LHCb Tracking System: Past, Present and Future

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LPHE – EPFL
Overview

- Introduction to LHCb:
  - Motivation.
  - Detector requirements.
- LHCb Tracking System:
  - Vertex Detector (VELO).
  - Silicon Tracker (ST).
- Upgrade of LHCb:
  - Motivation.
  - Trigger / physics!
  - Scintillating Fibre Tracker.
  - Schedule.
- Conclusions.

http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_all.html

16th February 2016
Seminar @ Clermont-Ferrand
Large Hadron Collider @ CERN

- Large Hadron Collider @ CERN
  - 26.7 km in circumference.
  - ~100 metres below Geneva!
  - proton-proton collisions.
  - $\sqrt{s} = (7, 8, 13)$ TeV.

- Four experiments:
  - ATLAS and CMS (general purpose).
  - LHCb (heavy flavour).
  - ALICE (heavy ion).

- All searching for New Physics!
Why LHCb?

- Dedicated heavy flavour experiment at LHC.
  - Measure $CP$-violation in $b$ sector.
  - Search for $CP$-violation in $c$ sector.
  - Study rare $b$- and $c$- hadron decays.

- **Indirect searches for New Physics!**

- New particles in internal loops.
  - Modify $CP$-violating phases.
  - Change branching ratios.
  - Angular distributions and rates.

- Precise predictions in SM.
  - Particle – anti-particle asymmetries.

- Sensitive to higher mass scales than direct searches.

- Many $b$-hadrons at LHC!
**b-production @ LHC**

- Forward production of b-pairs with low angle.
  - Cross-section $\approx 290 \, \mu b$ @ $\sqrt{s}=7$ TeV [arXiv:1009.2731].
  - 27% of $b$-pairs in LHCb acceptance @ $\sqrt{s}=7$ TeV.

- $B$-hadrons have large Lorentz boost.
  - Flight length $\sim 1$ cm $\rightarrow$ good decay time resolution.

![Diagram of LHC and LHCb detectors with theta and eta variables](image.png)
Detector Requirements

- Separation of primary and secondary vertices.
- Proper time resolution \( \rightarrow \) e.g. \( B_s \) mixing.
- Excellent momentum resolution:
  - \( \delta p / p = 0.4\% \) (5 GeV) to 0.6\% (100 GeV).
- Particle Identification:
  - Separation between \( \gamma, e^{\pm}, \mu^{\pm}, \pi, K, p \).
- Trigger Selection:
  - Efficient trigger for leptonic and hadronic final states.
  - Fast reconstruction of primary and secondary vertices.
2 < \eta < 5

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**Design:**

- $\sqrt{s} = 14$ TeV
- 2622 bunches, 25 ns spacing.
- $L = 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$.
- Average number of visible pp interactions / bunch crossing ($\mu$) = 0.4.

**Reality (2011+2012):**

- $\sqrt{s} = 7$ TeV / 8 TeV
- $\approx 1300$ bunches, 50 ns spacing.
- $L \approx 2 - 4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$.
- Higher pile-up.
  - $<\mu> \approx 1.4 / 1.7$
- Luminosity levelling.
- Exceeding design by factor two
  - fill for physics
Trigger in 2012

40 MHz bunch crossing rate

L0 Hardware Trigger: 1 MHz readout, high \( E_T/P_T \) signatures

- **450 kHz** \( \pi^\pm \)
- **400 kHz** \( \mu/\mu\mu \)
- **150 kHz** \( e/\gamma \)

Software High Level Trigger

- 29000 Logical CPU cores
- Offline reconstruction tuned to trigger time constraints
- Mixture of exclusive and inclusive selection algorithms

5 kHz Rate to storage

- **2 kHz** Inclusive Topological
- **2 kHz** Inclusive/Exclusive Charm
- **1 kHz** Muon and DiMuon

LHCb Average L0 Physics Rate in 2012

LHCb Average HLT Physics Rate in 2012
LHC Run 1

Integrated luminosity = 3.22 fb$^{-1}$
Design, construction, commissioning
Performance in LHC Run 1

VERTEX LOCATOR

J. Instrum. 9 (2014) P09007
Two retractable halves.
- 5.5 mm from beam when closed, ~29 mm during injection.
21 R-ϕ modules per half.
Operates in secondary vacuum.
300 μm aluminium foils separates detector from beam vacuum.
Cooling using bi-phase CO₂ system.
- Operates @ -30°C, Sensors @ -10°C.
VELO Sensors

- 300 μm n⁺-on-n sensors (Micron).
  - One module with n⁺-on-p (Micron).
- Double metal layer for signal routing.
- R-sensors:
  - 45 degree quadrants.
  - Pitch = 40.0 – 101.6 μm.
- Phi-sensors:
  - 2 regions (short/long strips).
  - Pitch = 35.5 – 96.6 μm.
  - Stereo angle.
- 2048 strips / sensor.
  - 172032 strips / VELO.
- First active strip @ R ≈ 8 mm.
- Sensor-sensor alignment measured to ~10 μm.
- Analogue read-out from 16 Beetle ASICs / sensor.
- Off detector pre-processing of data by FPGA.
  - Common TELL1 Board for (nearly) all detectors in LHCb.
  - Cross-talk, suppression of common mode noise.
  - Clustering, zero suppression of data.
Module production

Hybrid Electrical Test → Hybrid Cleaning/Visual Inspection → Hybrid Metrology → PA/Chip Attachment → Visual Inspection → Back-end Wirebond → Electrical Test

Laser Test ← Sensor Wirebonding ← Sensor IV ← Sensor-Sensor Metrology ← Sensor Attachment ← Electrical Test ← Front-end Wirebond

Visual Inspection ← Pedestal Attachment ← Module Metrology ← Cable Attachment ← Module Metrology ← Vacuum Test ← Module Metrology

Electrical Test ← Assemble onto VELO half ← Visual Inspection ← Module Burn-in ← Visual Inspection ← Ship to CERN ← Pack/Visual Inspection

Thermflow Cooling ← Electrical Test ← Vacuum Test ← VELO Metrology ← Vacuum Test ← Test of Final Electronic Chain ← Install in Pit

6 Visual Inspections, 6 Metrologies, 7 Electrical Tests, 4 Vacuum Tests
Commissioning

- Installation in 2008 → test services (LV, HV, read-out, etc.)
- Forward geometry → low rate cosmic muons.
- Use particles from LHC injection tests.
  - Beam stopper 350 m from LHCb.
  - $10^9$ protons every 48 seconds.
- Time alignment (internal + w.r.t beam).
- Secondary particles for spatial alignment.
First LHC induced tracks!

