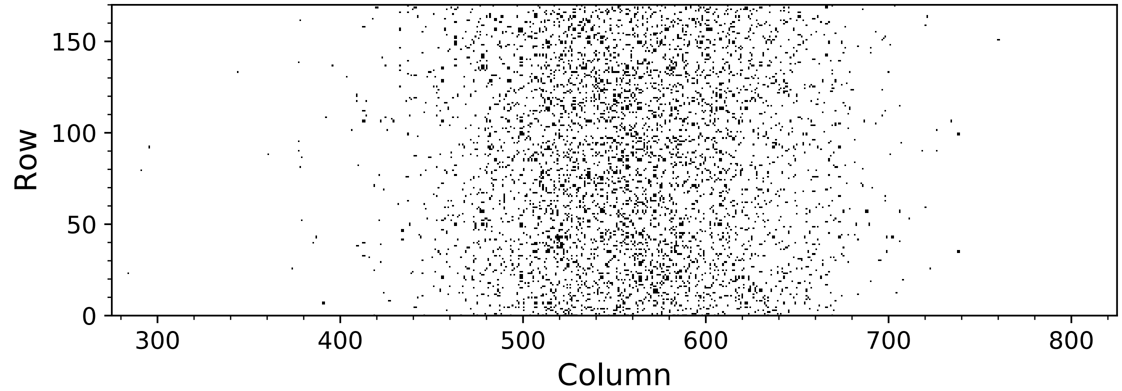
- ILHC200#2b_2018_partial_strip
- Intensity = 8.9×10^{10}
- Vacuum = 9.8×10^{-11} mbar

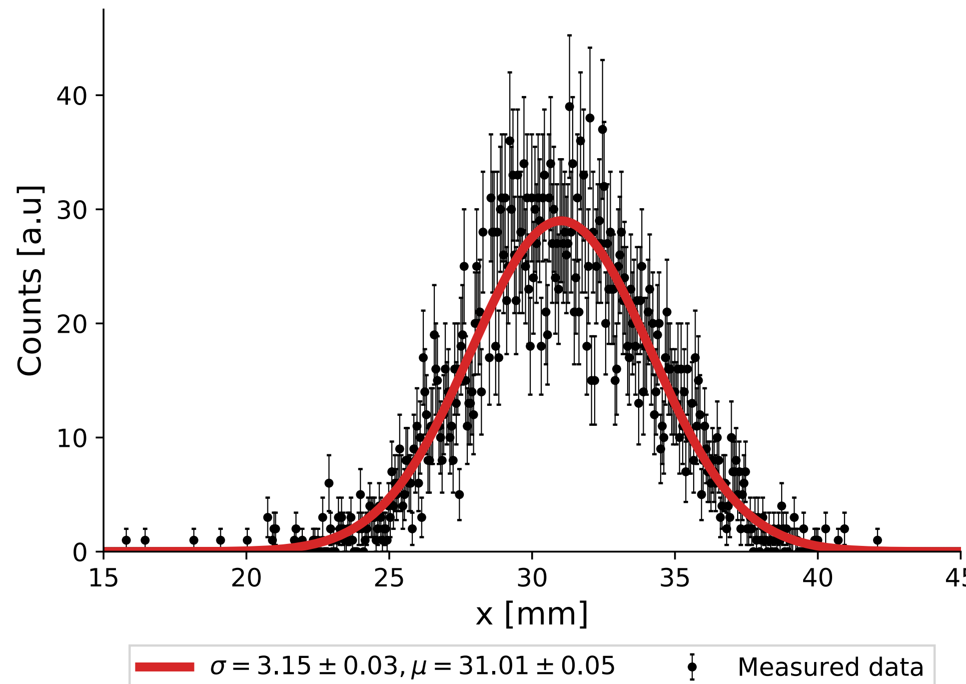
After processing to remove unresponsive pixels

Beam profile measurement

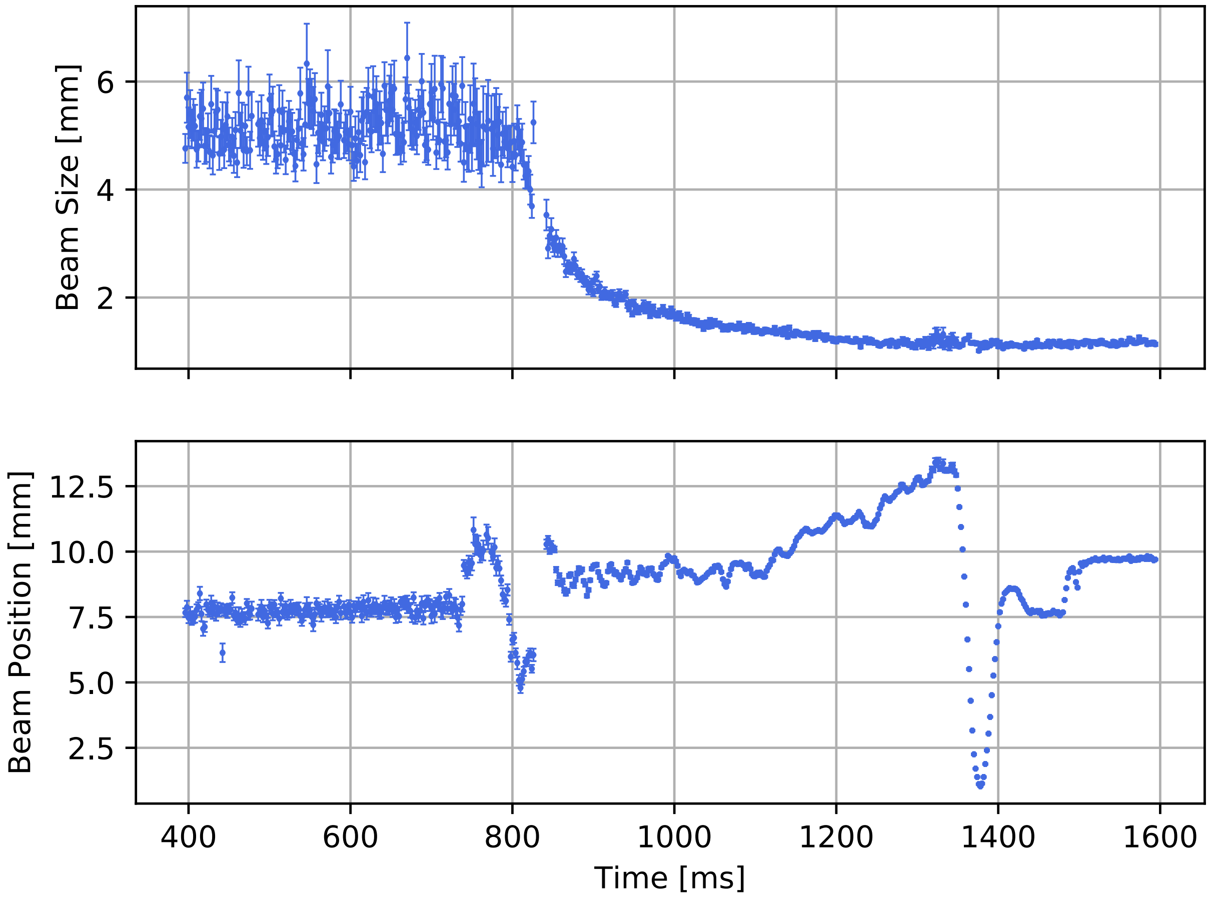
Compute beam profile by summing counts in each column.





