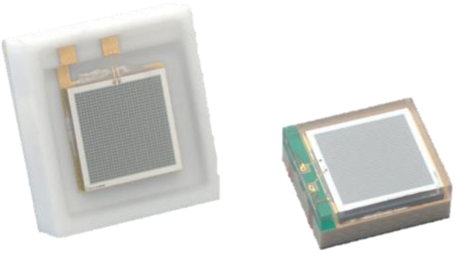
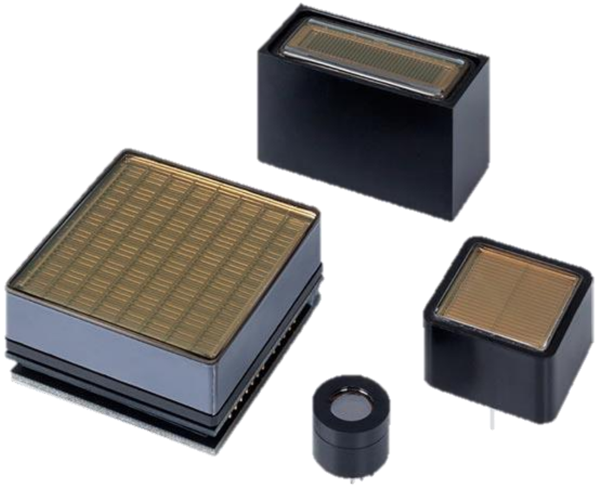
Introduction to photodetectors and there applications in HEP

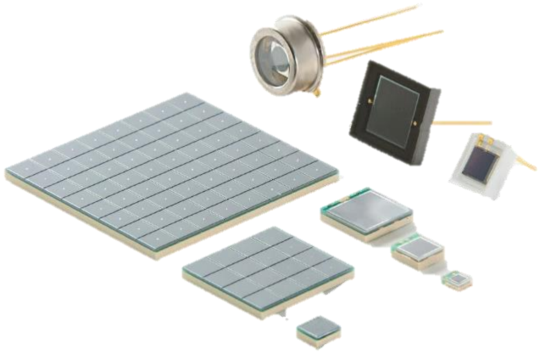




Lecture 2

25-04-2023

Sune Jakobsen (CERN EP-DT-TP)



Lecture overview

Lecture 1

Introduction to photodetectors
Classical photomultiplier Tubes
Scintillators
Use case of classical photomultipliers and plastic scintillators
Classical PMTs in calorimetry
Use cases of classical PMTs and calorimeters

Lecture 2

MultiAnode photomultiplier Tubes (MAPMTs)
Ring-Imaging CHerenkov (RICH) detectors
Use case of MAPMTs and in RICH detectors
Scintillating fibers and fiber trackers
Use case of MAPMTs in scintillating fiber tracking detectors
Silicon photodetectors
Use case of SiPMs and Time of Flight
Use case of SiPMs in scintillating fiber tracking detectors

MultiAnode photomultiplier Tubes

Figure from [4]

MultiAnode PhotoMultiplier Tubes - MAPMTs

To understand the MAPMT, we first need to introduce the metal package PMT.

This is s modern small size version of the classical PMT, but made significantly smaller by fine machining technologies.

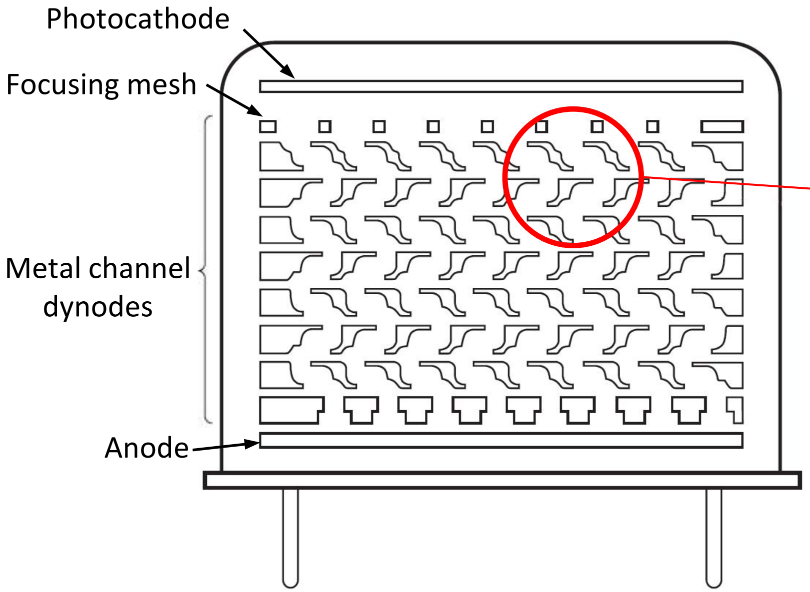
This is actually the type used in ATLAS TILE calorimeter and the additional veto station for FASER shown in the first lecture

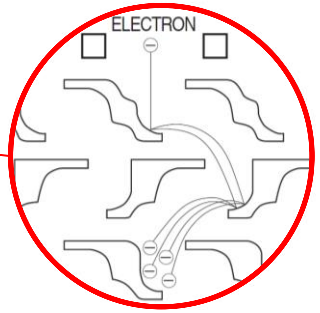
In the MultiAnode version, a segmentation is introduced to divide the anode into separate channels.

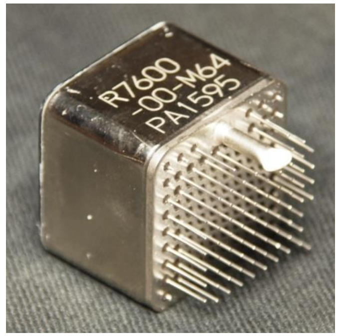
Each anode has a separate pin for measuring the signal.

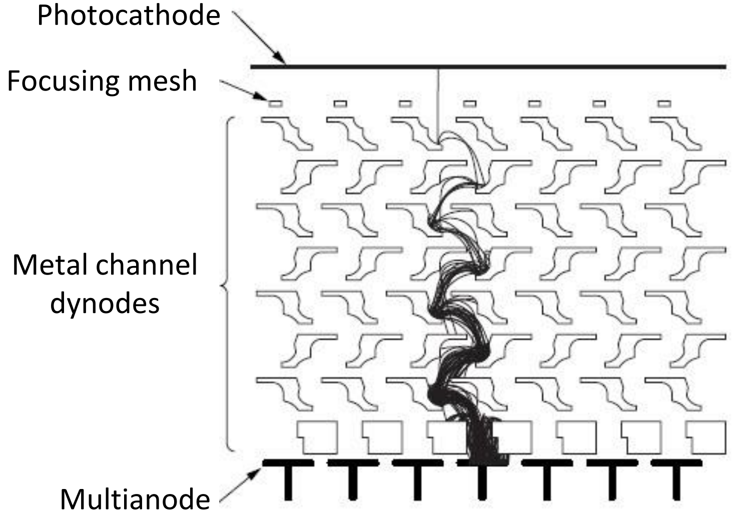
The dynode structure naturally also need a segmentation at least as fine as the anode

In the shown 64 channel version, it can be seen that dynode structure actually is twice as segmented as the anode



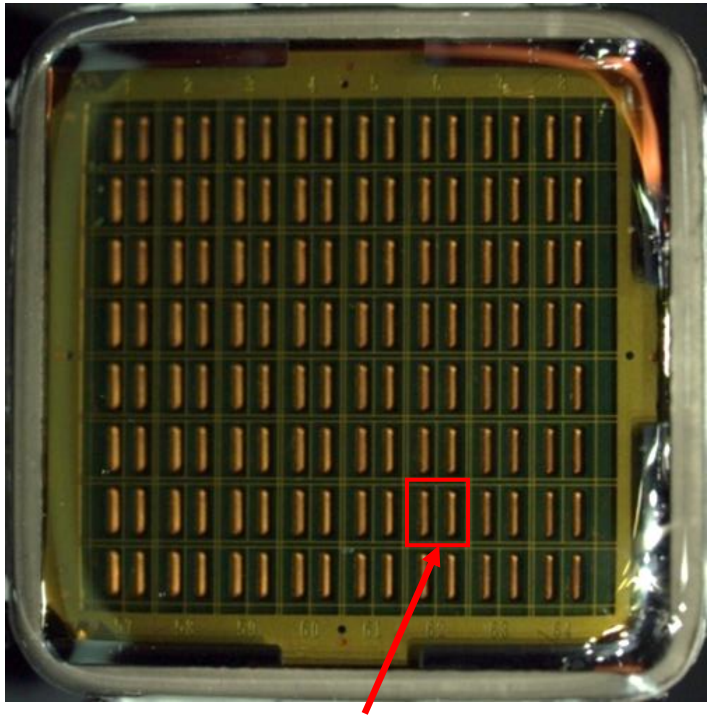






Figres from [4] and [13]

Photo from the photocathode of a MAPMT



MultiAnode photomultiplier Tubes – Pros and cons

Pros for MultiAnode photomultiplier Tubes

- Radiation tolerant
- High gain (so cheap electronics can be used)
- Low noise per active area
- Temperature insensitive
- Significantly more compact per channel than classical PMTs.
- Significantly cheaper per channel than classical PMTs

Cons for MultiAnode photomultiplier Tubes

- Typically large gain fluctuations (also internally in a unit)
- Fragile
- Requires high voltages
- Gets noisy over time (many years, dominated by degrading vacuum)
- Sensitive to magnetic fields
- Cross-talk between channels

Gain uniformity of a state of the art MAPMT (Hamamatsu H13700, 256 channels)

P1 → P16 (columns); P16 → P256 (rows)

51	67	72	71	66	73	75	78	85	90	92	95	92	90	100	64
78	84	77	74	73	75	78	80	85	86	87	88	91	86	100	74
81	85	78	76	76	76	76	77	84	85	87	89	91	84	99	70
79	83	76	79	78	75	74	75	82	84	87	92	89	90	97	71
79	81	71	74	76	73	71	69	79	82	84	85	87	88	95	69
79	81	73	73	74	73	70	67	76	82	82	84	84	88	96	71
80	81	73	71	70	71	68	63	74	77	81	84	85	88	97	70
78	81	71	69	67	69	66	63	72	77	79	84	86	89	96	72
80	77	70	68	67	67	66	61	71	78	80	83	86	87	96	69
79	77	69	69	68	66	66	63	72	79	82	86	84	86	95	71
76	75	68	68	68	66	65	63	72	79	85	85	82	84	93	68
72	73	67	69	71	70	67	66	74	81	86	87	82	84	91	68
74	73	67	69	70	70	70	67	76	82	85	87	84	85	93	65
73	75	68	67	65	67	69	71	75	80	84	87	87	92	96	65
65	72	69	57	48	64	69	74	81	81	85	88	87	91	94	60
42	51	64	62	55	68	70	69	61	89	90	96	82	69	81	46

TOP VIEW

Cross-talk of a state of the art MAPMT (Hamamatsu H13700, 256 channels)

P1 → P16 (columns); P16 → P256 (rows)

100	2.7	—	—	—	—	—	6.3	100	2.8	—	—	—	—	4.0	100
3.3	0.6	—	—	—	—	—	0.8	3.4	0.5	—	—	—	—	0.8	3.8
—	—	—	—	—	—	—	—	—	—	0.4	2.3	0.3	—	—	—
—	—	—	0.4	2.0	0.3	—	—	—	—	3.4	100	1.8	—	—	—
—	—	—	3.3	100	1.7	—	—	—	—	0.5	2.6	0.3	—	—	—
—	—	—	0.5	2.4	0.3	—	—	—	—	—	—	—	—	—	—
2.3	0.3	—	—	—	—	—	0.4	2.2	0.3	—	—	—	—	0.4	2.2
100	1.7	—	—	—	—	—	3.0	100	2.0	—	—	—	—	3.3	100
2.1	0.3	—	—	—	—	—	0.6	2.8	0.4	—	—	—	—	0.5	2.9
—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

TOP VIEW

Figures from [4]

MultiAnode photomultiplier Tubes – Producers

There is unfortunately only one producer of MAPMTs.

HAMAMATSU

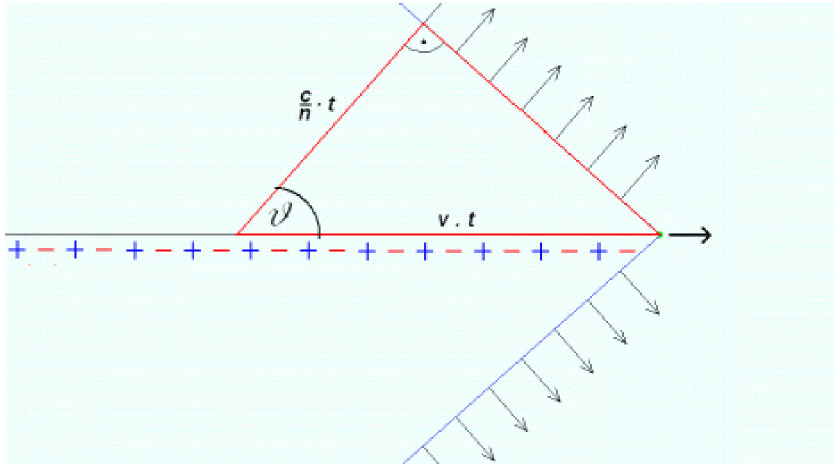
PHOTON IS OUR BUSINESS

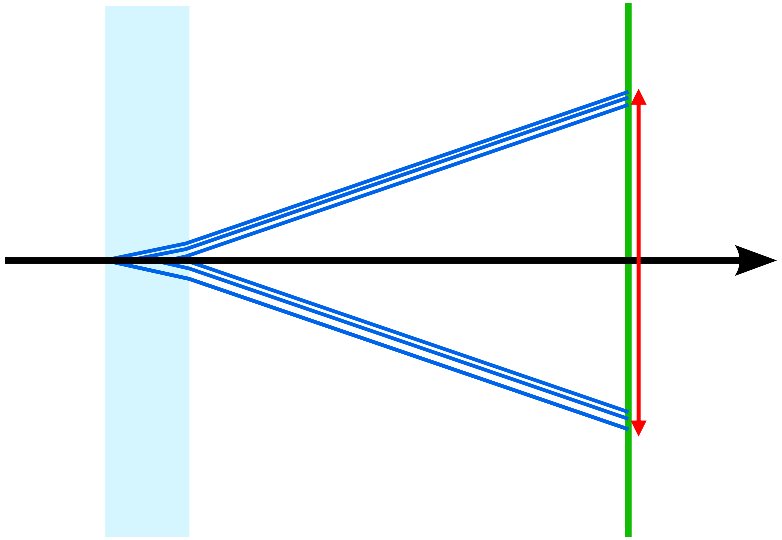
Ring-Imaging Cherenkov (RICH) detectors

Basics of Ring-Imaging Cherenkov (RICH) detectors – Cherenkov radiation

Cherenkov radiation is electromagnetic radiation emitted when a charged particle passes through a dielectric medium at a speed treater than light in that medium:

$$\cos \vartheta = \frac{c}{nv}$$





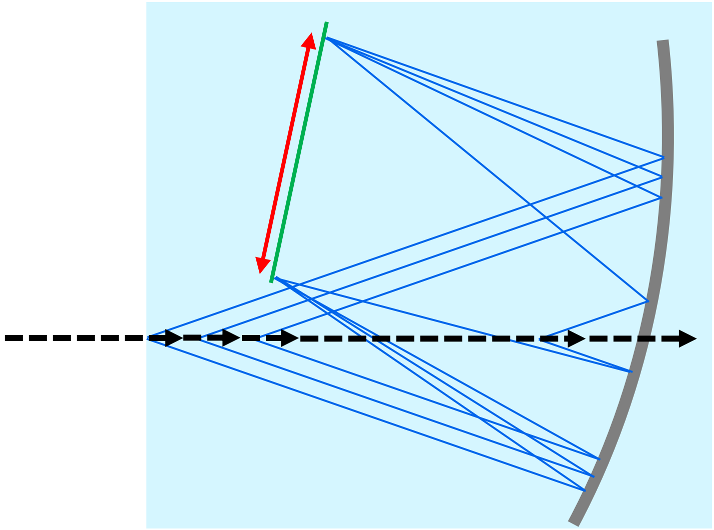
Since the reflective index, n, is known, this gives a correlation between the Cherenkov angle, ϑ, and the velocity of the particle, v. (c being the velocity of light in vacuum)

So if the Cherenkov angle can be determined, then the velocity of the particle can be derived, which together with the momentum measured by other systems can be used for identification of the particle

In 3 dimensions the Cherenkov light form a cone while the particle passes the medium

If the medium is short, the cone becomes a ring when projected onto a plane and the Cherenkov angle can be determined by the ring diameter

A more advanced type of RICH uses a spherical mirror to focus the light onto a focal plane, making a ring (the focusing means that the position is only depending on the Cherenkov angle, not the emission point)



Figures from [14]

Use case of MAPMTs and in RICH detectors
The LHCb RICH detectors

Use case of MAPMTs and in RICH detectors - The LHCb RICH detectors

Two RICH detectors are part of LHCb

RICH1:

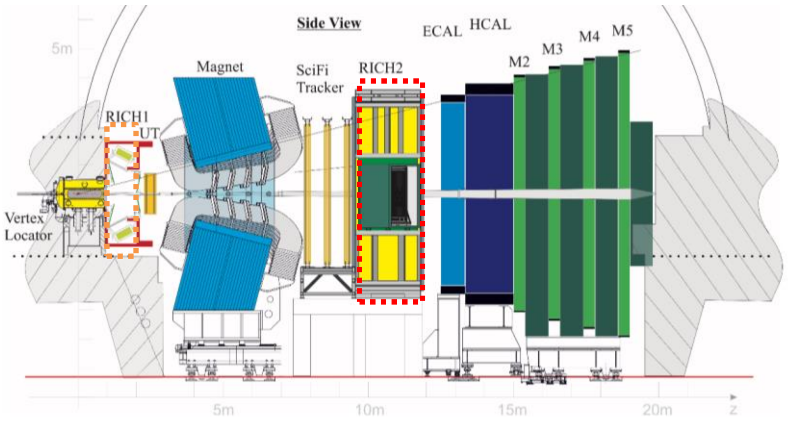
- Cherenkov medium: C_4F_{10} gas
- Momentum range: 2 GeV/c - 60 GeV/c
- Coverage: 25 mrad - 300 mrad

RICH2:

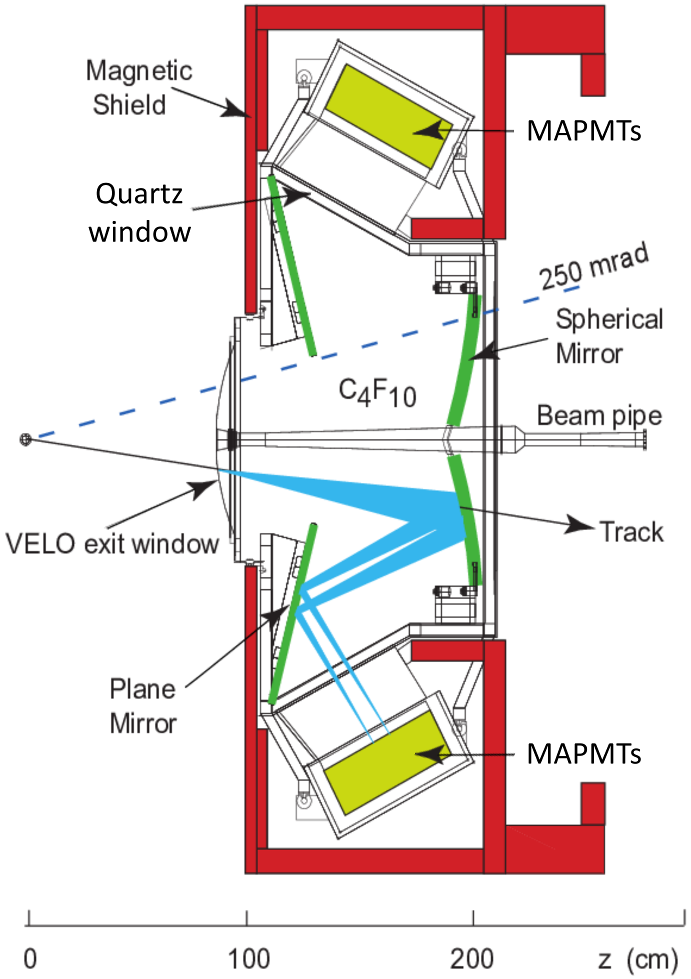
- Cherenkov medium: CF_4 gas
- Momentum range: 30 GeV/c - 100 GeV/c
- Coverage: 15 mrad - 120 mrad

Both uses spherical mirrors for parallel to point focusing

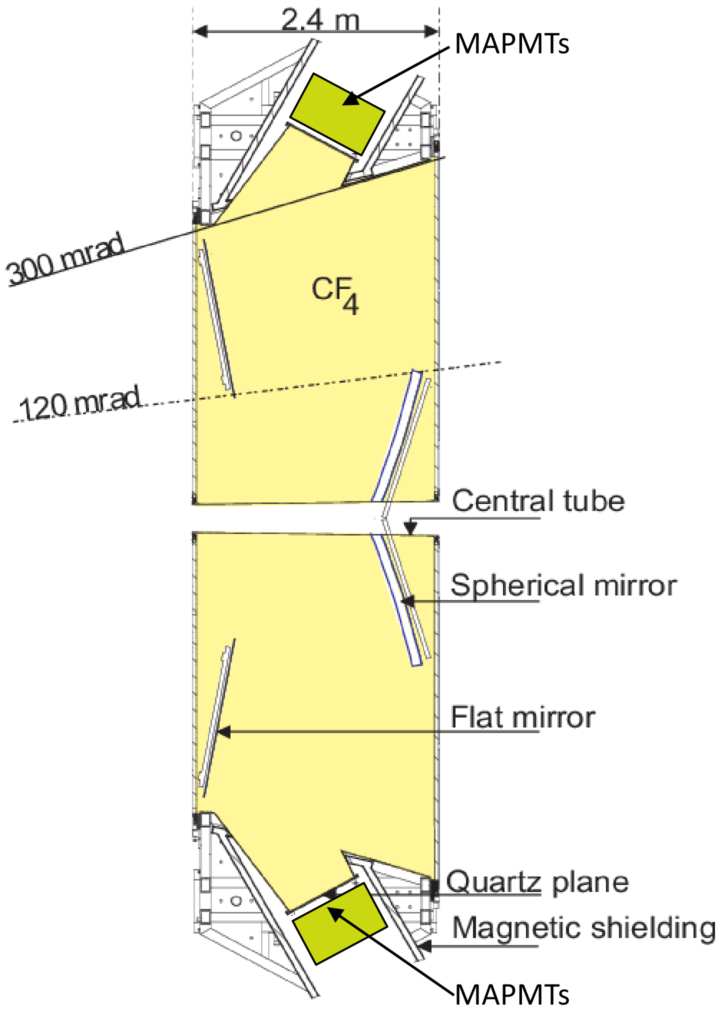
Both have the photodetectors moved out of the detector acceptance (to minimize material in the acceptance)



RICH1 side view



RICH2 top view



Figures from [15]

Use case of MAPMTs and in RICH detectors - The LHCb RICH detectors - MAPMTs

The LHCb RICH detector uses two different MAPMTs:

Hamamatsu R13742:

- 1 inch
- 8 x 8 channels
- 12 stage
- 2528 units (161792 channels) in use

Hamamatsu R13743:

- 2 inches
- 8 x 8 channels
- 12 stage
- 384 units (24576 channels) in use

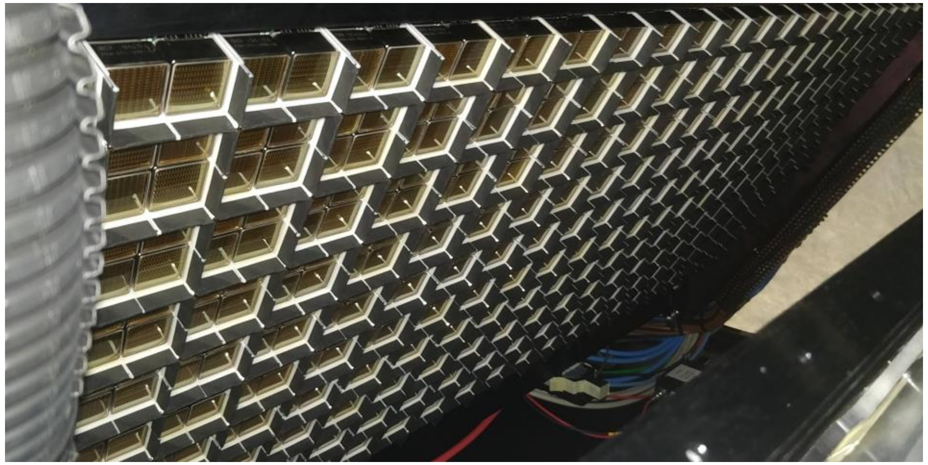
For optimal active area, the MAPMTs are installed side by side.

The smaller one (with higher granularity) are installed in the positions with higher photon flux to keep down the occupancy

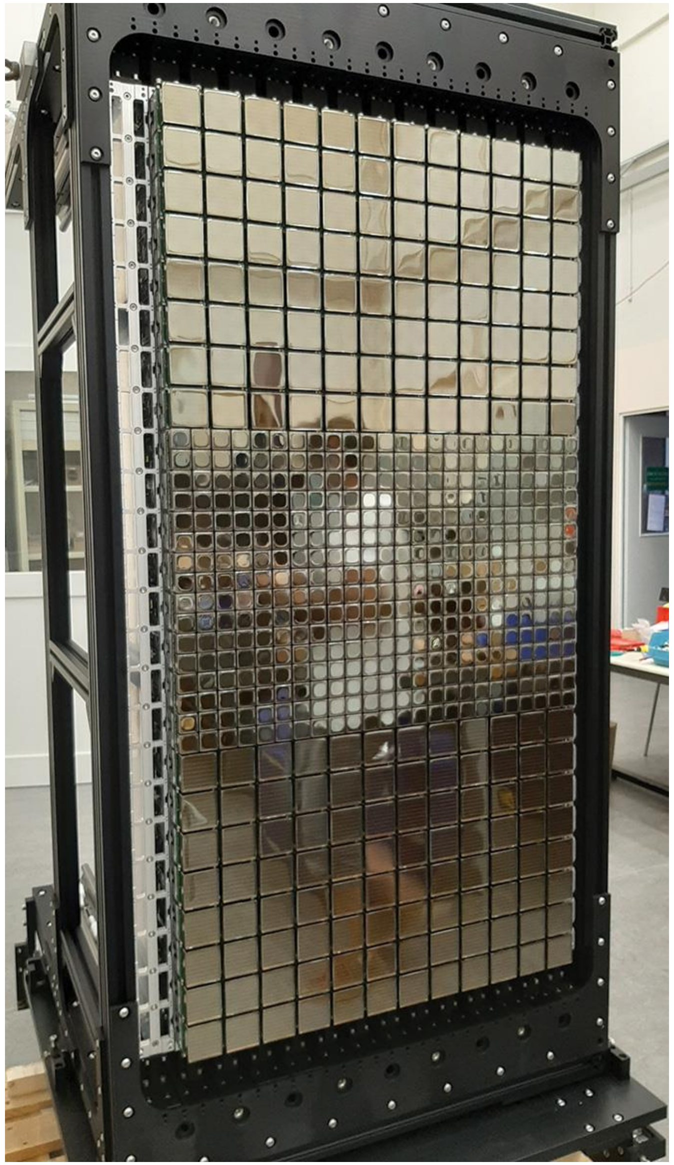
Hamamatsu R13743

Hamamatsu R13742

MAPMT plan of RICH1



MAPMT plan of RICH2



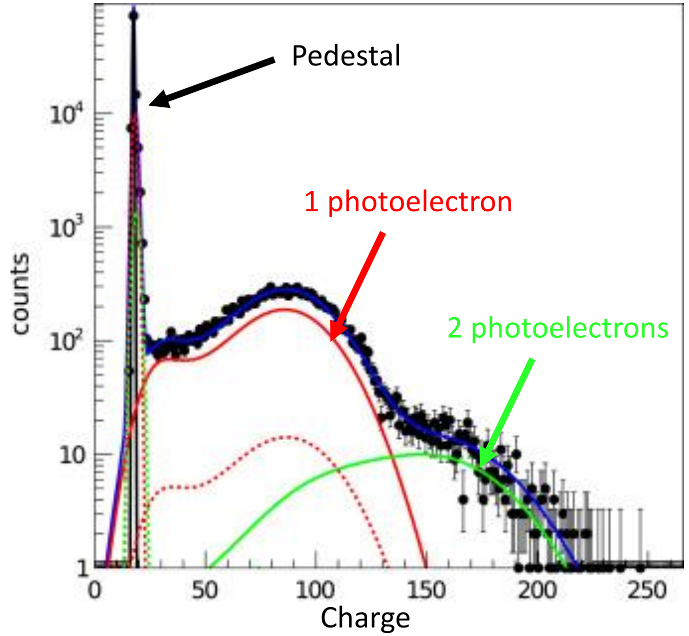
Figures from [15]

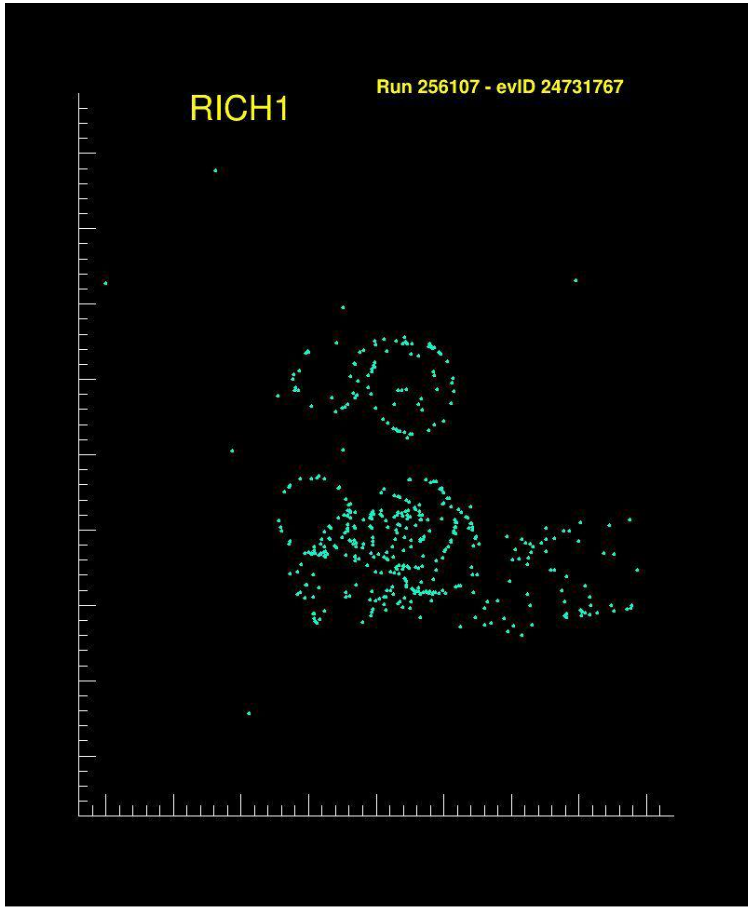
Use case of MAPMTs and in RICH detectors - The LHCb RICH detectors - Signals

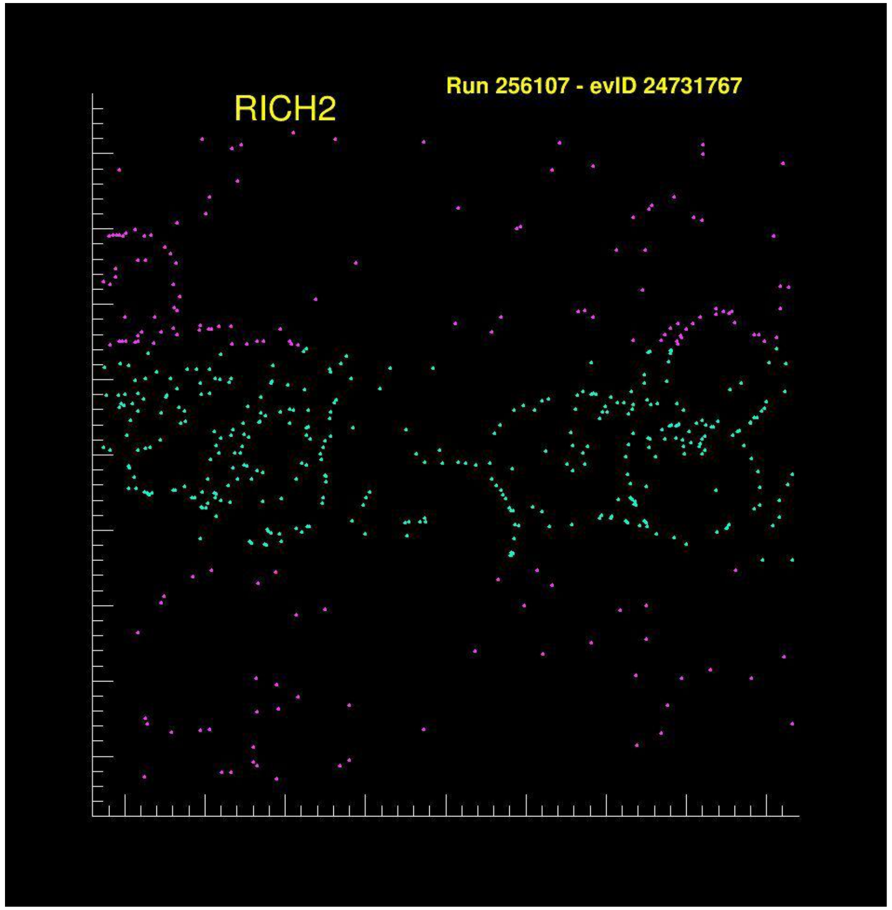
The MAPMT signals are typical signal photoelectrons

- Important to have almost no noise
- Thresholds must be adjusted with great care

Early event displays:







Figures from [15]

Scintillating fibers and fiber trackers

Scintillating fibers

The core of the fiber is polystyrene doped with scintillator and wavelength shifter, just like the plastic scintillators covered in the first lecture

Around is a cladding made of Plexiglass

When a charged particle passed the core, photos are emitted in all directions

The majority of the photons (eventually) leaves the fiber

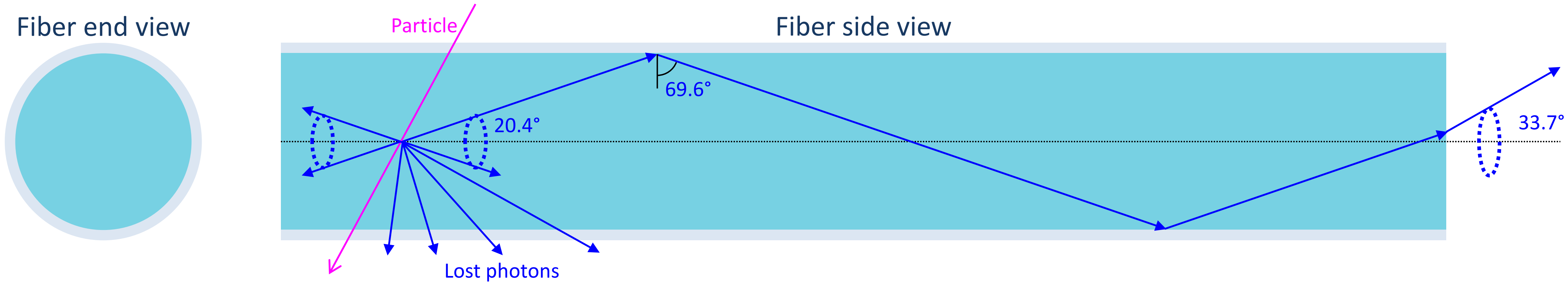
A minor part of the photons are trapped in the fiber by total internal reflections

The critical angle is determined by:

$$\theta_{critical} = arcsin\left(\frac{n_{plexiglass}}{n_{Polystyrene}}\right) = arcsin\left(\frac{1.49}{1.59}\right) \approx 69.6°$$

The trapping efficiency per side is about ~3.1 %

- Square fibers: ~4.2 %
- Double cladded: ~5.4 %

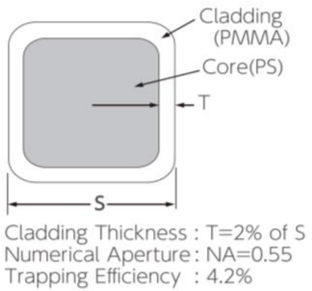


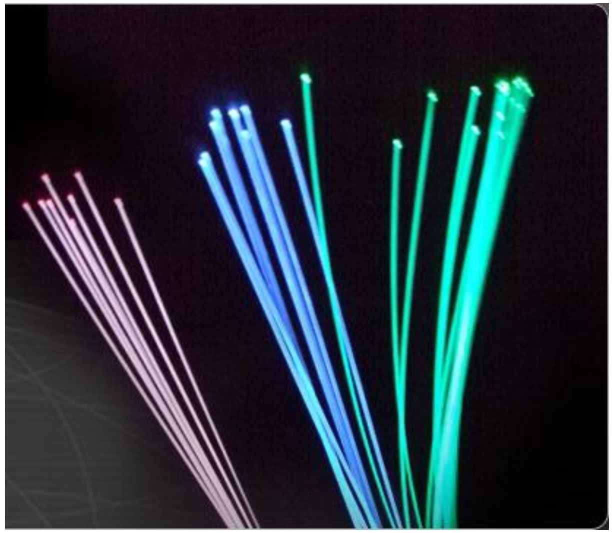
Scintillating fibers producers and typical products

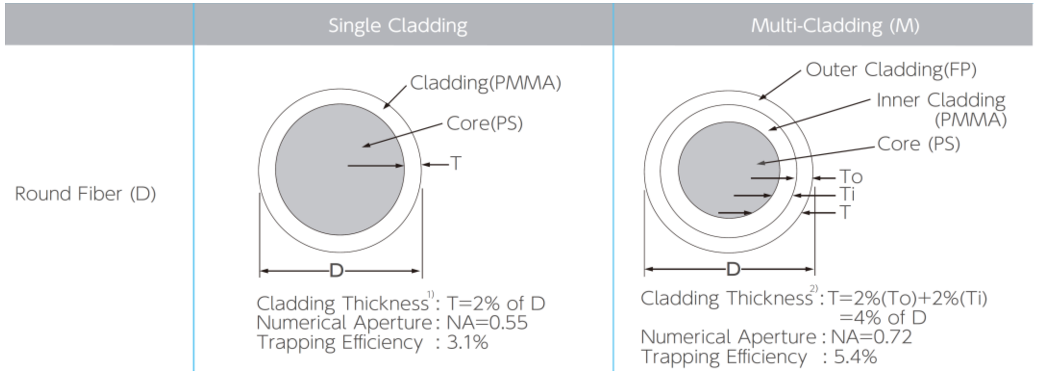
There are only two producer of high quality plastic scintillator fibers (link on the logos):

Both have standard products of round and square with single or double cladding and diameters between 0.25 and 3 mm

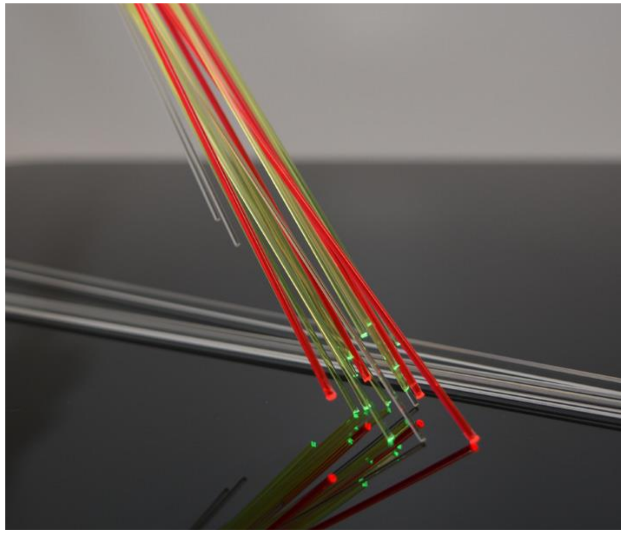
kuraray







LUXIUM SOLUTIONS



(former Saint-Gobain Crystals)

Fiber	Emission Color	Emission Peak, nm	Decay Time, ns	# of Photons per MeV**	Characteristics / Applications
BCF-10	blue	432	2.7	~8000	General purpose; optimized for diameters >250µm
BCF-12	blue	435	3.2	~8000	Improved transmission for use in long lengths
BCF-20	green	492	2.7	~8000	Fast green scintillator
BCF-60	green	530	7	~7100	3HF formulation for increased hardness
BCF-91A	green	494	12	n/a	Shifts blue to green
BCF-92	green	492	2.7	n/a	Fast blue to green shifter
BCF-98	n/a	n/a	n/a	n/a	Clear waveguide

Scintillating fiber trackers

To illustrate the concept of a fiber tracker, start with a single square scintillating fiber

Then position several fibers parallel to it next to one another

This makes up a fiber layer

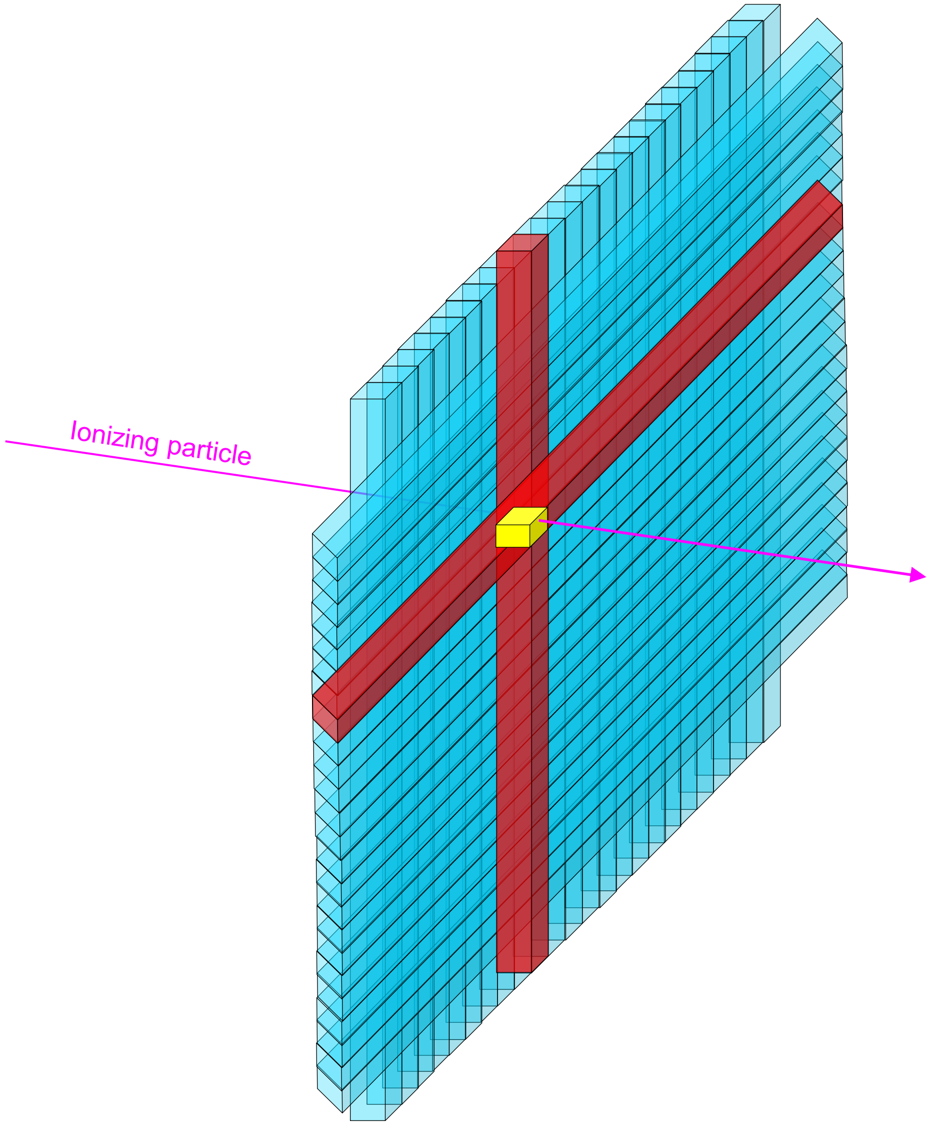
Position a another fiber layer perpendicular to the first one