- First injection tests:
  - August / September 2008.
  - 5 modules / full detector.
  - 700 reconstructed tracks.
- Initial spatial alignment.
VELO (Signal/Noise)

**Graph 1:**
- *X-axis:* R strip number
- *Y-axis:* Average noise in ADC counts
- Legend: LHCb VELO

**Graph 2:**
- *X-axis:* Phi strip number
- *Y-axis:* Average noise in ADC counts
- Two sub-plots:
  - Inner Phi strips
  - Outer Phi strips, with routing line
  - Outer Phi strips, no routing line
- Legend: LHCb VELO

**Graph 3:**
- *X-axis:* ADC counts: clusters on tracks
- *Y-axis:* LHCb VELO
- Details:
  - Sensor 104, radius = 10 - 15 mm
  - Most Probable Value = 37.1
  - FWHM = 17.0

**Graph 4:**
- *X-axis:* Radius [mm]
- *Y-axis:* SIN for clusters
- Details:
  - Sensor 40 (R): Red points
  - Sensor 104 (Phi): Blue circles
VELO Alignment

- Survey before installation:
  - Relative sensor-sensor position:
    - 3 µm (translations in x,y), 20 mrad (rotations around x,y)
  - Relative module position in each half: 10 µm (translations in x,y)
  - Position of two halves: 100 µm and 100 µrad.

- Module and half alignment based on Millipede.

- Global $\chi^2$ minimisation based on Kalman track fit residuals
  - NIM A600 (2009) 471

Sensor misalignment < 4 µm.
- Depends on pitch and projected track angle
  - Angle between track and strip in plane perpendicular to the track.
- Measure unbiased residuals of cluster to track.
- Best resolution achieved is 4 μm.
Design
Performance in LHC Run 1

SILICON TRACKER

LHCb Silicon Tracker

Installation completed in June 2008.
- Long programme of commissioning:
  - Running detector without beam.
  - Test read-out.
  - Cosmic data taking.
  - Rate extremely low.
  - LHC injection tests.
    - Protons dumped on beam stopper 350m from LHCb.
    - First tracks seen.
    - Initial time and spatial alignment of detector.
  - Proton-proton collisions.
    - Final time alignment of detector.
    - Spatial alignment.
    - Study detector performance.
    - Radiation damage.

Common project: 5 institutes, ≈ 50 people.
Tracker Turicensis (TT)

- Silicon micro-strip detectors.
  - $p^+$-on-n from Hamamatsu Photonics K.K.
- Four planes (0°, +5°, -5°, 0°).
- Pitch: 183 μm; Thickness: 500 μm.
- Long read-out strips (up to 37 cm).
- 143360 read-out channels.
- Total Silicon area is 8 m².
  - Covers full acceptance before magnet.
- Cooling plant operates at 0°C.
  - Sensors @ 8°C.
Silicon micro-strip detectors.
- $p^+$-on-$n$ from Hamamatsu Photonics K.K.

Three stations in $z$.
- Four boxes in each station.
- Four planes ($0^\circ$, $+5^\circ$, $-5^\circ$, $0^\circ$)

- Pitch: 198 $\mu$m
- Thickness: 320 or 410 $\mu$m
- 129024 read-out channels.
- Total Silicon area is 4.2 $m^2$.
  - Covers region around beam with highest flux.

- Cooling plant operates at 0°C.
  - Sensors @ 8°C.
read-out chain

Digitization: Service box near detector 15 krad in 10 years

Service Box (up to 16 Digitizer Boards)

Data from other digitizer boards

Data from other Beetles on the same hybrid

4 GOLs

4 VCSEL

QPLL

Optical link

Patch panel

Single optical fibers

Concrete shielding

100 m 12-fiber ribbon cable

1 Rx module

SNAP12 Rx

12 TLK2501

Tell1 Board

16 bits @ 80MHz

Crystal oscillator

ORx mezzanine card (per ribbon cable)

COUNTING HOUSE

Front end on detector < 1 Mrad in 10 years

Tell1 read-out boards in counting House: Zero Suppression

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Time Alignment

Optimize charge collection:
- Different length cables.
- Time of flight different for each station.

Perform time delay scan.
- Read out successive samples spaced by 25ns
- Fit Landau $\times$ Gaussian to charge distribution for each sample.
- Shift sampling point
**Time Alignment**

Optimize charge collection:
- Different length cables.
- Time of flight different for each station.

Perform time delay scan.
- Read out successive samples spaced by 25ns
- Fit Landau $\times$ Gaussian to charge distribution for each sample.
- Shift sampling point
- Plot MPV vs sample time.
- Fit pulse shape.

**Internal Time Alignment < 1 ns**
Clusters from tracks (p > 5 GeV):

Signal to Noise:
- IT: 16.5 (Long), 17.5 (Short).

Within 10 – 20% of expectation.
Alignment and resolution

- Use tracks from VELO+T stations.
- Global $\chi^2$ minimisation based on Kalman track fit residuals
- Additional mass constraint applied to vertices from $D^0 \rightarrow K^-\pi^+$.  
- Alignment precision $\approx 10 \, \mu m$.

