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Performance, Radiation Damage Effects and Upgrade of the LHCb Vertex Locator

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Overview

- Introduction to LHCb
- The LHCb Vertex Locator and its performance.
- Radiation damage effects.
- Upgrade.

- H. Schindler:
The LHCb detector upgrade
- M. Tobin:
The LHCb Silicon Tracker
- F. Dettori:
Performance of LHCb

The LHCb detector

The LHCb detector

The VELO detector

- 2 retractable detector halves at 5 (30) mm from beam when closed (open).
- 21 stations per half with an R and ϕ sensor.
- 2 Pile-Up stations per half (trigger).
- Operates in secondary vacuum.
- 300 μm foil separates detector from beam vacuum.
- CO₂ cooling system (Operates @ -30°C, Sensors @ -10°C).

The VELO sensors

- 300 μm n+-on-n sensors (Micron).
 - One module with n+-on-p (Micron)
- R-sensors:
 - 45 degree quadrants
 - Pitch = 40-101.6 μm .
- Φ -sensors:
 - 2 regions (short/long strips)
 - Pitch = 35.5-96.6 μm
- 2048 strips / sensor
 - 172,032 strips in total
- Double metal layer for signal routing.
- First active strip @ $R \approx 8$ mm.

Alignment

- VELO halves centered around beam at each fill, when beams declared stable.
- Beam position determined from vertex reconstruction with tracks in right or left half.
- Misalignment from distance between the two reconstructed vertices.
- Fully automated procedure (~210 s).
- Stable within $\pm 5 \mu\text{m}$ (x).

Performance

- Single hit resolution:
 - linear dependence on the strip pitch in projected angle bins.
 - better resolution for larger angles.
- IP resolution of $\sim 13 \mu\text{m}$ for infinite momentum tracks.
- $S/N(R) \approx 19$, $S/N(\Phi) \approx 21$

Performance

X and Y resolution - offline, exactly 1 PV

- Excellent cluster finding efficiency:
 - $\text{CFE} = 99.51 \pm 0.02 \%$ [all channels]
 - $\text{CFE} = 99.98 \pm 0.02 \%$ [bad strips excl, 0.77%]
- PV resolution of $13 \mu\text{m}$ for 25 tracks (typical case).
- Excellent tracking efficiency.

Radiation damage

- High particle fluence (up to 5×10^{13} 1MeV n_{eq}/cm^2) due to proximity to the beams.
- Particle irradiation causes surface and bulk damages in the silicon
=> affects leakage current and effective doping concentration.
- 4 independent and complementary methods to monitor these effects:
 - changes in currents vs. voltage (IV curve)
 - changes in current vs. temperature (IT curve)
 - changes in Full Depletion Voltage
 - changes in Cluster Finding Efficiency

Current vs Voltage/Temperature

- Bulk current increases with fluence proportionally to the delivered luminosity.
- All sensors at nominal bias (150 V) and at -8 °C.
- Typically 1.9 μA per 100 pb^{-1} .
- Good agreement with expectation from fluence.

Effective Depletion Voltage

- During assembly measured by comparing capacitance to bias voltage across the sensor. Not possible after installation
=> dedicated runs every 3-4 months.
- Method: extrapolate tracks to test sensor (every 5th module) and determine amount of charge collected.
- Voltage of test sensor varied between 0-150 V. At each bias voltage the most probable value (MPV) of ADC counts distribution is determined. Effective Depletion Voltage (EDV) defined as the voltage at which the MPV is 80% of the plateau.

Effective Depletion Voltage

Minimum EDV ~ 18 V before type inversion, which occurs at $\sim 15 \times 10^{12}$ 1 MeV n_{eq} . Subsequent increase is $\sim$ linear.

EDV initially decreases with fluence for all radius. After type inversion, EDV increases with fluence. Type inversion starts at inner radius.

Sensors are operated at 150 V and can be operated up to 500 V.

