The LHCb VELO Upgrade

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on behalf of the LHCb VELO group
Overview

LHCb / Current VELO / VELO Upgrade

Posters

- M. Artuso: The Silicon Micro-strip Upstream Tracker for the LHCb Upgrade
- R. Quagliani: SciFi - A large Scintillating Fibre Tracker for LHCb
- D. Saunders: The Timepix3 Telescope and LHCb Upgrade R&D measurements

Overview

[Image of a schematic diagram showing various components of a high-energy physics detector system, including RICH, Calorimeter, Muon system, VELO, and Tracking stations.

**VELO**

**VErtex LOcator** is a silicon detector surrounding the collision region, providing excellent
- impact parameter resolution
- identification of secondary vertices

[J. Instrum. 9 (2014) P09007]
The current VELO microstrip detector

- 2 retractable detector halves at 5 (30) mm from beam when closed (open).
- 21 stations per half with an R and $\phi$ sensor.
- First active strip @ 8 mm from the beam.
- Operates in secondary vacuum.
- 300 $\mu$m foil separates detector from beam vacuum.
- CO$_2$ cooling system (Operates @ -30°C, Sensors @ -10°C).
LHCb Upgrade concept

Precision of many physics measurements at LHCb will be statistically limited at end of Run II:

- Increase luminosity to boost statistics:
  \[ 4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} \Rightarrow 2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1} \]
- 50 fb\(^{-1}\) expected after LS2

- Many hadronic channels saturate, due to energy cuts in the trigger

- Remove hardware trigger
- 1 MHz \(\Rightarrow\) 40 MHz readout rate
- Data taking starting in 2021 (Run III)

[16 June 2016 Manchester Group Meeting]
VELO Upgrade

- To be operated @ 40 MHz and $2 \times 10^{33} \, \text{cm}^{-2}\text{s}^{-1}$ and at 5 mm from the beams
  - 10× data rates
  - 10× max fluence
  - sensors to be kept @ -20 °C

- Improve detector performance
  - track reconstruction
  - resolution

- The plan:
  - new pixel detector
    - no ghost tracks
    - faster reco algorithm
  - new front-end electronics
  - thinner RF-foil
  - more efficient cooling interface

[CERN-LHCC-2013-021]
**VELO Upgrade in numbers**

<table>
<thead>
<tr>
<th>Feature</th>
<th>VELO</th>
<th>Upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sensors</strong></td>
<td>R &amp; $\phi$ strips 0.22 m$^2$</td>
<td>Pixels 0.12 m$^2$</td>
</tr>
<tr>
<td></td>
<td>172,032 strips electron collecting 300 $\mu$m thick</td>
<td>41 M pixels electron collecting 200 $\mu$m thick</td>
</tr>
<tr>
<td># of modules</td>
<td>42</td>
<td>52</td>
</tr>
<tr>
<td>Max fluence</td>
<td>$1.3 \times 10^{14}$ MeV $n_{eq}$ cm$^{-2}$</td>
<td>$8 \times 10^{15}$ 1 MeV $n_{eq}$ cm$^{-2}$</td>
</tr>
<tr>
<td>HV tolerance</td>
<td>500 V</td>
<td>1000 V</td>
</tr>
<tr>
<td>ASIC Readout rate</td>
<td>1 MHz</td>
<td>40 MHz</td>
</tr>
<tr>
<td>Total data rate</td>
<td>150 Gb/s</td>
<td>2.8 Tb/s</td>
</tr>
<tr>
<td>Total Power consumption</td>
<td>1 kW</td>
<td>1.6 kW (30 W/module)</td>
</tr>
</tbody>
</table>
VELO Upgrade Module concept

cf rods
CO₂ cooling pipes
kapton hybrid
Si micro-channels cooling plate

data tapes
cooling connector
Si sensors (4 per module)
Micro-channel cooling interface

- baseline: silicon substrate metallized with Ti+Ni+Au
- same CTE as sensors + low material budget
- routing of channels customizable
- pressure: 14 bar @ -30 °C, 60 bar @ 22 °C, (to be qualified at 180 bar)

- 120 \times 200 \mu m micro-channels (19\times)
- 60 \times 60 \mu m high impedance restrictions
- cooling power > 36 W
Cooling interface prototype

- Prototype design
  - close to real layout
  - thermal capacity = 1 VELO module

- Pyrex-Silicon sample

First full-size plates in March 2017
Aluminium RF-foil

- Accommodate modules
- Vacuum tight
- Light (300 μm $\rightarrow$ 250 μm)
- Corrugated
- Thermally stable
- Rad-hard

RF foil

LHCb simulation

cooling
corrugated
other
RF box
hybrids
ASICs
sensors

Cooling conn.

