LHCb Silicon Detectors: Operational Experience and Run I → Run II Transition

Vertex 2014, Lake Mácha, September 15 - 19, 2014
Christian Elsasser [on behalf of the LHCb VELO and ST groups]
The LHCb Experiment

Experiment dedicated to the studies of rare heavy quark decays and $CP$ violation

Single-arm forward spectrometer
$(2 < \eta < 5)$

Tracking System
RICH
Calorimetry
Muon system
The LHCb Experiment

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$\sigma_{IP} = 25 \, \mu m$ for $p_T = 2 \, \text{GeV}/c$

$\sigma_{PV,x/y} = 13 \, \mu m$ for $N_{\text{tracks}} = 25$

$\sigma_m = 12 \, \text{MeV}/c^2$ for $J/\psi \rightarrow \mu^+ \mu^-$

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$(2 < \eta < 5)$

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The LHCb Experiment

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Single-arm forward spectrometer
($2 < \eta < 5$)

Silicon Detectors

- VELO
- TT
- IT
The LHCb Experiment

Experiment dedicated to the studies of rare heavy quark decays and CP violation

Single-arm forward spectrometer
(2 < \( \eta \) < 5)

Silicon Detectors
- VELO
- TT
- IT

H. Schindler (VELO upgrade)
E. Bowen (Tracking & Vertexing)
F. Lionetto (UT upgrade)
Vertex Locator (VELO): Detector

- 21 module in each half
- First active strip at $r \approx 8$ mm
- Sensors retractable for injection
- Sensors kept in a secondary beam vacuum separated by an undulated aluminum foil
- $\sim 172k$ readout channels
Vertex Locator (VELO): Sensor

- Two single-sided silicon microstrip sensors (n+ on n by Micron; n+ on p in the most upstream module)
  - r-sensors: four 45° quadrants
  - Φ-sensors: two regions (inner and outer)
- Thickness: 300 µm;
  Strip pitch: 38-102 µm
- Double metal layer for signal routing
- Sensors at ~ −10°C
- 99.6% of channels working
The Tracker Turicensis (TT)

- Silicon micro strip sensors (p+-on-n by Hamamatsu Photonics K.K.)
- Thickness: 500 µm; Strip pitch: 183 µm
- Readout strips length up to 37 cm ⇒ up to 60 pF
- ~ 144k readout channels
- Total area: 8 m²
- Sensors at ~ 8°C
- 99.7% of channels working (averaged over Run I)
The Inner Tracker (IT)

- Silicon micro strip sensors (p⁺-on-n by Hamamatsu Photonics K.K.)
- Twelve layers
- Thickness: 320 (1 sensor, 11 cm) or 410 µm (2 sensors, 22 cm); Strip pitch: 198 µm
- ~130k read out channels
- Total area: 4.2 m²
- Sensors at ~8°C
- 98.6% of channels working (averaged over Run I)
Signal-to-Noise Ratio (VELO)

Measured with 1-strip clusters assigned to VELO tracks
Ratio of most probable ADC value to 1-strip common-mode subtracted noise

Impact of routing lines on 1-strip common-mode subtracted noise
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Impact of routing lines on 1-strip common-mode subtracted noise
Signal-to-Noise Ratio (TT + IT)

Measured with clusters assigned to tracks with $p > 5$ GeV/c
Ratio of most probable ADC value to 1-strip common-mode subtracted noise

- Tracker Turicensis: 12-15
- Inner Tracker: 15-18
Hit Resolution (VELO)

Hit resolution dependent on strip pitch and projected angle

Unbiased track residuals used to determine the resolution

Hit resolution of 4 \(\mu\)m achieved for small pitch and optimal angle
Spatial Alignment (VELO): Sensors

- Optical and mechanical measurements before installation
- Software alignment based on
  - the Millipede method [NIM A596 (2008), 157]
  - the residuals of a Kalman filter fit [NIM A600 (2009), 471]

⇒ alignment precision for sensors better than 4 μm
Spatial Alignment (VELO): Halves

Centering of the VELO required due to the closing of the VELO at the beginning of each fill
Based on the $x$- and $y$-measurement of the reconstructed primary vertices in each half
Fully automated and done within 210 s after stable beams
⇒ stability of the alignment within 5 $\mu$m

\[ \Delta x \]

\[ \Delta y \]
**Spatial Alignment (TT + IT)**

Tracking stations are aligned by minimising all track residuals from a Kalman filter fit [NIM A600 (2009), 471]

Mass constraints ($J/\psi(1S) \rightarrow \mu^+\mu^-$ and $D^0 \rightarrow K^{\pm}\pi^{\mp}$) used to suppress weak modes. [NIM A712 (2013), 48]

TT hit resolution (incl. alignment): 53.4 µm (Binary resolution: 53 µm)

