The LHCb Mighty-Tracker

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on behalf of the LHCb Mighty-Tracker group

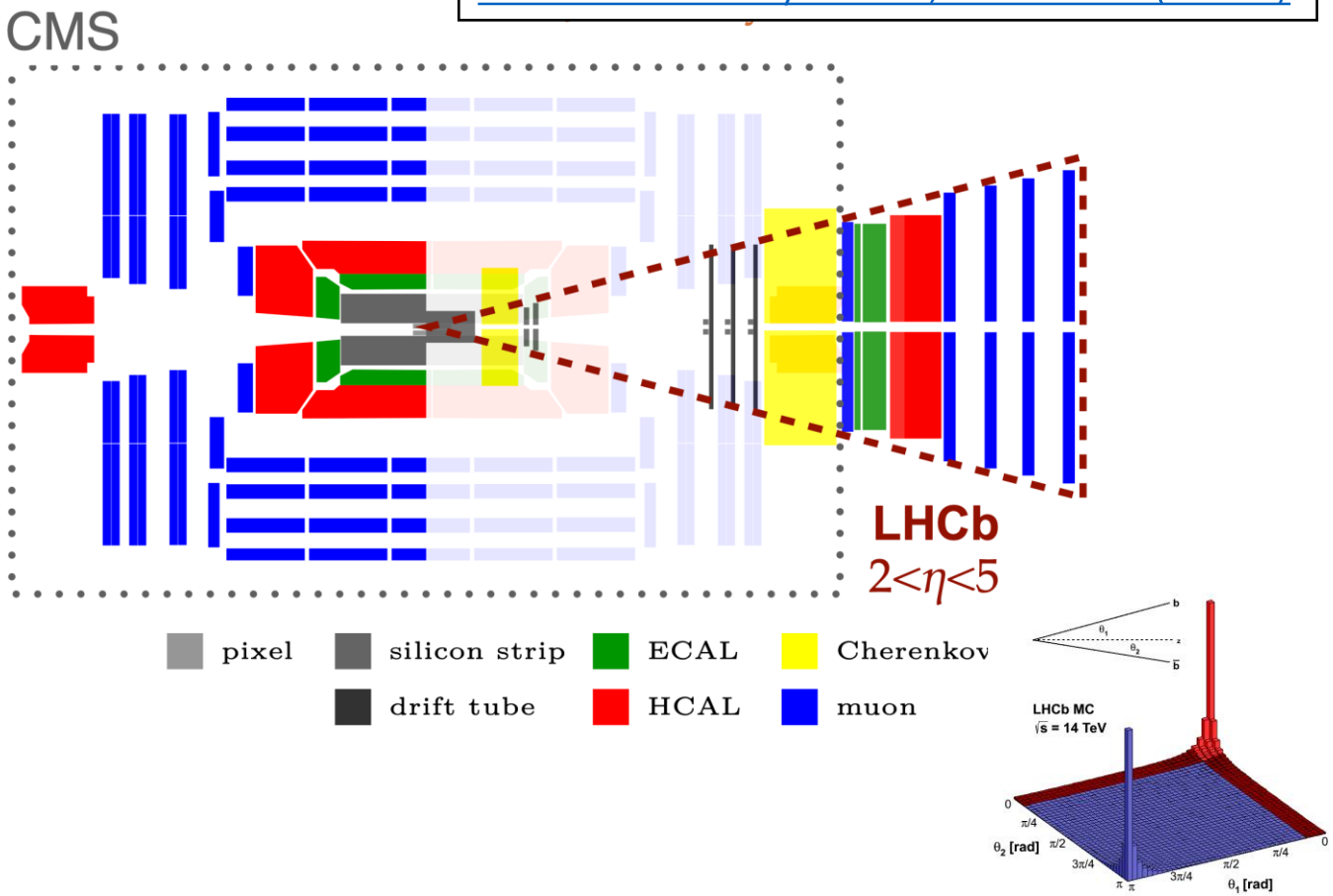
The Vienna Conference
20/02/2025

LHCb

LHCB-TDR-023

Int. J. Mod. Phys. A30, 1530022 (2015)

- One of the four main experiments at the large hadron collider (LHC)
- Forward spectrometer designed for CP violation, b and c-hadron rare decays, beyond standard model physics
  - But capable of much more (QCD, EW-physics, heavy ion, …)
- Unique coverage complementary to ATLAS and CMS ($2 < \eta < 5$)
- Fully flexible software trigger at 40MHz
  - Around 4Tb/s processed in real-time
- Excellent charged particle identification (e, μ, π, p, K) over a wide momentum range (1-150GeV/c)
  - Kaon ID ~ 95% for 5% π → K mis-ID probability



European Strategy Update 2020 " The full potential of the LHC and the HL-LHC, including the study of flavour physics, should be exploited"

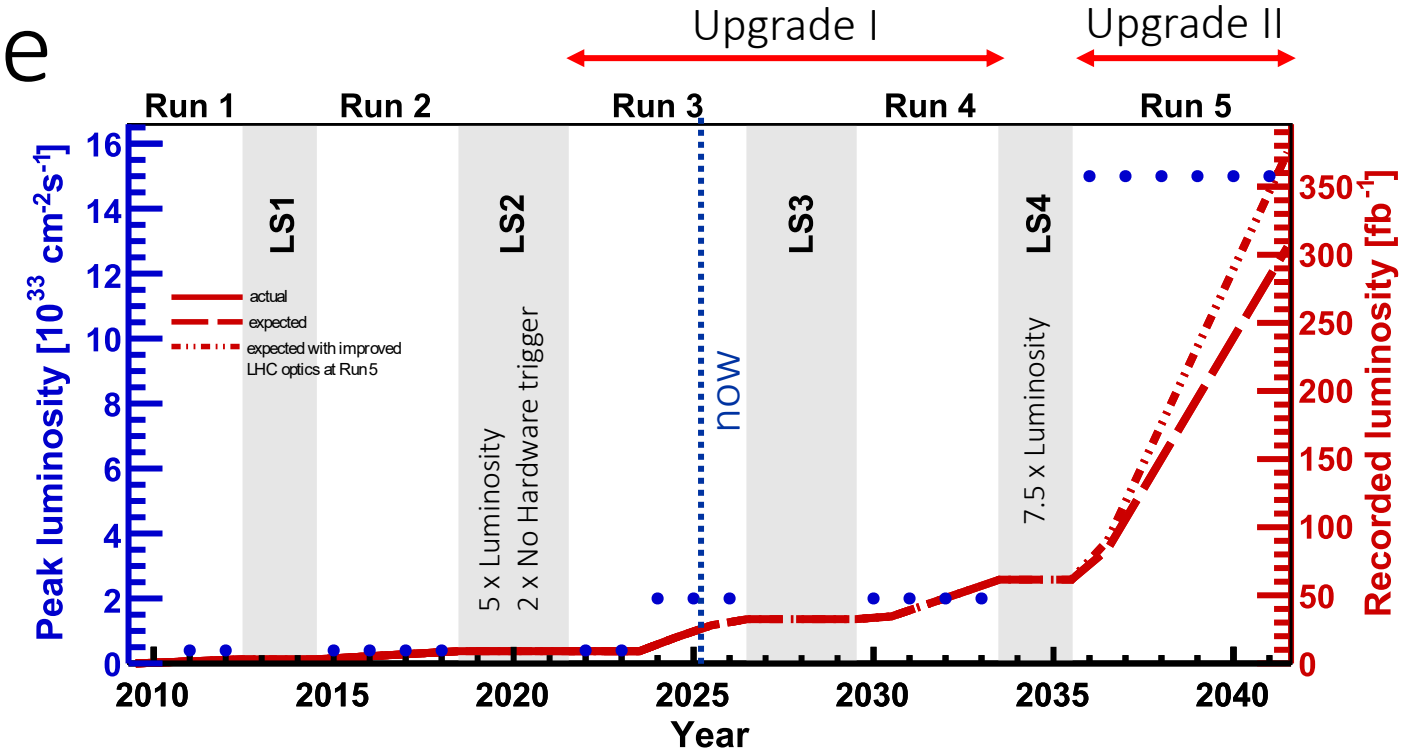
LHCb Upgrade II

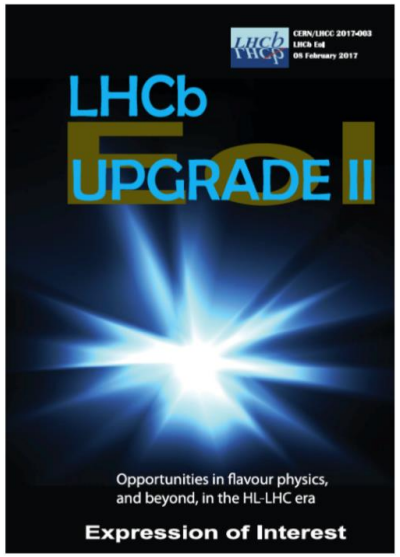
LHCb Upgrade 2 Schedule

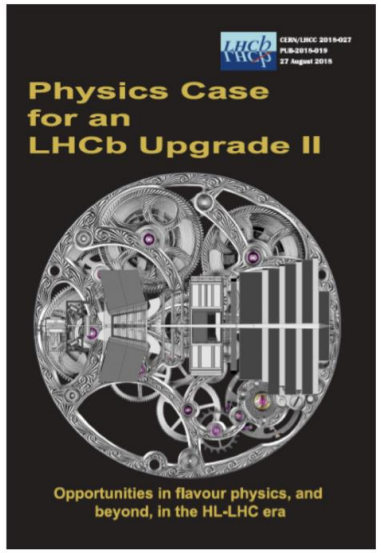
Current: Upgrade I in full operation

2017: Expression of interest
2018: Physics case
2022: Framework Technical design report

2021-2025: Initial R&D phase
2025: Scoping TDR
2026: Technical design reports
2029-2033: (R&D+) Production phase
2035: LHCb Upgrade II / Start of Run 5

