Timepix3 based Detectors

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Outline

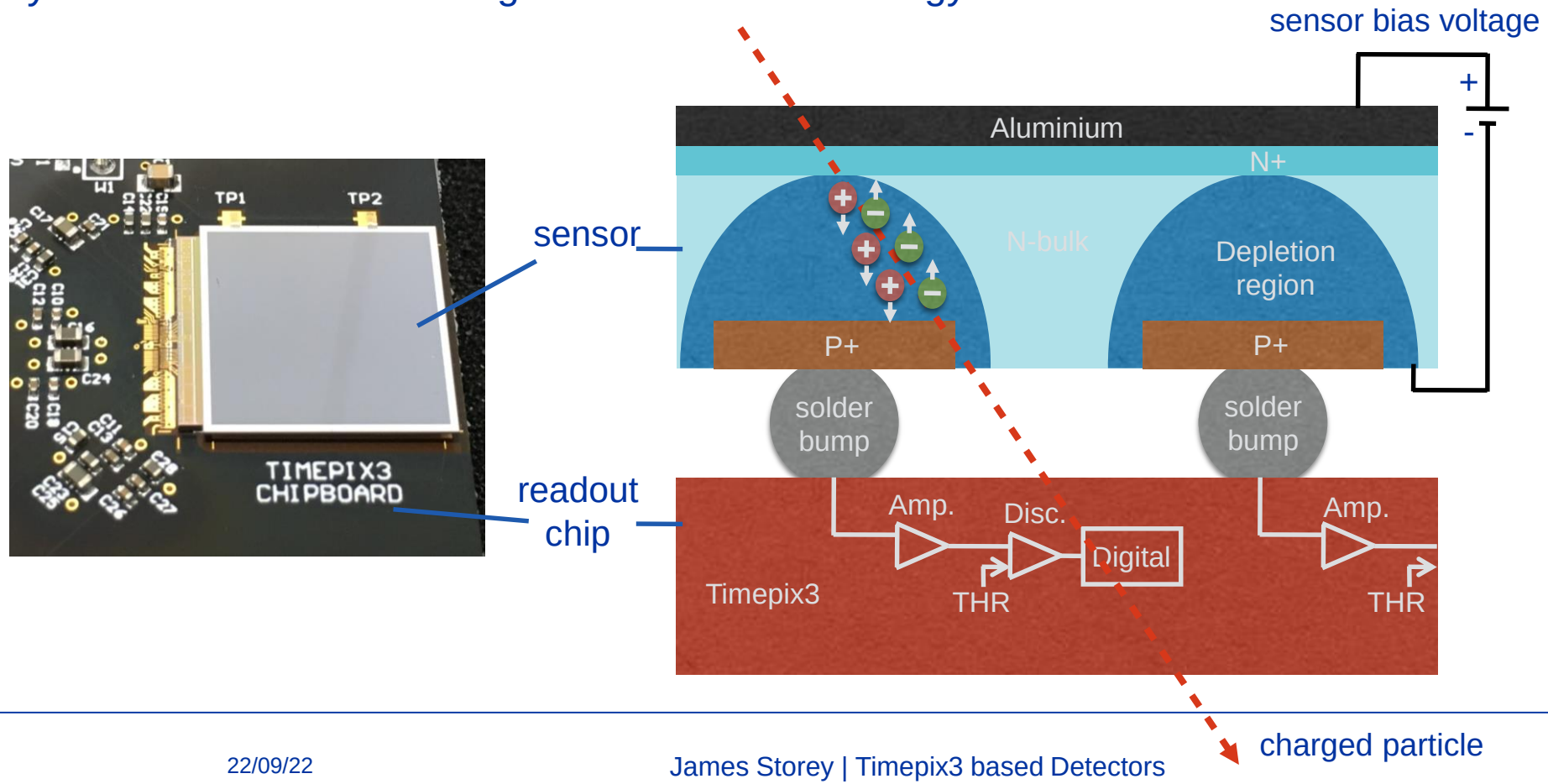
1. Brief introduction to Timepix3 & 4 Hybrid Pixel Detectors (HPD's)

2. Example applications of particle detection with Timepix3 HPD for Beam Instrumentation at CERN:
   - Rest gas ionisation profile monitor (electron detection)
   - Beam Gas Vertex & Fast Beam Loss Monitor (high energy charged particle detection)

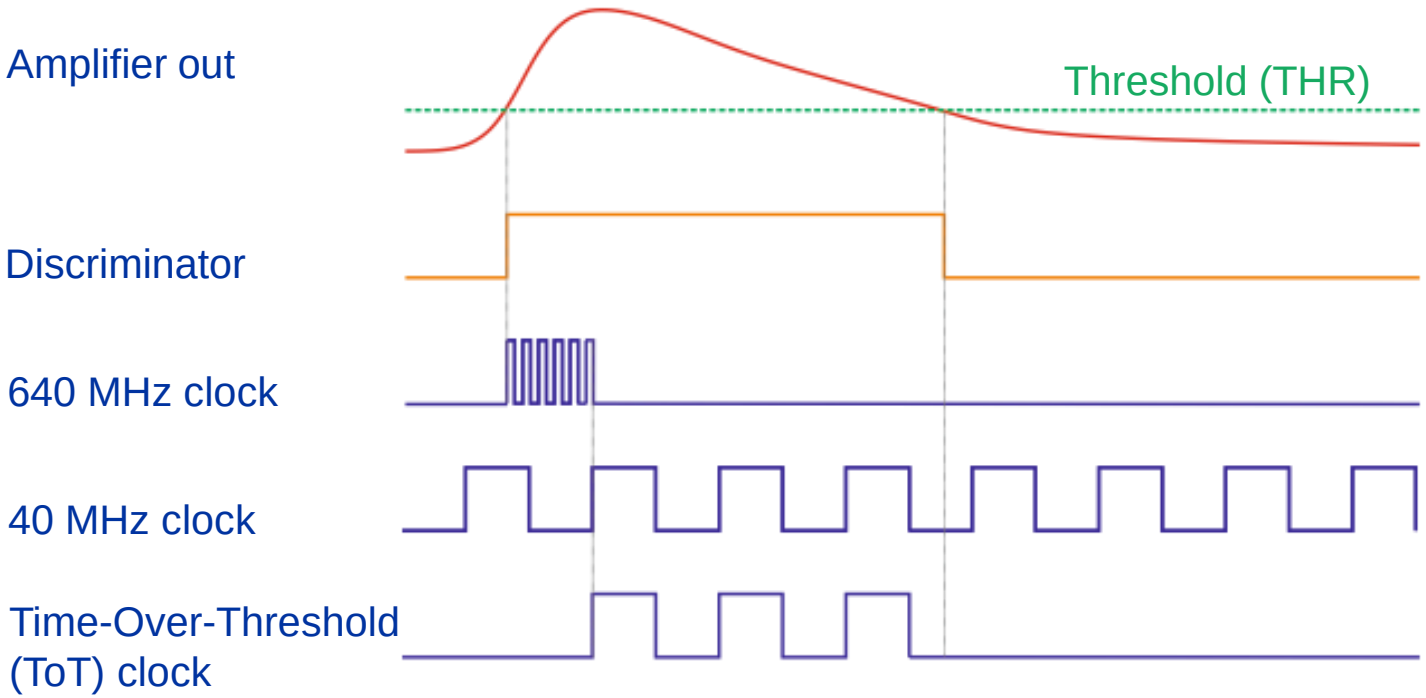
Hybrid pixel detector

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

Sensor: 2-dimensional array of PN-diodes processed (for example) in high-resistivity silicon.
Readout chip: array of readout channels designed in CMOS technology.



