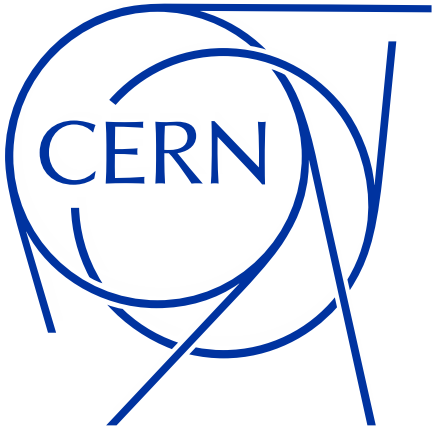


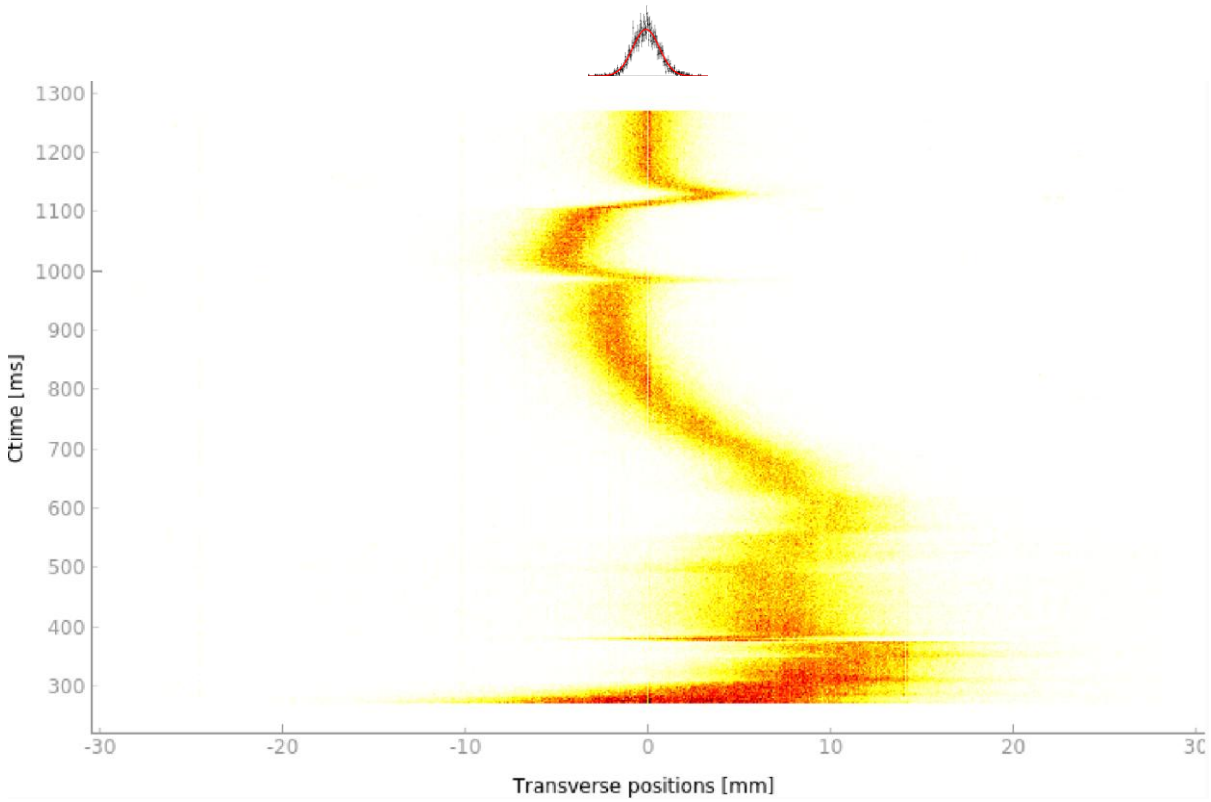
A next-generation hybrid pixel detector readout system for beam instrumentation at CERN

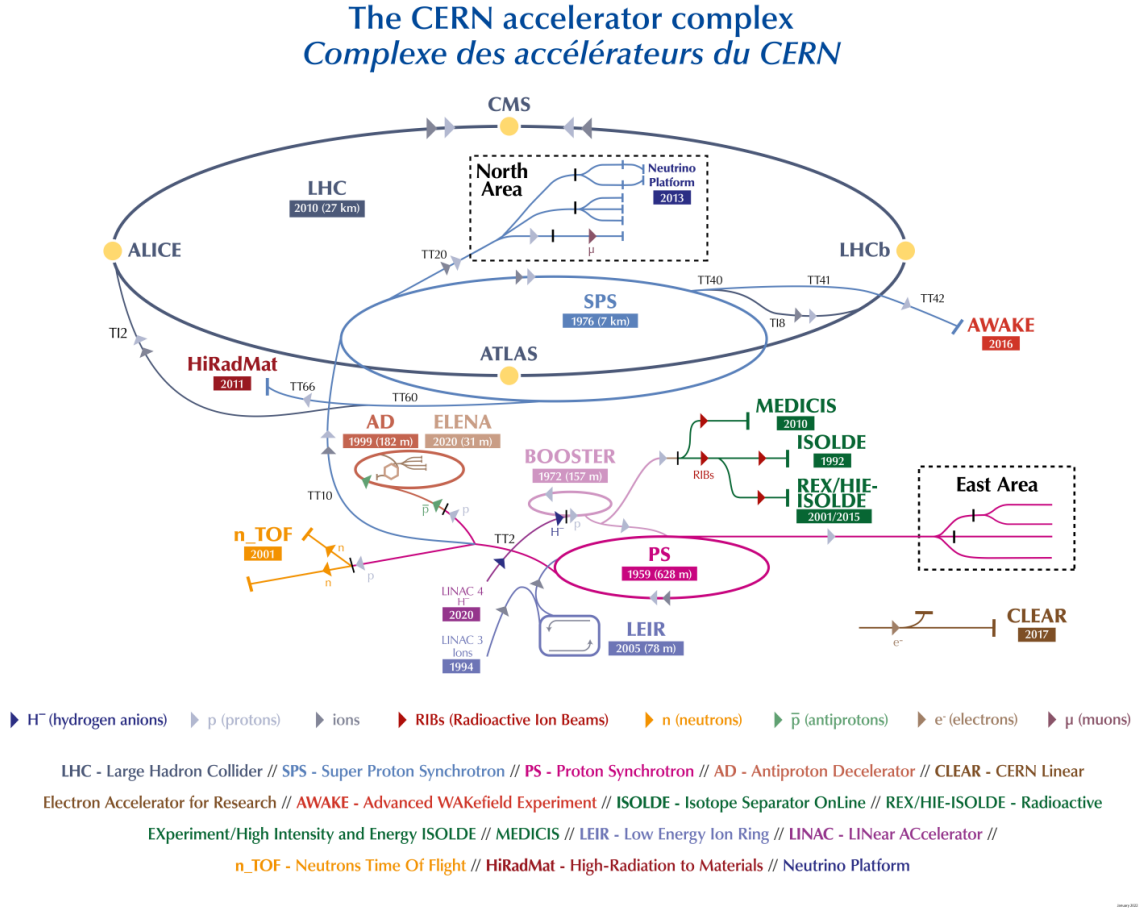
Jüri Jõul, G. Cabrera, L. M. Golino, S. Jensen, M. McLean, H. Sandberg, J. Storey

02/09/2026, IBIC2026 - 15th International Beam Instrumentation Conference, Whistler, Canada