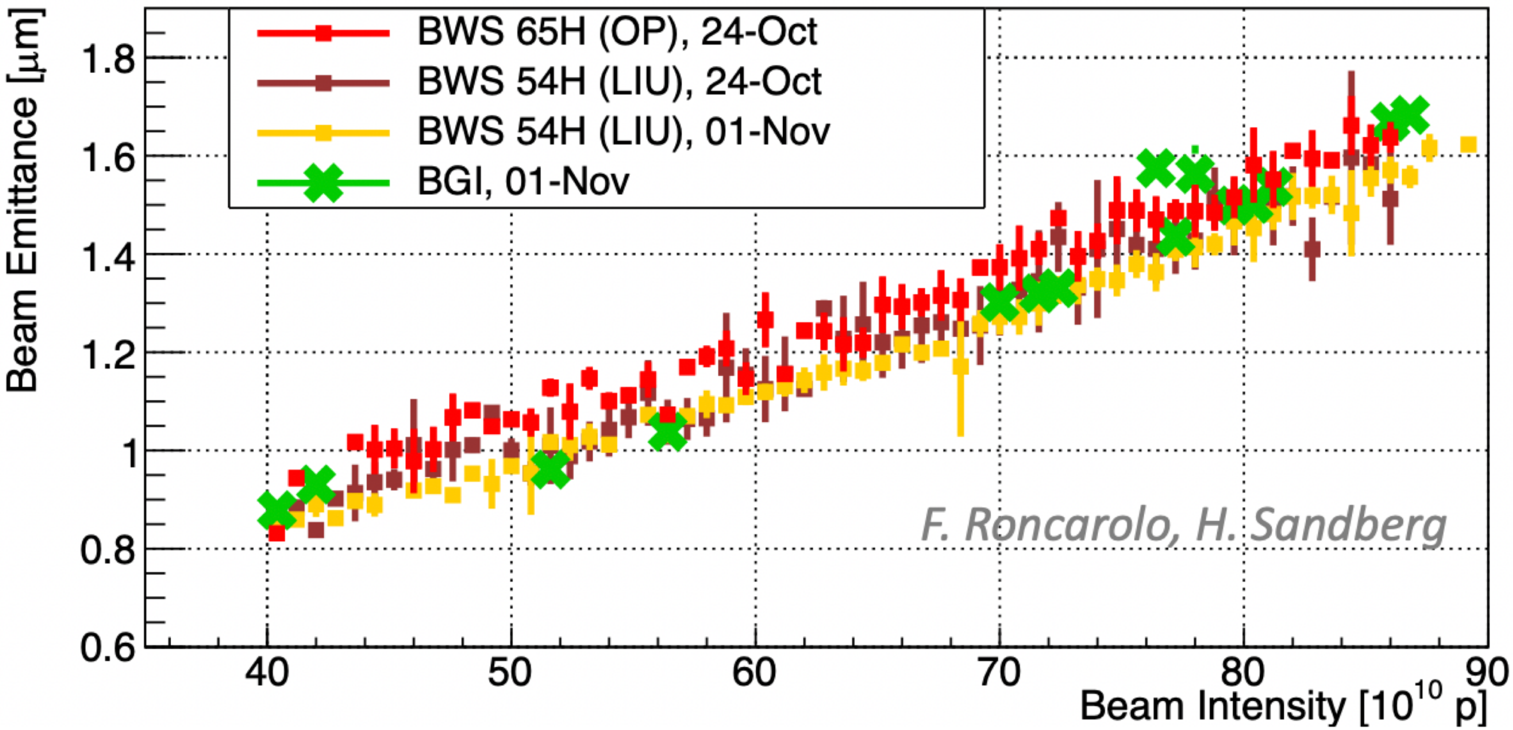


Evolution of beam size & position



Continuous beam profile measurements of a single PSB bunch at 2 kHz c.f. ~10 Hz for MCP-based BGI design.

Brightness curve



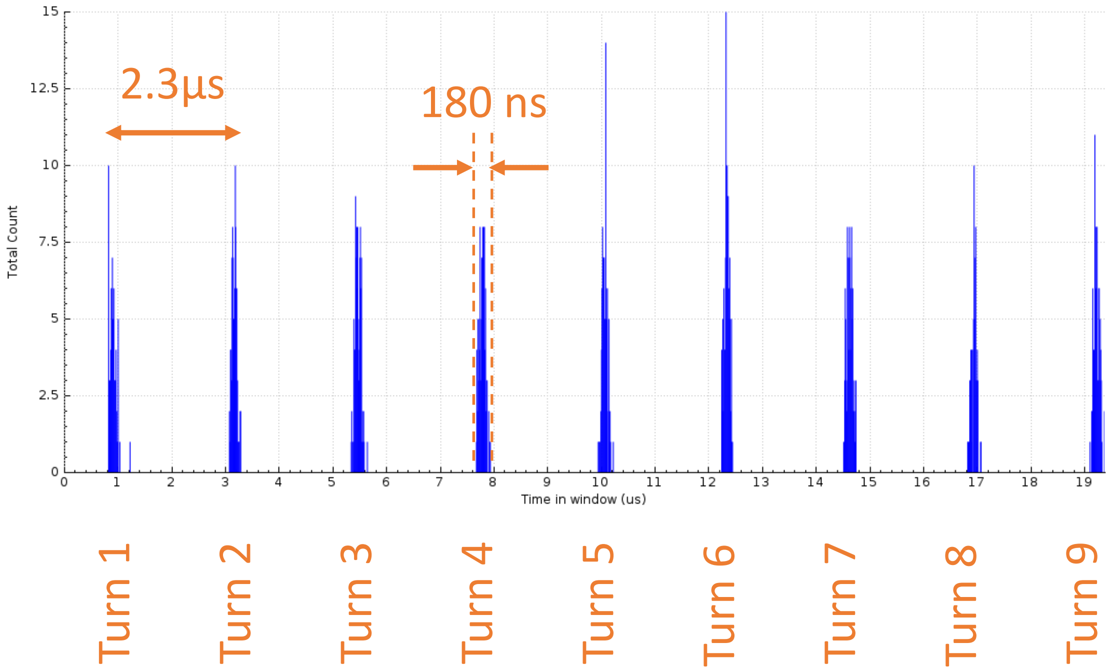
Good agreement between the Beam Wire Scanner (BWS) & BGI :

- → Timepix3-BGI point spread function is negligible.
- BGI beam size measurement independent of other profile monitors & beta function.