If an ionizing particle passes the two layers, light will be emitted in the fibers that are hit

Some of the light is transported to the end of the fibers

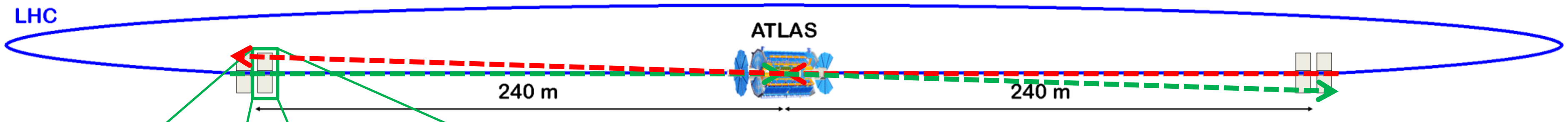
At the end of the fibers, photodetectors are positioned

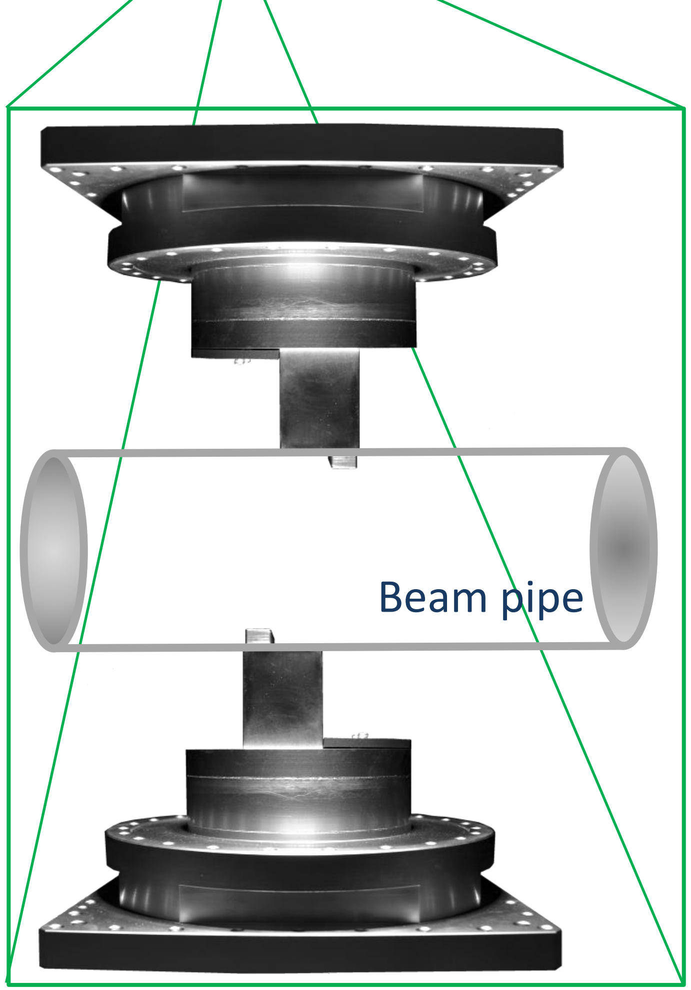
By knowing which fibers had light, the particle position can be reconstructed



Use case of MAPMTs in scintillating fiber tracking detectors
The ATLAS ALFA detector

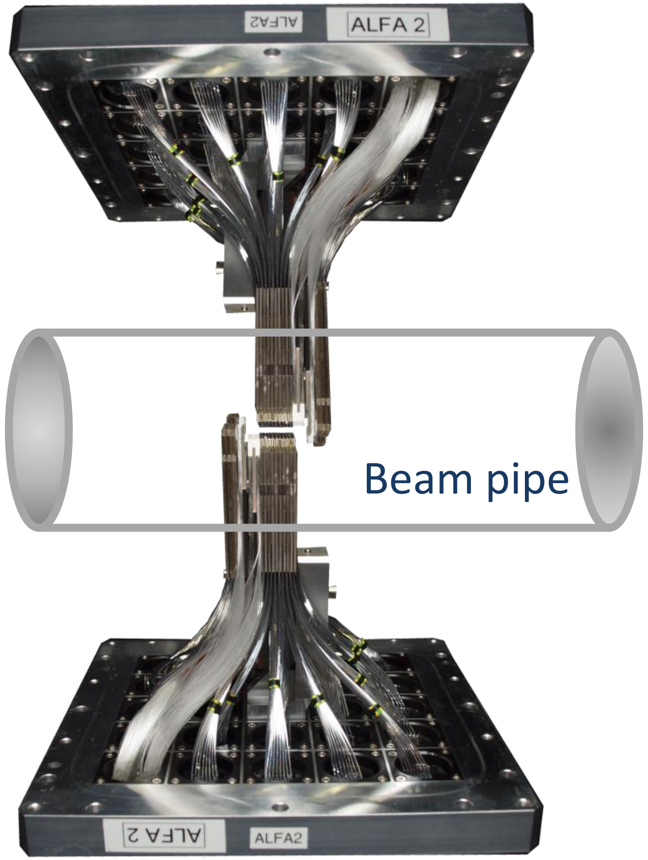
MAPMT and scintillating fiber – Use case: ATLAS ALFA: Introduction



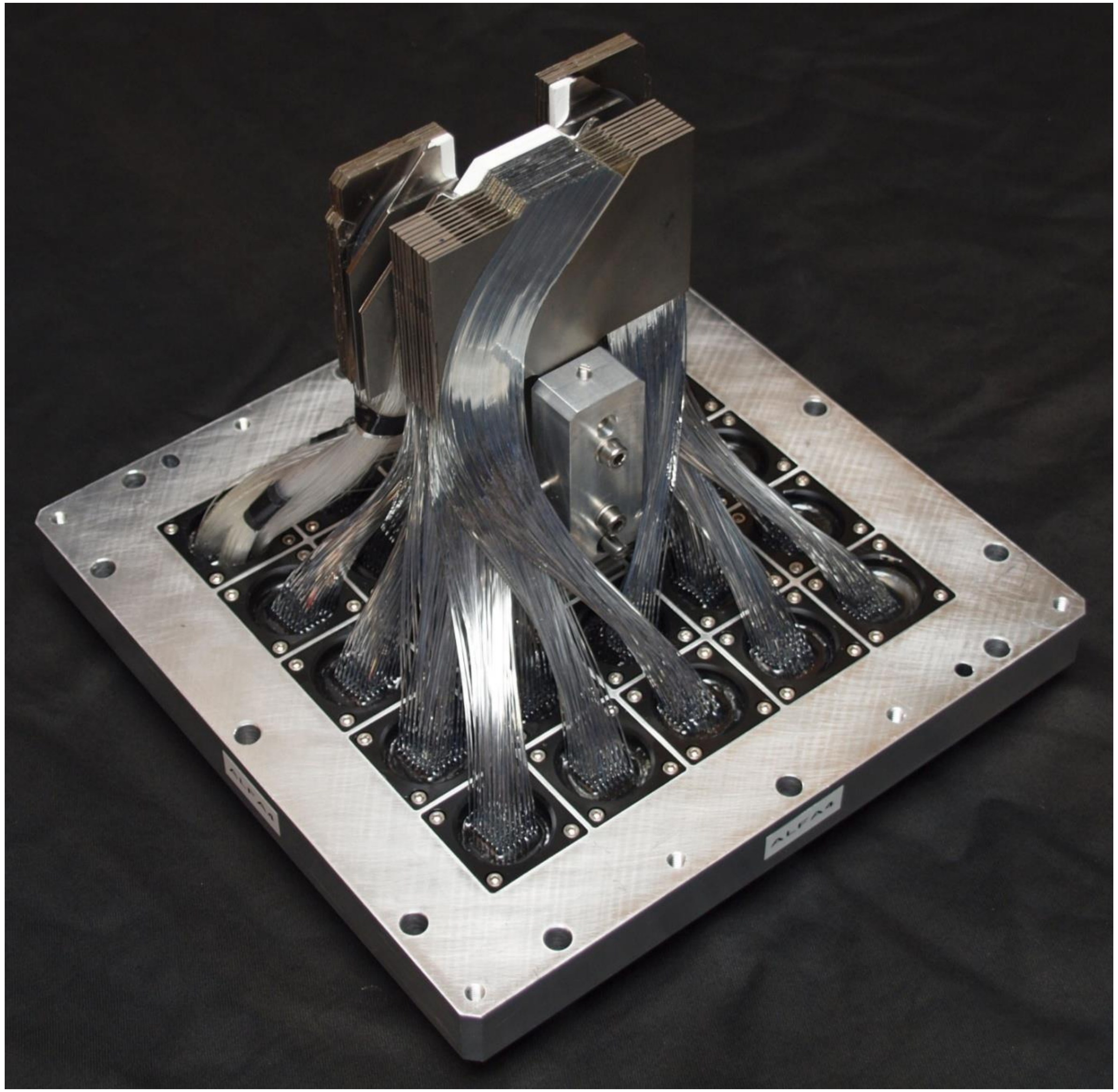


Approach the beam to few mm with Roman Pot.

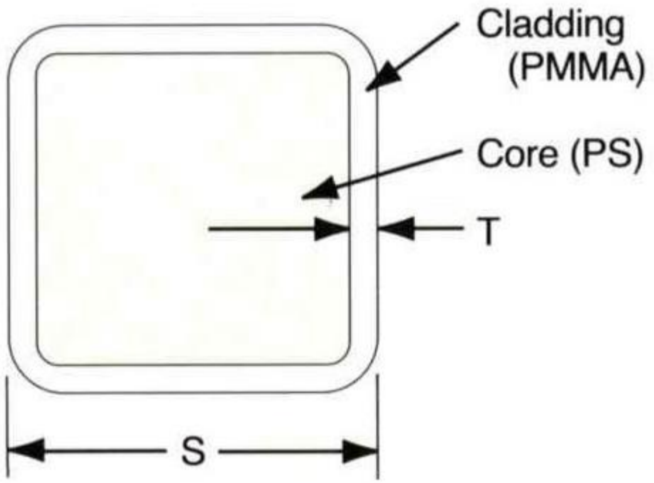
Only used in dedicated high β* runs.



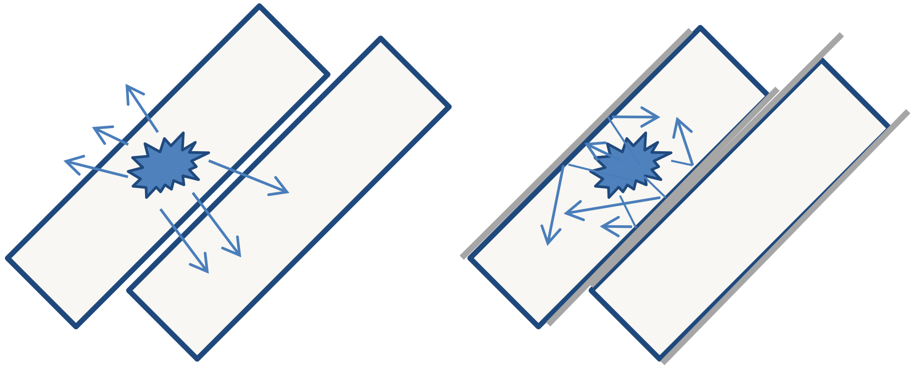
MAPMT and scintillating fiber – Use case: ATLAS ALFA: Fibers



500 µm scintillating square fibers (Kuraray SCSF-78, s-type)

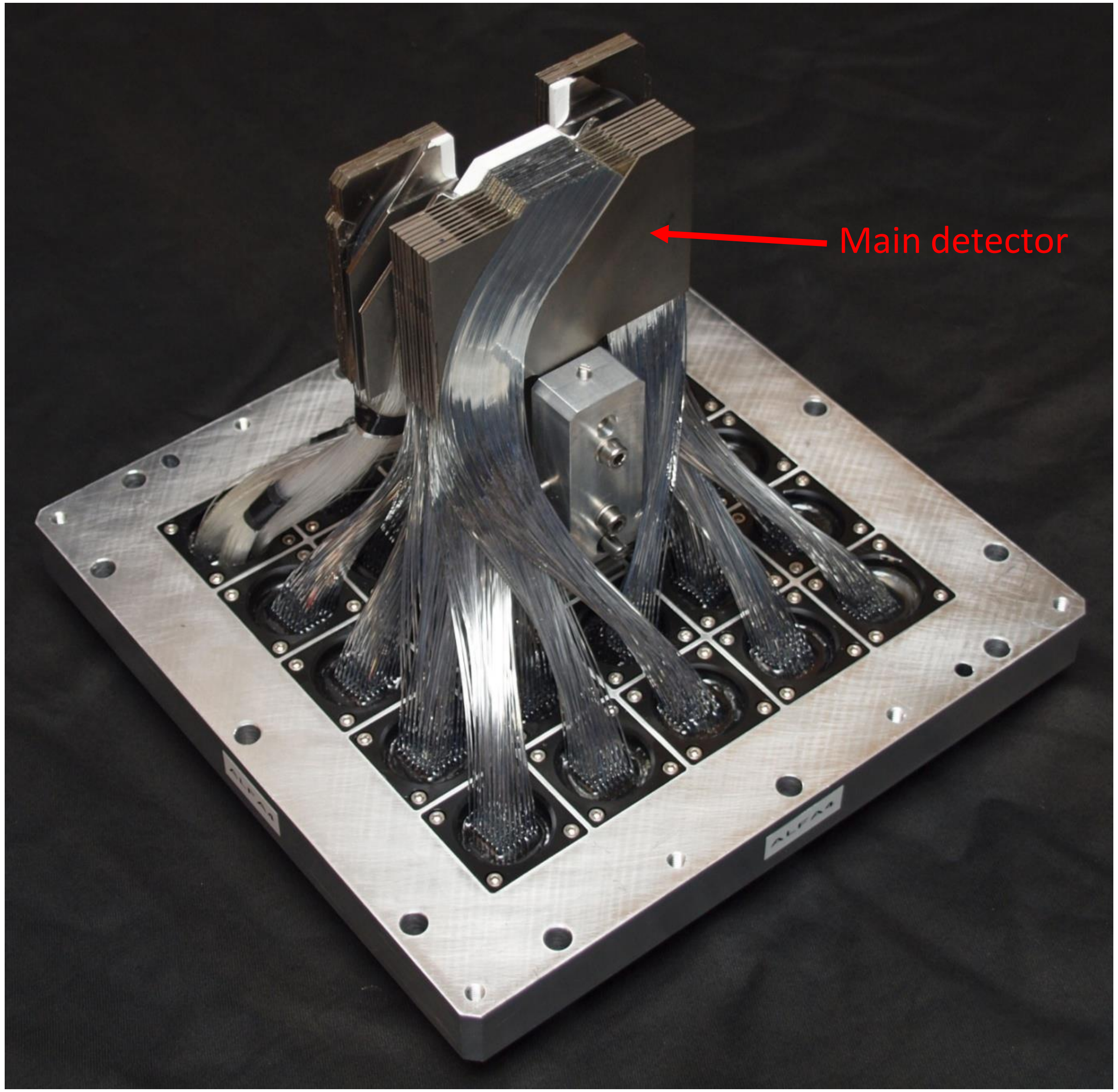


Aluminum coated to avoid the primary scintillating light to reach another fiber and make cross-talk



Figures from [1] and [16]

MAPMT and scintillating fiber – Use case: ATLAS ALFA: Main detector



The main detector has 64 fibers per layer:

- 24 with 90 degree cut
- 40 with 45 degree cut

Another layer is mounted on the backside of the support plate

The fibers are active ~20 μm from the cut

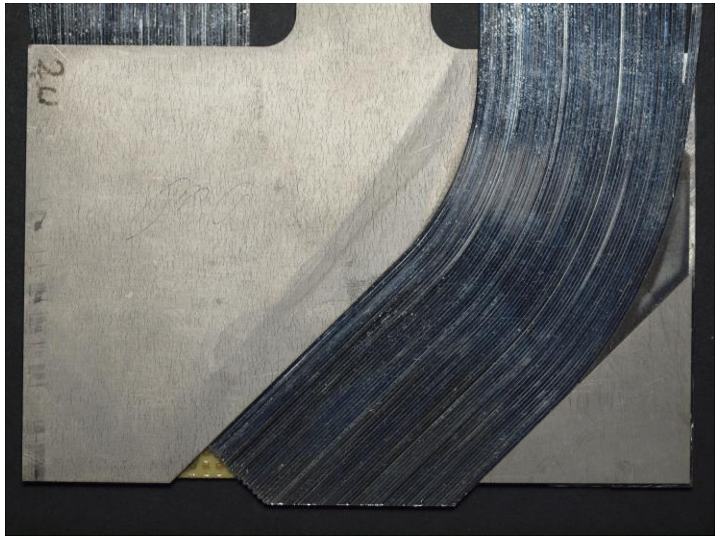
10 U-layer and 10-V layers are stacked to improve resolution

Measured resolution is better than 30 μm

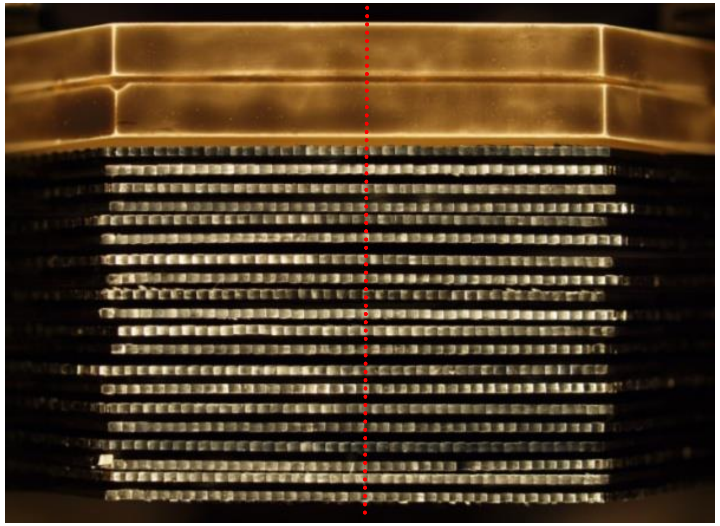
1460 fibers in a detector

11680 fibers in the full system

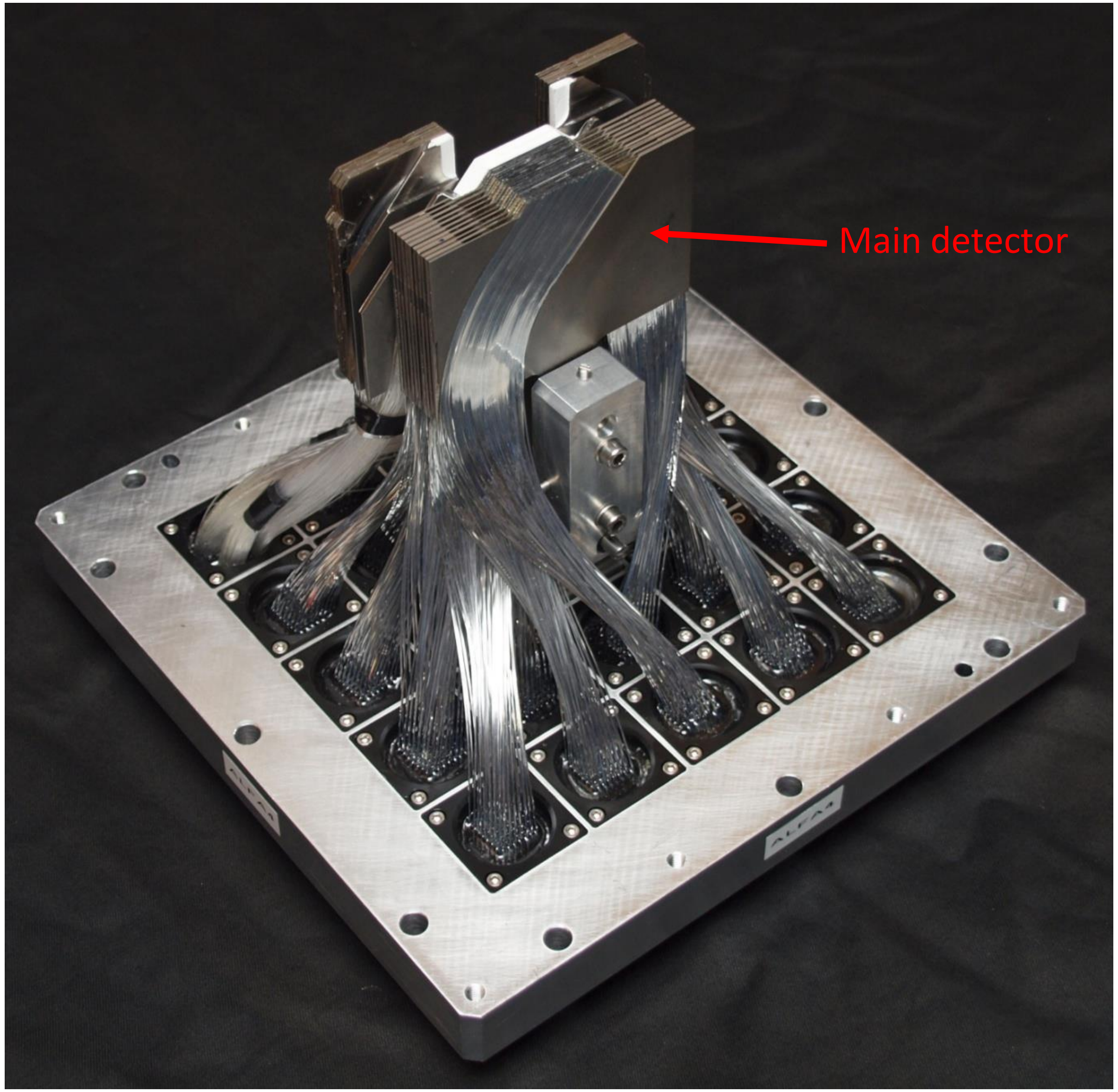
Main detector plate



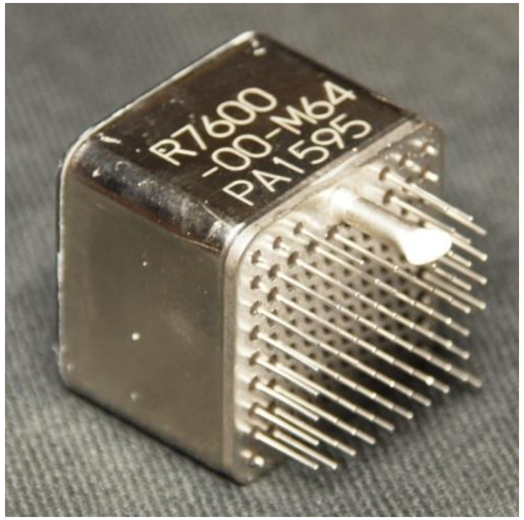
Staggering of plates



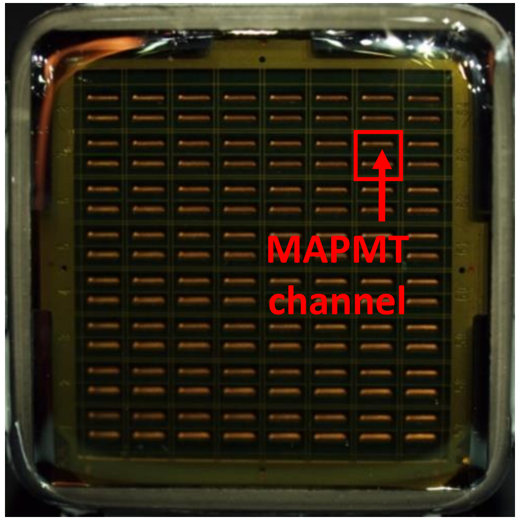
MAPMT and scintillating fiber – Use case: ATLAS ALFA: MAPMTs



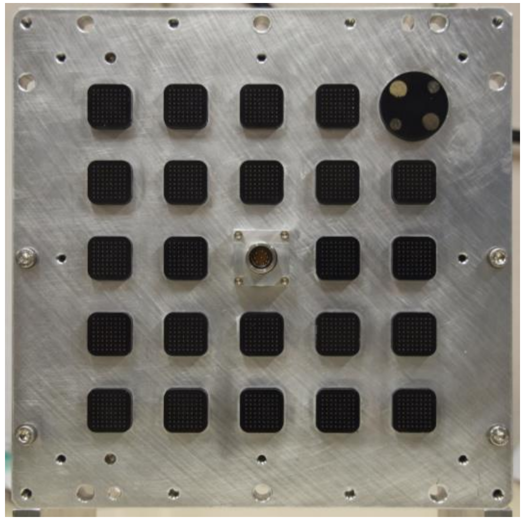
Hamamatsu R7600-00-64



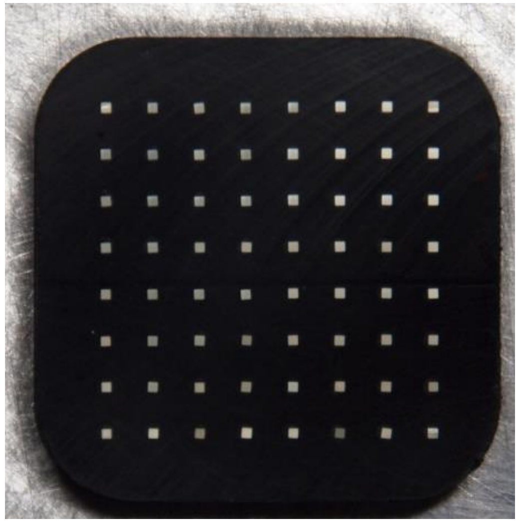
64 MAPMT channels



Fiber connectors

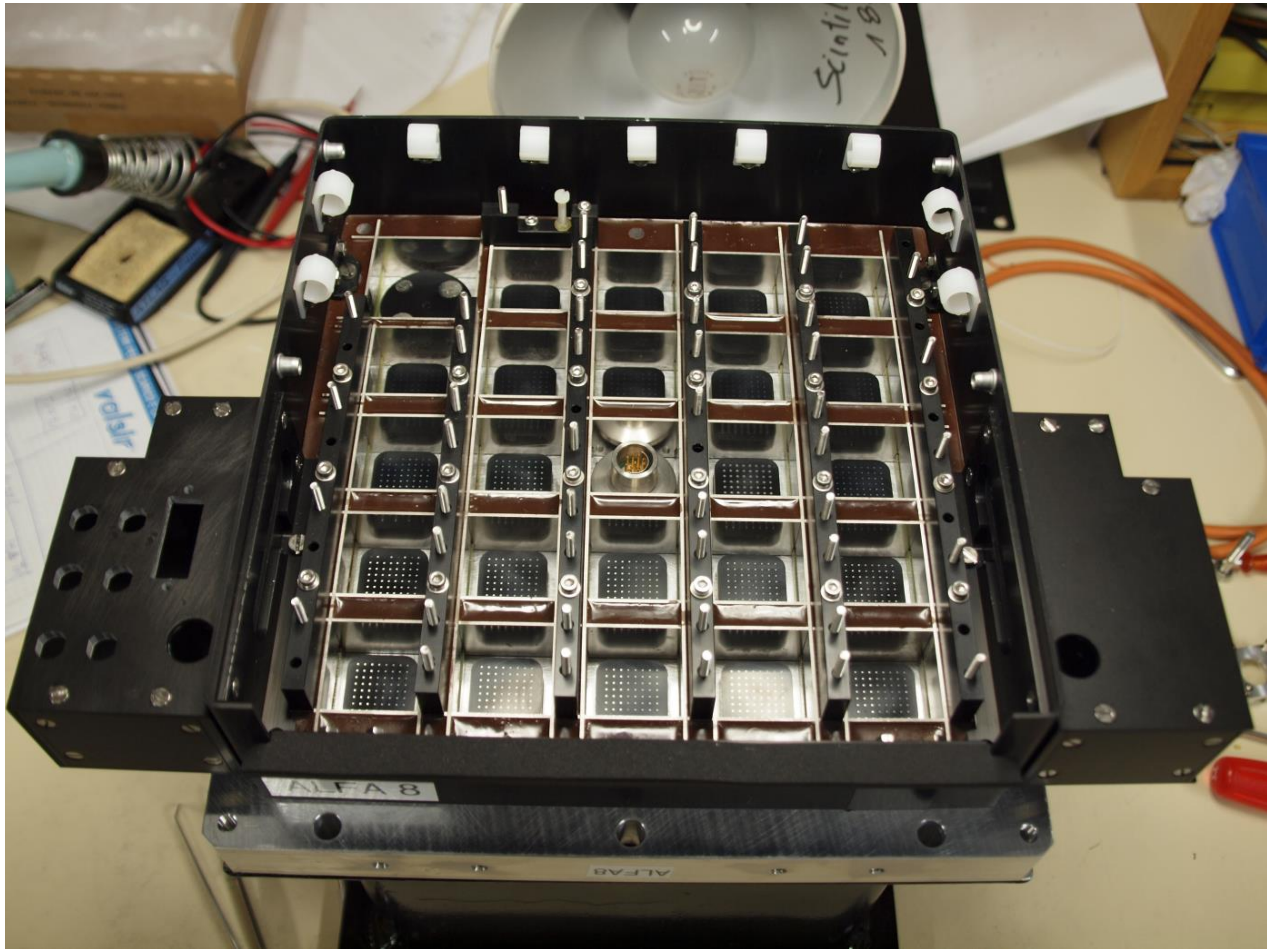


64 fibers in connector

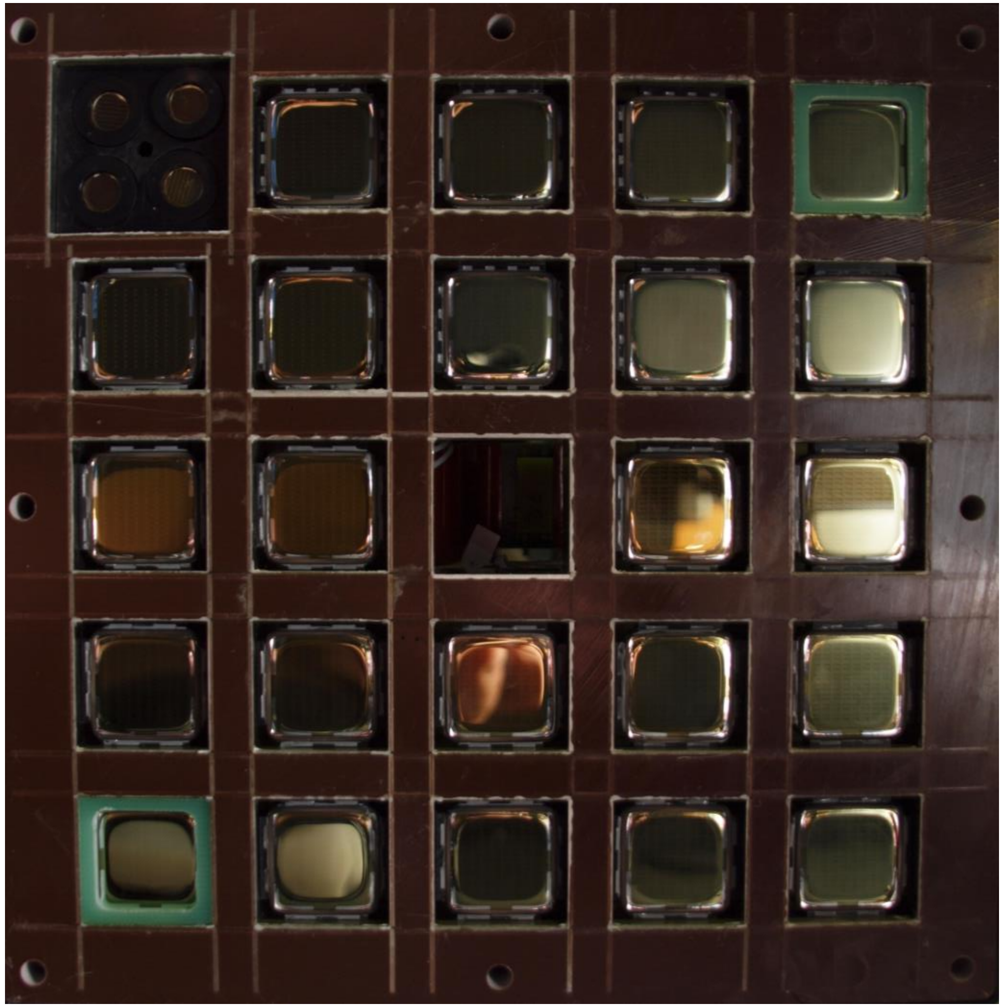


MAPMT and scintillating fiber – Use case: ATLAS ALFA: MAPMTs support

MAPMT support and magnetic shielding (mu-metal)

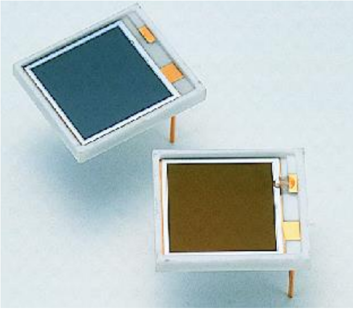
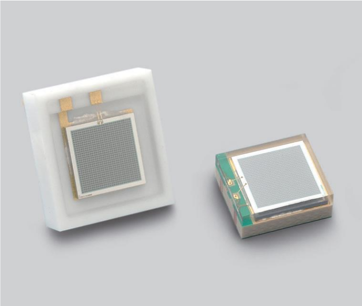


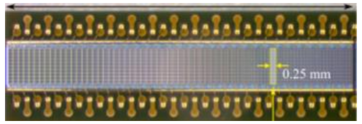
MAPMTs for one detector

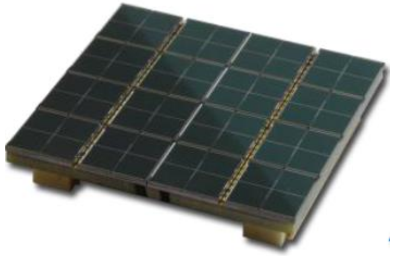
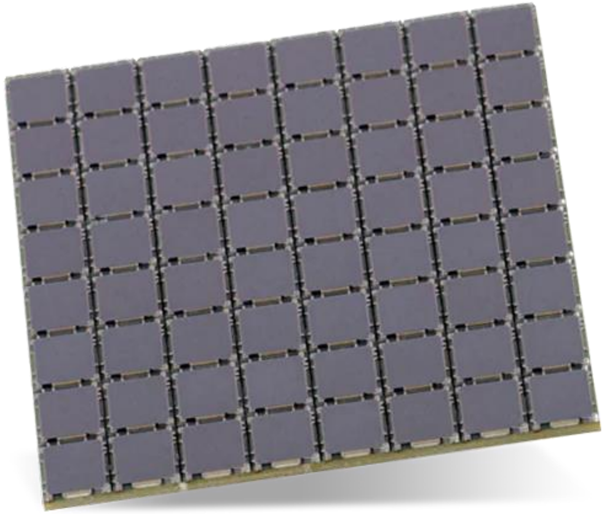
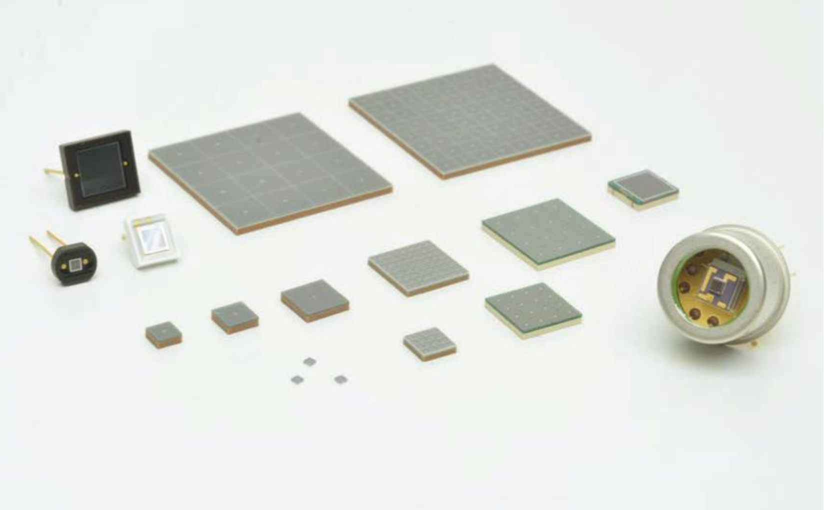


Silicon photodetectors





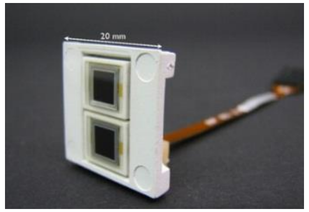
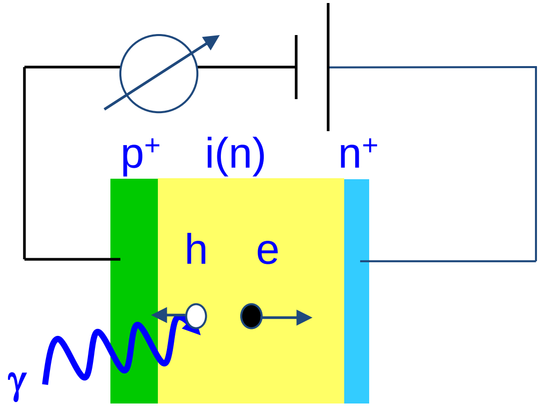


Figure from [1] and [3]

Silicon photodetectors – Internal photoeffect

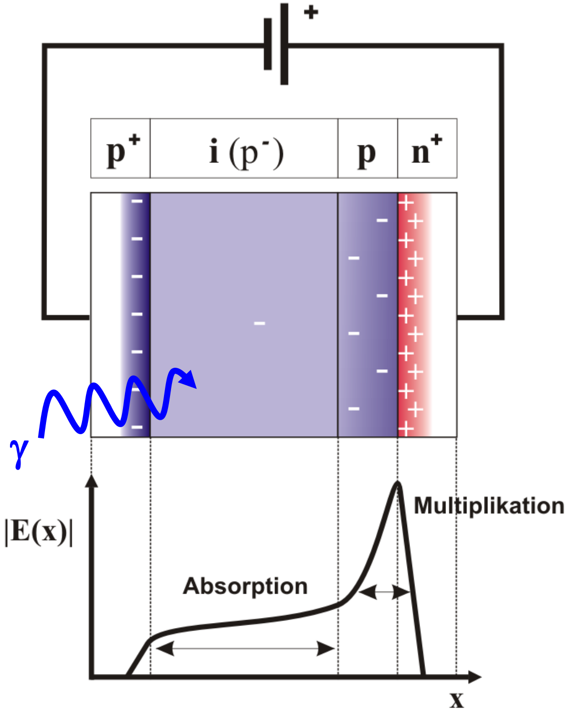
Photodiodes (PIN diodes)

- P(I)N type: p-region(intrinsic)n-region
- P layer needs to be very thin (below 1 μm), as visible light is rapidly absorbed by silicon
- Main drawback: Gian = 1, so many photons needed to a good signal



Avalanche photodiode (APD)

- Similar to the PIN diode, but with a high reverse bias voltage applied
- Due to the doping profile, some region has a high internal field
- The free electrons makes avalanches in the region due to impact ionization
- This leads to internal gain of 100-1000
- Very high sensitivity to temperature and bias voltage



Figures from [3] and [17]

Silicon photodetectors – Geiger Mode Avalanche Photodiode (GM-APD)

Geiger mode Avalanche Photodiode (G-APD or GM-ADP)

Operation beyond the linear mode

Operation sequence

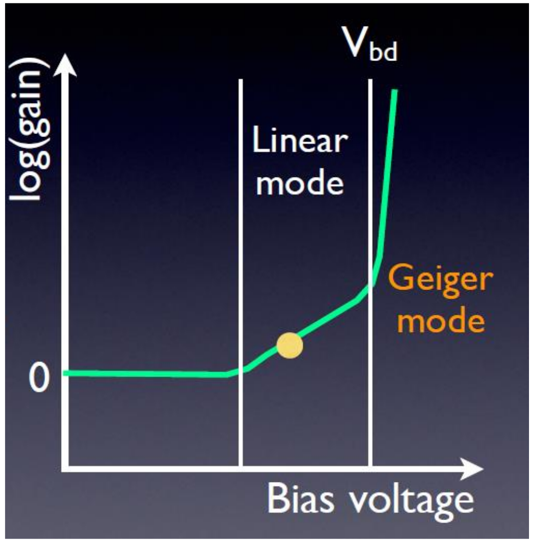
Ready, C_D charged to V_{BIAS}

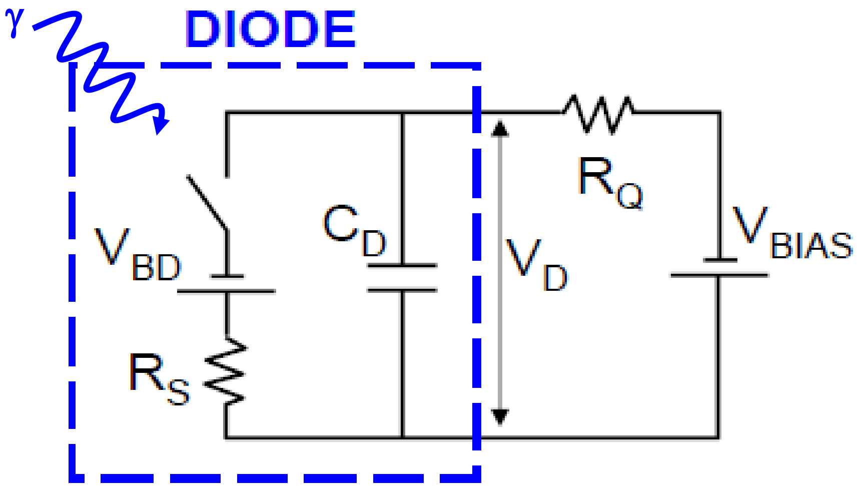
Avalanche triggered by photon, switch turned ON, C_D discharging towards break down voltage (V_{bd}), I_D grows to $\frac{V_{BIAS}-V_{bd}}{R_Q}$

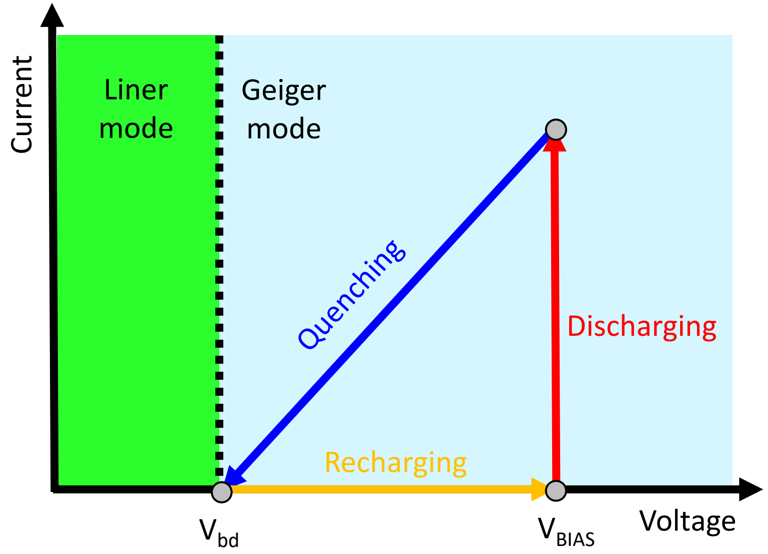
Quenching, the avalanche stopped by the voltage reaching the break down voltage

