13th Terascale Workshop
6 - 8 April 2021

LHCb Upgrade Tracking Systems

Paula Collins, CERN
April 7th, 2021

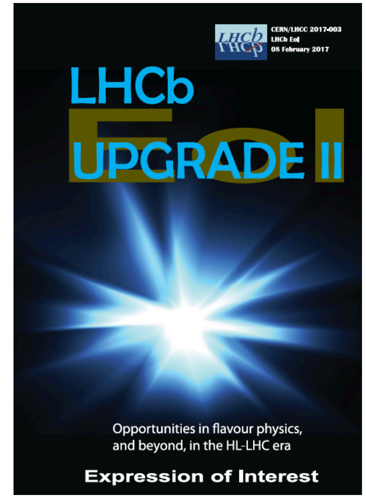
Timepix3 bumps, photograph courtesy S. Vahanen, ADVACAM

LHCb Upgrade I & II

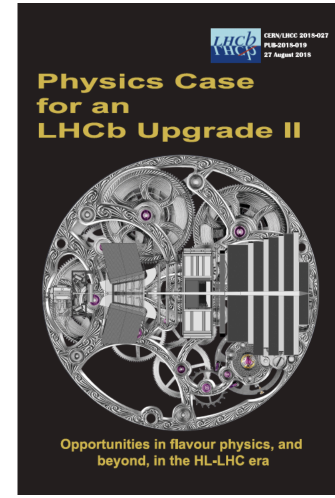
Upgrade I
- currently being built/installed

Upgrade II:
- Expression of Interest & Physics case
- Support from 2020 European Strategy

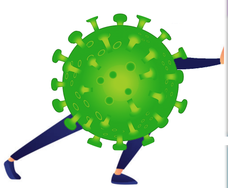
- 2021: Framework TDR
- 2021 - 2024: R&D
- ~ 2024: Technical Design Reports
- ~ 2025-2030: (R&D+) production
- ~ 2032: start of LHC Run 5

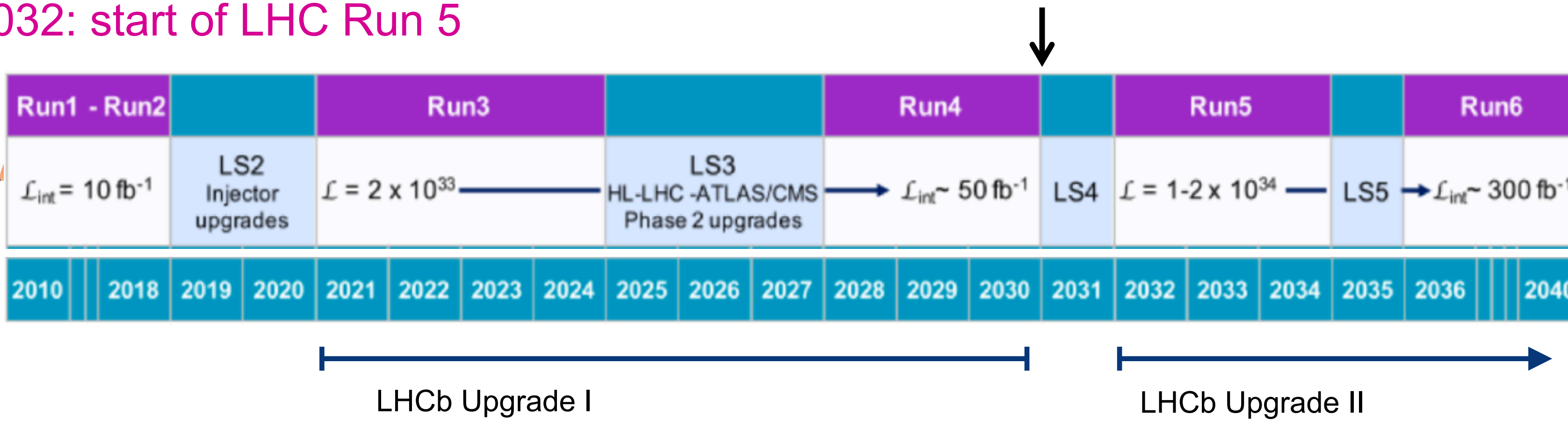


[LHCC-2017-003]



[LHCC-2018-027]



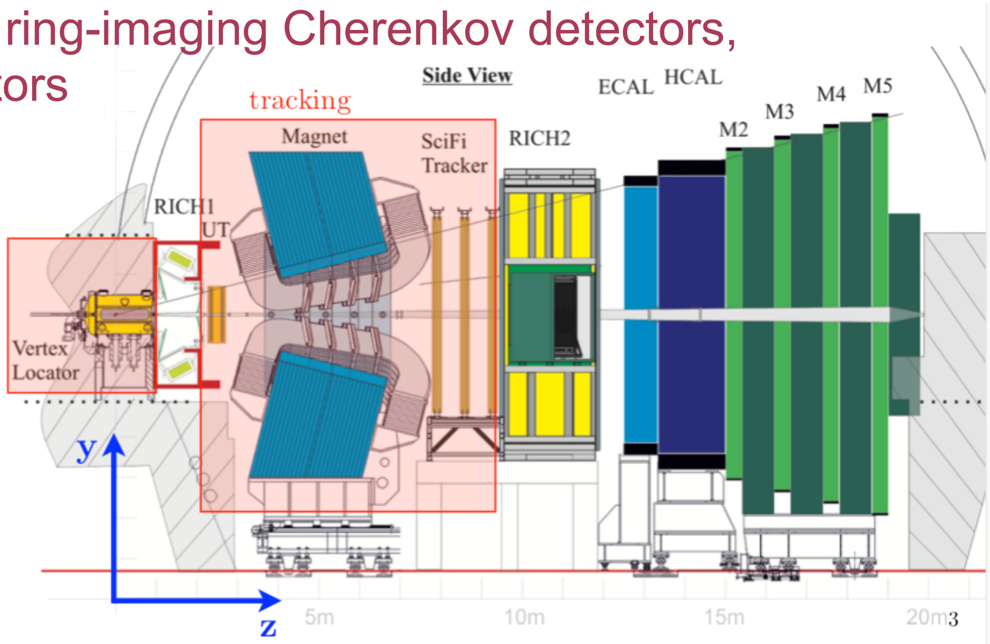


Upgrade I tracking system

- LHCb is a single-arm forward spectrometer at the LHC ($2 < \eta < 5$)
  - Fully instrumented in the forward region
  - excellent vertex resolution
  - tracking stations before and after 4 Tm dipole magnet
  - particle identification with two ring-imaging Cherenkov detectors, calorimeters and muon detectors

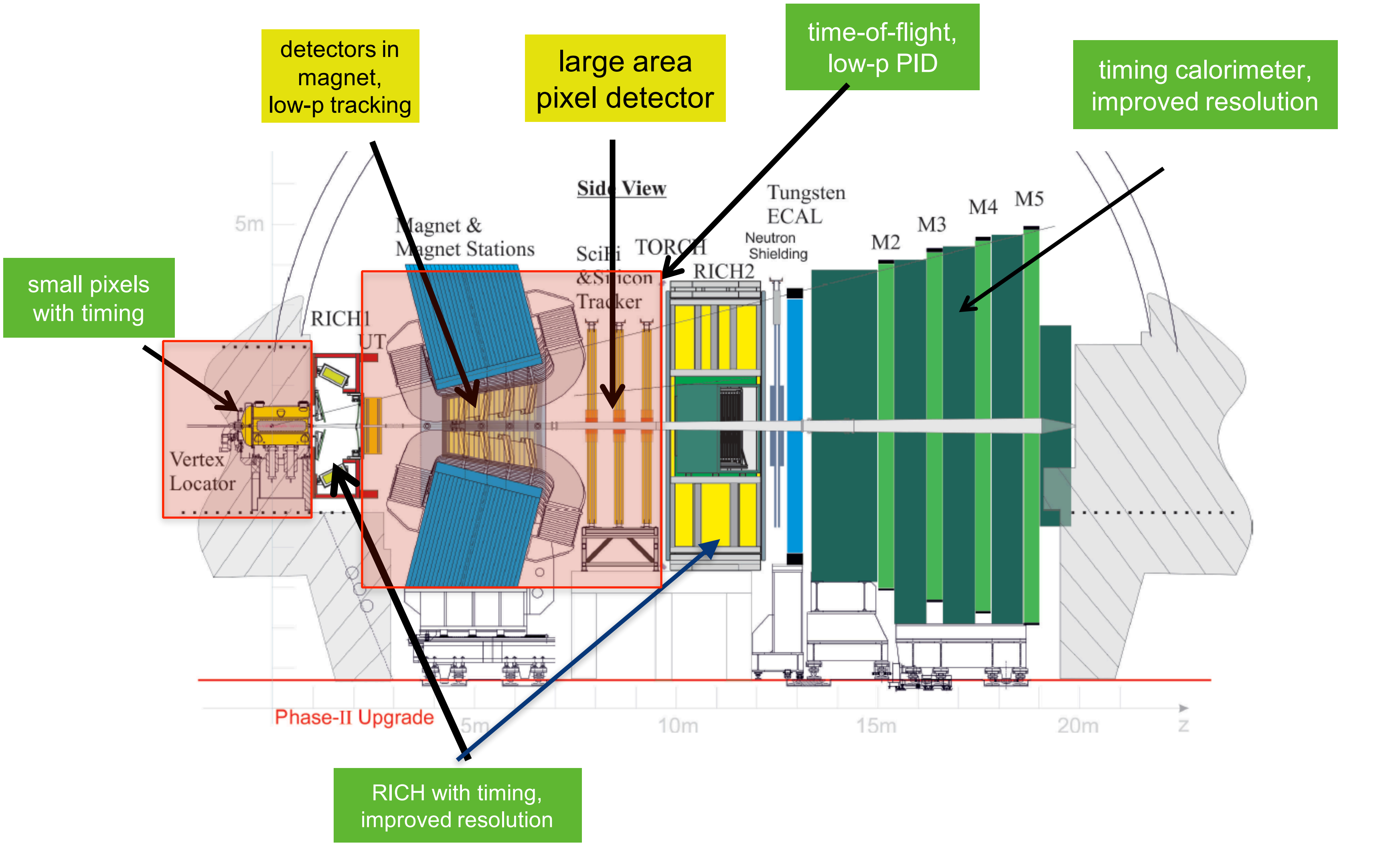
LHCb Upgrade I

- Full software trigger
  - readout at 40 MHz
- luminosity = 2×10^{33} $cm^{-2}s^{-1}$



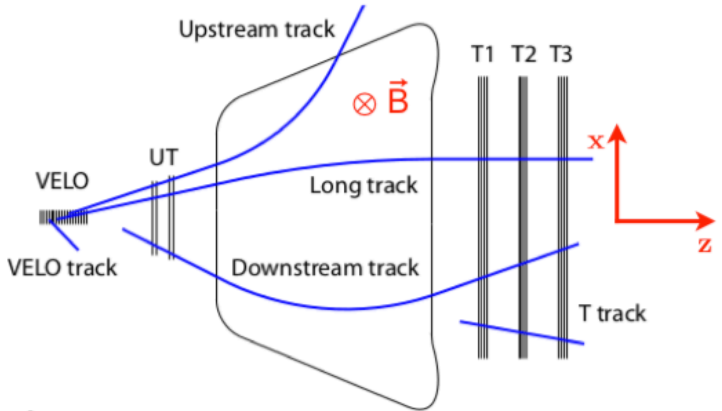
Upgrade II tracking

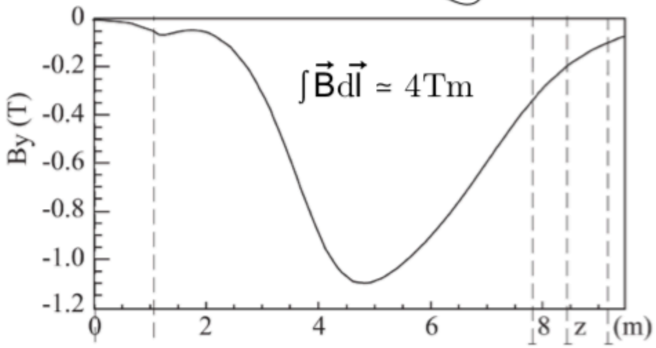
LHCb Upgrade II - move to luminosity = 1.5×10^{34} $cm^{-2}s^{-1}$



