The LHCb VELO upgrade

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on behalf of the LHCb Velo group

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LHCb characteristics

- Single arm spectrometer
- Luminosity $4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
- Integrated luminosity of 8 $\text{fb}^{-1}$ by end of Run 2
- Collision rate reduced from 40 to 1.1 MHz using a hardware trigger

Check also talk from S. de Capua on the *Performance of and Radiation Damage Effects in the LHCb Vertex Locator* today at 17:00.
Reasons to upgrade

- A factor 5 higher luminosity $(2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1})$
- Capable of accumulating $50 \text{ fb}^{-1}$

Features of the upgrade

- Full software trigger at 40 MHz
- Increased yield by a factor 10 (depending on the channel)
- Installation by 2018

⇒ Upgrade of all subdetectors
Upgrade of the Vertex Locator

Basic building blocks are 14◊14 mm² pixel chips. Three chips in a row are flip-chipped to a common silicon sensor. Each module contains four sensor “tiles” arranged in an L shape. Two tiles glued to back, two tiles to front of microchannel cooling substrate (400µmSi).

Detector half box comprising 26 modules.

- One of the retractable halves

Main features of Vertex Locator upgrade

- strips → pixels
- VeloPix ASIC with a 200 µm thick sensor
- 52 modules divided in two retractable halves
- Edge of detector closer to beam (8.2 mm → 5.1 mm)
- Microchannel cooling of modules with two-phase CO₂
- Expected reconstruction efficiency > 99% at upgrade beam conditions
- Detector is in secondary vacuum separated from beam vacuum by a 250 µm thick RF foil

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The LHCb Vertex Locator upgrade
Module description

- All module components made of silicon
  ⇒ minimal mismatch in thermal expansion coefficient
- 2 tiles mounted on each side
- 3 chips in a row bump-bonded to a single sensor form a tile
Box with corrugated foil

- Separates beam vacuum from secondary vacuum
- Shields modules from beam interference
- Guides mirror currents
- Milled to a thickness of $\sim 250 \, \mu m$ from a solid block of AlMg4.5
- Further thinning by chemical etching is being investigated
- Particles may traverse the foil multiple times: main contribution to material budget

RF box and foil

LHCb simulation
RF box
hybrids
ASICs
sensors
RF foil
cooling substrate
cooling conn.
other

total material: $21.3\%X_0$
Sensors

Sensor characteristics

- 200 µm thick (exploring other thicknesses too)
- 400-450 µm wide guard rings
- n-on-p (n-on-n)
- Vendors
  - Micron
  - Hamamatsu
- Radiation hard up to $\sim 10^{16} \text{ } n_{eq}/\text{cm}^2$
- Non-homogeneous irradiation (factor 40 difference from hottest to coolest point)

First prototype sensors arrived recently. Lab & beam tests are ongoing.
VeloPix - a pixel ASIC for Velo

- based on Timepix3
- 256 x 256 square pixels of 55 µm size
- 130 nm CMOS technology
- measures
  - Position (x, y)
  - Time of Arrival with 25 ns resolution
- Peak hit rate 900 MHits/s per ASIC
- Radiation hard up to 400 Mrad
- Zero suppressed data driven readout

Picture of Timepix3 chip, predecessor of VeloPix.
All 19 channels have nearly the same length and fluidic resistance.