Beam Gas Ionization (BGI) profile monitors

- **Non-destructive continuous transverse beam profile measurement**





Source: The CERN accelerator complex, layout in 2022

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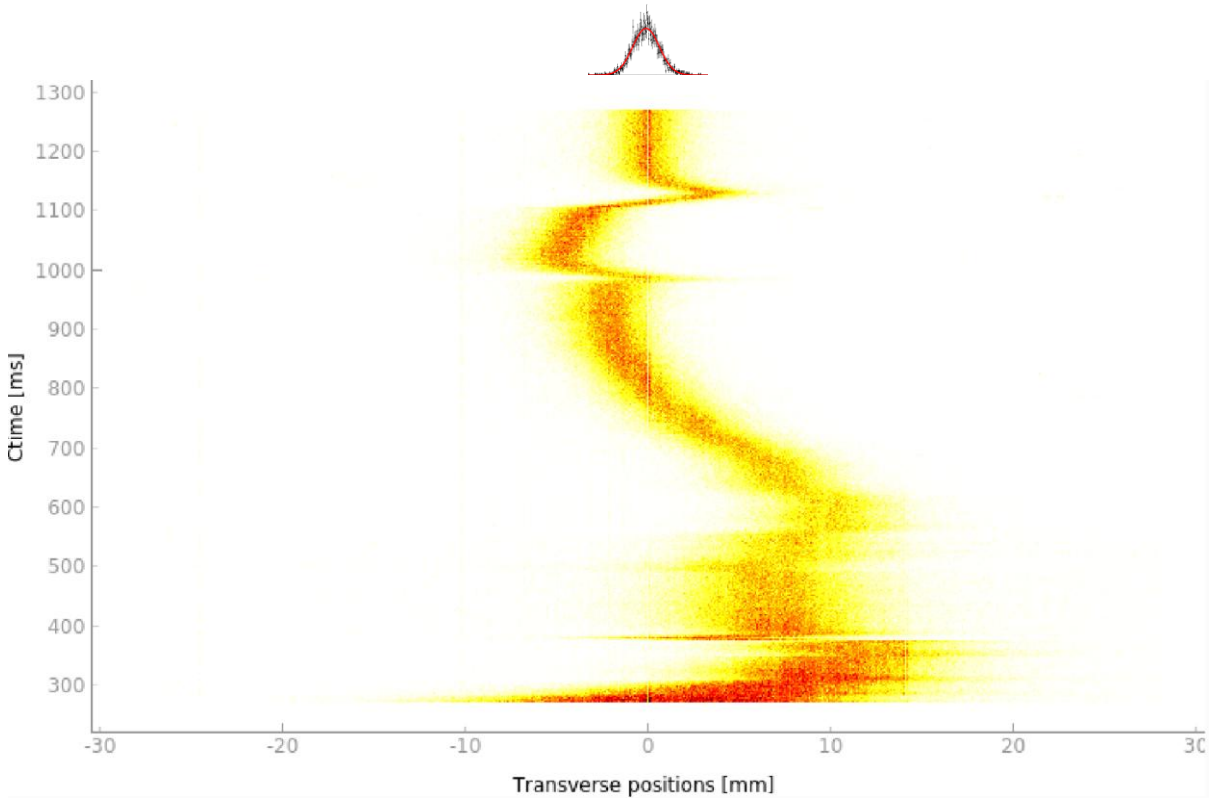
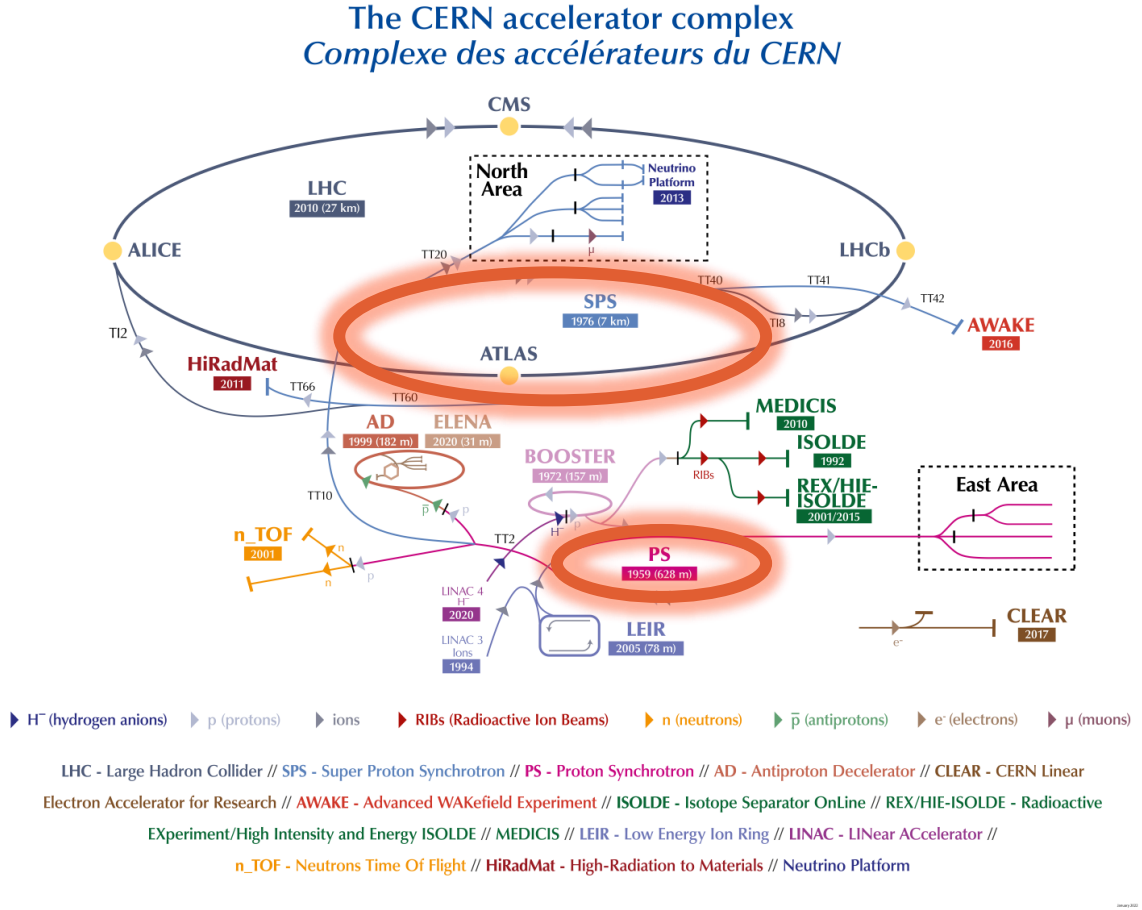
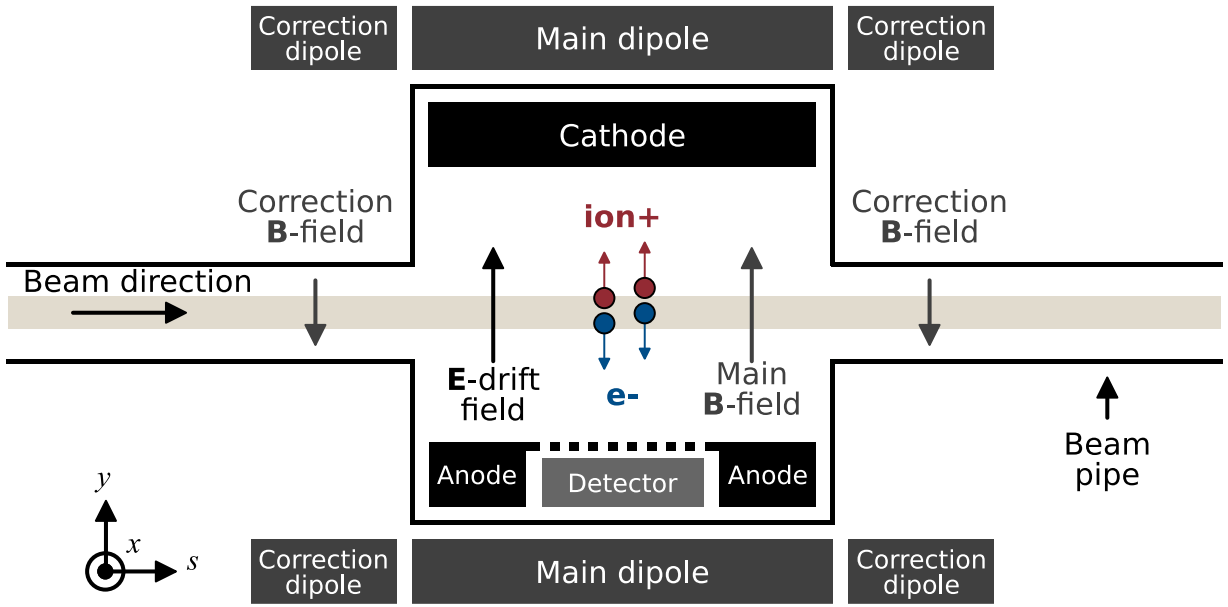




Source: The CERN accelerator complex, layout in 2022

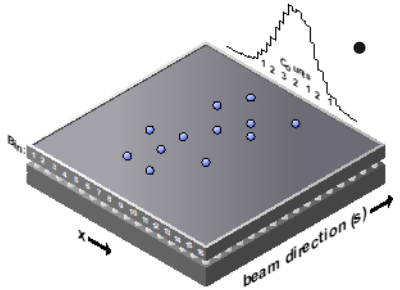
Working principle of the BGI

1. **Beam ionises rest gas**
2. **Electrons transported onto detectors**
   - Hybrid pixel detector: silicon sensor + Timepix3
3. **Hits counted per column → beam profile**



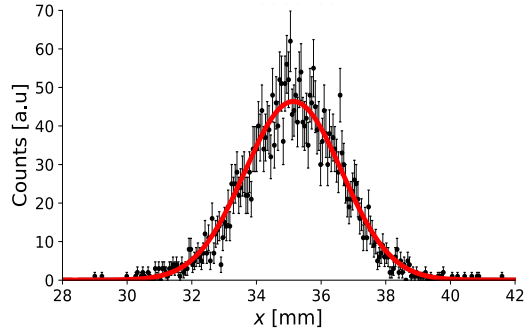
Pixel event (48 bits) includes:

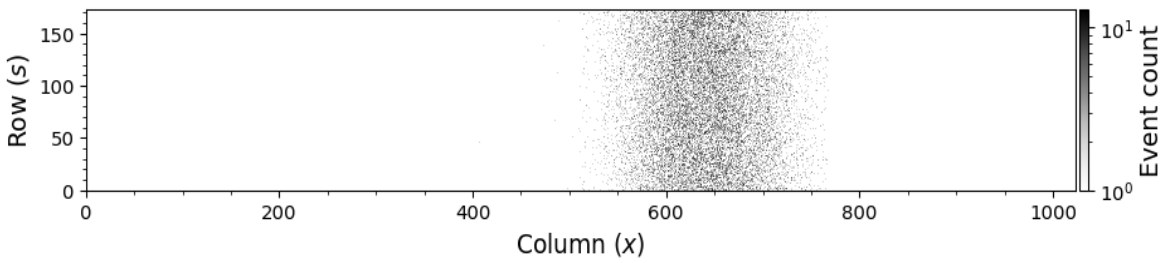
- Location in pixel matrix (256x256)
- Timestamp (1.56 ns)