Upgrade I tracking system

- Tracking system aims to reconstruct with high efficiency tracks down to low momenta and accurately reconstruct primary, secondary and tertiary vertices
- Trajectory of charged particles reconstructed by matching track stubs up and down-stream of the magnet
- Tracks bend in horizontal (xz) plane
- The upstream tracker (UT) consists of one station, and the downstream tracker (SciFi) consists of 3 stations
- each station has 2 vertical (X) and 2 stereo (UV) detection planes

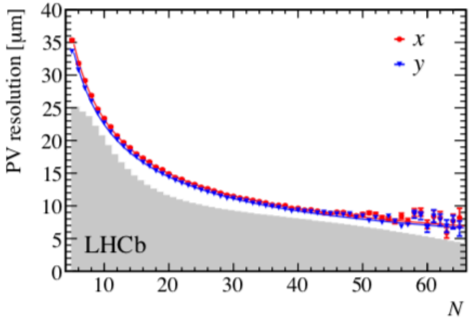




- Momentum resolution dominated by multiple scattering
- Downstream tracker resolution requirement driven by occupancy considerations

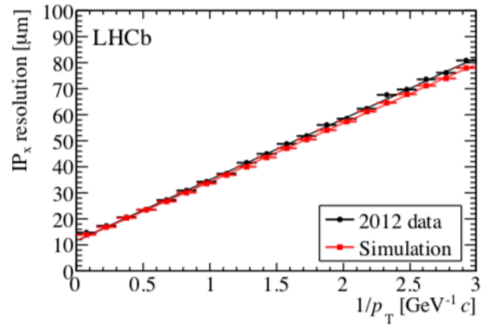
Upgrades build on success of Run 1 tracking

Vertex Resolution



+

Impact Parameter Resolution



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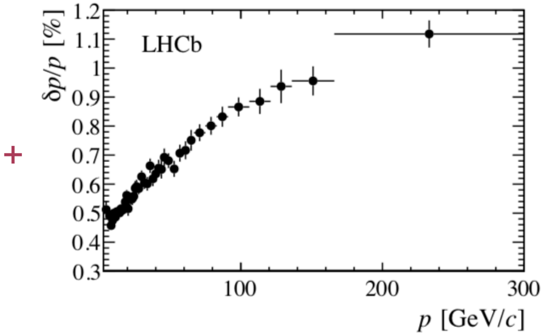
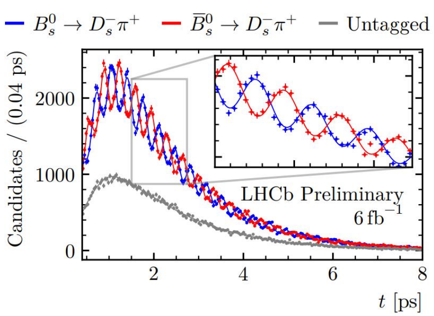
Momentum Resolution



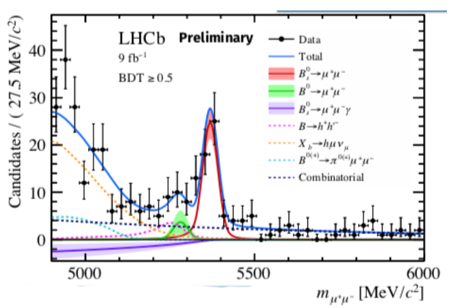
e.g.

$\langle\sigma_t\rangle \approx 37\text{fs} \ll 2\pi/\Delta m_s \approx 350$ fs

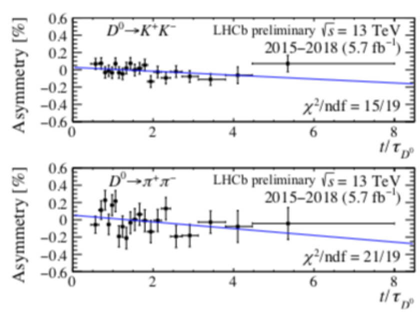
$\Delta m_s = (17.757 \pm 0.007 \pm 0.008)\text{ps}^{-1}$



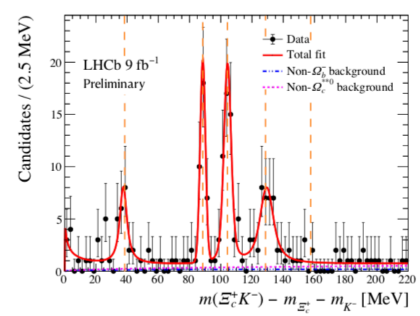
Standalone Bs→μμ > 10 σ



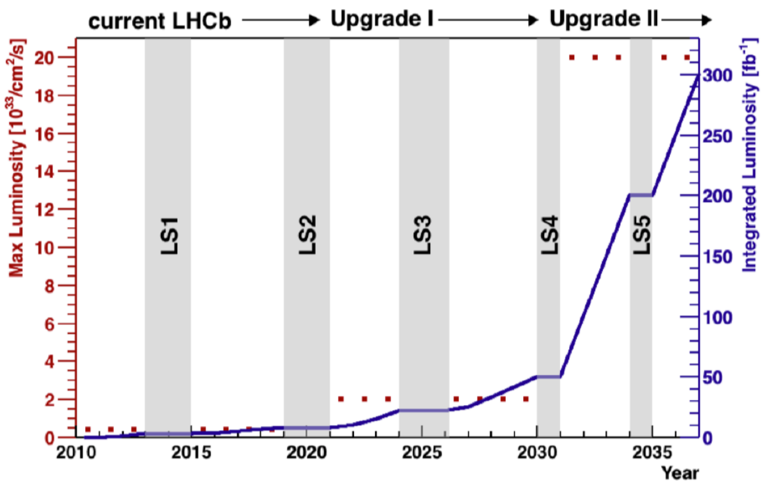
Time dependent CP asymmetry in charm



>50 new hadrons
here excited Ω_c^0 states

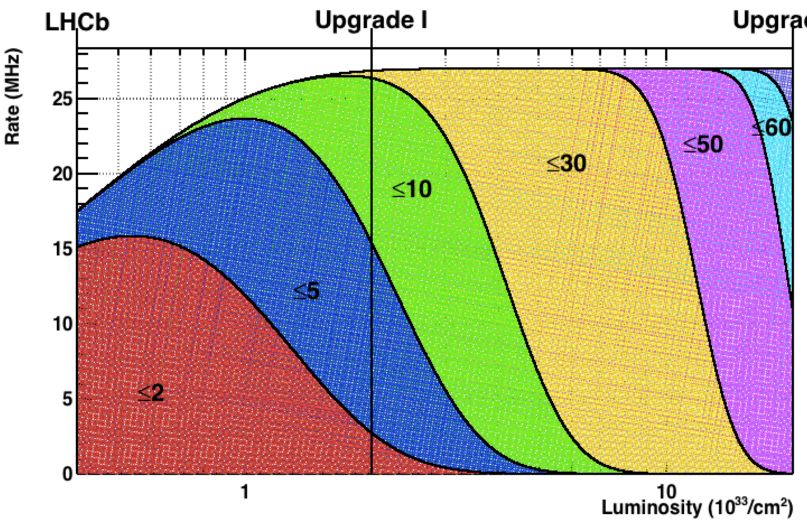


Upgrade operating conditions



- Upgrade I
  - Increase in luminosity by factor 5, to L = 2 x 10^{33} cm^{-2} s^{-1}
  - Transform entire detector to 40 MHz readout
- Upgrade II
  - Further increase by factor 7.5, to L = 1.5 x 10^{34} cm^{-2} s^{-1}

- Upgrade II pileup conditions:
  - mean pile-up ~ 50
  - σ_z ~ 45 mm
  - σ_t ~ 185 ps



Upgrade I SciFi Tracker

New tracking system:

- **Vertex detector** Si strips → pixels
- TT Si strips → new **Si strip detector**
- Inner (Si) and Outer (straws) Tracker
  → Novel **Scintillating Fibre Tracker**

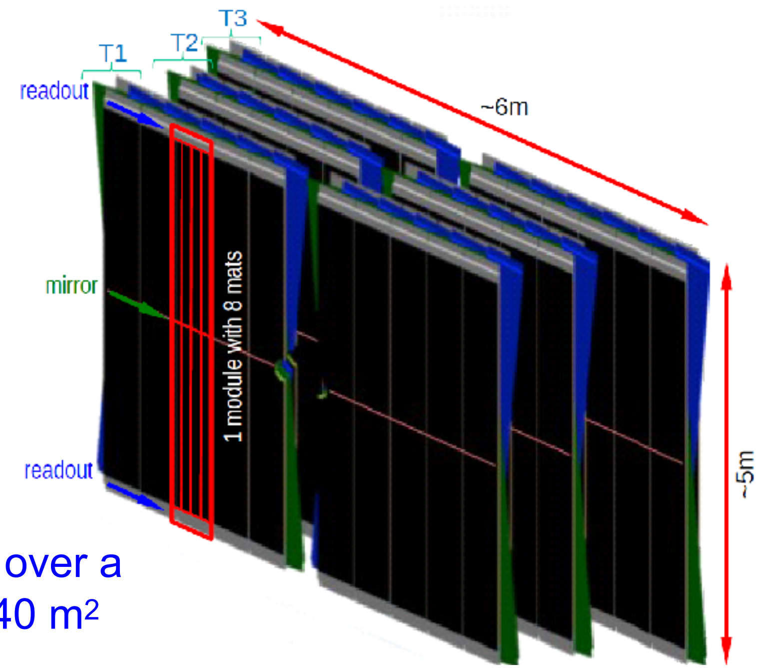
fast, high efficiency (~99%)
high granularity (250μm),
high spatial resolution (<100μm),
light (<1% X_0 /layer), up to 35 kGy

128 modules (0.5 x 5 m²)
arranged in 3 stations × 4 layers (XUVX)

Mirror on one end, readout at top/bottom with multichannel Silicon Photomultipliers (SiPM)

11,000 km of fibres,
524k channels

Goal: <100 μm resolution over a total active surface of ~ 340 m²



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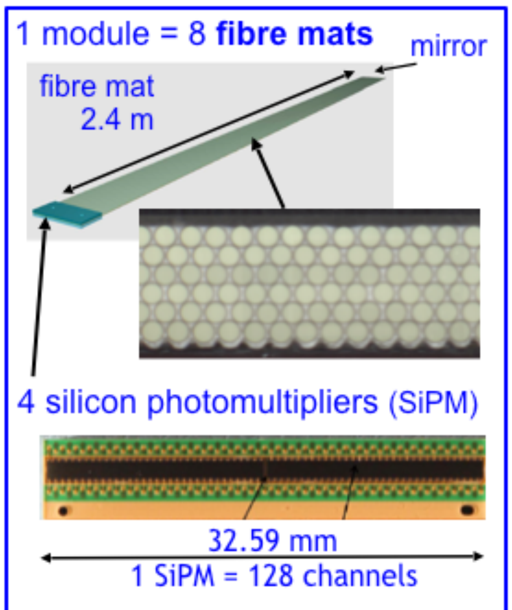

