The LHCb Silicon Tracker – Performance & Radiation Damage

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Christian Elsasser [on behalf of the LHCb Silicon Tracker Group]
The LHCb Experiment

Experiment dedicated to the search for 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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- K. Senderowska (Performance)
- G. Casse (Radiation Damage)
- P. Rodriguez Perez (Upgrade)
- D. Hynds (Timepix)

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Silicon Tracker
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The Tracker Turicensis (TT)

- Silicon micro strip sensors (p⁺-on-n by Hamamatsu Photonics K.K.)
- Thickness: 500 µm; Pitch: 183 µm
- Strip length of 9.44 cm ⇒ upto 37 cm long readout strips ⇒ upto 60 pF
- Four layers
- ~ 144k readout channels
- Total area: 8 m²
- Detector operated at 0° C ⇒ sensors at ~ 8° C
- 99.72 % of channels working
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); Pitch: 198 µm
- ~ 130k read out channels
- Total area: 4.2 m²
- Detector operated at 0° C ⇒ sensors at ~ 8° C
- 98.71 % of channels working
Signal-to-Noise Ratio

Measured with clusters assigned to $p > 5$ GeV/c tracks

- Tracker Turicensis: 12-15
- Inner Tracker: 16-18

Agreement to the test beam results within 10-20%
Spatial Alignment

Tracking stations are aligned by minimizing all track residuals from a Kalman filter fit.

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

[W. Hulsbergen (NIM A600, 471), arXiv:hep-ex 1207.4756v1]

TT hit resolution: 59 $\mu$m
(Binary resolution: 53 $\mu$m)

IT hit resolution: 50 $\mu$m
(Binary resolution: 57 $\mu$m)
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IT hit resolution: 50 $\mu$m
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Average alignment precision: $\sim 14 \mu$m
Running Conditions

Delivered integrated luminosity:
2010: \(42 \text{ pb}^{-1}\)
2011: \(1220 \text{ pb}^{-1}\)
2012: \(1594 \text{ pb}^{-1}\)
(Oct, 9)

Integrated luminosity in 2010-2012

Planned lifetime of ST: 10 years with \(2 \text{ fb}^{-1}/y\)
Running Conditions

Delivered integrated luminosity:
2010: $42 \text{ pb}^{-1}$
2011: $1220 \text{ pb}^{-1}$
2012: $1594 \text{ pb}^{-1}$
(Oct, 9)

Design luminosity:
$2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$

Luminosity 2012:
$4 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$

Average instantaneous luminosity per fill
Running Conditions

Delivered integrated luminosity:
2010: $42 \text{ pb}^{-1}$
2011: $1220 \text{ pb}^{-1}$
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Design luminosity:
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$\Phi_{n,1 \text{ MeV}}$ at TT (cm$^{-2}$ s$^{-1}$)
Fluka simulation with $1 \times 1 \text{ cm}^2$ scoring
Maximal fluence $\langle \Phi_{n,1 \text{ MeV}} \rangle_{\text{max}} \sim 1.25 \cdot 10^6 \text{ cm}^{-2} \text{ s}^{-1}$ in region covered by TT with average 2012 luminosity
Leakage Currents

Bulk damage caused by the radiation leads to an increased leakage current:

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

Decrease of leakage current by lowering temperature of silicon bulk:

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

with \( E_g = 1.2 \text{ eV} \) (Band gap of silicon)
Leakage Currents for TT

- Evolution of leakage currents qualitatively as expected!
- Signs of annealing taking place during shut downs/technical stops
Leakage currents for IT

- Again evolution of leakage currents qualitatively as expected!
Depletion Voltage (I)

Possibility to measure $V_d$ directly from data:
Analysis of charge collection efficiency scans $\Rightarrow$ Variation of $V_{bias}$ and sampling time (charge collection time!)
Variation only done in one layer per sub-detector (TT/IT) $\Rightarrow$ other layers used for tracking
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Depletion Voltage (II)

\[ \text{ADC}_{\text{max}}(V_{\text{bias}}) \] fitted by a sigmoid function:

\[ \text{ADC}_{\text{max}}(V_{\text{bias}}) = \frac{A_{\text{max}}}{1 + \exp\left(r(V_{\text{bias}} - V_0)\right)} \]

\(V_d\) extracted as voltage where 80 % of the maximum value is reached.

