Applications of Timepix technology for Beam Instrumentation at CERN

EP Detector Seminar, 29th April 2022

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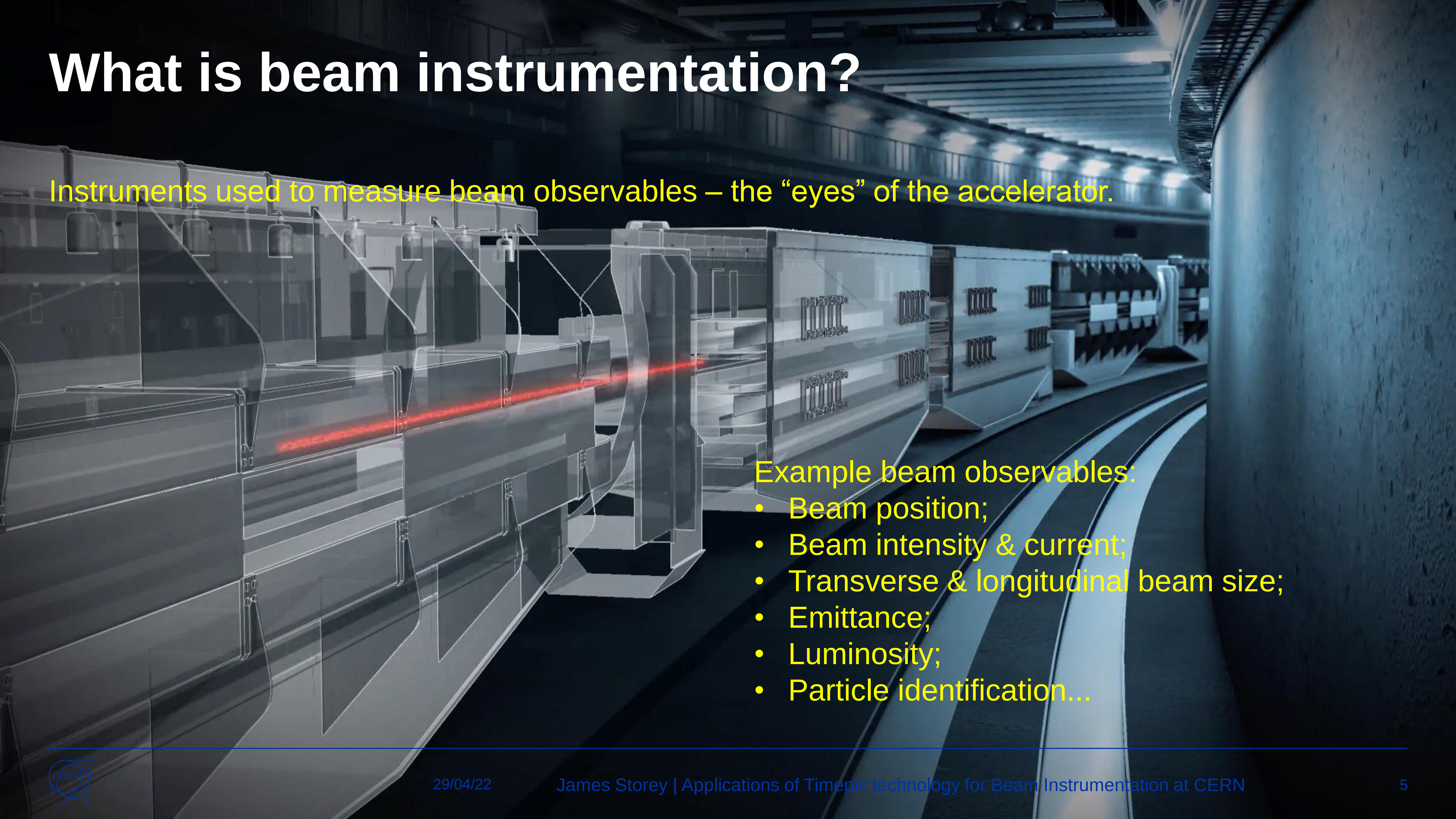
Outline

1. Overview of beam instrumentation at CERN

2. Realisation of a non-destructive beam size monitor based on Timepix3
    - Based on Timepix3 HPD's installed directly inside the accelerator beam pipe UHV
    - Providing interesting new beam diagnostic insights

3. Future applications of Timepix technology for beam instrumentation at CERN

Beam Instrumentation & Diagnostics at CERN



What is beam instrumentation?

Instruments used to measure beam observables – the “eyes” of the accelerator.

Example beam observables:

- Beam position;
- Beam intensity & current;
- Transverse & longitudinal beam size;
- Emittance;
- Luminosity;
- Particle identification...

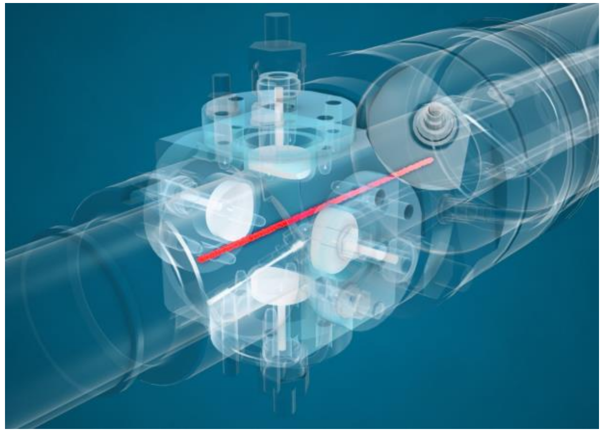
Beam instrumentation in a nutshell

How to measure the beam parameters?

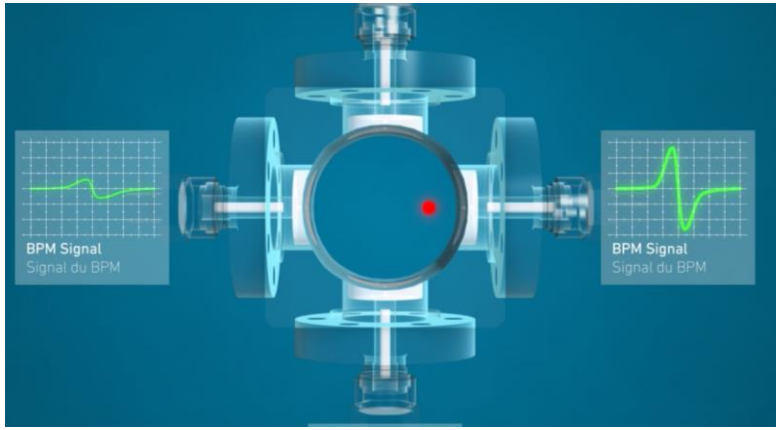
1. Interact with the **electromagnetic field** of the beam
   - Used for measurements of beam **position**, **intensity** & **current**
   - + (Almost) no effect on the beam & no effect on the monitor
   - - Can't measure beam profile (size)

LHC electrostatic button electrode

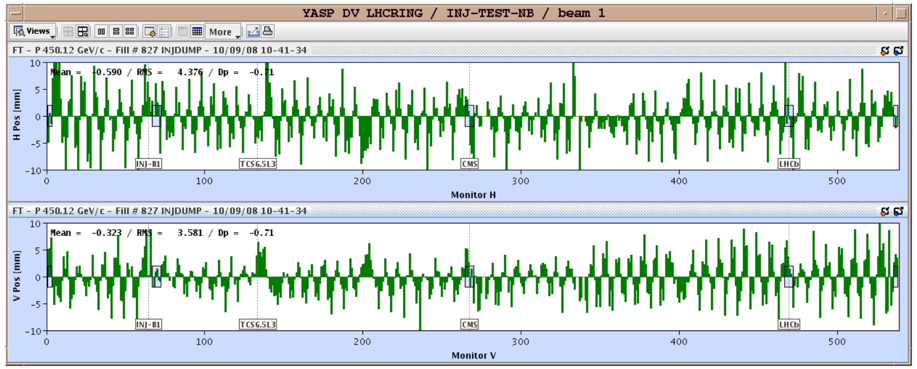
Example – Beam position monitor (BPM)



1. Electrostatic pickup consists of metallic (button) electrodes situated on opposite sides



2. As beam passes electric charges induced on electrodes, with more induced on the side closer to the beam



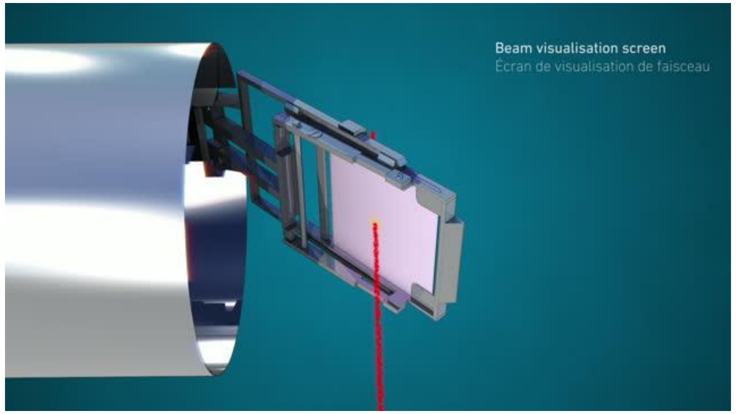
3. Horizontal (top) and vertical (bot.) position vs. LHC BPM position

Beam instrumentation in a nutshell

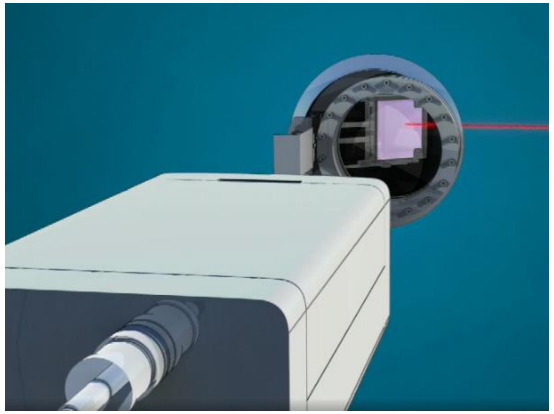
How to measure the beam parameters?

2. Interact with the **beam itself** (insert material into the beam path)
    - Used for measurements of **beam profile (size) & loss**
    - + Allows to measure beam profile (size)
    - - Destructive to the beam & damaging to the instrument

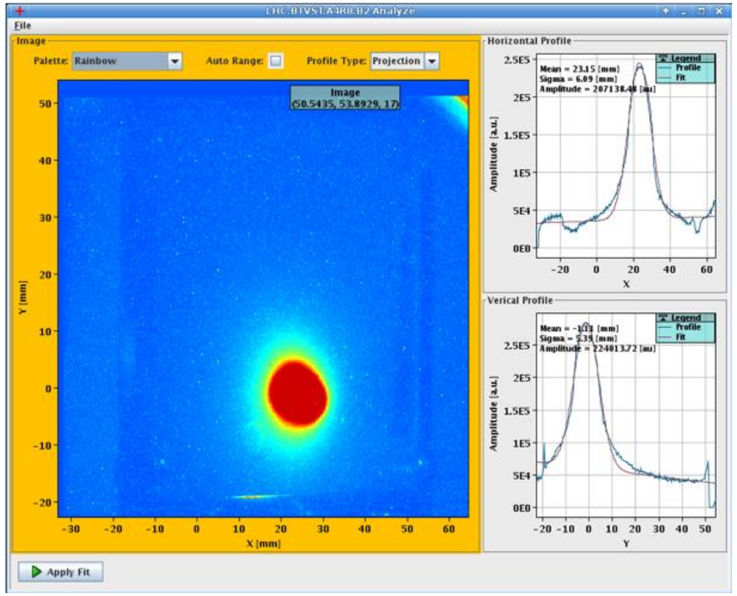
Example – Beam observation TV (BTV)



1. Beam interacts with phosphor screen inserted into beam path



2. Emitted light passed though viewport & detected by camera



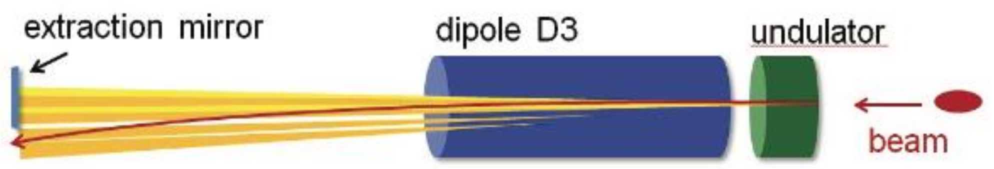
3. Direct measurement of beam profiles in the transverse (x,y) planes

Beam instrumentation in a nutshell

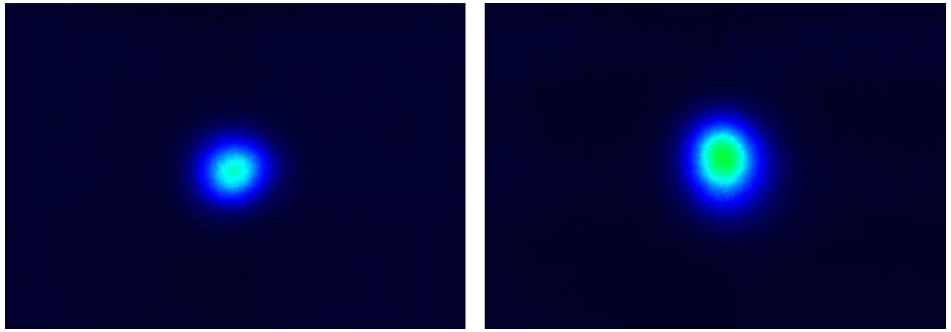
How to measure the beam parameters?

3. Use the **synchrotron light** emitted by the beam
   - E.g. Transverse & longitudinal beam profile monitors
   - + Completely non-destructive & continuous measurement
   - - For proton accelerators can only be applied for energies above 100 GeV
   - - Spatial resolution limited by diffraction & depth of field effects

Example – LHC synchrotron light monitor (BSRT)



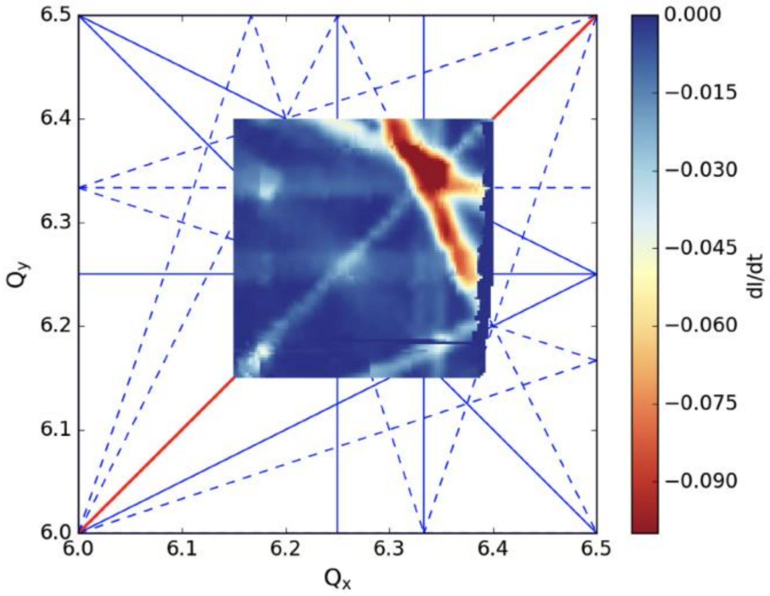
1. Beam traverses superconducting undulator and dipole magnets – extract & detect visible range light produced by the undulator (450 GeV to 1.5 TeV) and dipole (>1.5 TeV)



2. LHC Beam 1 (left) and Beam 2 (right)

What is meant by beam diagnostics?

Beam loss vs. Tune in the PS



Using measurements of the beam parameters to:

1. **Operate the accelerators** i.e. using instruments to measure & control:
   - Beam orbit;
   - Tune
     - Need precise control (= measurement) of tune to avoid beam loss inducing resonances

(b) Improve the performance of the accelerators to optimise luminosity (colliders) / brightness i.e. measuring & optimizing:
   (b) Emittance growth, beam intensity
   (c) Beam loss, instabilities
   (d) Equipment faults e.g. aperture restrictions

Focus of the instrumentation development detailed today

Ref. https://cds.cern.ch/record/941318/files/p361.pdf

Event Rate & Luminosity

Accelerator goal #1 = maximise collision energy
Accelerator goal #2 = maximise number useful interactions (events) by maximising the **collider luminosity**

Event rate (R)

$$R = \frac{dN_{ev}}{dt} = \mathcal{L}(t)\sigma_{ev} \qquad N_{ev} = \sigma_{ev} \int \mathcal{L}(t)dt$$

Luminosity ($\mathcal{L}$)

$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\sigma_*^2} .W.e^{\frac{B^2}{A}}.S$$

particles per bunch (N_1, N_2)
revolution frequency (f)
number of bunches (N_b)
beam size at the IP (σ_*)

reduction factors due to ($W.e^{\frac{B^2}{A}}.S$):
- crossing angle;
- offset between beam 1 & 2
- both of the above at the same time

Improving LHC luminosity

1. Higher intensity

$$\mathcal{L} = \frac{\boxed{N_1 N_2} f N_b}{4\pi\sigma_*^2}.W.e^{\frac{B^2}{A}}.S$$

2. Reduce beam size at IP

$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\boxed{\sigma_*^2}}.W.e^{\frac{B^2}{A}}.S$$

How to reduce the beam size at the IP?

$$\sigma_* = \sqrt{\epsilon_g \beta^*}$$

Geometrical emittance   Beta-function

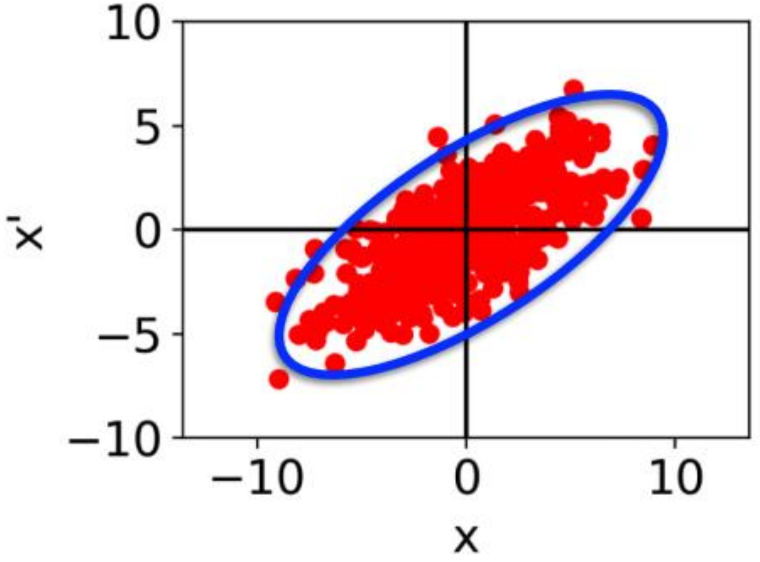
1. Smaller emittance & emittance preservation through the injector chain
2. Stronger focusing insertion magnets (inner-triplets)

Emittance

Geometrical emittance (ε_g) is the area of the ellipse in the x (particle position), x' (particle angle) plane occupied by (90%) of the beam particles

Geometrical emittance is only constant without acceleration, however, **normalised emittance (ε_N)** is preserved with acceleration:

$$\epsilon_N = \beta_{rel}\gamma_{rel}\epsilon_g$$



Emittance is a measure of the beam quality (i.e. we want small dense beams)

Challenge is to form beams with the smallest possible emittance & to preserve this throughout the acceleration chain up to the point of collision at the LHC IP's

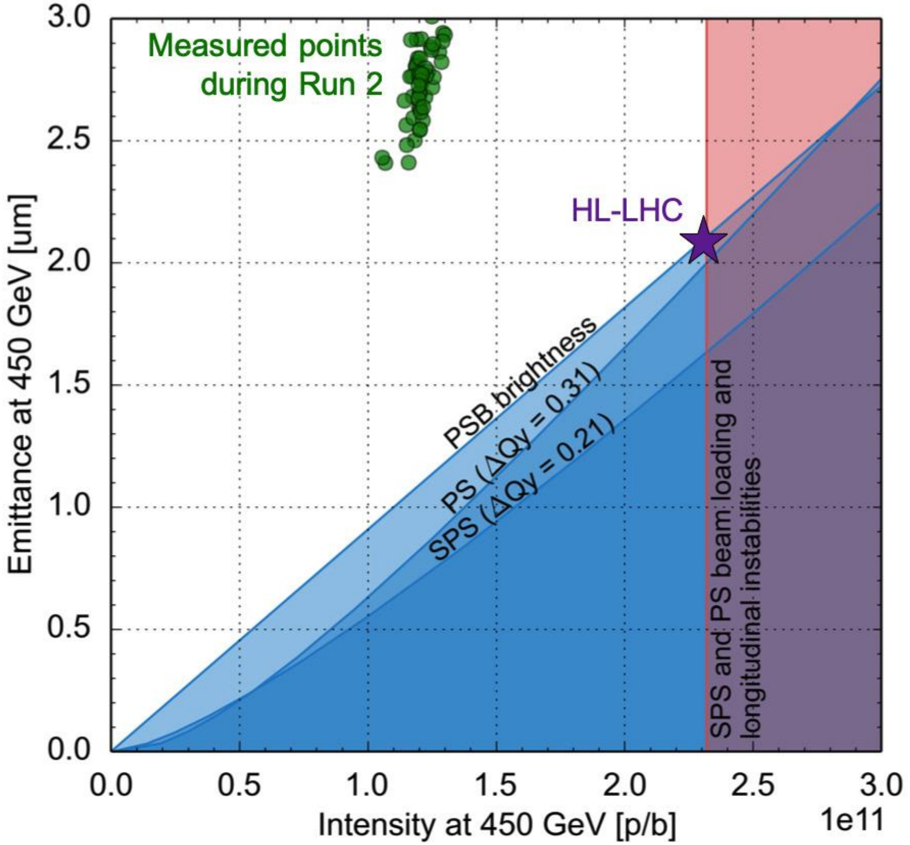
→ Require measurements of emittance throughout the injectors in order to identify, understand & possibly mitigate source(s) of emittance growth

LHC Injector Upgrade (LIU)

Goal of the LIU project (2010-2022) is to improve the intensity & emittance in the injectors (Linac4, PSB, PS, SPS) to meet the HL-LHC requirements

Highlights:

- Replacement of Linac2 with Linac4 → double brightness (∝ intensity / emittance^2) of beams out of the PSB
- ...
- Upgrade of beam measurements monitors – including emittance monitors



Limitation diagram for LHC standard 25ns beam
Ref. doi:10.18429/JACoW-IPAC2019-THXPLM1

How to measure emittance in synchrotron or storage ring?

Need to measure at one location:

- **Transverse beam profile**
- Optical beta function (e.g. with BPM measurements)

$$\epsilon_g = \frac{\sigma^2}{\beta(z)}$$

beam halfwidth (measured) → σ^2

optical beta function (measured) → $\beta(z)$

Complication:

- Need to locate profile monitor at a location with low dispersion (D(z)):

$$\sigma(z) = \sqrt{\underbrace{\beta(z)\epsilon_g}_{\text{betatronic component}} + \underbrace{\left(D(z)\frac{\delta p}{p}\right)^2}_{\text{dispersive component}}}$$

longitudinal momentum spread → $\frac{\delta p}{p}$

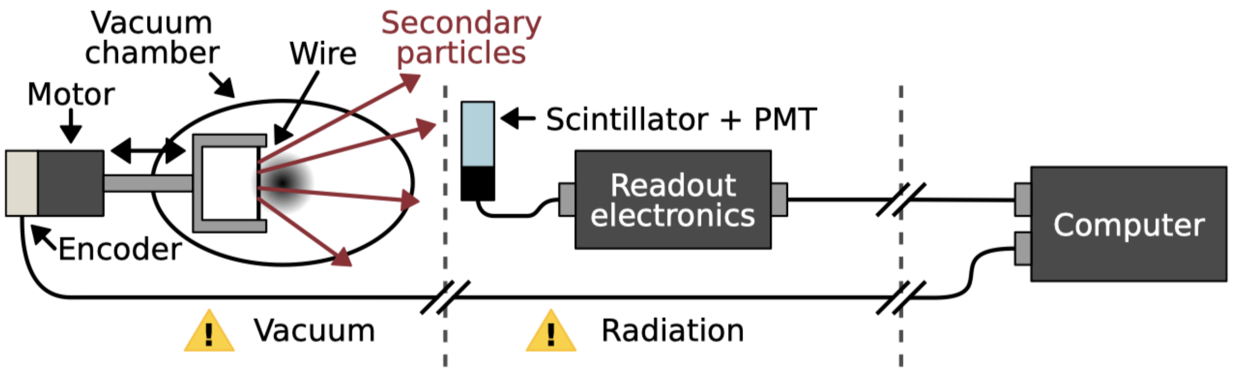
How to measure the beam profile of high power beams in a synchrotron?

