



The LHCb Upgrade and the VELO

**THE 15th
VIENNA CONFERENCE
ON INSTRUMENTATION**
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On behalf of the LHCb
collaboration



Contents

- ▶ **The LHCb Upgrade Programme**
- ▶ **The VELO sub-detector**
 - ▶ **VELO Upgrade I**
 - ▶ Tiles
 - ▶ Cooling
 - ▶ Mechanics
 - ▶ **Upgrade II - VELO perspective**



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The LHCb Upgrade I

Indirect search strategies for New Physics e.g. precise measurements & the study of suppressed processes in the flavour sector become ever-more attractive; current LHC experience is that direct signals are elusive.

Our knowledge of flavour physics has advanced spectacularly thanks to LHCb. Maintaining this rate of progress beyond Run 2 requires significant changes

The LHCb Upgrade

- 1) Full Software trigger
 - Removal of current 1 MHz bottleneck
 - Allows effective operation at higher luminosity
 - Improved efficiency in hadronic modes
- 2) Raise operational luminosity to $2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
 - Necessitates redesign of several sub-detectors and overhaul of readout

Huge increase in precision, in many cases to the theoretical limit, and the ability to perform studies beyond the reach of the current detector



Flexible trigger and unique acceptance opens up opportunities in topics apart from flavour → a general purpose detector in the forward region

Upgrade I detector challenges

image from LHCb twitter
@LHCbExperiment

Maintain Physics Performance in very high occupancy and pile up conditions

- combinatorial complexity and fake tracks
- Pile-up energy
- mitigated by **granularity**, **high readout speed** and **trigger** innovations (**timing** will be for Upgrade II)

Operate with detector elements exposed to very high radiation doses

- **Radiation hardness** needed for all subdetectors

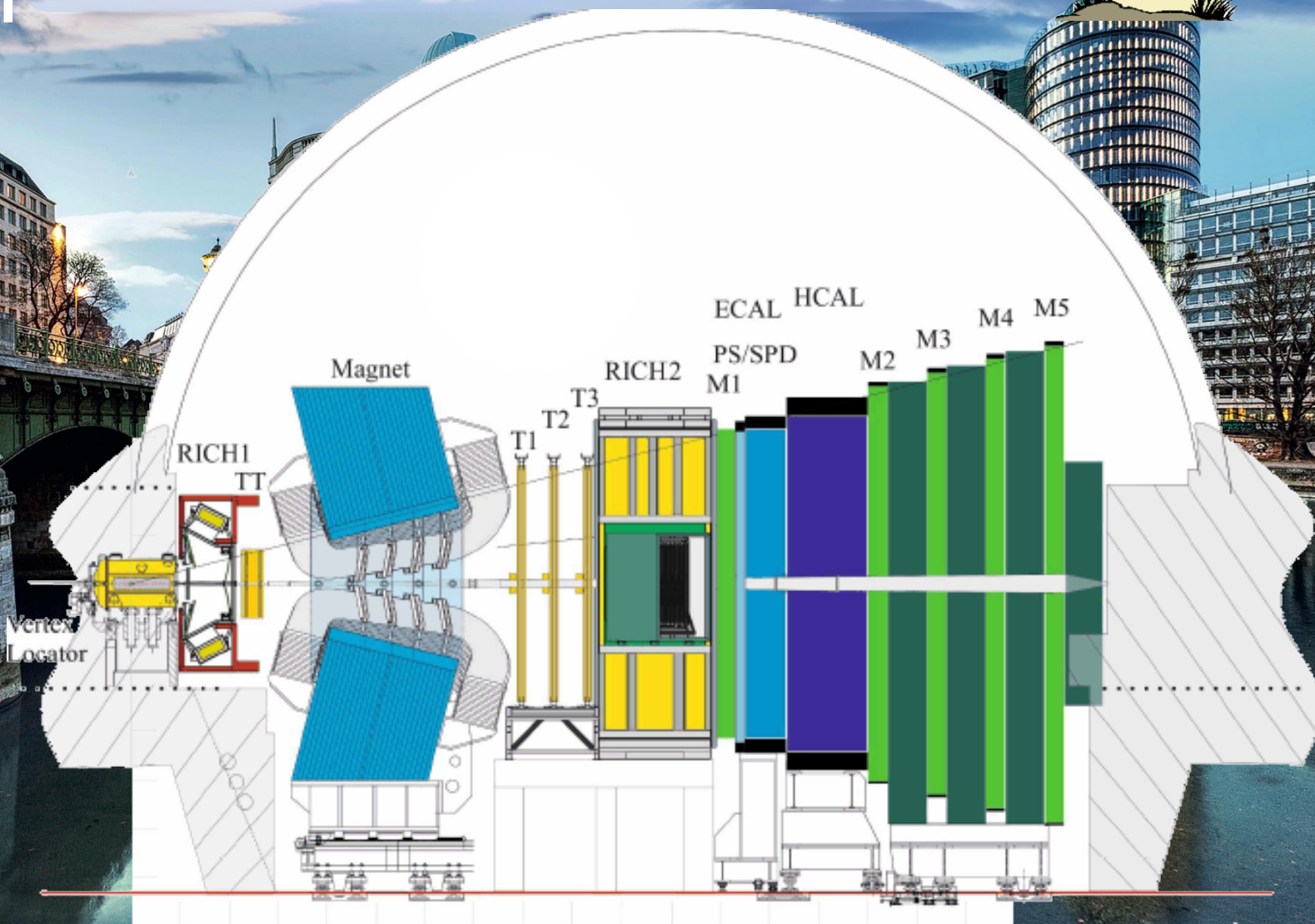
Control Systematics to match statistics

- **low material budget** hence creative solutions needed at mechanics level; support structures, cooling, power delivery, and **thin detectors** for innermost regions
- **Cope with tremendous DAQ and data processing challenges**

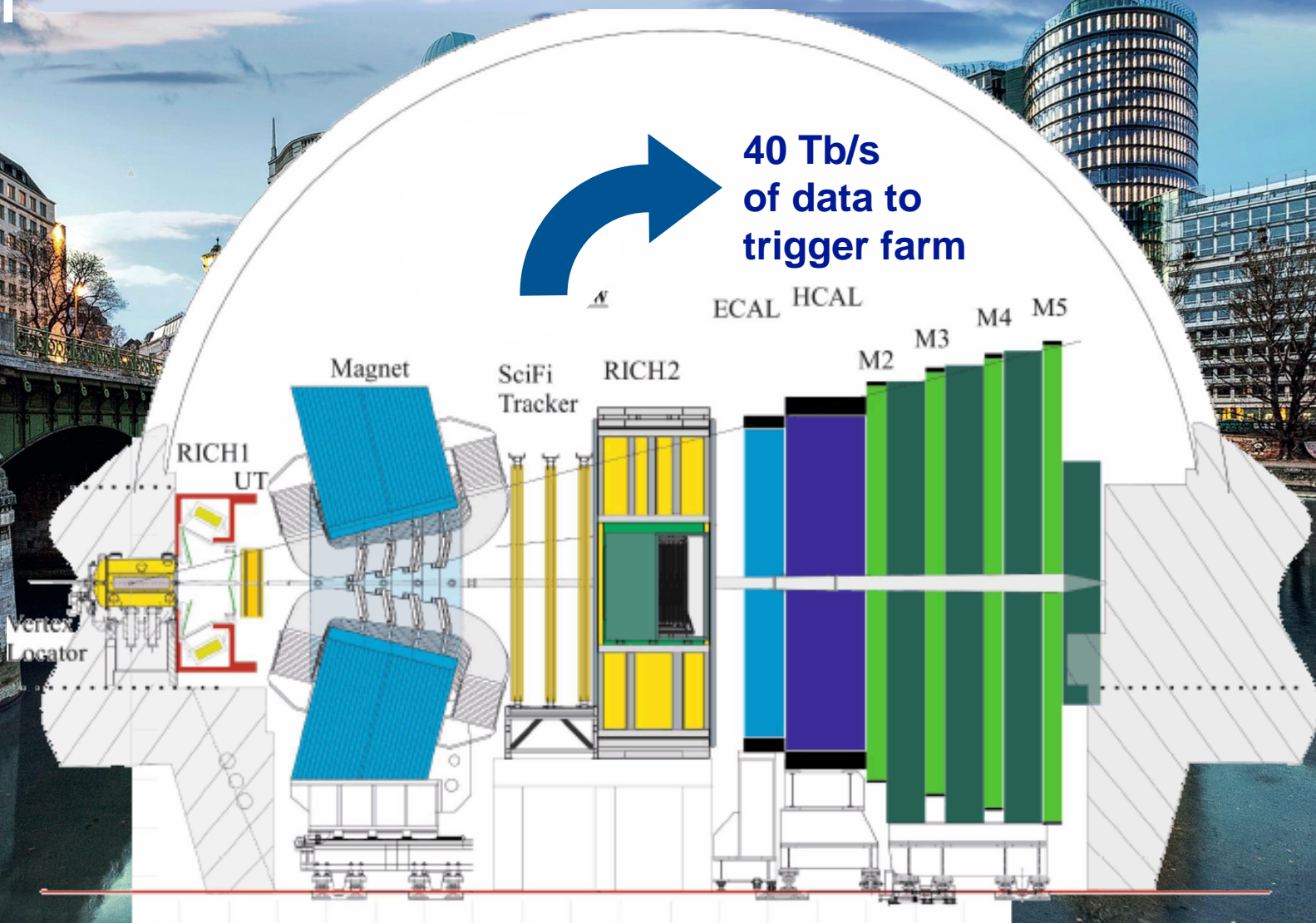
image courtesy
Matthias Karacson
#indico 69667

