Sensor development for the LHCb VELO upgrade

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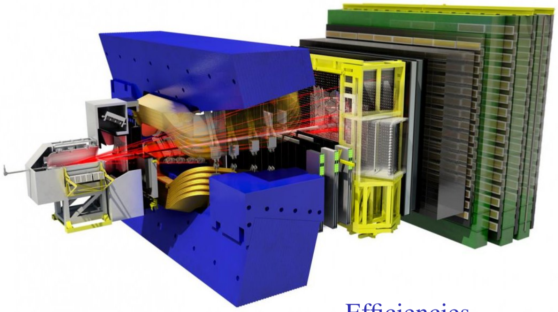
USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA
VERTEX LOCATOR
LHCb

Outline

The LHCb experiment

LHCb is a forward spectrometer designed to study flavor physics exploiting the enormous production cross sections of heavy hadrons at the LHC



Characteristics

- Built for $\mathcal{L} = 2 \times 10^{32} cm^{-2} s^{-1}$ at 25 ns spacing, with an average of $\mu = 0.4$ interactions per bunch crossing
- In 2012 it ran at a $\mathcal{L} = 4 \times 10^{32} cm^{-2} s^{-1}$ at 50 ns spacing with $\mu = 1.4$
- Has recorded 1.1 fb^{-1} in 2011 and 2.1 fb^{-1} in 2012

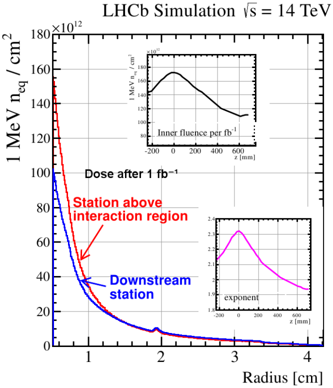
Efficiencies

- All detectors with >∼99% active channels
- ϵ(operation)>94%
- ∼98% are good data

VELO upgrade

Requirements and challenges

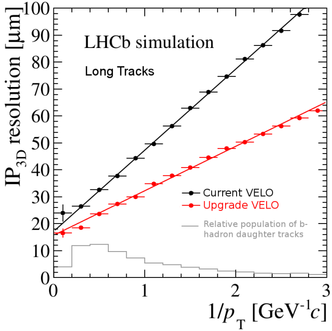
- Data-driven readout at 40 MHz $\Rightarrow$ up to 2.85 Tbit/s from whole VELO
- Radiation hardness at 8×10^{15} 1 MeV n_{eq} cm^{-2}.
  Highly non-uniform radiation: $5.2 \times r^{-1.9}$ hits $event^{-1}cm^{-2}$
- Keep/improve performance
- Increase granularity to allow operation at $\mathcal{L} \geq 2 \times 10^{33} cm^{-2}s^{-1}$
- Minimise material in acceptance
- Provide fast and robust track reconstruction (essential for the new software trigger)

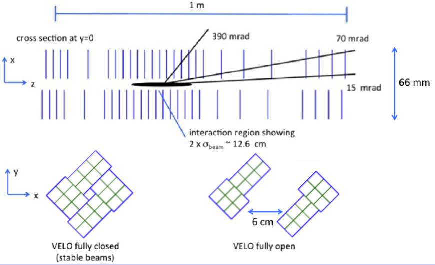


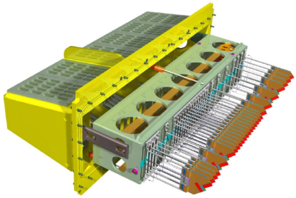
VELO upgrade

Characteristics of the new VELO

- From micro-strips to pixels
- Full detector consists of 26 stations (1 station = 2 modules, one on either side of the beam)
- Closest pixel is at 5.1 mm from the beam centre
- Separated from the beam vacuum by a 250 μm RF foil
- Geometrical efficiency > 99 % for R < 10 mm
- Track rate (and radiation damage) will be 10x higher