IT hit resolution (incl. alignment): 54.9 µm (Binary resolution: 57 µm)
Running Conditions

Delivered integrated luminosity:
- 2010: 0.04 fb\(^{-1}\)
- 2011: 1.22 fb\(^{-1}\)
- 2012: 2.21 fb\(^{-1}\)

Integrated luminosity in 2010-2012: 3.5 fb\(^{-1}\)

Designed lifetime of TT and IT: 10 years with 2 fb\(^{-1}\)/year
Designed lifetime of VELO: 5 years with 2 fb\(^{-1}\)/year
Running Conditions

FLUKA simulation tuned to dose measurements in the cavern:

Maximal 1 MeV neutron equivalent flux:

<table>
<thead>
<tr>
<th>Detector</th>
<th>Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>VELO</td>
<td>$8.0 \times 10^7$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>TT</td>
<td>$1.0 \times 10^6$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>IT</td>
<td>$9.2 \times 10^4$ cm$^{-2}$s$^{-1}$</td>
</tr>
</tbody>
</table>
Radiation Damage Monitoring

Leakage Currents:
- Change in the band structure of the silicon (bulk current)

Depletion Voltage:
- Change in the effective doping concentration induced by irradiation
Radiation Damage Monitoring

Leakage Currents:

- Change in the band structure of the silicon (bulk current)

\[ I_{\text{leak}} = \alpha \cdot \Phi \cdot V \]

Temperature dependence of the bulk current:

\[
\frac{I_{\text{leak}}(T_1)}{I_{\text{leak}}(T_2)} = \left( \frac{T_1}{T_2} \right)^2 \cdot \exp \left( - \frac{E_g}{2k_B} \left( \frac{1}{T_1} - \frac{1}{T_2} \right) \right)
\]

*E_g*: band gap of silicon
*T_{1,2}*: temperatures
Leakage Currents (VELO)

Measurements normalised to $-7^\circ C$

Prediction based on mean 1-MeV-n equivalent fluence

$\Rightarrow$ Good agreement between measurements and predictions
Leakage Currents (VELO): Temperature scans

Temperature scans allow to measure contributions from surface and bulk currents.

Expected exponential variation of bulk currents.

Surface currents in the VELO behave ohmically and anneal with particle fluence.
Leakage Currents (TT + IT)

![Graph showing leakage currents]

Data normalised to a temperature of 8° C ($E_g = 1.21$ eV)
Leakage Currents (TT + IT)

Data normalised to a temperature of 8° C ($E_g = 1.21$ eV)
Leakage Currents (TT + IT)

![Graph showing leakage currents over time]

Data normalised to a temperature of 8° C ($E_g = 1.21$ eV)
Depletion Voltage

Charge Collection Efficiency (CCE) scans:
Dedicated runs (3-4 times per year) with scanning of bias voltage in VELO/tracking stations
Depletion Voltage

Charge Collection Efficiency (CCE) scans:

Extraction of effective depletion voltage by fraction of plateau ADC counts ⇒ calibrated with depletion voltage measurements after production and early CCE scans
Depletion Voltage (VELO)

- Type inversion of sensors at \( \Phi_{\text{1-MeV-n eq}} = (1.0 - 1.5) \times 10^{13} \text{ cm}^{-2} \)
- Good agreement with the Hamburg model [NIM A426 (1999) 87]
- Sensors can be operated up to 500 V.
Depletion Voltage (VELO)

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Depletion Voltage (TT): Pulse Shape

Thicker sensor $\Rightarrow$ larger ballistic deficit

High bias voltage (400 V):  
Low bias voltage (60 V):

Timing scan performed in each voltage step

Extraction of Charge Equivalent as integral of the pulse shape
Depletion Voltage (TT)

- No type inversion so far
- Good agreement with the Hamburg model (also for considering annealing and reverse annealing terms for single sensor)
- Sensors can be operated up to 500 V.
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Work during LS1

Detectors perform very well

⇒ No major intervention on all three sub-detectors
  ▶ Replacement of the TT/IT chiller and maintenance of the cooling system
  ▶ Maintenance of the VELO vacuum system
  ▶ Scheduled maintenance of HV/LV supplies
  ▶ Minor repair work on the electronics (DAQ, Slow control)
  ▶ Restructuring of ECS software (e.g. transition from PVSS to WinCC)
  ▶ Installation of alignment monitor system in IT based on two BCAMs (Brandeis CCD Angle Monitor) per station
50 ns → 25 ns Transition

Aim for 25 ns bunch spacing ⇒ Higher spill-over hit rate

Possible modifications:

- Modification of sampling time and signal shaping
- Usage of “spill-over” bit to identify tracks reconstructed from spill-over hits
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Summary & Conclusion

- Excellent performance of LHCb’s silicon detectors during Run I
  - excellent hit resolution
  - measured signal-to-noise ratios close to expectations
  - contributing to very precise impact parameter
  - ... and invariant mass measurements

- Radiation damage monitored via leakage currents and Charge Collection Efficiency scans also in good agreement with predictions

- No significant degradation of the physics performance observed

- Standard maintenance work performed during LS1

- Possible changes in the operation due to 25 ns bunch spacing

- VELO, TT and IT are looking forward to LHC Run II
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Backup
Material Budget (VELO)

High vertex resolution ⇒ less multiple scattering ⇒ small amount of material between the interaction point and the first measurement.