Photo courtesy
Oscar Francisco
Wiktor Byczynski

Pre-Upgrade Detector



Upgrade I Detector



Required Modifications

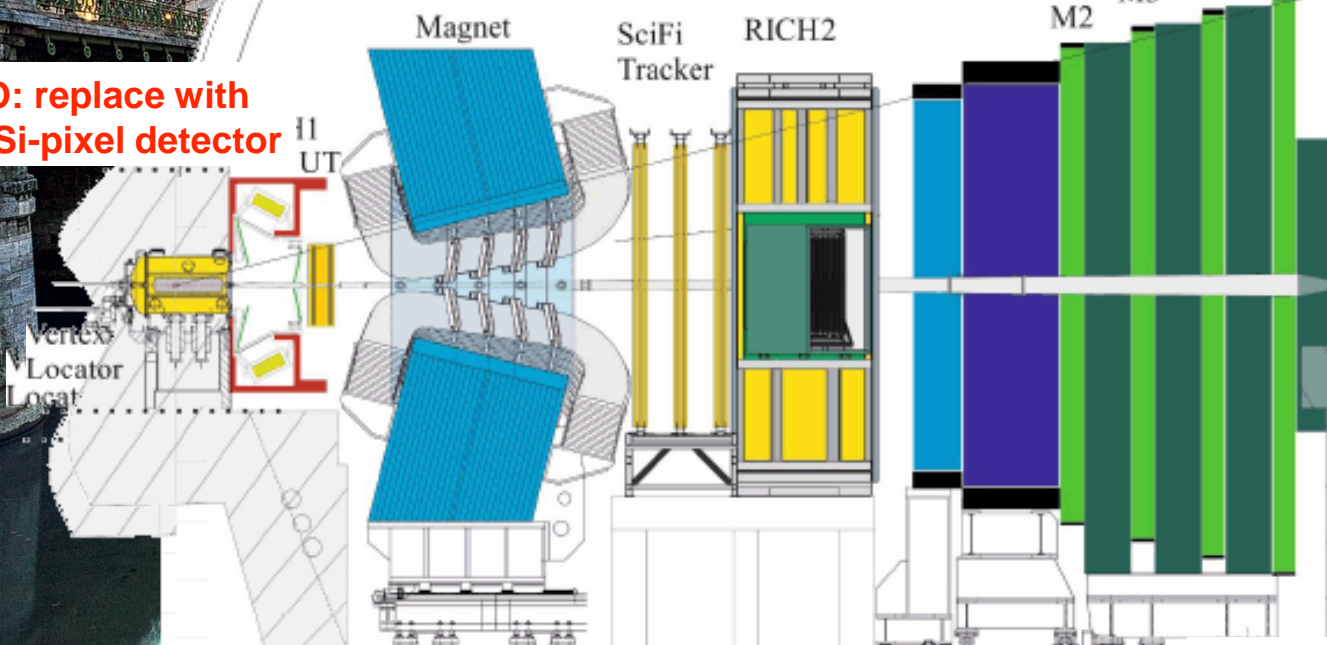
Full s/w trigger →
Replace read-out
boards and DAQ

TT: replace with
new Si-strip detector

OT and IT: replace with
scintillating fibre
(Sci-Fi) tracker

Calo system:
replace FE electronics
and remove PS/SPD

VELO: replace with
new Si-pixel detector



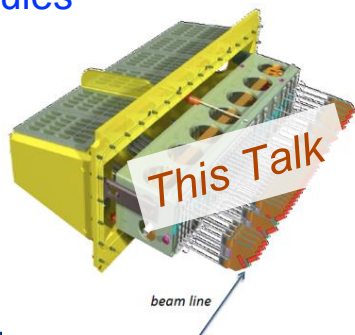
RICH: new photodetectors
and FE electronics, and modify
RICH1 optics and mechanics

Muon system:
replace FE electronics
and remove M1

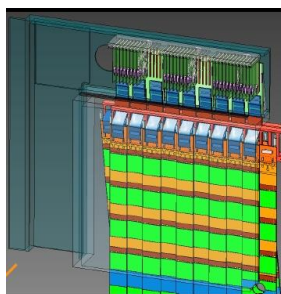
New Subdetector Elements

Tracking

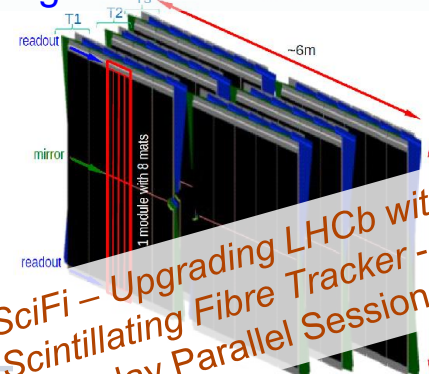
VELO: 52 hybrid pixel modules



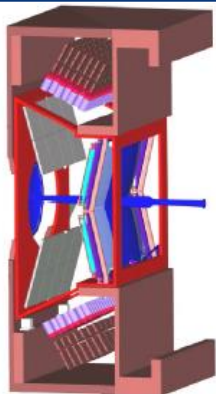
UT: 4 planes of Si microstrip detectors: ~1000 sensors



SciFi: 128 modules ($0.5 \times 5 \text{ m}^2$) arranged in 3 stations \times 4 layers



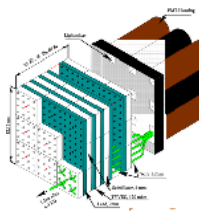
CALO and PID



RICH system:

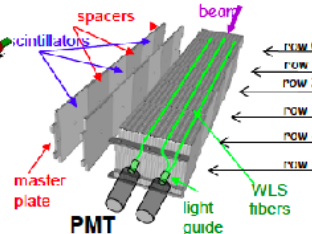
Redesigned mechanics to cope with increased occupancy; new MaPMTs and readout electronics

ECAL



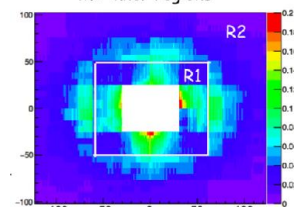
New FE electronics and PMTs adjusted to high occupancy: preshower removed

HCAL



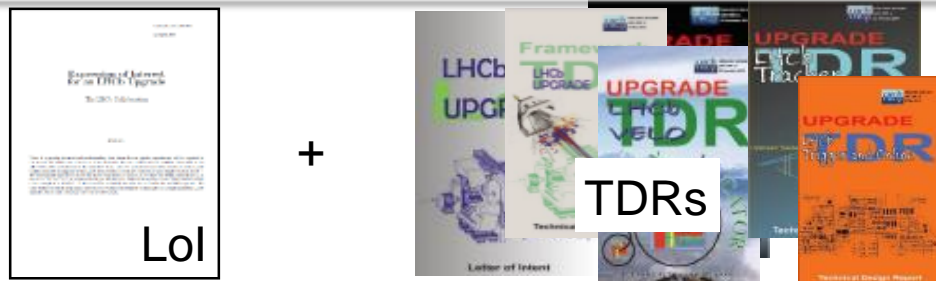
Muon

$\mu\pi$ inner regions



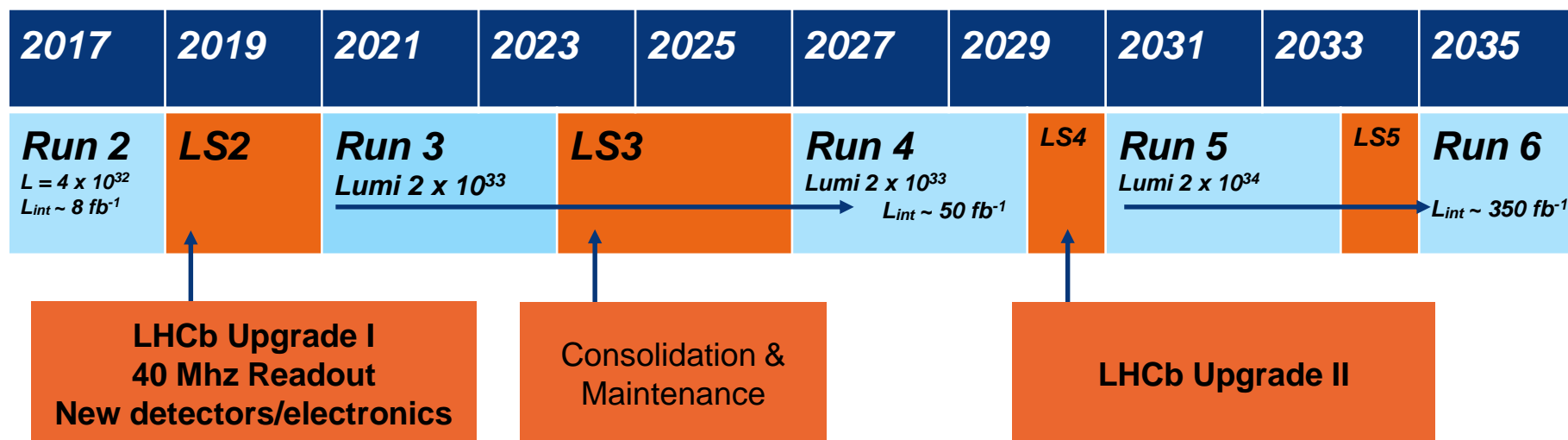
MWPCs kept; new FE electronics for increased granularity; PAD detectors for inner regions

