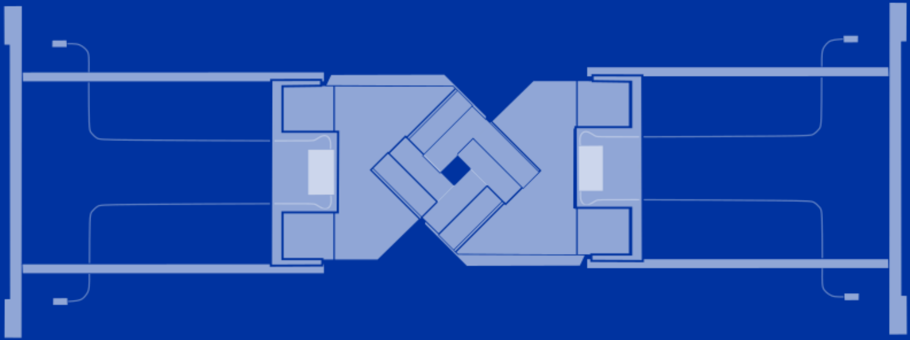
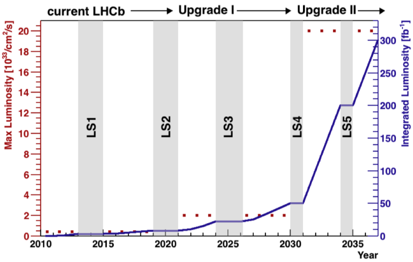


The LHCb VELO Upgrade Programme for High Luminosity running at the LHC and HL-LHC

T. Evans, On behalf of the LHCb VELO group

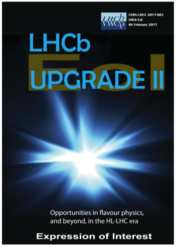
ICHEP 2020

High Luminosity LHC

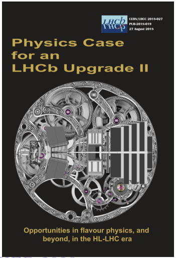


- HL-LHC will increase luminosity for LHCb by a factor of 7.5 from Upgrade-I.
- 7.5× radiation damage, multiplicity, data rates and track density.
- Improvements to the detector needed to maintain the physics performance.
- Upgraded Sensors, ASICs and mechanics needed to survive rates and doses.

Huge amount of physics can be done with all of this data:

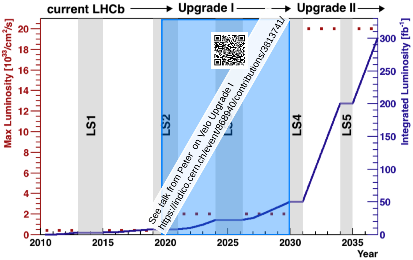


LHCb Upgrade II Expression of interest (`CERN-LHCC-2017-003`)



Physics case for an LHCb Upgrade II (`LHCb-PUB-2018-009`)

High Luminosity LHC



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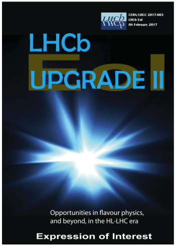

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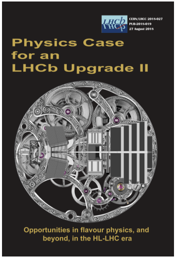
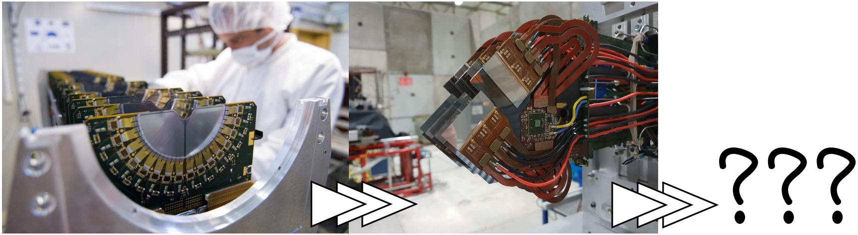


Physics case for an LHCb Upgrade II (`LHCb-PUB-2018-009`)