Timepix3 response to charge



minimum threshold = 500 e^- (1.8 keV)

time resolution = 1.5625 ns

Amplifier out > threshold

→ **Event**

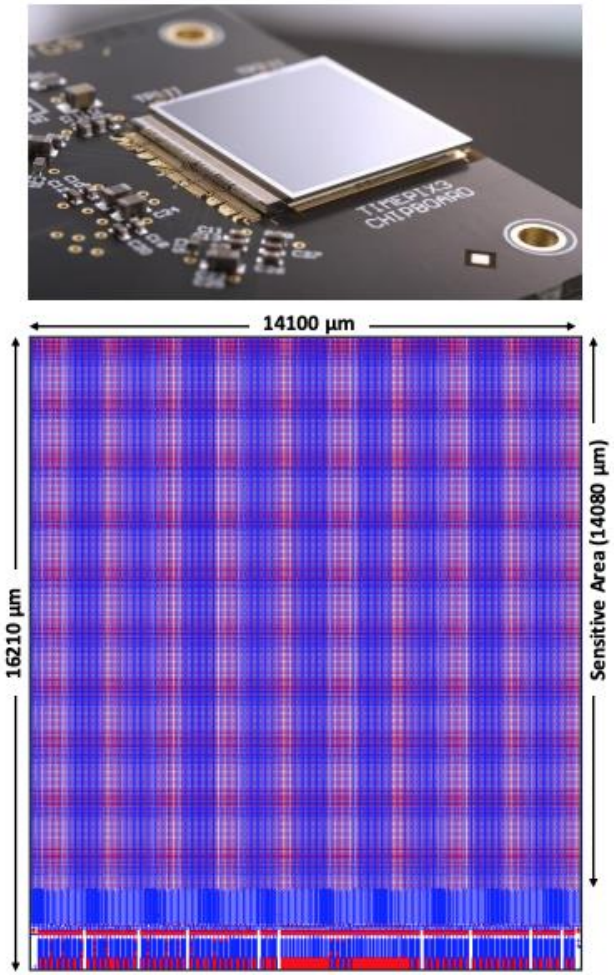
Each **event** consist of:

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

Max. 80M events / s

Timepix3 specifications

Application	General Purpose particle tracking
Technology	IBM 130nm
Pixel	(h^+/e^-) with 55 x 55 μm^2
Pixel arrangement	256 x 256 (2x4 superpixels)
Acquisition modes	1) Time (TOA) AND Charge (TOT) 2) Time (TOA) 3) PC & integral charge (iTOT)
Readout Type	1) Data driven (Shutter-less) 2) Frame-based (Shutter)
Thresholds	1
Minimum threshold	> 500 e-
Time resolution (TOA)	1.562 ns
Energy Resolution (TOT)	~2 keV FWHM (Si)
Power consumption	<1.5W @1.5 V
Floorplan	3 sides buttable and minimum periphery
TSVs possibility	YES. With 1.2mm periphery
Count Rate	Data-Driven: ~0.43 x 10^6 hits/mm^2/s Frame-based: 826 x 10^6 hits/mm^2/s
Output bandwidth	1 to 8 SLVS DDR @640Mbps each



Slide from Xavier Llopart - EP Detector Seminar on 11th Feb. 2022 (https://indico.cern.ch/event/1121147/)

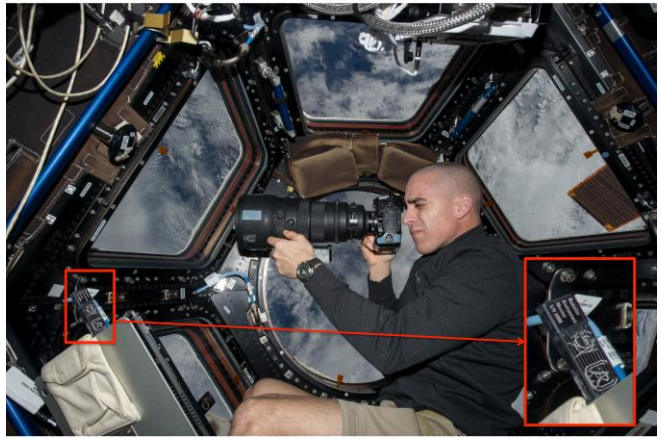
Applications of Timepix HPD's

High Energy Physics (HEP):

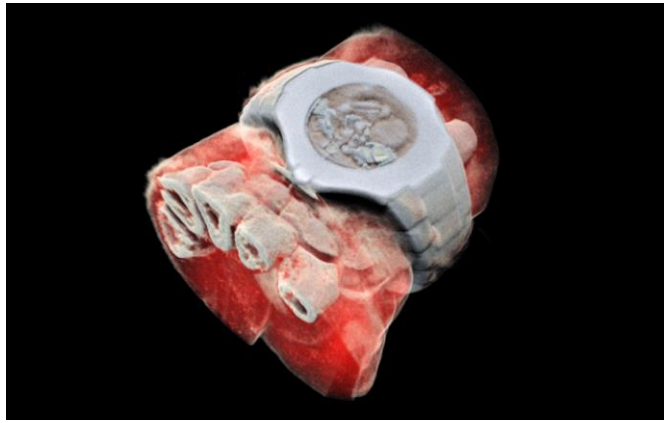
- Charged particle tracking (e.g. Telescope, TPC, etc.)
- Neutron detection (e.g. Convertor + MCP + Timepix3)
- Electron detection
  - **Beam instrumentation**
- X-ray detection

Outside HEP:

- Dosimetry
- Time-of-flight mass spectroscopy
- Electron microscope
- Compton cameras
- Education

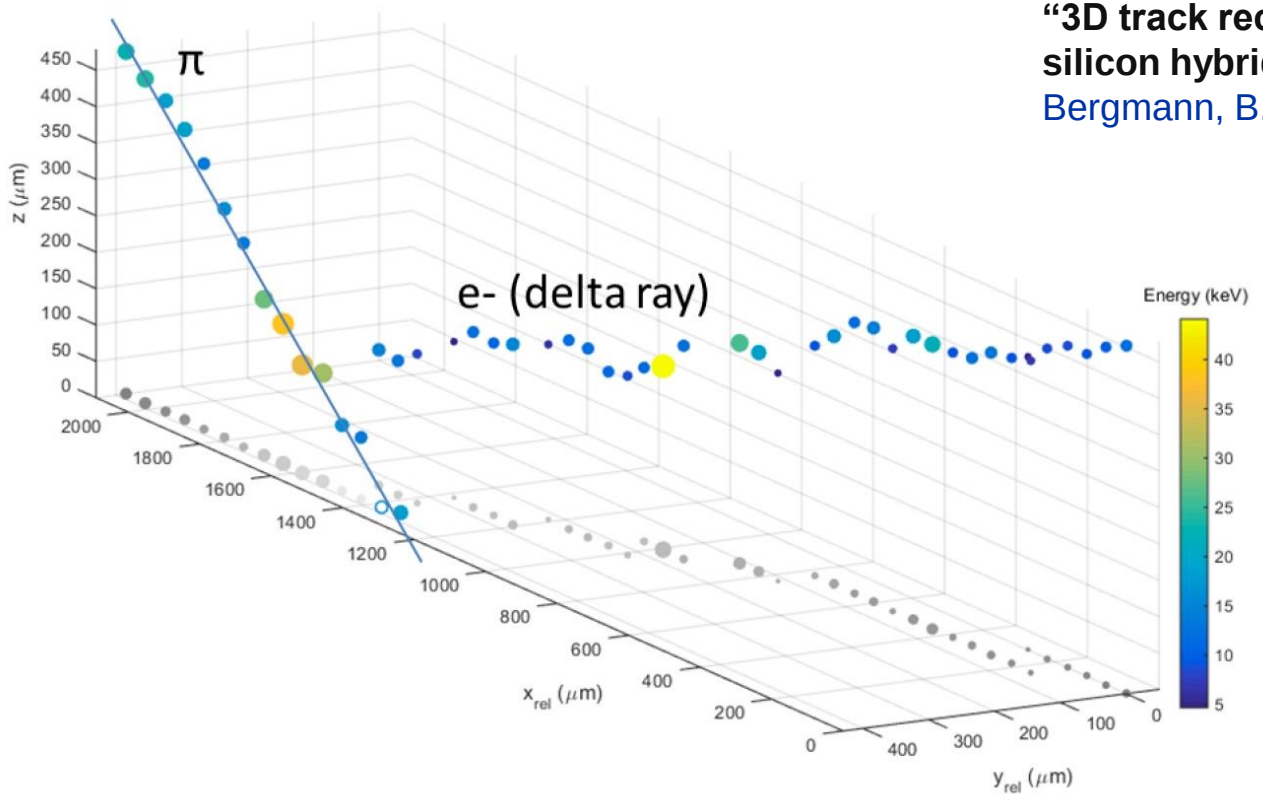


Space dosimetry - Timepix on International Space Station
(Courtesy of NASA, photo ref. no. iss036e006175)



Spectral CT X-ray imagine
(Courtesy of MARS Bioimaging Ltd.)

