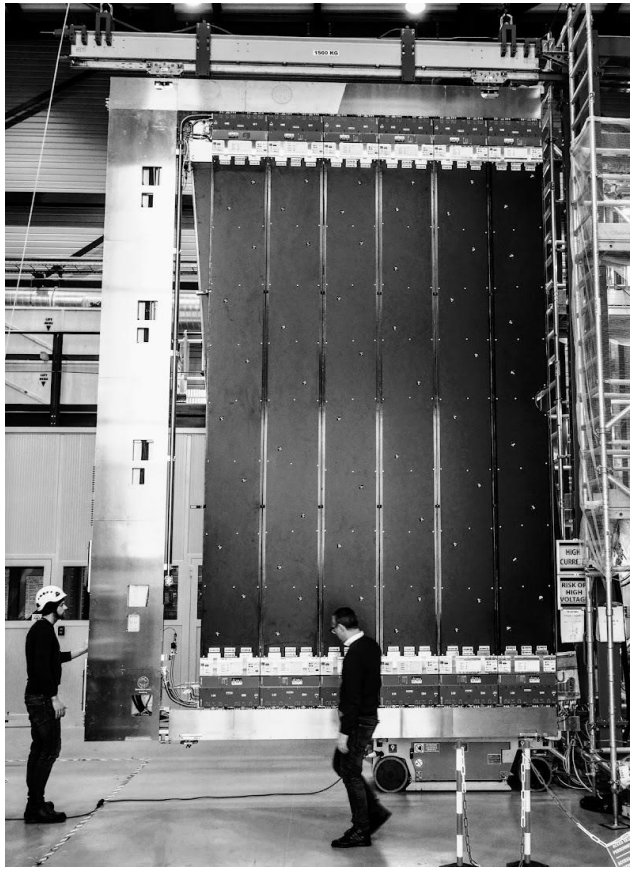
The LHCb Scintillating Fibre Tracker U1 and U2 + The Ion-therapy Beam Profile Monitor

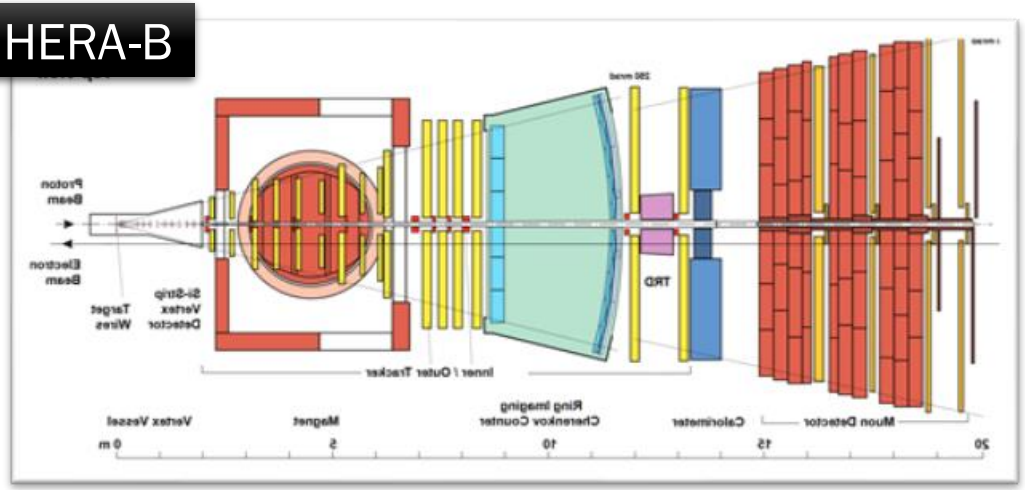


Blake Leverington, PhD., on behalf of the LHCB Scintillating Fibre Tracker group
Physikalisches Institut, Universitaet Heidelberg

Forward Flavour Physics Detectors

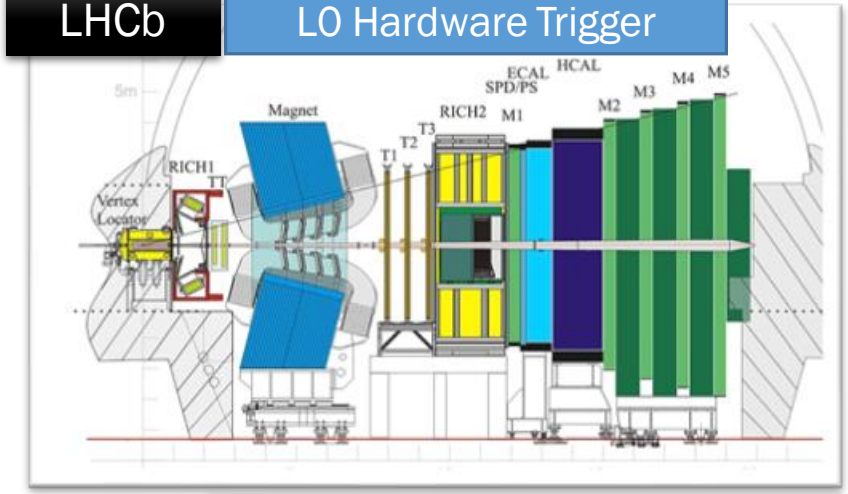
at hadron colliders

HERA-B

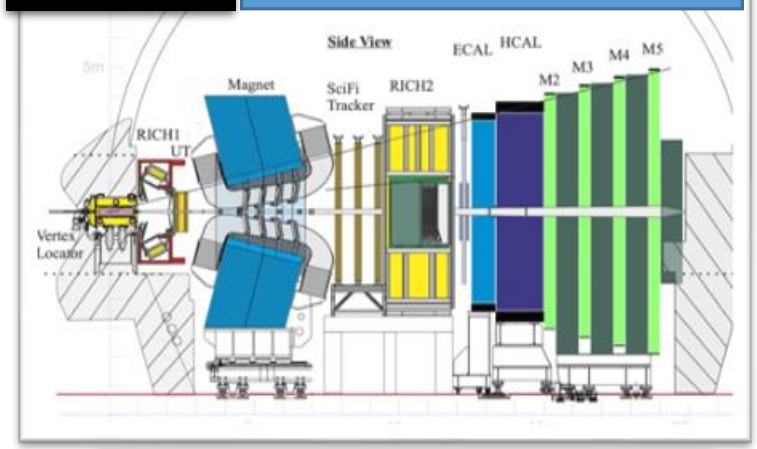


0.5 fb-1 per year at DESY, fixed target,
Didn't meet its performance goals ;
20 physics and 23 detector papers

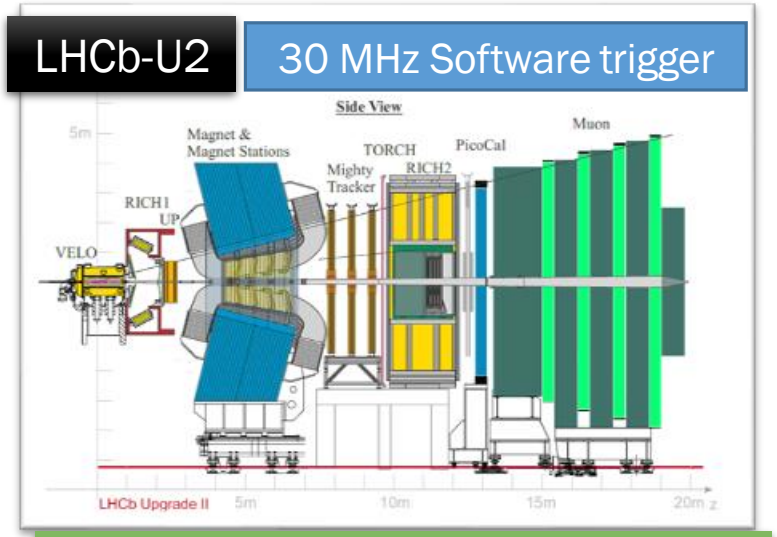
LHCb — L0 Hardware Trigger



LHCb-U1 — 30 MHz Software trigger



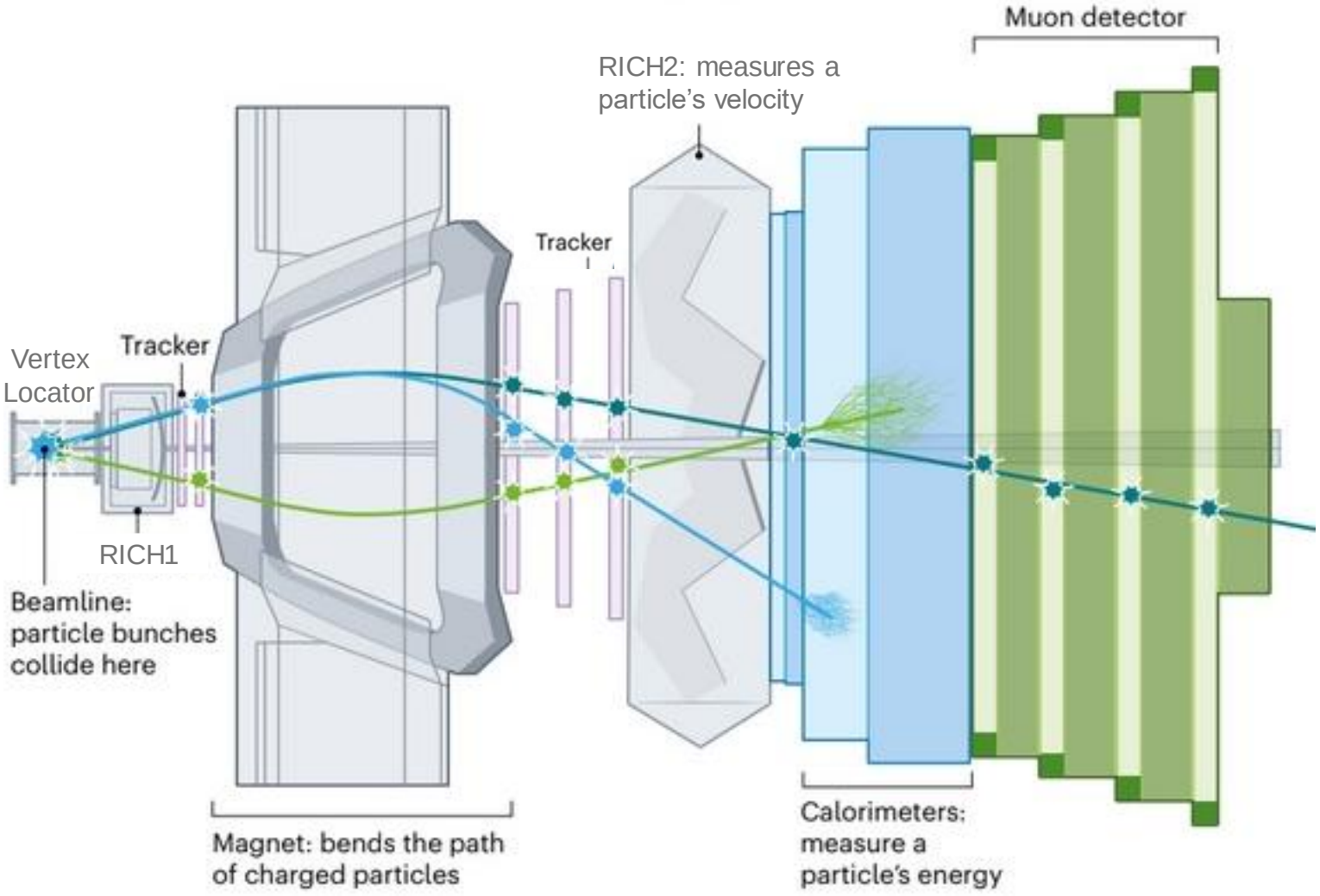
LHCb-U2 — 30 MHz Software trigger



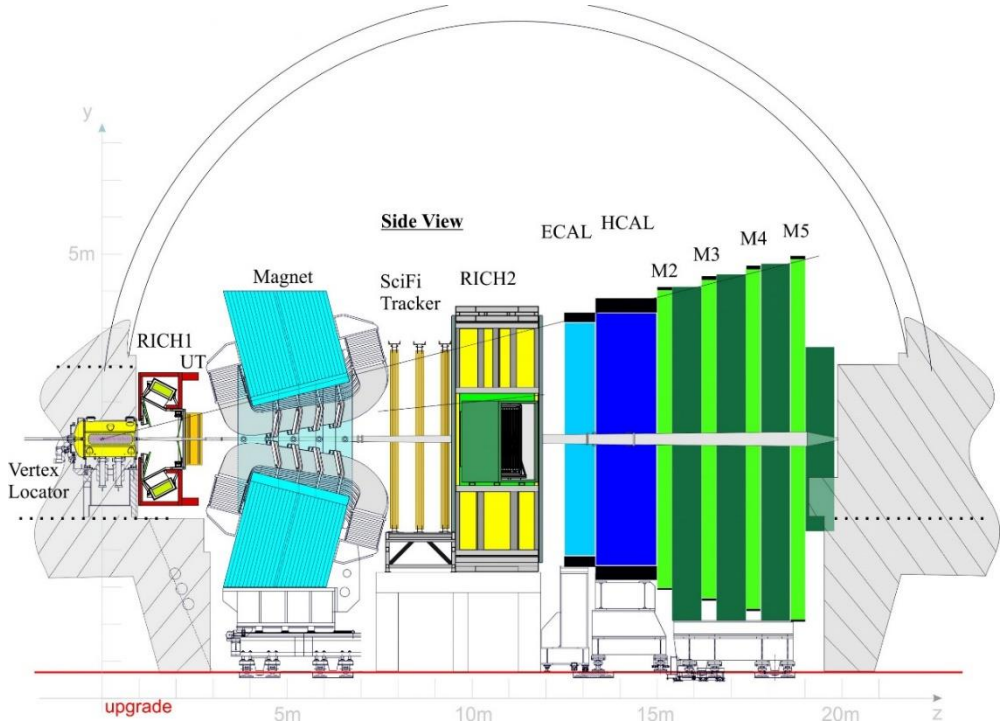
Design:

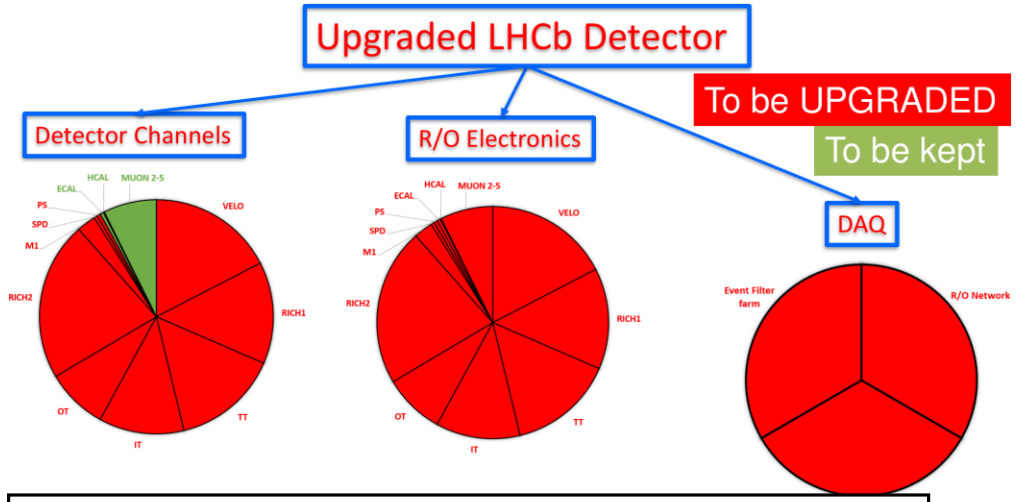
LHCb	LHCb-U1	LHCb-U2
L = 0.4 10^{33} Goal: 10 fb^{-1} 1 to 2 fb^{-1} per year ; mu = 1.1	L = 2 10^{33} Goal: +45 fb^{-1} ~7-9 fb^{-1} per year; mu = 5.3	L_{peak} = 10-15 10^{33}; +200-300 fb^{-1} ~40-50 fb-1 per year; mu = 42

Tracking


Muon detector
RICH2: measures a particle's velocity
Tracker
Vertex Locator
Tracker
RICH1
Beamline: particle bunches collide here
Magnet: bends the path of charged particles
Calorimeters: measure a particle's energy

LHCb Upgrade 1





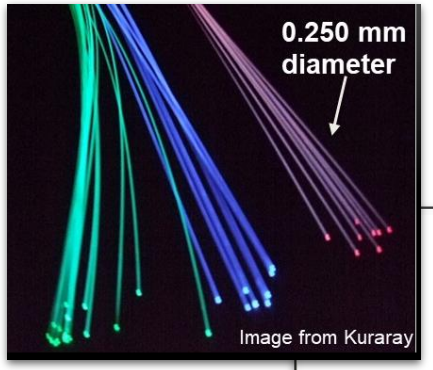
Magnet, Muon, and Calorimeters mostly the same, but everything else is new.

- Average visible interactions per BX 1→5
- VELO strip→pixels; 5→3.5 mm to beam
- Heterogeneous software trigger @ 30 MHz average
- New tracking detectors
- New RICH photo-detectors
- Detector readout @ 40 MHz

Central Tracking Detector Requirements

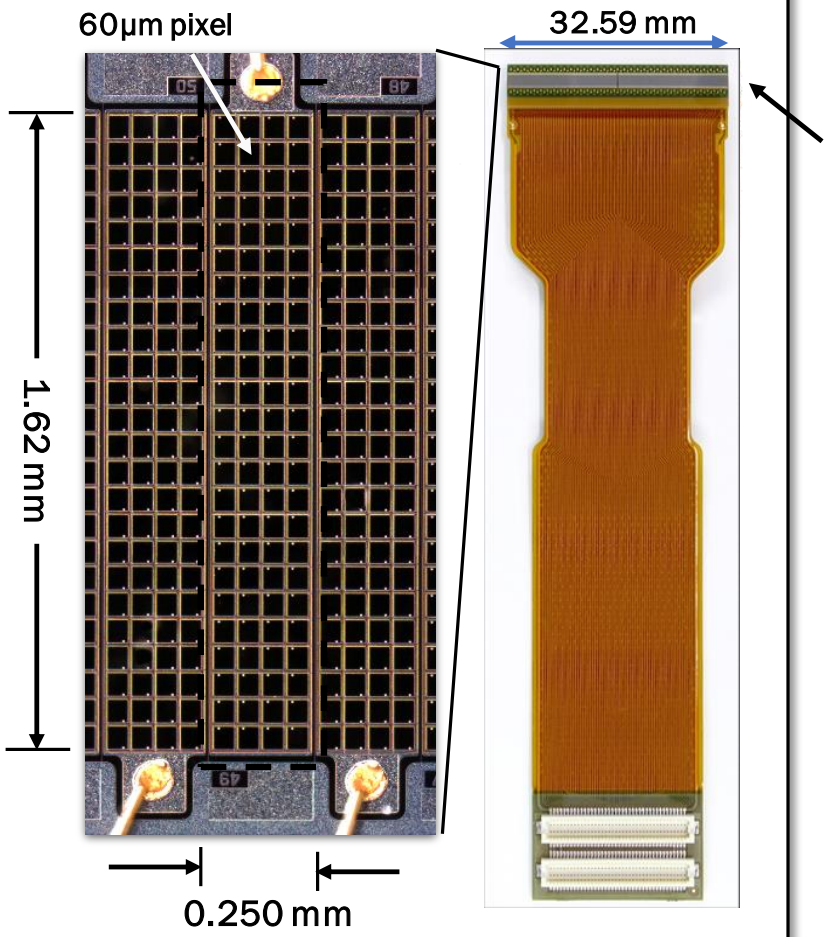
- The material should be minimized. ~10-12% of an interaction length or radiation length in total
- Cover 5 x 6 m^2 with 3 stations of X-U-V-X layers.
- Single hit efficiency of 99%.
- Spatial resolution better than 100 μm.
- Readout at a rate of 40 MHz [25ns bunch crossing period], no dead-time, for a full software trigger.
- Low noise rate (few fake signals).
- Operate in a high radiation environment: peak 35 kGy for fibres, 10^{12} neutron eq./cm^2 for sipms/front-end.

SciFi Basics



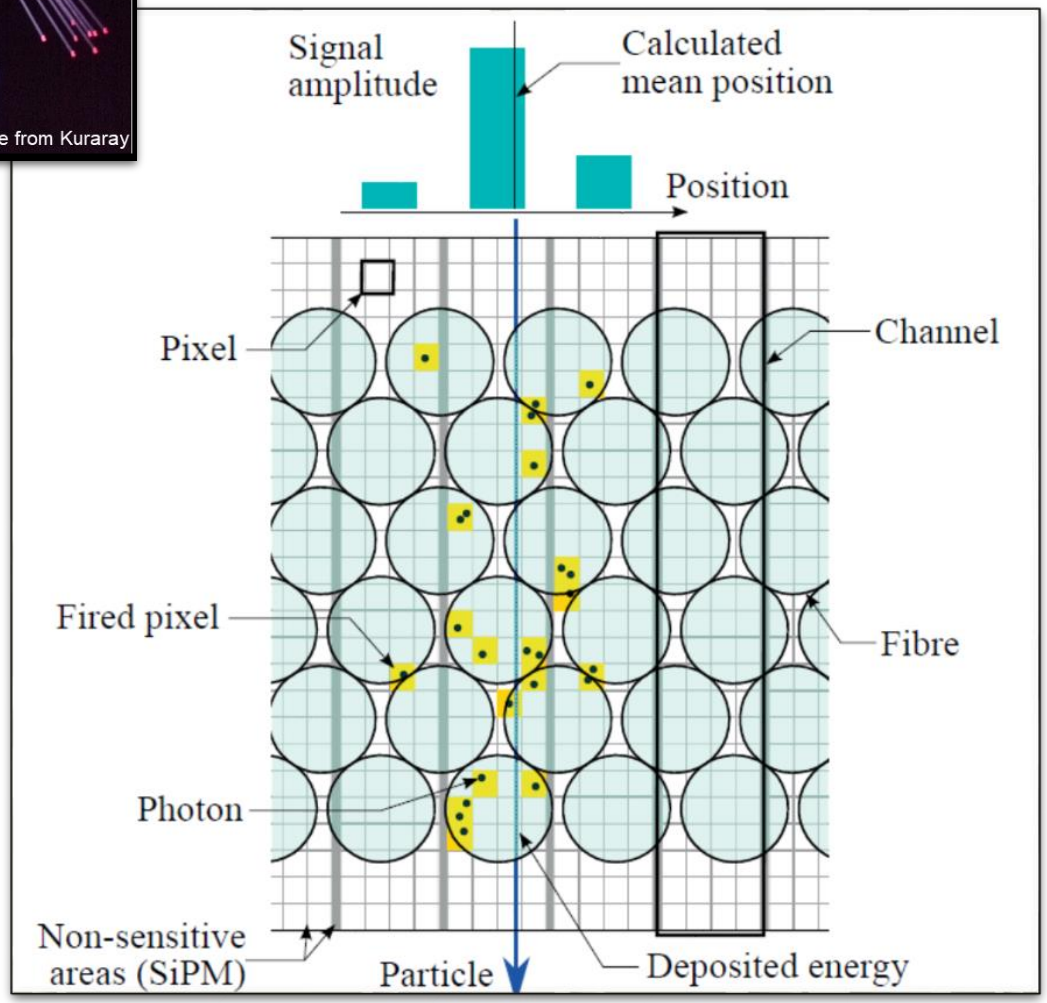
SCSF-78MJ fibres from Kuraray.
(fast 2.8 ns decay time)

Silicon Photomultipliers (SiPM) from Hamamtsu

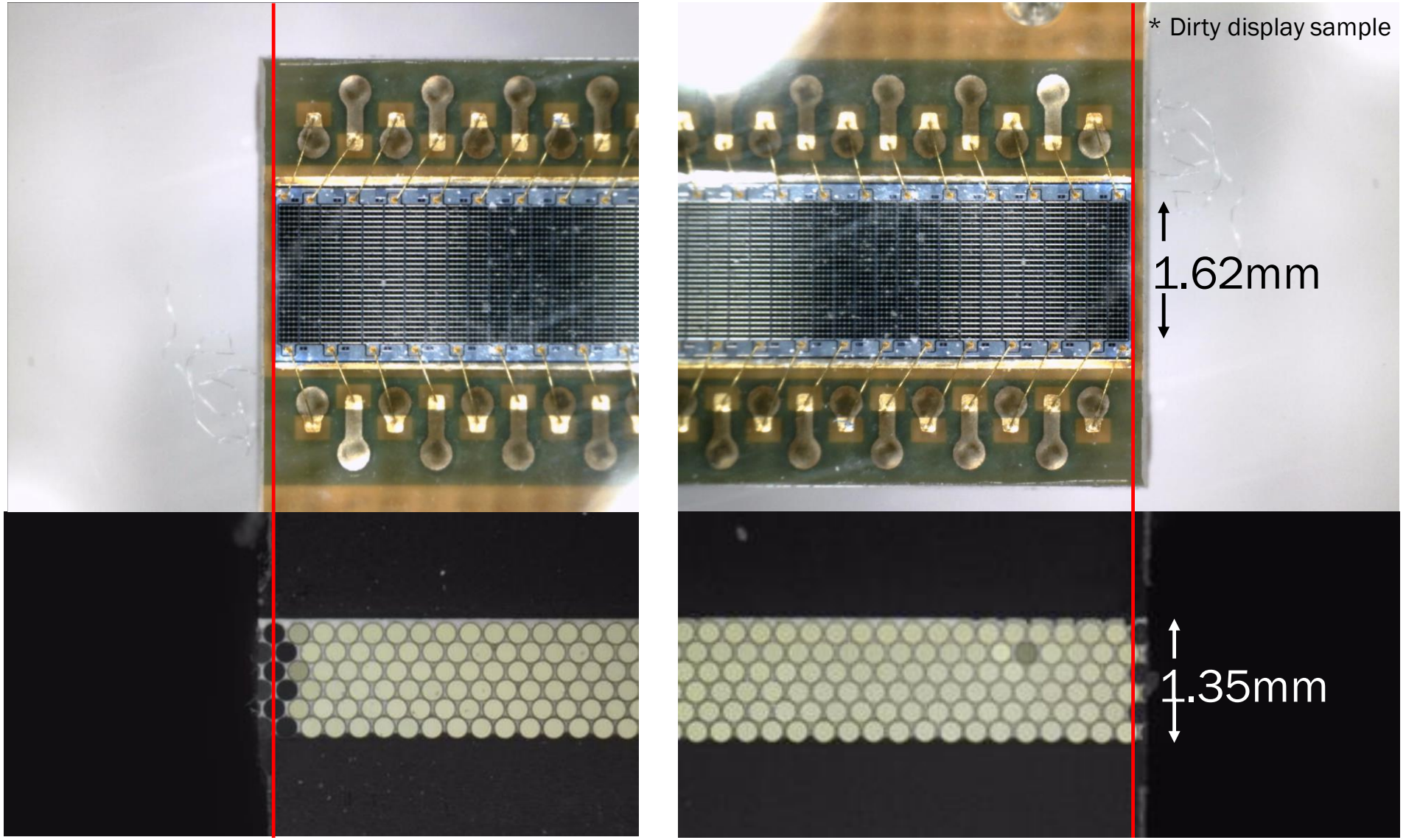


2 x 64 channel arrays

We need 4096!



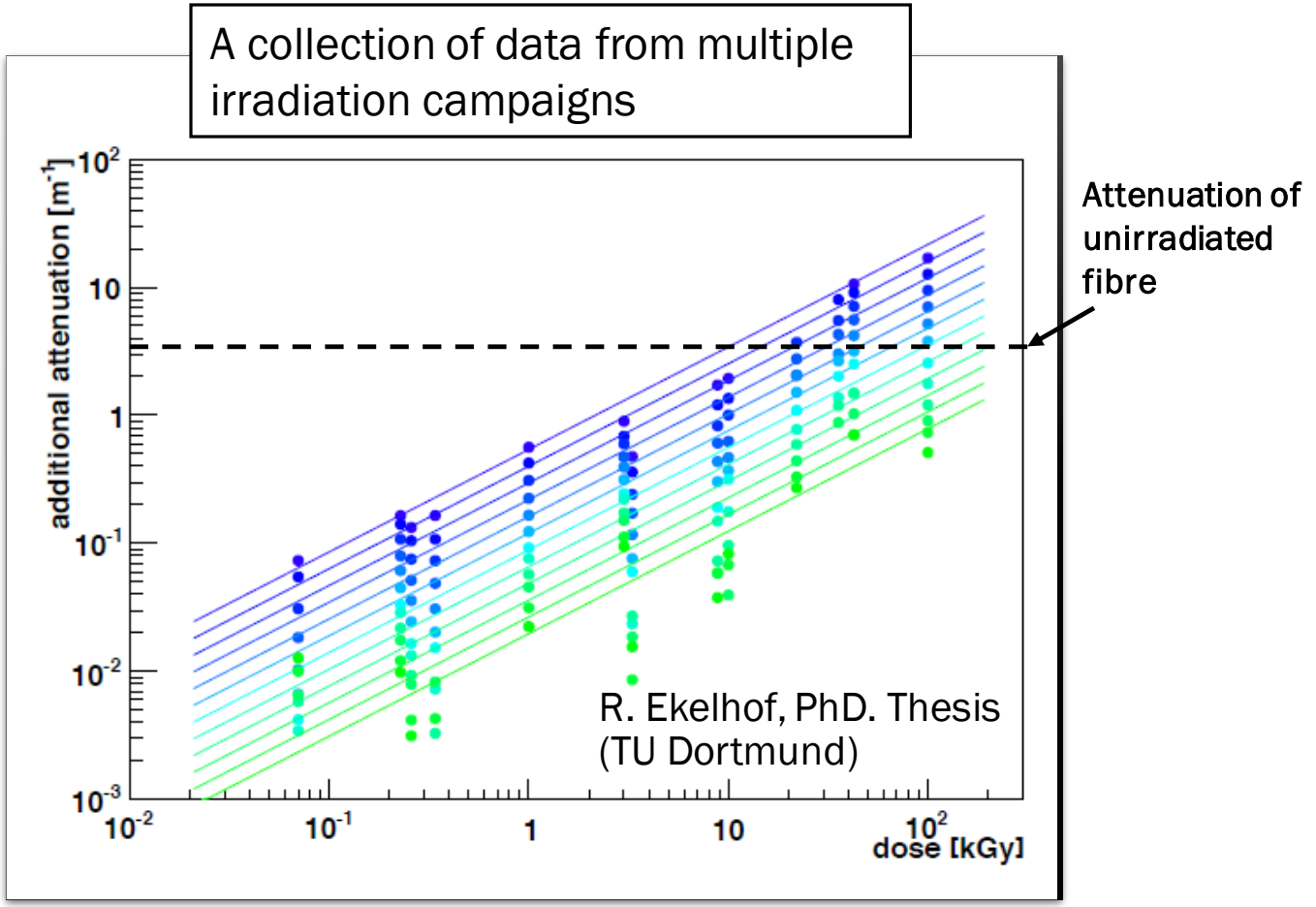
(a parallel array of Avalanche Photodiodes in Geiger-Mode)



Photos of fibre mats and SiPMs approximately to scale

Ionising Radiation Damage (Fibres)

- Formation of radicals produces absorption/scattering centres
- Strong wavelength dependence (greener is better)
- Annealing over time with air exposure observed
- Difficult to study equivalent dose rate effects as in experiment
  - Evidence of oxygen effects
  - Slight aging even without radiation (~1% loss in attenuation length/year)



Ionising Radiation Damage (Fibres)

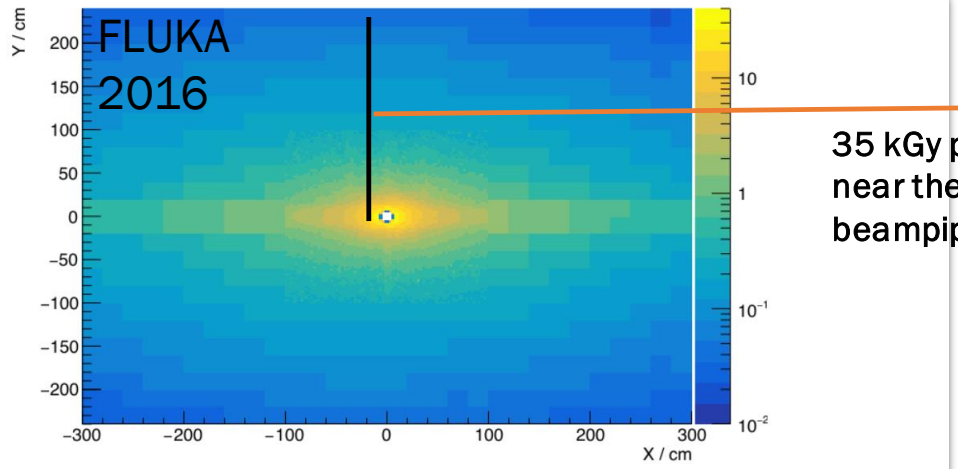
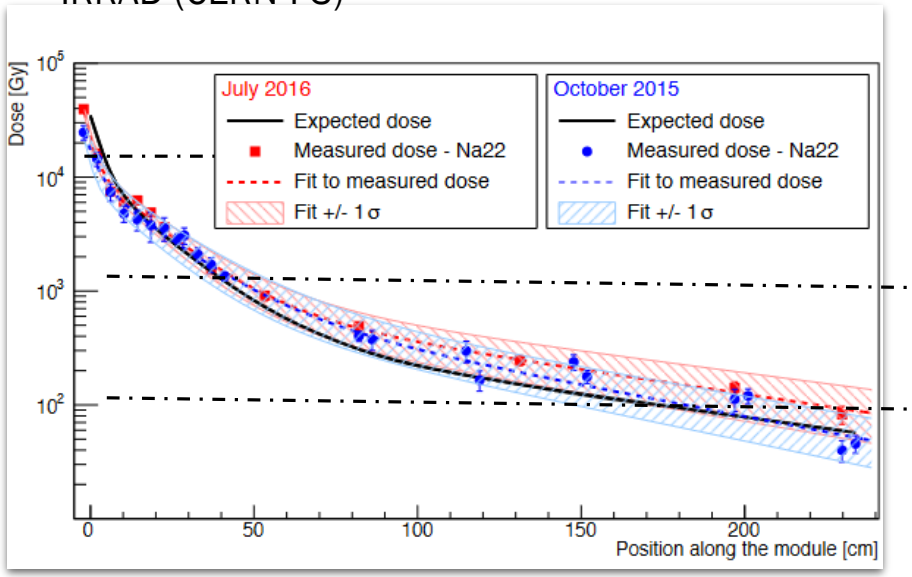


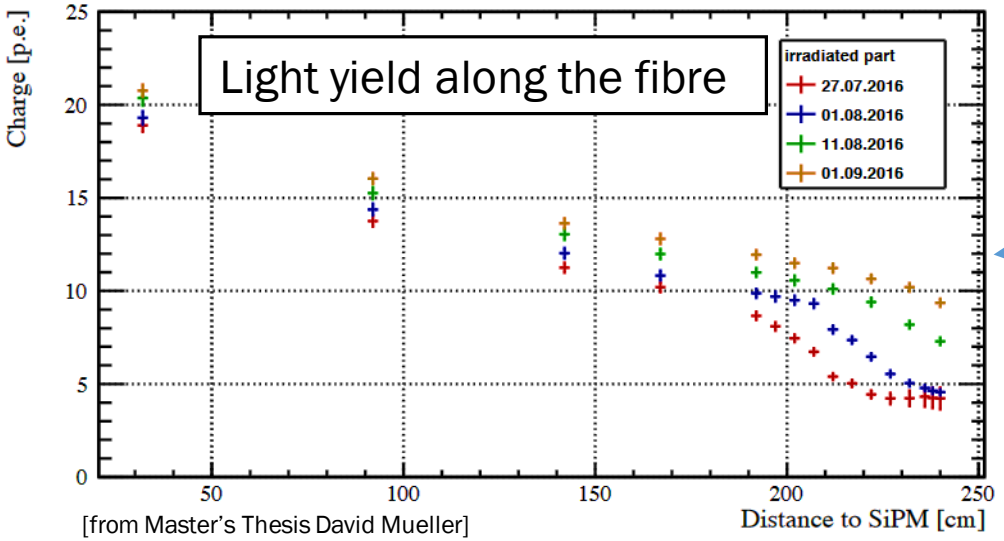
Figure 43: Map of the total expected ionising dose in kGy for an integrated luminosity of 50 fb^{-1} at the T1 station of the SciFi Tracker from FLUKA simulations of the LHCb detector.

