Timing at LHCb post LS4
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on behalf of the LHCb Collaboration

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The LHCb Upgrade II

- Major detector upgrade during LS4 of LHC
  \( \sim 2030 \)
- \( \mathcal{L} = 1.5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1} \times 7.5 \) increase from U1
- 300-350 fb\(^{-1} \)
- Very challenging environment
  \( \rightarrow \sim 42 \) Pile-up
  \( \rightarrow 1.5-3.5k \) charged particles per bunch-crossing
  \( \rightarrow \) Increase ghost rate and PV mismatch
  \( \rightarrow \times 10 \) radiation dose
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  \( \times 10 \) radiation dose
- Many subsystems with fast timing
  VELO, RICH, TORCH, ECAL

[Expression of Interest for a Phase-II LHCb Upgrade, 2017]
[Luminosity scenarios for LHCb Upgrade II, 2019]
Role of timing in detector performance

- Suppress combinatorics & enabling time-dependent CP-violation measurements
- Correct PV association/reconstruction
- Increase in tracking efficiency and matching
- Reduction in ghost rate
- PID and Calorimetry

Adding time information resolves this problem by providing an additional metric (with the VELO, these stations provide a high precision momentum measurement. They also improve the PV association performance, leading to the correct PV ('A' closest to $0^\circ$) being assigned. Studies have shown that without timing the Upgrade II PV mis-association levels may reach 5% with a timing precision of 50–100 ps. However, even with a resolution of 200 ps, a performance benefit of reducing the ghost rate even further. Figure 4.3 repeats the tracking performance of fast-timing information, discussed below in the context of vertex association, will also bring additional gains are almost certainly possible from a more comprehensive redesign of the track-finding software. Furthermore, the addition of timing will also have crucial benefits in track reconstruction since it allows to reduce the track reconstruction efficiency and fake rate can be addressed by decreasing the pixel pitch and mimicking the removal of the RF foil. In both cases the pattern recognition algorithms developed for the Phase-I Upgrade have been coarsely optimised for the new conditions by scanning the parameter space for the most important tuneable thresholds. Additional gains are almost certainly possible with the VELO, which would reduce this contribution to a negligible value. Such a change would result in a substantial improvement in 4D spatial and timing information in the VELO in this high-radiation environment is clearly well motivated.

The timing and rate capabilities required from the ASIC are ambitious but achievable.

[Expression of Interest for a Phase-II LHCb Upgrade, 2017]

Figure 4.2: Simulated performance of the Phase-I Upgrade VELO design, with no further improvements, shows that without timing the Upgrade II PV mis-association levels may reach 5% with a timing precision of 50–100 ps. Studies have also shown that even with a resolution of 200 ps, a performance benefit of reducing the ghost rate even further. Figure 4.3 repeats the tracking performance of fast-timing information, discussed below in the context of vertex association, will also bring additional gains are almost certainly possible from a more comprehensive redesign of the track-finding software. Furthermore, the addition of timing will also have crucial benefits in track reconstruction since it allows to reduce the track reconstruction efficiency and fake rate can be addressed by decreasing the pixel pitch and mimicking the removal of the RF foil. In both cases the pattern recognition algorithms developed for the Phase-I Upgrade have been coarsely optimised for the new conditions by scanning the parameter space for the most important tuneable thresholds. Additional gains are almost certainly possible with the VELO, which would reduce this contribution to a negligible value. Such a change would result in a substantial improvement in 4D spatial and timing information in the VELO in this high-radiation environment is clearly well motivated.

[Expression of Interest for a Phase-II LHCb Upgrade, 2019]

[Physics case for an LHCb Upgrade II, 2019]

- Improvement in CP-asymmetry measurements, as well as increase the combinatoric background levels.
- Phase-II Upgrade I
- Phase-II Upgrade II
- $\sigma_{\mu} = 5\%$ with a timing precision of 50–100 ps.
- Studies have shown that even with a resolution of 200 ps, a performance benefit of reducing the ghost rate even further. Figure 4.3 repeats the tracking performance of fast-timing information, discussed below in the context of vertex association, will also bring additional gains are almost certainly possible from a more comprehensive redesign of the track-finding software. Furthermore, the addition of timing will also have crucial benefits in track reconstruction since it allows to reduce the track reconstruction efficiency and fake rate can be addressed by decreasing the pixel pitch and mimicking the removal of the RF foil. In both cases the pattern recognition algorithms developed for the Phase-I Upgrade have been coarsely optimised for the new conditions by scanning the parameter space for the most important tuneable thresholds. Additional gains are almost certainly possible with the VELO, which would reduce this contribution to a negligible value. Such a change would result in a substantial improvement in 4D spatial and timing information in the VELO in this high-radiation environment is clearly well motivated.