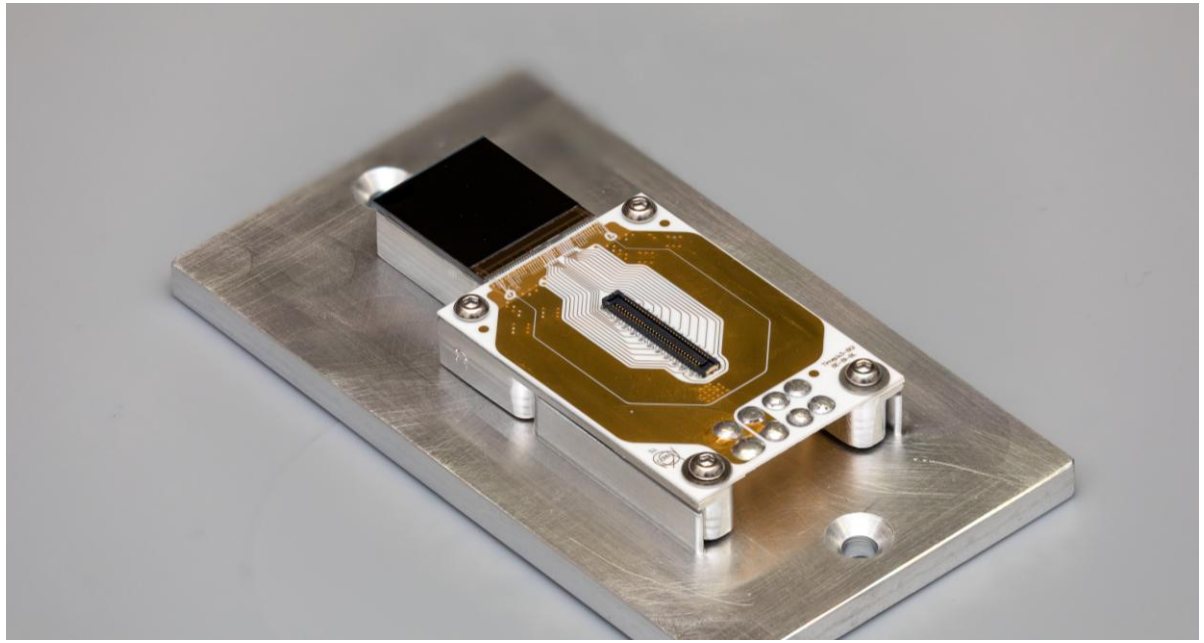


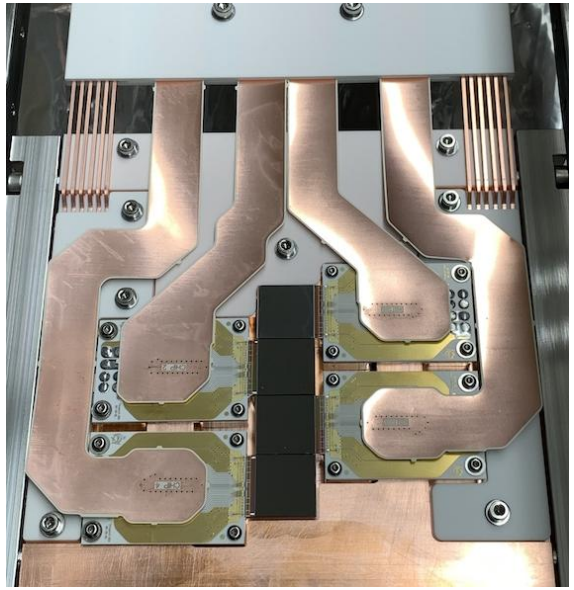
4 detectors: up to 10.24 Gb/s

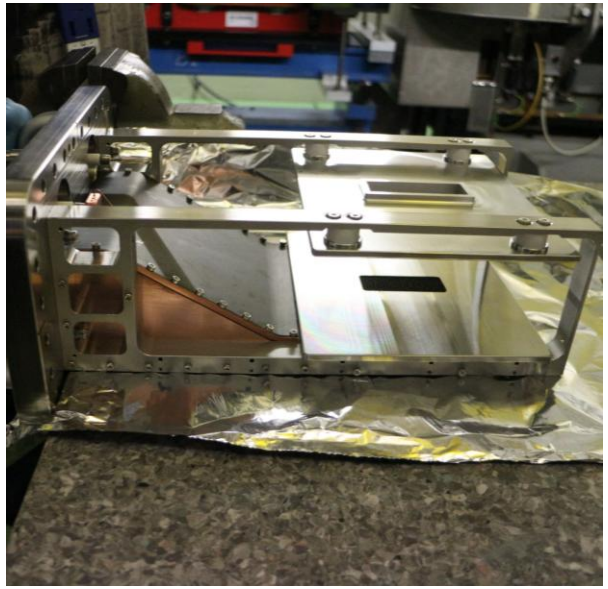
1 profile ~= 1000 events











Motivation and requirements

Historical limitation: single, intensity-limited beam profile measurement in the cycle

Goal: continuous, non-destructive, intensity-independent beam profile measurement throughout the cycle

Online processing:

- **Performance:** up to 1000 beam profiles + 1000 bunch profiles
- **Latency:** all profiles published by the end of the acceleration cycle
  - PS: 1.2 s to 3.6 s
  - SPS: 3.6 s to 57.6 s

Offline processing:

- **Raw data availability**: raw measurement data must be available
  - Needed for offline analysis, post-processing, etc.

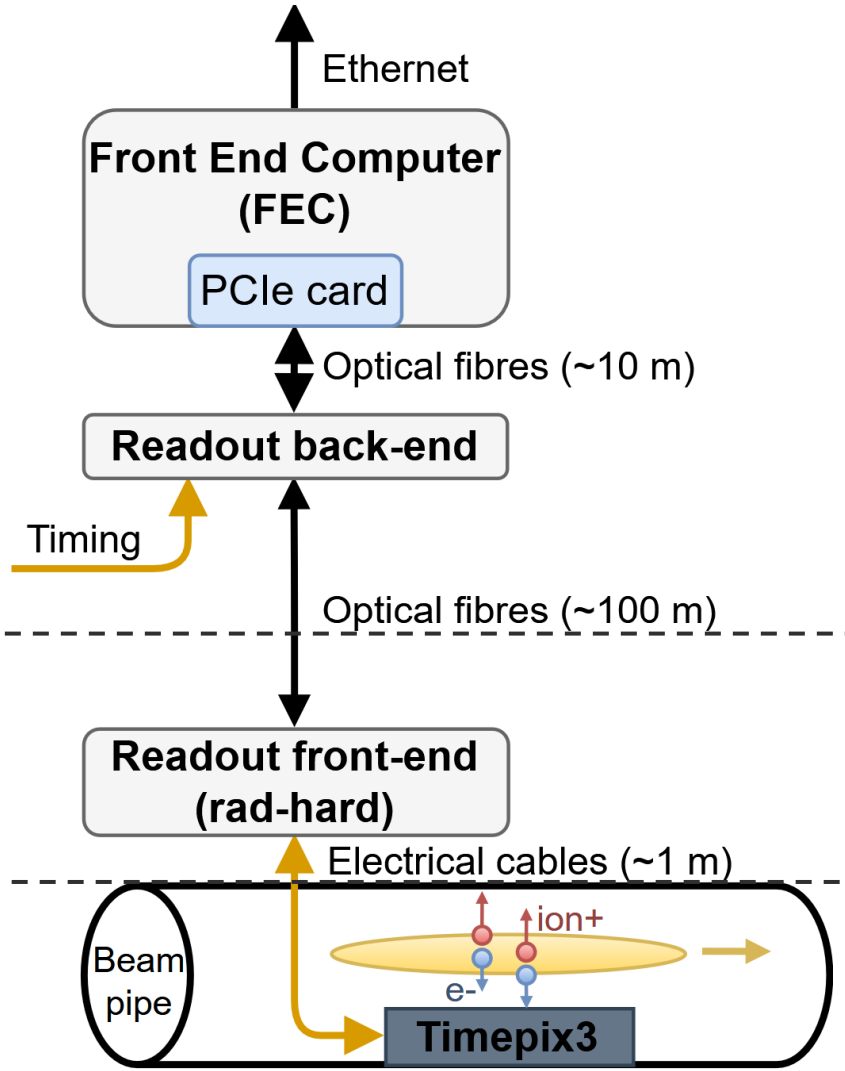
Reliability: continuous operation without expert supervision