35 kGy peak near the beampipe

Dose profile of the most irradiated fibre. Irradiated at IRRAD (CERN PS)



[from Master's Thesis David Mueller, Uni Heidelberg.]



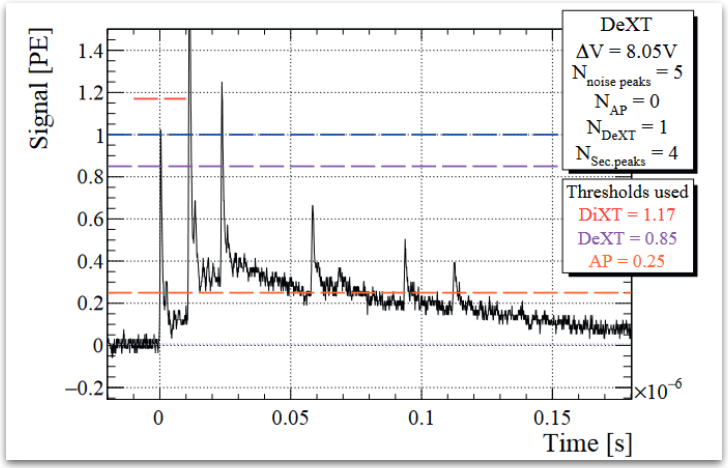
[from Master's Thesis David Mueller]

Annealing with a time constant of 12 days with 35% permanent loss at the mirror with LHCb dose distribution.

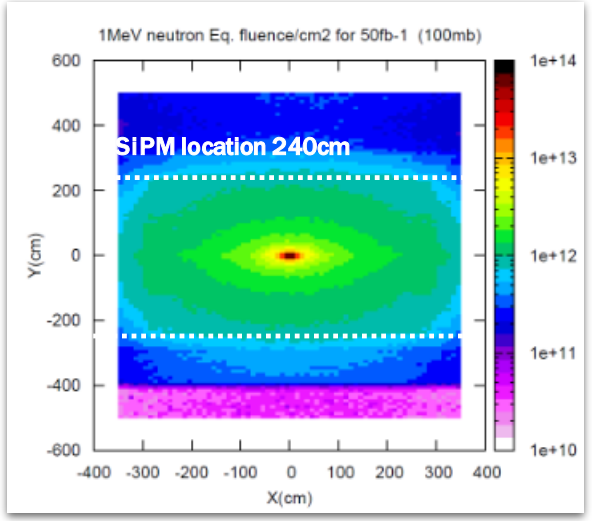
We will measure this again directly in the LS3 shutdown (2026-2028).

Non-Ionising Radiation Damage (SiPMs)

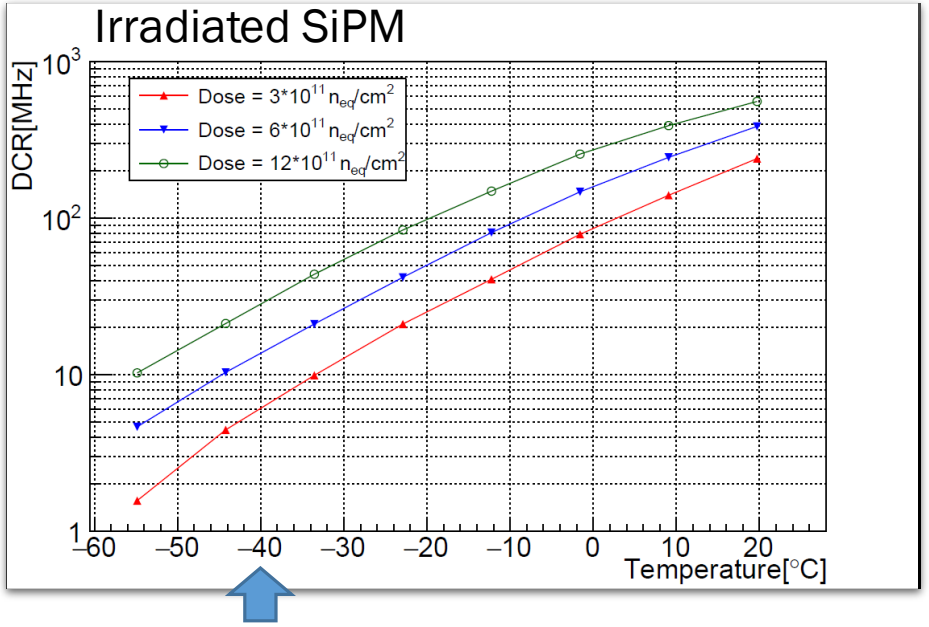
- Non-Ionising Energy Loss (NIEL) causes damage to the silicon structure
  - Allows thermal excitations to cross the bandgap more easily (dark avalanches!)
  - Cooling helps reduce the effect
  - Borated polyethylene shielding (2x reduction) before the ECAL
- 1 photoelectron uncorrelated signals
  - Pixel-cross talk produces 7% 2p.e. Signal, 0.49% 3 p.e. signals, etc...
  - Eventual overlap at high rates.
  - Annealing (~30% recovery)



Pulse waveform classified as delayed cross-talk with additional secondary pulses recorded at high ΔV (H2017 at ΔV = 8.0 V)

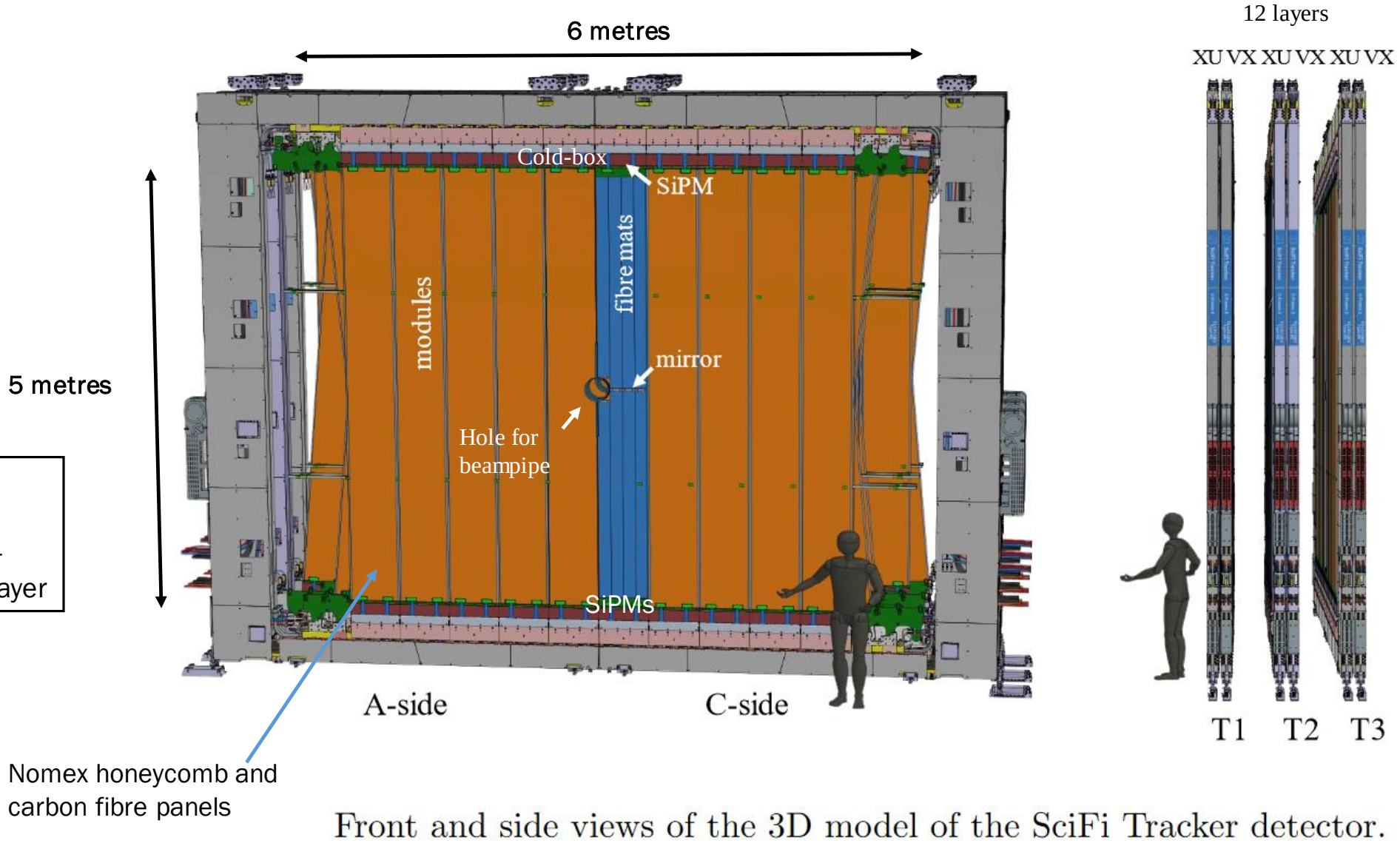


Fluka simulation



SciFi Operation Point = -40°C
→ DCR = 14 MHz of single p.e. noise at EOL

The SciFi Tracker



Fibres = 0.4% X0
Other = 0.6% X0

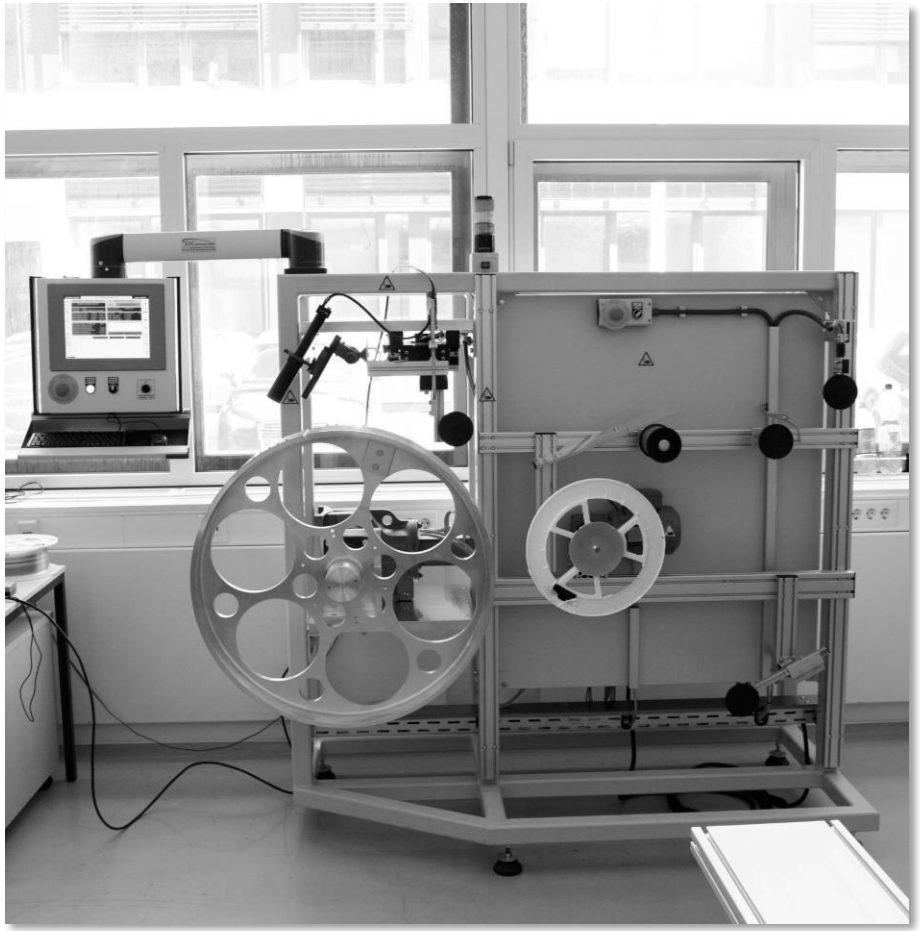
Total = 1% X0 per layer

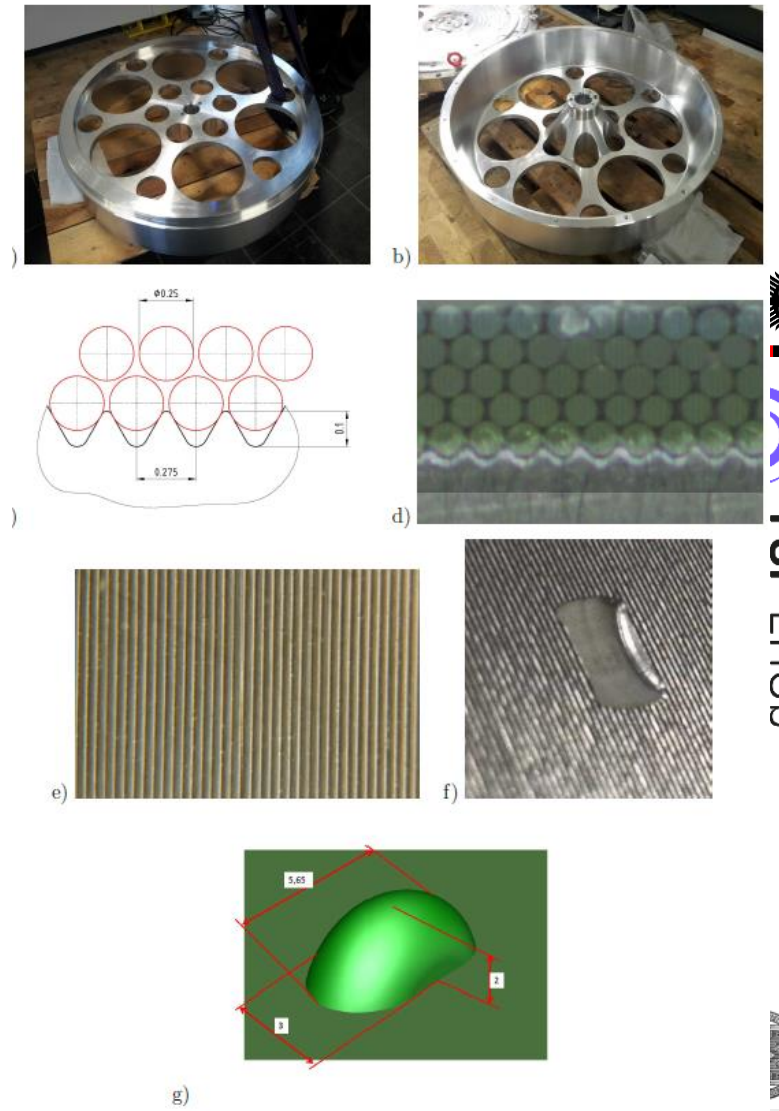
Nomex honeycomb and carbon fibre panels

Front and side views of the 3D model of the SciFi Tracker detector.

The LHCb Production Winding Machine

- Custom grooved winding wheels (2.5m mats)
- Pins inset in the wheel to create alignment pins
- Tension control and jump detection
- 4 production machines produced producing ~ 1 mat per day for 1.5 years



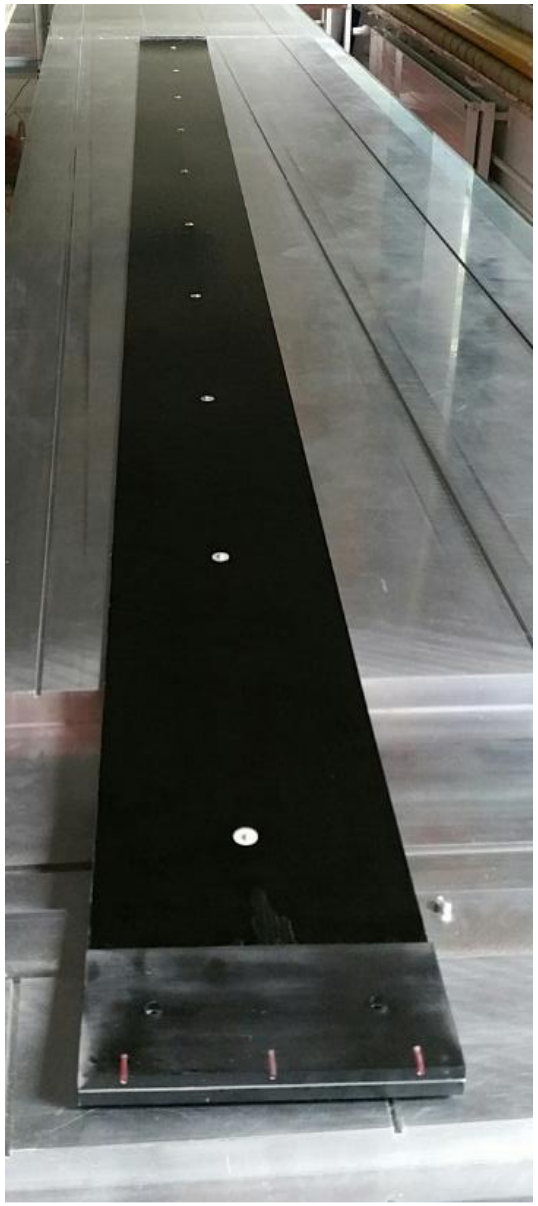


LHCb Fibre mats

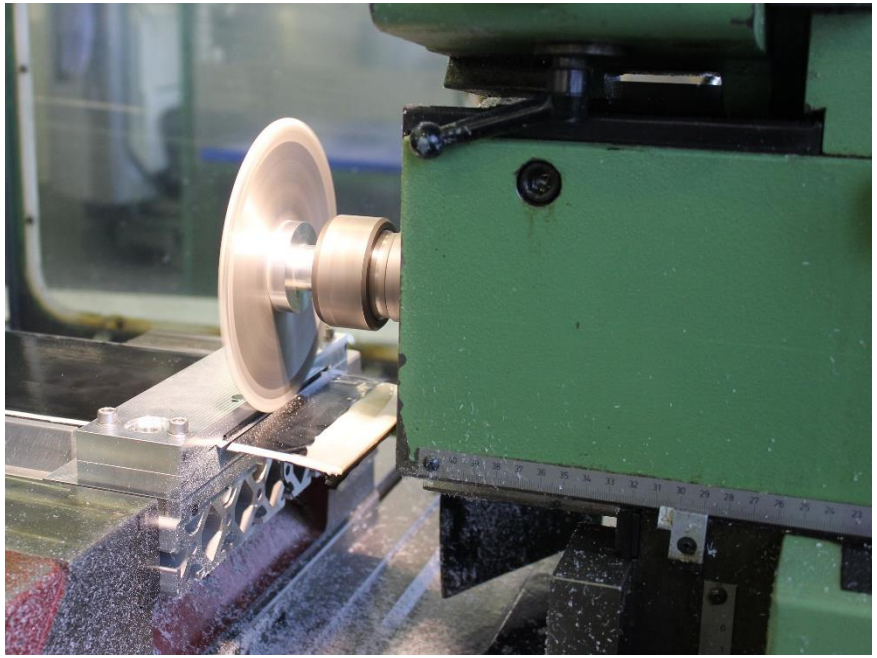
Fibre mat removal from the winding wheel in Aachen

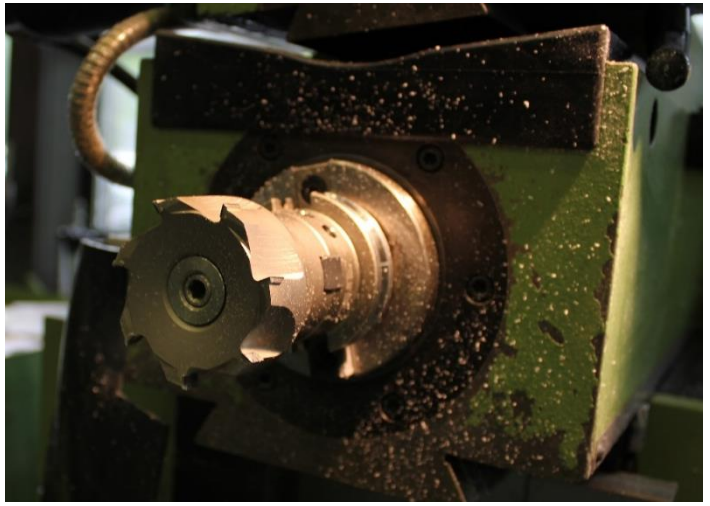
Black Kapton foil added for handling and shielding

Polycarbonate endpieces for optical milling and alignment of sipms



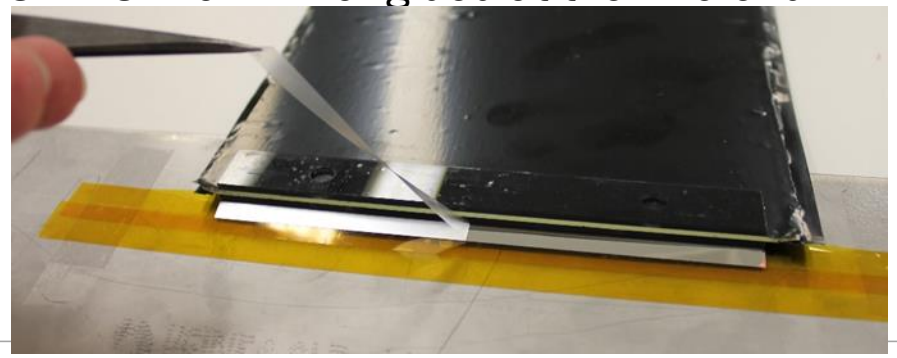
Optical Ends





- Diamond head milling (no polishing)

- Remove the excess
- 3M ESR foil mirror glued at the Y=0 end

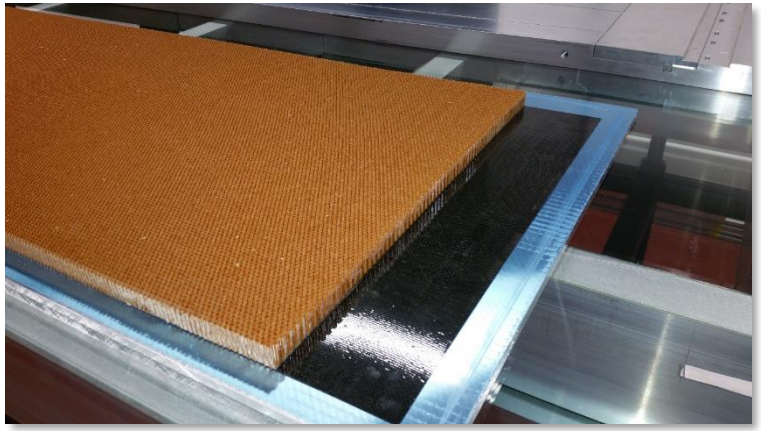


Module Production

5m template for alignment of components

+

Nomex-honeycomb (self-extinguishing): 32 kg/m3
Single-sided composite panel



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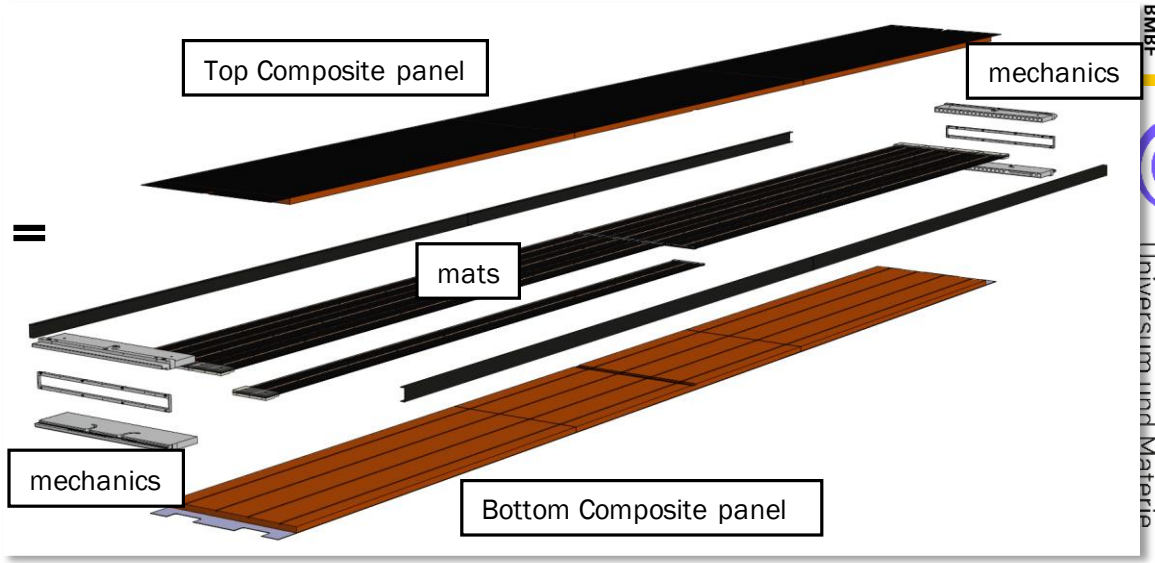
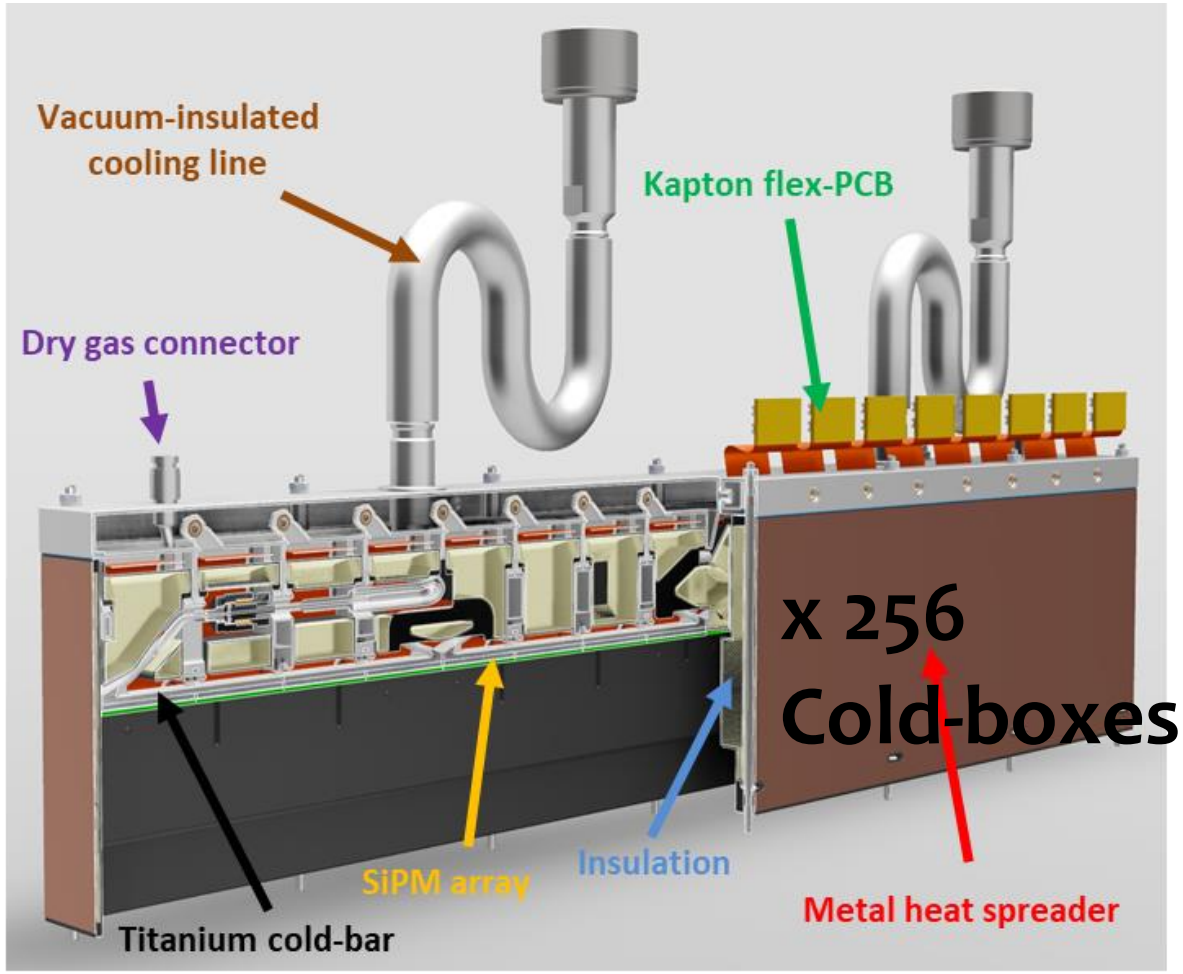
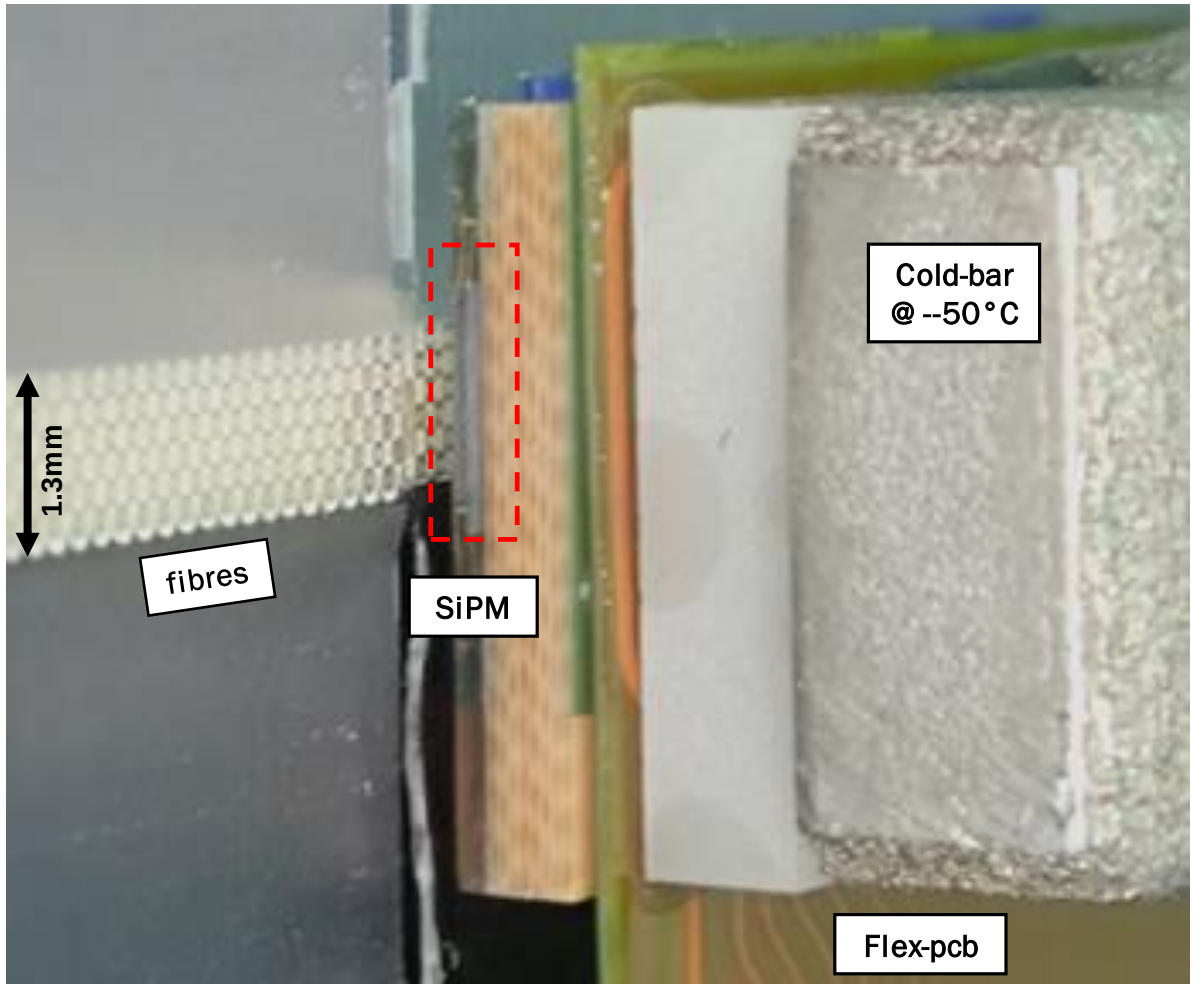