Timeline

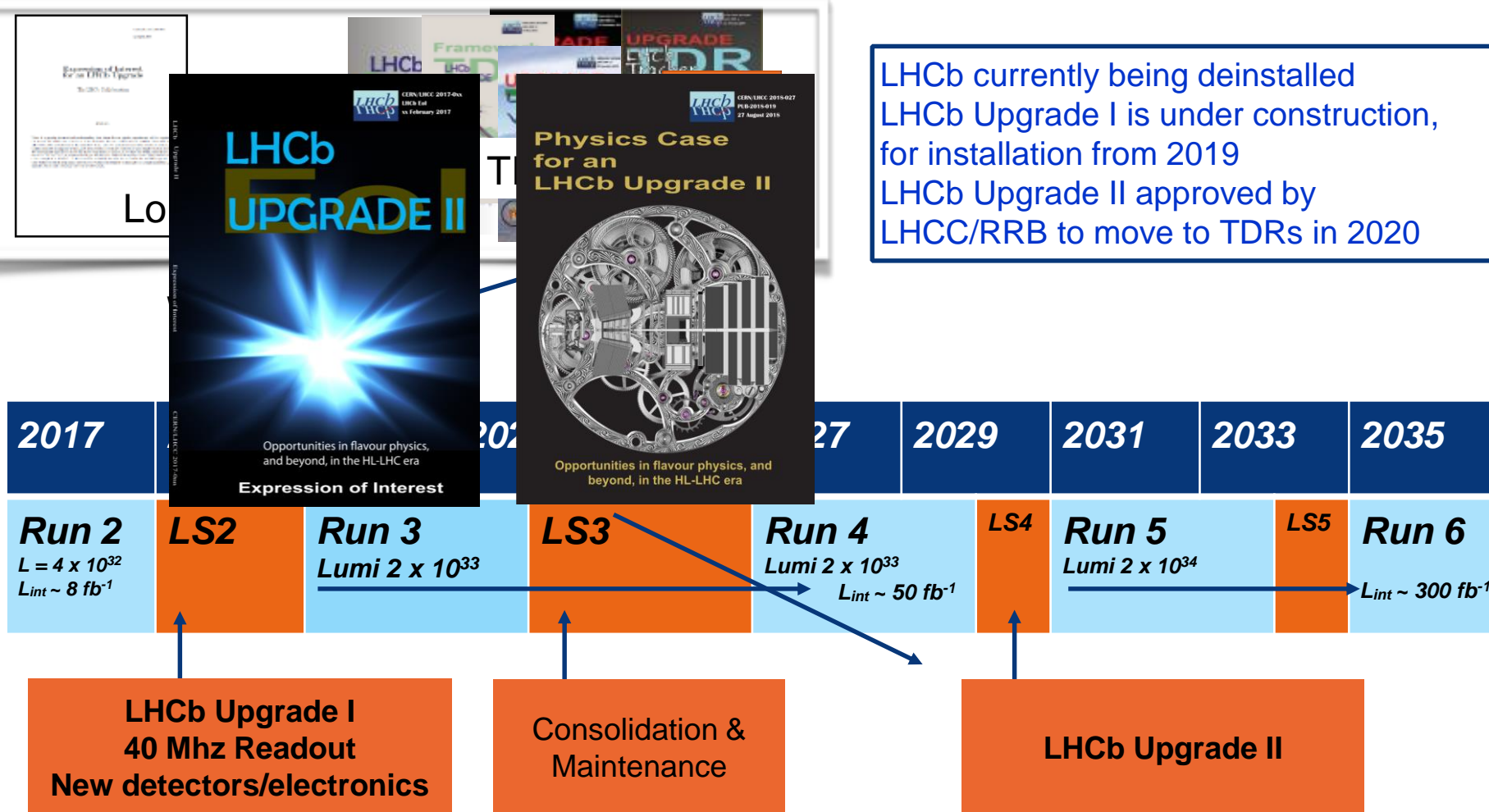


LHCb currently being deinstalled
LHCb Upgrade I is under construction,
for installation from 2019

We are here



Timeline





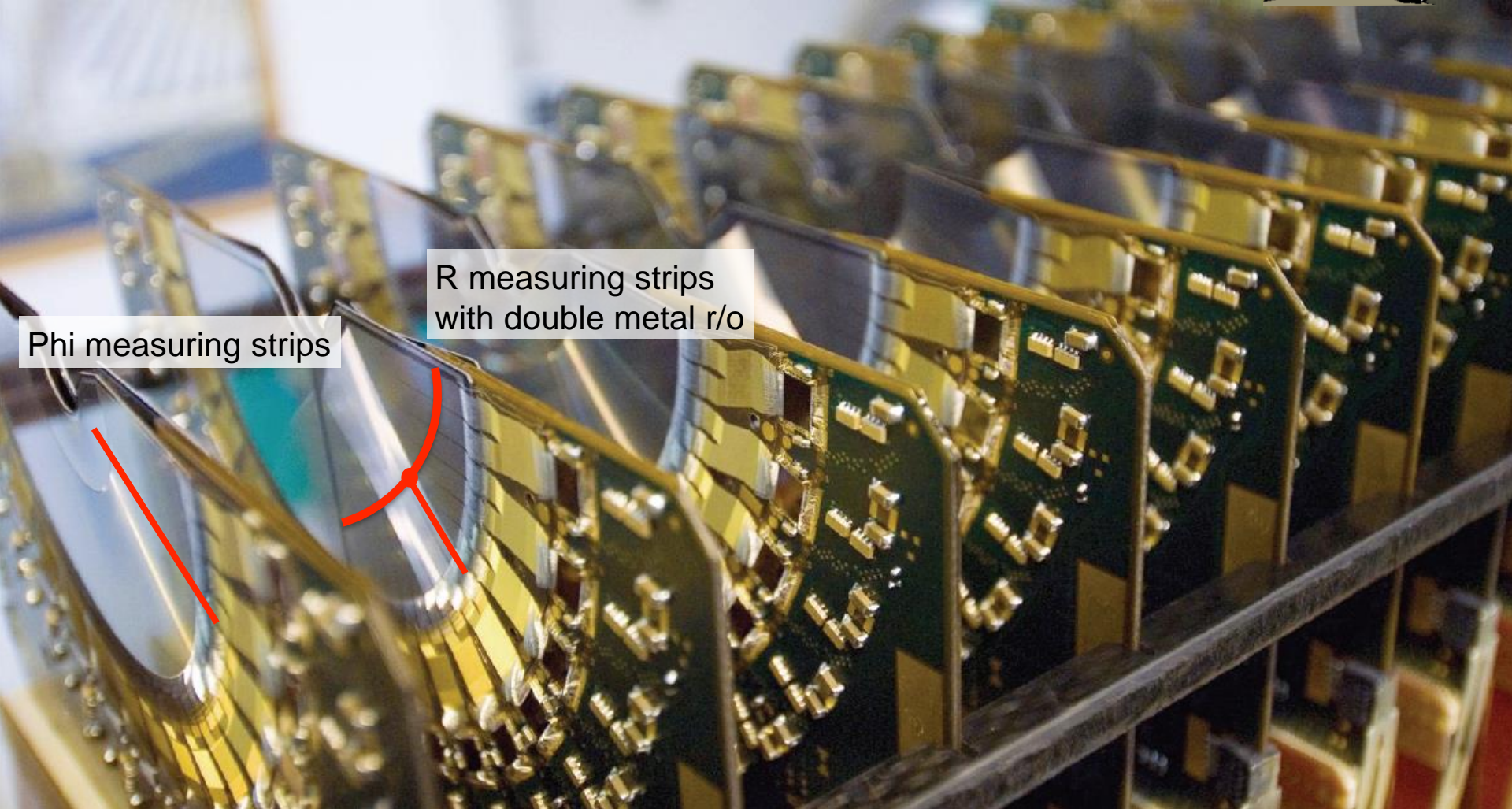
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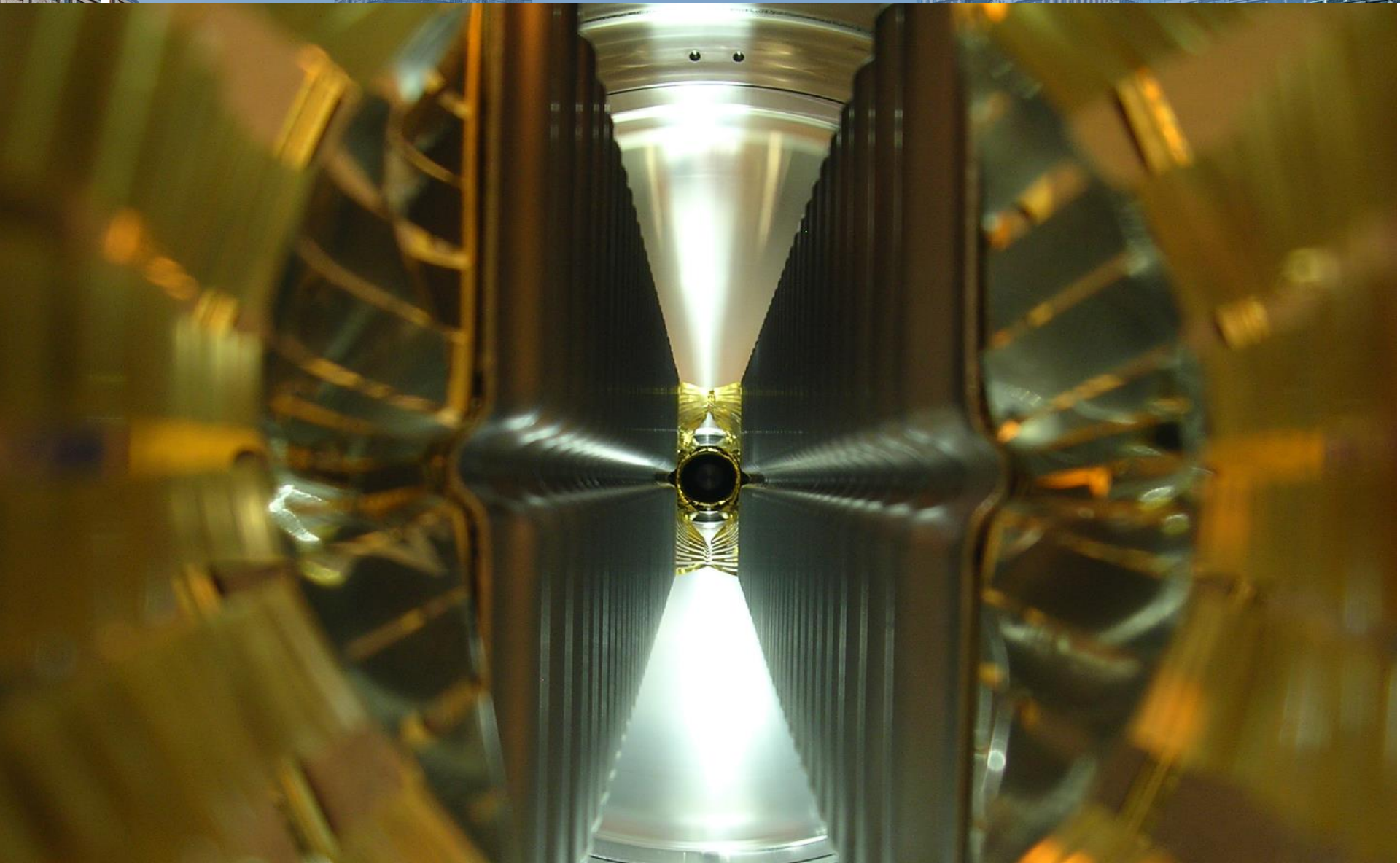
The LHCb Vertex Locator (VELO)