Example Timepix3 application: 3D particle tracking



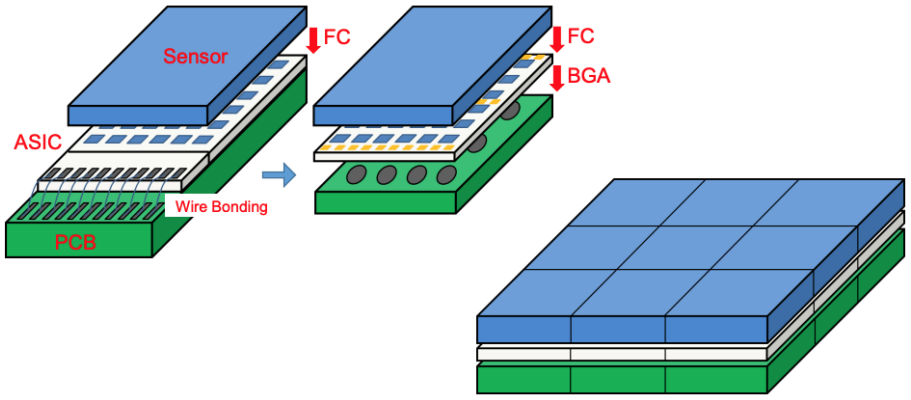
"3D track reconstruction capability of a silicon hybrid active pixel detector,"
Bergmann, B. et al. Eur. Phys. J. C (2017)

- Timepix3 with 500um p-on-n silicon sensor irradiated by 120 GeV/c pion beam at 60 degree.
- Depth (z-axis) information inferred from Time-of-Arrival information → **3D particle tracking**

Timepix4 specification

			Timepix3 (2013)	Timepix4 (2019)	
Technology			130nm – 8 metal	65nm – 10 metal	
Pixel Size			55 x 55 µm	55 x 55 µm	
Pixel arrangement			3-side buttable 256 x 256	4-side buttable 512 x 448	**3.5x**
Sensitive area			1.98 cm^2	6.94 cm^2	
Readout Modes	Data driven (Tracking)	Mode	TOT and TOA		
		Event Packet	48-bit	64-bit	**33%**
		Max rate	0.43x10^6 hits/mm^2/s	**3.58x10^6 hits/mm^2/s**	**8x**
		Max Pix rate	1.3 KHz/pixel	**10.8 KHz/pixel**	
	Frame based (Imaging)	Mode	PC (10-bit) and iTOT (14-bit)	CRW: PC (8 or 16-bit)	
		Frame	Zero-suppressed (with pixel addr)	Full Frame (without pixel addr)	
		Max count rate	~0.82 x 10^9 hits/mm^2/s	~5 x 10^9 hits/mm^2/s	**6x**
TOT energy resolution			< 2KeV	**< 1Kev**	**2x**
Time resolution			1.56ns	**195.3125ps**	**8x**
Readout bandwidth			≤5.12Gb (8x SLVS@640 Mbps)	≤163.84 Gbps (16x @10.24 Gbps)	**32x**
Target global minimum threshold			<500 e^-	<500 e^-	

4-side buttable



Timepix4 HPD's can be combined to form (infinitely) large detector areas

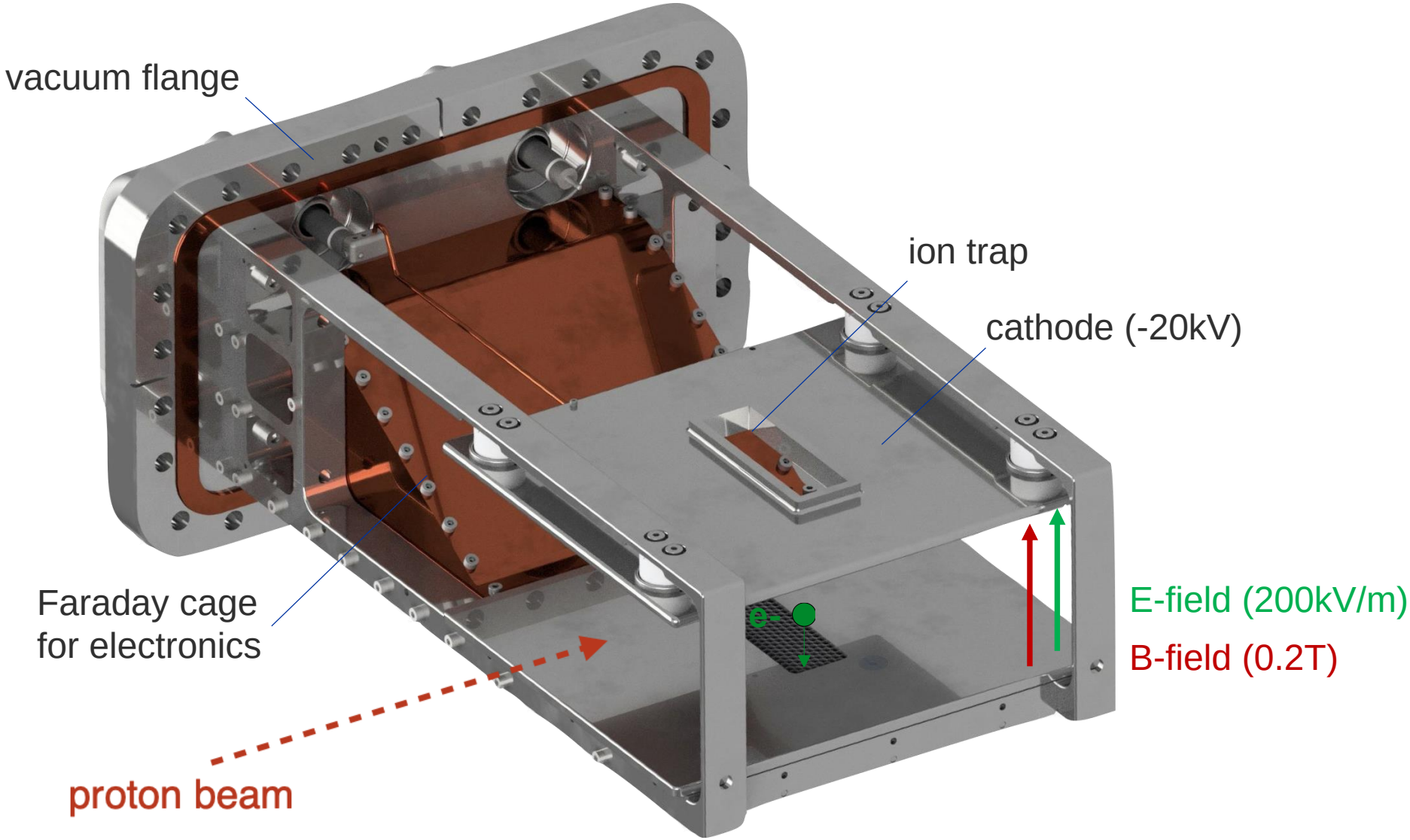
Slide from Xavier Llopart - EP Detector Seminar on 11th Feb. 2022 (https://indico.cern.ch/event/1121147/)