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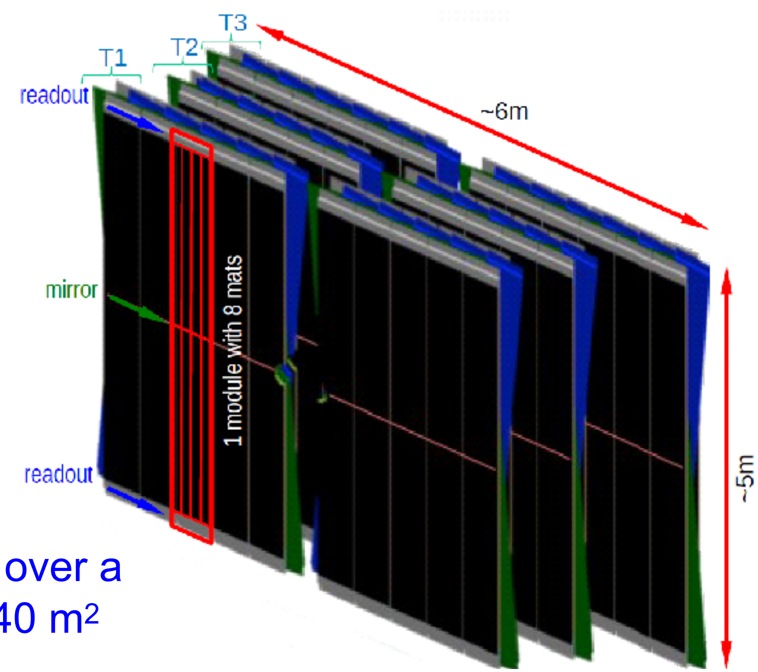

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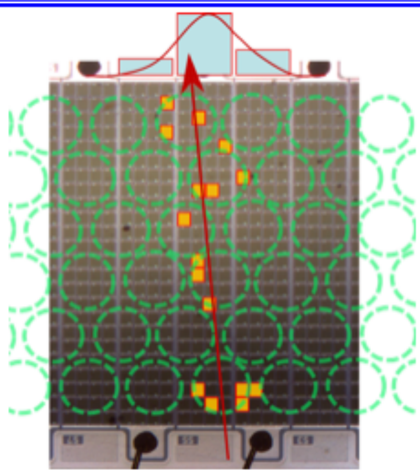

Light yield for 6-layer mat:
16–20 photo-electrons
(for particles near mat mirror)

128 modules (0.5 x 5 m²)
arranged in 3 stations × 4 layers (XUVX)

Mirror on one end,
readout at top/bottom with multichannel Silicon Photomultipliers (SiPM)

11,000 km of fibres,
524k channels

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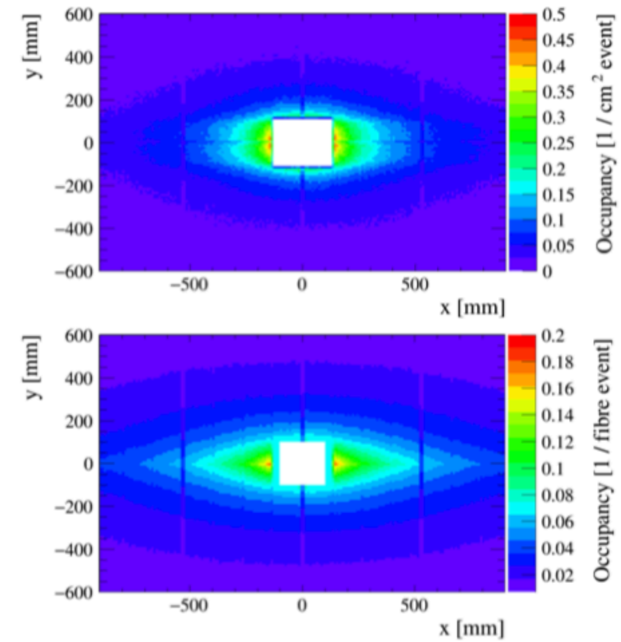
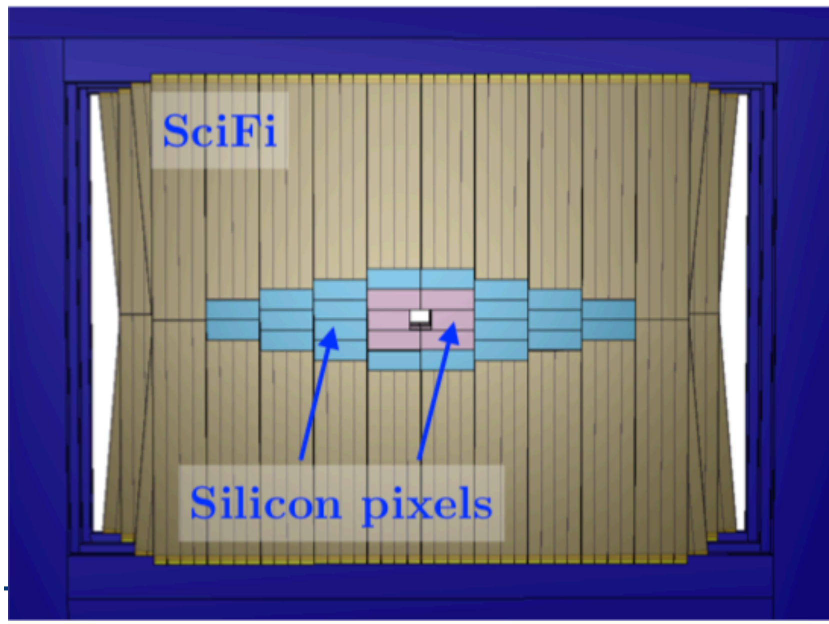
Upgrade II Mighty Tracker

$\int \mathscr{L} = 300\ \mathrm{fb}^{-1} \Rightarrow$ significant fibre radiation damage in inner region

- $\mathscr{L}_{inst} = 1.5 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
- very high occupancy (up to 20% / fibre / event)
- SciFi must be replaced near beam pipe to maintain the same (or better) tracking performance
- Solution: instrument the inner region with a pixel detector, while keeping scintillating fibres in the outer region





Inner + Middle + SciFi Tracker = Mighty Tracker

Option to install Inner part for Run 4

For more details see talk of Fred Blanc https://indico.cern.ch/event/991698/

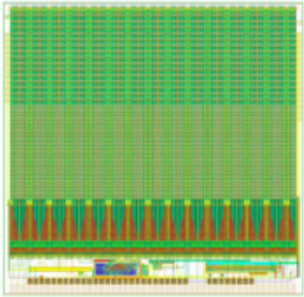
Sensor for Inner + Middle Tracker

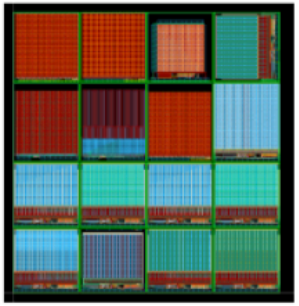
- High-Voltage Monolithic Active Pixel Sensors (HV-MAPS) proposed for MightyPix
  - based on existing MuPix & ATLASPix designs [arXiv:2002.07253]

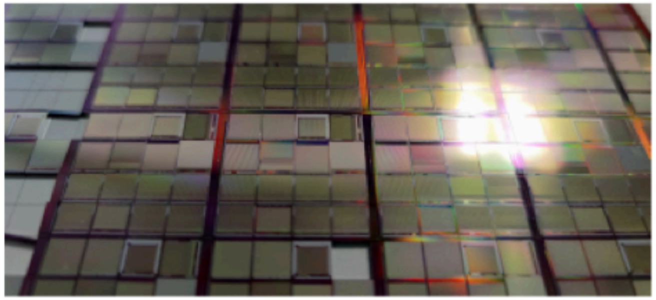
Parameter	Specifications
Sensor Thickness (μm)	150
Pixel size (μm²)	100 x 300
Time Resolution (ns)	3
Power Consumption (W/cm²)	0.3
NIEL (1 MeV n_{eq}/cm²)	2 x 10^{15}
Time Resolution	~ 8 ns
Readout	zero-suppressed

- Pixel dimensions
  - Size along bending plane (x) constrained by momentum resolution
  - Size in orthogonal dimension (y) set by multiple scattering and pattern recognition
  - Save as much as possible power and readout bits

May/2020 submitted to TSI — **7 September/2020** arrived from TSI — **14 September** arrived after Dicing at KIT

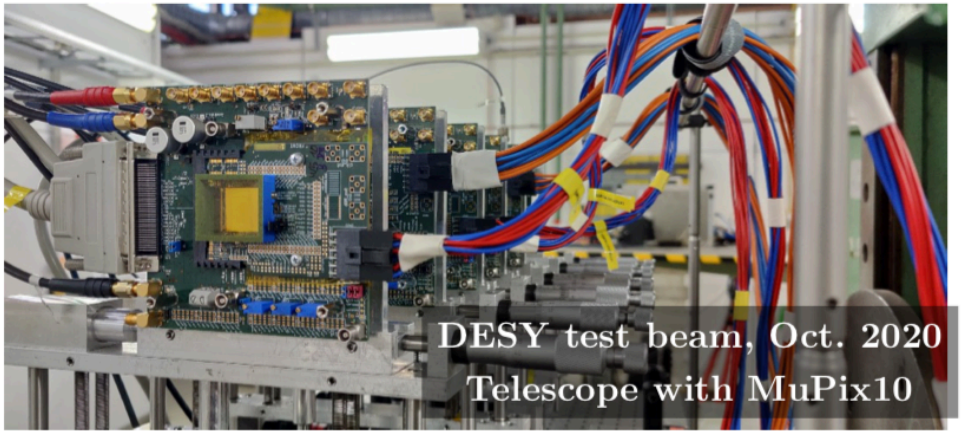


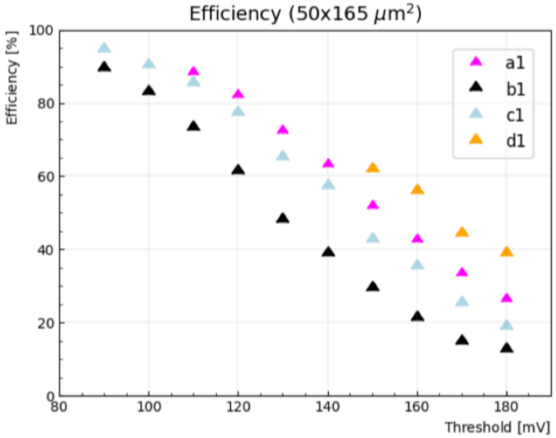




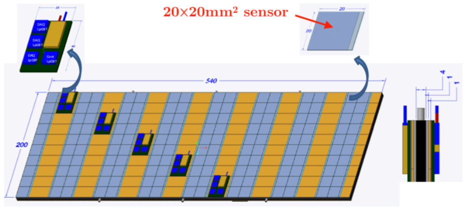
MightyPix R&D

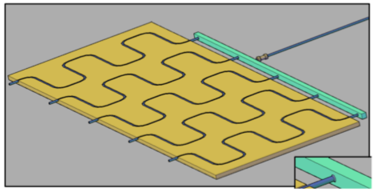
- MuPix10 Telescope
  - 3 reference layers
  - pixel size: 80 x 80 μm²
  - active area: 20.5 x 20 mm²
- DUT sensor
  - 4 different PMOS amplifier designs
  - two different pixel sizes (50 x 165) and (100 x 165) μm²





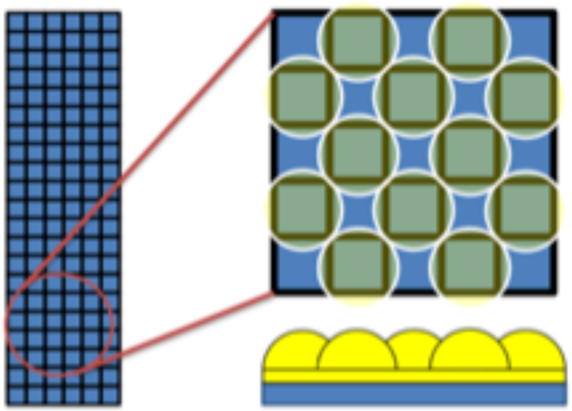
- Data analysis underway, for first results see BTTB 2021 workshop
- MuPix chips irradiated up to 9 x 10^{15} n_{eq}/cm^2
- Sensor integration and cooling designs in progress





SiPM for Upgrade II Mighty Tracker

- Ongoing R&D for scintillating fibre tracker technology
  - main goal is to mitigate radiation damage
- Improved SiPM performance
  - reduce active area in each pixel
    - lower noise and cross talk
    - reduced after pulsing
    - lower DCR
    - shorter recovery time
  - recover light by introducing micro-lenses
    - expect +20% light yield
  - Reduced number of fibre layers per detection plane
    - smaller clusters → less channel occupancy
    - lower material budget
  - Reduce SiPM noise with cryogenic cooling (-150^{o}C)
    - bring light into insulated SiPM vessel via a flexible clear-fibre interface
    - noise reduction by as much as three orders of magnitude over Run 3 conditions



