LHCb Upgrade II: Adding Precise Timing to the Vertex Locator

Workshop on the physics of HL-LHC, and perspectives at HE-LHC

CERN
1 Nov 2017
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Introduction: The LHCb Vertex Locator

Vertex Locator (VELO) – a silicon strip detector surrounding the LHCb luminous region
Provides precise measurements of charged particle trajectories:
• Primary and secondary vertex reconstruction
• Precise lifetime measurements
• Rejection of backgrounds
**Introduction: The LHCb Vertex Locator**

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- Primary and secondary **vertex reconstruction**
- Precise **lifetime measurements**
- Rejection of backgrounds

**Special Features:**

- Within beam pipe (separated from primary vacuum by thin RF foil)
- Detector retracts during injection

(One half of VELO)
We are here

Timeline

Run 2  LS2  Run 3  LS3  Run 4  LS4  Run 5,6,...

Install LHCb Upgrade I  LS3 Consolidation  HL-LHC: Upgrade II

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HL-LHC: Upgrade II

VELO

Silicon strip detector
\[ \mathcal{L} = 4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} \]
1.1 visible interactions / crossing

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VELO Upgrade I

Silicon pixel detector
\[ \mathcal{L} = 2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1} \quad (5\times) \]
5.5 visible interactions / crossing

VELO

Silicon strip detector
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VELO Upgrade I

Silicon pixel detector
\[ \mathcal{L} = 2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1} \] (5x)
5.5 visible interactions / crossing

VELO-II

Pixel detector with timing
\[ \mathcal{L} = 1-2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \] (5-10x)
55 visible interactions / crossing
Major Changes:

- **Pixels** (55μm) to handle higher particle multiplicity
- **Closer to beam** (5.1mm)
- **Full 40 MHz read-out**
We need:

- Precision spatial measurements of charged particles
- High track-finding efficiency
- Low ghost/clone rate
VELO Upgrade II?

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- Low material
- Close to beam line
- Precise single-hit measurements
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- **High track-finding efficiency**
  - Full coverage within acceptance
  - High granularity

- **Low ghost/clone rate**
  - Multiple $O(10)$ hits per particle
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+ Radiation hard

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Inside beam pipe (and retractable)
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- High read-out rate
- High performance, low material cooling

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Inside beam pipe (and retractable)
Silicon pixels

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Sound familiar?

VELO Upgrade-I must fulfil same basic requirements

Inside beam pipe (and retractable)  Silicon pixels  High read-out rate  High performance, low material cooling

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Sound familiar?
VELO Upgrade-I must fulfil same basic requirements

Additional challenges:
• 10x higher particle multiplicity
• 10x denser vertex environment
• 10x higher radiation damage

Inside beam pipe (and retractable)
Silicon pixels
High read-out rate
High performance, low material cooling
How can Timing Help

Adding timing information to the pixel hits can potentially recover / gain performance:

• Improved pattern recognition – reduces hit combinatorics in tracking
• Improved background rejection – reduces track combinatorics when reconstructing decay chains
• Improved PV association – reduced vertex combinatorics
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The main topic of this talk:
using timing to reduce PV mis-association for long-lived particles
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- Improved pattern recognition – reduces hit combinatorics in tracking
- Improved background rejection – reduces track combinatorics when reconstructing decay chains
- Improved PV association – reduced vertex combinatorics

However, must consider impact on (1) pixel size, and (2) radiation hardness

(non-linear scales! – illustration only)

+ extra time information increases required bandwidth
**Upgrade II Challenge: 10x particle multiplicity**

VELO Upgrade-I performance breaks down at HL-LHC luminosity ($L=2\times10^{34}$ cm$^{-2}$s$^{-1}$)

![Graph showing track efficiency vs. pseudorapidity]

**Tracking efficiency reduced to 96% (not so bad)**

+ less flat
**Upgrade II Challenge: 10x particle multiplicity**

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- **Ghost rate explodes ($\sim2\% \rightarrow 40\%$)**

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Upgrade II Challenge: 10x particle multiplicity

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- Tracking efficiency reduced to 96% (not so bad)
- Less flat
- Ghost rate explodes (~2% $\rightarrow$ 40%)
- Spatial resolution degrades due to reduced track-finding performance
Upgrade II Challenge: 10x particle multiplicity

Can recover most performance with modest improvements:

- Smaller pixels (55μm → 27.5μm)
- Thinner silicon (200μm → 100μm)
- Re-optimised pattern recognition

Only simple re-optimisation for this study – likely significantly more gains to be made
Upgrade II Challenge: 10x particle multiplicity

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Does this mean that we can live without precise timing?

No!
**Upgrade II Challenge: 10x vertex multiplicity**

At Upgrade-II luminosity, ~50 visible interactions / crossing

PV separation ~3mm on average, but peaks at very small values (<500μm)

With Upgrade-I detector, PVs start to merge

PV reconstruction recovered with smaller pixels

BUT we start to suffer from PV-track mis-association…
Main modules have two technologies:

- **Small-r:** small pixels, radiation hard, timing information optional
- **Large-r:** larger pixels, fast timing, reduced rad hardness

**Starting point:** use same z-layout as Upgrade-I
Use similar-sized sensor units (15x15mm² per square)
Upgrade II Challenge: 10x radiation damage

Highly non-linear radiation dose

Upgrade I: Maximum dose of $8 \times 10^{15}$ 1 MeV $n_{eq}$ cm$^{-2}$ after 50fb$^{-1}$

Upgrade II will see $5-8 \times 10^{16}$ 1 MeV $n_{eq}$ cm$^{-2}$ over course of lifetime

This is beyond the limits of current silicon technology – very important to find a solution
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Upgrade II Challenge: Hit Occupancy