Recharging, switch turned OFF, C_D is recharged from break down voltage to V_{BIAS}

Ready to repeat



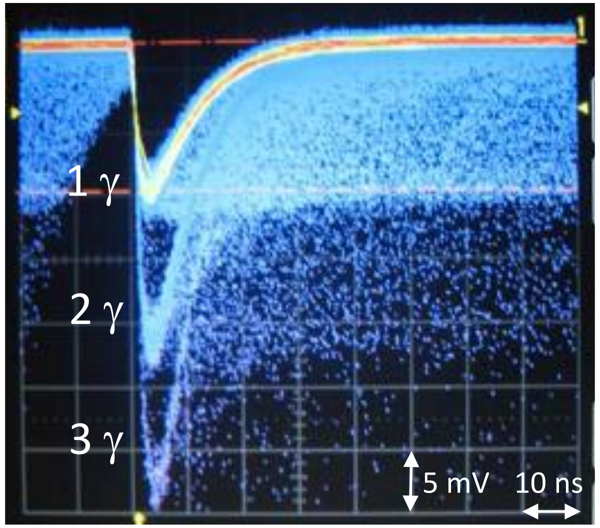


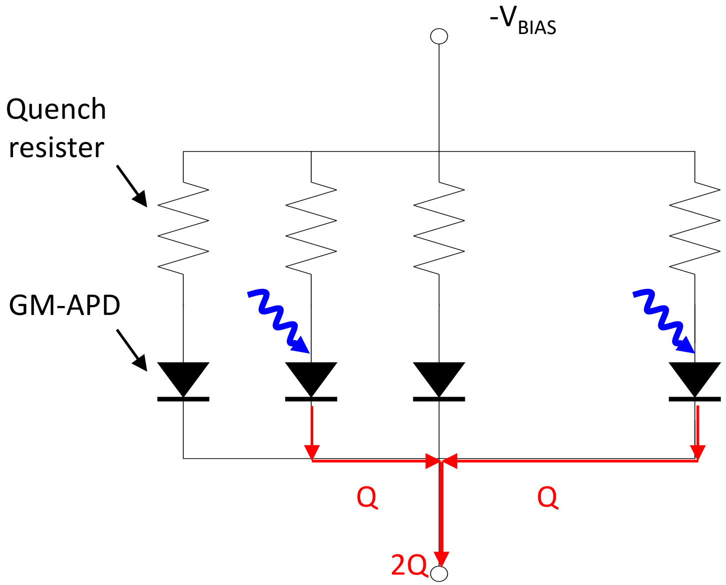


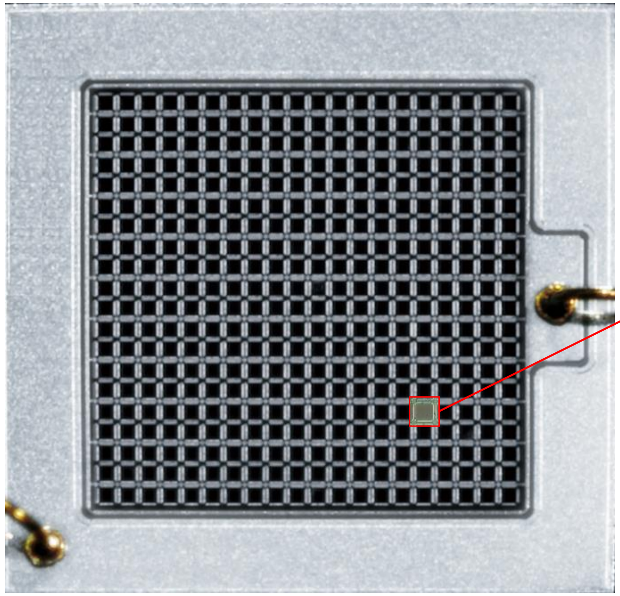
Figures from [18]

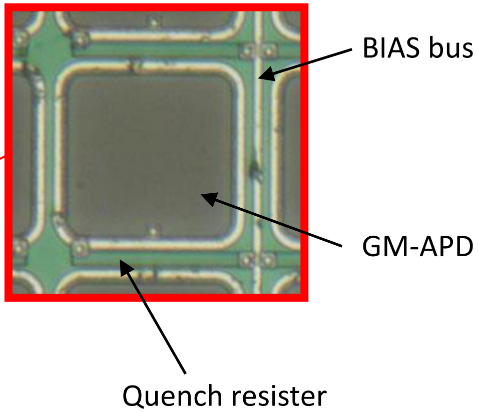
Silicon photodetectors – SiPMs (aka MPPC, MGPD, SPM, PSiPs, MRS-APD…)

- Multipixel GM-APD array
  - Known under many names: *SiPMs, MPPC, MGPD, SPM, PSiPs, MRS-APD…*
  - Commonly now referred to as SiPM (Silicon PhotoMultipliers)
- It is build up from serial connected GM-APDs
  - Serial connected GM-APDs
  - Quench resisters
- The charge from each GM-APD is analogy summed
- Since the charge from each GM-APD is equal and has a small spread, the summed signal directly showed how many GM-ADPs fired => Photon counting









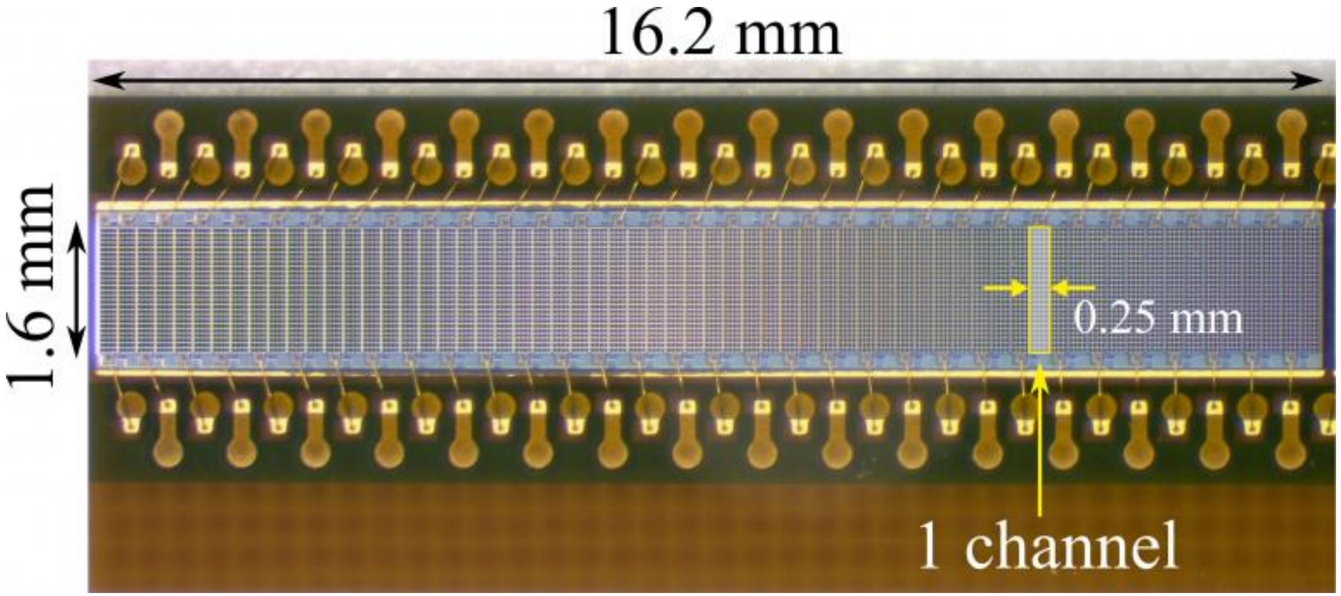
Notice that only part of the surface is photosensitive (lots of optimization to minimize this in the last years)

Figures from [18]

SiPMs – Pros and cons

Pros for SiPMs

- High quantum efficiency and detection efficiency
- Mechanically robust
- Tolerant to even very high magnetic fields
- Small and easy to integrate
- Operates at moderate voltage (below 100 V)
- Available in arrays
- Cheap per unit and per channel
- Very good time resolution
- High gain (so cheap electronics can be used)



Cons for SiPMs

- The gain is very temperature depended
- The gain is very BIAS voltage depended
- Linearity is limited (depending on the number og GM-ADPs)
- Very noisy per area (~100s kHz/mm^2 1 PE noise) at room temperature
- The noise dramatically scales with neutron radiation

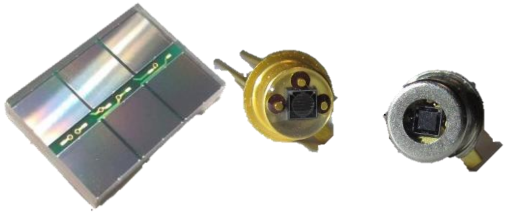
Figure from [19]

SiPMs – Producers

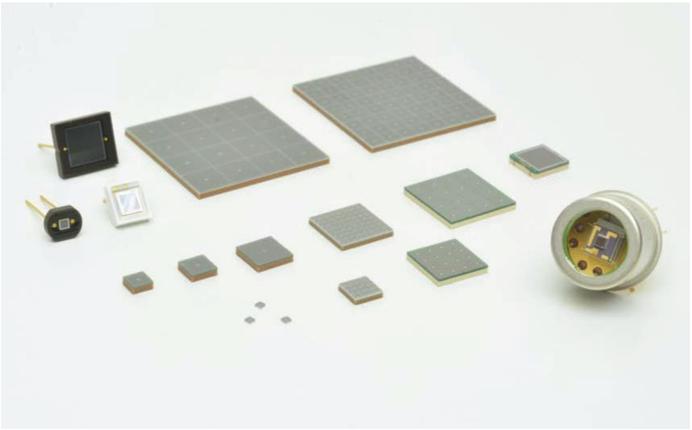
There are many producers of SiPMs (links under the logos), the list is not exhaustive:

BROADCOM

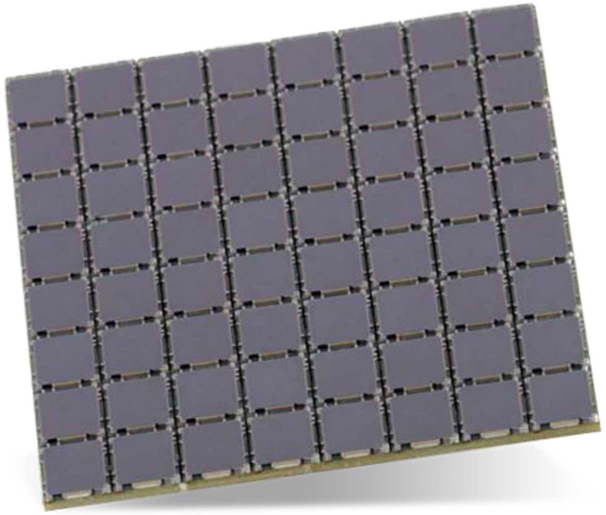
FBK
CENTER FOR SENSORS & DEVICES
FONDAZIONE BRUNO KESSLER



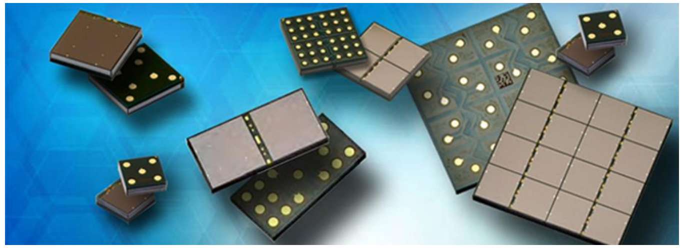
HAMAMATSU
PHOTON IS OUR BUSINESS



onsemi™



APTechnologies



Use case of SiPMs and Time of Flight
The proposed CMS MTD

Section based on [21]

SiPMs and Time of Flight: CMS MIP Timing Detector (MTD)

Precise timing information can be used to cope with high pileup

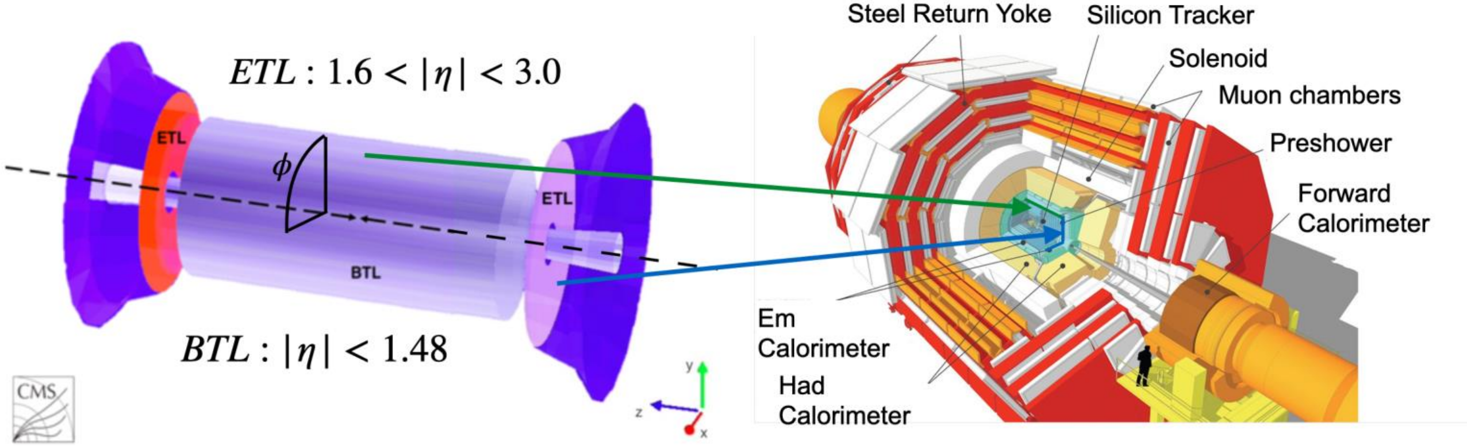
CMS is therefore planning to add a "MIP Timing Detector"

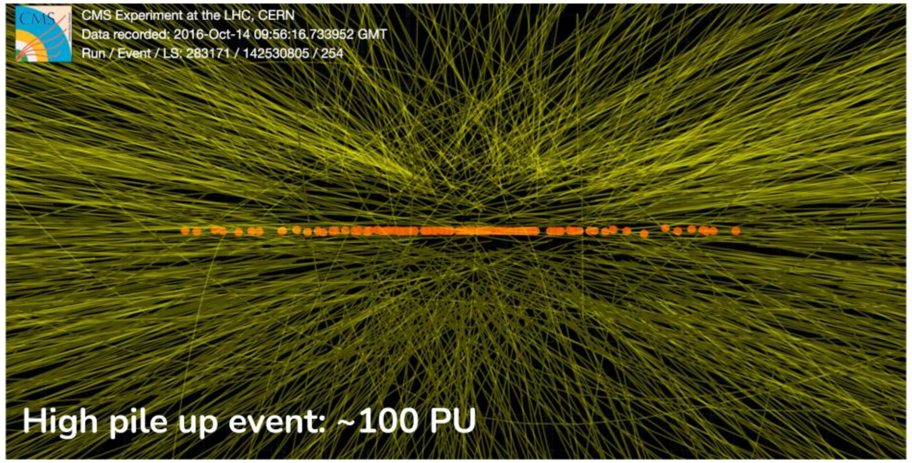
- The aim is a time resolution of 30 ps

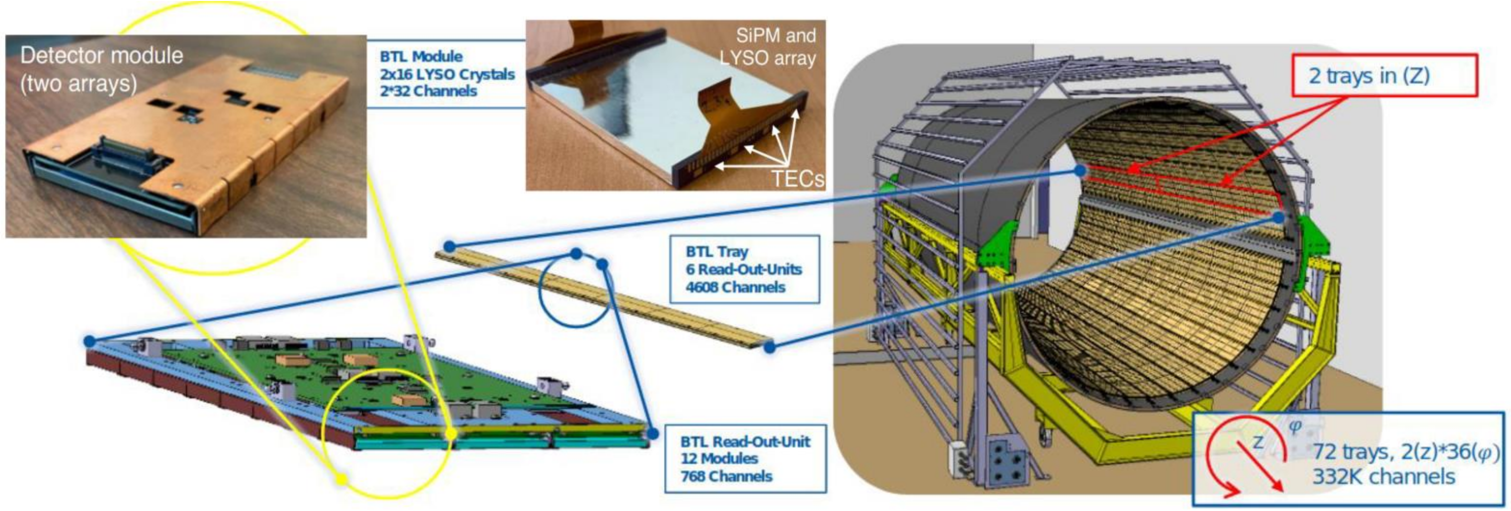
The "Barrel Timing Layer" (BTL) is composed of:

- Inorganic scintillator: 165888 crystals
- Photo detector: 331776 SiPMs

To minimize noise (Dark Count Rate, DCR) of the SiPM, the plan is to operate them at -45 °C







Figures from [21], [22] and [23]

SiPMs and Time of Flight: CMS MIP Timing Detector (MTD) - Crystals

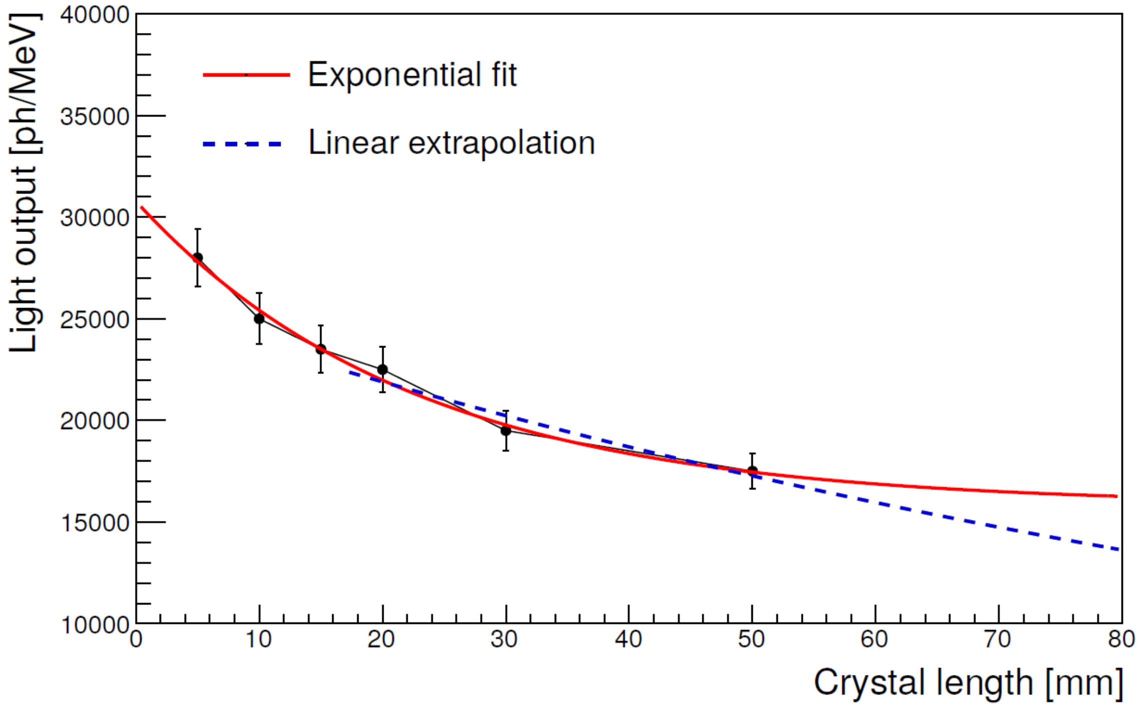
Crystal details:

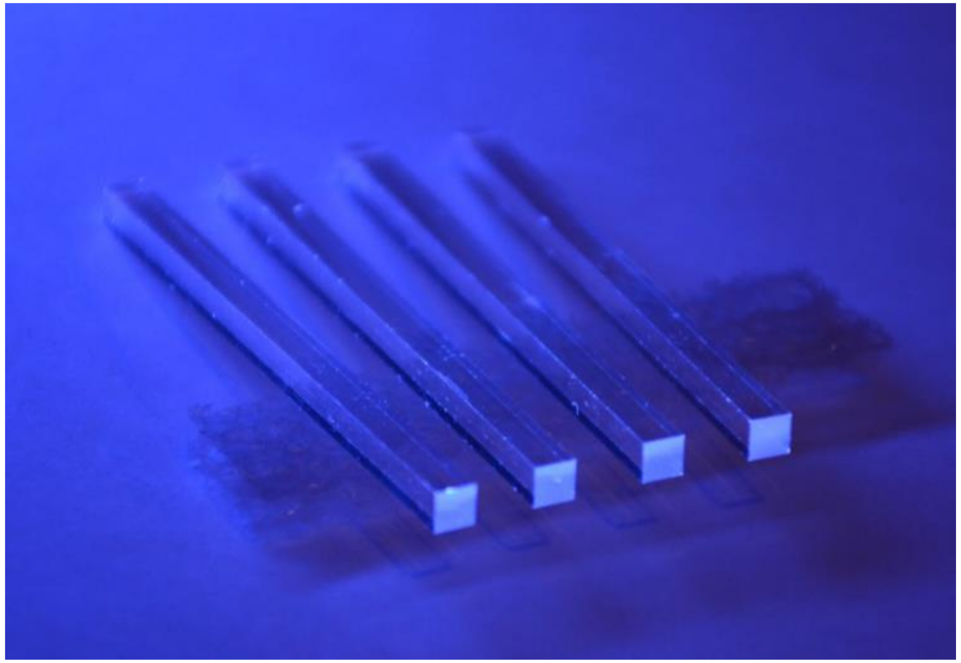
Lutetium Yttrium Orthosilicate crystals doped with Cerium (LYSO:Ce)

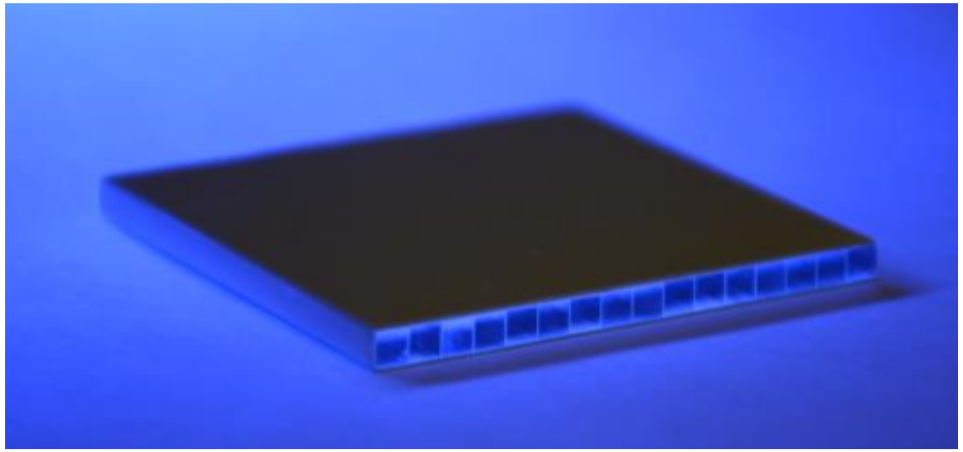
Size: ~3 mm x 3 mm x 57 mm

Density: ~7.1 g/cm^3

Refractive index 1.82







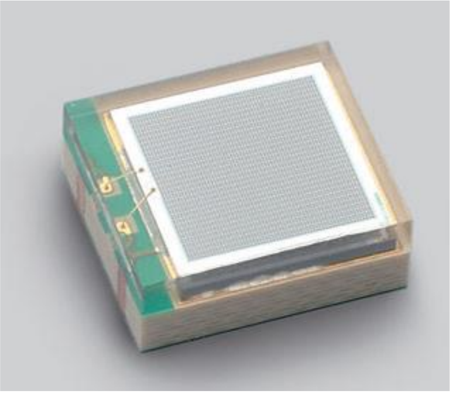
Figures from [21], [22] and [23]

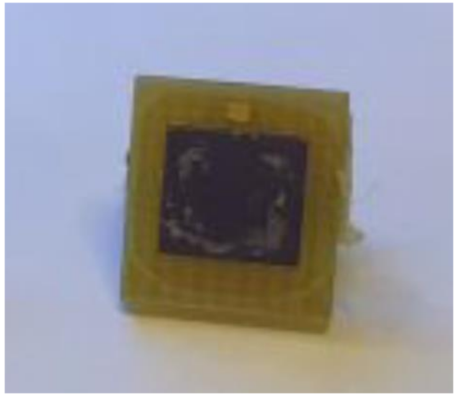
SiPMs and Time of Flight: CMS MIP Timing Detector (MTD) - SiPMs

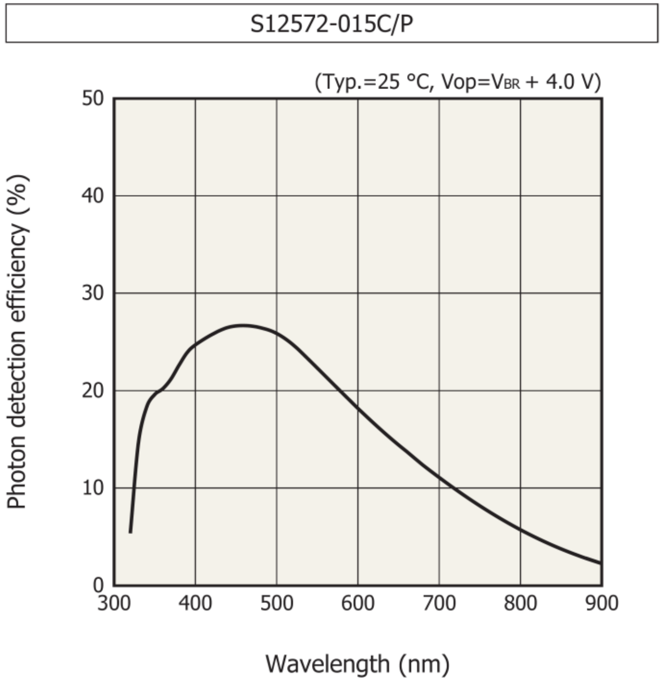
SiPM details (2 companies in competition):

3 mm x 3 mm active surface

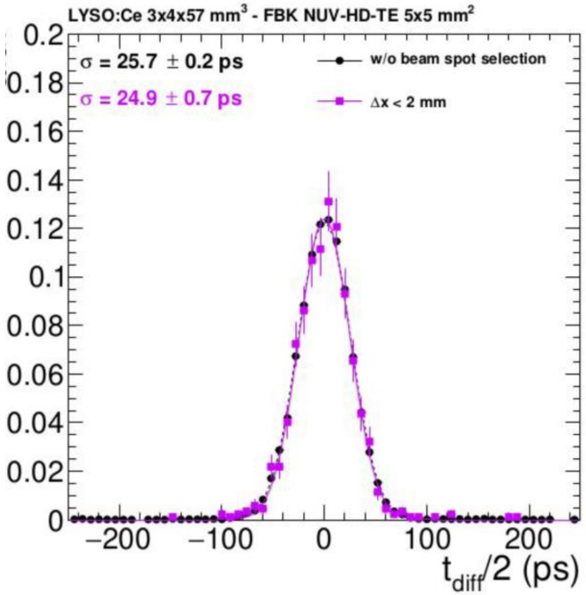
SiPM parameter	Specification	FBK-NUV-HD	HPK-S12572	HPK-HDR2
Active area	–	~ 9 mm^2	~ 9 mm^2	~ 9 mm^2
Cell pitch	$< 20\ \mu$m	15 μm	15 μm	15 μm
Cell recovery time	< 10 ns	7 ns	8.5 ns	< 10 ns
Capacitance	< 600 pF	530 pF	295 pF	585 pF
Number of cells	> 20k	~ 40k	~ 40k	~ 40k
V_{br} ($-30\,^\circ$C)	–	34.2 V	63.0 V	35.8 V
dV_{br}/dT	–	41 mV/ °C	59 mV/ °C	37 mV/ °C
$\delta V_{br}/10^{13}\ n_{eq}/\text{cm}^2$	≤ 0.2 V	< 0.1 V	0.2 V	< 0.1 V
DCR-T coefficient	–	1.76	1.90	1.79
ENF	< 1.1	< 1.05	1.07	< 1.05
Parameters after 3000 fb^{-1}				
Optimal OV	> 1V	1.6 V	1.5 V	1.2 V
PDE	–	15%	13%	23%
Current/device	–	1.32 mA	0.77 mA	1.30 mA
Static power consumption	≤ 50 mW	50 mW	50 mW	50 mW
Gain	$\geq 1.3 \times 10^5$	2.1×10^5	1.45×10^5	1.55×10^5
DCR/SiPM	–	42 GHz	37 GHz	55 GHz
PDE/$\sqrt{\text{DCR}}$	≥ 2.0	2.3	2.1	3.1







Test beam results:



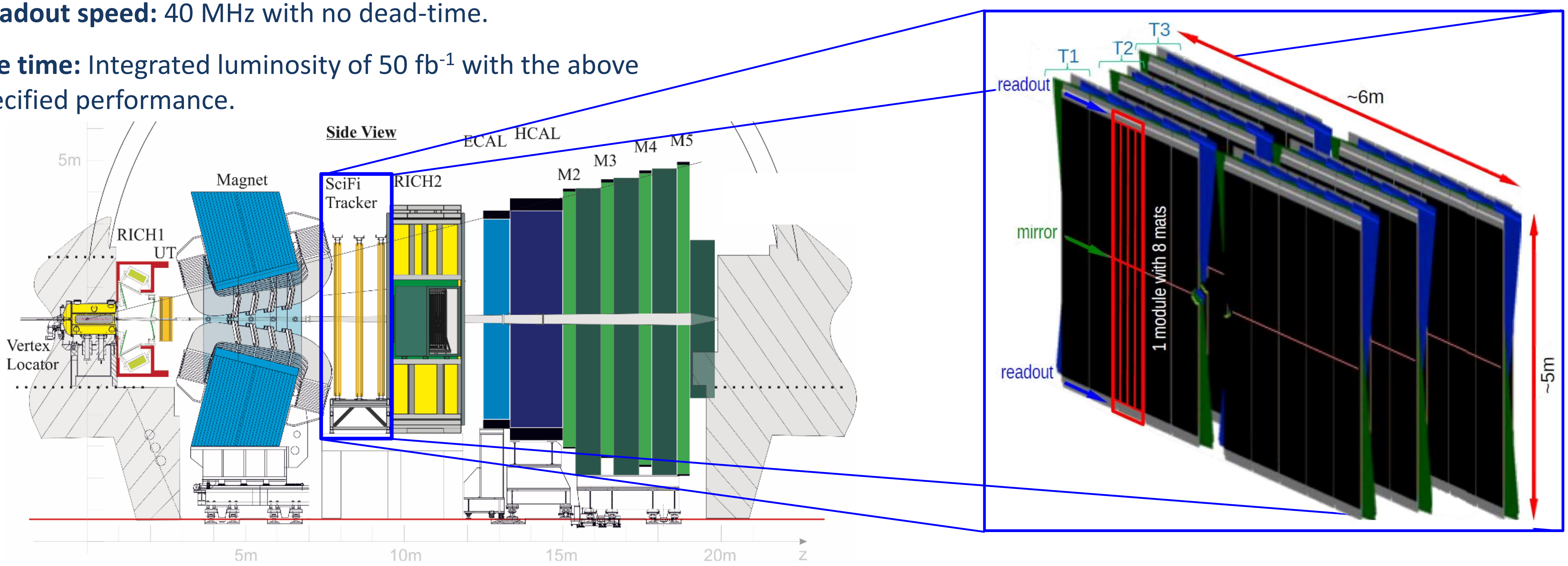
Figures from [3],[21], [22] and [23]

Use case of SiPMs and in tracking detectors
The LHCb SciFi detector

Section based on [20]

SiPMs and scintillating fiber – use case: LHCb SciFi tracker

1) **Area**: Active area of about 340 m^2.
2) **Hit detection efficiency:** Larger than 99 %.
3) **Spatial resolution:** Better than 100 μm in the bending plan of the magnet (vertical).
4) **Noise cluster rate:** Below 10 % of signal in all region of the detector.
5) **Material budget:** Less than 1 % radiation length per each of the 12 detection layers.
6) **Readout speed:** 40 MHz with no dead-time.
7) **Life time:** Integrated luminosity of 50 fb^{-1} with the above specified performance.



SiPMs and scintillating fiber – use case: LHCb SciFi tracker – Scintillating fibers

Double cladded round fibres Ø 250 µm (Kuraray SCSF-78MJ) was selected:

About 300 photons/MIP

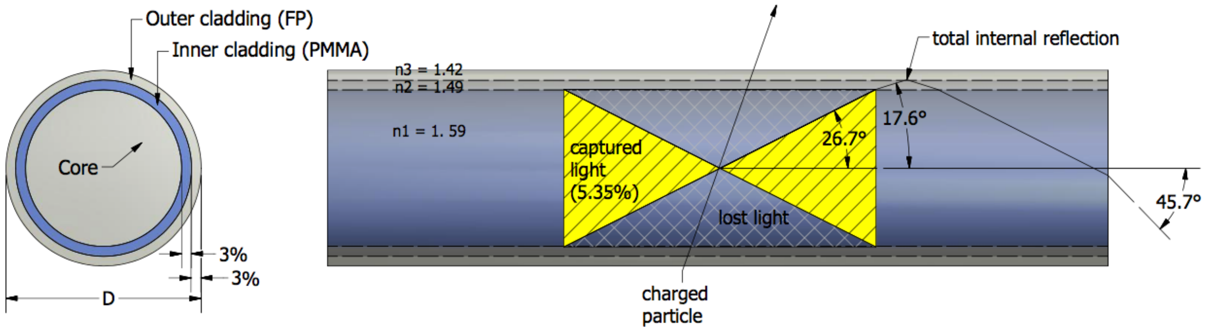
Attenuation length ~3.5 m

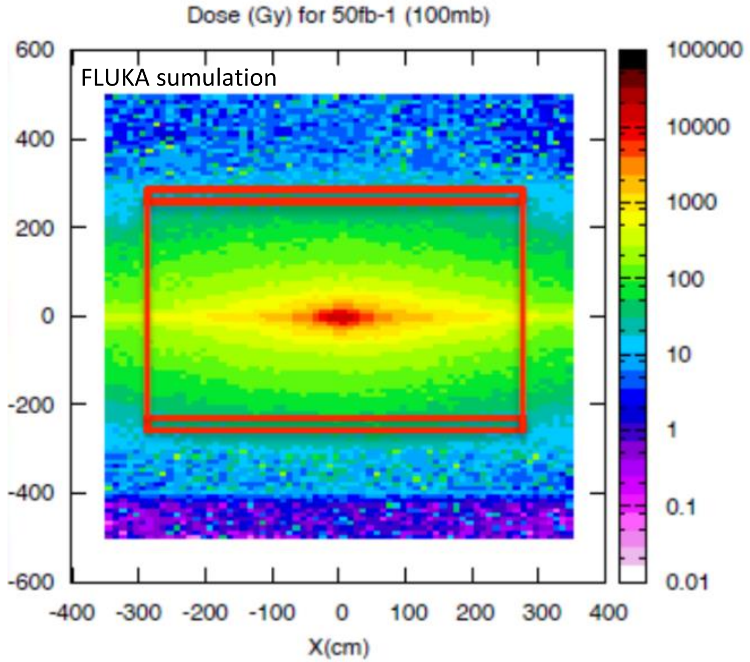
3-4 p.e. detected @ 240 cm for a single fiber (trapping fraction, attenuation and PDE of Silicon photomultiplier)

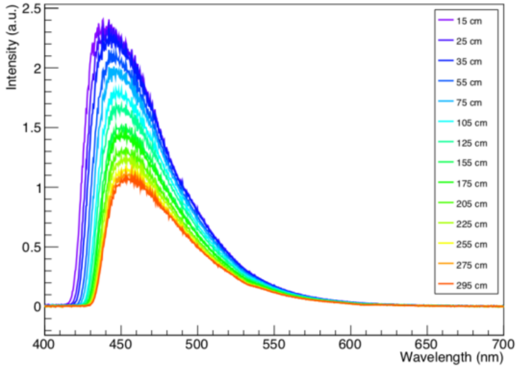
Emission peak ~450 nm

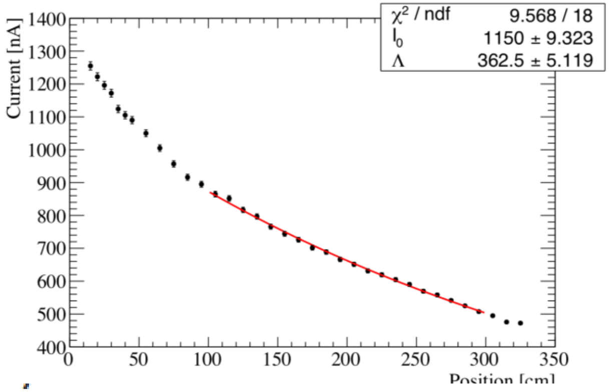
Very non-uniform dose profile expected

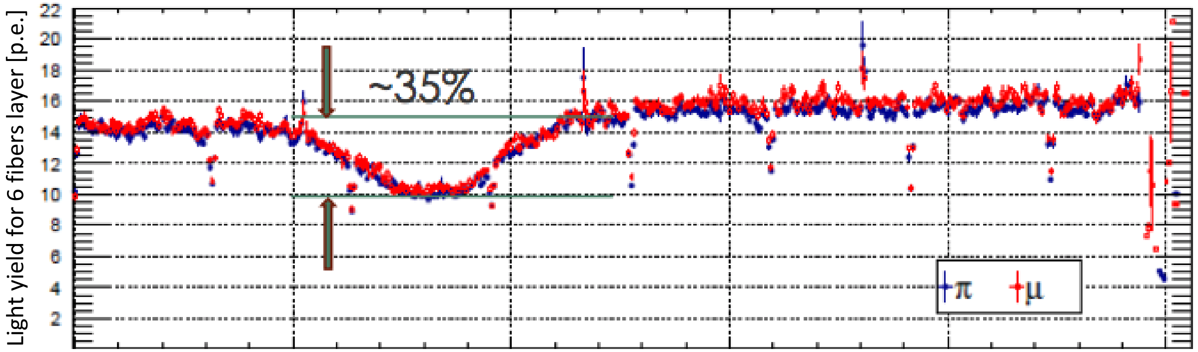
Irradiation campaigns shows about 35 % loss of signal at the expected dose











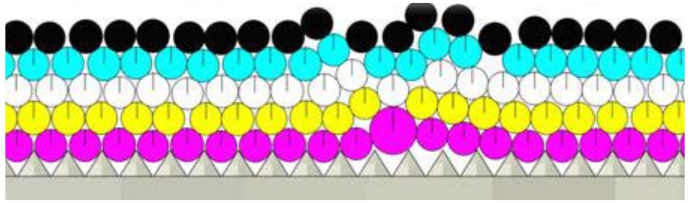
SiPMs and scintillating fiber: LHCb SciFi – Scintillating fibers quality assurance

12000 km of fiber (incl. pre-production & spare), 950 spools

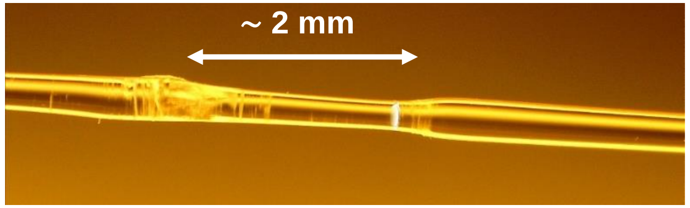
Quality assurance procedure:

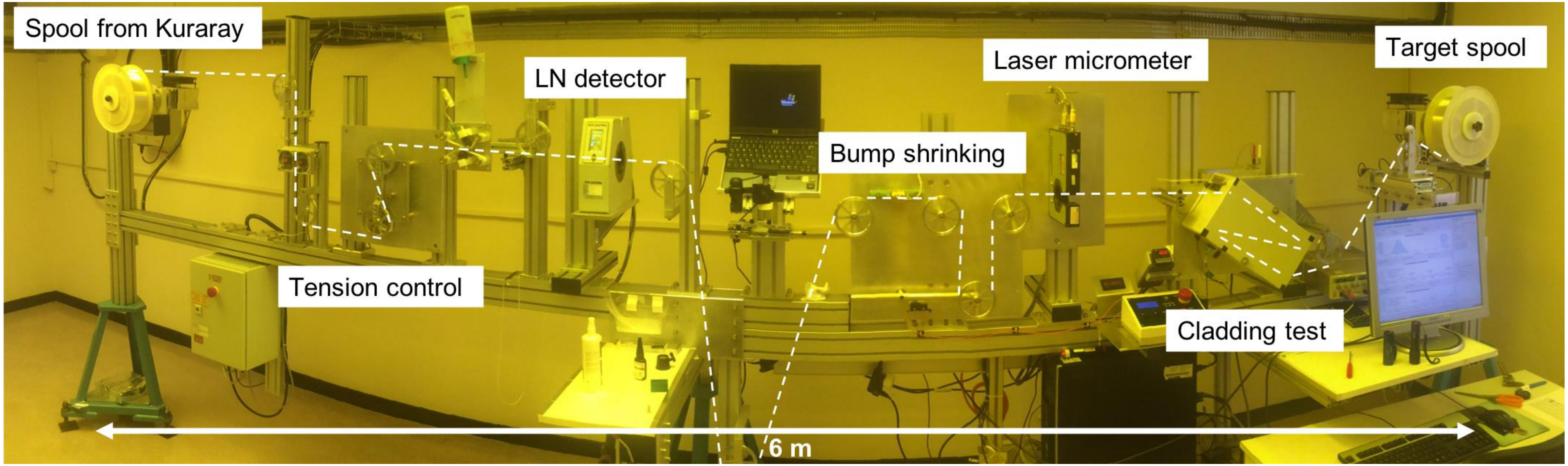
- Attenuation length and light yield (for every spool).
- Radiation hardness (X-rays), decay time, bending radius (for a fraction of spools).
- Scanning for diameter anomalis (bumps).
- Removal of big bumps (ΔD > 100 μm) without cutting/gluing the fiber.
- The light yield suffers at the removed bumps, but with 6 fibers in a mat it is tolerable.
- Verification of cladding integrity.