Examples of 1) electron & 2) high energy charged particle detection with Timepix3/4 based detectors for Beam Instrumentation

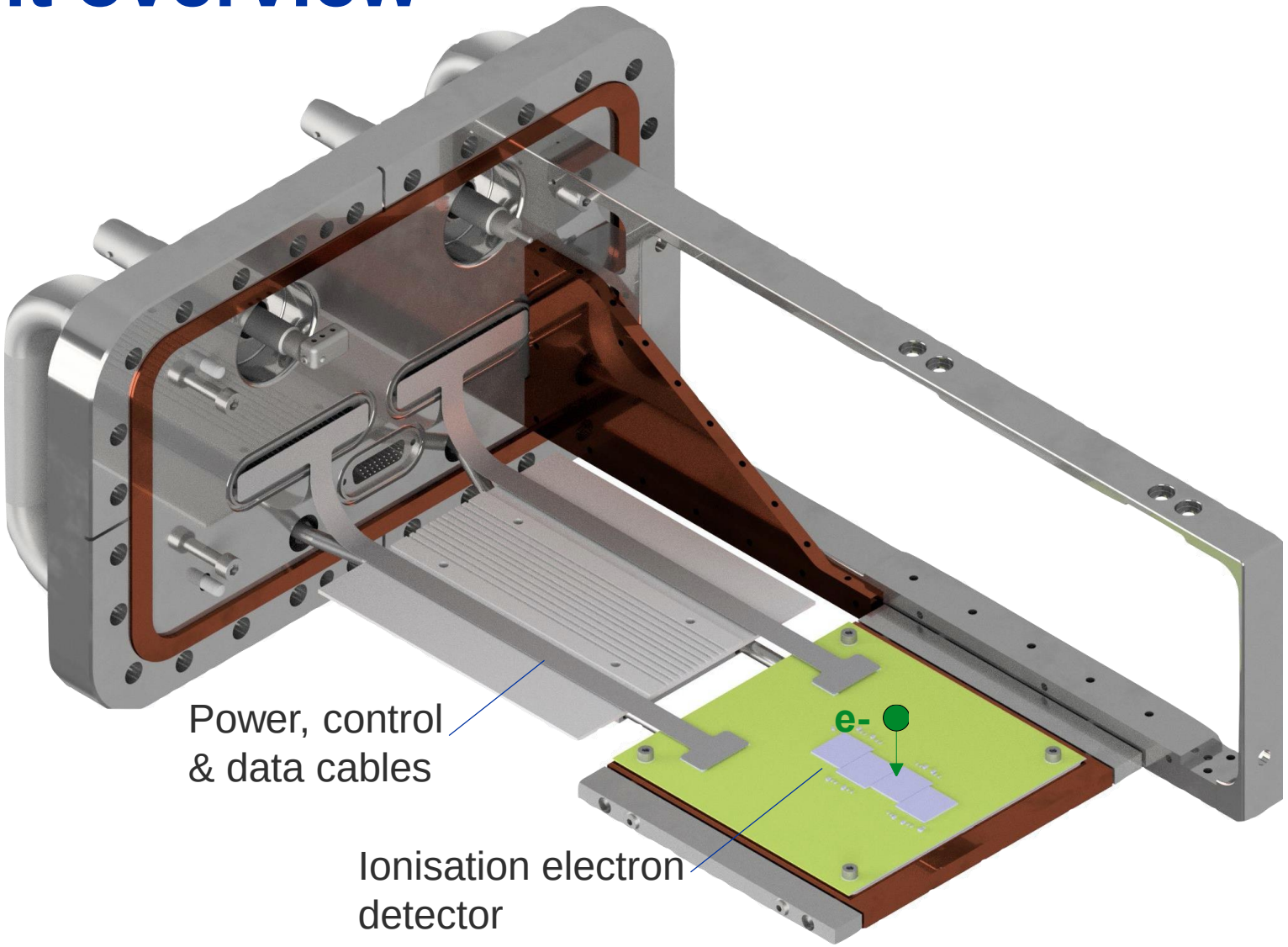
1. Example of electron detection with Timepix3 HPD

Instrument overview

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



Instrument overview



Ionisation electron detector based on Timepix3 HPD

Ionisation electron detector requirements

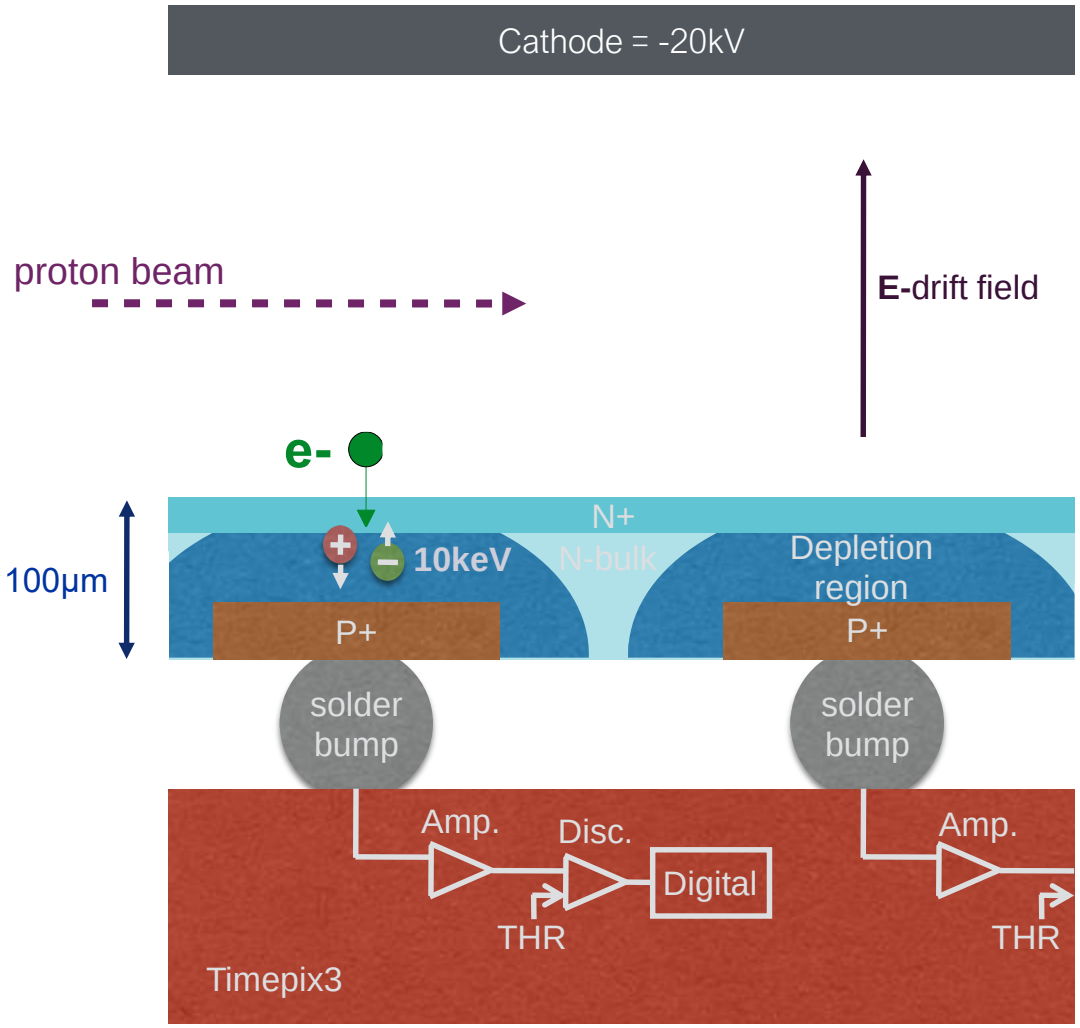
- Detect 10keV electrons (penetration depth in silicon = 1.5μm)
- Detect each electron with time resolution < 25ns & spatial resolution < 100μm
- Meet outgassing requirements for installation in the UHV of the PS beam pipe
- Operate during the acceleration cycle

