The VELO Pixel Detector Upgrade

Emma Buchanan
University of Bristol

On behalf of the LHCb VELO Upgrade Group
Pixel 2016, 5th September 2016, Sestri Levante
Overview

- LHCb Experiment and Upgrade Motivations
- Current VELO vs Upgraded VELO
- VELO Challenges and Upgrade Specifics
- Timeline of the Upgrade Campaign
- Sensor prototype testing
- Conclusions
The Large Hadron Collider Beauty Experiment (LHCb)

Searching for New Physics through measuring CP violation and rare decays of heavy flavour mesons

LHCb experiment: Utilising a tracking system, 2 RICH detectors for PID, Electromagnetic and Hadronic Calorimeters and a muon system.

Single arm spectrometer optimised to study particles containing b and c quarks
Why do we need to upgrade?

To Improve the physics performance!

Increased statistics

→ improved sensitivities to very rare decays

To achieve this we need to increase the luminosity

![Instantaneous Luminosity: LHCb runs at ~20% of ATLAS and CMS Luminosity. Achieved using offset beams, moving closer during the fill.]

\[
4 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1} \quad \rightarrow \quad 2 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}
\]

Limited by the trigger and the radiation damage

* Design luminosity of LHCb is \( 2 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1} \)
Challenges faced with increased luminosity

Current readout and trigger limits the amount of data that can be recorded

✦ 1.5 interactions per bunch crossing
✦ Hardware trigger limited to a 1MHz readout

Will remove hardware trigger and replace with a flexible software trigger

✦ Readout at 40MHz
✦ 3.6 - 7.2 interactions per bunch crossing

To achieve this we must

✦ Upgrade all front end readout electronics
✦ Upgrade certain sub detectors to improve tracking and withstand the increased luminosity
Reconstructs primary and secondary vertices
• 88 semi circular silicon sensors
  • 300µm
  • n-on-n strips
  • R-φ geometry
• ~8mm from the beam
• Retractable during unstable beams
• Separated from LHC vacuum by RF Foils
• Cooling provided by evaporative CO₂
The Upgraded VERTex LOcator (VELO)

New Hybrid Pixel Sensors with custom made VeloPix ASIC

- New L shaped geometry
- Thinner Sensors
  
  \[300\mu m \rightarrow 200\mu m\]
- Closer to the beam
  
  \[8 \text{ mm} \rightarrow 5.1 \text{ mm from first active pixel}\]
- Micro channel cooling
- Thinner RF foil
- Read out rate of 40MHz
- Main mechanical infrastructure will remain
Challenges for the VELO

Highly inhomogeneous irradiation damage

Max hadron fluence, $8 \times 10^{15} MeV_{eq}/cm^2$ at innermost tip
- Factor 40 lower expected on opposite side
- Due to irradiation effects sensors needs to withstand greater HV

Cooling system

Greater power dissipation
- Cooling to avoid thermal runaway
- Power consumption $\sim 1.5W$ per cm$^2$

Closer to the beam

Lower Material budget
- Keep module design as thin as possible
- Closer and thinner RF foil
The Sensors and ASIC

**Hybrid Pixel Detectors**

**Sensors**
- n-on-p
- 200µm thick silicon
- Bump bonded to VeloPix ASIC
  - based on TimePix/MediPix family

**VeloPix**
- 256x256 pixels/ASIC, 55x55µm² pixels
- Binary readout
- Thinned to 200µm
- Zero suppressed, data driven readout
  - every hit is time stamped and immediately sent of the chip
- Fast - Time walk ~25ns
Cooling

Evaporated CO2 flows via micro channel etched in the silicon substrate

Will act as the mechanical backbone of the module

✦ 2 sensors mounted on either side
✦ High thermal efficiency
  ✦ Direct contact with ASIC surface
  ✦ 19 channels under each ASIC
✦ Lower material budget
  ✦ Combined thickness of 400µm
  ✦ Trenches are 120µm deep
✦ Full sensor maintained at -30°C
✦ Radiation hard

Thermal map from simulation (°C), variation of less than 1°C
RF Foil

Two thin RF foils, leak tight barrier between LHC and VELO Vacuums

- Accommodate the modules
- 250µm thick Aluminium
- Close to the beam (~3.5mm)
- Allowing modules to close around interaction region
- Radiation Hard
- Thermal stability
Where are we?

