Plans and Status of the LHCb Upgrade

Tomasz Szumlak on behalf of the LHCb Collaboration
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LHCb Detector and its Performance

- LHCb experiment was designed to studying CP-violation and search for New Physics phenomena in heavy flavour (beauty and charm) quark sector
- It proved itself to be a **General-purpose Forward Detector** (nicely complementary to ATLAS/CMS)
- Main features
  - Single-arm spectrometer, fully instrumented in pseudo rapidity range $2 < \eta < 5$ (solid angle coverage ~ 4%, 40% B mesons)
  - High performance tracking system (critical!)
    - Spatial resolution ~ 4 $\mu$m at vertex detector
    - $\frac{\Delta p}{p} = (0.4 - 0.6\%)$ for tracks with momentum between $p \rightarrow (5 - 100) GeV$
    - Impact parameter resolution ~ 20 $\mu$m for high $p_T$ tracks
    - Decay time resolution ~ 45 $f$s ($B_s \rightarrow J/\psi\phi$)
    - Excellent particle identification capability
Collected data (on tape):
- Run 1: $3 \, fb^{-1} @ (7 - 8) \, TeV$
- Run 2: $2 \, fb^{-1} @ 13 \, TeV$

High hopes we get another 3 to 4 $fb^{-1}$ within next two years

Note! With higher x-sections (due to higher energy) we expect to get 5 Times larger data samples (w.r.t. Run I) in key physics channels!
Current Detector

[Image of a diagram showing various components of a detector system, including Particle ID, Calorimeters, Muon, Vertrexing, and Tracking, with a reference to "Int. J. Mod. Phys. A 30 (2015)""]
Current Detector Limitations

- The amount of data that can be taken (recorded) is limited by the present detector
  - The luminosity of the LHC will be increasing
    - At present LHCb is running at instantaneous luminosity that is roughly 40 times smaller than ATLAS/CMS
  - At the same time the data bandwidth for LHCb detector would be limited to 1.1 MHz
  - Sub-detectors could not cope with radiation damage (performance degradation)
    - Designed to survive 5 years of data taking at $\mathcal{L} = 2 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$
    - We successfully operated at $\mathcal{L} = 4 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$ and still have two years to go in Run II!
  - Physics yields for hadronic channels would be saturated
  - At higher luminosities the current detector could not perform successfully track reconstruction
    - Much higher track/primary vertex multiplicity
    - Processing time in the online farm to high
The most severe bottleneck is due to hardware trigger

- Yield is almost factor 2 smaller for hadronic channels
- This is mainly due to trigger criteria (cuts on $p_T$ and $E_T$) to fit the trigger rate into the 1.1 $MHz$ readout bandwidth
Phase-I Upgrade Strategy

- Remove the hardware trigger completely – read-out the full detector at each LHC bunch crossing
  - New trigger-less readout front-end electronics
  - Redesign current readout network to cope with multi-TB/s data stream
  - Readout at 40 MHz

- Flexible fully software trigger system
  - Information from each sub-detector available to enhance trigger decision
  - Maximise signal efficiencies at high event rate

- Detectors incompatible with higher luminosities must be re-designed
  - The target peak luminosity of $\mathcal{L} = 2 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$, that is 10 times higher than the nominal and 5 times higher than the one we running at today
  - Finer granularities and more radiation hardness
Phase-I Upgraded LHCb Detector

- **New Vertex Detector**
- **New Tracking stations**
- **Particle ID Replace HPDs + electronics**
- **Calorimeters Reduce PMT gain + new electronics**
- **Muon new electronics**
- **+ trigger-less readout system**
LHCb Upgrade – Timeline I

- **We are here/Jsme zde**

2015 - 2033

**Run 2**
- Install **Phase I** upgrade

**LS2**

**Run 3**
- Potential **Phase Ib**

**LS3**
- upgrade projects in preparation for Phase II

**Run 4**

**LS4**
- **Phase II** Upgrade

**Run 5, 6,...**

Fully approved and fundings are secured
LHCb Upgrade – Timeline II

We are here/Jsme zde

Install Phase I upgrade

Potential Phase Ib upgrade projects in preparation for Phase II

Phase II Upgrade

$\mathcal{L} = 4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$

1.1 visible interactions / crossing

8 fb$^{-1}$ collected
LHCb Upgrade – Timeline II

Run 2 | LS2 | Run 3 | LS3 | Run 4 | LS4 | Run 5,6,...