128 modules needed for production

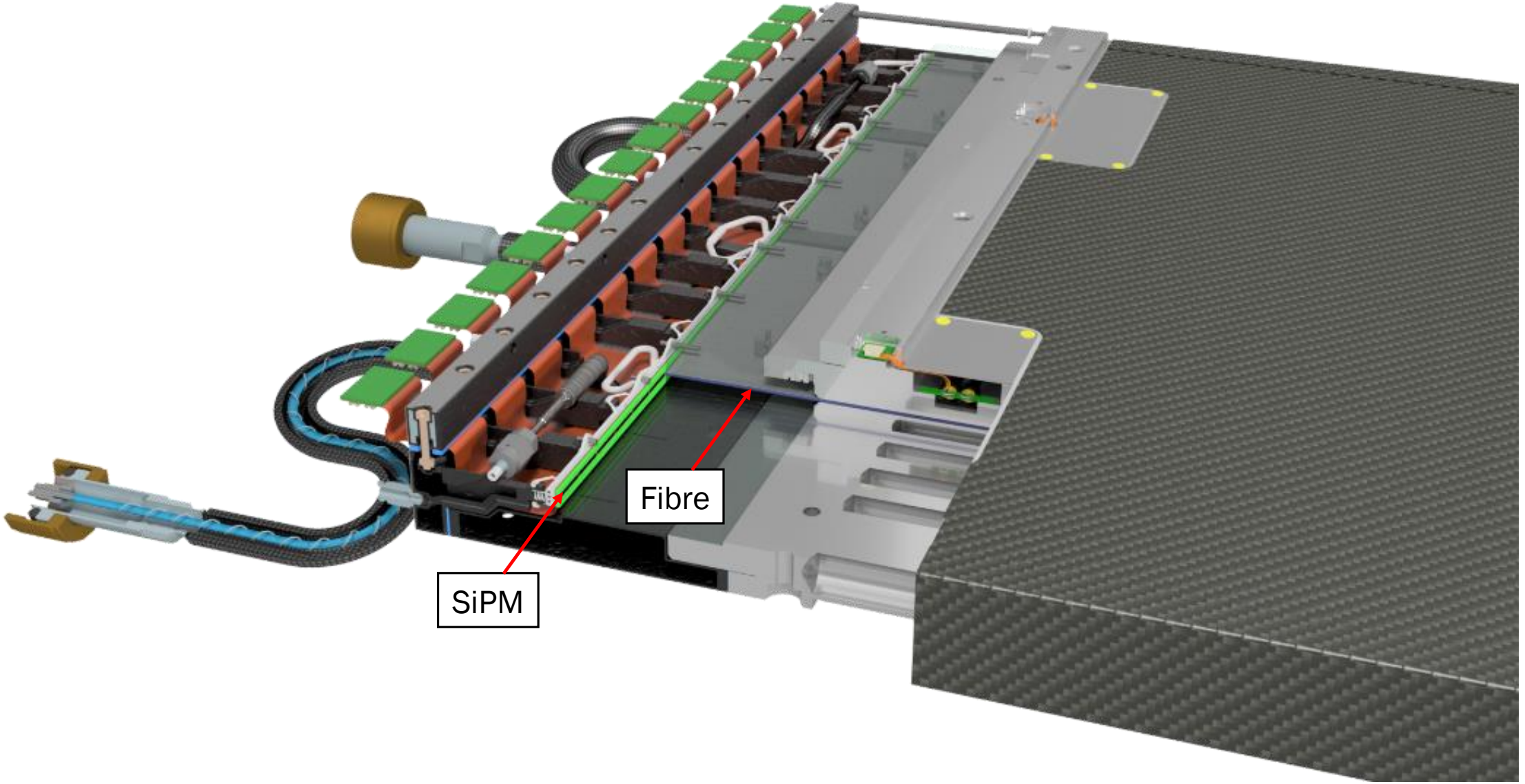
Cold-Boxes

The SiPMs need to be cooled to -40C to keep increased dark noise from radiation to an acceptable level.

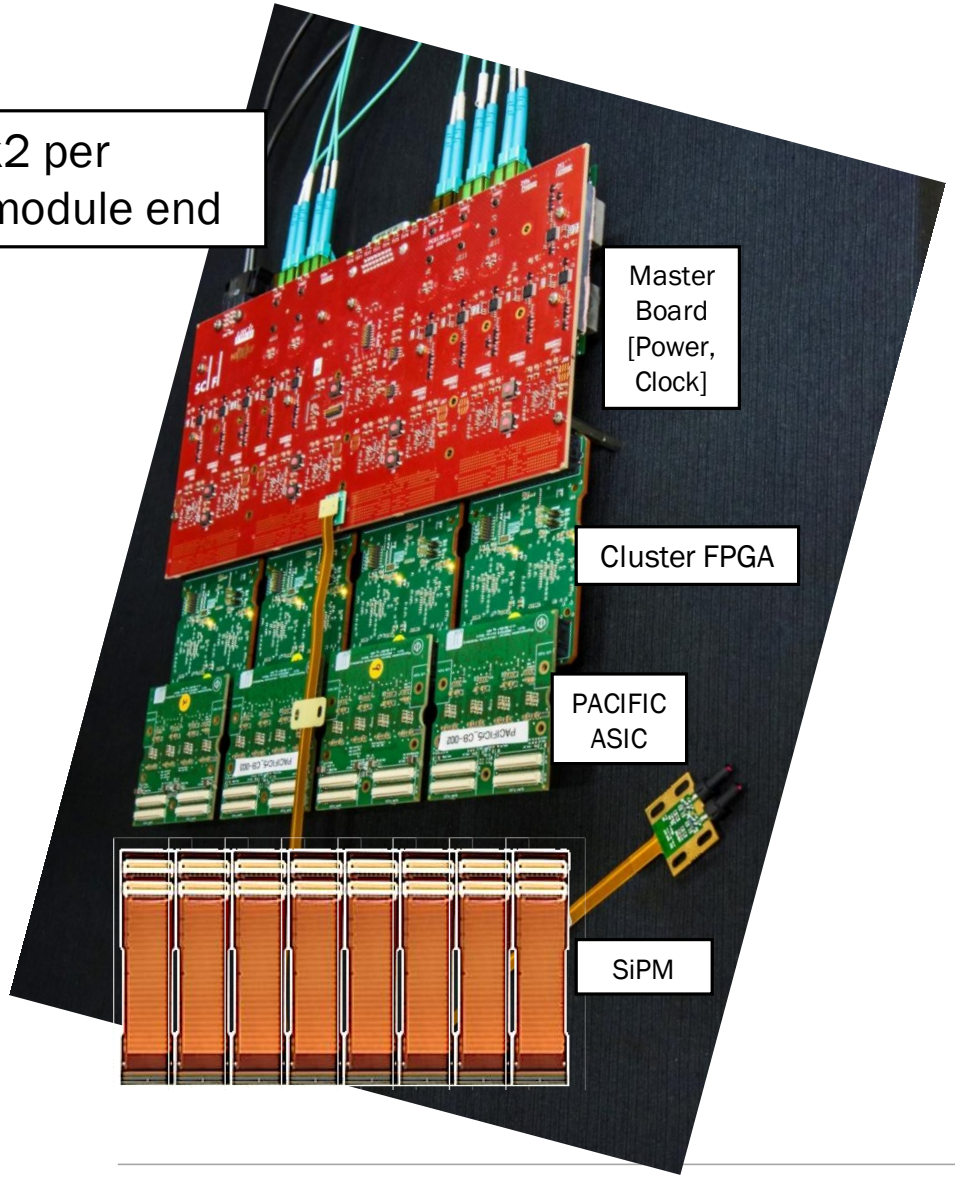


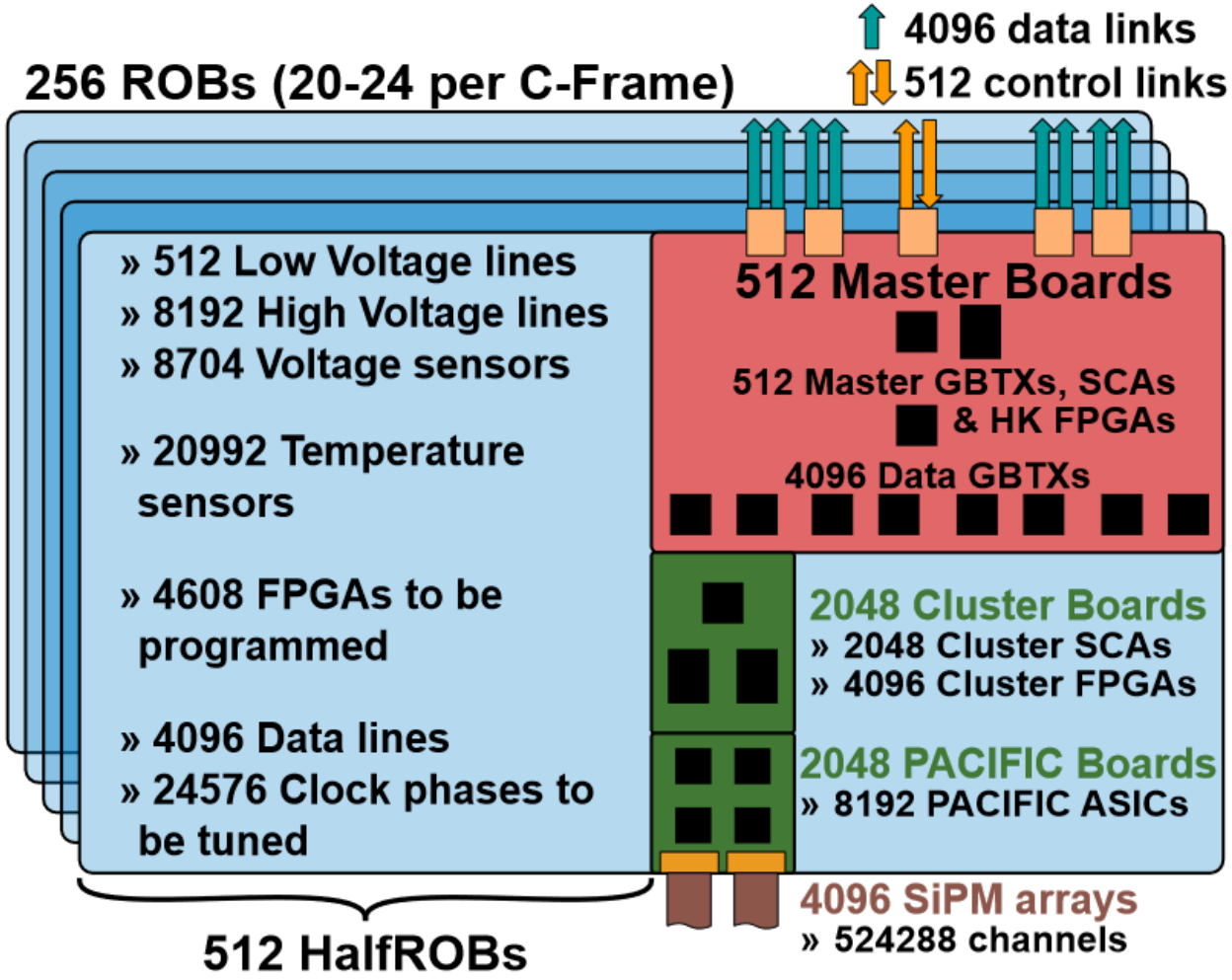


SciFi Module Production Model



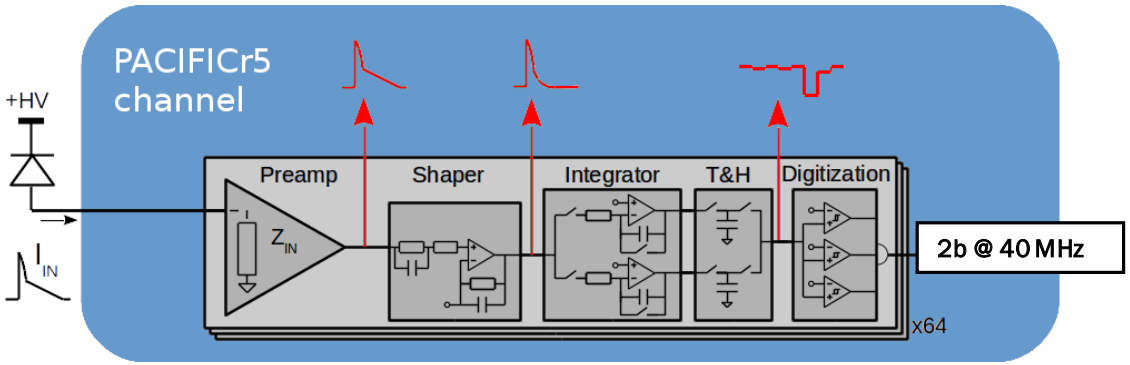
Electronics

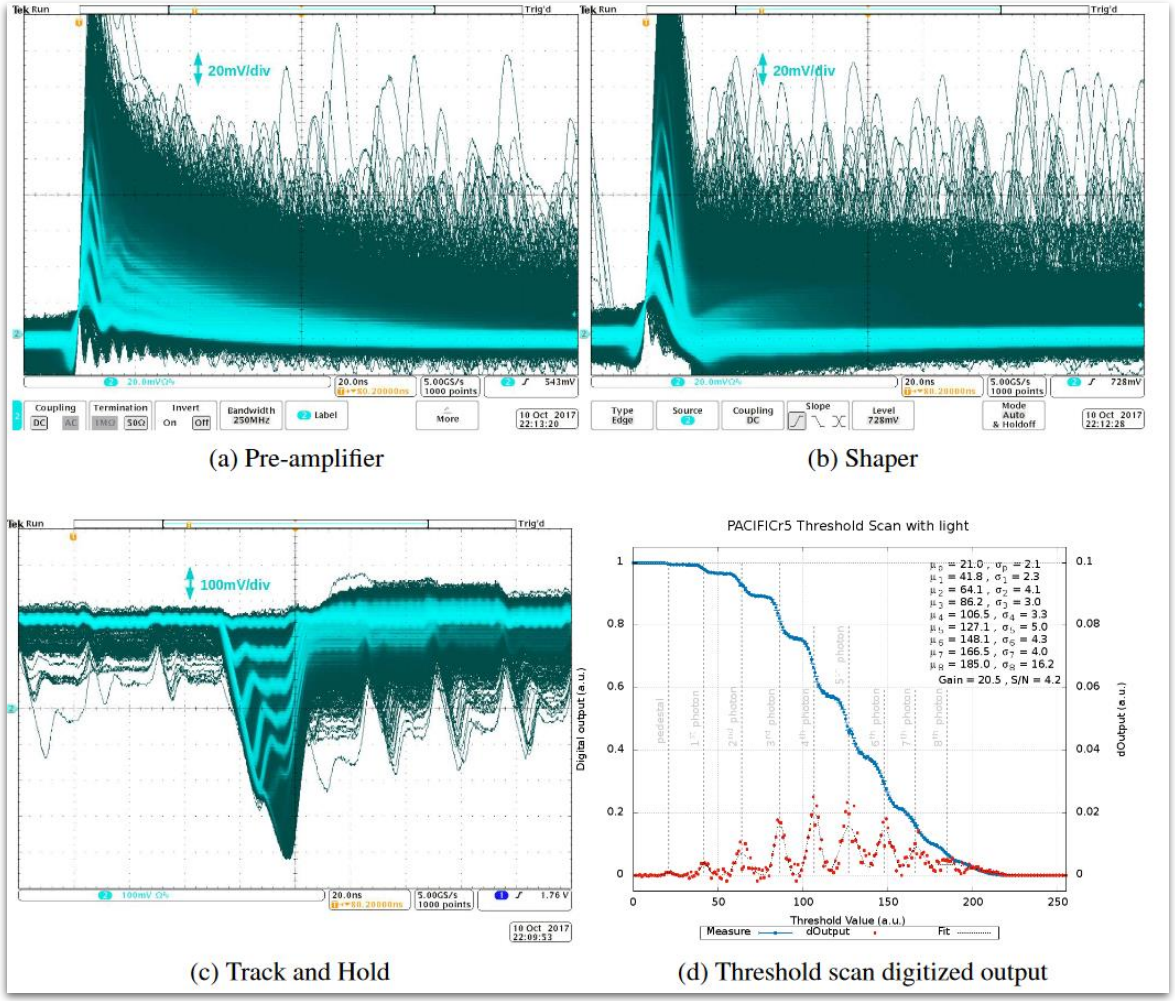




READOUT ASIC: the PACIFIC

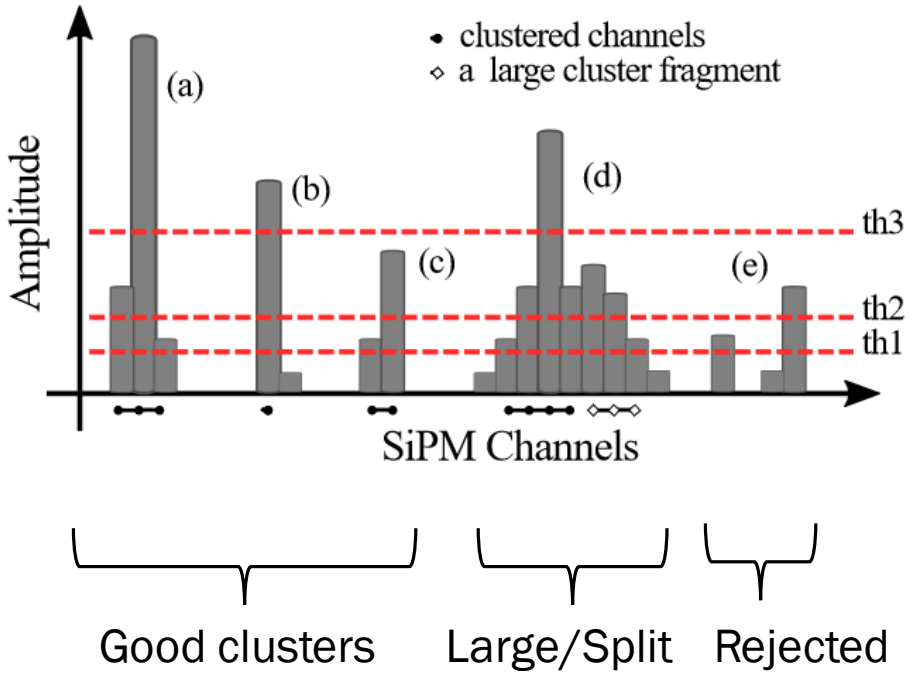
- Fast (10ns) shaping to reduce spill over
- Double integrators to avoid dead time
  - Alternates BX
  - Integrate signal charge over the crossing
- 2-bits /channel from 3 hysteresis comparators
  - Optimal thresholds are (1.5,2.5,4.5) p.e. for SciFi



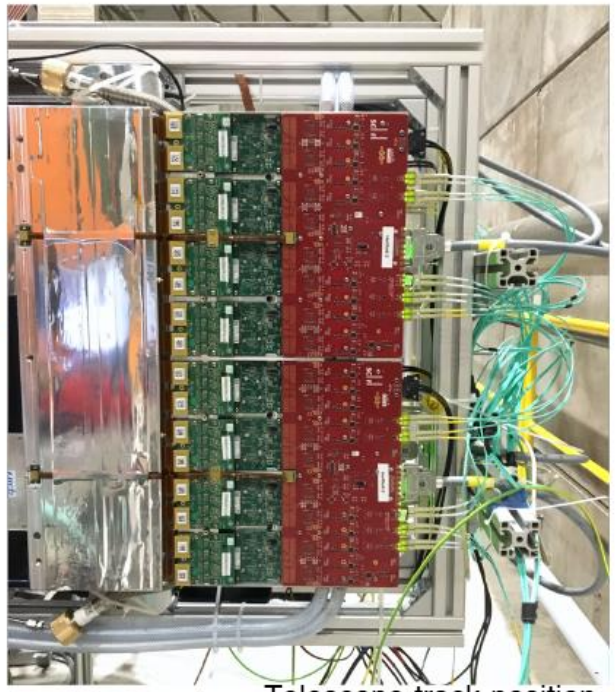


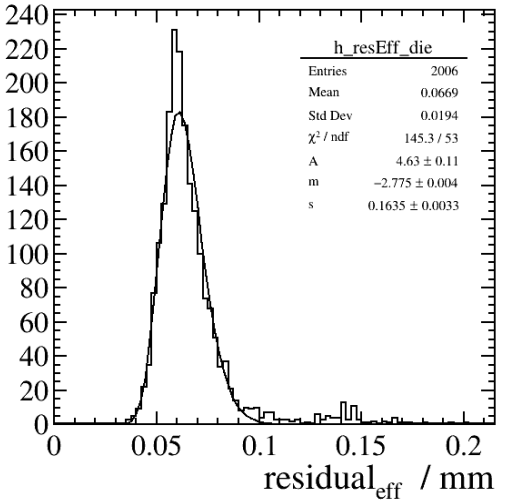
Clustering on FPGA

- Separate signal and noise
  - Zero-suppression (2x bandwidth reduction)
  - Cluster bandwidth is limited to DAQ (10 per data link, 16 per link for nearest to beampipe)
- Some-what radiation tolerant IGLOO2 FPGA provides the clusterization algorithm
  - Loses programmability early (but still works)
- also prepares the data for the backend
  - 20 Tb/s to the backend (4096 data links)
  - ~40% of LHCb data links

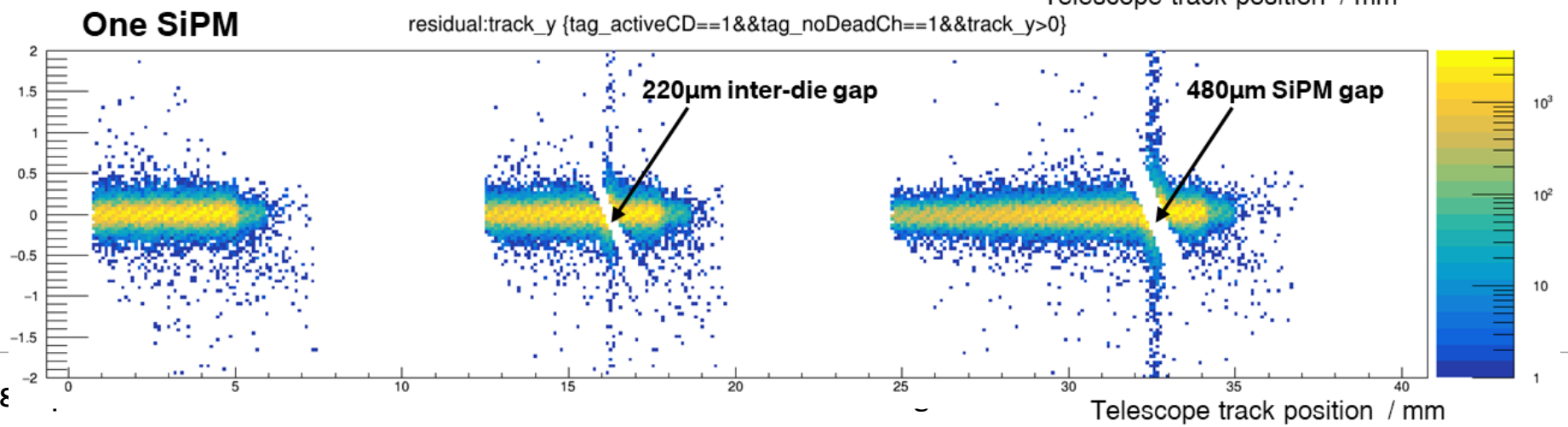


Testbeam with final electronics and production modules (July 2018)





99% hit eff. on die,
70 micron hit resolution



The Assembly Hall @ Point 8

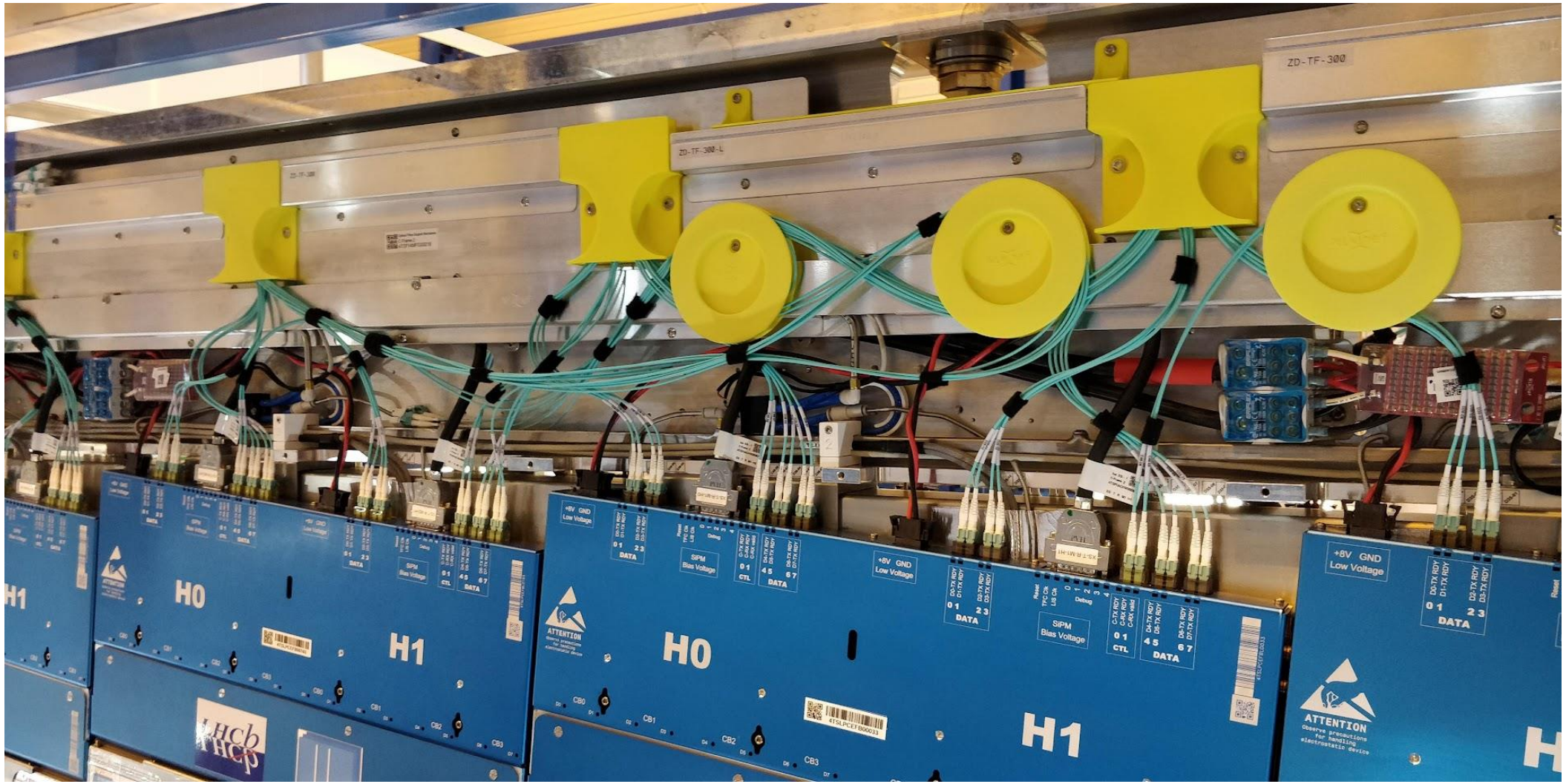
x 4 Assembly Stations

Staged parallel production

Modules with Cold-boxes mounted on the C-frame.

Water lines are checked for leaks, dry gas lines for correct flows. Vacuum and SiPM cooling lines checked for leaks.

Electronics and Fibres.



Every fibre and front-end is inspected before and after installation in the assembly hall.

2019 - 2022

1 prototype + 12 C-Frames

A completed c-frame with 12 modules, and Front-end electronics and optical fibres installed.

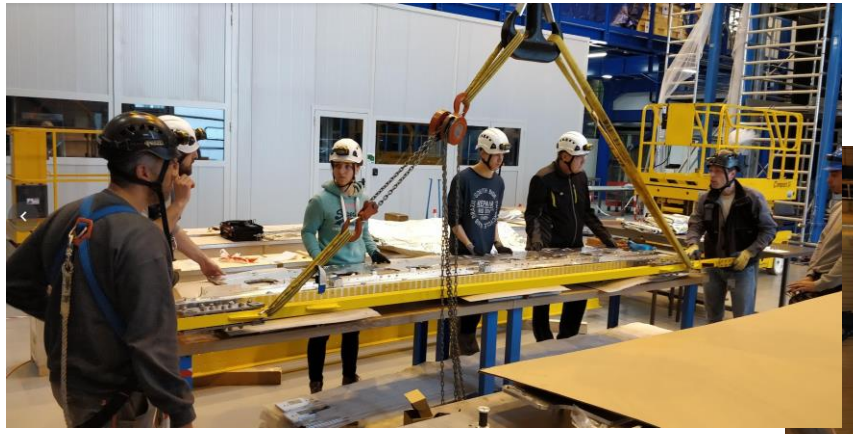
The functionality of all systems have been checked and had an initial calibration.

Participating institutes:

2019 - 2022

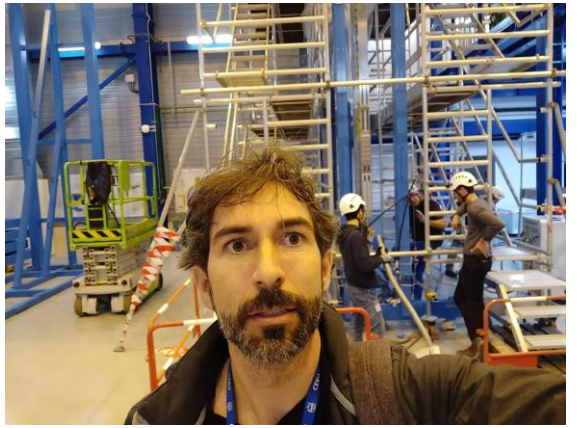
Checking Front-end electronics currents.