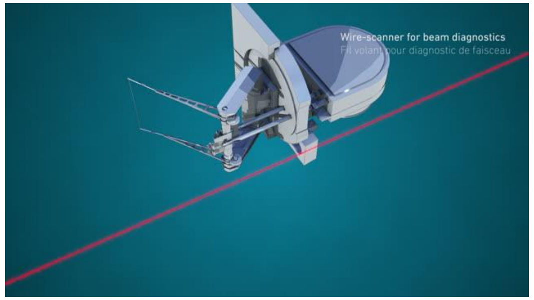
Measure beam profile by means of:

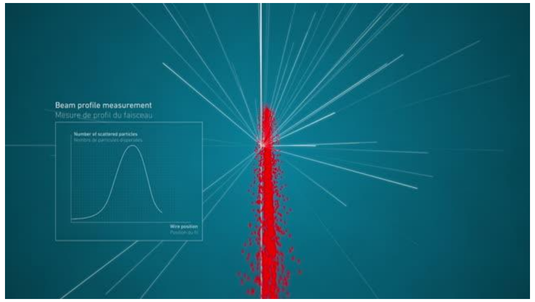
- ~~Electromagnetic field~~ (can’t measure beam profile)
- ~~Synchrotron light~~ (only for proton beams > 100 GeV)
- Interact with the beam itself:
  - ~~Phosphor screen~~ (destroys the beam and/or the screen)
  - **With wires:**
    - **Secondary Emission Monitor (SEM)**
      - Beam profile from secondary electrons emitted from wire grid
      - Destructive measurement
    - **Beam Wire Scanner (BWS)**
      - Single wire moving through beam – correlate wire position with secondary shower
      - Work-horse at CERN – installed in all accelerators
      - But has limitations...

Secondary electron emission monitor

Measuring the beam profile of high power beams: Beam Wire Scanner



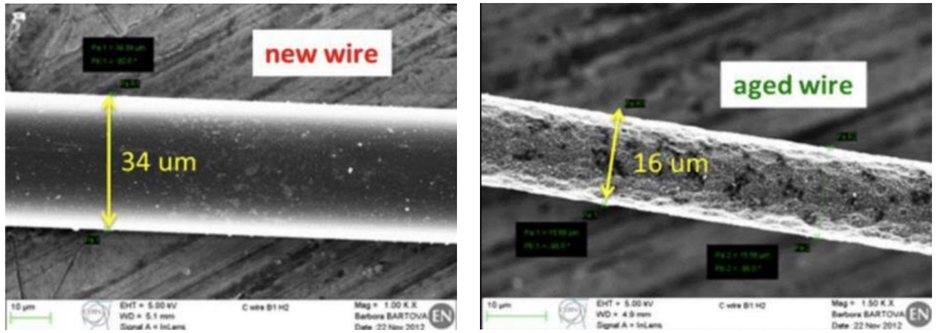




1. Thin carbon wire (34µm) passes through the beam at up to 20m/s
2. Correlate wire position with secondary shower

Limitations:

1. Wire does not withstand energy deposition
   - Can't use with full LHC beam



2. Measurement at a single moment in the acceleration cycle i.e. not a continuous measurement that could reveal moment of emittance blowup

Wishlist for an ideal beam profile monitor

1. Beam doesn't damage the instrument & the instrument doesn't perturb the beam

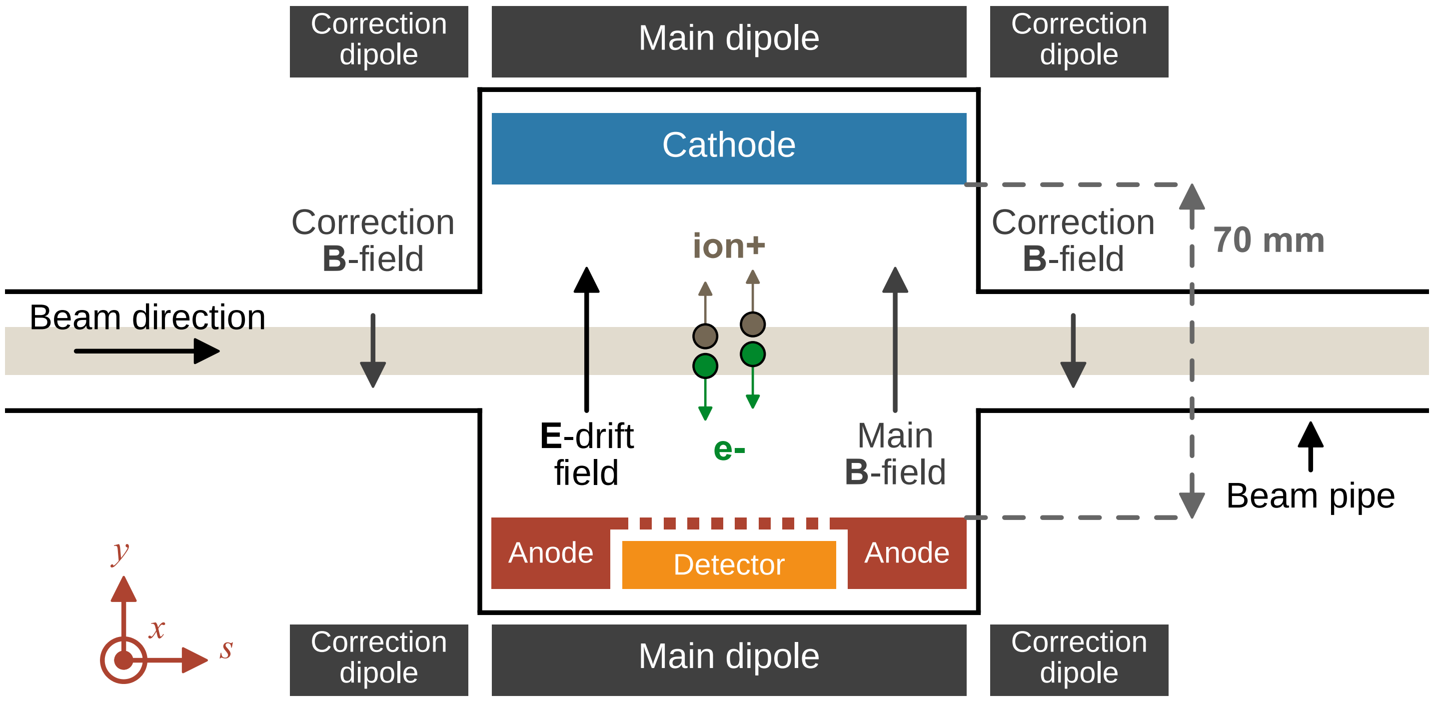
2. Continuous measurement throughout the acceleration cycle;
    - Ideally every revolution of the accelerator, e.g. PS = 2.3 μs per turn.

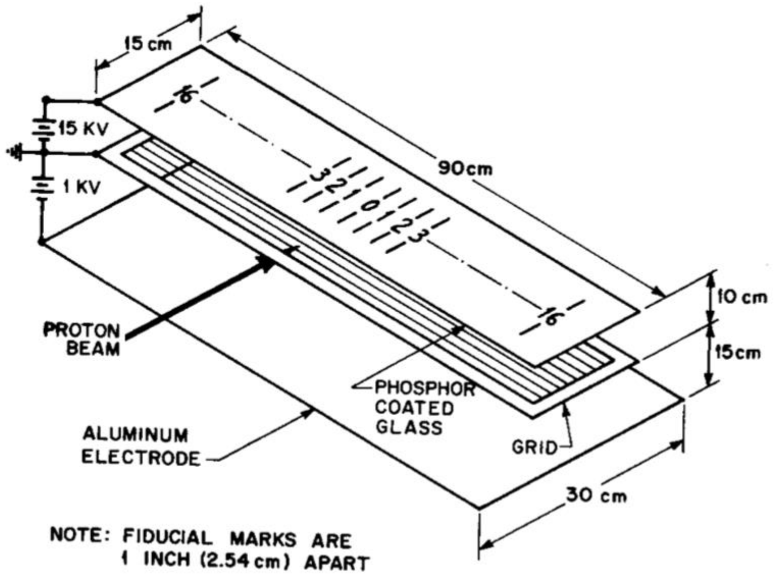
3. Independent measurement with high accuracy & precision;
    - Beam size = 270 μm in the LHC at 6.5 TeV.

4. Bunch-by-Bunch (BbB) and Turn-by-Turn (TbT) measurements
    - e.g. LHC beam made up of 2556 bunches separated by 25 ns.

(Very promising) solution:
Rest gas ionisation beam profile monitor based on Timepix3 hybrid pixel detectors.

Rest gas ionisation beam profile monitor




NONDESTRUCTIVE BEAM PROFILE DETECTION SYSTEMS FOR THE ZERO GRADIENT SYNCHROTRON*

Fred Hornstra, Jr. and William H. DeLuca

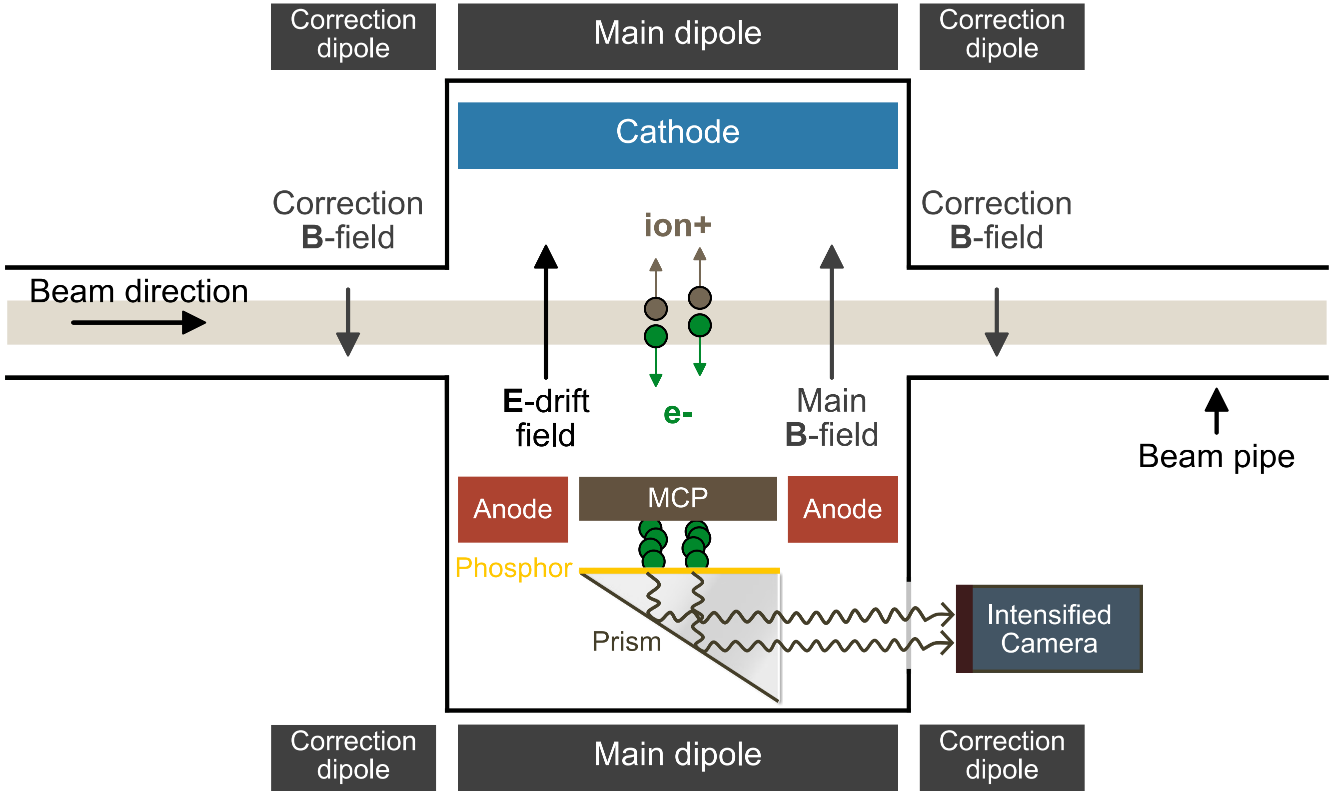
Argonne National Laboratory
Argonne, Illinois

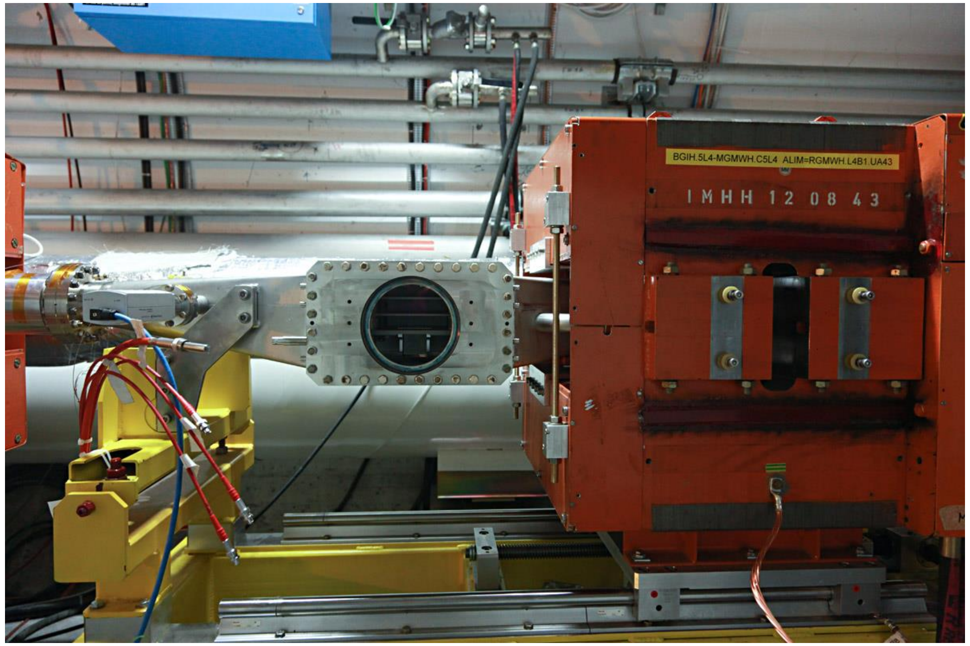
Original proposal for nondestructive beam profile monitor (1967)

Basic principle of operation:

1. Beam ionizes rest gas particles in the beam pipe vacuum
2. Transport ionization electrons with E-field and B-field
3. Image ionization electrons with a detector

MCP based BGI (IPM) for CERN SPS & LHC (2007-...)



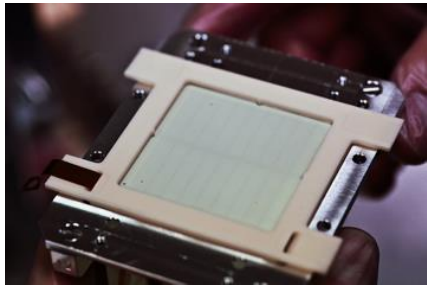


LHC BGI installed at Pt.4

Ionisation electron detection:

- Electron signal amplified by microchannel plate (gain = $10^3 - 10^4$)
- Electrons accelerated onto phosphor screen (P46) deposited on right angle prism
- Light from phosphor screen transferred through optical viewport onto intensified radiation hard camera ($$$)

MCP-based BGI vs. Wishlist

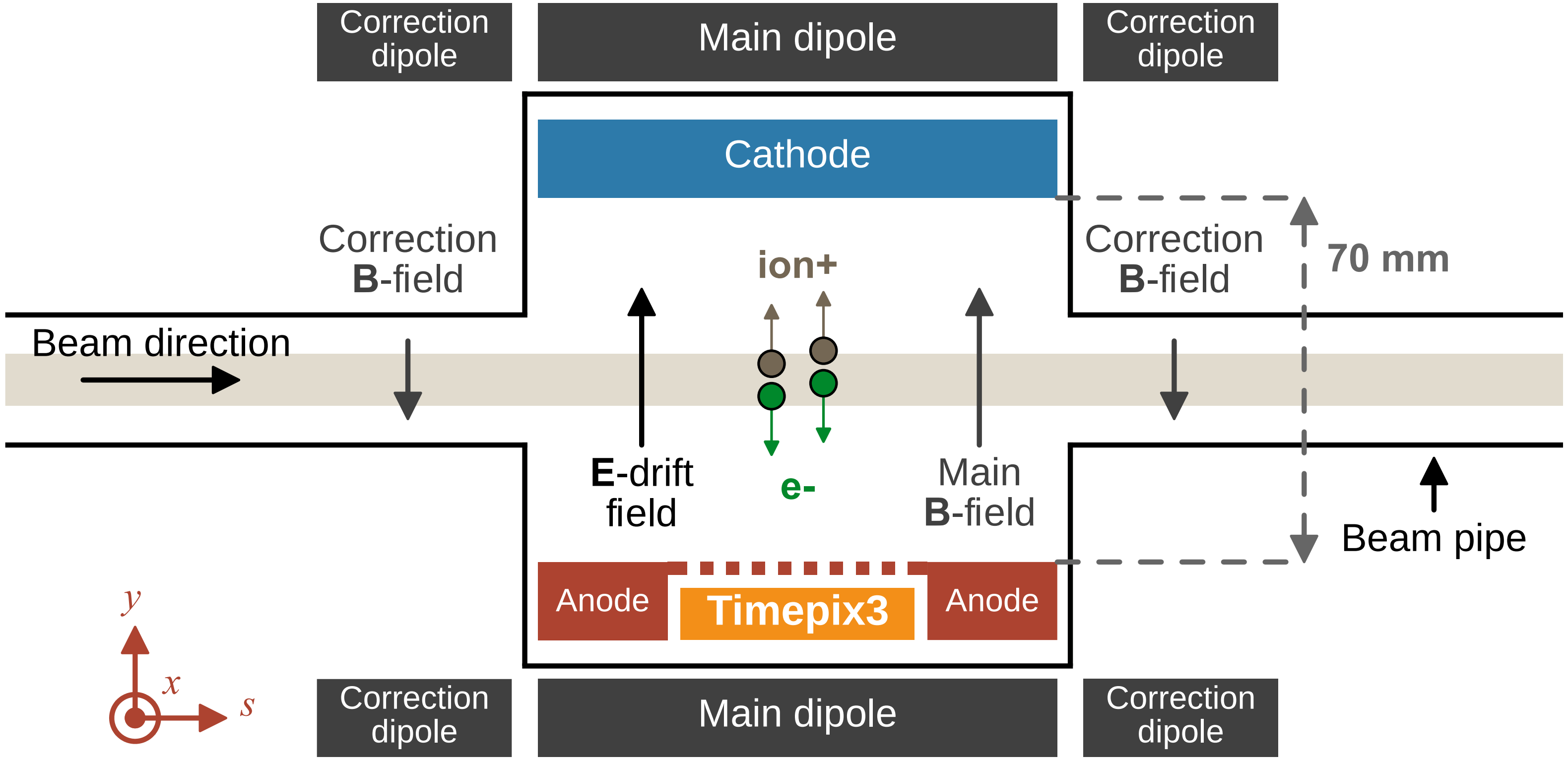


Aging of phosphor screen

1. Beam doesn't damage the instrument & the instrument doesn't perturb the beam
   - Inhomogeneous aging of MCP & phosphor screen
   - Limits lifetime & distorts profile measurement
2. Continuous measurement throughout the acceleration cycle
   - Limited by analogue video output of rad. tol. intensified camera (~30 measurements / s)
3. Independent measurement with high accuracy & precision
   - MCP + imaging optics cause a smearing of the image
   - Correction factor (optical point spread) determined by comparing BGI with BWS measurement
     - → Not an independent measurement
4. Bunch-by-Bunch and Turn-by-Turn measurements
   - Gate intensified camera MCP to measure 1 bunch, but can't measure >1 bunch
   - Need to integrate beam for >100 turns to yield sufficient signal
     - → Ionisation electron detection efficiency insufficient for TbT measurements

+ Additional technical problems e.g. EMI on analogue camera signal, radiation damage to electronics, ...

Timepix3-based solution?



(Potential) Timepix3-based BGI vs. Wishlist

1. Beam doesn't damage the instrument & the instrument doesn't perturb the beam
    - Removes MCP & phosphor screen
2. Continuous measurement throughout the acceleration cycle
    - Data driven readout of individual ionisation throughout the cycle tagged with position (pixel) & time (ToA)
3. Independent measurement with high accuracy & precision
    - Direct detection of ionisation electrons inside the beam pipe → no need to cross calibrate with another instrument
4. Bunch-by-Bunch and Turn-by-Turn measurements
    - Each electron tagged with a time resolution (1.6ns) << bunch spacing (25ns)
        - Bunch-by-bunch measurements
    - Electron detection efficiency >> (MCP + Phosphor + Optics + Camera) efficiency
        - Turn-by-turn measurements possible

~~+ Additional technical problems e.g. EMI on analogue camera signal, radiation damage to electronics, ...~~

Realisation of a non-destructive transverse beam profile (size) monitor based on Timepix3

Beam Gas Ionisation (BGI) profile monitor for the CERN Proton Synchrotron (PS)

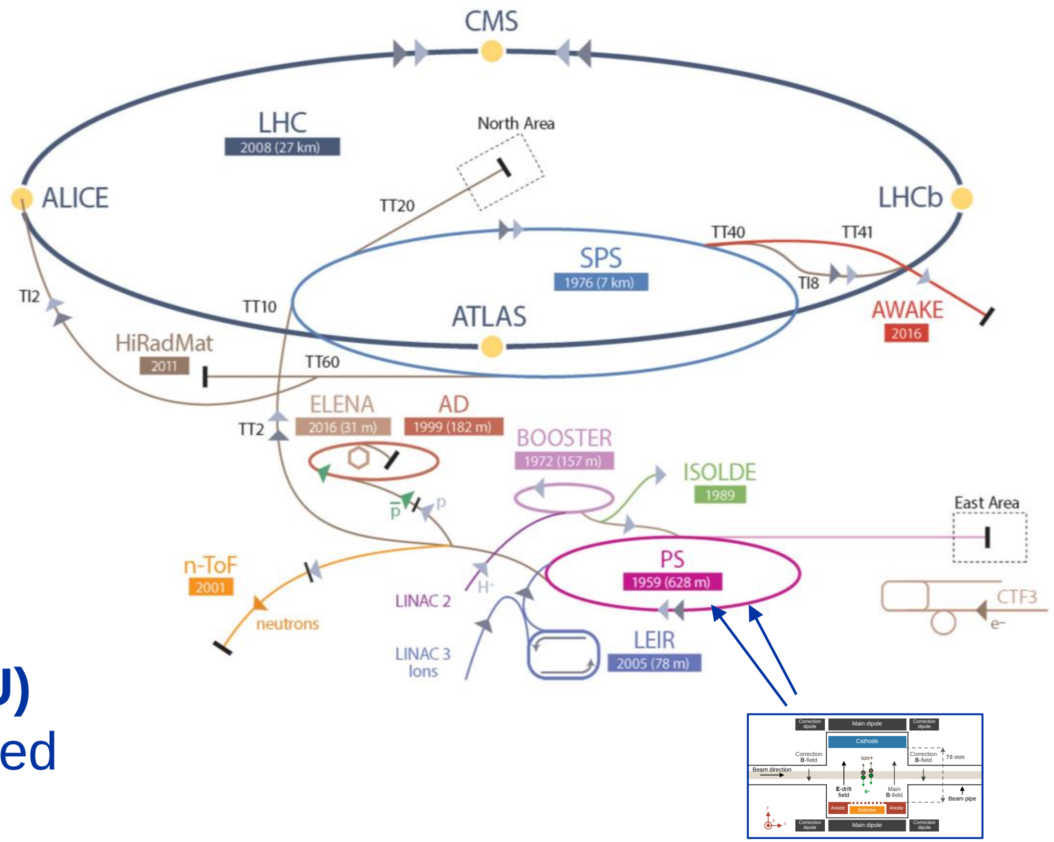
Requirements:

- **Non-destructive;**
- **Continuous** (1000 profiles / s);
- **Bunch-by-Bunch & Turn-by-Turn;**
- Measure beam size with 1% accuracy.

Typical use case e.g. LHC type beam (BCMS)

Intensity = 13×10^{10} protons per bunch
Number of bunches at extraction = 48
Beam size = ~1mm

Development is part of **the LHC Injector Upgrade (LIU)** programme to deliver the high brightness beams required for the High Luminosity LHC.

