The LHCb Silicon Tracker

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On behalf of the LHCb Silicon Tracker group
Overview

- The LHCb experiment.
- Silicon Tracker:
  - Tracker Turicensis.
  - Inner Tracker.
- Performance in LHC Run 1.
- Long Shutdown 1.
- Radiation damage studies.
- First results from LHC Run 2.
  - Real-time alignment.
- Summary
LHCb

- Dedicated heavy flavour experiment at LHC.
  - Measure CP-violation in $b$- and $c$- sector.
  - Study rare $b$- and $c$- hadron decays.
- **Indirect searches for New Physics.**
- Forward production of $b$-pairs with low angle.
  - Single-arm forward spectrometer.
  - 27% of $b$-pairs in LHCb acceptance @ $\sqrt{s}=7$ TeV.
- Over 270 physics papers published.

$2 < \eta < 5$
LHCb Tracking System

- Silicon Tracker:
  - Silicon micro-strip detectors.
  - Pitch: 183 μm (TT), 198 μm (IT).
  - Resolution ≈ 50 μm.
  - Common project: 6 institutes, ~50 people.
  - Designed for integrated luminosity up to 20 fb⁻¹.

Tracker Turicensis

Inner Tracker

Outer Tracker

\[ \int B \cdot dl = 4 Tm \]
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 m$^2$.
  - Covers full acceptance before magnet.
- Cooling plant operates at 0°C.
  - Sensors @ 8°C.
Inner Tracker (IT)

- 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.
Current Status

- Number of working channels:
  - 99.6% (current).
  - 99.7% (Run 1 average).

- Repairs possible for electronics outside detector box.

- Access for repairs is difficult.
  - One module not configurable.

- Common cause of inefficiency: VCSEL diodes stop working.

- VCSELs used to transmit optical data after off-detector digitisation.

* ULM-Photonics (ULM850-05-TN-USMBOP) (VCSEL=Vertical-cavity surface-emitting laser)

27th September 2015 10th International "Hiroshima" Symposium
• Production problem with early batch:
  – ≈30% replaced before start of Run 1.
• During Run 1:
  – Around one VCSEL per month died.
• Total of 48 / 2218.
  – Replaced in technical stops or end of year shutdowns.

![Graph showing VCSEL death rate over time](image-url)

### Table: VCSEL Deaths by Year

<table>
<thead>
<tr>
<th>Year</th>
<th>IT</th>
<th>TT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>2010</td>
<td>5</td>
<td>13</td>
</tr>
<tr>
<td>2011</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>2012</td>
<td>3</td>
<td>11</td>
</tr>
</tbody>
</table>
Signal to noise
Spatial alignment
Hit efficiency

PERFORMANCE: RUN 1

CERN-THESIS-2014-059
• Clusters from tracks \( p > 5 \text{ GeV} \):
• 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)
Maintenance
BCAM system

LONG SHUTDOWN 1

27th September 2015
10th International "Hiroshima" Symposium
Maintenance in LS1

- **Detectors were kept cold:**
  - Only warmed up for maintenance of cooling system.

- **New cooling plant:**
  - Problems with cooling plant in Run 1.
  - Required manual intervention every 2—3 days.
  - New plant installed and running since April 2014.

- **Positioning of Inner Tracker:**
  - Detectors were opened at start of LS1.
  - New beam-pipe installed.
    - Previous beam-pipe was moved from nominal position.
    - Boxes can be moved to their nominal positions again.
  - Improved detector acceptance.

- **New alignment monitoring system based on BCAMs.**

- **Migration of ECS software:**
  - Siemens bought PVSS → WinCC-OA.
  - Additional improvements to control software.

- **Regular operation periods scheduled.**
Alignment Monitoring System

- IT stations move when magnet polarity changed.
- New monitoring system based on BCAMs:
  - Brandeis CCD Angle Monitor.
  - Camera with flash.
  - Reflective targets on each half station.
- Accuracy < 1 mm on relative movements.

Movements observed closing OT stations.

Picture from Pascal Sainvitu (CERN EN/MEF-SU)
Expected fluence
Leakage currents
Charge collection efficiency scans

RADIATION DAMAGE

CERN-THESIS-2015-015
Expected fluence (FLUKA)

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!
Leakage current (TT)

- Current increases linearly with integrated luminosity.
- Data normalised to $T = 8^\circ C \ (E_g = 1.21 \text{ eV})$. 
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

July 2011

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

January 2013

\[ L = 0.48 \text{ fb}^{-1} \]

\[ L = 3.47 \text{ fb}^{-1} \]
Results

- Good agreement with Hamburg model.
  - M. Moll et al., NIM A426, p. 87 (1999)
- No type inversion observed.
Trigger scheme
Real-time alignment

RUN 2
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]

Fill number

05/07/2015 - 19/08/2015

IT1 ASide
IT1 Bottom
IT1 Top
IT1 CSide
Summary

- Excellent performance in Run 1:
  - Fraction working channels: 99.7% (TT), 98.6% (IT).
  - Resolution: 53.4 μm (TT), 54.9 μm (IT).
  - Hit efficiency: 99.7% (TT), 99.8% (IT).