Problem if there is a bump on a fiber



Bump after shrinking





SiPMs and scintillating fiber: LHCb SciFi – Fiber mat production

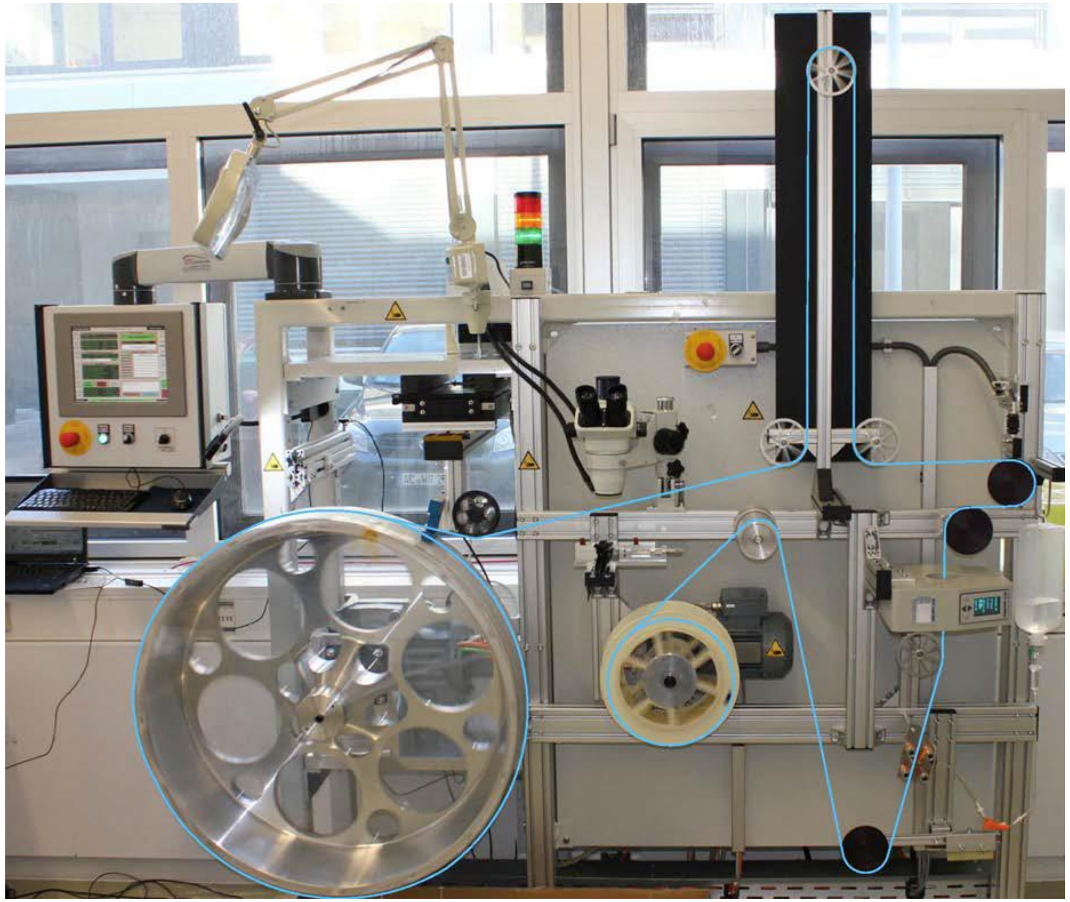
Custom winding machine (Ø = 80 cm wheel with fine thread).

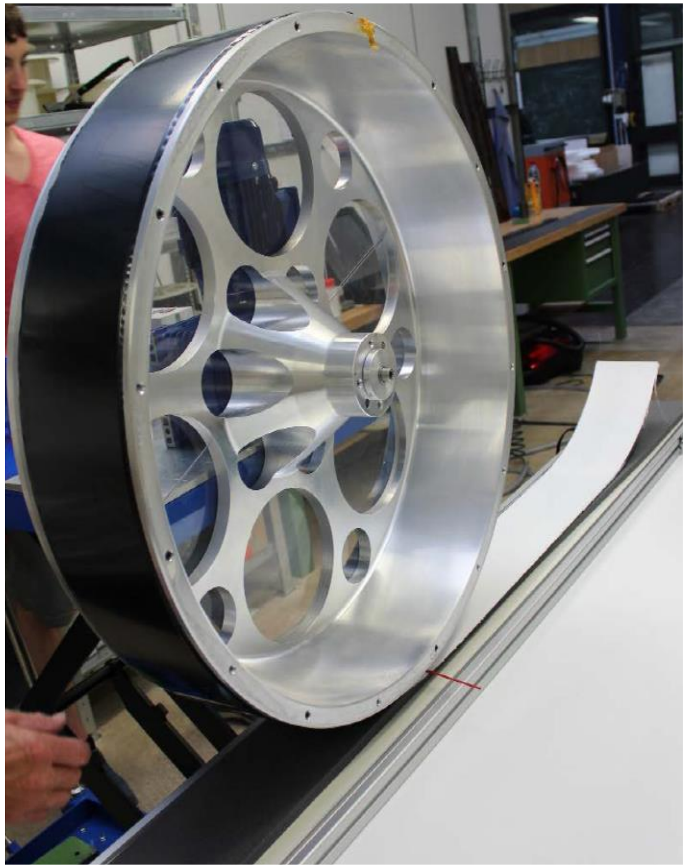
Mat size: 2650 mm x 140 mm.

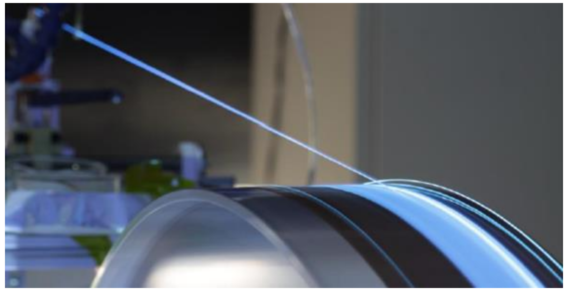
1500 mats produced at 4 sites (incl. spares).

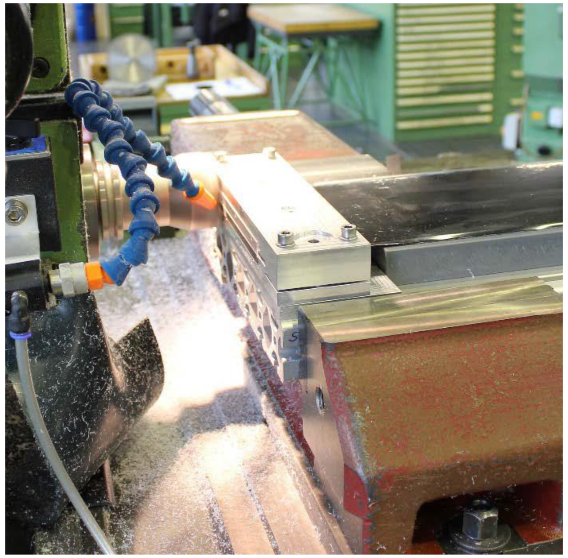
The ends of the fiber mats were milled to optical quality.

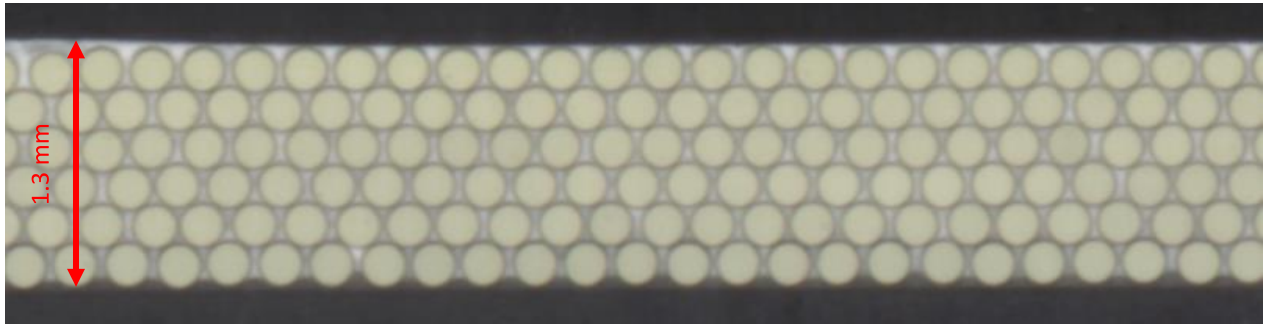
One fiber mat end gets a mirror glued onto it.











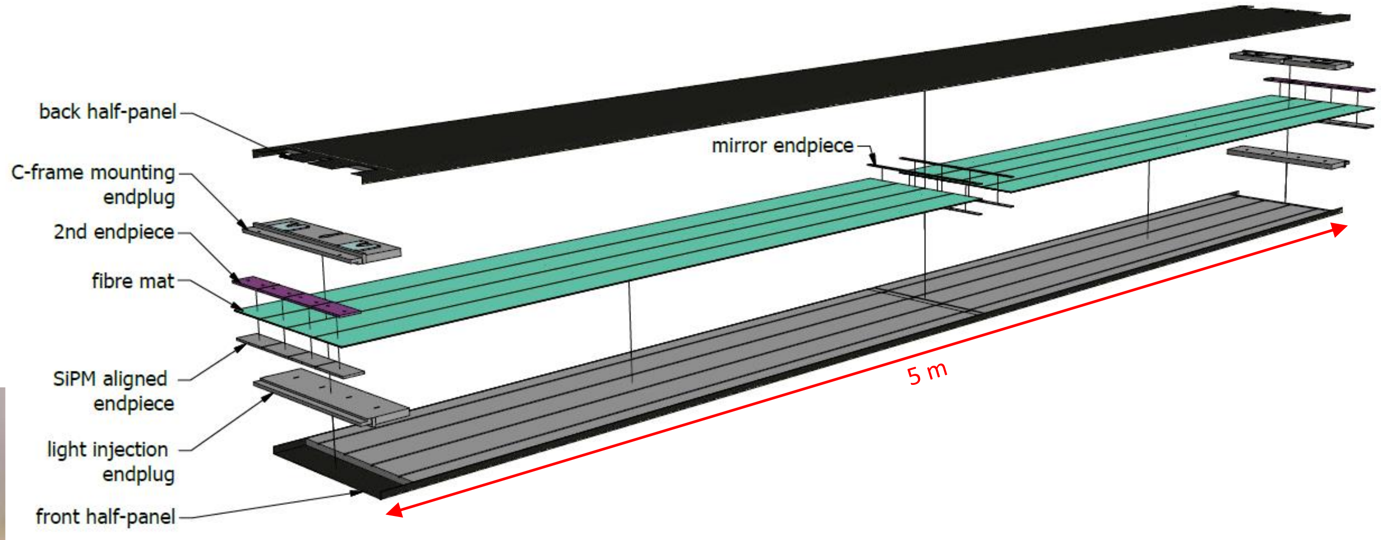
SiPMs and scintillating fiber: LHCb SciFi Fiber module production

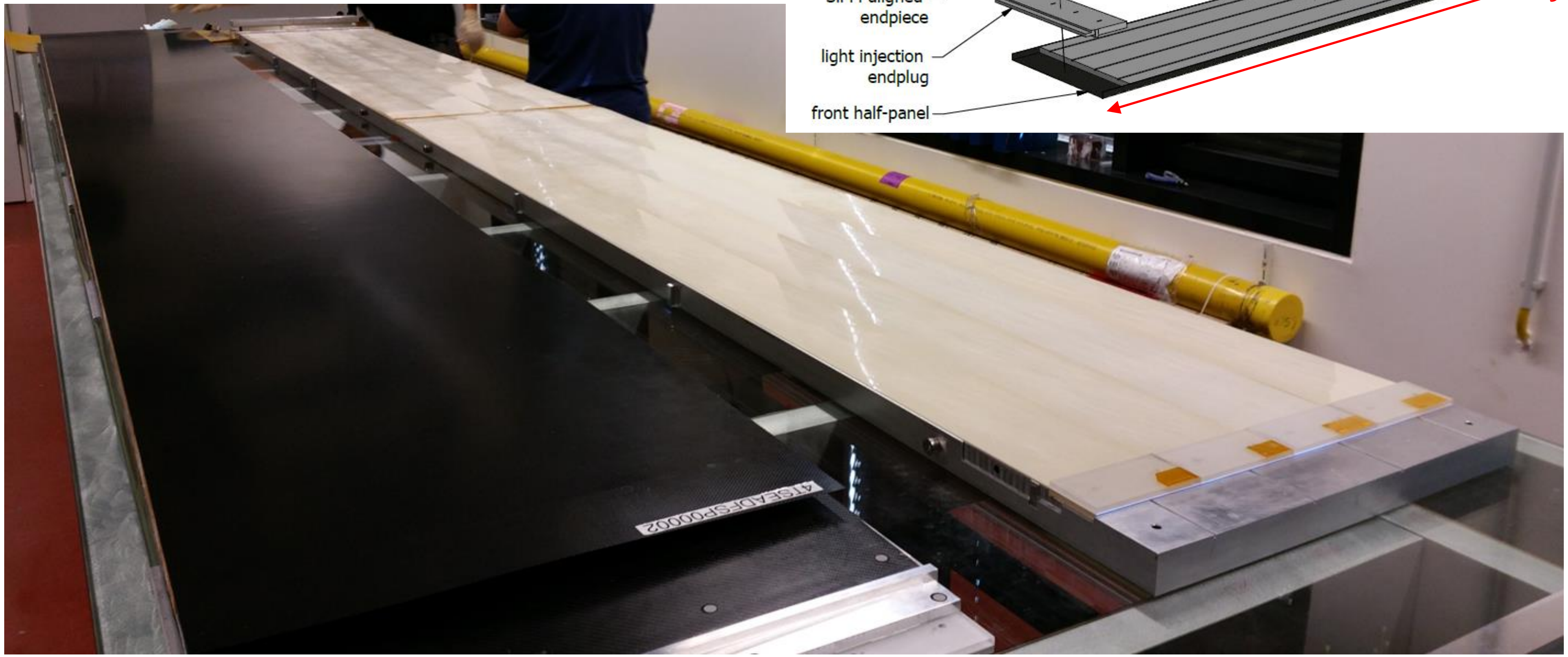
8 fiber mats built into one fiber module.

Mechanical alignment w/r to straight line better than 50 µm over 5 m length.

Mechanical stiffness and protection added with honeycomb and carbon fiber panels.

128 modules needed, 144 produced.





SiPMs and scintillating fiber: LHCb SciFi – SiPMs

Each SiPM channel comprises 104 parallel Avalanche Photodiodes in Geiger-Mode (pixels).

Each pixel (GM-APD) is 62 µm x 57 µm.

One 128 channel array is made of 2 chips of 64 SiPMs.

- Array model: Hamamatsu MPPC S13552 – H2017.

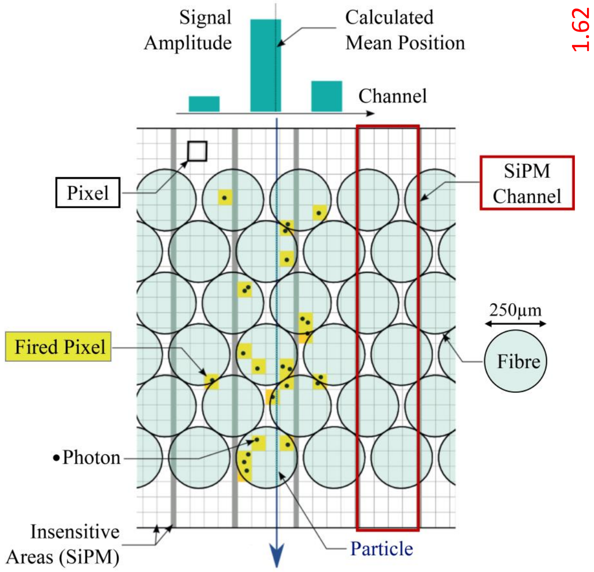
The 128 channel array is mounted on a Kapton flex-PCB.

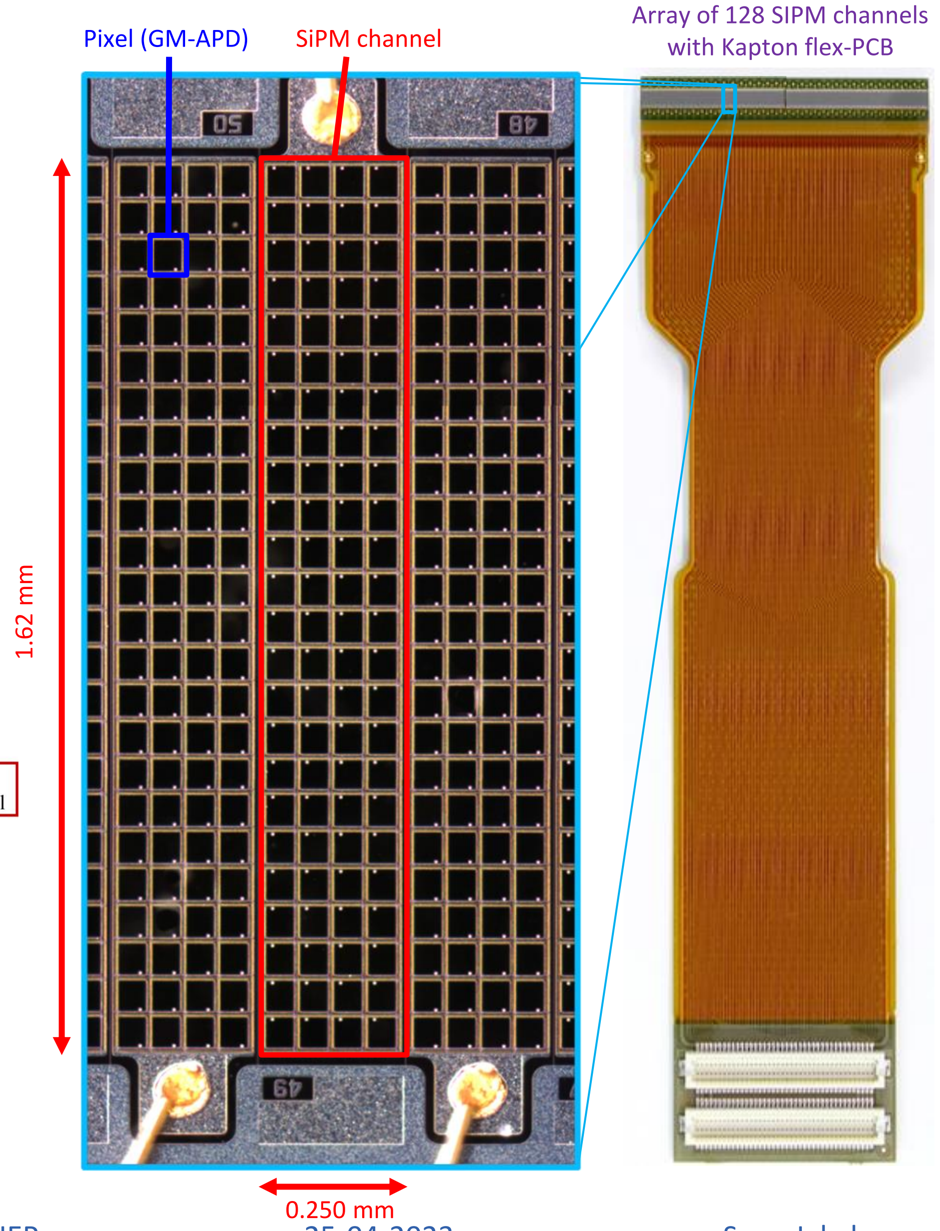
LHCb Scifi needs:

- 4096 SiPM array with Kapton flex-PCB.
- 524288 SiPM channels in total.

Fiber to SiPM coupling

- Each fiber does NOT have its own SiPM channel.
- A SiPM channel covers a cross section of a fiber mat.
- A single particle is therefore likely to induce signal in more than one SiPM channel.
- Clustering reconstruct the particle position
- Noise is randomly spread over the SiPM pixels.





SiPMs and scintillating fiber: LHCb SciFi – SiPM performance

Key performance

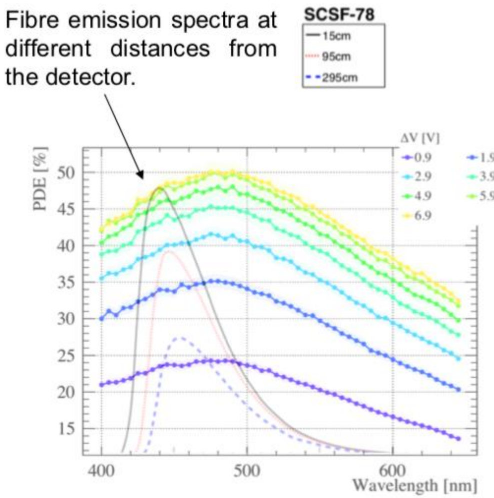
Peak Photon Deletion Efficiency (PDE): 45 %
(at over-votlage ΔV = 3.5 V).

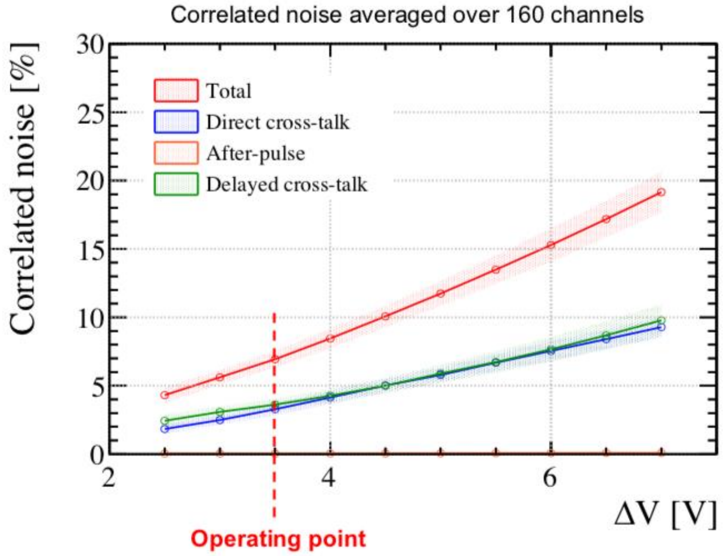
After-pulse < 0.1%.

Direct cross-talk ~ 3.5%.

Delayed cross-talk ~ 3.5%.

Total correlated noise = 7% (at ΔV = 3.5 V).





Dark count rate per SiPM channel (DCR)

DCR (not irradiated): 0.04 MHz.

DCR is increasing with neutron radiation.

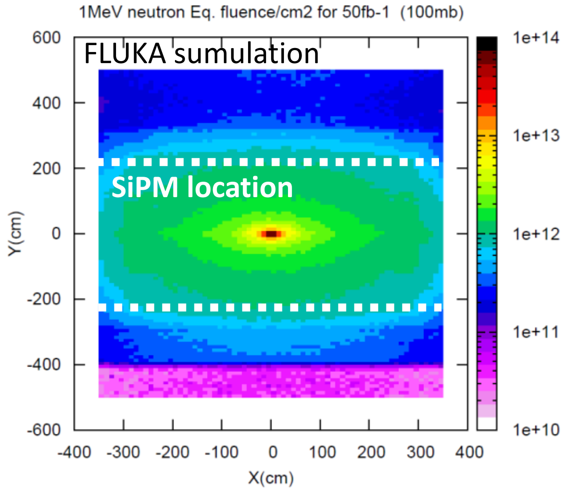
The SiPMs are positioned far from the beam center.

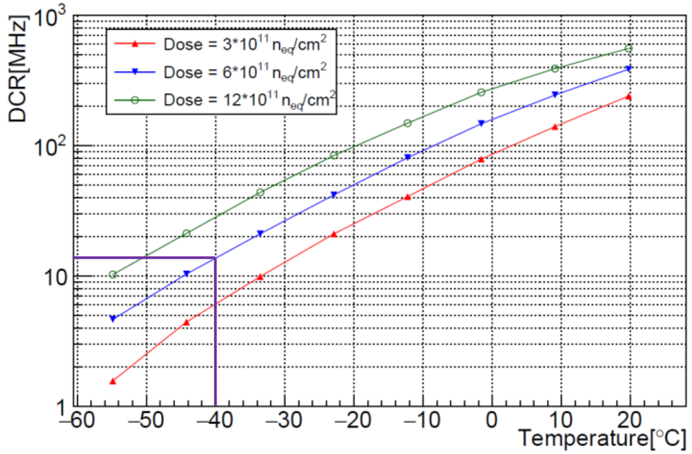
Neutron radiation expected: $6 \cdot 10^{11}\ n_{eq}/cm^2$.

DCR ($6 \cdot 10^{11}\ n_{eq}/cm^2$): 400 MHz.

The DCR can be reduce by cooling the SiPM.

DCR ($6 \cdot 10^{11}\ n_{eq}/cm^2$ @ -40 °C): 14 MHz.





SiPMs and scintillating fiber: LHCb SciFi – SiPM cooling

Goal: Cool SiPMs to -40 °C.

Monophase cooling selected.

Design criterias:

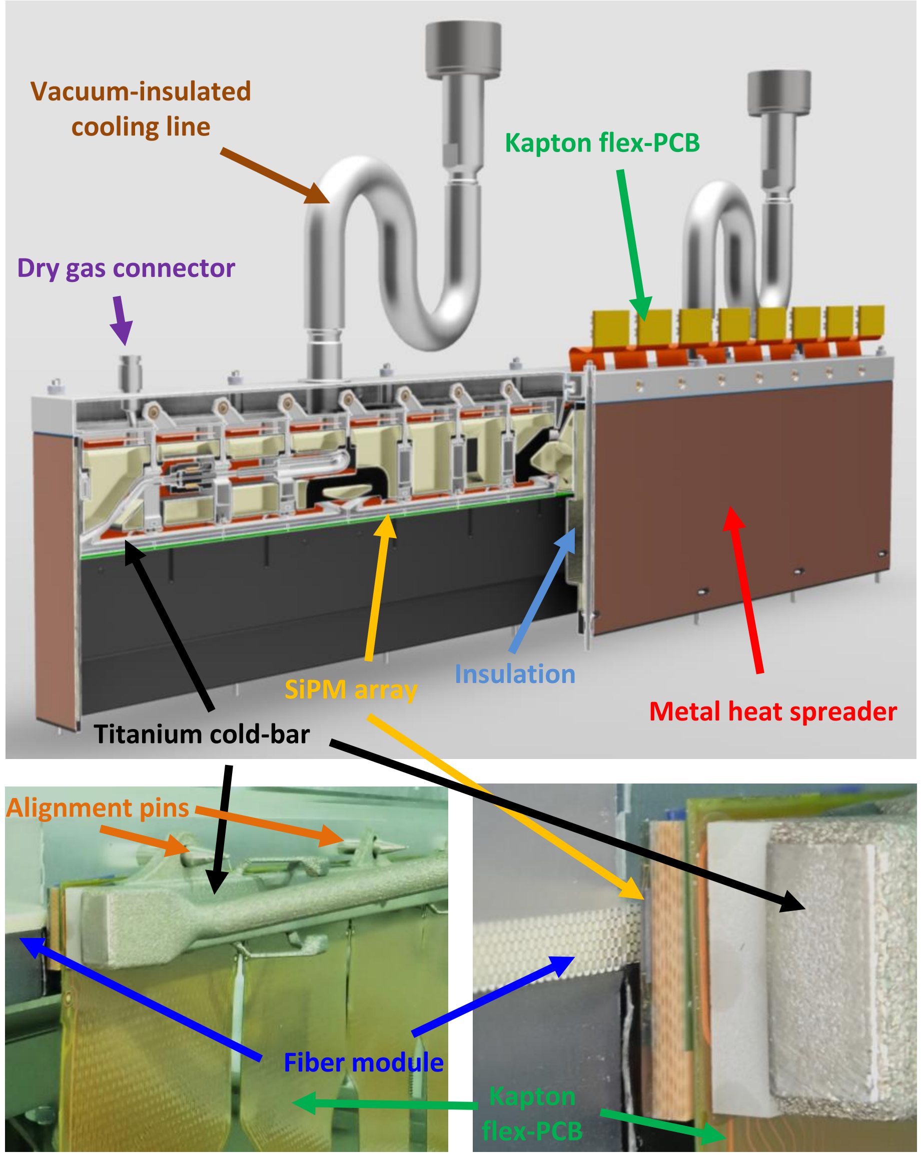
- Thermal isolation with very limited space.
- Cold SiPMs, warm fibers.
- Humidity management.

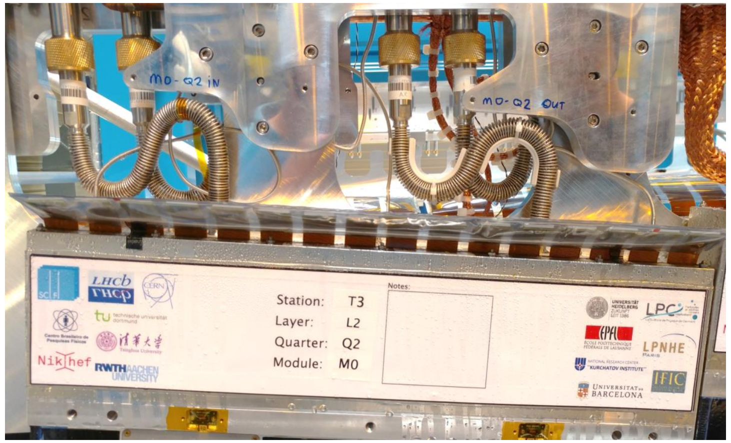
Coldbox design:

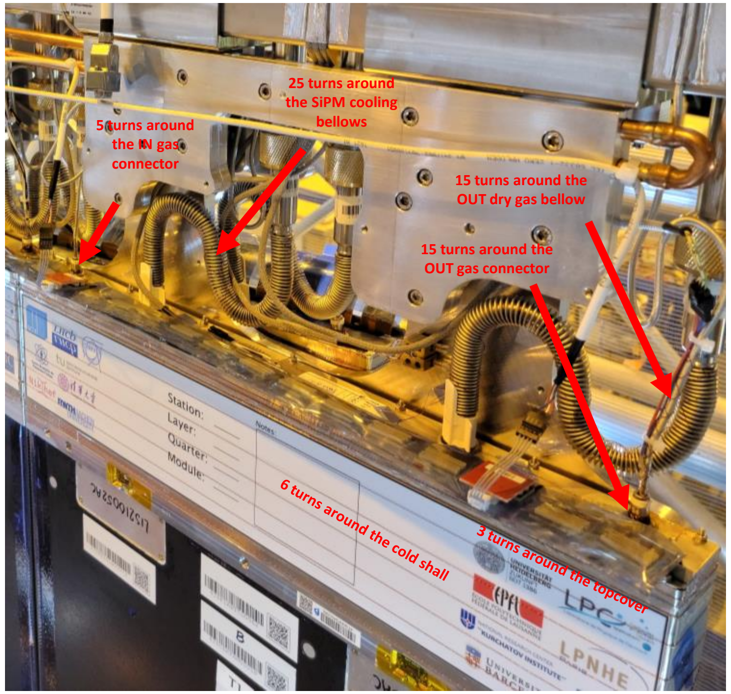
- Segmented 3D printed titanium hollow cold-bar for fluid with 4 segments per coldbox.
- 16 SiPMs arrays with Kapton flex-PCB bounded directly on the cold-bar.
- Each cold-bar segment has alignment pins to the 4 individual fibre mats of the module.
- Foam insulation with metallic heat spreader to counteract cold spots.
- Vacuum isolated cooling lines.
- The inside of the box can be continuesly flushed with dry gas to control humidity.

Heating wire:

- Added around the bellows and coldbox during assembly as condensation was observed.







SiPMs and scintillating fiber: LHCb SciFi – SiPM cooling

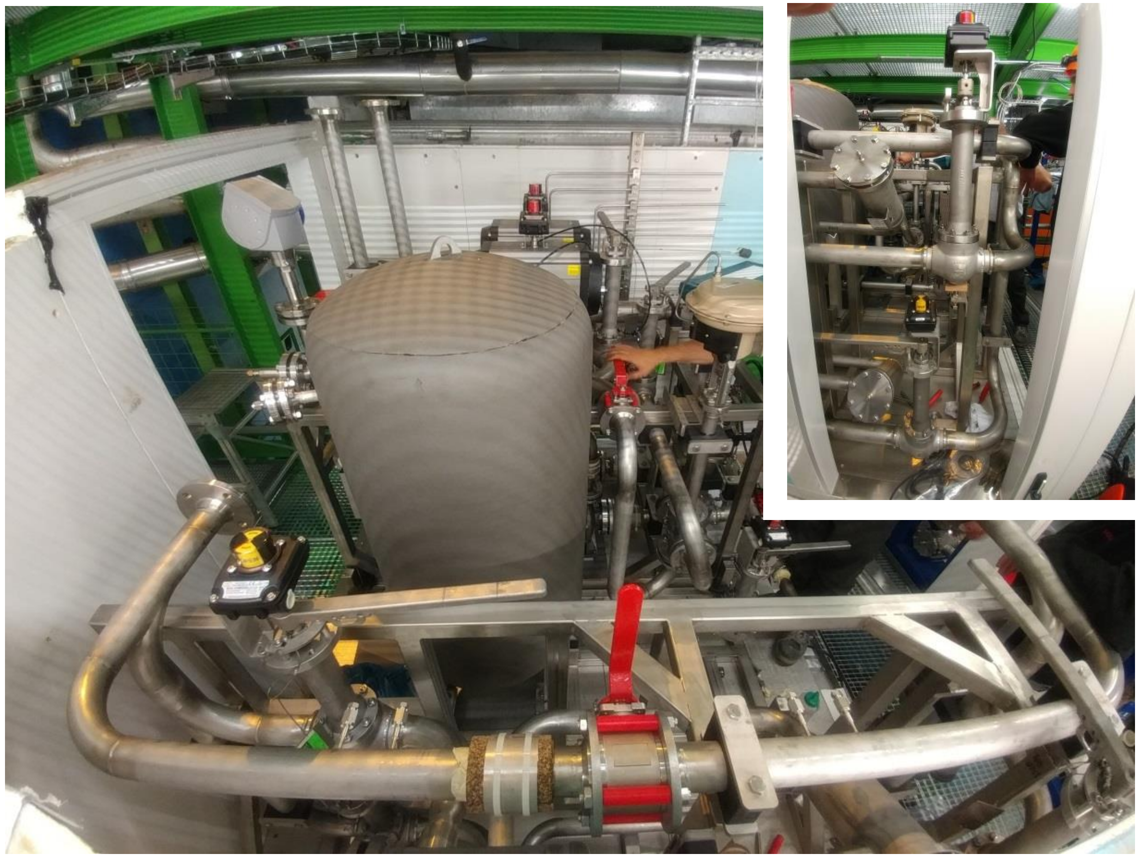
The cooling plant for the SiPMs are build at CERN.

Cooling liquid: NOVEC 649 or C_6F_{14}, NOVEC 7100 under study.

Fully redundant with 2 pumps etc.

It is located in a zone always accessible and therefore the distribution lines are long.

Part of the main distribution lines are vacuum insulated.



SiPMs and scintillating fiber: LHCb SciFi – Vacuum insulation og SiPM cooling lines

The insulation vacuum system is mainly located close to the C-frames.

2 pumping stations for 6 C-frames consisting of:

- 1 scroll pump.
- 2 turbo-molecular pumps (for redundancy).

The turbo-molecular pumps are housed in a shielding cabinet consisting of to layers of iron for magnetic shielding.

The vacuum manifold is located about 2 m from the turbo-molecular pumps.

The distribution lines consist of a bellow (SiPM cooling) inside a bellow (vacuum).

All vacuum and SiPM cooling circuit has passed helium leak tests.

- It was a long way to get it thigh as the system consist of about 1250 VCR connections.
- Since the SiPM cooling is inside the insulation vacuum finding a leak can be very challenging.

SiPMs and scintillating fiber: LHCb SciFi – Dry gas and temperature control

The dry gas is produced in the assessable site of the cavern.

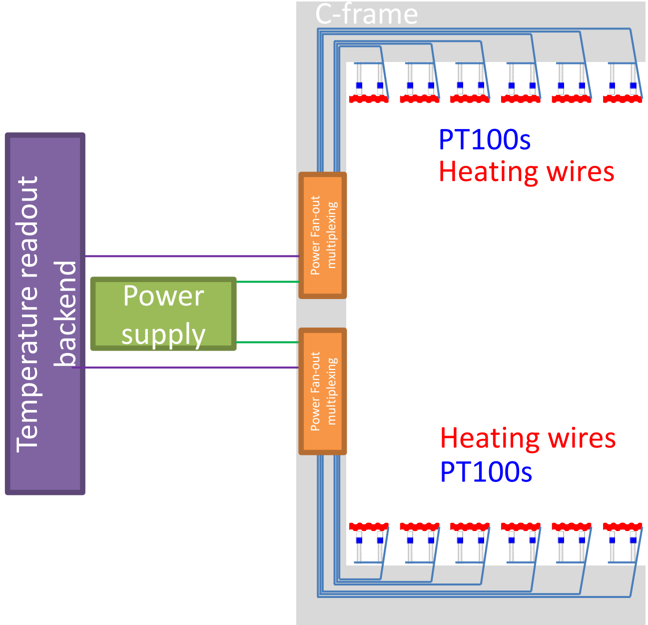
2 commercial dryers of model AtlasCopco CD65+ are used for redundancy.

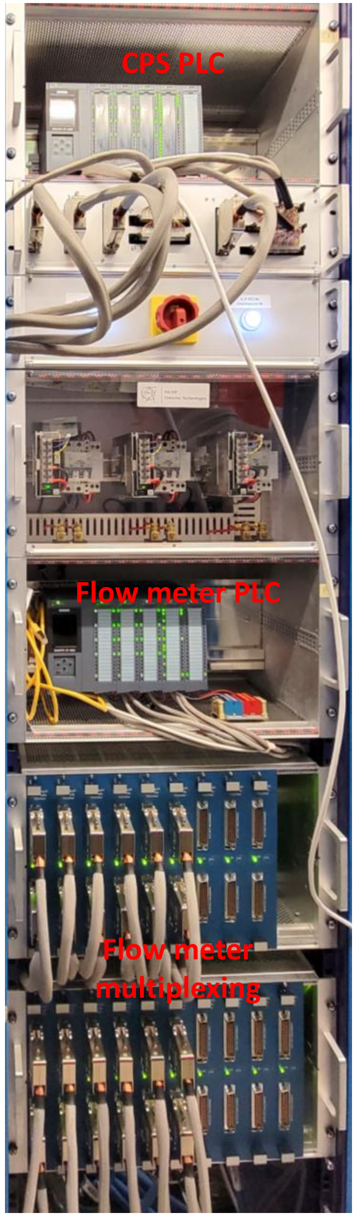
The dry gas is backed-up by bottled nitrogen in case of e.g. a power failure.

The dry gas is monitored and distributed to each C-frame.

The ~500 flowmeters are readout by back-end multiplexing (redundant) + a PLC.

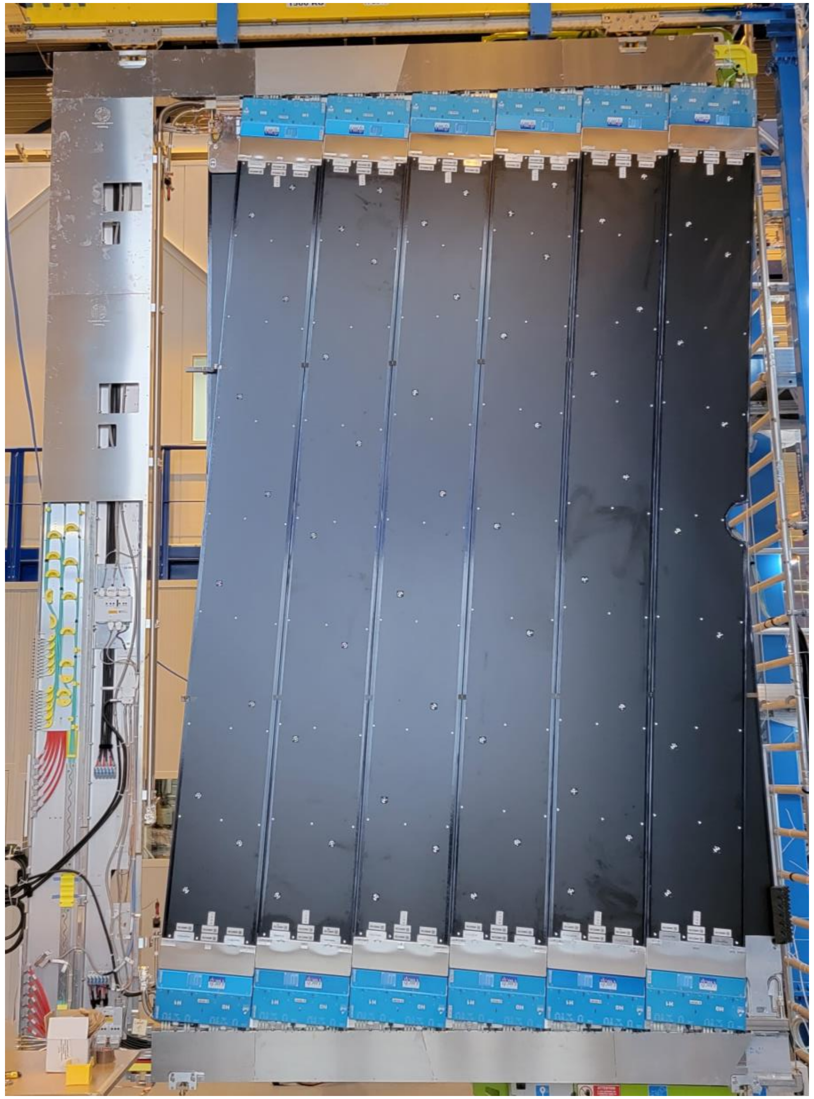
Temperature readout (~600 sensors) and control system for heating wires (Condensation Prevention System, CPS).



