The LHCb Upgrade and the VELO

Paula Collins
On behalf of the LHCb collaboration
Contents

- The LHCb Upgrade Programme
- The VELO sub-detector
  - VELO Upgrade I
    - Sensors and ASICS
    - Cooling
    - Foil
    - Modules
    - Assembly and Installation
- Upgrade II - VELO perspective
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The LHCb Upgrade

Indirect search strategies for New Physics e.g. precise measurements & the study of suppressed processes in the flavour sector become ever-more attractive; current LHC experience is that direct signals are elusive.

Our knowledge of flavour physics has advanced spectacularly thanks to LHCb. Maintaining this rate of progress beyond Run 2 requires significant changes

The LHCb Upgrade

1) Full Software trigger
   - Removal of current 1 MHz bottleneck
   - Allows effective operation at higher luminosity
   - Improved efficiency in hadronic modes

2) Raise operational luminosity to \(2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}\)
   - Necessitates redesign of several sub-detectors and overhaul of readout

Huge increase in precision, in many cases to the theoretical limit, and the ability to perform studies beyond the reach of the current detector

Flexible trigger and unique acceptance opens up opportunities in topics apart from flavour \(\rightarrow\) a general purpose detector in the forward region
Upgrade I detector challenges

Maintain Physics Performance in very high occupancy and pile up conditions
- combinatorial complexity and fake tracks
- Pile-up energy
- mitigated by granularity, high readout speed and trigger innovations (timing will be for Upgrade II)

Operate with detector elements exposed to very high radiation doses
- Radiation hardness needed for all subdetectors

Control Systematics to match statistics
- low material budget hence creative solutions needed at mechanics level; support structures, cooling, power delivery, and thin detectors for innermost regions
- Cope with tremendous DAQ and data processing challenges
Pre-Upgrade Detector
Upgrade I Detector

40 Tb/s of data to trigger farm
Required Modifications

**VELO:** replace with new Si-pixel detector

**TT:** replace with new Si-strip detector

**OT and IT:** replace with scintillating fibre (Sci-Fi) tracker

**Calo system:**
- replace FE electronics and remove PS/SPD
- Full s/w trigger → Replace read-out boards and DAQ

**RICH:** new photodetectors and FE electronics, and modify RICH1 optics and mechanics

**Muon system:**
- replace FE electronics and remove M1

**OT and IT:** replace with new Si-strip detector
**New Subdetector Elements**

**Tracking**

**VELO:** 52 hybrid pixel modules

**UT:** 4 planes of Si microstrip detectors: ~1000 sensors

**SciFi:** 128 modules (0.5 x 5 m²) arranged in 3 stations × 4 layers

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**CALO and PID**

**RICH system:**
Redesigned mechanics to cope with increased occupancy; new MaPMTs and readout electronics

**ECAL:**
New FE electronics and PMTs adjusted to high occupancy: preshower removed

**HCAL:**

**Muon:**
MWPCs kept; new FE electronics for increased granularity; PAD detectors for inner regions

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SciFi – Upgrading LHCb with a Scintillating Fibre Tracker - Lukas Gruber
Thursday Parallel Session
LHCb Upgrade Programme

Upgrade I
- Major upgrade; about to start data taking
  - Increase in luminosity by factor 5, to $\mathcal{L} = 2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$
  - Transform entire detector to 40 MHz readout

Upgrade II:
- Expression of Interest & Physics case
- Support from 2020 European Strategy
  - Further increase in luminosity by factor 7.5, to $\mathcal{L} = 1.5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$

### Run 2
- $L = 4 \times 10^{32}$
- $L_{\text{int}} \sim 8$ fb$^{-1}$

### Run 3
- Lumi $2 \times 10^{33}$

### Run 4
- Lumi $2 \times 10^{33}$

### Run 5,6
- Lumi $1-2 \times 10^{34}$

- $L_{\text{int}} = 50$ fb$^{-1}$
- $L_{\text{int}} = 300$ fb$^{-1}$
LHCb Upgrade Programme