Upgrade I VELO

- **Vertex LOcator** **Si strips → pixels**
- TT Si strips → new **Si strip detector**
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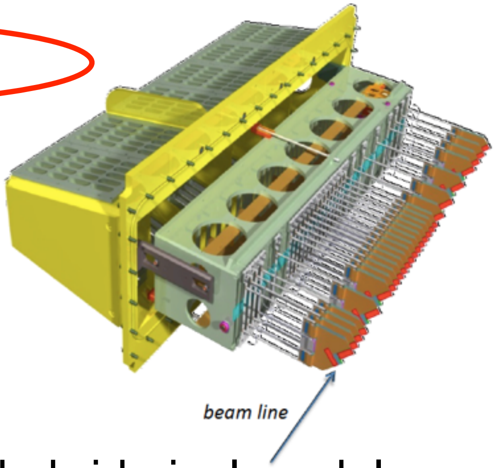
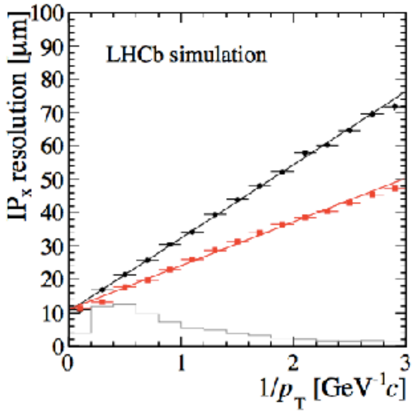
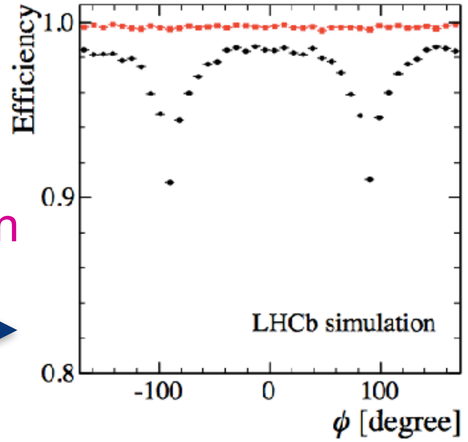
rows of silicon microstrip modules



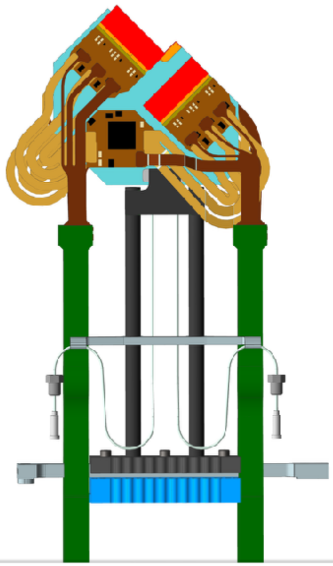
rows of silicon hybrid pixel modules

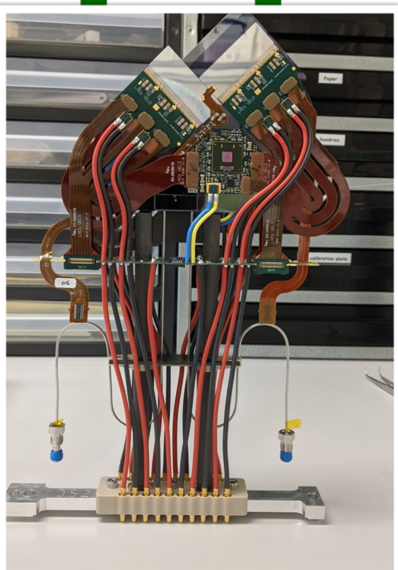


Pixel design with uchannel cooling superior to strips for impact parameter resolution and efficiency



VELO U1 Sensors and ASICs





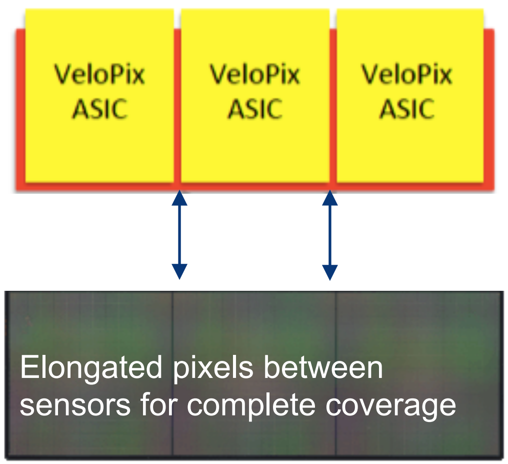
Challenges:

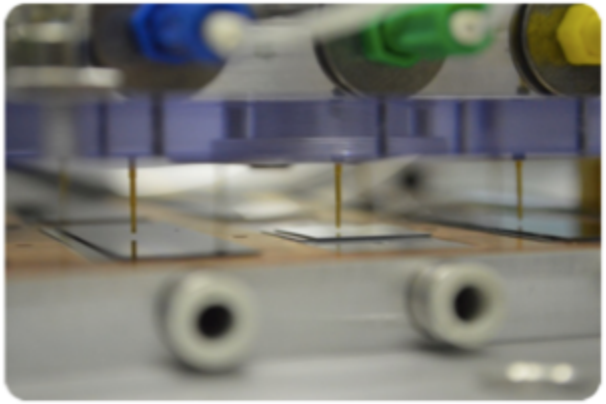
Very high (8×10^{15} n_{eq}/cm^2 for 50 fb^{-1}) & non-uniform irradiation ($\sim r^{-2.1}$)

Huge data bandwidth: up to 20 Gbit/s for central ASICs and ~ 3 Tbit/s in total

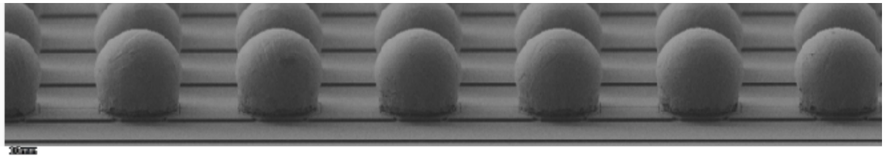
Sensor temperature must be maintained < -20°C with minimal cooling

Four sensors per module (sensors on other side shown with dotted lines)
Each sensor (43 x 15 mm) bonded to three VeloPix ASICs





Sensors are bump bonded and automatically probed before vacuum testing to 1000V with spring loaded needle contacts to ASIC backplane



SEM image of 55 μm pitch SgAn bumps courtesy Sami Vähänen, ADVACAM Oy

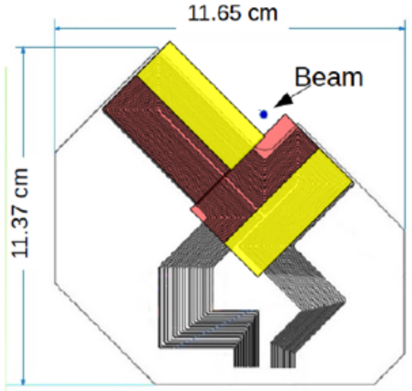
VELO U1 Cooling

Due to the harsh radiation environment an efficient cooling solution is required to maintain the sensors at < -20°C

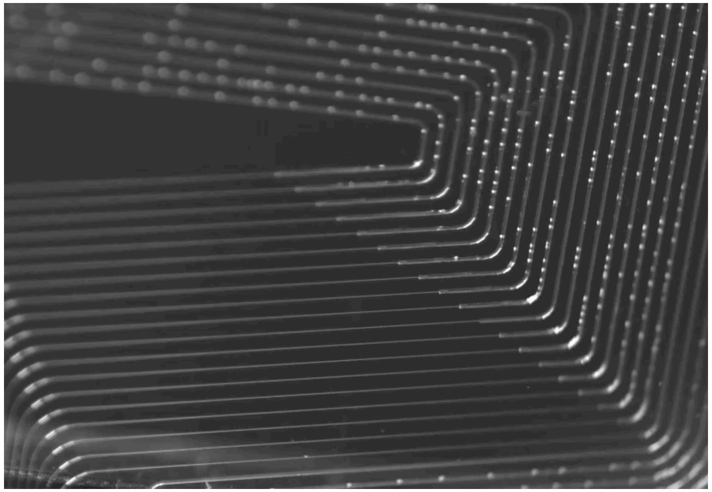
This is provided by the novel technique of evaporative CO_2 circulating in 120 µm x 200 µm channels within a silicon substrate.

Total thickness: 500 µm

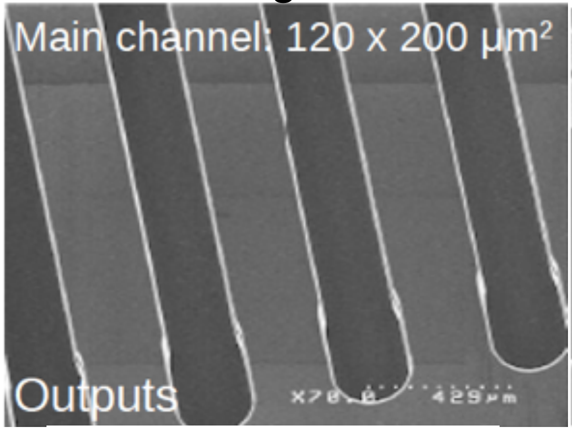
- High thermal efficiency
- CTE match to silicon components
- Minimum and uniform material
- radiation hard



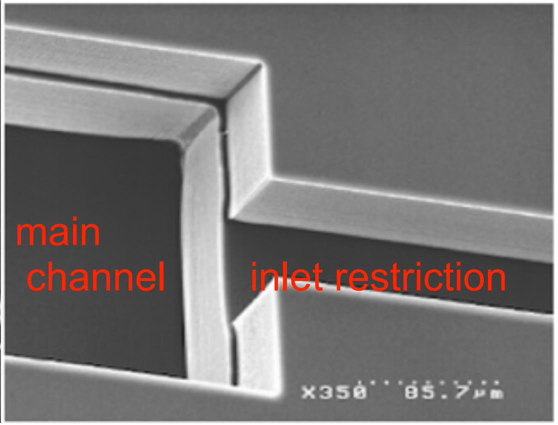
SEM images of etched wafer before bonding



(click for movie)