Time structure of the ionisation electron counts

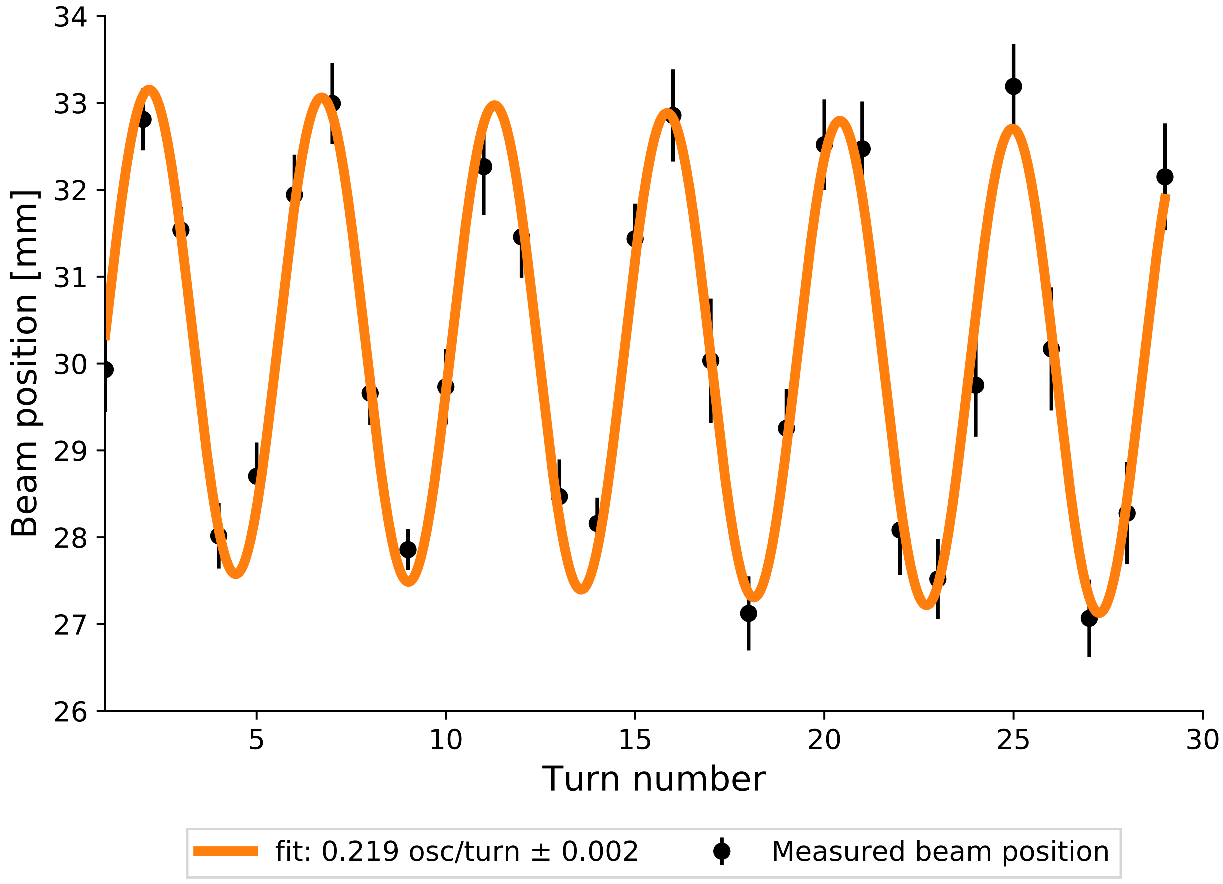
- Time for 1 revolution (turn) of the PS = **2.3 µs.**

Timepix3-BGI measurements of a single PSB bunch



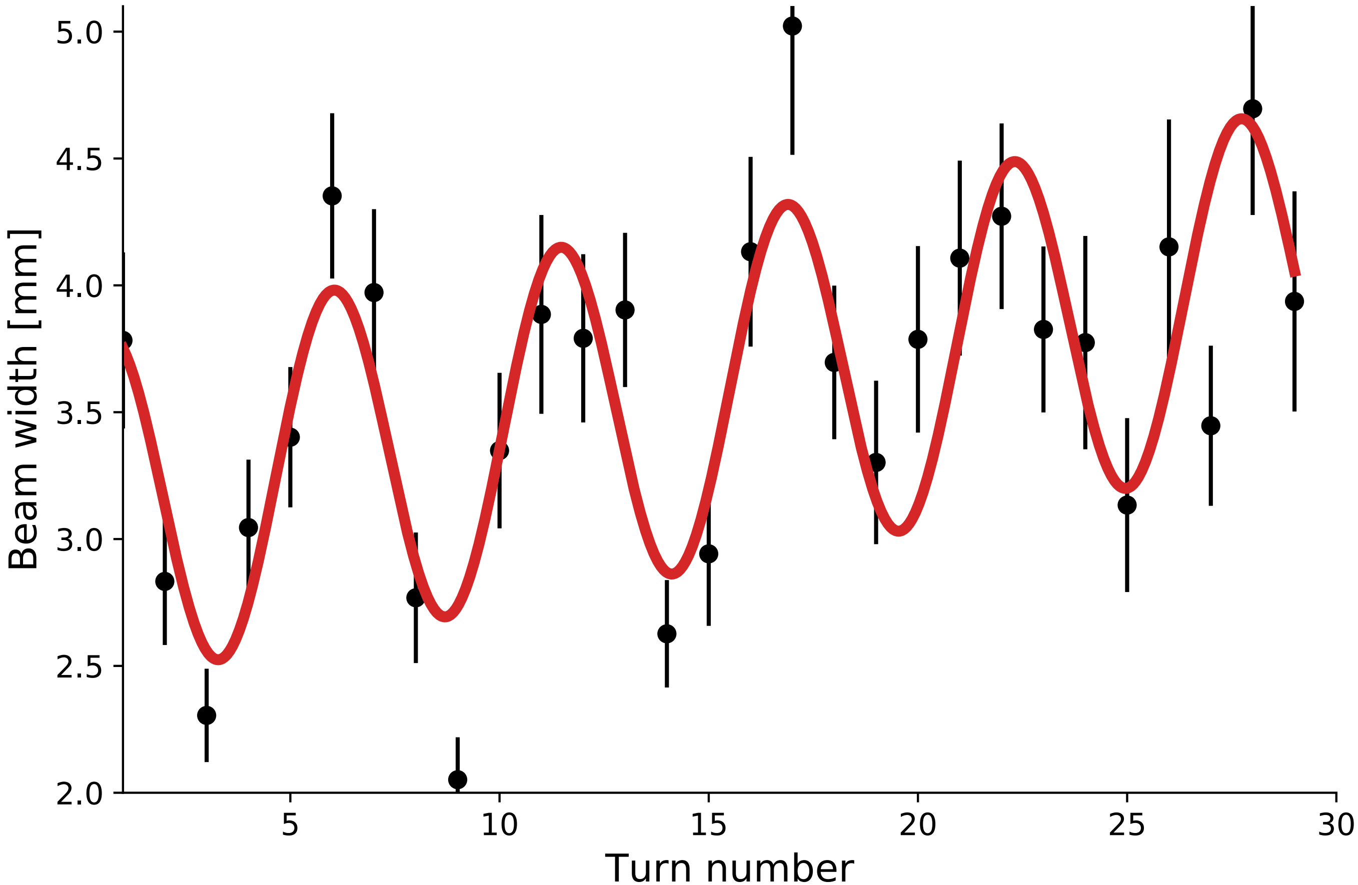
→ Longitudinal bunch length consistent with Wall Current Monitor (WCM).

Turn-by-turn **beam position** at injection



Measurement consistent with fractional tune measurement.

Turn-by-turn **beam size** at injection



Frequency of beam size beating consistent with SEM grid measurement.

Summary of Timepix3-BGI

- Timepix3 hybrid pixel detectors operated directly inside the beam pipe primary vacuum over a 2 year period **without measurable effect on either the vacuum or beam loss**.

- **Direct detection of ionisation electrons with Timepix3** has significant benefits :

  - **No need for MCP**, phosphor and intensified cameras.

  - Beam size measurements are **independent** of other instruments.

  - Allows to **count individual ionisation electrons**; facilitates efficient data processing & estimation of the measurement precision.