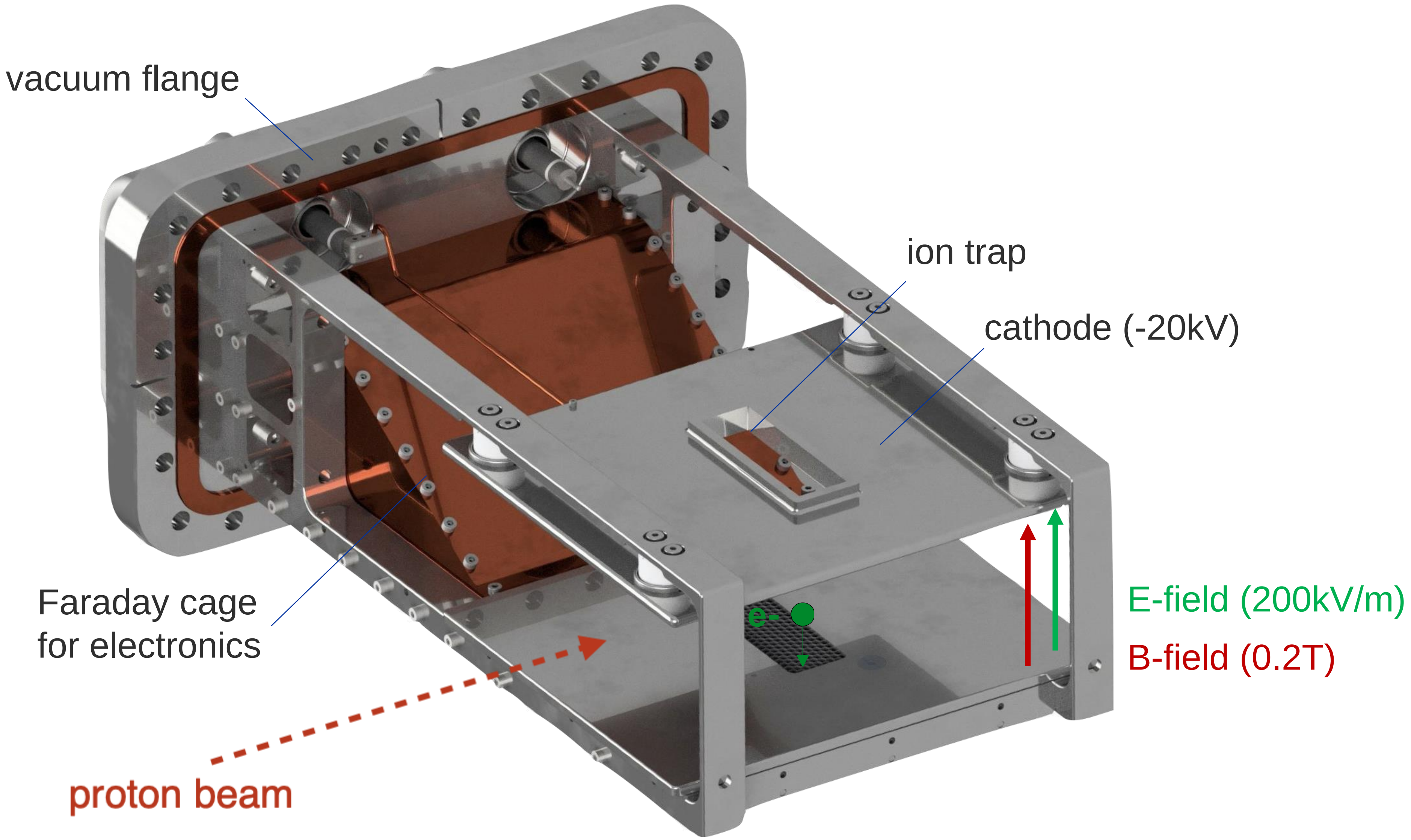


Instrument operating constraints

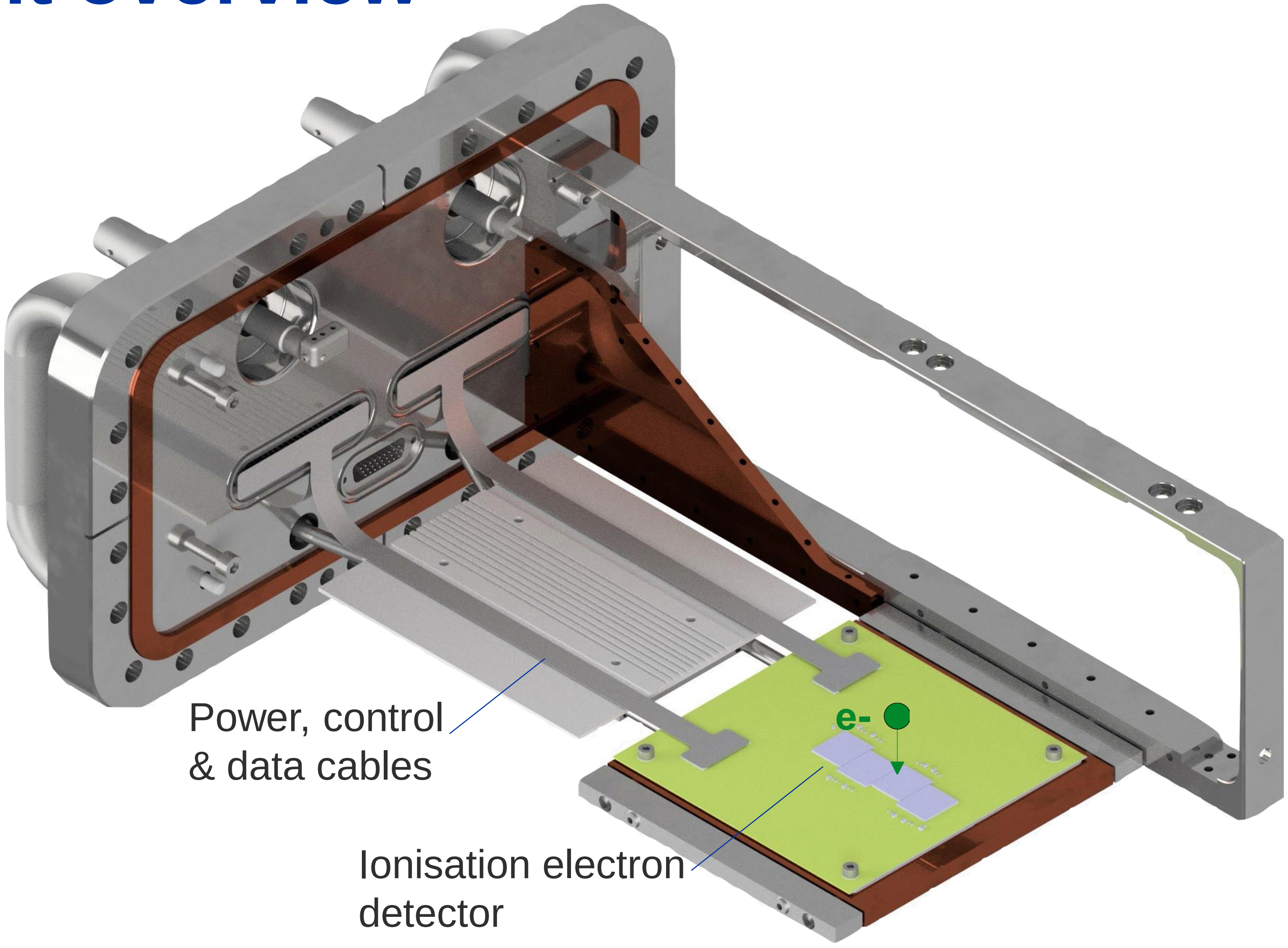
1. Operate **directly inside the ultra-high vacuum of the accelerator beam pipe**
    - Vacuum pressure = $10^{-9} – 10^{-10}$ mbar
    - Degassing < $5x10^{-6}$ mbar l s^{-1}
    - Criteria for the gas composition – concentration of:
        - Gas species 18 – 44u < (1 / 100th) of water (un-baked vacuum system)
        - Gas species 44 – 100u < (1 / 1000th) of water
2. Operate during the **acceleration cycle**
    - EMI from the beam
    - Beam impedance and beam induced heating
3. Operate in a **radiation environment**
    - 10 kGy/yr at beam pipe
    - 1 kGy/yr at 40cm

Instrument overview

Measures beam profile in horizontal plane (x, s) –
second instrument design for vertical plane measurement



Instrument overview



Ionisation electron signal

	detector length	protons(ions) per bunch	vacuum pressure

ionisation electrons $n_e = L.\sigma_{ion}.N.p.\frac{1}{k.T}$

ionisation electrons - detected $n_e^d = n_e.\epsilon_{det}$ electron detection efficiency

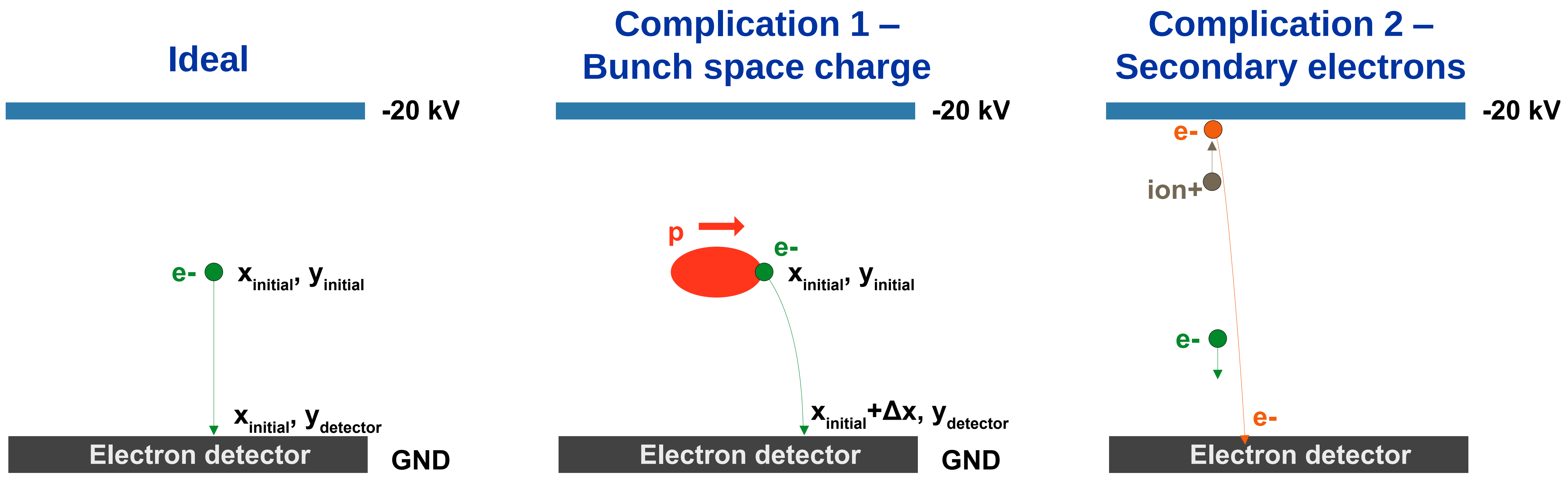
Residual gas ionisation electron signal:
- Vacuum pressure = $1x10^{-9}$ mbar
- Intensity = $60x10^{10}$ protons / bunch
- → **10 ionisation electrons per bunch per turn**

How many ionisation electrons are needed?
- 1000 electrons → 2% precision (stat. error) *on the beam size of a Gaussian distribution*
- Assume ~**1000 electrons** are needed for a meaningful beam profile
- Residual gas insufficient for turn-by-turn measurements

How to do **turn-by-turn measurements**?
- Inject (very small) quantity of argon gas to locally bump pressure to $2x10^{-8}$ mbar
- Argon ionisation cross section = ~5 x hydrogen (residual gas)
- → **1000 ionisation electrons per bunch per turn**

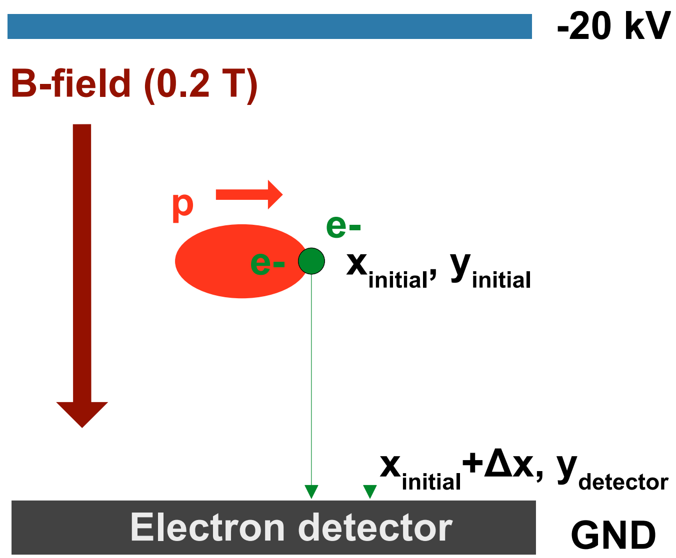
Transport of ionisation electron

Field cage transports ionisation electron from the point of creation to the detection plane, while preserving the initial transverse position of the electron:

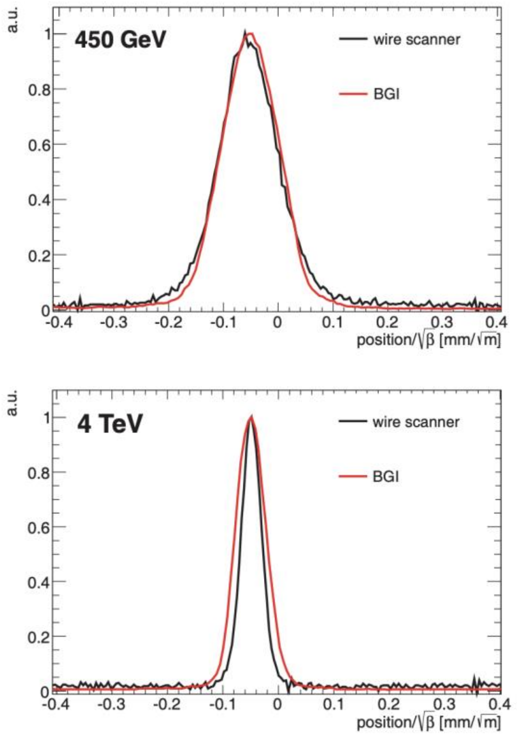


Beam profile distortion due to bunch space charge

Solution = B-field parallel to the drift E-field



Strength of LHC BGI B-field (0.2T) insufficient for E > 4 TeV



Ref. Sapinski et al., IBIC2012, TUPB61

Simulation tool to aid instrument design

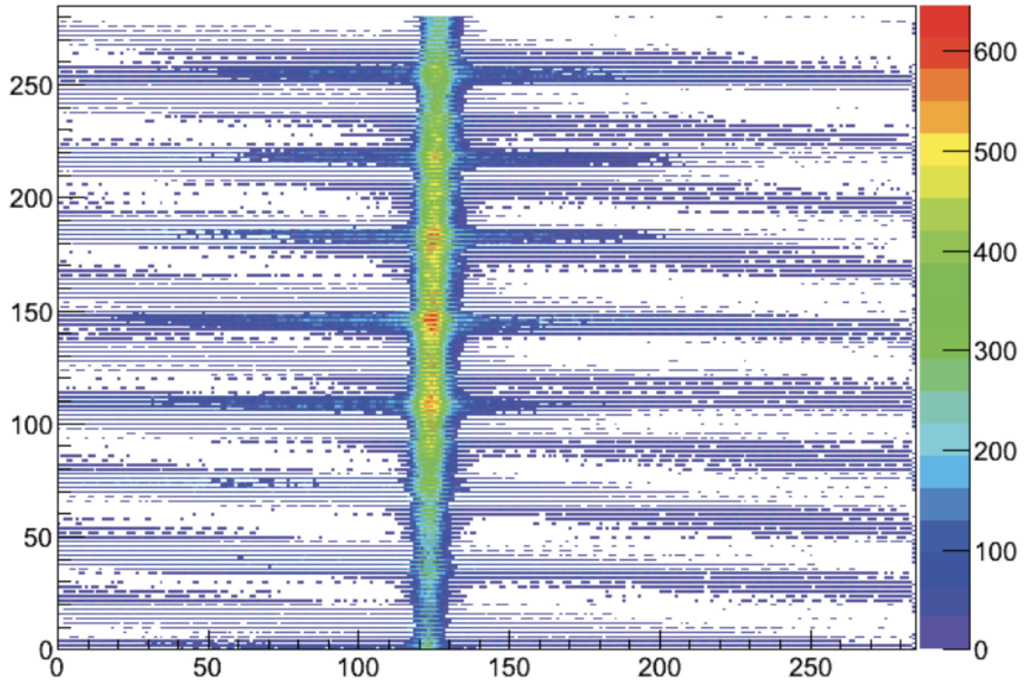
Common interest among several accelerator labs (GSI, J-PARC, CERN, ESS, FNAL) to develop a common IPM simulation tool

Virtual-IPM (D.Vilsmeier GSI):

- Ionisation process
- Electron / ion tracking in the EM-fields due to:
  - Field cage
  - Dipole magnet
  - Bunch space charge
- ipmsim.gitlab.io/Virtual-IPM

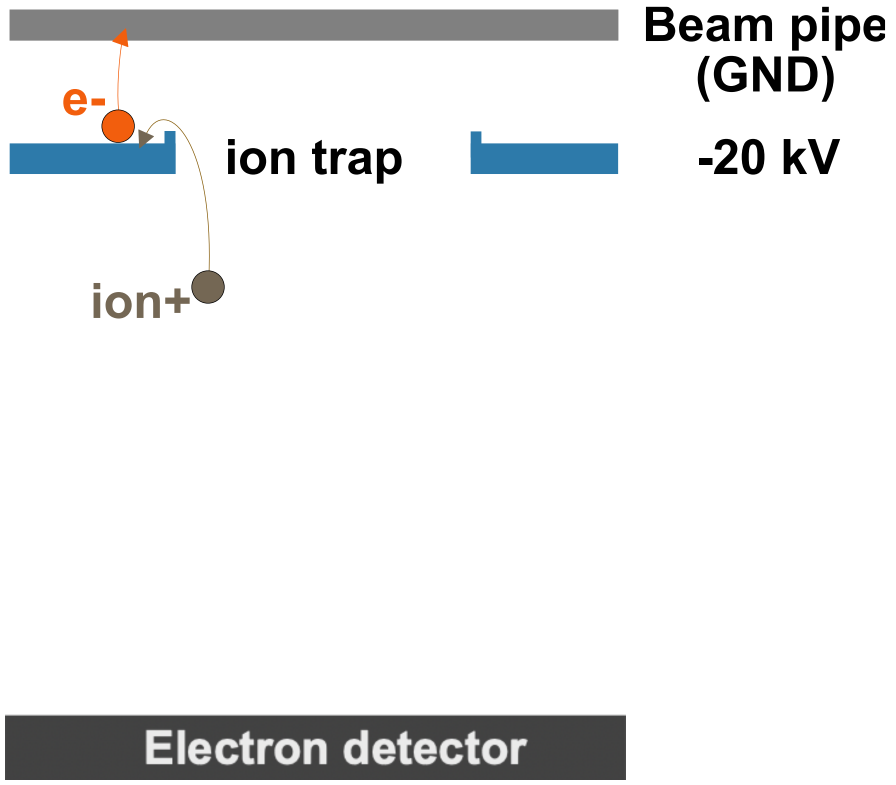
Suppression of secondary electrons

1. Wire grid – LHC BGI (2007)



Secondary electrons repelled by wire grid, but secondary electrons generated by ions bombarding the wires

2. Ion trap – PS BGI

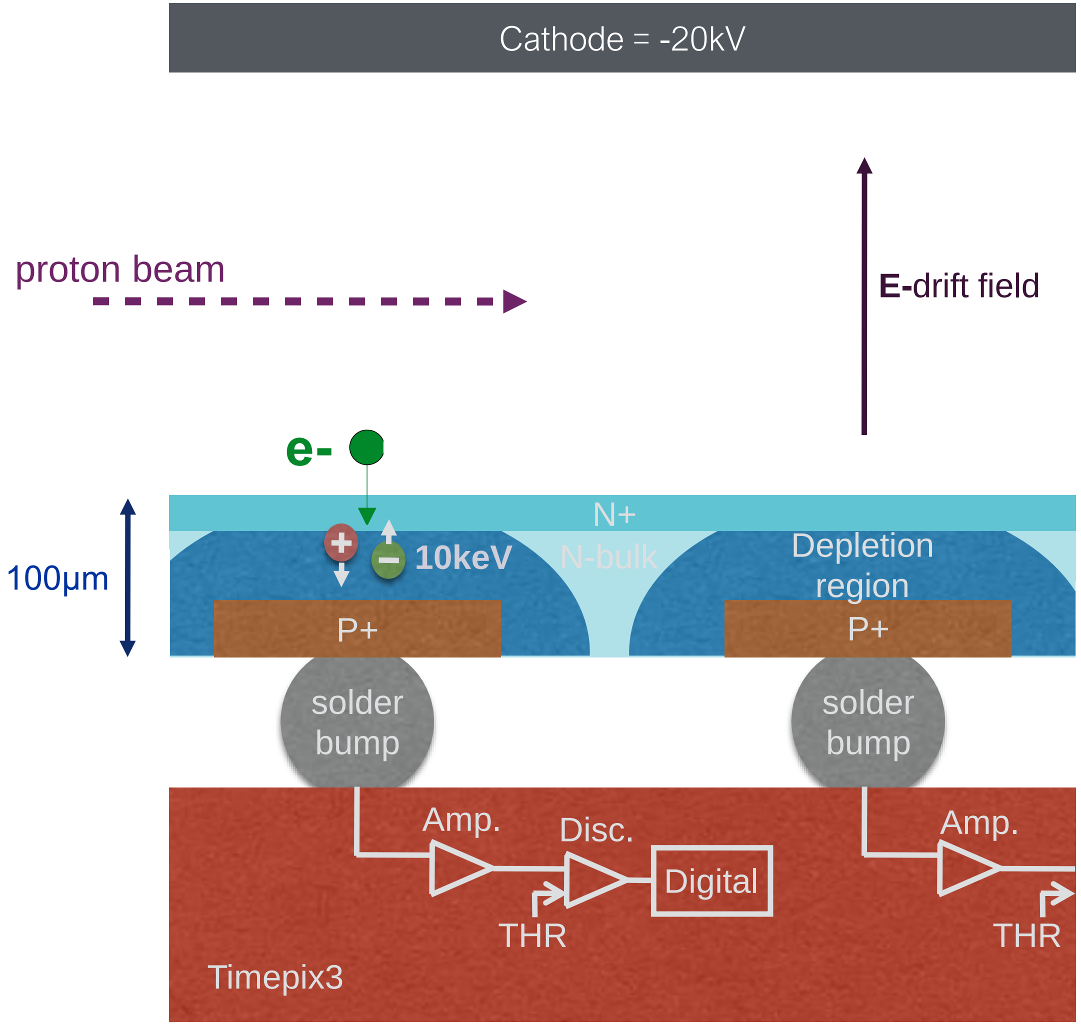


Ions directed through an opening on the cathode – no path for secondary electrons back to the detector (”ion trap”)

Ionisation electron detector based on Timepix3 HPD

Ionisation electron detector requirements

- Detect 10keV electrons (penetration depth in silicon = 1.5µm)
- Detect each electron with time resolution < 25ns & spatial resolution < 100µm
- Meet outgassing requirements for installation in the UHV of the PS beam pipe
- Operate during the acceleration cycle