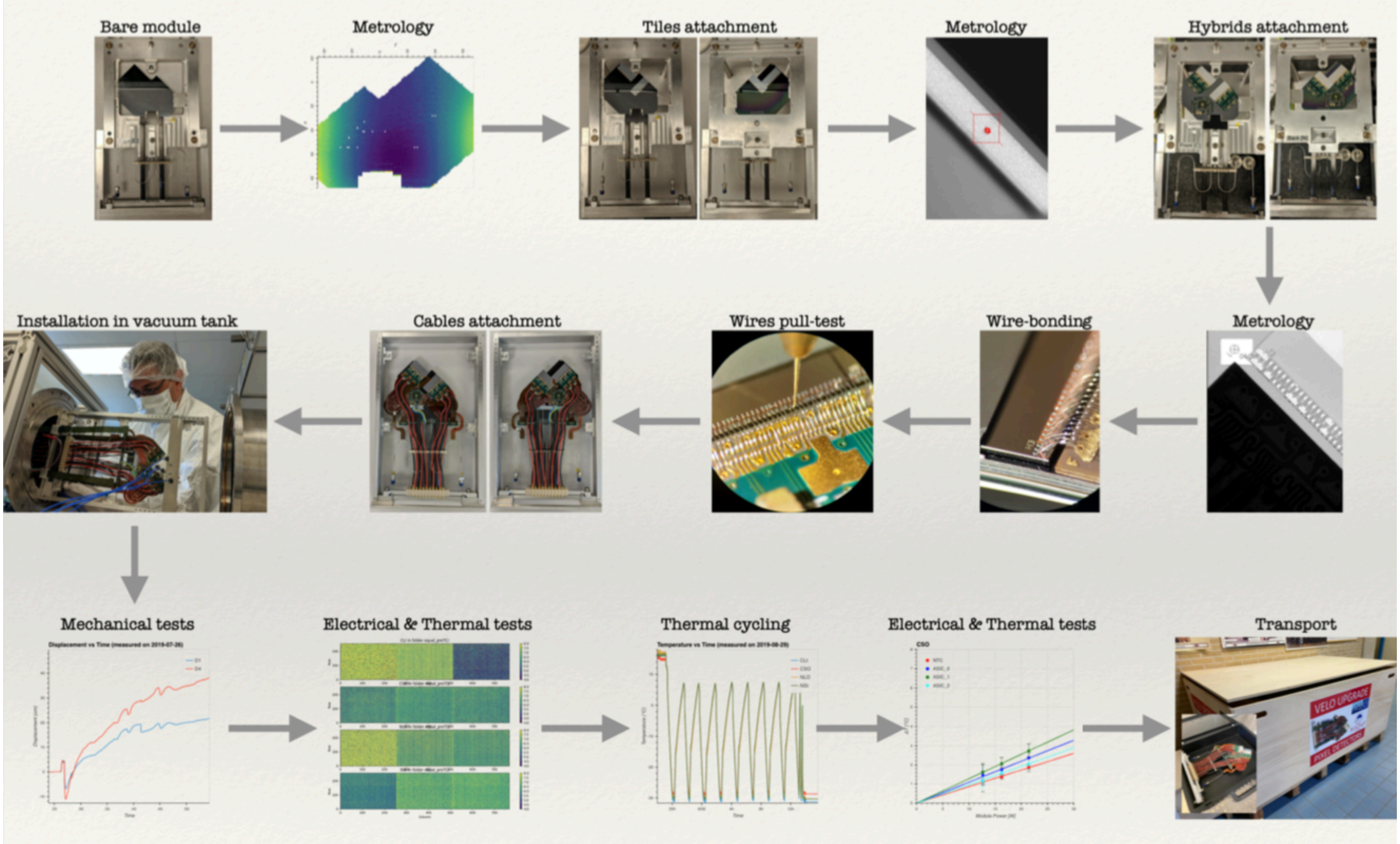


channels output directly to connector



Two step channel etching

Module Construction Flow



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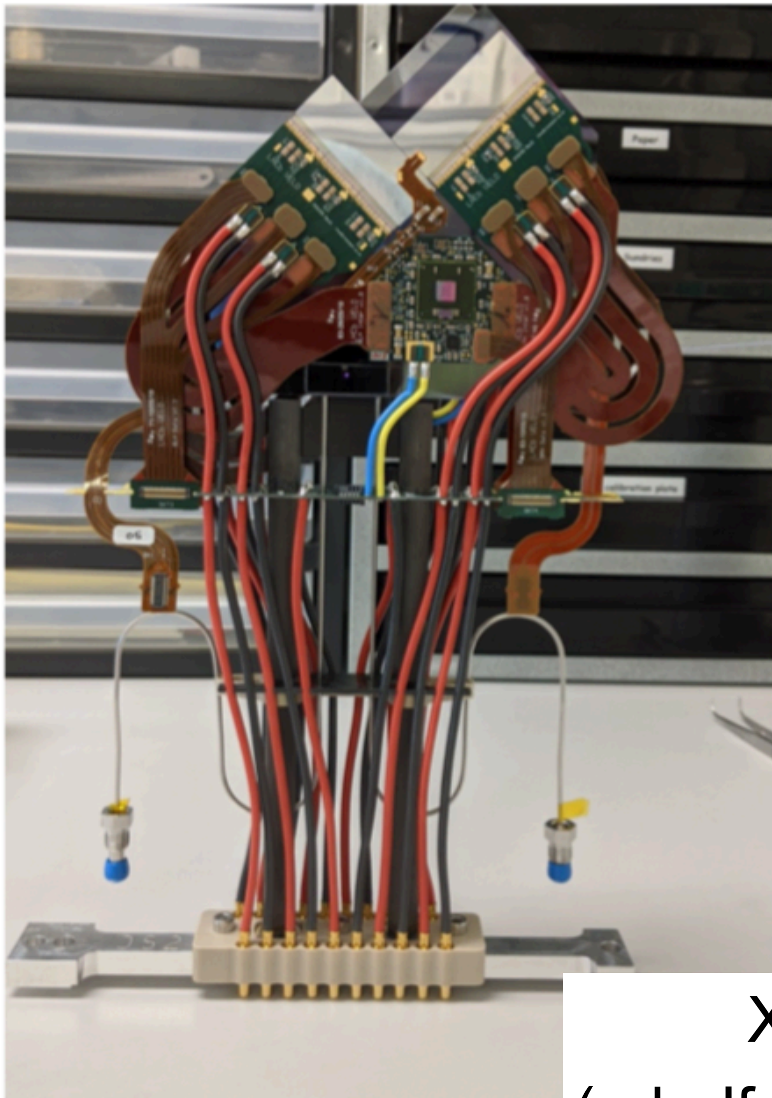
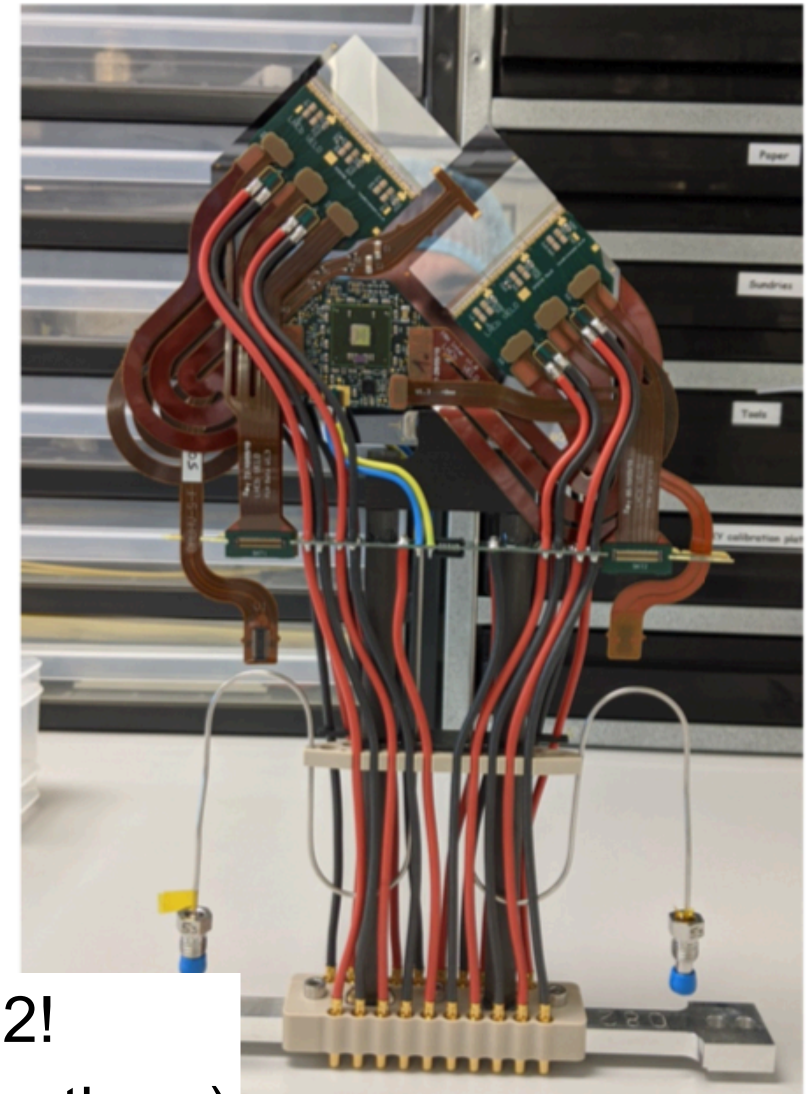
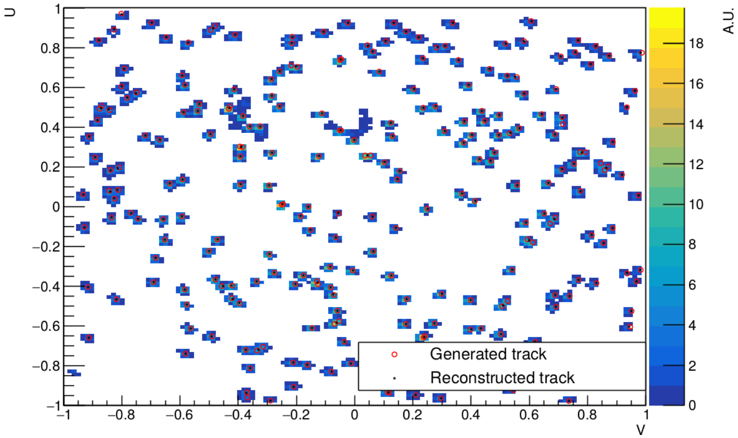




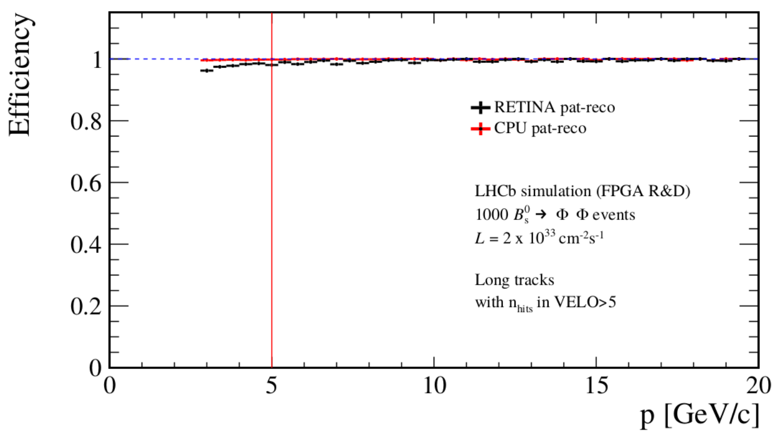
X 52!

(~ half way there)

FPGAs for VELO Upgrades



Simulated excitation levels of cellular processor arrays in VELO parameter space

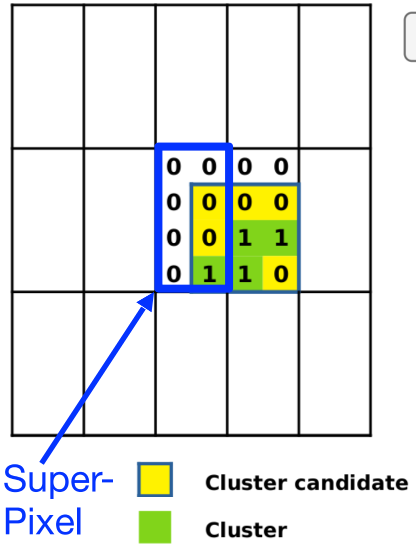


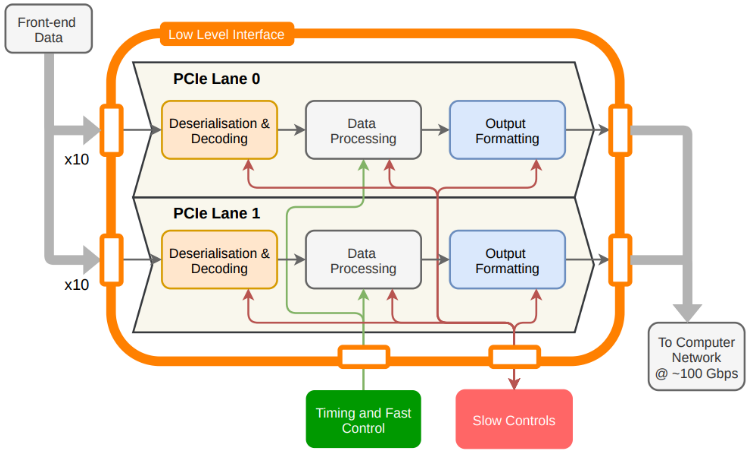
Efficiency of FPGA reconstruction, compared to a standard CPU-based algorithm