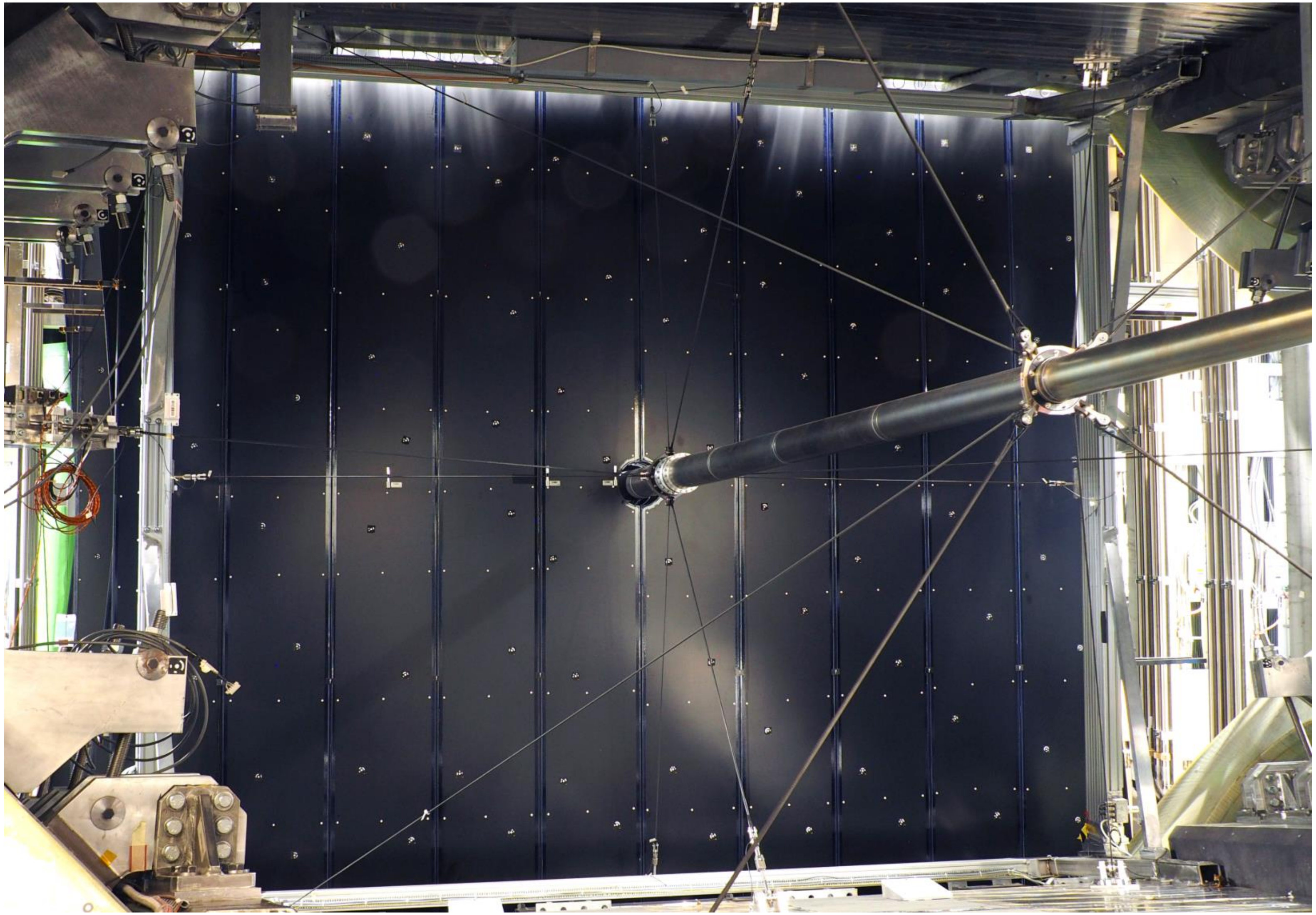


SiPMs and scintillating fiber: LHCb SciFi – Scintillating fibers

Full C-frame with 2x6 modules



Installed and closed LHCb SciFi detector (seen trough the magnet)



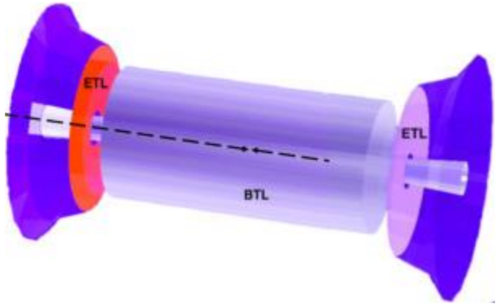
Summary

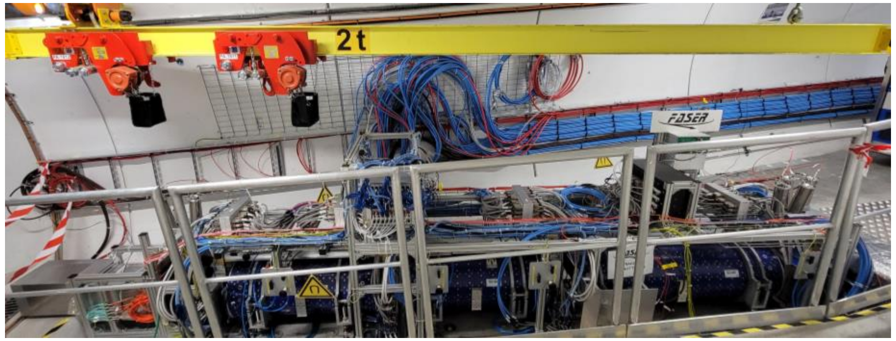
Summary

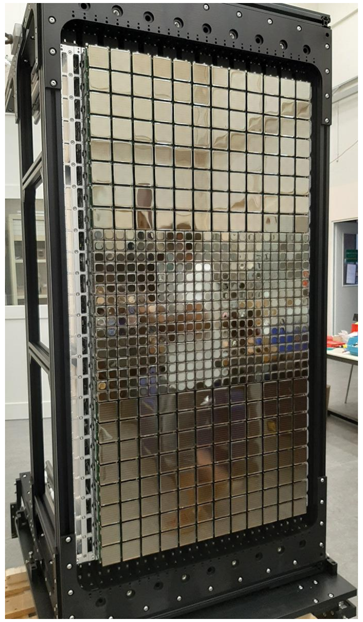
Photodetectors are one of the main detector technologies for HEP

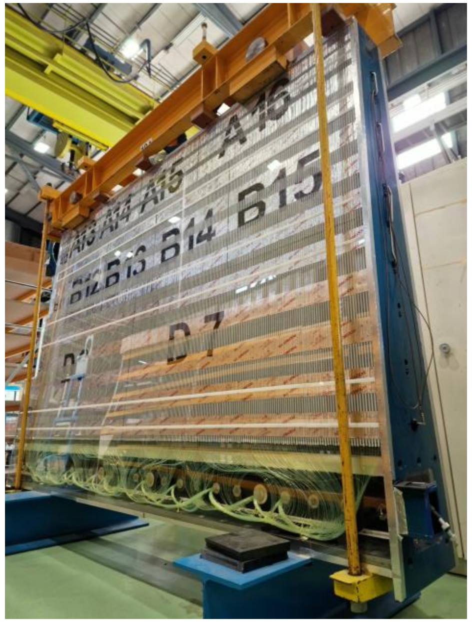
Photo detectors are used for many different purposes:

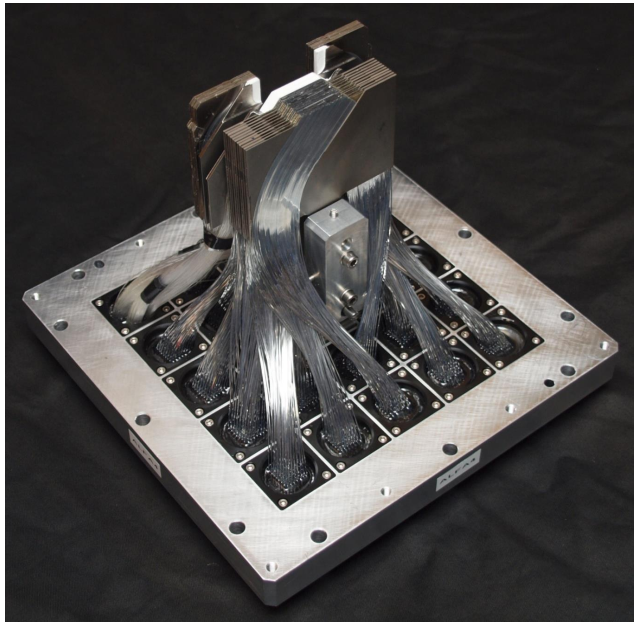
- Veto/triggering with extremely high efficiency
- Determining the energy of particles in calorimeters
- Particle identification in e.g. RICH detectors
- Time of Flight to e.g. handle high pileup
- Tracking even for very large areas

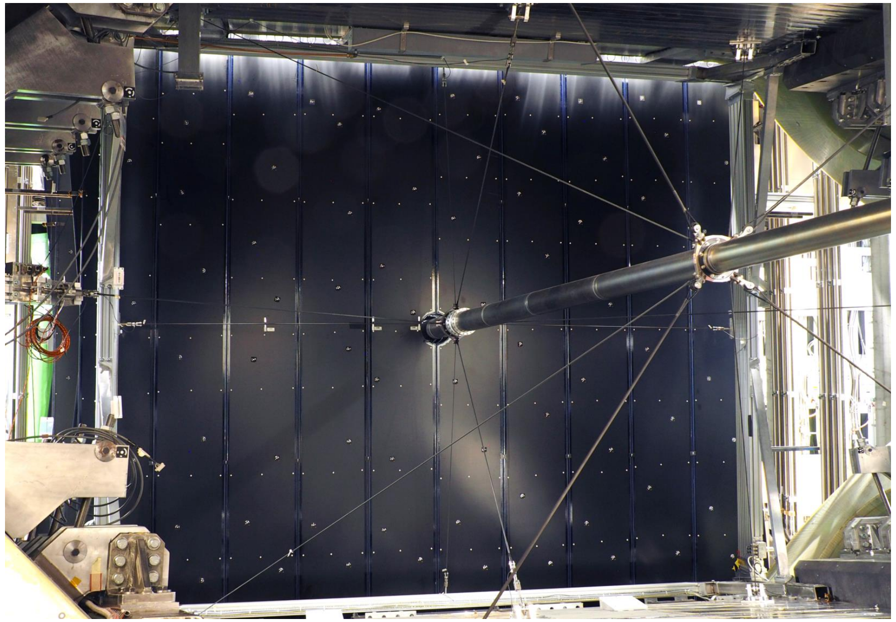












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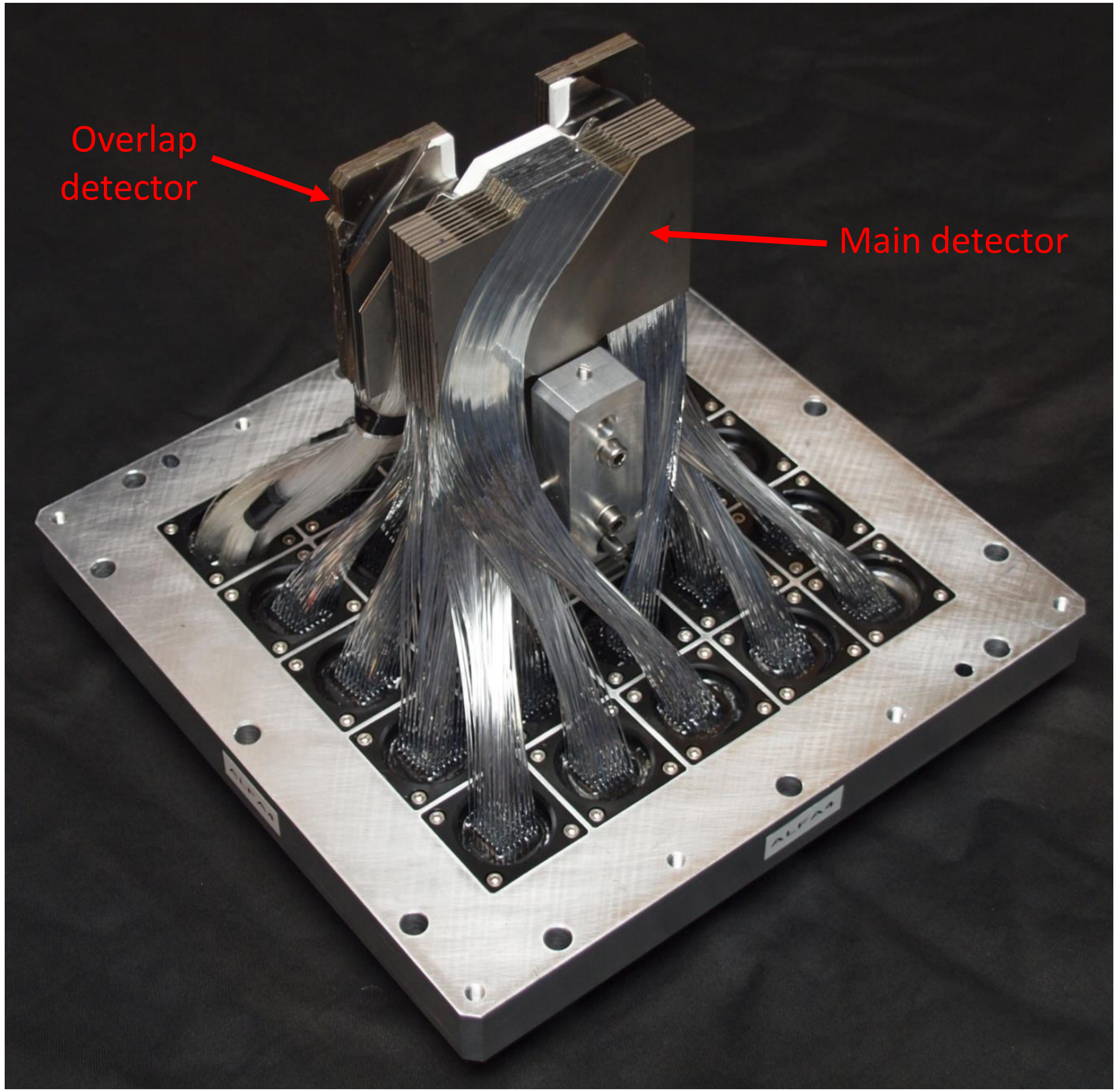
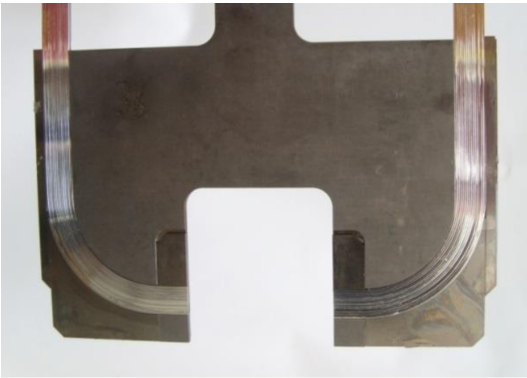
Backup

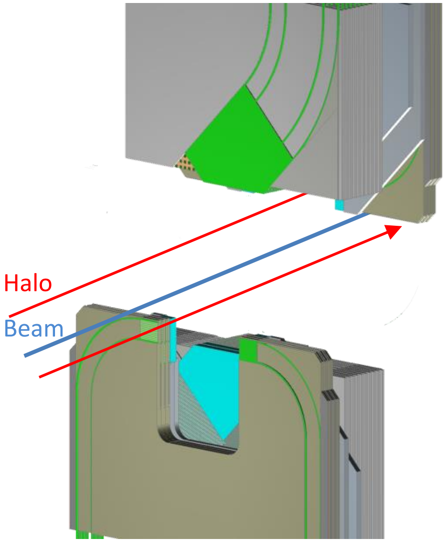
ALFA detector



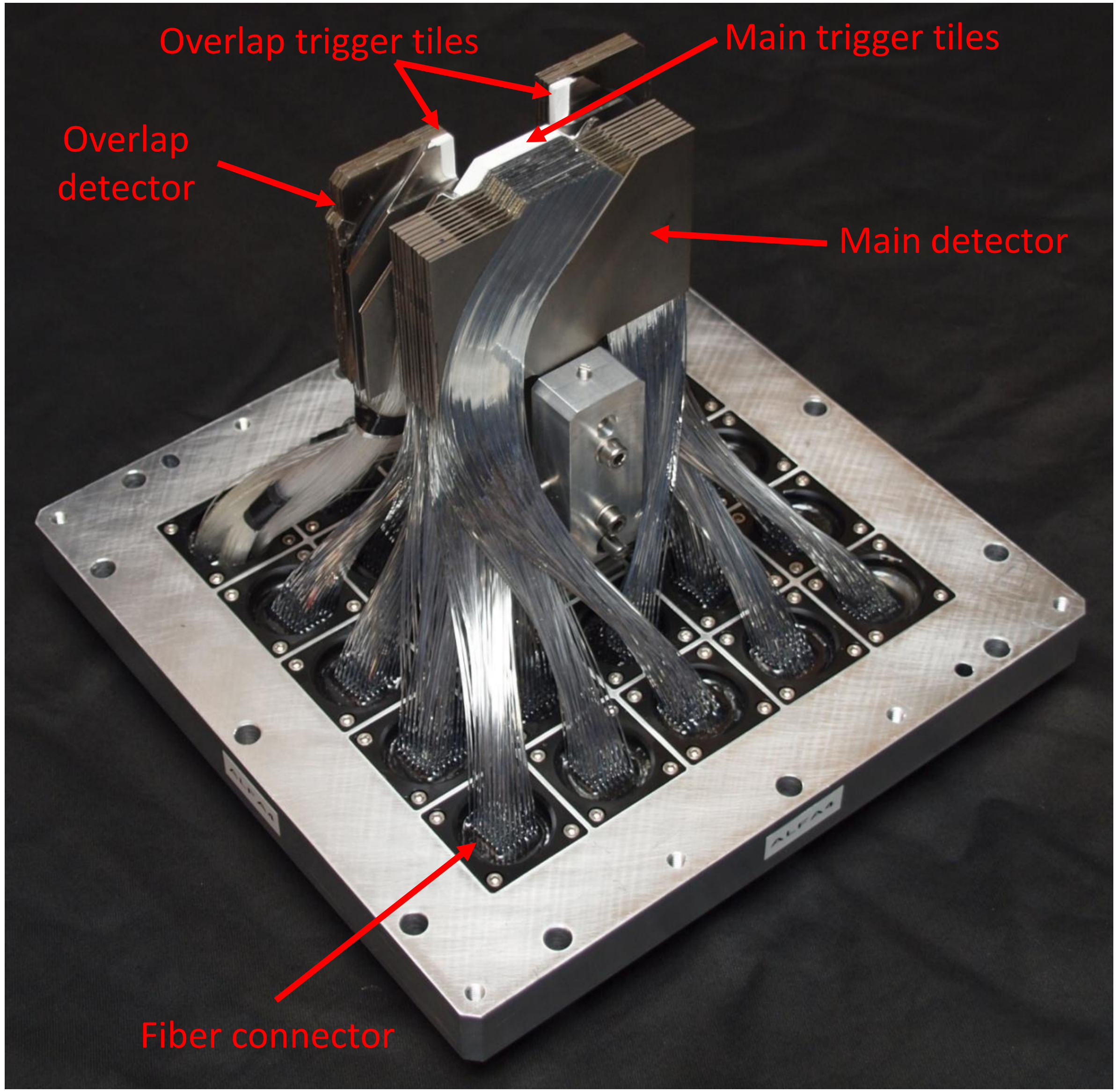
Overlap detector plan



Overlap detector is used for alignment of an upper detector to a lower detector

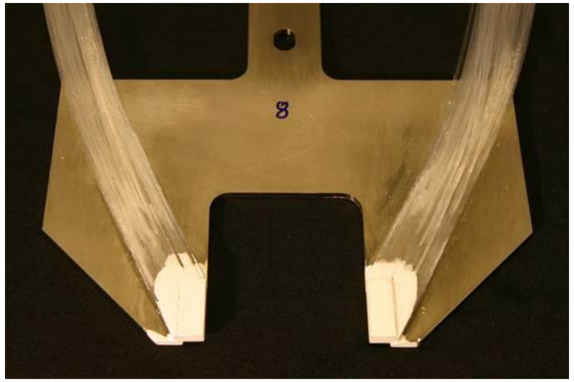


ALFA detector

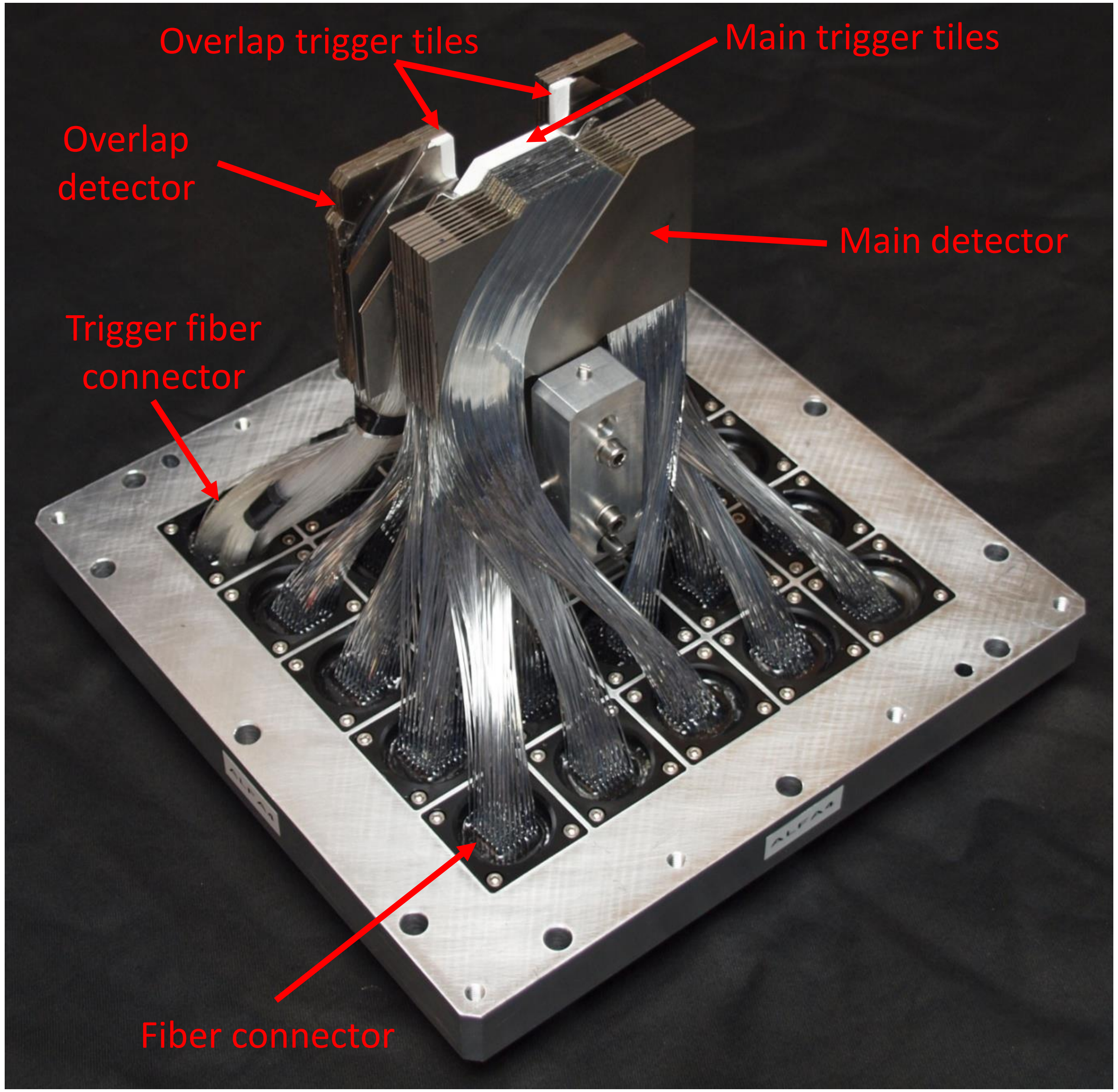


Main trigger scintillator tile

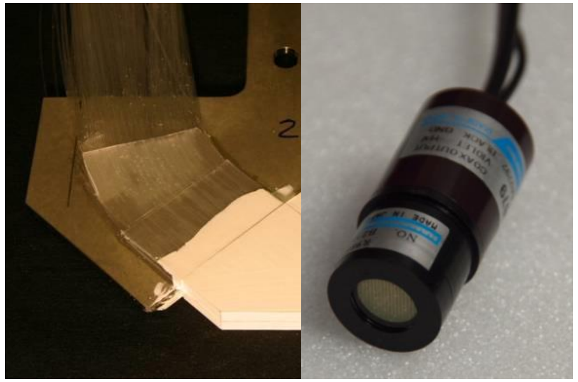
Overlap trigger scintillator tiles



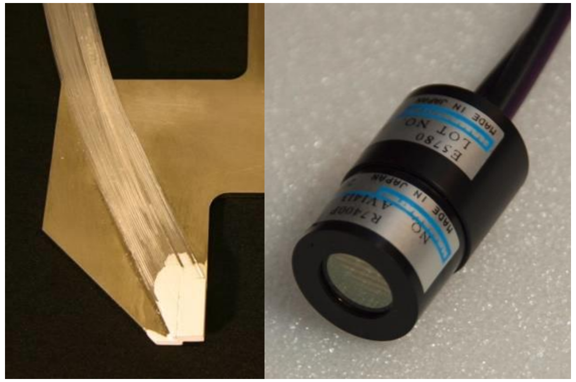
ALFA detector



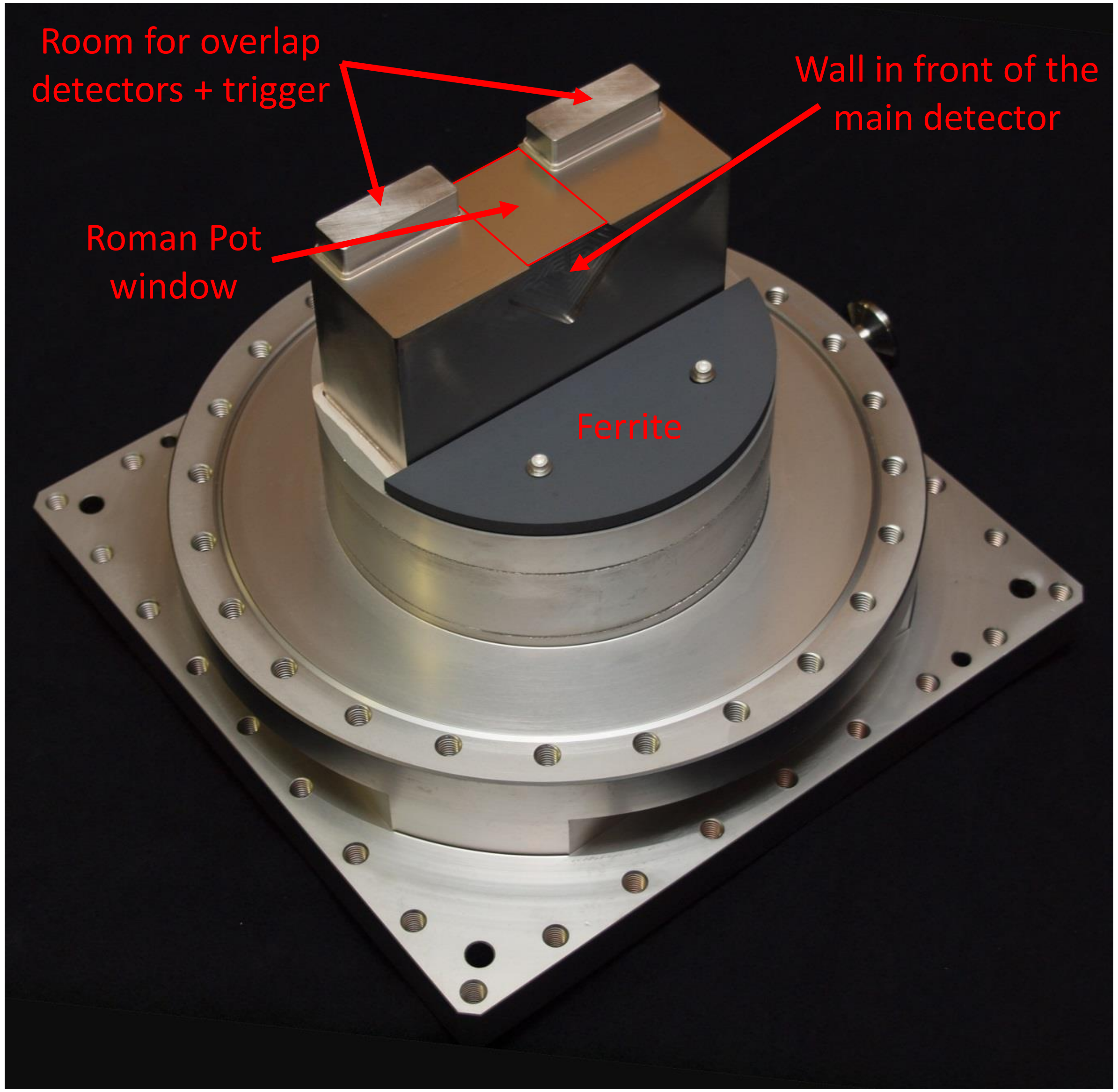
Main trigger scintillator tile



Overlap trigger scintillator tiles



ALFA Roman Pot before LS1



Separates the detector from the ultra high beam vacuum.

Window thickness 200 µm.

Secondary vacuum inside (detector side) to keep window flat.

LHCb SciFi:

From performance requirements to operational detector

09-09-2022

Sune Jakobsen (CERN EP-DT-TP)
on behalf of the LHCb SciFi collaboration and with material from the full collaboration

NBI Detector Seminar

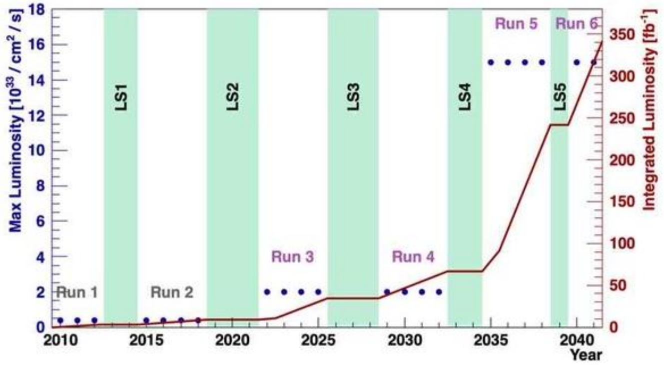
LHCb detector upgrade

LHCb is optimized for heavy flavour physics: It has a forward geometry and features very precise vertexing and tracking.

LHCb detector upgrade during LHC LS2 (2019-2021).

Main changes:

- Instantaneous luminosity $L_{inst}=2\cdot10^{33}$ $cm^{-2}s^{-1}$ (5 times Run2).
- Goal: Integrated luminosity of 50 fb^{-1} over a period of ~10 years.
- 40 MHz trigger-less read-out electronics (25 ns spacing).
- Full software trigger for every bunch crossing (40 MHz).

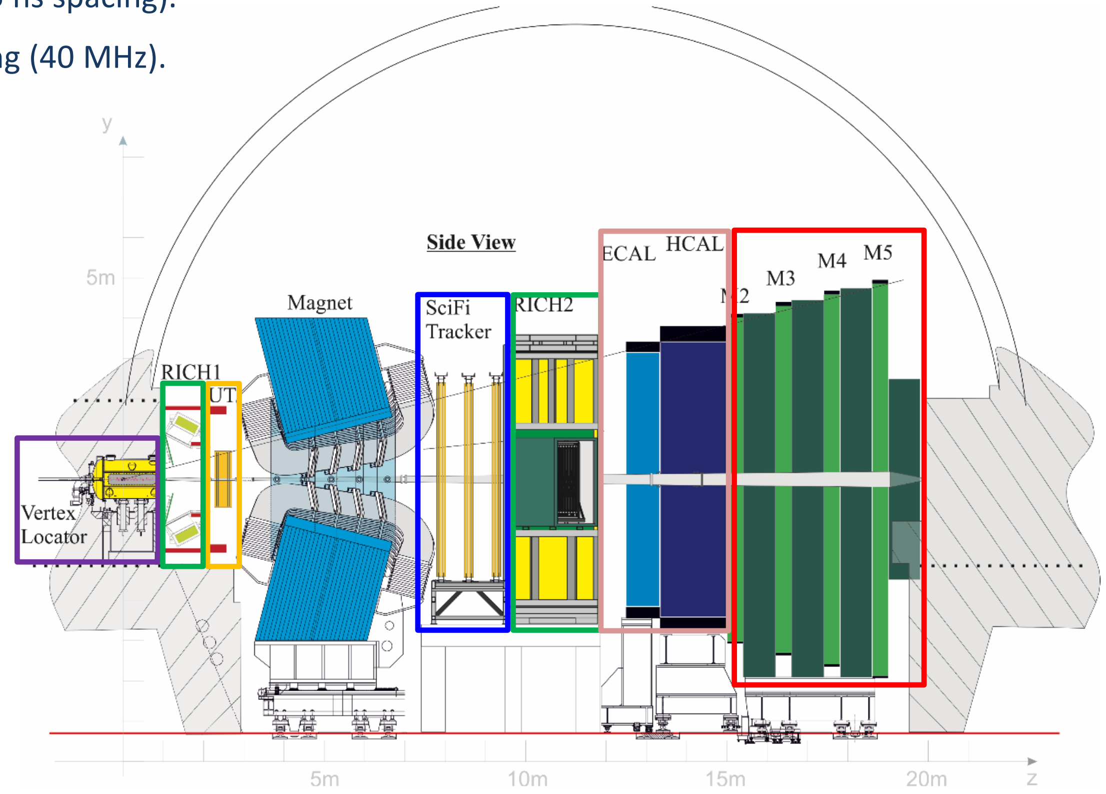


Full replacement of all trackers:

- Vertex Locator (VELO)
- Upstream Tracker (UT)
- Downstream tracker (SciFi)

Upgrade of photodetectors and electronics for the RICHes.

Upgrade of readout electronics for calorimeters and muon system.



LHCb SciFi performance requirements at design start

1) **Area**: Active area of about 340 m^2.

2) **Hit detection efficiency:** Larger than 99 %.

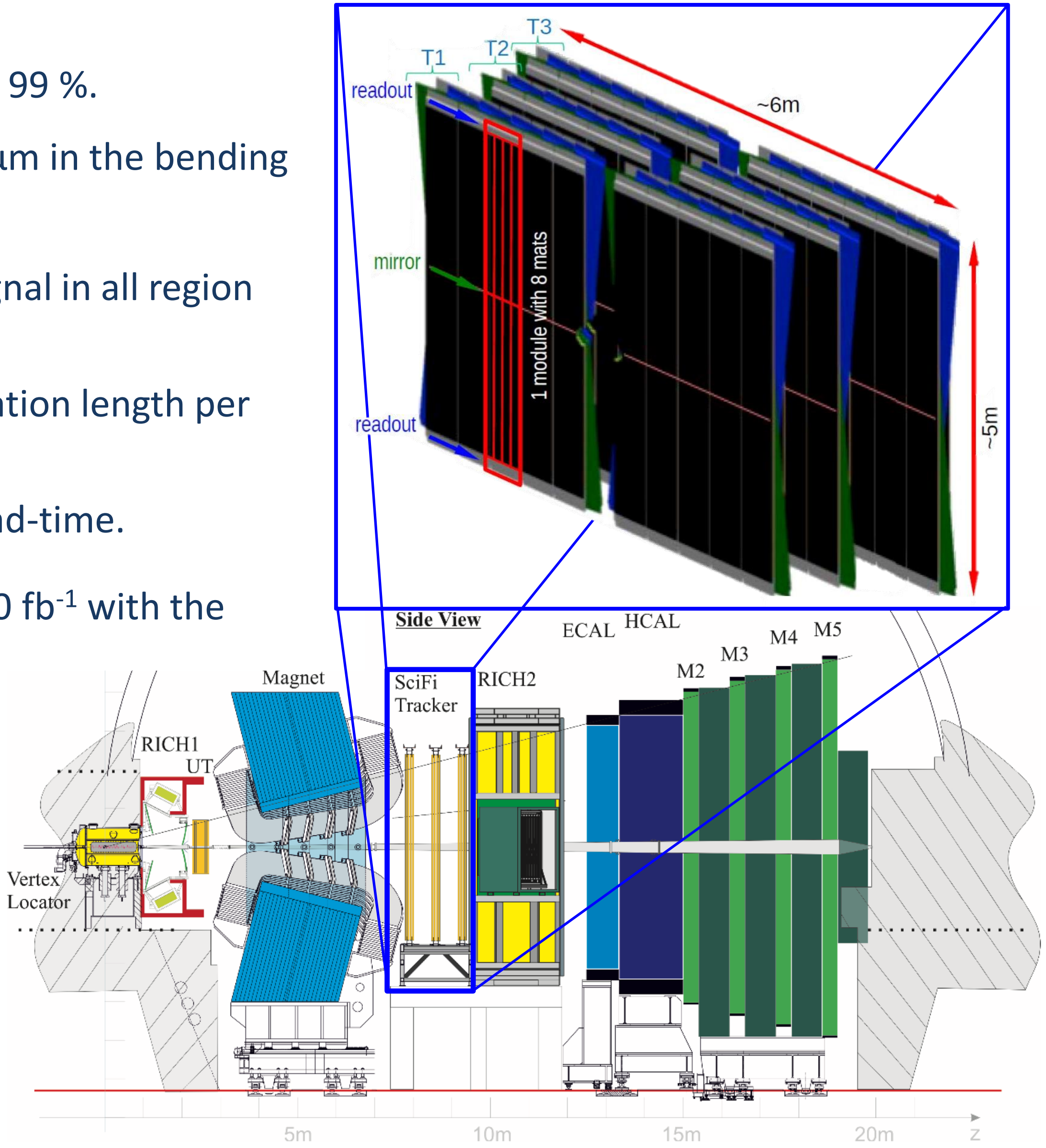
3) **Spatial resolution:** Better than 100 µm in the bending plan of the magnet (vertical).

4) **Noise cluster rate:** Below 10 % of signal in all region of the detector.

5) **Material budget:** Less than 1 % radiation length per each of the 12 detection layers.

6) **Readout speed:** 40 MHz with no dead-time.

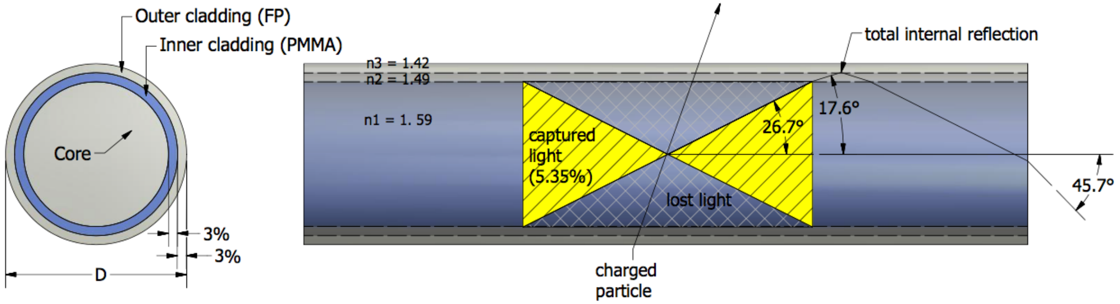
7) **Life time:** Integrated luminosity of 50 fb^{-1} with the above specified performance.

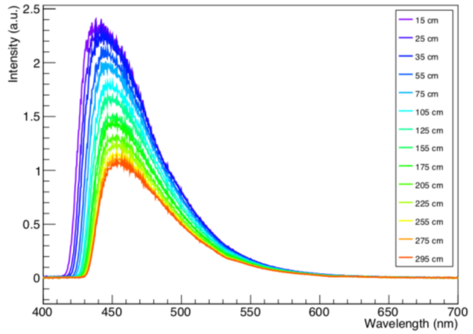


Technology and production

Scintillating fibers

Double cladded round fibres Ø 250 µm (Kuraray SCSF-78MJ) was selected:



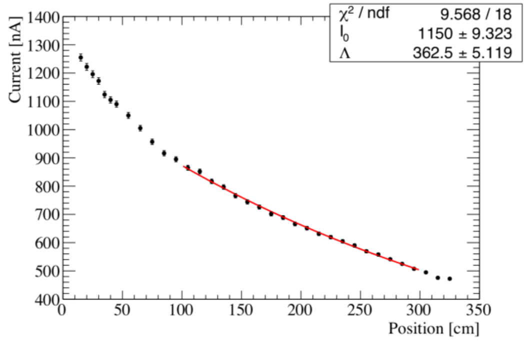


About 300 photons/MIP

3-4 p.e. detected @ 240 cm for a single fiber (trapping fraction, attenuation and PDE of Silicon photomultiplier)

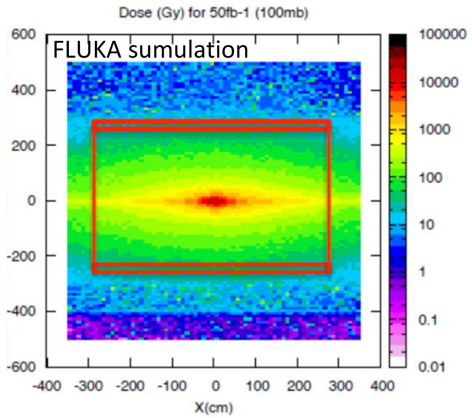
Emission peak ~450 nm

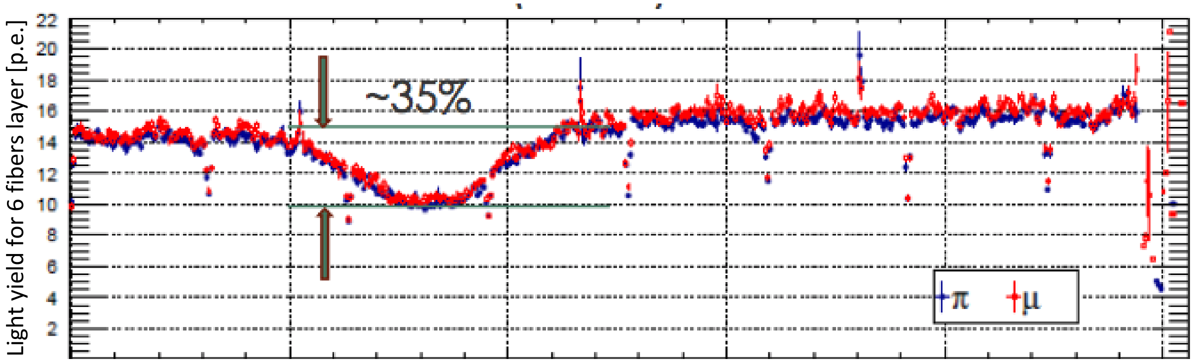
Attenuation length ~3.5 m



Very non-uniform dose profile expected

Irradiation campaigns shows about 35 % loss of signal at the expected dose





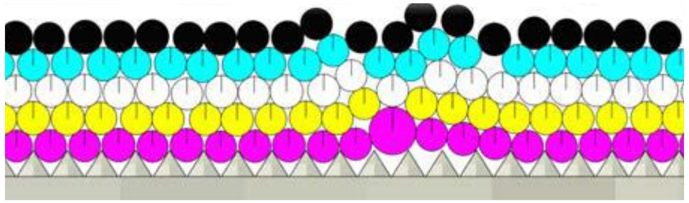
Scintillating fiber quality assurance

12000 km of fiber (incl. pre-production & spare), 950 spools

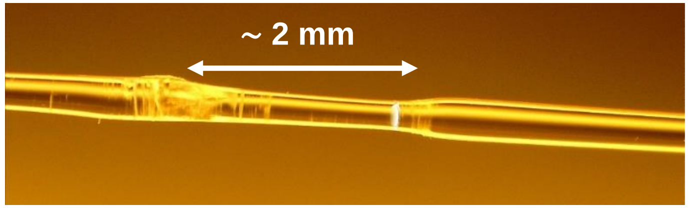
Quality assurance procedure:

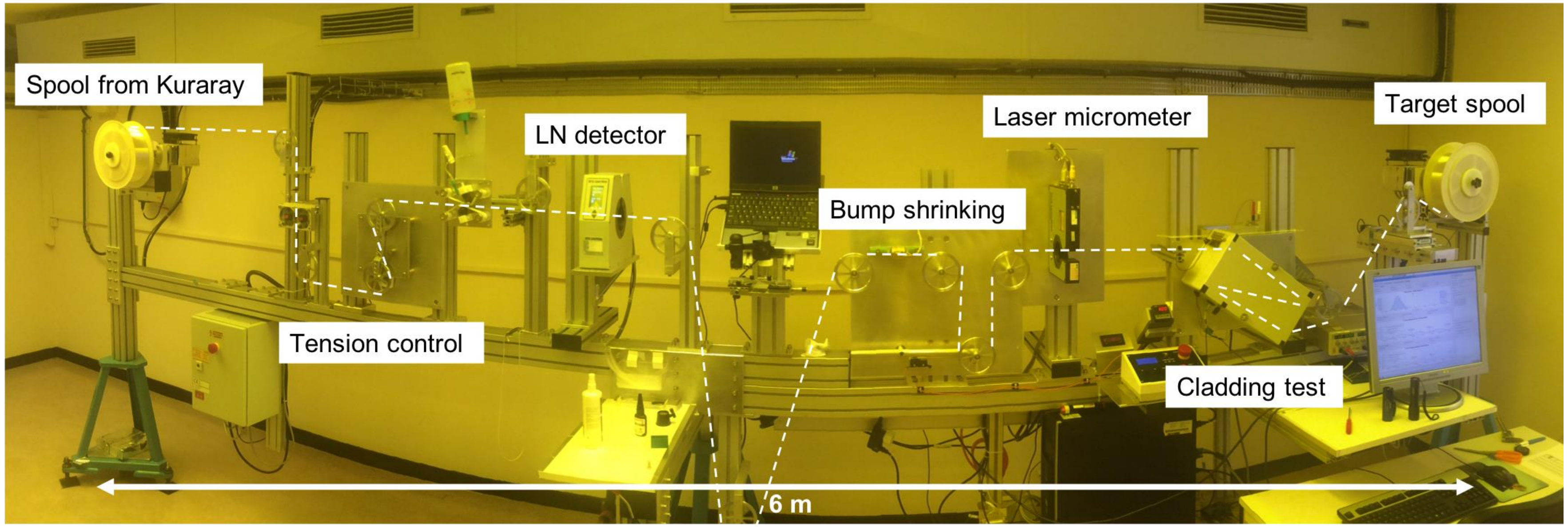
- Attenuation length and light yield (for every spool).
- Radiation hardness (X-rays), decay time, bending radius (for a fraction of spools).
- Scanning for diameter anomalis (bumps).
- Removal of big bumps (ΔD > 100 μm) without cutting/gluing the fiber.
- The light yield suffers at the removed bumps, but with 6 fibers in a mat it is tolerable.
- Verification of cladding integrity.

