Performance and operational aspects of LHCb's VELO and ST

Eduardo Rodrigues
University of Manchester

On behalf of the LHCb VELO and ST Groups
The LHCb experiment

Mission statement:
- Indirect searches for New Physics using heavy flavour particles
- Study CP violation and rare decays of heavy hadrons and leptons

Approach:
- Focus mainly on loop-mediated processes giving access to scales > LHC production scale, i.e. the TeV
LHCb physics programme – system requirements

\[ B \rightarrow D^0 X \]

\[ D^0 \rightarrow K \pi^+ \pi^- \]

\[ B \rightarrow \ell^+ \nu \]

\[ IP \rightarrow \text{PV} \]

\[ \sim 1 \text{ cm} \]

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**LHCb-CONF-2012-029**
LHCb physics programme – system requirements

Separation of secondary from primary vertices

Excellent tracking:
- Primary vertex resolution
- Impact parameter resolution
- Momentum resolution

~ 1 cm

Excellent decay time resolution
(On average a $B_s$ oscillates 9 times before it decays)

Excellent particle identification

The LHCb detector

Heavy-flavour production at the LHC:
- Large production cross-section, correlated in forward/backward region
- Access to all b-hadrons: $B_x$, $\Lambda_b$, etc.

Tracking System
- Vertex Locator
- Tracker Turicensis
- Inner Tracker
- Outer Tracker

Calorimetry

Muon system
Silicon trackers – VELO

- 2 retractable detector halves
- 2 semi-circular micro-strip Si sensors / module
- Radial (R) and azimuthal angle (φ) coords
- Sensors:
  - 300 μm thick, n-on-n, 2048 strips
  - Strip pitches from 40 to 120 μm

21 stations per half, each with 1 R and 1 φ sensor

- Operation in secondary vacuum
- 300 μm foil separates detector from beam vacuum
- Bi-phase CO₂ cooling system
  - Operates at -30 °C
  ⇒ sensors @ -10 °C
Silicon trackers – TT

- **Silicon micro-strip detectors**
  - p⁺-on-n
- **Four planes (0°, +5°, -5°, 0°)**
- **Pitch: 183 μm; thickness: 500 μm**
- **Long readout strips (up to 37 cm)**
- **Total Silicon area is 8 m²**
  - Covers full acceptance before magnet
- **Cooling plant operates at 0°C**
  - Sensors @ 8°C
Silicon trackers – IT

- **Silicon micro-strip detectors**
  - p⁺-on-n
- **Three stations in z**
  - Four boxes in each station
  - Four planes (0°, +5°, -5°, 0°)
- **Pitch: 198 μm**
- **Thickness: 320 or 410 μm**
- **Total Silicon area is 4.2 m²**
  - Covers region around beam with highest flux
- **Cooling plant operates at 0°C**
  - Sensors @ 8°C
LHC(b) run I
As everyone knows ...

- Excellent performance of the accelerator!

- E. g. ~ 200 proton physics days in 2012:

Design:
- \( \sqrt{s} = 14 \text{ TeV} \)
- 2808 bunches, 25 ns spacing
- \( L = 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} \)
- Average number of visible pp interactions / bunch crossing (\( \mu \)) = 0.5

Reality (2011+2012):
- \( \sqrt{s} = 7 \text{ TeV} / 8 \text{ TeV} \)
- \( \approx 1300 \) 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
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LHC operation – luminosity of pp collisions in Run I

- Total recorded lumi in run I: 3.2 fb⁻¹
Conclusions:

- LHCb improved with time – run I average operational eff. ~ 93%
- Velo safety = closing (~210 s to close and restart the DAQ)
- Velo close to optimal from early on ;-)
- We invented luminosity levelling
  - Now completely automated and being copied by other experiments
- We have a versatile trigger
  - Very quick reactions to changing conditions, fixes, etc.
- We use deferred triggering routinely
  - It actually makes operations safer and simpler
Si trackers operation

Other LHCb talks of interest
- Eddy Jans – VELO cooling experience
- Martin van Beuzekom – VELO upgrade
**VELO operations in a nutshell**