- Track reconstruction in the VELO is the first step in event reconstruction at LHCb, requires significant HLT1 resources (~50%)
- This could be important in U2 (even more if timing is added)
- Studies underway to move part of the processing to FPGA-based coprocessors integrated in the readout, to provide ready-made tracks to HLT1 -> reduce data flow and jump-start reconstruction -> allow better trigger selections [Vertex-19]
- Preliminary studies with current VELO geometry show promising tracking performances from a fully parallel architecture (RETINA) [CHEP-19]
- Hardware prototype in construction, to be tested in RTA coprocessor testbed during Run3.
- First-stage reconstruction (cluster finding) already implemented for Run3 (next slide), embedded in readout cards

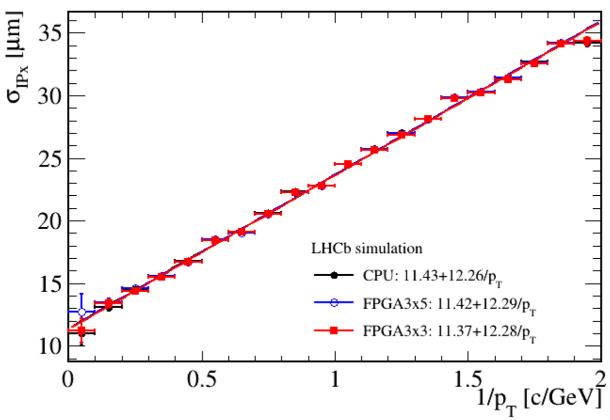
FPGAs for VELO Upgrades

- Finding pixel clusters is the first necessary step in VELO reconstruction
- Reconstructing 2D-clusters in real time computationally non trivial.
- FPGA implementation was developed and tested in simulation and in real hardware. Measured throughput of 38.9 MHz, tracking performances
- Clustering firmware integrated within the VELO readout firmware, ready to be used in upcoming Run 3.
- Proof of principle for feasibility of more complex FPGA reconstruction in U2





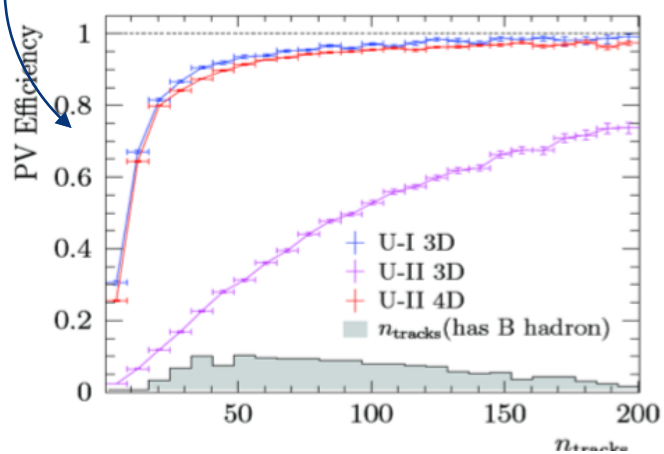
PCIe40 firmware schematics - clustering contained in “Data Processing” block

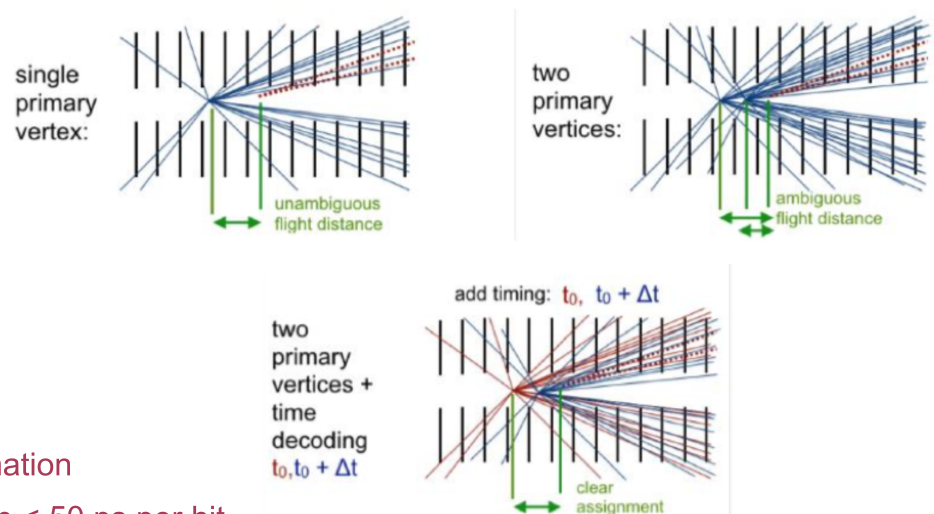


IP resolution, comparing FPGA clustering with a standard CPU-based algorithm

VELO Upgrade II

- Challenge: Maintain performance at ~ 7.5 times **occupancy** and 6 x **radiation damage**
- Occupancy issue makes the addition of timing **mandatory**
  - Pattern recognition
  - Primary vertex reconstruction
  - Assign secondary vertices to correct primary vertices
  - Flavour tagging and background rejection





Primary vertex efficiency collapses without timing information

Recovery best achieved by 4D tracking in the VELO with < 50 ps per hit

4D pixel tracker for Upgrade II

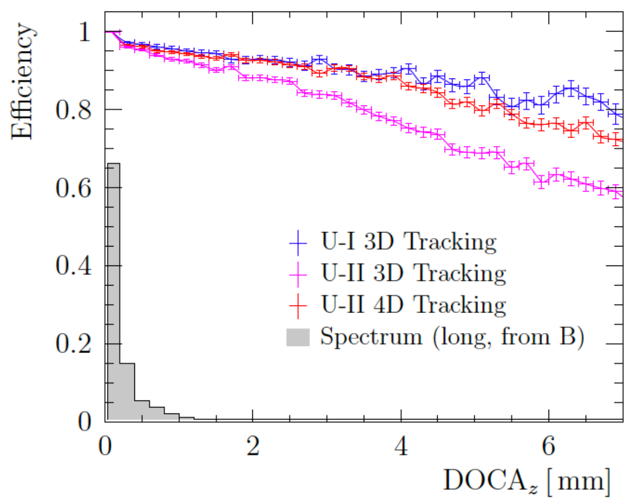
- Challenge: Maintain performance at ~ 7.5 times **occupancy** and 6 x **radiation damage**

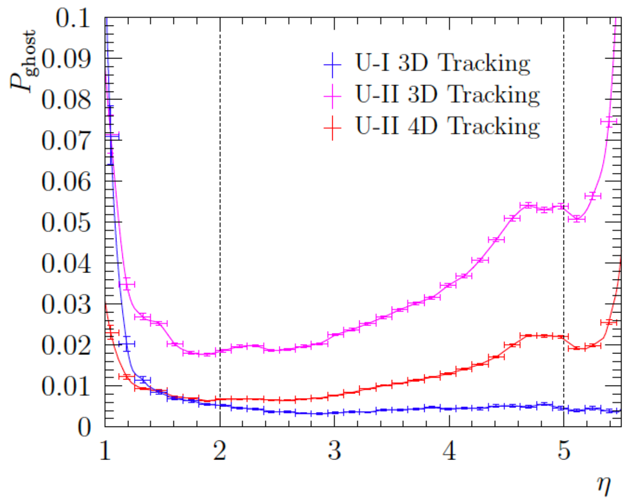
Timing layer(s) not ruled out, but

- Poorer performance and less efficiency due to smaller geometric coverage
- Tighter timing requirements (track time) and smearing due to heavy particles
- Development of two technologies, complex mechanics, and additional material
- System level tuning harder due to less redundancy

Benefits of 4D tracking

- Pattern recognition efficiency
- Ghost rate reduction, saving of CPU power
- Studies ongoing of 4D tracking on CPU, GPU, and FPGAs



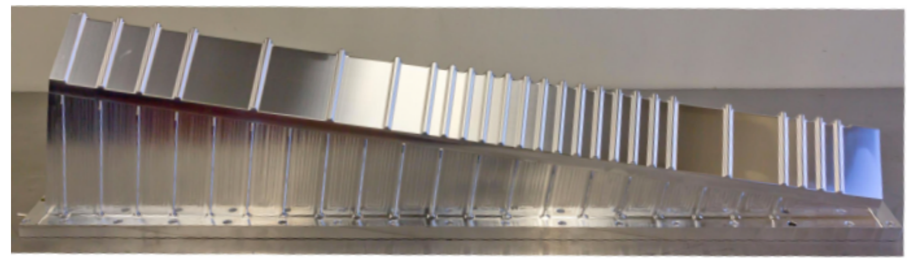


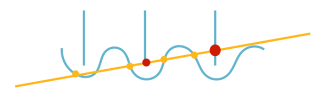
VELO Upgrade II

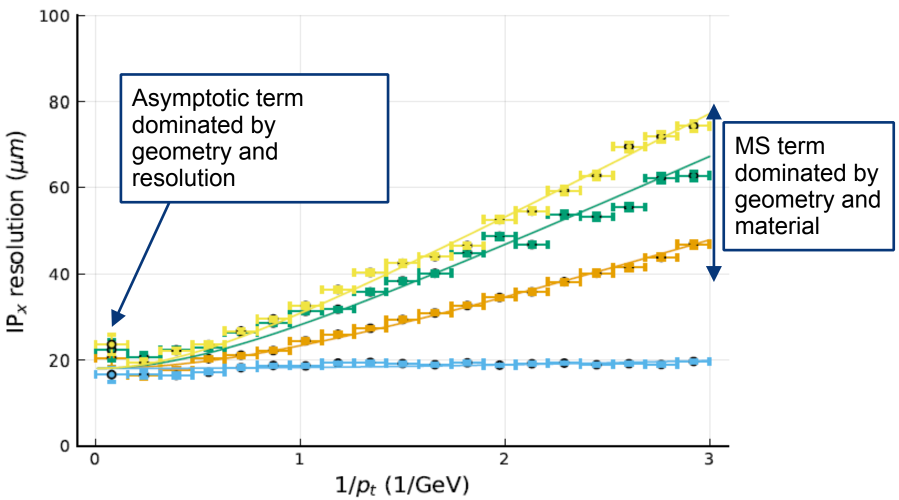
- Challenge: Maintain performance at ~ 7.5 times **occupancy** and 6 x **radiation damage**
  - Solutions entwined with the **material budget** and **mechanics**

Current VELO is in a secondary vacuum enclosure (foil)

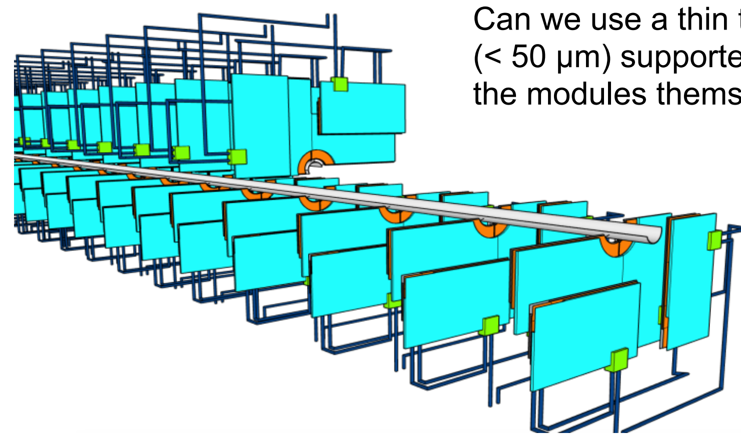
- Guides beam mirror currents, avoids wakefields
- Minimises RF pickup on sensor modules
- Lowers constraints on material outgassing
  - which pollutes beam pipe surfaces
- Corrugated foil is significant factor for IP resolution
- 150 µm achieved for current VELO







Can we use a thin tube (< 50 µm) supported by the modules themselves?