  - **Continuous beam profile measurement at ~1kHz.**

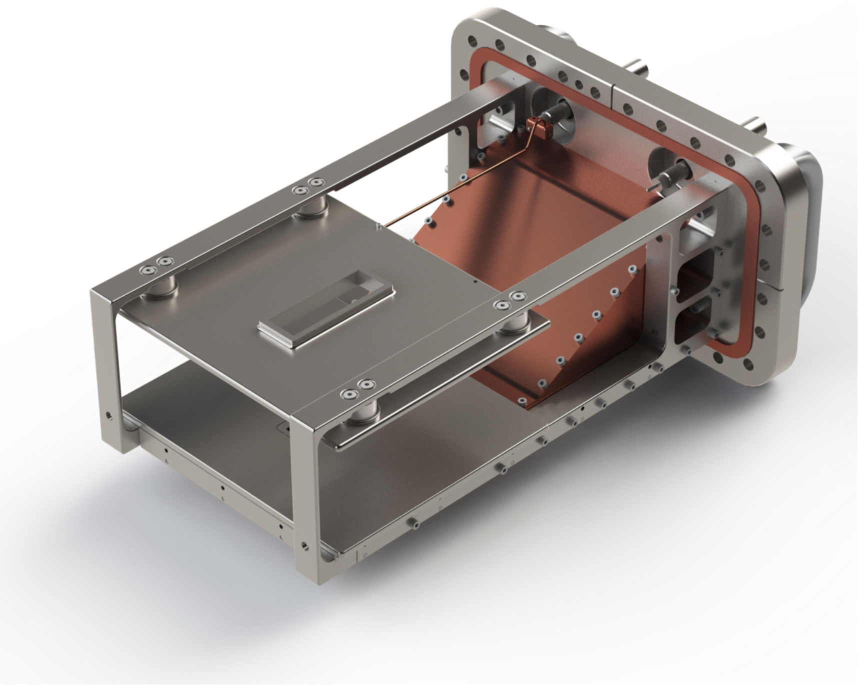
  - Time-resolution allows for **bunch-by-bunch** and **turn-by-turn** measurements.

3. Proposal for a Timepix3 based BGI profile monitor for HL-LHC

MCP-BGI problems vs. Timepix3-BGI solutions

Problems & limitations	Possible solutions
1. Instrument damage due to beam induced heating	Smaller electrodes & vacuum chamber; detector components hidden behind Faraday cage and actively cooled.
2. Profile distortion due to ageing of MCP, phosphor & intensified cameras	MCP, phosphor & intensified camera replaced with Timepix3 hybrid pixel detector.
3. Distortion to **proton** beam profiles for E > 4 TeV	Not solved.
4. Not an independent beam profile measurement.	Independent measurement due to direct detection of ionisation electrons.

Instrument dimensions



PS BGI-Horizonal :
Anode – cathode distance = 70 mm ;
Vacuum chamber aperture = 118 mm ;
Magnet aperture = 128 mm.

Current LHC MCP based BGI :
Anode – cathode distance = 84 mm ;
Vacuum chamber aperture = **182 mm ;**
Magnet aperture = 200 mm.

Proposed LHC Timepix3 based BGI :
Anode – cathode distance = 60 mm ;
Vacuum chamber aperture = **108 mm ;**
Possible to ~half magnet aperture.

Dimensions of LHC Timepix3-BGI similar to PS BGI-Horizontal.

Simulation of Timepix3-BGI performance for HL-LHC

1) Simulation of rest gas ionisation electron generation & transport to the imaging detector plane with IPMSim.

2) Simulation of the response of the Timepix3 pixel detector to the ionisation electron image.

Ions: Simulation of ionisation electron production & transport to imaging detector plane

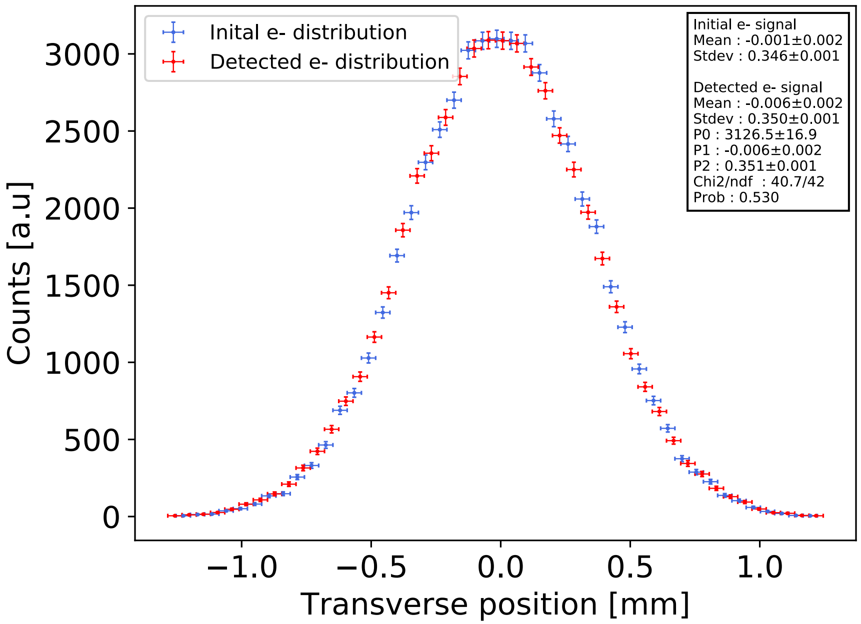
Input to IPMSim:

- Pb82+ at 7 TeV / proton
- Emittance = 1.65µm
- Beam size = 346 µm
- Intensity = 1.8x10^8
- **BGI B-field = 0.2 T**

Simulation of 50,000 ionisation electrons.

Output:

$\sigma_{initial} - \sigma_{detected} / \sigma_{initial} = 1.4\ \%$



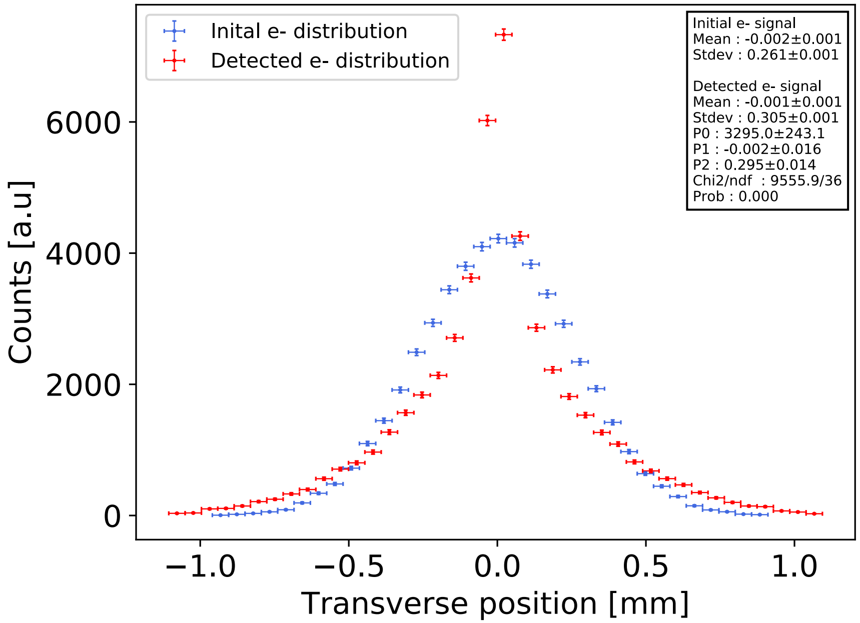
Conclusion for ions: Systematic error due to electric bunch field on trajectories of ionisation electrons < 2 % - at all stages of the LHC cycle.

