LHC beam monitoring via real-time hit reconstruction in the LHCb VELO pixel detector

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Why real-time reconstruction? Leveraging the FPGA power

It is now becoming widely recognised the usefulness to reconstruct relevant physical proxies, such as particle hits and tracks, at the earliest stages of the DAQ in order to speed up the reconstruction stages.

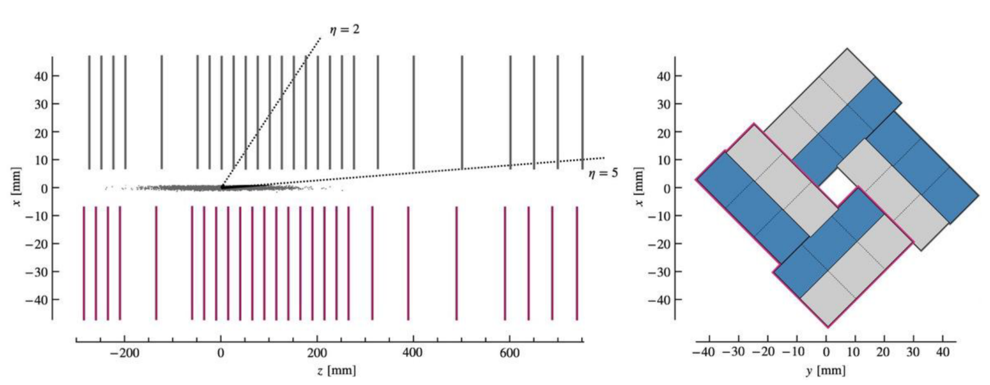
The **FPGAs** (Field Programmable Gate Arrays) are unique in this sense, as they can process huge amount of data at the readout level and in a fully parallel way, relieving the High-Levels Triggers of logically simple but time-consuming tasks.

The availability of high-quality primitives at high rates also creates an opportunity to do valuable measurements in real time that were not previously possible.

The LHCb experiment and the VELO detector

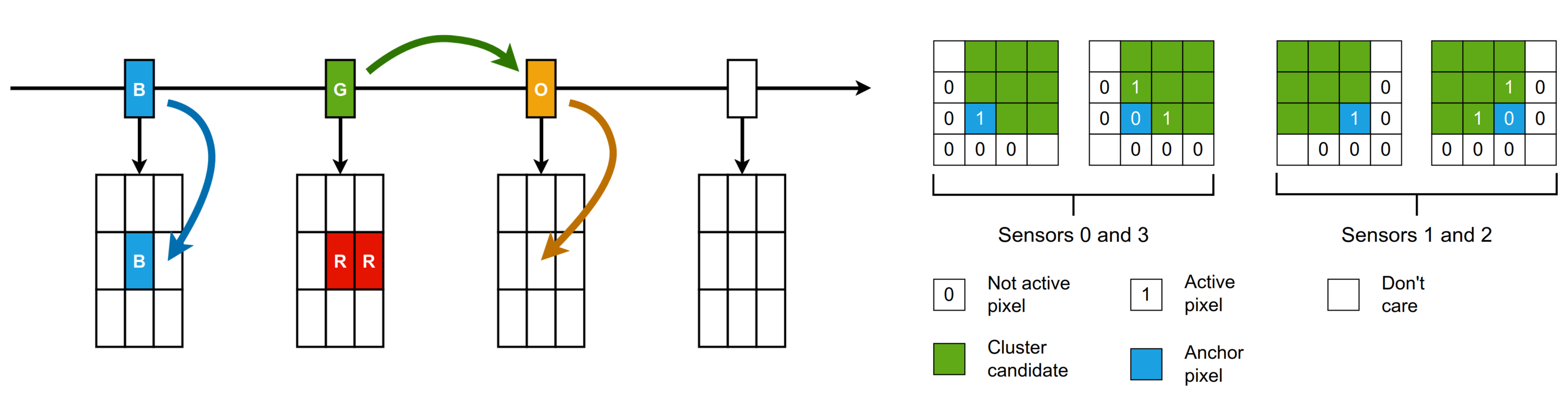
The LHCb Upgrade-I experiment[5] is designed for precision studies of *b*- and *c*-hadrons, covering the pseudorapidity range $2 \leq \eta \leq 5$.

The LHCb Vertex Locator (VELO) is composed of 26 layers of silicon sensors, for a total of ~41M digital pixels, with pitch of 55 μm.