Hit resolution:
- $52.6 \, \mu m$ (TT, 2011)
- $53.4 \, \mu m$ (TT, 2012)
- $47.9 \, \mu m$ (TT, MC)
- $50.3 \, \mu m$ (IT, 2011)
- $54.9 \, \mu m$ (IT, 2012)
- $53.9 \, \mu m$ (IT, MC)
Hit efficiency

- Measure hit efficiency with high momentum tracks (p > 10 GeV).
- Search for hits in window around track.
  - Efficiency varies with window size.
- Efficiency = #found / #expected.

99.7% (TT) & 99.8% (IT)
Broken bonds in TT

- Every 4th channel broken.
- Innermost bond row.

Problem with bonds breaking between pitch adapter and Beetle chip.
- New hybrids produced with distance between PA and chip increased.
- 9 broken modules removed and repaired during winter shutdown (2010/11).
Track Finding Efficiency
Primary Vertex (PV)
Impact Parameter (IP)
Decay Time.

**TRACKER PERFORMANCE**

- Tag and probe using with $J/\psi \rightarrow \mu^+\mu^-$
- Reconstruct $J/\psi$ mass.
- Associate probe track to long track.
- Efficiency = #associated/#total

<table>
<thead>
<tr>
<th>Method</th>
<th>Probe track</th>
<th>Measured Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>VELO</td>
<td>TT+T stations</td>
<td>VELO Tracks</td>
</tr>
<tr>
<td>T station</td>
<td>VELO-muon</td>
<td>Downstream tracks</td>
</tr>
<tr>
<td>Long</td>
<td>Muon-TT</td>
<td>Long tracks</td>
</tr>
</tbody>
</table>
- PV resolution depends on number of tracks.
- Split track sample in two and reconstruct same PV.
  - Method limited to $N \approx 60$.
- Measurement of separation $\rightarrow$ PV resolution.
  - Resolution: $(x, y, z) = (13, 13, 71) \, \mu m$ with $N = 25$ tracks.
- Resolution parameterised as $\sigma_{PV} = \left( \frac{A}{N^B} \right) + C$
Impact Parameter Resolution

Impact parameter (IP) is distance of closest approach of track to PV.
- Useful variable for selecting B meson decays.

Depends mainly on 3 factors:
- Multiple scattering in detector material.
- Hit resolution.
- Distance between PV and first measurement.

Good agreement between data and simulation.
Decay time in rest frame of decaying particle:
- \( t = ml / p \).
- decay length, mass and momentum in LHCb frame.

- Computed from vertex fit.
  - Decaying particle constrained to originate from PV.
- Decay time resolution \( \sim 50 \) fs.
Trigger
Real-time alignment

LHC RUN 2
LHC Run 2

LHCb Integrated Luminosity at p-p 6.5 TeV in 2015

- LHC restarted in May 2015.
- Higher energy: √s = 8 TeV → 13 TeV.
- Bunch spacing: 50 ns → 25 ns.
- Lower pile up: μ = ~1.5 → 1.1.

Delivered Lumi: 362.75 /pb
Recorded Lumi: 320.66 /pb
Online architecture

- Trigger scheme changed significantly for Run 2.

- HLT1: First software trigger on partially reconstructed events.

- Determine calibration and alignment constants using data selected by HLT1.

- HLT2: Run offline reconstruction in second software trigger.
- New alignment framework uses trigger farm.
  - 1700 CPUs available.
  - Evaluation of constants needed in minutes...
- Event reconstruction parallelised to 1700 analysers.
- Data combined to single *iterator* to determine new constants.
  - $\chi^2$ minimisation of Kalman track residuals.
  - Convergence within 2—3 iterations.
- Update tracker alignment every few weeks.
Alignment Stability

LHCb Tracker

Preliminary

ΔX Variation [μm]

05/07/2015 - 19/08/2015

Fill number

IT1 ASide
IT1 Bottom
IT1 Top
IT1 CSide
Expected fluence
Leakage currents
Charge collection efficiency scans

RADIATION DAMAGE (TT)

CERN-THESIS-2015-015
Nominal LHC conditions:
- 10 years with $\sqrt{s} = 14$ TeV.
- Integrated luminosity 20 fb$^{-1}$.
- Expected fluence:
  - IT: $5 \times 10^{13}$ 1-MeV n$_{eq}$/cm$^2$.
  - TT: $8 \times 10^{13}$ 1-MeV n$_{eq}$/cm$^2$.

Actual LHC conditions:
- Delivered luminosity (Run 1):
  - 1.2 fb$^{-1}$ @ 7 TeV, 2.2 fb$^{-1}$ @ 8 TeV.
- Expected luminosity (Run 2):
  - 5 fb$^{-1}$ @ 13 – 14 TeV.
- Upgrade in 2019/20!
Current increases linearly with integrated luminosity.
Data normalised to $T = 8^\circ{}C$ ($E_g = 1.21$ eV).
Measure depletion voltage with dedicated scans.
Collect data at different voltages.
Charge Collection Efficiency

- Mini-timing scan at each voltage.
- Charge collected is extracted from fit to pulse-shape.
Depletion voltage

- Plot charge vs voltage.
- Depletion voltage @ 95% of plateau value.
Depletion Voltage vs Time
Depletion voltage vs fluence

\[ \frac{V_{\text{depl}}}{V_0} \]

TT sectors \( V_{\text{depl}} \)

- \( V_{\text{depl}} \in [220, 280] \) V
- \( V_{\text{depl}} \in [160, 220] \) V
- Hamburg Model (\( V_{\text{depl}} = 200 \) V)

Innermost region

\( \phi_{1 \text{ MeV-n,eq}} \) [cm\(^{-2}\)]

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Abstract

There is a growing international understanding that future flavour physics experiments will be needed in the second half of the next decade in order to either study the flavour structure of new particles discovered at the LHC or to probe new physics at the multi-TeV scale. Here we present an expression of interest of the LHCb collaboration for an upgrade of the LHCb detector after it will have collected a data sample of about 10 fb$^{-1}$. We envisage the upgrade to enable the LHCb experiment to operate at 10 times the design luminosity, i.e. at about $2 \times 10^{33}$ cm$^{-2}$s$^{-1}$, to improve the trigger efficiency for hadronic decays by a factor of two and to collect a data sample of $\sim 100$ fb$^{-1}$. In this document we briefly describe the motivation for an LHCb upgrade. We then outline the R&D programme necessary to evaluate the required technologies for a high-luminosity LHCb upgrade, which must take place over the next few years.
No evidence for New Physics in LHC Run 1.
- Look for deviations from Standard Model.
- More data to challenge theoretical predictions.

