VELO Upgrade II: Overview

TTFU Workshop III
Annecy

22 March 2018  Mark Williams
Preamble

Previous TTFU contributions:

• Feb 2015: TTFU CERN (PC) [https://indico.cern.ch/event/373857/]
• Apr 2015: TTFU @ A&S Week (VG) [https://indico.cern.ch/event/331664/]
• Apr 2016: TTFU Manchester (PC, JH) [https://indico.cern.ch/event/481359/]
• Jul 2016: TTFU CERN (PC, MW) [https://indico.cern.ch/event/549406/]
• Oct 2016: TTFU CERN (MW, MJ) [https://indico.cern.ch/event/571360/]
• May 2017: TTFU Elba (MW, MO, NB) [https://indico.cern.ch/event/607139/]

Other presentations:

• Jul 2017: Impedance meeting (NB) [https://indico.cern.ch/event/653098/]
• Sep 2017: LHCb week @ Lake Placid (MW) [https://indico.cern.ch/event/657180/]
• Oct 2017: HL-LHC Workshop (MW, GC) [https://indico.cern.ch/event/647676/]
• Dec 2017: U1b/U2 T&A meeting (MW) [https://indico.cern.ch/event/678774/]

Dedicated meetings:

• Oct 2017: “New Dimensions in Silicon Detectors” IoP meeting on pixels with timing [http://indico.hep.manchester.ac.uk/event/NewDimensions2017]
• March 2018: “VELO U2 Retreat” [https://indico.cern.ch/event/681201/]

Nicolo Biancacci, Greg Ciezarek, Paula Collins, Vava Gligorov, Jon Harrison, Manuel Jahn, Margherita Obertino, Mark Williams
Silicon pixel detector
\( \mathcal{L} = 2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1} \) (5×)
5.5 visible interactions / crossing
(1) High efficiency
VELO Upgrade-I tracking efficiency already very high – aim to sustain

![Graph showing efficiency comparison between Current VELO and Upgrade-I VELO](image)
What can the U2 VELO do for you (i.e. your analysis)?

(1) High efficiency!
VELO Upgrade-I tracking efficiency already very high – aim to sustain

(2) Reduced material (esp. in RF foil)
- can improve:
  - IP / SV / PV resolution
  - BG modelling for searches
  - Precision on detector asymmetries
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  • BG modelling for searches
  • Precision on detector asymmetries

(3) Time stamp for tracks (~30ps) / vertices (~10ps)
In Brief...

We want to achieve same or better physics performance as Upgrade-I VELO, at 10x luminosity...

• 10x higher particle multiplicity
• 10x denser vertex environment
• 10x higher radiation damage

Can it be done? How?

Inside beam pipe (and retractable)
Silicon pixels

High read-out rate
High performance, low material cooling
For Upgrade-I VELO design (55 μm pixels), performance at \( \mathcal{L} = 2 \times 10^{34} / \text{cm}^2 / \text{s} \) is heavily degraded ⇒ e.g. Ghost rate increases by factor 20
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Reducing pixel size to 27.5μm, and re-optimising PR parameters (e.g. cone size), most of the losses are recovered.

So, smaller pixels almost certainly needed – although probably only in inner radial region...
Even with perfect tracking performance, the 
**PV mis-association rate** for long-lived particles 
is unacceptably high (>10%) at U2 luminosities

⇒ Direct degradation of decay time precision
Even with perfect tracking performance, the **PV mis-association rate** for long-lived particles is unacceptably high (>10%) at U2 luminosities.

⇒ Direct degradation of decay time precision

Adding modest timing information to every VELO hit can reduce this rate significantly (from \(~14\% \rightarrow 1\%)@200\text{ps} precision)

(caveat: preliminary study with unrealistic beam conditions, but general statement holds)
Limiting factors (radiation, occupancy) are highly dependent on radius
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Limiting factors are expressed as

\[ L = 2 \times 10^{34} \, \text{cm}^{-2} \text{s}^{-1} \]
Radial dependence motivates a dual-technology design

**Small-r:** small pixels, radiation hard, timing information optional

**Large-r:** larger pixels, **fast timing**, reduced rad hardness
Run toy simulations of two-body B decays to assess PV mis-association rate from dual-technology design.