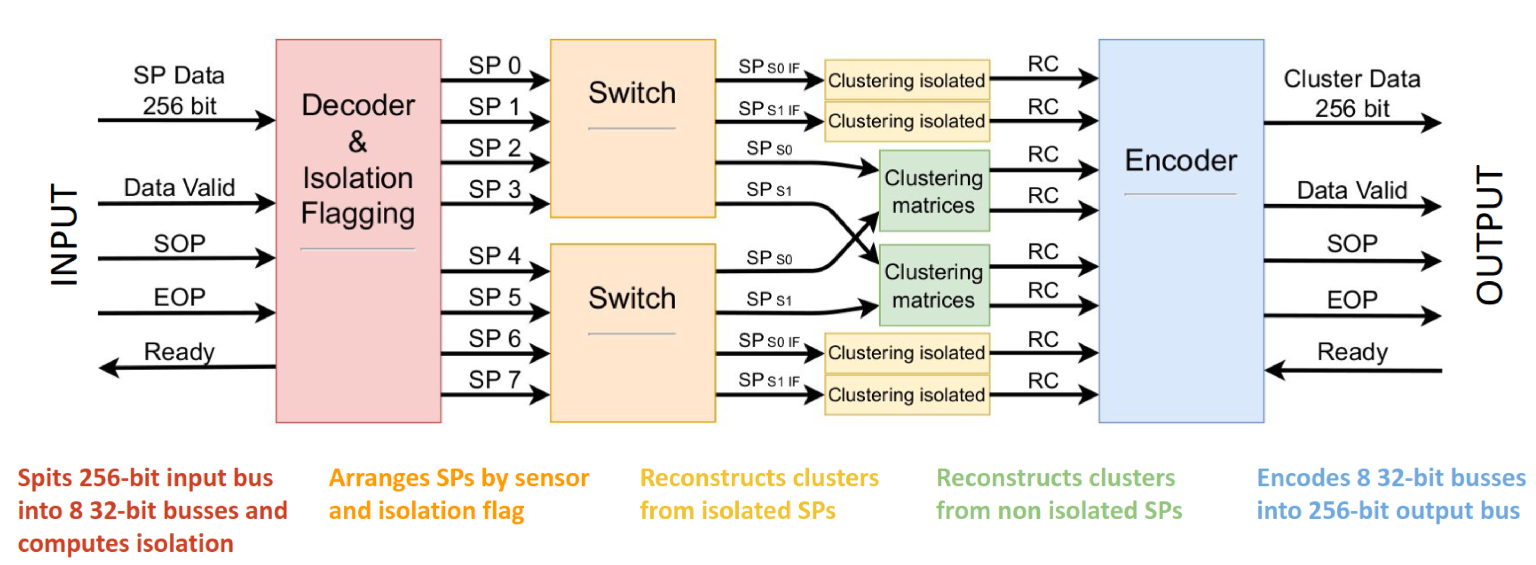


VELO's pixel cluster-finding algorithm on FPGAs

A real-time bi-dimensional cluster-finding algorithm[2,3] has been developed and deployed on the readout boards of the VELO detector. Pixels are readout in groups of 2×4 pixels (SuperPixels). Isolated SPs are revolved very quickly with a LookUp Table. Neighboring active SPs are grouped together in a matrix-filling process and then resolved in a fully parallel way.



The clustering algorithm has been implemented in pure VHDL. The cluster-finder firmware design is composed of four main stages:



Beam monitoring at LHCb

Why is it important to have a real-time monitoring of the beamline parameters at the LHCb interaction point ?

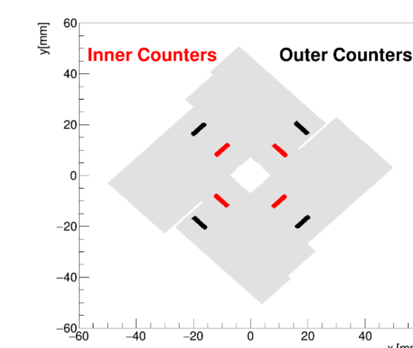
- **Luminosity levelling**
  Online luminosity estimation is needed as feedback to the LHC
- **Online alignment**
  Knowledge of beam position is relevant for the experiment's operations