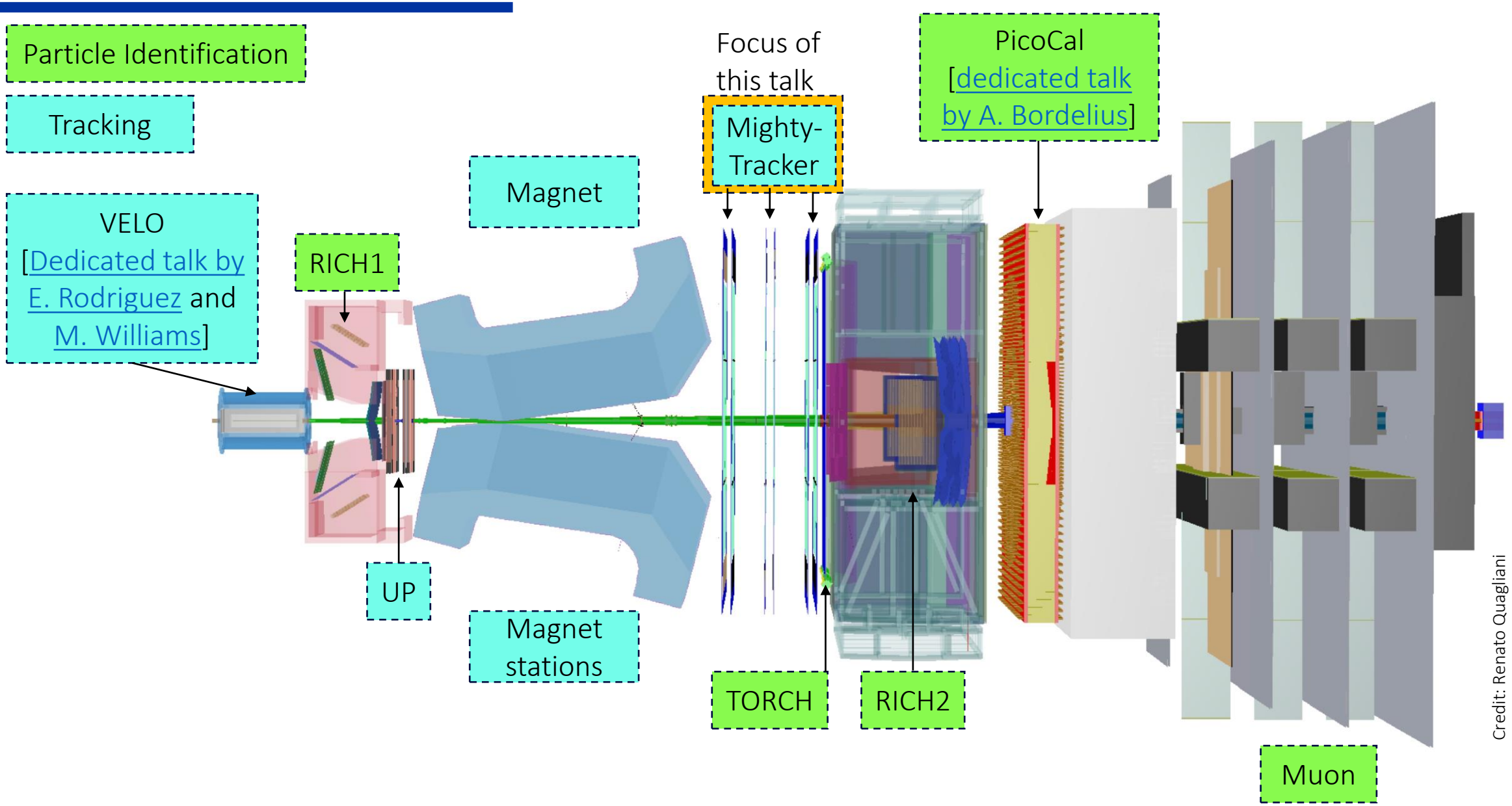






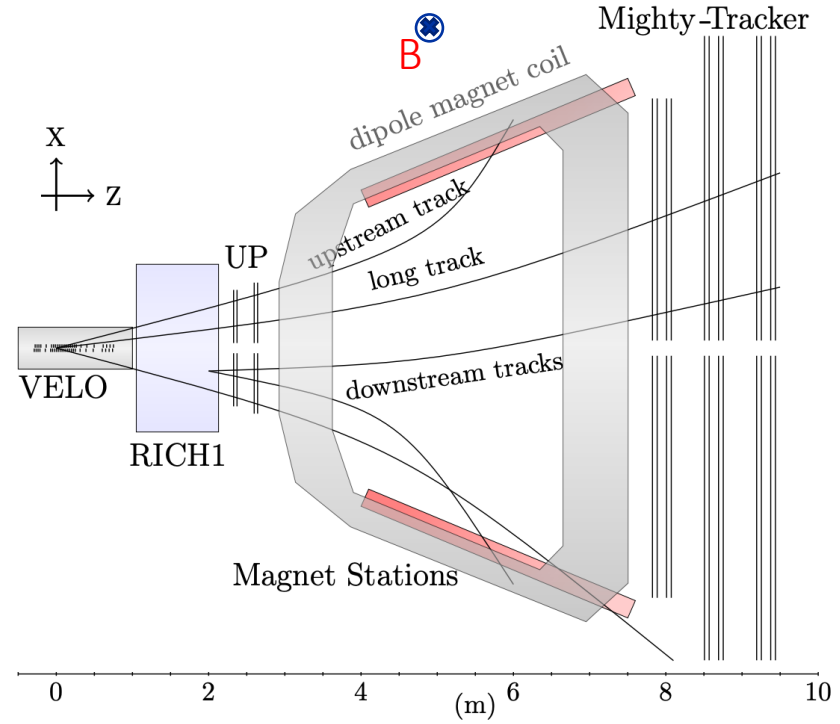
LHCb Upgrade II

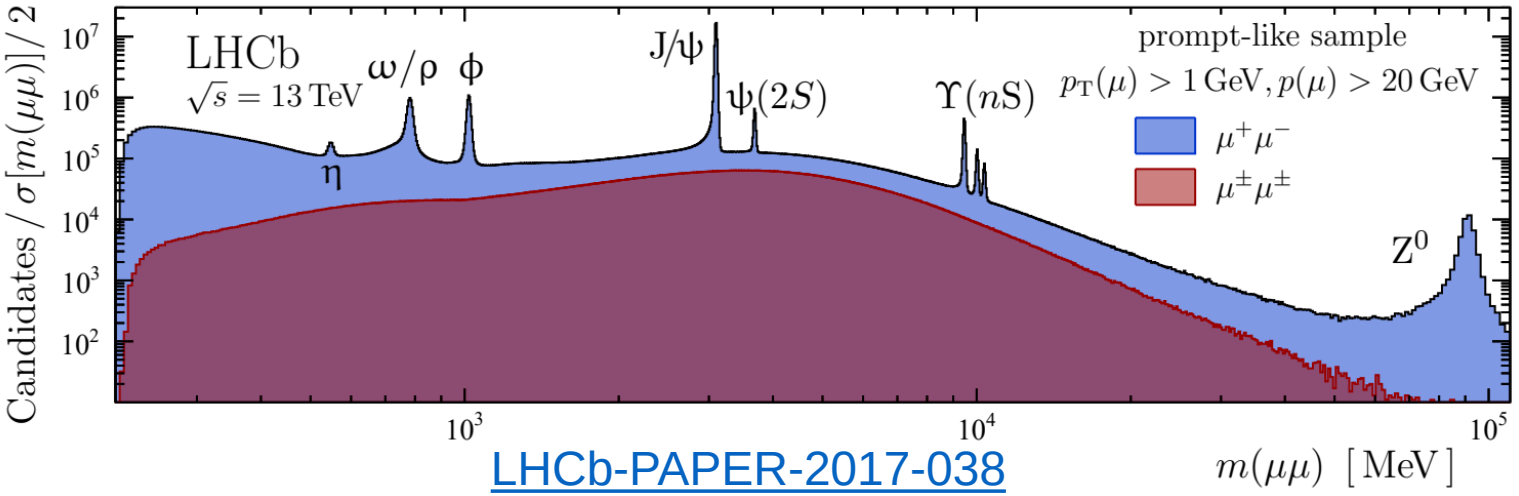
CERN-LHCC-2021-012



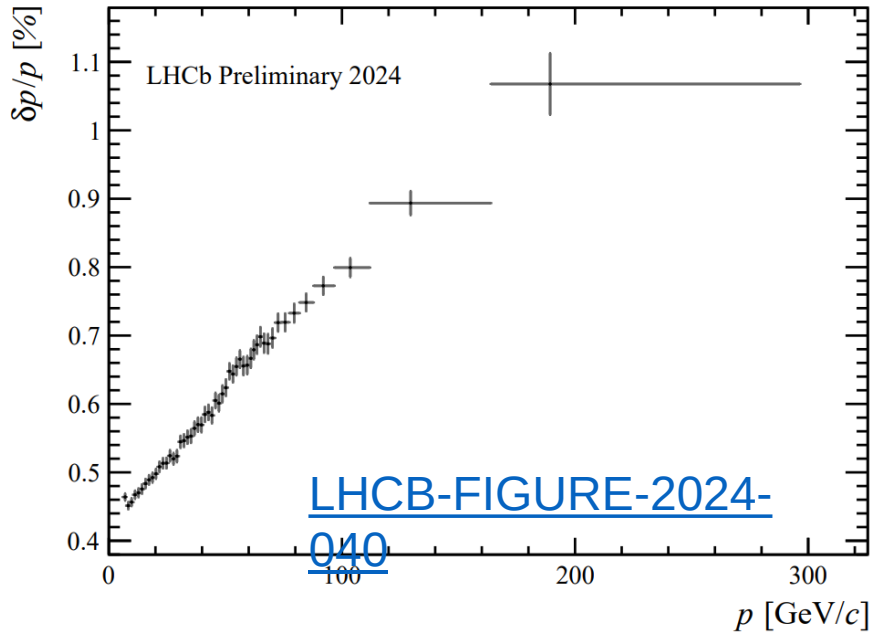
LHCb Tracking system

- Combination of different track segments coming from different subdetectors (VELO, UP, Magnet Stations and Mighty-Tracker)
- Excellent momentum resolution for the LHCb ranging from 0.5% up to 1.1% (up to a momentum of 200 GeV)
- Challenge: harsher radiation levels and particle rates in the upgrade II
  - Lightweight as possible ($< 1 - 2\%\ X_0$ per station/layer)





LHCb-PAPER-2017-038



LHCB-FIGURE-2024-040

Current Scifi (Upgrade I)

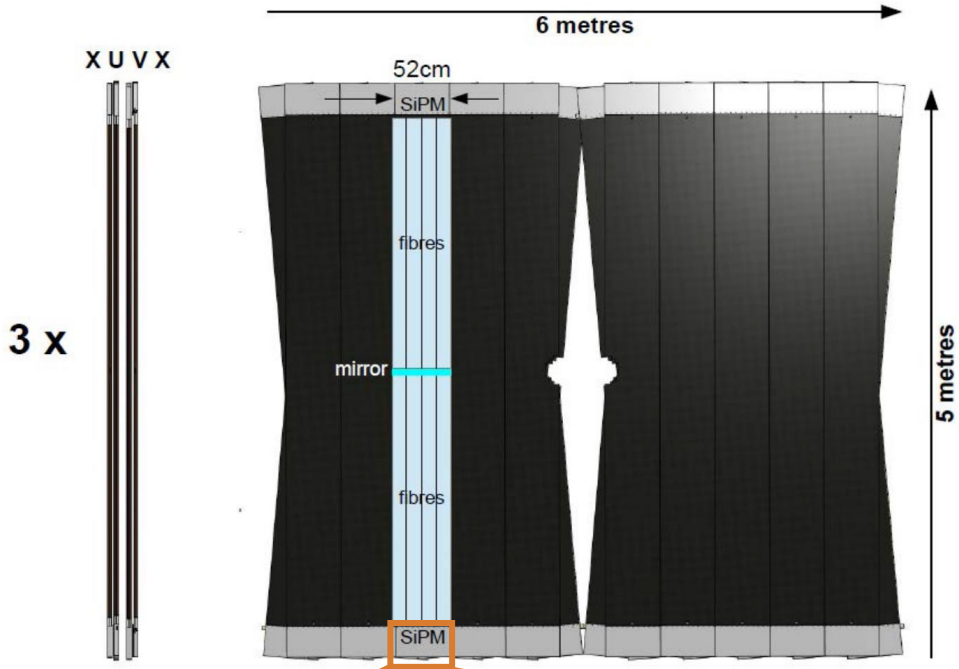
LHCb-TDR-015 j.nima.2019.03.080

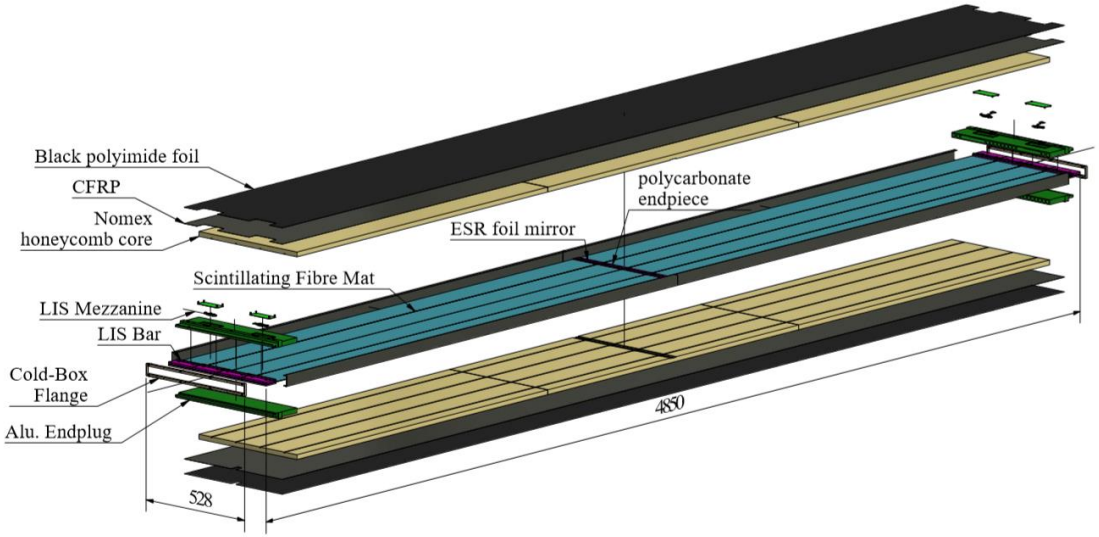
Scintillating fibre have a diameter of $250\mu m$

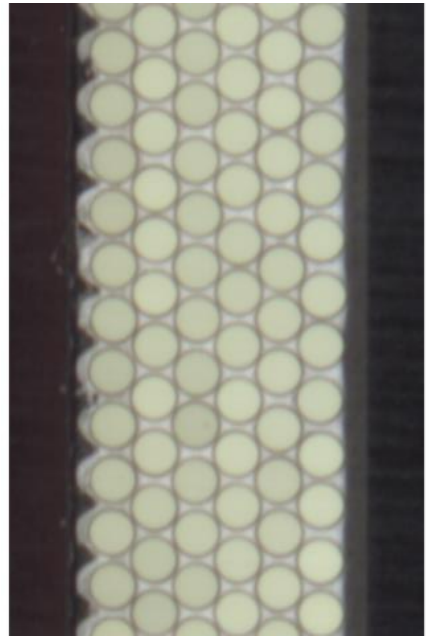
- grouped in 6 fibre layers per detector layer
- 3 groups of XUVX planes ($0°, -5°, +5°$ and $0°$)
- more than 10000km of fibres were winded to produce all modules

Hit efficiency $\approx 99\%$ and hit resolution $< 100\mu m$

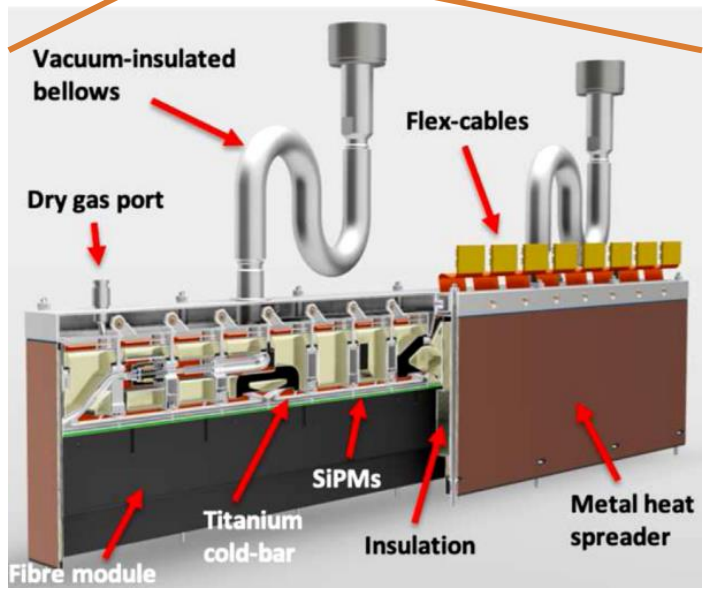
Total material budget $< 1\% X_0$ per layer