With timing: additional power to select correct PV using both IP and timing information: 
**2-4%** mis-association rate

No timing: pick PV with lowest IP: **~15%** mis-association rate
Added **realistic beam conditions** based on full simulations from the HL-LHC experts

- $\mathcal{L} = \{1.0, 1.5, 2.0\} \times 10^{34}$ /cm$^2$/s
- $\beta^* = \{1.4, 2.0, 3.0\}$ m
- Xing angle: $\{230, 770\}$ µrad

<table>
<thead>
<tr>
<th>$\beta^*$ [m]</th>
<th>$\mathcal{L}_{\text{lev}}$</th>
<th>230 µrad</th>
<th>770 µrad</th>
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<tbody>
<tr>
<td></td>
<td>1.0</td>
<td>1.5</td>
<td>$2.0 \times 10^{34}$</td>
</tr>
<tr>
<td>1.4</td>
<td>[ (a) ]</td>
<td>(b)</td>
<td>(c) $]_i$</td>
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<tr>
<td>2.0</td>
<td>[ (d) ]</td>
<td>(e)</td>
<td>- $]_ii$</td>
</tr>
<tr>
<td>3.0</td>
<td>[ (f) ]</td>
<td>-</td>
<td>- $]_iii$</td>
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L. Medina, R. Tomas, et al.  
([https://indico.cern.ch/event/676473/](https://indico.cern.ch/event/676473/))
**New** studies

Added realistic beam conditions based on full simulations from the HL-LHC experts

- $\mathcal{L} = \{1.0, 1.5, 2.0\} \times 10^{34}$/cm$^2$/s
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<tbody>
<tr>
<td>1.4</td>
<td>(a)</td>
<td>(b)</td>
<td>(c) $i_i$</td>
<td>(a)</td>
<td>-</td>
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<tr>
<td>2.0</td>
<td>(d)</td>
<td>(e)</td>
<td>- $i_{ii}$</td>
<td>(D)</td>
<td>-</td>
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<tr>
<td>3.0</td>
<td>(f)</td>
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<td>- $i_{iii}$</td>
<td>-</td>
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<table>
<thead>
<tr>
<th>Case</th>
<th>mean N(PV)</th>
<th>$\sigma(x,y)$ [µm]</th>
<th>$\sigma(z)$ [mm]</th>
<th>$\sigma(t)$ [ps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>27.5</td>
<td>15.3244</td>
<td>51.9</td>
<td>190</td>
</tr>
<tr>
<td>(b)</td>
<td>41.25</td>
<td>15.3244</td>
<td>51.9</td>
<td>190</td>
</tr>
<tr>
<td>(c)</td>
<td>55</td>
<td>15.3244</td>
<td>51.9</td>
<td>190</td>
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<tr>
<td>(d)</td>
<td>27.5</td>
<td>18.3104</td>
<td>53.1</td>
<td>189</td>
</tr>
<tr>
<td>(e)</td>
<td>41.25</td>
<td>18.3104</td>
<td>53.1</td>
<td>189</td>
</tr>
<tr>
<td>(f)</td>
<td>27.5</td>
<td>22.4216</td>
<td>54.0</td>
<td>188</td>
</tr>
<tr>
<td>(A)</td>
<td>27.5</td>
<td>15.3187</td>
<td>32.7</td>
<td>202</td>
</tr>
<tr>
<td>(D)</td>
<td>27.5</td>
<td>18.3074</td>
<td>36.7</td>
<td>200</td>
</tr>
</tbody>
</table>

No longer levelling over entire fill

Strong dependence of $\sigma(z)$ on Xing angle
At $L = 2.0 \times 10^{34} \text{ /cm}^2/\text{s}$, PV mis-association rate ($\text{PV\%}$):

- No timing: 20%
- Timing only in inner detector: 5-13%
- +200ps timing in outer region: 4-9%

Caveat: work-in-progress!
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As expected, PV\% scales ~linearly with luminosity.
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**No strong effect from $\beta^*$ value**
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As expected, $\text{PV}\%$ scales \textsim linearly with luminosity

No strong effect from $\beta^*$ value

Significant degradation for larger crossing angle (i.e. for one choice of LHCb magnet polarity)

Significantly different performance for different polarities... no longer obvious that instrumental effects cancel
*New* studies

Pixel size versus timing precision: what matters most for outer radial region?