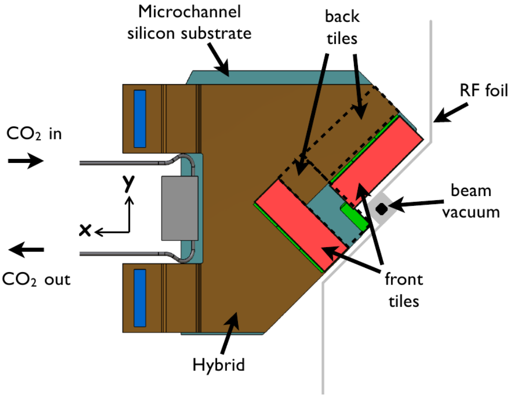


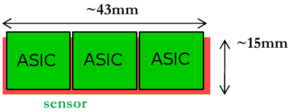




Modules

- 4 sensor tiles (14x42 mm^2), 2 on each side of substrate
- Each tile is bump bonded to 3 ASIC for readout
- Silicon substrate with integrated micro-channels for cooling
- Material in active region $\sim$0.9% X_0



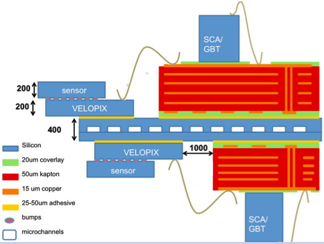


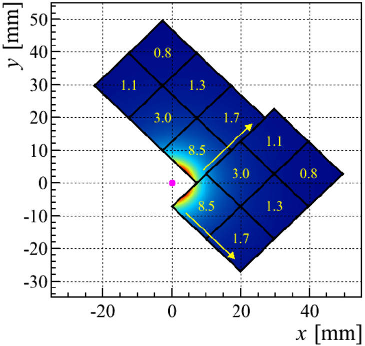
ASIC

Velopix

The upgraded VELO will be based on Velopix ASIC (branch of Timepix3) 55 µm x 55 µm pixel size, 256 x 256 matrix

- Binary readout
- Hit rate up to 900 MHits/s. (Above 15.1 Gbit/s)
- Data driven readout: each hit is time-stamped, labeled and sent off chip immediately in a superpixel structure
- Radiation hard up to 400 MRad
- Submission planned for 2015 Q4

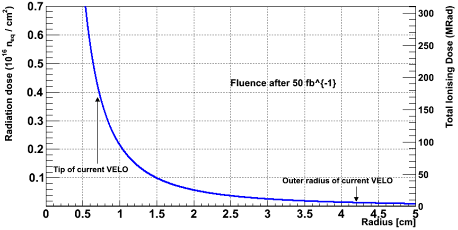


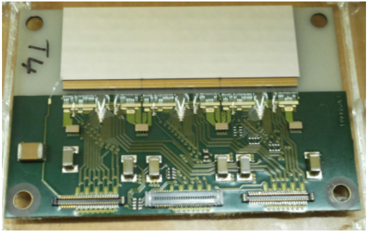


Mean number of particles crossing an ASIC per event

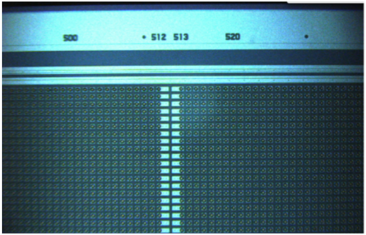
Silicon sensors

- Planar silicon n-in-p (evaluating n-in-n)
- Tile for 3 VeloPix chips: ∼43 mm × 14 mm, thickness 200 µm
- 55 µm × 55 µm pixel size
- 110 µm gap between ASICs bridged by elongated pixel implants
- Non homogeneous irradiation sets constraints on guard ring design
  - → factor ∼140 difference in fluence from tip to far corner
  - → bias voltage at end on life ∼1000 Volts for tip
  - → distance pixel to edge ∼450 µm