<table>
<thead>
<tr>
<th>Year</th>
<th>Motion / Closing</th>
<th>Cooling</th>
<th>Vacuum</th>
<th>Data quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>Controlled by experts</td>
<td>Fully automated, monitored</td>
<td>Fully automated, monitored</td>
<td>Controlled by experts</td>
</tr>
<tr>
<td>2011</td>
<td>Fully automated</td>
<td>Monitored</td>
<td>Monitored</td>
<td>Automated prod. of histos, DQ shifters / week</td>
</tr>
<tr>
<td>2012</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td>Unchanged</td>
<td>Unchanged</td>
<td>Unchanged</td>
<td>Automated</td>
</tr>
</tbody>
</table>
VELO operations in a nutshell – details

- Generally speaking, very stable running / smooth operation
  - Problems normally solved quickly by piquets

- Motion system:
  - VELO closed more than 500 times
  - Operated manually for special LHC runs/conditions
  - Very rare erroneous readings of potentiometer (used for monitoring)

- Vacuum system:
  - Approx. twice a year, need to go from vacuum to 900 mbar neon atmosphere, and back again

- Cooling system:
  - No loss of data due to cooling problems
  - Temperature stability very good (~ 0.1 °C)
  - CO₂ pumps require maintenance approx. once per year
  - See full account in Eddy Jans’ presentation …
ST operations in a nutshell

- **VCSEL Diodes**
  - Problem with manufacturing process. 30% exchanged before start of LHC
  - Rate ~1 / month need to be exchanged

- **Broken bonds in TT**
  - 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)

- **TT High Voltage Problem**
  - Large spikes in the HV seen with beam
  - Trips of HV, dead regions
  - Reason not fully understood but cured by installation of Kapton shielding

- **Cooling system**
  - Oil mixed with coolant in chiller
  - Flow of mixed water increases
  - Lead to higher temperature of C6F14 coolant
  - Requires a lot of babysitting
  - Intervention every two days – cooling system stopped for five minutes (during interfill period.)

- **Synchronisation problems**
  - Unphysical temperature readings due to communication problem
  - Fast control fibers touched when exchanging VCSEL diodes
  - Required cleaning of fibers
  - (Flaw in design of temperature monitoring)
Si trackers performance

Detector-specific performance

Channel efficiency
Signal over noise
Radiation damage
**Channel efficiency**

<table>
<thead>
<tr>
<th>% working channels</th>
<th>VELO</th>
<th>TT</th>
<th>IT</th>
</tr>
</thead>
<tbody>
<tr>
<td># channels</td>
<td>172032*</td>
<td>143360</td>
<td>129024</td>
</tr>
</tbody>
</table>

- Many VCSEL diodes replaced
- 1 dead VCSEL diodes
- 3 ports disabled
- Access for repairs is difficult
- 3 dead VCSEL diodes
- 10 ports disabled
- 2 modules not configurable

(VCSEL=Vertical-cavity surface-emitting laser. Used to transmit optical data after off-detector digitisation.)

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Vertex 2013, Lake Starnberg, Germany, 16 Sep. 2013
Average noise in R and $\phi$ sensors ~ $1.6-2$

- Average noise in each strip for the R sensors
- RMS of the scatter from the 42 sensors shown as errors

Signal and S/N larger for $\phi$ than R sensors

- S/N (R) $\approx 19$
- S/N ($\phi$) $\approx 21$
Signal over noise - ST

<table>
<thead>
<tr>
<th>TT</th>
<th>IT</th>
<th>VELO</th>
</tr>
</thead>
<tbody>
<tr>
<td>S/N</td>
<td>12−15</td>
<td>16.5 (long)</td>
</tr>
<tr>
<td></td>
<td>17.5 (short)</td>
<td>21 (ϕ)</td>
</tr>
</tbody>
</table>

- S/N decreases with capacitance
- IT: peak ~ 23 due to thicker sensors used in short ladders
- Within 10-20% of expectations
Radiation damage