[Expression of Interest for a Phase-II LHCb Upgrade, 2017]
The upgrade of the VELO detector

- VErtex LOcator: Silicon pixel detector
- $\sim 200$ ps time resolution needed to keep PV mismatch to current performance
- 4D tracking: hits separated in time $\sim 170$ ps RMS
  $\rightarrow$ tens of ps/hit to distinguish spatially overlapping hits
- Fast timing needed to maintain adequate efficiency
- Needs to cope with high radiation environment without sacrificing spatial and timing resolution
  $\rightarrow$ Up to $\sim 10^{17}$ 1 MeV $n_{eq}/\text{cm}^2$
- 50 ps/hit, 20 ps/track seems optimal

![Image of graphs showing PV mismatch and PR efficiency vs. time resolution.](parametric sim w/o full sim)

Approximate VELO upgrade performance

LHCb Velo preliminary

Patterns of recognition improvement

15 Dec 2019 – 12 HSTD 2019 Kazu Akiba

LHCb Velo
preliminary

LHCb Velo
preliminary

(50 ps, 100 ps)
There are two critical challenges for the VELO mechanical system that require dedicated programmes of R&D.

The first relates to the RF foil, that is the thin corrugated aluminium shield which encapsulates each detector half. The RF foil serves to minimise electrical coupling between VELO components and LHC beams and provides a surface free of abrupt changes in geometry which would generate heat and perturb both the VELO electronics and the beam parameters. It also provides a non-evaporable getter (NEG) coating, which contributes to the control of dynamic vacuum effects and separates the high-vacuum region of the LHC beam-pipe from the volume containing the detectors. The RF foils are the single largest contributor to the material in the VELO and of particular importance as the foil is before the first measured point. Solutions which reduce the material contribution of the foil, by extending the thinning programme already underway for the Phase-I Upgrade, or using alternative materials such as CFRP composites may enable a reduction of material. Based on the experience gained with LHC operation, it may also be possible to consider alternative solutions, such as a system of wires or an ultralight tube to guide the beam mirror currents, combined with local cryo-pumping to remove outgassing.

- **ASIC**: Based on VeloPix/TimePix family
- **Some options include**:  
  - Thin Planar  
  - LGADs  
  - 3D  
  - Monolithic design  
  - Others (Diamond, CMOS, ...)
- **No single technology exist yet (ASIC or sensors) that satisfies**: small pixel size, fast timing, rad-hard
Timing with RICH

- RIng Imaging CHERenkov (RICH) detectors
- Same occupancy level of current RICH1 needs:
  - smaller pixel size - Precise timing
- Timing information can improve pattern recognition and ratio of signal photons to background
- Separating different PV using hit time:
  - 0.2-1 ns/photon → 50-150 ps/track
- Resolution of 1 ns enough to reject out of time photons
  - 3 ns gate to remove background (sim)
  - a few % in RICH1, ~10% in RICH2

[https://arxiv.org/abs/1703.09927v2]

Figure 3: Left: Hit arrival time distribution on RICH1 photodetector arrays, for fully simulated events. Right: the same for RICH2. The events originate at $z \pm 150$ mm and $t = 0$ s. The main peak is due to hits from particles generating photons (signal), while the first peak(s) in time are due to particles interacting directly with the photodetectors. Other background is attributed to late particles, scintillation, multiple reflections, etc.

References


[LHCb-PUB-2017-014]
- Time Of internally Reflected CHERenkov light
- ToF Detector
- Comprises position-sensitive Micro-Channel Plate Photo-Multiplier Tubes (MCP-PMT) detectors
- Time resolution:
  \( \sim 70 \text{ ps/photon} \)
  \( \rightarrow \sim 15 \text{ ps/track} \)
- Fast timing helps with:
  - Possibly suppressing ghosts stemming from mismatching between VELO & UT
  - Timestamp particles decaying after VELO
  - ToF measurement to improve low momentum 2-10 GeV/c PID of \( \pi/K \)

![TORCH schematic](https://example.com/torch_schematic.png)

[Expression of Interest for a Phase-II LHCb Upgrade, 2017]
A large-scale TORCH demonstrator

- Quartz plate of dimensions $660 \times 1250 \times 10$ mm$^3$
- Read out by customized $53 \times 53$ mm$^2$ MCP-PMTs with $8 \times 128$ pixel-equivalent granularity
- Tested at CERN PS T9 beamline at 8 GeV/c
- 70 ps/photon time resolution

![Graph showing TORCH Preliminary data](image1)

[T. H. Hancock et al., Nuclear Inst. & Meth., A 958 (2020)]
Challenge to optimize simultaneously energy resolution, radiation hardness, cell size

Fast timing:
- Suppress combinatorics when forming $\pi^0$ candidates and $b$-hadron decays
- Allow combinatorics from high pile-up to be rejected
Spatial and timing provided by silicon detectors

- Embedded in the absorber layers or at front of the module OR
- Deeper within detector to benefit from larger signal
- Time resolution of a few tens of ps needed
LHCb Upgrade 2 will provide a challenging detector environment

×10 higher Luminosity
→ Increased Pile-up, ghost rate, PV mismatch and radiation dose

Fast timing in many subsystems becomes crucial to maintain physics performance
VELO, RICH, TORCH, ECAL