Dominated by the 300 µm thin aluminum foil separating the primary and the secondary beam vacuum.
Material Budget (VELO)

LHCb VELO  
average = 0.227 $X_0$

<table>
<thead>
<tr>
<th>Category</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>R.F. foil</td>
<td>42.6%</td>
</tr>
<tr>
<td>Sensors</td>
<td>20.3%</td>
</tr>
<tr>
<td>hybrids</td>
<td>14.1%</td>
</tr>
<tr>
<td>Detector Supports</td>
<td>6.6%</td>
</tr>
<tr>
<td>R.F. Box</td>
<td>5.8%</td>
</tr>
<tr>
<td>Kapton Cables</td>
<td>2.8%</td>
</tr>
<tr>
<td>Constraint System</td>
<td>2.5%</td>
</tr>
<tr>
<td>Connectors</td>
<td>2.3%</td>
</tr>
<tr>
<td>Paddle+Base</td>
<td>1.8%</td>
</tr>
<tr>
<td>W.F. Suppressor</td>
<td>0.9%</td>
</tr>
<tr>
<td>Cooling Block</td>
<td>0.4%</td>
</tr>
<tr>
<td>LHCb VELO</td>
<td>1.2%</td>
</tr>
<tr>
<td>Total material</td>
<td>0.227 $X_0$</td>
</tr>
</tbody>
</table>
TT Module

- silicon sensors
- pitchadapter
- front-end hybrids
- carbon-fibre support rails
- Kapton interconnect cable
Detector Readout

Front end (Beetle Chip) on the detector
< 1 Mrad in 10 years

Digitisation in Service Boxes near the detector
~ 10 krad in 10 years

TELL1 readout boards in the counting house
(Common mode noise and pedestal subtraction, zero suppression)
Hit Efficiency (IT)

Analysis of tracks from $D^0 \rightarrow K^+ K^-$ decays ($p > 10$ GeV/c)
Extrapolate each track to the sensors and search hit within a certain window Average hit efficiency $\varepsilon > 99\%$

Note the scale

$\varepsilon > 99\%$
Cluster Size (VELO)

Dominating cluster size (1-, 2-, 3- or 4-strip cluster) dependent on projected angle and strip pitch
Cluster Finding Efficiency (VELO)

Cluster Finding Efficiency decreases with increasing irradiation and bias voltage.

Possible explanation based on charge collection by the routing lines on the 2nd metal layer:

- A possible explanation lies in sensor design.
- n⁺ on n⁻ type (82 sensors).
- The 2nd metal layer carries signal to read-out electronics.
- Routing lines in R-type sensors are perpendicular to strips.
- Charge is deposited also on routing lines.
- Effect visible when distance to routing lines is less than to strip (outer region).

Efficiency depends on distance to nearest strip and nearest routing line.

No measurable effect on the tracking.
Time Alignment (TT + IT)

Synchronization of trigger and control signals in the entire LHCb detector necessary (time of flight, cable length)

Samples spaced by 25 ns with internal shift of sampling point by $-6, 0, +6, +12$ ns

Extract most probable value from distribution of ADC counts and fit pulse shape

Timing alignment of TT and IT with collision data better than 1 ns
Broken Bond Problem (TT)

- Breaking of bonds between pitch adapter and readout chip
- Only inner most row affected

<table>
<thead>
<tr>
<th>Channel number</th>
<th>Noise (ADC counts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2600</td>
<td>0</td>
</tr>
<tr>
<td>2700</td>
<td>1</td>
</tr>
<tr>
<td>2800</td>
<td>2</td>
</tr>
<tr>
<td>2900</td>
<td>3</td>
</tr>
<tr>
<td>3000</td>
<td>4</td>
</tr>
</tbody>
</table>

Figure 7: The noise for each channel in a sector with broken bonds between the last readout chip and the pitch adaptor. The broken bonds are observed on every fourth channel from 2944 to 3068.

4.3 High Currents in TT

Abnormally high currents were observed during the early data taking in 2010 and 2011. The leakage current was expected to be below 10 µA but currents of the order of hundreds of µA were seen. The current would rise suddenly and then decrease slowly over the course of a fill as shown in Fig. 8. In the most extreme case, this caused a number of high voltage channels to trip in the power supply leading to large dead regions in the detector. This effect was only observed for the modules in the layers closest to the walls of the detector box.