Expand physics programme:
- Electroweak, lepton flavour sector, exotica, QCD.

Limited by Level-0 hardware trigger.
- Maximum rate is 1.1 MHz.

Higher luminosities:
- Trigger yield saturates.
- Harder cuts on $E_T$ and $p_T$.
- No real gain in statistics.

Higher occupancy.
- Degraded detector performance.
- Radiation damage of detectors.
Upgrade strategy

- Remove Level-0 hardware trigger.
  - Read out every bunch crossing (40 MHz).
  - Replace all front-end electronics.
    - Replace also detectors with embedded read-out (VELO, Silicon Tracker, RICH, ...)

- Trigger-less read-out system.
  - Full software trigger for every 25 ns bunch crossing.

- Run at higher instantaneous luminosities.
  - Higher occupancy.
    - Redesign several sub-detectors (OT, RICH).

- Install during LHC Long Shutdown 2.
Upgrade

- **Conditions:**
  - Instantaneous luminosity $= 2 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$.
  - # visible interactions / crossing $= 5.2$
  - Integrated luminosity $= 50 \text{ fb}^{-1}$.

- **Challenge:**
  - Maintain current reconstruction performance in harsher environment.
  - And read out the complete detector at 40 MHz.
## Physics reach!

<table>
<thead>
<tr>
<th>Type</th>
<th>Observable</th>
<th>Current precision</th>
<th>LHCb 2018</th>
<th>Upgrade $(50 \text{ fb}^{-1})$</th>
<th>Theory uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0$ mixing</td>
<td>$2\beta_s (B_s^0 \to J/\psi \phi)$</td>
<td>0.10 [9]</td>
<td>0.025</td>
<td>0.008</td>
<td>$\sim 0.003$</td>
</tr>
<tr>
<td></td>
<td>$2\beta_s (B_s^0 \to J/\psi f_0(980))$</td>
<td>0.17 [10]</td>
<td>0.045</td>
<td>0.014</td>
<td>$\sim 0.01$</td>
</tr>
<tr>
<td></td>
<td>$A_{fs}(B_s^0)$</td>
<td>$6.4 \times 10^{-3}$ [18]</td>
<td>$0.6 \times 10^{-3}$</td>
<td>$0.2 \times 10^{-3}$</td>
<td>$0.03 \times 10^{-3}$</td>
</tr>
<tr>
<td>Gluonic penguin</td>
<td>$2\beta_s^{\text{eff}} (B_s^0 \to \phi \phi)$</td>
<td>$-$</td>
<td>0.17</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$2\beta_s^{\text{eff}} (B_s^0 \to K^*0 K^*0)$</td>
<td>$-$</td>
<td>0.13</td>
<td>0.02</td>
<td>$&lt; 0.02$</td>
</tr>
<tr>
<td></td>
<td>$2\beta_s^{\text{eff}} (B_s^0 \to \phi K_S^0)$</td>
<td>0.17 [18]</td>
<td>0.30</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>Right-handed currents</td>
<td>$2\beta_s^{\text{eff}} (B_s^0 \to \phi \gamma)$</td>
<td>$-$</td>
<td>0.09</td>
<td>0.02</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td></td>
<td>$\tau^{\text{eff}} (B_s^0 \to \phi \gamma)/\tau_{B_s^0}$</td>
<td>$-$</td>
<td>5 %</td>
<td>1 %</td>
<td>0.2 %</td>
</tr>
<tr>
<td>Electroweak penguin</td>
<td>$S_s(B^0 \to K^*0 \mu^+\mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/c^4)$</td>
<td>0.08 [14]</td>
<td>0.025</td>
<td>0.008</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$s_0 A_{FB}(B^0 \to K^*0 \mu^+\mu^-)$</td>
<td>25 % [14]</td>
<td>6 %</td>
<td>2 %</td>
<td>7 %</td>
</tr>
<tr>
<td></td>
<td>$A_1(K^+ \mu^+\mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/c^4)$</td>
<td>0.25 [15]</td>
<td>0.08</td>
<td>0.025</td>
<td>$\sim 0.02$</td>
</tr>
<tr>
<td></td>
<td>$B(B^+ \to \pi^+ \mu^+\mu^-)/B(B^0 \to K^+ \mu^+\mu^-)$</td>
<td>25 % [16]</td>
<td>8 %</td>
<td>2.5 %</td>
<td>$\sim 10%$</td>
</tr>
<tr>
<td>Higgs penguin</td>
<td>$B(B_s^0 \to \mu^+\mu^-)$</td>
<td>$1.5 \times 10^{-9}$ [2]</td>
<td>$0.5 \times 10^{-9}$</td>
<td>$0.15 \times 10^{-9}$</td>
<td>$0.3 \times 10^{-9}$</td>
</tr>
<tr>
<td></td>
<td>$B(B^0 \to \mu^+\mu^-)/B(B_s^0 \to \mu^+\mu^-)$</td>
<td>$-$</td>
<td>$\sim 100%$</td>
<td>$\sim 35%$</td>
<td>$\sim 5%$</td>
</tr>
<tr>
<td>Unitarity triangle</td>
<td>$\gamma (B \to D^{(<em>)} K^{(</em>)})$</td>
<td>$\sim 10-12^\circ$ [19, 20]</td>
<td>$4^\circ$</td>
<td>0.9$^\circ$</td>
<td>negligible</td>
</tr>
<tr>
<td>angles</td>
<td>$\gamma (B_s^0 \to D_s K)$</td>
<td>$-$</td>
<td>$11^\circ$</td>
<td>2.0$^\circ$</td>
<td>negligible</td>
</tr>
<tr>
<td>angles</td>
<td>$\beta (B^0 \to J/\psi K_S^0)$</td>
<td>$0.8^\circ$ [18]</td>
<td>$0.6^\circ$</td>
<td>0.2$^\circ$</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm</td>
<td>$A_T$</td>
<td>$2.3 \times 10^{-3}$ [18]</td>
<td>$0.40 \times 10^{-3}$</td>
<td>$0.07 \times 10^{-3}$</td>
<td>$-$</td>
</tr>
<tr>
<td>CP violation</td>
<td>$\Delta A_{CP}$</td>
<td>$2.1 \times 10^{-3}$ [5]</td>
<td>$0.65 \times 10^{-3}$</td>
<td>$0.12 \times 10^{-3}$</td>
<td>$-$</td>
</tr>
</tbody>
</table>

