Past Present and Future of the Vertex Locator

Kazu Akiba on behalf of the LHCb VELO
A few words on why we do this

• Some particles “live” longer than others (b and c hadrons)
• The shorter they live the harder it is to separate them from the collision point.
• Precise measurements of the collision and displaced vertices, allow a wide range of physics observations
  • CP violation, rare decays
  • Higgs → bb, bb resonances
  • particle oscillations, lifetime measurements
  • New particles
How: IP Resolution

- Depends on 3 main parameters
  - Intrinsic hit resolution
  - Distance to the first measured point and lever arm
  - Multiple scattering in detector material, worse at low $p_T$

$$\sigma_{d_0} = \frac{r}{p} 13.6 \text{MeV} \sqrt{\frac{x}{X_0}} \left[ 1 + 0.038 \log \left( \frac{x}{X_0} \right) \right]$$

$$\sigma_{d_0}^2 \approx \sigma_{geom}^2 + \left( \frac{f(x/X_0)}{p_T \sqrt{\sin \theta}} \right)^2$$
The Goal of LHCb is to discover new physics through the precise measurements of CP-violation and rare decays using b (and c) hadrons.
R measuring strips with double metal r/o

Phi measuring strips with stereo angle
Proton view – injection

Wakefield suppressor

RF-foil
Proton view – stable beams
Proton view – stable beams
10 years of operation

- Detector has accumulated fluence of approximately $7 \times 10^{14}$ 1 MeV $n_{eq}/cm^2$
- Leakage currents and depletion voltages have followed expectations
- Detector has been operated and maintained below $-7^\circ C$; underwent deliberate annealing warm up at end of lifetime
- Charge loss experienced to double metal layer, but no degradation on IP resolution.
- Irradiation profile is very non uniform $\sim 1/r^2$
The original detector deinstallation
• LHCb upgrades to look for more collisions/s in order to select the most interesting ones.
• Smart trigger algorithms to increase the yield of hadronic decays and more luminosity for rare decays.
• The LHCb Upgrade increases the luminosity (x5) and the readout rate (x40).
• This means more radiation damage, more occupancy, more data to transport.
Overview of the Velo upgrade

- 52 modules, 55 µm pitch sensors
- 40M pixels
- Data driven readout
- 5.1 mm sensitive distance to beam.
- Operate in Vacuum
- Innovative micro-channel cooling (-20 °C)
- Separated from the beam by an milled foil
Overview of the Velo upgrade

- 52 modules, 55 µm pitch sensors
- 40M pixels
- Data driven readout
- 5.1 mm sensitive distance to beam.
- Operate in Vacuum
- Innovative micro-channel cooling (-20 °C)
- Separated from the beam by a milled foil

![Velo upgrade diagram]

Graph showing upgrade conditions with 1/p_T vs. IP resolution.

Kazu Akiba
6 Sep 2019 – DESY Seminar
Modules

Modules to be built in Manchester and Nikhef

Ultra high speed copper links developed in Glasgow

Hybrids designed by Liverpool

Sensors developed by Rio/CERN/USC Liverpool

Microchannels developed by CERN and Oxford

ASICs created by Nikhef and CERN

Ultra high speed copper links developed in Glasgow

Microchannels developed by CERN and Oxford

Sensors developed by Rio/CERN/USC Liverpool

Hybrids designed by Liverpool

ASICs created by Nikhef and CERN

Ultra high speed copper links developed in Glasgow

Microchannels developed by CERN and Oxford

Sensors developed by Rio/CERN/USC Liverpool

Hybrids designed by Liverpool
Sensor Prototypes

• Round 0 with CNM and VTT
• Round 1 quite some variants:
  • Hamamatsu:
    • n-on-p 200 µm thick
    • 450 and 600 µm PTE
    • 35 and 39 µm implant
    • UBM
  • Micron:
    • n-on-n and n-on-p
    • 36 µm implant
    • 150, 250 and 450 µm PTE
Testing programme

• Resolution, efficiency, charge collection: Measurements at the SPS using the Timepix3 telescope.