Installing bias cables.



Assembling C-Frame mechanics.

Paella after completing the first C-frame



Connecting SiPMs.

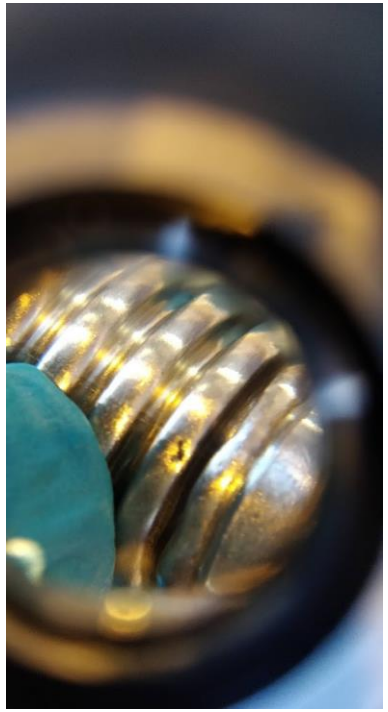
2019 - 2022

Replacing a defective cooling and vacuum manifold.

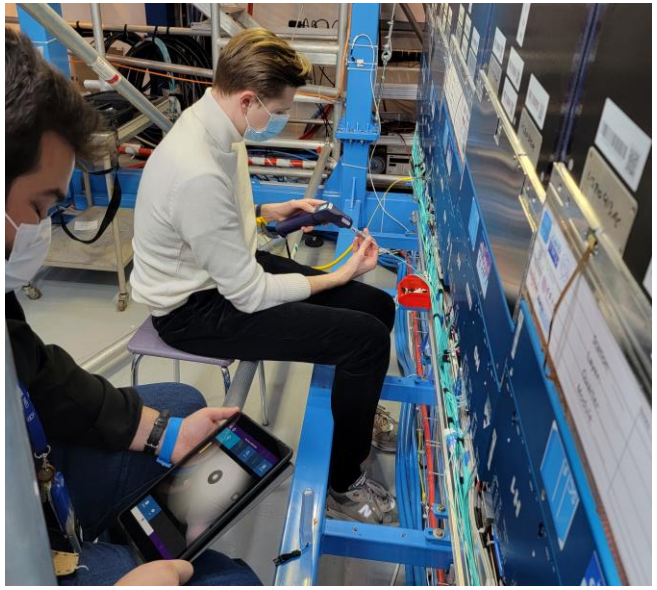
Preparing Front-end electronics.

Testing installation of the mechanics.

Connecting cooling lines.

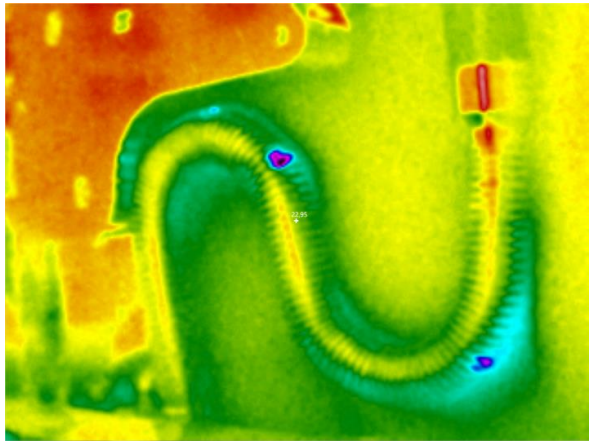


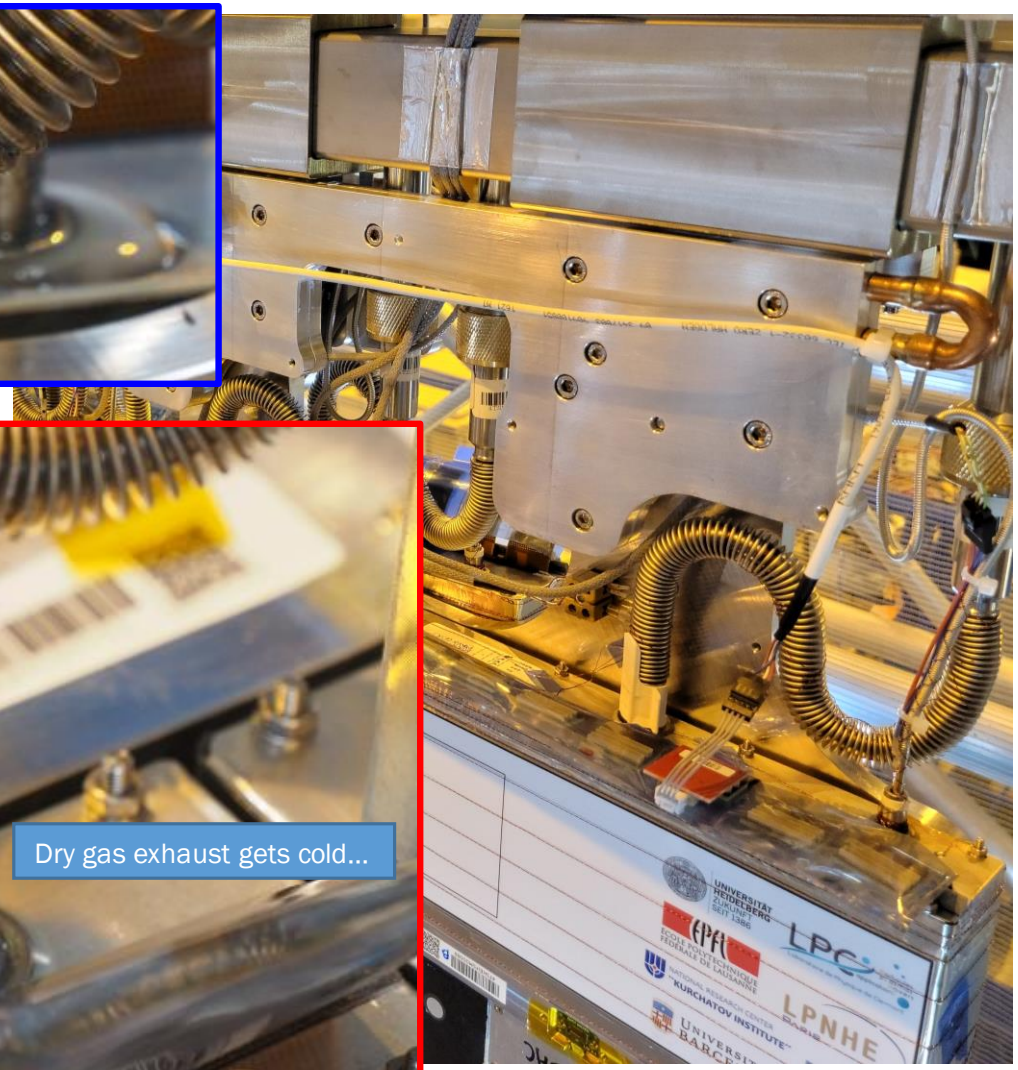
Vacuum bellow with a pin-hole.

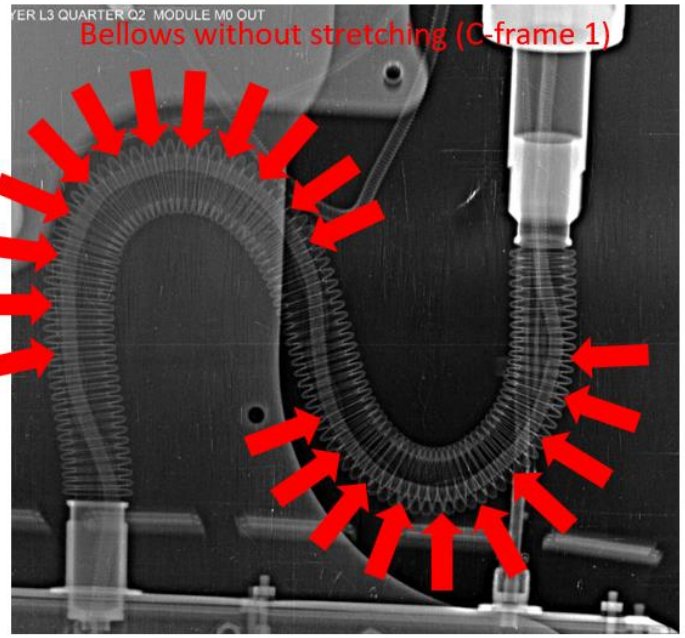


Inspecting and cleaning optical fibres

Condensation (Prevention System)





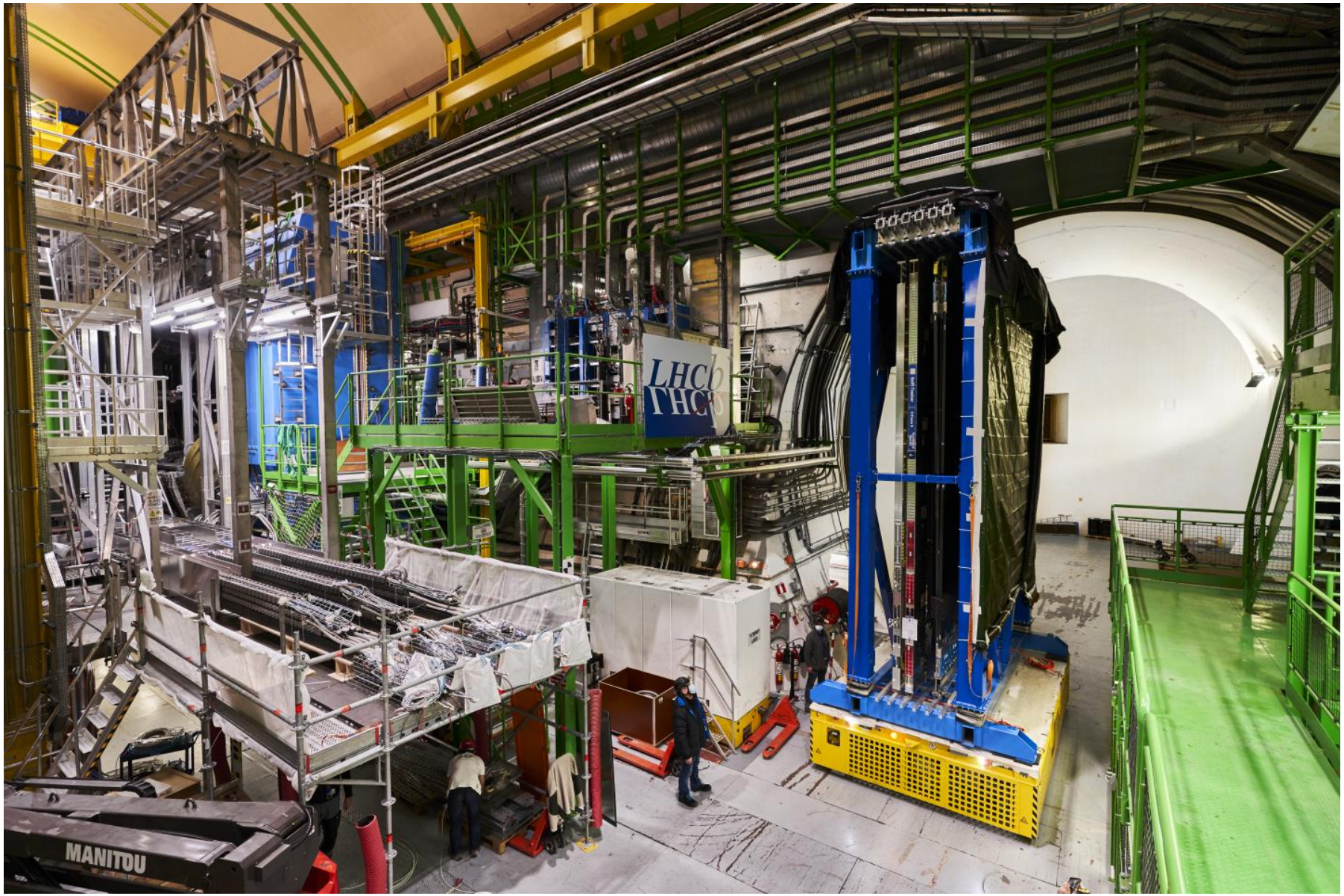


Transportation of C-Frames from the Assembly Hall to the Cavern (July 2021)

We were always lucky with the weather…

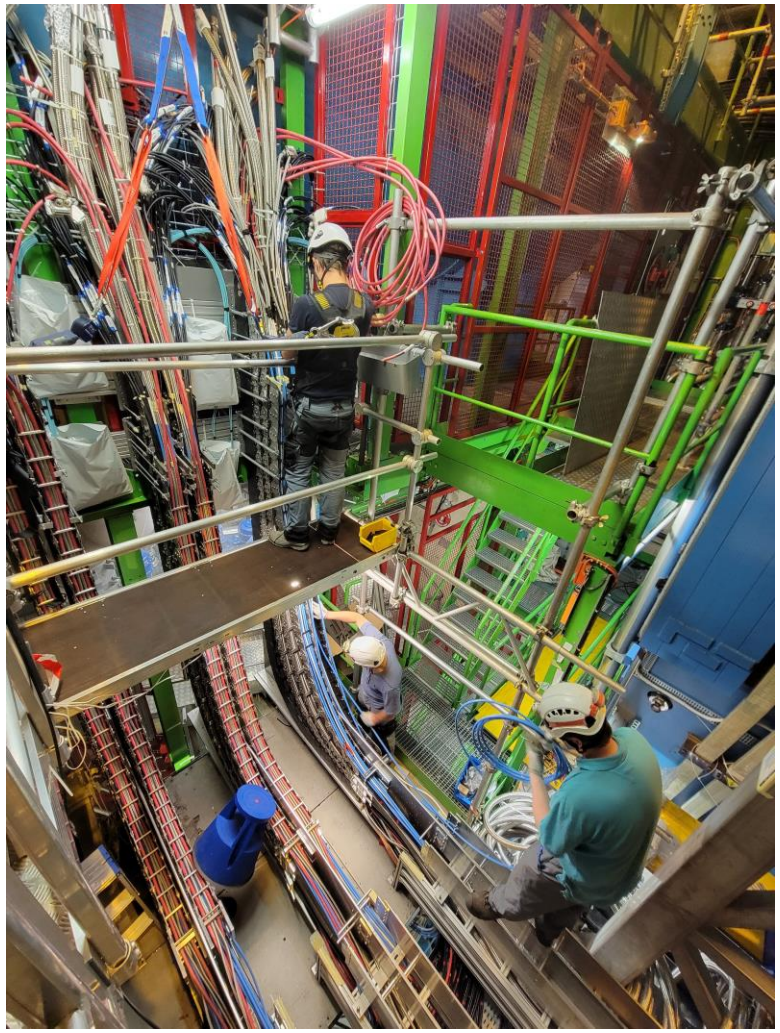
I made friends with the crane team.

And had some fun too.

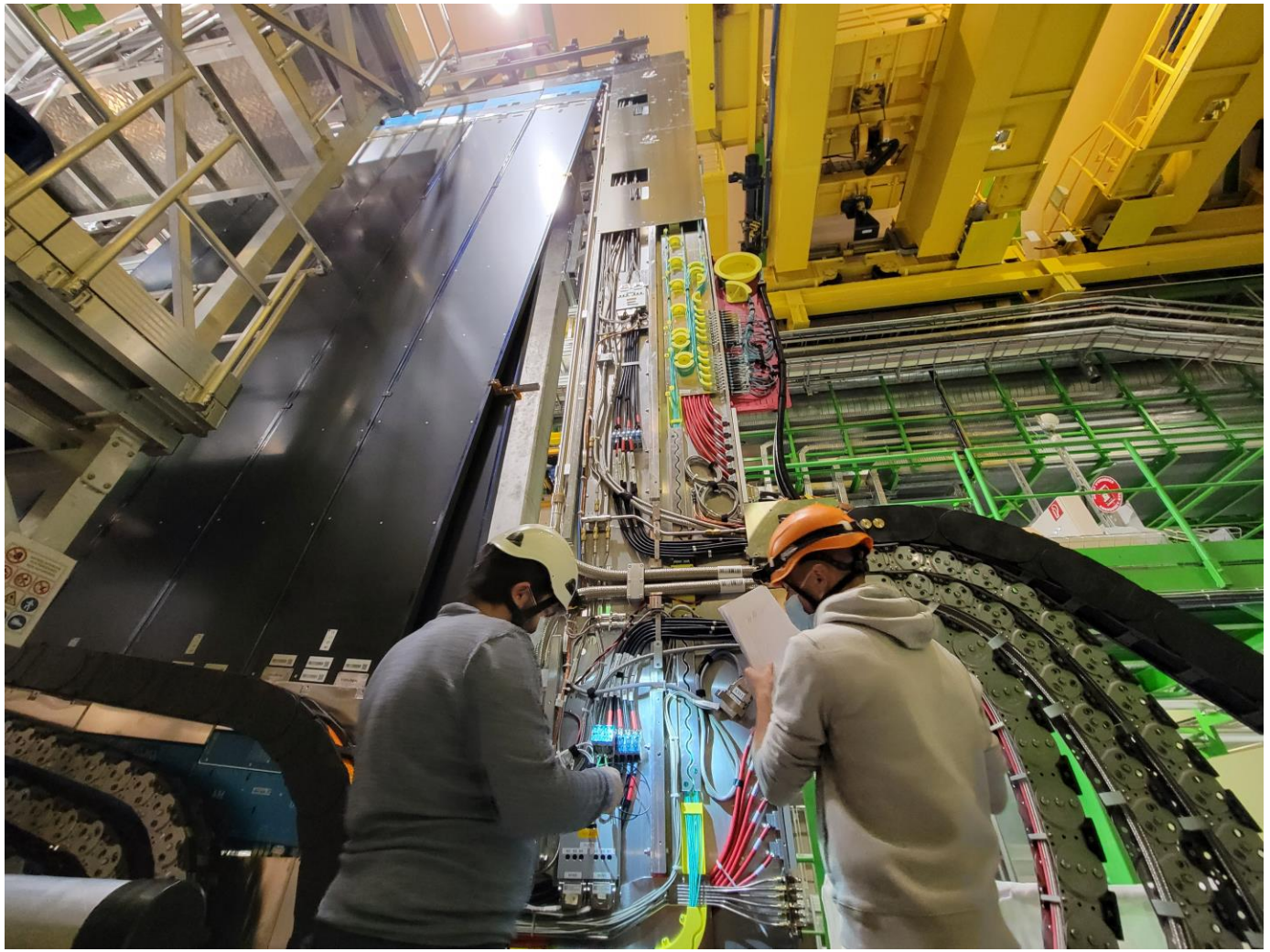


Unser Baustelle.

Cables and Chains (2020-2022)

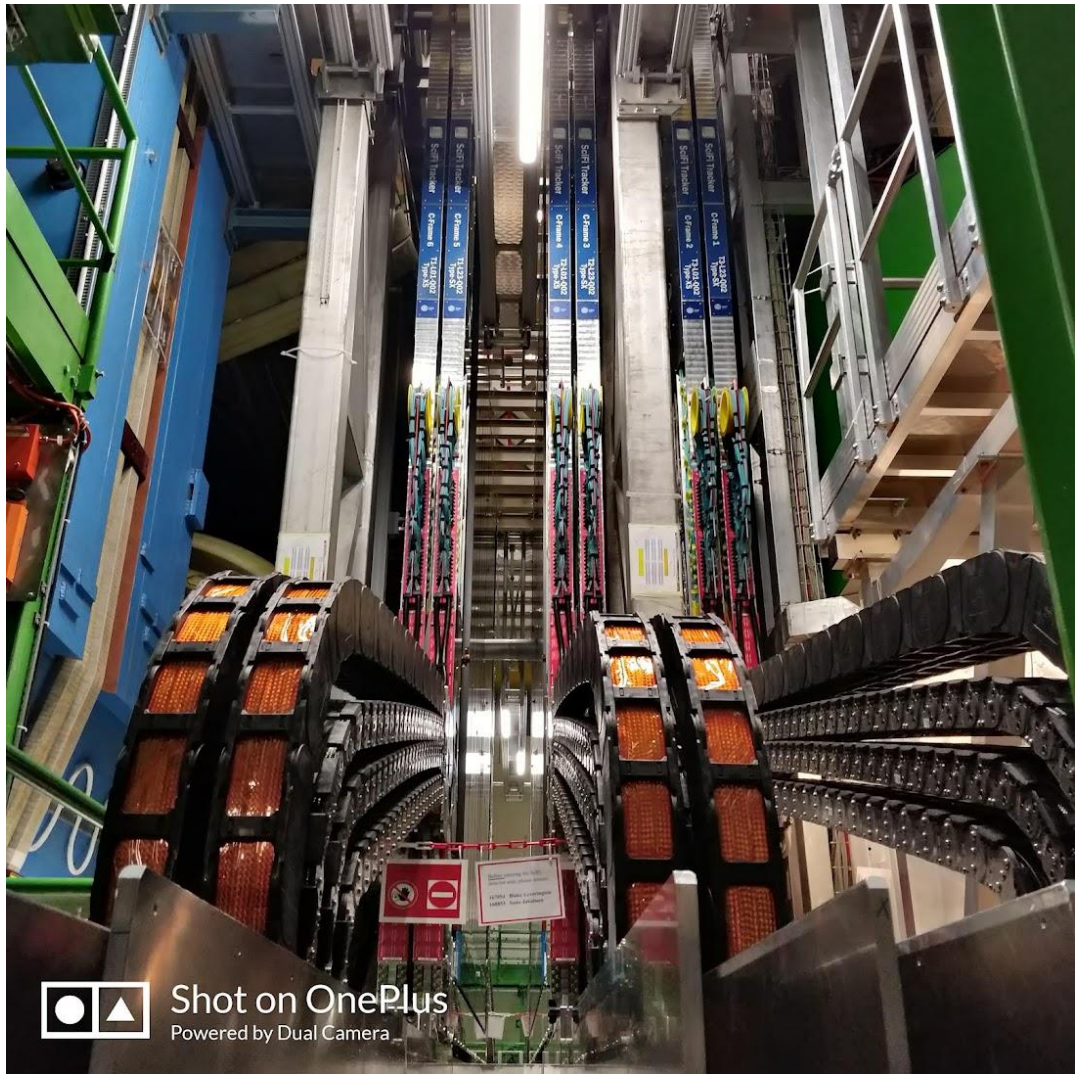


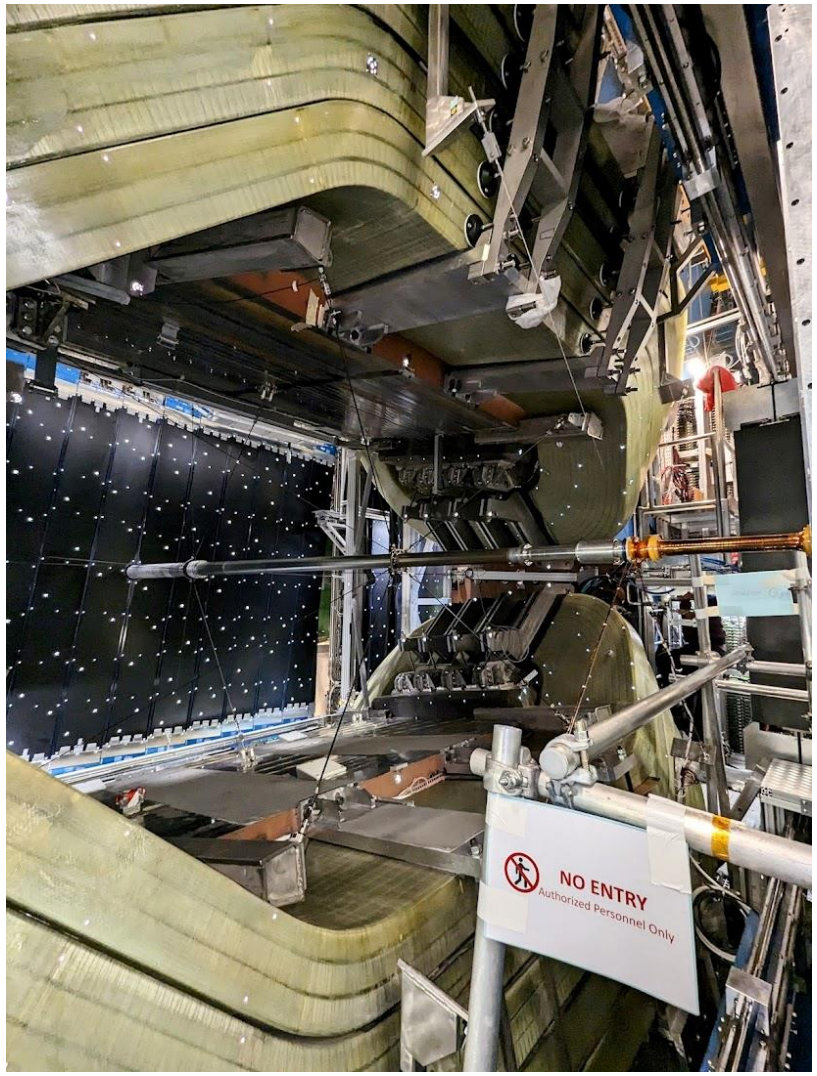
A lot of work underground in parallel to the above ground assembly.



Connecting all the cables, pipes, and fibres in the correct order.

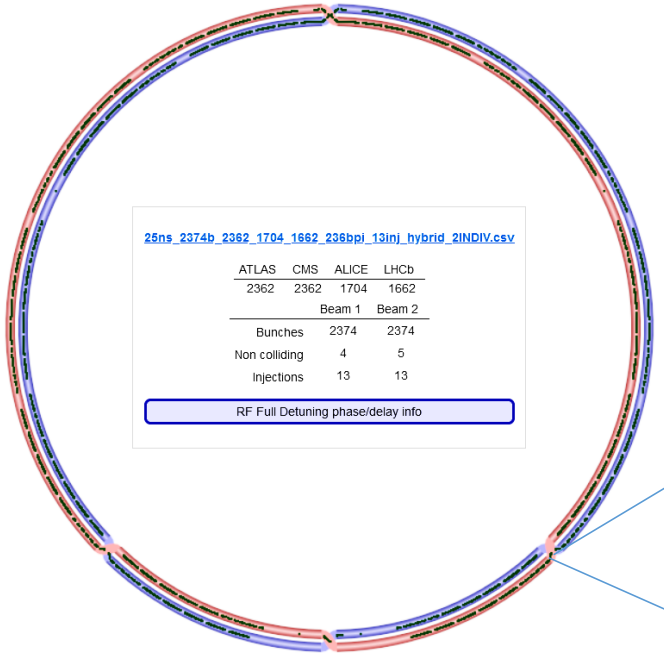
Habemus detector (April 2022)

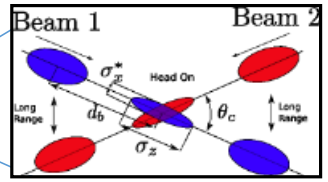


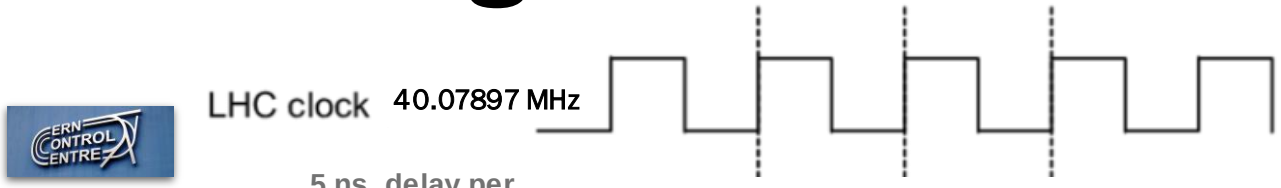


An aligned and closed SciFi Tracker.

Beam Collision Phase Alignment

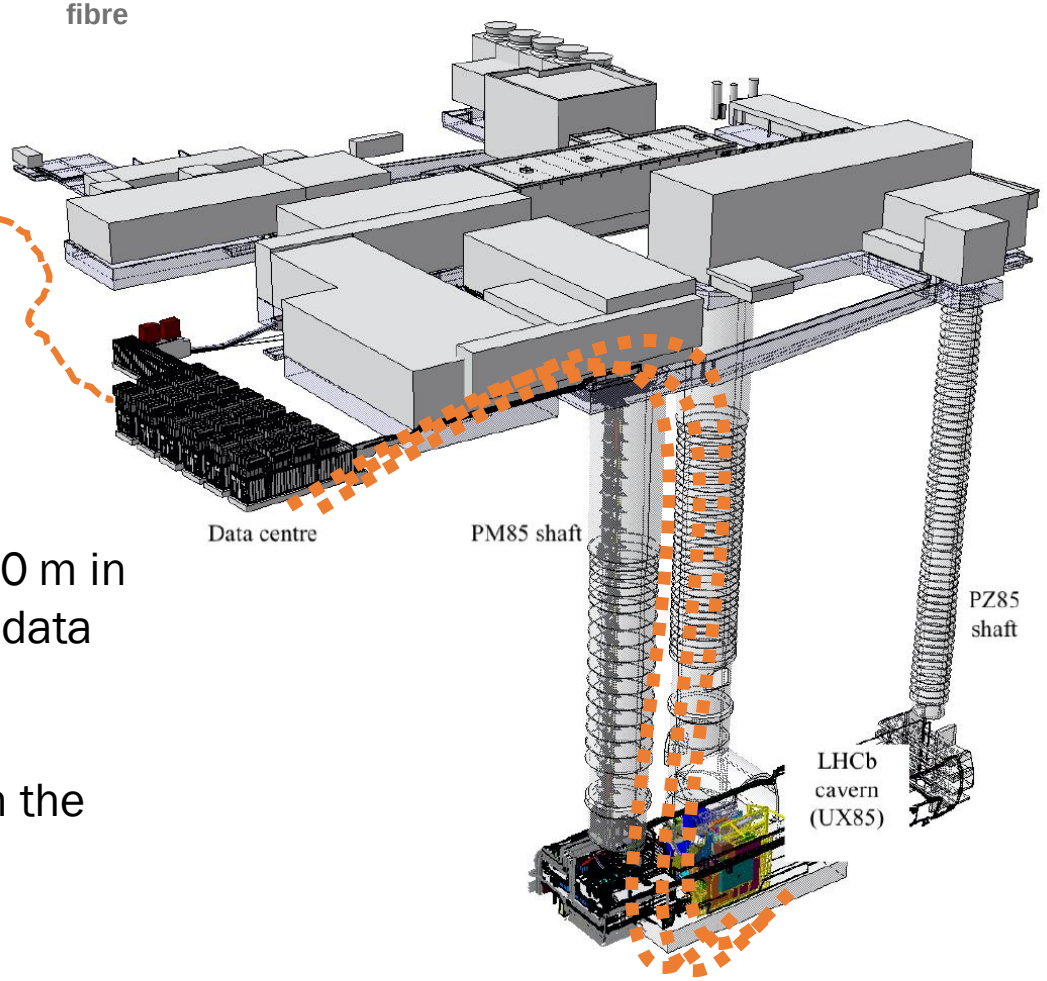






5 ns delay per metre of optical fibre

4km

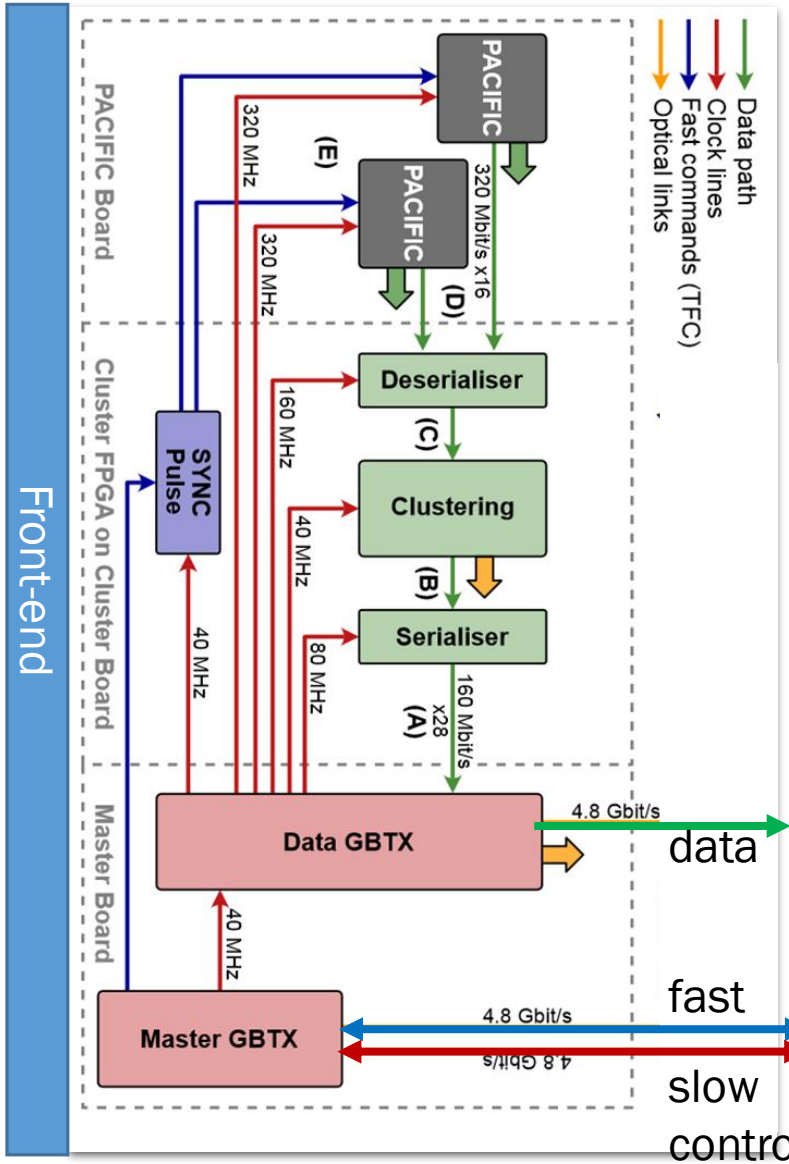


1 orbit = 3564 steps of 24.951 ns (11.2455 kHz)

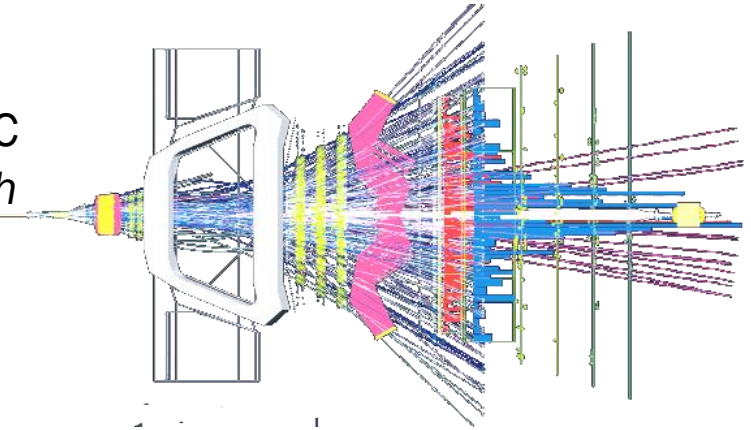
Optical fibres (some with different lengths… but~300 m in total) carry the clock signals from the SOL40s in the data centre down to SciFi.