Poster by L. Witola

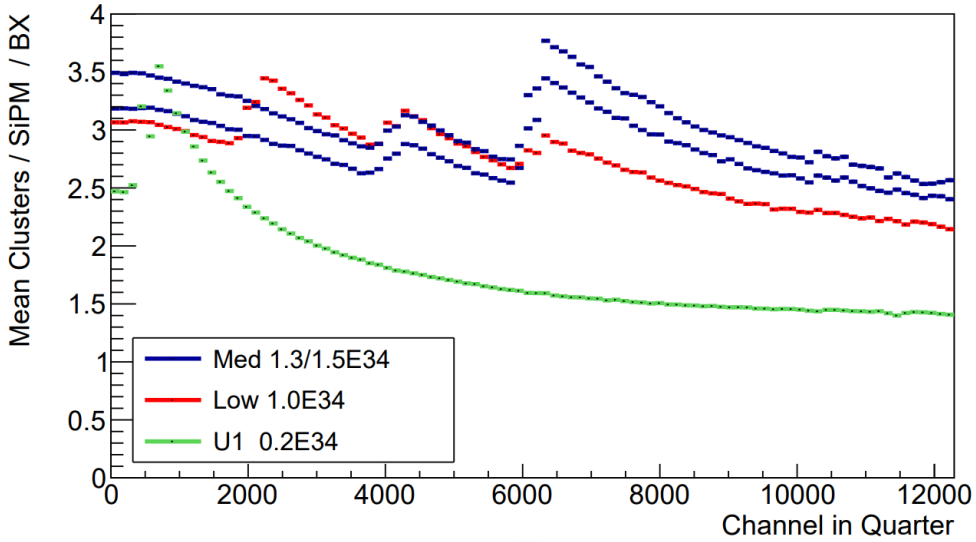


Mighty-Tracker (Upgrade II)

LHCb-TDR-023

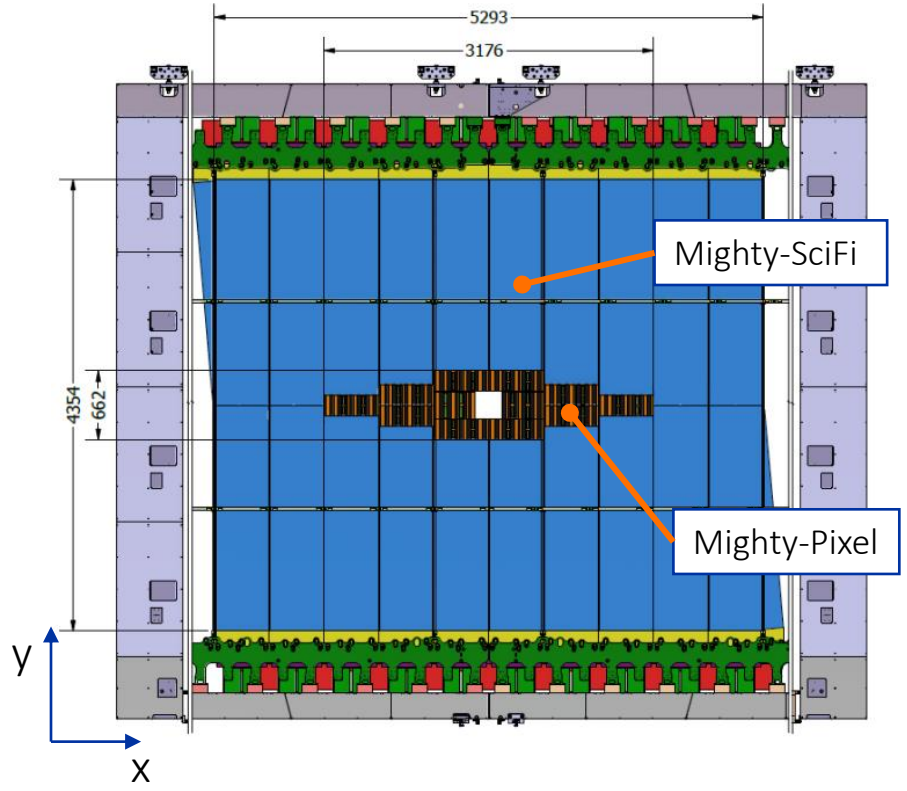
Run 5

- $L_{inst} = 1.5 \times 10^{34} cm^{-2} s^{-1}$
  - 7.5 times higher than Upgrade 1 luminosity
- Radiation up to 3×10^{14} MeV neq/cm²
- Fibres would have a sizeable radiation damage in the inner region and suffer with high occupancy (up to 16%/fiber)

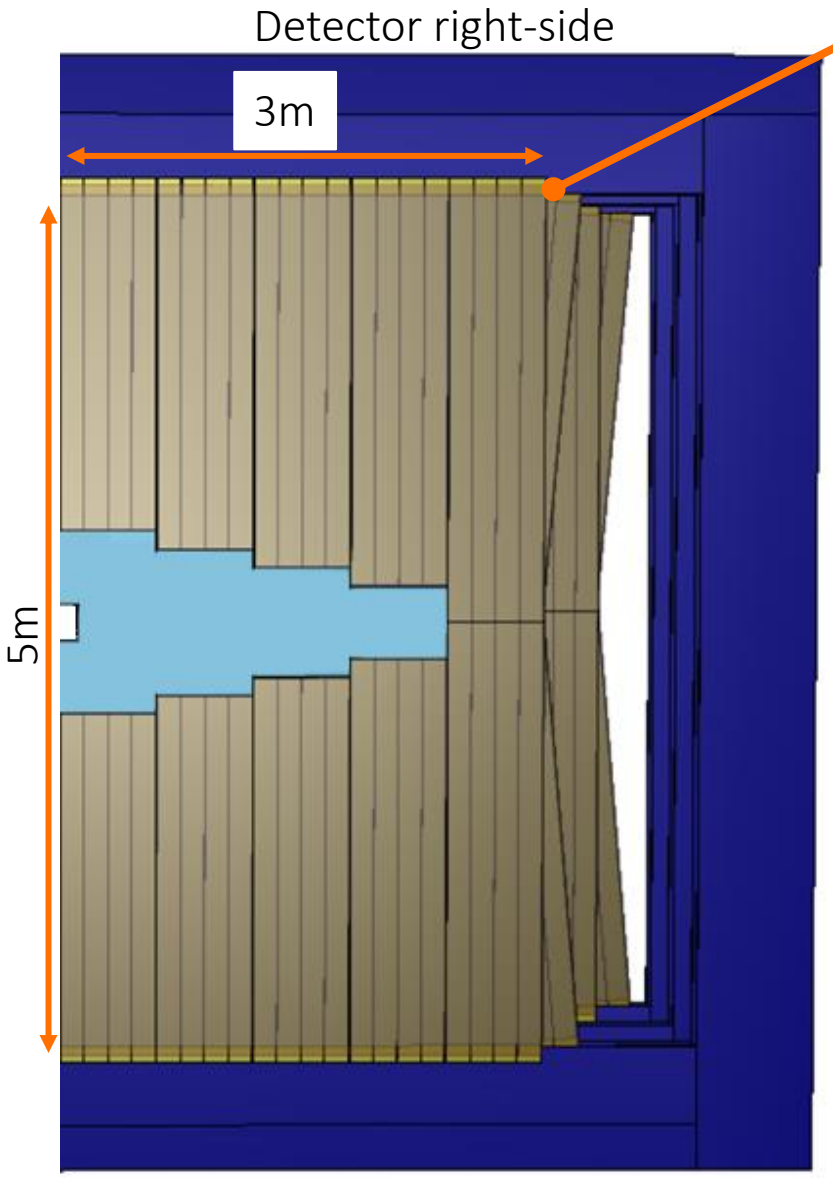


Solution

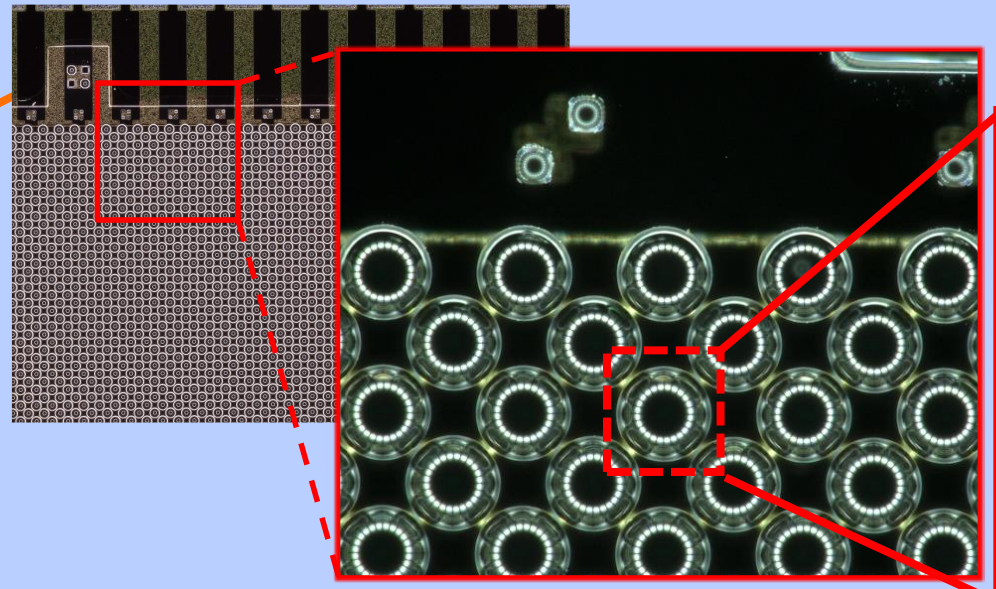
- Scintillating fibres (Mighty-SciFi) cover most of the surface
  - ~10x more cost effective
- Inner region based on silicon detector technology (Mighty-Pixel)
  - Localised in the region of higher particle rates
  - Asymmetric shape due to the bending plane over x

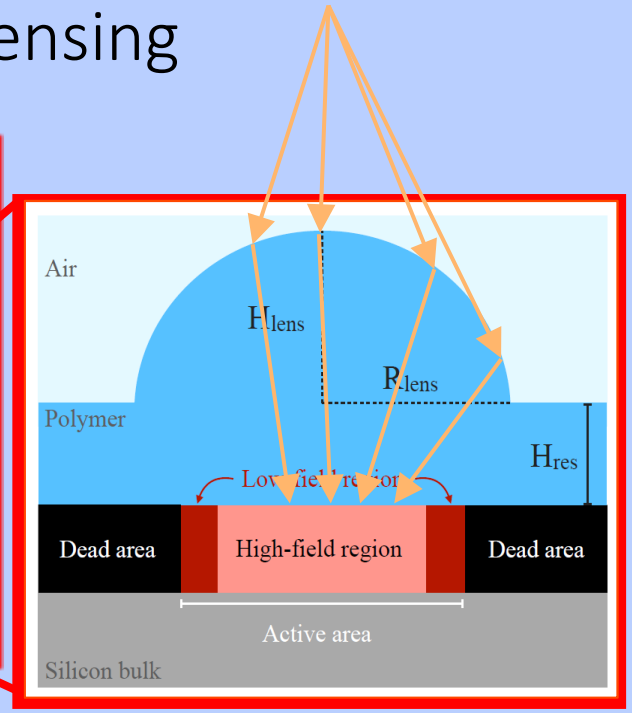


Mighty-SciFi



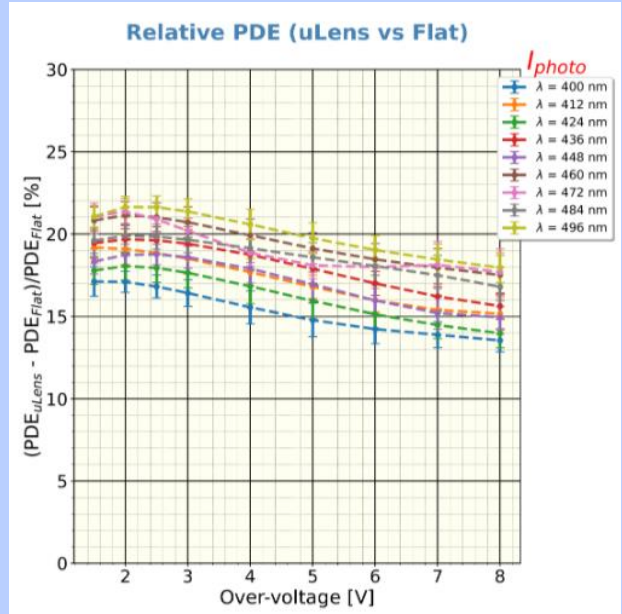
Silicon photomultiplier + microlensing





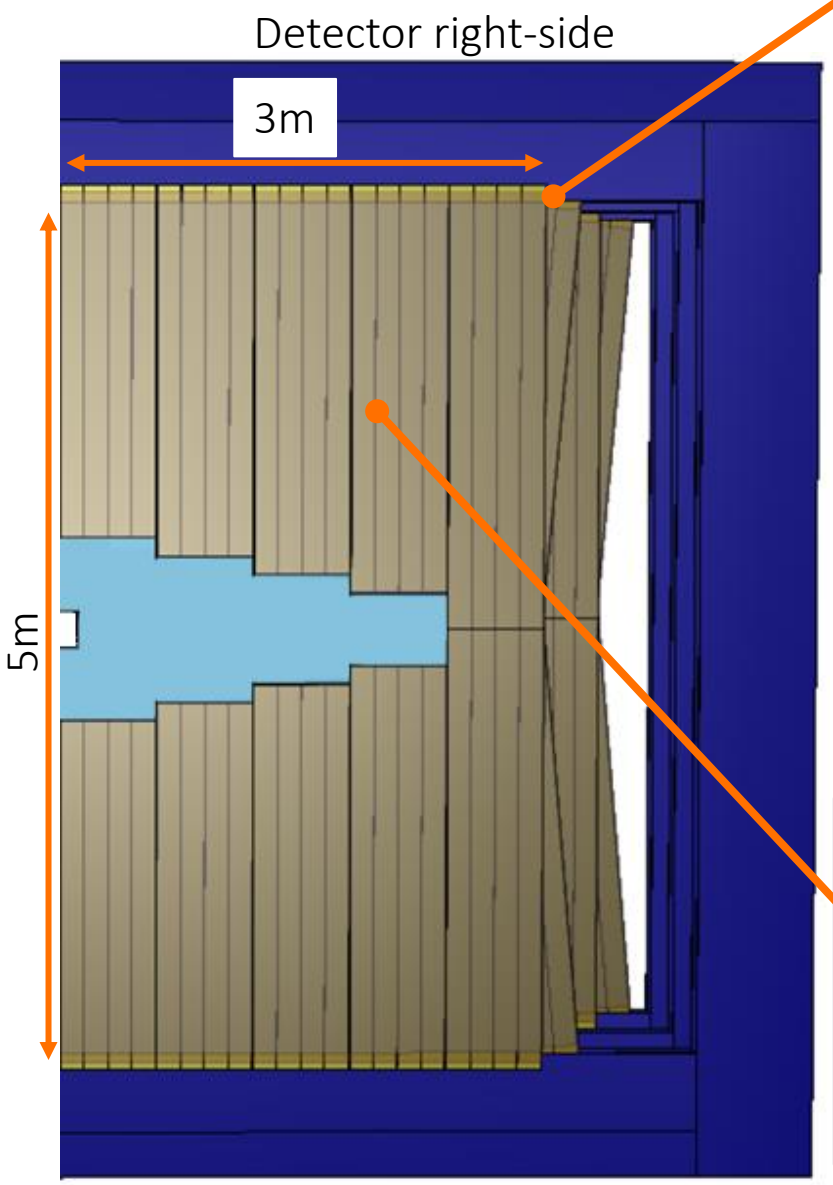
Photon detection efficiency is improved by focusing the incident photons in the active area