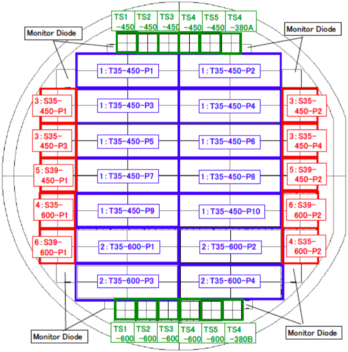
Sensor tile on a hybrid board



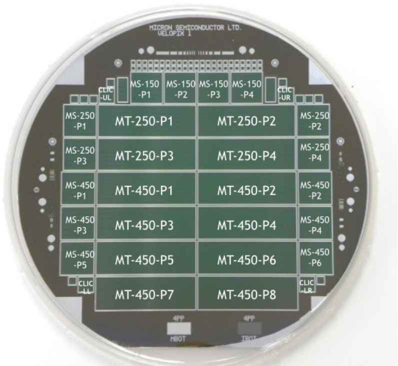
Hamamatsu prototype sensor

Silicon sensors

HPK sensor wafer layout

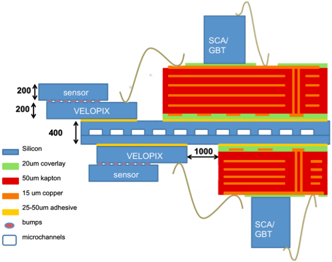


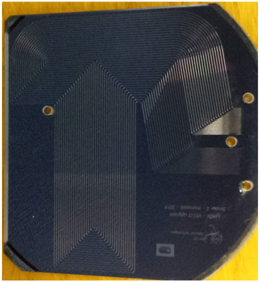
Micron sensor wafer layout

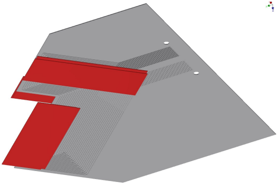


Cooling

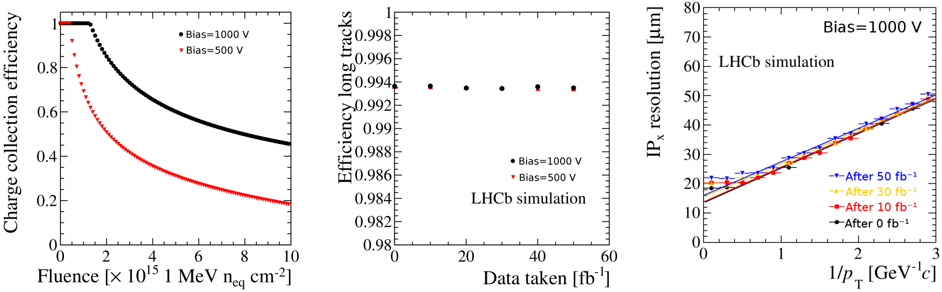
- High speed pixel readout chips produce a lot of heat (∼1.5 W/cm^2)
- Keep the sensors at < -20°C to minimize the effects of radiation damage, and to avoid thermal runaway
- Novel method: evaporate CO_2 via micro-channels etched in Si substrate
- Bring the cooling power where you need it, using least material
- No CTE difference (Si on Si)







Expected performance after irradiation

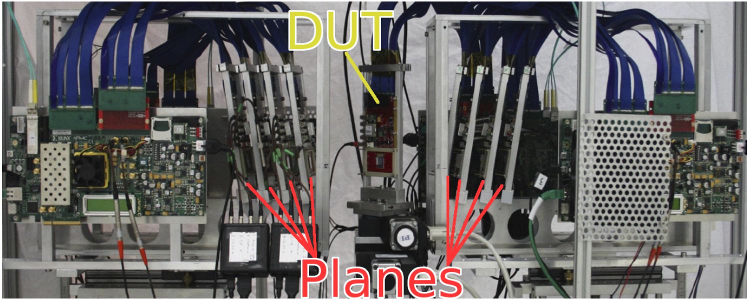


Charge collection efficiency decreases with radiation radiation damage, but this effect is not propagated to the track reconstruction efficiency and the IP resolution