• The Velo sensors must collect $6000 \text{e}^-/\text{MIP} - 99\% \text{ eff}$ at $370 \text{ Mrad} \sim 8 \times 10^{15} 1 \text{ MeV n}_{\text{eq}}/\text{cm}^2$. This is equivalent to 5 years of LHCb Upgrade $50 \text{ fb}^{-1}$
  • The ATLAS IBL – at $550 \text{ fb}^{-1}$ – expects $3.3 \times 10^{15} 1 \text{ MeV n}_{\text{eq}}/\text{cm}^2$ or 160 MRad.

• Prototypes used Timepix3 – TOT allows charge measurements.

• Calibrations performed in the lab with test pulses, radioactive sources and synchrotron x-rays.

• HV tolerance to 1000 V.
Irradiation

- Sensors were irradiated at
  - JSI/IST (n/reactor)
  - KIT (26 MeV p/beam),
  - IRRAD (24 GeV p/beam)
- collected charge > 6000 e⁻.
- The sensors must withstand 1000 V without breakdown after non uniform irradiation.
- Measure efficiency and resolution after irradiation.
Testing prototypes with SPS beam

- Using **Timepix3** telescope
- 4 Timepix3 on 2 “arms”
- Pointing resolution below **1.6 µm**
- Precise **time stamps** (**1.56 ns**) yield a clean Pat. Rec.
- 350 ps track time resolution

- **JINST 14 (2019) no.05, P05026**
Efficiencies

At 1000 V the corners are recovered.
Hit resolution

HPK 200 µm n-on-p
Micron 200 µm n-on-p
Micron 150 µm n-on-n

Best resolutions just below 5 µm.
Charge weighted – Non Binary data.
Charge calibration

- Performed with radioactive sources, Synchrotron (LNLS) and test pulses.

Am 241 per pixel fit

Am 241 spectrum all pixels
Collected Charge – neutron irradiated

- Even if the charge is shared up to 6 pixels the signal would cross the threshold.
Charge Multiplication – IRRAD

- Heavily irradiated regions show higher charge collection at the same voltage.
- The effect increases with the voltage.
- Still under analysis
Temperature dependent Breakdown

- Some sensors show early breakdown which is temperature dependent.
- This effect seems slightly mitigated after some time biased.
- Operate at lower temperatures to gain radiation hardness?
Microchannel cooling

- Efficient cooling solution is required to maintain the sensors at \(-20^\circ\text{C}\)
- No CTE mismatch
- This is provided by the novel technique of evaporative CO\(_2\) circulating in 120 \(\mu\text{m} \times 200 \mu\text{m}\) channels within a silicon substrate.

SEM images of etched wafer before bonding
Silicon on pyrex
Manufacturing and assembly

Channel etching
Cap wafer bonding
Thinning (both sides)
Inlet/Outlet etching

Silicon pre-tinning
Alignment
Soldering

Final assembly can withstand 200 bar
Module Production

- Mechanical construction
- Precision tile placement to 10 μm
- Flex circuit placement
- Wire bonding and HV/LV/data cable attachment

Three modules in SPS test beam
Module Production

- Mechanical construction
- Precision tile placement to 10 μm
- Flex circuit placement
- Wire bonding and HV/LV/data cable attachment

Three modules in SPS test beam
Upgrade I – Status

- Final items for the upgrade under production
- Modules being assembled
- Mechanical installation final planning
- Time to think of the next upgrade?
The Future