Problem if there is a bump on a fiber



Bump after shrinking





Fiber mat production

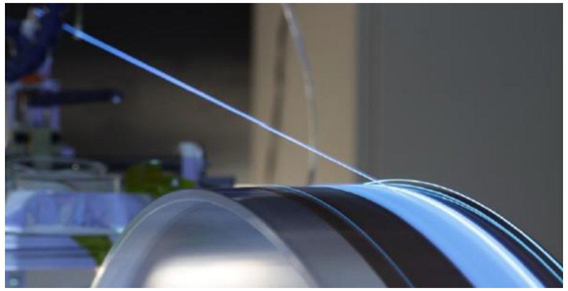
Custom winding machine (Ø = 80 cm wheel with fine thread).

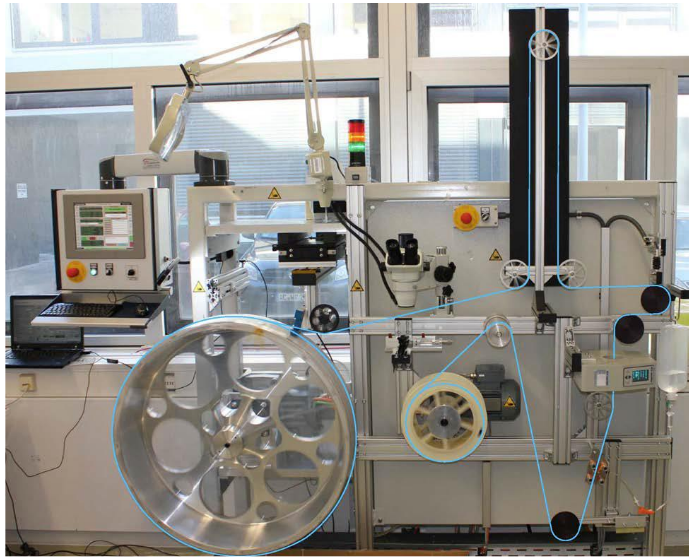
Mat size: 2650 mm x 140 mm.

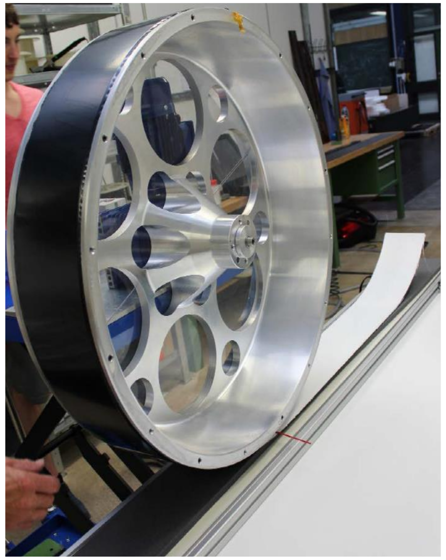
1500 mats produced at 4 sites (incl. spares).

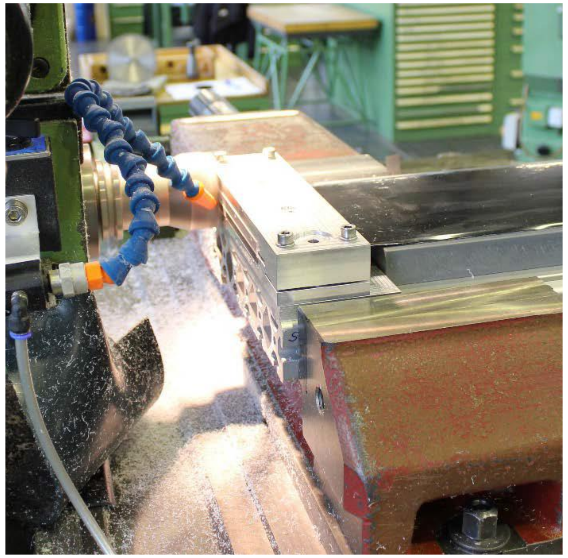
The ends of the fiber mats were milled to optical quality.

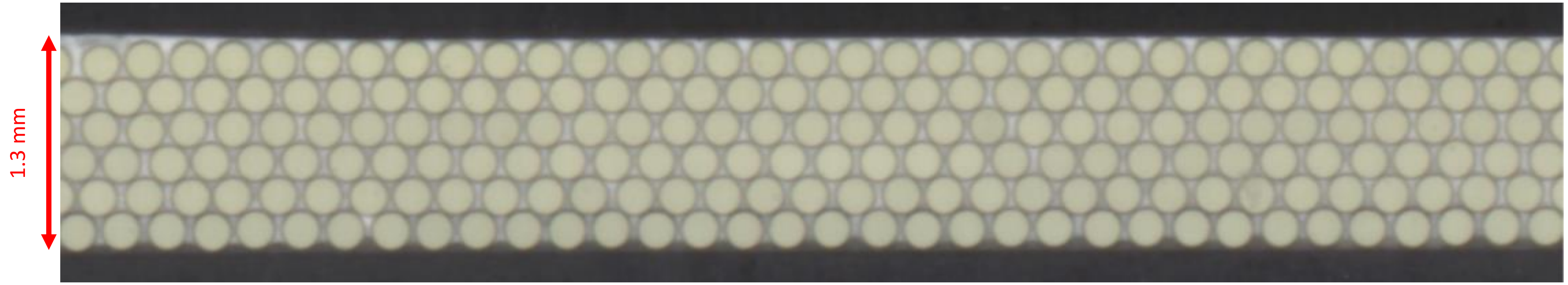
One fiber mat end gets a mirror glued onto it.











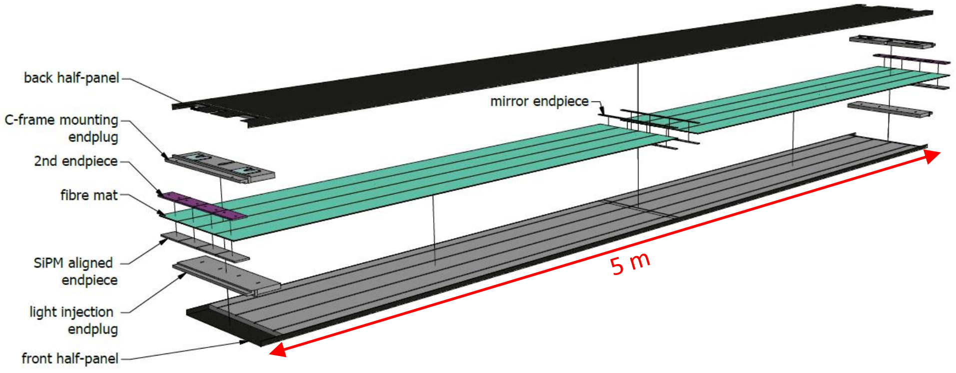
Fiber module production

8 fiber mats built into one fiber module.

Mechanical alignment w/r to straight line better than 50 µm over 5 m length.

Mechanical stiffness and protection added with honeycomb and carbon fiber panels.

128 modules needed, 144 produced.



Silicon Photomultipliers (SiPMs)

Each SiPM channel comprises 104 parallel Avalanche Photodiodes in Geiger-Mode (pixels).

Each pixel is 62 µm x 57 µm.

One 128 channel array is made of 2 chips of 64 SiPMs.

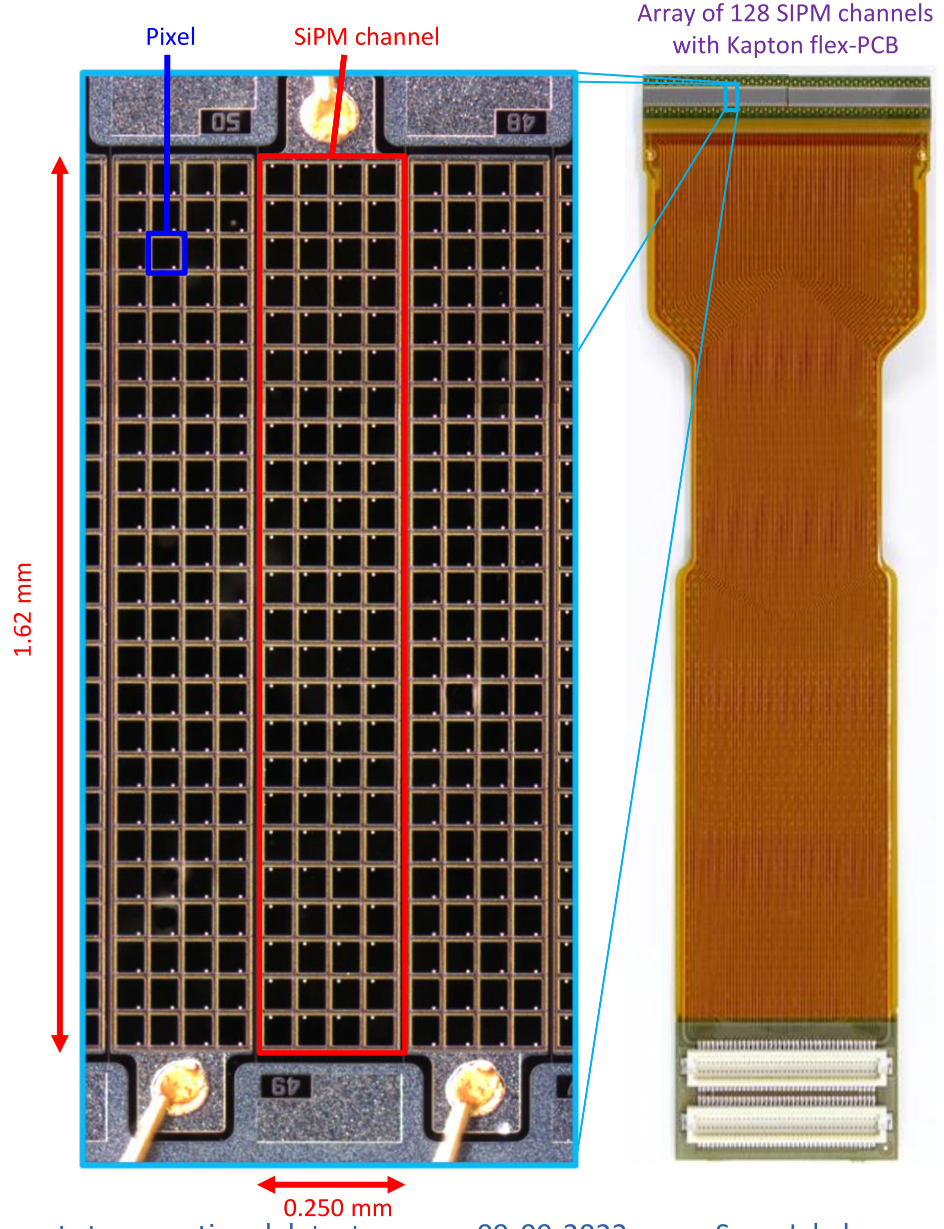
Array model: Hamamatsu MPPC S13552 – H2017.

The 128 channel array is mounted on a Kapton flex-PCB.

LHCb Scifi needs:

4096 SiPM array with Kapton flex-PCB.

524288 SiPM channels in total.



Silicon Photomultipliers performance

Key performance

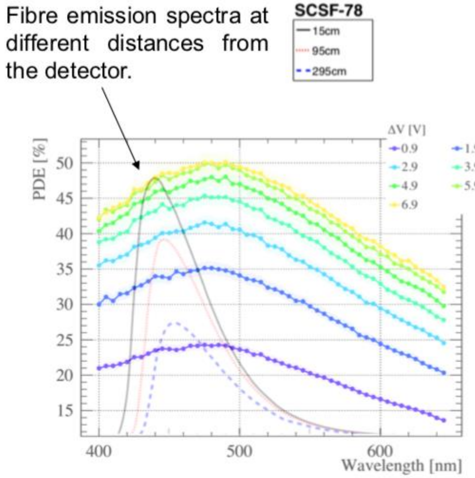
Peak Photon Deletion Efficiency (PDE): 45 % (at over-votlage ΔV = 3.5 V).

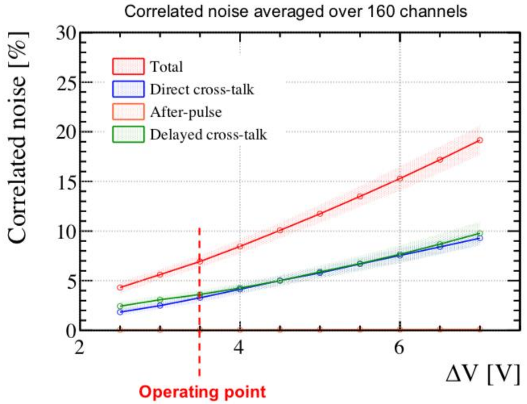
After-pulse < 0.1%.

Direct cross-talk ~ 3.5%.

Delayed cross-talk ~ 3.5%.

Total correlated noise = 7% (at ΔV = 3.5 V).





Dark count rate per SiPM channel (DCR)

DCR (not irradiated): 0.04 MHz.

DCR is increasing with neutron radiation.

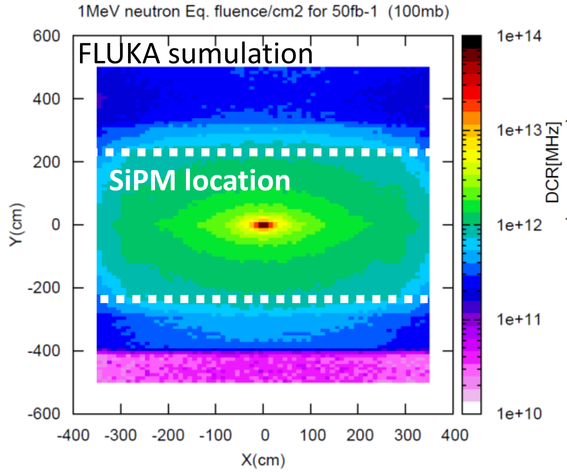
The SiPMs are positioned far from the beam center.

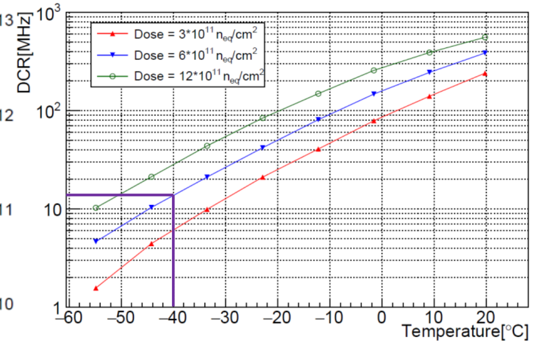
Neutron radiation expected: $6 \cdot 10^{11}\ n_{eq}/cm^2$.

DCR ($6 \cdot 10^{11}\ n_{eq}/cm^2$): 550 MHz.

The DCR can be reduce by cooling the SiPM.

DCR ($6 \cdot 10^{11}\ n_{eq}/cm^2$ @ -40 °C): 14 MHz.





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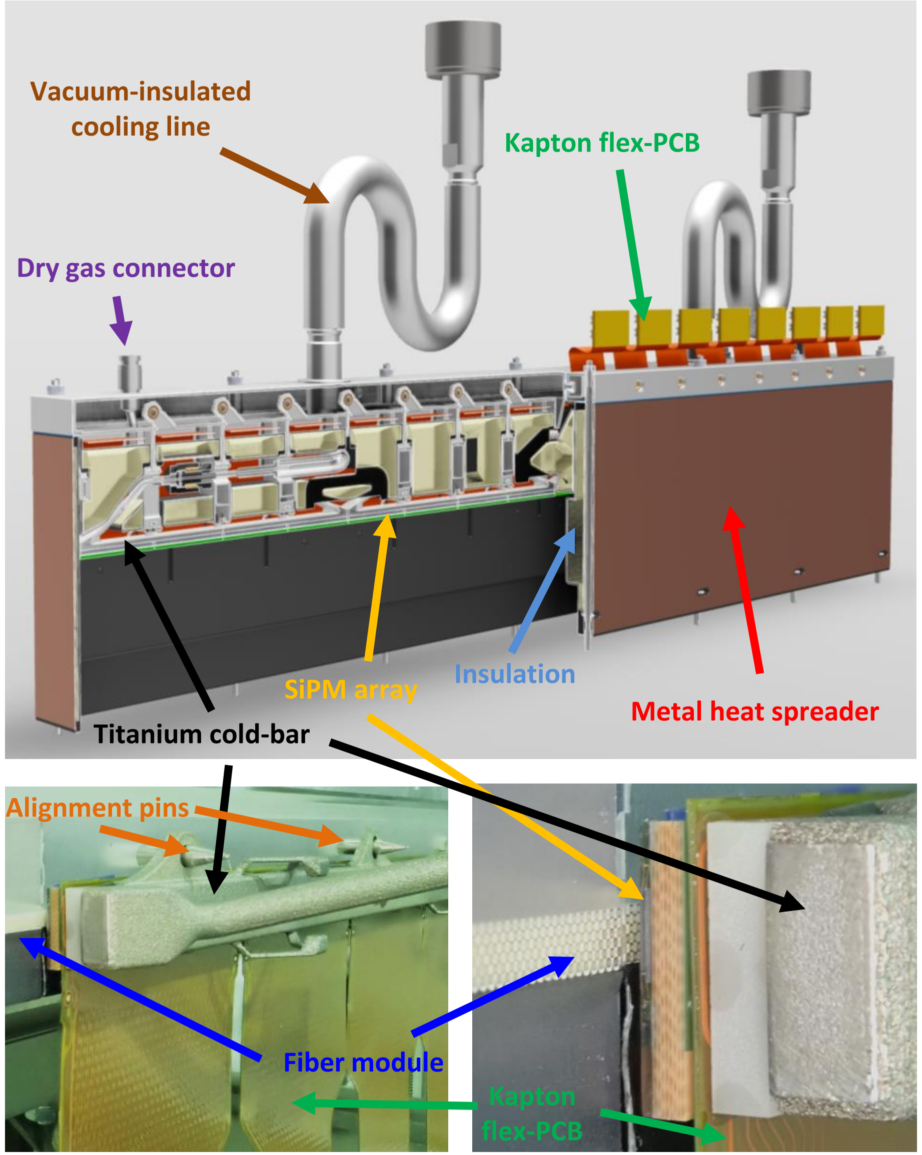


Front End electronics

Goals:

- 2048 SiPM channels per module end (524288 total) to be read-out at 40 MHz.
- Reduce data rate to manageable level: Efficient noise rejection, signal digitization and data processing.
- Minimal spillover and dead time (fast shaping and integration).
- Low power consumption.
- Calibration system: Light injection.
- Radiation tolerant (neutrons + 100 Gy ionizing dose).

The SciFi Front End electronics is made in a modular design:

PACIFIC Board (2048 needed):

- Carries the custom front-end chip (next slide).
- Digitization of 2 x 128 channel SiPM arrays.

Cluster board (2048 needed):

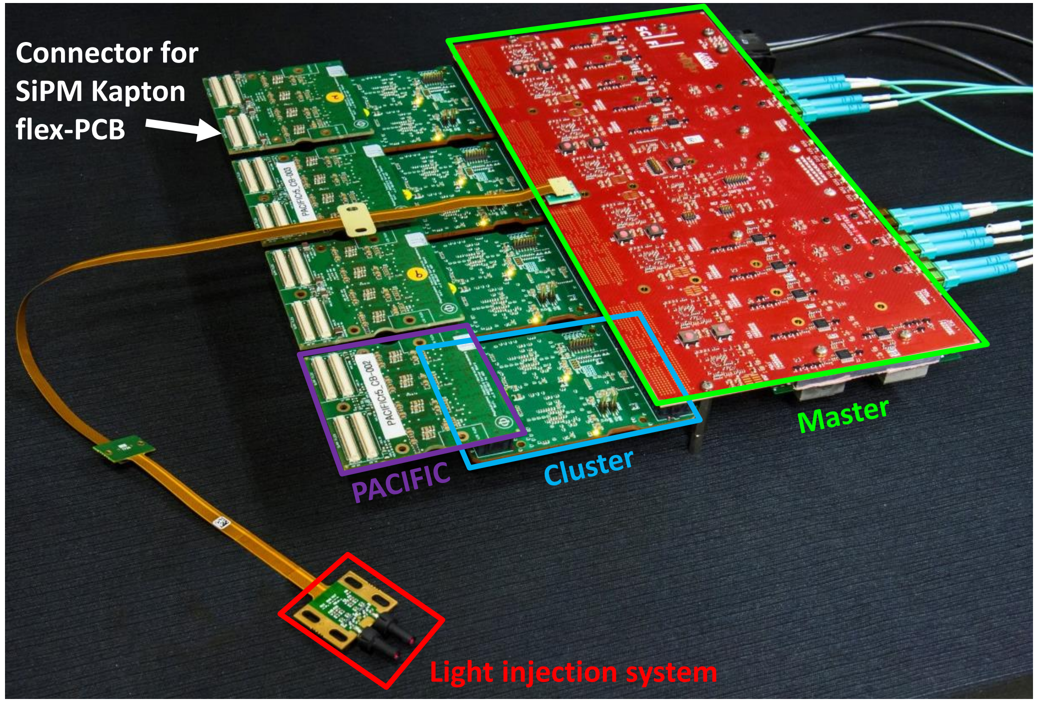
- FGPA (antifuse) based clustering and zero suppression.

Master board (512 needed):

- High rate data transfer via optical link.
- Timing and fast control.
- Slow control.
- Power distribution.

Light injection system:

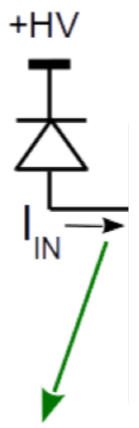
- Generate light pulses for SiPMs for calibration.



Front End electronics – Details of the PACIFIC

PACIFIC: a low Power Asic for the sCIntillatong FIbre traCker

- 64-channels current mode input (8196 ASIC needed).
- Preamp with 4 different gain settings.
- Configurable fast shaper (90 % charge collected within 10 ns).
- Interleaved gated-integrator per channel (minimize dead time).
- Digitization by 3-comparators per channel (tunable threshold for each comparator).



2 bit/channel @ 40 MHz

Front End electronics - Clustering

Reminder:

Each fiber does NOT have its own SiPM channel.

A SiPM channel covers a cross section of a fiber mat.

A single particle is therefore likely to induce signal in more than one SiPM channel.

Noise is randomly spread over the SiPM pixels.

Basic clustering: A good signal

One channel with high charge.

Neighbor channels with some charge.

Cluster FPGA:

Input the 2 bit (no signal, low, middle, high) per SiPM channel from the PACIFIC.

Tunable conditions to make a cluster.

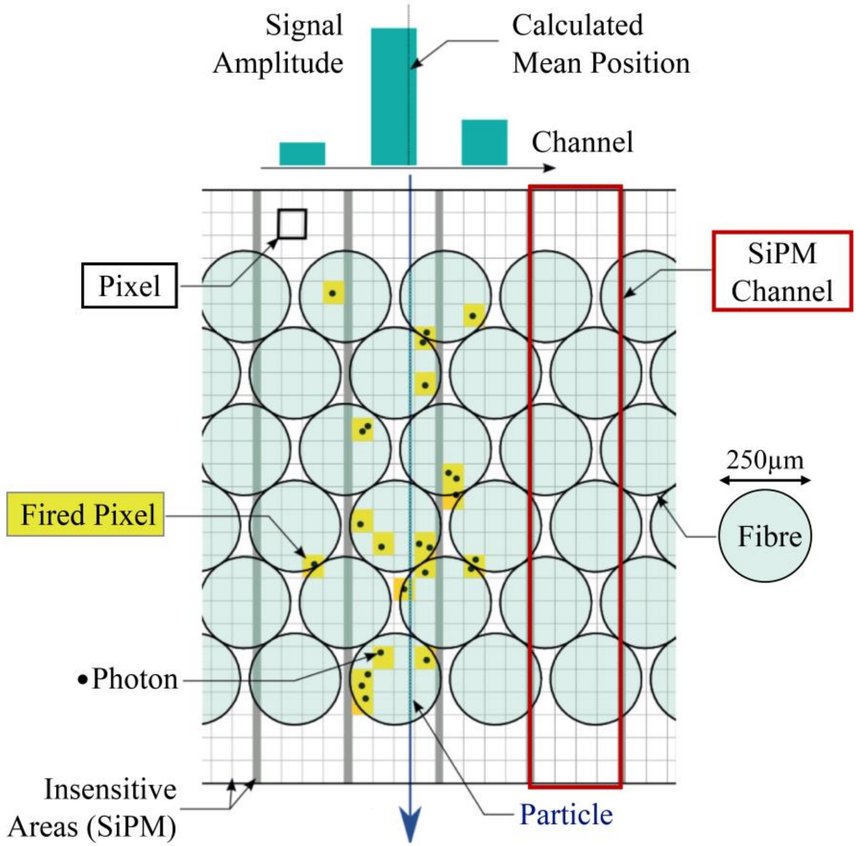
Throughput at 40 MHz.

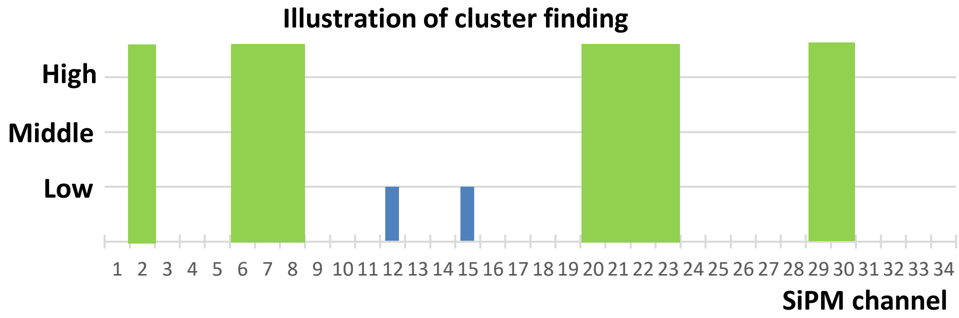
Performance (at full irradiated detector):

Reduce noise from 14 MHz/channel to below 2 MHz/array (128 channels).

Maintain ~99 % efficiency.

This is achieved by tuning the PACIFIC thresholds and the clustering condition.





C-frames: *Putting it all together*

C-frames mechanics

Basic principal:

Mechanical support outside the detector acceptance.

The support should be stiff and steady enough not to add significant uncertainty to the tracking.

Non-magnetic.

The full structure should be moveable for maintenance and installation.

The full structure should be light enough to use the existing support mechanics in the cavern.

The structure should also support all cables and services.

Solution: C-frames

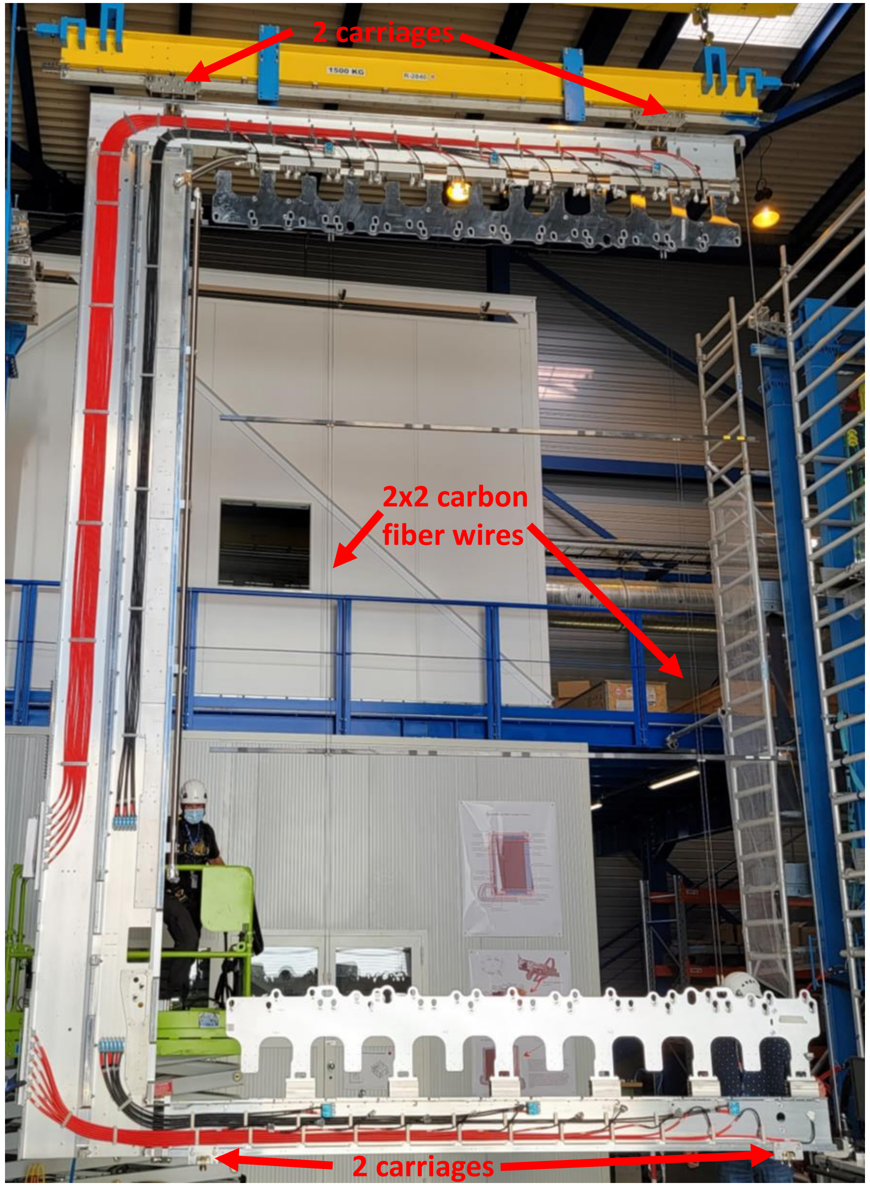
The shape insures no additional material inside the acceptance.

Made extruded aluminum I-shaped profiles.

The C-frame is hanging on 2 adjustable carriages.

The lower part of the C-frame is mainly supported by 2 x 2 carbon fiber wires.

Lateral guidance is ensured by 2 additional carriages on the lower part



C-frame main assembly

Dedicated teams of experts assembled each part of the C-frame.

Fiber modules with coldboxes:

- 5 or 6 vertical modules.
- 5 or 6 modules tilted by 5 degree (next layer is tilted by - 5 degree).
- Special modules with a cut out are installed at the edge of the C-frame.

Bias cables.

Low voltage cables.

Cooling blocks for Front-End electronics.

Support for optical fibers:

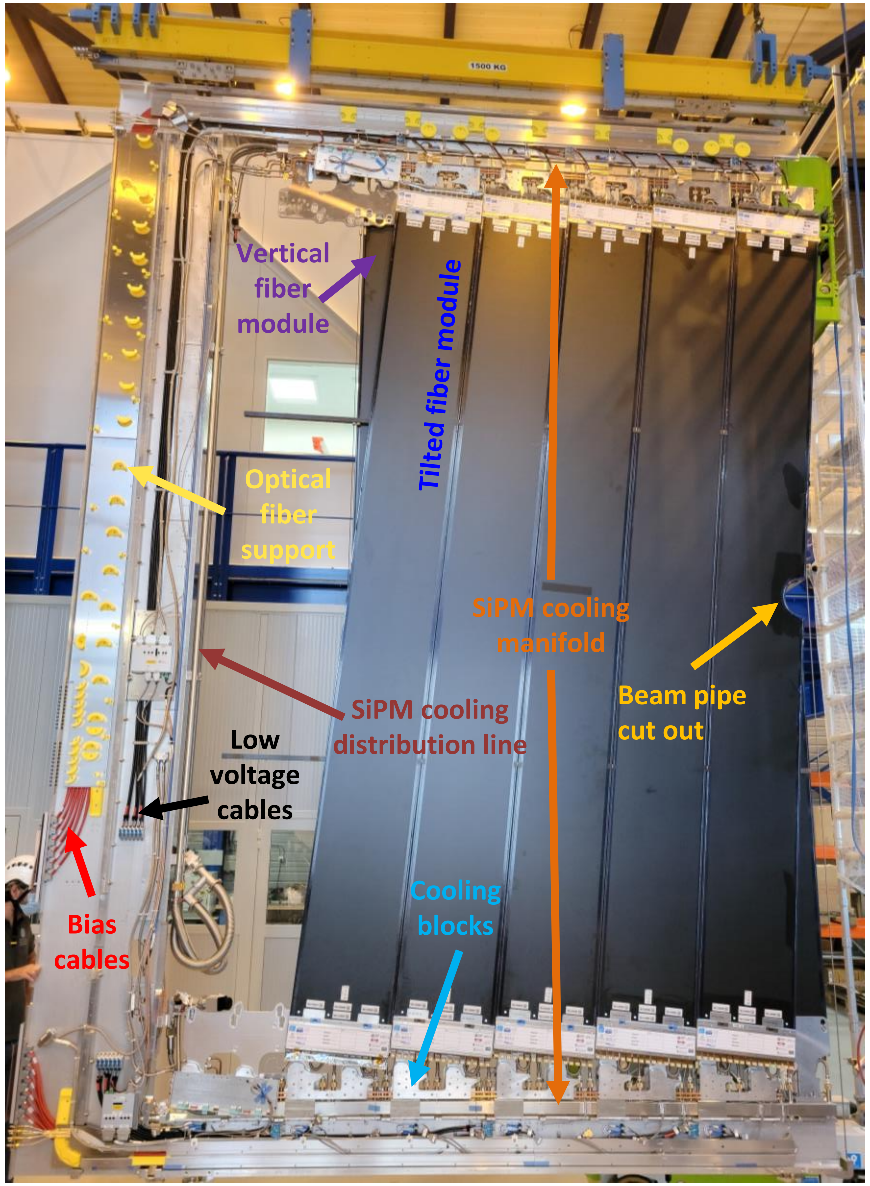
- All optical fibers has identical length to equalize timing, so the optical fiber slag is to be rolled up.

Manifold for SiPM cooling liquid.

- Vacuum insulated.

Distribution lines for SiPM cooling liquid.

- Vacuum insulated.

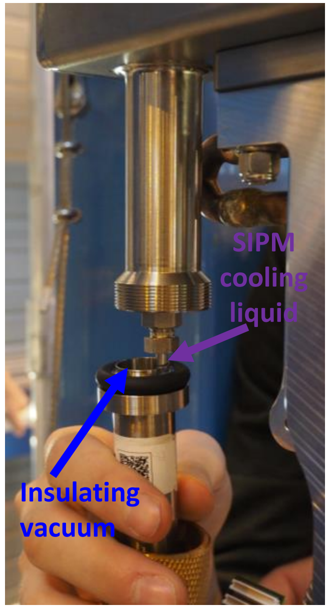


C-frame SiPM cooling, insulation vacuum and dry gas

The cooling lines for each coldbox needed to be connected the SiPM cooling manifold.

Inner small bellow with cooling liquid.

Outer large bellow for insulating vacuum.



2 Pirani vacuum sensors per C-frames

The electronics of the Pirani are move out of the C-frames as it is not sufficient radiation tolerant.

Dry gas system:

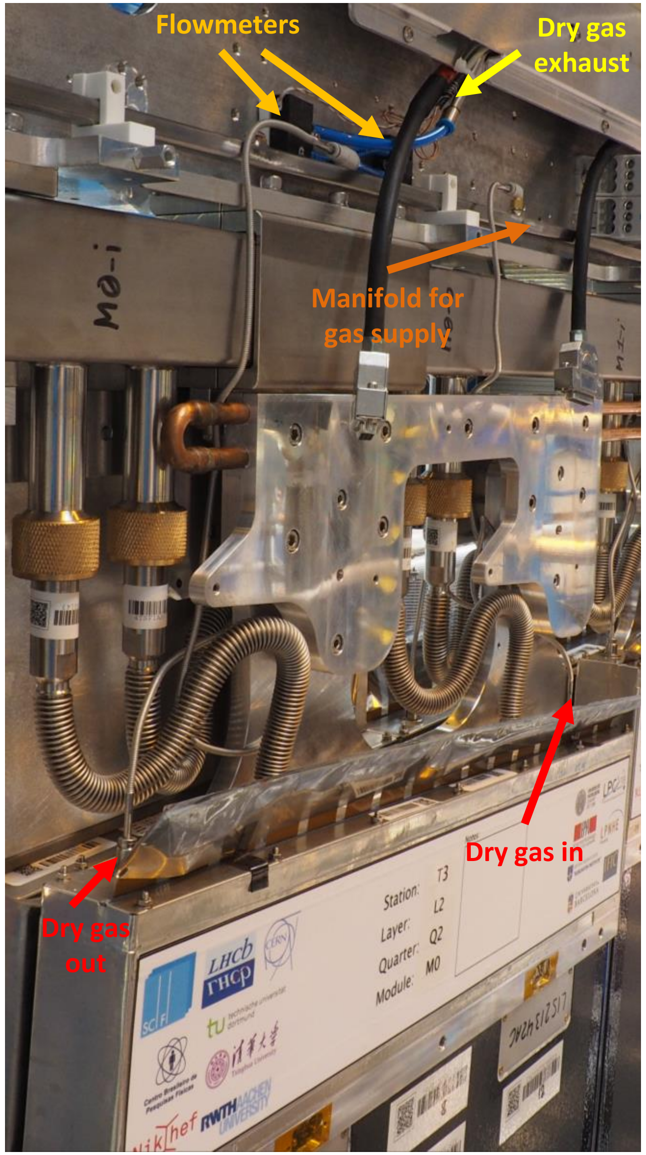
One gas line arrives to the C-frame and is split by a manifold.

4 Long square manifolds are installed along the top and bottom of the C-frame.

The gas connections to the coldbox are made with small metallic bellows (not plastic as it is partly transparent to water).

All gas bellows have equal length to ensure the same pressure drop (the small bellows have the dominant pressure drop of the full system).

The flow of each coldbox is monitored with 2 redundant flowmeters.



Condensation problems

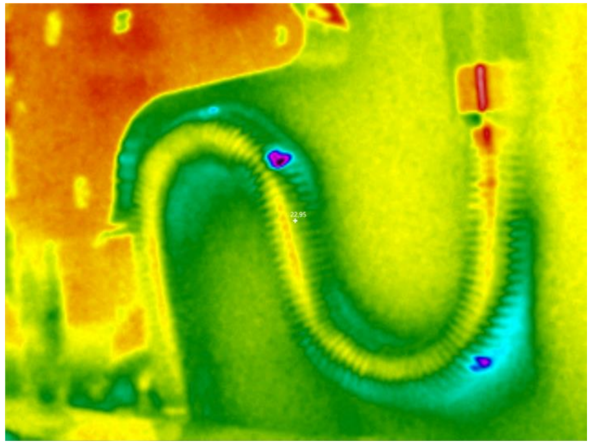
During assembly testing a major problem was discovered:

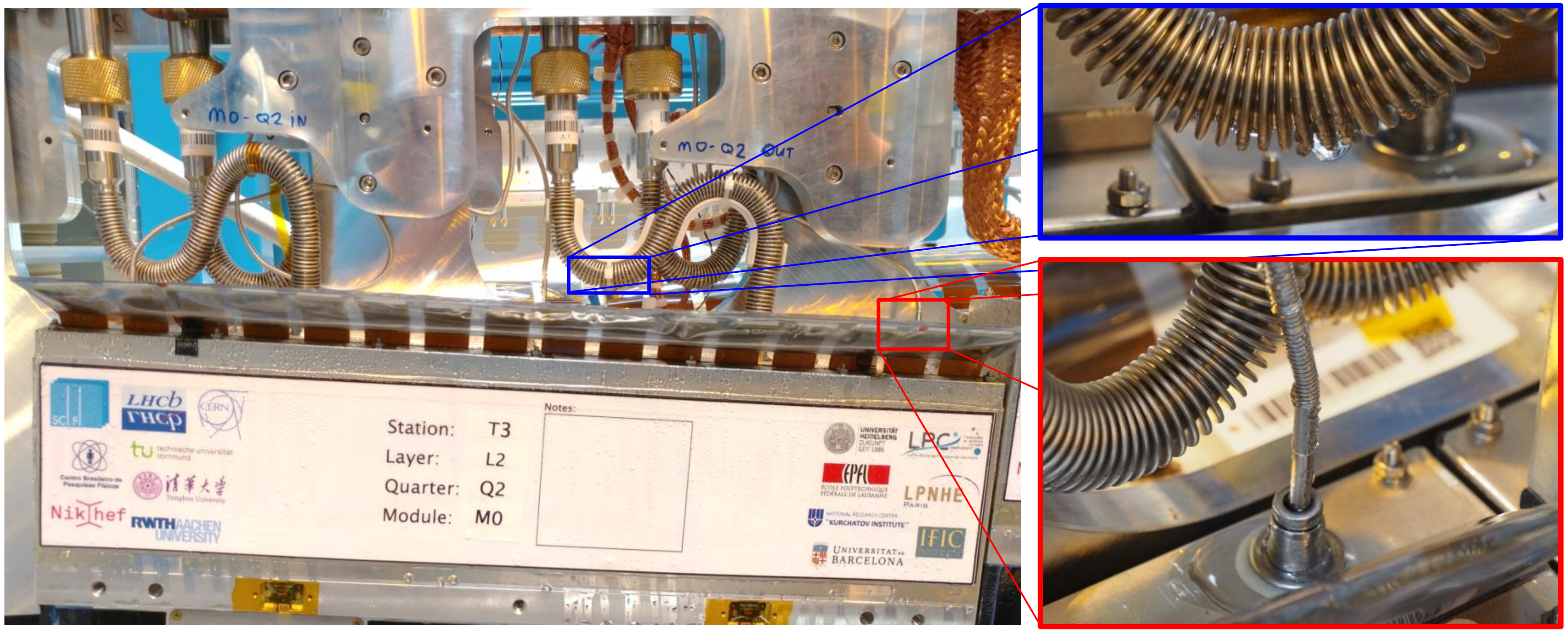
- Condensation observed on the first assembled C-frame (July 2019).