- Improvements during LS1:
  - New cooling plant.
  - New alignment monitoring system for Inner Tracker.

- Radiation damage measurements:
  - Excellent agreement with predictions.

- First results from Run 2:
  - Real-time alignment implemented and tested.
10th International “Hiroshima” Symposium on the Development and Application of Semiconductor Tracking Detectors

25 to 29 September, 2015 Xi'an Jiaotong University, Xi'an, China

https://indico.cern.ch/event/340417/

Abstract submission: July 31, 2015

TOPICS:
- Simulations
- Technology
- Pixel and Strip Sensors
- Radiation Tolerant Materials
- ASICS
- Large Scale Applications
- Applications in Bio, Medical, Astro and Material Sciences
- New Ideas and Future Applications

For further information and to solicit an invitation – email: hstd10@ihep.ac.cn
MORE?

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

**Reality (2011+2012):**
- $\sqrt{s} = 7$ TeV / 8 TeV
- $\approx 1300$ bunches, 50 ns spacing.
- $L \approx 2 - 4 \times 10^{32}$ cm$^{-2}$s$^{-1}$.
- Higher pile-up.
  - $\langle \mu \rangle \approx 1.4 / 1.7$
- Luminosity levelling.
- Exceeding design by factor two fill for physics
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

100 m 12-fiber ribbon cable

Concrete shielding

TELL1 Board

1 Rx module

SNAP12 Rx

12 TLK2501

16 bits @ 80MHz

Crystal oscillator

COUNTING HOUSE

Front end on detector < 1 Mrad in 10 years

Tell1 read-out boards in counting House: Zero Suppression

27th September 2015

10th International "Hiroshima" Symposium
Resolution (TT)

![Graph showing resolution for C-side, Central, and A-side with LHCb label and sector numbers]
Resolution (IT)

C-side, Top, Bottom, A-side

LHCb

Sector number

X1, U, V, X2
## Summary Run 1 Performance

<table>
<thead>
<tr>
<th>Detector</th>
<th>Measurement</th>
<th>2011 Data</th>
<th>2012 Data</th>
<th>2011 MC</th>
<th>2012 MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>TT</td>
<td>Hit efficiency</td>
<td>99.7%</td>
<td>99.8%</td>
<td>99.9%</td>
<td>99.9%</td>
</tr>
<tr>
<td></td>
<td>Hit resolution</td>
<td>52.6 μm</td>
<td>53.4 μm</td>
<td>47.8 μm</td>
<td>48.0 μm</td>
</tr>
<tr>
<td>IT</td>
<td>Hit efficiency</td>
<td>99.8%</td>
<td>99.9%</td>
<td>99.9%</td>
<td>99.9%</td>
</tr>
<tr>
<td></td>
<td>Hit resolution</td>
<td>50.3 μm</td>
<td>54.9 μm</td>
<td>53.8 μm</td>
<td>53.9 μm</td>
</tr>
</tbody>
</table>

- Small differences between data and MC due to remaining misalignments.
- Hit efficiency well above 99% in all cases!
Expected fluence (IT)
Depletion voltage

- Vary voltage / timing in one layer only.
- Use other layers for tracking.
- Use full data (non-zero suppressed)
Cooling Plant Problems

- Oil mixed with coolant in chiller.
- Requires increases flow in mixed water circuit.
- \( C_6F_{14} \) temperature starts to rise.

1. Build up of “junk” in flow regulators.
   - Flow of \( C_6F_{14} \) decreased over period of months causing increase of temperature.
   - Filters were exchanged in October 2013.

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.
Cooling system

Problem in Run 1:
- Oil mixed with coolant in chiller.
- Mixed water flow increases.
- $C_6F_{14}$ temperature rises.
- Re-circulation of plant every 2—3 days!

Solution:
- New cooling Plant.
- Based on commercial air chiller.
- Installed and running since April 2014.
- Old cooling plant kept as back-up.

Major intervention during LS1
Alignment Monitoring System

- Monitor movement of IT half-stations.
  - New system based on BCAMs.
  - Developed for ATLAS muon detector.
  - Accuracy < 1 mm on relative movements.
- Installed two/three BCAMs per station.
  - Four on VELO wall for IT1.
  - Two each on the bunker, under the table for IT2 and IT3.
  - Installed in October / November.
- Passive, reflective targets on each half station.
  - System calibrated during IT closing tests.
- First results from magnet tests and OT closure.

Figure 2: The measuring principle of a BCAM.
Trigger Scheme in Run 1

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
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

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 $e/\gamma$

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 Rate to storage
Broken bonds in TT

- Every 4\textsuperscript{th} 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).

![Diagram of silicon sensors and hybrid connections](image_url)