The Phase II Upgrade challenge



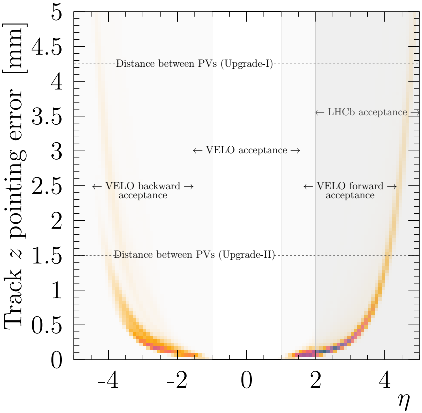
Some idea of what the (very challenging) requirements for the detector will be:

	Classic	Upgrade I	Upgrade II	
Luminosity / year $\left[\mathrm{fb}^{-1}\right]$	2	7	~ 50	
Pileup	1.8	7	~ 50	Can we readout and reconstruct with this much pileup?
Integ. Fluence $\left[1 \cdot \mathrm{MeV} n_{\mathrm{eq}}/cm^2\right]$ (@8.2mm for classic, @ 5.1mm for U-I/II)	4.3×10^{14}	8×10^{15}	$\sim 6 \times 10^{16}$	Will the detector require regular replacements?
Readout rate (hottest chip) $\left[10^6 \mathrm{hits/s}\right]$		600	~ 4500	

At these intensities, flexibility and power of hybrid pixels is still essential. But otherwise what kind of detector can meet this challenge?

Vertex Reconstruction @ $\mu \sim 50$

The Phase II Upgrade Challenge



- At ~ 50 interactions / bunch crossing, PV separation is comparable to the per-track pointing resolution to the beam axis ($\sim 1\,\mathrm{mm}$) : Reconstruction becomes tough.

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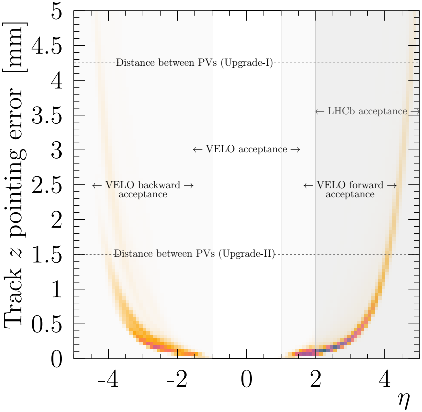
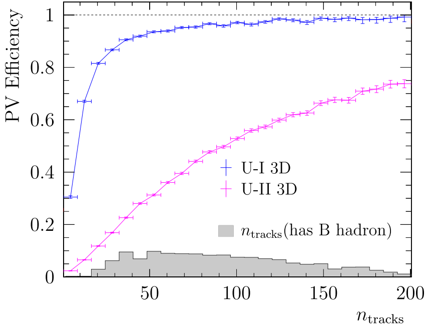
The Phase II Upgrade Challenge





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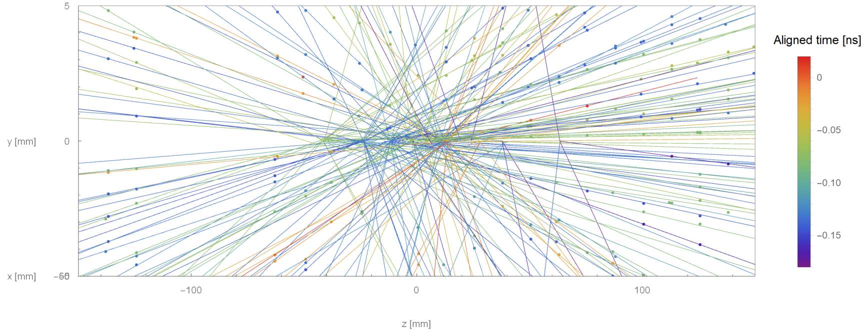
So what can be done?