What about **protons at 7 TeV?**

Input to IPMSim:
- Protons at 7 TeV
- Emittance = 2.50 µm
- Beam size = 260 µm
- Intensity = 22×10^{10} ppb
- **BGI B-field = 0.2 T**

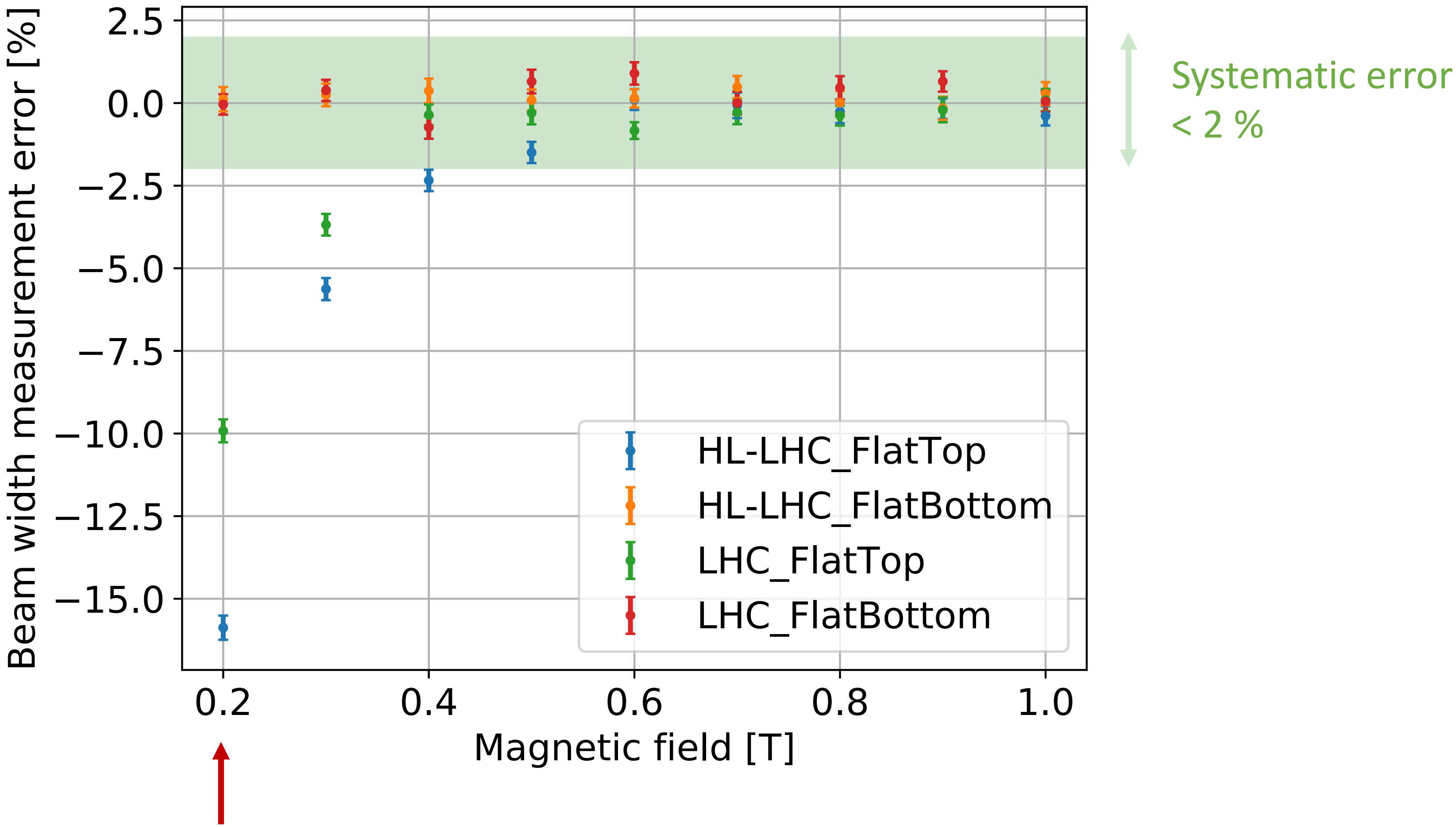
Simulation of 50,000 ionisation electrons.

Output:
$RMS_{initial} - RMS_{detected} / RMS_{initial} = 17\ \%$



As expected from Run1 - significant distortion to beam profile.

Simulation of systematic beam size error vs. magnetic field strength



Current BGI dipole magnets = 0.2 T

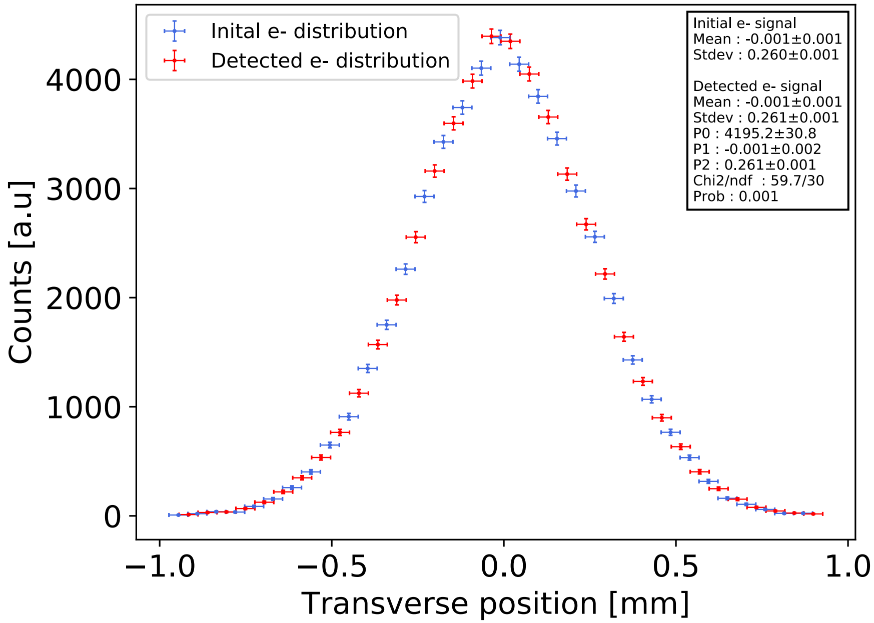
Simulation of protons at 7 TeV with **0.6 T magnetic field**

Input to IPMSim:
- As before, except…
- **BGI B-field = 0.6 T**

Simulation of 50,000 ionisation electrons.

Output:

$\sigma_{initial} - \sigma_{detected} / \sigma_{initial} = 0.1\ \%$



With 0.6 T magnetic field the distortion to proton beam profile at 7 TeV is negligible.

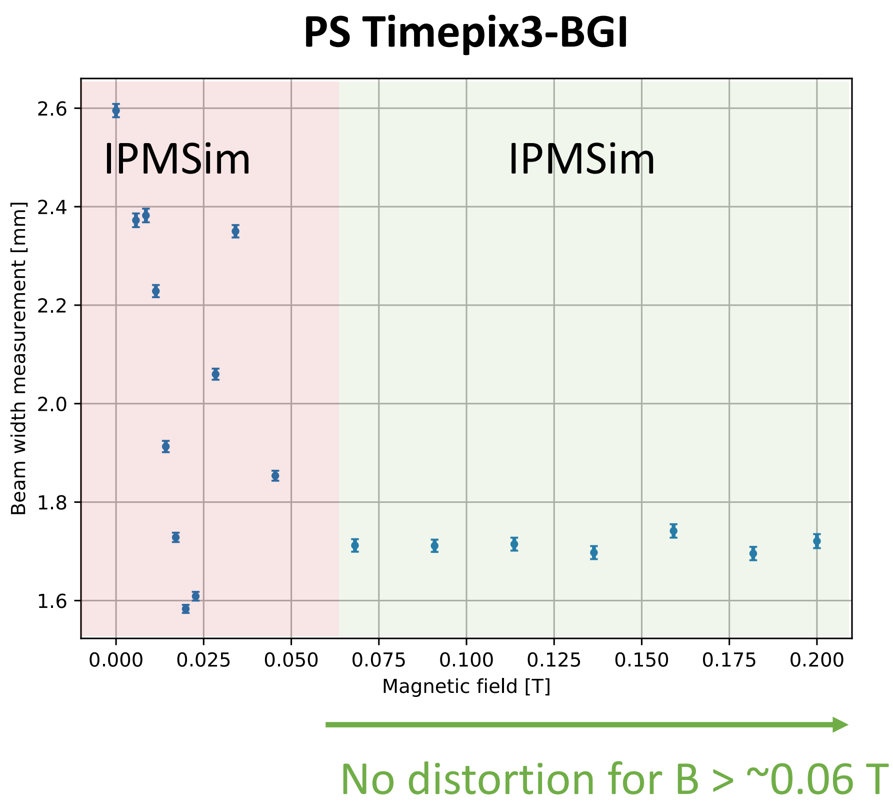
Can we trust this prediction? Measurements of PS Timepix3-BGI beam size vs. magnetic field strength

Prediction: IPMSim predicts B-field of at least 0.07 T is needed to prevent distortion to proton beam profile at E = 26 GeV.