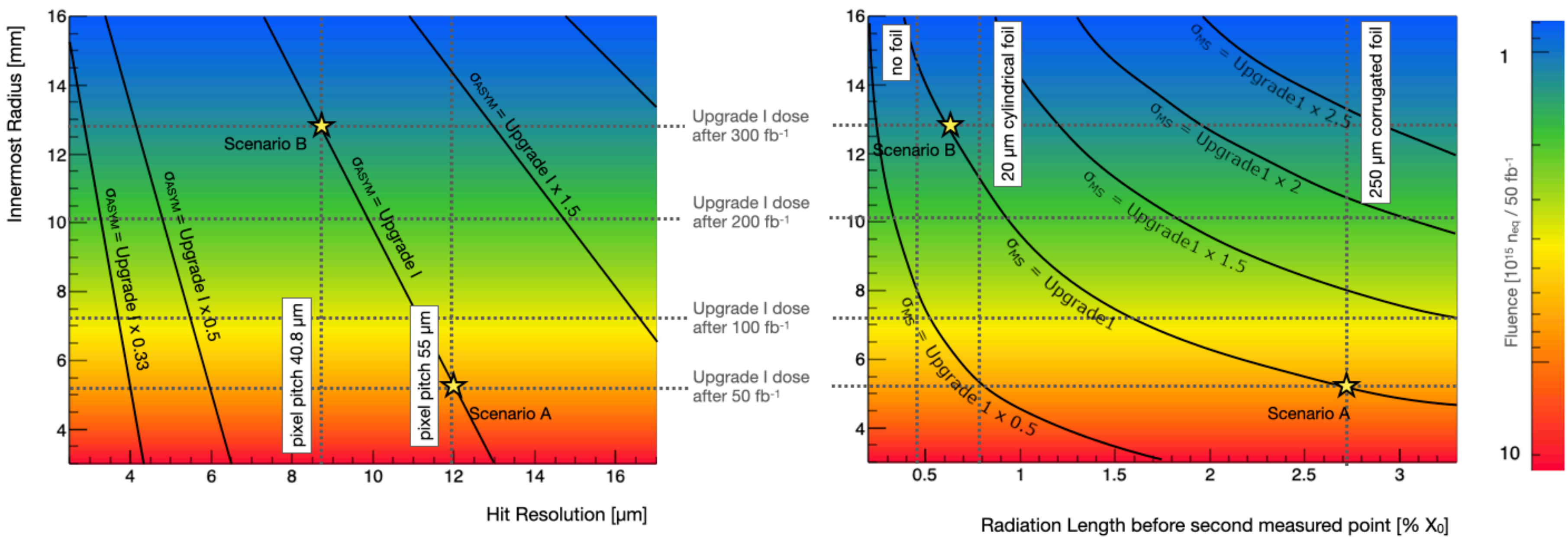


VELO Upgrade II

- Challenge: Maintain performance at ~ 7.5 times **occupancy** and 6 x **radiation damage**

IP Resolution Performance - asymptotic term

IP Resolution Performance - multiple scattering term



Upgrade I sensors are at 5.1 mm from beam

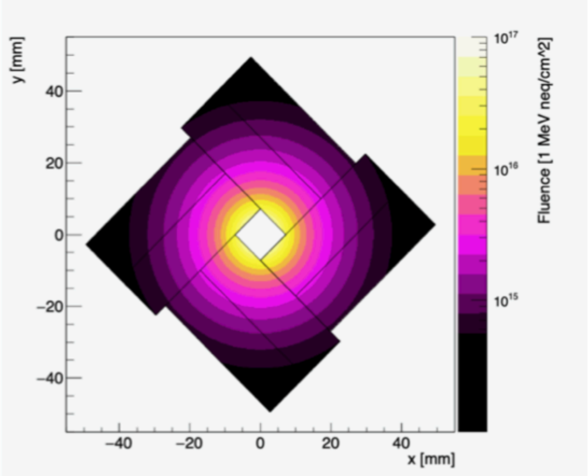
Upgrade II could retreat to 12.5 mm (for same integrated dose) and achieve the same performance, **only if:**

- **Pixel pitch is reduced from 55 to 41 µm (→55 % of area for pixel electronics)**
- **Material in RF foil and first detection layer is drastically reduced (→ huge mechanical implications)**

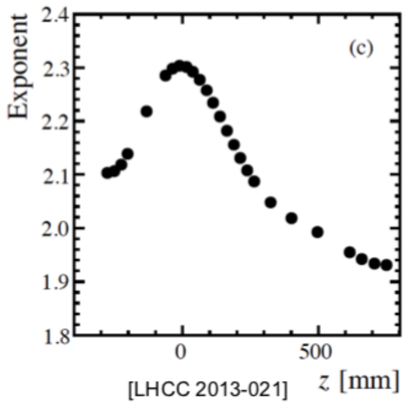
VELO Upgrade II

Radiation Levels

- **High in an absolute sense:** ~ 5 x 10^{16} 1 MeV n_{eq} /cm^2 @ 5.1 mm
- **Highly non-uniform**
  - **Factor 40-100** difference in fluence within a single sensor
  - Is a challenge for sensors, especially those with gain
  - Is a challenge for the ASIC: it is all about locally high rates
- To date no single sensor technology has been shown to survive the required life time fluence
- (bi)-annual replacement could be an option



- fluence in radial direction drops as AR^{-k}
- somewhat smaller k for downstream stations



[LHCC 2013-021]

VELO II sensor and electronics

- Challenge for sensor and electronics

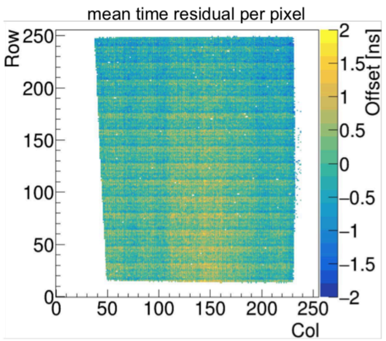
Parameter	Scenario A	Scenario B
Pixel Pitch (μm)	< 55	< 42
Time resolution RMS (ps)	< 30	< 30
TID lifetime (MGy)	> 24	> 3
Pixel rate hottest pixel (kHz)[MHz]	> 350	> 40
Power per pixel [μW]	23	14
Max discharge time [ns]	< 29	< 250
Bandwidth per ASIC of 2 cm^2 [Gb/	> 250	> 94
Radiation lifetime (1 MeV neq)	> 5 x 10^{16}	> 8 x 10^{15}

Additional challenge: System level timing

- pixel to pixel time offsets can be larger than resolution
- Corrections are possible but extra info requires on-chip logic and/or bandwidth
- Correlation of time measurements can degrade performance due to combination of hits

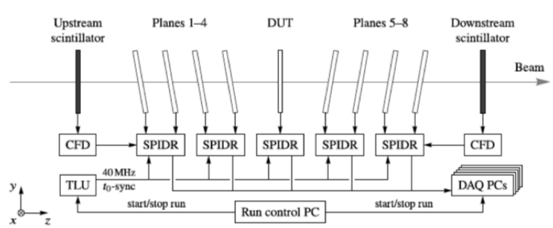
Examples from Timepix 3 telescope:

Pixel to pixel variations

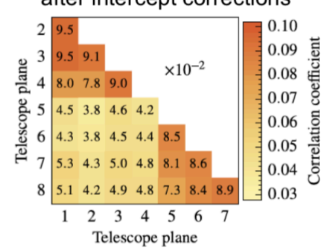


[K. Heijhoff: 2020 JINST 15 P09035]

Timing correlations between planes

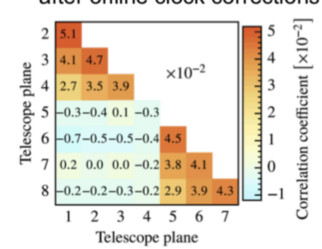


plane to plane correlations after intercept corrections



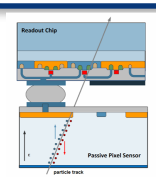
[K. Heijhoff: 2020 JINST 15 P09035]

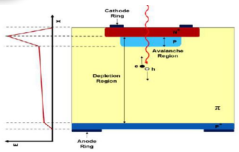
plane to plane correlations after offline clock corrections

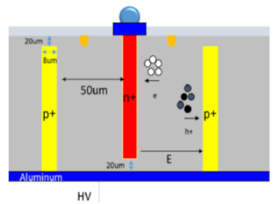


VELO II sensor and electronics

Sensors



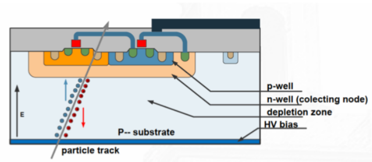


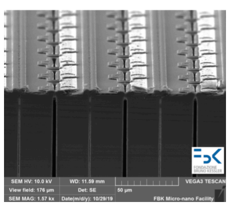


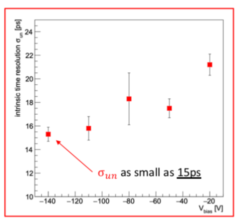
Candidate technologies:

Hybrid planar, LGAD, 3D, depleted monolithic…

High and non uniform irradiation main challenge





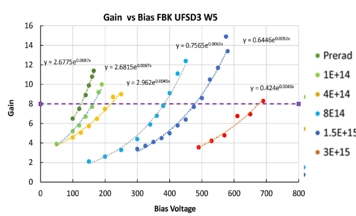


Timespot 3D sensors

have demonstrated very good intrinsic time resolution and in principle are radiation hard

LGADs good intrinsic time resolution

Is it possible to define multiple bias regions in one LGAD sensor?



H. Sadrozinski, HSTD12

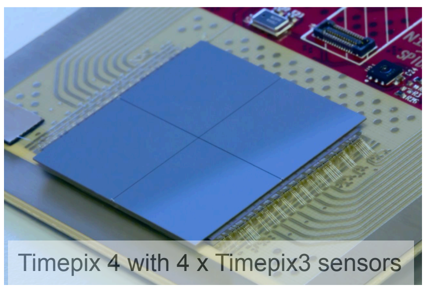
Electronics

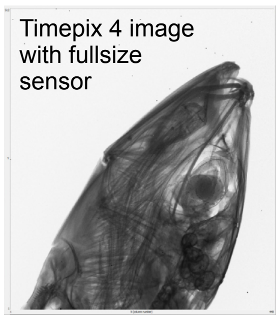
Timepix4: Full scale ASIC with fast timing capabilities

General purpose 65 nm CMOS, 55 μm pitch pixels

Per pixel TDC achieving 200 ps / 60 ps (bin / rms)

160 Gbit/s output bandwidth





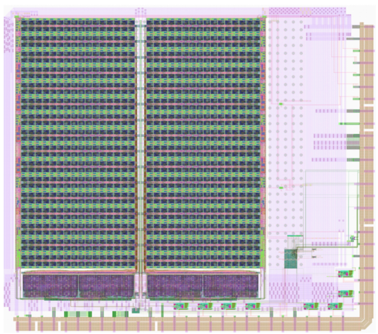
Timespot:

Addressing VELO Upgrade II challenge in 28 nm technology

Optimised for 3D trench sensors, TDC per pixel

Target < 16 ps rms / pixel

6 mm² MPW run ready and testing starting

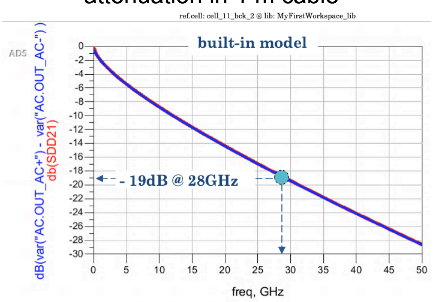


VELO II Readout and Cooling

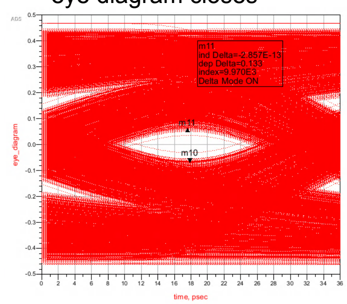
Data Transmission

- Smaller ASIC technologies very performant
- Low power 28+ Gbit/s serialisers seem feasible in 28 nm
- Much harder to scale the cable technology
  - 0.5 - 1 meter needed to get out of LHC vacuum
  - Must be vacuum compatible, radiation hard
  - There are large dielectric losses