- Photons heading towards low/field dead areas refracted to the active area
- Better geometric fill factor obtained
- Improvement of $\sim +20\%$



Dedicated talk by F. Ronchetti

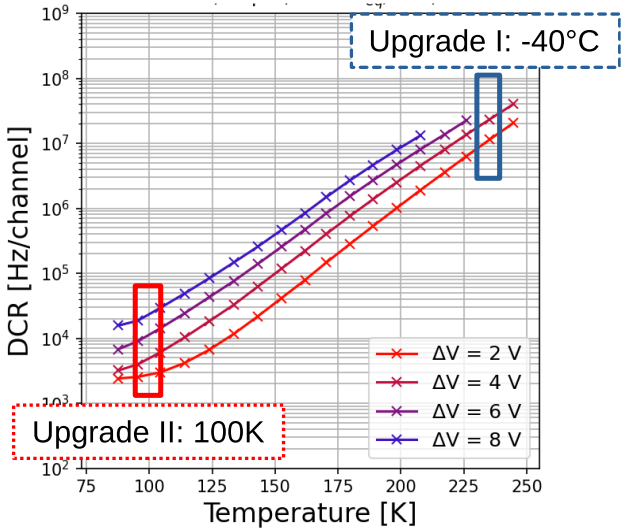
Mighty-SciFi

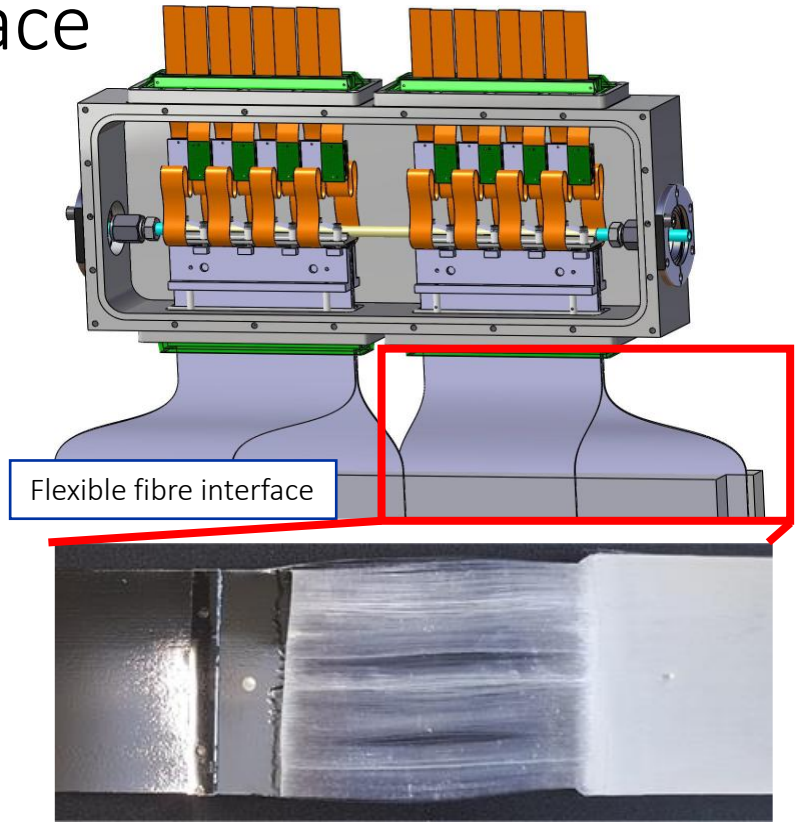


Cryogenic and interface

Operating temperature SiPM around 100K to reduce the dark count rate of thermal electrons

Flexible interface shows no sizeable loss



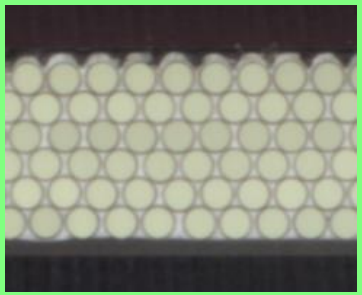


Dedicated talk by E.C Rivera

Scintillating fibre

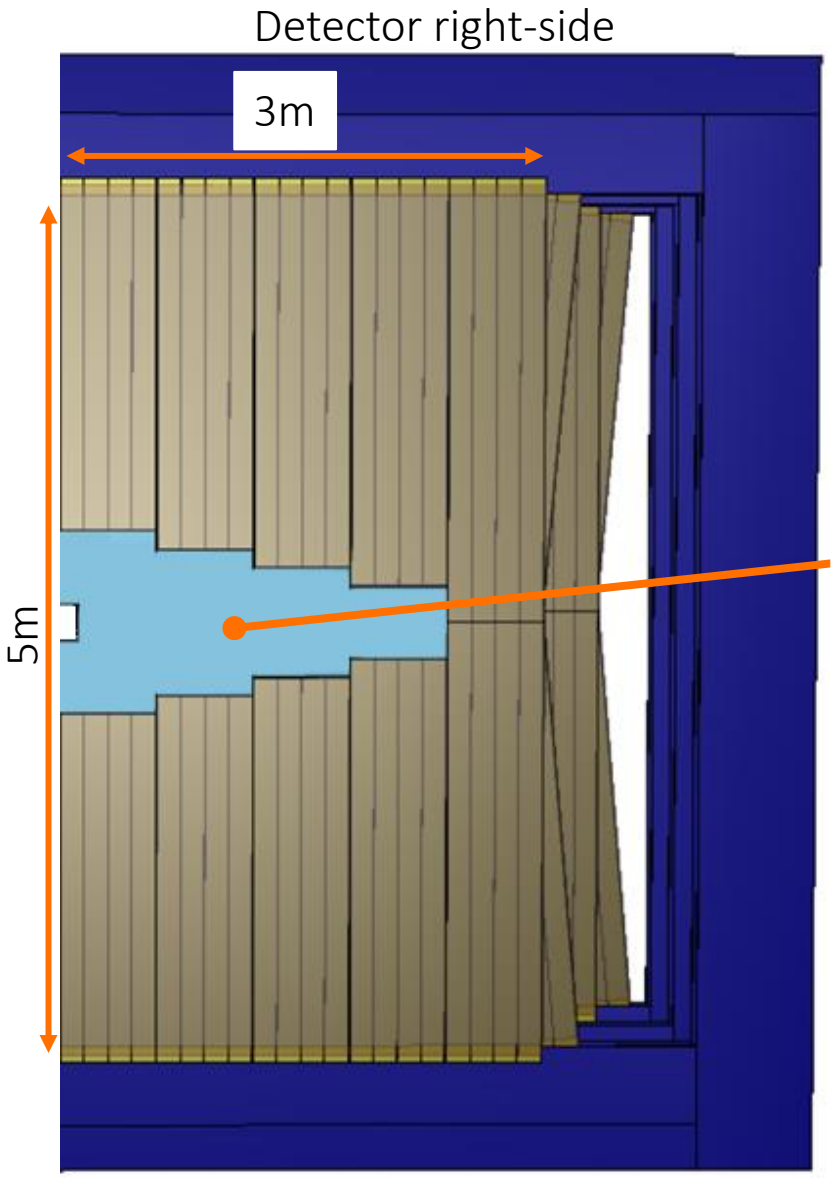
SciFi Upgrade 1 – 6 layers

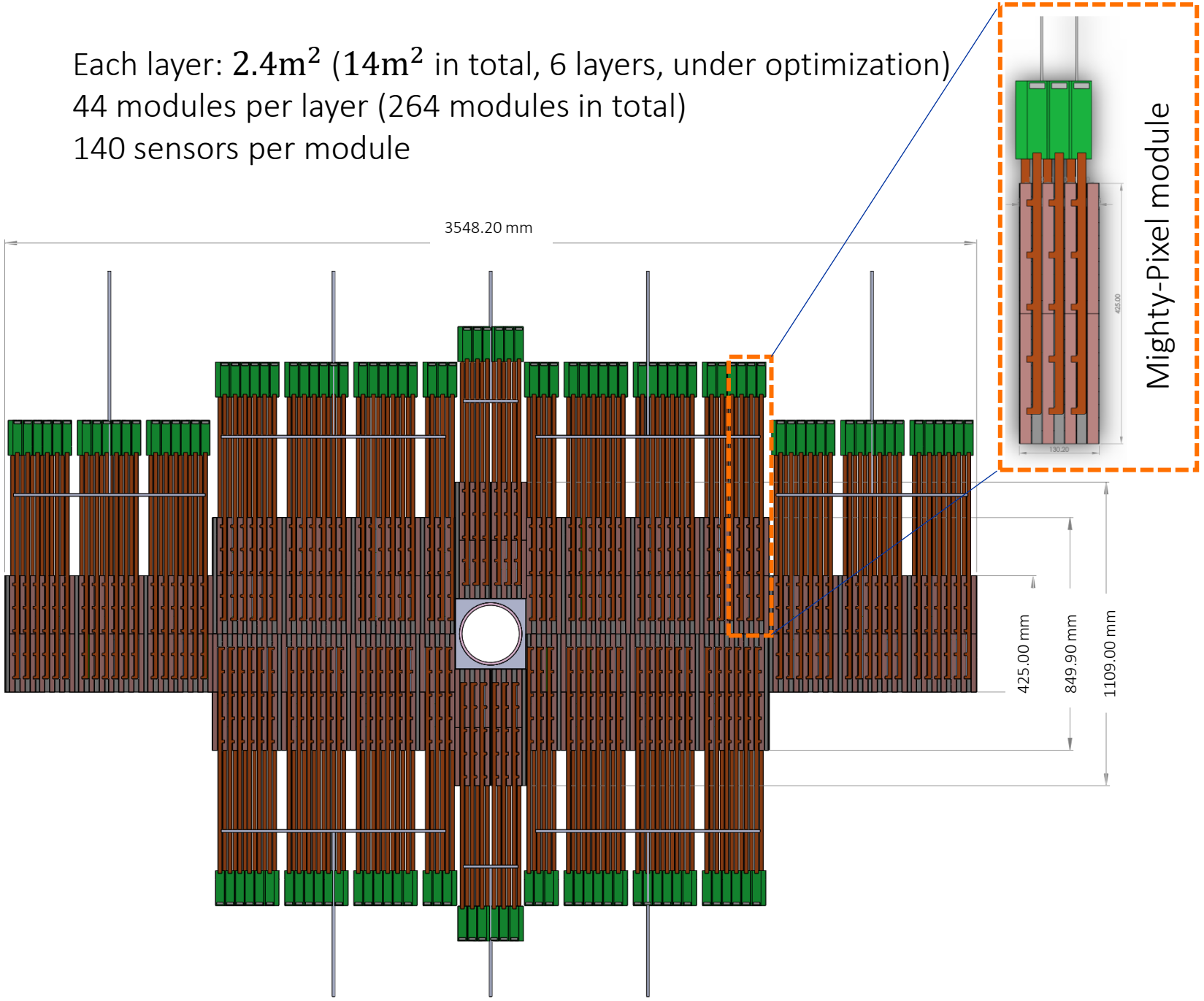
- Reduction in the fibre layers from 6 to 4 to further reduce the material budget contribution (under study)
- Fibre with better attenuation length are being investigated
- Reduction in the hit cluster size would improve the σ_x and less material



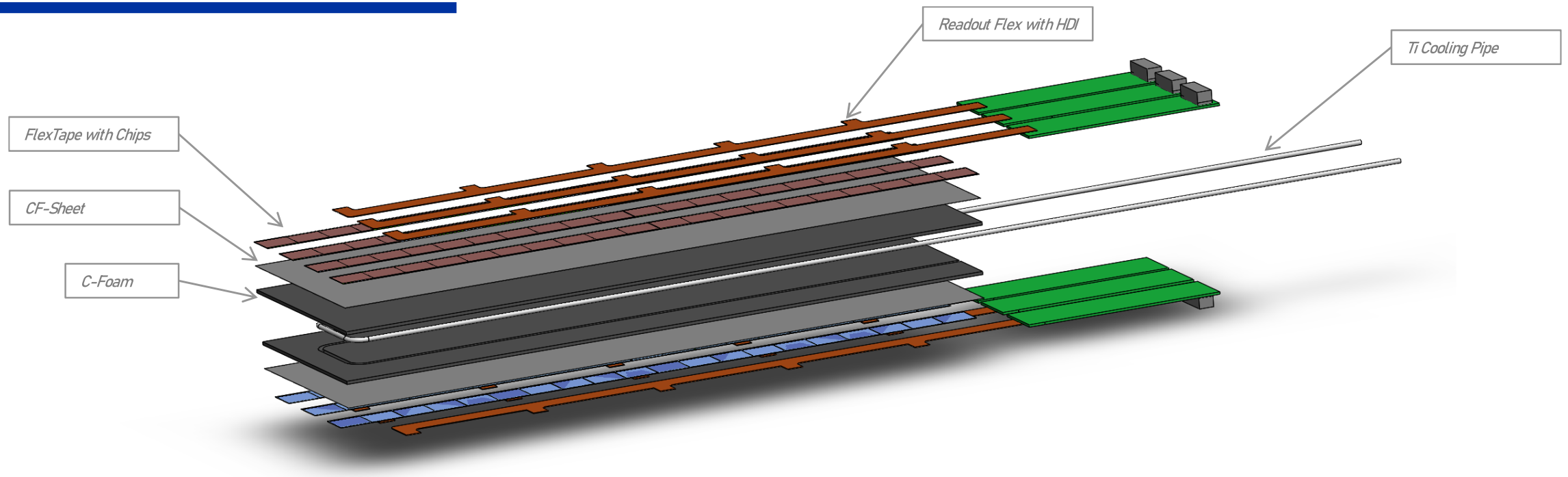
Mighty-Pixel layer

Each layer: 2.4m^2 (14m^2 in total, 6 layers, under optimization)
44 modules per layer (264 modules in total)
140 sensors per module