Al mould 1 mm smaller than box

Mill inside of box

Mill outside of box

Half box prototype
Sensor is bump-bonded to 3 VeloPix ASICs

- 256 x 256 pixels, 55 x 55 µm pixel size with elongated pixels (137.5 µm) in the region between ASICs

- Sensor baseline: n-on-p 200 µm thickness

VeloPix: up to 900 Mhits/s (data driven readout)
Testbeam campaign 2014-15

- Rigorous series of testbeams to qualify the sensors
- Velo Sensors must collect at least 6000 e-/MIP @ 99% efficiency

- At 50 fb\(^{-1}\) ➔ \(8 \times 10^{15}\) 1 MeV \(n_{eq}\) cm\(^{-2}\) (or 370 MRad)
- ATLAS IBL @ 550 fb\(^{-1}\) = \(3.3 \times 10^{15}\) 1 MeV \(n_{eq}\) cm\(^{-2}\) (or 160 MRad)

- Non-uniformity of radiation dose (factor 100 edge-to-edge)

- Testing HPK and Micron:
  - n-in-p (200 μm)
  - n+-in-n (150 μm)
  - 250-600 μm guard ring sizes
  - 35-39 μm implant widths

- Sensors bump-bonded to Timepix3 ASICs

- Sensors irradiated \((2-8 \times 10^{15}\) MeV \(n_{eq}\) cm\(^{-2}\)) in 5 different facilities with neutrons (uniform) and protons (non uniform)
Testbeam campaign 2014-15

Intra-pixel efficiency on neutron-irradiated sensors:
- Decreases in the corners at low bias.
- Scales with implant width.
- For normal incidence tracks.
- Efficiency reaches 99% at 1000 V.
- baseline: 39 μm implant

Conditions:
- bias voltage: 300 V
- irradiation: $8 \times 10^{15}$ 1 MeV $n_{\text{eq}} \text{cm}^{-2}$
- sensor thickness: 200 μm

(pixel corner (18 × 18 μm))
The new VELO will have to cope with $10 \times$ radiation and $10 \times$ data rates.

- New module design based on pixels sensors mounted on a Si micro-channel substrate.
- Bi-phase CO$_2$ micro-channel prototype performs as expected.
- Aluminium RF-foil prototypes progressing well.
- Sensor tiles irradiated and extensively characterised in test-beams.
- VeloPix ASIC submitted in May 2016.

Install in LHC Long Shutdown 2 and take data in Run III
Thanks
Spares
The LHCb detector

~20 μm IP resolution @ $p_T > 2$ GeV

$\sigma_m \sim 8$ MeV for $B^+ \rightarrow J/\psi K^+$, 25 MeV for $B \rightarrow \mu^+ \mu^-$

Excellent muon identification $\varepsilon = 97\%$, misid 2%

$\varepsilon(K \rightarrow K) 90\%$ for $\varepsilon(K \rightarrow \pi) < 10\%$

$\sigma(E)/E \sim 10\%/\sqrt{E} \ominus 1\%$

$\sigma_m \sim 90$ MeV for $B^0 \rightarrow K^* \gamma$
LHCb Upgrade

- **VELO** Si strips (replace all)
- **Silicon Tracker** Si strips (replace all)
- **Outer Tracker** Straw tubes (replace R/O)
- **Muon MWPC** (almost compatible)
- **RICH** HPDs (replace HPD & R/O)
- **Calo** PMTs (reduce PMT gain, replace R/O)
Alignment

- VELO halves centered around beam at each fill, when beams declared stable.
- Beam position determined from vertex reconstruction with tracks in right or left half.
- Misalignment from distance between the two reconstructed vertices.
- Fully automated procedure (~210 s).
- Stable within ±5 μm (x).
- Single hit resolution:
  - linear dependence on the strip pitch in projected angle bins.
  - better resolution for larger angles.
- IP resolution of $\sim 13$ $\mu$m for infinite momentum tracks.
- $S/N(R) \approx 19, \ S/N(\Phi) \approx 21$
Performance

- Excellent cluster finding efficiency:
  - CFE = 99.51 ± 0.02 % [all channels]
  - CFE = 99.98 ± 0.02 % [bad strips excl, 0.77%]

- PV resolution of 13 μm for 25 tracks (typical case).

- Excellent tracking efficiency.
Testbeam

- **Timepix telescope**
  - Designed for the LHCb upgrade
  - Composed by 9 Timepix assemblies (with 300 μm thick sensors)
  - DUT can be moved/rotated and cooled
  - Resolution at DUT plane < 2 μm

- **Focus on:**
  - sensor performance after irradiation (Medipix3)
  - evaluation of guard-rings, edge efficiency
  - prototype strip module
μ-channel wafer bonding

Hydrophilic bonding

Hydrophobic bonding

Rupture and delamination (shiny surface)

Rupture at higher surfaces

With more realistic samples

<table>
<thead>
<tr>
<th>Hydrophilic</th>
<th>Hydrophobic</th>
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<tr>
<td>Rupture at ~400 bars</td>
<td>No rupture at 700 bars (limit of the pump)</td>
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X-ray imaging of soldering samples

Sample pictures (good and bad):
expected performance after irradiation

Charge collection efficiency decreases with radiation damage...

...but effect **not propagated** to track reconstruction efficiency or IP resolution thanks to hit redundancy in the tracking system!
VeloPix & DAQ

- Derived from Timepix3 ASIC.
- Based on 130 nm CMOS technology (TSMC).
- Data-driven readout.
- 2×4 pixels grouped to SuperPixel.

- Timepix3 is general purpose.
- VeloPix is optimized for speed: VELO will produce 3 Tbit/s.
- Radiation hardness and SEU robustness.
- Binary hit information.

- Data gathered in SuperPixels:
  - shared BCID and address
  - 30% data reduction
- SP data propagated downwards:
  - arbiter decides who can send.
  - time continuity lost.

- Back end electronics must cope with a huge amount of data:
  - TELL40 (upgrade of TELL1, current DAQ board) receives and builds events using FPGAs.
  - All the information is assembled and passed on to computing farm, stripping down redundant data.
  - Further processing and full reconstruction in the trigger farm.
PlanB

2 pieces 25 mm thick of poco foam HTC with milled profile for capillary, glued together