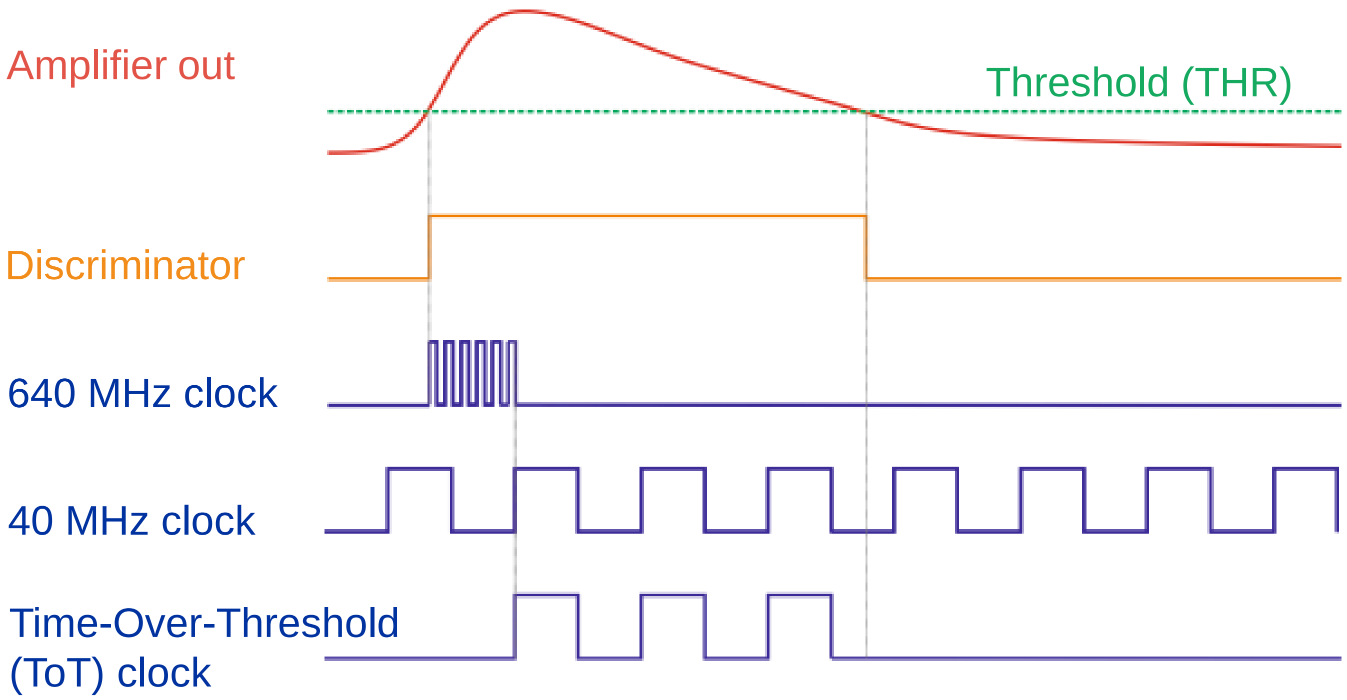
Sensor

- **Non-metalized**, p-in-n, 100m deep
- 256 x 256 array of PN-diodes
- Pixel size = 55um x 55um
- Sensor area = 14mm x 14mm

Timepix3 readout chip

- Each sensor pixel is connected to an individual readout channel (pixel)

Timepix3 response to charge



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

time resolution = 1.5625 ns

Amplifier out > threshold

→ **Event**

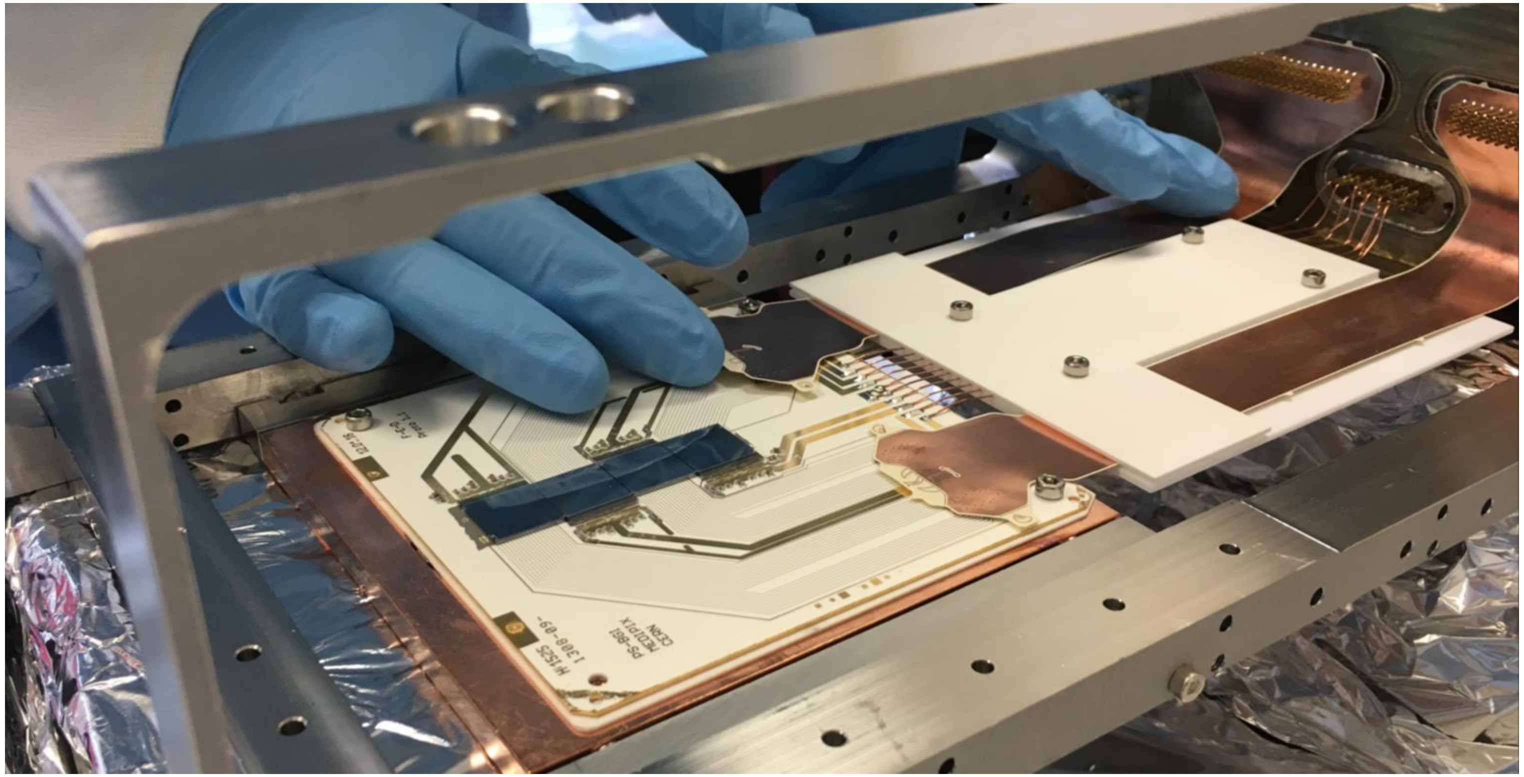
Each **event** consist of:

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

Max. 80M events / s

Ref. Swann Levasseur CERN-THESIS-2019-354

Ionisation electron detector – Prototype



Ceramic carrier board

- 2 metal layers, Al_2O_3 substrate
- 4 x Timepix3 HPD's attached with Staystick 672 and wire bonded
- Sensor bias wire glued (Mk.1) / wire bonded to Al pad (Mk.2)

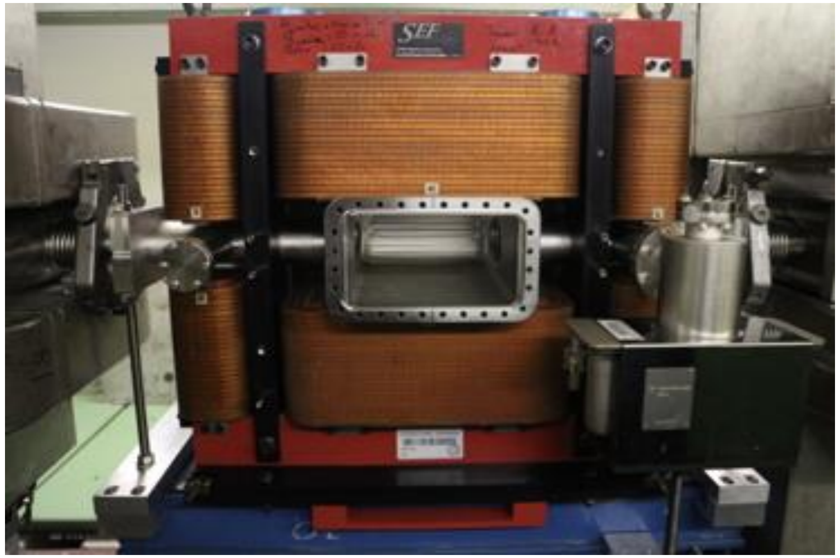
Flexible cables

- Connects ceramic board to electrical feedthroughs on vacuum flange
- Two metals layers with a Liquid Crystal Polymer (LCP) substrate

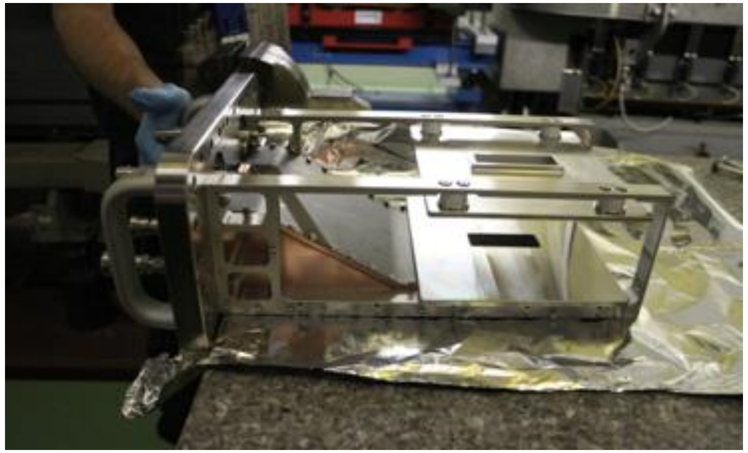
Qualified for installation in the PS accelerator beam pipe

Installation in the CERN PS

0.2T self-compensating triplet dipole magnet (Dominique Bodart TE-MSC) & instrument vacuum chamber



Instrument prior to installation



Installation at PS SS82

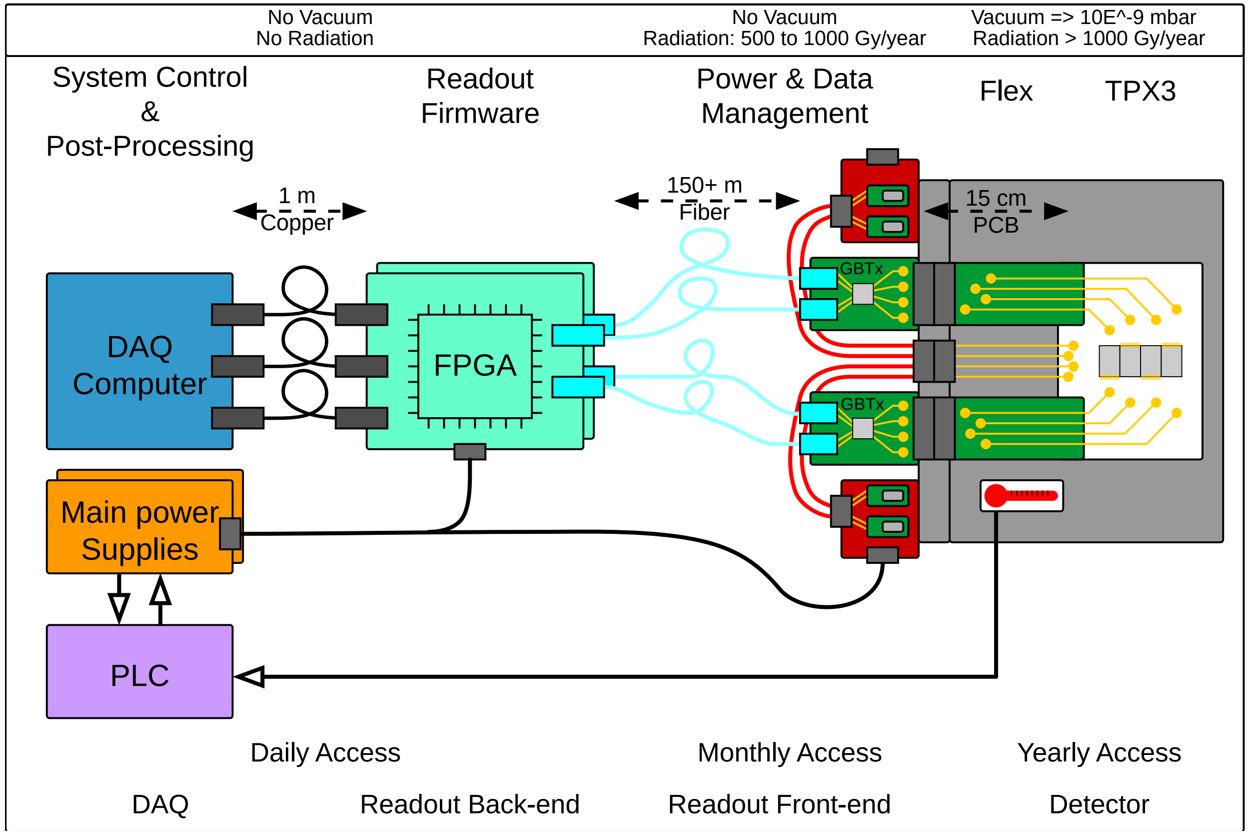
Vacuum pump down:

- 1 x 10^{-8} mbar after 24 hours
- **2 x 10^{-10} mbar steady state**

Radiation tolerant readout of Timepix3 - BIPXL

Front-end (in the tunnel) based on:

- Microsemi ProASIC3 & Xilinx Kintex-7 (EDA-03830 + EDA-03812), and
- EP-ESE radiation tolerant optoelectronic components (GBTx, VTRx) & FEAST DC/DC
- New architecture in development to improve radiation hardness & simplicity based on direct connection between GBTx transceivers and the Timepix3



Back-end (no radiation) based on:

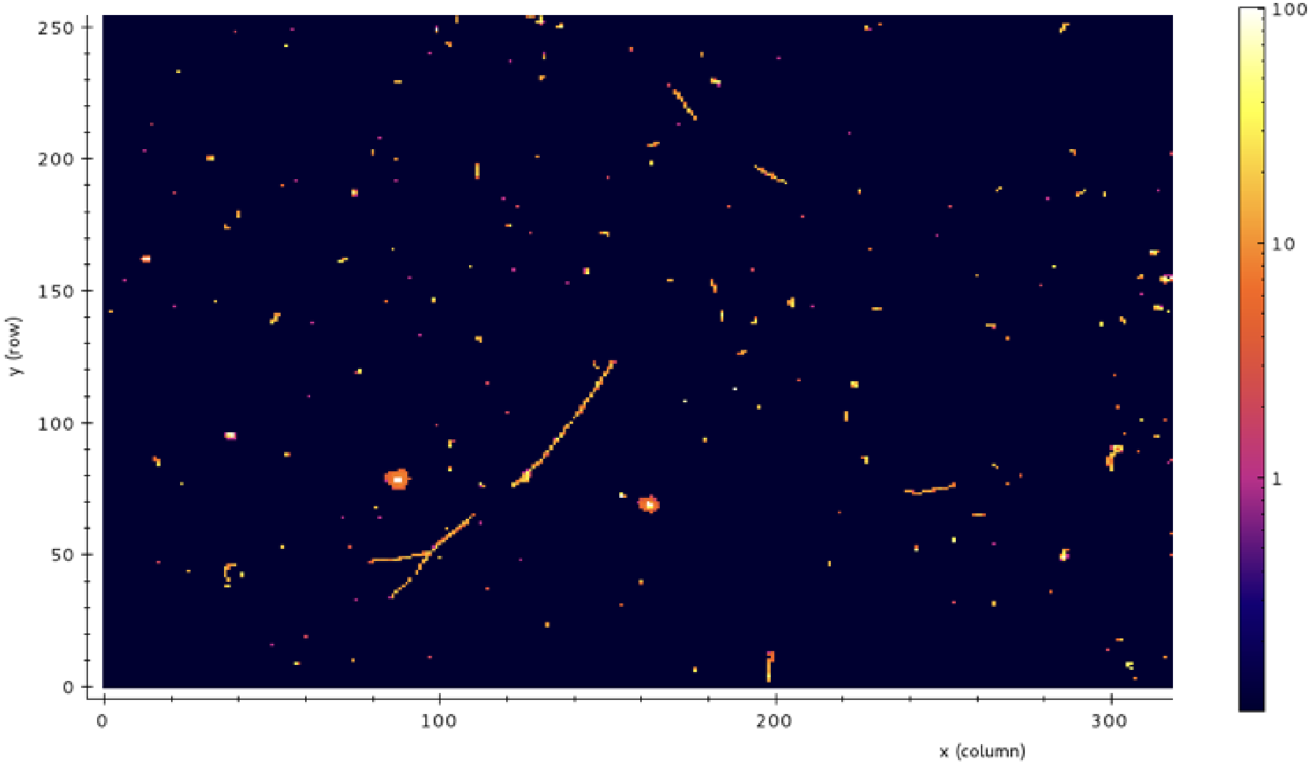
- Xilinx Virtex 7 development board
- New back-end in development based on Xilinx Zynq SoC for improved performance

Interface to the instrument via Front-End Software Architecture (FESA) framework (generic model for real-time programming in the domain of accelerator control)

Generic readout system (BIPXL) for the operation of Timepix3 in radiation environments

Operation of the Timepix3 inside the beam pipe during the acceleration cycle

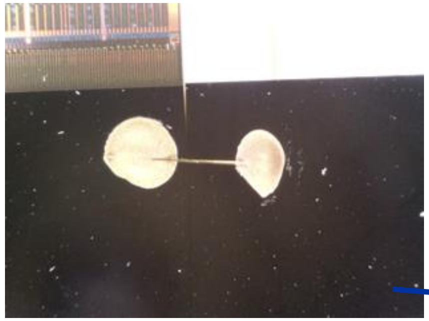
Acquisition for 100 ms during acceleration cycle with **high voltage off (no ionisation electrons)**



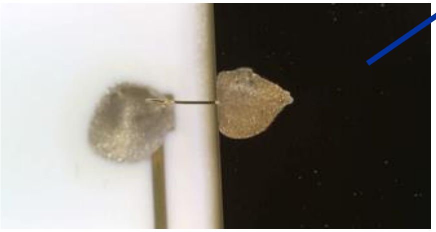
Time-Over-Threshold
(∝ √Energy)

Timepix3 successfully operated inside the beam pipe during the acceleration cycle.

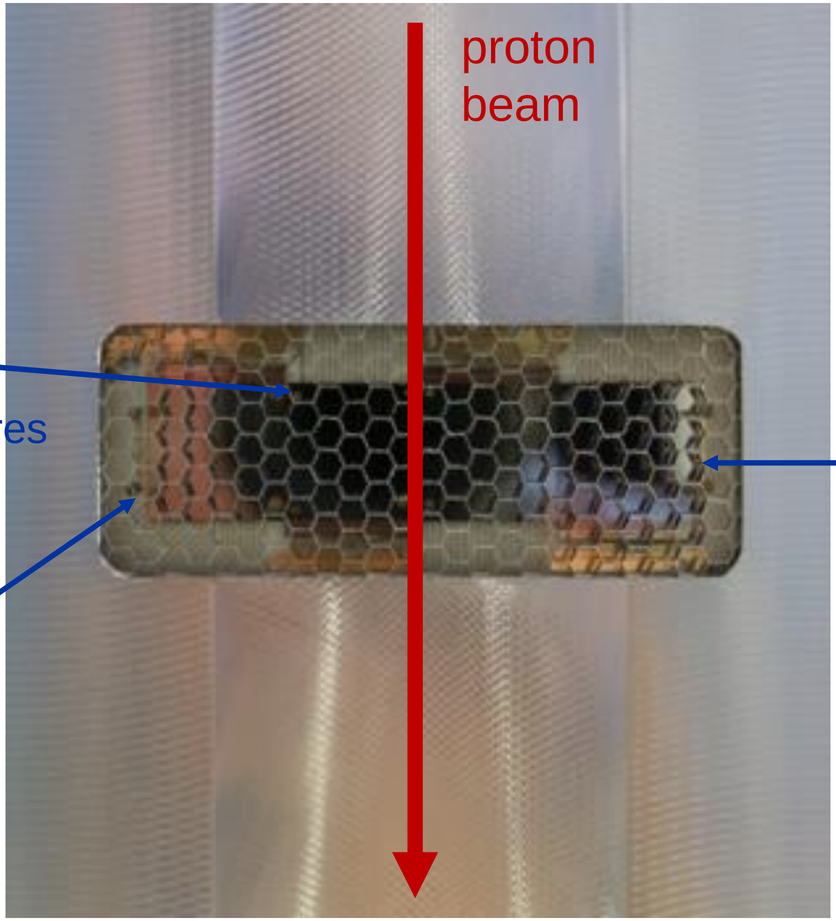
Detection of rest gas ionisation electrons

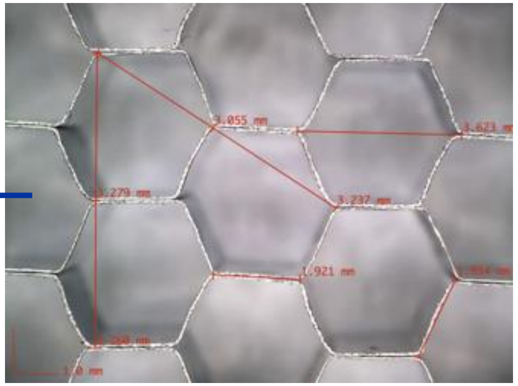


sensor-to-sensor bias wires



ceramic carrier-to-
sensor bias wires

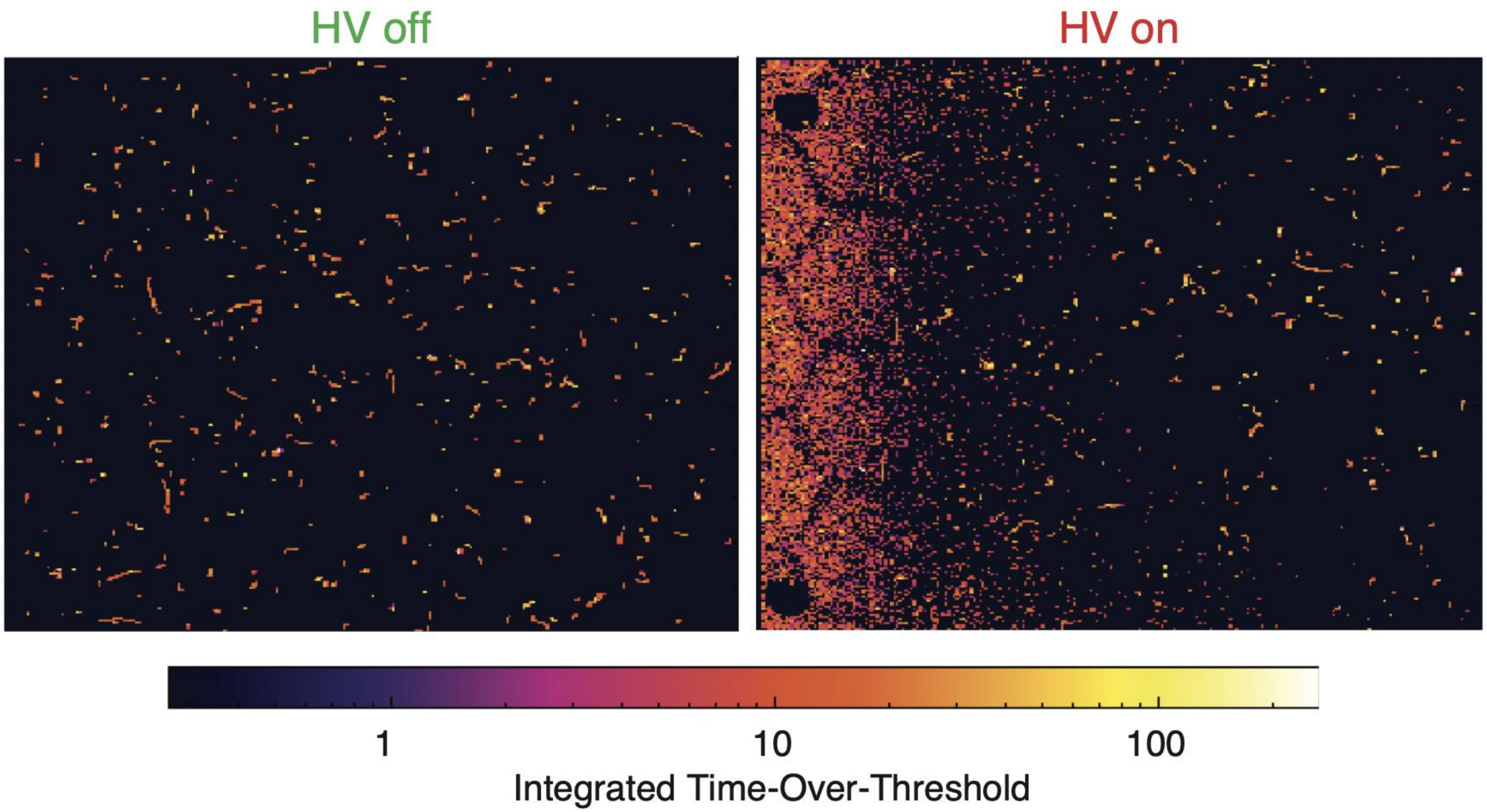




honeycomb
structured RF shield

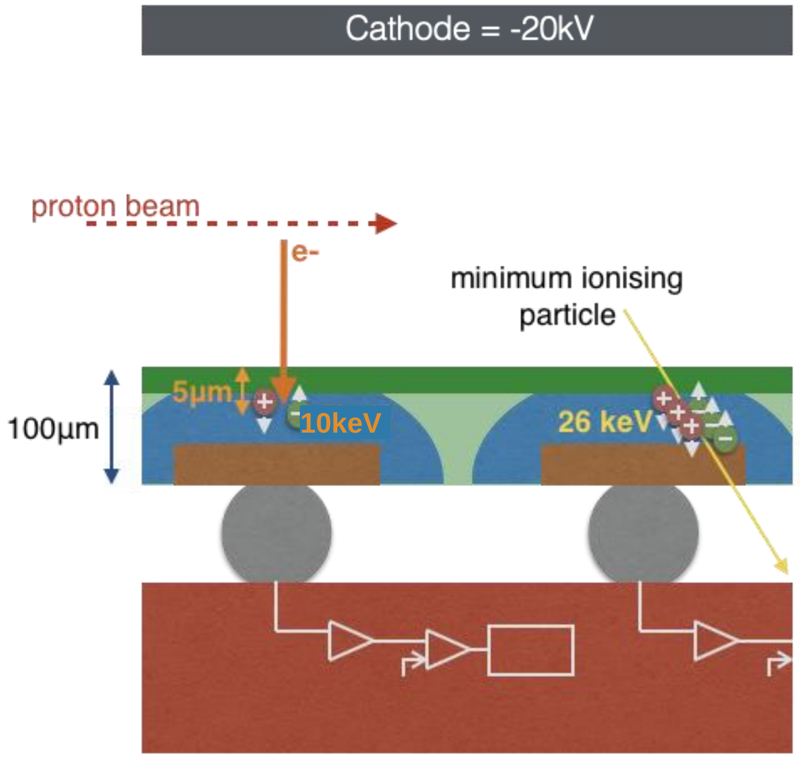
Ref. http://dx.doi.org/10.18429/JACoW-IBIC2017-WE2AB5