Extensibility and maintainability: suitable for future instruments and updates

System architecture

Overview, design choices, software architecture

Readout system overview



FEC

- Standard platform
- PCIe card for FPGA communication

Back-end with FPGA

- Interfaces with detectors
- Timestamps accelerator timing signals

Radiation

Front-end

- Converts between electrical and optical signals

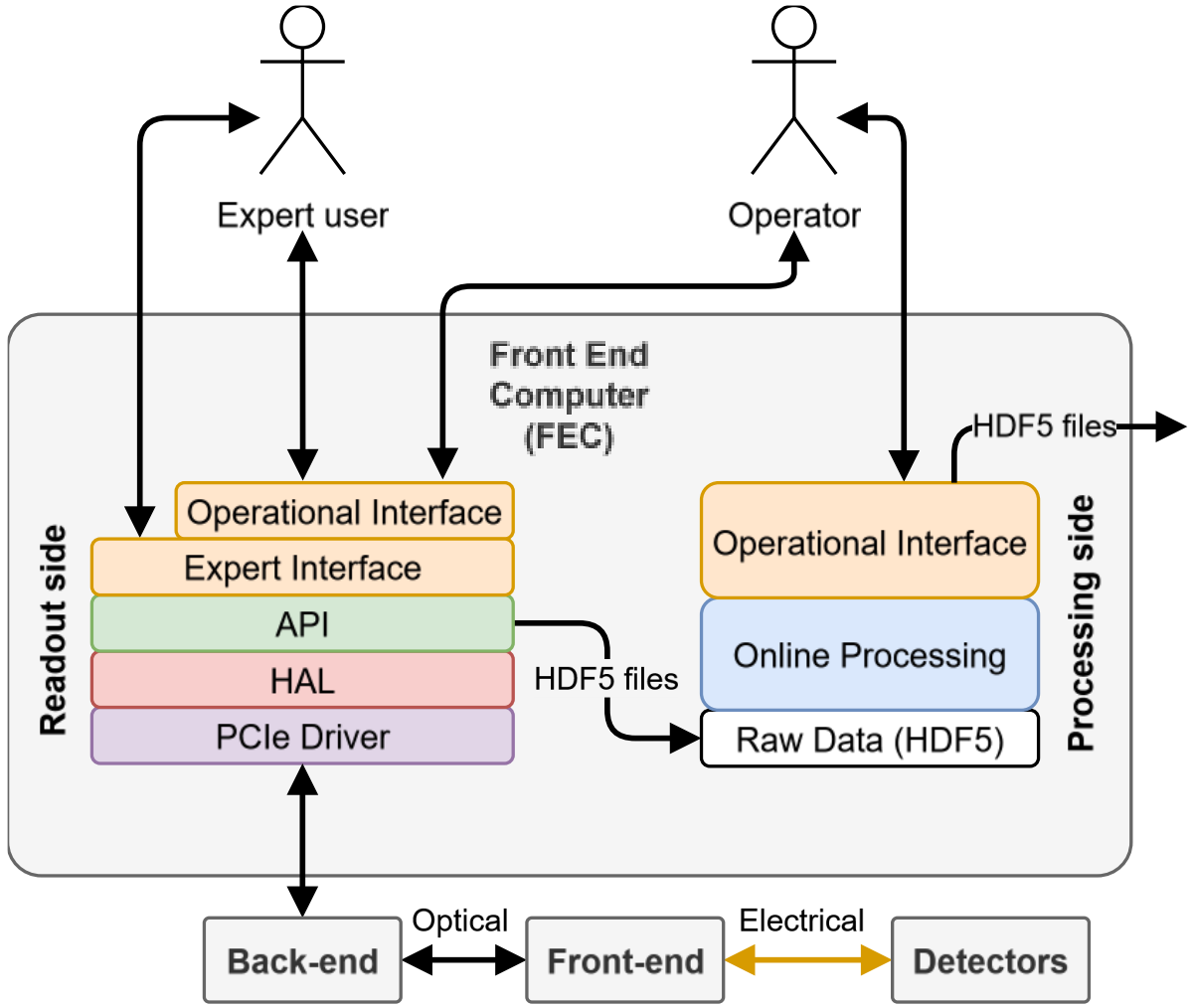
Vacuum

Design choices

- **FEC with a PCI Express (PCIe) card**
  - Sufficient computing power
  - Scalability in form of computational offloading
- **Existing readout front-end**
  - Proven radiation-hardened design (TID: 50 Mrad)
- **Updated back-end using SLAC ready-to-use open-source gateware and software**
  - Flexibility in choice of hardware
  - DMA-based, high-throughput (current setup: 40 Gb/s)
- **Raw data availability from ground up**
- **Automated detector management**

Software architecture

- **Split into readout and processing stacks**
  - Support for BGI and spin-off projects
  - Support for post-processing
- **Hierarchical Data Format 5 files**
  - Intermediate and long-term storage
  - Standard at CERN
  - Self-contained
  - In-memory filesystem + SWMR
- **Abstractions and extensibility**
  - Future technologies, e.g. Timepix4 with lpGBT
- **CERN-developed and open-source code**
  - Custom C++ libraries + SLAC framework



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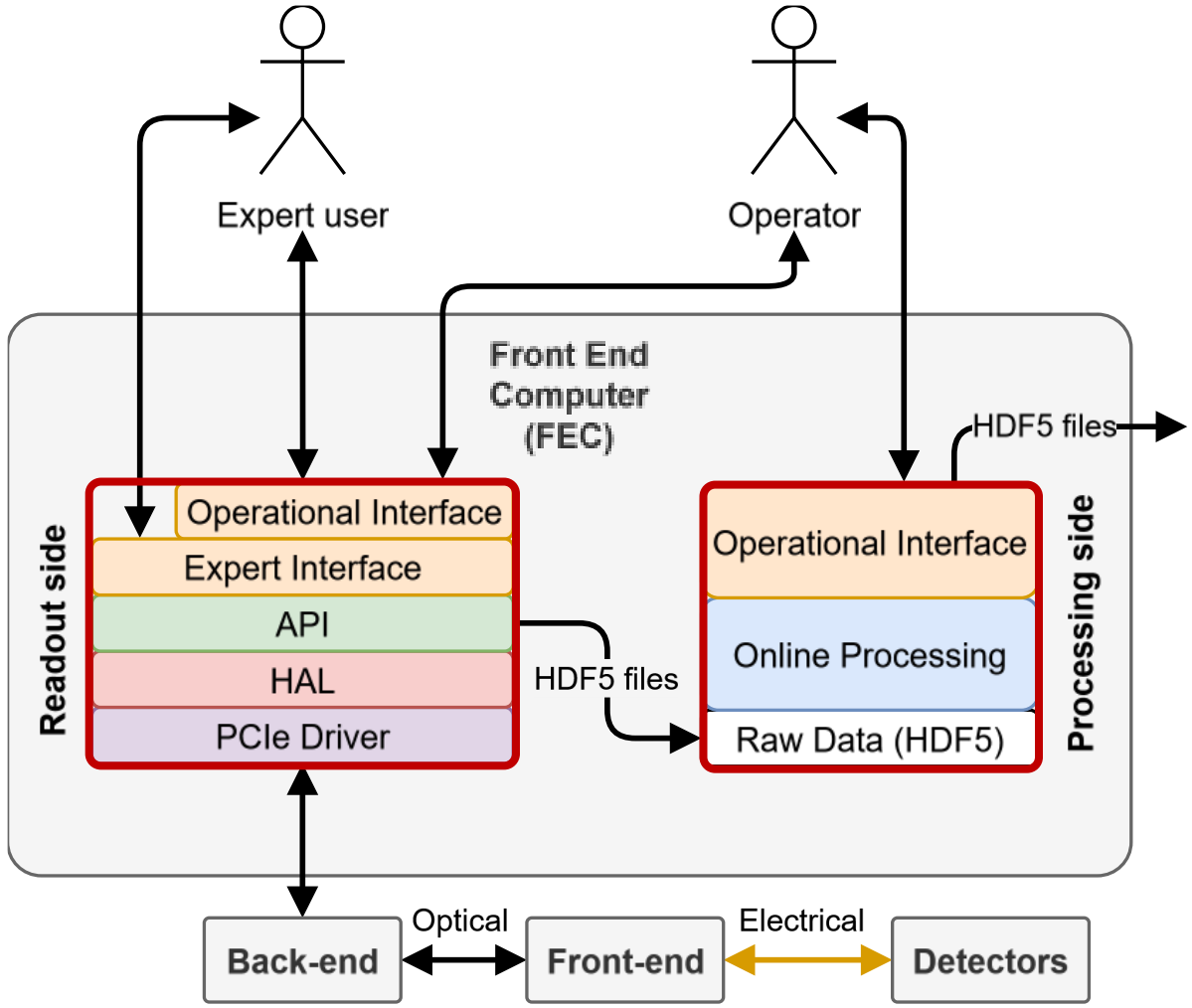

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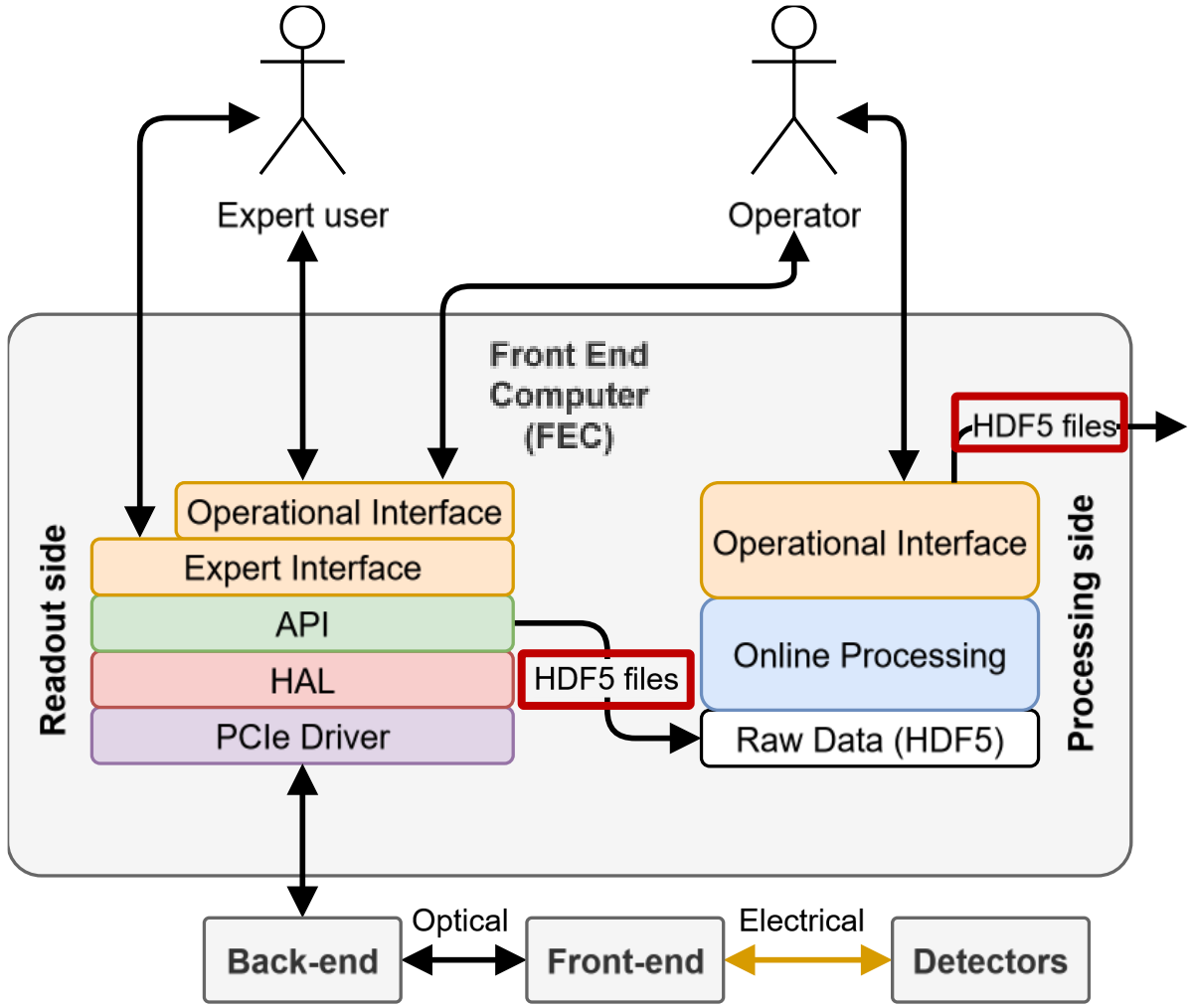

