Upgrade of the LHCb Vertex Locator

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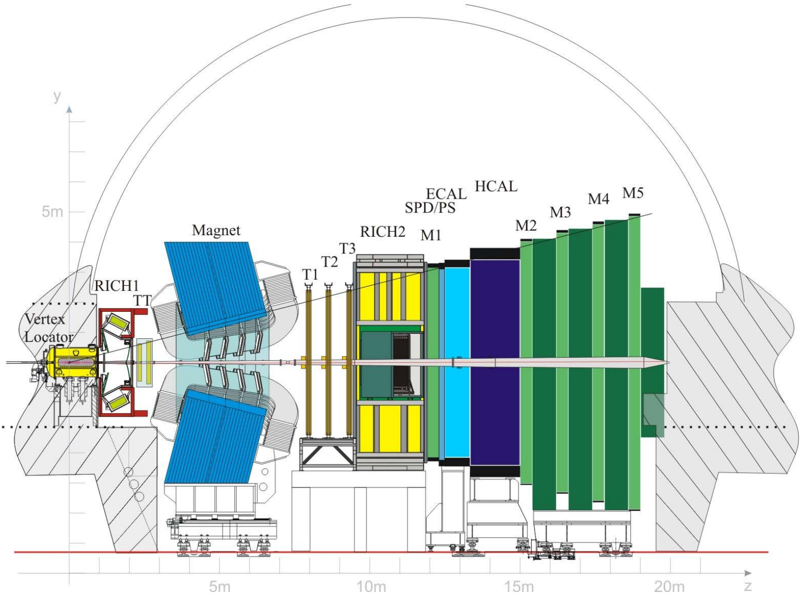
VERTEX2014, 15 – 19 September 2014

LHCb (Reminder)



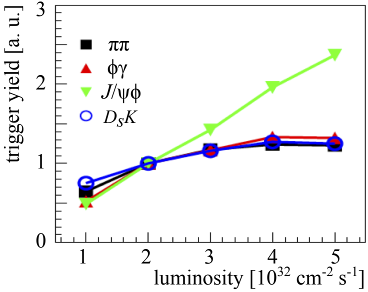
LHCb Upgrade

LHCb until LS2

- During LHC Run 1, LHCb has collected $\sim 3\,\text{fb}^{-1}$ of data, operating in 2012 at a (levelled) instantaneous luminosity of $4 \times 10^{32}\,\text{cm}^{-2}\,\text{s}^{-1}$.
- Until the end of Run 2, the total integrated luminosity is expected to increase to $8\,\text{fb}^{-1}$.
- Without increase in luminosity, further doubling the sample would then take a long time.
- Main bottleneck of existing experiment is 1 MHz readout rate in combination with limited discriminating power of L0 hardware trigger.
  - L0 trigger is based on high E_T cluster in calorimeter or high p_T track in muon system.
  - Higher $\mathcal{L}$ requires higher E_T cut, resulting in saturation of signal yield for hadronic channels.

Upgrade strategy

- Triggerless readout at 40 MHz.
- Fully software-based event selection.
- Increase yield by factor $\gtrsim 10$.
- To be installed in LS2 (2018/19).

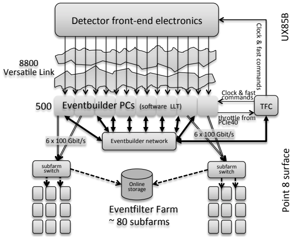


Simulated L0 trigger yield (existing experiment), normalised to $\mathcal{L} = 2 \times 10^{32}\,\text{cm}^{-2}\,\text{s}^{-1}$.

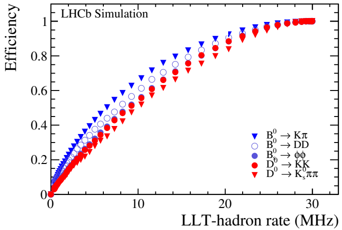
LHCb Upgrade

LHCb after LS2

- Upgraded detector is designed to run at $\mathcal{L} = 2 \times 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.
- Upgraded experiment is foreseen to accumulate $\gtrsim 50\,\mathrm{fb}^{-1}$ over 10 years.
- Expected statistical sensitivities become comparable to theoretical uncertainties.
- General purpose detector with forward acceptance thanks to enhanced trigger flexibility.