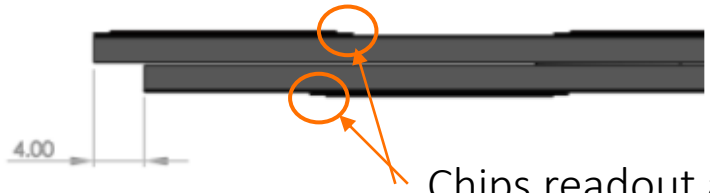


Mighty-Pixel: Module

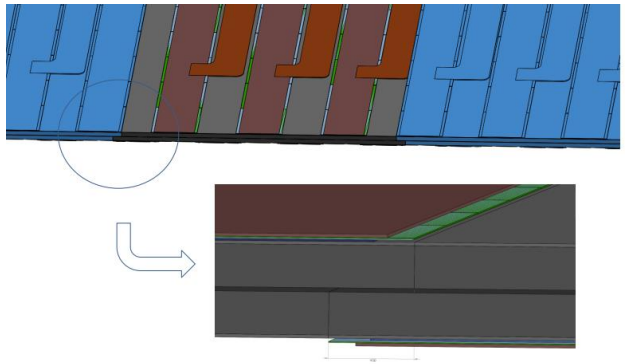


Reduction in dead areas

Double side population to compensate the sensor readout area



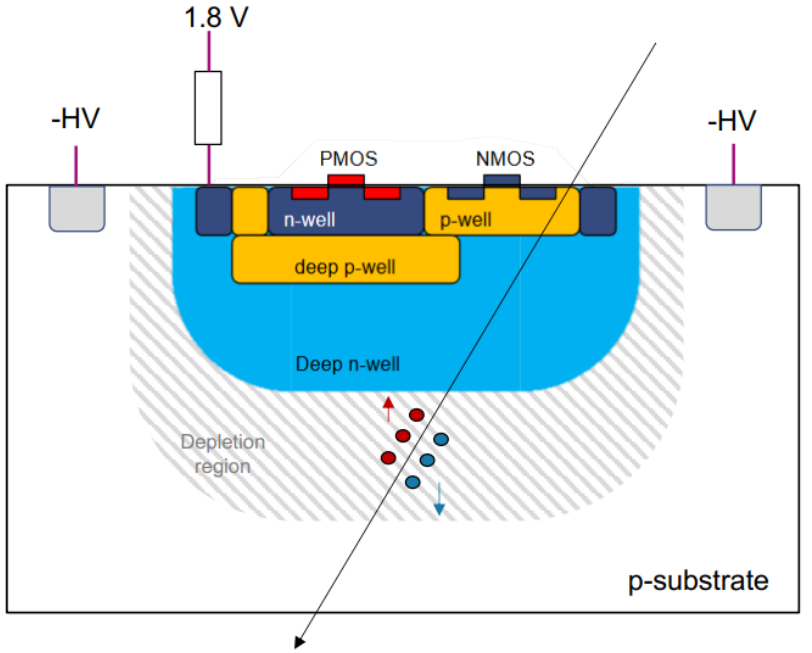
No dead areas between modules



MightyPix

Based on HV-CMOS design based on the experience of ATLASPix and MuPix

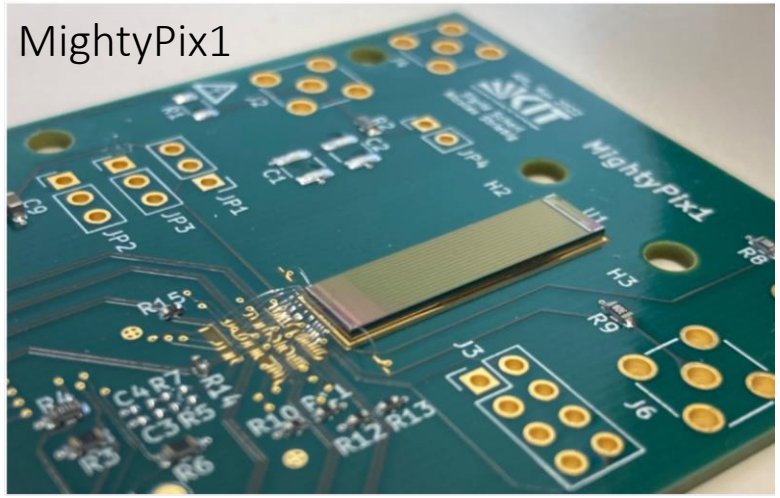
- Sensor and readout electronics are integrated in the pixel (amplifier and comparator)

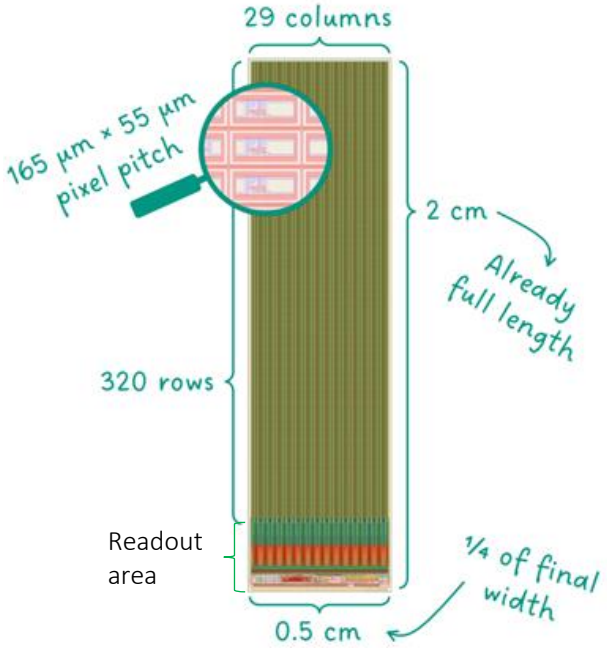


Working principle of HV-CMOS sensors.

MightyPix1

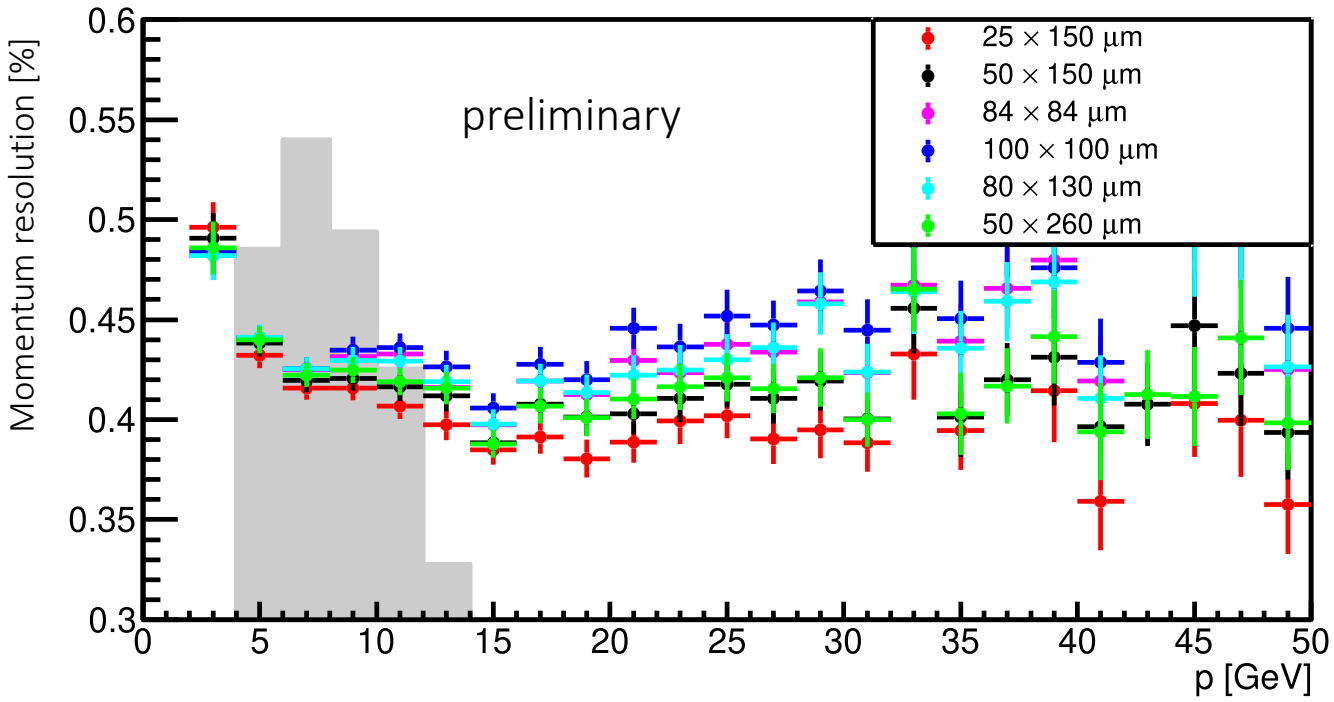
- TSI 180 nm process (ended)
- Pixel:
  - $165\mu m \times 55\mu m$
  - CMOS amplifier and comparator
  - Including LHCb time and fast control
  - Data output rate: 1.28 Gbit/s
- First version of the chip with ¼ of the total area (MightyPix1)





MightyPix

Parameter	MightyPix specification
Pixel size (bending plane)	$\leq 100\mu m$ ($84\mu m$ baseline)
Pixel size (non bending plane)	$\leq 200\mu m$ ($84\mu m$ baseline)
Substrate thickness	$< 200\mu m$
Max. Particle Hit Rate	$17 MHz/cm^2$
Noise rate (End of life)	$< 400 kHz/cm^2$
Non-ionizing energy loss (NIEL)	$3 \times 10^{14} MeV\ neq/cm^2$
Total ionizing dose (TID)	$40 MRad$
Cooling	$< 0°C$
Power consumption	$150 mW/cm^2$
In-time efficiency	$> 99\%$ within 25 ns (<3 ns intrinsic time resolution)



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2024 JINST 19 C04045

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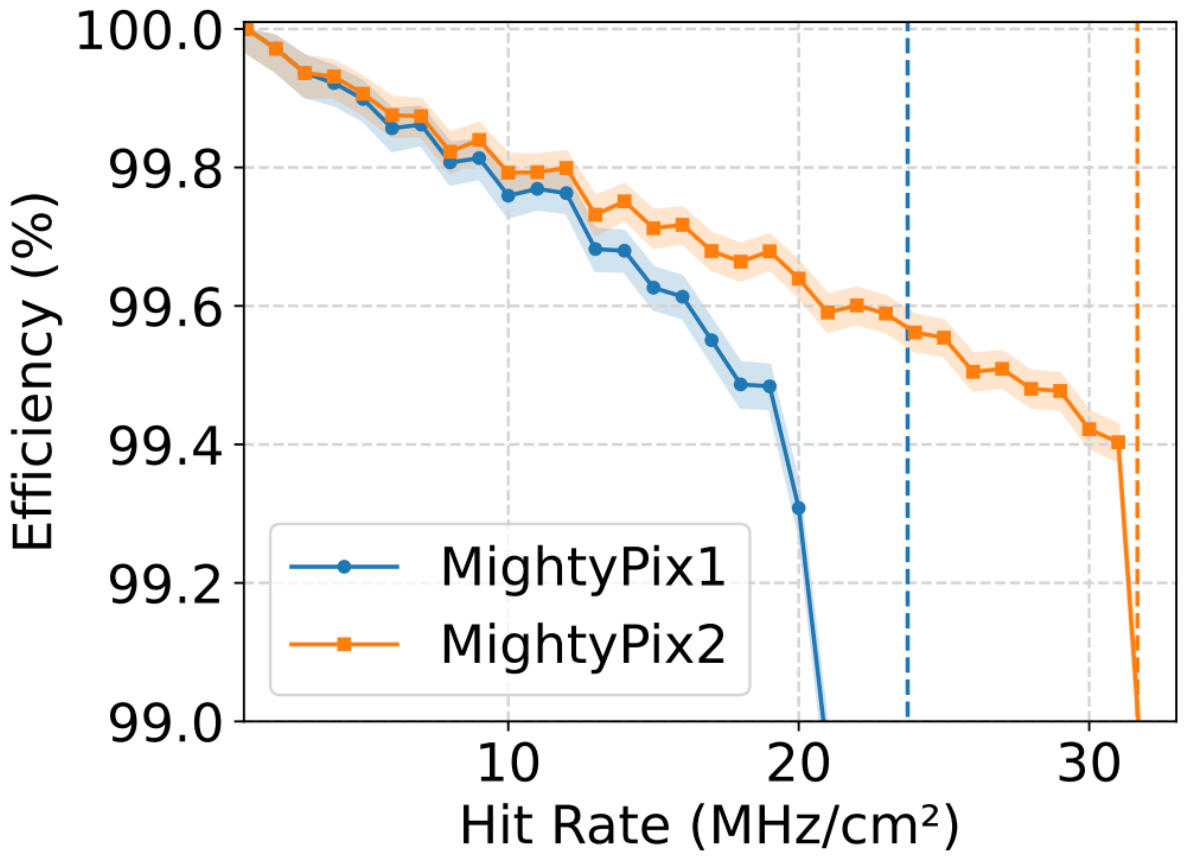