LHCb

Run 2

LHCb Upgrade I
Installation starts

Run 3

LHCb Upgrade I

Run 4

LHCb Upgrade I(b): Incremental improvements/prototype detectors

Run 5

LHCb Upgrade II

Run 6

LHCb Upgrade II

LHC = 1.5 \times 10^{34}

L_{int} \sim 8 \text{ fb}^{-1}

LS2

Injector upgrades

L = 2 \times 10^{33}

LS3

HL-LHC Installation, ATLAS/CMS Phase 2 upgrades

LHCb-PUB-2018-009
28/05/2018

LHCb Upgrade I
Installation starts

Run 5

LHCb Upgrade II

Run 6

LHCb Upgrade II

LHC = 2 \times 10^{33}

L_{int} \sim 50 \text{ fb}^{-1}

2029

2030

Run 4 and Run 5
2030 ++
Accumulate 250-350 fb^{-1}

\text{LHCb Upgrade II}

Run 3

Run 2

Run 4

Run 5

Run 6
Baseline (nominal) beam parameters and levelling at IP1&5
- Range of potential solutions to operate LHCb Upgrade II at up to $1.5 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$
- Horizontal and vertical crossing angle scenarios under consideration
- Number of colliding bunches at IP8: 2572
- Levelling by parallel separation at IP8
- Reduction of yearly integrated luminosity at IP1&IP5 - 1% - 2.5%

$\sigma_z^{\text{RMS}} \approx 44.7 \text{ mm}$
$\sigma_t^{\text{RMS}} \approx 186 \text{ ps}$
$\sigma_{\text{comb}}^{\text{RMS}} \approx 240 \text{ ps}$

Pile up $\approx 42$
Baseline (nominal) beam parameters and levelling at IP1&5
- Range of potential solutions to operate LHCb Upgrade II at up to $1.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- Horizontal and vertical crossing angle scenarios under consideration
- Number of colliding bunches at IP8: 2572
- Levelling by parallel separation at IP8
- Reduction of yearly integrated luminosity at IP1&IP5 - 1% - 2.5%

\[ \sigma_{z}^{\text{RMS}} \approx 44.7 \text{ mm} \]
\[ \sigma_{t}^{\text{RMS}} \approx 186 \text{ ps} \]
\[ \sigma_{t}^{\text{comb}} \approx 240 \text{ ps} \]

Pile up $\approx 42$

This is the intensity frontier!
Major hardware development mandatory to install new hybrid pixel detector which can address rates and integrated doses, and add functionality.

10 x higher particle multiplicity
10 x higher radiation damage
10 x higher data-out rates
10 x denser primary vertex environment
Physics considerations

In an environment of ~50 PVs, how can we make B-tagging? How can we map the B to the right PV?

- The cross section of b-bar at 14 TeV is 150 µbarn
- At Upgrade I \( L = 2 \times 10^{33} \text{cm}^{-2}\text{s}^{-1} \)
  - \( \Rightarrow \) 300k b-bar/second! 1 bbar every 100 bunch crossings.
  - At upgrade II this will be 10 times bigger
- High PT and High IP particles coming from many other PVs
  - can we really tag the B?
- Can we really find to which PV the reconstructed B points to?
- Can we do it fast enough?
4D tracking and vertexing

Move towards 4D tracker concept with addition of hit timing:

- Real time track reconstruction critical for Upgrade I and II: Only High Level Trigger
- Timing information will contribute to Pattern Recognition speed and efficiency
- Track time stamping for PV association, PV timing, and combination with downstream detectors for beam gas and background control, calorimetry and time of flight
Move towards 4D tracker concept with addition of hit timing:

- Real time track reconstruction critical for Upgrade I and II: Only High Level Trigger
- Timing information will contribute to Pattern Recognition speed and efficiency
- Track time stamping for PV association, PV timing, and combination with downstream detectors for beam gas and background control, calorimetry and time of flight
Pattern recognition improvement

LHCb Velo
Very preliminary

LHCb Velo
Very preliminary

PR efficiency

efficiency

search window (μm)

efficiency

search window (μm)

13μm

27μm

55μm

100 ps

50 ps

no timing

$d = 1\%X_0, a = 55\mu m$

$d = 1\%X_0, a = 27\mu m$

$d = 1\%X_0, a = 13\mu m$

$d = 1\%X_0, a = 55\mu m$

$d = 1\%X_0, a = 55\mu m, \sigma_t = 100\,\text{ps}$

$d = 1\%X_0, a = 55\mu m, \sigma_t = 50\,\text{ps}$
Timing gain

LHCb Velo
Very preliminary

gain in number of operations

Gain ≈ \# interpolations (seeding)
\# \Delta a \ comparison (extension)