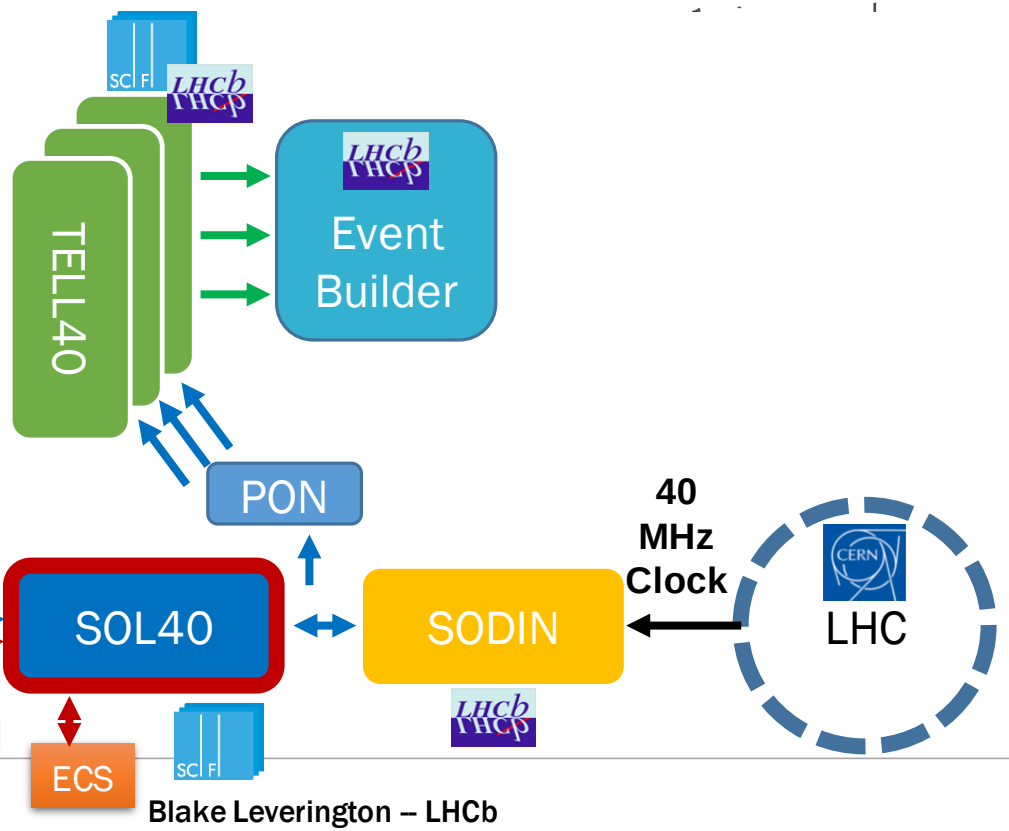
Different detectors need to stamp each collision with the same BX number.

Clock Complexity, Data Integrity

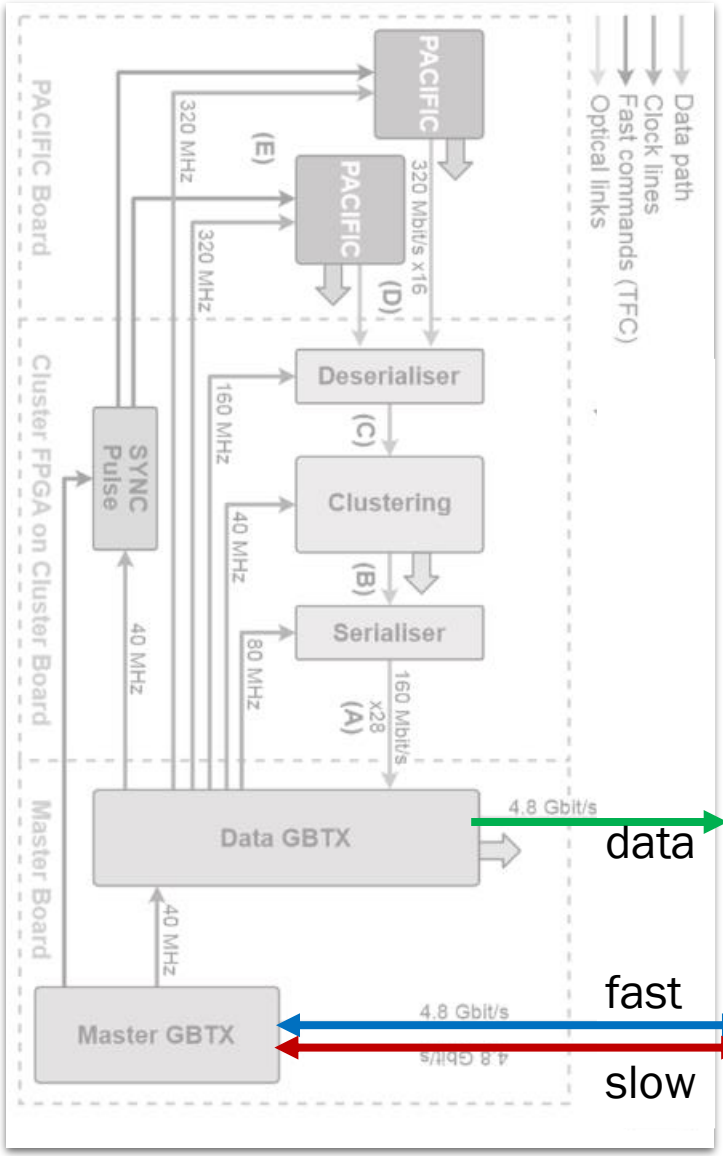


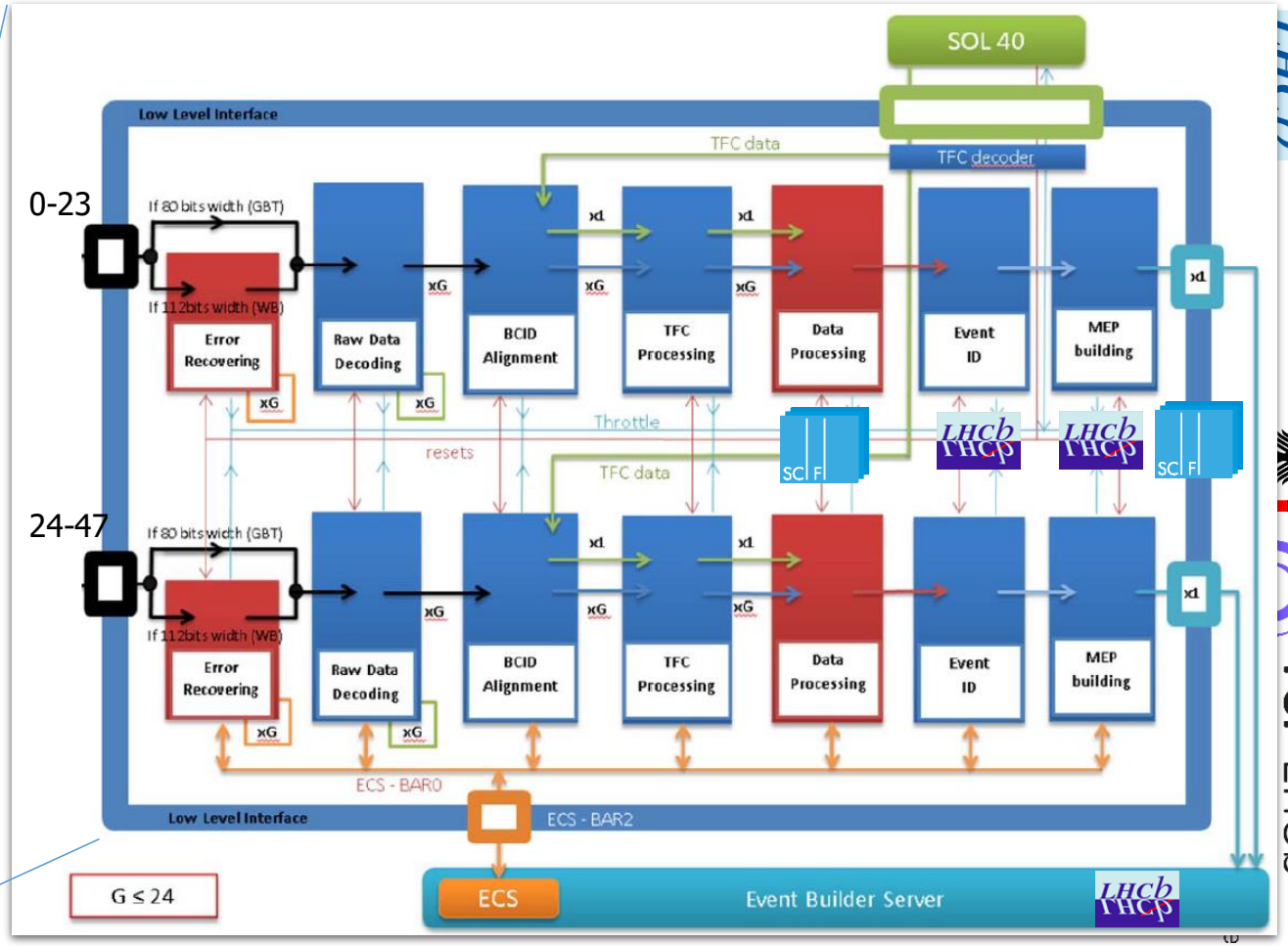
Send our data at 40 MHz for several hours of an LHC fill with minimal errors *with synchronous time stamps (BX-id) to LHCb.*

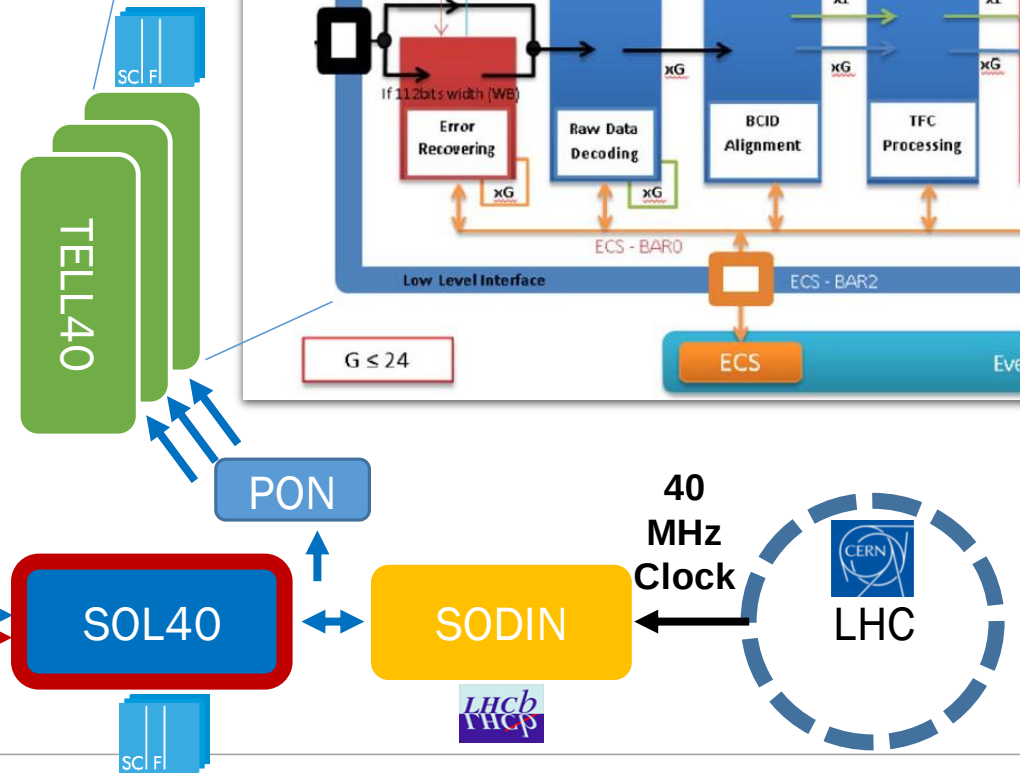




FPGA Firmware

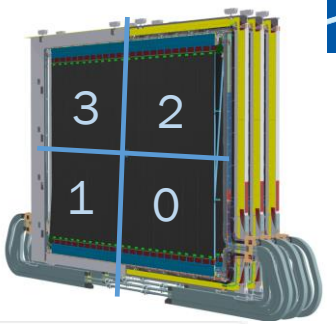


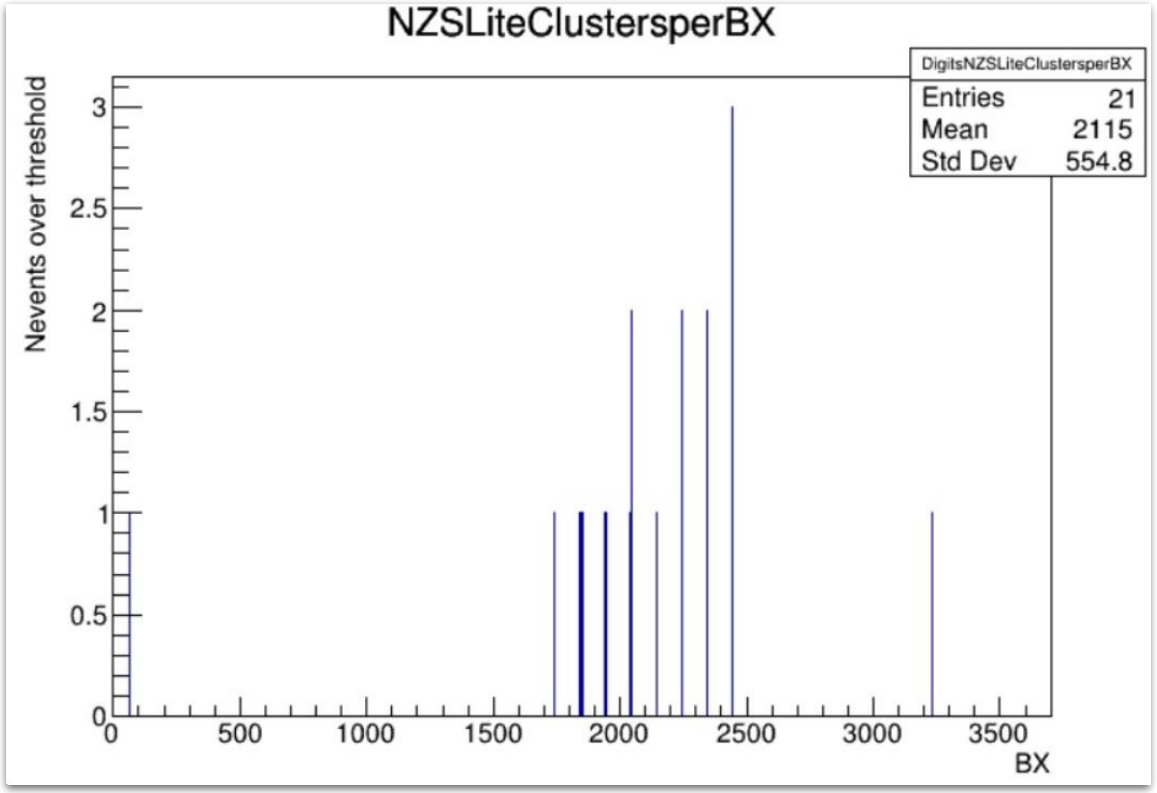


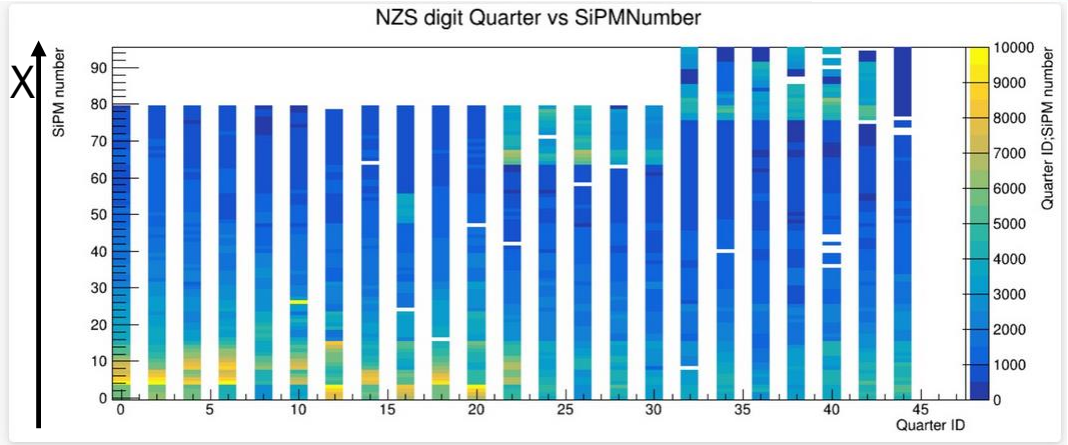


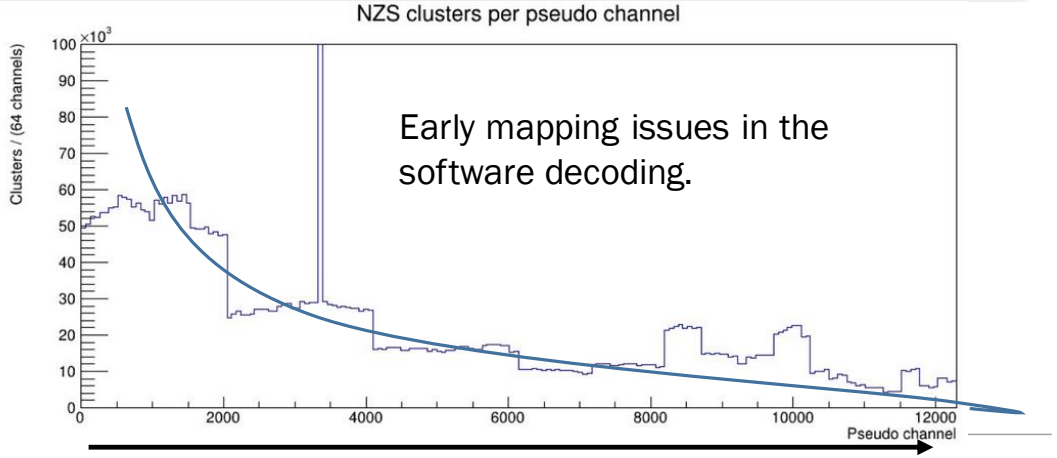
First collisions seen in SciFi June 29th, 2022

- 450 GeV beams, Quarters 0 & 2 only
- Random trigger (sample every BX)
- Offset of 849 BX observed wrt LHC filling scheme (easy correction to apply)

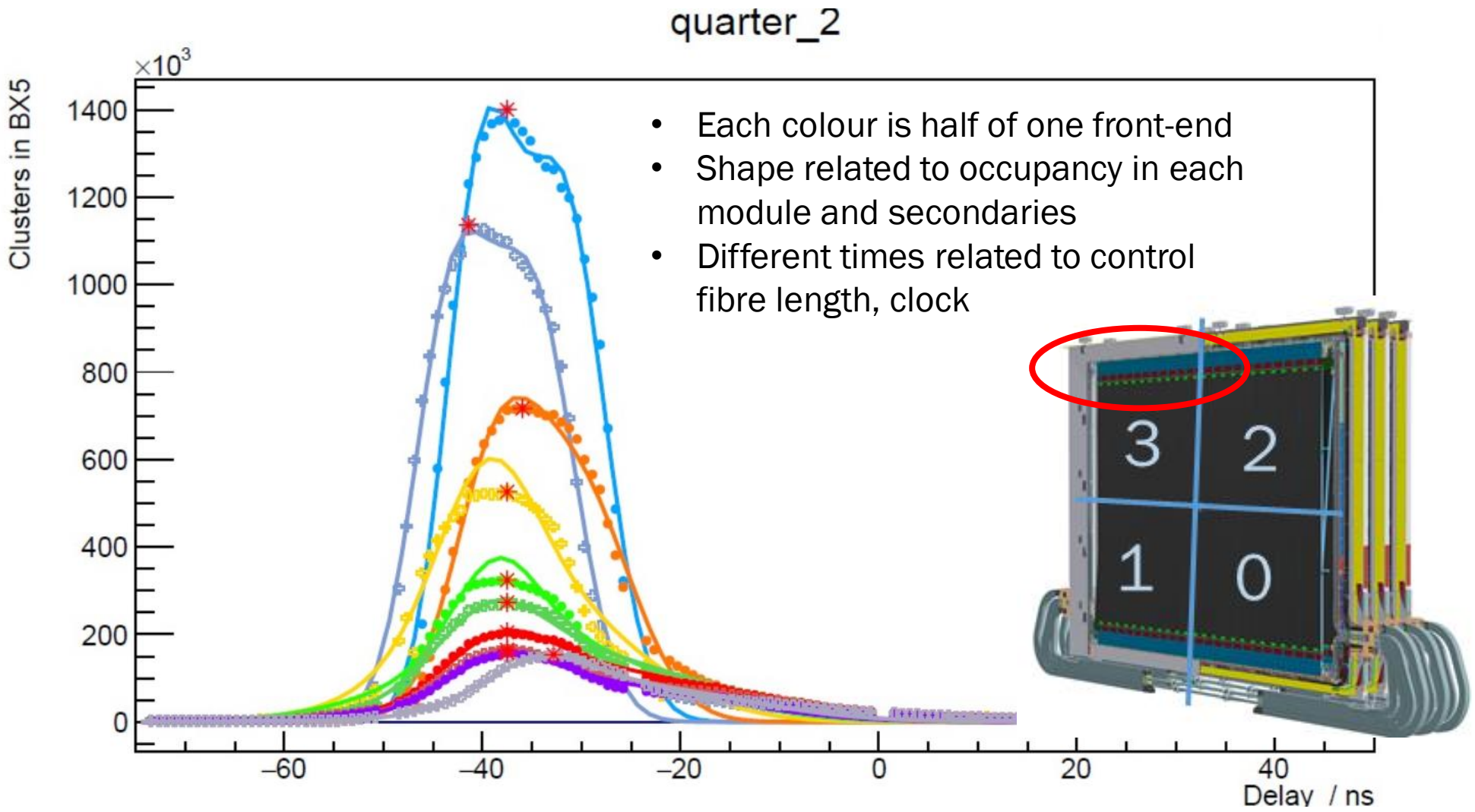






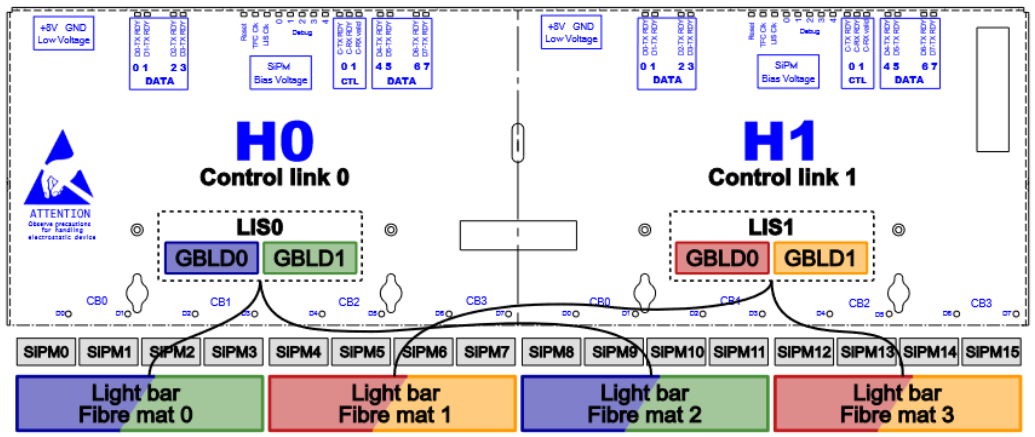


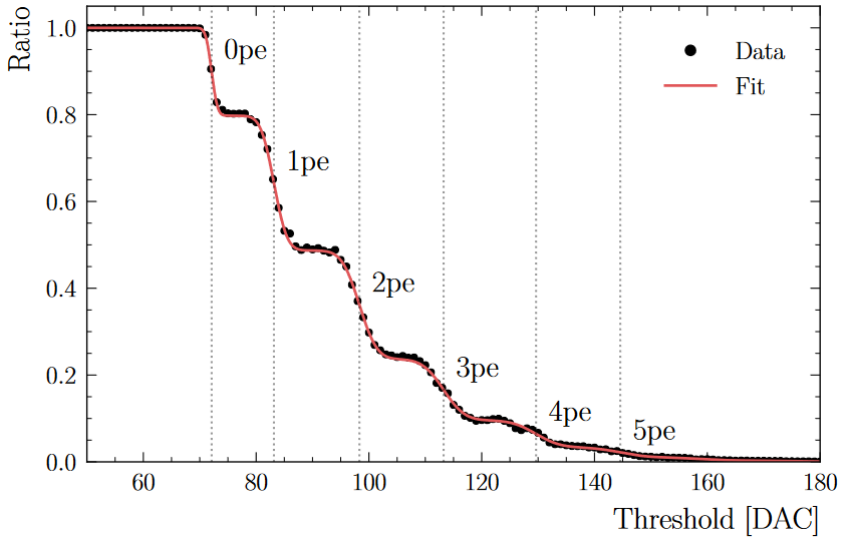
Fine-time scan (end of Aug. 2022)

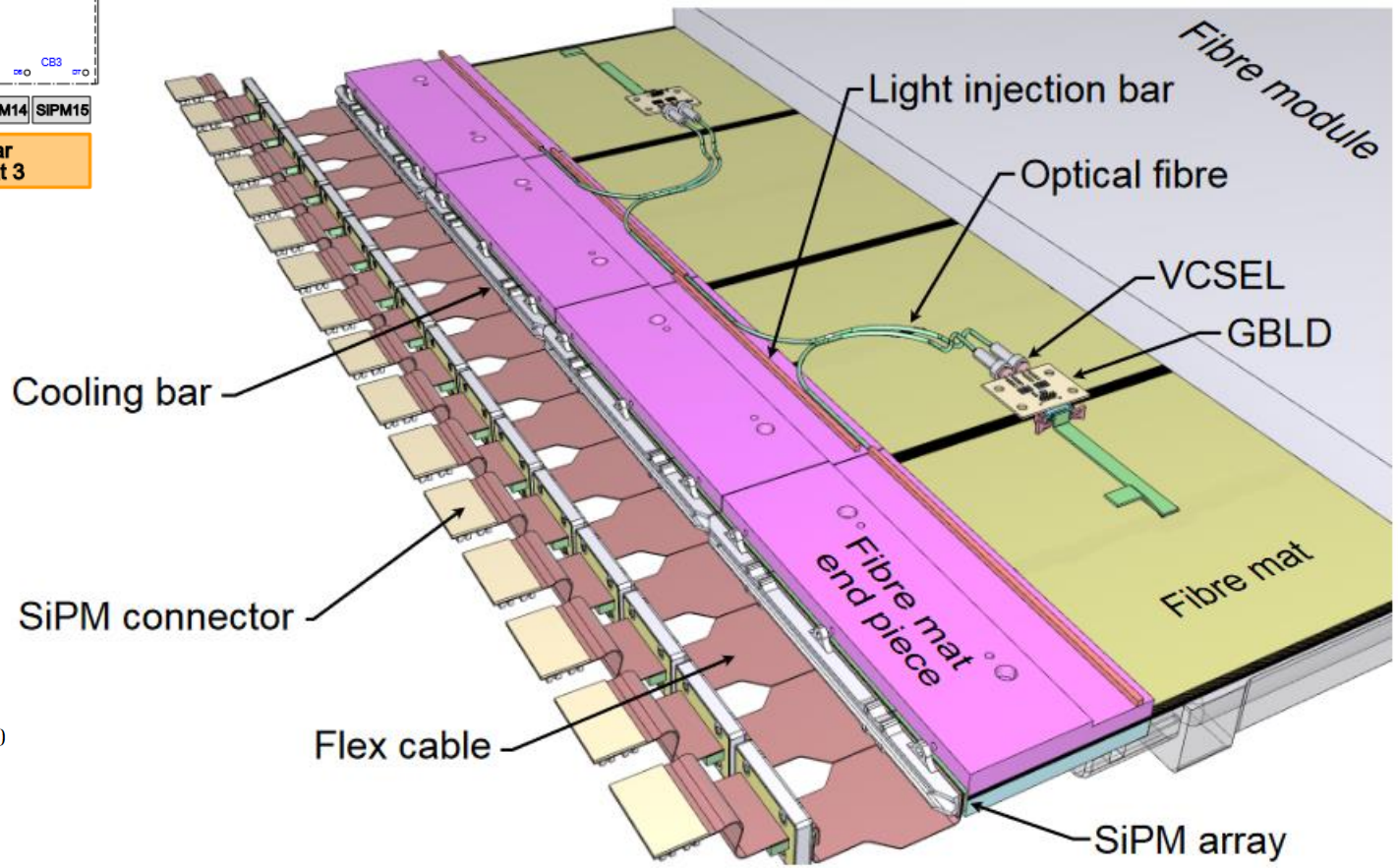


Threshold Optimisation / Light Injection Sys.