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<table>
<thead>
<tr>
<th>Year</th>
<th>Run 2</th>
<th>Run 3</th>
<th>Run 4</th>
<th>Run 5,6</th>
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<tbody>
<tr>
<td>2017</td>
<td>LS2</td>
<td>LS1</td>
<td>LS3</td>
<td>LS4</td>
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<tr>
<td>2018</td>
<td>$L = 4 \times 10^{32}$</td>
<td>$L \text{int} \sim 8 \text{ fb}^{-1}$</td>
<td>$L \text{int} = 50 \text{ fb}^{-1}$</td>
<td>$L \text{int} = 300 \text{ fb}^{-1}$</td>
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<tr>
<td>2019</td>
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CERN-LHCC-2017-003  LHCb-PUB-2018-009

22/02/22  The LHCb VELO Upgrade I, VCI 2022
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The (old) LHCb Vertex Locator (VELO)
The LHCb Vertex Locator (VELO)

R measuring strips with double metal r/o

Phi measuring strips
Placed around the LHC beams
Placed around the LHC beams
Placed around the LHC beams

1 cent coin

5.5 mm

8 mm
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VELO Upgrade I

rows of silicon microstrip modules  
rows of silicon hybrid pixel modules

Pixel design with micro-channel cooling superior to strips for impact parameter resolution and efficiency
## Systems Comparison

<table>
<thead>
<tr>
<th>Feature</th>
<th>old VELO</th>
<th>VELO Upgrade I</th>
</tr>
</thead>
<tbody>
<tr>
<td>operation</td>
<td>2010 – 2019</td>
<td>2022 – 2030</td>
</tr>
<tr>
<td>Sensors</td>
<td>R, $\phi$ strips, semicircular</td>
<td>pixels, L-shaped geometry</td>
</tr>
<tr>
<td></td>
<td>173,032 strips (~0.2 M)</td>
<td>41 M pixels</td>
</tr>
<tr>
<td>Distance From Beam</td>
<td>8.2 mm</td>
<td>5.1 mm</td>
</tr>
<tr>
<td>Maximum Fluence</td>
<td>$4.3 \times 10^{14}$ 1 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>$\sim$150 Gb/sec</td>
<td>2.8 Tb/sec</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>$\sim$0.8 kW</td>
<td>$\sim$1.6 kW</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>$\sim$-8 °C</td>
<td>$\sim$-25 °C</td>
</tr>
</tbody>
</table>
System Overview

- Proton beam
- RF foils
- Primary vacuum
- Secondary vacuum
- Readout chain
- Proton beam

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VELO Upgrade Sensors and ASICs

Challenges:
Very high \(8 \times 10^{15} \, \text{n}_{\text{eq}}/\text{cm}^2\) for 50 fb\(^{-1}\) & non-uniform irradiation \(\sim r^{-2.1}\)
Huge data bandwidth: up to 20 Gbit/s for central ASICs and \(~ 3 \, \text{Tbit/s in total}\)
Sensor temperature must be maintained \(< -20^\circ\text{C}\) with lightweight cooling

Four sensors per double sided module.
Each sensor \((43 \times 15 \, \text{mm})\) bonded to three VeloPix ASICs

Sensors are bump bonded and characterised on an automatic probe setup. They are then ramped to 1000V in vacuum via spring loaded needle contacts to ASIC backplane

SEM image of 55 µm pitch SgAn bumps courtesy Sami Vähänen, ADVACAM Oy
The VeloPix ASIC

Developed together with the Medipix collaboration

**HEP Requirements**
- vertexing for flavour physics
- Triggerless readout
- New Technologies
- Hybrid pixels

**Other Scientific fields**
- synchrotons/biology/industry

**Medipix, Timepix, VeloPix family of ASICS used in HEP and beyond**
- Timepix3 telescope
  - > 5 MHz of <350 ps,
  - <2 um resolution tracks
- ATLAS radiation monitoring
- Space Dosimetry
- X ray histology
- Imaging at low threshold
- Spectral imaging

**VeloPix characteristics include:**
- Triggerless, Data driven readout
- Radiation hardness to 400 MRad
- SEU/SEL tolerance
- Readout out 800 Mhits/s/ASIC