Extensive test campaign was made:

- Thermal photos revived that the parts were overall colder than expected and very cold spots on the SiPM cooling liquid bellows.

The problems had to be understood and mitigated without major design modifications during the on-going assembly.

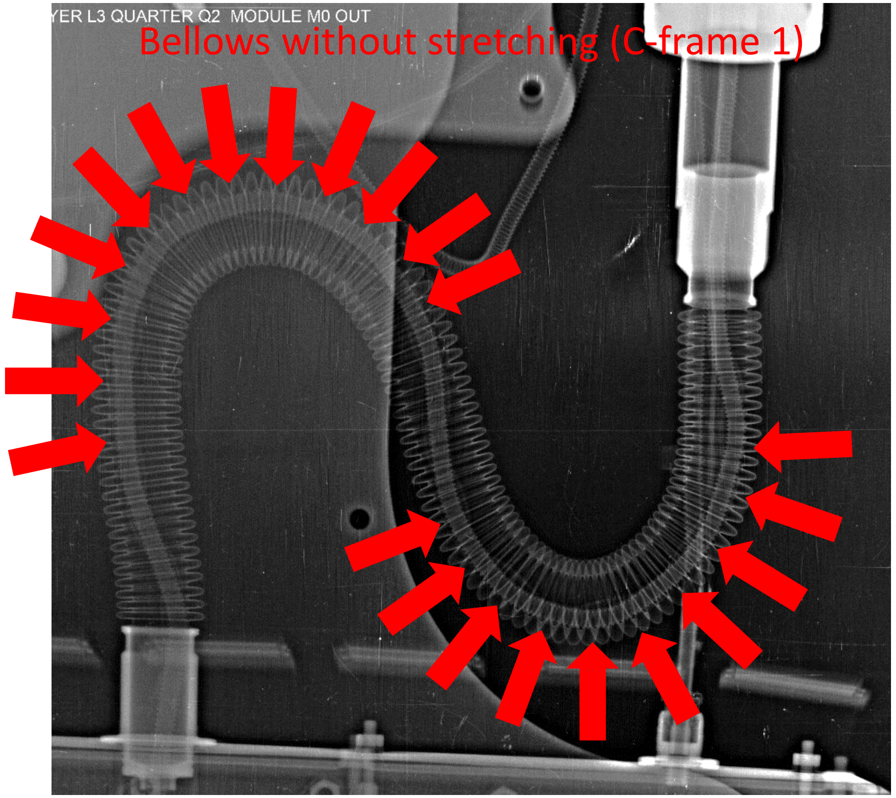


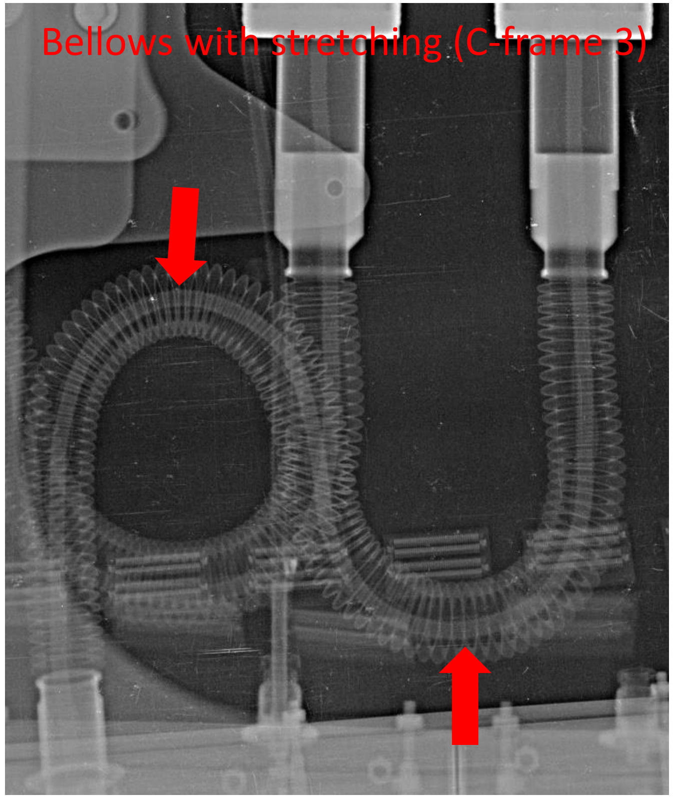


Condensation problem – Solution part 1

The SiPM cooling bellows on the modules were X-rayed for a C-frame.

Conclusion: The outer bellow (insulation vacuum) is too short compared to the inner bellow (SiPM cooling liquid) and this forces the be bellows to touch => Cold spots.





The bellows of a C-frame was then stretched to optimize the relative length and then X-rayed.

All bellows were then optimized in length during installation.

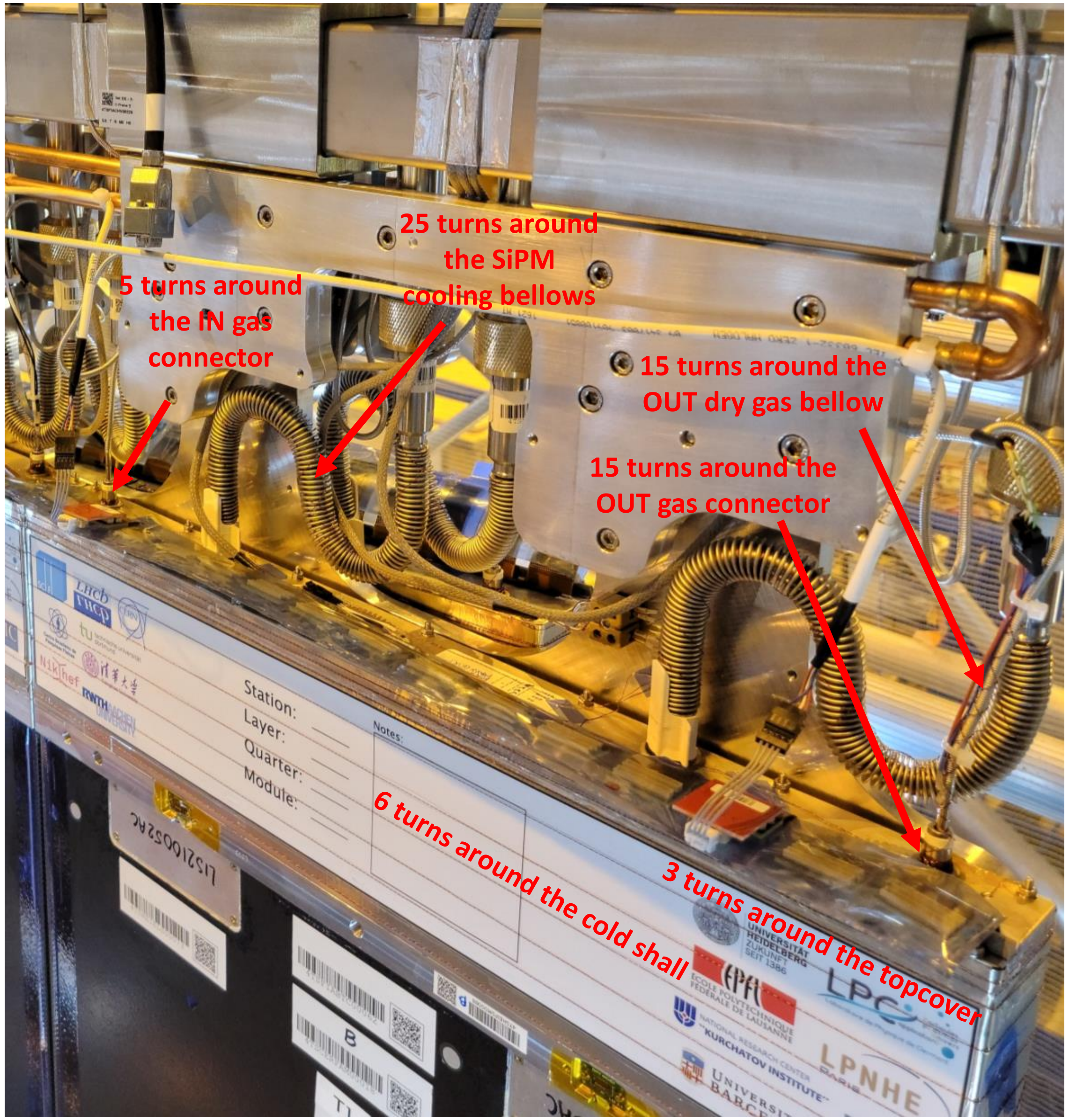
This solved/improved the cold spot problem.

Condensation problem – Solution part 2

For the low coldbox temperature and cold components like the gas-out connector several solutions have been investigated.

The most effective solution was active heating using an heating wire:

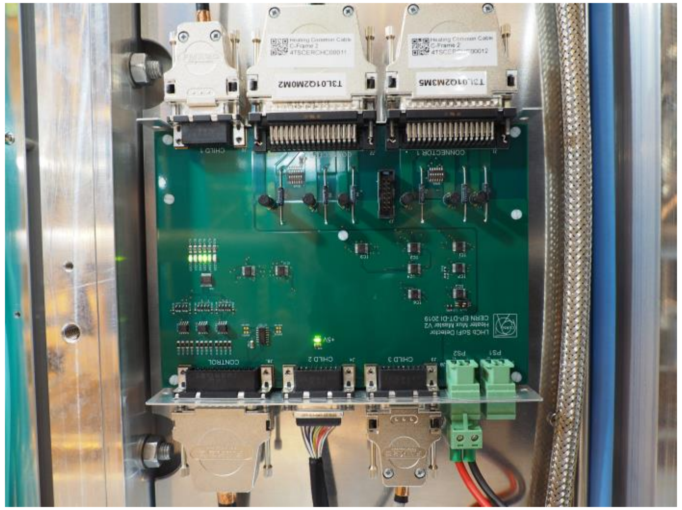
- A thin Kapton wire was wound several times around each component.
- Each coldbox + corresponding bellows etc. carries about 15 m of wire.
- The amount of wire around each part was balanced to get all components to safe temperature with the same wire current.
- The wire is actually a twisted pair with current in opposite direction to avoid introducing a magnetic field.



Condensation problem – Solution part 2 continued

Monitoring was also added: 2 PT100 temperature sensors per coldbox (512 total).

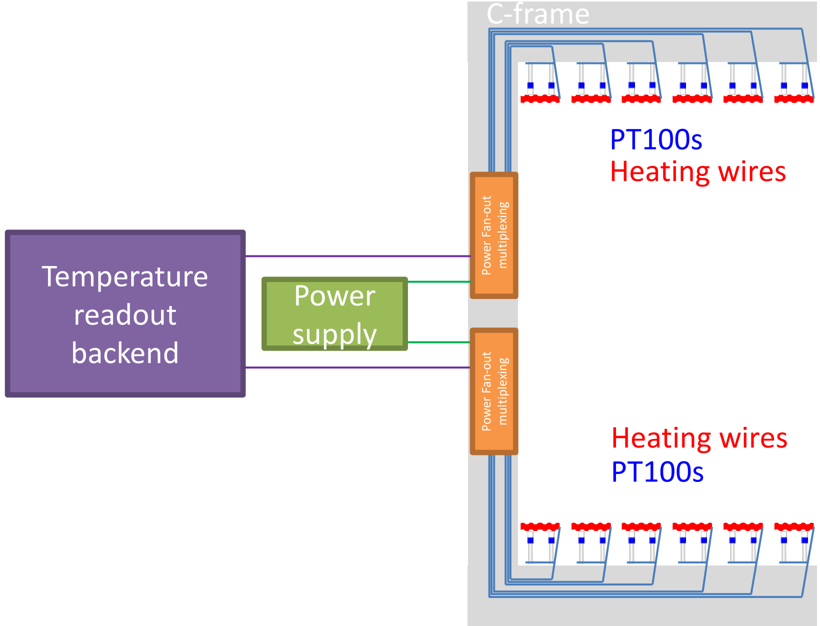
Custom made radiation tolerant multiplexing board for the PT100 readout was integrated on the C-frame.



The full system of heating wires and temperature sensors, cables, boards etc. got integrated on the C-frame.

The system is called Condensation Prevention System, CPS.

Using the system all C-frame was cooled down to a setpoint of - 50 °C during assembly without any condensation.



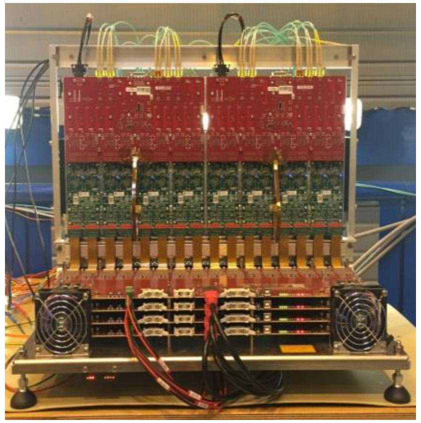
C-frame assembly – The last bit

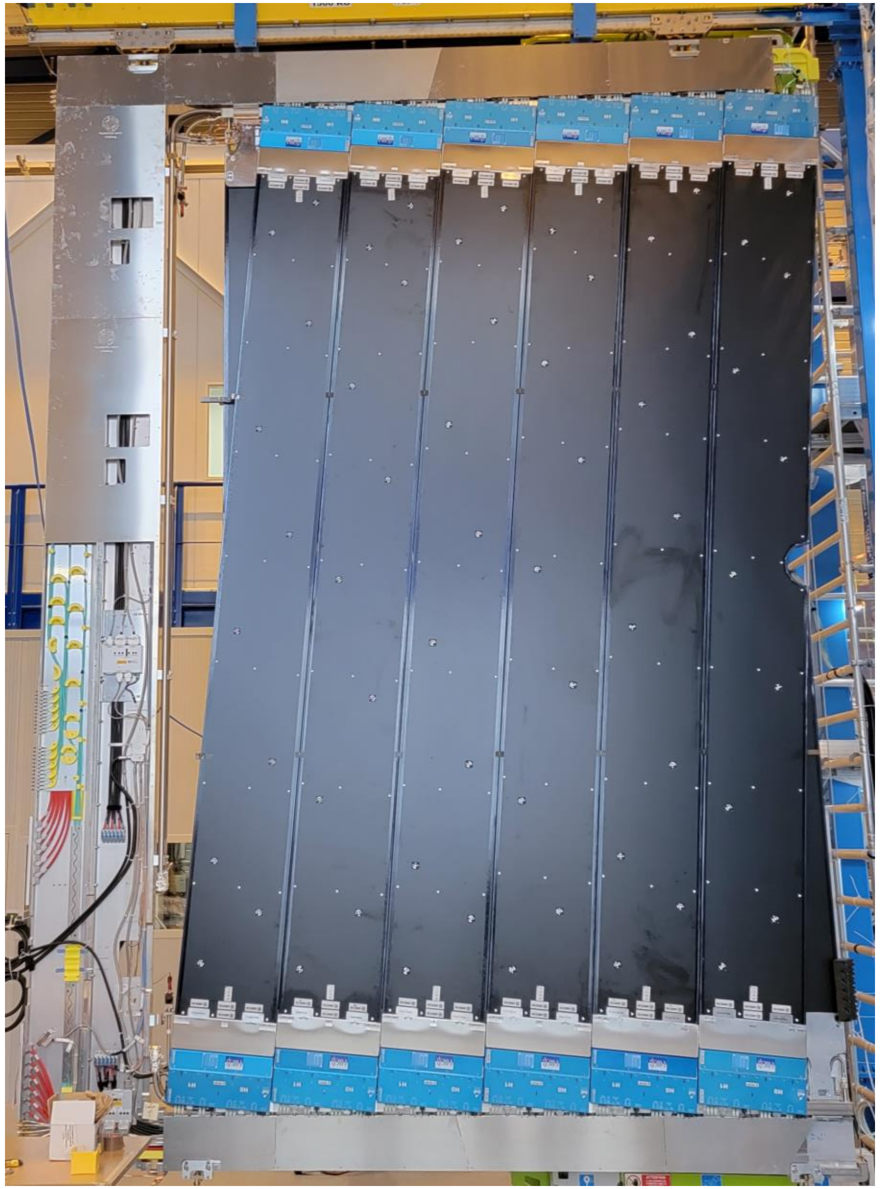
All Front-End electronic was thoroughly tested on 2 dedicated test benches by providing input signals to all channels and measuring the optical output.

The 256 Front-End boards were installed using custom mounting tools.

All optical fibers were routed, optically inspected and plugged (totally 6144 LC connectors).

Cover plats added to protect and add stability.

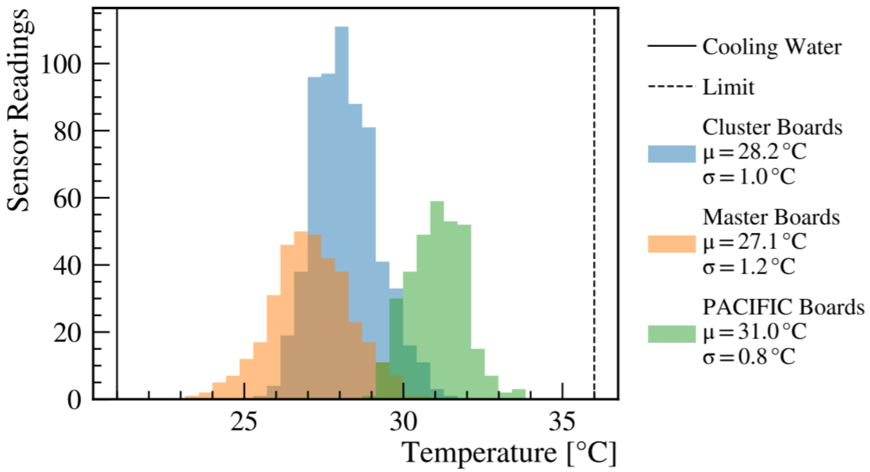




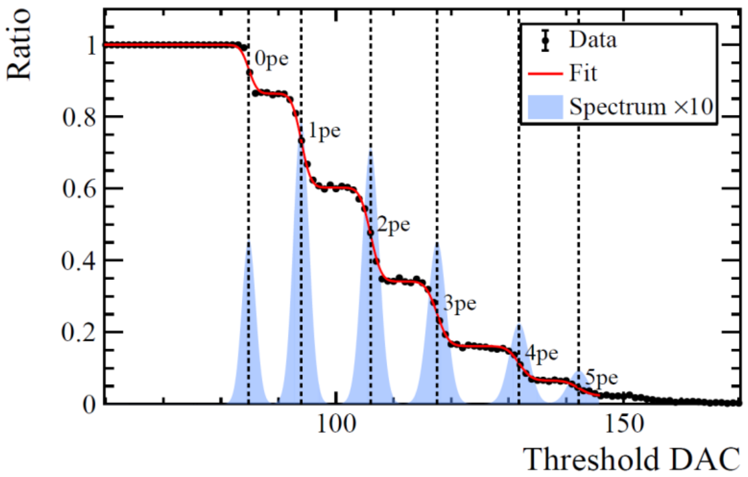
Testing of full C-frames – Front-End electronics

Systematic tests of Front-End electronics of all C-frames have been performed:

Temperature distribution



Threshold scan using light injection



Testing of full C-frames – Services

Functional tests of all systems on all C-frames.

External dew point measurement connected to measure the dew point after the coldboxes.

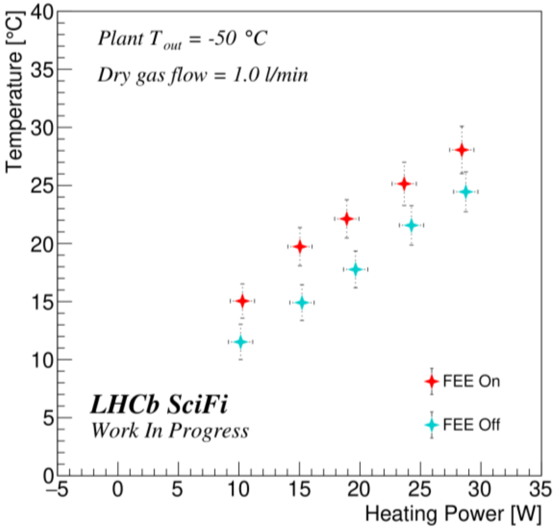
Helium leak test on all SiPM cooling and vacuum circuits.

Systematic studies to map out correlations for one C-frame.

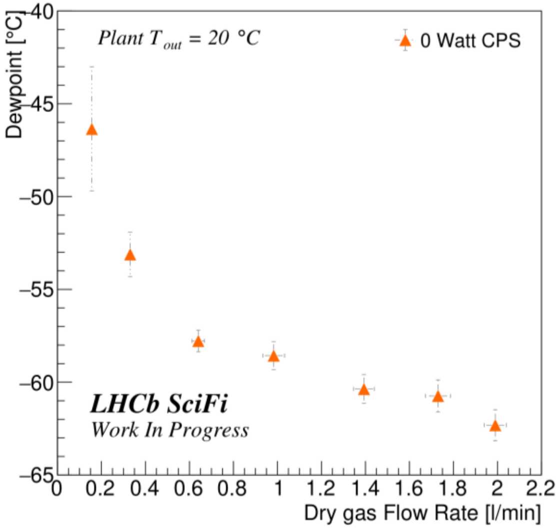
Results used to select operation parameters.

Gas multiplexer for dew point measurements of the exhaust from coldboxes on C-frames

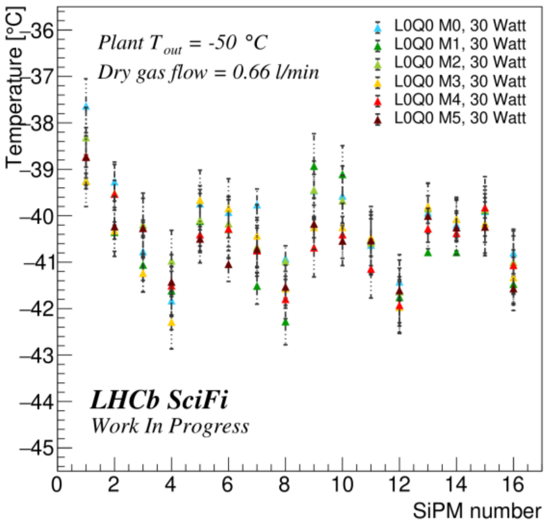
Gas connector temperature vs heating wire power



Dew point AFTER coldbox vs flow



Temperature distribution in coldboxes – systematic same pattern in all



C-frame assembly – Survey of the detector

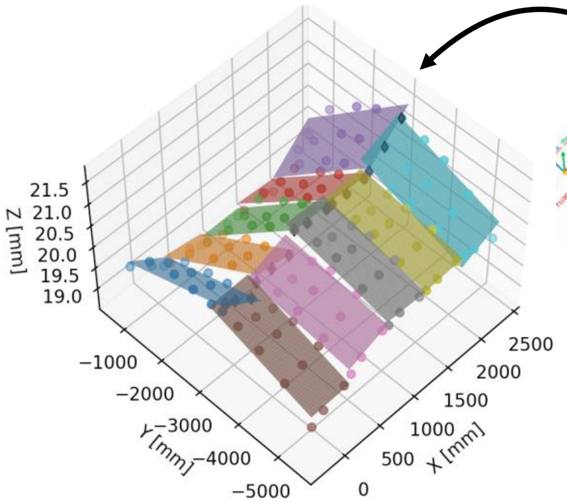
The detector was hang on a dedicated installation frame and reflective stickers installed on the modules.

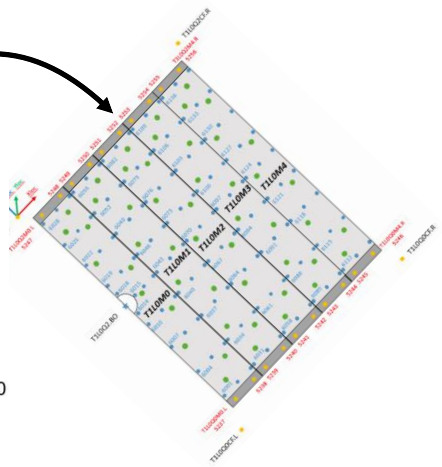
Using photogrammetry the exact shape of the modules of each C-frame has been determined.

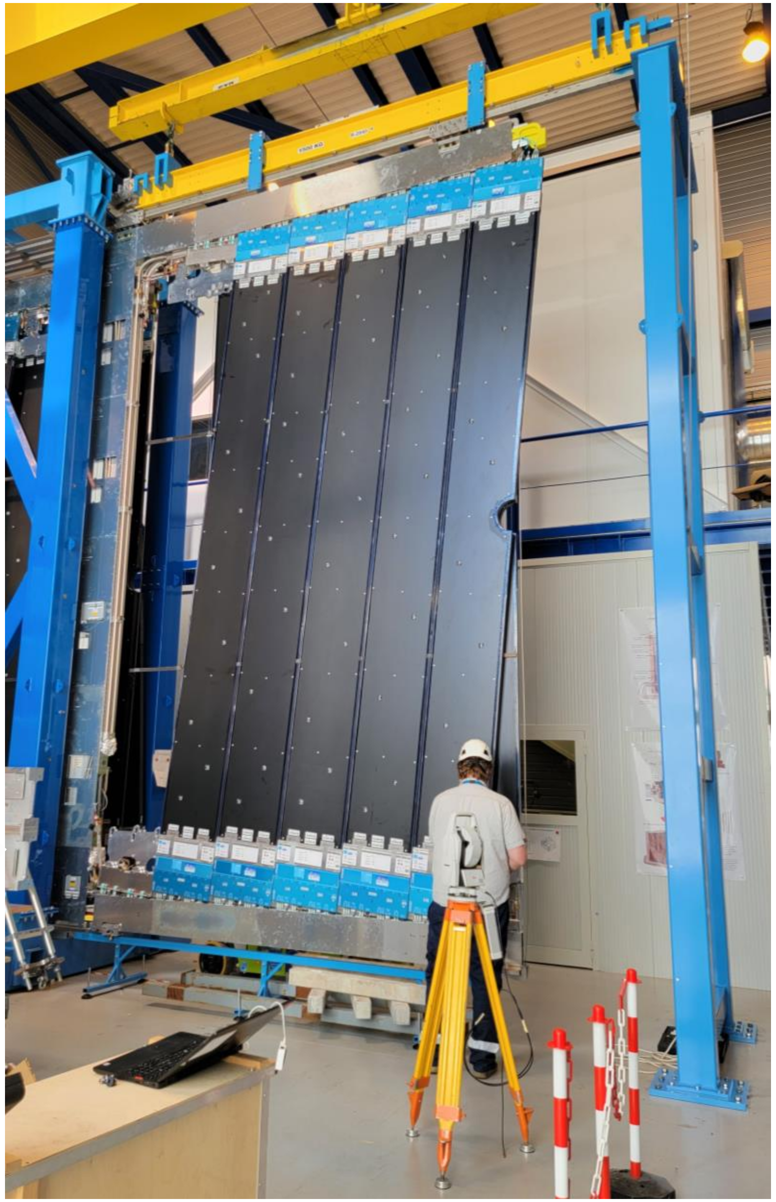
Each half module is then fitted to a plan.

A few point on the detector was measured using high precision laser targets.

This was done for all C-frames as the last step to finish assembly.







Installation

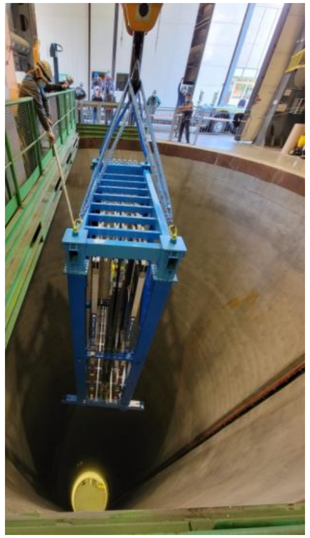
C-frame installation

The SciFi C-frames were put into a transport cage.

The cage was transported to the cavern.

The C-frames were moved onto the final rails.

The C-frame we installed as they got ready in pairs (first installation 4 frames).



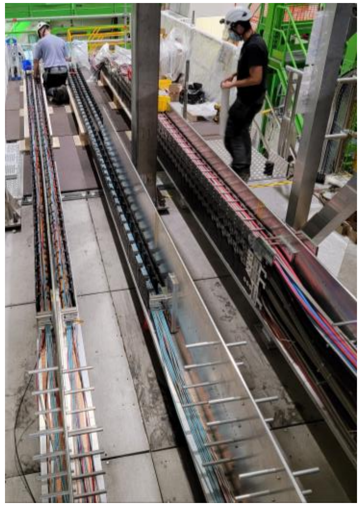
Moveable cable chains

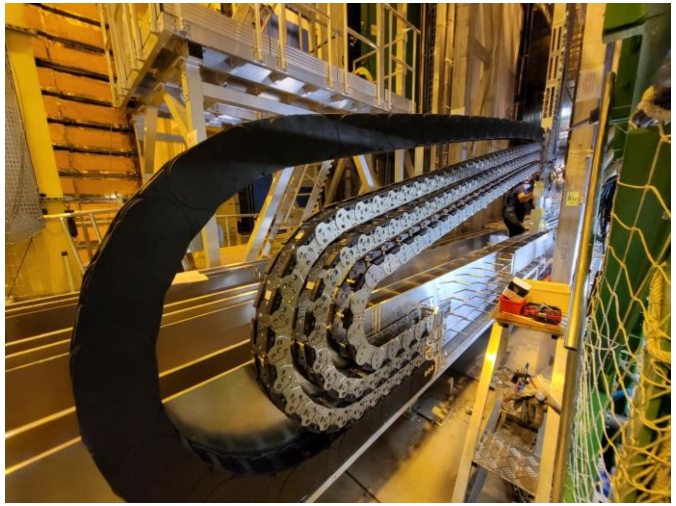
To allow for maintenance, the C-frames are moveable, so the cable chains also need to be moveable

- 4 cable chains are needed for all the cables and services for a C-frame.

The chains were filled with cables before the C-frames were installed.

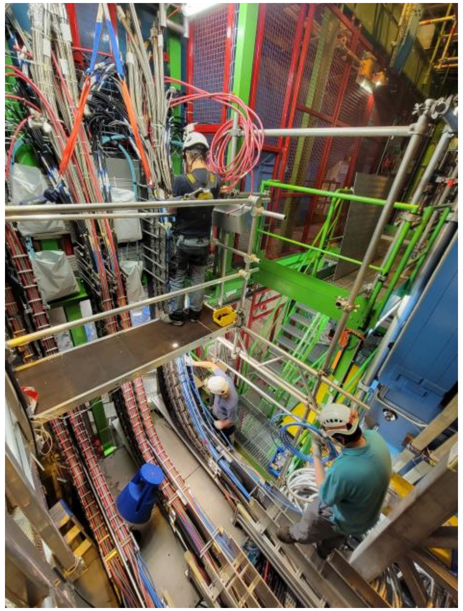
- A-side: Easy, the chains could by laid flat.
- C-side: Difficult, the chains had to be filled hanging on the wall due to space constrains.

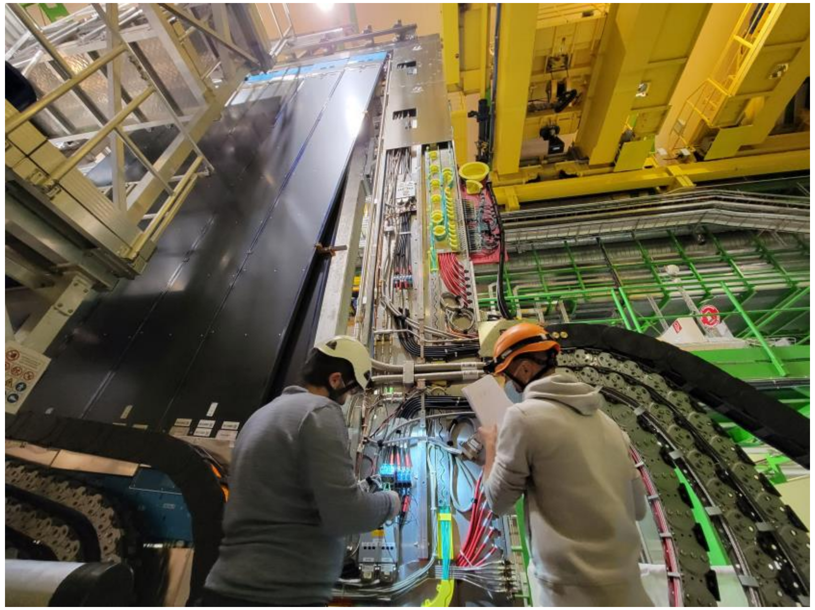




Connection of chains to C-frame.

Connections inside C-frame.





Alignment and positioning of C-frames

The C-frames can be adjusted at the 2 carriages and by 2 similar carriages at the bottom of the C-frame.

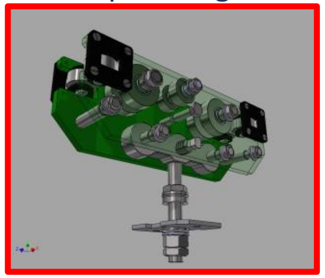
Main priorities of alignment:

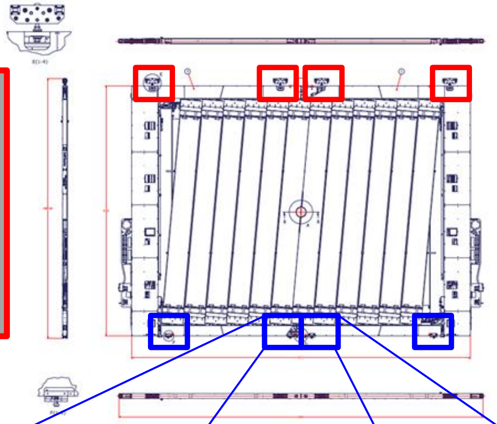
- Adjust such that the cut-out fits around the beam pipe.
- A-side and C-side C-frames can overlap without touching.
- Check reproducibility (important after interventions where the C-frames needs to be open).
- Provide a starting point for track based alignment.

Movement and securing of C-frame:

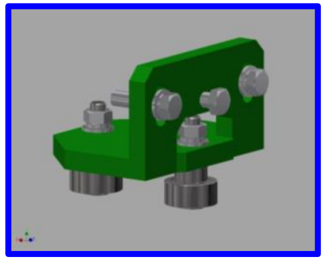
- Far from the beam pipe, the C-frames are moved by hand.
- The last ~2 m movement are done with a threaded rod.
- The system also keeps the C-frame in the desired position.
- Precision toward beam pipe by mechanical stopper.

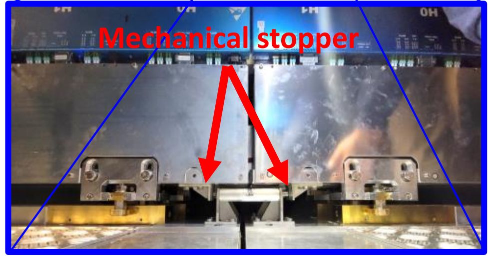
Top carriage

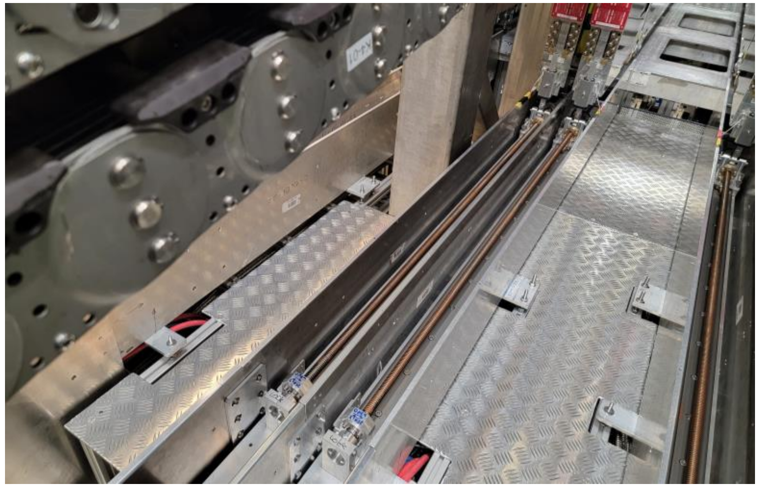


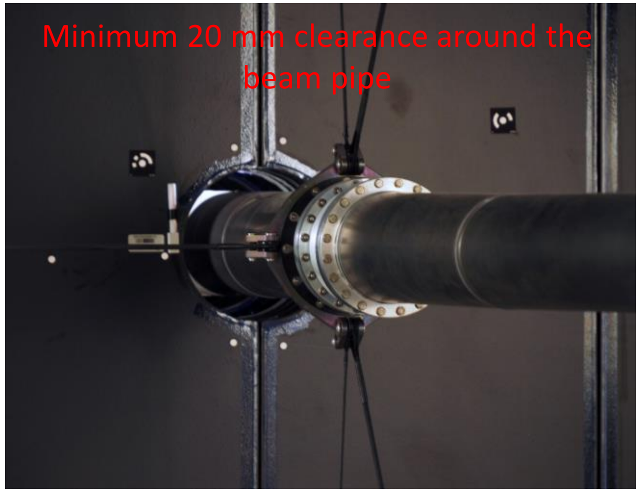


Bottom carriage

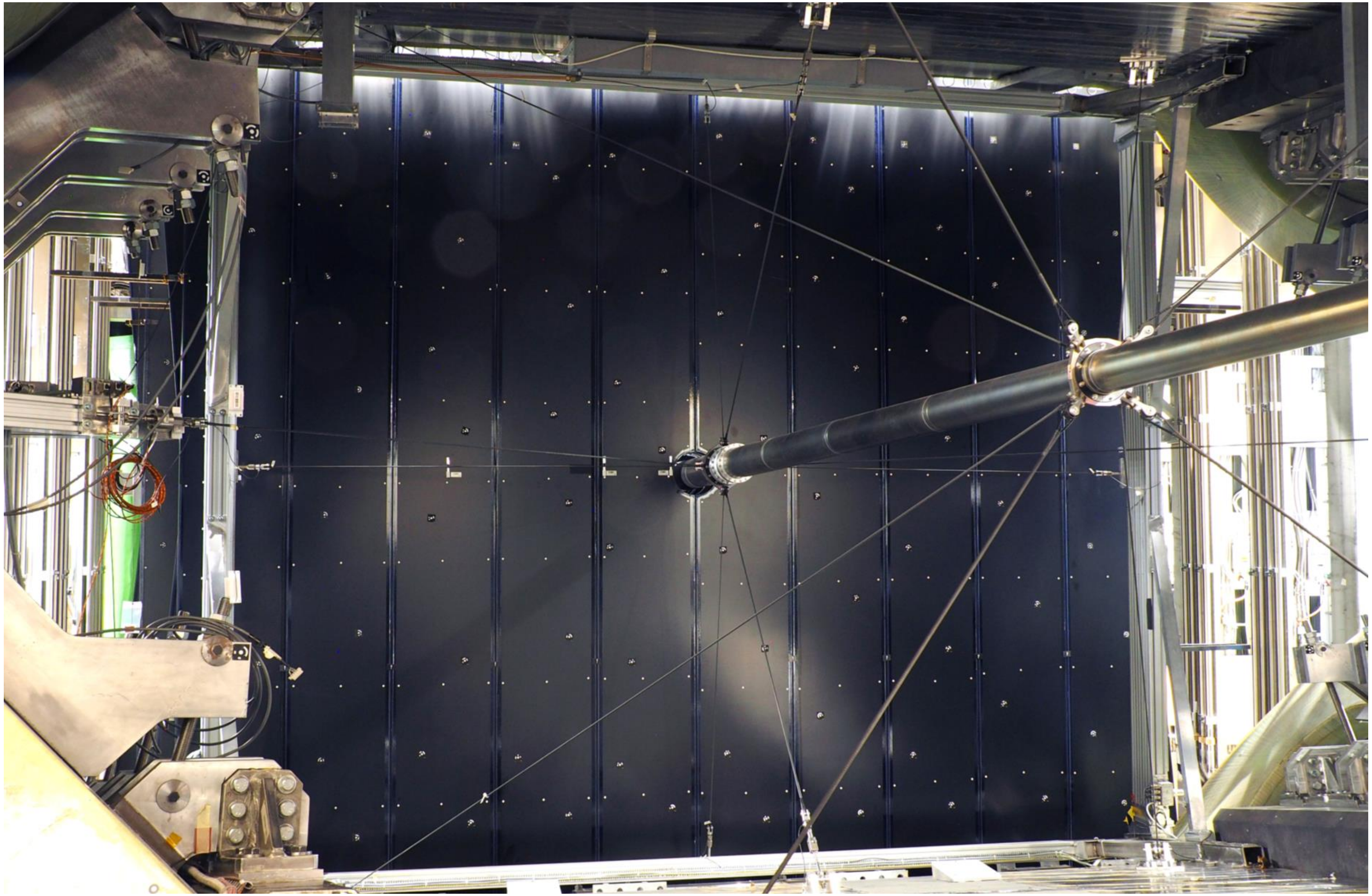








The closed SciFi detector seen from the magnet



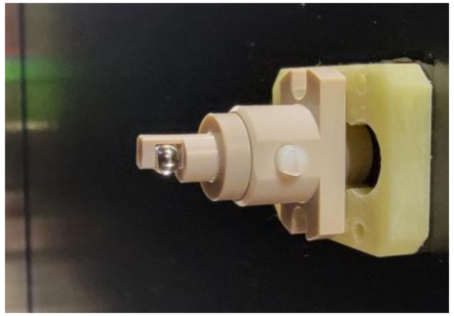
Monitoring of position over time – BCAM system

Main purpose of the BCAM (Brandeis CCD Angle Monitor) system:

- Measure multiple points on the SciFi active surface over time.
- Register changes if temperatures changes.
- Register changes if magnet turns on/off.
- Register changes if electronics powered on/off.

Method:

- 24 cameras are installed under the floor of SciFi.
- 42 targets (ø4-6 mm high index glass balls) are installed on the C-frames.



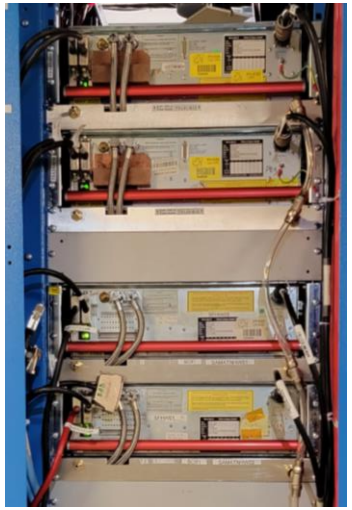
- The targets are illuminated with 650 nm diode lasers and photographed by multiple cameras.

Expected performance:

- 20-100 µm for a single measurement.
- ~10 µm when averaging over an hour.

Low voltage and bias voltage

MARATON rack



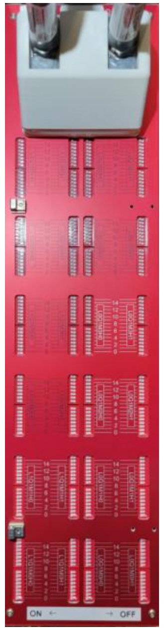
The low voltage power supplies are installed close (~15-20 m) from the detector (as high current of about ~10 A per Front-End box is required)

- 8 volt radiation tolerant wiener MARATONs (MAgnetic and and RAdiation TOleraNt) are used.
- 12 units (one per C-frame) with 12 channels are used (so 2 or 4 master board per channel).