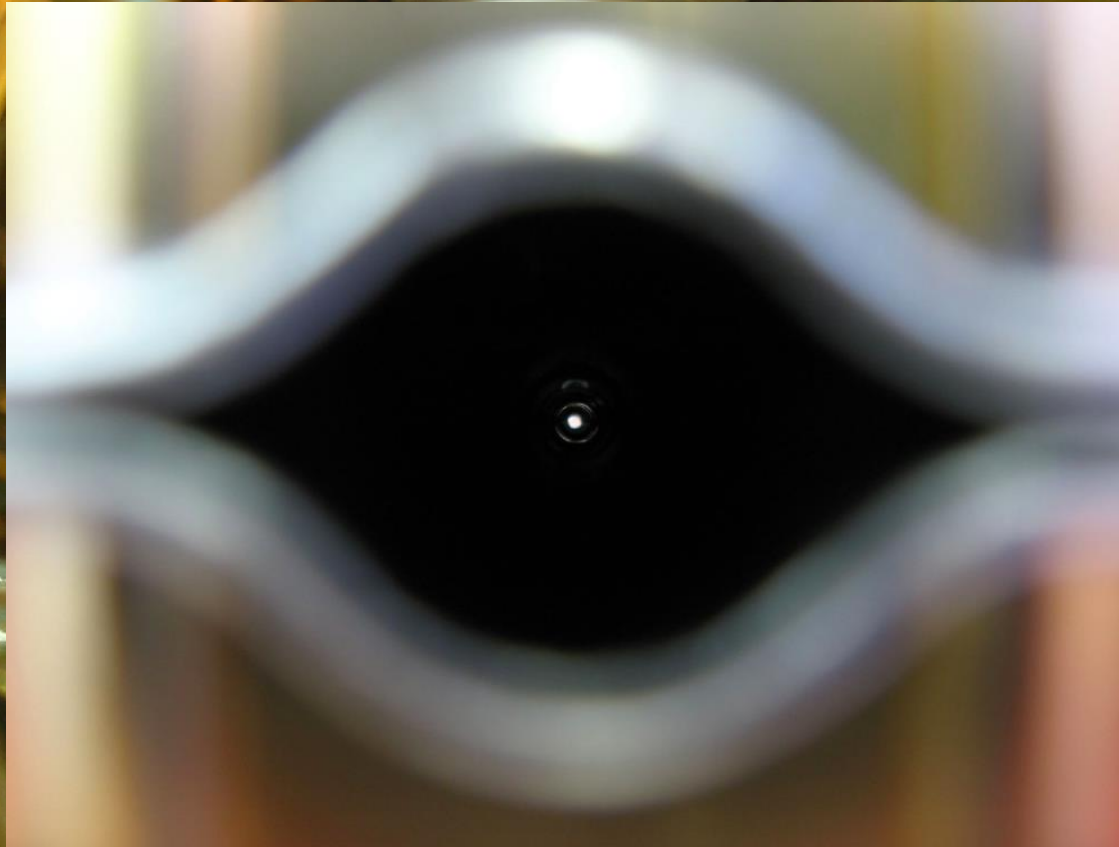
The LHCb Vertex Locator (VELO)



Placed around the LHC beams



Placed around the LHC beams



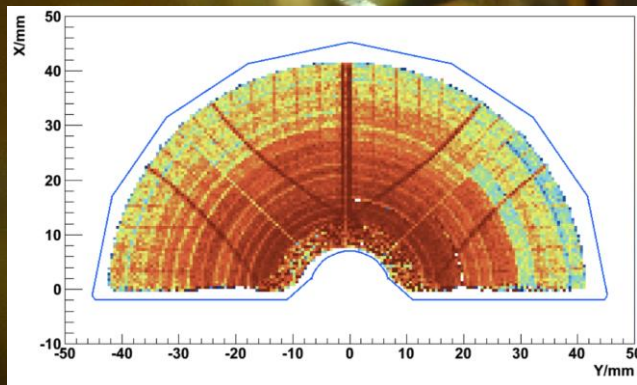
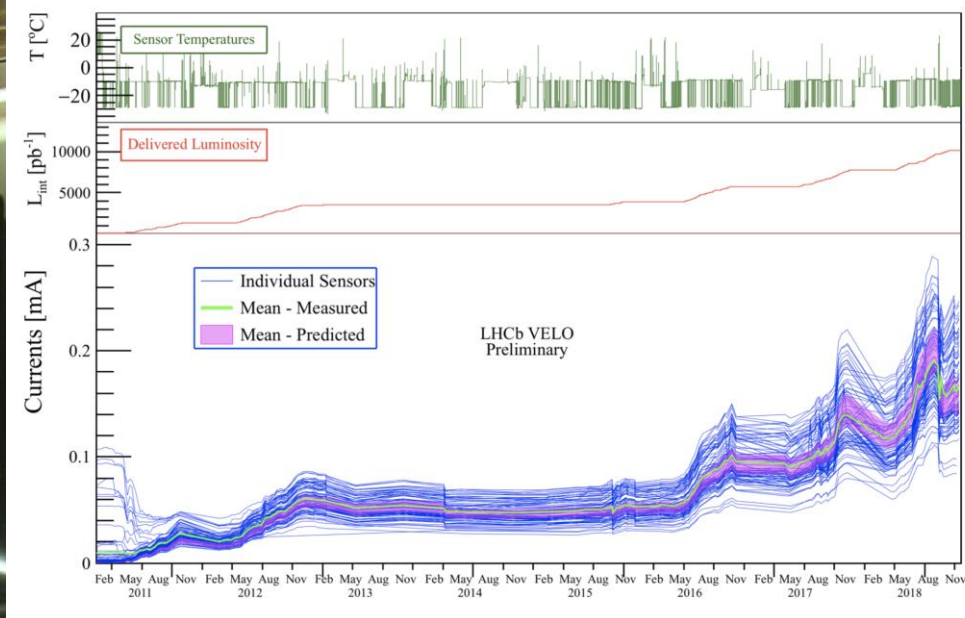
Placed around the LHC beams



And receiving a radiation damage hit

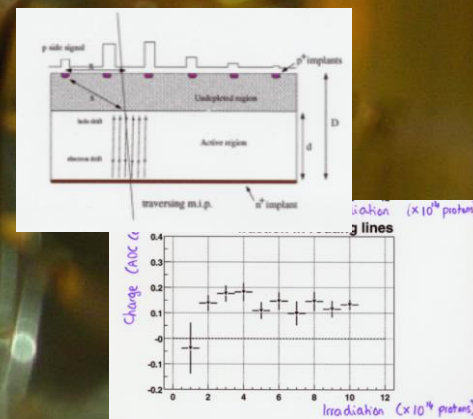
Detector has accumulated fluence of approximately $7 \times 10^{14} \text{ 1 MeV n}_{\text{eq}}/\text{cm}^2$

- Leakage currents and depletion voltages have followed expectations
- Detector has been operated and maintained below -7°C ; underwent **deliberate annealing warm up** at end of lifetime



Charge loss experienced to double metal layer

As predicted at VCI 2001!