Test beam

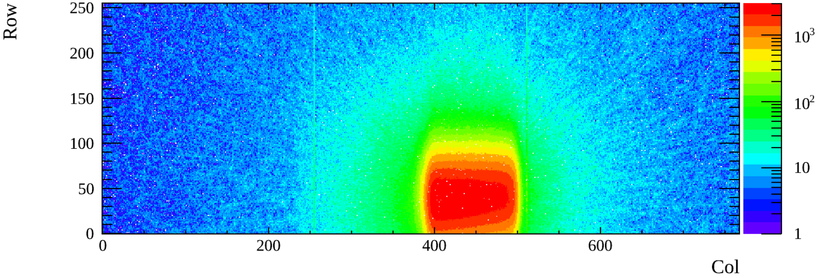
TimePix3 telescope

- 8 planes divided in two arms
- Each plane consist in a Timepix3 chip bump bonded to a 300 µm *p*-on-*n* Si sensor
- Track rate > 5 MHz. Only limited by beam intensity
- Resolution at the DUT plane 2 µm (with 180 GeV/c π beam)
- 1.4×1.4 cm^2 of active area
- Data driven readout



Test beam

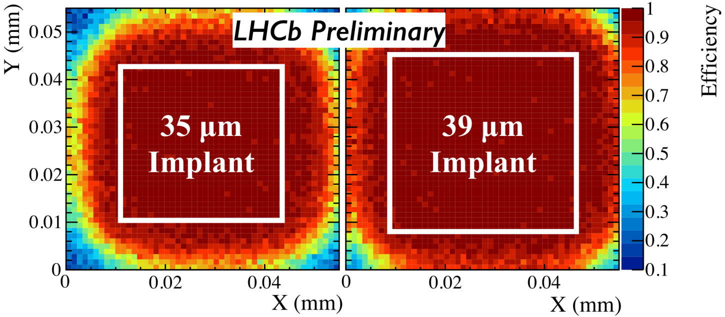
200 μm thick Hamamatsu 3×1 tile on 3 Timepix3 chips bump-bonded by Advacam



Hit map of a 3×1 tile in a 180 GeV SPS beam

Test beam

Intrapixel efficiencies

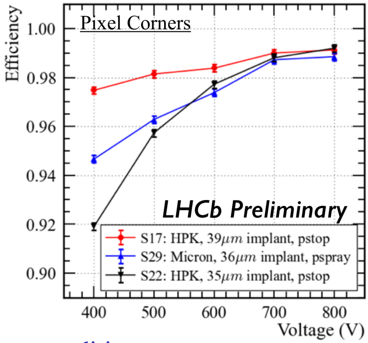


Sensor conditions:

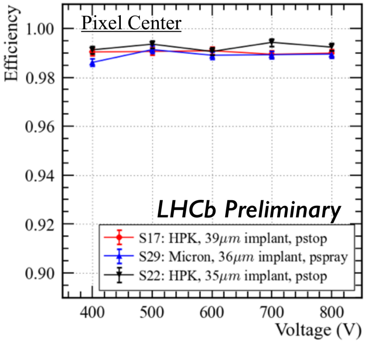
- Manufactured by HPK
- 200 µm *n*-on-*p*
- Irradiated homogeneously to 8×10^{15} 1 MeV n_{eq} cm^{-2}
- Bias -300 V
- Threshold 1000 e^{-}

Test beam

Intrapixel corners efficiency



Intrapixel centre efficiency

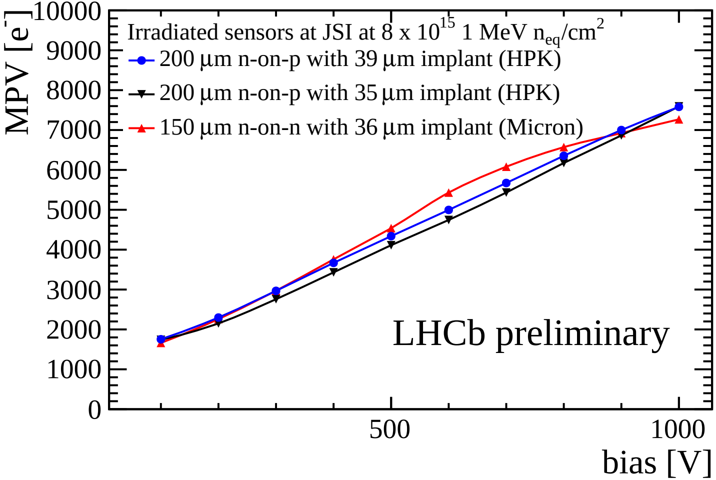


Sensor conditions:

- 200 μm *n*-on-*p* (S22 & S17)
- 150 μm *n*-on-*n* (S29)
- Irradiated homogeneously to 8×10^{15} 1 MeV n_{eq} cm^{-2}
- Threshold 1000 e^{-}

Test beam

Charge collection efficiency



Conclusions

The requirements for the LHCb VELO upgrade are very demanding:

- Luminosity will be increased by a factor ≥ 5
- Keep or improve the performance of the current VELO

Upgrade VELO characteristics:

- Vertex Locator will consist of planar silicon pixels, 55 x 55 μm^2
- The first pixel will be only at 5.1 mm from the beam axis
- Evaporative CO2 cooling in Silicon micro-channel substrate
- Material budget reduction in elements placed in the acceptance (modules, RF-Foil)

Still a lot of work to do:

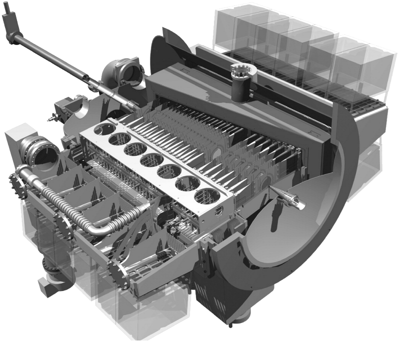
- Intense testbeam program to validate: sensor technologies, radiation hardness, cooling schemes and readout electronics
- Sensor, electronics, modules and mechanics production

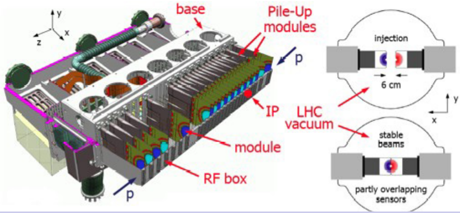
Installation during Long Shutdown 2 in 2019

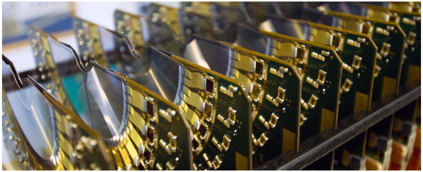
Backup

The Vertex Locator (VELO)

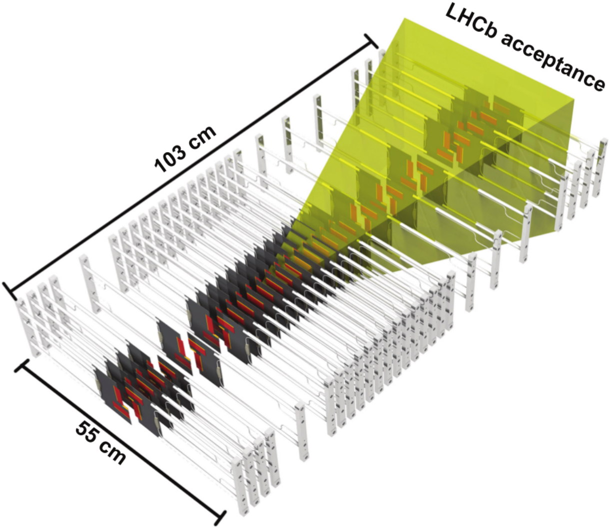
- Silicon strip detector surrounding the interaction point
- 88 silicon n^{+}-on-n sensors, 300 μm thick, R-ϕ design
- Located only 8 mm from the beams
- Enclosed into a separated vacuum box (RF Foil)
- Halves are separated for beams injection
- 1 MHz trigger rate
- Bi-phase CO_2 cooling system