LHCb Velo
Very preliminary

Gain ≈ \# interpolations (seeding)
\# \Delta a \ comparison (extension)

efficiency

search window (μm)

a = 55 μm

a = 27 μm

time resolution (ps)

a = 55 μm
System wide implementation

- Pixel matrix variations affect the resolution.
- With better resolutions, per pixel corrections become more and more important.
- Telescope is based on 300 µm thick p-on-n sensors, which are not optimized for timing.
Improving the timing

- Raw resolution
- Time walk compensation
- Pixel matrix systematics
- Track based drift time (coming soon)

\[ \sigma = 1.040 \text{ ns} \]
\[ \sigma = 0.991 \text{ ns} \]
\[ \sigma = 0.850 \text{ ns} \]

K. Heijhoff Open Medipix meeting - may 2019
ASIC challenges

- Cope with increase in Radiation damage
- Analog front-end does not scale much -> about the same size as VeloPix/Timepix4 (25% of pixel)
- Cope with hit pile up:
  - @Upgrade I, MIP discharge time ~300 ns for 1% max pileup.
  - Upgrade II would need 10 times faster rate.
- Per pixel TDC with time resolution < 50 ps.
- More information in output and higher hit rate.
- Time-walk correction?
- Clock distribution effects?

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>technology</td>
<td>130 nm</td>
<td>65 nm</td>
<td>28 nm</td>
</tr>
<tr>
<td>Pixel size</td>
<td>55x55 µm²</td>
<td>55x55 µm²</td>
<td>55x55 µm²</td>
</tr>
<tr>
<td>Sensitive area</td>
<td>2 cm²</td>
<td>7 cm²</td>
<td>2 cm²?</td>
</tr>
<tr>
<td>Packet size</td>
<td>24 bit</td>
<td>64 bit</td>
<td>64 bit?</td>
</tr>
<tr>
<td>Max rate</td>
<td>400 Mhits/cm²/s</td>
<td>180 Mhits/cm²/s</td>
<td>4000 Mhits/cm²/s</td>
</tr>
<tr>
<td>Time resolution</td>
<td>25 ns</td>
<td>200 ps</td>
<td>20-50 ps?</td>
</tr>
<tr>
<td>Output data rate</td>
<td>20 Gb/s</td>
<td>81 Gb/s</td>
<td>500 Gb/s?</td>
</tr>
</tbody>
</table>

- Fruitful collaboration with the Medipix group has yielded the VeloPix ASIC for the LHCb Upgrade I.
- the Timepix4, with impressive fast timing capabilities is scheduled to appear soon.
- LHCb Upgrade II requirements more demanding still but could draw on similar concepts
**Sensors**

- Sensor R&D considering:
  - Thin planar
  - LGAD and iLGAD
  - 3D concepts
- Starting an evaluation programme using Timepix4 as a prototype FE.

- Final temporal resolution under consideration between 20 and 200 ps per hit.
- Many manufacturers shown prototypes: CNM, FBK, HPK…

![Diagram of sensor design](image_url)
Cooling for next upgrade

- Operation in vacuum demands active cooling.
- Microchannel approach could be too complex if a replacement is planned.
- Studying the possibility to operate at lower temperatures $< -30^\circ C$
  - Avoid runaway at high radiation damage
  - Mobility gets better at low temperatures
  - Requires the R&D of different cooling fluids...

General needs: lightweight, possibly partially replaceable modules and mechanics

Micro channels could get cheaper

3d printed Titanium substrates, already prototyped for Upgrade I
Design considerations – Radiation

- At 5 mm, fluence translates to: $1.6 \times 10^{14} \, 1\text{MeV} \, n_{eq}/fb$. 
  after 300/fb $\Rightarrow$ $\sim 5 \times 10^{16} \, n_{eq}$
- Very challenging constraint for fast timing devices.
- A dual technology system could combine radiation hardness at the inner part and timing resolution at the outer region.
- Planning for a replacement could allow a less resistant sensor technology.