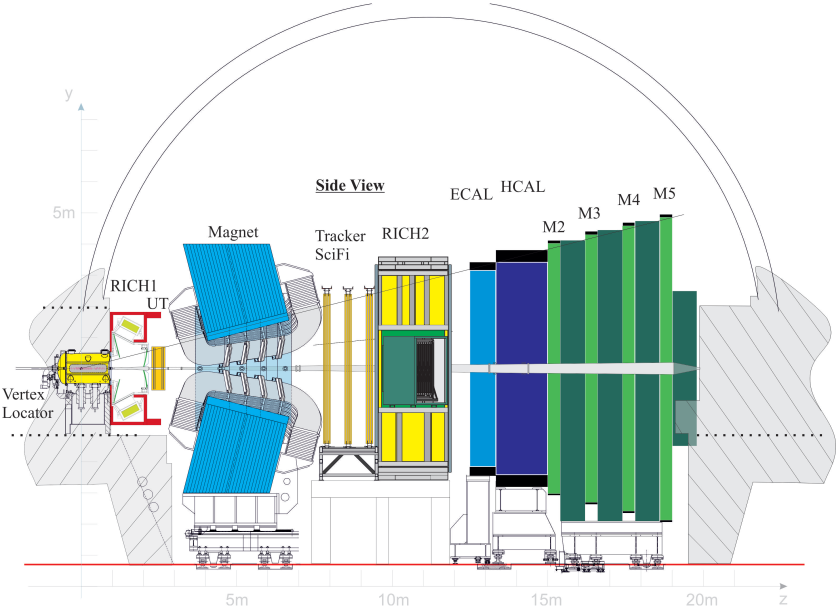
Upgrade readout architecture.



Detector upgrade

- As a consequence of 40 MHz readout, front-end electronics need to be replaced.
- Tracking detectors need to be rebuilt, RICH photodetectors to be replaced, . . .

LHCb Upgrade



Vertex Locator Upgrade

Requirements

- Maintain (or improve on) performance of existing VELO (despite higher occupancy).
- Provide fast and robust track reconstruction (essential for software trigger).
- Cope with increased data rates and fluence.
- Minimise material in acceptance.

In a nutshell

- Overall layout is similar to existing VELO.
    - Two moveable halves housing array of detector modules perpendicular to the beam line.
    - Modules are located in a secondary vacuum, separated from the beam vacuum by a thin aluminium box with corrugated walls (“RF shield”).
- Hybrid pixel detectors instead of of strip sensors.
- Microchannel-cooled modules with two-phase CO_2 as coolant.
- Move active area closer to the beam (5.1 mm instead of 8.2 mm).

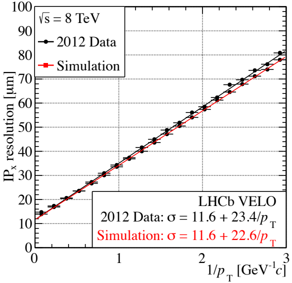
Vertex Locator Upgrade

Why closer to the beam?

- Based on Run 1 experience, aperture limit (RF foil) can be reduced to 3.5 mm.
- Impact parameter resolution can be described by

$$\sigma_{\mathrm{IP}}^2 = \underbrace{\frac{r_1^2}{{p_\mathrm{T}}^2}\left(0.0136\,\mathrm{GeV}/c\sqrt{\frac{x}{X_0}}\left(1+0.038\ln\left(\frac{x}{X_0}\right)\right)\right)^2}_{\sigma_{\mathrm{MS}}^2} + \underbrace{\frac{\Delta_{02}^2\sigma_1^2+\Delta_{01}^2\sigma_2^2}{(\Delta_{02}-\Delta_{01})^2}}_{\sigma_{\mathrm{extrap}}^2},$$

- First term scales with radius of first measurement r_1.

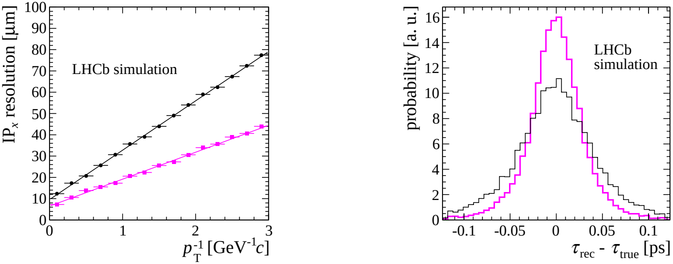


IP resolution (of existing VELO) as function of $1/p_\mathrm{T}$.

