The LHCb Vertex Locator - Performance and Radiation Damage

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on behalf of LHCb VELO Group
LHCb spectrometer

The detector dedicated for studying flavour physics at LHC. Especially CP violation and rare decays of beauty and charm mesons.

see the talk Christian Elsasser

\[ \sigma_{bb} \sim 280 \, \mu b \, (7 \, \text{TeV}) \]

10^{12} b\bar{b} pair/year

LHCb 2<\eta<5

ATLAS, CMS: |\eta|<2.5

σbb ~280 μb (7 TeV)
LHCb spectrometer

TRACKING DETECTORS:

Tracker Turicensis (Si)

Inner (Si)/Outer Tracker (straws)

VErtex LOcator (Si)
LHCb physics program

- Search for **new physics** using heavy flavour mesons
- Study **CP violation** and **rare decays** with **beauty** and charm **hadrons**

To achieve such wide scientific program the crucial requirements for a detector are:
- very good **vertex** separation power,
- fast **tracking** for the HLT trigger,
- withstand severe **radiation** environment

The main task for the **VELO** is fast 3D tracking and vertexing crucial for the performance of LHCb experiment
LHCb Vertex Locator

- The closest to the proton beam detector of all LHC detectors.
- VELO halves are movable,
- The movement is steered by a precise system (accuracy of 10 μm),
- When stable beams, the silicon edge is only 7mm from the proton beam.
- Operated in a secondary vacuum, separated from the LHC vacuum by 300 μm thick aluminium foil.
VELO - modules

- VELO consist of 42 modules (two halves)
- Modules have two (R and Phi) microstrip silicon oxygenated n⁺-on-n sensors (two sensors are n⁺-on-p)
- Sensors are 300 μm thick, strip pitches: 40-100 μm
- Evaporative CO₂ cooling system to keep sensors in -7°C
- The geometrical acceptance of the VELO is 15-390 mrad – defines the acceptance for whole LHCb
VELO performance

- Signal and Noise
- Primary Vertex and Impact Parameter Resolution
- Hit Resolution
VELO performance – signal and noise

**Signal** distributions for clusters on track

- S/N is calculated as an average MPV of the cluster/noise of that strip,
- varies with the sensor radius
  - R-sensors: S/N =19,
  - Φ-sensors: average S/N=21

**Noise** – proportional to the length of the strip.

R sensors 2012

> Average noise in ADC counts
> RMS of the scatter from the 42 sensors shown as errors

Φ sensors 2012

> LHCb VELO Preliminary
> Sensor 104: Phi type
> Inner
> Outer, with routing line
> Outer, without routing line

R, Φ 2012

> LHCb VELO Preliminary
> Average noise in each strip for the R sensors
> Signal-to-noise ratio for 1 strip clusters on tracks

Sensor 40 (R): Red points
Sensor 104 (Phi): Blue circles
Radius (mm)
VELO performance – PV and IP Resolution

**Primary Vertex** resolution depends on:
- the track multiplicity (separately for 1, 2, 3 PVs).

- For 1 PV and 25 tracks:
  - $\sigma_x = 13.5 \mu m$
  - $\sigma_y = 12.5 \mu m$
  - $\sigma_z = 90 \mu m$

- Slightly worse for multi-PV events

**Impact Parameter** resolution depends on:
- multiple scattering of particles,
- resolution of single hit position,
- track distance between first hit in detector and interaction point

- Best IP resolution$= 12 \mu m$ for high $p_T$ tracks
Hit resolution depends on pitch and projected track angle (angle between track and perpendicular to the strip).

- Unbiased residuals used to determine the spatial resolution
- Vital for track fitting

The best hit resolution at LHC! For optimal angle and small pitch.
Radiation damage

The main macroscopic effects caused by the radiation:

- **Increase in leakage current**, caused by creation of generation and recombination centres.

- **Change** of the effective doping concentration with significant influence on operating **voltage** needed for total **depletion**.

- **Loss of charge collection efficiency** due to charge carrier trapping.

Selected methods to monitor radiation influence on VELO:

- Current-Temperature scans (IT)
- Charge Collection Efficiency scan (CCE)
Radiation damage

- VELO is currently the **most exposed** detector in the LHC- fluence up to $50 \times 10^{12}$ 1MeV $n_{eq}/cm^2$,
- LHCb has collected more than 3 fb$^{-1}$ in 2009-13, VELO designed to cope with $\sim 6$-10 fb$^{-1}$

- Leakage currents as a function of time - increase with fluence, proportional to the delivered luminosity, typically 2 μA per 100 pb$^{-1}$.
- Periods of annealing
Radiation damage – leakage current monitoring

- Measurement of current as a function of temperature (**IT scans**) for each sensor,
- **Effective band gap** from exponential fit:
  \[ E_{\text{eff}} = 1.16 \pm 0.06 \text{ eV} \]

- Current scaled to 0°C - good agreement with simulation (z dependence).

- After irradiation bulk current dominates over surface current
Radiation damage – Charge Collection Efficiency (CCE)

- Standard method for $U_{\text{dep}}$ measurement uses C-V scans – possible before installation

Alternative method - CCE
- A tested sensor is excluded from the track fit,
- A voltage bias scan is performed on it and the charge deposited in sensor around the track intercept is measured
- plot the MPV vs bias voltage

CCE scan is used to measure:
- Effective Depletion Voltage (EDV)
- Cluster Finding Efficiency (CFE)
Radiation damage – effective depletion voltage

- When sensor is fully depleted - all charge is collected - MPV reaches plateau.
- Effective Depletion Voltage (EDV) - bias voltage at 80% of maximum MPV of ADC distribution
- At the production, initial depletion voltage was \( \sim 25\text{-}70 \text{ V} \).
- Sensors in 2011-12 were biased at 150 V (can be operated up to 500V)
- Type inversion occurred at \((10\text{-}15) \times 10^{12}\) 1MeV \(n_{eq}/\text{cm}^2\), inversion started at inner radius.
- Good agreement with Hamburg model (except the EDV minimum – need a sufficient electric field to collect the charge)
Radiation damage – EDV – type inversion

The recent data with division into radial regions

Change in EDV for a single sensor at different delivered luminosities

- **type inversion** starts at inner radial region
Cluster Finding Efficiency (CFE) – a percentage of clusters obtained at the extrapolation point

▸ > 99% before irradiation,
▸ noticeable reduction for downstream R-type sensors observed during 2011,
▸ no effect in tracking

![Cluster Finding Efficiency graph](image)
Radiation damage – CFE – a closer look

Decrease in CFE more rapid with:
- delivered luminosity,
- bias voltage

![Graph showing the effect of delivered luminosity and bias voltage on CFE]

![Graph showing the cluster finding efficiency for different bias voltages and delivered luminosities]
Radiation damage – CFE – second metal layer

A possible explanation lies in sensor design:

- 2nd metal layer carries signal to read-out electronics
- Routing lines in R-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)

No measurable effect on tracking efficiency
LHCb is an experiment for beauty and charm hadrons, CP violation, rare decays and search for New Physics.

The program requires excellent vertex reconstruction precision, tracking and particle identification.

VELO performed superbly, according to the expected assumptions, during Run I data taking period.

VELO has been exposed to severe radiation conditions.

Its state is monitored on regular basis by especially dedicated scans.

Change of the depletion voltage and leakage currents agree with expectations.

Currently no significant physics performance degradation effects observed - operation until 2018.

see talk by Kazu Akiba on Upgrade Plans