Possible design with 2 technologies: outer sensors with better timing but lower radiation resistance.
Considerations for the trigger

• VELO is an essential part of trigger decision.
  • Highest granularity, secondary vertices search, real time candidates.
  • Time measurement can provide input info ($t_0$) to other sub detectors

• VELO data must be processed quickly
  • Clustering might need to be done at the ASIC or in FPGAs.
  • Time ordering is needed in the further processing (time consuming).

• Could use time stamps to suppress tracks unrelated to the triggered candidate ➔ clean up the event.
  • Need to prove that association across subdetectors is possible.
Mechanics

- RF box construction is a very complex and demanding procedure.
- No foil would be ideal design.
- Issues:
  - Outgassing detectors.
  - Harmful wakefield
  - Beam mirror current.
- Construction without a foil also makes more difficult to replace detectors.
Mechanics

- RF box construction is a very complex and demanding procedure.
- **No foil** would be the ideal design.
- Issues:
  - Outgassing detectors.
  - Harmful wakefield
  - Beam impedance.
- Construction without a foil also makes more difficult to replace detectors.

Initial solid forged Al alloy block

>98% of material removed

Internal mould support during machining steps

Possible sensor replacement mechanism
Summary

• LHCb is building and installing a whole new detector. NOW.

• We are also planning a next upgrade to run at up to 10 times higher instantaneous luminosity.

• The high Primary Vertex density motivates a Vertex detector with high resolution timing.

• The Secondary Vertex reconstruction and association to its origin PV require precise Impact Parameter. Fast timing can allow this matching at the high pile up regime.

• Fast timing shows promising results in the pattern recognition as well.

• An ultra high radiation resistant sensor and ASIC technology is required to operate through the whole lifetime.

• Alternatively a suitable replacement strategy drives mechanical technology R&D.
Thanks

Look at this! This is the biggest luminosity in the world!

Ha ha! I can’t wait to take data with it!

How about the radiation damage?

Reality continues to ruin my life.

Maybe you could place your detector a bit further from it.
First test beam with final modules in 2006
Luminosity ambitions Upgrade II

![Graph showing luminosity ambitions and upgrade stages]

- Current LHCb
- Upgrade I
- Upgrade II

- LS1
- LS2
- LS3
- LS4
- LS5

- Max Luminosity [10^{33} cm^{-2} s^{-1}]
- Integrated Luminosity [fb^{-1}]

Year:
- 2010
- 2015
- 2020
- 2025
- 2030
- 2035
Timing experience: Timepix3

• Timepix3 telescope experience shows that “4D” tracking is the way forward.
• The telescope shows virtually no ghost track in the 10 ns window used in the reconstruction.
• Possible to calculate the slope inside the ASIC in a cluster: every cluster would be also a stub.
System-wide implementation

- Precise **hit timing** over several planes has been used in the **Timepix3 (1.56 ns TDC)** Telescope for pattern recognition and for **track time** measurement.

- Sensors were not optimized for **time resolution** → results can still be improved.

- We are investigating new sensors for more precise timing.

- Track reconstruction is clean and **time resolution** from the combination of planes is compatible with combination of independent measurements.

Time resolution determined internally, only with the telescope planes and also with scintillators.
Charge calibration: LNLS*/Campinas

XAFS1 - X-ray Absorption and Fluorescence Spectroscopy
4 to 24 keV photons with $\sigma E/E \sim 0.01\%$. 

*National Synchrotron Light Lab
Charge calibration: LNLS*/Campinas

*National Synchrotron Light Lab/Brazil
**IV Model**

- Current generated due to avalanche in the sensor.
- Avalanche is proportional to the radiation damage.
- (Shot noise increases with temperature and induces breakdown)*
- Related to the charge multiplication
Motivations for Upgrade II

Many channels will still be statistically limited by the end of Runs 3 and 4.

LHCb has no competitor in many decay channels.
Foil

- Separation from primary LHC vacuum introduces material which degrades the IP performance
  - physics performance benefits from no foil.

Velo.0

Corrugations needed to minimize material.

Upgrade I

Foil is the biggest contribution before second hit