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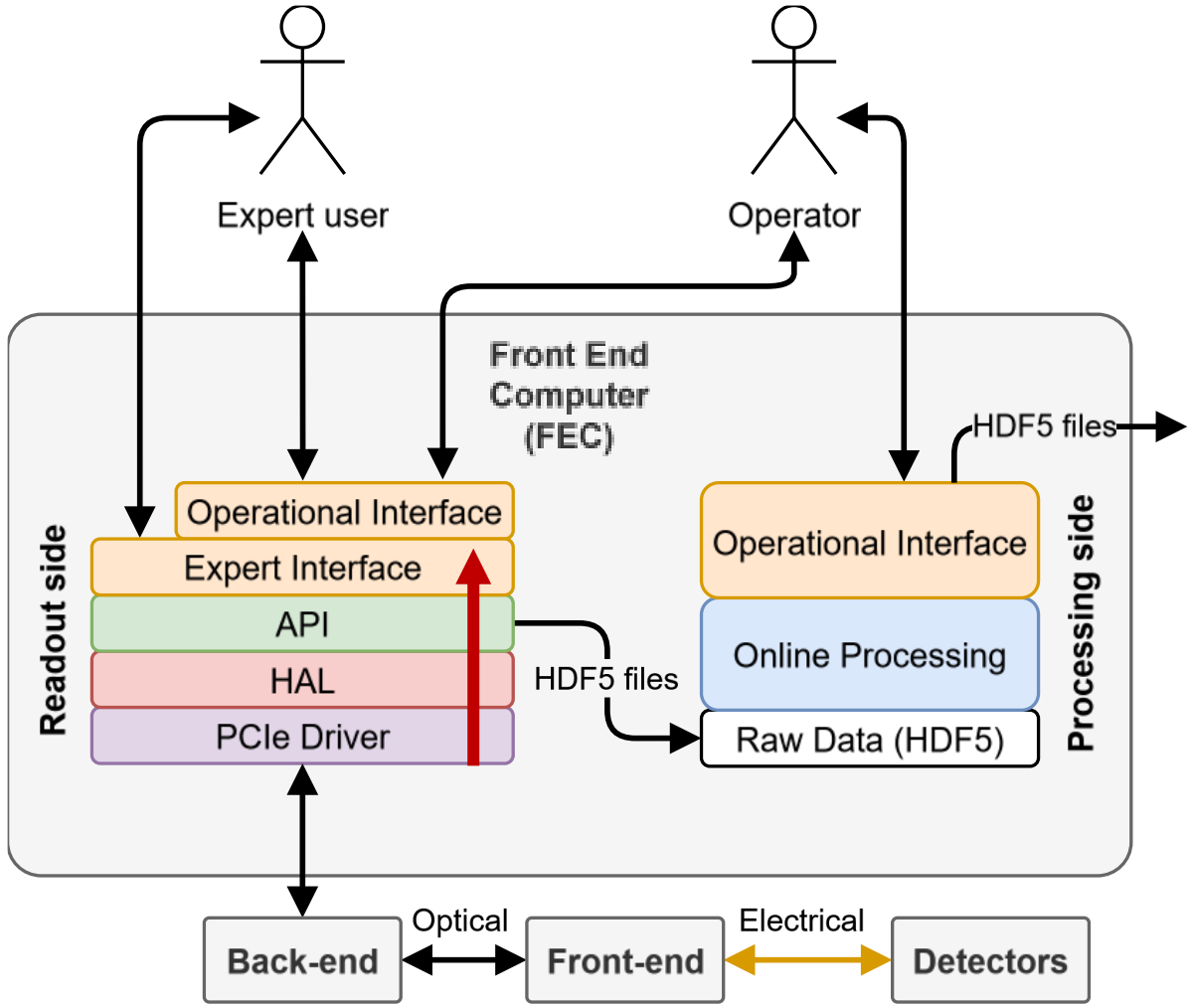

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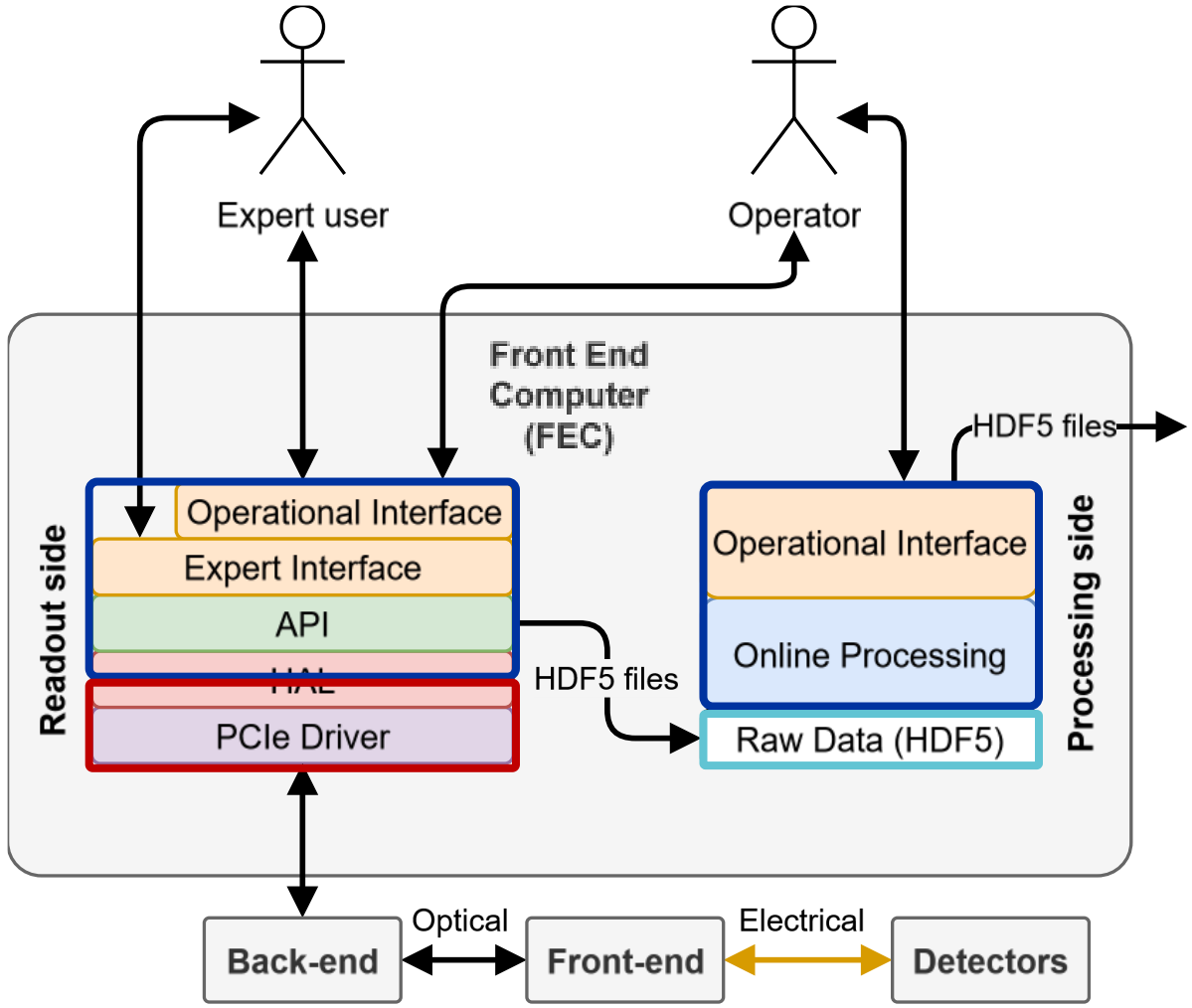
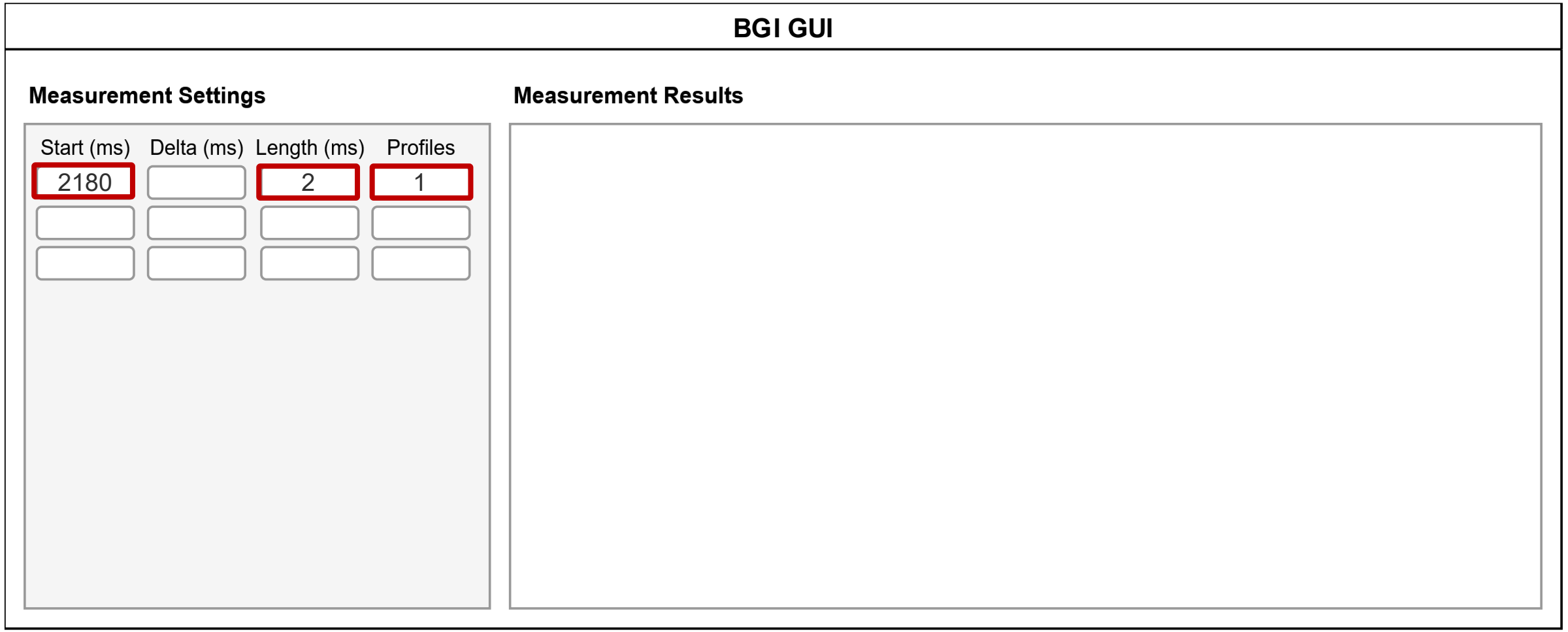


How to use the BGI?