Hit counters as beamline's parameter proxy

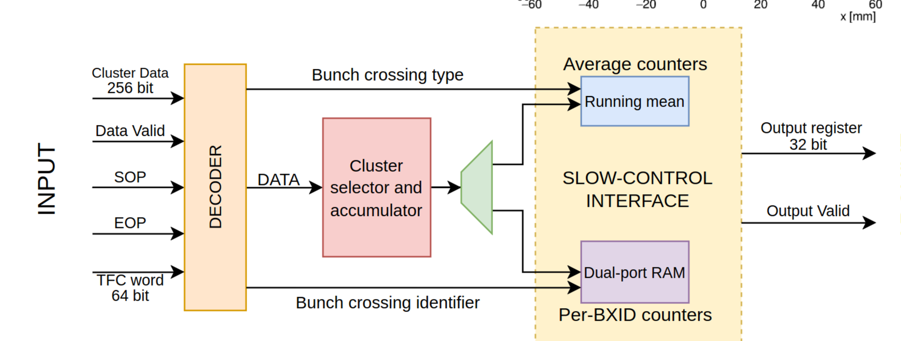
The occupancy on the VELO sensors depends on

1. the number of collisions *i.e.* luminosity
2. beamline spatial parameters

Counting the number of hits provides a powerful tool to perform a real-time diagnostic of the luminous region.



A set of real-time hit counters has been implemented[7] on the readout FPGA boards of each VELO sensor. Both counters divided per each collision and averaged in time have been implemented:



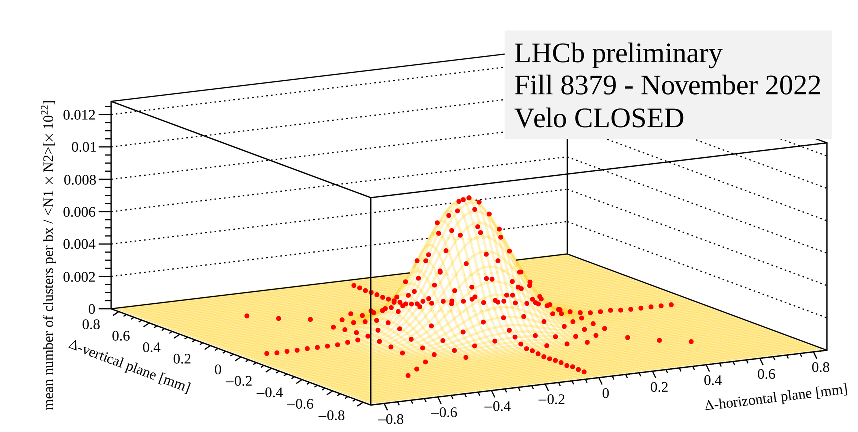
- Averaged counters as feedback to the LHC beam control
- Per-bunch-crossing counters as feedback to the LHC injection operations

