The Timepix3 Telescope and Sensor R&D for the LHCb VELO Upgrade

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on behalf of the LHCb VELO Upgrade Group

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VELO Upgrade

LHCb Detector (Upgrade 2019/2020)

Luminosity:
\[4 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1} \times 5 \rightarrow 2 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}\]

**VERtex LOcator**
from strip sensors to hybrid pixel detectors
Prototype Sensors

Challenges
- Increased data rate and fluence
- Non uniform radiation exposure:
  - $8 \times 10^{15}$ 1 MeV $n_{\text{eq}}/\text{cm}^2$ at the close edge
  - $0.2 \times 10^{15}$ 1 MeV $n_{\text{eq}}/\text{cm}^2$ at the outer edge
- Minimise material in the acceptance

Requirements
- Sensor must withstand 1000V at the end of lifetime
- Charge collection > 6000 e-
- Efficiency > 99% and uniform
- Excellent spatial resolution
- Narrow edge

for impact parameter resolution
minimise material before the first measured point
Prototype Sensors

- two different vendors (HPK and Micron)
- n-on-p and n-on-n type
- different thickness (150-200 µm)
- different implant width (35-39 µm)
- different guard ring size (150-600 µm)
- irradiated up to a fluence of $8 \times 10^{15}$ 1 MeV n$_{eq}$/cm$^2$ (uniformly and non-uniformly irradiated)

**Sensors tested in combination with Timepix3 ASIC**

**Timepix3**
- matrix 256x256 square pixels
- pixel size 55x55 µm$^2$
- can measure simultaneously ToA and ToT (can be converted to charge)
- gives a timestamp with 1.6 ns resolution (bin size of the TDC)
- calibration with test pulse, cross checked with radioactive sources

**ideal for sensor testing!**
Timepix3 Telescope

- Operated on a 180 GeV hadron beam at the CERN SPS
Timepix3 Telescope

• VELO Upgrade
• Prototype Sensors
• Timepix3 Telescope
  › Time Resolution
  › Pointing Resolution
  › Rate Performance
• Sensor Characterisation
  › HV Tolerance
  › Charge Collection
  › Efficiency
  › Spatial Resolution
• Summary

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Performance: Timing Resolution

- Telescope planes are time aligned

**Mean of the biased track time residuals**

*Biased time residuals for one plane after time alignment*

- Measured intrinsic resolution of each plane ~1.1 ns
- Telescope time resolution:
  \[
  \sigma_{\text{telescope}} = \frac{\sigma_{\text{intrinsic}}}{\sqrt{N_{\text{planes}}}}
  \]

Telescope time resolution 0.39 ns at 150 V bias voltage
Performance: Spatial Resolution

- Pointing resolution depends on: resolution of each plane, space between planes and material traversed
- Pointing resolution is obtained from simulation
- Simulation is validated by comparing resolution of telescope planes obtained from data and simulation

Pointing resolution at DuT position < 2 µm

- Resolution per plane ~ 5 µm in both x and y directions
- Good alignment: residual variation across the beam spot < 0.2 µm
- Width very stable
Performance: High Rate

- fraction of non-associated clusters studied as a function of rate
- no significant dependence found
- rate limited by the SPS beam: the telescope should be able to operate at least twice the maximum rate

No degradation in efficiency up to the high rate of 5 million tracks / s / cm²
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HV Tolerance

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sensors must withstand 1000 V after full fluence (in both hottest and coolest part)

**typical fluence profile at IRRAD**

**sensors non-uniformly proton irradiated at IRRAD**

![Graph showing IV curves for sensors irradiated at IRRAD](image_url)

Figure 3.4: IV curves for sensors irradiated at IRRAD.

Figure 3.5: IV curves for sensors non-uniformly irradiated at KIT.

HPK n-on-p
Micron n-on-p
Micron n-on-n

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Full fluence, -34°C
<10^{15} \text{ MeV n}_{eq}\text{/cm}^2, -22°C
sensors must collect >6000 e- at -1000V after full irradiation

Figure 9.3: Most probable number of collected electrons for sensors irradiated at JSI. The red dotted line shows most probable value of collected charge of 6000 electrons. The Hamamatsu sensors are displayed in green; the 200 µm thick Micron sensors are displayed in blue and the 150 µm thick Micron sensors are shown in purple whilst maintaining a good cluster finding efficiency. The range of voltages in which the sensors collect 6000 electrons ranges between 600 V and 800 V. The thinner sensors achieve this before the thicker sensors. This is because for the same voltage, the electric field in the thinner detector is higher. This leads to higher charge carrier velocities and thus higher induced signals and less trapping. These effects all lead to larger collected signals.