Install Phase I upgrade

Potential Phase I\textsubscript{b} upgrade projects in preparation for Phase II

Phase II Upgrade

$\mathcal{L} = 4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$

1.1 visible interactions / crossing

8 fb\textsuperscript{-1} collected

$\mathcal{L} = 2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$

5.5 visible interactions / crossing

50 fb\textsuperscript{-1} collected
LHCb Upgrade – Timeline II

We are here / Jsme zde

Install Phase I upgrade

Potential Phase Iib upgrade projects in preparation for Phase II

Phase II Upgrade

\[ \mathcal{L} = 4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} \]
1.1 visible interactions / crossing
8 fb\(^{-1}\) collected

\[ \mathcal{L} = 2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1} \]
5.5 visible interactions / crossing
50 fb\(^{-1}\) collected

\[ \mathcal{L} = 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \]
55 visible interactions / crossing
300 fb\(^{-1}\) collected
Upgraded Trigger System

LHCb 2012 Trigger Diagram
- 40 MHz bunch crossing rate
  - L0 Hardware Trigger: 1 MHz readout, high E_{T}/P_{T} signatures
    - 450 kHz h^{+}, 400 kHz μ/τ, 150 kHz e/γ
  - Defer 20% to disk
  - Software High Level Trigger
    - 29000 Logical CPU cores
    - Offline reconstruction tuned to trigger time constraints
    - Mixture of exclusive and inclusive selection algorithms
  - 5 kHz (0.3 GB/s) to storage

LHCb 2015 Trigger Diagram
- 40 MHz bunch crossing rate
  - L0 Hardware Trigger: 1 MHz readout, high E_{T}/P_{T} signatures
    - 450 kHz h^{+}, 400 kHz μ/τ, 150 kHz e/γ
  - 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

LHCb Upgrade Trigger Diagram
- 30 MHz inelastic event rate (full rate 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

Run 1
Run 2
Run 3, 4

[LHCb-TDR-016]
Vertex Locator
Vertex Locator (VELO) I

- Current detector
  - Two retractable halves separated by a thin RF foil from LHC vacuum
  - Semi-circular silicon microstrip sensors
  - First active strips at 8 mm from the proton beams
  - Coping well with ~ 1 proton interaction per beam crossing
  - $\sigma_{IP} \sim 20 \mu m$ for high $p_T$ tracks

- Vertex detector for the upgrade
  - Much higher radiation dose comparing with the current detector ($\sim 8 \times 10^{15} neq cm^{-2}$)
  - Must cope with ~ 5 interactions per crossing
  - High tracking efficiency
  - Measure impact parameter with high precision
  - Higher granularity
Vertex Locator (VELO) II

- Similar construction concept
  - Two retractable halves, separated by RF foil (0.25 mm thick) from LHC vacuum
  - 52 modules perpendicular to the proton beams
  - First active part 5.1 mm from the beams (aperture 3.5 mm)
Silicon pixel sensors
- Four per module, powered and readout via kapton cables and hybrid boards
- $55 \times 55 \, \mu m$ square pixels (resolution the same in $x$ and $y$ direction)
- Versatile sensor evaluation program is on the way (test beam campaign)
Vertex Locator (VELO) IV

- Hard requirements for VELO pixels
  - High enough charge collection efficiency after irradiation (~ 6000 electrons)
  - Must tolerate high bias voltage (~ 1000 V)
  - High cluster finding efficiency after irradiation
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![Graph showing collected charge vs. bias voltage with a requirement to collect more than 6000 electrons at a bias of 1000 V.](image-url)
Vertex Locator (VELO) IV

- Readout front-end chip – VeloPix ASIC
  - Each sensor (43 × 15 mm) bump-bonded to three VeloPix chips
  - Must cope with high data rate: ~ 800 × 10^6 hits / s
  - Power dissipation: ~ 1.5 W / ASIC
  - All testbeam results very good – final chip to arrive this year

- Sensors and read-out electronics are mounted on cooling substrate with CO₂ micro-channels
  - Excellent cooling performance
  - Minimal material within detector acceptance
  - Now in full production
Tracking System I

Upstream Tracker (UT)

Scintillating Fibre Tracker (SciFi)

Tracking System II

- Current detector – TT
- Four planes of silicon strip detectors vital for reconstructing tracks outside VELO
- Not radiation hard enough for the upgrade
- New front-end read-out electronics needed for 40 MHz trigger
- Need finer granularity to cope with higher occupancies

- Current detector – IT and OT
- Four planes of silicon sensors close to the beam (high $\eta$ tracks)
- Four planes of straw tube gas detectors outside
- New read-out electronics needed in both cases
- Cannot cope with high occupancies

[Image of the tracking system diagram]
Tracking System – UT I

- Four planes of silicon strip detectors mounted to very lightweight staves – **less material**
- Sensors are on both sides of the staves and are closer to the beam – larger coverage
- Finer granularity – strip pitch 95–190 μm
- Four different types of sensors – to flatten out occupancy and fit to the beam pipe (cut-outs)
- Embedded pitch adapters to ASIC (with 73 μm pitch)
Tracking System – UT II

- Stave design well advanced – now switching to construction phase

- Staves provide support for 14 or 16 hybrid modules, data flex connectors and $CO_2$ cooling tubes

- Staves are $\sim 10 \text{ cm}$ wide and $\sim 1.6 \text{ m}$ long

- Dedicated read-out ASIC chip SALT (Silicon ASIC for LHCb Tracking) is being extensively tested

