Upgrade of
The LHCb Tracking System

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The LHCb Detector Before LS2

Goals: CP-violation in $b$ & $c$, rare decays, new physics.

$b\bar{b}$ correlation $\Rightarrow$ flavor tagging
Z boost $\Rightarrow$ decay length meas.

- Spatial resolution $\sim 4\ \mu m$ @ VELO
- $\Delta p/p = 0.4\%$ @ 5 GeV, 0.6% at 100 GeV.
- IP resolution $\sim 20\ \mu m$ for high-pT tracks.
- Decay time resolution 45 $fs$ ($B_s \rightarrow J/\psi \phi$).
In runs 1&2 LHCb records 9.2 fb\(^{-1}\) data, \(\sim1-2\) fb\(^{-1}\)/yr.

LHCb operated at a reduced luminosity.

- Lower efficiency for hadronic decays at higher luminosity due to the hardware trigger.
- Overall performance degrades with higher occupancy.
- Limited radiation hardness of the trackers.
The LHCb Upgrade Plan

Phase I

- Initial Plan
- Run 2: Phase I
- Run 3: Phase I.b
- Run 4: Phase II

Phase II

- Likely?
- Run 2
- LS2
- Run 3
- LS3
- Run 4
- Run 5,6

Data

- \( \mathcal{L} \sim 4 \times 10^{32} \text{cm}^{-2}\text{s}^{-1} \)
- Data \( \sim 9 \text{ fb}^{-1} \)
- \( \sim 1 \text{ interaction/Xing} \)

- \( \mathcal{L} \sim 2 \times 10^{33} \text{cm}^{-2}\text{s}^{-1} \)
- Data \( \sim 50 \text{ fb}^{-1} \)
- \( \sim 5 \text{ interactions/Xing} \)

- \( \mathcal{L} \sim 1.5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1} \)
- Data \( \sim 300 \text{ fb}^{-1} \)
- \( \sim 42 \text{ interactions/Xing} \)
Remove The Hardware Trigger

LHCb Run 2 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger: 1 MHz readout, high $E_T / P_T$ signatures

- 450 kHz $h^\pm$
- 400 kHz $\mu / \mu \mu$
- 150 kHz $e / \gamma$

Software High Level Trigger

- Partial event reconstruction, select displaced tracks/vertices and dimuons
- Buffer events to disk, perform online detector calibration and alignment
- Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz (0.6 GB / s) to storage

Eliminated

LHCb Upgrade Trigger Diagram

40 MHz bunch crossing rate (30 MHz inelastic event building)

Software High Level Trigger

- Full event reconstruction, inclusive and exclusive kinematic/geometric selections
- Buffer events to disk, perform online detector calibration and alignment
- Add offline precision particle identification and track quality information to selections
- Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

2-5 GB / s to storage

All detectors read out @ 40 MHz
The Phase-I Upgraded Detectors

- New silicon pixel detector
- New silicon strip detector
- New scintillating fiber detector
- New optics, new photon detectors
- Remove SPD/PS & M1
- Reduce PMT gain + New electronics
- New electronics
- trigger-less readout system
**VELO Upgrade**

- Similar overall geometry as the old one, total 26×2 modules, 2.5 cm gaps in Z. Two halves are retractable.
- Strip detector ⇒ pixel detector.
- VeloPix readout ASIC, 256 × 256 pixel matrix, binary readout at 40 MHz.
- Significantly increased number of channels: ~0.2 M ⇒ ~40 M
- More radiation hard sensor:
  \[ \Phi_{\text{max}} \sim 7 \times 10^{14} \Rightarrow 8 \times 10^{15} n_{\text{eq}} \text{cm}^{-2} \]

**n⁺-in-n sensor**
- Pitch = 40-100 μm
- Thickness = 300 μm
- r = 42 mm
- r = 8.2 mm
- 2048 strips

**n-in-p sensor**
- Size ~43×15 mm²
- Pixel size 55×55 μm²
- Thickness = 200 μm
- \( d / 2 = 5.1 \text{ mm} \)
A sensor is bump-bonded to 3 VeloPix ASICs

Micro-channel substrate

Prototype modules

On both sides for overlap

Up to 900 Mhits/s/ASIC (data driven readout)
VELO Cooling Substrate

- VELO uses evaporative CO$_2$ cooling. So that the silicon sensor operates $<-20^\circ$C.
- 120×200 μm$^2$ micro channels are etched in 500 μm silicon substrate, 60×60 μm$^2$ at the entrance for stability.
- It is a real challenge. But enough good quality substrates have been produced.