Table 1: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the current sensitivity is compared to that which will be achieved by LHCb before the upgrade, and that which will be achieved with $50 \text{ fb}^{-1}$ by the upgraded experiment. Systematic uncertainties are expected to be non-negligible for the most precisely measured quantities.
DETECTOR UPGRADES:
TECHNICAL DESIGN REPORTS

16th February 2016  Seminar @ Clermont-Ferrand
Upgraded LHCb detector

Tracking System: NEW DETECTORS!

Calorimetry

Muon system

NEW READ-OUT BOARDS!

Calorimeters:
Remove SPD/PS – no L0 trigger.
Operate PMTs at lower gain
NEW READ-OUT!

Ring Imaging Cherenkov detectors:
Remove aerogel from RICH1+modify optical system.
NEW PHOTON DETECTORS AND READ-OUT!

16th February 2016
Upgrade Trigger

30 MHz

Full Software Trigger

LLT (optional)

\( p_T \) of \( h, \mu, e, \gamma \)

15 to 30 MHz

Full track reconstruction

1 to 2 MHz

Track fit

RICH particle ID

Inclusive and exclusive selections

20 to 100 kHz

- Trigger-less read-out.
- Zero suppression in front-ends.
- Full detector data to Full Software Trigger.
- Inelastic collision rate is 30 MHz.

- Low level trigger as throttle.
- Partial information from muon system and calorimeters.

- Full event reconstruction.
- Run-by-run detector calibration.

- Perform simplified Kalman track fit.
- Add RICH information.
- Inclusive and exclusive selections.

- 2 – 10 GBytes/s to storage.
Requirements and design.
Fibres, SiPMs and electronics.
Module production.
Schedule.

SCINTILLATING FIBRE TRACKER

Brazil (CBPF) - China (Tsinghua) - France (LPC, LAL, LPNHE) - Germany (Aachen, Dortmund, Heidelberg, Rostock), Netherlands (Nikhef) - Russia (Kurchatov, ITEP, INR) - Spain (Barcelona, Valencia) - Switzerland (CERN, EPFL)
Current Tracker

Silicon Tracker:
- Silicon micro-strip detectors.
- Pitch: 183 μm (TT), 198 μm (IT).
- Resolution ≈ 50 μm.
- Common project: 5 institutes, ~50 people.

Outer Tracker:
- Gaseous straw tube detector.
- 12 detection layers (~ 6 x 5 m²).
- Straw tubes: 2.4 m long, 4.9 mm diameter.
- Resolution ≈ 200 μm.

\[ \int B \cdot dl = 4 Tm \]
Requirements on Upgrade Tracker

- **Detector performance:**
  - Hit efficiency > 98%
  - Noise rate < 10% signal rate (in same region).
  - Resolution ≈ 100 μm (in bending plane).

- **Material:** $X/X_0 \leq 1\%$ per layer.

- **40 MHz read-out.**

- **Integrated luminosity:** $\approx 50 \text{ fb}^{-1}$. 
Redesign and replace IT+OT.
- Occupancy too high in OT in upgrade conditions.
- Electronics designed for 1 MHz.

SciFi Tracker:
- Scintillating fibres read out with Silicon Photomultipliers (SiPMs).
- Single fast and light technology.
- Read-out electronics and services outside acceptance.
Detector design

- 12 modules per detection plane.
- Scintillating fibres.
  - 2.4 m long, 250 μm diameter.
  - Mirrored at one end.
  - Six layers of fibres in each module.
  - 10,000 km needed for full detector.
- Total active area is 360 m².
- SiPMs and front-end electronics inside light-tight read-out box.
10,000 km (ish)
Radiation environment

NIEL (neutrons):
- SiPMs at ±250 cm
  - $9.5 \times 10^{11} \text{n}_{\text{eq}} / \text{cm}^2$ (T1).
  - $13 \times 10^{11} \text{n}_{\text{eq}} / \text{cm}^2$ (T3).
- Shielding of SiPMs.
  - Polyethylene with 5% boron.
  - $6 \times 10^{11} \text{n}_{\text{eq}} / \text{cm}^2$.

Ionising dose:
- $35 – 25 \text{ kGy}$ (fibres).
- $40 – 80 \text{ Gy}$ (SiPMs).
Challenges

- Procurement of scintillating fibres:
  - High light yield.
  - High attenuation length.

- Radiation hardness of fibres & SiPMs.

- Mechanical design and construction.

- Fast read-out / data reduction.

- Cooling requirements.

- Timescale.
Scintillating fibres

Baseline fibre: Kuraray SCSF-78MJ

- Polystyrene core with two wavelength shifting dyes.
- Around 300 photons / MIP.
- Only a few photons after 2.4 m.
- Fibres must have long attenuation length (> 300 cm).