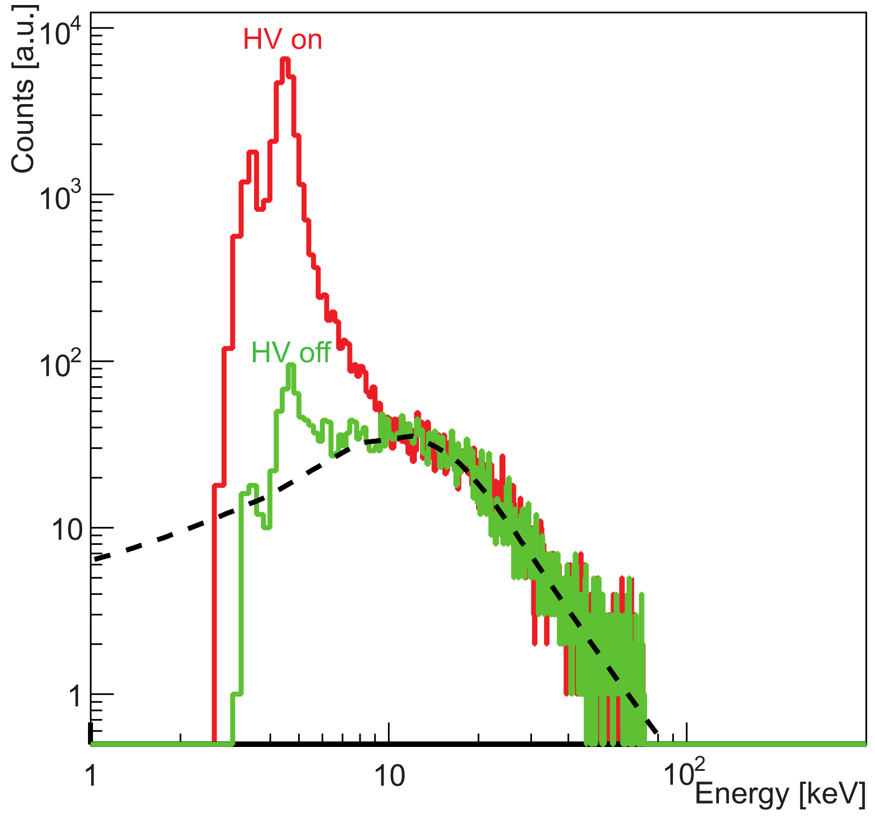
Detection of rest gas ionisation electrons



Ref. doi:10.18429/JACoW-IBIC2017-WE2AB5

Detection of rest gas ionisation electrons





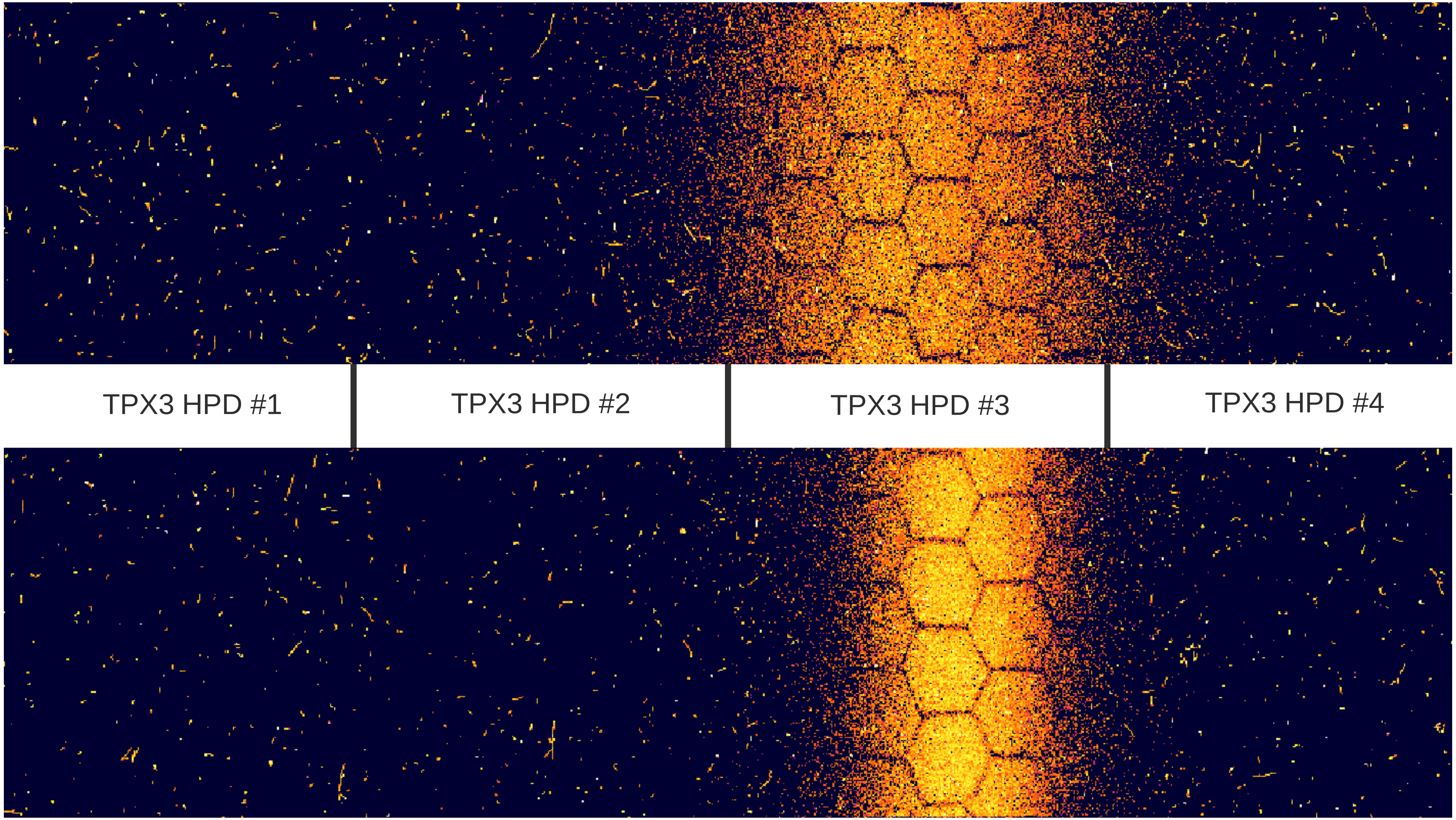
Successful detection of rest-gas ionisation electrons!

Example beam images

Beam direction

Example 1

Example 2

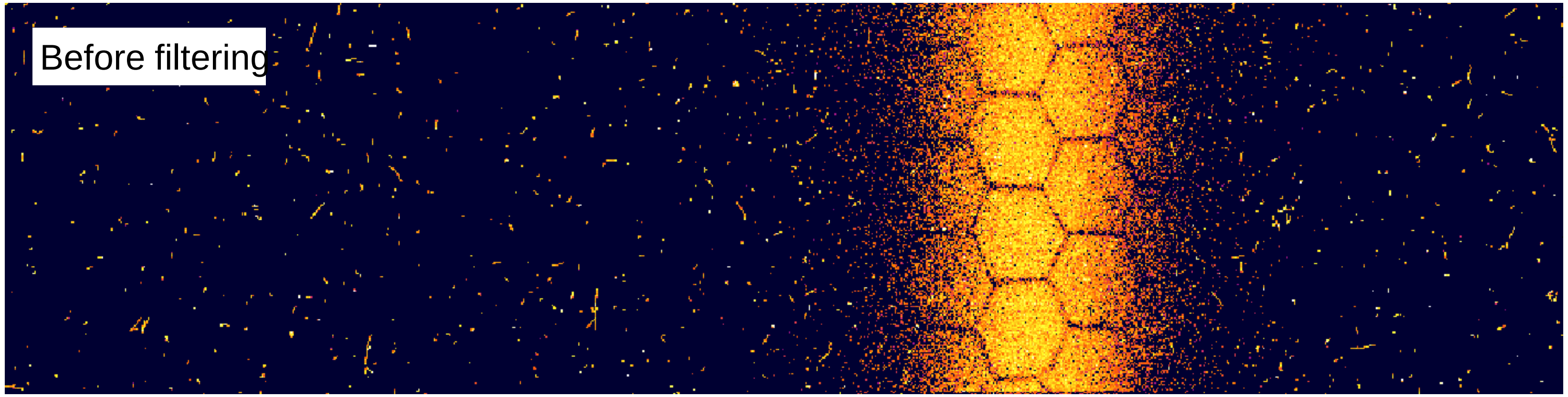


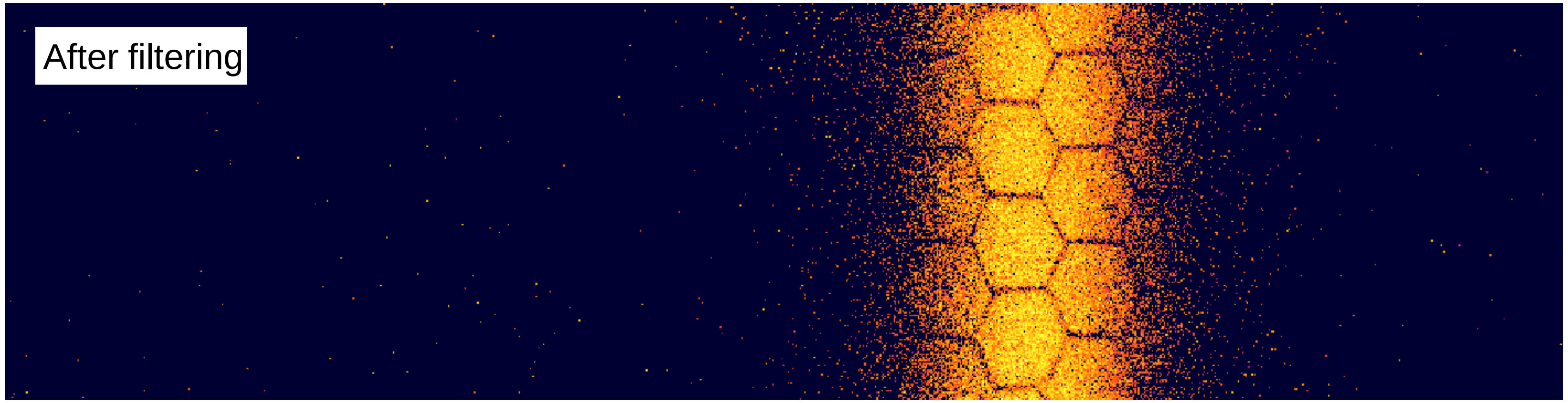
Selecting ionisation electrons

Signal – ionisation electrons:
- Mostly single pixel events
- Energy < 10keV

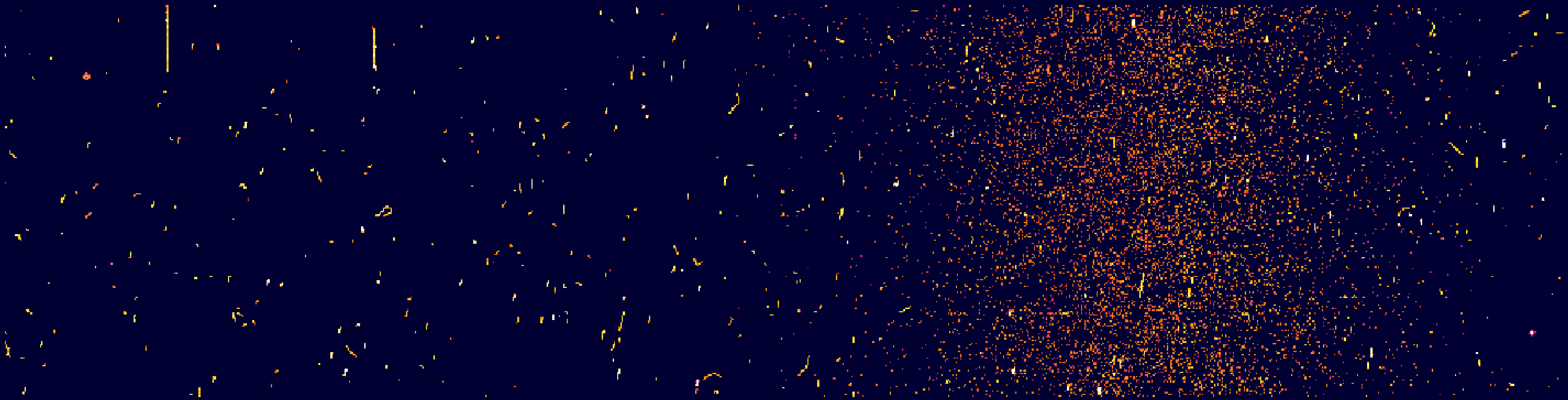
Background – shower of secondary particles due to beam loss:
- Multi-pixel events
- Energy > 26keV

Signal selection:
- Cluster finding to identify particle events
- Size & energy criteria to select ionisation electrons





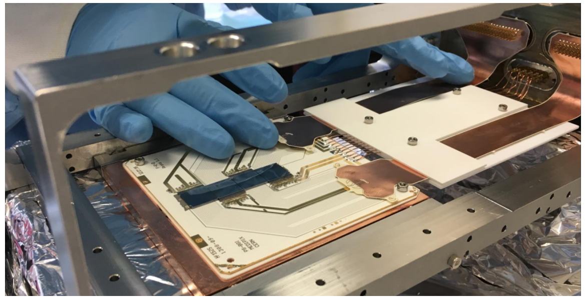
Preparation of LHC beam in the PS

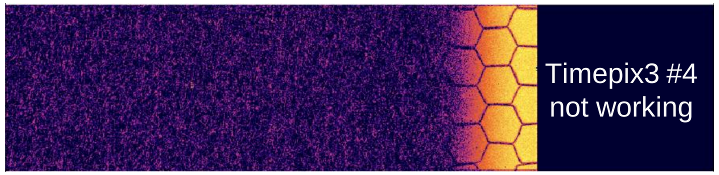


- Timepix3 data-driven readout enables "live" display of the beam throughout the cycle
- 1.5 seconds in real time: slowed down here for viewing purpose
- Each frame is 10 ms of data
- Not filtered: *background particles are interesting to look at!*
- LHC type beam, single bunch (I = 20×10^{10} p)

Ionisation electron detector – Limitations of the prototype design

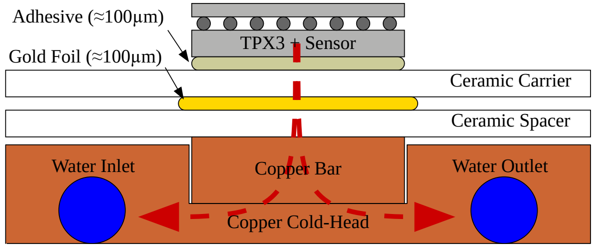
Low production yield

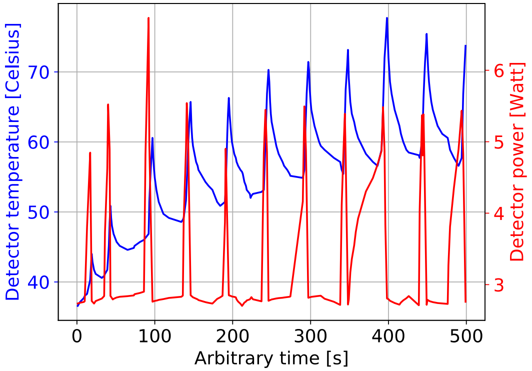




Problem:
- None of the assembled detectors fully functional

Limited detector cooling

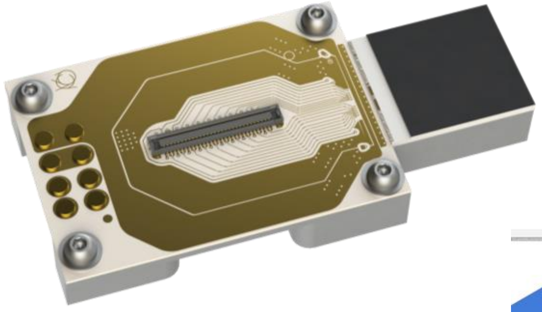


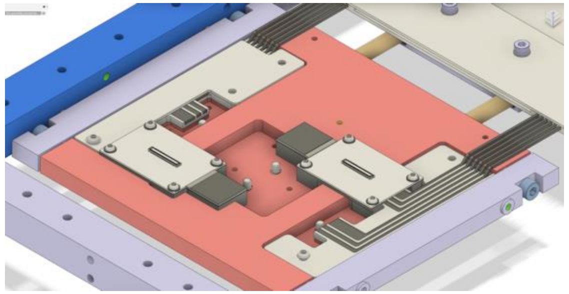


Problem:
- Long term reliability

Ionisation electron detector – Modular design

Low production yield

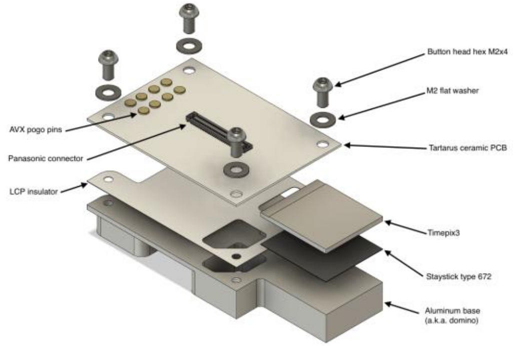


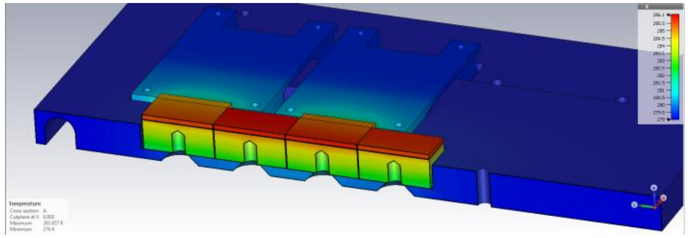


Solution:

- Modular single chip design

Limited detector cooling

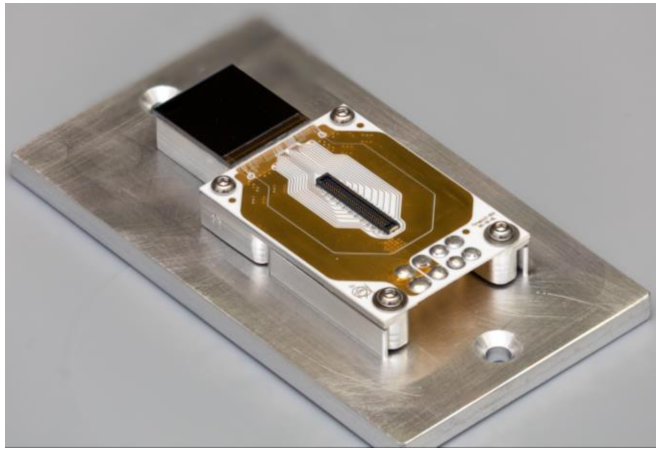


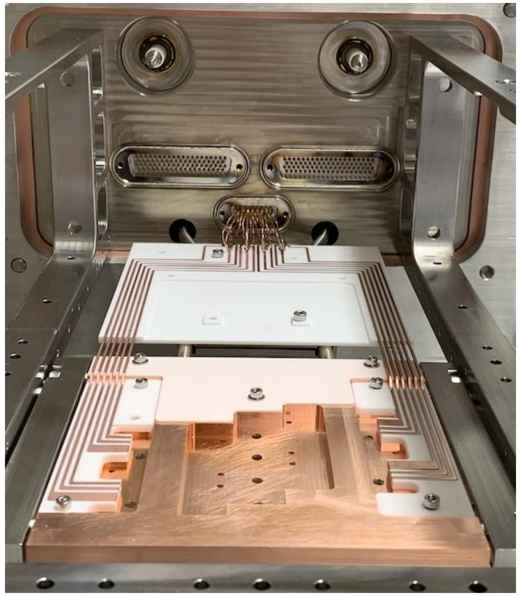


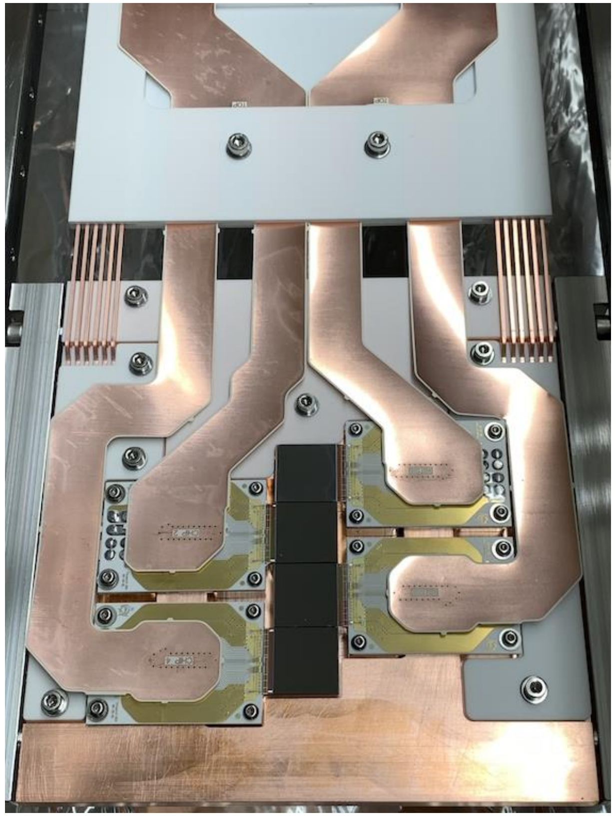
Solution:

- Fewer thermal interfaces → significantly improves thermal performance

BGI based on Timepix3 UHV modules







Final assembly

Timepix3 UHV modules:

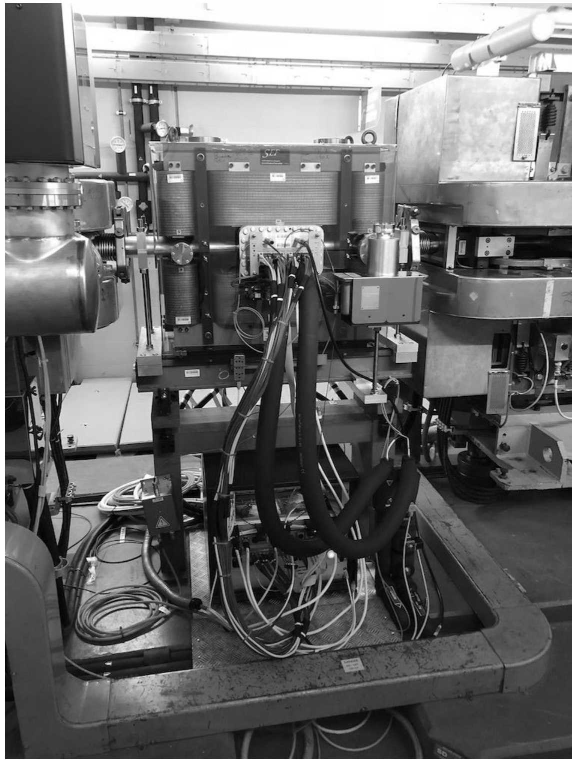
- Timepix3 attached to aluminum base with Staystick (672)
- Ceramic thin-film PCB to fan out TPX3 control & data signals to Panasonic narrow pitch connectors (A4S)
- Connect to DC power (mini-Cu bus bars) via pogo-pins