Result:

Significant beam profile distortion when B-field is less than ~0.06 T.

Reasonable agreement with IPMSim prediction.

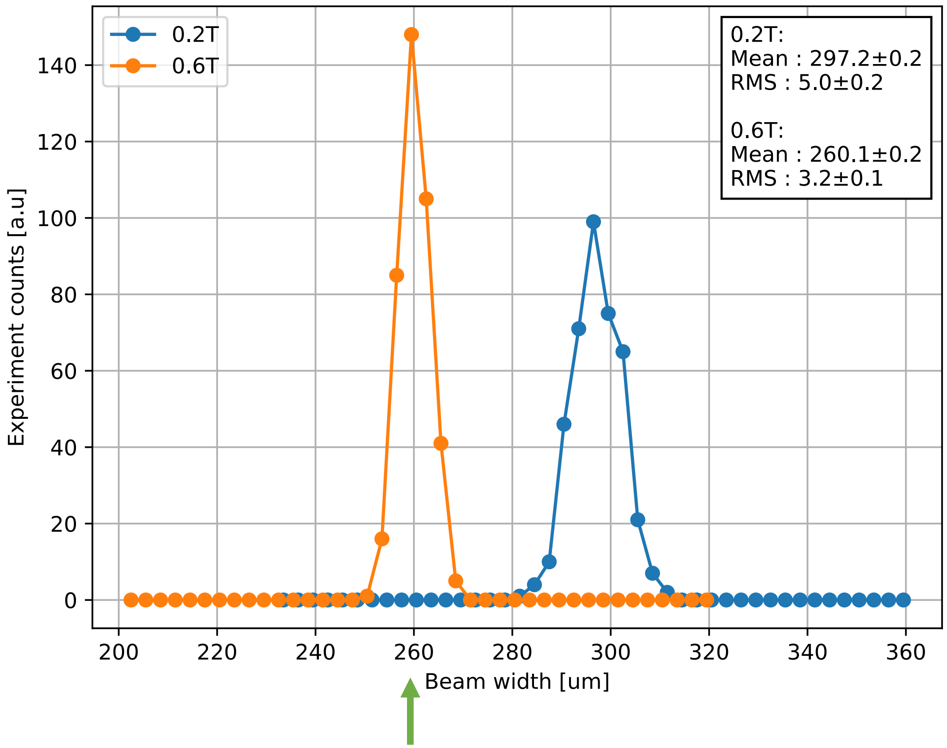


Simulation of multiple measurements

Input: HL-LHC proton beam parameters at E=7 TeV.

Method:

- 1 x simulation = beam size measurement with **4000 ionisation electrons.**
- Repeat simulation x400 times with **B = 0.6 T** and then again with **B = 0.2 T.**



true beam size = 260 µm

Result with B = 0.6 T :

Measurement spread (statistical error)
= 3.2 µm / 260 µm
= 1.2 % (*)

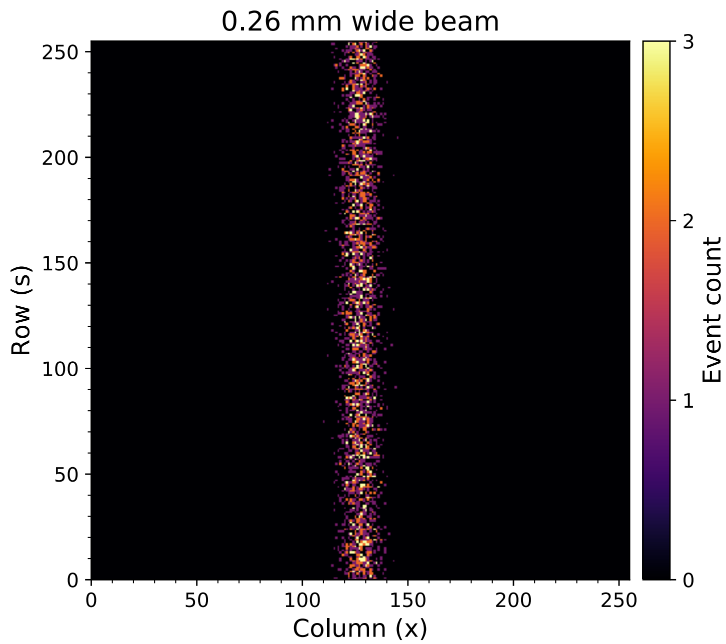
Measurement offset (systematic error)
= 260.1 µm – 260 µm / 260 µm
= 0.1 %

(*) consistent with statistical error expected for 4000 samples of a Gaussian distribution = 1 / sqrt(2*4000 – 2) = 1.1 %.

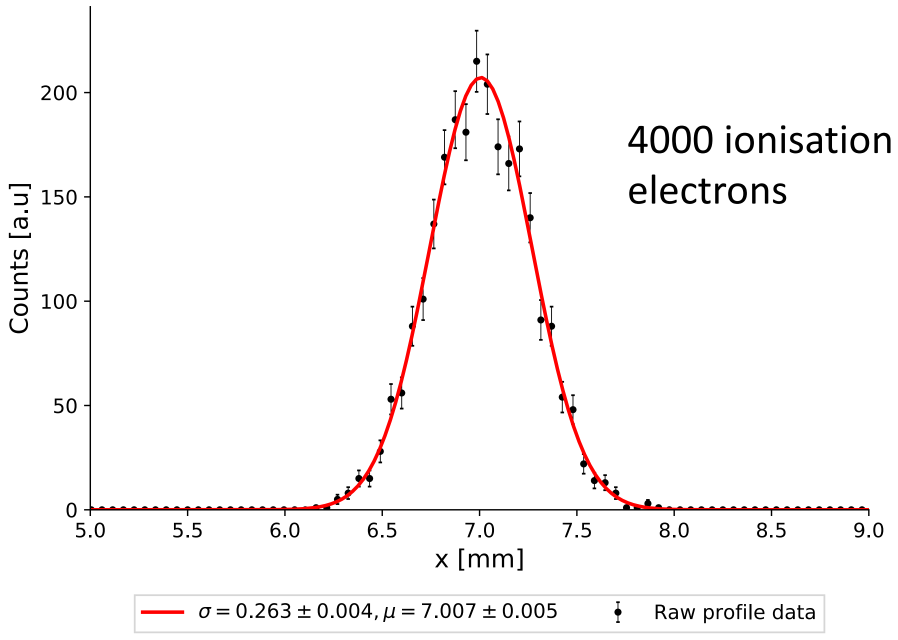
Simulation of the Timepix3 pixel detector response

Toy Monte-Carlo simulation of Timepix3 pixel detector response.
Studied response of detector to a **260 µm beam**, e.g.