Good agreement with Hamburg model at low and high fluences. Discrepancy around type inversion because of finite charge collection time.

2nd metal layer

- 1st metal layer capacitively couples to strips. 2nd metal layer carries signal out to electronics.

- Routing lines are perpendicular to strips in R-sensors and parallel to strips in Φ -sensors.

Routing lines

- Light blue: 1st metal layer.
- Dark blue: 2nd metal layer.

Cluster Finding Efficiency

- Clusters defined as one or more adjacent strips with charge over threshold.
- Finding and reconstructing clusters efficiently is a key aspect for physics performance.
- Measured with dedicated scans as well as during physics runs.

March 2011, 40 pb⁻¹

CFE ~ 100%

Cluster Finding Efficiency

- Cluster Finding Efficiency drops with fluence, especially in outer radial regions.
- Higher efficiency where no routing lines !

Strip distance dependence

- Drop of CFE in regions far away from strips and close to routing lines.
- No effect on tracking efficiency observed.

VELO Upgrade

- Why upgrade LHCb? Current limitation due to hardware trigger
 => no gain for hadronic channels from higher luminosity => move to a full software trigger!
- Detector to be operated @ 40 MHz and $2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
 - huge data rates ($> 2 \text{ Tbit/s}$): new front-end electronics and sensors
 - radiation hard (radiation levels up to $5 \times 10^{15} \text{ 1MeV n}_{\text{eq}} \text{ cm}^{-2}$)
 - new cooling interface
 - improve performance
- Two options: Microstrips or pixels
 - $200 \mu\text{m}$ n-on-p thick silicon
 - high thermally conductive spine
 - re-use of existing infrastructures (CO₂, HV/LV, vacuum, motion)
 - new custom RF-foil
 - dead material (at periphery for strips, i.e. out of acceptance)
 - pixel option uses a single flip chip assemblies per module

Proposed strip detector layout

Proposed pixel detector layout

Strips

- Conservative option ($R\Phi$ geometry)
- Increase number of strips (20 chips x 128 channels per sensor), reduce pitch (30 μm minimum) $\Rightarrow$ keep occupancies $< 0.6\%$ at $10^{33}\text{cm}^{-2}\text{s}^{-1}$
- Sensitive area close to the edge: active @ 7 mm from the beam
- Sensor prototypes (Hamamatsu) being tested, sensor hybrid to be developed
- New ASIC chip under development: on-chip common mode subtraction, zero suppression and possibly clustering
- 1 ADC per strip

Pixels

- Based on VeloPix, successor of TimePix
- Silicon Planar Sensors $55 \times 55 \mu\text{m}$ pixel, 256×256 array
- Simultaneous measurement of time-over-threshold (ToT) and time-of-arrival (ToA)
=> ideal for time stamp and inter pixel positioning
- Requirements: peaking time $< 25 \text{ ns}$, timewalk $< 25 \text{ ns}$ @ 1 ke^-
- Count rate up to 500 MHz/chip
- Power consumption $< 3 \text{ W/chip}$

Cooling interface

- Three cooling options currently being pursued.
- TPG substrate/blocks
 - Baseline and more conservative option
- Micro channels
 - silicon substrate (no stress due to CTE)
 - low material budget
 - routing of channels customizable
 - ~60 bar pressure under chip
- C-foam and invar tubes
 - low material budget
 - integrated cooling

Conclusion

- The LHCb VELO has been operated smoothly during the physics data taking and has showed excellent performance.
 - $S/N(R) = 19$, $S/N(\Phi) = 21$.
 - Single hit resolution = $4 \mu\text{m}$ at $40 \mu\text{m}$ pitch.
 - Typical IP resolution = 13 (12) μm in $x(y)$.
 - Typical PV resolution = 13 (71) μm in $x,y(z)$.
 - Excellent Cluster Finding and tracking efficiencies.
- Radiation damage effects have been studied.
 - Currents increase $\sim 1.9 \mu\text{A}$ per $100/\text{pb}$.
 - Type inversion observed.
 - Increase of Effective Depletion Voltage.
 - 2nd metal layer effect observed.
- The detector will be upgraded in 2018 to cope with a 40 MHz readout trigger.
 - Two options under investigation: strips or pixels.
 - R&D of cooling interface, module design, FE electronics.