Vertex Locator Upgrade

Would it work with strips? Yes, but . . .

- Pattern recognition less robust and more time consuming.
- Larger vulnerability to radiation effects.

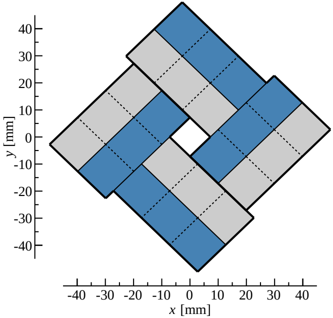


Impact parameter resolution (left) and decay time resolution ($B^0 \to K^{*0}\mu^+\mu^-$)
for existing VELO (black) and upgraded **strip-based** VELO with 5.1 mm inner radius (magenta).

Layout

Module

- Basic building blocks are 14 × 14 mm^2 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 (400 µm Si).



Schematic layout of active area.

Layout

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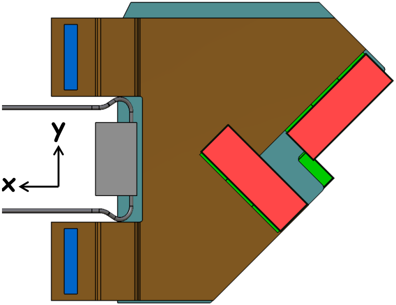

Conceptual module design.

Layout

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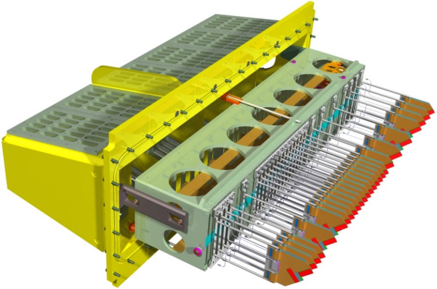

Detector half box comprising 26 modules.

Layout

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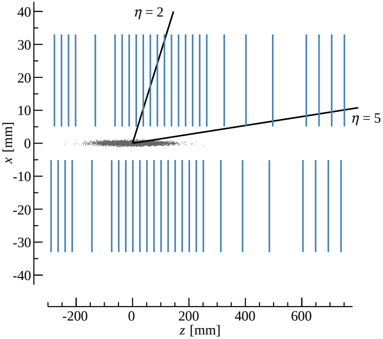
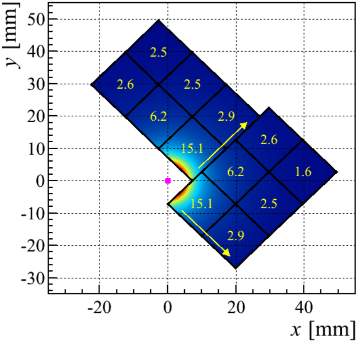


Schematic layout of module positions.

ASIC

VeloPix

- Derived from Timepix3 ASIC.
    - 256 × 256 pixels, 55 × 55 µm^2 cell size.
    - Based on 130 nm CMOS technology.
    - Data-driven readout.
    - 2 × 4 pixels grouped to super-pixel.
- Main differences are
    - increased data rate,
    - radiation hardness and SEU robustness.
- First submission planned for mid 2015.
- ASIC is foreseen to be thinned to 200 µm.



Data rate [Gbit/s] for hottest module.

	Timepix3	VeloPix
peak pixel hit rate [MHz]	80	900
timestamp resolution [ns]	1.6	25
timewalk [ns]	< 25	< 25
time-over-threshold	10 bit	binary
radiation hardness	not specified	$>$ 400 Mrad
power consumption [W]	< 2	< 3

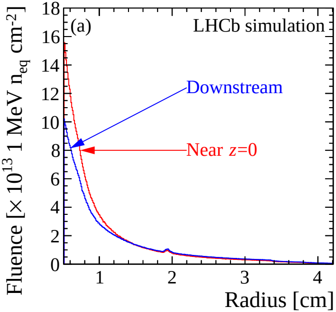
Sensors

Requirements

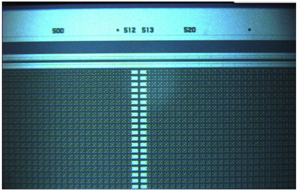
- Tip of hottest sensor accumulates fluence of 8×10^{15} 1 MeV n_{eq} cm^{-2} after 50 fb^{-1}.
- Outer region of the same sensor will see by factor 10 – 20 lower fluence.
- Sensors must be able to withstand 1000 V bias without breakdown.