It was also observed that the spikes in the current were partially correlated with the instantaneous luminosity as shown in Fig. 9. This effect was seen in the early data taking period where the LHC was running with lower instantaneous luminosities than the nominal value. This could have limited the ability of the experiment to collect data with a high efficiency at higher luminosities.
High Voltage Problem (TT)

- Abnormally high currents (far above 10 µA)
- Correlation with instantaneous luminosity
- Sectors which are closest to the wall of the detector box are affected

⇒ Installation of Kapton shielding on the detector box walls and bias voltage kept on in between fills
High Voltage Problem (TT)

No High Currents after installation of the Kapton shielding:
Depletion Voltage (TT + IT)

High bias voltage (400 V):

Low bias voltage (60 V):

Residual background from missed extrapolation or ghost tracks

Photon conversion taken into account
Depletion Voltage (TT + IT)

High bias voltage (400 V):

Low bias voltage (60 V):

Timing scan performed in each voltage step

Extraction of Charge Equivalent as integral of the pulse shape
Depletion Voltage (TT + IT)

July 2011:

January 2013:

Depletion voltage $V_{\text{depl}}$ extracted from a third-order spline as the voltage where the fit function reaches about 95% of its maximal value (calibration with measurements from the first CCE scan and $V_{\text{depl}}$ measured after production)
Depletion Voltage (TT + IT)

Also good agreement between $V_{\text{depl}}$ values measured from CCE scans and estimated from the Hamburg model and running conditions in less irradiated sensors.
Depletion Voltage (TT + IT)

Change in the depletion voltage:

July 2011: January 2013:

Average fluence for the six innermost sensors is not equal.
## Model Parameters for Leakage Currents

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_0$</td>
<td>$(6.67 \pm 0.09) \times 10^{-17}$ A/cm</td>
</tr>
<tr>
<td>$\alpha_1$</td>
<td>$(7.23 \pm 0.06) \times 10^{-17}$ A/cm</td>
</tr>
<tr>
<td>$k_0$</td>
<td>$(4.2 \pm 0.5) \times 10^{13}$ s$^{-1}$</td>
</tr>
<tr>
<td>$E_a$</td>
<td>$(1.11 \pm 0.05)$ eV</td>
</tr>
</tbody>
</table>
## Model Parameters for Depletion Voltage

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>$N_{C0} \cdot c$</td>
<td>$(7.5 \pm 0.6) \times 10^{-2} \text{ cm}^{-1}$</td>
</tr>
<tr>
<td>$g_c$</td>
<td>$(1.60 \pm 0.04) \times 10^{-2} \text{ cm}^{-1}$</td>
</tr>
<tr>
<td>$g_a$</td>
<td>$(1.40 \pm 0.14) \times 10^{-2} \text{ cm}^{-1}$</td>
</tr>
<tr>
<td>$g_Y$</td>
<td>$(5.70 \pm 0.09) \times 10^{-2} \text{ cm}^{-1}$</td>
</tr>
<tr>
<td>$k_{0,a}$</td>
<td>$(2.4 \pm 1.0) \times 10^{13} \text{ s}^{-1}$</td>
</tr>
<tr>
<td>$k_{0,Y}$</td>
<td>$(1.5 \pm 1.1) \times 10^{15} \text{ s}^{-1}$</td>
</tr>
<tr>
<td>$E_{aa}$</td>
<td>$(1.09 \pm 0.03) \text{ eV}$</td>
</tr>
<tr>
<td>$E_{Y}$</td>
<td>$(1.31 \pm 0.03) \text{ eV}$</td>
</tr>
</tbody>
</table>
Impact Parameter and Decay Time Resolution

- Impact parameter and decay time resolution are important features for $B$ physics (identification of $b$ hadrons and oscillation/CP measurements)
- Impact parameter resolution of about 25 µm for a track with $p_T = 2$ GeV/$c$
- Primary vertex resolution of about 13 µm ($x/y$) and 80 µm ($z$) (vertex with 25 tracks)
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- Impact parameter resolution of about 25 μm for a track with $p_T = 2$ GeV/c
- Primary vertex resolution of about 13 μm ($x/y$) and 80 μm ($z$) (vertex with 25 tracks)
Invariant Mass Resolution

Very good mass resolution an essential ingredient for precision measurements and high signal-to-background ratio

LHCb performed the most precise mass measurements for several $B$ hadrons.

Most precise mass resolution among the LHC experiments for particles with masses below the $Z$ mass

$J/\psi \rightarrow \mu^+ \mu^- : 12 \text{ MeV}/c^2$, $D^0 \rightarrow K^- \pi^+ : 7.5 \text{ MeV}/c^2$