- Optimizes noise and signal separation (efficiency)
- 3 thresholds in each of 512k channels = **1.5 Million** to set
- Need to collect the data (counters in the FPGA), and apply
- Some firmware issues to debug & clock optimization

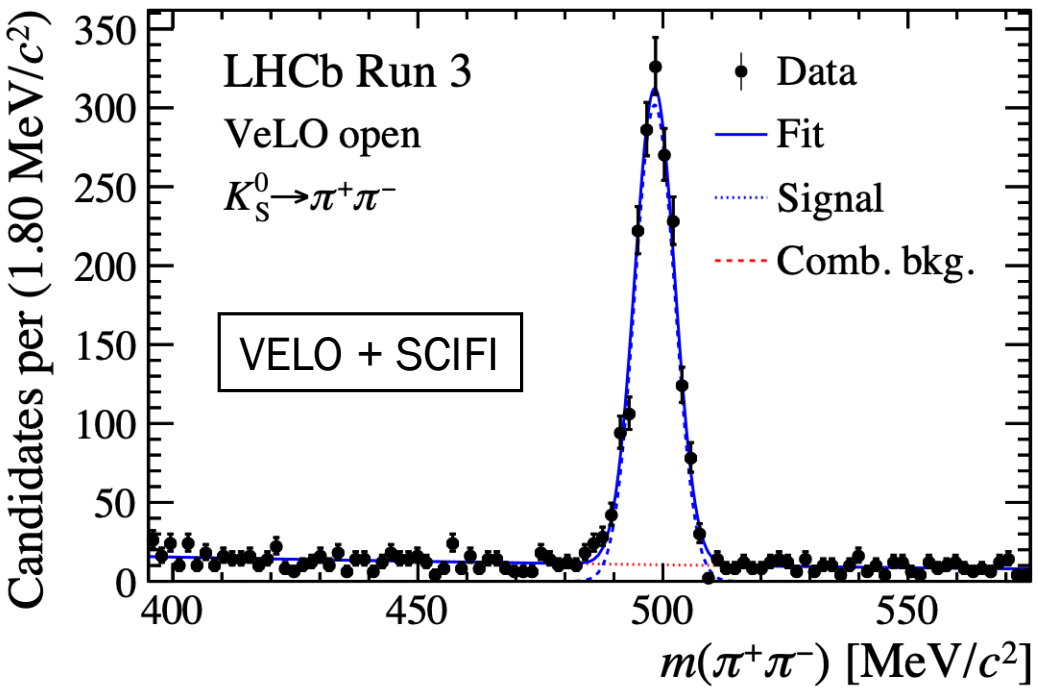






2022 Results

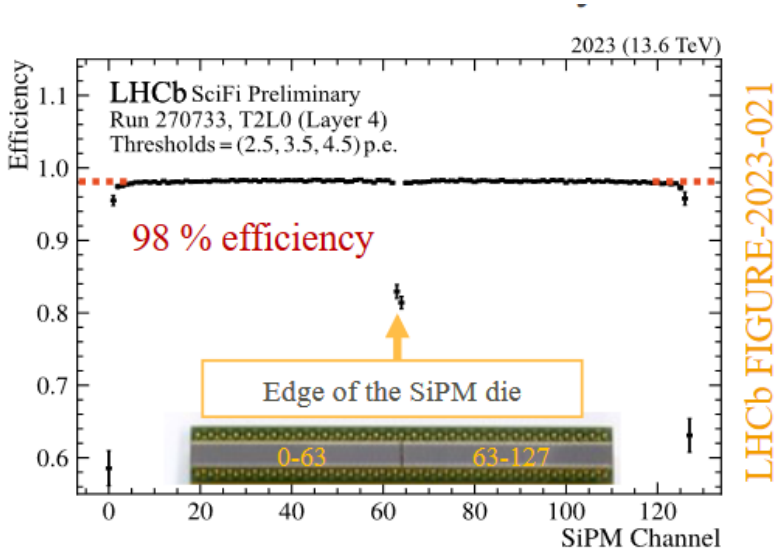
First mass peak observed October 26, 2022



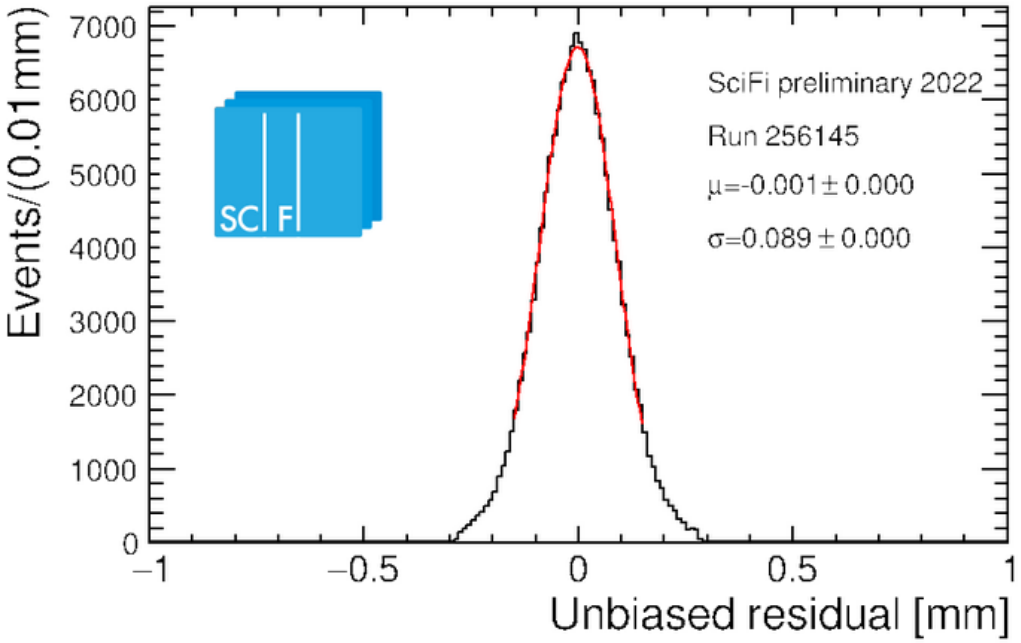
Tracker Performance 2022/2023

SciFi:

- 98 % hit efficiency
- close to design goal of 99 %



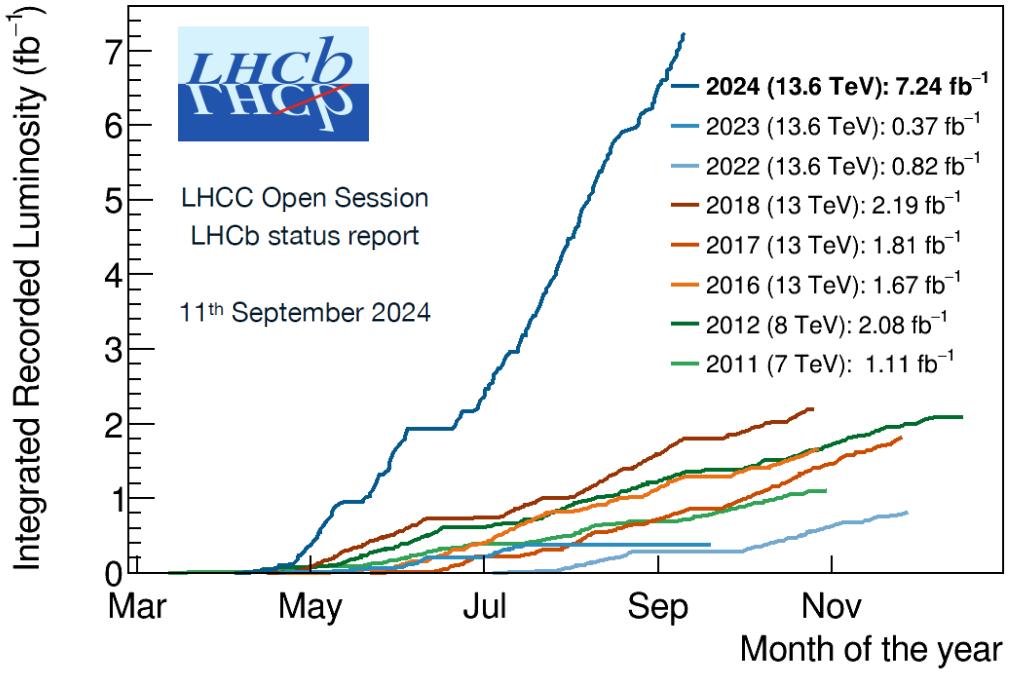
Single Hit Resolution

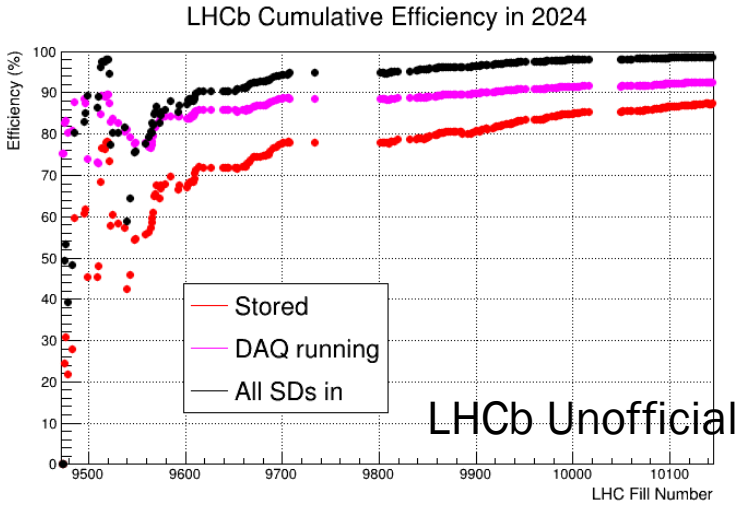


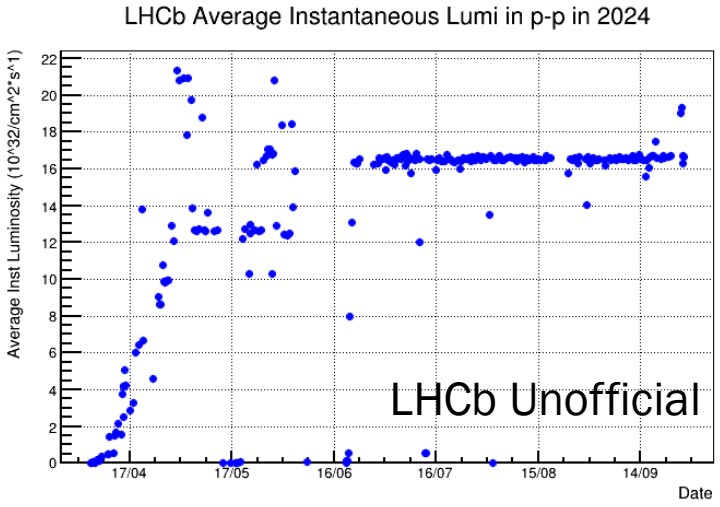
2024

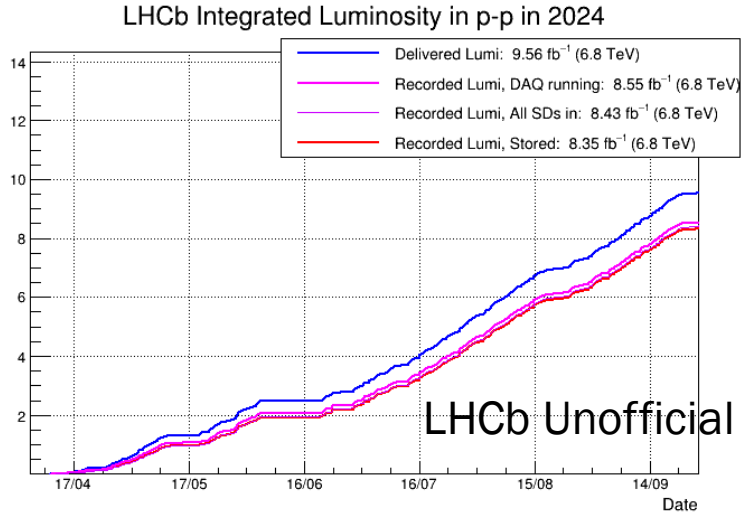
- All detectors are running well
- Achieved nominal and stable running since TS1 in June

LHCC Sept Open Session:
https://indico.cern.ch/event/1444045/#143-lhcb-status-report









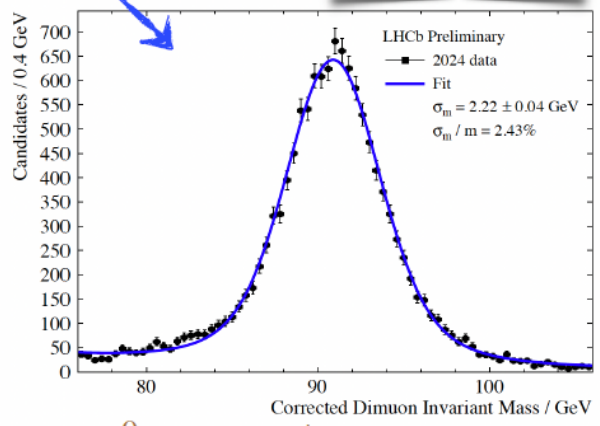
2024 data analysis

Partial datasets:

The analysis of the large 2024 data sample is already ongoing.

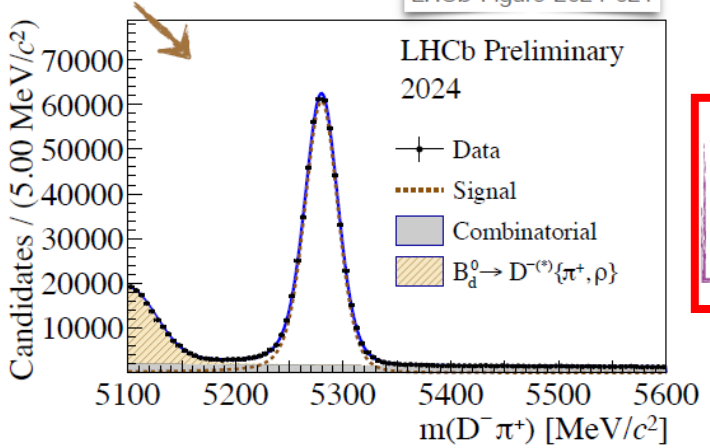
$Z^0 \to \mu^+\mu^-$

LHCb-Figure-2024-020



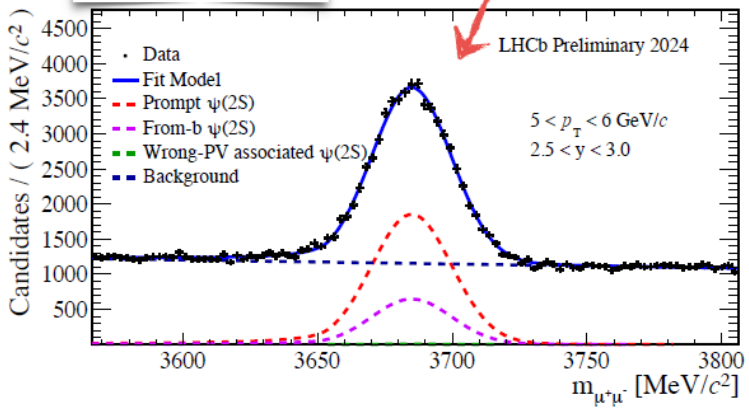
$B^0 \to D^-\pi^+$

LHCb-Figure-2024-021



$\psi(2S) \to \mu^+\mu^-$

LHCb-Figure-2024-024

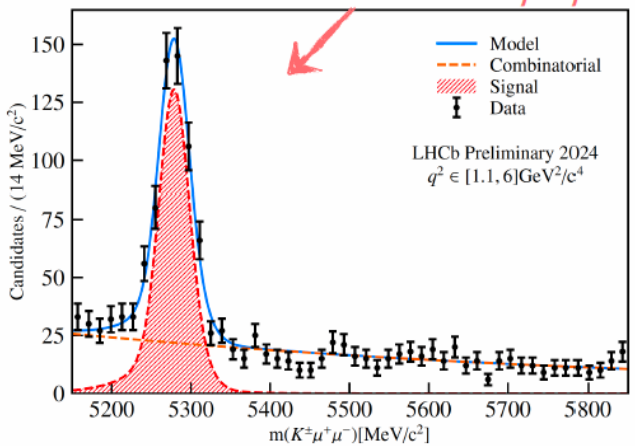


Total yields in 2024 ~[1-2] × Run 1 and 2 (2012-2018)
[channel dependent]

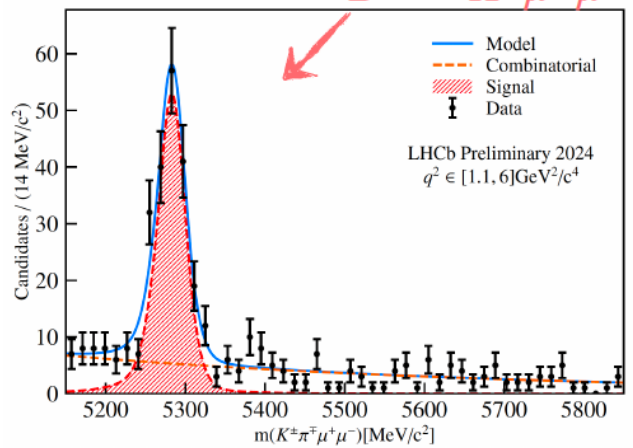
And many others…

$B^+ \to K^+\mu^+\mu^-$

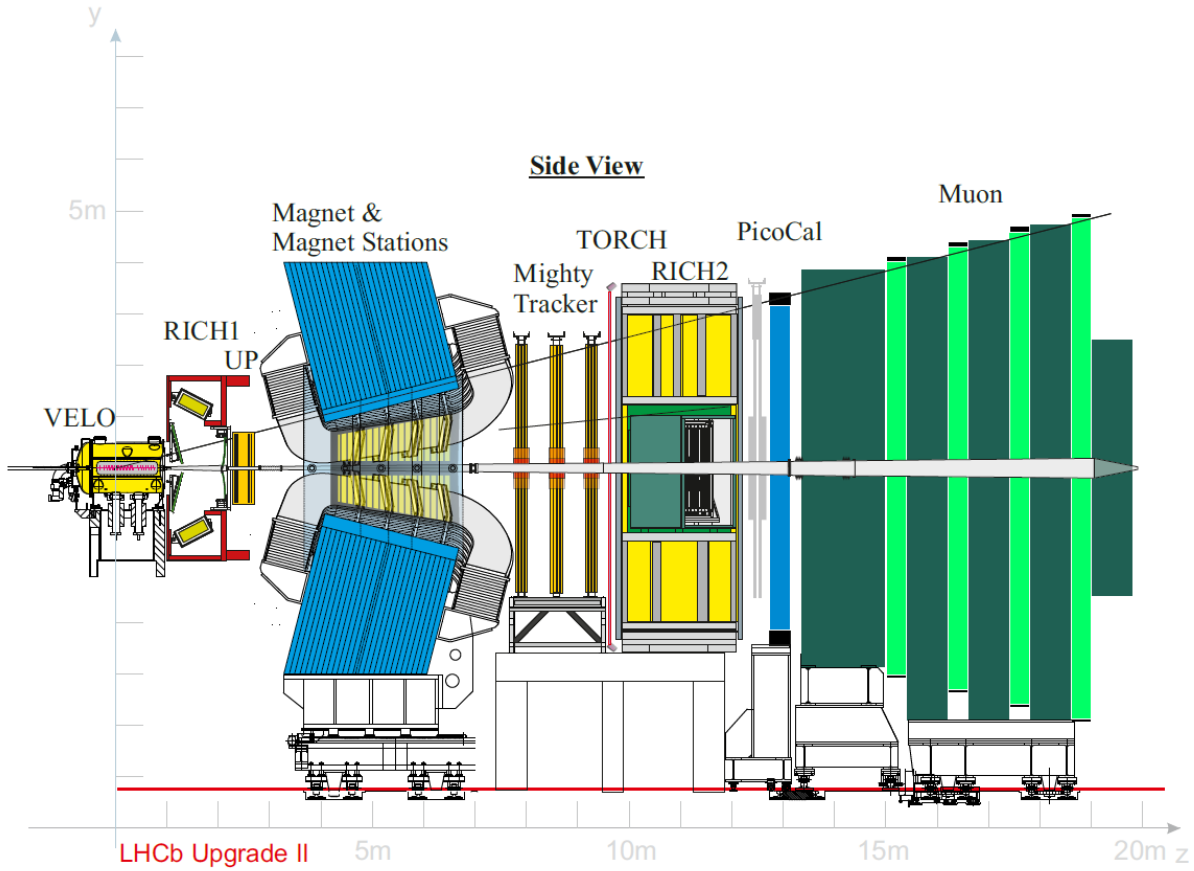
LHCb-Figure-2024-022

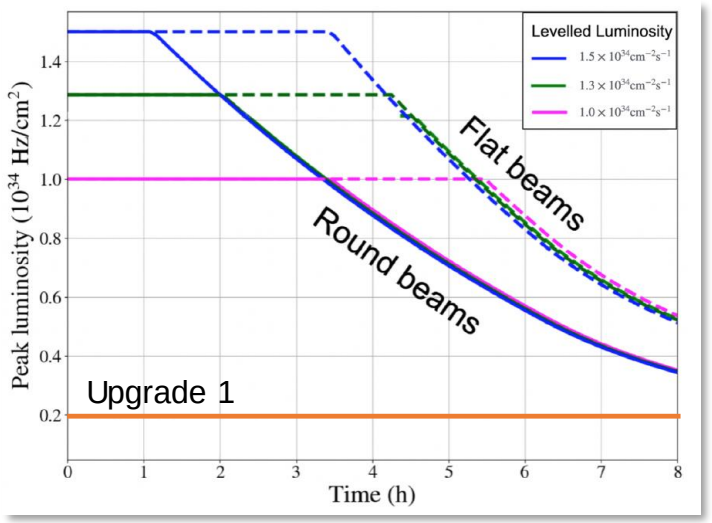


$B^0 \to K^*\mu^+\mu^-$



Upgrade 2





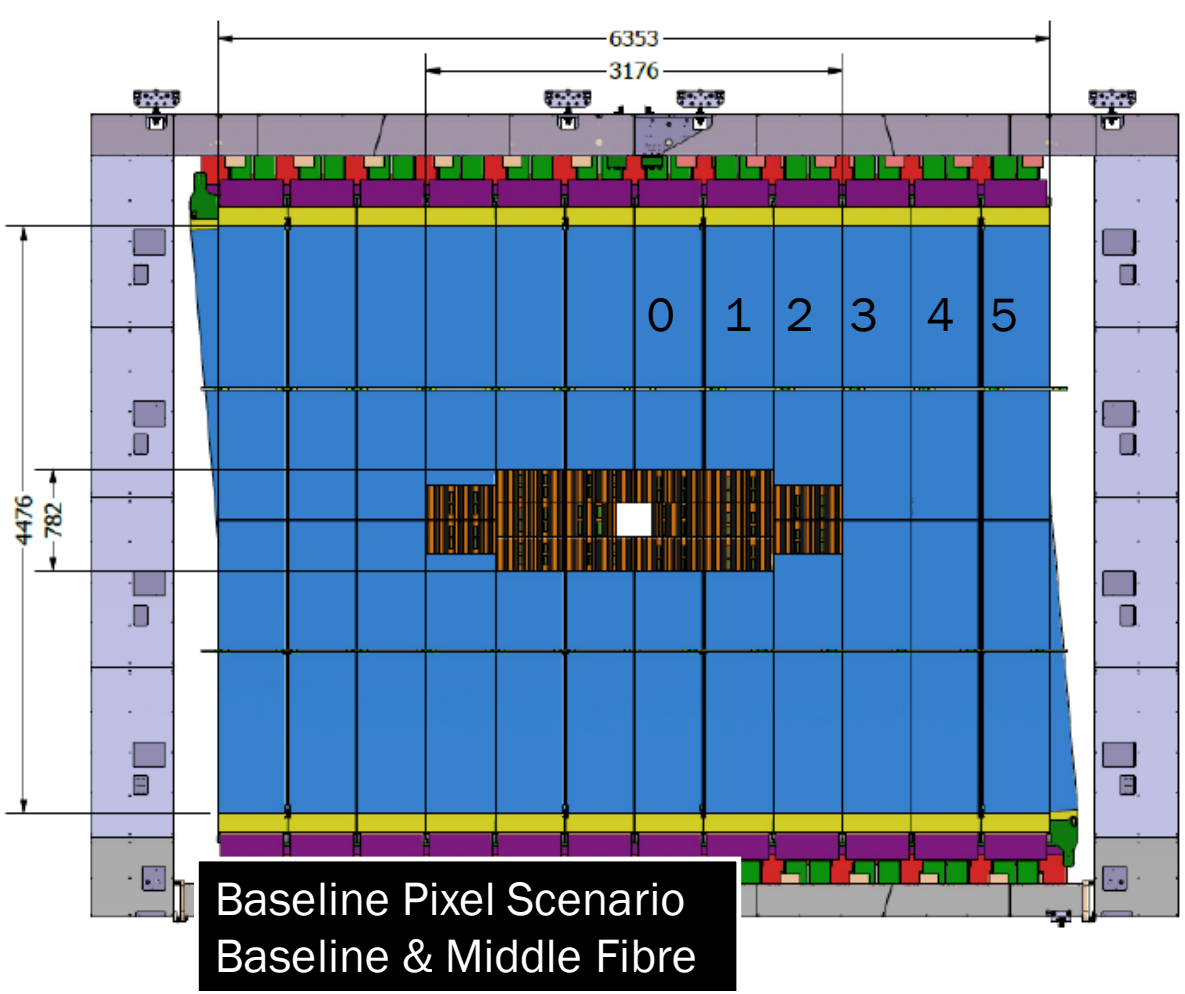
- Peak Luminosity 2 10^{33} → 10-15 10^{33}
- Visible collisions 5 → 25-35
- Collect another 200-300 fb^{-1}
  - Higher radiation requirements

- Add timing to VELO pixels and PID to match hits to tracks
- Trackers add pixels in high occupancy regions

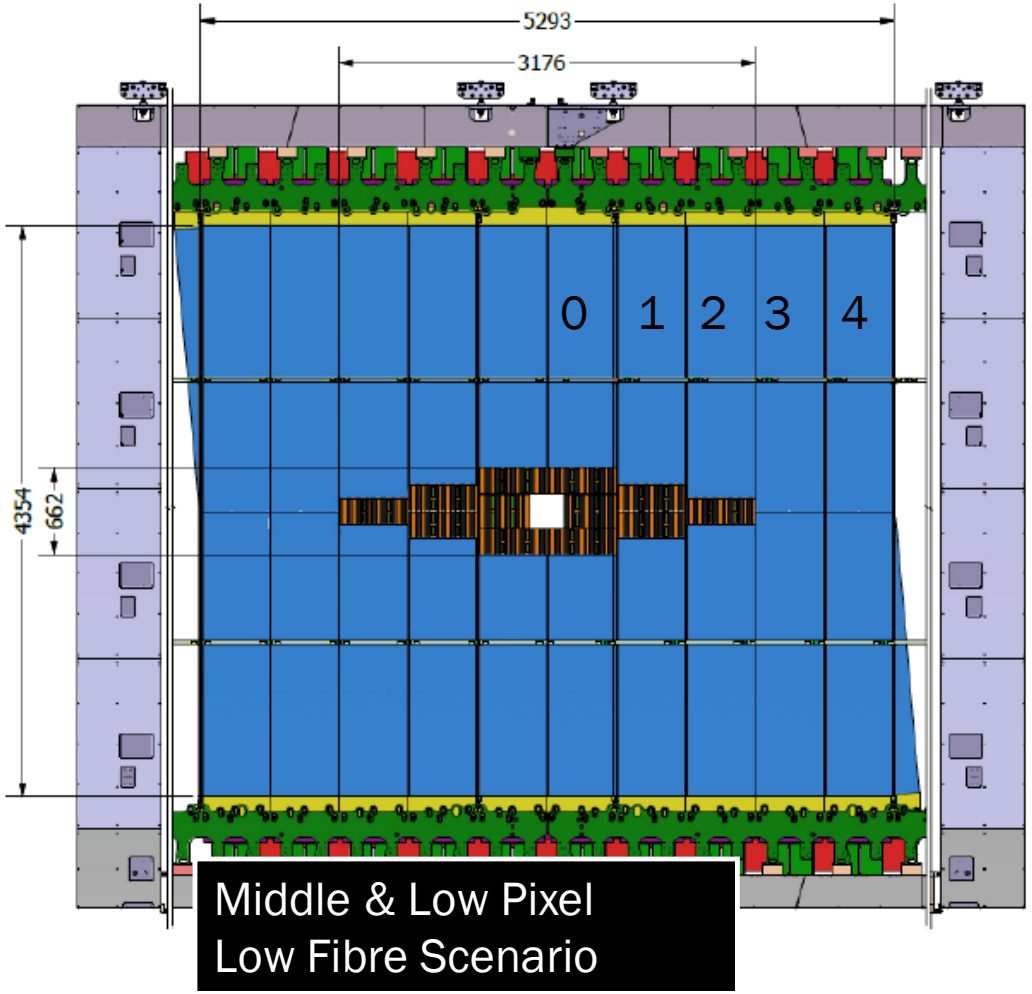
Scoping document submitted to the LHCC in September to outline the planned installation scenarios and detectors in LS4 (2033-2034)

The Mighty Tracker in the Scoping Doc.