16th February 2016 Seminar @ Clermont-Ferrand
Irradiation effects in fibres

- Irradiation test at CERN PS with 24 GeV protons.
  - 3 m long SCSF-78 fibres (Ø 0.25 mm).
  - Embedded in glue (EPOTEK H301-2).
- Other irradiations with X-ray, gamma, electrons.
Irradiation effects in fibres

\[ \chi^2 / \text{ndf} \]
\[ p^0 \quad 0.003638 \pm 0.0002556 \]
\[ p^1 \quad 7.209e-06 \pm 3.078e-06 \]

Expected losses:
\[ \Lambda_{\text{irr}} \]

\[ \frac{\Lambda_{\text{irr}}}{\Lambda_0} \]

Dose (kGy)

16th February 2016
Seminar @ Clermont-Ferrand
Silicon Photomultipliers

- 128 channels / array.
- \(~ 100\) pixels connected in parallel /channel.
- Avalanche photo-diode operated in Geiger mode.
- Channel width: 250 \(\mu m\).
- 147m instrumented:
  - 590k channels.
  - 4608 SiPMs.
- Connected to read-out electronics via flex PCB.

Many different devices:
- Various pixel sizes.
- With/without trenches.

Co-development with:
- Hamamatsu (Japan).
- KETEK (Germany).

Picture from Hamamatsu
High gain: $10^6 - 10^7$.
High PDE at $\Delta V = 3.5\text{V}$!
   – 39% @ 490 nm.
Dark count rate.
Cross-talk.
Temperature dependent.
**SiPMs:**

- **PDE = QE × GF × ε\textsubscript{AT}**
  - PDE: Photon detection efficiency.
  - QE: Quantum Efficiency.
  - GF: Geometrical factor.
  - ε\textsubscript{AT}: Avalanche trigger probability.
- Single channel device.
- 50 μm pixels.
Signal Clusters

Clusters:
- Signals shared over two (or more) channels.

SiPMs:
- Dark noise increases with neutron radiation.
- Cooling and annealing.

Fibres:
- Darken after irradiation.
- Six layers of fibres to maximise light yield.

Expected signal:
- ~ 12 – 16 photo-electrons after irradiation.
- Trigger-less read-out.
  - Zero-suppression in front-ends.
  - Development of custom front-end ASIC.
- PACIFIC:
  - 64 channels, 130 ns CMOS (TSMC).
  - Three hardware thresholds = 2-bit.
  - Bandwidth: ~ 300 MHz.
  - Low input impedance: 20 – 40 Ω.
  - Low power ~ 8 mW / channel.
  - Fast shaping with zero dead-time.
Fibre mat production

Measure fibre diameter

- Spool with 12.5 km of fibre
- Tension control
- Threaded winding wheel

1. Optical cut ends
2. Attach mirror
3. Machine cut sides

Inject glue

Casting mould
Read-out Box

- Every module has one read-out box at each end.
  - Light tight and gas tight.
- Ensures precise optical coupling of cold (-40°C) SiPMs to fibres.
- Houses warm front-end electronics.
- Provide mechanical coupling to support structure.

Cold part of box (illustrative).
Coolant: C6F14 or Novec 649.
Heat load: 20 W / box.

- Design is being finalised.
- Major engineering challenge.
Test beam

- Test beam at CERN SPS:
  - October / November 2014.
  - May / October 2015.
- Goals:
  - Attenuation length.
  - Hit efficiency.
  - Resolution.
- Compare with measurements made in the lab and with the simulation.

- Four DUTs.
- 5 and 6 layer mats.
- ~ 2.5 m long.
- Hamamatsu SiPMs.

Beam

Telescope (AMS Silicon)

Timepix3 telescope
<table>
<thead>
<tr>
<th>Year</th>
<th>R &amp; D</th>
<th>Production</th>
<th>Installation</th>
<th>New Physics?</th>
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<tbody>
<tr>
<td>2015</td>
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</tbody>
</table>

- Installation during LS2.
- Collect 50 fb\(^{-1}\) after upgrade (Run 3 + HL-LHC).

LHC Run 2: 5 – 7 fb\(^{-1}\) @ 13 TeV
Long Shutdown 2
Run 3
SUMMARY
The Past

- LHCb operated well above design parameters.
  - $L = 2 - 4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$.
  - $\mu = 1.3 - 1.7$.
- Total integrated luminosity = 3.22 fb$^{-1}$.
- Excellent performance during LHC Run 1.
  - S/N: $>17$ (VELO), 12-15 (TT), 16.6/17.5 (IT)
  - Hit efficiency: 99.5 (VELO), 99.7 (TT), 99.8 (IT)
  - Hit resolution: 4 μm (VELO), 53 μm (TT), 50 μm (IT)
- 298 physics papers published.
The Present

- LHCb is over 20 years old!
- LHC Run 2 started in 2015.
- Improvements to LHCb trigger system.
  - Real-time calibration and alignment.
- Collect 5 – 7 fb\(^{-1}\) during Run 2.
- Another ~ 460 – 650 physics papers?
The Future

- Upgrade LHCb during LS2.
  - Instantaneous luminosities up to $2 \times 10^{33}$ cm$^{-2}$s$^{-1}$.
  - Trigger-less read-out system.

- New tracking system with scintillating fibres.
  - Scintillating fibres produced by Kuraray.
    - High attenuation length and light yield.
  - Silicon photomultipliers:
    - Co-development with Hamamatsu and Ketek.
    - High PDE and low cross-talk.
  - Radiation damage studied up to 50 fb$^{-1}$.
    - Six layers of fibres to ensure sufficient light yield.
    - Shielding required for SiPMs.
  - Production starts now!

- Installation during 2019/20 → Data taking in 2021!
Luminosity

- LHC design:
  - \( L = 10^{34} \text{ cm}^{-2}\text{s}^{-1} \)
  - Pile up at high luminosity.

- Tunable by defocusing beams.
  - LHCb @ \( 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} \)
  - \( \langle n \rangle = 0.5 \)

- Most events have single interaction.
Reconstruct vertices from hadronic interactions.
Use to build up material map.
VELO Half Alignment

- VELO halves centred around beam each fill.
  - Beam position determined from vertex reconstruction.
  - Fully automated procedure.
  - \( \approx 210 \) seconds from declaration of stable beams.