Simple measurement



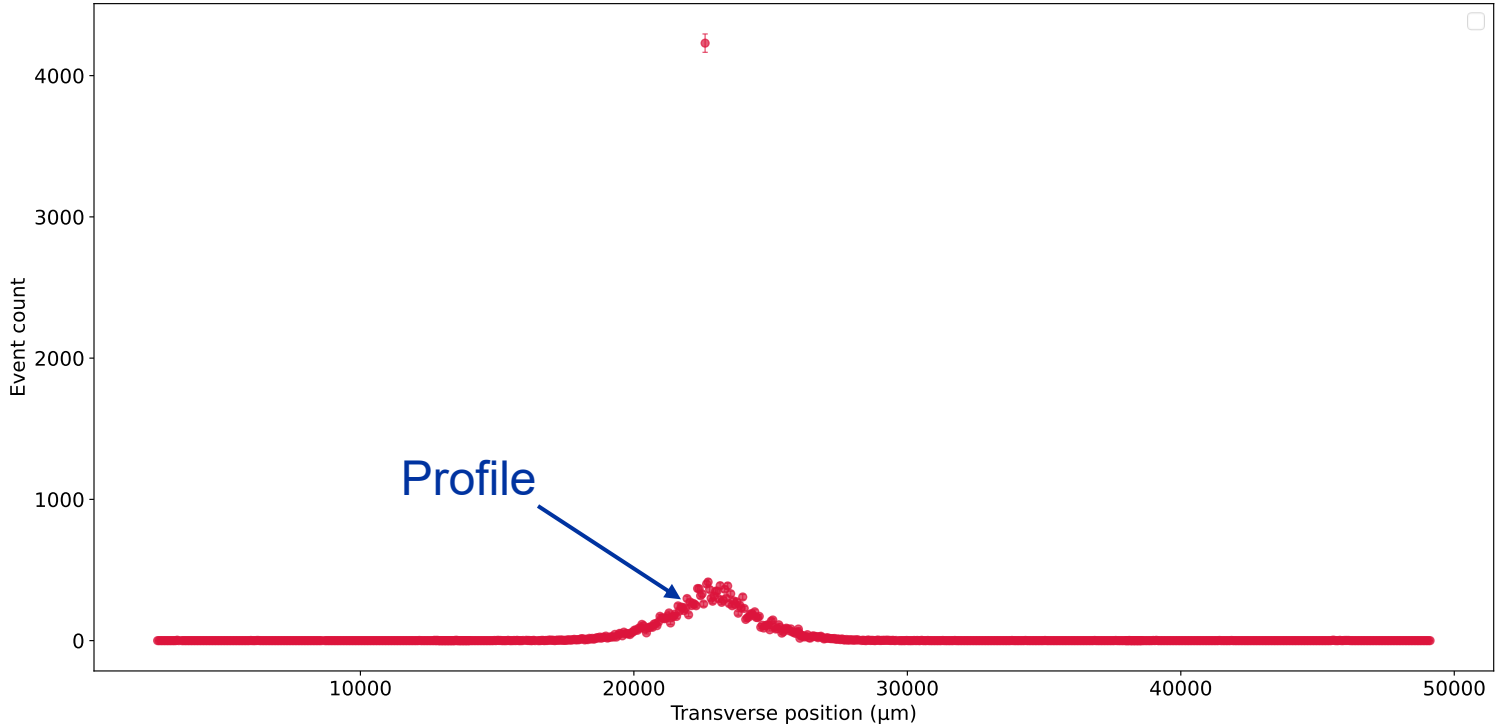
Simple measurement

BGI GUI

Measurement Settings

Start (ms)	Delta (ms)	Length (ms)	Profiles
2180		2	1

Measurement Results



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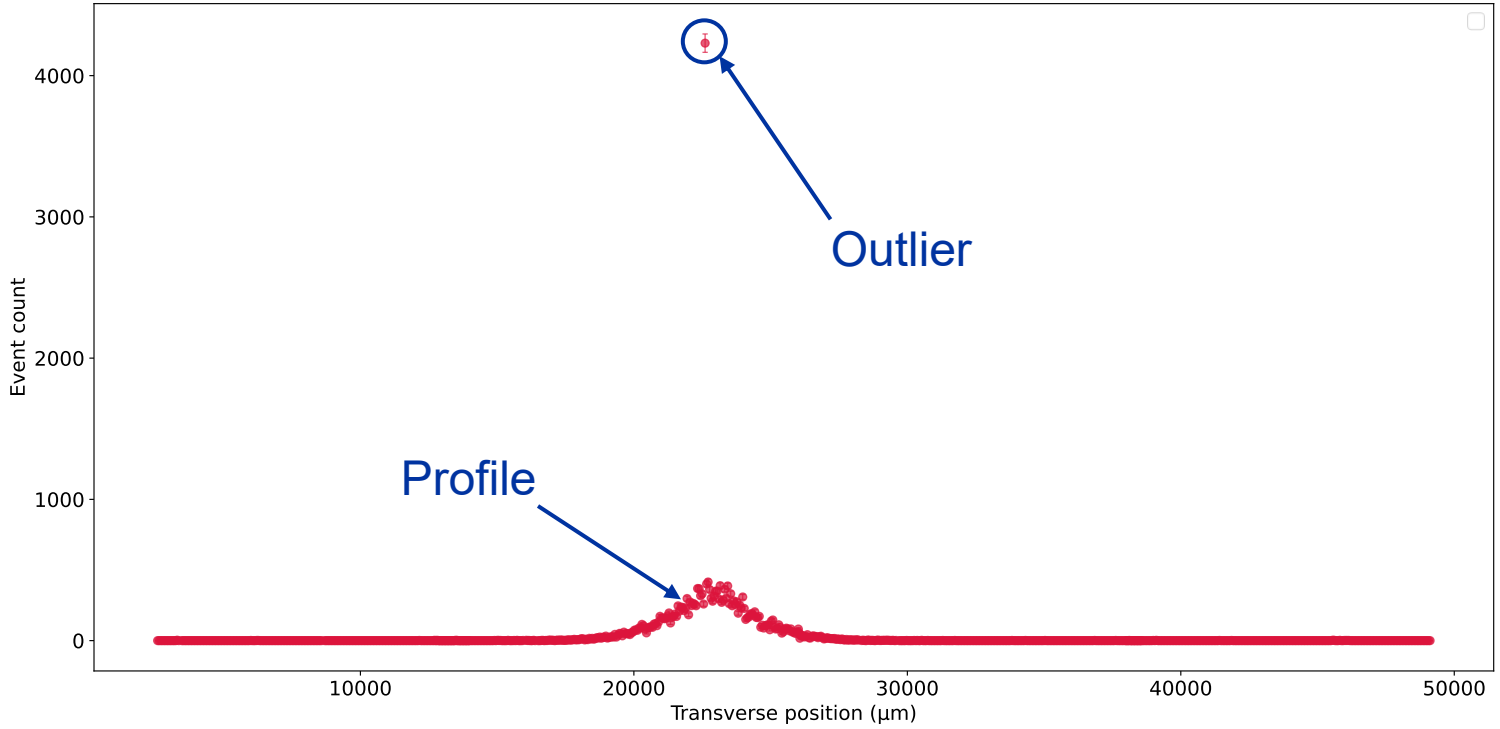
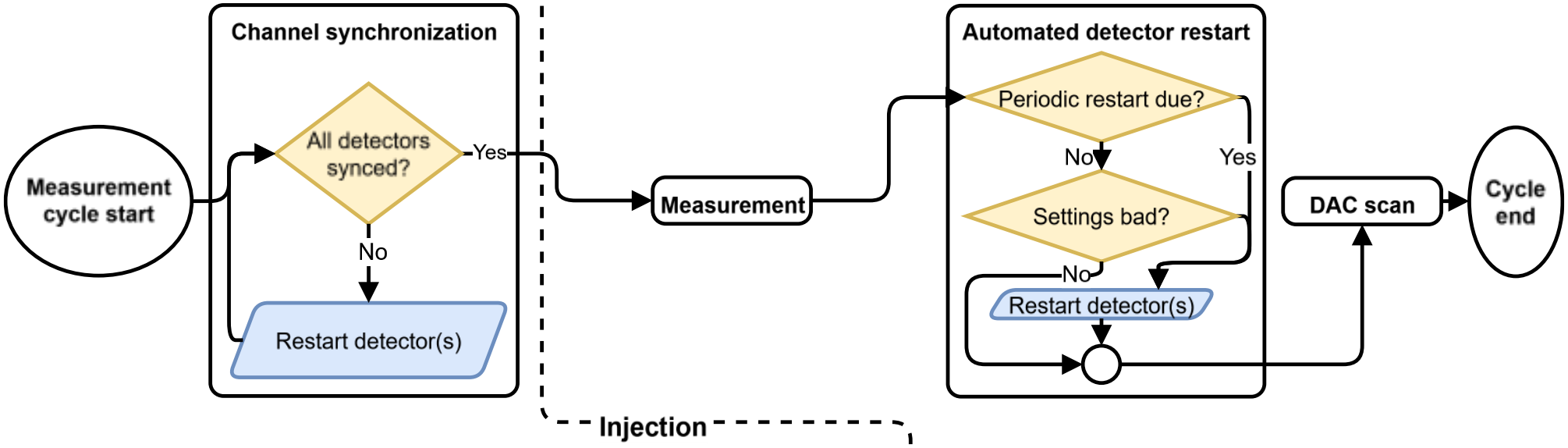
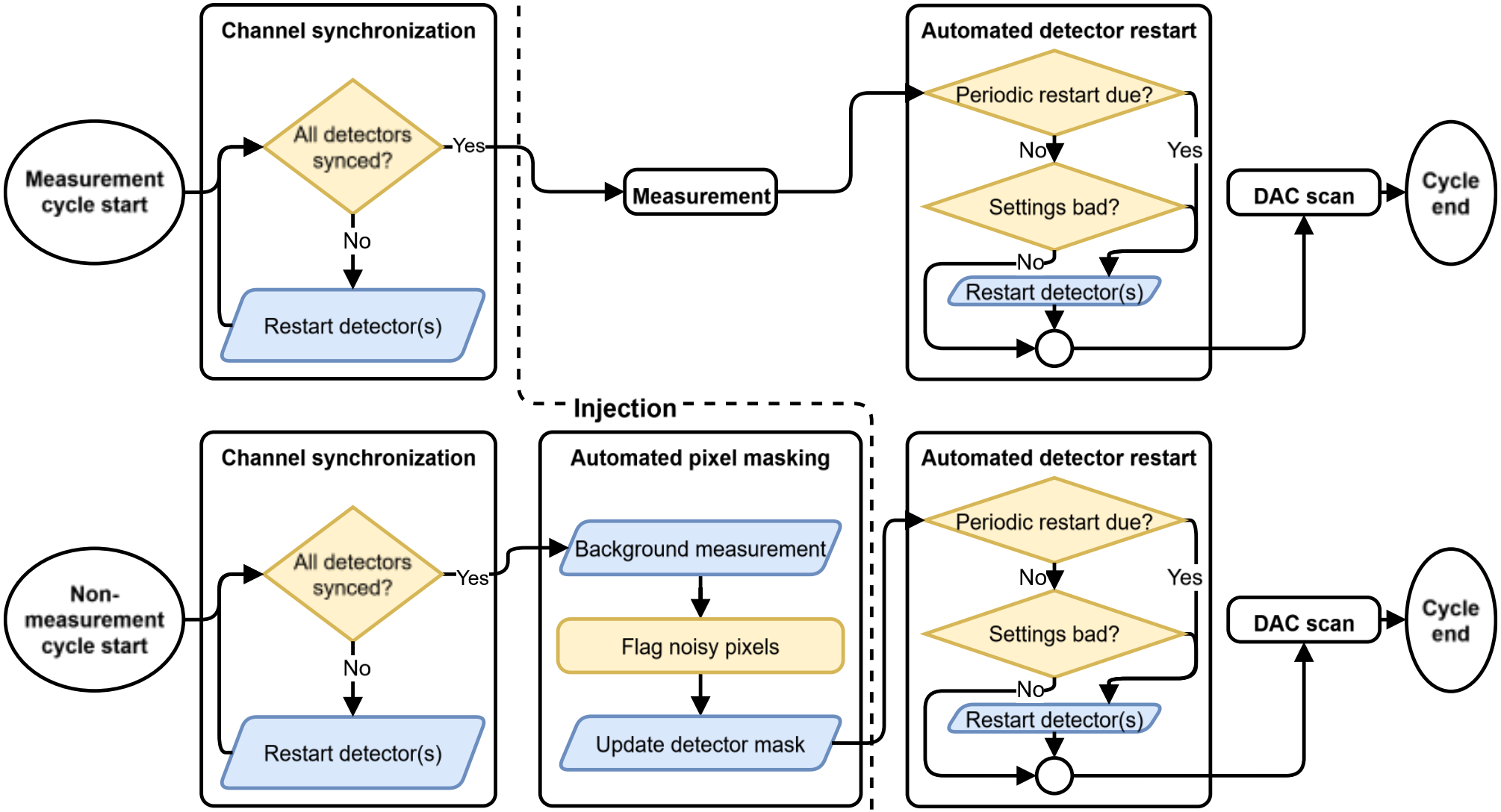
Measurement Results