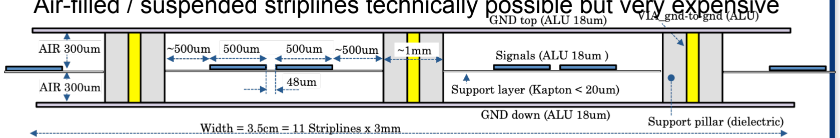
attenuation in 1 m cable



eye diagram closes



Air-filled / suspended striplines technically possible but very expensive

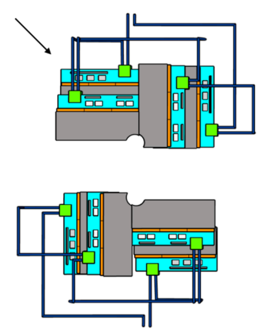


Is going optical a possibility? VCSEL reaches 1 MGy/ 10^{15} n_{eq}

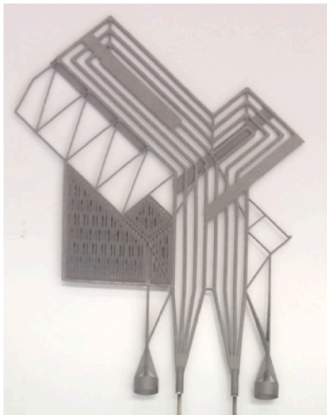
Cooling

- Evaporative CO2 cooling introduced by VELO to HEP
- VELO Upgrade I: CO2 cooling in silicon microchannel plates
  - Elegant, but expensive and limited in geometry
- Upgrade II modules may need to run cooler
  - Bi-phase Krypton might be a possibility

Smaller microchannel plates to reduce cost



3D printed titanium pipes already prototyped for Upgrade I

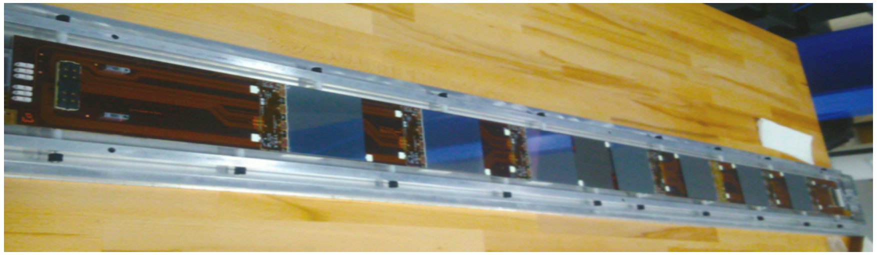


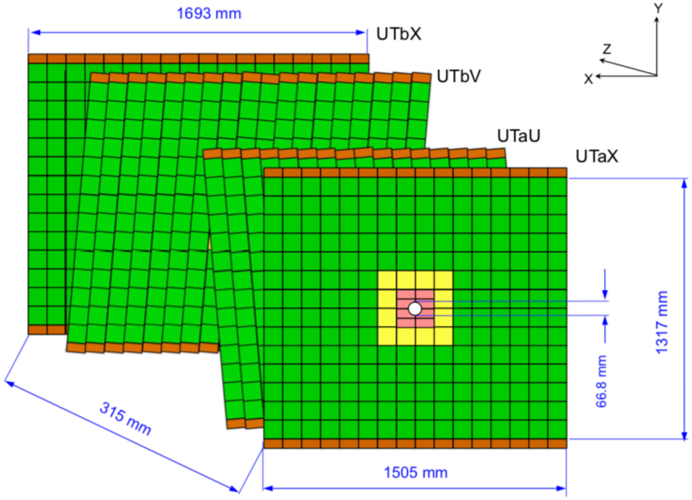
For more details on VELO UII see talk of Martin van Beuzekom https://cds.cern.ch/record/2740959

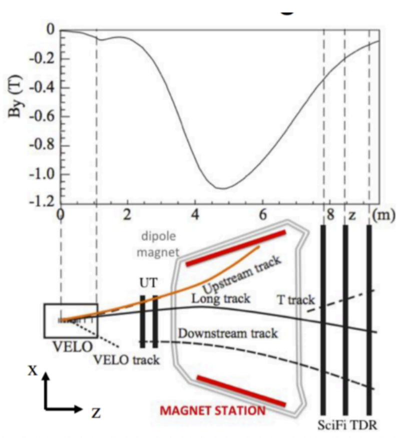
Completing the tracking system

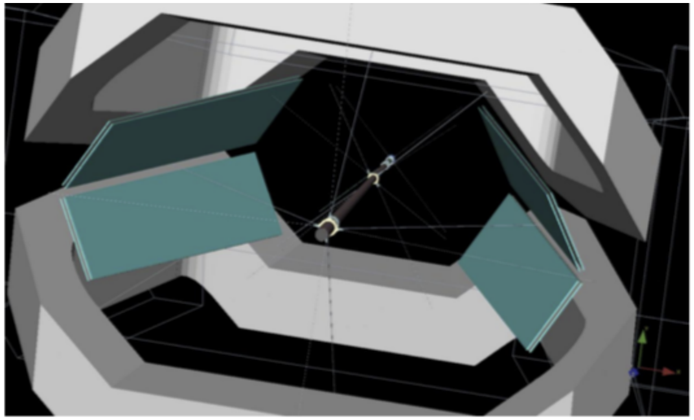
UT currently being constructed for Upgrade I

- Four detection planes ~2 m^2 each
- two planes with vertical strips, two rotated by $\pm 5^{\circ}$
- Finer granularity than previous TT, closer to beampipe









Magnet side stations could be added after LS3 to improve momentum resolution of tracks upstream of the magnet

These stations and the future UT will benefit from synergy with the Mighty Tracker

Conclusions

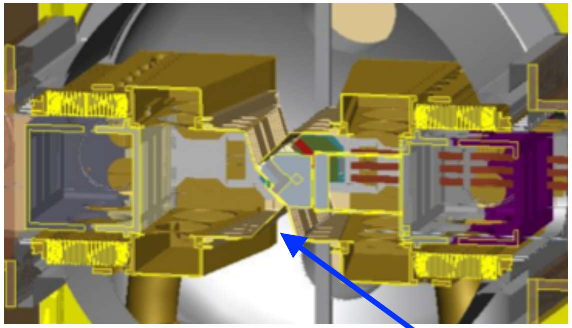
- The tracking system for the LHCb Upgrade I is being constructed and installed
  - VELO Hybrid pixels + UT silicon strips + SciFi scintillating fibres
  - All with 40 MHz readout and a full software trigger

- The tracking system for the Upgrade II is in the R&D phase
  - Timing and enhanced data rates and radiation hardness for the VELO
  - A combination of Sci-Fi and HV-CMOS technologies for the downstream trackers

- Many aspects of the mechanical design, cooling, electronics design and sensor choices remain open
  - LHCb welcomes technical associate members interested in contributing in any of these areas

Backup

VELO RF Foil

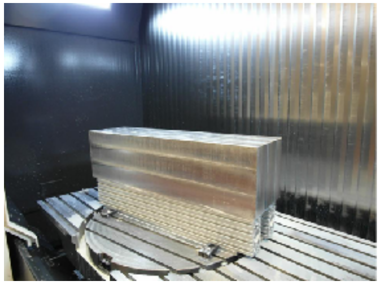


The VELO is separated from the primary vacuum by the 1.1 m long thin walled "RF foil" which also shields the detector and guides the beam wakefields

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

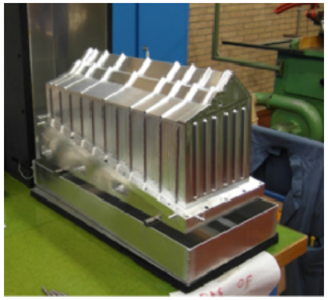
The final foil withstands 10 mbar pressure variations, is leak tight, and has a final thickness of 250 μm, with an option to go to 150 μm maintained

RF foil: some production steps

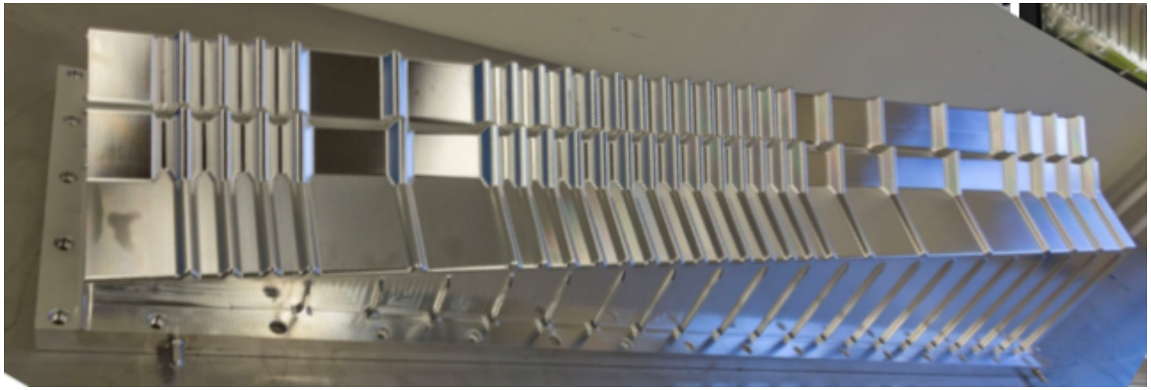


Initial solid forged Al alloy block

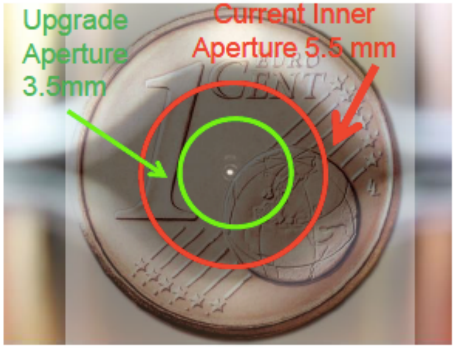
>98% of material removed



Internal mould support during machining steps



VELO RF Foil



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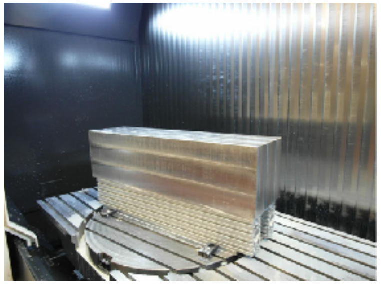

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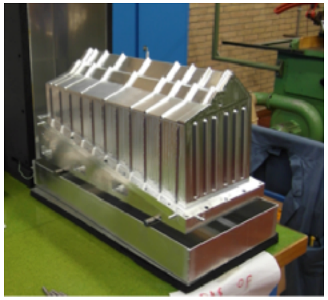

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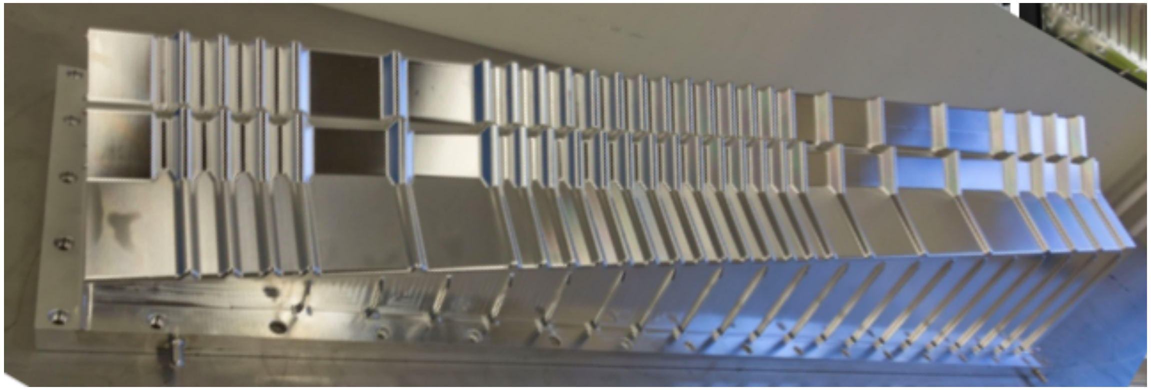

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VELO Assembly underway