<table>
<thead>
<tr>
<th>Beam Crossing</th>
<th>50 ns</th>
<th>-</th>
<th>25 ns</th>
<th>-</th>
<th>25 ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>TeV</td>
<td>0.9-7</td>
<td>8</td>
<td></td>
<td>13-14</td>
<td></td>
</tr>
<tr>
<td>Instant Luminosity</td>
<td>$10^{32}$</td>
<td>3-4 x $10^{32}$</td>
<td>LS 1</td>
<td>$4 \times 10^{32}$</td>
<td>LS 2 LHCb Upgrade</td>
</tr>
<tr>
<td>Integrated Luminosity</td>
<td>3 fb$^{-1}$</td>
<td></td>
<td>5-7 fb$^{-1}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Upgrade will be during Long Shutdown 2!

Making good progress

- Prototypes of both the RF foil and cooling substrates
- VeloPix has been submitted
- Wafers on their way to CERN now for testing
- Sensor prototype testing has been ongoing since July 2014

Start of LS2 upgrade delayed until 2019
Sensor Prototypes

Testing sensors from both Hamamatsu and Micron

- Micron n-on-p
  - 250 µm GR
  - 36 µm implant
  - 150 µm thick

- Micron n-on-n
  - GR on back
  - 150 µm thick

- HPK n-on-p
  - 450 µm GR
  - 200µm thick

- HPK n-on-p
  - 200 µm thick
  - 39 µm implant

✦ n-on-n and n-on-p
✦ 150 - 200µm thickness
✦ 250, 450, 500µm inactive edge
✦ 35 & 39µm implant width

- 256x256 pixels/ASIC, 55x55µm² pixels
- Bump bonded to TimePix3

Uniform and non-uniformly irradiated at KIT, IRRAD, JSI at fluences

05/09/2016
Emma Buchanan PIXEL 2016
Sensor Requirements

As previously discussed the VELO is exposed to highly inhomogeneous irradiation damage

Require that sensors perform well both before and after irradiation

Benchmarks for detector performance are:

- Operate at high bias voltage
- No breakdown before 1000V for irradiated sensors
- Uniform efficiency >99%
- Charge collection >6000e at the end of lifetime
- Excellent spatial resolution

Prototype sensors are tested in both the lab and testbeam environments
Test beam

- Commissioned the TimePix3 telescope in July/August 2014 at CERN PS
- Successful test beam campaign at CERN SPS in November/October 2014 and May 2015
- Characterization of prototype assemblies
- High rate test of TimePix3
- Irradiated sensors were also tested

01/06/2015

S.Richards VERTEX 2015

Constructed specifically for LHCb Upgrade studies

- Two arms with 4 TimePix3 devices each (bonded to 300µm silicon)
- Device Under Test (DUT) installed in the centre
  - Temperature controlled dry air cover
  - x, y and θ motion controls
  - HV controls
- Pointing resolution ~ 2µm for 180 GeV beam
- Timing resolution ~ 1ns
Testbeam Results - Bias Voltage

Irradiated sensors must reach 1000V without breakdown

- Radiation induced trapping centres degrade the signal
- Signal can be recovered by applying high bias voltages

Non-Uniform irradiation profile across sensor

- Innermost region will require a high bias
- Outer region needs to sustain this voltage without breakdown

Plot of the IV curves for irradiated Hamamatsu sensors

Majority of prototypes reach this requirement
Testbeam Results - Efficiency

Require a uniform efficiency > 99% pre and post irradiation

\[ e = \frac{n_{\text{DUT Associated Clusters}}}{n_{\text{Tracks}}} \]

**Efficiency as a function of in-pixel position for** non-irradiated **sensor**

In-pixel efficiency for non irradiated sensor

Distribution of In-pixel efficiencies to determine average

Sensor: 200 µm n-on-p sensor from Hamamatsu, 450 µm inactive edge, 39 µm implant width.

Average efficiency is \((99.857 \pm 0.003)\)% over full sensor
Testbeam Results - Efficiency

Efficiency as a function of in-pixel position for **irradiated** sensors

Inefficiencies are caused by decreased charge collection at the corners.