Sensor

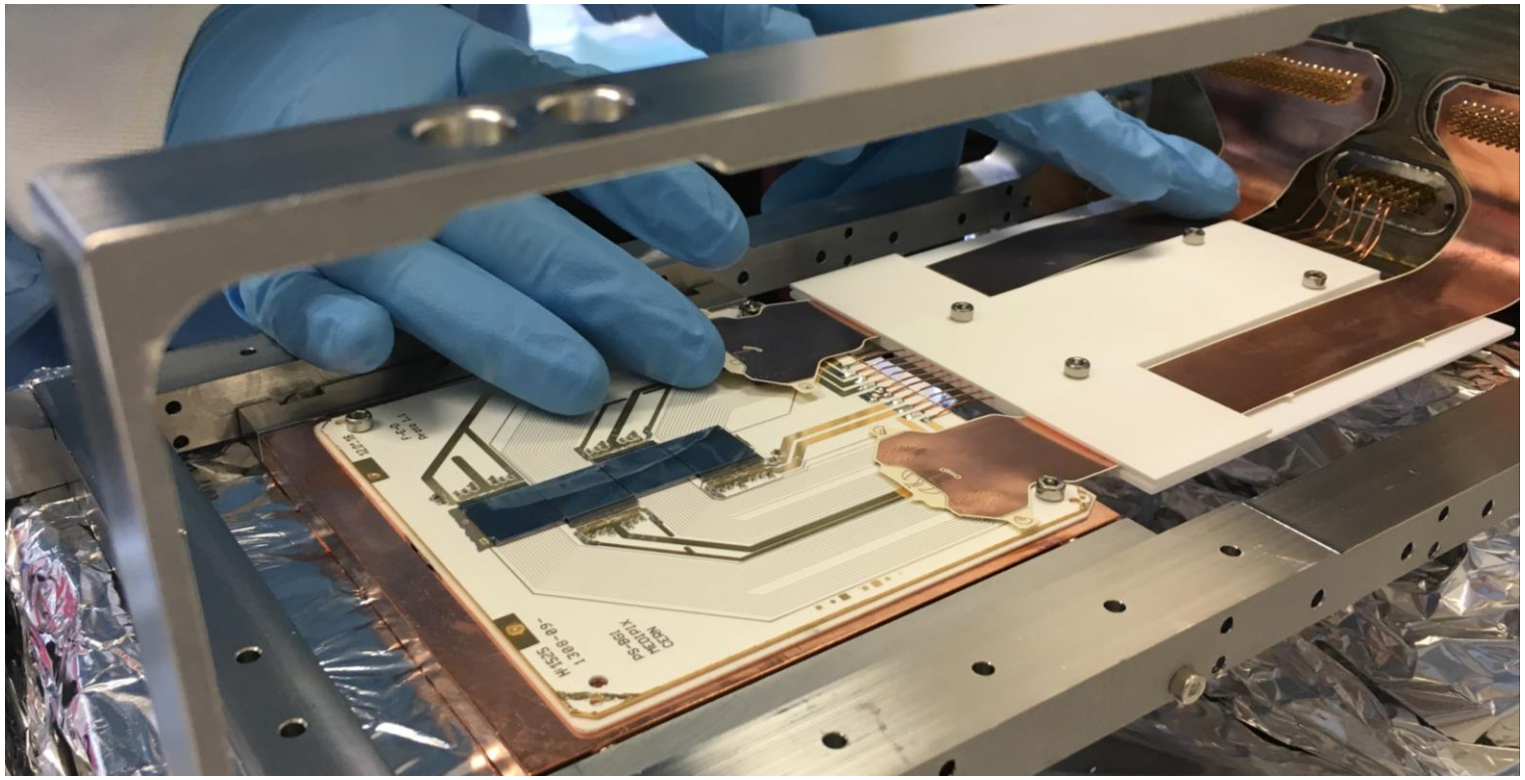
- **Non-metalized**, p-in-n, 100m deep
- 256 x 256 array of PN-diodes
- Pixel size = 55um x 55um
- Sensor area = 14mm x 14mm

Timepix3 readout chip

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



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)

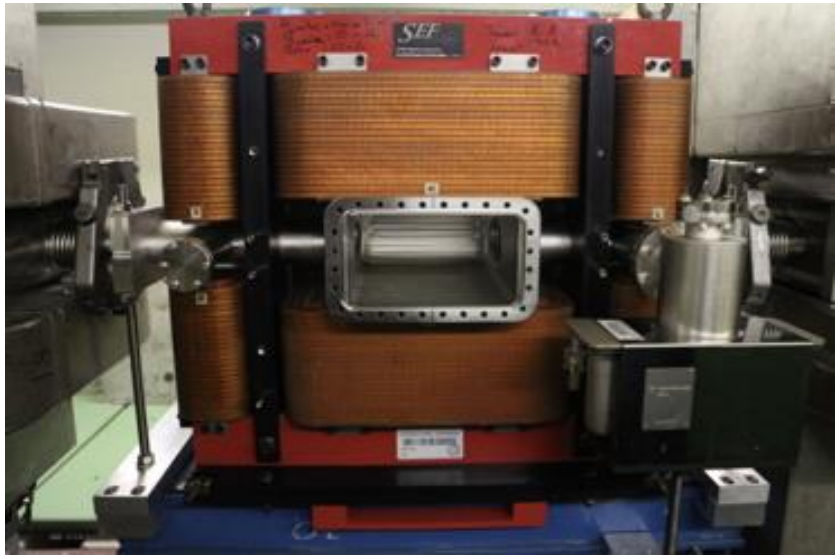
Flexible cables

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

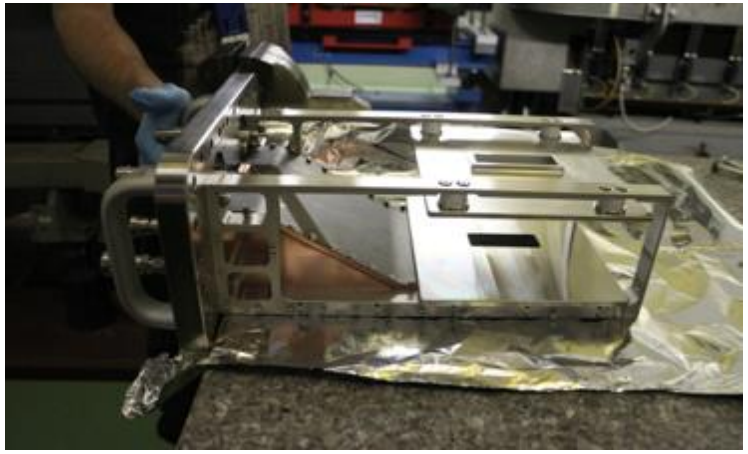
Qualified for installation in the PS accelerator beam pipe

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:

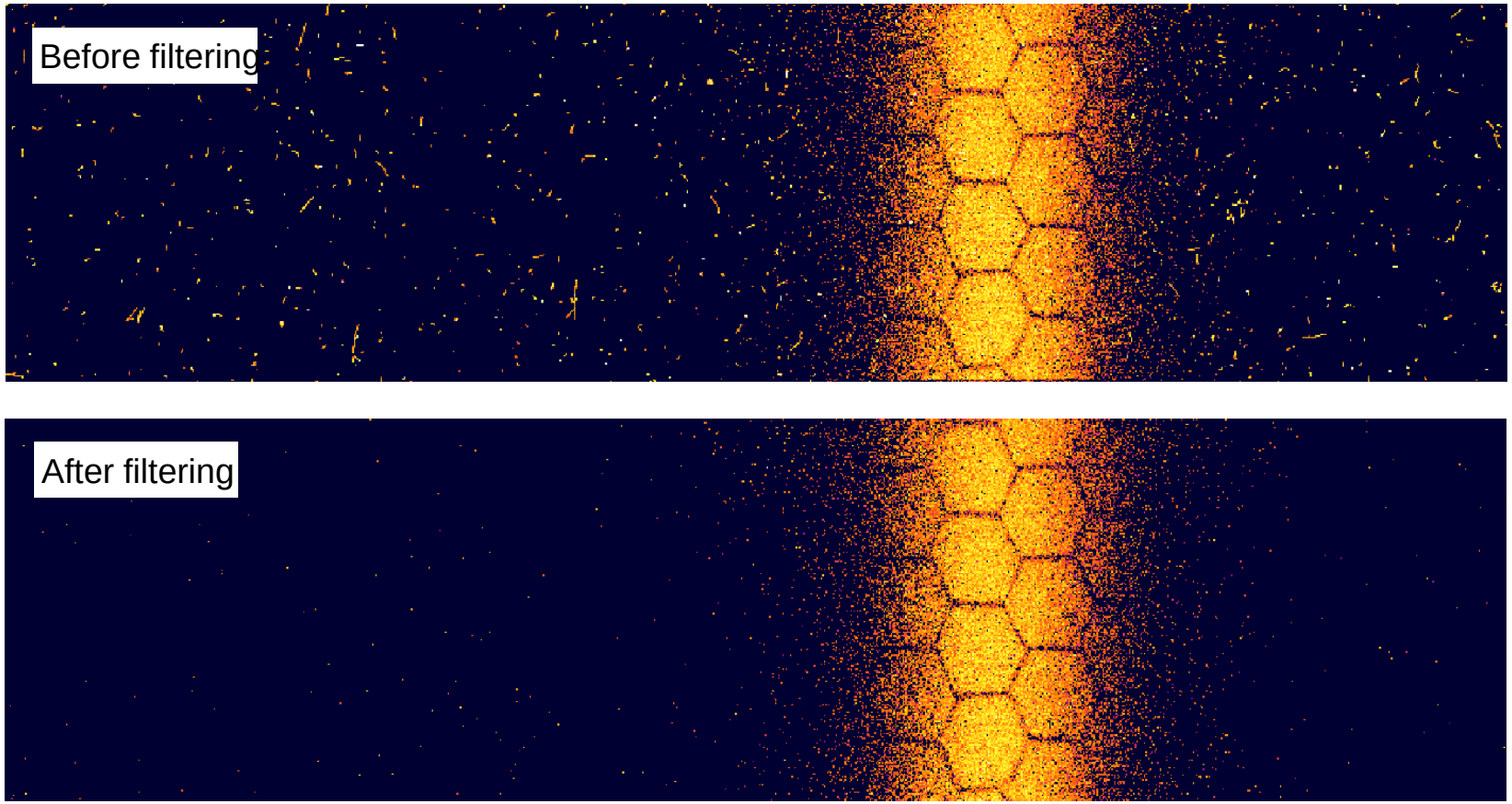
- 1 x 10^{-8} mbar after 24 hours
- **2 x 10^{-10} mbar steady state**

Selecting ionisation electrons

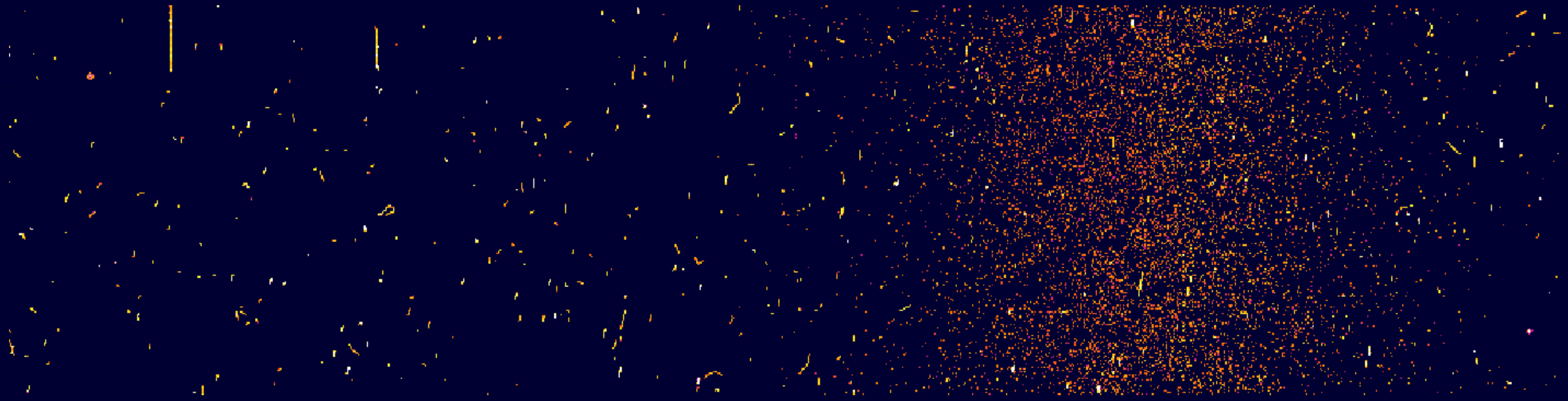
Signal – ionisation electrons:
- Mostly single pixel events
- Energy < 10keV

