Radiation Hard Pixel Development for the LHCb VELO Upgrade

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LHCb overview

RICH-1

Magnet

RICH-2

Calorimeters

Tracker

ECal

OT

HCal

IT

M1

VELO

Muon System

TT

Tracker

SPD

OT

PS

IT

HCal

ECal
LHCb overview

LHCb: Single arm spectrometer, wide physics goals, e.g.
- Study of CP violation
- Rare decays
**LHCb overview**

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- Study of CP violation
- Rare decays

**LHCb strong points**:
- PID
- Vertexing and IP
- Momentum and mass resolution
LHCb Vertex Locator (VELO)

- **VErtex LOcator**: silicon microstrip detector surrounding collision region
  - Two halves can be moved in with stable beams: safer operation!
  - Readout rate of 1MHz
  - 84 sensors in 42 modules: 2048 silicon strips. One sensor for radial and and one for azimuthal position
  - 8 mm away from beam line
  - Excellent performance, crucial for physics
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LHCb Run III: provide order of magnitude increases in precision on physics key parameters

- Will increase luminosity x5 (up to $2 \times 10^{33}$ cm$^{-2}$s$^{-1}$) and move to software-based trigger
- 40 MHz read-out of the detector

Requires upgrade of VELO! We’ll move from strips to pixels (VeloPix)

- Allow less occupancy and irradiation
- Easier pattern recognition!
Other requirements

- 52 modules, closer from beam (5.1mm)!
- Higher track multiplicity
  ... withstand the larger irradiation expected: 370 MRad or $8 \times 10^{15} \text{n}_{\text{eq}} / \text{cm}^2$

- Hottest region with pixel hit rates of 900 Mhits/s: total data rate more than 3 Tbit/s!
- Separated from the beam vacuum by a 250 μm RF foil
- Better physics performance (e.g., in terms of IP resolution)
The modules will be composed by 4 sensors (2 on each side of substrate) and a substrate for cooling.

- Sensors powered and read-out via hybrid board and Kapton cables
- Silicon substrate, with internal micro-channels for CO₂ cooling
- Each sensor (43mm x 15mm) bonded to three VeloPix ASICs
- Elongated pixels between ASICs give complete coverage
**VeloPix**: pixel readout chip designed specifically for VELO upgrade
- 256 x 256 pixel matrix
- 130 nm technology
- Data driven binary readout
- Design to be submitted for production later this year

**Timepix3**: precursor to VeloPix, similar, but...
- Analogue readout
- High precision timing information ($\sigma_t = 1.5$ ns)
- Ideal chip for testing and characterizing sensor performance
55 x 55µm pixel size, with baseline thickness 200µm

Currently undertaking extensive sensor evaluation program using test beam and source data:

- Two different vendors (Hamamatsu (HPK), Micron)
- n-in-p (baseline) and n-in-n type (150µm thick)
- Need to withstand non homogeneous irradiation and 1000 V bias: constraints on guard ring design (different sizes 150-600µm)
- Different implant widths (35-39µm): try to maximize efficiency
Expected performance after irradiation

- Charge collection efficiency decreases with radiation damage...

...but effect **not propagated** to track reconstruction efficiency or IP resolution thanks to hit redundancy in the tracking system!
Testing sensors

- Sensors **irradiated** in 5 different facilities, with both neutrons and protons, uniformly and non-uniformly
  - Example sensor irradiation fluence: non uniform dose, to best reflect final running conditions

- Performance post-irradiation has been measured in testbeams and lab
Telescope for testbeams

- **Telescope** built specifically for VELO upgrade studies
  - 8 Timepix3 detector planes
  - Provides precise measurement of particle locations and timing
  - Resolution at the DUT plane 2 µm (with 180 GeV/c π and p beam)
Sensors alive!

- Sensors tolerate required 1000V bias after non-uniform irradiation ($<4 \times 10^{15} \text{n}_{\text{eq}} / \text{cm}^2$)

![Graph showing current vs. bias for different conditions](image)
Intrapixel efficiency on neutron irradiated sensors:

- Efficiency decreased in the corners (expected)
- Larger implant significantly increases efficiency in pixel corners
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Charge collection efficiency

- Same charge collected for different thickness
- Results both from source and test beam data!

Different fluence regions in non-uniformly irradiated HPK single
Timepix3 gives hit time information and telescope gives accurate track time!

- Tail in time residual distribution due to discriminated time-walk effects - larger for irradiated sensors

- Resolution < 1ns!
Look into **Time of Arrival** (ToA) for different pixels in a cluster at **grazing angle** (86°)

- For every pixel, compare ToA with average ToA from cluster
- Difference between pixels affected by bias
- Effect more important for irradiated sensors

![Diagram showing Time of Arrival analysis](image)
Parylene coating

- Parylene coating: **avoid sparking** on n-in-p sensors
  - Parylene is a thin transparent coating
  - Provides protection and acts as an electrical insulator
  - Have parylene coated some of our sensors under scrutiny....
  - Some coated HPK irradiated triples breakdown before 1000 V (parylene coating damaged)
  - Degradation with respect to pre-irradiation! Temperature? Currently under study
Conclusions

- Luminosity increased by a factor of 5: keep or improve the performance of the current VELO (thinner, closer to beam line)

- New silicon pixels ASIC under design: VELOPIX

- Now in sensors R&D phase, with several prototypes and irradiation campaign

- Extensive testing program using lab, source, and testbeam data, VELO upgrade well on its way, start thinking about construction!