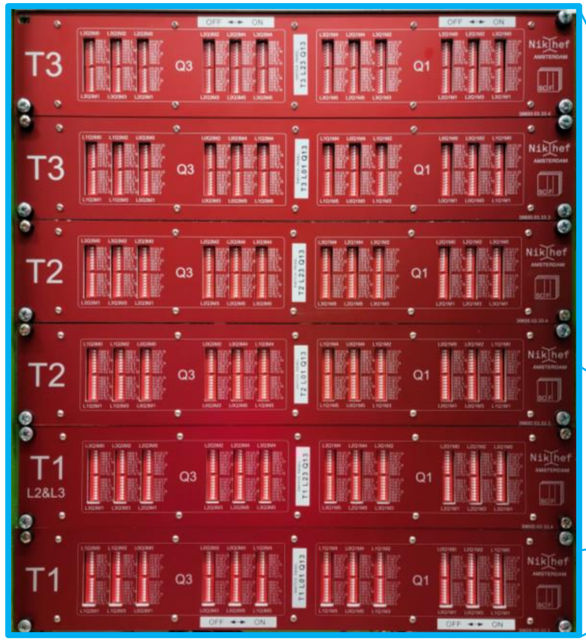
The bias voltage power supplies are installed in a zone with permanent access and about 80 m (cable length) from the detector (as very low current is required).

- CAEN SY4527 mainframes are used.
- About ~60 V per channel.
- It would require too many cables and power channels to have one SiPM array supplied by one power channel.
- Therefore one power channel powers 8 SiPM arrays of 64 channels, so a total of 1024 power channels is used.
- To limit the performance degradation if e.g. one SiPM gets shorted, there are panels both at the Back-End (always accessible) and at the C-frames (only accessible with no beam) to disconnect a subsection of the SiPMs powered by a single power channel.

C-frame switch panel



Back-end switch panel



Back-end rack

Front-End electronics cooling

The Front end electronics are cooled by water at about 17 °C:

- A heat load of about 30 kW needs to be removed.
- The water plant is located in a zone always accessible.
- The manifolds to distribute the water are located just next to the C-frames.
- The flow is controlled on the return lines.
- All water lines are made in metallic bellows (fire resistance).

SIPM cooling

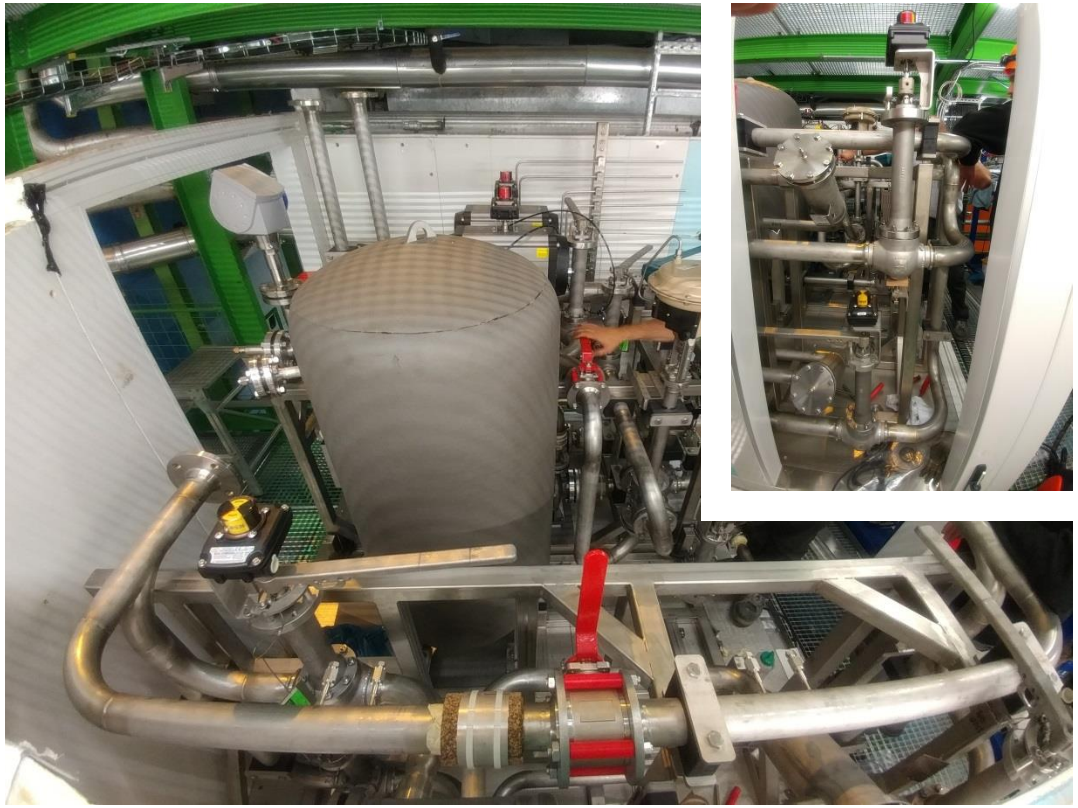
The cooling plant for the SiPMs are build at CERN.

Cooling liquid: NOVEC 649 or C_6F_{14}.

Fully redundant with 2 pumps etc.

It is located in a zone always accessible and therefore the distribution lines are long.

Part of the main distribution lines are vacuum insulated.



Insulation vacuum

The insulation vacuum system is mainly located close to the C-frames.

2 pumping stations for 6 C-frames consisting of:

- 1 scroll pump.
- 2 turbo-molecular pumps (for redundancy).

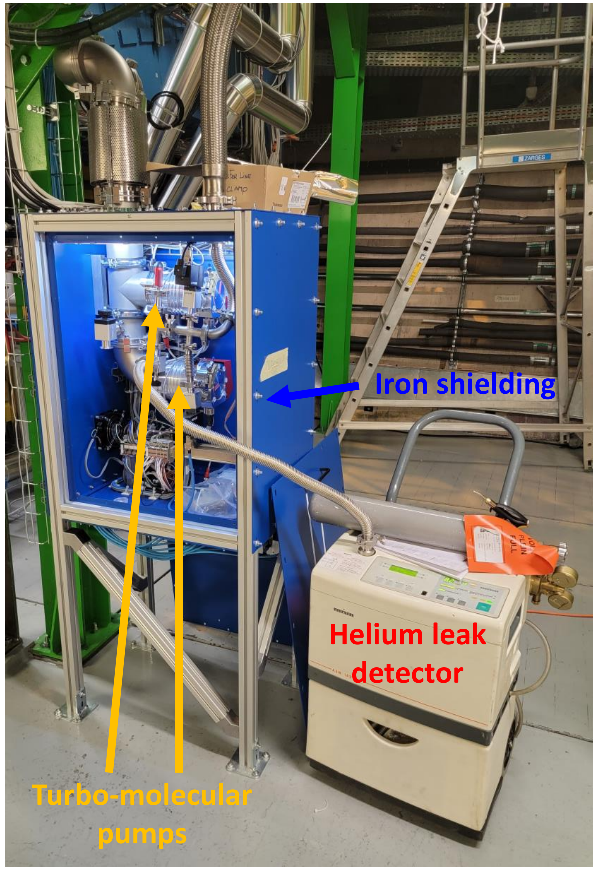
The turbo-molecular pumps are housed in a shielding cabinet consisting of to layers of iron for magnetic shielding.

The vacuum manifold is located about 2 m from the turbo-molecular pumps.

The distribution lines consist of a bellow (SiPM cooling) inside a bellow (vacuum).

All vacuum and SiPM cooling circuit has passed helium leak tests.

- It was a long way to get it thigh as the system consist of about 1250 VCR connections.
- Since the SiPM cooling is inside the insulation vacuum finding a leak can be very challenging.



Dry gas and CPS

The dry gas is produced in the assessable site of the cavern.

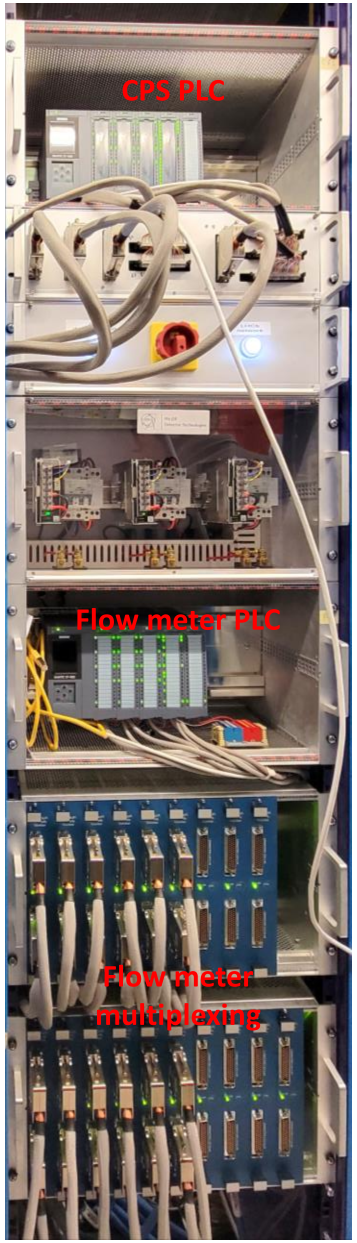
2 commercial dryers of model AtlasCopco CD65+ are used for redundancy.

The dry gas is backed-up by bottled nitrogen in case of e.g. a power failure.

The dry gas is monitored and distributed to each C-frame.

The flowmeters are readout by back-end multiplexing (redundant) + a PLC.

The CPS is readout only with a PLC (as the multiplexing are done on the C-frame).



First commissioning

Front-End electronics cooling

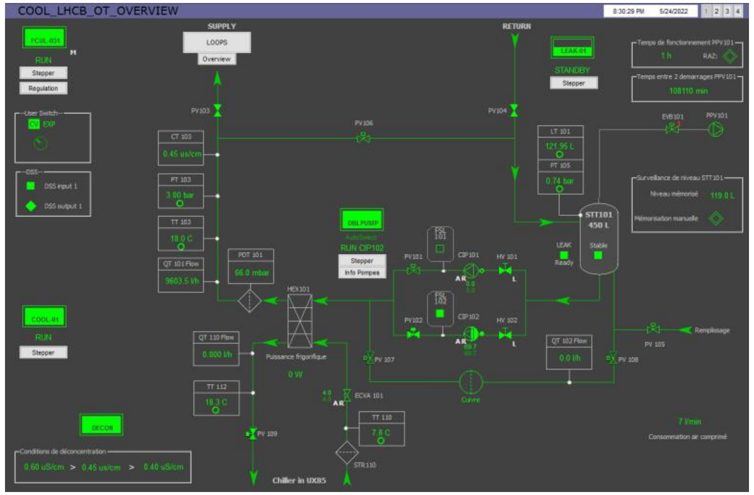
Low level UNICOS and high level LHCb Detector Control System (DCS) has been made to control and monitor the services.

Finite State Machine (FSM) made for all services.

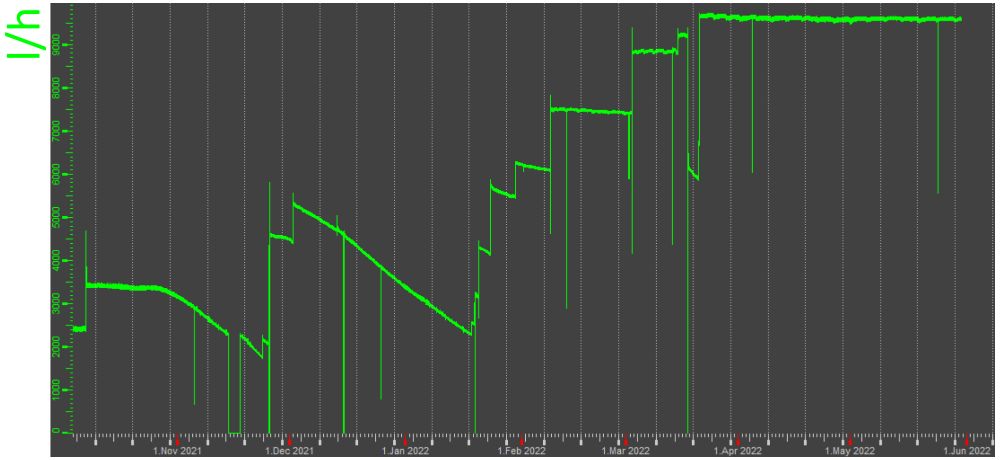
The Front-End cooling system has been fully commissioned.

After some initial problems with the water cooling (some valves slowly getting clogged), it has been running very smoothly.

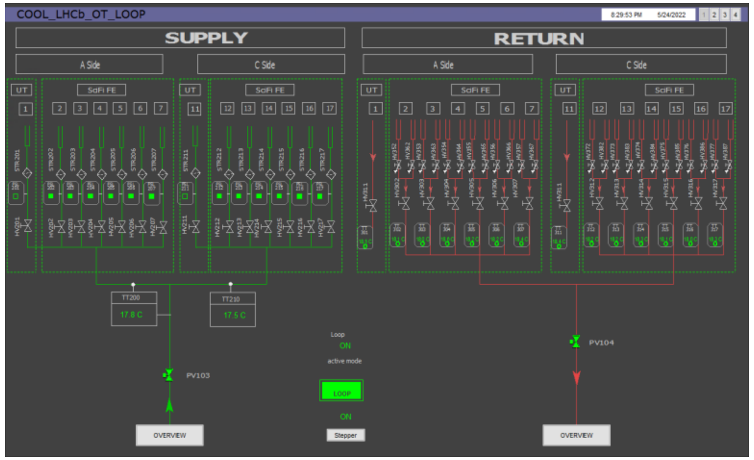
Plant



Overall flow during clogging problem after it was fixed



Manifolds



SiPM Cooling

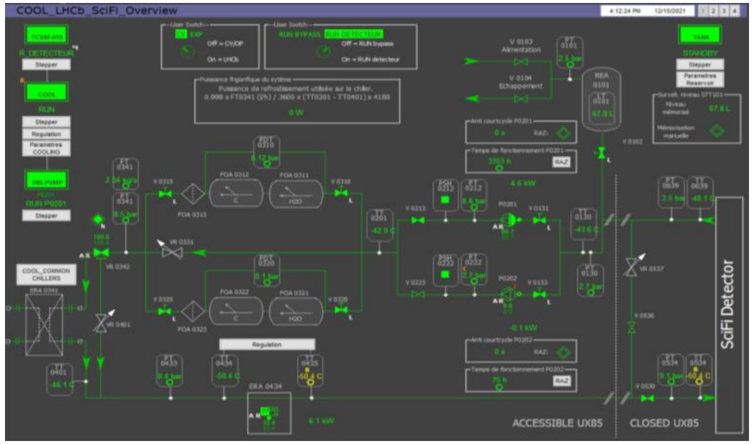
The SiPM cooling system has been fully commissioned.

The full detector has been cooled down to a setpoint of -50 °C and are routinely operated at this temperature.

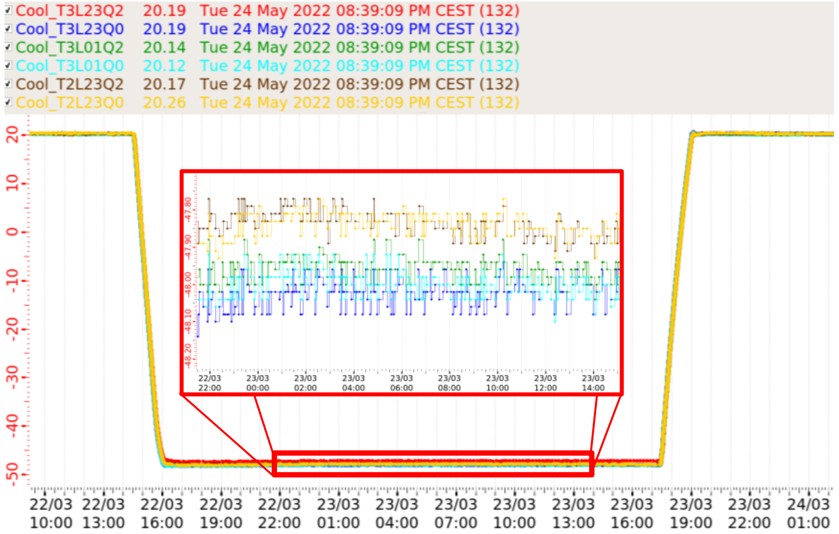
Temperature stability very good.

However the plant also have some problems and is still being tuned.

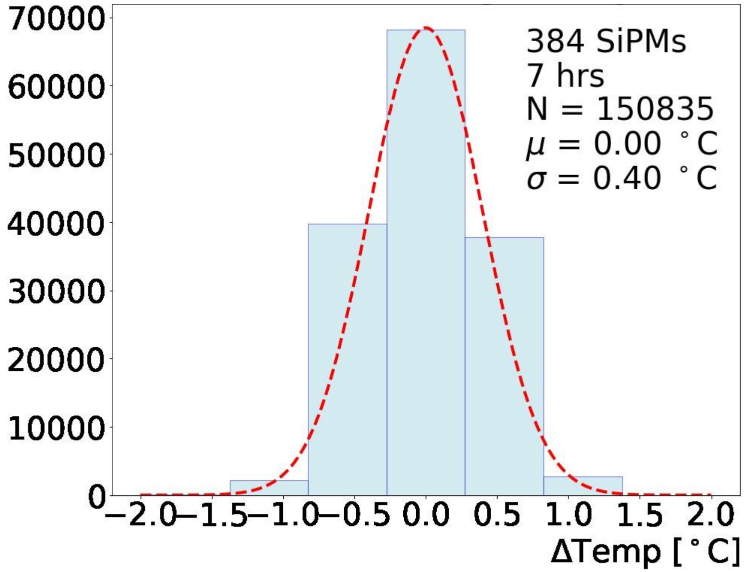
SiPM cooling plant



Temperatures on return lines



SiPM temperature stability for all SiPMs on a C-frame



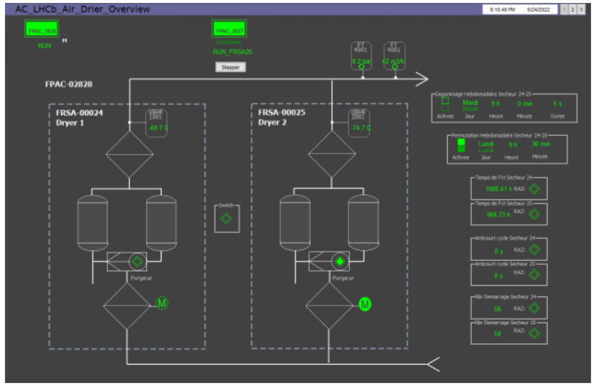
Dry gas

The dry gas system has been fully commissioned.

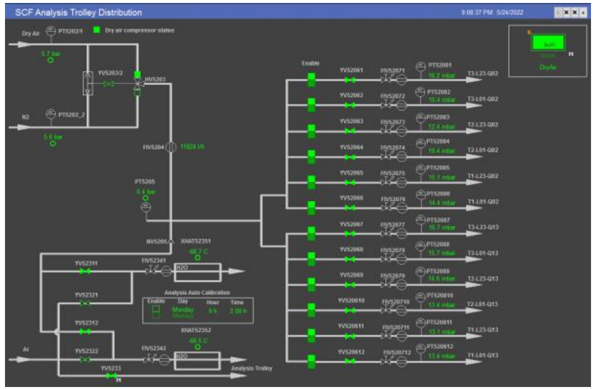
For one C-frame the dew point was measured with the external measurement device (dew point trolley).

The measurement confirmed the dew point vs flow measured during assembly.

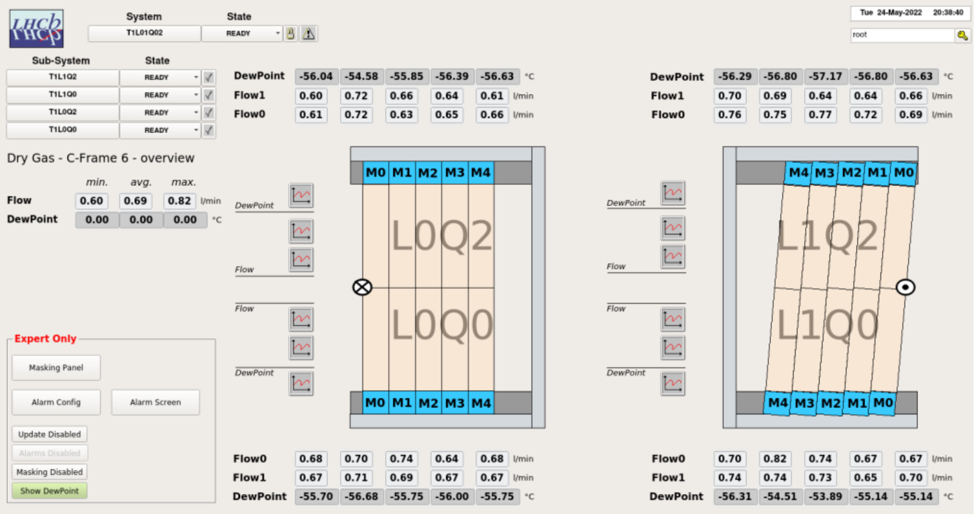
Dry gas supply



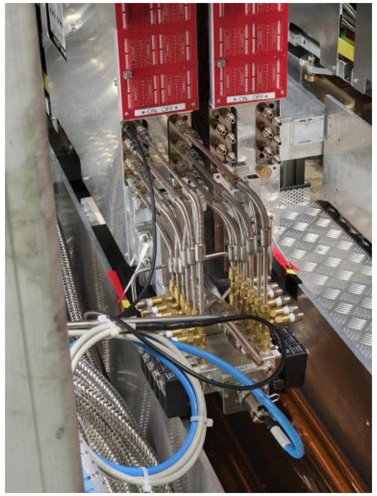
Dry gas distribution



Monitoring on C-frames

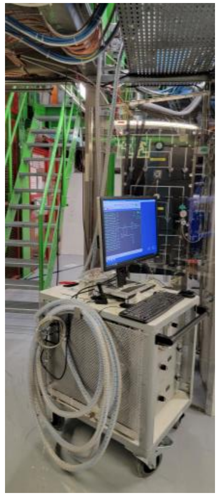


Bottom gas multiplexer



Top gas multiplexer

Dew point trolley



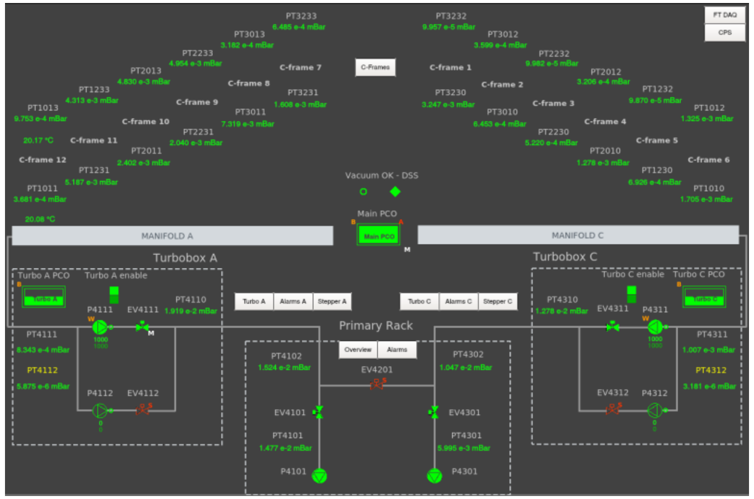
Vacuum and CPS

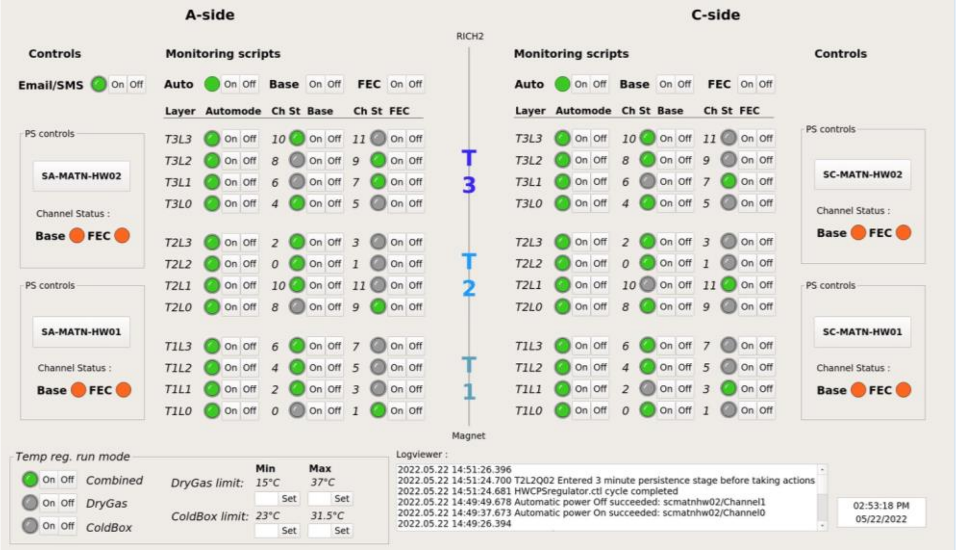
The vacuum system has been fully commissioned and is running with very stable.

The CPS system has been fully commissioned.

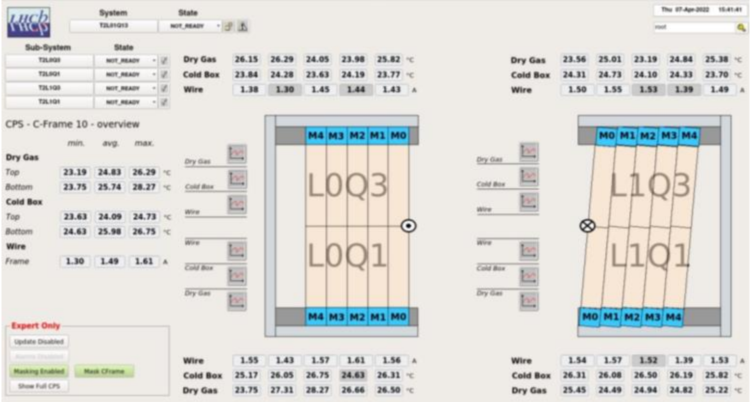
The CPS automatically power on/off MARATON channels to change the heating power depending on the measured temperatures.

Vacuum system





CPS for one C-frame



Controls and DAQ

Connection established to all Front-End electronics.

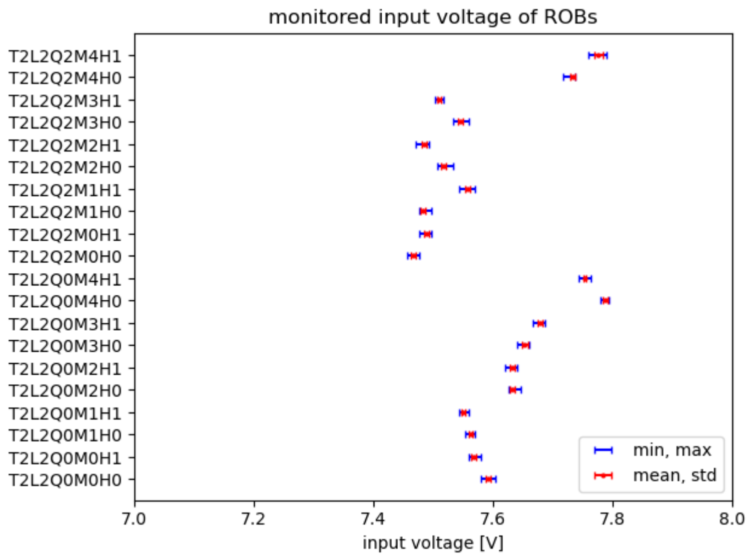
Basic monitoring of Front-End electronics.

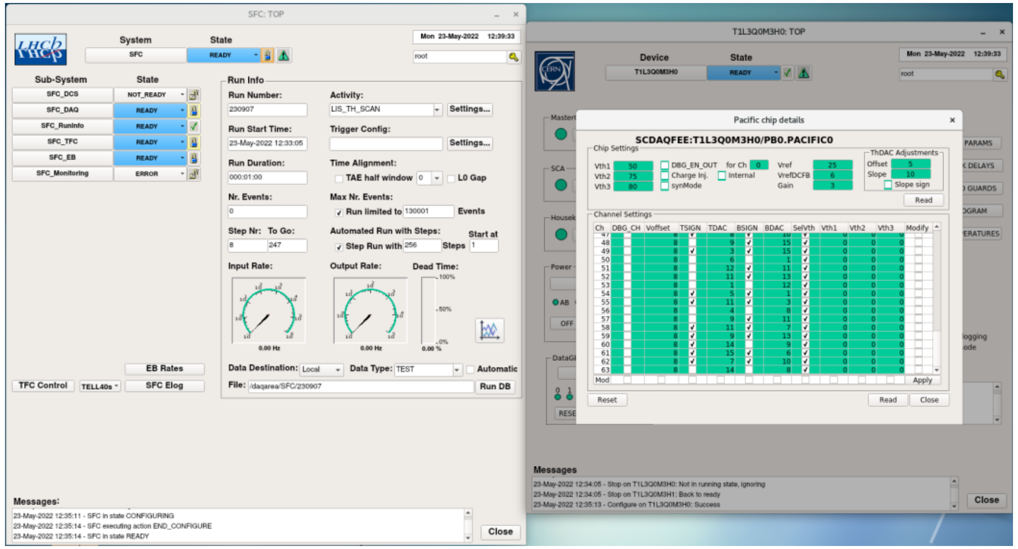
Monitoring of SiPM temperatures.

Standalone DAQ operational.

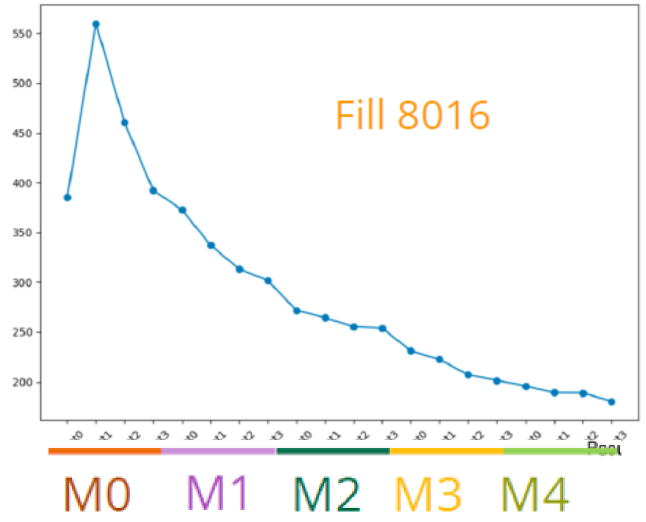
Current from SiPMs clearly scales with occupancy (and can likely be used a luminosity meter).

Combined DAQ (with rest of LHCb) operational and routinely operated.





Bias voltage currents measured with the power supply (in µA)



Timing in

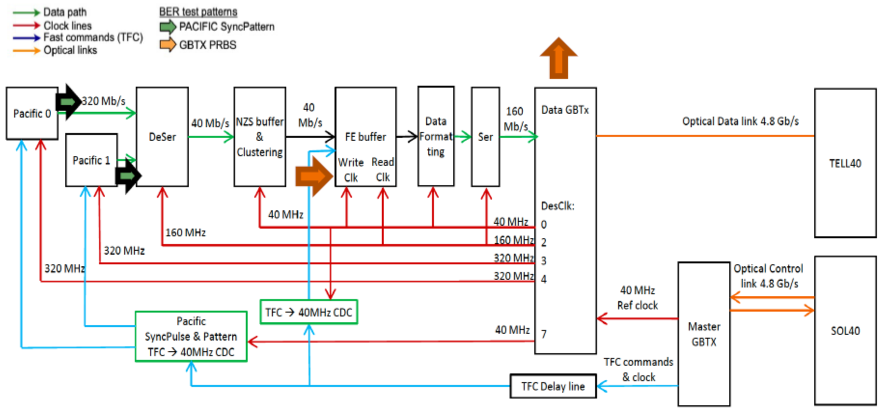
There are several level to time in for LHCb SciFi:

1) Internal clocks (between boards).
2) Course time alignment to bunch crossing in LHC.
3) Fine time alignment inside a bunch crossing to optimize performance.

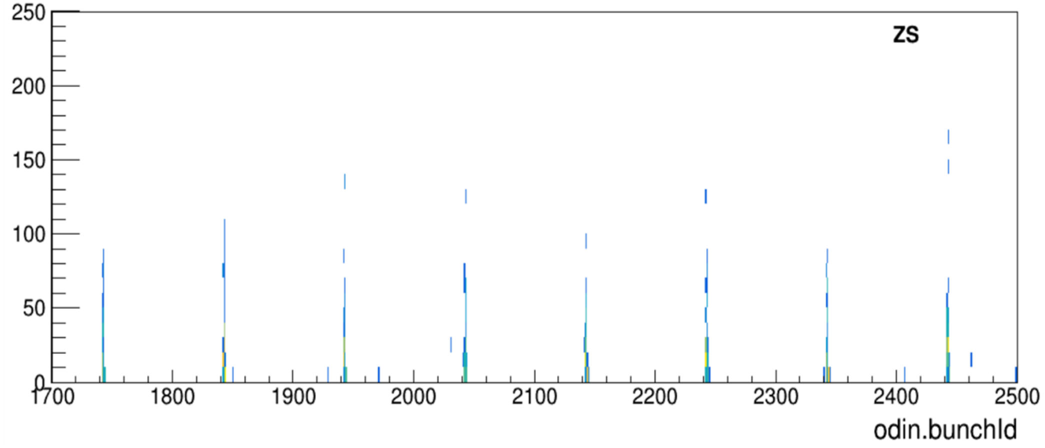
1) and 2) is done (to first order).

3) is also done (to first order), but not tested (no been in LHC at the moment).

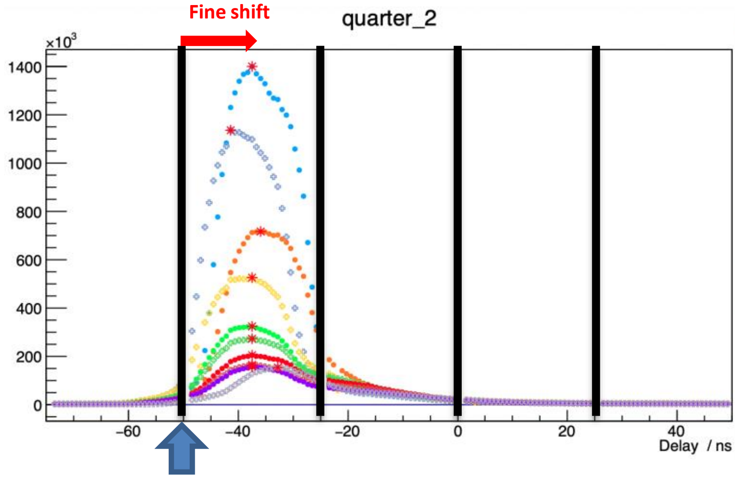
Overview of internal clocks



Course time alignment to the correct bunch crossing in LHC (based on SciFi clusters)



Fine timing based on SciFi clusters



LHCb SciFi performance – Requirements vs. achieved

1) **Area**: Active area of about 340 m^2.

Covered with scintillating fibers.

2) **Hit detection efficiency:** Larger than 99 %.

Larger than 99.4 % achieved (test beam result).

3) **Spatial resolution:** Better than 100 µm in the bending plan of the magnet achieved (vertical).

Better than 70 µm (test beam result).

4) **Noise cluster rate:** Below 10 % of signal in all region of the detector.

Achieved by advanced front-end clustering and cooling the SiPM distributed over ~130 m to below -40 °C.

5) **Material budget:** Less than 1 % radiation length per each of the 12 detection layers.

About 1.1 % actually achieved (longer detector life-time at high performance prioritized).

6) **Readout speed:** 40 MHz with no dead-time.

Largest data-source of LHCb: After zero-suppression and data reduction: 20 Tbits/s

7) **Life time:** Integrated luminosity of 50 fb^{-1} with the above specified performance.

Radiation campaigns concludes the performance is preserved at the expected radiation.

Extra complicating factor: The assembly and installation were performed during the pandemic!

Summary

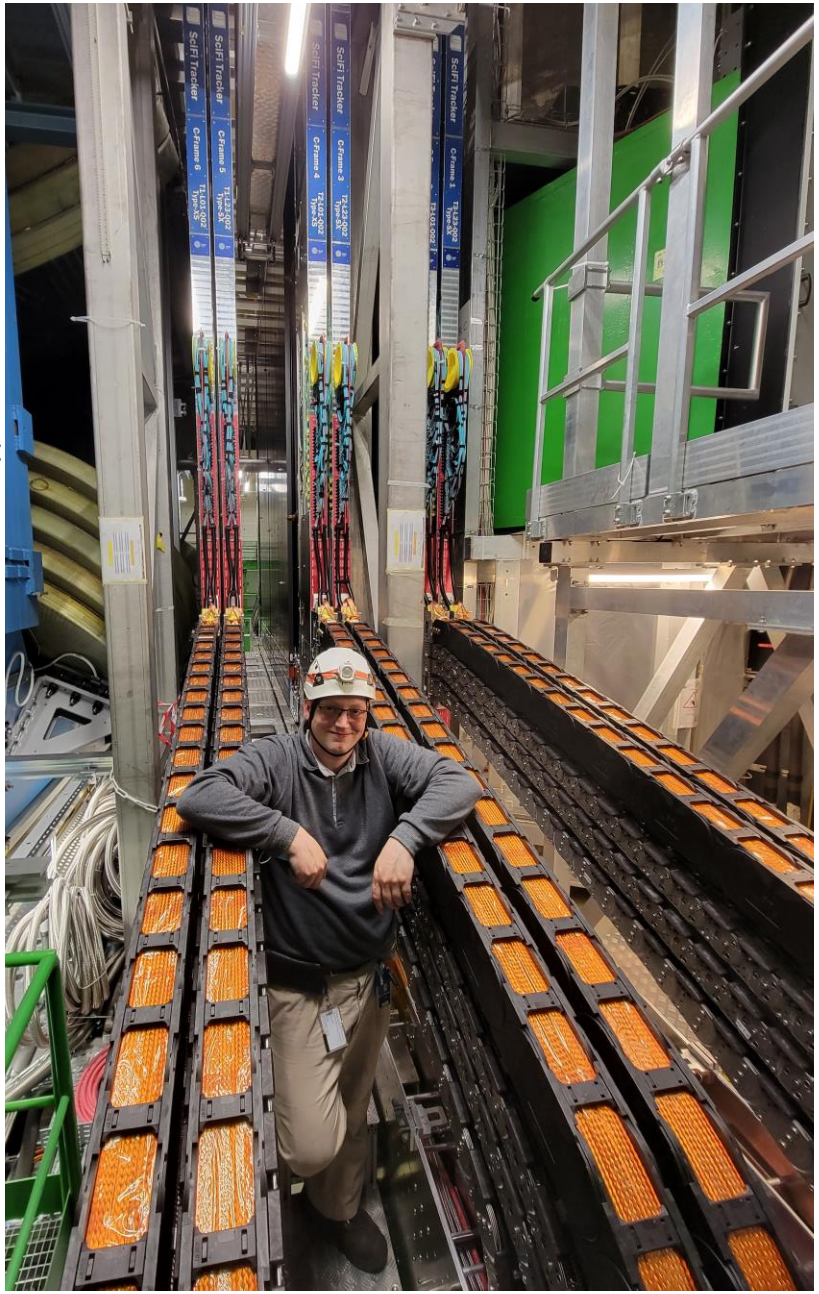
The LHCb SciFi is a large area tracking detector using Ø250 µm fibers and readout by SiPMs.

The SciFi detector has been successfully produced, assembled and installed until the end of LHC LS2.

The commissioning of all service systems has been successfully concluded.

The commissioning of the electronics readout is on-going: SciFi accounts for 40 % of the new LHCb detector.

Looking forward for a very successful data-taking in Run3 and Run 4.



Backup

Detector Safety System

To operate the detector safely a Detector Safety System (DSS) is needed.

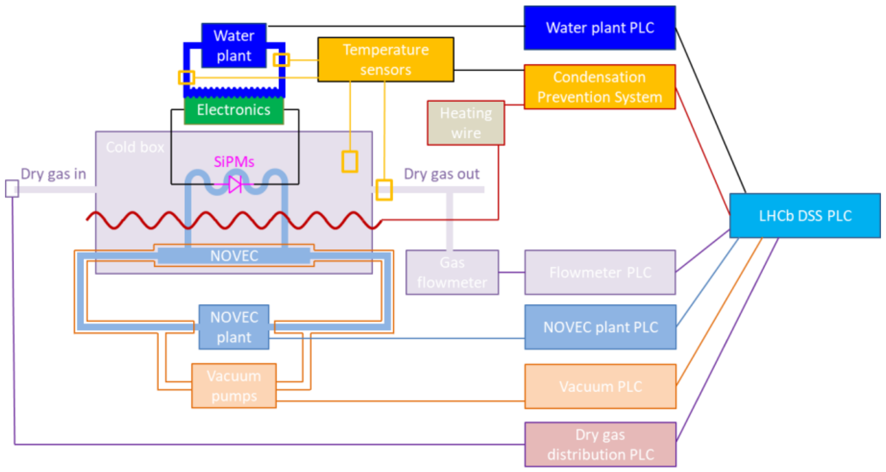
DSS is fully hardware based.

For SciFi much of it is integrated directly in the PLCs of the services.

Before any hardware safety action, a software layer has been implemented to act earlier.

- E.g. power off bias or low voltage in software before DSS cut the rack power.

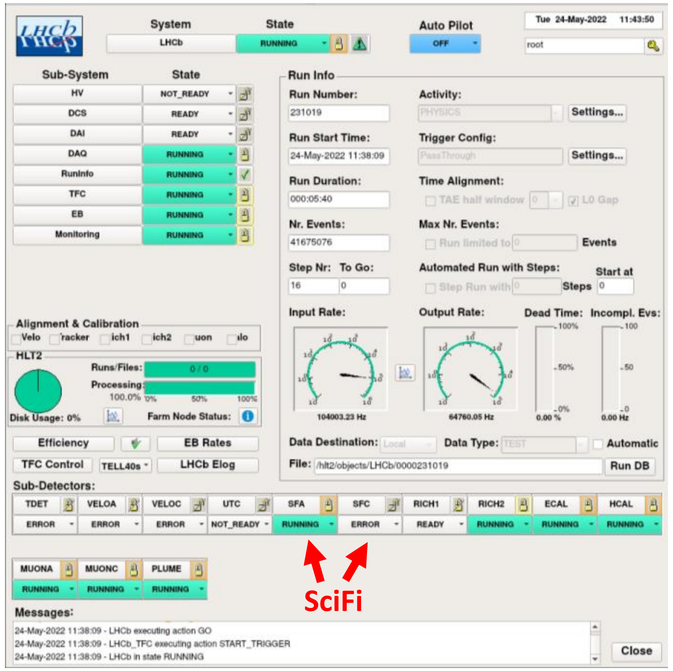
DSS overview



Software safety system

Controls and DAQ

Integration into the global LHCb DAQ ongoing.



Magnetic field in and near the vacuum turbo pumps cabinets

The magnetic field were mapped during week 4, where the LHCb magnet was tested.

A sensor was installed inside each of the blue turbo pump cabinets and connected to the same readout as for the general field mapping.

Outside the field where measured with various hand devices.

The field measured outside is highly dependent on the location and the cabinet seems to influence the field (as is to be expected).

Results:

- Outside the cabinets: 3-40 mT.
- Inside side-C: 1 mT
- Inside side-A: 0.5 mT
- Pump tolerance: 5.5 mT

Conclusion: **The pumps are well protected** and it was very good that the shielding was made (the need was not so clear at the design phase as the field was not mapped in details at this location before).

A special thanks to Nicola Pacifico (CERN EP-DT) for arranging the dedicated measurement for SciFi.

Temporary magnetic sensors

Photo by Freek Sanders