- Second engineering run before summer
Tracking System – UT III

- Stave design well advanced – now switching to construction phase
Tracking System – SciFi I

- 3 x 4 layers of scintillating fibre mats of total area close to $340 \, m^2$ (each mat features material thickness of $1.1 \, X_0$)

- Excellent coverage up to $3 \, m$ from the beam pipe

- Each mat comprises 6 layers of $250 \, \mu m$ thick fibres (total length for SciFi $\sim 11000 \, km$)

- Signal read-out by SiPMs that are cooled to $-40^\circ$ (significant radiation levels and neutron fluence)

- Spatial efficiency close to $80 \, \mu m$

- Single hit efficiency close to $99\%$
Tracking System – SciFi II

- Extensive test beam experiments

**Yield:** 15-24 p.e. depending on position

*May 2015 test beam @ SPS*

**Cluster resolution = 80μm**
Very promising results, all systems seems to surpass the current detectors in the most crucial metrics at higher luminosity.
Tracking System – Simulated Performance

- Very promising results, all systems seem to surpass the current detectors in the most crucial metrics at higher luminosity.

- LHCb Simulation

- Momentum from UT alone

- $\sigma(p_T) / p_T$ [%]

- Current TT
- Upgrade UT

- UT reduces ghost rate by $\sim x4$

- LHCb simulation

- $P$ [MeV/c]
Tracking System – Simulated Performance

- Very promising results, all systems seem to surpass the current detectors in the most crucial metrics at higher luminosity

SciFi
RICH Detectors II

- Currently LHCb features two of these:
  - Upstream RICH1: 2 GeV/c – 40 GeV/c over 25 mrad – 300 mrad
  - Downstream RICH2: 30 GeV/c – 100 GeV/c over 15 mrad – 120 mrad

- Excellent performance in Run 1 and Run 2

- Charged hadrons interact with gaseous radiator and produce Cherenkov photons, that in turn are focused on Hybrid Photon Detectors (HPD)

- Current HPDs are equipped with embedded read-out electronics that is not compatible with new 40 MHz DAQ system
  - Need to replace all HPDs
  - Move to higher granularity
Upgrade plans for RICH detectors comprise of two main changes:

- New optics for RICH 1
- Increase image area and bring down the occupancy
- We need new mirrors, mechanics and radiator box
- Simulation studies show drop in occupancy from 40% (current) to 27% (upgraded)
Upgrade plans for RICH detectors comprise of two main changes:

- New photon detectors
- Allow 40 MHz read-out
- Finer granularity
- Improvement in single photon angular resolution by 50% (RICH1) and 20% (RICH2)

Two types of MaPMTs:

- 48 x 48 mm with 16 pixels
- 23 x 23 mm with 16 pixels

Test beam campaign ongoing to validate both new detectors and read-out chip CLARO
- Full signal processing chain to be tested soon
Calorimeter & Muon Systems

[ LHCb-TDR-014 ]
Calorimeter & Muon Systems

- Since both Calo & Muon Systems were contributing to hardware trigger they are 'almost' ready to go

- Calo Modifications
  - Remove Pre-Shower (PS) and Scintillating Pad Detector (SPD) used for hardware trigger
  - Hadron Calo (HCAL) modules can survive up to 50 fb, Electromagnetic Calo (ECAL) inner-most modules must be replaced after 20 fb
  - Reduce PMTs gain and exchange read-out electronics

- Muon Modifications
  - New read-out electronics
  - Remove the first station M1 (needed by the hardware trigger)
  - Increase shielding around the beam pipe in front of the M2 station – reduce fake hit rate
Beyond Upgrade Phase I – Phase Ib

- Expression of Intent document has been released in February 2017 (CERN-LHCC-2017-003)
- Two step approach – potential initial modifications installed already in LS3
  - Addition tracking stations inside magnet
  - TORCH (Time-of-Flight PID Detector), high-precision timing ($\sigma_t \approx 15\, ps$ per particle) and low momentum tracks PID
  - Improve technology w.r.t. radiation damage and granularity in the highest occupancy regions (Tracker, Calo, RICH and Muon)
Beyond Upgrade Phase I – Phase II

- 4D Pixels
  - Timing information needed for correct long lived tracks association to PVs
  - \( \sigma_t \approx 200 \, \text{ps} \) time resolution enough to match the performance of the current VELO
  - Smaller pixels \( 25 \times 25 \, \mu m \)

- Enhance fibre tracker with inner silicon detector
- Smaller cells and timing information for ECAL
Summary

- **Ambitious plans for Phase I**
  - R&D well underway – transition to construction phase
  - Development of advanced and sophisticated r/o electronics (e.g. SALT chip)
  - Trigger and computing model is being tested during Run 2
  - Major changes to the LHCb spectrometer – new VELO, UT and SciFi, also deep technology update for RICH detectors

- **Future upgrades to exploit HL LHC era**
  - Potential huge data samples
  - Major challenge for detector design
  - Timing information and radiation hardness critical