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 $\mathcal{CP}$ violation

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

Tracking System
RICH
Calorimetry
Muon system

The LHCb Experiment

Experiment dedicated to the search for rare heavy quark decays and $\mathcal{CP}$ violation

15 m

LHCb MC
 $\sqrt{s} = 8 \text{ TeV}$

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0 m

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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 $\Rightarrow$ upto 37 cm long readout strips $\Rightarrow$ upto 60 pF
- Four layers
- $\sim 144\text{k}$ readout channels
- Total area: 8 m^2
- Detector operated at $0^\circ\text{C} \Rightarrow$ sensors at $\sim 8^\circ\text{C}$
- 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
- $\sim 130\text{k}$ read out channels
- Total area: 4.2 m²
- Detector operated at 0° C $\Rightarrow$ sensors at $\sim 8^\circ\text{C}$
- 98.71 % of channels working

Signal-to-Noise Ratio

Measured with clusters assigned to $p > 5 \text{ GeV}/c$ 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: $59 \mu\text{m}$
(Binary resolution: $53 \mu\text{m}$)

IT hit resolution: $50 \mu\text{m}$
(Binary resolution: $57 \mu\text{m}$)

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IT hit resolution: $50 \mu\text{m}$
(Binary resolution: $57 \mu\text{m}$)

Average alignment precision:
 $\sim 14 \mu\text{m}$

TT Sector Biased Residuals

IT Sectors Biased Residuals

Running Conditions

Delivered integrated luminosity:

2010: 42 pb^{-1}

2011: 1220 pb^{-1}

2012: 1594 pb^{-1}

(Oct, 9)

Integrated luminosity in 2010-2012

Planned lifetime of ST: 10 years with 2 fb^{-1}/y

Running Conditions

Average instantaneous luminosity per fill

Delivered integrated luminosity:

2010: 42 pb^{-1}

2011: 1220 pb^{-1}

2012: 1594 pb^{-1}

(Oct, 9)

Design luminosity:

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

Luminosity 2012:

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

Running Conditions

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2011: 1220 pb⁻¹

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Luminosity 2012:

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$\Phi_{n,1 \text{ MeV}} \text{ at TT (cm}^{-2} \text{ s}^{-1})$

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:

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

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

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

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

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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:

$$\begin{aligned}g_a &= 1.4 \cdot 10^2 \text{ cm}^{-1}, k_{0a} = 2.4 \cdot 10^{13} \text{ s}^{-1}, \\E_{aa} &= 1.086 \text{ eV}, g_Y = 5.7 \cdot 10^2 \text{ cm}^{-1}, \\k_{0Y} &= 1.5 \cdot 10^{15} \text{ s}^{-1}, E_Y = 1.3125 \text{ eV}, \\g_c &= 1.6 \cdot 10^2 \text{ cm}^{-1}, N_{C0} \cdot c = 7.5 \cdot 10^{-2} \text{ cm}^{-1}\end{aligned}$$

[M. Moll, *Radiation Damage in Silicon Particle Detectors*, DESY-THESIS-1999-040]

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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

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

Hits within $r < 45 \text{ mm}$

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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**University of
Zurich** ^{UZH}

Physics Institute

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
laser

surface-emitting

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 $\epsilon > 99\%$

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 use 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

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

60 V

400 V

Backup: Sampling Time

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

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

60 V

400 V

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!