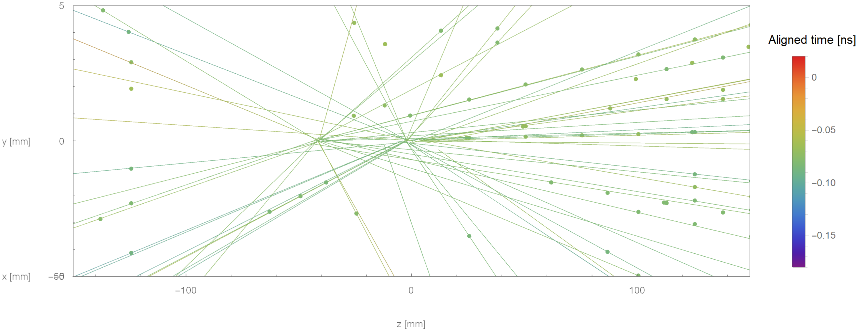
The Phase II Upgrade Challenge



- ▷ Each bunch crossing is very busy in U-II conditions.
- ▷ But, the proton bunches overlap for a finite time (RMS $\sim 180\,\mathrm{ps}$) $\rightarrow$ what if we could resolve them in time (within each crossing) as well space?

So what can be done?

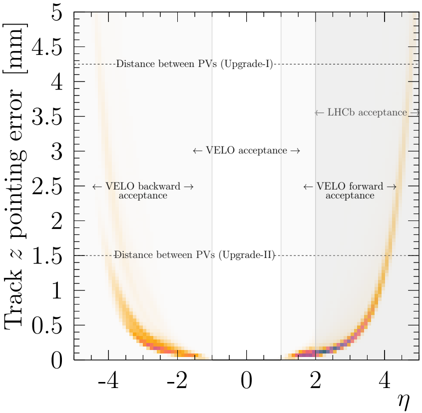
The Phase II Upgrade Challenge

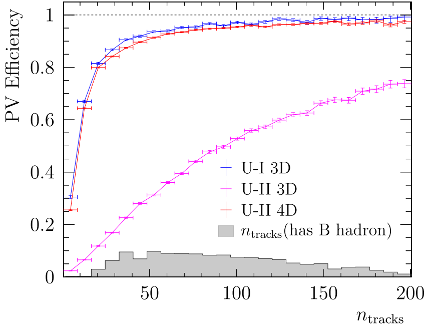


- ▷ Each bunch crossing is very busy in U-II conditions.
- ▷ But, the proton bunches overlap for a finite time (RMS $\sim 180\,\text{ps}$) → what if we could resolve interactions in time (within each crossing) as well space?
- ▷ Looks a lot better in slices of time → need but will need excellent temporal resolution (10s of ps per hit).

Vertex Reconstruction @ $\mu \sim 50$

The Phase II Upgrade Challenge



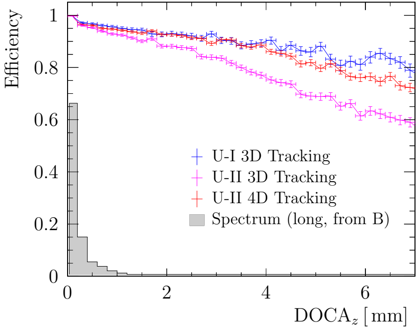


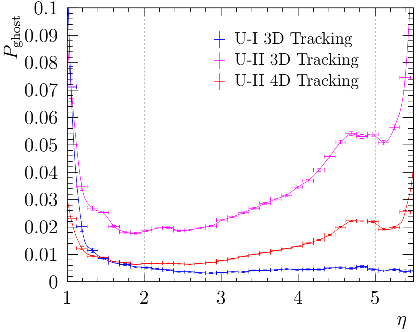
- At ~ 50 interactions / bunch crossing, PV separation is comparable to the per-track pointing resolution to the beam axis ($\sim 1\,\mathrm{mm}$) : Reconstruction becomes tough.
- Initial studies show adding 50 ps / hit timestamp almost completely recovers the Upgrade-I vertex reconstruction efficiency.