Spares

LHCb operation

LHCb Integrated Luminosity pp collisions 2010-2012

- Lumi-Leveling: semi-continuous (automatic) adjustment of offset of colliding beams allowing luminosity to be constant.
- 4 times more collisions per bunch crossing than in the design!

Alignment

- Crucial for hit/impact parameter/decay time resolution !
- Starting point: survey before installation
 - Relative R- sensor to Φ -sensor position measured with accuracy of $3\text{ }\mu\text{m}$ (translations in x,y) and $20\text{ }\mu\text{rad}$ (rotations around x,y)
 - Relative module positions in each half measured with accuracy of $10\text{ }\mu\text{m}$ (translations in x,y)
 - Position of two halves with accuracy of $100\text{ }\mu\text{m}$ (transl.) and $100\text{ }\mu\text{rad}$ (rotat.).
- Software alignment: 2 methods based on minimising the residuals btw tracks and hits.
 1. Sensors, modules and halves alignment based on Millipede [NIM A596 (2008) 157 and 164].
 2. Global χ^2 minimisation based on Kalman track fit residuals [NIM A600 (2009) 471].

Survey align.

Track align.

misalignment better than $4\text{ }\mu\text{m}$

Cluster finding efficiency

- Determined by excluding a sensor in the pattern recognition, and interpolating tracks to this sensor. Tracks are required to have:

- hits in both the R and Φ sensors in the 2+2 modules before/after the sensor under test.
- hits in at least six modules.
- These requirements place some restrictions on the region and sensors that can be probed.

- Track quality selection cuts are applied to remove fake.

- The efficiency for finding a cluster depends on the applied bias voltage.

CFE = 99.51 ± 0.02 % [all channels]

CFE = 99.98 ± 0.02 % [bad strips excluded]

Signal, Noise and S/N

Single hit resolution

- Determined from the hit residuals.
- Charge sharing algorithm to improve resolution.
- Linear dependence on the strip pitch in projected angle bins.
- Significantly better resolution obtained for larger projected angles.

hit resolution = 4 μm (best @ LHC!)

Comparison with model

- Comparison with Hamburg model.
- Good agreement at low and high fluences.
- Discrepancy around type inversion because of finite charge collection time.

IP & PV resolution

IP_X Resolution Vs $1/p_T$

IP_Y Resolution Vs $1/p_T$

X and Y resolution - offline, exactly 1 PV

Z resolution - offline, exactly 1 PV

Testbeam

Timepix telescope

- Designed for the LHCb upgrade
- Composed by 9 Timepix assemblies (with 300 μm thick sensors)
- DUT can be moved/rotated and cooled
- Resolution at DUT plane < 2 μm

Focus on:

- sensor performance after irradiation (Meapix3)
- evaluation of guard-rings, edge efficiency
- prototype strip module

Telescope planes

Telescope planes

Device Under Test (DUT)

Data rates

- Occupancy is “low” but the detector is fully read every 25 ns.
 - Strips read out ZS data for each FE chip.
 - Strip design compensates occupancy with shorter strips.
 - Pixels summarize information from a 4x4 super pixel and time stamp the hits → 30% reduction on the rate.
 - Intelligent column to readout data from hot to cold area
- Back end electronics must cope with a huge amount of data:
 - TELL40 (upgrade of TELL1, current DAQ board) receives and builds events using FPGAs.
 - All the information is assembled and passed on to computing farm, stripping down redundant data.
 - Further processing and full reconstruction in the trigger farm.