9.2.1 Annealing
Three of the JSI irradiated assemblies were annealed in a controlled situation for 80 minutes at 60°C. Figure 9.4 shows the collected charge before and after annealing. There is no noticeable difference between the charge collection before and after the controlled annealing. This might be because of the lack of cooling during transport. Without cooling during this period, it is possible that the sensors could have annealed during transport, i.e. before the set of measurements were taken.
Efficiency

- Efficiency must be > 99% everywhere in the sensor
  - \( e = \frac{n_{\text{DUT Associated Clusters}}}{n_{\text{tracks}}} \)
  - Non-irradiated assemblies are fully efficient over the entire pixel cell
  - Irradiated assemblies show inefficiencies at pixel corners at lower applied \( V \), but are fully efficient at 1000 \( V \)

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**Figure:**

- **Preliminary**
- **Average Efficiency**
- **Voltage [V]**
- **Efficiency as a function of in-pixel position for S17, S15 & S22: 200 µm Micron, n-on-n, 450 µm inactive edge**
- **Efficiency as a function of voltage for a range of sensors**
- **Inefficiencies are caused by decreased charge collection at the corners.**
- **Average efficiency is reduced but still close to 99% at high bias voltage**
- **Inefficiencies are caused by decreased charge collection at the corners.**

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**Graphs:**

- **Efficiency**
- **Distribution of In-pixel efficiencies to determine average efficiency**

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**Notes:**

- **Requirement:** Average efficiency > 99% pre and post irradiation
- **Sensor Characterisation**
- **Timepix3 Telescope**
- **Prototype Sensors**
- **VELO Upgrade**
- **Pointing Resolution**
- **Rate Performance**
- **Sensor Characterisation**
- **HV Tolerance**
- **Charge Collection**
- **Efficiency**
- **Spatial Resolution**
- **Edge**
- **Grazing Angles**
- **Summary**
Spatial Resolution

- analog resolution: position reconstructed using the Centre of Gravity technique
- binary resolution: position reconstructed ignoring the charge information

Spatial resolution must be excellent after full dose
• Guard ring structure to gradually reduce the electric field towards the edge of the sensor
• Occupancy is already higher close to edge
• Distortion of the electric field that would lead to a worst spatial resolution must be avoided

sensor must be fully efficient up to edge
Grazing Angles

The sensor is rotated at a very large angle (83-89 deg) with respect to the beam.

Exploiting the relation between the hit pixel position in the cluster and the depth sampled by the track:
- Charge collection as a function of depth
- Time required to cross the threshold as a function of depth

HPK n-on-p, 200 µm thick

Non-irradiated

charge migration
Grazing Angles

The sensor is rotated at a very large angle (83-89 deg) with respect to the beam

Exploiting the relation between the hit pixel position in the cluster and the depth sampled by the track:

- Charge collection as a function of depth
- Time required to cross the threshold as a function of depth

Uniformly neutron irradiated (8 x 10^{15} 1 \text{ MeV n}_{eq} \text{ cm}^{-2})

HPK n-on-p, 200 \mu m thick
Grazing Angles

Non uniformly proton irradiated full fluence

Typical fluence profile at IRRAD

250 V

HPK n-on-p, 200 µm thick

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Grazing Angles

Non uniformly proton irradiated full fluence

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HPK n-on-p, 200 µm thick

Typical fluence profile at IRRAD

500 V

VELO Preliminary

Column

Row

Fluence profile at IRRAD

Fluence [$10^{15} \text{n}_{eq} \text{cm}^{-2}$]

MPV [ke-]

Depth: 29 µm
Depth: 57 µm
Depth: 86 µm
Depth: 114 µm
Depth: 143 µm
Depth: 171 µm
Depth: 200 µm
Grazing Angles

Non uniformly proton irradiated full fluence

HPK n-on-p, 200 µm thick

VELO Preliminary

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Non uniformly proton irradiated full fluence

typical fluence profile at IRRAD

1000 V

HPK n-on-p, 200 µm thick

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Summary & Outlook

- Timepix3 telescope has outstanding performance
- Allowed to characterise a large variety of prototype sensors for the LHCb VELO upgrade
- 400 sensors already delivered and under test
- First VELO upgrade modules are being constructed

VELO modules tested in beam a couple of weeks ago using the Timepix3 telescope!
Back Up
Grazing Angles

The sensor is rotated at a very large angle (83-89 deg) with respect to the beam.

- long tracks through multiple adjacent pixels
- The number of columns traversed by the track depends on the angle
- a fit of the nominal cluster length as a function of the angle allows to extract the effective depletion depth!
Spatial Resolution

Spatial Resolution as a function of angle

fractions clusters as a function of angle

before irradiation

after irradiation

Sensor Characterisation

Prototype Sensors

Timepix3 Telescope

VELO Upgrade

Time Resolution

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Efficiency

Spatial Resolution

Edge

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Summary
Grazing Angles

Non uniformly proton irradiated full fluence

1000 V

750 V

500 V

250 V

HPK n-on-p, 200 µm thick

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