Remember

- High particle fluence (up to $5 \times 10^{13}$ 1 MeV n$_{eq}$/cm$^2$) due to proximity to the beams
  - Especially relevant for the VELO

- Particle irradiation causes surface and bulk damages in the silicon
  - affects leakage current and effective doping concentration

Investigation methods – 4, independent and complementary

- Changes in currents vs. voltage (IV curves)
- Changes in current vs. temperature (IT curves)
- Changes in full Depletion Voltage
- Changes in Cluster Finding Efficiency (CFE)

VELO radiation damage paper

- Published in August: JINST 8 (2013) P08002
- Also in arXiv: 1302.5259
Radiation damage in VELO – effective depletion voltage

**Determination method for each sensor**

- At each voltage, extrapolate tracks to test sensor (every 5\textsuperscript{th} module) ⇒ determine amount of charge collected
- Bias voltage varied from 0 till 150 V
- At each V, determine most probable value (MPV) of ADC count distribution ⇒ Effective depletion voltage = voltage @ 80% of MPV plateau value
Minimum effective depletion voltage (EDV) decreases with fluence down to ~ 18 V …

Until type inversion is observed around 15 \times 10^{12} \ 1 \text{MeV } n_{\text{eq}}/\text{cm}^2 and EDV increases, approximately linearly

Type inversion observed first in sensors closest to the beam, as expected

General good agreement with the Hamburg model at low and high fluences

Model inappropriate around type inversion point

N. B.: equivalent study for TT & IT close to being released
Radiation damage in ST – leakage current vs time

Leakage current seen to follow the evolution with fluence

Peak current = max current during fill
Radiation damage in ST – leakage current vs time

- Leakage current seen to follow the evolution with fluence

Peak current = max current during fill

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Observations in excellent agreement with predictions
Si trackers performance

Global aspects

Alignment
Hit resolutions
Cluster finding efficiencies
Tracking efficiencies
Primary vertex resolutions
Impact parameter resolutions
Momentum and mass resolutions
Alignment – VELO halves

- Reminder: for each fill, halves are closed and centred around beam once beams declared stable
  - Fully automated procedure (~210 s)

- Beam position determined from vertex reconstruction with tracks in right or left half

- Misalignment from distance between the 2 reconstructed vertices

- Stable within ±5 μm (x)

- Example from 2010 (2011&12 figures to be released soon):
Alignment and hit resolutions – ST

- Use tracks from VELO + IT stations
- Global $\chi^2$ minimisation based on Kalman track fit residuals [1,2]
- Improvements applying mass constraint to vertices from $D^0 \rightarrow K^+ \pi^-$ [3]
  - Suppression of weak modes

⇒ ST alignment precision ≈ 14 $\mu$m

<table>
<thead>
<tr>
<th></th>
<th>TT</th>
<th>IT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hit resolution ($\mu$m)</td>
<td>59</td>
<td>50</td>
</tr>
</tbody>
</table>
Hit resolutions - VELO

- Hit resolutions from track hit residuals
- Single hit resolution vs strip pitch
  - For 2 ranges of track projected angle
- Linear dependence on the strip pitch
- Hit resolution better for larger projected angles:
  
  Best hit resolution ~ 4 μm
**Method**

- CFEs determined by excluding test sensor in pattern recognition and interpolating tracks to this sensor
- Tracks are required to have:
  - Hits in both R and $\phi$ sensors in the 2+2 modules before/after the test sensor
  - Hits in at least six modules

(These requirements place restrictions on the region and sensors that can be probed)

<table>
<thead>
<tr>
<th>CFE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All channels</td>
</tr>
<tr>
<td>Bad strips excluded</td>
</tr>
</tbody>
</table>

N.B.:

- Track quality cuts applied to remove fakes
- Efficiency for finding a cluster depends on applied bias voltage $\leftrightarrow$ radiation damage
Track finding efficiencies

Method

- Tag and probe with sample of $J/\psi \rightarrow \mu \mu$
- Use in turn a tag track from a subdetector, match to another track stub to get probe track
- From the possible combinations, determine track efficiency for all track types in LHCb
  - Efficiency = # associated / # total