Efficiency improves with bias voltage

Larger implant improves efficiency in corners

Average efficiency is reduced but still close to 99% at high bias voltage

---

Efficiency as a function of voltage for a range of sensors

In-pixel efficiency for irradiated sensor for two different implant widths, uniform efficiency is seen in the corners when voltage is increased

S17, S15 & S22: 200µm HPK, n-on-p, 450 µm inactive edge
S29: 150µm Micron, n-on-n, 450 µm inactive edge

05/09/2016

Emma Buchanan PIXEL 2016
Testbeam Results - Charge Collection

Investigate the required bias voltage to recover lost charge at different operation times

- Radiation induced trapping centres degrade the signal -> reduced S/N
- Signal can improved by applying high bias voltages

Collected charge for a range of irradiated sensors, as a function of the bias voltage

8 × 10^{15} 1MeVn_{eq}/cm^2 is the full lifetime dose

S6, S17 & S22: 200µm HPK, n-on-p, 450 µm inactive edge
S27 & S29: 150µm Micron, n-on-n, 450 µm inactive edge

Collected charge improves with bias to sufficient level

05/09/2016
Emma Buchanan PIXEL 2016
Testbeam Results - Spatial Resolution

Need excellent spatial resolution

Resolution degrades due to charge trapping

\[ \sigma = \text{Cluster position} - \text{Predicted track position} \]

Resolution as a function of angle, for two sensors pre and post irradiation

Resolution is \(~5\, \mu m\) pre irradiation and better than \(~9\, \mu m\) at optimal angle.
Testbeam Results - Sensor Depth Properties

Can test timing and charge collection as a function of depth

- DUT placed 85 degrees w.r.t the beam
- Incoming particle travels through many pixels
- Long clusters ~42 pixels
- Each pixel is assigned a depth

Can calculate depth: \( d(i) = \frac{P \times N(i)}{\tan(\theta)} \)

For charge collection

Charge distribution collected for each depth is fitted with a landau

For time walk

The time charge takes to cross threshold is compared to the time predicted by the tracking information
**Testbeam Results - Sensor Depth Properties**

**S6: 200µm HPK, n-on-p, 450 µm inactive edge, non irradiated**

**Collected charge profile as a function of depth**

- At depletion all charge is collected
  - Below depletion the charge diffuses between the depletion edge and sensor backplane

**Time to threshold as function of depth**

- At depletion the time walk is < 4ns
  - Below depletion charge needs more time
  - > 10ns
  - Again due to diffusion
Testbeam Results - Edge Effects

Excess charge was found during a corner scan of a Micron n-on-p DUT
- Only seen in the first row and column next to the edge
- Suggests that the guard ring is not correctly draining the charge from tracks travelling through the inactive area

Hit map from testbeam, with zoom of one corner where excess charge is seen in the 1st row and column

To test this theory, need to investigate the deposited charge as a function of the predicted hit position from tracking
Testbeam Results - Edge Effects

The tracking does not use DUT cluster information

- Can extrapolate where the track passed through the sensor or guard ring

Can clearly see charge deposited past the edge of the 1st row of pixels

This effect is not observed in Hamamatsu n-on-p

Guard ring is not draining the charge correctly
Testbeam Results - Edge Effects

The opposite is seen for Micron n-on-n

The guard ring is draining the charge from the neighbouring pixels

Results for angle analysis found…

- Tilted border between collection region of guard ring and pixel matrix
- Field shape of the guard ring is such that it collects charge from tracks travelling through the first row/column

Effects are seen in the Micron n-on-n 250μm and n-on-p 250μm & 450μm guard ring designs

Potential to add 2 extra rows and columns of floating pixels to the edges to drain the charge
Conclusions

Redesign of the VELO to allow for increased data rate

- Silicon strips ➔ Hybrid pixel detector

Cooling system and RF foil prototypes progressing well

Successful testbeam campaigns to test sensor performance

- Able to sustain high bias voltages
- Efficiencies ~99%
- Charge collection >6000e
- Excellent spatial resolution

VeloPix was submitted in May and has arrived

Presentation on physics benchmarks for the upgraded VELO will be presented tomorrow

On course to install during long shutdown 2!
Backup
One module consists of 4 sensors in a L shape geometry

- Two on each side
- Glued onto the micro channel silicon substrate
- Wire bonded to two hybrids
- Providing the power, HV & chip control etc.
Collect maximum number of hits within a bunch crossing - 25ns

Hits with low charge will suffer time walk

\[ t_{\text{hit}} - t_{\text{track}} \] Is the difference between hit and track timestamps

---

Testbeam Results - Timing

The TimePix3 has shown adequate timing, can expect similar performance in VeloPix