- Stability of alignment:
  - Reconstruct vertices separately for each half.
  - Stable within 5 \( \mu \text{m} \).
What does the LHC see during injection?
TED beam blocker

- Absorber 300m from LHCb
- Beam injection every 48s
- $5 \times 10^9$ protons/shot
TED run I (22/08/08)

- 5 modules powered in each half.
- Data taken with 15 consecutive triggers
  - 350ns window around expected signal.
- Around 80 tracks seen in total.
TED runs II and III

Sunday 24th August
- Detector fully powered
- 76 TELL1s read-out
- 8 faulty TELL1 boards
- Timing window reduced
- ~700 tracks

5th and 6th September:
- Detector fully powered.
- ~700 tracks

- Data used for first spatial alignment of VELO.
Silicon Tracker Status

- 99.62% working channels.
  - Many VCSEL diodes replaced.
- Repairs possible for electronics outside detector box.

- VCSELs used to transmit optical data after off-detector digitisation.
- Problem with production process for early batch (≈30% replaced!)

98.71% working channels
- 2 modules are not configurable.
- 3 dead VCSEL diodes.
- Access for repairs is difficult.

(VCSEL=Vertical-cavity surface-emitting laser)
High voltage problem

- Located in sectors closest to insulation wall.
- Correlated with instantaneous luminosity.
- Potential show-stopper for high luminosity.
- Installation of Kapton shielding and changes to operation procedures cured problem.
Gaseous straw tube detector.
12 detection layers covering area ~ 4 x 6 m².
53760 straw tubes (2.4 m long, 4.9 mm diameter).
Gas mixture: Ar/CO₂/O₂ (70%/28.5%/1.5%).
Nominal operating voltage is 1550 V.
Track types

![Graph showing different track types with labels for upstream, long, and downstream tracks, along with T1, T2, and T3 markers.](image-url)
Reconstruction sequence

<table>
<thead>
<tr>
<th>Offline</th>
<th>Upgrade HLT</th>
</tr>
</thead>
<tbody>
<tr>
<td>VELO tracking</td>
<td>VELO tracking</td>
</tr>
<tr>
<td>VELO-UT</td>
<td>VELO-UT</td>
</tr>
<tr>
<td>Forward reco $p_T &gt; 70$ MeV/c</td>
<td>Forward reco $p_T &gt; 200$ MeV/c</td>
</tr>
<tr>
<td>PV finding</td>
<td>PV finding</td>
</tr>
<tr>
<td>Full Kalman Fit</td>
<td>Trigger cuts to reduce rate to 1 MHz</td>
</tr>
<tr>
<td>RICH PID</td>
<td>Muon ID</td>
</tr>
<tr>
<td></td>
<td>Simplified Kalman Fit</td>
</tr>
<tr>
<td></td>
<td>Online RICH PID</td>
</tr>
</tbody>
</table>
- Measure diameter every 3 mm with laser micrometer.
- Once per km, diameter goes above limit (300 μm).
- Manually remove during winding process.
Radiation damage in fibres

Figure 3.16: The combined attenuation length data shown with statistical errors versus dose from three fibre irradiation studies and fits to 4 models. Model 1 assumes a linear damage with dose effect \( \Lambda'(D)/\Lambda_0 = 1/(1 + (D/A)) \). Model 2 assumes a power law function \( \Lambda'(D)/\Lambda_0 = 1/(1 + (D/A)^B) \). Model 3 is the logarithmic function \( \Lambda'(D)/\Lambda_0 = \alpha + \beta \log(D) \). Model 4 has an exponential-like behaviour \( \Lambda'(Dose)/\Lambda_0 = \exp((D/\alpha)\gamma) \). The LHCb-Pit data are not yet included in these fits as they likely have much larger systematic errors that are currently being determined.
- Standard hamamatsu.
- Non-irradiated.
- Nominal voltage.
- Temperature: 25°C.

- $2 \times 10^{11} \text{n}_{\text{eq}} / \text{cm}^2$.
- Nominal voltage.
- Temperature: -60°C.
- Ratio between 1\textsuperscript{st} and 2\textsuperscript{nd} p.e. peaks is same.
  - Cross-talk unchanged.
Annealing in SiPMs

- Multi-channel hamamatsu arrays without trenches.
- Irradiated with neutrons up to 50 fb$^{-1}$.
- Dark current increases linearly with fluence.

- Hamamatsu with trenches.
- Different annealing scenarios.
KETEK Microcell Construction

Standard technology

Avalanche zone

Quenching Resistor

Antireflective layer

Bias

N-doped body

P-doped entrance window

Trench technology

Trench

http://www.ketek.net/products/sipm-technology/microcell-construction/
## Summary of SiPM measurements

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface [mm²]</td>
<td>1</td>
<td>1</td>
<td>1/3</td>
<td>1/3</td>
<td>1/3</td>
</tr>
<tr>
<td>Pixel size [μm²]</td>
<td>50×50</td>
<td>50×50</td>
<td>60×62.5</td>
<td>60×62.5</td>
<td>82.5×62.5</td>
</tr>
<tr>
<td>$T_C$ [mV/K]</td>
<td>56</td>
<td>53</td>
<td>15</td>
<td>26</td>
<td>22</td>
</tr>
<tr>
<td>Over-voltage [V]</td>
<td>1.3</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>X-talk + After-pulsing</td>
<td>17%</td>
<td>7%</td>
<td>8%</td>
<td>9%</td>
<td>3%</td>
</tr>
<tr>
<td>V_{BD} [V]</td>
<td>69</td>
<td>55</td>
<td>23.5</td>
<td>23.5</td>
<td>32.4</td>
</tr>
<tr>
<td>Gain [e/PE]</td>
<td>0.75×10⁶</td>
<td>2.0×10⁶</td>
<td>8.5×10⁶</td>
<td>6.4×10⁶</td>
<td>9.5×10⁶</td>
</tr>
<tr>
<td>PDE @peak</td>
<td>30%</td>
<td>37%</td>
<td>42%</td>
<td>41%</td>
<td>40%</td>
</tr>
<tr>
<td>Weighted PDE integral</td>
<td>1.26</td>
<td>1.61</td>
<td>1.44</td>
<td>na</td>
<td>1.47</td>
</tr>
<tr>
<td>Scaled DCR in [MHz] at -40°C, $2\times10^{11}$ $n_{eqv/cm^2}$, 1/3mm²</td>
<td>1.5</td>
<td>6</td>
<td>22</td>
<td>3.8</td>
<td>12</td>
</tr>
</tbody>
</table>
Module Production