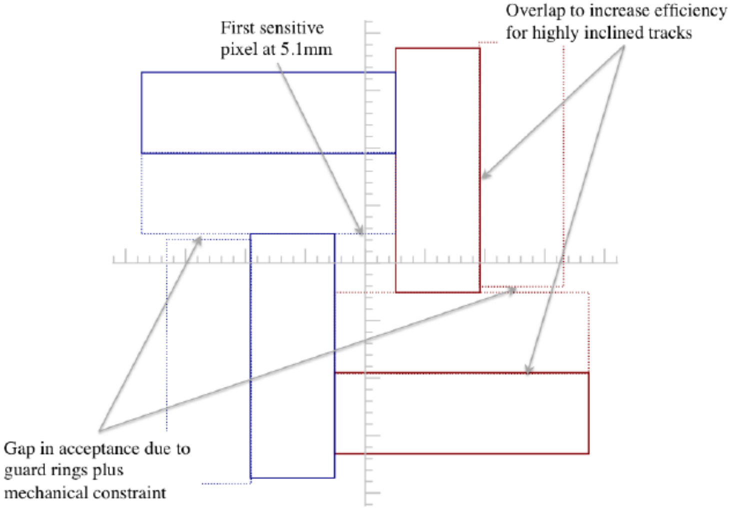




Backup



Backup

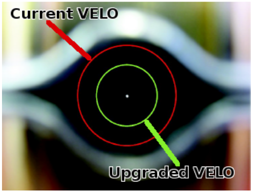

First sensitive
pixel at 5.1mm
Overlap to increase efficiency
for highly inclined tracks
Gap in acceptance due to
guard rings plus
mechanical constraint

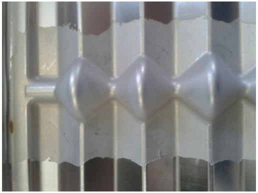
RF foil

The RF foil is a *de facto* beam pipe

Severe requirements:

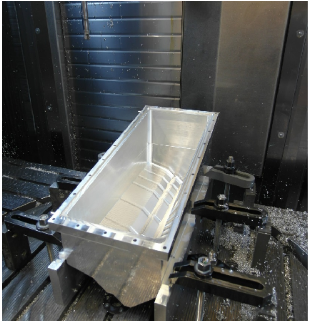
- Vacuum tight ($< 10^{-9}$ mbar l/s)
- Radiation hard
- Low mass but mechanically stable
- Good electrical conductivity to mirror beam currents and shield against RF noise pick-up in FE electronics
- Thermally stable and conductive (heat load from the beam)





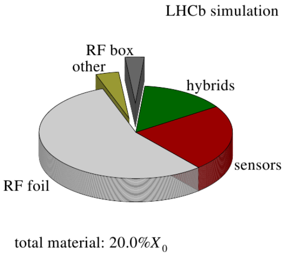
Sample with central part thinned to 150 μm

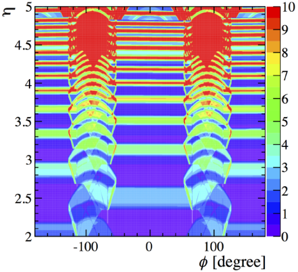
Material and fabrication:

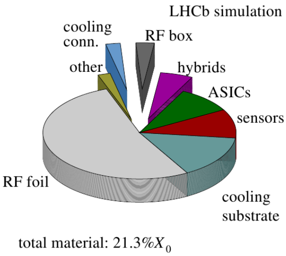


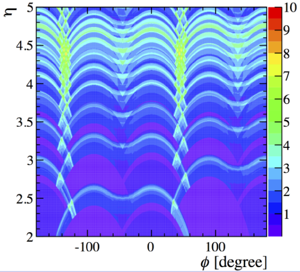
- Mill foil from solid Al alloy block
- Achieve 250 μm thickness
- Chemical thinning being investigated to reduce the central part

Backup


LHCb simulation
RF box
other
hybrids
sensors
RF foil
total material: 20.0%X_0


η
ϕ [degree]


LHCb simulation
cooling conn.
RF box
other
hybrids
ASICs
sensors
RF foil
cooling substrate
total material: 21.3%X_0

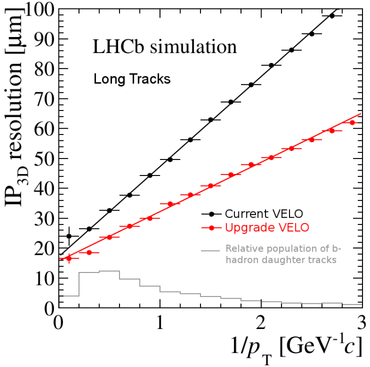

η
ϕ [degree]