4D Tracking

The Phase II Upgrade Challenge

Per hit time measurements can also be used in the track reconstruction:





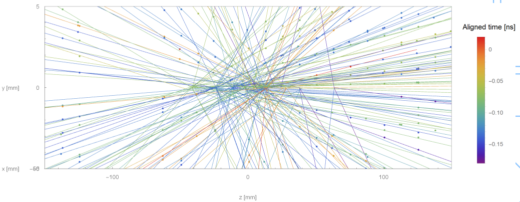
Four-dimensional tracking brings improvements to:

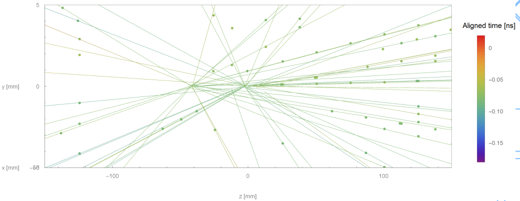
- ▷ Tracking efficiency and its spatial uniformity, important for control of systematic uncertainties as correlated with decay times.
- ▷ Large reduction in ghost rate (down to $\sim 1\%$).

Studies ongoing of 4D tracking on CPU, GPUs and FPGAs.

The Phase II Upgrade challenge

- ▷ Timing in the VELO is mandatory in HL conditions for the reconstruction of vertices.
- ▷ Could a per-track measurement (i.e. a timing plane with a more precise $\sim 30\,\text{ps}$ timestamp) work?
  - × Only plausible to cover ∼ LHCb acceptance: no timing for VELO only tracks.
  - × Lose the substantial benefits to track reconstruction.
  - × Time-of-flight differences a problem if plane is @ $\sim 1m$.
  - × Could have large pixels, but then the higher occupancy may be a problem.
  - × Would require the development of two readout ASICs (one for VELO, one for timing plane)





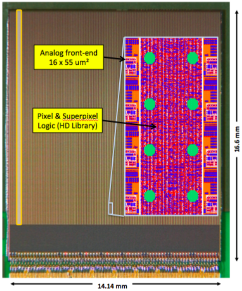
A full, four-dimensional detector is clearly the preferred solution. So how do we get there?

Future ASIC requirements

First steps towards a 4D Vertex Locator

What are the possibilities for the frontend ASIC?

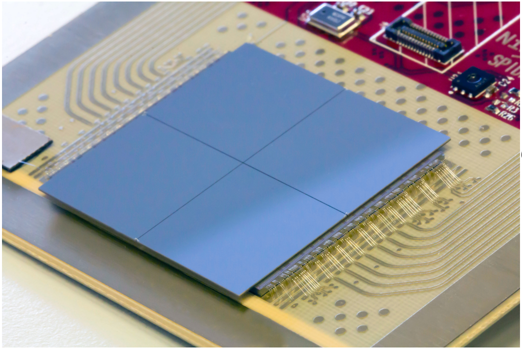
	VeloPix (2016)	Timepix4 (2018/9)	Picopix? (2024)?
Technology [nm]	130	65	< 65
Pixel Size [µm]	55×55 µm	55×55 µm	55×55 µm?
Pixels	256×256	512×448	256×256?
Area $[\text{cm}^2]$	1.98	6.94	1.98
Event packet [bit]	24	64	64?
Max. Rate $[10^6 \text{Hits/cm}^2/\text{s}]$	~ 400	~ 180	~ 4000?
Time resolution (TDC)	25 ns	200 ps	$20 - 50$ ps?
Readout bandwidth [Gb/s]	19.2	≤ 81.92	~ 500?



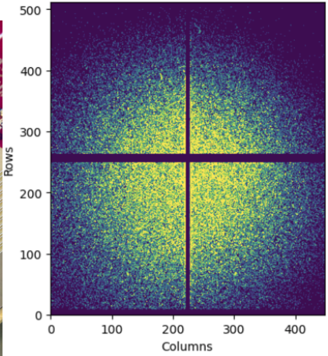
VeloPix ASIC

- VeloPix ASIC for Upgrade I developed in collaboration with the Medipix group.
- The Timepix4 is the next generation, with already impressive fast timing at ~ 200 ps.
- Can the next-to-next generation (Picopix?) get us to $20 \rightarrow 50$ ps?
- Other requirements (i.e. data rates) on the chip also extremely demanding.

Timepix4 has arrived!