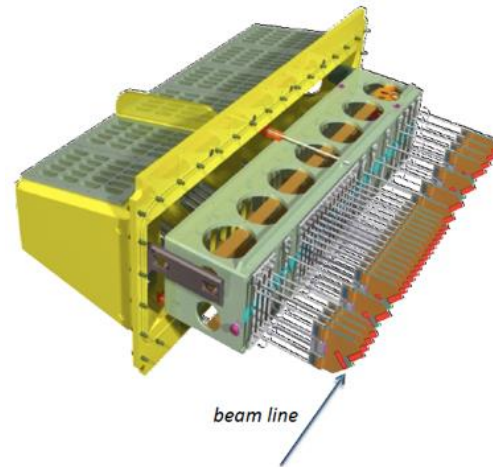
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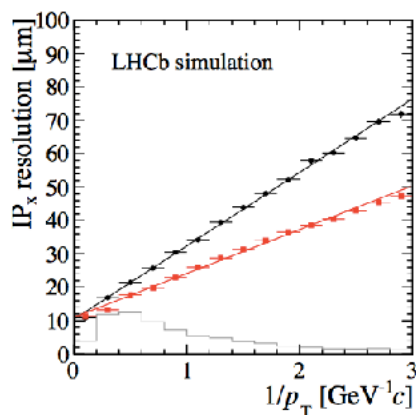
VELO Upgrade I



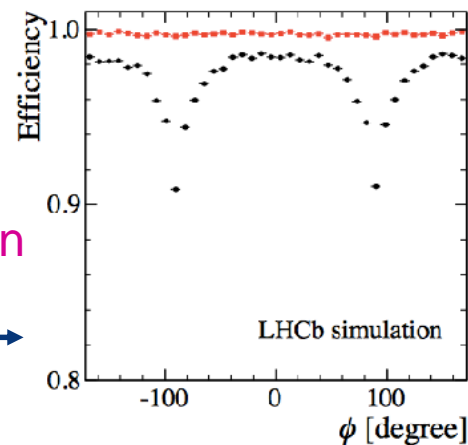
rows of silicon microstrip modules



rows of silicon hybrid pixel modules



Pixel design with
micro-channel cooling
superior to **strips** for
impact parameter resolution
and
efficiency



VELO Upgrade Sensors and ASICs

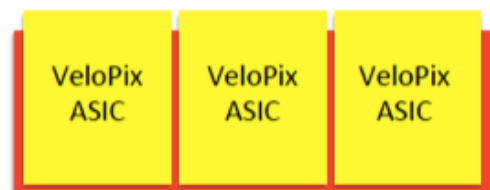
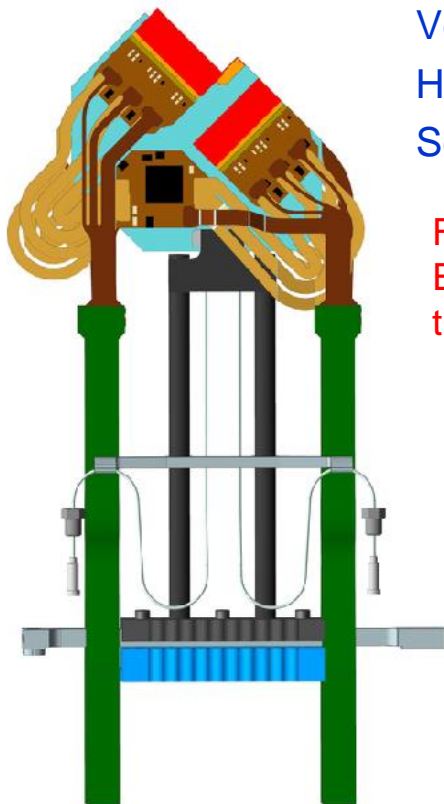
Challenges:

Very high ($8 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ for 50 fb^{-1}) & non-uniform irradiation ($\sim r^{-2.1}$)

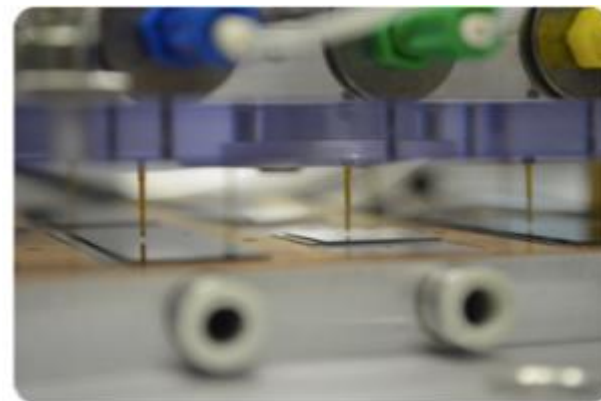
Huge data bandwidth: up to 20 Gbit/s for central ASICs and $\sim 3 \text{ Tbit/s}$ in total

Sensor temperature must be maintained $< -20^\circ\text{C}$ with lightweight cooling

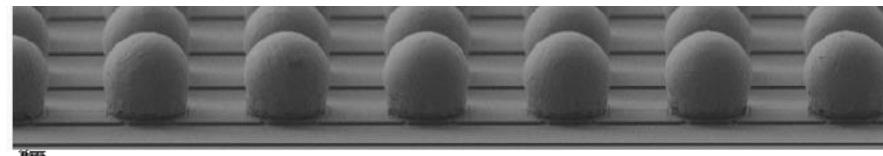
Four sensors per double sided module.
Each sensor ($43 \times 15 \text{ mm}$) bonded to
three VeloPix ASICs



Elongated pixels between
sensors for complete coverage



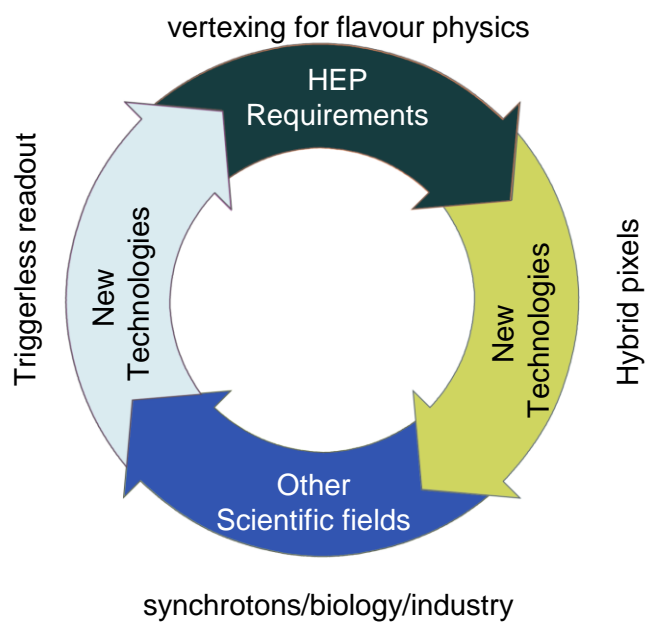
Sensors are bump bonded and characterised on an automatic probe setup. They are then ramped to 1000V in vacuum via spring loaded needle contacts to ASIC backplane



SEM image of $55 \mu\text{m}$ pitch SgAn bumps
courtesy Sami Vähänen,
ADVACAM Oy

The VeloPix ASIC

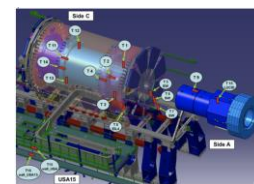
Developed together with the Medipix collaboration



Medipix, Timepix,
VeloPix family of
ASICs used in
HEP and beyond



Timepix3 telescope
> 5 MHz of <350 ps,
<2 μ m resolution tracks



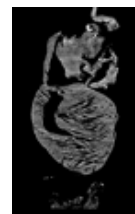
ATLAS radiation
monitoring



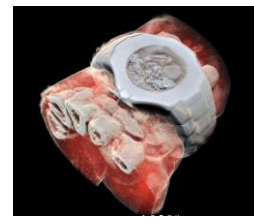
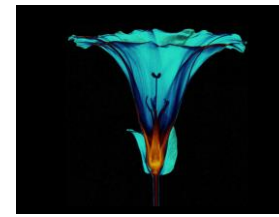
Space Dosimetry