Simulated Timepix3 image



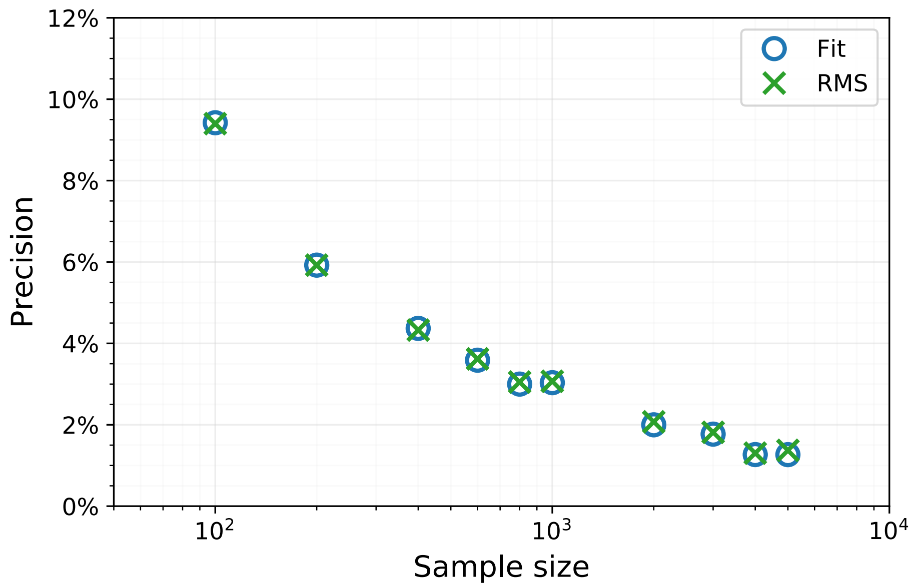
Reconstructed beam profile



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

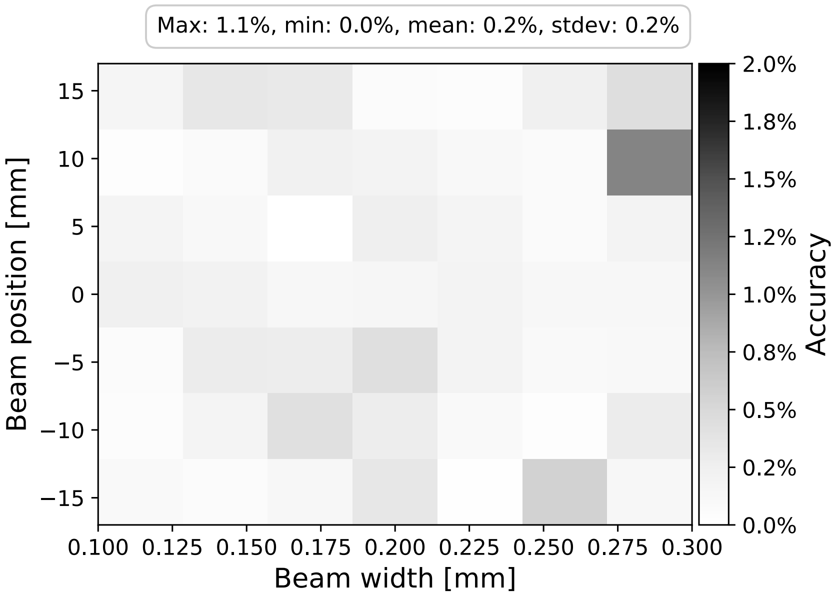
Response of the Timepix3 pixel detector

Statistical error (precision)
= standard deviation (residual distribution)



e.g. single measurement with a sample size of 2000 ionisation → 2 % statistical error.

Systematic error (accuracy)
= mean(residual distribution)



→ Timepix3 detector predicted to have a negligible contribution to the measurement systematic error.

Estimated performance of **Timepix3-BGI with B = 0.6 T dipole magnet**

Performance estimates for beam profile measurements at **injection, ramp and collision,** assuming residual gas pressure 1×10^{-10} mbar (**no gas injection**) :

HL-LHC Pb82+

- Average beam size
  - Integration window = **0.1 ms** → 4000 electrons → **statistical error = 1%**
- Bunch – by – bunch size
  - Integration window = **10 ms** → 400 electrons per bunch → **statistical error = 5%**
- **Systematic error < 2 %** (IPMSim + Timepix3 detector response)

HL-LHC protons

- Average beam size
  - Integration window = **1 ms** → 4000 electrons → **statistical error = 1%**
- Bunch – by – bunch size
  - Integration window = **100 ms** → 400 electrons per bunch → **statistical error = 5%**
- **Systematic error < 2 %** (IPMSim + Timepix3 detector response)

Realisation

Starting point for the design = PS Timepix3-BGI

Additional developments needed for LHC Timepix3 –BGI:

1. After installation in the vacuum the pixel detector needs to be **vacuum bakeable** → R&D effort in collaboration with vacuum group.

2. Need to optimise design to **minimise beam induced heating** of the instrument → R&D effort in collaboration with RF group.

The **Timepix3 readout electronics & software** (BIPIX) & the PLC based instrument slow control system will be the **same as the PS instruments.**

Proposal summary

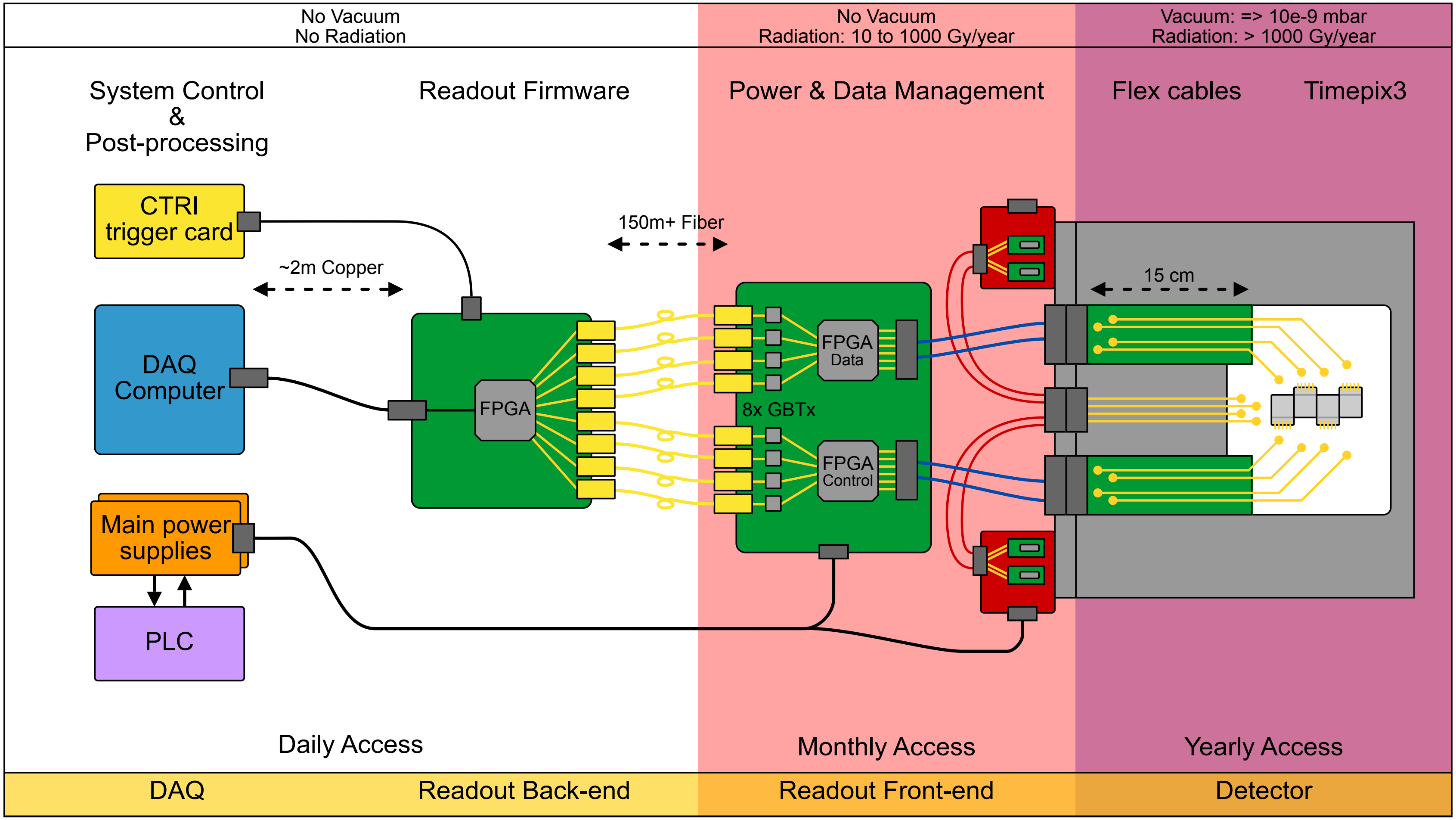
Timepix3-BGI with 0.6 T self-correcting dipole magnet :

- **Independent** beam profile measurements of **ions & protons** at **all stages** of HL-LHC cycle ;
- Residual gas ionisation – **no gas injection** ;
- **Fast average beam** and **bunch-by-bunch** measurements.