3 VeloPix ASICs / sensor
4 sensors / module
1 cooling substrate / module

Good

Defected

SEM images
RF shields separate the beam vacuum and the detector volume (~10 mbar difference).

The thickness significantly affects the performance.

The RF shields were milled from AlMg3 alloy blocks, to reach ~250 μm at tips of the VELO module.

Chemical etching down to 150 μm.
The tracking stations consist of 4 planes TT before the magnet, and 3x4 planes of IT & OT after the magnet.

Four planes \((x,u,v,x)\) at \((0^\circ,+5^\circ,-5^\circ,0^\circ)\), provide stereo measurements, with horizontal precision.

TT & IT are silicon strip detectors, read out by Beetle ASICs outside active area.

OT is made of Kapton/Al straw drift tubes \(d=5\) mm, with \(\text{Ar}+\text{CO}_2+\text{O}_2\) gas, providing \(~200\ \mu\text{m}\) resolution.
Upstream Tracker (UT)

- Similar geometric configuration as TT.
- Improved coverage and segmentation.
- Sensor is more radiation resilience, \( \Phi_{\text{max}} \approx 5 \times 10^{14} \, n_{eq} \text{cm}^{-2} \).

- Read out at 40 MHz by custom design SALT ASICs in the sensor proximity.
- Digital events are packed in ASIC, sent out at the end of detector via optical fibers.
- Detector performance were verified in a slice system.
- UT stave production started.
- Installation will start in March 2020..
- Tracking stations are replaced by 3-station (12-plane) scintillation fiber detector.
- Read out with arrays 4096 SiPMs (-40°C) + custom made PACIFIC ASICs. In total ~0.59 M readout channels.
- Spatial resolution better than 100 μm in X.
- Single hit efficiency ~99%.

SciFi Modules are being mounted on the support frames.
The Phase II Upgrade

$\mathcal{L} \sim 1.5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$
Data $\sim 300 \text{ fb}^{-1}$

**New Vertex Detector**
(4D?)

**Add**
Magnet Station (Scint.+SiPM)

**New ECAL Technology?**

**Remove**
HCAL

More MUON filter + replace MWPC

**Add TORCH?**

**Keep** triggerless readout

**Add @ center**
Mighty Tracker

**LHCb Upgrade II**
approved by LHCC/RRB to move to TDRs in 2020

Improve granularity
Better radiation hardness
Better coverage for low momentum tracking
Use timing to distinguish vertices (high-pileup)
Possible Phase II Upgrade Plans

- The VELO detector may be upgraded to a 4D pixel tracker. The design could be improvement based on the phase I detector design:
  - Pixel size $55 \times 55 \, \mu m^2 \Rightarrow 27.5 \times 27.5 \, \mu m^2$, sensor thickness $200 \, \mu m \Rightarrow 100 \, \mu m$.
  - Time resolution 25 ns (BX) $\Rightarrow$ 20-50 ps.
  - Silicon micro-channel cooling $\Rightarrow$ 3D printed Titanium substrates.
  - 150 $\mu m$ RF shield $\Rightarrow$ further thinned or no RF foil.

- The main tracker (SciFi in phase I) could be split into 3 regions:
  - Outer part (OT) keeps the SciFi design.
  - Middle part (MT) uses UT-like strip detector.
  - Inner part (IT) uses HV-CMOS detector.

- The UT also upgrades the central part:
  - Outer part keeps the same design.
  - Inner part uses HV-CMOS detector.

Will benefit from joint effort, e.g. with ATLAS, CEPC, …
The LHCb is upgrading its detectors during LS2, to operate at an increased luminosity (x5), and with trigger-less readout.

The vertex detector + tracking detectors are completely new in this phase I upgrade. Other detectors all have new electronics.

Expect to start operation in the 2\textsuperscript{nd} half of 2021.

The phase II upgrade had been approved by LHCC to proceed to a Framework TDR.
Backup Slide
Performance of Phase I Upgrade

LHCb simulation

- Current VELO
- Upgraded VELO

Relative population of b hadron daughter tracks

LHCb Simulation