In short

- Track efficiency for “long” tracks $\approx 98%$
  - long track = track traversing all tracking subdetectors
- $\varepsilon_{\text{data}} / \varepsilon_{\text{MC}} = (100.9 \pm 0.6) \%$ for 2010+11 data

Primary vertex resolutions

- Resolutions versus number of tracks on vertex (computed separately for 1-, 2-, 3-PV events)
- Data points fit to function \( a/N^b + c \)
- Typical resolution for 1-PV event with 25 tracks

<table>
<thead>
<tr>
<th>Typical resolution</th>
<th>x (( \mu )m)</th>
<th>y (( \mu )m)</th>
<th>z (( \mu )m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-PV event, 25 trks/PV</td>
<td>13.5</td>
<td>12.5</td>
<td>90</td>
</tr>
</tbody>
</table>

- Slightly worse resol. in events with pile-up, i.e. multi-PV events

\[
\begin{align*}
\text{LHCb preliminary} & \quad \sqrt{s} = 7 \text{ TeV} \\
& \quad \sqrt{s} = 8 \text{ TeV}
\end{align*}
\]
Impact parameter resolutions

- Impact parameter (IP) = distance of closest of track to PV

- IP resolution in (x,y) \( \sim 12 \, \mu m \)
  for high-\( p_T \) tracks

- Data-MC agreement reasonable (with new MC)

Resolution depends on

- Hit resolution
- Multiple scattering \( \Leftrightarrow \) detector material
- Distance from PV to first measurement
Resolutions in mass, decay time

- Momentum resolution typically 0.35-0.55%
- Mass resolutions typically in range 7-20 MeV

Various world-best mass measurements

E. g. D⁰ mass measured with a 0.008% relative accuracy!

<table>
<thead>
<tr>
<th></th>
<th>$M(A_b^0)$</th>
<th>$M(\Xi_b^-)$</th>
<th>$M(\Omega_b^-)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>5619.7 ± 1.3</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>CDF</td>
<td>5619.7 ± 1.7</td>
<td>5790.9 ± 2.7</td>
<td>6054.4 ± 6.9</td>
</tr>
<tr>
<td>D0</td>
<td>–</td>
<td>5774 ± 19</td>
<td>6165 ± 16</td>
</tr>
<tr>
<td>PDG</td>
<td>5619.4 ± 0.7</td>
<td>5791.1 ± 2.2</td>
<td>6071 ± 40</td>
</tr>
<tr>
<td>LHCb</td>
<td>5619.5 ± 0.5</td>
<td>5795.8 ± 1.0</td>
<td>6046.0 ± 2.3</td>
</tr>
</tbody>
</table>
Conclusions & outlook
Run I Si trackers performance summary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>VELO</th>
<th>TT</th>
<th>IT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical PV resolutions (25 trks/vertex)</td>
<td>13 (90) μm in x, y (z)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Typical IP resolutions</td>
<td>~12 μm in x, y (2012 data)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Signal-over-noise ratio</td>
<td>19–21</td>
<td>12–15</td>
<td>~ 17</td>
</tr>
<tr>
<td>Single-hit resolutions</td>
<td>4 μm at 40 μm pitch</td>
<td>59 μm</td>
<td>50 μm</td>
</tr>
<tr>
<td>Cluster finding efficiencies</td>
<td>99.5%</td>
<td>99.3%</td>
<td>99.7%</td>
</tr>
<tr>
<td>Tracking efficiency for “long” tracks</td>
<td>eff ~ 98%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Conclusions and outlook

**General**

- Detectors performed very well and smoothly overall!
- Excellent performance, matching the needs
- Radiation damage carefully monitored
- Type inversion observed for the VELO, not for the ST
- So far no impact on physics due to radiation damage
- Programme of maintenance during LHC’s long shutdown being carried on

**What about the future?**

- The future is bright, the future is ...
- Upgrade activities full steam. See Martin van Beuzekom’s talk …
Back-up slides
The LHCb collaboration