Based on successful development of Timepix3-BGI for LIU-PS and well established IPMSim simulation.

Special thanks to :
Swann Levasseur &
Hampus Sandberg (BE-BI-BL)

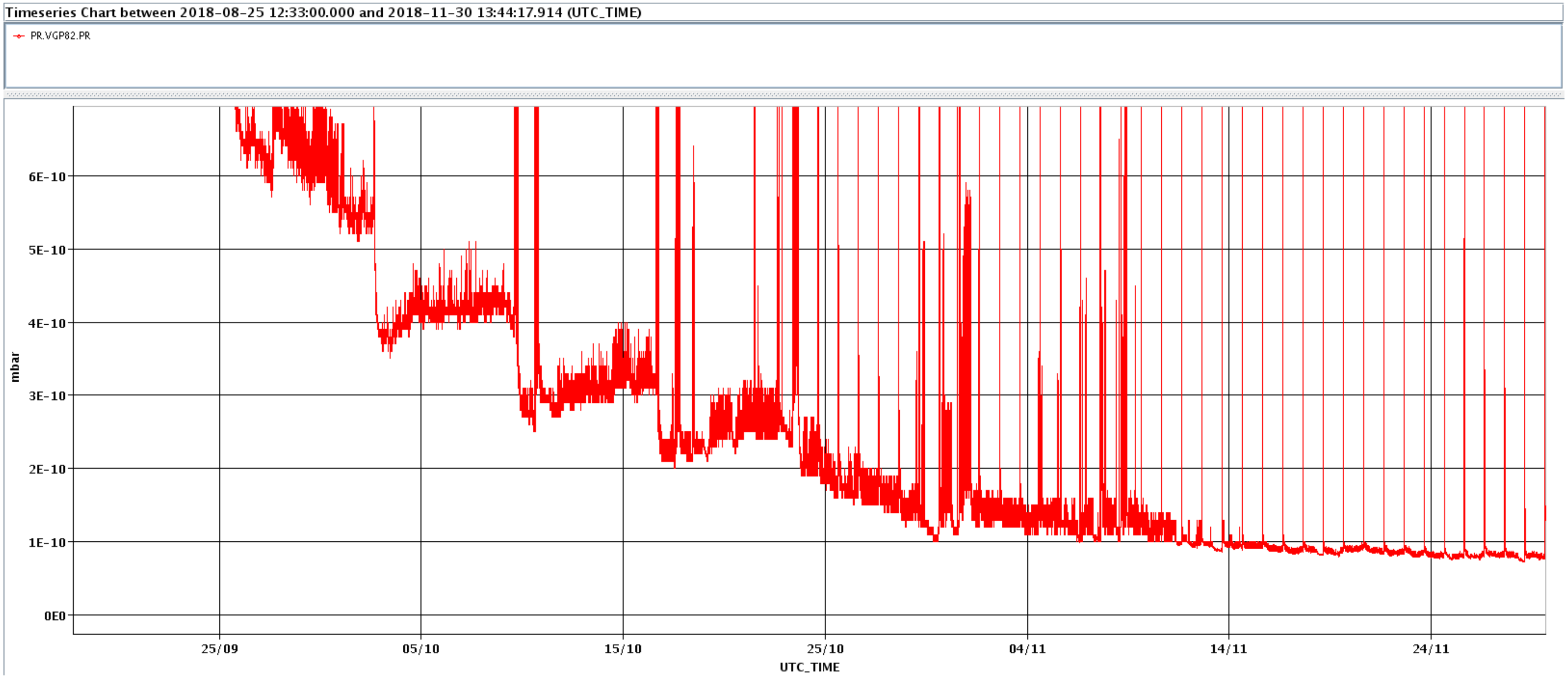
Radiation tolerant readout for Timepix3 (BIPIX)



Timepix3 specification

CMOS node	130nm
Pixel Array	256 x 256
Pixel pitch	**55µm**
Charge collection	e^-, h^+
Pixel functionality	**TOT (Energy) and TOA (Arrival time)**
Preamp Gain	~47mV/ke$^-$
ENC	~60e$^-$
FE Linearity	Up to 12ke$^-$
TOT linearity (resolution)	Up to 200ke$^-$ (<5%)
TOA resolution	**1.6ns**
Time-walk	<20ns
Minimum detectable charge	**~500e$^-$ → 2 KeV (Si Sensor)**
Max Analog power (1.5V)	500 mA/chip
Digital Power (1.5V)	~400mA data driven
Maximum hit rate	80Mhits/sec (in data driven)
Readout	Data driven (44-bits/hit @ 5Gbps)

PS vacuum pressure close to the Timepix3-BGI



Estimate of ionisation electron yields

Residual gas & gas injection parameters

Parameter	Units	PS	LHC
Vacuum pressure	10^{-10} mbar	1	1
Vacuum pressure with gas injection - minimum used in Run 1	10^{-10} mbar	-	30
Vacuum pressure with gas injection - maximum used in Run 1	10^{-10} mbar	-	700
Ionisation cross section of Neon	/ cross section of hydrogen	1	2.39

Protons beam parameters

Parameter	Units	PS	LHC
Bunch population	10^{10} ppb	70 (flat bottom)	12.5
Number of bunches		1	2556
Turn period	us	2.3	88.9
Ionisation electrons per bunch per turn - residual gas only	electrons	2.3 (1000 in 1ms = 1000 / 435 turns = 2.3 e/turn)	0.41
Integration time for **beam size** with 1% precision (= 4000 electrons)	ms (turns)		**0.340 (3.8)**
Integration time for **bunch size** with 5% precision (= 400 electrons)	ms (turns)		**86.732 (976)**
Timepix3 electrons per turn	events per turn		1000
Timepix3 electrons per pixel (assume spead over 1280 hot pixels)	events per pixel per second		9000 (TPX3 max. 975,000; sustainable 1,200)
Timepix3 electrons per chip per second	events per chip per second		10M (TPX3 max. 80 M/s)

Ion beam parameters Pb82+

Parameter	Units	PS	LHC
Charge	q		82
Bunch population	10^{10} ppb		0.018
Number of bunches		1	1232
Turn period	us	2.3	88.9
Ionisation electrons per bunch per turn - residual gas only	electrons	2.3 (1000 in 1ms = 1000 / 435 turns = 2.3 e/turn)	4
Integration time for **beam size** with 1% precision (= 4000 electrons)	ms (turns)		**0.089 (1)**
Integration time for **bunch size** with 5% precision (= 400 electrons)	ms (turns)		**8.890 (100)**
TImepix3 electrons per turn	events per turn		5000
Timepix3 electrons per pixel (assume spead over 1280 hot pixels)	events per pixel per second		43,000 (TPX3 max. 975,000; sustainable 1,200)
Timepix3 electrons per chip per second	events per chip per second		55M (TPX3 max. 80 M/s)