Timepix3 DC power:

- FEAST DC/DC on air side of vacuum flange (can’t place in UHV)
- Network of mini-Cu bus bars, embedded in ceramic, to minimise voltage drop

From prototype to operational instruments

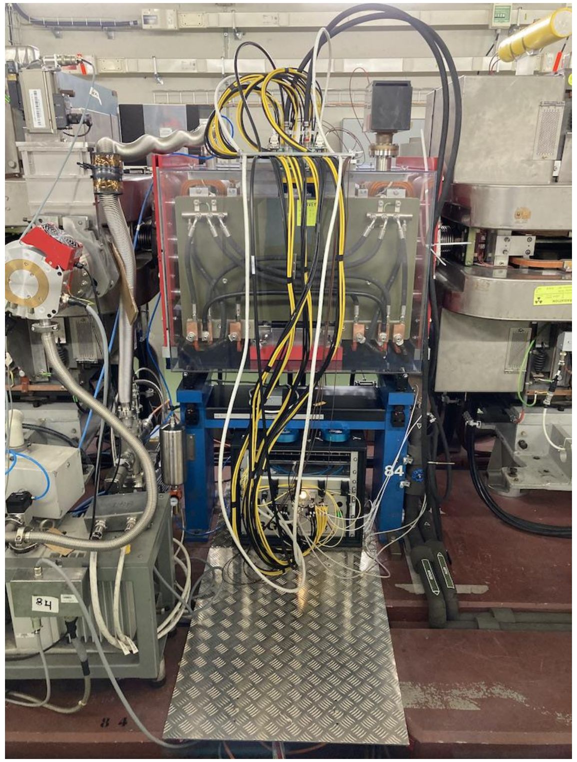
BGI-Horizontal prototype
2017-2018



- Proved feasibility to operate TPX3 in the beam pipe

BGI-Horizontal operational
2021

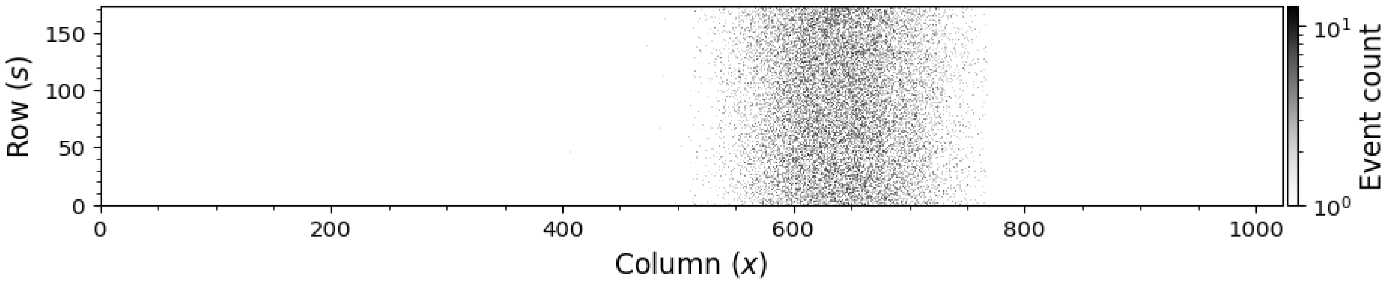
BGI-Vertical operational
2021

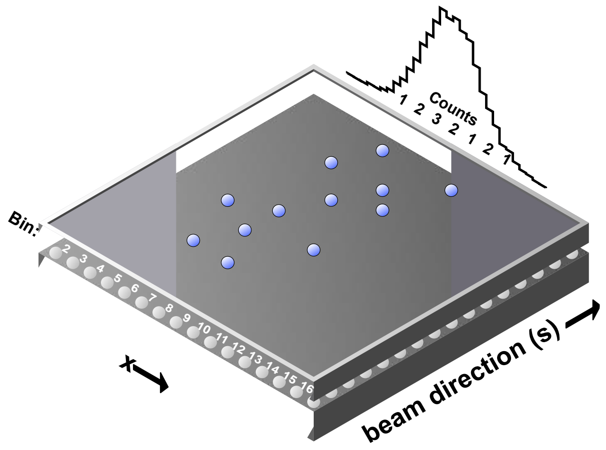


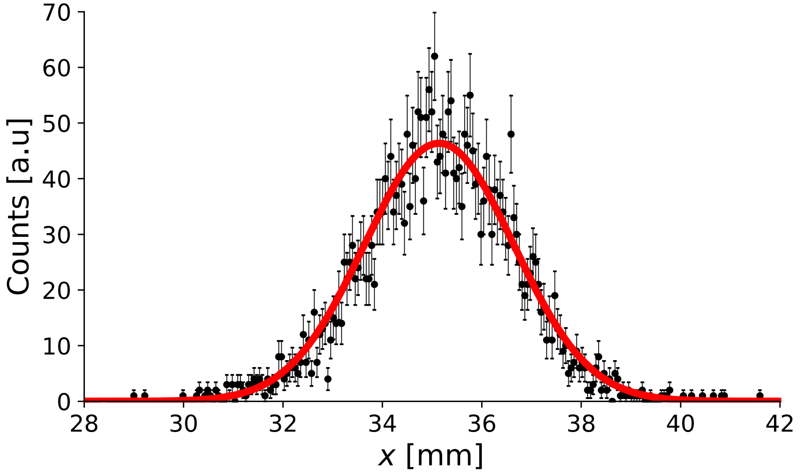
- New modular in-vacuum electronics to improve Timepix3 cooling & production yield

Beam profile measurement

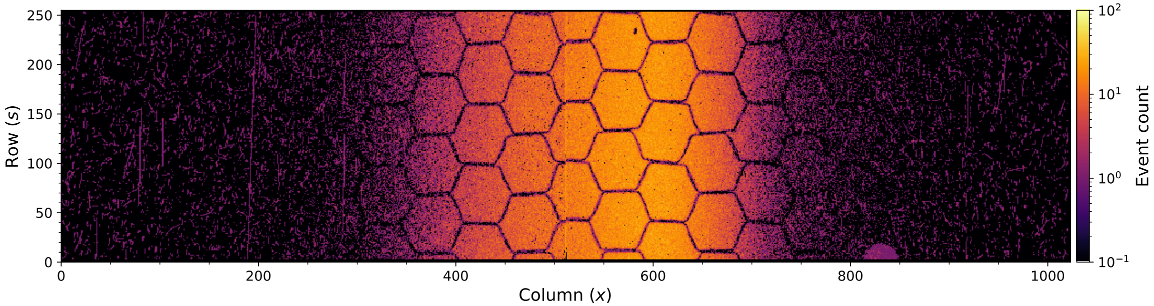
Compute beam profile by summing counts in each column

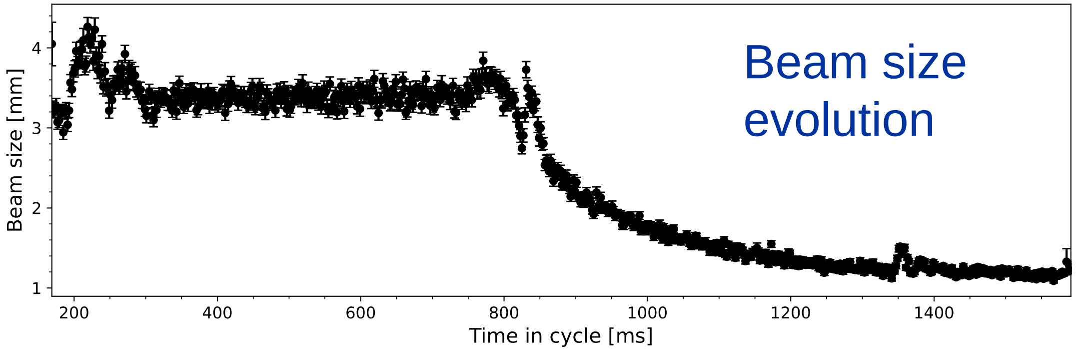


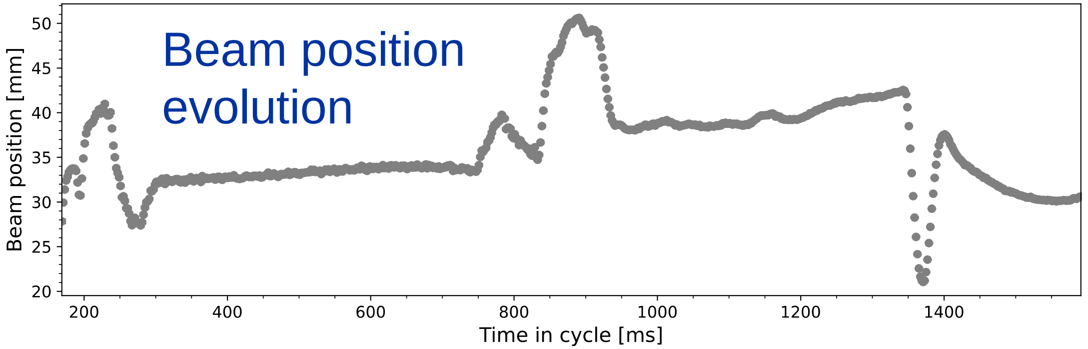




Single bunch measurements







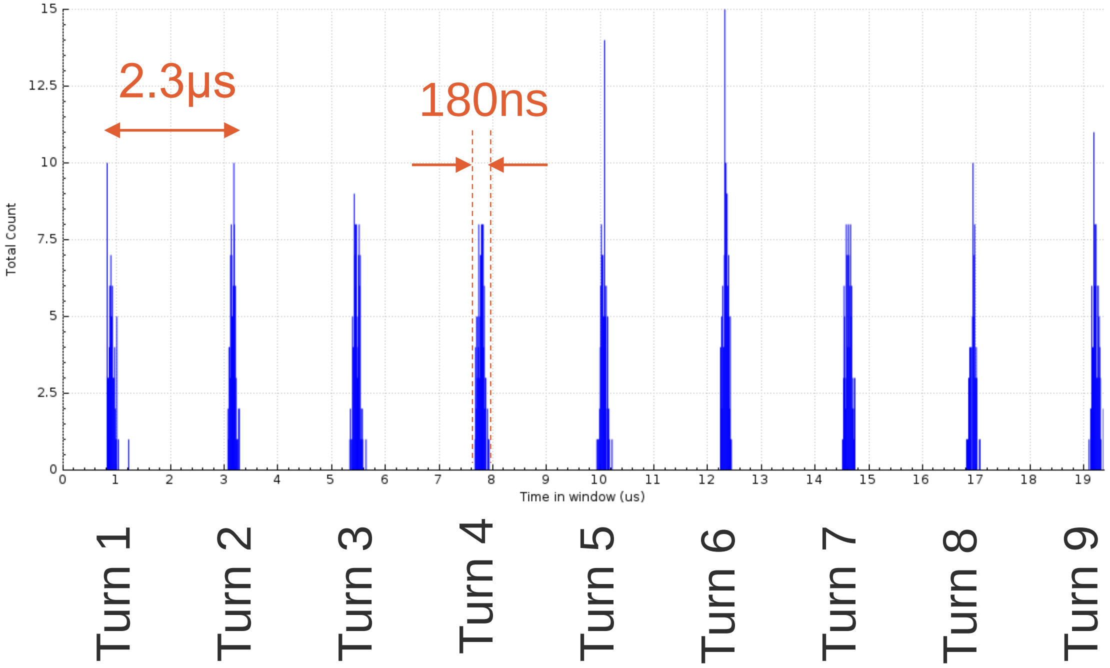
Single bunch in the PS at the start of beam commissioning

Continuous & non-destructive measurement of of beam size and position throughout the PS cycle (1.2s)

Time structure of ionisation electrons

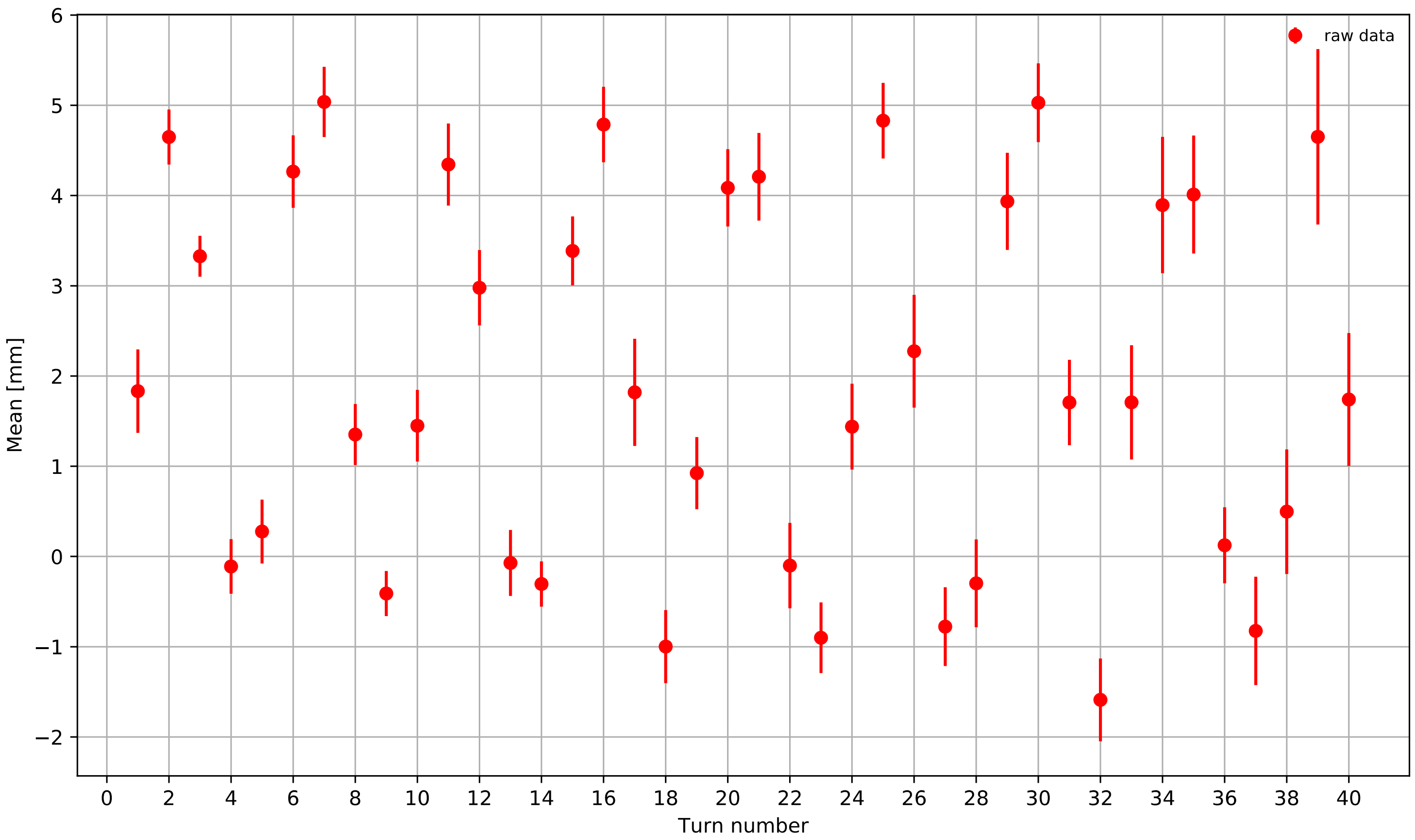
Time for 1 revolution (turn) of the PS = **2.3 µs.**

Ionisation counts from a single bunch circulating in the PS



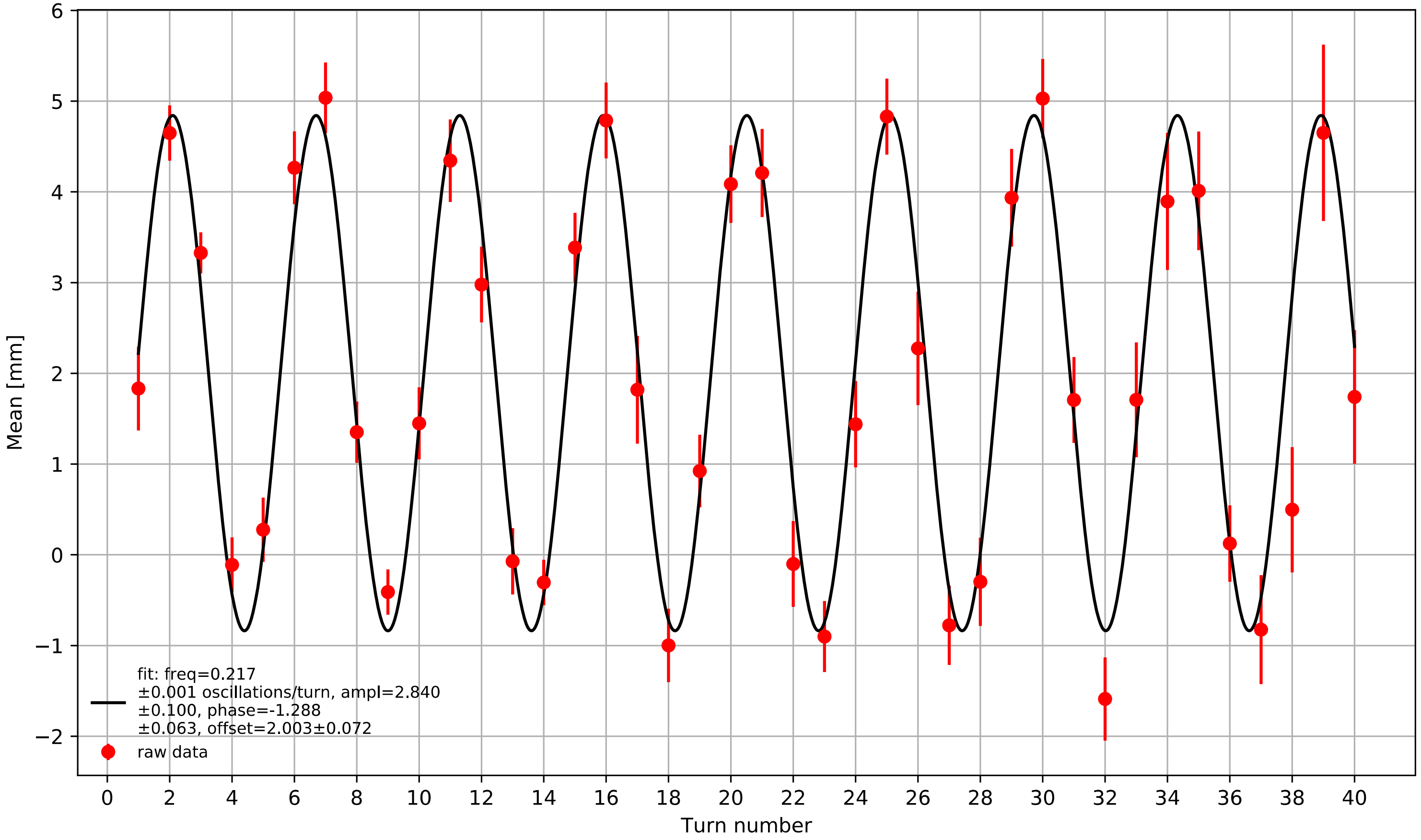
→ Longitudinal bunch length consistent with Wall Current Monitor (WCM).

Beam position vs. turn number after injection



doi:10.18429/JACoW-IBIC2019-TUBO04

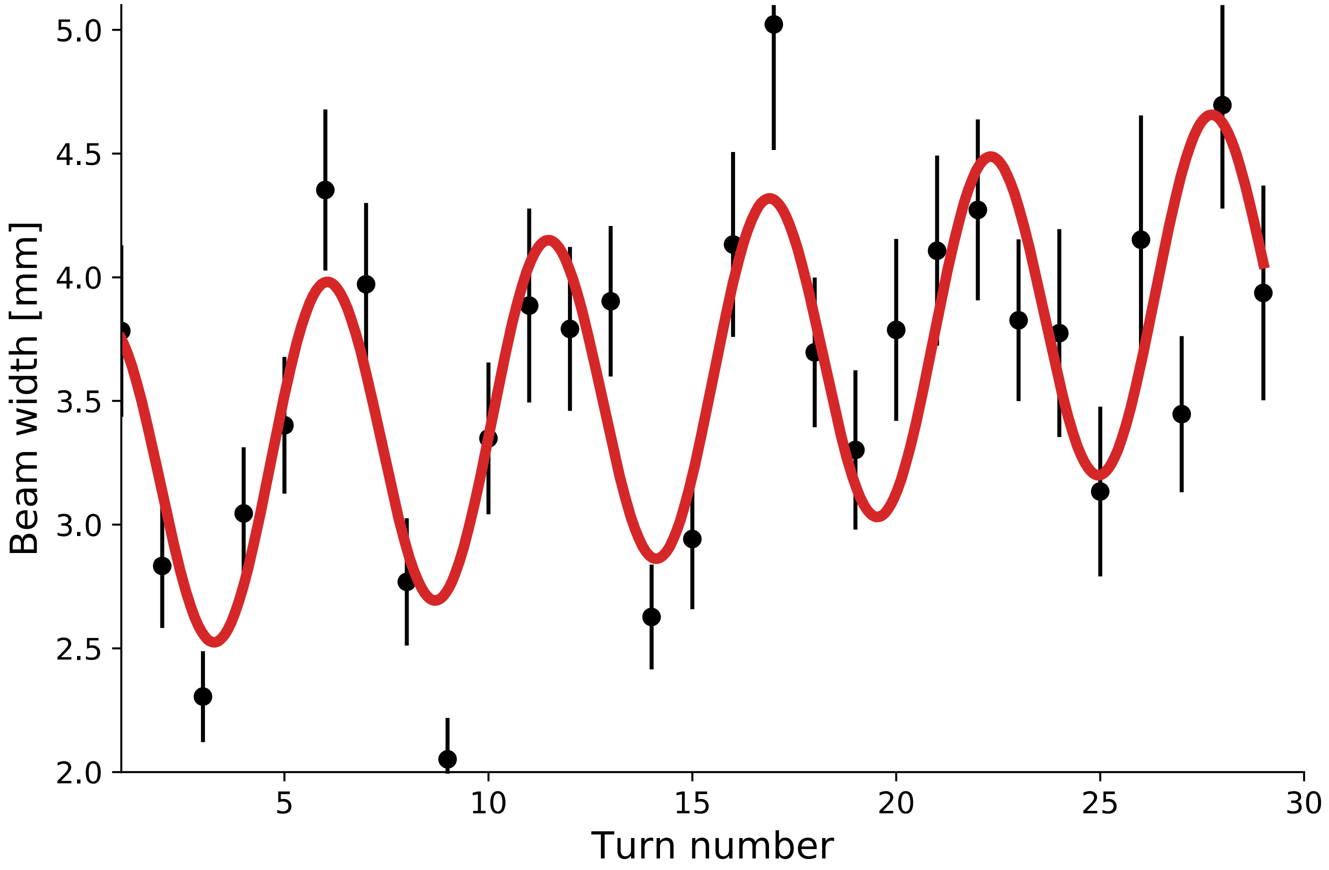
Beam position vs. turn number after injection



Measure 0.217 ± 0.001 oscillations/turn → Consistent with PS fractional tune!