Backup

$$\sigma_{\text{IP}}^2 = \frac{r_1^2}{p_{\text{T}}^2\sqrt{2}}\left(0.0136\sqrt{\frac{x}{X_0}}\left(1+0.038\ \ln\left(\frac{x}{X_0}\right)\right)\right)^2 + \frac{\Delta_{02}^2\sigma_1^2+\Delta_{01}^2\sigma_2^2}{\Delta_{12}^2}$$

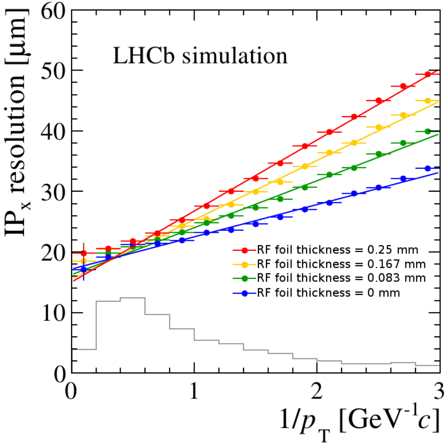
Comparison between current and upgraded VELO

- A smaller RF foil inner radius (3.5 versus 5.5 mm)
- A smaller inner edge distance to the beams for the sensitive part; $R_{det} \sim 5.1$ mm versus 8 mm
- A coarser inner pitch (p = 55 μm pixels versus 40 μm strips)
- A smaller Si thickness ($t_{det} + t_{ASIC} = 0.4$ versus $t_{det} =$ 0.6 mm for an R-*phi* station)
- A smaller z distance between stations (Δz = 25 versus 30 mm)



Backup

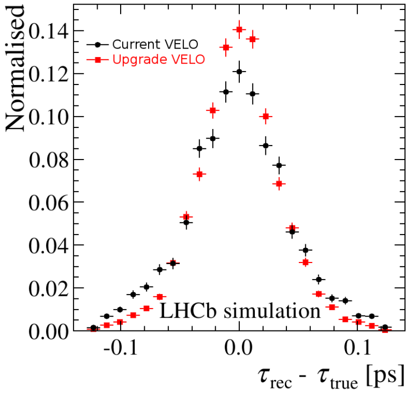
Expected performance (IP resolution)



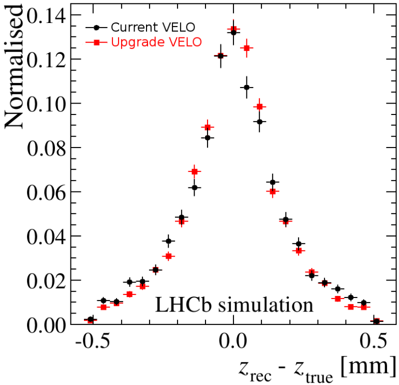
Impact parameter resolution in x for the upgrade VELO for the nominal RF foil thickness (0.25 mm) and three additional thicknesses.

Backup

Expected performance (τ and z resolutions)



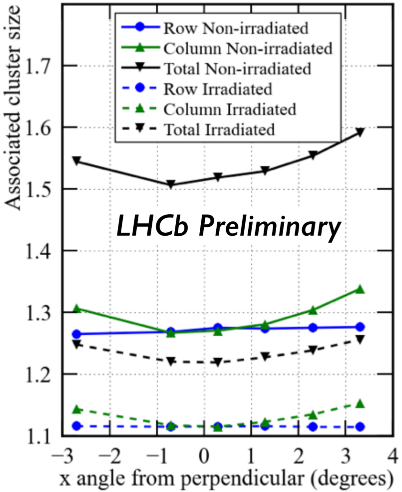
Decay time for $B^0 \to K^{*0}\mu^+\mu^-$ resolution



z of the B vertex resolution

Backup

Cluster size



- S17: 200 µm *n*-on-*p*. Irradiated homogeneously to 8×10^{15} 1 MeV n_{eq} cm^{-2}
- S6: 200 µm *n*-on-*p*. Non irradiated
- Threshold 1000 e^{-}