934 members
17 countries
65 institutes
LHCb silicon detectors – VELO & Si trackers

**VELO**

- 2 retractable detector halves
- 21 R-$\phi$ modules / halve
- 2 semi-circular micro-strip Si sensors / module
  - Radial (R) and azimuthal angle ($\phi$) coords
- Operates in secondary vacuum
- Bi-phase CO$_2$ cooling system
  - Operates at -30 °C
  - Sensors @ -10 °C

- Sensors:
  - 300 $\mu$m thick, n-on-n, 2048 strips
  - Strip pitches from 40 to 120 $\mu$m

**ST – TT**

- 4 det. layers: 0 °, +5 °, -5 °, 0 ° tilted
- p-on-n sensors
  - Pitch = 183 $\mu$m, thickness = 500 $\mu$m
- Read-out strips up to 37 cm long

**ST – IT**

- 3 stations each with 4 layers
- p-on-n sensors
  - Pitch = 198 $\mu$m, thickness = 320,410 $\mu$m
- Read-out strips up to 22 cm long
  (since sensors paired)

- TT & IT operated at 0 °C
  - Sensors @ about 8 °C
Luminosity leveling

What is it ?

- Maintain the instantaneous luminosity at a roughly constant value for the whole duration of a fill
- Achieved by intentionally and continuously displacing both colliding beams with respect to each other (offset)

What for ?

- Safe operation of LHCb detector only when instantaneous lumi. $\lesssim 4 \times 10^{32}$ cm$^{-2}$ s$^{-1}$
  - Been running on average $\sim 3 \times 10^{32}$ cm$^{-2}$ s$^{-1}$
- But LHC runs well above for ATLAS/CMS
- LHCb main limitation from 1 MHz first-level trigger bandwidth
- (Situation to change with LHCb upgrade: inst. lumi up to $2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$)
Primary vertex resolutions - methodology

- Take all tracks in a given event ⇒ split them into 2 equal-size samples
- Reconstruct PVs in each sample
- Search for “matched” vertices requiring their $\Delta z < 2$ mm
- Fit Gaussian to the obtained $\Delta(x,y,z)$ distributions
- PV resolution = Gaussian width/$\sqrt{2}$ if both PVs with same number of tracks
- Resolutions studied for 1-, 2-, multi-PV events

- Simulation reproduced reasonably the data
Impact parameter resolutions - methodology

- Use minimum bias data - dominated by prompt tracks
- Extrapolate all long tracks to same z co-ordinate as PV
- Measure separation in x and y (IPx and IPy)
- Plot IPx and IPy vs. variable of interest, eg, $1/p_T$
- Fit IPx and IPy distributions in each bin of variable of interest with a single Gaussian
- Take Gaussian width as the resolution

Track selection: Select only long tracks satisfying:
- $\chi^2/NDF < 4$
- N. VELO R hits $> 5$
- N. TT hits $> 0$
- $p < 500 \text{GeV}$

From events with:
- Only 1 reconstructed PV.
- $> 25$ tracks used to fit the PV.
VELO2 – the replacement detector

Why build one?

- In case of macroscopic damage due to beam accidents
- Also for redundancy
- Assembled in case radiation damage would seriously degrade detector performance

Executive summary of tests

- Series of performance tests performed:
  - Sensor noise, IV curves, thermal performance, etc.
- In most cases Velo2 at least as good as present Velo
- Velo2 ready if needed
  - Metrology to be re(done) this year
- Will go in display at the LHCb pit, for outreach

(LHCb public note in preparation)
ST – cooling plant problems

1. Build up of “junk” in flow regulators.
   – Flow of $C_6F_{14}$ decreased over period of months causing increase of temperature.
   – Will be cured when filters are exchanged in October.

2. Loss of cooling power in plant (see box).
   – Can be “solved” by performing recirculation during inter-fill period.
   – System adjustment in June 2012 worked for three weeks.
   – Now require re-circulation every 2-3 days.
   – Harder alarm limits set on mixed water flow.
**TT – broken bonds**

- 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).