Fe_{14} Source (5.9 keV)

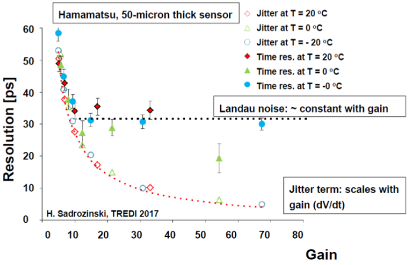


Sensors

Will require a very fast ($\sigma \sim 10 \to 50\,\text{ps}$) sensor as well as readout ASIC. Some possibilities:

Low Gain Avalanche Detectors (LGADs)

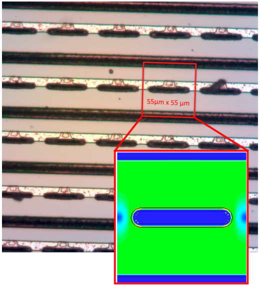
- ▷ Excellent time resolution.



- ▷ But low fill factors for small pixels.
- ▷ And probably not radiation hard enough.
- ▷ R&D ongoing to see if these factors can be overcome.

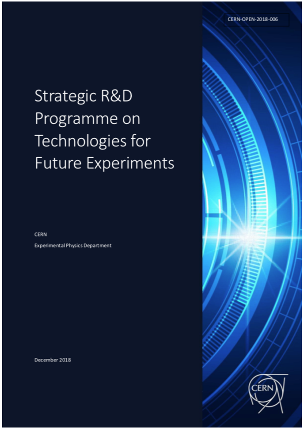
3D sensors

- ▷ 3D sensors optimised for timing measurements by the TimeSpot collaboration.



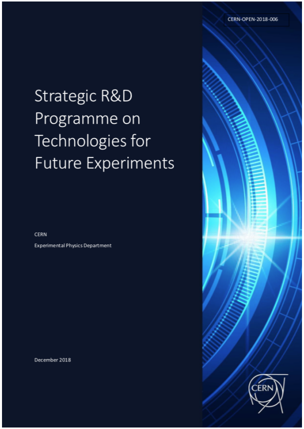
- ▷ Also excellent timing resolution ($\sim 15\,\text{ps}$) demonstrated.
- ▷ But also has inactive areas → can detector design mitigate their impact?

CERN EP R&D



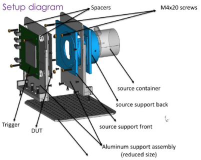
- General interest for fast-timing detectors from CERN for next generation experiments, FCC, BDF, ...
- One of the 11 WPs for CERN detector R&D dedicated to novel hybrid silicon detectors (WP1.1)

CERN EP R&D

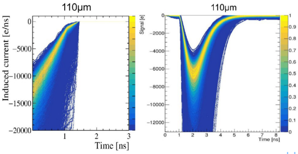


- General interest for fast-timing detectors from CERN for next generation experiments, FCC, BDF, ...
- One of the 11 WPs for CERN detector R&D dedicated to novel hybrid silicon detectors (WP1.1)
- Example activities include building test bench β sources and weighting-field simulation.

Upgrade of the beta source **[V. Gkougkousis]**

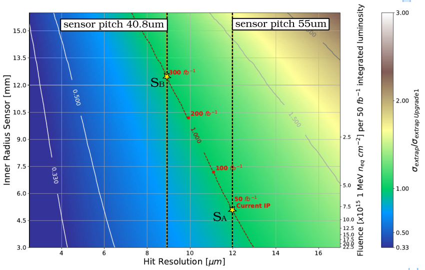


Signal generation simulation **[M. Halvorsen]**
(Garfield++ / amplifier transfer function)



Mechanical Design and Radiation Damage

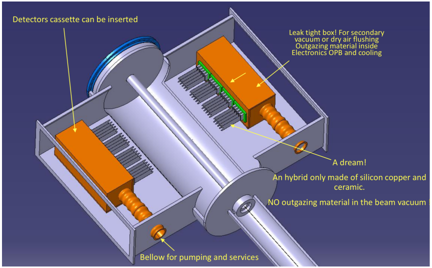
- The radiation damage at the inner edge of the detector is enormous, $\sim 10^{16}\,1\,\text{MeV}\,n_{\text{eq}}/\text{cm}^2$ every year of operation.
- This is about the fluence where planar sensors are basically useless. Will the detector need to be replaced regularly or is there another option?
- Fluence varies strongly as a function of the distance to the luminous region. Could the detector be moved further away?
- Why is the VELO so close to the interaction region in the first place? → driven by impact parameter resolution.
- So, can we optimise the other detector parameters (hit resolution, material) to maintain the performance but at lower fluence?