X ray histology



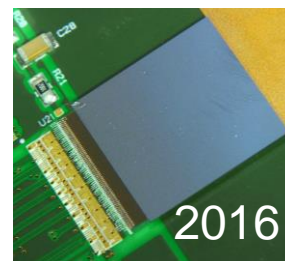
Imaging at low threshold



Spectral imaging

VeloPix characteristics include:

- Triggerless, Data driven readout
- Radiation hardness to 400 MRad
- SEU/SEL tolerance
- Readout out 800 Mhits/s/ASIC



2016



2019: Fully produced for LHCb,
70% of tiles completed

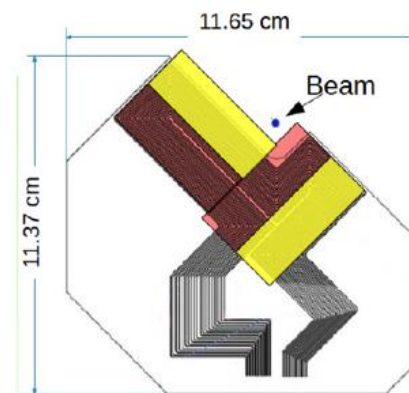
VELO Upgrade Cooling

Due to the harsh radiation environment an efficient cooling solution is required to maintain the sensors at $< -20^{\circ}\text{C}$

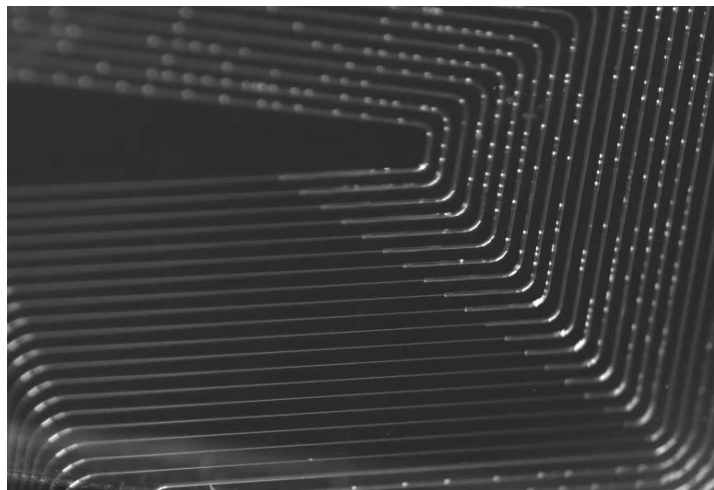
This is provided by the novel technique of evaporative CO_2 circulating in $120\text{ }\mu\text{m} \times 200\text{ }\mu\text{m}$ channels within a silicon substrate.

Total thickness: $500\text{ }\mu\text{m}$

- High thermal efficiency
- CTE match to silicon components
- Minimum and uniform material
- radiation hard



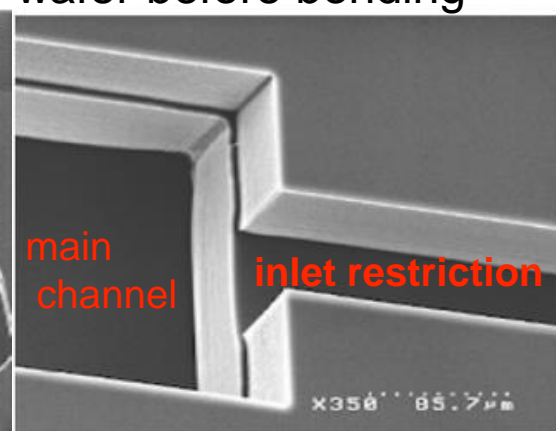
SEM images of etched wafer before bonding



(click for movie)



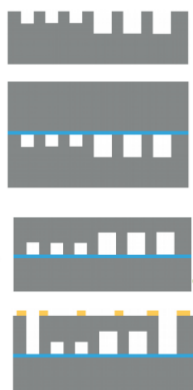
channels output directly
to connector



Two step channel
etching

VELO Upgrade Cooling

Manufacture



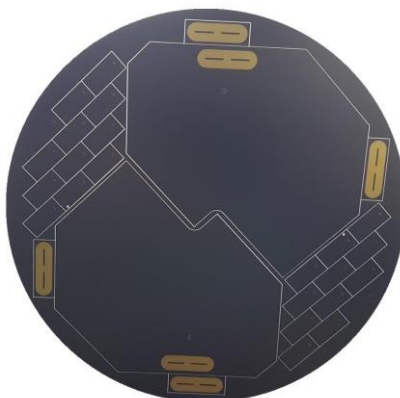
Channel etching

Cap wafer bonding

Thinning (both sides)

Inlet/Outlet etching

8" wafer



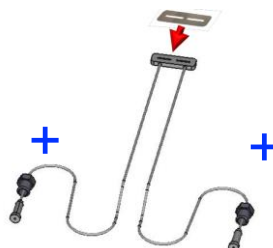
Production ongoing, 40% pre-series in hand, A grade delivery weeks away

Assembly

Silicon pre-tinning

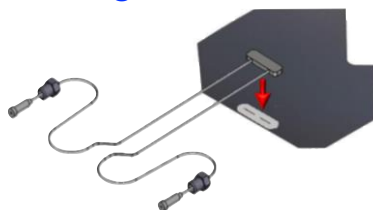


+



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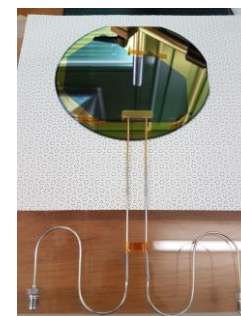
Alignment



+



=



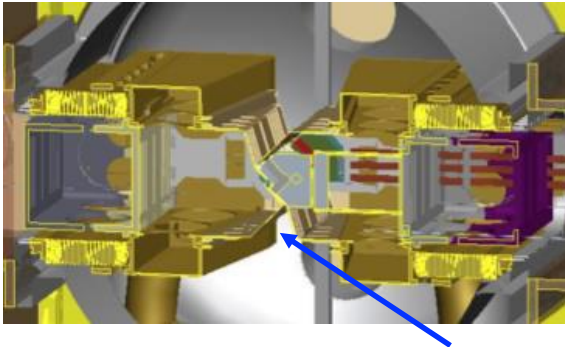
Connector pre-tinning

Soldering

Final assembly
Can withstand 200 bar

VELO Upgrade RF Foil

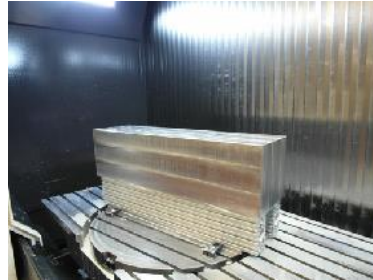
RF foil: some production steps



The VELO is separated from the primary vacuum by the 1.1 m long thin walled “RF foil” which also shields the detector and guides the beam wakefields

At just 3.5 mm clearance from the beam and 900 μm clearance from the sensors, production represents a huge technical achievement

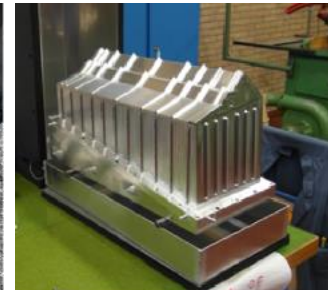
The final foil withstands 10 mbar pressure variations, is leak tight, and has a final thickness of 250 μm , with an option to go to 150 μm maintained



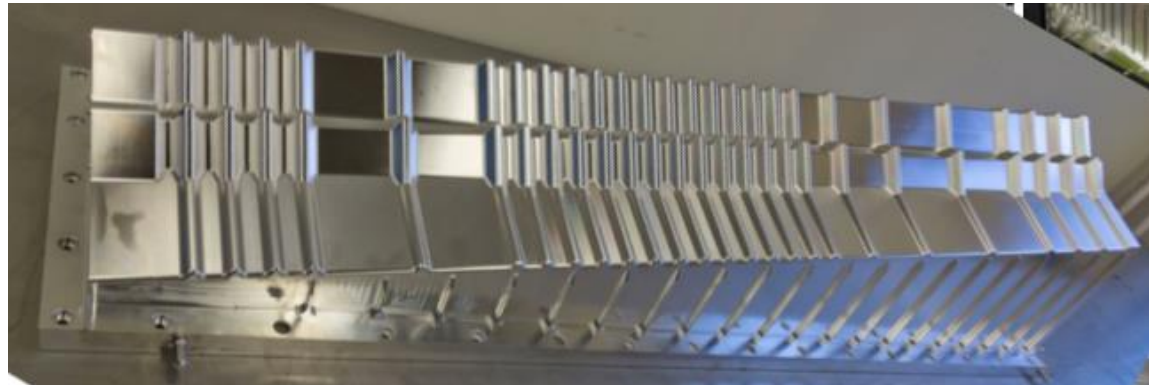
Initial solid forged Al alloy block



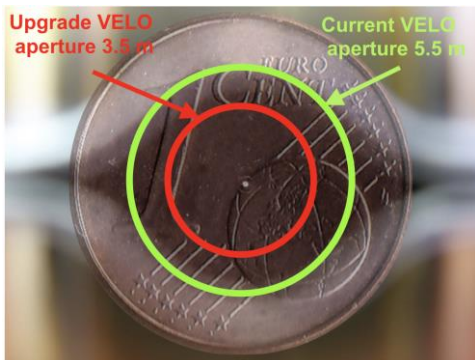
>98% of material removed



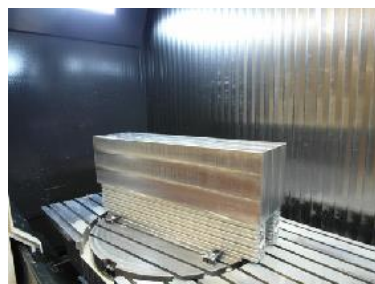
Internal mould support during machining steps