July 2011: 222 V

July 2012: 195 V
Depletion Voltage (III)

TTaU (2nd layer): Central region
Depletion Voltage (III)

TTaU (2nd layer): Central region

Only look at hits within $r < 45\,\text{mm}$

\[\langle \phi_{N,1\text{ MeV}} \rangle = 9 \cdot 10^5 \text{ cm}^{-2}\text{s}^{-1}\]
**Depletion Voltage (III)**

TTaU (2nd layer): Central region

\[ \langle \phi_{N,1 \text{ MeV}} \rangle = 9 \cdot 10^5 \text{ cm}^{-2} \text{s}^{-1} \]

Data from charge collection efficiency scans from three technical stops in 2011 and two in 2012

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Depletion Voltage (III)

TTau (2nd layer): Central region

Input for expected depletion voltage evolution:
- Measured $V_d$ after production
- Temperature inside detector box
- Running conditions ($\mathcal{L}$) and Fluka simulation

Input parameters of the Hamburg model:
$g_a = 1.4 \cdot 10^2 \text{ cm}^{-1}$, $k_{0a} = 2.4 \cdot 10^{13} \text{ s}^{-1}$, $E_{aa} = 1.086 \text{ eV}$, $g_Y = 5.7 \cdot 10^2 \text{ cm}^{-1}$, $k_{0Y} = 1.5 \cdot 10^{15} \text{ s}^{-1}$, $E_Y = 1.3125 \text{ eV}$, $g_c = 1.6 \cdot 10^2 \text{ cm}^{-1}$, $N_{C0} \cdot c = 7.5 \cdot 10^{-2} \text{ cm}^{-1}$

$\langle \phi N,1 \text{ MeV} \rangle = 9 \cdot 10^5 \text{ cm}^{-2} \text{s}^{-1}$

Data from charge collection efficiency scans from three technical stops in 2011 and two in 2012

Depletion Voltage (III)

TTaU (2nd layer): Central region

\[ \langle \phi_{N,1\text{ MeV}} \rangle = 9 \cdot 10^5 \text{ cm}^{-2}\text{s}^{-1} \]

Data from charge collection efficiency scans from three technical stops in 2011 and two in 2012

Good agreement between expected evolution of depletion voltage and measured one
Depletion Voltage (IV)

TTaU (2nd layer): Central region

\[ \langle \phi_{N,1 \text{ MeV}} \rangle = 8 \cdot 10^5 \text{ cm}^{-2}\text{s}^{-1} \]

Also good agreement between expectation and measurement!
Summary

– Excellent performance of the LHCb Silicon Tracker
  – TT: 99.72 % of channels are working
  – IT: 98.71 % of channels are working
– Signal-to-Noise ratio in good agreement with expectations
– Hit resolution close to what is expected from binary resolution
– Monitoring of radiation damage using leakage currents and charge collection efficiency scans
  ⇒ good agreement with expectations
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Backup
Backup: Details on Silicon Tracker Performance

Tracker Turicensis:
- 99.72% of the channels working
- Repairs possible for electronics outside detector box

Clearing of problems in LS1 planned

VCSEL:
Vertical-cavity surface-emitting laser

Inner Tracker:
- 98.71% of the channels working
  - 2 modules not configurable
  - 5 dead VCSELs
  - Difficult access for repair
Backup: Timing Alignment

Synchronization of trigger and control signals in the entire LHCb detector necessary
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
Backup: Hit Efficiency

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

For each track, extrapolate where we expect them in the silicon. Use isolation criteria.

Within some search window, $\epsilon = \# \text{hits found} / \# \text{hits expected}$.
Two sectors have high common mode noise ($\epsilon > 98\%$).

$\epsilon > 99\%$

Note the scale
Backup: Broken Bond Problem

- Breaking of bonds between pitch adapter and readout chip
- Only inner most row affected
Backup: CCE scan tracking

TTaU and IT3X2 are scanned. All other layers are used for tracking (CCE scan in VELO in parallel).

Pseudo cluster of three strips around extrapolated impact point of track on scanned layers
Backup: Sampling Time

Noise shape $f_{\text{noise}}(\text{ADC})$ determined from sample without tracks passing the particular readout sector in the event

$$f(\text{ADC}) = f_{\text{noise}}(\text{ADC}) \otimes \left( \delta(\text{ADC}) + f_{\text{Landau}}(\text{ADC}) \right)$$
Backup: Sampling Time

Signal pulse is not integrated, but sampled at a defined time. Pulse is described by a semi gaussian (\(CR - RC\) shaper)

\[
ADC(t) = A_0 \cdot e^{-\frac{t-t_0}{\tau}} \left( \frac{1}{2} \left( \frac{t - t_0}{\tau} \right)^2 - \frac{1}{6} \left( \frac{t - t_0}{\tau} \right)^3 \right)
\]

![Graphs showing ADC vs. time for 60 V and 400 V](image-url)
Backup: Depletion Voltage

TTaU (2nd layer): Outer region

\[ \langle \phi_{N,1\text{ MeV}} \rangle = 1 \cdot 10^5 \text{ cm}^{-2} \text{ s}^{-1} \]

Three-sensor readout sector

Agreement also in the less irradiated region!