Measuring the instantaneous luminosity

$$\mathcal{L}_{inst} = N_{bb} \frac{\mu}{\sigma_{vis}} f_{LHC}$$

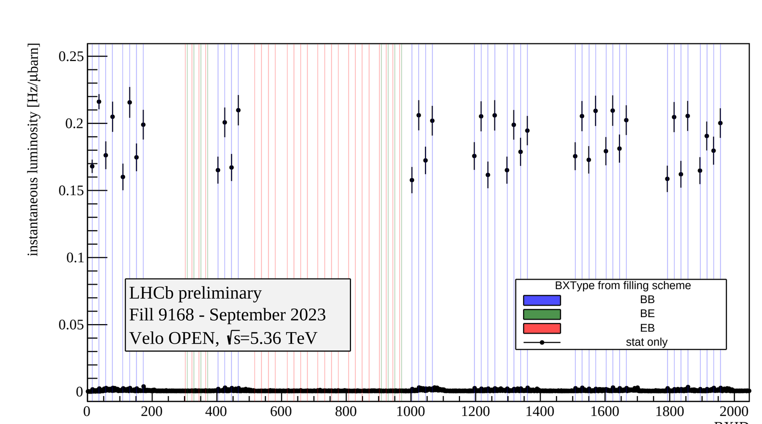
where

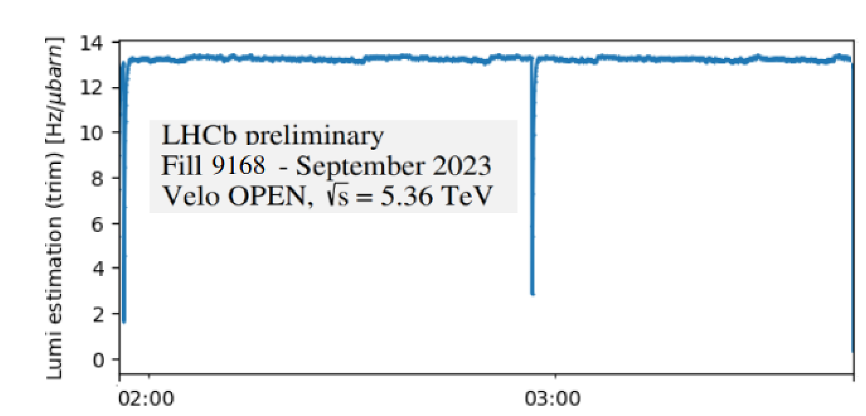
- N_{bb} = number of colliding bunches
- $\mu = \langle$hits per event$\rangle$ or
  $= -\log Prob$(empty event)
- $\sigma_{vis} = \int \frac{\mu(\Delta x, \Delta y)}{N_1 N_2} d(\Delta x) d(\Delta y)$
  = visible cross section specific to each counter (VdM scan[1])
- f_{LHC} = 11.245 kHz



Relative precision (no systematics):

- $\mathcal{O}(1\%)$ every ~ 3 min for the per-bxID measurement
- < 0.5% every ~ 3 s for the time-averaged one

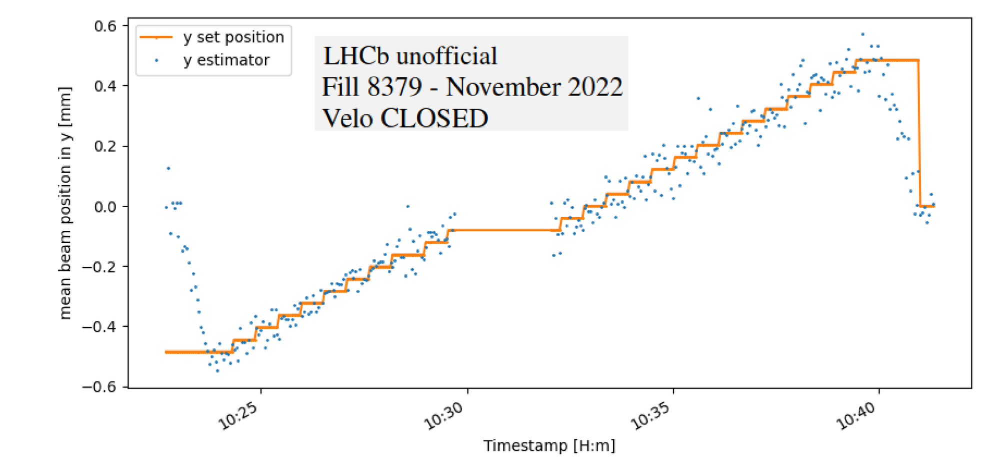




Track-less beamline position monitoring

The hit distribution on the VELO is - at the first order - linear with small displacements of the beamline position. It is possible to use the real-time hit counters to define a **linear estimator** for the *xyz* mean position of the luminous region. The estimator is found by diagonalizing the covariance matrix of the hit counters *i.e.* through a *Principal Component Analysis* on MC samples with different beam positions. The first eigenvector components c_i^{PCA} are used as coefficients of the linear estimators.

$$\hat{x} \propto \sum_{i=0}^{N\ counters} c_i^{PCA} \frac{\langle hits \rangle_i}{\mathcal{L}_{inst}}$$



Conclusion and Future prospects

These results represent a successful implementation of on-the-fly hit-statistics evaluation, transparently embedded in the readout in a complex detector at the full LHC average collision rate of 30 MHz. The availability of reconstructed hits at the readout level makes possible to compute even more complex statistics:

1. Luminous region longitudinal width
2. Beam-crossing angles in the horizontal and vertical plane
3. Spillover and efficiency monitoring of the VELO sensors
4. Monitoring of the relative positions of each module with respect to any other

The LHCb collaboration is now planning to implement part of the track reconstruction using FPGAs during Run-4 (2029) (Downstream Tracker[6,4]). This opens up the possibility to have a general FPGA-based approach to track reconstruction for Run-5. The availability of reconstructed tracks at the readout level would constitute an opportunity to further improve the hit-based beam monitoring, taking full advantage of the real-time reconstruction.

References

[1] V. Balagura. Van der Meer scan luminosity measurement and beam–beam correction. *The European Physical Journal C*, 81(1), January 2021.

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[6] LHCb LHCb collaboration. LHCb Data Acquisition Enhancement TDR. Technical report, CERN, Geneva, 2024.

[7] D. Passaro. Real-time luminosity and detector monitoring using FPGAs at LHCb experiment. Master's thesis, University of Pisa, 2022.

Acknowledgements

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