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



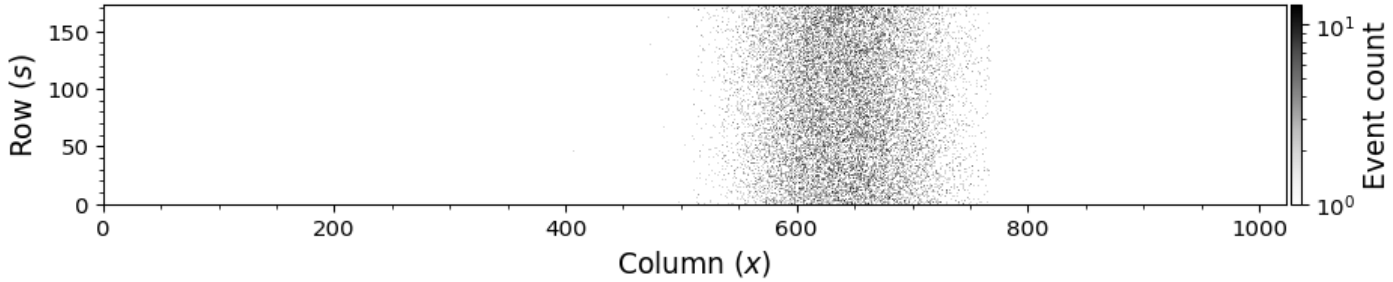
Preparation of LHC beam in the PS

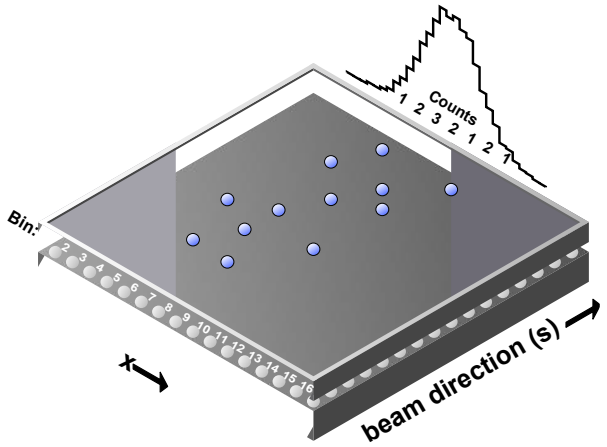


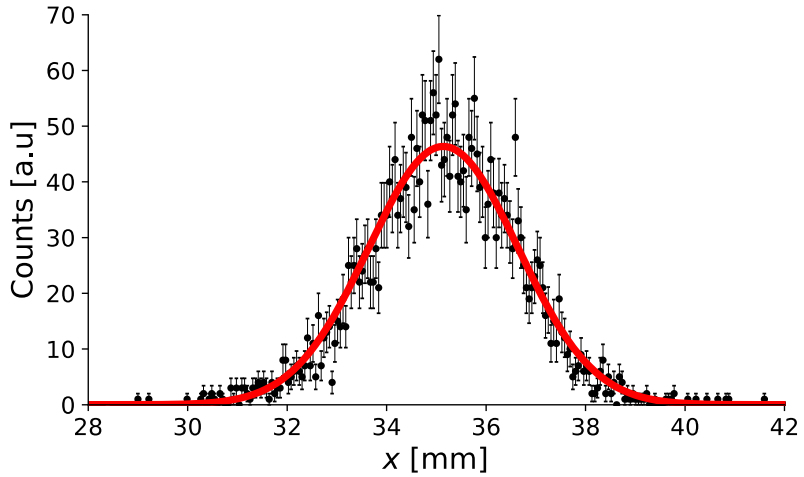
- Timepix3 data-driven readout enables "live" display of the beam throughout the cycle
- 1.5 seconds in real time: slowed down here for viewing purpose
- Each frame is 10 ms of data
- Not filtered: *background particles are interesting to look at!*
- LHC type beam, single bunch (I = 20×10^{10} p)

Beam profile measurement

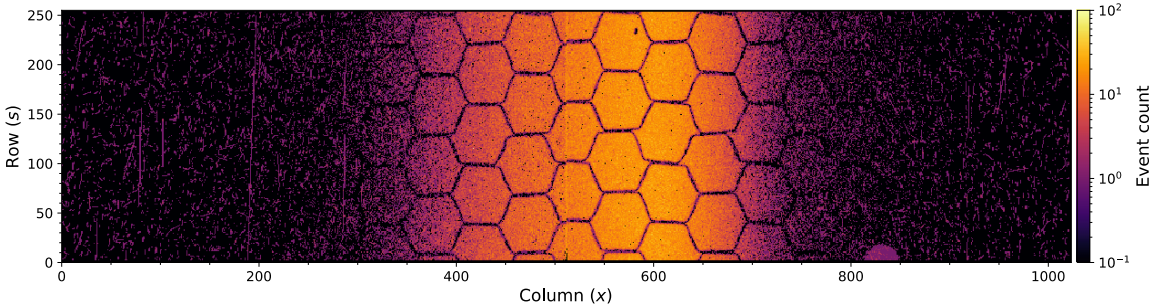
Compute beam profile by summing counts in each column

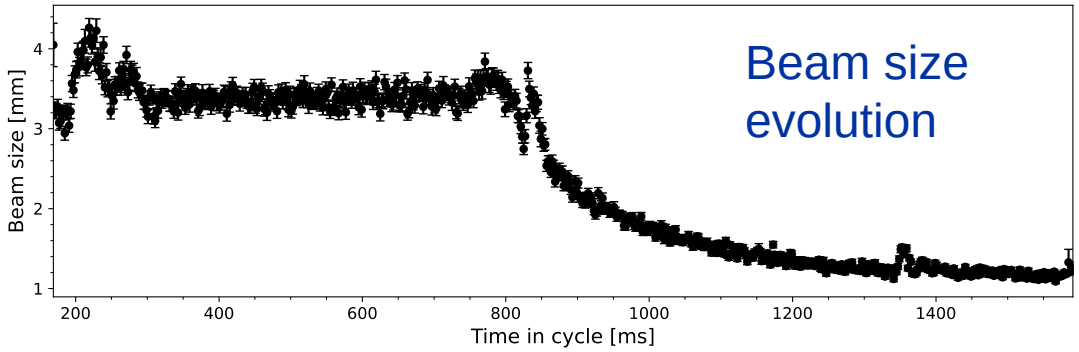


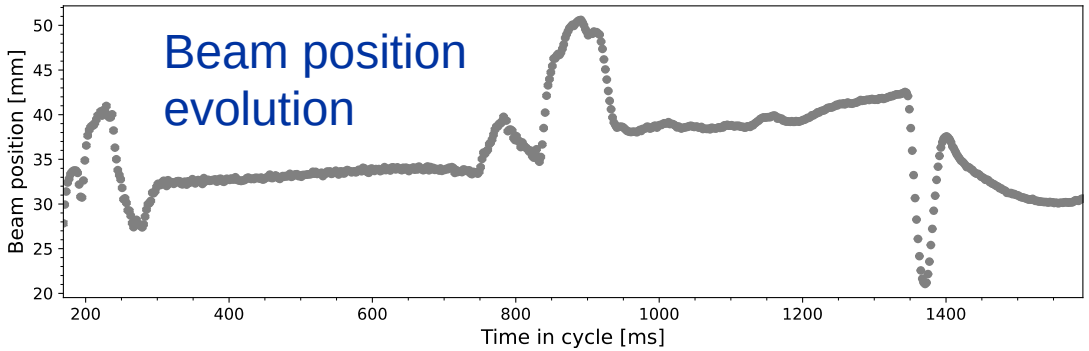




Single bunch measurements







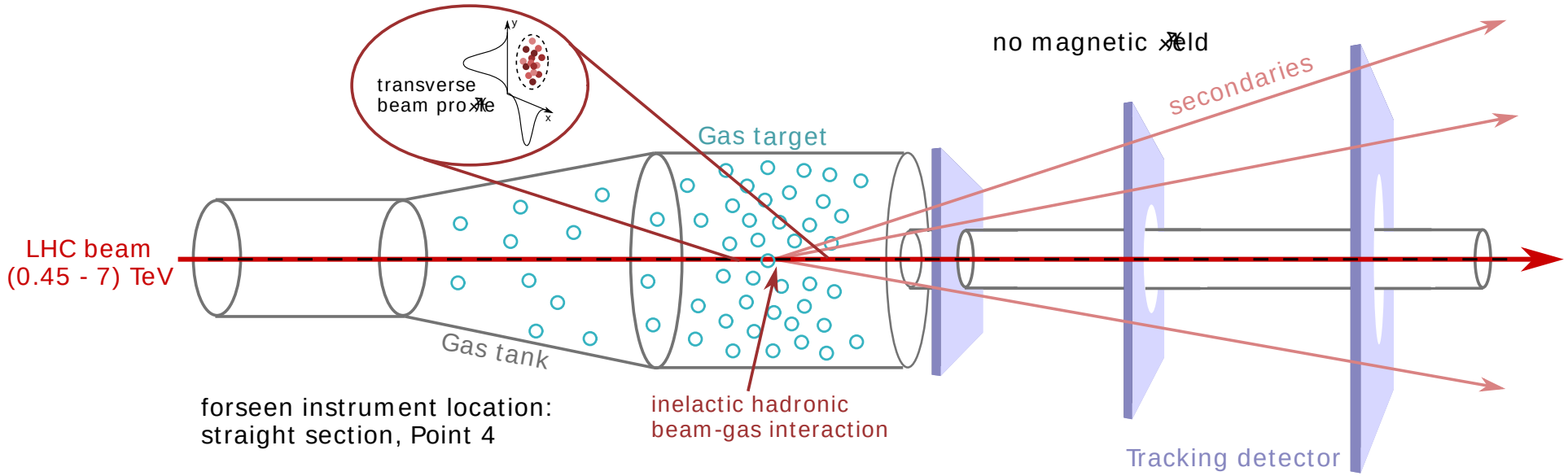
Single bunch in the PS at the start of beam commissioning