VELO Upgrade RF Foil



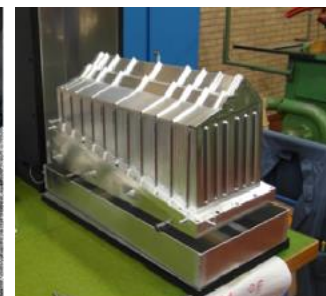
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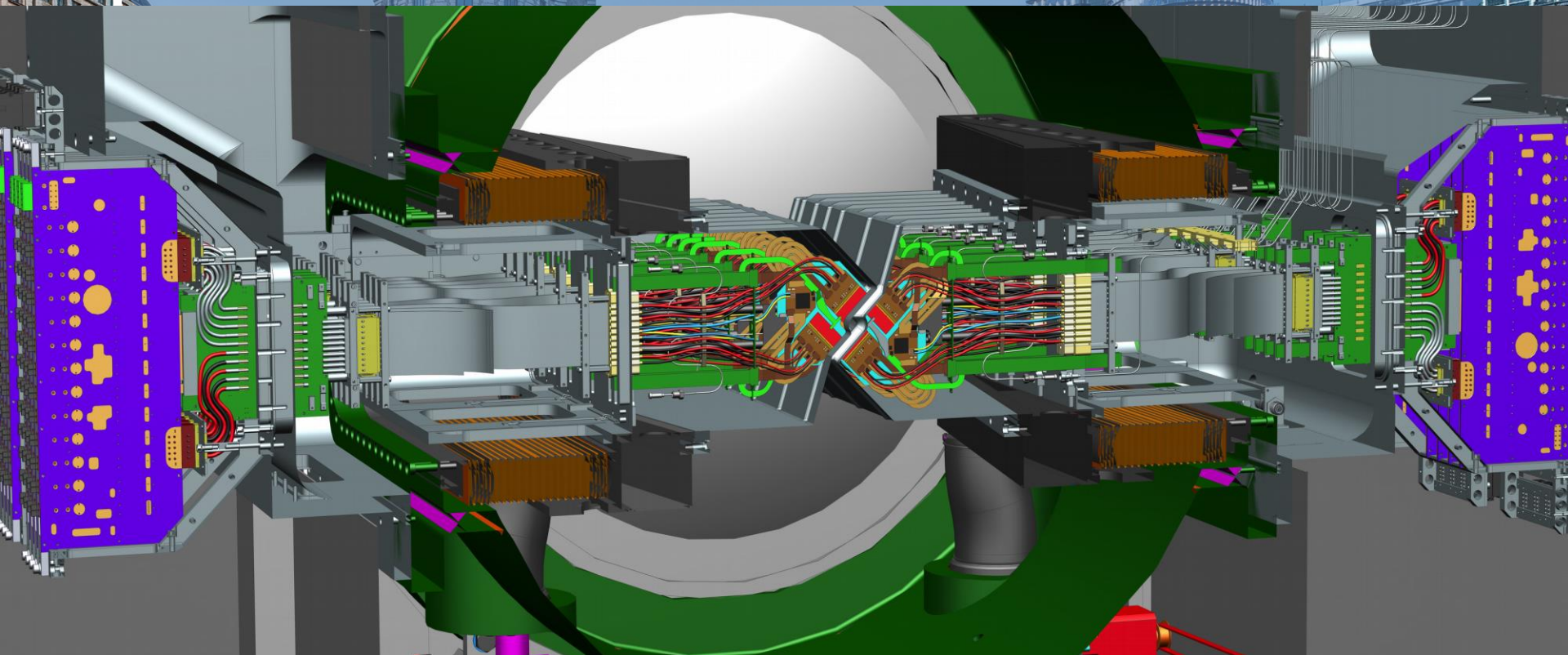
At just 3.5 mm clearance from the beam and 900 μm clearance from the sensors, production represents a huge technical achievement

The final foil withstands 10 mbar pressure variations, is leak tight, and has a final thickness of 250 μm , with an option to go to 150 μm maintained

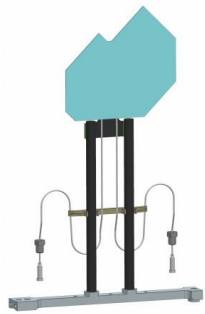


First pair of boxes produced, spares started, R&D on pilot box ongoing

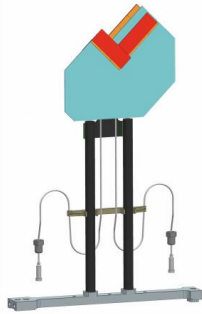
VELO Upgrade Assembly



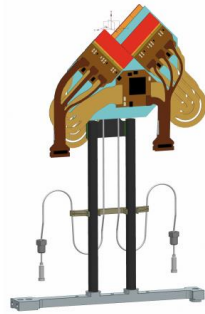
VELO Upgrade Assembly and first slice



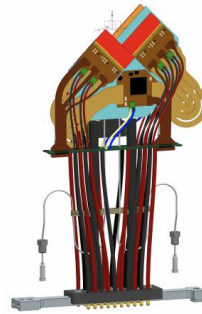
Mechanical Construction



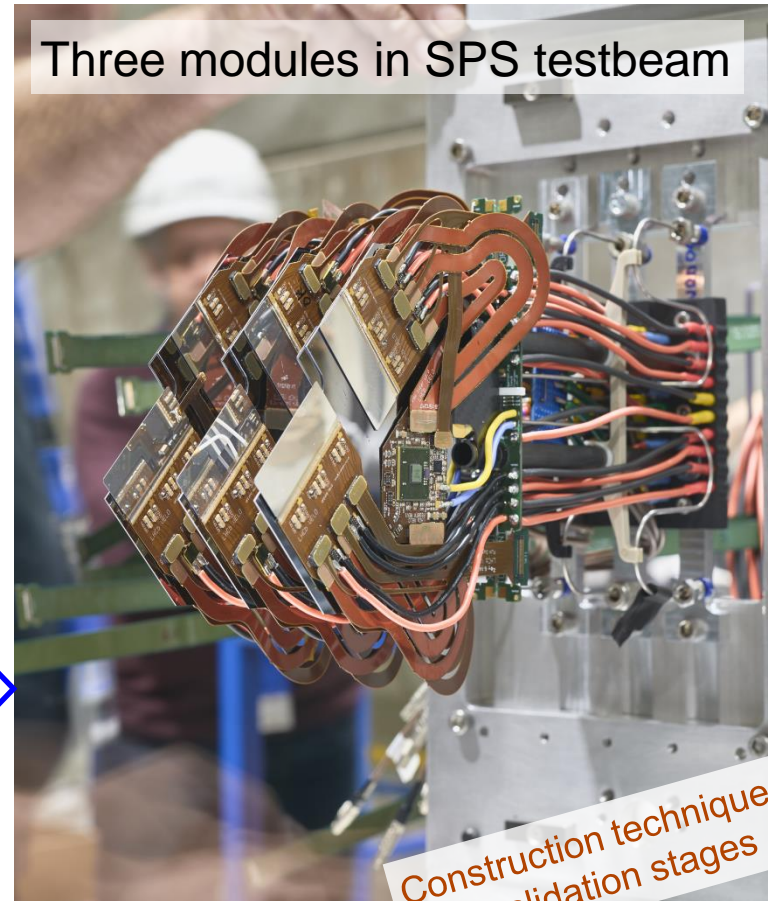
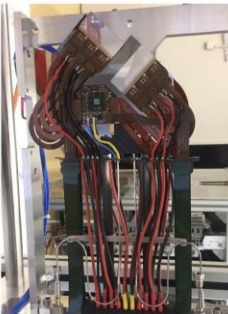
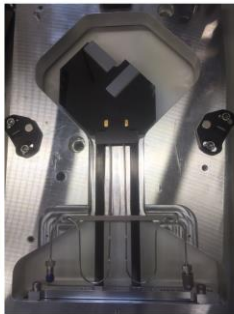
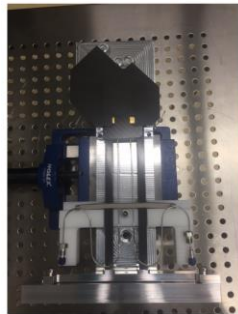
Precision tile placement to 10 μm



Flex circuit placement



wire bonding and HV/LV/data cable attachment



Three modules in SPS testbeam

Construction techniques in final validation stages



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LHCb Upgrade II - VELO Perspective