doi:10.18429/JACoW-IBIC2019-TUBO04

Beam size vs. turn number after injection



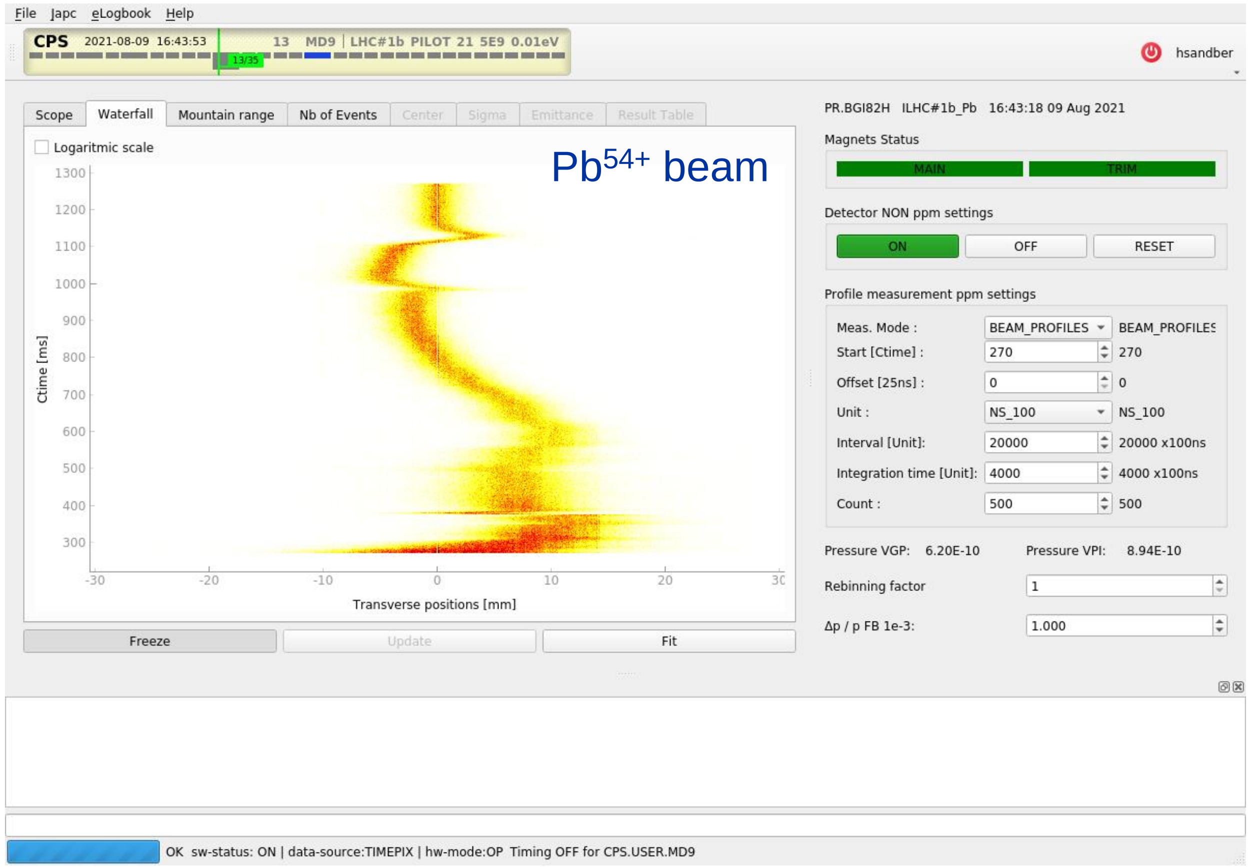
Beating of the beam size due to *injection mismatch* into the PS
→ causes **irreversible beam size growth, which ultimately limits the LHC luminosity.**

Examples of operational measurements

Following example measurements taken by PS operators & physicists in the CCC (*)

Operator defines the time to ”Start” the measurement in the cycle and the “Integration time” for each beam profile measurement, in units of seconds or turn revolutions

Up to 1024 profiles can be published per PS cycle (typically 1.2s)



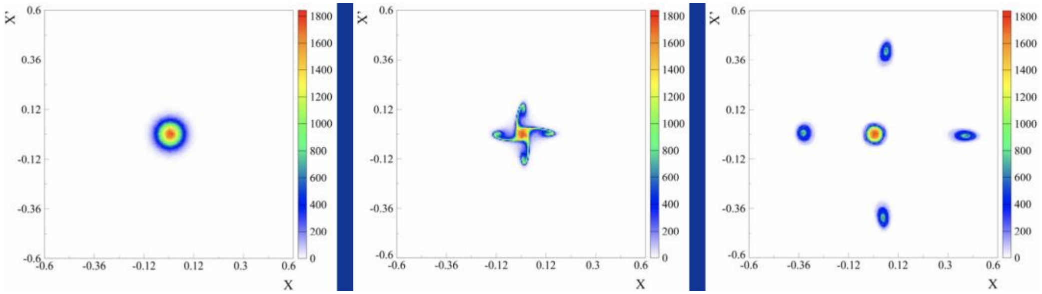
(*) Thanks to Marcel Coly, Matt Fraser & Alexander Huschauer

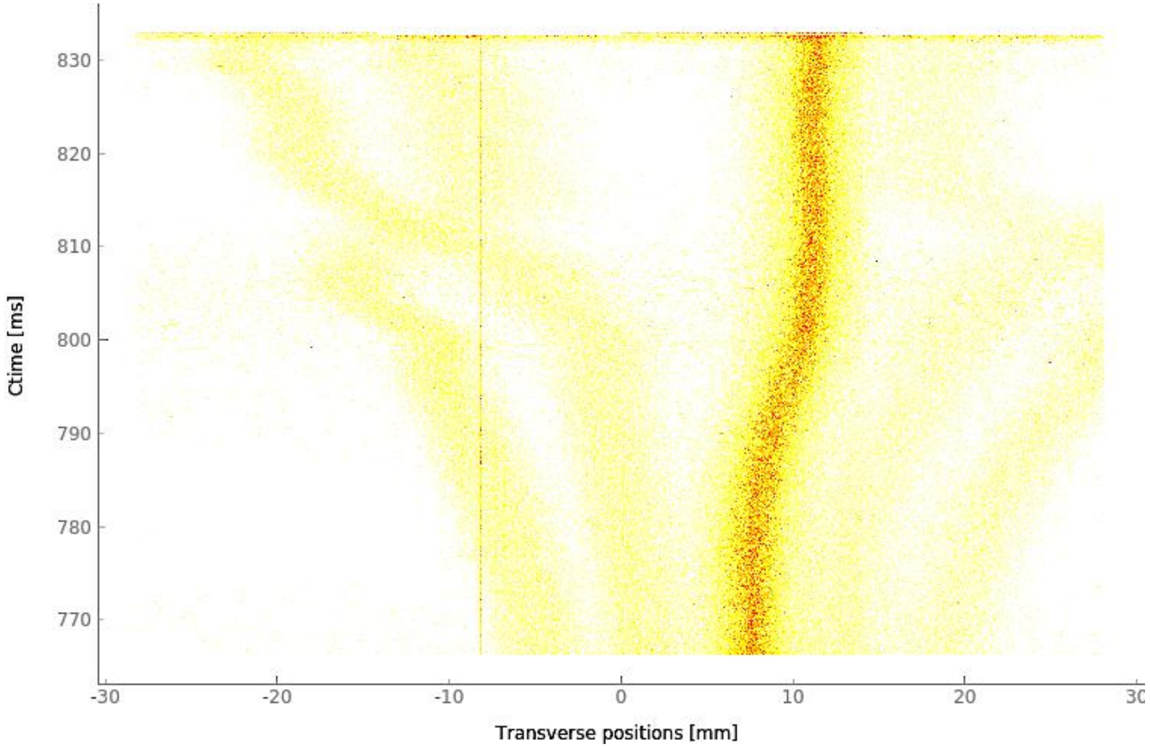
Example 1: Beamlets in Multi-Turn Extraction beam

Extraction method developed to minimise particle loss during extraction

Beam is split into several beamlets in the transverse phase space

Each beamlet is then extracted one by one





First time that is possible to see the time evolution of the beamlets

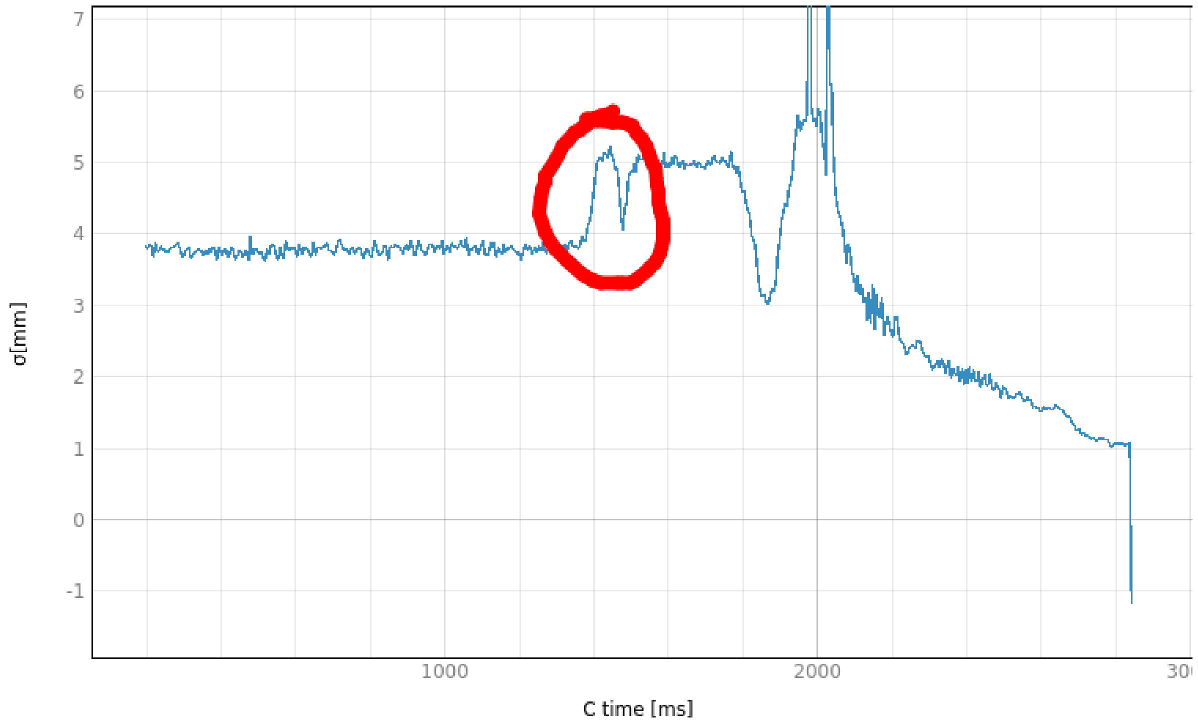
Example 2: Unexpected "bumps"

Observe unexpected sudden change of the horizontal beam size at 1450ms

Explanation: sudden change of the beam's **longitudinal momentum spread**, which couples to the horizontal plane through dispersion

New beam diagnostic insights.

Horizontal beam size



Example 3: Injection beam losses

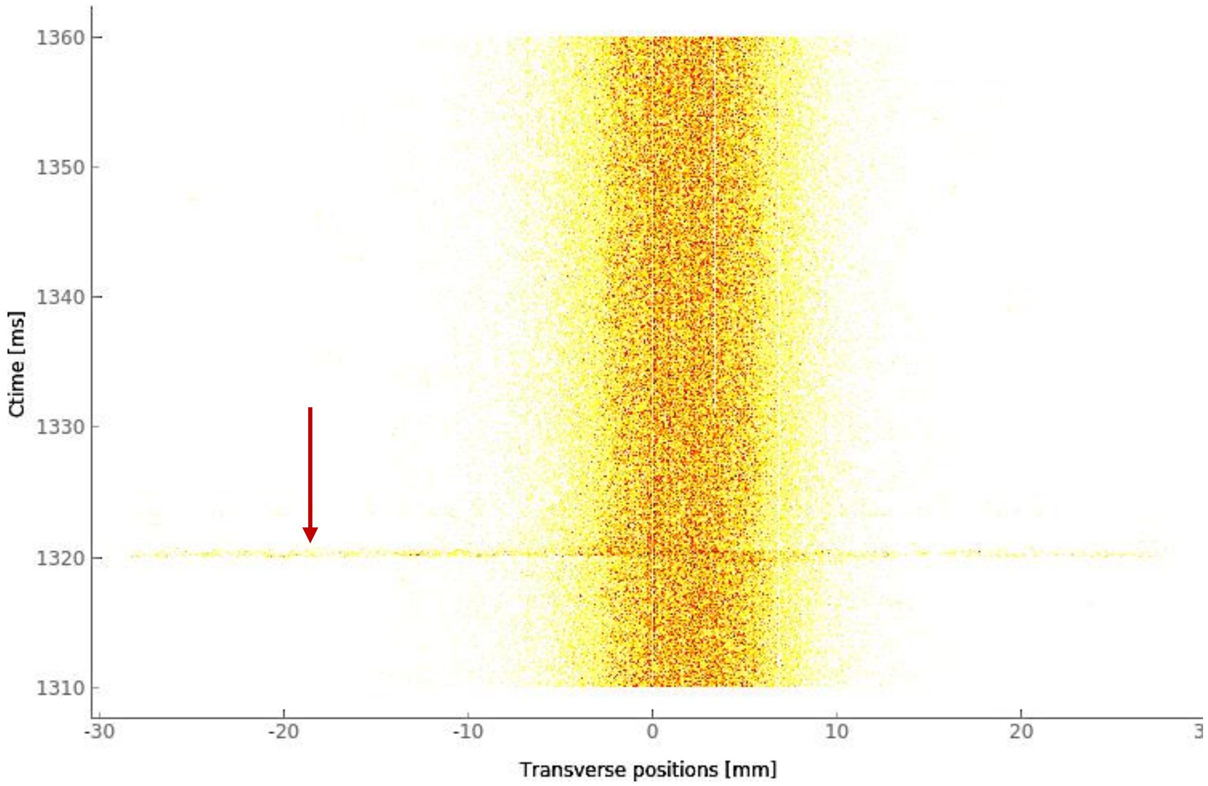
Part of a cycle with a stable transverse beam size

“Glitch” visible at 1320ms in the cycle

Can distinguish between ionisation electrons and charged particle interaction using ToT data

“Glitch” is actually beam loss, which was subsequently traced to an injection kicker magnet that was active (but no beam was injected)

Losses were not visible on other nearby beam loss monitors



Very sensitive beam loss monitor.

Future applications of Timepix technology for Beam Instrumentation at CERN

Operational needs

1. New non-destructive independent beam profile monitor for the LHC
   a) Beam Gas Vertex (BGV) profile monitor
   b) Beam Gas Ionisation (BGI) profile monitor

2. Beam halo monitoring for the LHC

3. Fast Beam Loss Monitor (BLM) for rapid deployment in the LHC

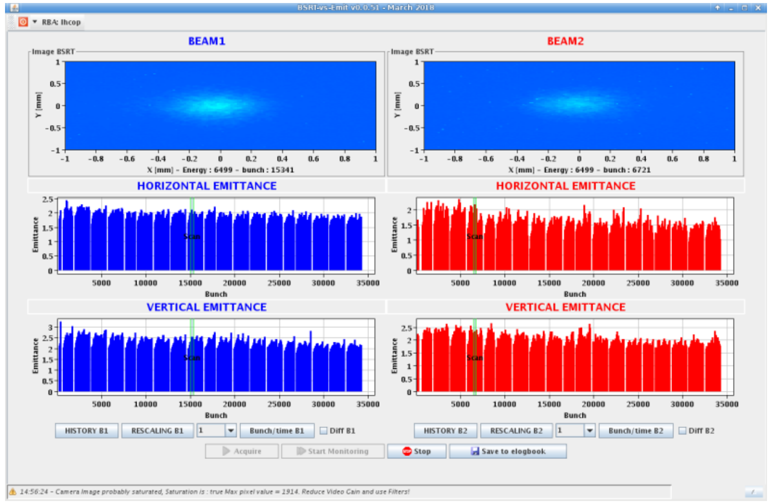
New beam profile monitor for the LHC

Current beam profile measurements based upon:

- Beam Wire Scanner (BWS)
  - Limited to low intensity (pilot) beams

- Beam Synchrotron Radiation Telescope (BSRT)
  - **Work-horse for bunch-by-bunch emittance measurements in the LHC**
  - Complex light source (undulator + dipole magnets), which changes with energy:
    - Light intensity increases by 3 orders of magnitude
    - Wavelength shifts from visible to NUV
    - Longitudinal position of the source shifts by ~3m
  - Requires cross-calibration with wire-scanner (links accuracy of measurement to the BWS) & assumption that beam profile is Gaussian

Requirement – new instrument to provide independent bunch-by-bunch beam profile measurements of the physics beam along the whole cycle.

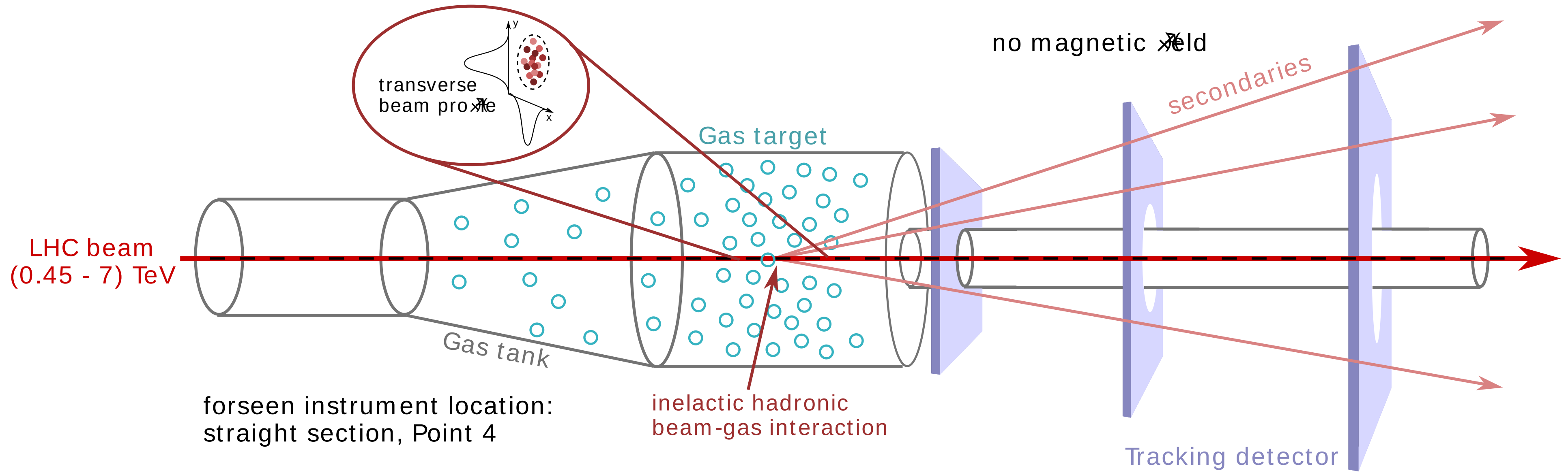


BSRT emittance measurements
– precision < 5% & accuracy ~10-20 %

BSRT light sources – undulator magnet (green) and dipole magnet (blue)

Ref. doi:10.18429/JACoW-IPAC2021-TUPAB278

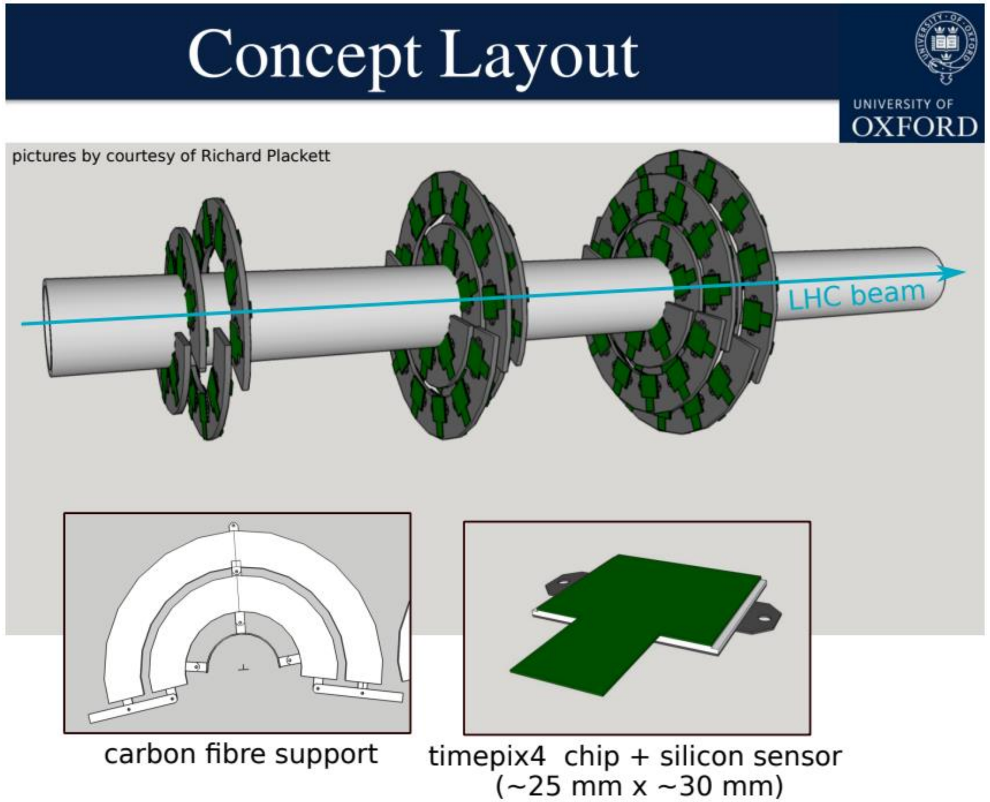
Beam Gas Vertex (BGV) profile monitor for HL-LHC



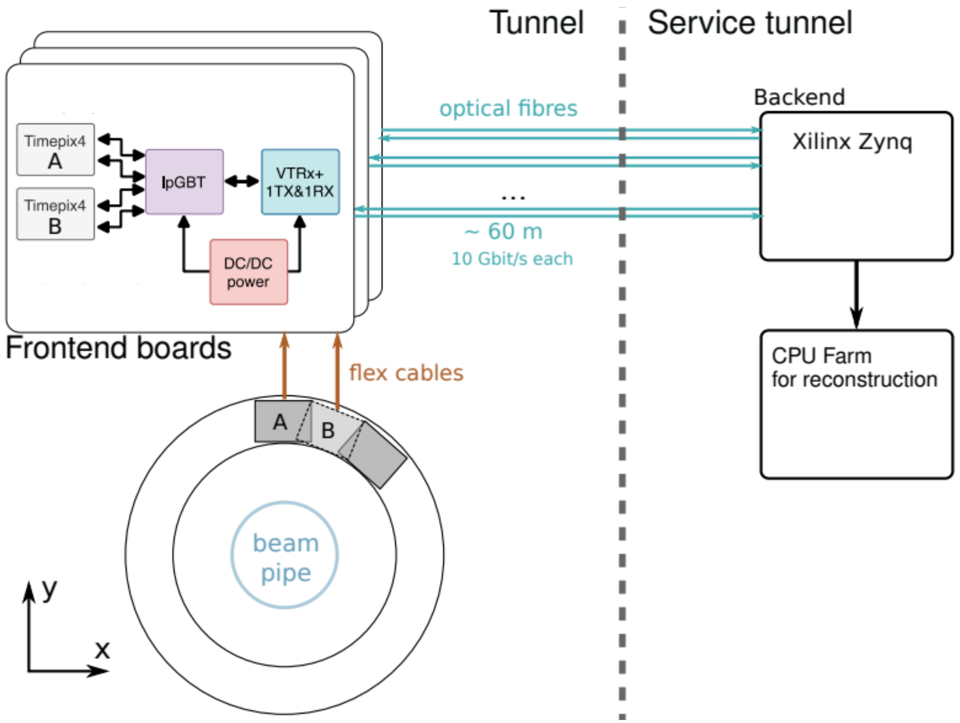
BGV consists of: 1) **Gas target** & 2) **Forward tracking detector**
Beam profile inferred from density of the reconstructed primary vertices of the inelastic beam gas interactions.