Detector management



Detector management



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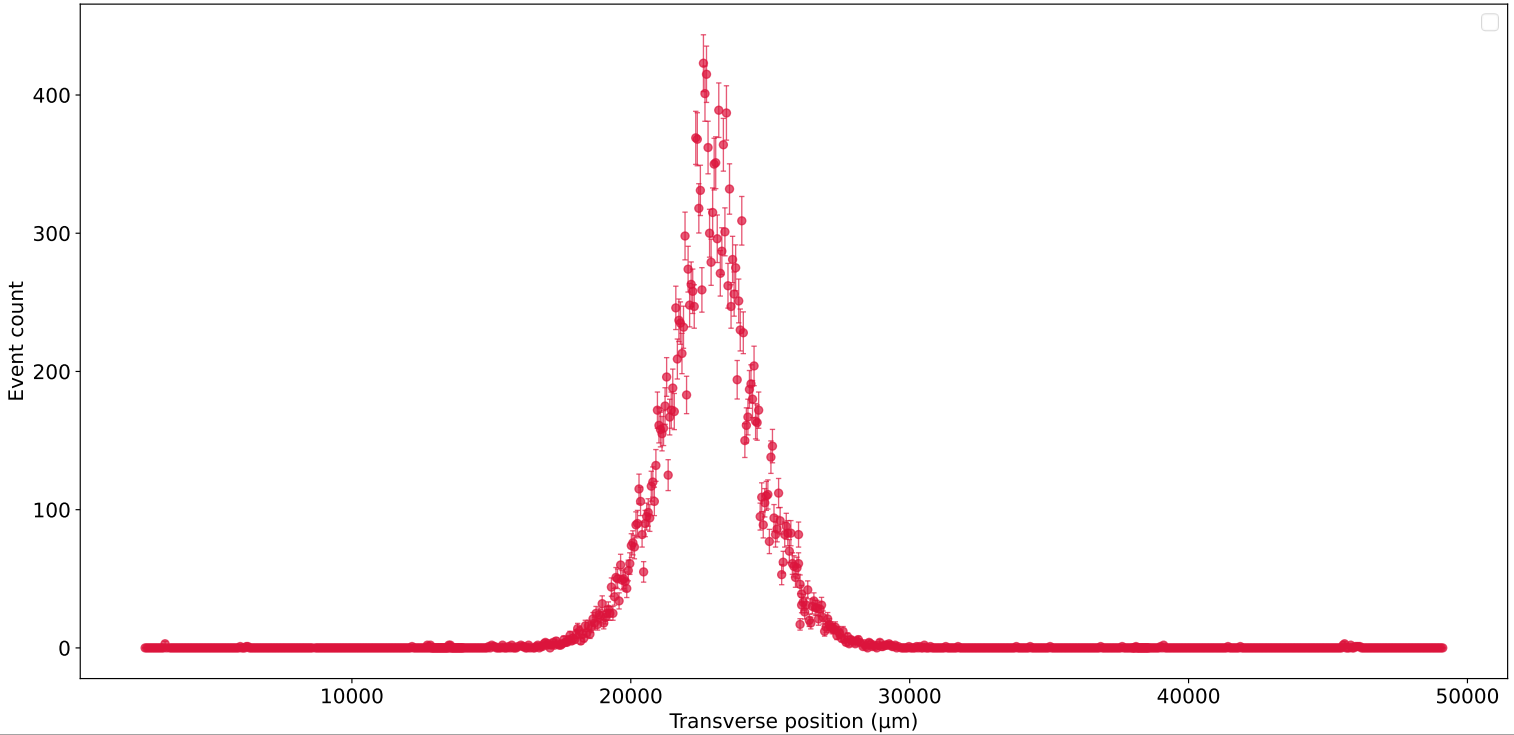