Microchannels in silicon substrate
- 400 µm thick silicon substrate
- 19 parallel microchannels of 200 µm width & increasing depth up to 120 µm
- Pressure up to \(~65\) bar at room temperature, system will be qualified to 170 bar
- Cooling requirement: > 3 W/ASIC, > 36 W/module
- From a \(6 \times 4\) cm\(^2\) Si-pyrex prototype 12.9 W of power can be removed
Impact Parameter resolution

- Distance between extrapolated particle trajectory and its primary vertex is a signature of a $B$ meson decay.

$$\sigma_{IP}^2 \approx \sigma_{MS}^2 + \sigma_{\text{extrapolation}}^2$$

Impact Parameter resolution: Current Velo (black) and Upgraded Velo (red)

Decay time resolution

- Dilution on the amplitude of a $B$ meson oscillation depends on the decay time resolution $\sigma_t$

$$D = e^{-\frac{1}{2} \Delta m_s^2 \sigma_t^2}$$

Decay time resolution: Current Velo (black) and Upgraded Velo (red)
Timepix3 telescope

- 8 Timepix3 detectors divided in 2 arms
- Active area of $\sim 2 \text{ cm}^2$
- Pointing resolution $< 2 \mu\text{m}$ for a 180 GeV beam
- Reconstruct up to 10 million tracks/s
- Extensive testbeams in PS & SPS at CERN
200 µm thick Hamamatsu sensor on a Timepix3 chip bump-bonded by Advacam

- Interpixel fractions of 1, 2, 3 and 4 pixel clusters (sensor perpendicular to the beam)

**Bias voltage: -100 V (close to depletion voltage)**

**Bias voltage: -500 V (over depleted)**
**Results with triples**

**200 µm thick Hamamatsu 3×1 tile on 3 Timepix3 chips bump-bonded by Advacam**

**Hit map of a 3 × 1 tile in a 180 GeV beam (data from testbeams in late October).**

### Data available
- Efficiency measurements
- Bias voltage & angle scans
- High rate tests (up to 80 Mhits/s)

### Further tests
- Examination of irradiated tiles both in lab & in testbeams
- HV tolerance testing (before/after irradiation)
- First assemblies irradiated now & planned to be tested in beam next week
Summary

- LHCb will have to cope with $5 \times$ higher luminosity and $100 \times$ more data
  - Move to software trigger and data driven readout
- Upgrade of the Vertex Locator is ongoing
  - All silicon module
  - A new pixel ASIC: VeloPix
  - Microchannel cooling
  - Highly non homogeneous illumination with a maximum fluence of $8 \times 10^{15} \, n_{eq}/cm^2$
- Very active testbeam program for sensor & ASIC characterisation
  - Telescope with Timepix3 (predecessor to VeloPix)
  - First sensors exposed to beam, data analysis ongoing

Outlook

- Extensive irradiation programme of sensors already started
- First version of VeloPix ASIC and prototype module expected mid 2015
- Module production scheduled for 2016
- Installation in 2018
back up slides
Fully software based event selection

- Higher luminosity results in saturation of signal yield for hadronic channels

![Graph showing trigger yield as a function of luminosity for different decay modes](image-url)
First results with a Timepix3 chip

Timewalk and ToT linearity

- Measurements done using test pulses

Cosmic rays through sensor

- 300 μm thick silicon p-on-n sensor

Figures taken from Massimiliano De Gaspari’s talk in TIPP 2014
Impact parameter for different Upgrade scenarios

Ghost rates for different Upgrade scenarios

IP resolution on X vs Inverse $p_T$

Total IP3D for VP

Total IP3D for VL

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The LHCb Vertex Locator upgrade

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Impact Parameter

**IP formula**

\[
\sigma_{IP_Y}^2 = \frac{\sigma_0^2}{(z_2 - z_1)^2} \left[ (z_1 - z_{PV})^2 + (z_2 - z_{PV})^2 \right] + \theta_0^2 (z_1 - z_{PV})^2
\]

becomes

\[
\sigma_{IP_Y}^2 = \frac{\sigma_0^2}{(z_2 - z_1)^2} \left[ (z_1 - z_{PV})^2 + (z_2 - z_{PV})^2 \right] + \frac{1}{p_T^2} \left( \frac{13.6 \text{ MeV}}{\beta c} q \sqrt{x/X_0} \left[ 1 + 0.038 \ln(x/X_0) \right] \right)^2 (y_1 - y_{PV})^2
\]