2016

2019: Fully produced for LHCb, 70% of tiles completed
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Microchannel Cooling
VELO Upgrade I Cooling Requirements

Silicon pixel modules will accumulate ~ 50 fb⁻¹ at a closest distance of 5.1 mm from the beam

- non-uniform Irradiation up to $8 \times 10^{15}$ MeV $n_{\text{eq}} / \text{cm}^2$
- Sensor tips must be kept < -20°C (almost) permanently while bump bonded directly to heat source

Cooling partially in acceptance for physics tracks

**Vital to minimise material over entire cooling plate**

Modules dissipate 30W in vacuum

- Total power: 1.5 kW
- silicon tip: 1W/cm² after irradiation

**High thermal efficiency mandatory**

Ideal to find a solution which uses the CO₂ evaporative cooling already developed for LHCb (-35°C)

However the previous solution of cooling pipes embedded in aluminium “cookie” heat spreaders does not satisfy the pixel upgrade requirements
Solution provided by the novel technique of evaporative CO$_2$ circulating in 120 µm x 200 µm channels within a silicon substrate.

Total thickness: 500 µm

- High thermal efficiency
- CTE match to silicon components
- Minimum and uniform material
- Radiation hard

SEM images of etched wafer before bonding

(click for movie)

Channels output directly to connector

Two step channel etching
VELO Upgrade Cooling

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

**Assembly**
- Silicon pre-tinning
- Connector pre-tinning
- Alignment
- Soldering

Final assembly can withstand 200 bar
Microchannel production completed in September 2021
81 production coolers produced with 87% yield, (plus 30 pre-production used for developing procedures)
Cooling Performance

The performance of a cooling system can be characterised by the Thermal Figure of Merit;

\[
\text{TFM} = \frac{\text{Difference in temperature between coolant and power dissipating element}}{\text{Power Density}}
\]

Expected values: ~ 20 for classical systems, ~12-13 for integrated pipe systems, ~5-6 for single phase microchannels

TFM measured value for all produced VELO modules between 2 and 3 (dependent on glue thickness)
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The VELO is separated from the primary vacuum by the 1.1 m long thin walled "RF foil" which also shields the detector and guides the beam wakefields.

At just 3.5 mm clearance from the beam and 900 µm clearance from the sensors, production represents a huge technical achievement.

The final foil withstands 10 mbar pressure variations, is leak tight, and has a final thickness of 250 µm, with an option to go to 150 µm maintained.
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Final Foil Installation

Completed in spring 2020

First large scale installation working in strict lockdown conditions
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Four sensors per double sided module
Each sensor bump bonded to 3 Velopix ASICs
Detector active area 0.12 m$^2$
VELO Module Construction Sequence

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

Three modules in SPS testbeam
Quality Assurance Central to Module Production

More than 31 extremely detailed steps and quality assurance procedures are meticulously recorded and tracked in the database (with resultant automatic grading) including metrology, noise, IV, thermal performance, photo inspections, thermal cycling, bonding....

All tests are uploaded to DB where automatic grading is performed.
Quality Tracking

1000’s of individual parameters tracked in detail for all assembled modules
Course corrections possible as assembly progressed

Tile metrology

Thermal measurements from > 600 ASICs

Module Production now complete
Some additional spares under construction
52 module milestone

Monumental achievement of the Manchester and Nikhef teams
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Impact of Covid extremely profound on a “small” highly complex and distributed project.
Fully assembled VELO Half
University of Liverpool, December 2021
VELO Assembly

Assembly of entire halves, cooling, readout, qualification
Extremely delicate work

Cooling and safety infrastructure manufactured, installed and qualified

Quality control is done on every single power and data channel for all 26 modules.

All followed by a database that tracks all tests and actions performed on every single item.
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Extremely delicate work

Cooling and safety infrastructure manufactured, installed and qualified

Quality control is done on every single power and data channel for all 26 modules.

All followed by a database that tracks all tests and actions performed on every single item.
VELO Transport

The VELO half is sent completely equipped and ready to be placed in its final position.