LHCb Simulation
Preliminary
- Pixel Occupancy
- Cluster Occupancy

\[ L = 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \]

Occupancy also falls with \(1/r^2\)

Two-technology approach allows us to loosen requirements on

- pixel size
- radiation hardness

for precision timing planes

IP resolution dominated by first 2 hits

⇒ Spatial hit resolution less important at large-\(r\)
PV mis-association study

Run toy simulation that models the two-technology geometry, and assess PV mis-association rate under different time-hit resolutions.
Use reasonable inputs from full simulation / data / upgrade-II projections

Step 1: Generate pp collisions according to expected \((x, y, z, t, N_{PV})\) distributions

\[
\sigma_{PV}(t) = 250\text{ps}
\]

\[
\sigma_{PV}(z) = 63\text{mm}
\]

In progress… Working with LHC beam experts to identify realistic collision conditions
Step 2: Generate charged particles from each PV, and one b hadron (2-body decay)
PV mis-association study

Step 3: Propagate tracks through detector model, picking-up hits in both types of sensor

- Use time information on hits to assign $t(\text{track})$, and then $t(\text{vertex})$
- Use spatial information to assign $\text{b-hadron trajectory}$
Step 4: Assign PV to B hadron using/excluding time information, and compare results

Just using IP:
- Select PV with lowest B hadron Impact parameter

Example for single event:
In this case, wrong PV was assigned using IP method

Gaussians drawn at each PV point to show significance
PV mis-association study

**Step 4:** Assign PV to B hadron using/excluding time information, and compare results

**Using IP and timing:**
- Select PV with lowest:
  $$\sqrt{\frac{(IP)^2}{\sigma_{IP}^2} + \frac{(\delta t)^2}{\sigma_t^2}}$$

For same event, correct PV is now selected [close to (0,0)]

**Gaussians drawn at each PV point to show significance**
With no time information: PV mis-association rate = 15%  (c.f. Upgrade I: ~1%)

With timing:

- **σ(t)[inner detector] = 200ps**
- **No timing for inner detector**

Two different scenarios for the time precision of inner detector:

1. No timing
2. 200ps timing (timepix4?)

Implies having timing in inner detector is not vital

Can get to ~2% mis-association rate with 40ps timing for outer detector
Impact on decay time precision

Incorrect PV association $\Rightarrow$ incorrect decay time measurement

One primary vertex:

Two primary vertices:

unambiguous flight distance

ambiguous flight distance
Incorrect PV association $\Rightarrow$ incorrect decay time measurement

Important for much of core LHCb programme:
- Lifetime measurements
- Precision mixing analyses
- Time-dependent CP violation

Effect will be even stronger for partially-reconstructed decays (e.g. semileptonics) where spatial pointing is distorted, but time is not
Further Studies: Timing for background rejection

With 50x track multiplicity, many more spurious combinations of tracks ⇒ larger contributions from combinatorial backgrounds

With modest per-hit timing, can cleanly reject combinations of tracks from different PVs

- e.g. 200ps inner region, 60ps outer region

⇒ **30ps mean track time resolution**

Will provide significant suppression of backgrounds, and boost sensitivity of many analyses (notably **Rare Decays**)

Full study to be done
Further Studies: Timing for reconstruction

Hit times will be spread over ~few 100 ps
Adding hit time as an extra dimension in the pattern recognition (4D tracking) can improve tracking performance

- **Reduced ghost rate**
- **Faster reconstruction** (very important given LHCb’s ‘offline quality’ trigger approach)
- **Higher efficiency** – can loosen some spatial requirements without increasing ghost rate

Same arguments hold for PV reconstruction – can recover merged / missing PVs and improve spatial resolution.

Full study to be done
Further Studies: Timing for extrapolation

Tracking stations upstream / downstream of magnet are separated by ~5m

Extrapolating tracks through magnet could be problematic in HL-LHC era

• High ghost rates

Adding timing plane in downstream tracker could help
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Adding timing plane in downstream tracker could help

c.f. ideas proposed by Atlas / CMS to place timing layers in their trackers (e.g. HGTD based on LGAD detectors)

Could also significantly speed-up reconstruction

Full study to be done
Summary and Future Work

HL-LHC: huge **opportunity** for LHCb to search for new physics in precision measurements

Also significant **challenges** – particularly for the VELO

- High track multiplicity, high radiation dose, high pile-up

Two-technology solution ⇒ reduced requirements on pixel size and radiation hardness for **timing technologies** for the outer radial region of the VELO

Even with timing only in the outer region, can reduce PV **mis-association** rate from **15% to ~2%**.

Will also significantly reduce track combinatorics, and hence backgrounds

Now starting to plan research programmes to **identify** and **develop** candidate technologies for both the inner and outer detector.
Possible Technologies: ASICS

Upgrade I will use **VeloPix** technology – based on **Timepix** family of ASICS

- 55µm pixels
- 130 nm technology
- 1 ns timing precision

**Timepix3**
- + Radiation hard
- + 800 Mhit/s readout
  (10x Timepix3)

**VeloPix**
- Under validation – all looks good!

**Timepix4**
- Same 55µm pixels
- 65 nm technology
- ~200 ps timing precision
- 4-sided buttable design

**SuperVeloPix**?
- Small pixels, timing, high rate, radiation hard, ...

- Reduced pixel size?
- Improved timing precision?
Possible Technologies: Sensors

Low Gain Avalanche Detectors (LGAD)

\[ \sigma(t) \approx 35\text{ps}, \text{ degrades with radiation} \]
(current prototypes \( \sim 1\text{mm pads} \))

3D Silicon detectors

New 3DSi trench topologies give more uniform fields – so uniform charge collection rates
⇒ potential to reach <100ps timing
Good radiation hardness
Scalable to smaller pixels (<50\( \mu \)m)