- Yes: Moving to $\sim 12\,\text{mm}$ we get the same integrated fluence as U-I.
- **But:** would need to drastically reduce the material (the RF foil, but also the modules) and reduce the pixel pitch to $\sim 40\,\mu\text{m}$ from $55\,\mu\text{m}$.

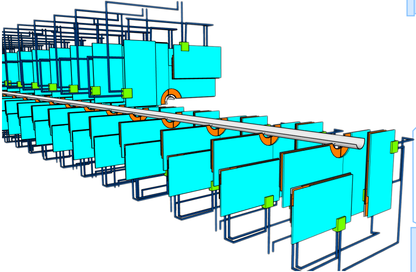
Mechanics

Replaceable detectors to deal with extreme integrated fluence?



Detector cassettes that can be swapped during technical stops?

RF foil separates detector from LHC primary vacuum Can it be simplified? Thinned? Removed entirely?

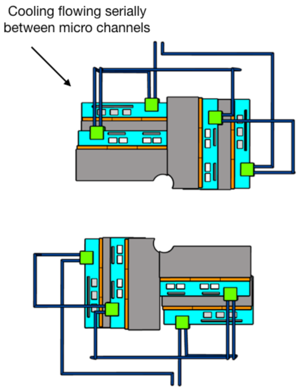


Once concept: Support a very thin ($\sim 20\,\mu$m) foil using the modules themselves.

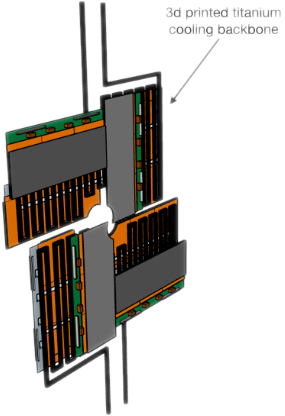
Cooling

Different ideas for providing cooling to the modules

- ▷ Modules must be kept cold to prevent thermal runaway caused by leakage current after sensors are irradiated.
- ▷ Upgrade I uses biphase CO_2 cooling, provided by silicon microchannel plates. Should we do something different for Upgrade-II?



- ▷ Much smaller microchannel plates to mitigate cost?



- ▷ 3D printed titanium pipes would be cheaper and more flexible.

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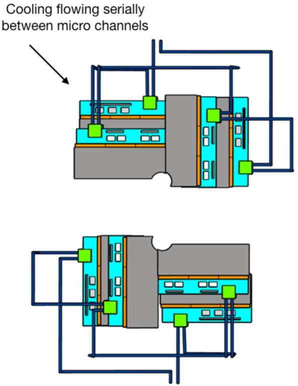

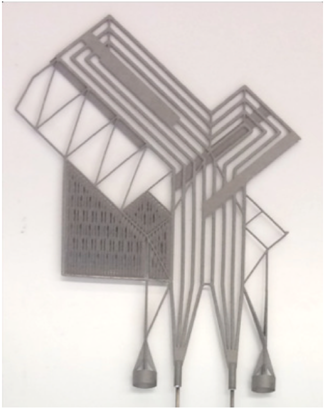

- ▷ Much smaller microchannel plates to mitigate cost?
- ▷ 3D printed titanium pipes would be cheaper and more flexible.
- ▷ Already prototyped for Upgrade-I.

Conclusions

- Precise timing in the VELO will be essential to maintain (or improve!) physics performance with pileup of ~ 50.
- Radiation environment for the detector will be extremely challenging, but several different strategies to deal with this on the table.
- Much work to be done on the ASIC design, but the path forward is clear.
- Lots of different ideas for how to achieve sensors with sufficient time resolution.
- The mechanical design and cooling are also crucial, particularly if detector will have to be replaced multiple times.
- No specific choices of technlogies are ruled in or out.