Multiple acquisitions

BGI GUI

Measurement Settings

Start (ms)	Delta (ms)	Length (ms)	Profiles
210	50	4	27
1560	50	2	60
4560	50	1	58

Measurement Results

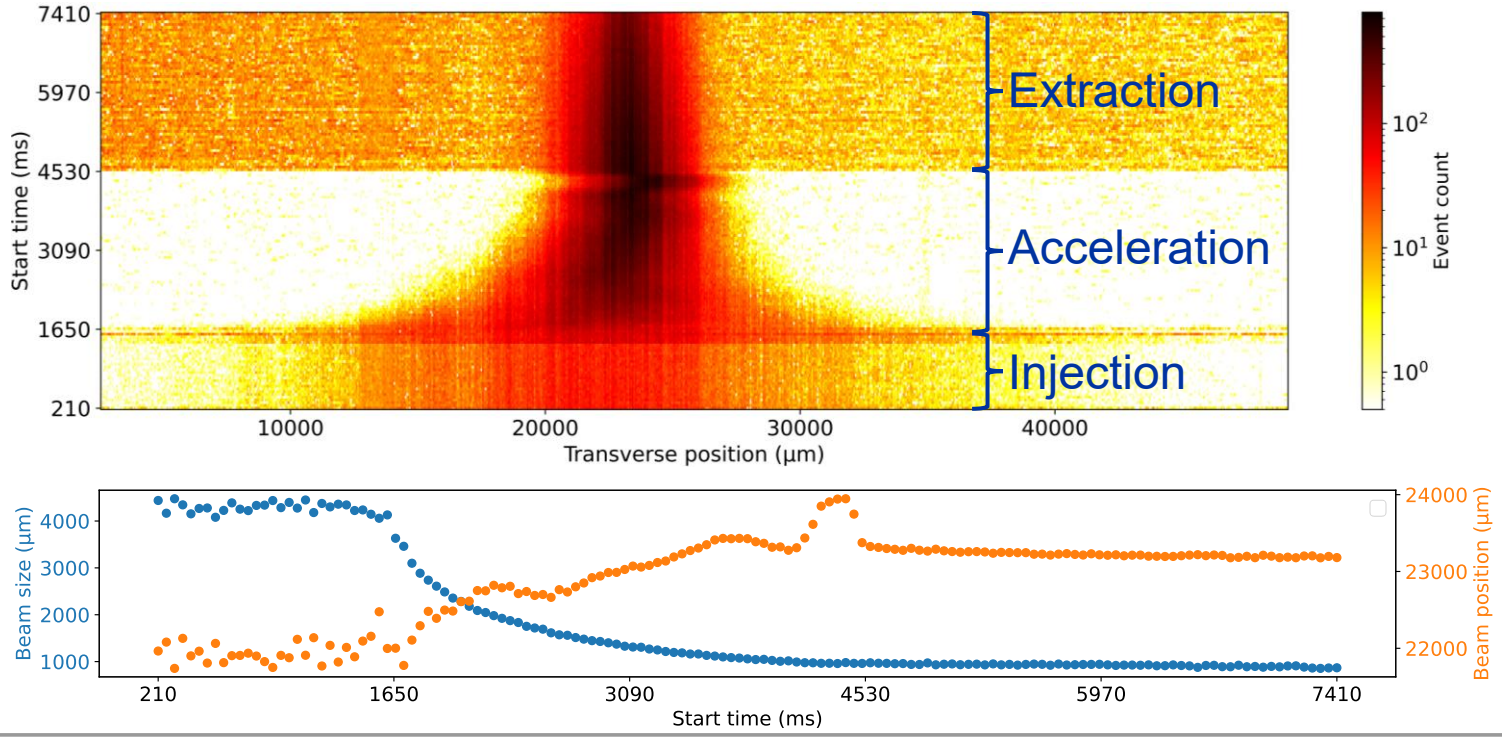
Multiple acquisitions

BGI GUI

Measurement Settings

Start (ms)	Delta (ms)	Length (ms)	Profiles
210	50	4	27
1560	50	2	60
4560	50	1	58

Measurement Results



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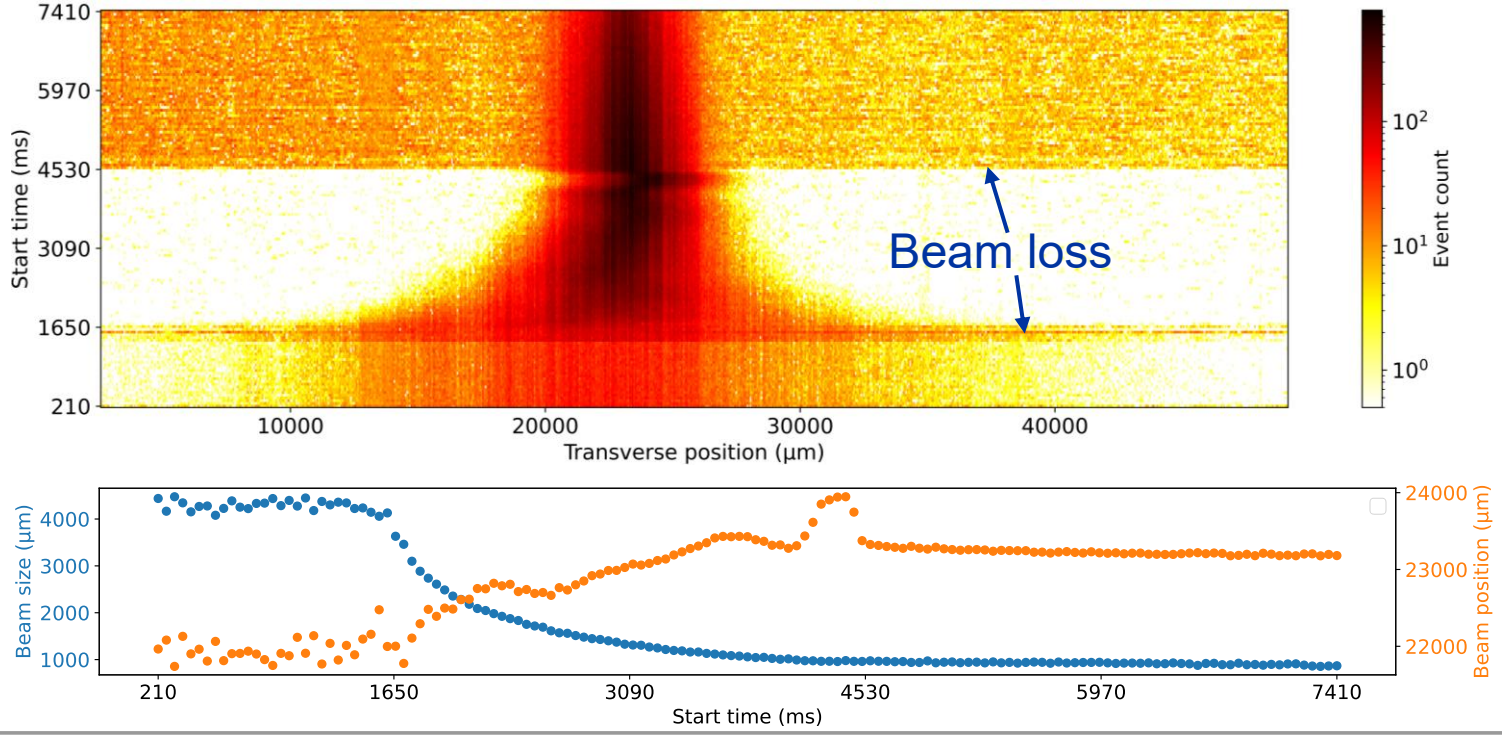
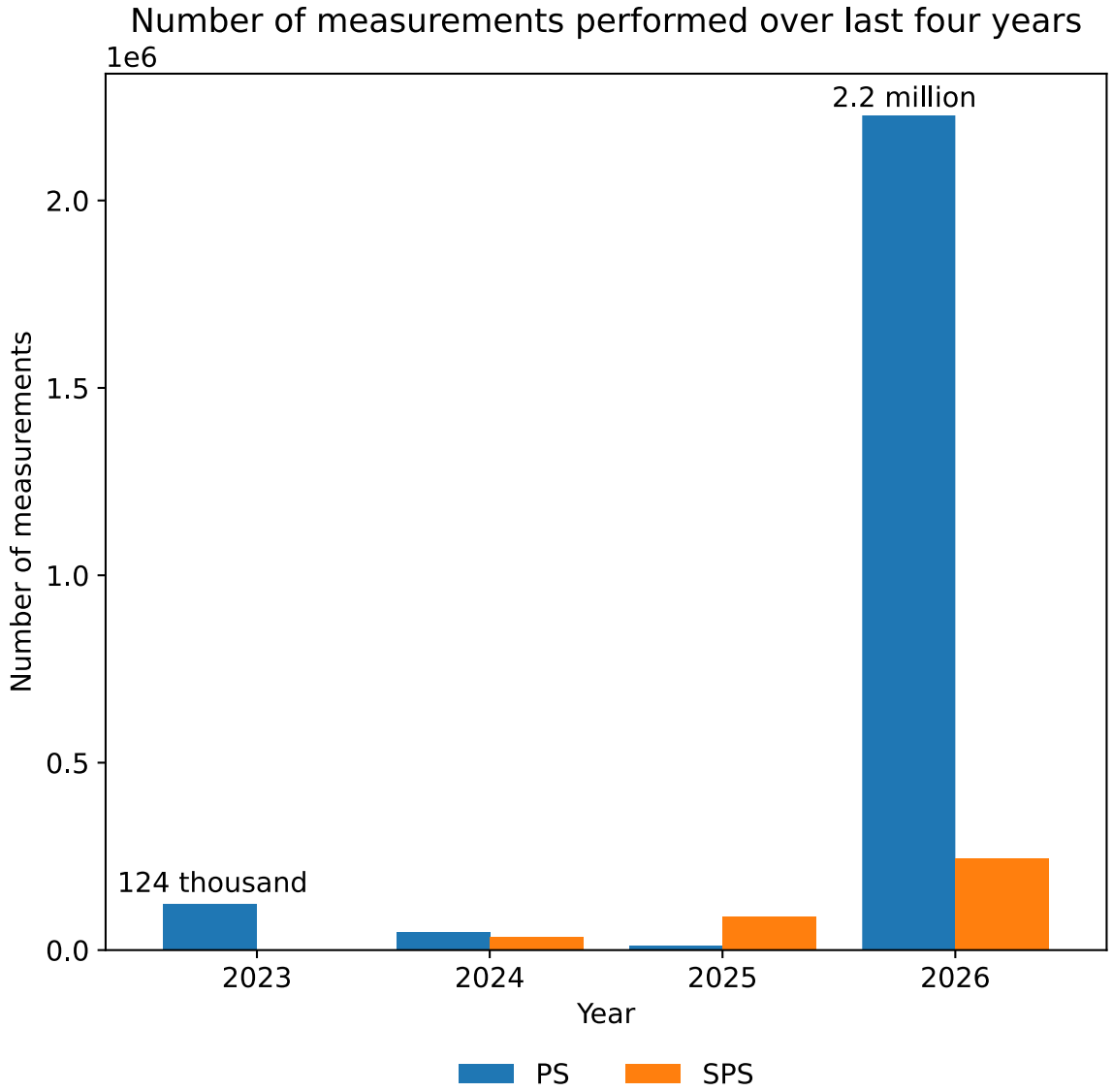


Results and conclusion

Operational results

- **April 2026**
  - Two PS BGIs operational
- **July 2026**
  - Two SPS BGIs operational
- **Preliminary overview of operations**
  - Satisfies operator needs under normal conditions
    - Couple hundred profiles per cycle
    - Timely profile publication
    - Stable operation
  - Increased usage



Conclusion

- **Operational use in the PS and SPS**
- **Readout system redesigned to**
  - be modular and scalable,
  - separate readout and processing,
  - provide raw data,
  - automate detector management.
- **Readout system extensible for Timepix4-based instruments, including:**
  - beam telescope to characterize bent crystals (see *MOP011*),
  - High-Luminosity Large Hadron Collider (LHC) BGI (see *MOP013*).

Thank you!

And big thanks to everybody involved with the BGI project over the years – in BI and beyond!