Great attention dedicated to building a safe transport frame for the long drive.

First half to be shipped to CERN was the C-side in Q1 2022.
Final touches at Liverpool
Delivery to CERN
Final touches at CERN
Final touches at CERN
Next Steps
Next Steps

Final installation of C side foreseen for March 3
A side is being prepared and will follow in weeks
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▶ Upgrade II - VELO perspective
Likely machine parameters for Phase II upgrade: Pileup ~ 42, $L_{\text{max}}=1.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
Phase II Upgrade must deliver the same quality performance as Upgrade I, with:

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

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

Move towards 4D tracker concept with addition of timing:

- Real time track reconstruction critical for Upgrade I and II:
  - Timing information will contribute to Pattern Recognition speed and efficiency
- Track time stamping from expected <8> hits/track for PV association, PV timing, and combination with downstream detectors for beam gas and background control, calorimetry and time of flight
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For more information see CERN-LHCb-PUB-2022-001
Sensors and ASICs

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<tr>
<td>Technology</td>
<td>130 nm</td>
<td>65 nm</td>
<td>28 nm?</td>
</tr>
<tr>
<td>Pixel Size</td>
<td>55 x 55 μm</td>
<td>55 x 55 μm</td>
<td>55 x 55 μm?</td>
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<tr>
<td>Pixel arrangement</td>
<td>3-side buttable 256 x 256</td>
<td>4-side buttable 512 x 448</td>
<td>4-side buttable 256 x 256?</td>
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<tr>
<td>Sensitive area</td>
<td>1.98 cm²</td>
<td>6.94 cm²</td>
<td>1.98 cm²?</td>
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<tr>
<td>Event Packet</td>
<td>24 bit</td>
<td>64-bit</td>
<td>64-bit?</td>
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<tr>
<td>Max rate</td>
<td>-400 Mhits/cm²/s</td>
<td>178.8 Mhits/cm²/s</td>
<td>~4000 Mhits/cm²/s?</td>
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<tr>
<td>Best time resolution</td>
<td>25 ns</td>
<td>~200ps</td>
<td>~20-50 ps?</td>
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<tr>
<td>Readout bandwidth</td>
<td>19.2 Gb/s</td>
<td>≤81.92 Gb/s</td>
<td>≤500 Gb/s?</td>
</tr>
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</table>

Fruitful collaboration with the Medipix group has yielded the VeloPix ASIC for the LHCb Upgrade I. A new generation chip, 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.

Sensor R&D draws on existing thin planar, LGAD, 3D concepts. Timing, pixel size and radiation hardness requirements might have to be factorised with a dual technology solution.

Mechanics and Cooling

General needs: lightweight, possibly partially replaceable modules and mechanics

- Bi-phase CO₂ circulating in silicon microchannels
- 3D printed Titanium substrates, already prototyped for Upgrade I
- Foil to be thinned or removed, access to secondary vacuum simplified

- Possible sensor replacement mechanism
- RF test stand for foil R&D

Time for brainstorming
The Upgrade VELO is rolling!

C side installation next week
A side installation to closely follow
Interesting challenges ahead for Upgrade II

THANK YOU for your attention
VeloPix: A New Hybrid Pixel Readout Chip for the LHCb Upgrade
CERN EP-ESE electronics seminar https://indico.cern.ch/event/580516/

Medipix: Pixel Detectors for Medical Imaging and Other Applications
EPS-HEP https://indico.cern.ch/event/466934/contributions/2524825/

Design and Production Challenges for the LHCb VELO Upgrade Modules; LHCb VELO Modules: controlling thermal deformations

R&D on CO₂ cooling using a silicon micro channel substrate for the LHCb VELO Forum on Tracking Detector Mechanics 2018
https://indico.cern.ch/event/695767/contributions/3014925/

The vacuum envelope of the upgraded LHCb VELO Detector,
Forum on Tracking Detector Mechanics
https://indico.cern.ch/event/363327/contributions/860764/

Expression of Interest for a Phase-II LHCb Upgrade
Physics case for an LHCb Upgrade II - Opportunities in flavour physics and beyond in the HL-LHC era