Mighty-SciFi: scintillating fibres for the majority of the area
Mighty-Pixel: a high-granularity silicon (DMAPS) pixel detector around the beampipe

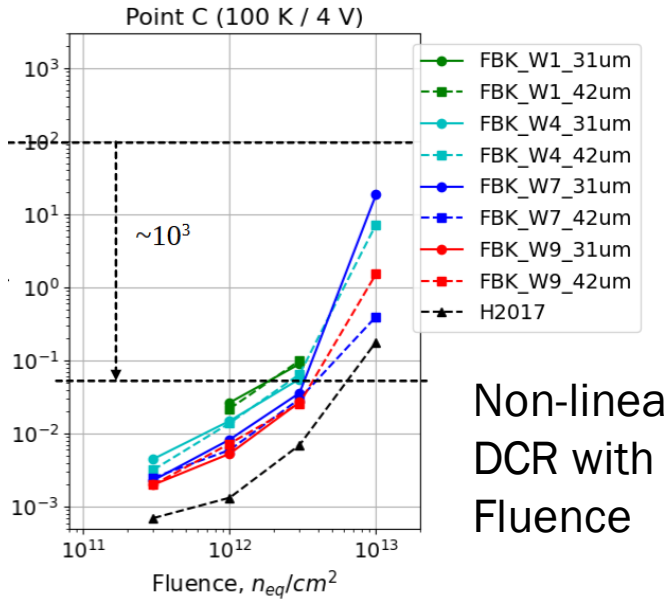


Baseline Pixel Scenario
Baseline & Middle Fibre



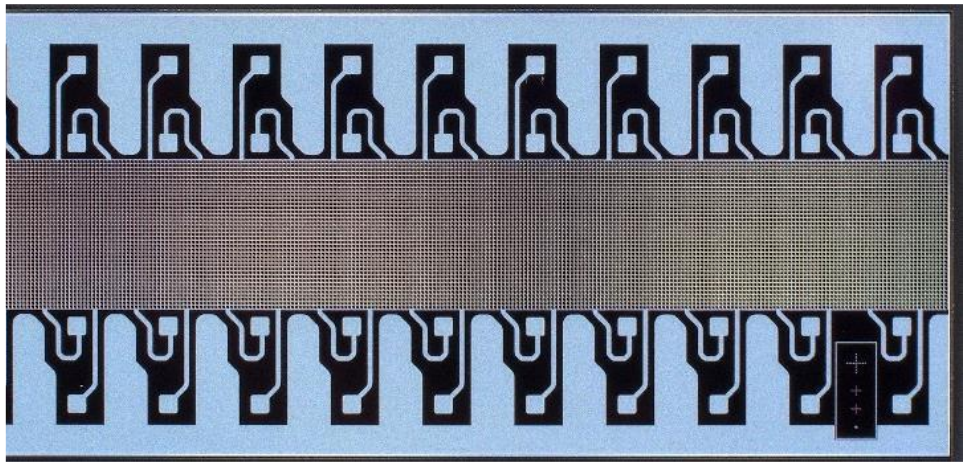
Middle & Low Pixel
Low Fibre Scenario

Micro-lenses and Cryo-cooling of SiPMs (100K)

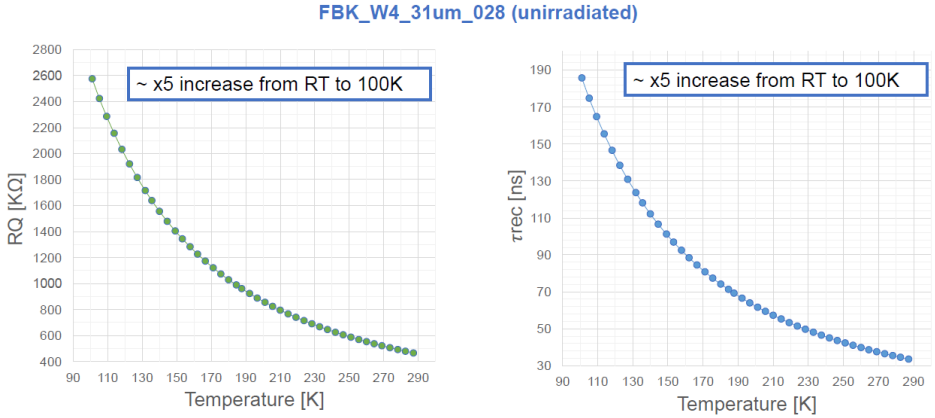


Non-linear DCR with Fluence

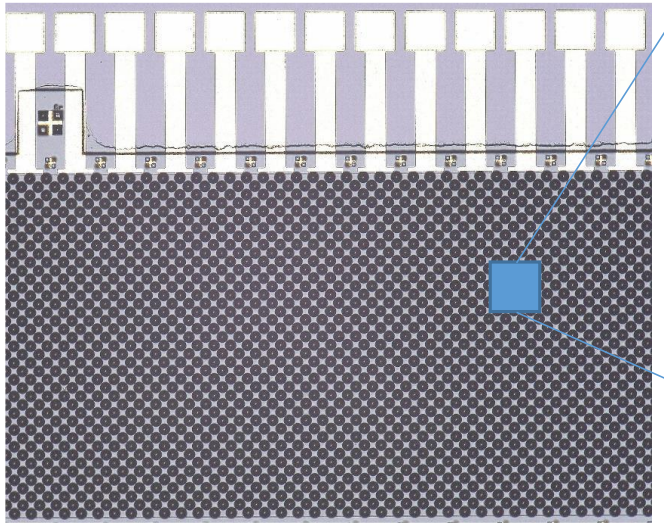
H2024 SiPMs with TSV

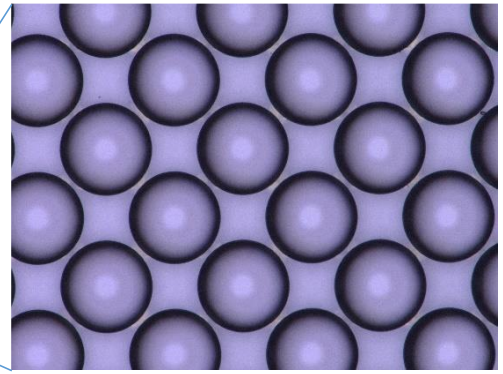


Quenching resistor and recovery time



EPFL

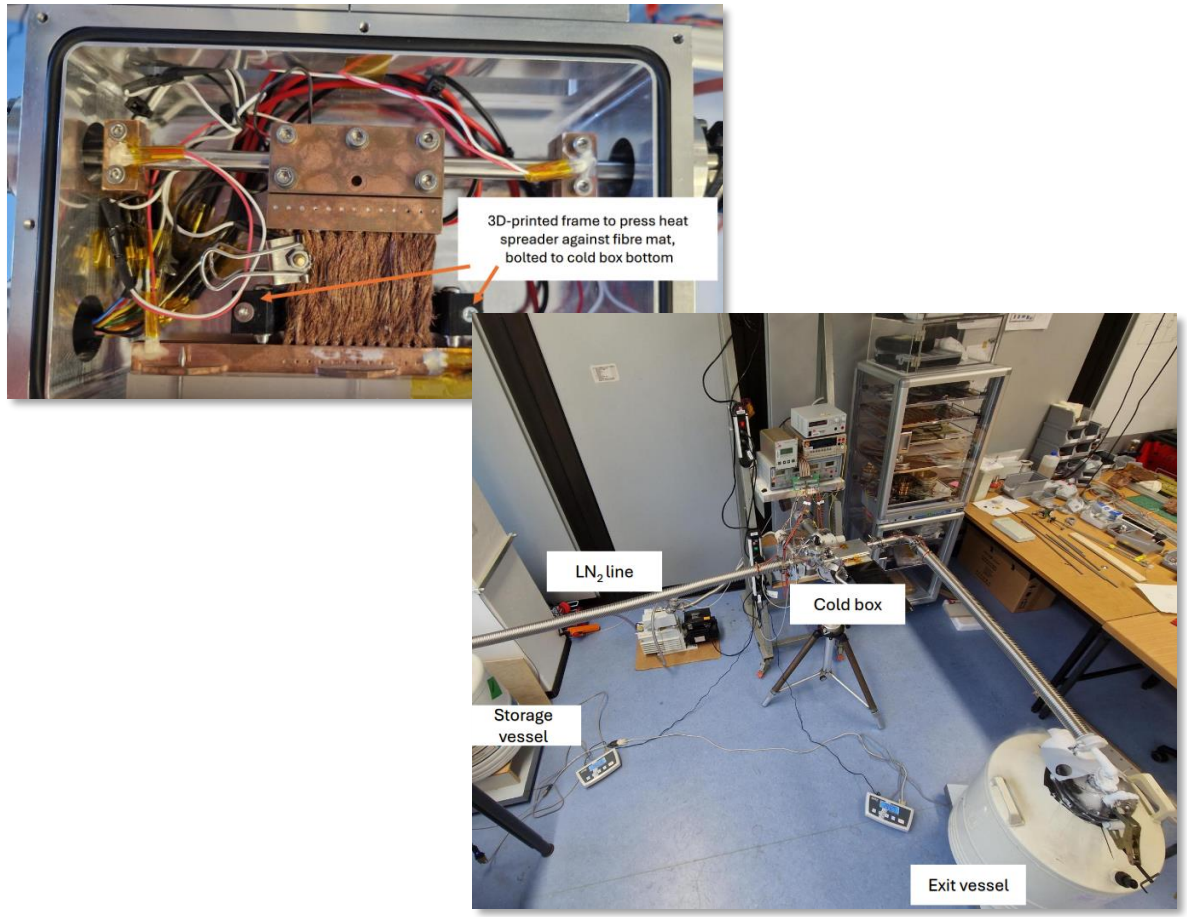




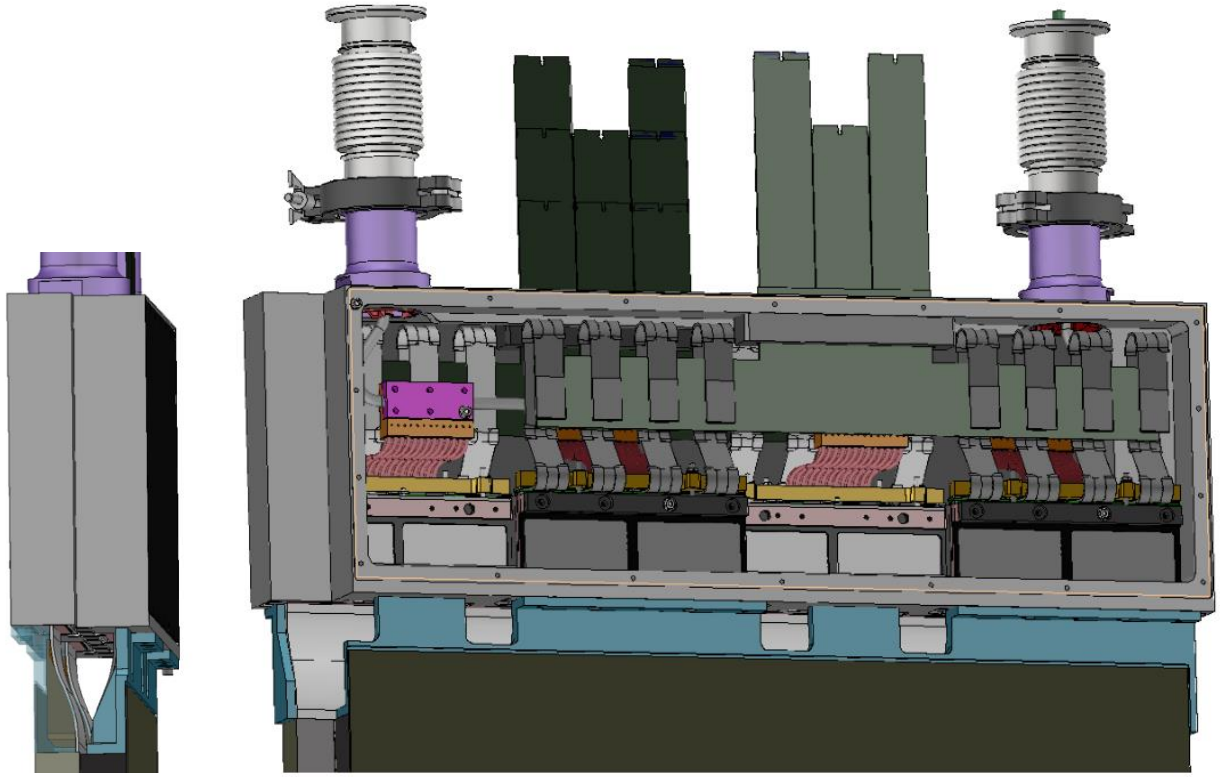
SiPM with microlenses (expect 10-30% gain, overvoltage dependant)

New Cold-boxes

Assume LN2 as the baseline. Maybe 2-phase Krypton or Argon?



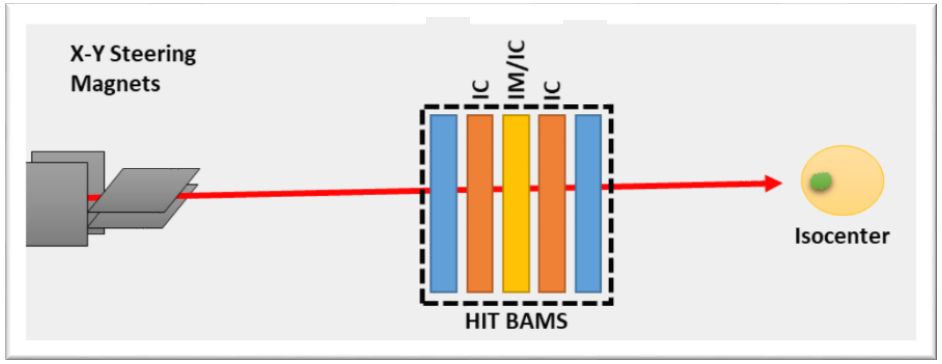
Test-boxes in development in Aachen and EPFL



Staggered modules to remove gaps and improve geometric coverage/

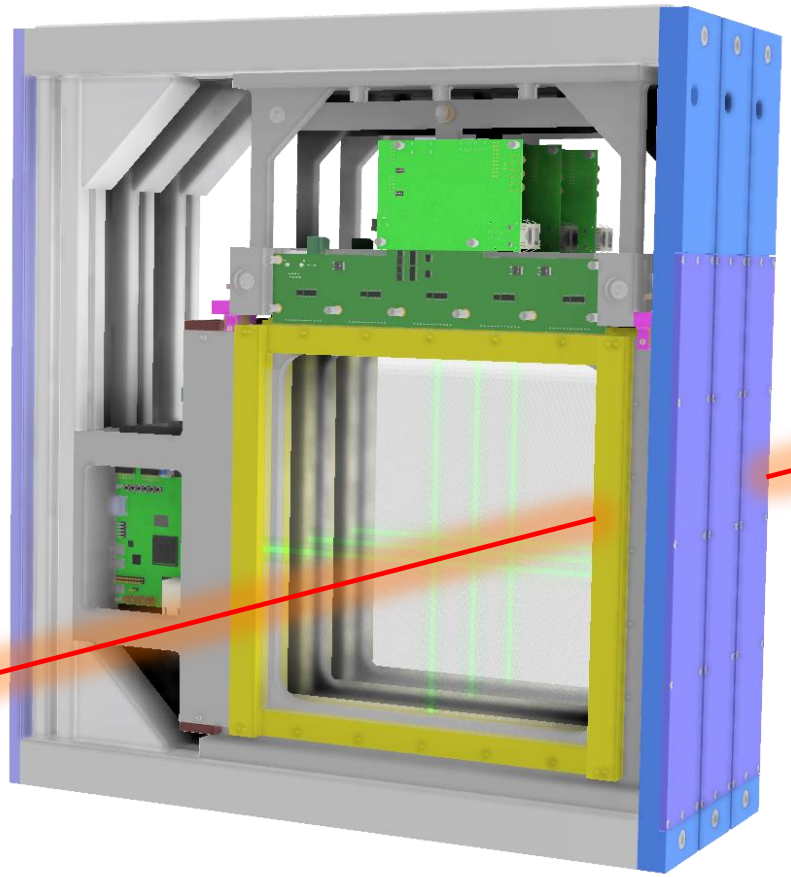
The Scintillating Fibre Beam Profile Monitor for Ion Therapy Beams

Liqing Qin, Blake Leverington, Michael Dziewiecki*

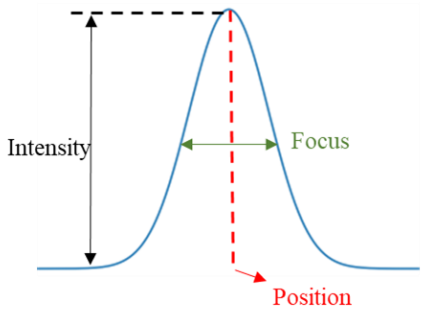


DFG Deutsche Forschungsgemeinschaft

Beam monitor for raster-scanning



2023 engineering prototype



Sketch for beam profile.

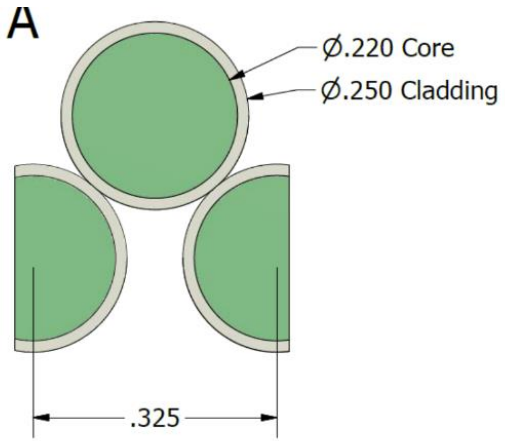
Parameter	Steps	Protons	Carbon
Energy	255	48 - 221 MeV/u	88 - 430 MeV/u
Penetration	255	20 - 300 mm	20 - 300 mm
Intensity	9	$8 \times 10^7 - 2 \times 10^9 s^{-1}$	$2 \times 10^6 - 8 \times 10^7 s^{-1}$
Beam Size	4	8 - 20 mm	4 - 12 mm

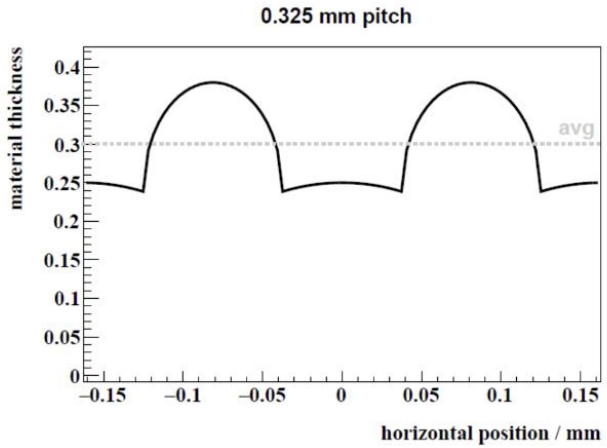
Prompt feedback of the beam position
- Interlocks for patient safety
- Feedback loops for position correction

- Replacement of the MWPCs currently used requires
  - >4 to 8 kHz readout
  - Light (<0.3mm Water Eq. per plane)
  - 0.2 (0.4) mm position (FWHM) resolution

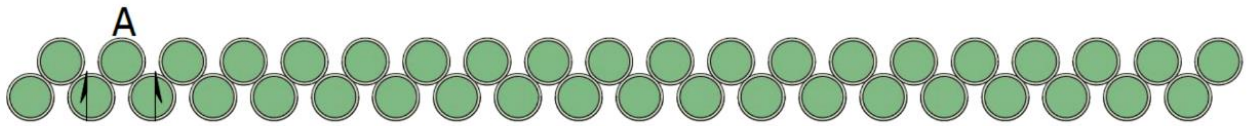
2-layer glueless* mats

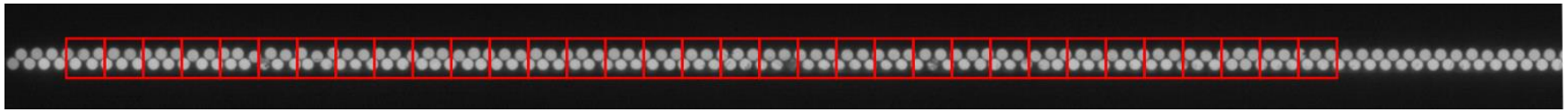
*Glueless in the acceptance but glued at the ends





Green SCSF-3HF from Kuraray
to be more “radiation hard”

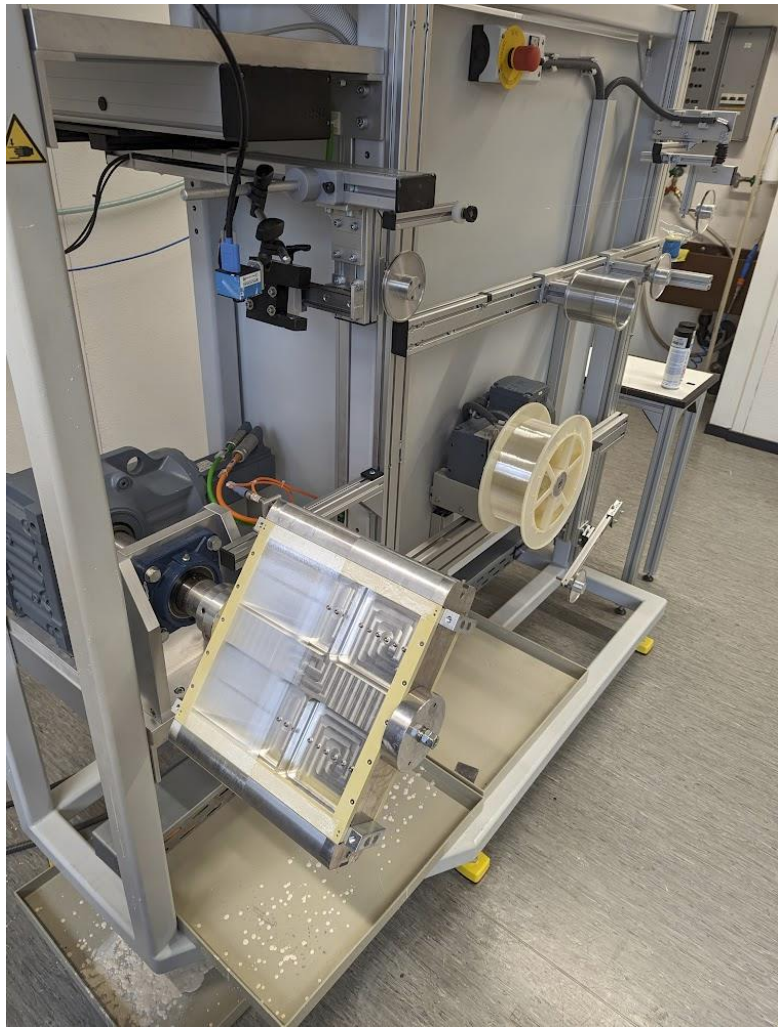


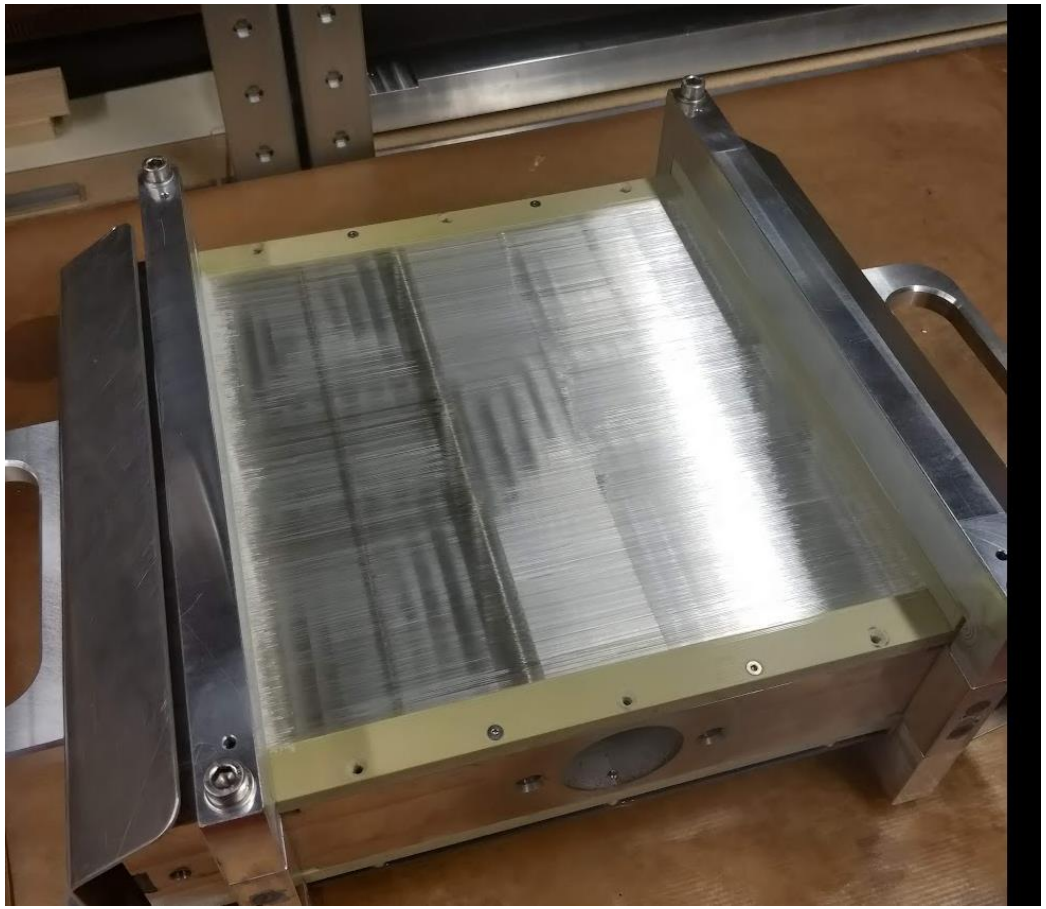


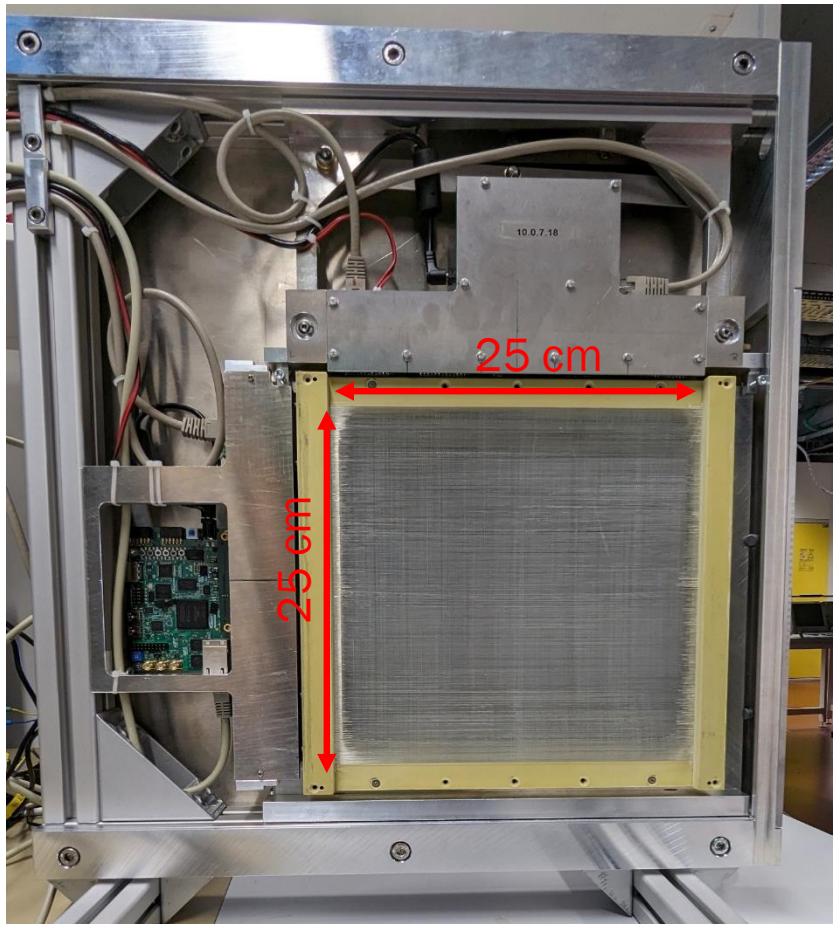
Scan of 1 fibre plane end

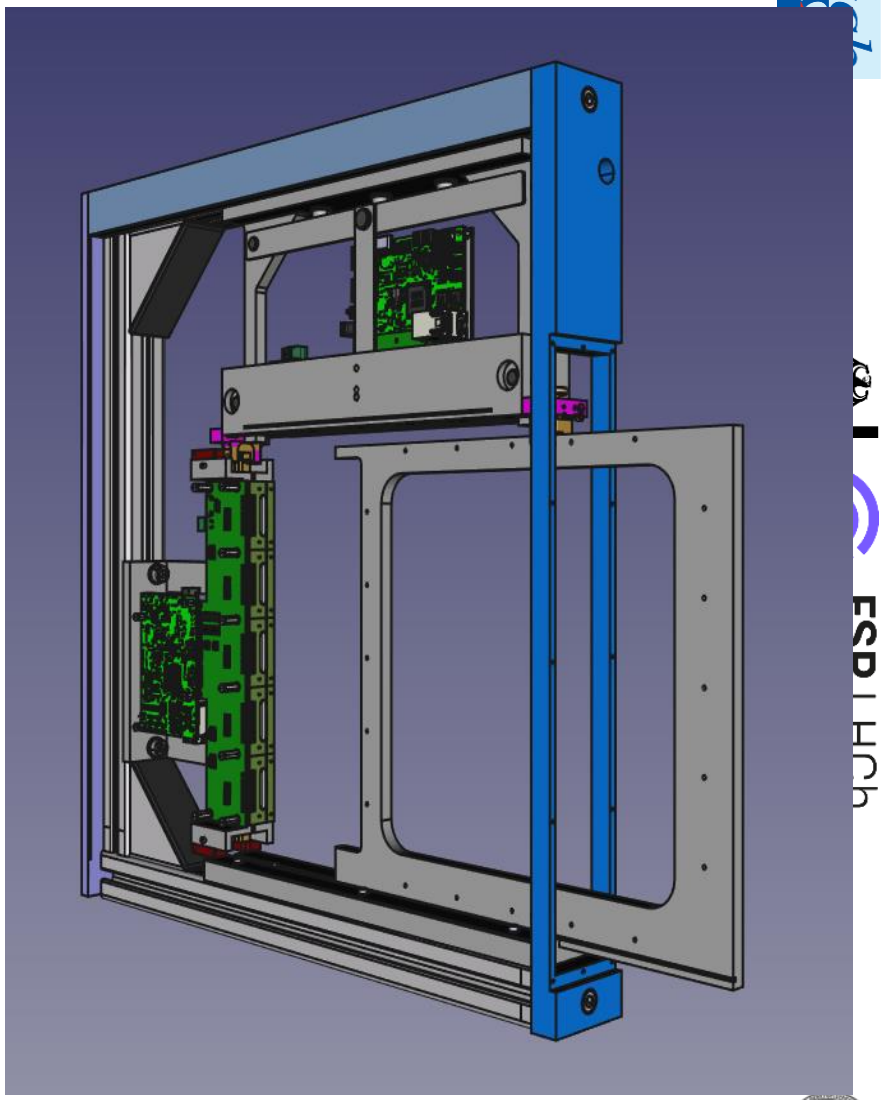
Photodiode pitch: 0.8 mm

Winding on the LHCb Machine





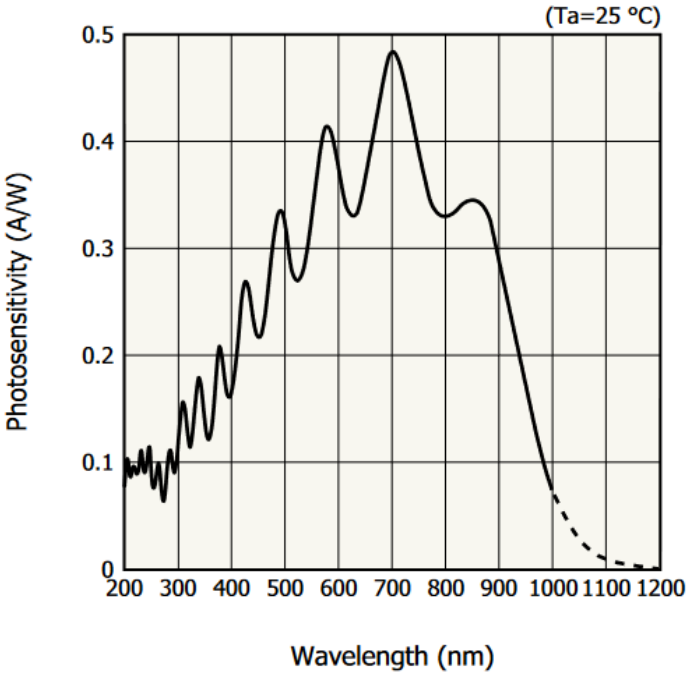

25 cm
25 cm

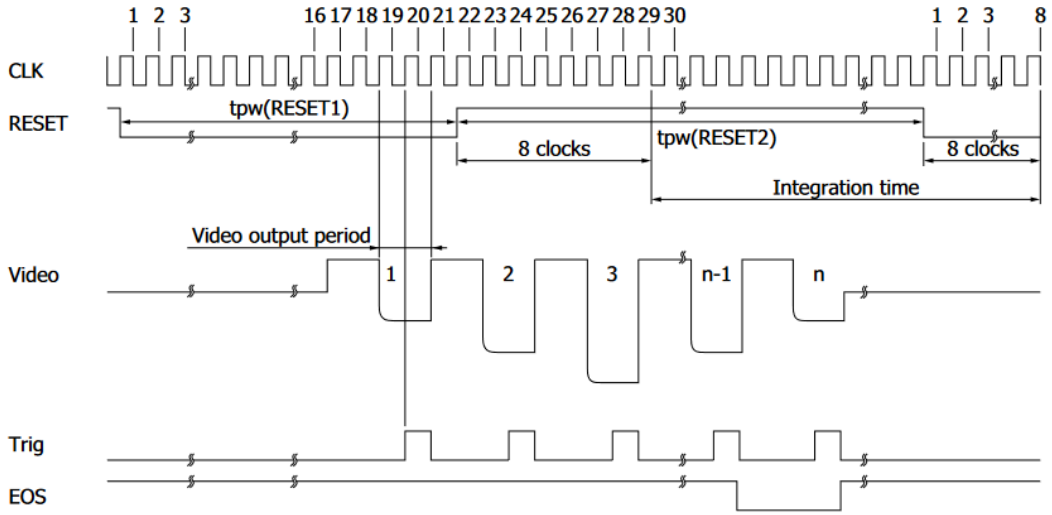


Photodiode arrays

Hamamatsu S11865-64

25cm



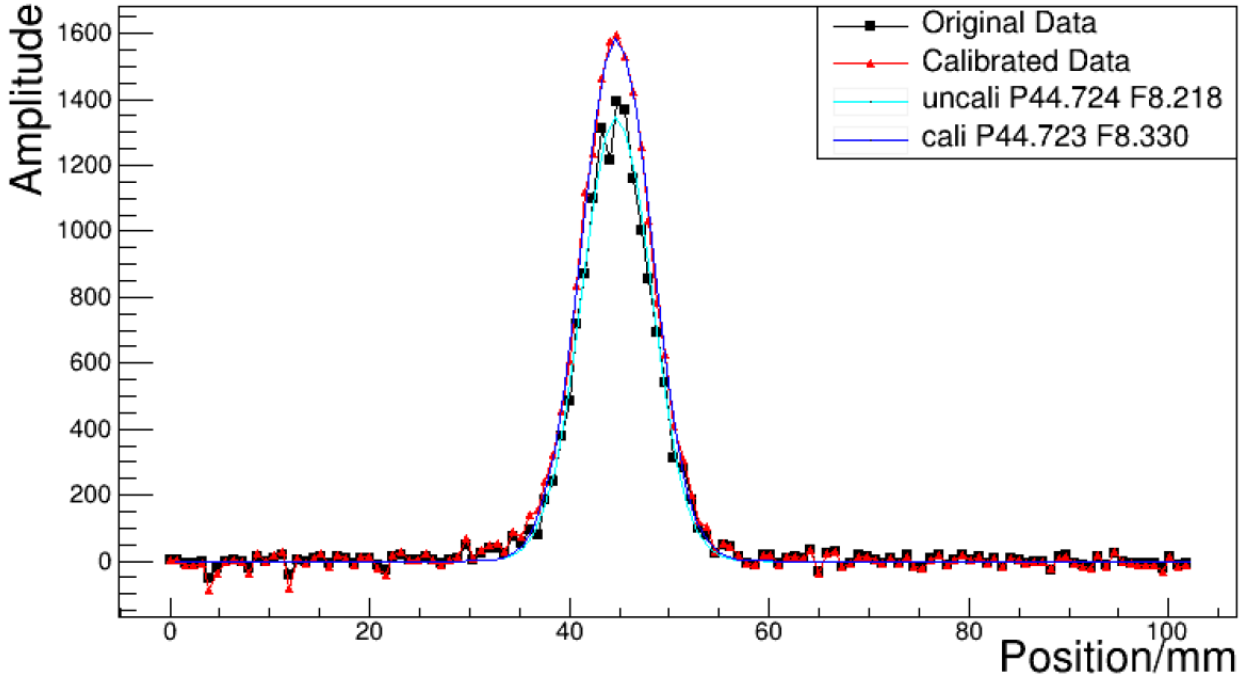


Measure with an ADC (4 MHz clock)