1. fibre inspection
2. winding
3. casting
4. optical cut
5. mounting of mirror
6. longitudinal cut
7. module assembly

Winding centres (4x)
- Winding machine
- Casting mould
- Milling machine + special milling head
- Gluing jig
- Milling machine + alignment device
- Tables + templates

Module assembly centres (2x)
Expected Performance

16th February 2016
Seminar @ Clermont-Ferrand
Read-out architecture

Detector front-end electronics

Eventbuilder PCs + software LLT

Eventfilter Farm
~ 80 subfarms

UX85B

8800 Versatile Link

500

Eventbuilder network

Point 8 surface

6 x 100 Gbit/s

Clock & fast commands

throttle from PCIe40

6 x 100 Gbit/s

subfarm switch

subfarm switch
Read-out scheme

- Trigger-less read-out.
- Zero suppression in front-ends.
- Hardware LLT kept as back-up.
VELO II

- Hybrid pixel detector.
  - Easier pattern recognition.
  - Thinner sensors (300 μm → 200 μm).
- Move closer to beam
  - First measurement: 8.13 mm → 5.1 mm.
- New RF foil.
  - Reduce material before first measurement.
- New ASIC (VeloPix)
  - Based on Medipix/TimePix.
  - 256x256 (55 μm x 55 μm)
  - 12 per module.
- Non-uniform irradiation.
  - Extremely high data rates.
  - Micro-channel cooling in substrate.
Expected performance

- Current VELO
- Upgraded VELO
Table 5: Pattern recognition performance parameters for current and upgrade Velo at upgrade beam conditions ($\nu = 7.6$, $\sqrt{s} = 14$ TeV) and for the current Velo at 2011 beam conditions ($\nu = 2$, $\sqrt{s} = 7$ TeV). For the reconstruction efficiency, the following categories are considered: all particles reconstructible in the Velo with $p > 5$ GeV/c, all particles reconstructible as long tracks with and without a momentum cut of 5 GeV/c, and particles from decays of $b$-hadrons with and without a momentum cut of 5 GeV/c. These parameters were measured using simulated events containing the decay $B^0 \to K^{\ast 0} \mu^+ \mu^-$. 

<table>
<thead>
<tr>
<th></th>
<th>Existing Velo [%]</th>
<th>Upgraded Velo [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\nu = 2$</td>
<td>$\nu = 7.6$</td>
</tr>
<tr>
<td>Ghost rate</td>
<td>6.2</td>
<td>25.0</td>
</tr>
<tr>
<td>Clone rate</td>
<td>0.7</td>
<td>0.9</td>
</tr>
<tr>
<td>Reconstruction efficiency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Velo, $p &gt; 5$ GeV/c</td>
<td>95.0</td>
<td>92.7</td>
</tr>
<tr>
<td>long</td>
<td>97.9</td>
<td>93.7</td>
</tr>
<tr>
<td>long, $p &gt; 5$ GeV/c</td>
<td>98.6</td>
<td>95.7</td>
</tr>
<tr>
<td>$b$-hadron daughters</td>
<td>99.0</td>
<td>95.4</td>
</tr>
<tr>
<td>$b$-hadron daughters, $p &gt; 5$ GeV/c</td>
<td>99.1</td>
<td>96.6</td>
</tr>
</tbody>
</table>
Primary Vertex Resolution

Figure 28: PV resolution in (left) $x$ and (right) $z$ as function of the number of reconstructed tracks in the vertex. The current VELO is shown with black circles and the upgrade VELO with red squares, both are evaluated at $\nu = 7.6$, $\sqrt{s} = 14$ TeV. The resolutions in $x$ and $y$ are similar.
Upstream Tracker (UT)

- Replace TT with new silicon strip detector.
  - Four layers (x, u, v, x) as now.
- Finer segmentation around beam-pipe.
  - Increased occupancy.
- Reduce material.
  - Thinner sensors.
  - $500 \mu m \to 300 \mu m$.
- Move sensors closer to beam.
  - Optimise shape of inner sensors.
  - Increase acceptance at large $\eta$.
- New read-out chip (SALT).
- Require hits on UT when matching VELO to downstream tracker.
- Use stray field to determine momentum.
- Reduce time taken for track reconstruction by factor 3.
- Allows UT to be used in trigger.
- Ghost rate reduced by requiring hits on UT.
Table 4.4: Pattern recognition performance parameters for long reconstructible particles reconstructed by the Forward tracking algorithm in the current and upgraded detector. Note that these numbers include the sum of the performance of the VELO and Forward pattern recognition. The tracks are fitted by a Kalman fit algorithm and a $\chi^2$ cut of 5 is applied afterwards.

<table>
<thead>
<tr>
<th></th>
<th>Current LHCb [%]</th>
<th>Upgrade LHCb [%]</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>$\nu = 2$</td>
<td>$\nu = 3.8$</td>
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<td>86.9</td>
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<tr>
<td>long, $p &gt; 5$ GeV/c</td>
<td>95.4</td>
<td>92.9</td>
</tr>
<tr>
<td>$b$-hadron daughters</td>
<td>93.9</td>
<td>91.9</td>
</tr>
<tr>
<td>$b$-hadron daughters, $p &gt; 5$ GeV/c</td>
<td>96.1</td>
<td>95.1</td>
</tr>
</tbody>
</table>

- Biggest difference for low momentum tracks.
- Ghost rate can be reduced by adding UT hits.
Nu, mu, pile-up

- ν (nu): average number of pp interactions per bunch crossing.
- μ (mu): average number of visible pp interactions per bunch crossing.
- pile-up: average number of pp interactions in visible bunch crossings.