Existing studies used parametric vertex smearing (PV and SV) based on Run 3 Monte Carlo
⇒ could only use for 55µm pixel size

Now added simplified Kalman fit (no material scattering yet)
⇒ can adjust pixel size and rerun study

Vertex resolution from Kalman fit matches full MC for 55µm pixels
**New** studies

Pixel size versus timing precision: what matters most for outer radial region?

Case (b) PV-f for 25μm inner detector pixel size

- 200μm outer: 10% lower PV%
- 40ps timing: 70% lower PV%

In this realm, timing more important for PV association
Future studies

Some natural extensions / additions to the **PV mis-association** study:

- Add material (to modules, and optionally to RF foil)
- Simulate different decays (charm, semileptonic B)
- Test alternative geometries (e.g. circular hole at same/larger radius as current square)

Benefits to **pattern recognition**:

- How much can be gained by adding timing to each pixel
  1. In performance?
  2. In reduced resource use?
- How large can the outer pixels be without degrading performance?

This is one of two limitations for current precise timing (LGAD) detectors (other is rad hardness)
https://indico.cern.ch/event/681201/
Summary at VELO parallel session @ LHCb Week: https://indico.cern.ch/event/707306/
VELO U2 Retreat

Brainstorming & lots of discussion

Stable beams! The piston is retracted, detectors slide in.

VELO U2 Overview: Annecy TTFU Workshop 22 March 2018

Mark Williams
Open Questions

How will we deal with radiation damage?

- More rad-hard silicon/ASICs/…?
- Replaceable detector components?
- Both?
- Move sensors further from beam?

Upgrade II will see $5-8 \times 10^{16}$ 1 MeV $n_{eq \ cm^{-2}}$ over course of lifetime (@ r=5.1mm)

$\Rightarrow$ 5-8x limits of current technology
Open Questions

How will timing information be used?

- Time **per vertex** for improved PV association?
- +Time **per track** for improved background rejection?
- +Time **per hit** for improved pattern recognition?

Fake 2-track candidate

Ambiguous flight distance

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Open Questions

Can we remove the RF foil?

Will static vacuum be a problem?

Can dynamic vacuum effects be overcome?

How to protect VELO from beam, and keep machine impedance within tolerance?
Open Questions

Will (and how will) reconstruction needs and limitations influence VELO design?

50% of resource use in pixel tracking goes into data preparation (sorting hits & clustering)

C. Fitzpatrick @ VELO U2 retreat 2/3/2018
https://indico.cern.ch/event/681201/
R. Quagliani @ T&A meeting 20/2/2018
https://indico.cern.ch/event/691555/
Conclusion

"...my fellow Americans: Ask not what your country can do for you – ask what you can do for your country."

And also

LHCb collaborators

Do ask!

U2 VELO

Solves & inspires

Motivate & Guide

Analysis needs

Detector design
Take away: Technology will exist, but £/kHz limited
Need to be smart, since we’re not rich
Read-out:
General limitations: Karol Hennessy
Fibres: Jan Troska

Take away: Commercially driven
Available tools will probably meet out needs
VELO U2 Retreat

Mechanics
Overview: Raphael Dumps
RF Foil: Massi Ferro-Luzzi

Module Integration:
Alessandro Mapelli

Take away: Will not limit/prevent our ability to build U2 VELO
Gives opportunities to do even better than now
**Sensors and ASICs:**
CMOS: Eva Vilella / Gianluigi Casse
UFSD: Nicolo Cartiglia
TimePix and ASICS: Michael Campbell / Vladimir Gromov (given by Martin VB)

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**Take away:**
Technology does not exist, may not unless we drive it
Interplay of requirements (timing, pixel size, rad hardness)