Improvement by reducing the data format from 64 bit to 48 bit
(further improvements expected when reduced to 32 bit)

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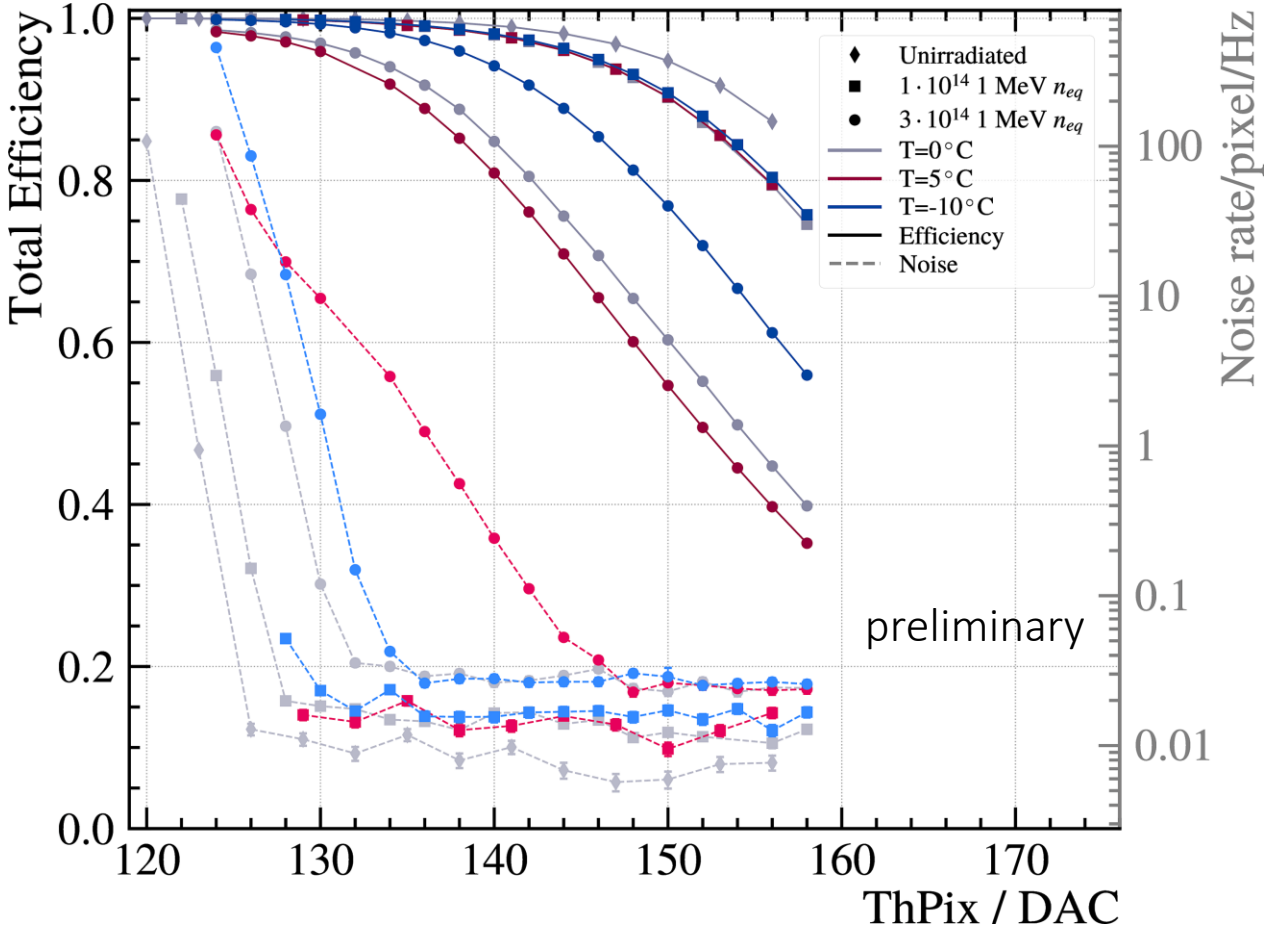
PoS Pixel2022 (2023) 084

Efficiency and noise with a similar sensor (ATLASPix 3.1)



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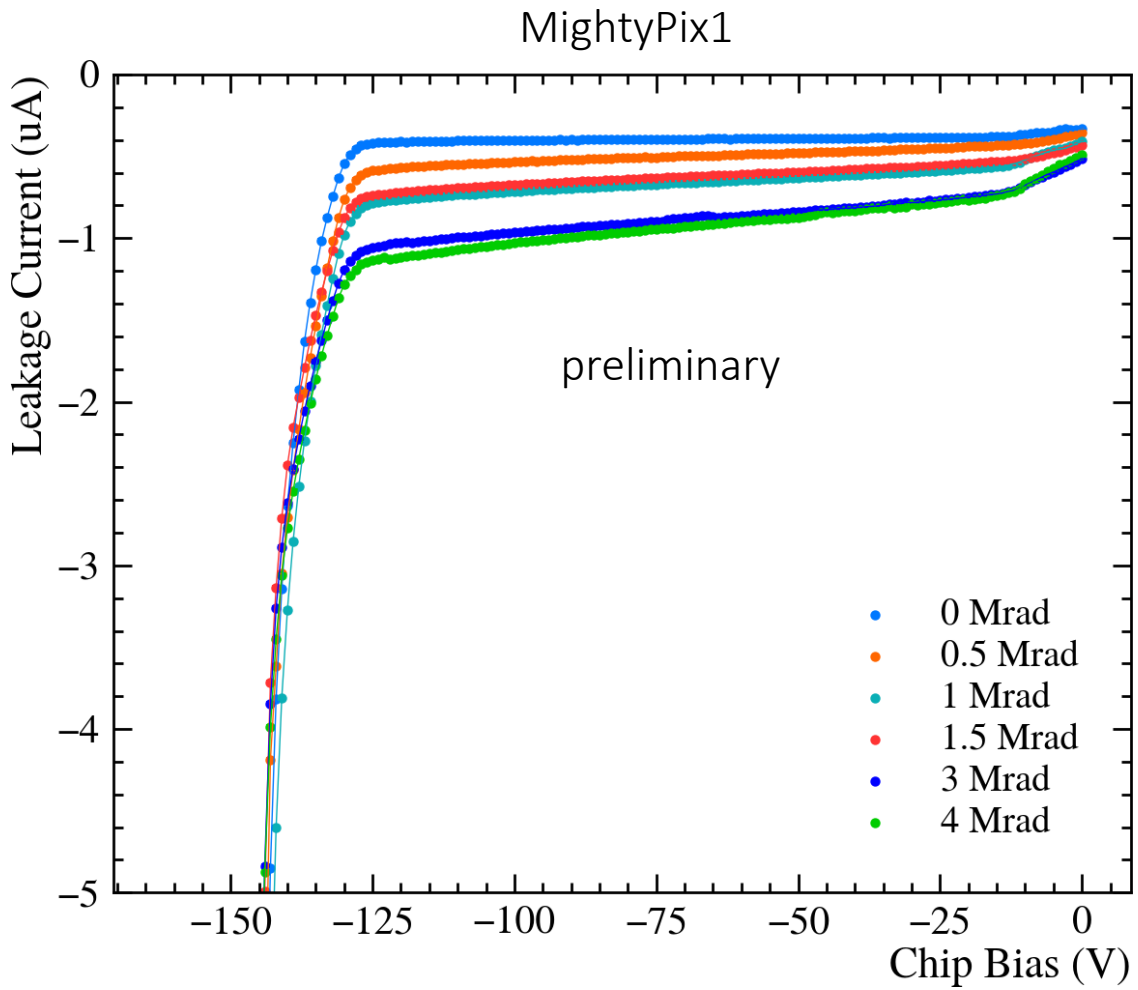

Higher ionizing doses results coming soon

MightyPix

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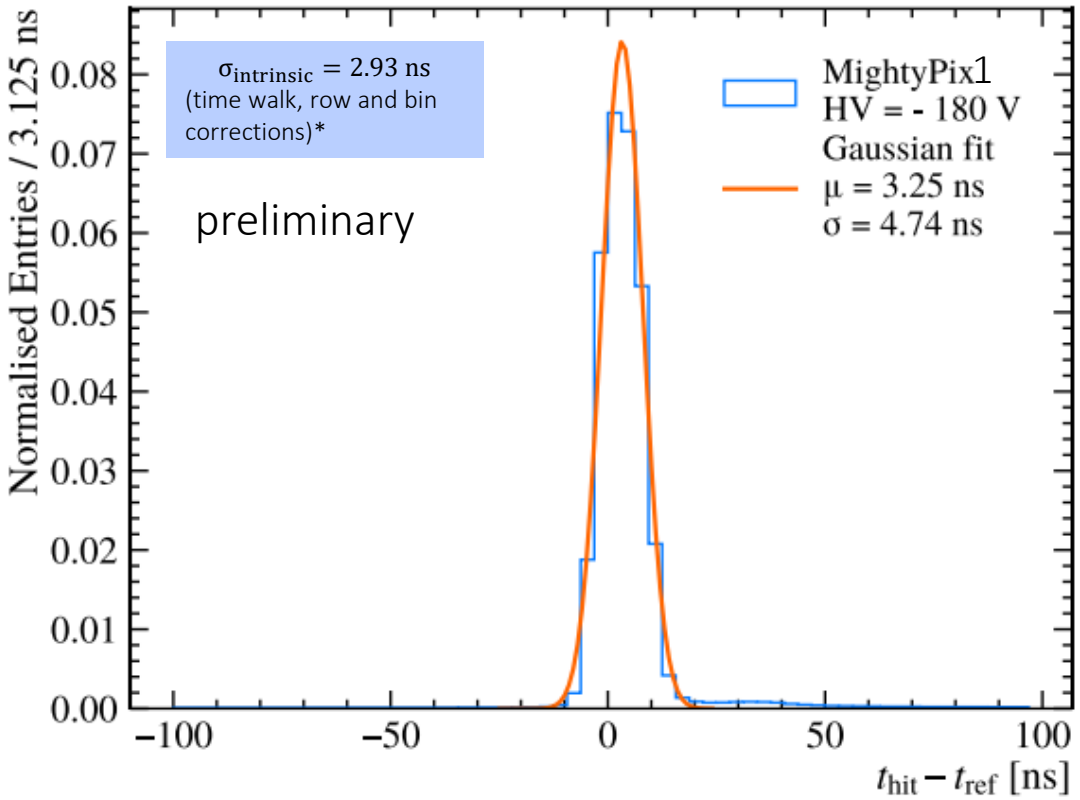
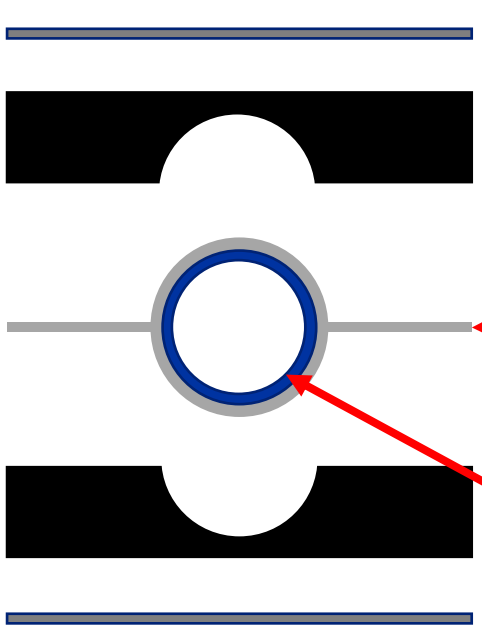


*Time bin of 12.5 ns used to calculate the intrinsic sensor resolution

Mighty-Pixel: *Baby* Modules

Exploded view



Carbon fibre - Cocuring in Liverpool University (~150um)

Carbon foam
- Lockheed-Martin
- Alternatives such as PocoFoam being considered

Carbon veil + Glue (Hysol)
- Foam-Foam attachment

Glue around tube (Hysol+Graphite)
- Similar to the local Atlas end-caps production

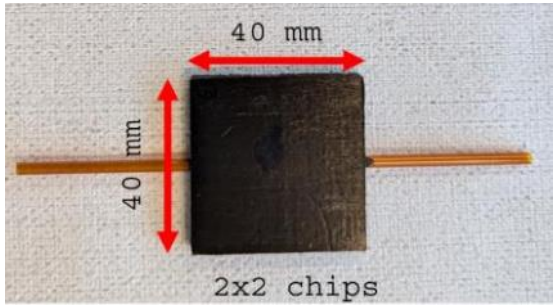
Tubes

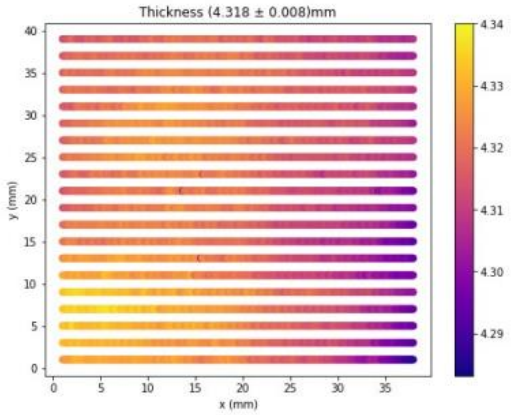
Polyimide tubes (initial prototypes, liquid cooling)