- Likely machine parameters for Phase II upgrade: Pileup ~ 42 , $L_{\max}=1.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- Phase II Upgrade must deliver the same quality performance as Upgrade I, with:

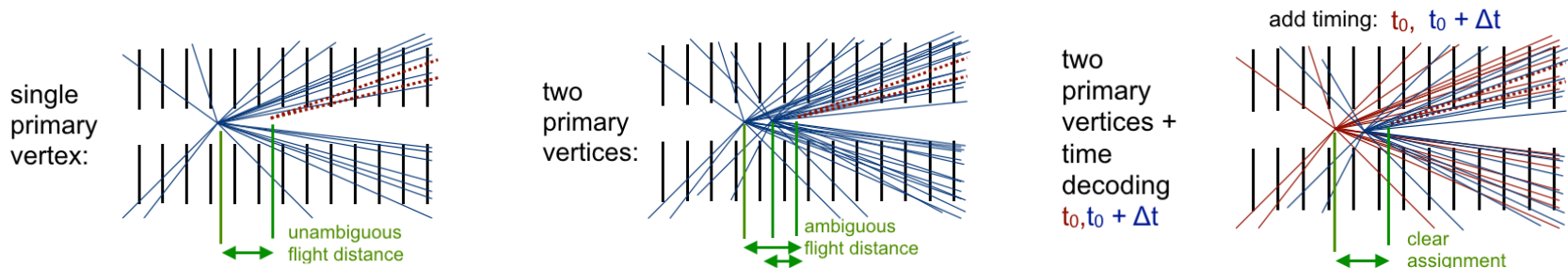
- 10 x higher particle multiplicity
- 10 x higher radiation damage
- 10 x higher data-out rates
- 10 x denser primary vertex environment

This is the intensity frontier!

Major hardware intervention mandatory to install new hybrid pixel detector which can address rates and integrated doses, and add functionality

Move towards 4D tracker concept with addition of timing:

- Real time track reconstruction critical for Upgrade I and II:
 - Timing information will contribute to Pattern Recognition speed and efficiency
- Track time stamping from expected $\langle 8 \rangle$ hits/track for PV association, PV timing, and combination with downstream detectors for beam gas and background control, calorimetry and time of flight



LHCb Upgrade II - VELO Perspective

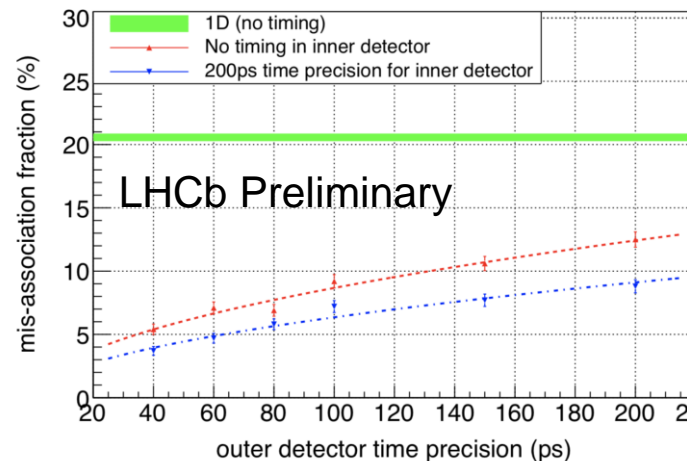
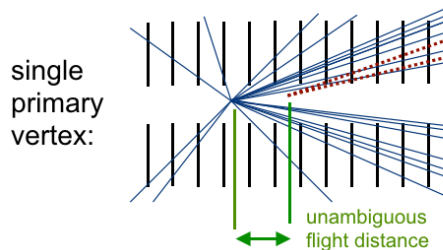
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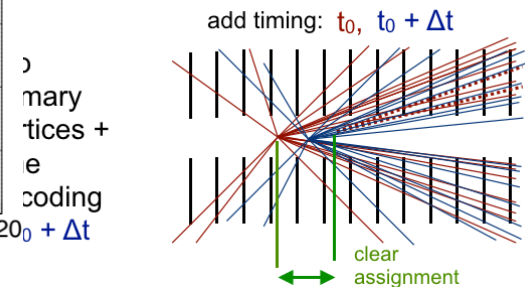
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Move towards 4D tracker concept with addition of timing:

- Real time track reconstruction with 4D information
 - Timing information
- Track time stamping from downstream detectors



and efficiency
on, PV timing, and combination with
imetry and time of flight



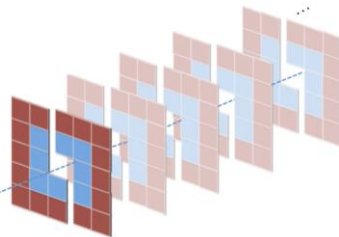
LHCb Upgrade II - VELO Perspective

Sensors and ASICs

	VeloPix (2016)	Timepix4 (2018/19)	Possible future Picopix? (2024?)
Technology	130 nm	65 nm	28 nm?
Pixel Size	55 x 55 μm	55 x 55 μm	55 x 55 μm ?
Pixel arrangement	3-side buttable 256 x 256	4-side buttable 512 x 448	4-side buttable 256 x 256?
Sensitive area	1.98 cm^2	6.94 cm^2	1.98 cm^2 ?
Event Packet	24 bit	64-bit	64-bit?
Max rate	~400 Mhits/ cm^2/s	178.8 Mhits/ cm^2/s	~4000 Mhits/ cm^2/s ?
Best time resolution	25 ns	~200ps	~20-50 ps?
Readout bandwidth	19.2 Gb/s	≤81.92 Gb/s	~500 Gb/s?

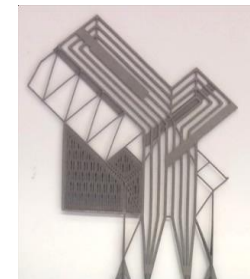
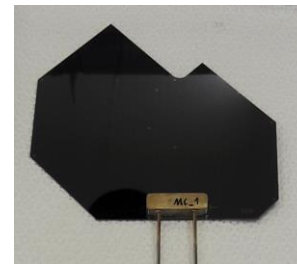
Fruitful collaboration with the Medipix group has yielded the VeloPix ASIC for the LHCb Upgrade I. A new generation chip, the Timepix4, with impressive fast timing capabilities is scheduled to appear soon. LHCb Upgrade II requirements more demanding still but could draw on similar concepts

Sensor R&D draws on existing thin planar, LGAD, 3D concepts. Timing, pixel size and radiation hardness requirements might have to be factorised with a dual technology solution.



Mechanics and Cooling

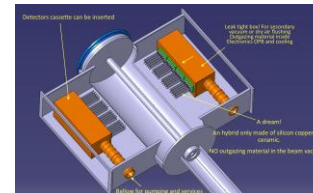
General needs: lightweight, possibly partially replaceable modules and mechanics



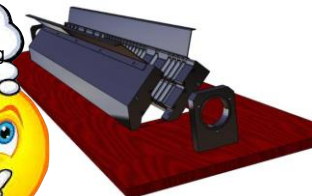
Bi-phase CO_2 circulating in silicon microchannels

3d printed Titanium substrates, already prototyped for Upgrade I

Foil to be thinned or removed, access to secondary vacuum simplified

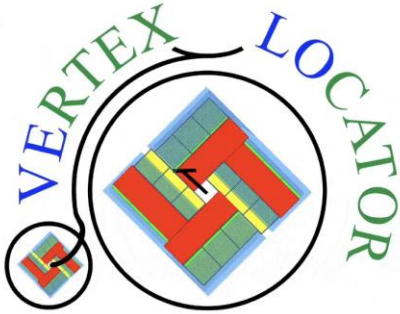


Possible sensor replacement mechanism



RF test stand for foil R&D

Conclusions



The Upgrade VELO is rolling!



Module construction and integration in 2019; aiming for installation in Q1 2020
LHCb Upgrade II scheduled for 2030: the design is starting.

Thank you for your attention

More Information and citations

VeloPix: A New Hybrid Pixel Readout Chip for the LHCb Upgrade

CERN EP-ESE electronics seminar <https://indico.cern.ch/event/580516/>

Medipix: Pixel Detectors for Medical Imaging and Other Applications

EPS-HEP <https://indico.cern.ch/event/466934/contributions/2524825/>

Design and Production Challenges for the LHCb VELO Upgrade Modules; LHCb VELO Modules: controlling thermal deformations

CERN Detector Seminar <https://indico.cern.ch/event/793299/> and Forum on Tracking Detector Mechanics <https://indico.cern.ch/event/469996/contributions/2148100/>

R&D on CO₂ cooling using a silicon micro channel substrate for the LHCb VELO Forum on Tracking Detector Mechanics 2018

<https://indico.cern.ch/event/695767/contributions/3014925/>

The vacuum envelope of the upgraded LHCb VELO Detector, Forum on Tracking Detector Mechanics

<https://indico.cern.ch/event/363327/contributions/860764/>

Expression of Interest for a Phase-II LHCb Upgrade

Physics case for an LHCb Upgrade II - Opportunities in flavour physics and beyond in the HL-LHC era

<https://cds.cern.ch/record/2244311>, <https://arxiv.org/abs/1808.08865>