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

2. Examples of high energy charged particle detection

Ref. doi:10.18429/JACoW-IPAC2021-TUPAB278

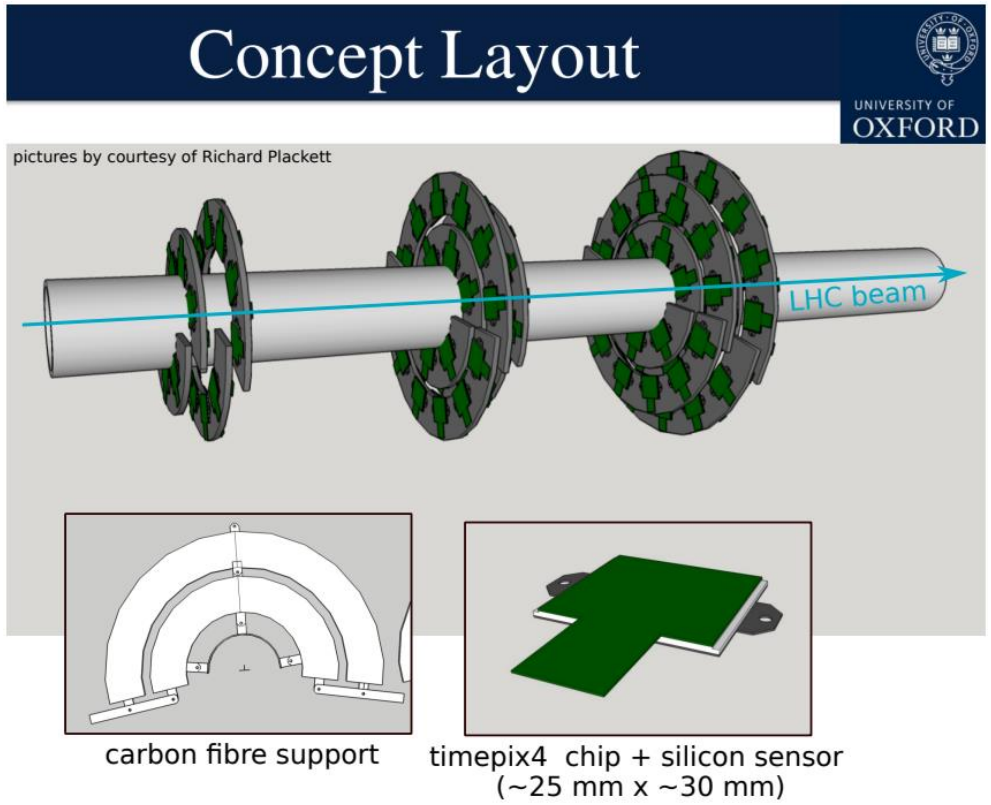
Beam Gas Vertex (BGV) profile monitor for HL-LHC



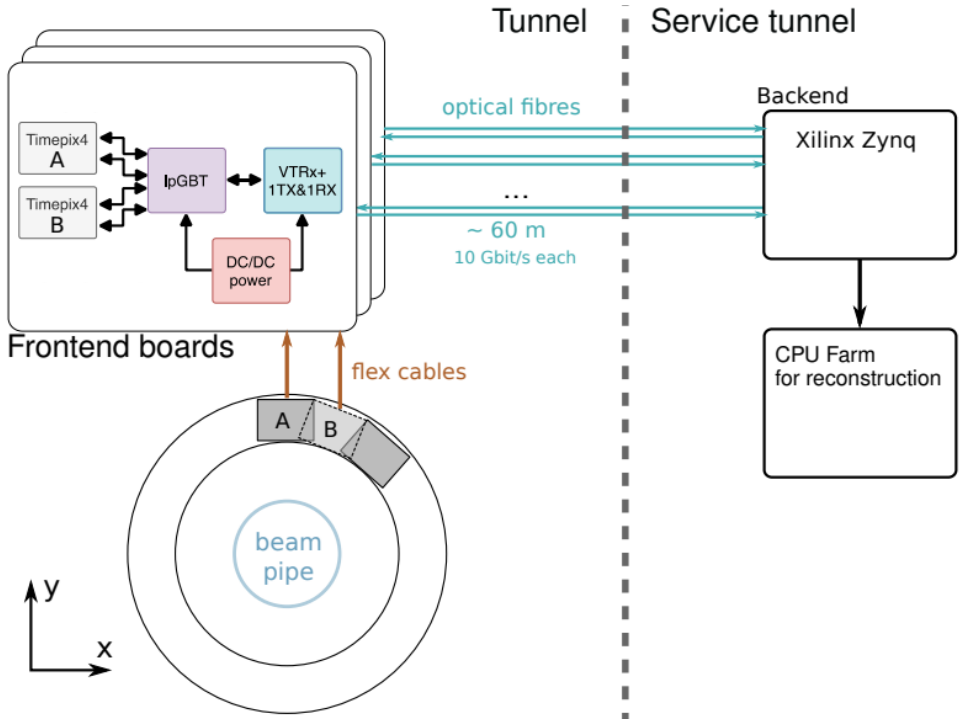
BGV consists of: 1) **Gas target** & 2) **Forward tracking detector**
Beam profile inferred from density of the reconstructed primary vertices of the inelastic beam gas interactions.

BGV - Tracking detector based on Timepix4 Hybrid Pixel Detectors

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



Tracking detector – readout + processing
(CERN)

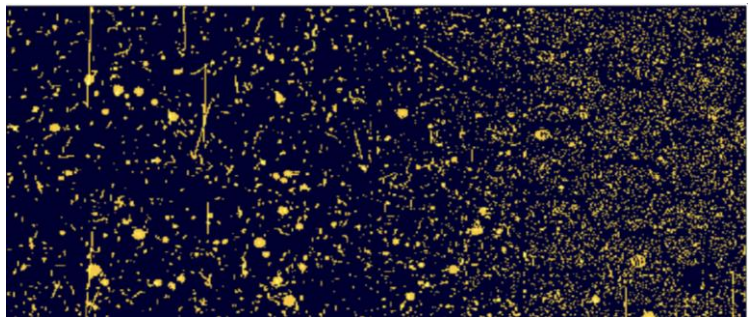


Architecture based on BIPXL readout developed for PS BGI

Fast Beam Loss Monitor (BLM) based on Timepix3

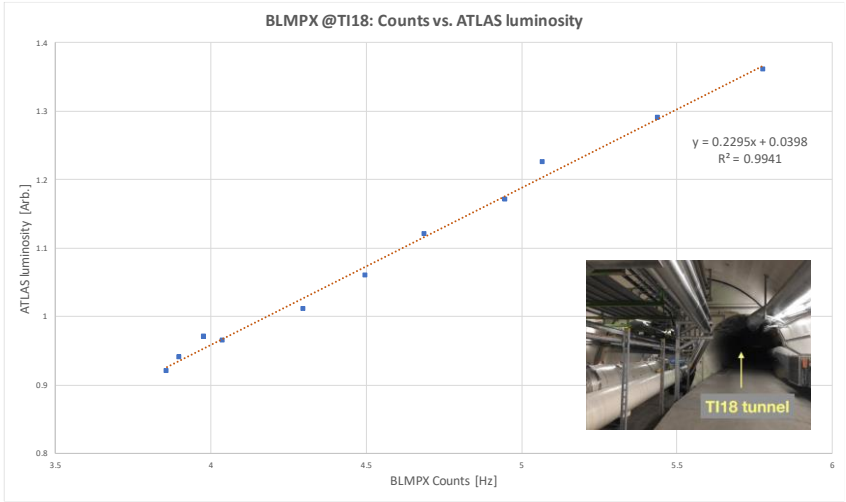
Operational need: Fast beam loss monitor for rapid deployment in the LHC

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

Summary

Timepix (& Medipix) family of Hybrid Pixel Detectors (HPD's) are an incredibly versatile tool for charged & neutral particle detection across a wide range of energies.

Diverse and well established community of users.

Very happy to discuss possible applications in the context of FCC EPOL…