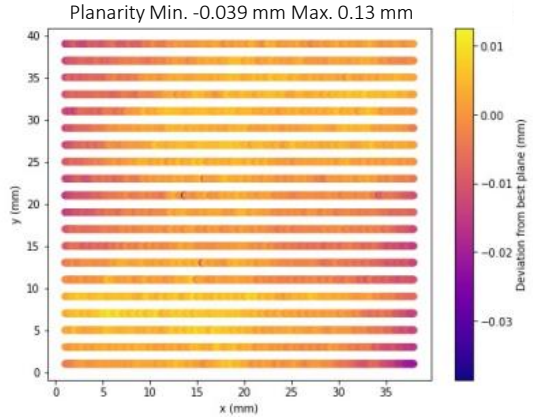
Titanium tubes (New baseline, Evaporative CO_2)

Requirements:
- Ultra-light structure ($< 1\% X_0$)
- Mechanically robust for module support
- Reproduceable thickness and good planarity

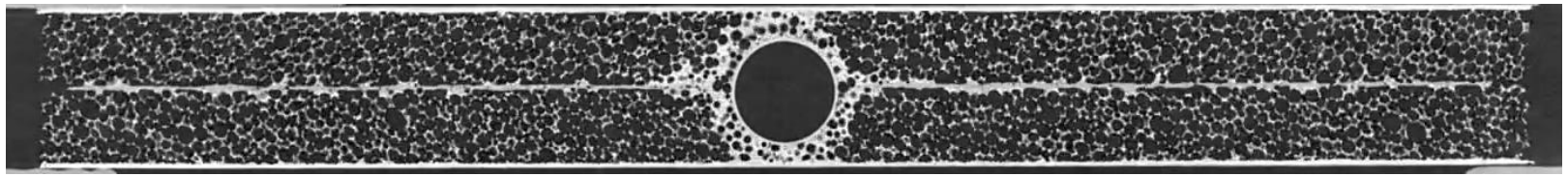
Sample







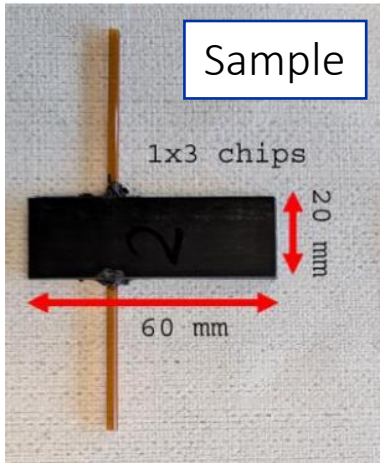
Cross section scan using x-ray tomography (NXCT UK)



Mighty-Pixel: cooling and thermal uniformity

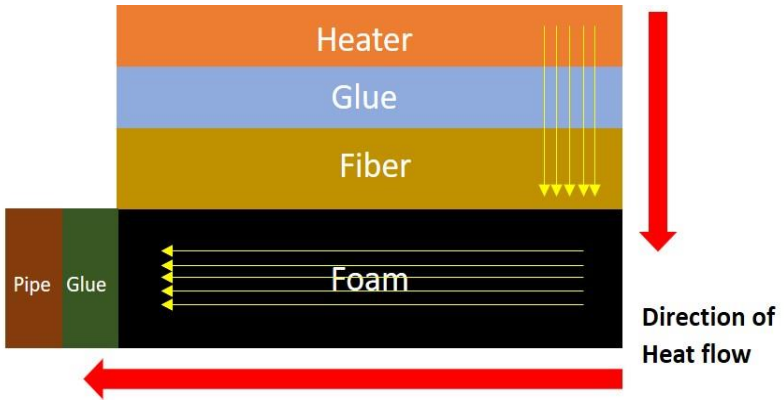
Requirements:

- Variation of temperature between coolant and hottest point on the surface (chip) below $20°C$
  - To allow the sensors to be operated $\leq -10°C$
- Including safety factor in power dissipation (x2)
- Good thermal uniformity within a sensor

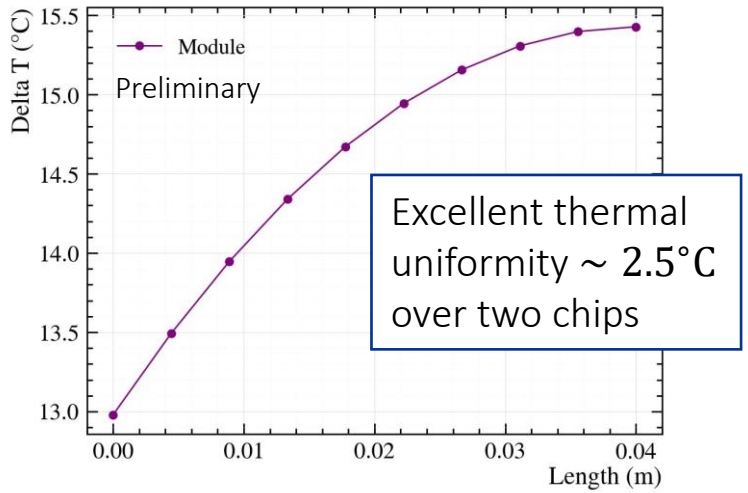


Simplified Analytical calculation

$$Heat\ load = 0.3 W/cm^2$$



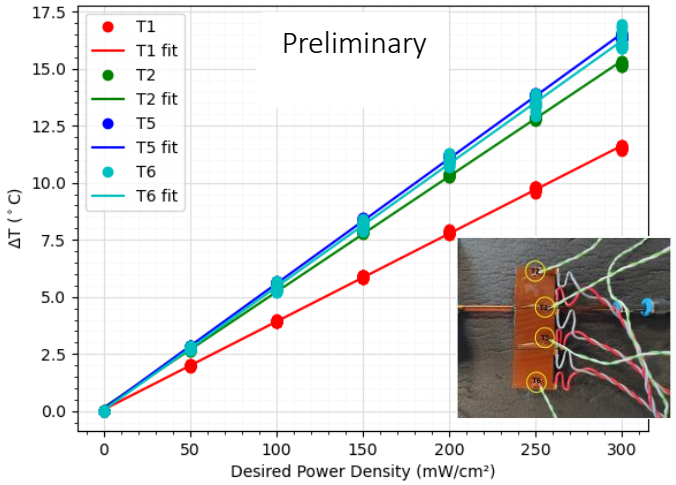
$\Delta T\ for\ 2\ chips$



Excellent thermal uniformity $\sim 2.5°C$ over two chips

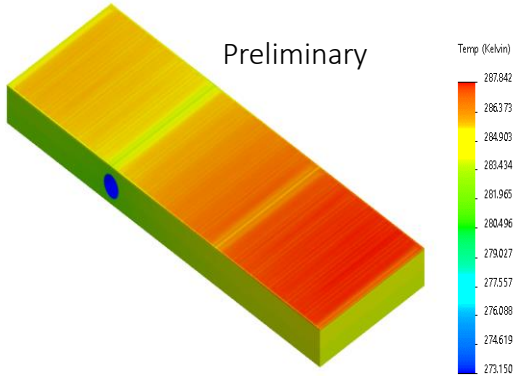
Thermal Measurements

$\Delta T = 16.5°C$ for $300 mW/cm^2$



FEA (Solid works)

$T\ Pipe = 0°C$
$T\ Hottest = 14.6°C$
$\Delta T = 14.6\ °C$



Predictions within 12% compared with the measurement!

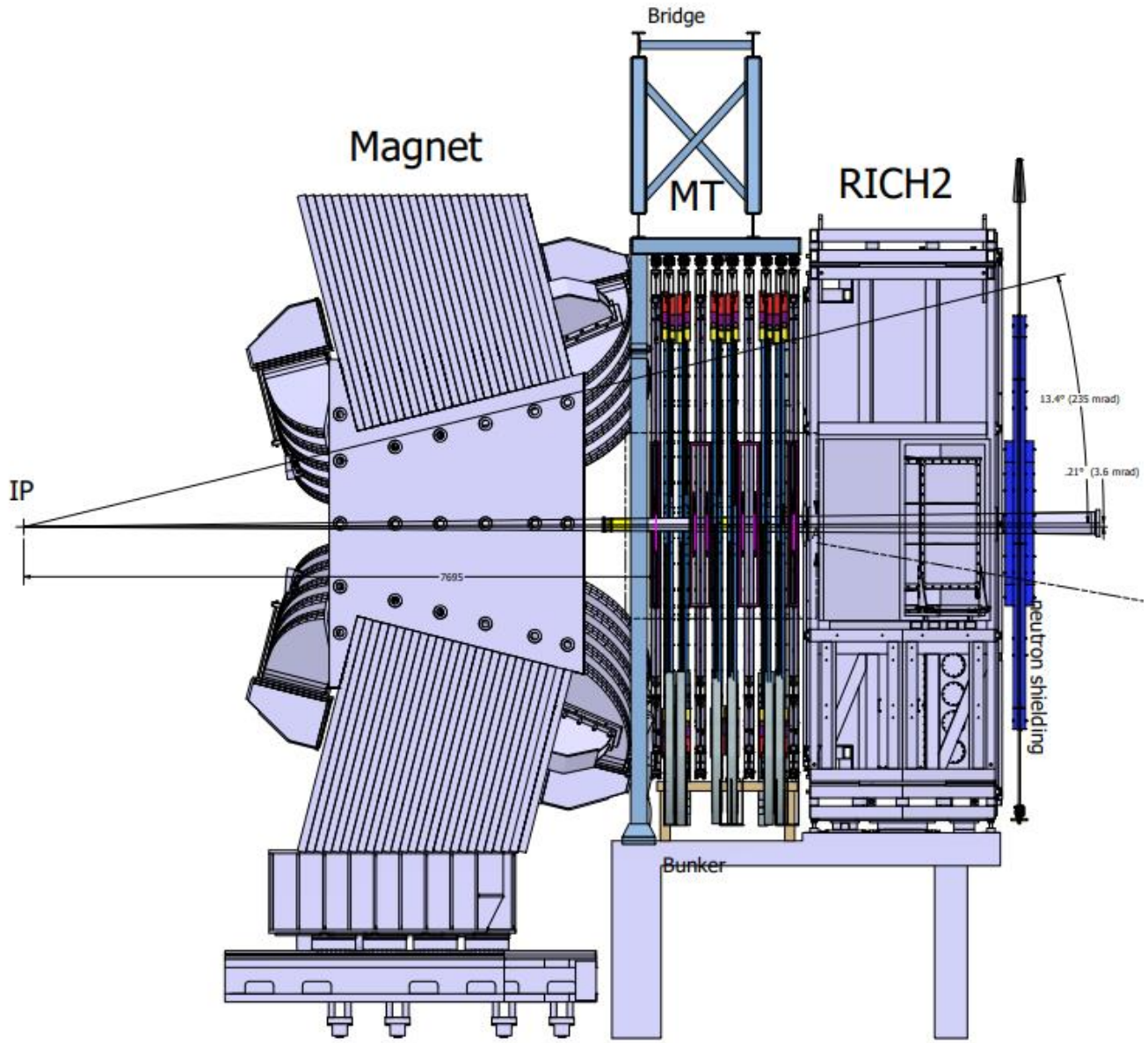
Final remarks

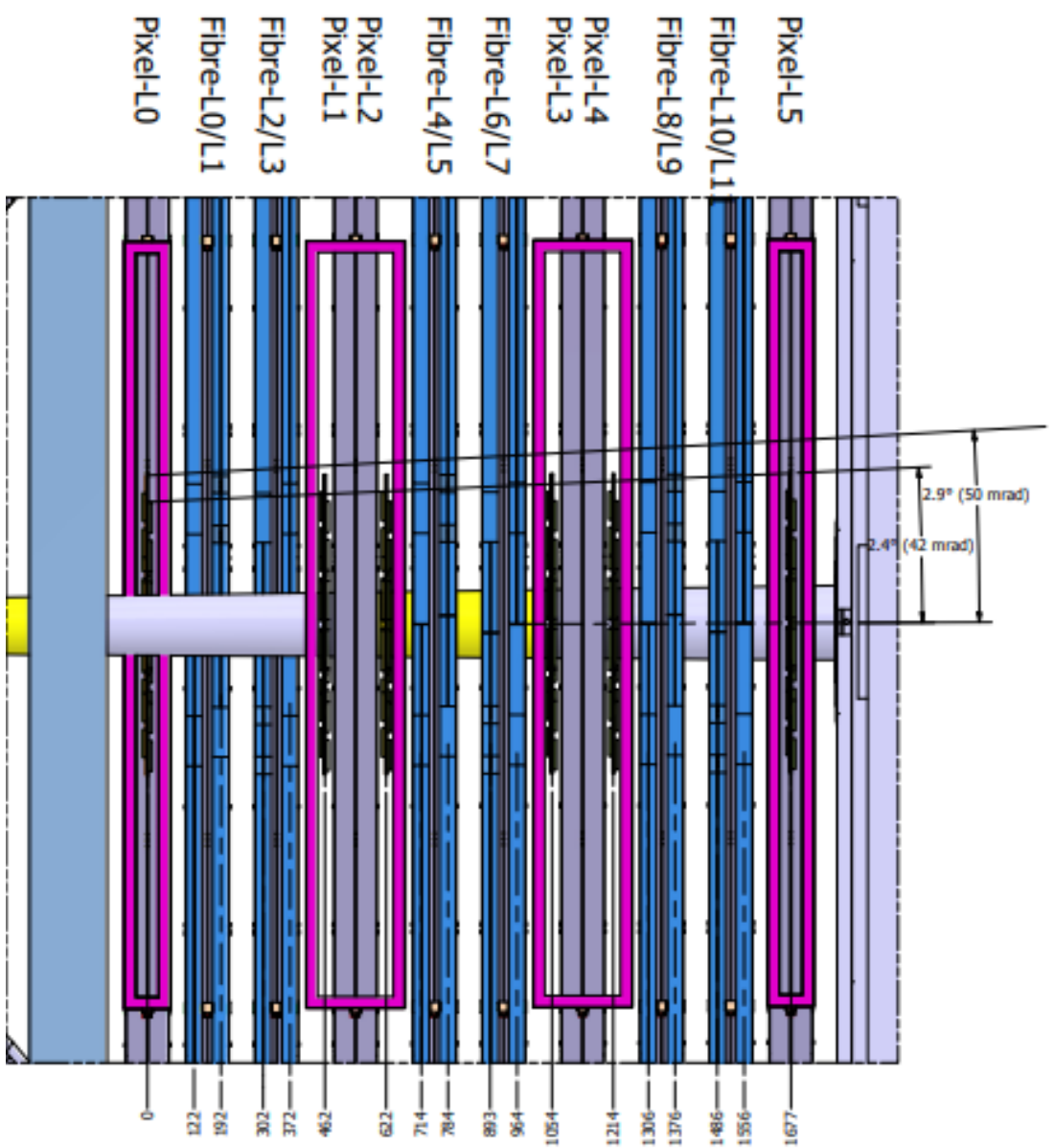
- LHCb upgrade 2 will take place before the Run 5 (2035)
- Mighty-SciFi improvements include SiPM PDE, microlens, cryogenic temperature for the silicon photomultipliers, timing information (O(ns)) and potential reduction of the number of fibers per layer
- A dedicated sensor is being developed for the Mighty-Pixel based on the HV-CMOS technology (180nm)
  - Many features validated with MightyPix1 or other chips from the HVCMOS family (time resolution, efficiency, noise, …)
  - MightyPix2 will be submitted Q2/2025
- Module design being consolidated
  - Vertical design allow some of front-end electronics outside inner acceptance and minimize dead areas
- Integration
  - Detector box, services routing and installation steps under investigation
- Exciting years of R&D and production ahead!
  - Technical design report by 2026

Thank you very much for your time!