BGV - Tracking detector based on Timepix4 Hybrid Pixel Detectors

Tracking detector – modules + support
(Collaboration with Oxford University)



Tracking detector – readout + processing
(CERN)

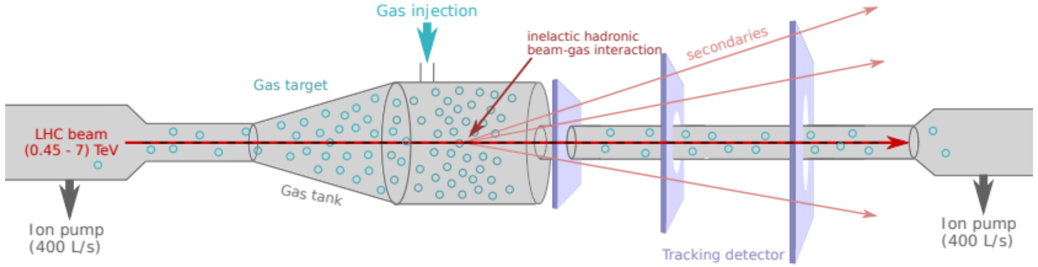


Architecture based on BIPXL readout developed for PS BGI

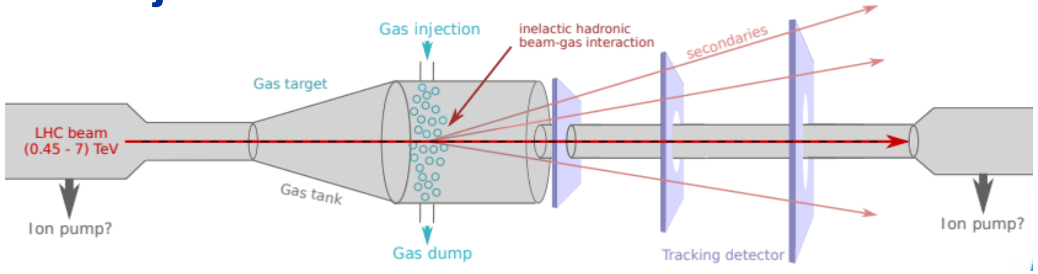
BGV - Performance study of different gas targets

Gas target options:

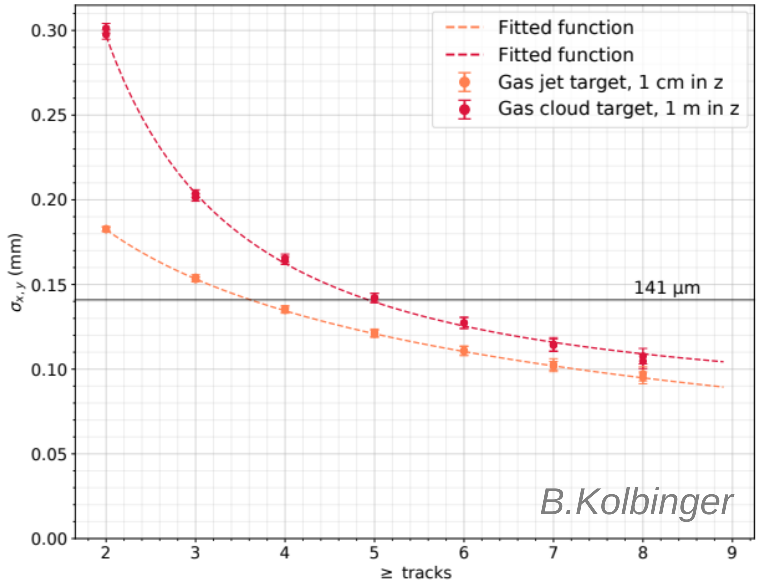
1. Gas **cloud**



2. Gas **jet**



Vertex resolution vs. # tracks for gas cloud & gas jet targets



Beam Gas Ionisation (BGI) profile monitor for LHC

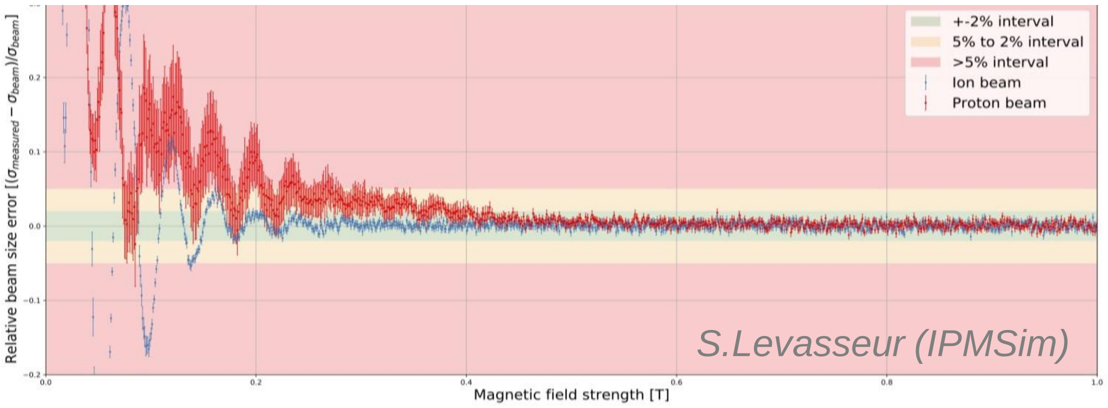
Problems with (former) LHC BGI:

- Beam profile **distortion** at E > 3TeV due **bunch space charge**
- Instrument **damage** due to **beam induced heating**

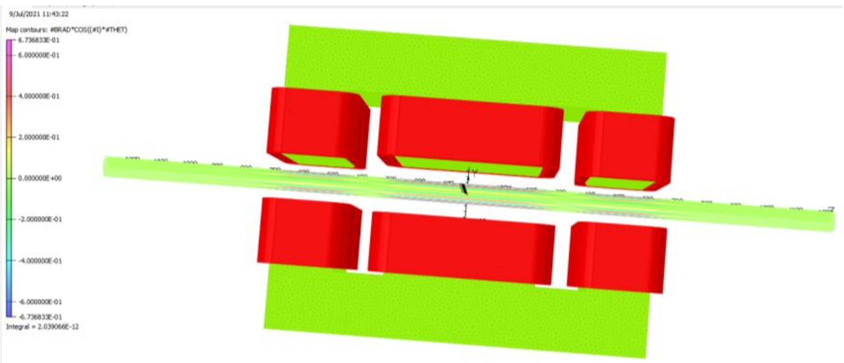
Solution:

- **Compact** BGI based on Timepix3 with 0.6T dipole magnet

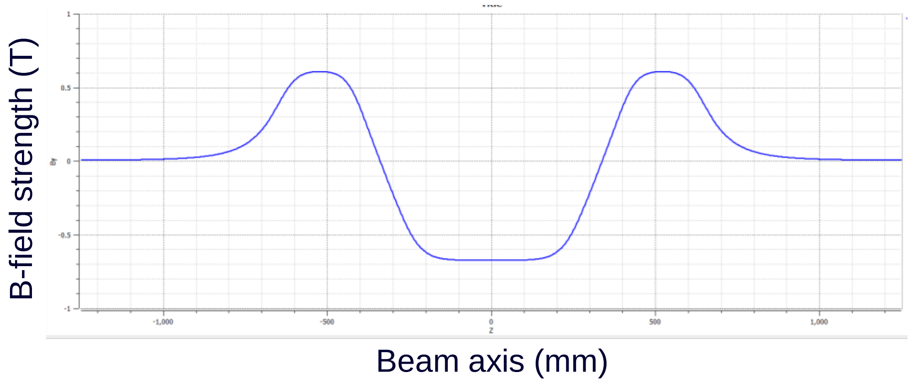
Beam size error vs. Magnetic field strength



Preliminary design for 0.6T self-compensating dipole magnet

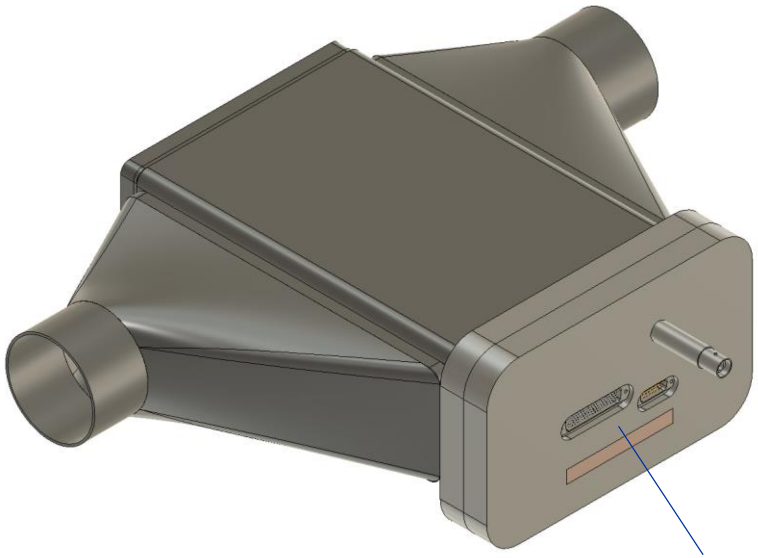


D.Bodart (TE-MSC)

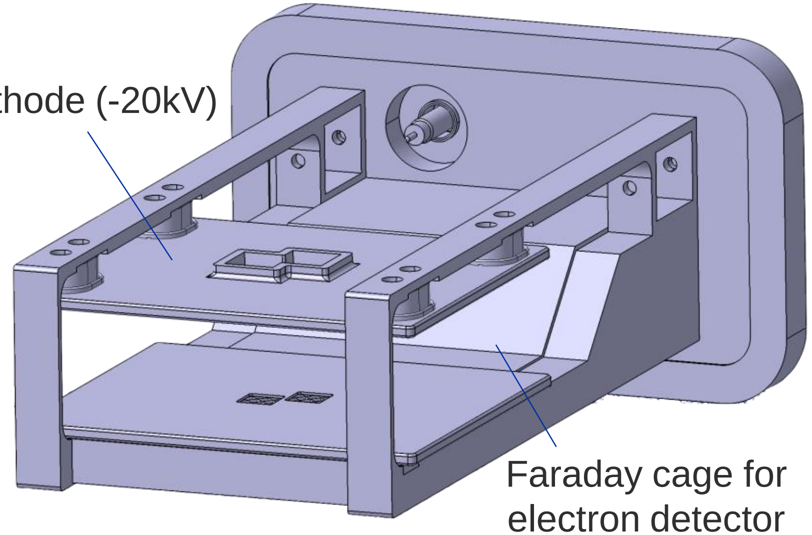


LHC BGI – Preliminary design

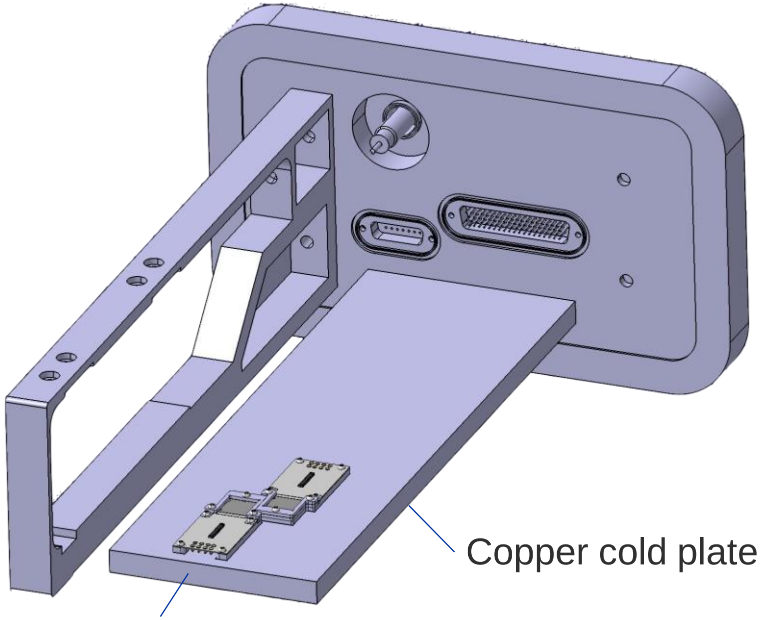
Vacuum chamber + instrumentation flange



Instrument



Ionisation electron detector



Swann Levasseur (CERN)

LHC BGI – Timepix3 Baked UHV modules

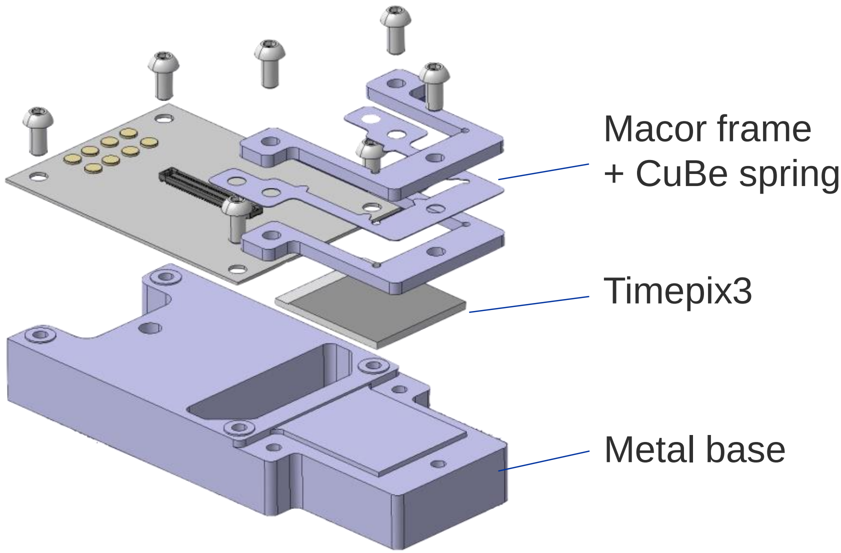
LHC vacuum – need to bake at (>) 120℃

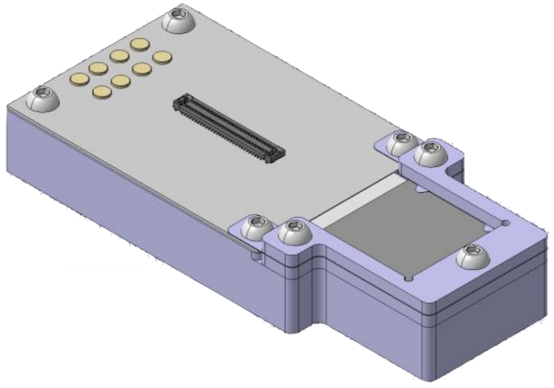
Problem:

- Not possible to use the Staystick (thermo-plastic) - used in PS BGI modules to attach Timepix3 chips and to provide thermal conductivity

Solution(s) under development (R&D):

1. Mechanically hold Timepix3 chip to base with Macor frame & CuBe spring + indium sheeting providing thermal conductivity between the chip & base.
2. Braze chip directly to the base by:
   I. Sputtering chromium / gold to the base of the chip
   II. Sputtering gold to a tungsten base
   III. Brazing together with Indium at 160 ℃





Swann Levasseur (CERN)

LHC BGI - Beam halo monitoring

Need to monitor particle population in the beam halo, which for HL-LHC beams can store up-to 30MJ of energy

Ionisation electron signal with gas injection:

- Gas pressure = $1x10^{-8}$ mbar Neon
- Ionisation electron rate of full LHC beam = **10^{10} electrons / beam / s**
  - **$5x10^{3}$ electrons / beam / s** are outside 5 sigma **= beam halo "signal"**

Timepix3 readout limitation:

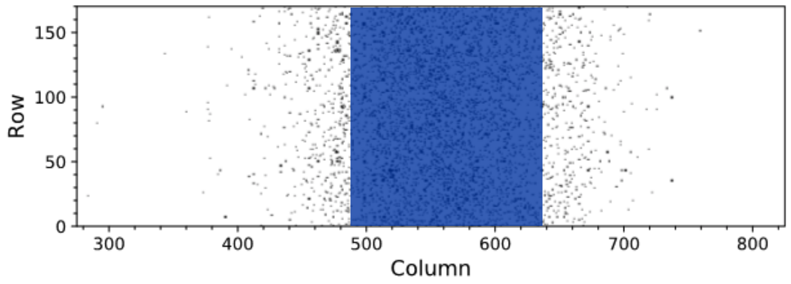
- Maximum detector readout of **$160x10^{6}$(*) events / s, << 10^{10} electrons / s** of the full signal

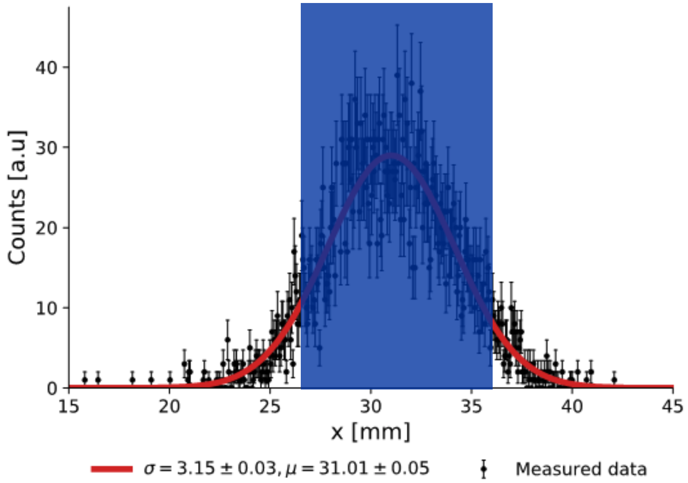
Possible solution:

- Significantly reduce data rate by **masking pixels** in the "core" of the signal (**"Digital-Coronagraph"**)
- e.g. Mask all pixels within a 3*sigma beam core window **reduces to data rate to $2x10^{6}$ electrons / beam / s**

(*) detector consists of 2 x Timepix3 HPD's

Mask pixels beneath the beam core to focus readout bandwidth on the beam halo





Backgrounds?

Signal = 5000 electrons / beam / s

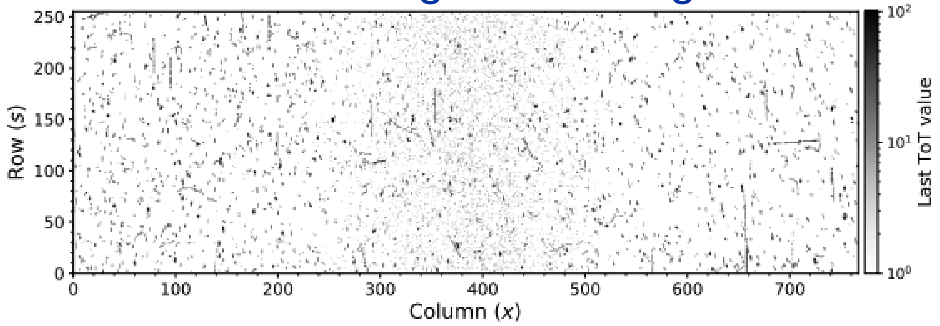
Backgrounds:

- Secondary particles from inelastic beam gas interactions
- Secondary particles from beam loss
- Material activation, etc...

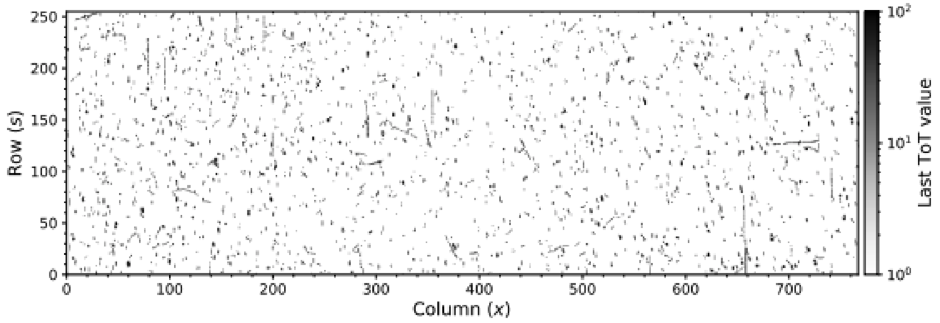
Background suppression:

- Transform Timepix3 events to particle events with **cluster finding methods** (DBSCAN)
- Apply selection criteria (e.g. cluster size, energy) to select only ionisation electron
- Method already demonstrated with the PS BGI to remove beam loss background from ionisation electron signal

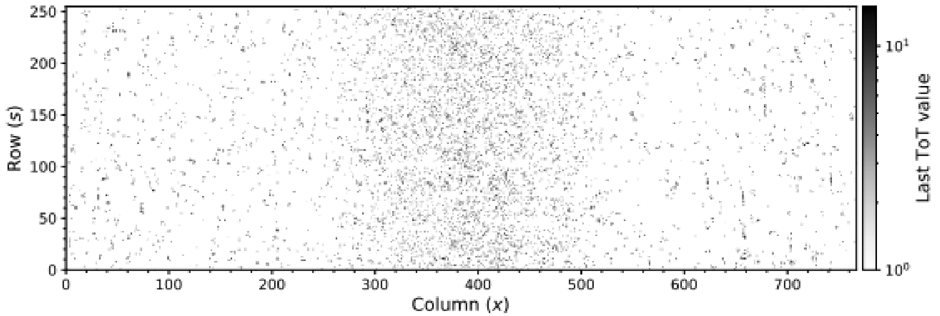
Raw data = Signal + Background



Clusters passing Background selection



Clusters passing Signal selection

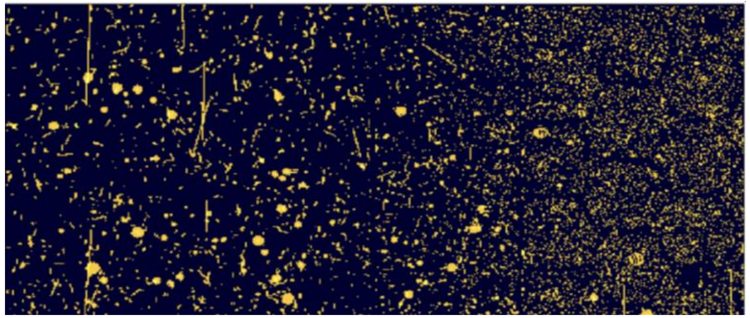


Hampus Sandberg (CERN)

Fast Beam Loss Monitor (BLM) based on Timepix3

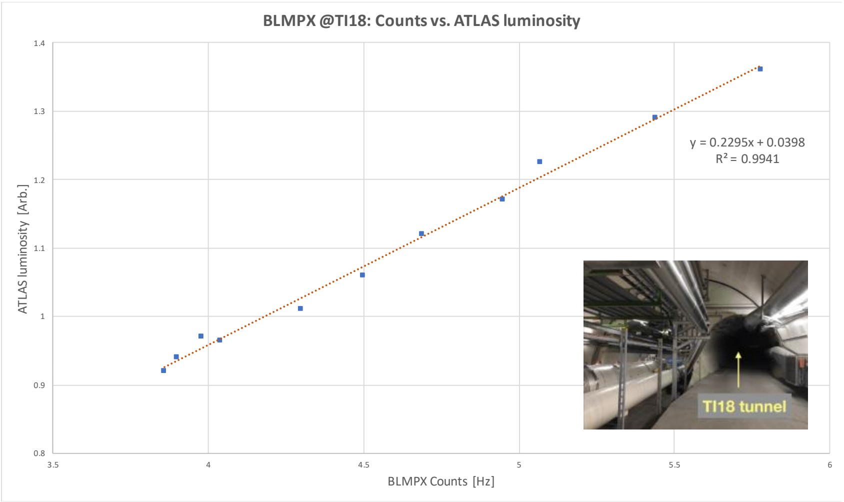
Operational need: Fast beam loss monitor for rapid deployment in the LHC

Timepix3-BLM = Timepix3 HPD + BIPXL readout systems (minimal amount of development)



Beam loss in the PS at injection as seen by PS BGI

Radiation tolerant Fast BLM based on Timepix3 with BIPXL readout



Measurement for FASER at TI18 – 2 hour installation

Conclusion

Timepix3(/4) technology

+ Direct operation in the accelerator beam pipe (UHV compatible electronics)

+ Common radiation tolerant readout (BIPXL)

+ Support of the Medipix community

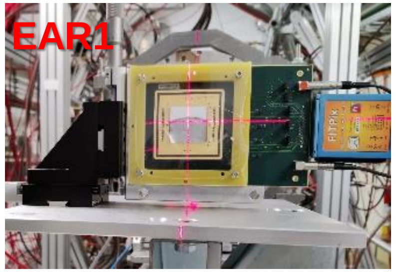
= **Fantastic potential for beam instrumentation applications!**

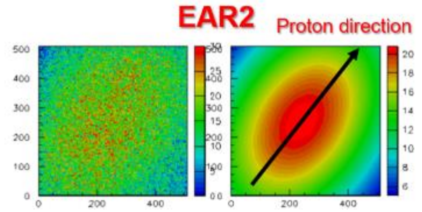
Finally...

Special thanks to the EP-ESE Medipix team for the great support!

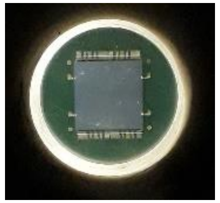
Other use of Timepix technology for beam diagnostics @CERN (Slide from F.Murtas INFN/CERN)

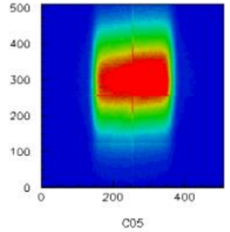
- **nToF** : for the beam laser alignment in :
  EAR1: EDMS 2715844
  EAR2: EDMS 2716039



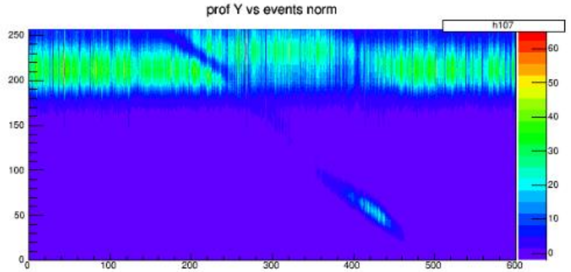


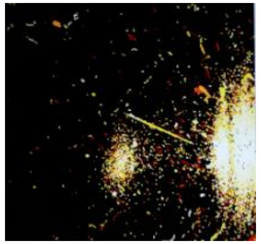
- **CERF** : for aligning the copper target to the beam
  EDMS 2646206





- **UA9** : for Crystal characterization in SPS and double channeling studies
  NIMA 1015 (2021) 165747





- **UA9** : new roman pot BHM (agreement KE4450/EN)
  and readout (Addendum 17 INFN - KN 5080/SY)
  - One device already installed in SPS
  - Other 4 in production at INFN Frascati