Baseline design

- 200 µm thickness, 450 µm inactive edge.
- 110 µm gap between ASICs bridged by elongated pixel implants.
- Prototype sensors from Micron and HPK expected to arrive in next weeks.
  - Micron: *n*-on-*n* and *n*-on-*p*, HPK: *n*-on-*p*.
  - Micron batch also includes more aggressive guard designs and wafers with 150 µm thickness.



Fluence per fb^{-1} as function of distance from beamline.

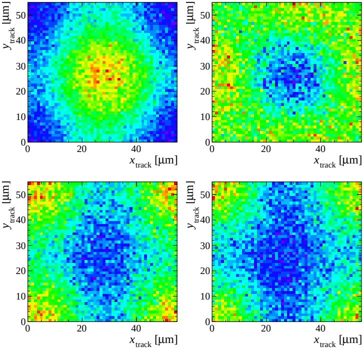


Hamamatsu prototype sensor (sneak peek).

Testbeam

Timepix3 telescope

- Timepix3 is an excellent device for a building a beam telescope.
  - Small pixel size.
  - Simultaneous measurement of charge deposit (ToT) and time.
  - No need for external trigger due to data-driven readout.
  - Virtually no dead time.
- Successfully commissioned in July/August at CERN PS.
- Upcoming testbeam campaign in November/October at CERN SPS.
  - Characterisation of prototype assemblies (resolution, efficiency, timewalk,. . .).
  - High-rate test of Timepix3 (up to $\sim 10\,\mathrm{MHz}$ track rate).



Track intercepts for clusters with 1, 2, 3, 4 pixels (300 µm thick sensor).

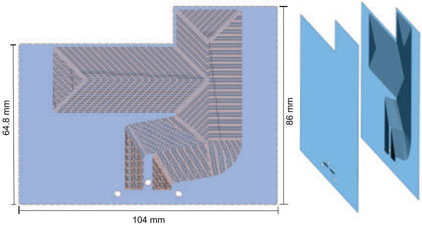
Cooling

Overview

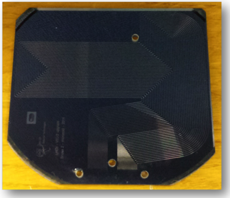
- Evaporative CO_2 cooling used in VELO, AMS, ATLAS IBL.
- Microchannel cooling (with single-phase coolant) used by NA62 GTK.
- VELO upgrade is first project to combine the two technologies.

Requirements

- Keep sensors at $< -20^\circ$ C to prevent thermal runaway.
- Drain heat from ASICs (up to $\sim 35\,$W per module), minimise ΔT.
- Minimise material in acceptance.
- Minimise mismatch in thermal expansion coefficients.
- Safe operation in secondary vacuum (pressure tolerance).



Cooling plate design.

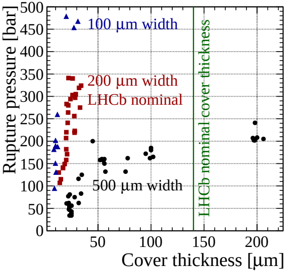


Prototype plate.

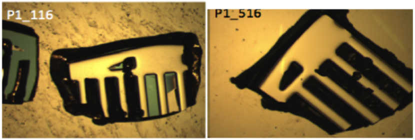
Cooling

R&D highlights

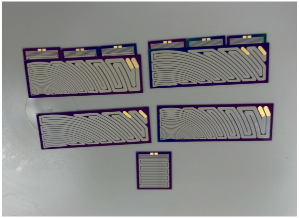
- Hydrophilic vs. hydrophobic bonding.
    - Hydrophobic samples (direct Si-Si bonding) shown to withstand 700 bar.
    - Required pressure tolerance is 170 bar.
- Pressure resistance vs. cover thickness.
- Endurance tests.
    - Temperature cycles between ±40° C.
    - Pressure cycles between 1 and 200 bar.
    - No sign of rupture after thousands of cycles.
- Performance tests with thermal mockups.
- Soldering of connector to silicon substrate.
- Optimisation of channel layout using finite-element simulations.