BACKUP

Integration





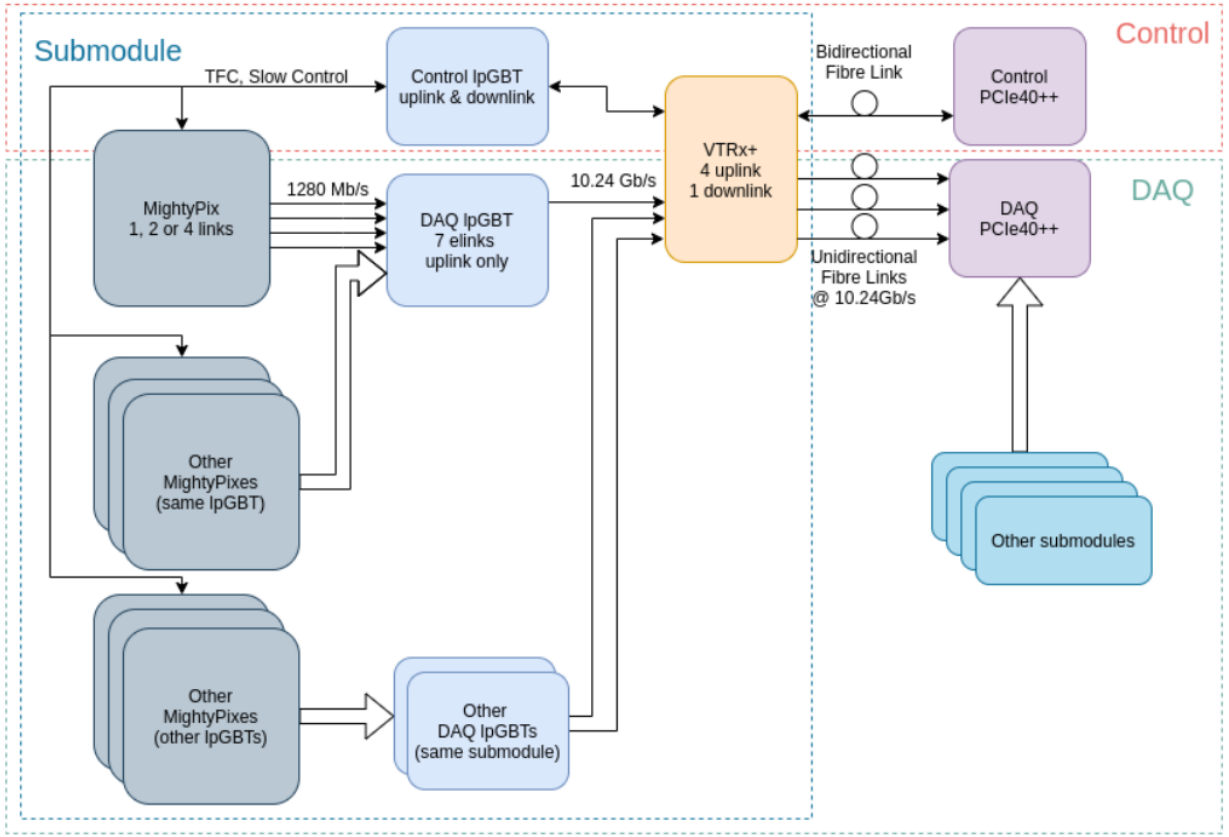
Power and DAQ/Control

DAQ and control

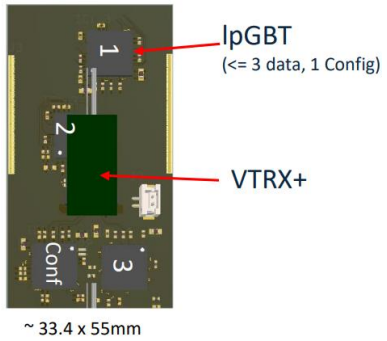
- CERN Radiation resistant front-end:
  - lpGBT -> low power GigaBit Transceiver, 65nm CMOS radiation tolerant
  - VTRx+ -> opto-electrical converter
- FPGA back-end
  - PCIE400

HDI

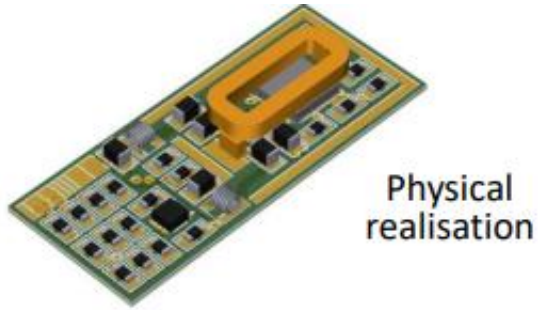
- Current version can accommodate up to 4 lpGBT
  - Each can accommodate 7 data elinks
- Power board
  - bPol12V with Wurth custom coil (as in ATLAS ITk strips)



HDI board
33.4 x 55 mm2



HDI power board
32 x 15 x 5 mm3



Serial Powering and High Voltage

Motivation

- Minimize the material budget required for the power and high voltage distribution in the detector area
- Trade-off between efficiency and risk

Sub-modules

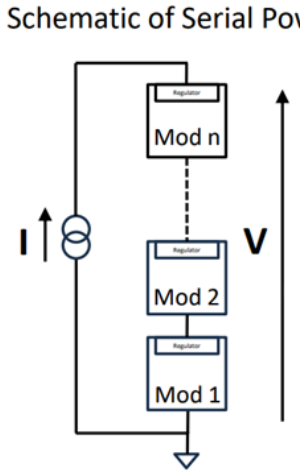
- 5 chips grouped by Readout flex
- ASICs wired in parallel
- 4 submodules per column

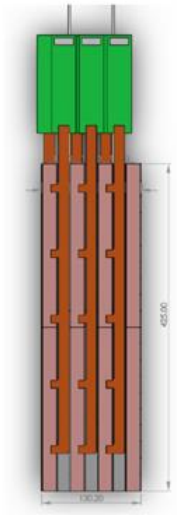
High voltage distribution per column

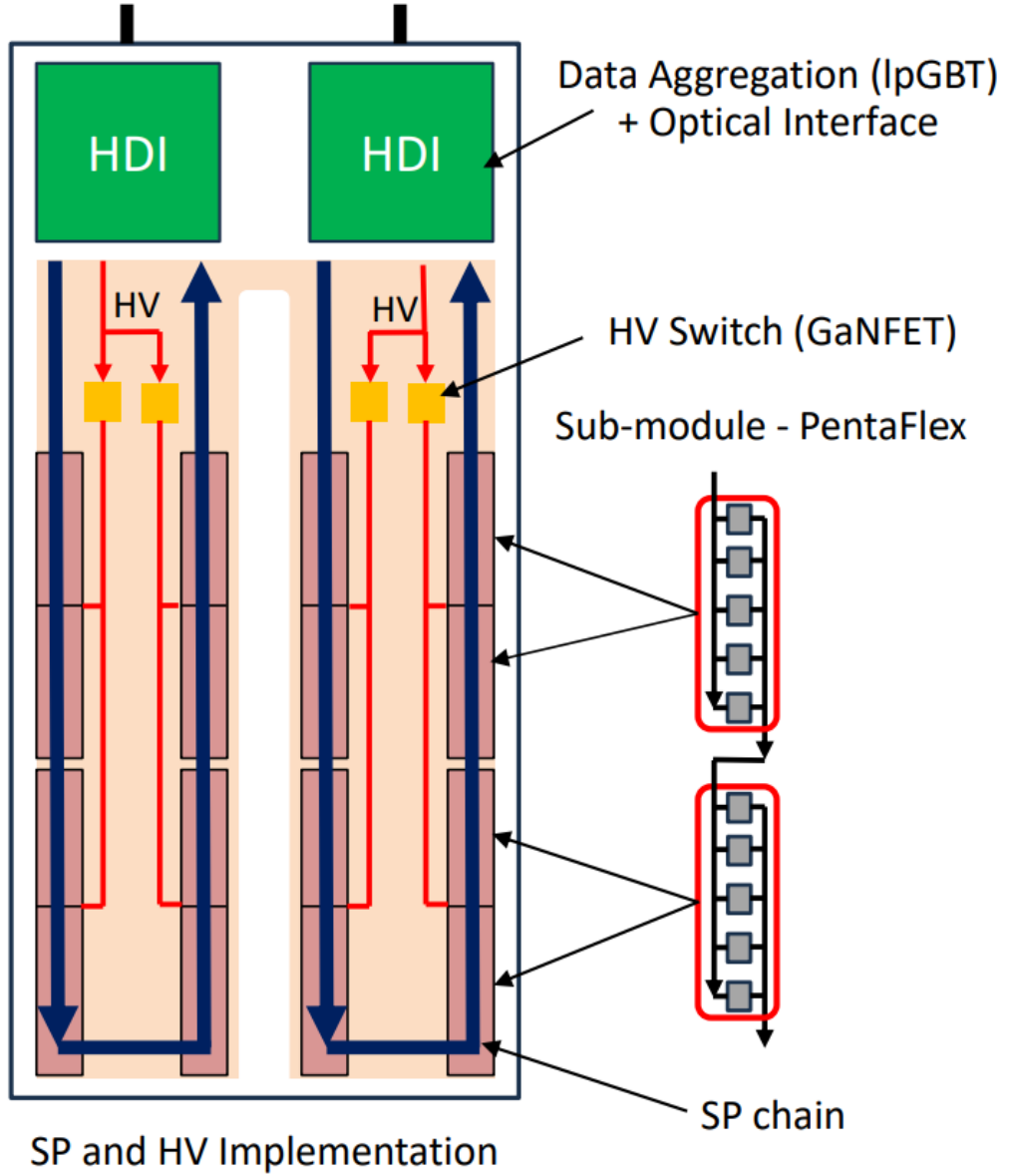
- One switch per column

Serial power distribution

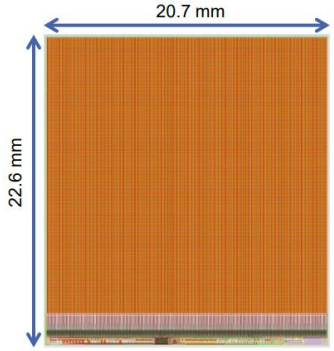
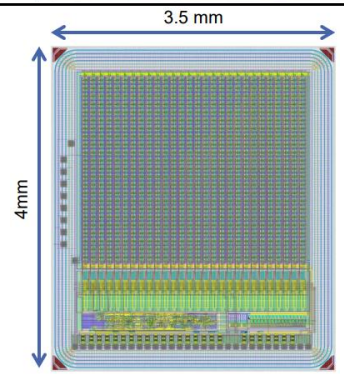
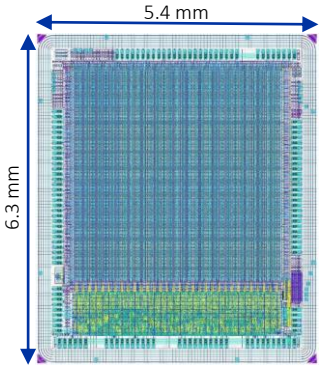
- One line for two columns
- 5 chips powered in parallel within a sub-module
- Constant current with voltage conversion on the CMOS sensor







MightyPix: next steps

TSI	MightyPix1 and other chips (AtlasPix, MuPix, …)	End of the 180 nm line
AMS	P2Pix  244x240 pixels (84×84 µm) MuPix based digital periphery Evaluate the full reticle size before the MightyPix2 submission	MightyPix2 submission on Q1 2025 (full area) MightyPix3 in Q3 2026
LFoundry	LF-Mightypix  Testchip 150nm 28 x 23 pixels LHCb compatible interfaces New Digital features (improved TFC, reduced data hit, …) Evaluate backup foundry and test new LHCb specific digital periphery	LF-MightyPix being tested ¼ RadPix1 prototype submission by Q3 2025 RadPix2 12-18 months after
	RD50-MPW4  **Based on the 150nm technology** 64×64 pixels ($62\mu m \times 62\mu m$) High radiation tolerance target ($10^{16}\ n_{eq}/cm^2 NIEL$ and 500MRad) Being tested	