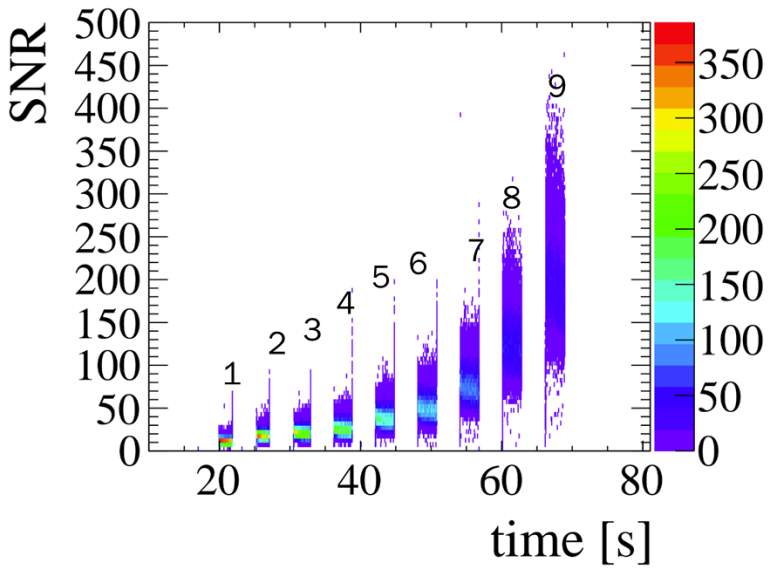
10 kHz full frame readout (adjustable for longer integration times)

Signals

221 MeV Proton Beam at the iso-centre



Original signal vs. calibrated signal for detection plane 3. Proton 221.06 MeV 8.1 mm 2 · 10^9/s

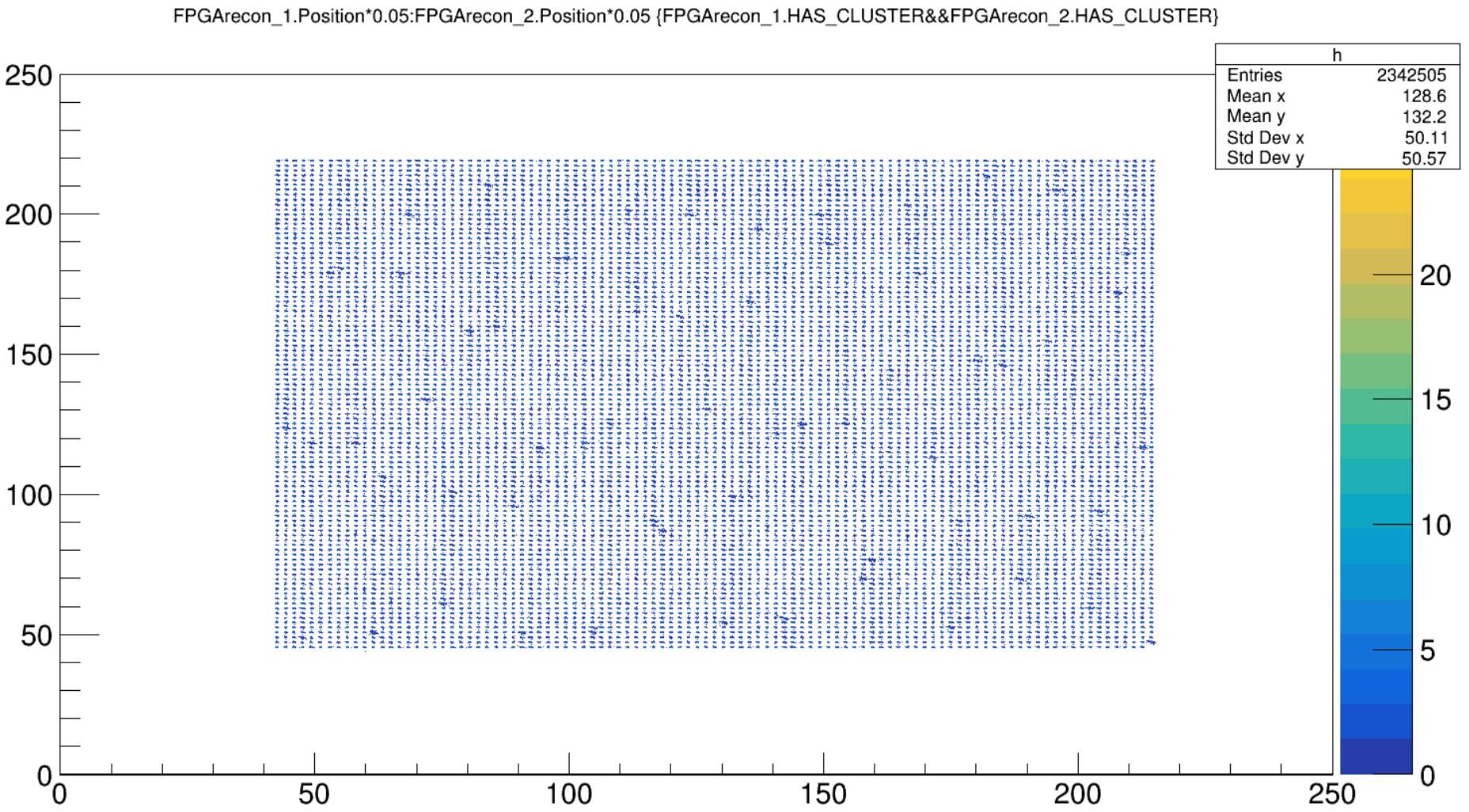


Intensity Setting	10^6 s^{-1}
1	80
2	120
3	200
4	320
5	400
6	600
7	800
8	1200
9	2000

Factor of 25 range in intensity

At the vacuum window, the beam is ~2mm FWHM

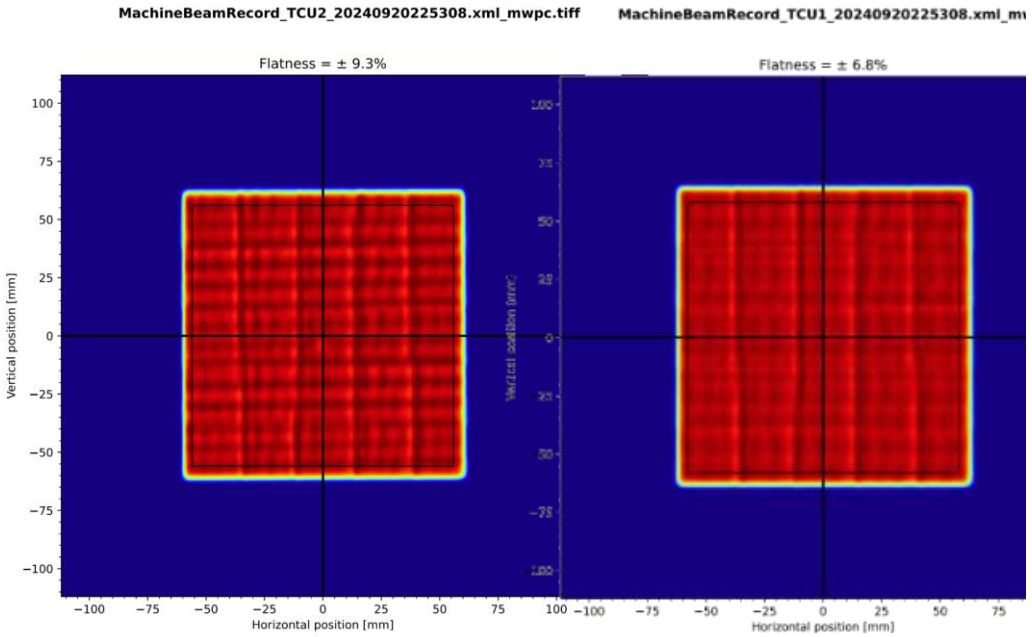
Uniform Field Scan



Uniform Field Scan*

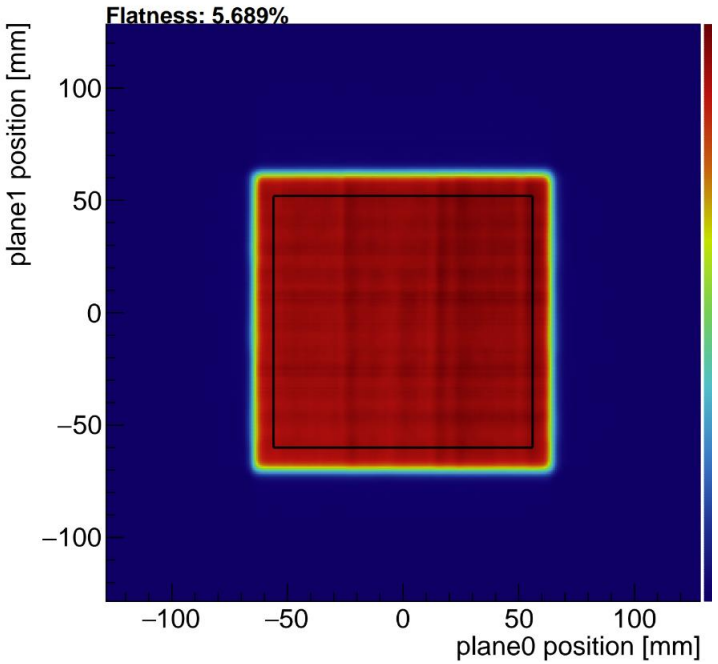
*MWPC Position Feedback-loop enabled in this data

MWPC assumes a gaussian shape (pos, width). Fibre = amp(X_i) *amp(Y_i) from raw per channel data.

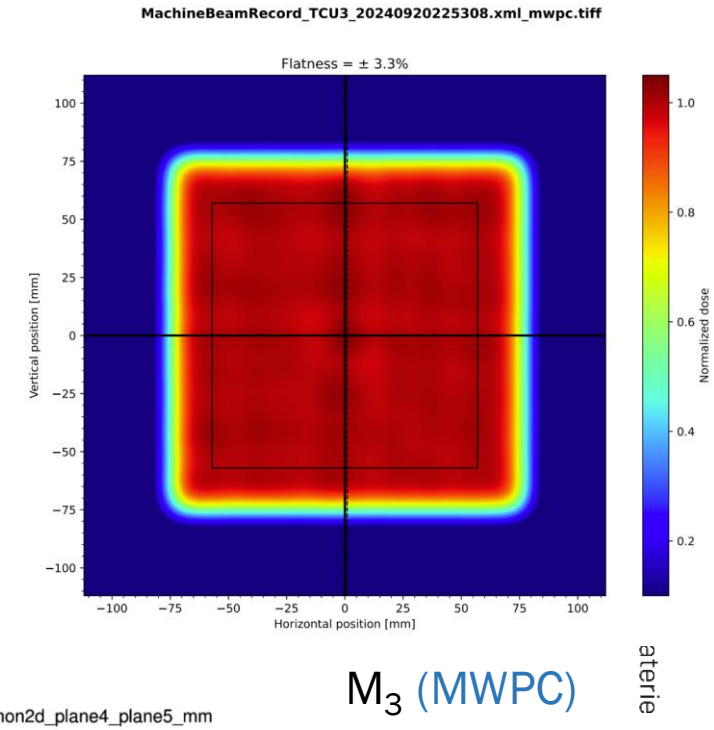


M_1 (MWPC)

M_2 (MWPC)

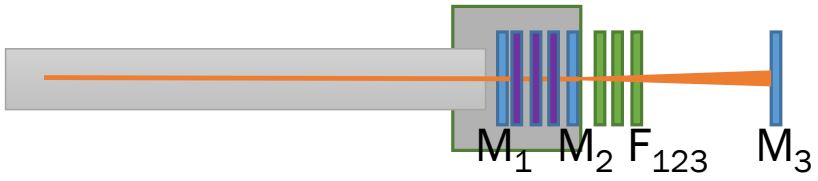


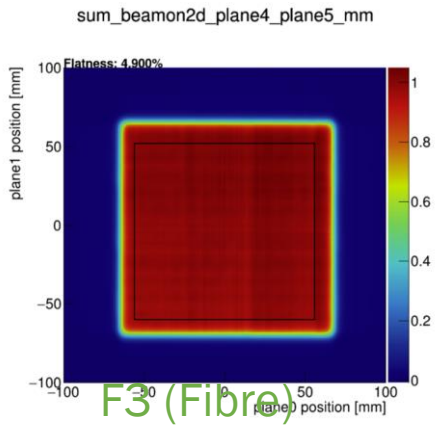
F1 (Fibre)



M_3 (MWPC)

aterie

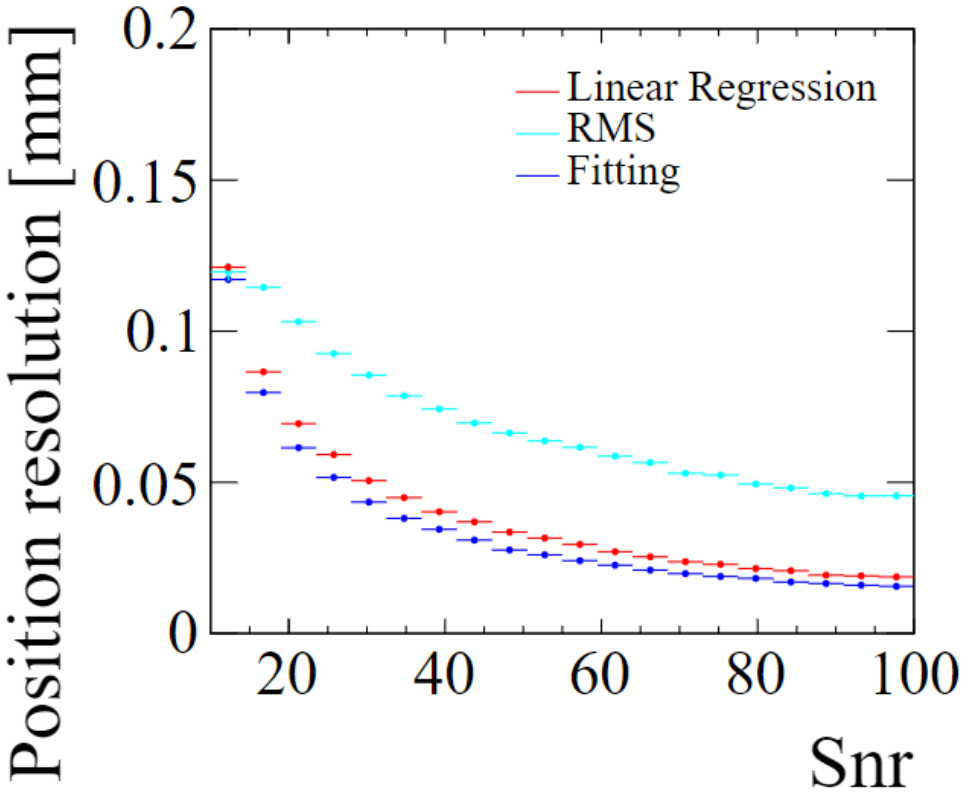




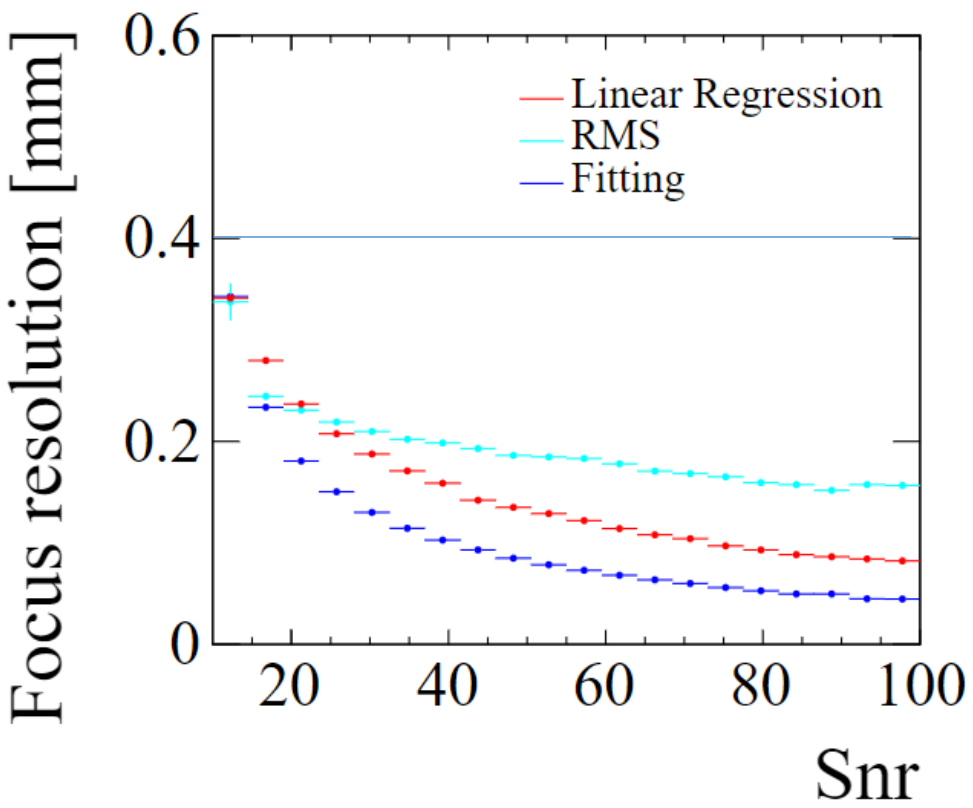
F3 (Fibre)

BPM Performance

RMS is currently performed directly on the FPGA (PhD work of Liqing Qin)



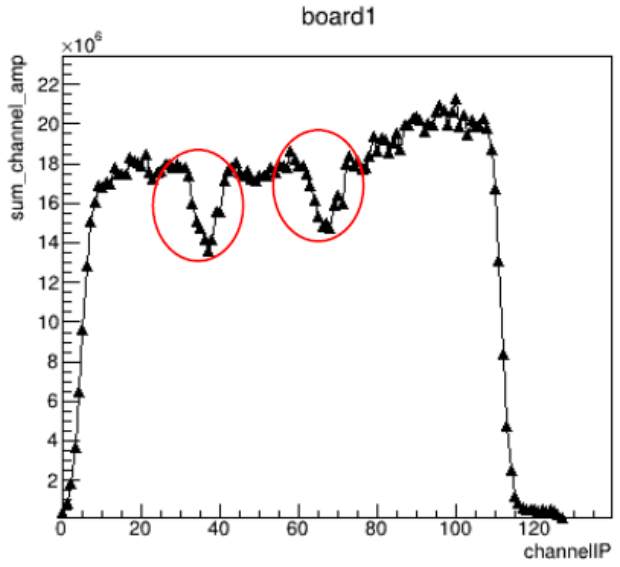
"Focus" = FWHM



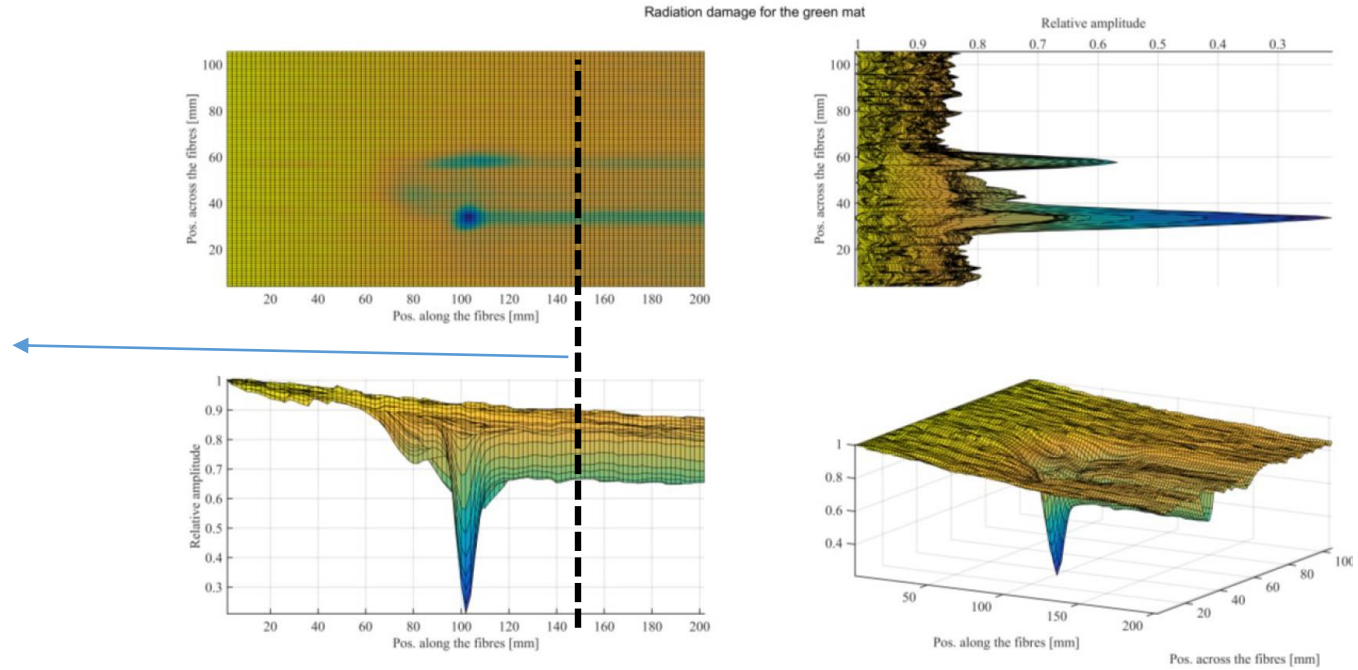
Here, the width of the residual / sqrt(2) between two neighbouring stations is taken for the resolution.
Position resolution should **be better than 0.2mm**
Focus resolution should be **better than 0.4mm**

What about radiation damage?

- Most of the beam dose in the fibre is from operations (1.5 MGy/a) and not therapy (7 kGy/a). QA is only 10%. Change of procedure?
- Weekly QA done already for MWPC.
- Plan to exchange the mats regularly (6-12 months).



Line scan from mat put in the beam dump



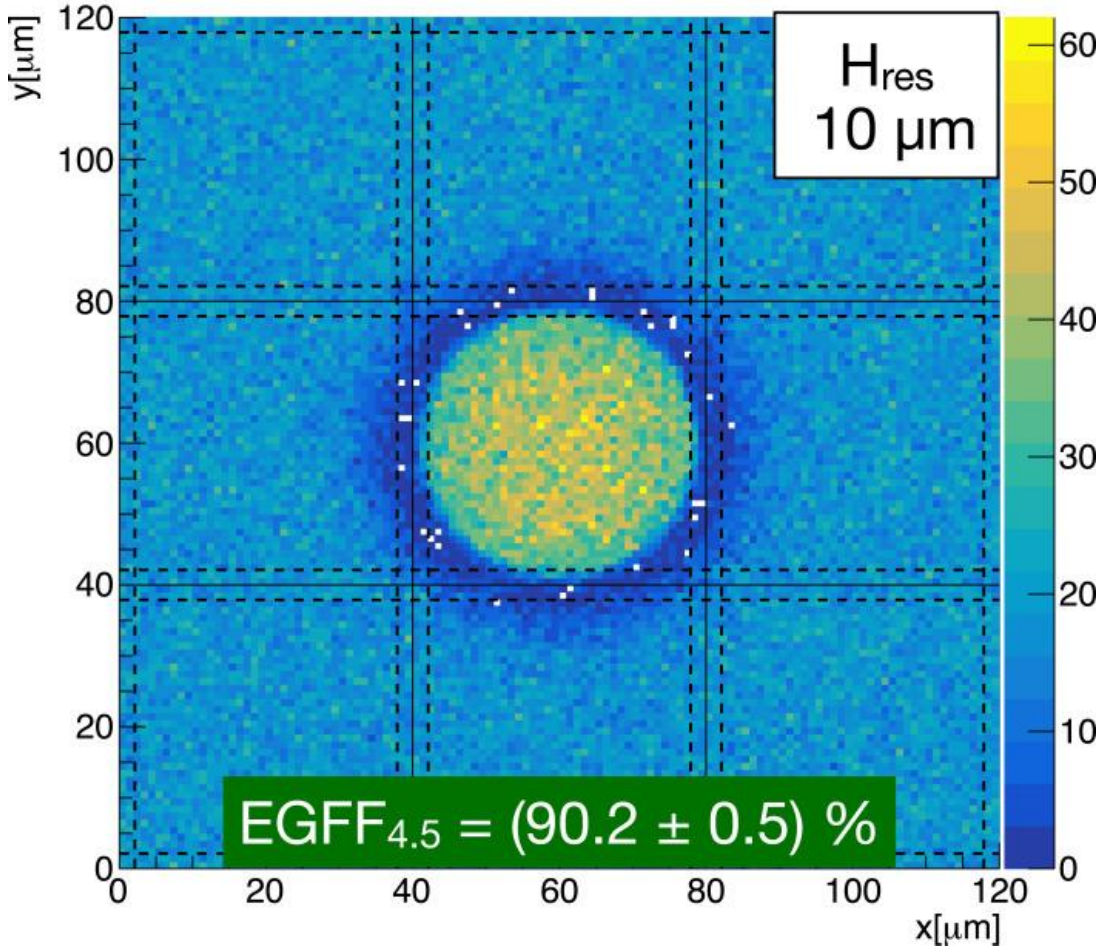
Area scan from mat put in the beam dump

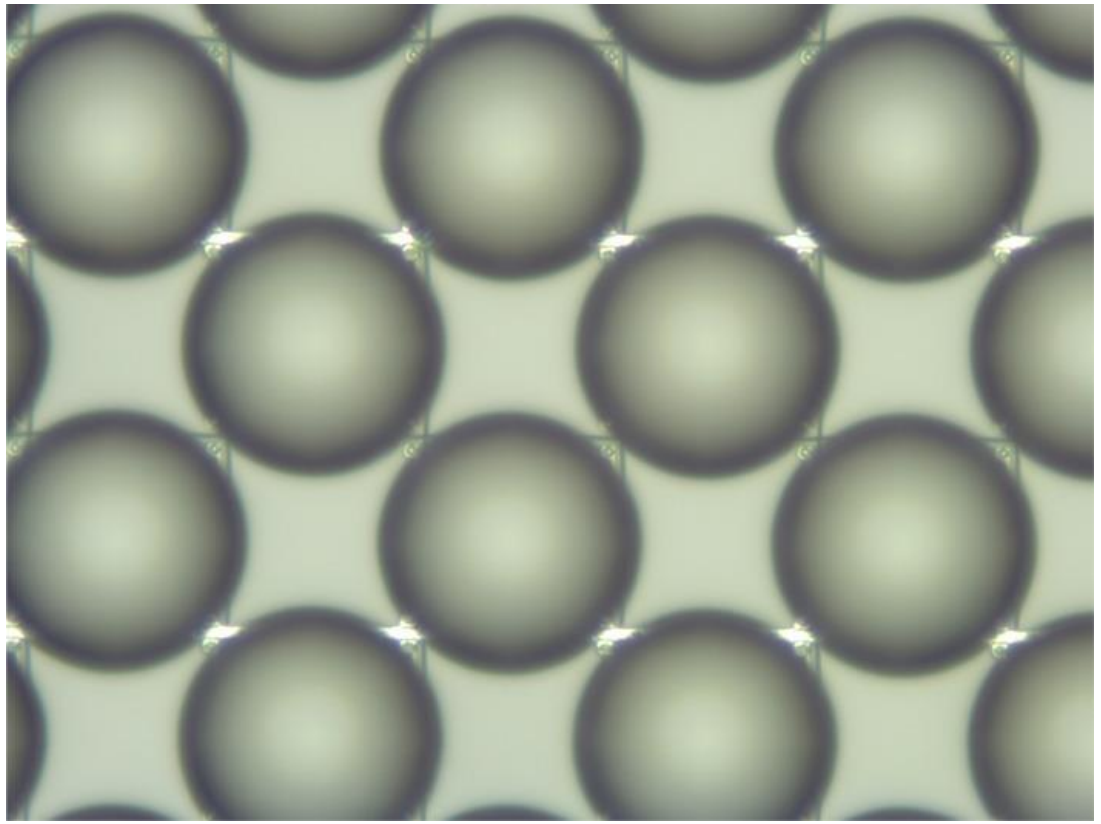
Summary

- The SciFi Tracker for Upgrade has been commissioned and is operating well.
- The second upgrade of LHCb is in the development stages, with cryo-cooling planned to enable the SciFi tracker to operate in higher radiation regimes.
- The beam profile monitor is currently being considered to replace the MWPCs at HIT.

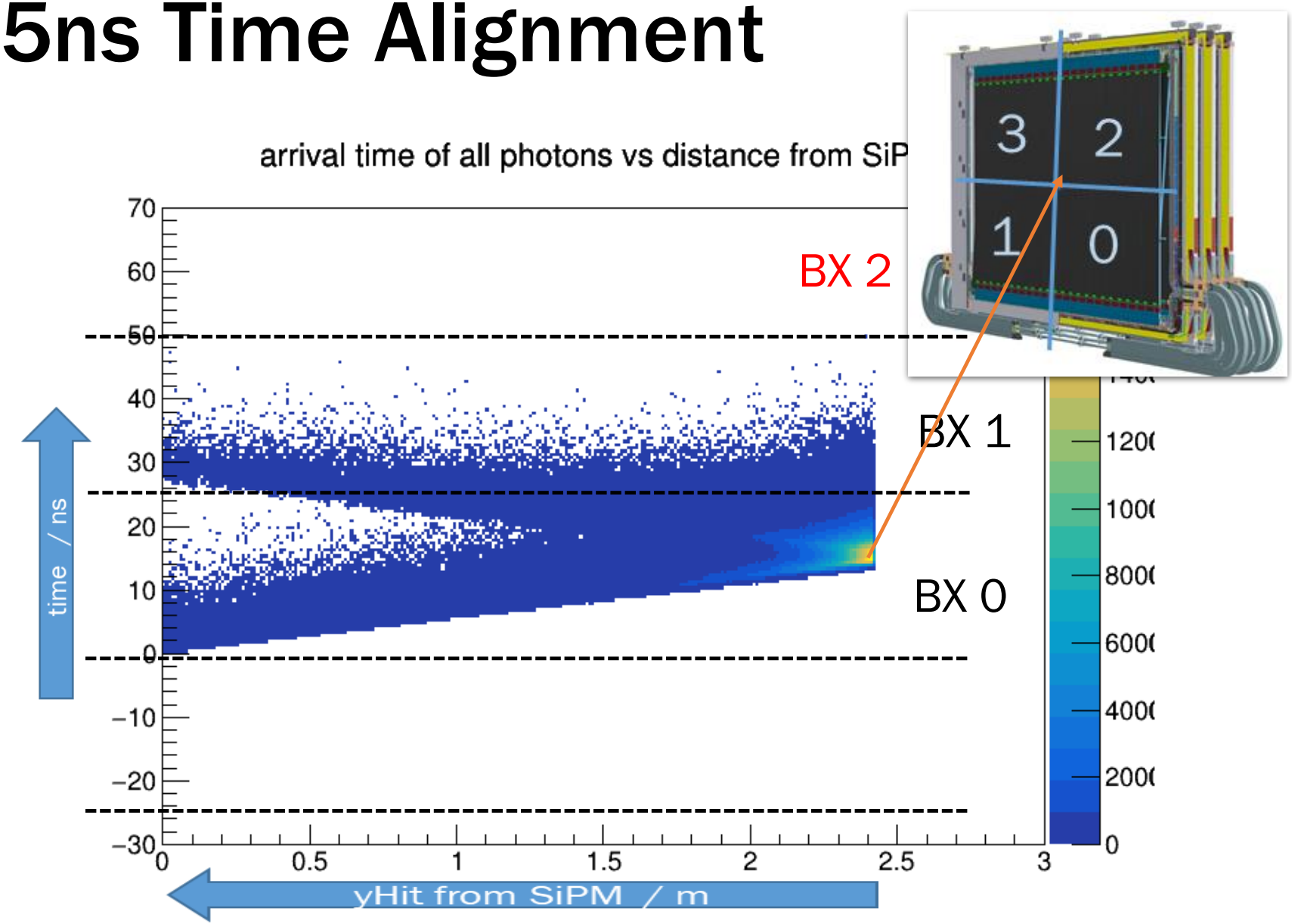
References

Photon distribution





Sub-25ns Time Alignment



Sub-25ns Time Alignment