Pressure tolerance vs. substrate thickness.



Rupture pattern for hydrophilic (left) and hydrophobic samples.

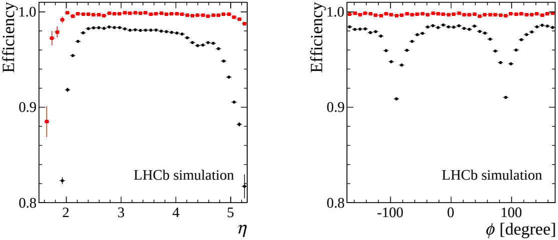


Thermal mockups.

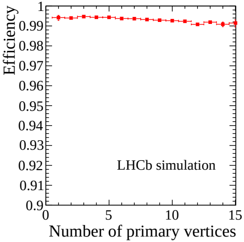
Performance

Track reconstruction

- Reconstruction efficiency $\gtrsim 99\%$ over LHCb acceptance, fake track rate $\sim 2\%$.
- Reconstruction of all tracks in VELO (including clustering) within $\sim 2\,\text{ms}$, compatible with HLT time budget.
- Less features in efficiency vs. η, ϕ, z, r compared to existing VELO.
- Robust against radiation damage and increase in pile-up.



Reconstruction efficiency of existing (black) and upgraded (red) VELO at upgrade luminosity ($\mathcal{L} = 2 \times 10^{33}\,\text{cm}^{-2}\,\text{s}^{-1}$).

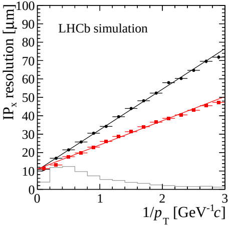


Reconstruction efficiency of upgraded VELO as function of nbr. of primary vertices

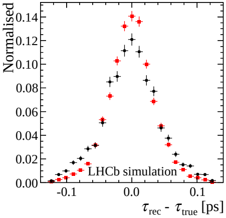
Performance

Impact parameter and vertex resolution

- Impact parameter, primary vertex and decay time resolution are improved compared to existing VELO, mainly due to closer distance to beamline.



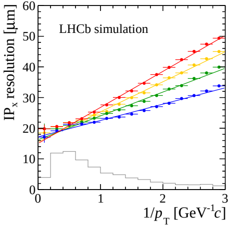
Impact parameter resolution for upgraded (red) and existing (black) VELO.



Decay time resolution for B^0 mesons in $B^0 \to K^{*0}\mu^+\mu^-$ decays.

Room for further improvement?

- Cannot go closer to the beam.
  Data rates, radiation damage, . . .
- Material is dominated by RF shield.
  Could benefit from reduced thickness.

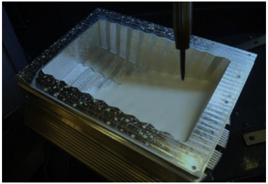


IP resolution for foil thicknesses between 250 μm and 0 μm.

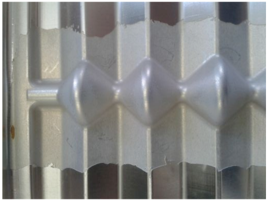
RF Foil

Manufacturing technique

- Milling solid block of AlMg alloy, allows high mechanical precision.
- Baseline foresees wall thickness of 250 μm.
- Local thickness reduction of corrugated part by chemical etching being investigated.



Milling of prototype box.



Sample with central part thinned to 150 μm

Summary

LHCb Upgrade

- LHCb will be upgraded in 2018/19 to exploit higher luminosity with better efficiency.
- This is achieved by triggerless readout and software-based trigger.

Vertex Locator Upgrade

- Upgraded VELO will be manufactured from hybrid pixel detectors (VeloPix ASIC).
- Microchannel CO_2 cooling chosen as cooling technology.
- Improved performance compared to existing VELO (closer to beamline).
- Data-driven readout at $\mathcal{L} = 2 \times 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.
- Technical Design Report submitted in December 2013 and approved in March 2014.
- R&D programme in final stage.