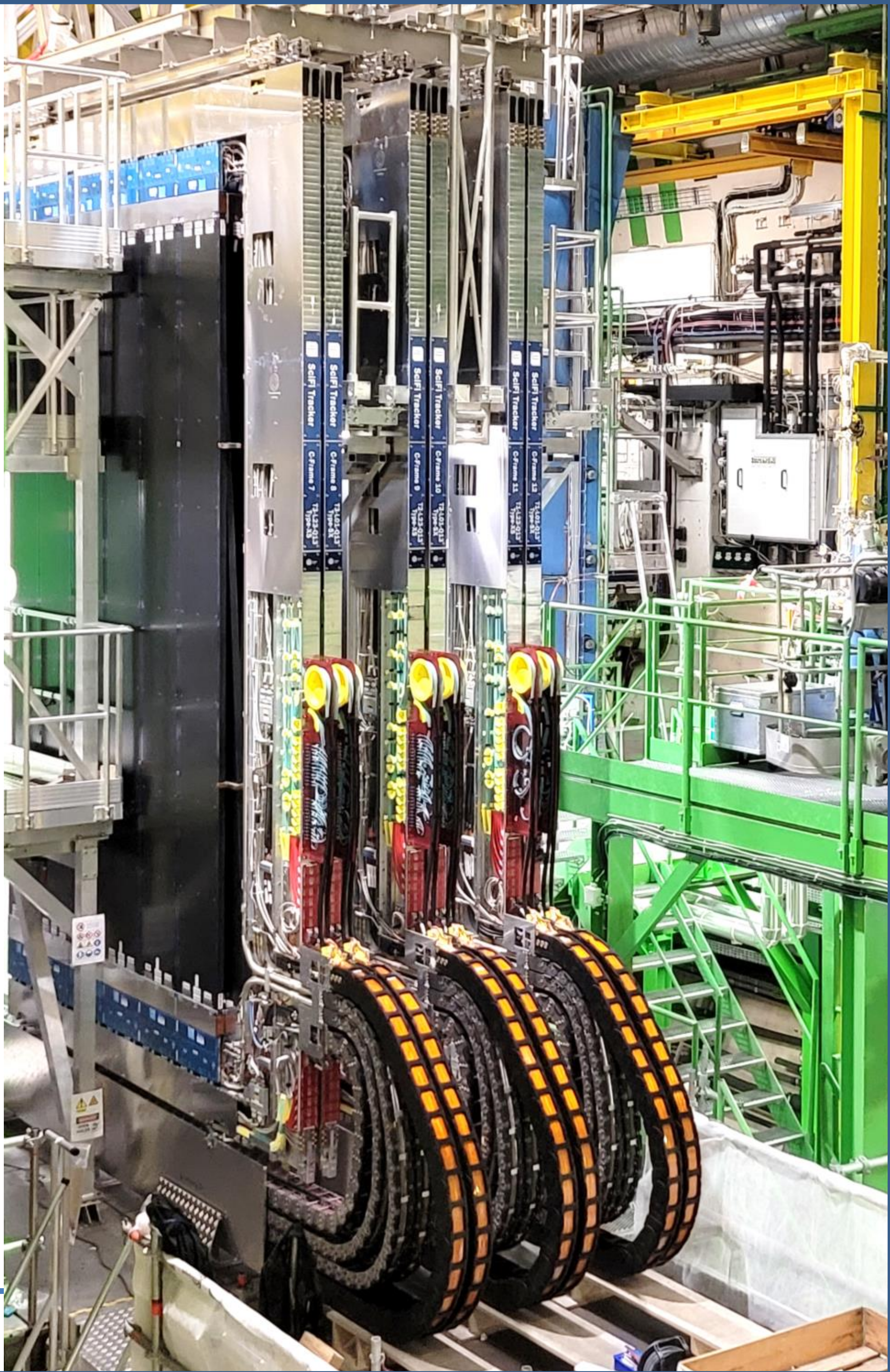
LHCb Scintillating fiber tracker:

From performance requirements to operational detector

30-09-2022

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

LPC Detector Seminar



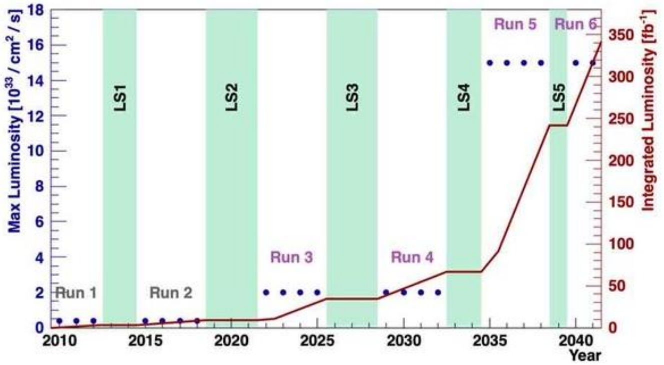
LHCb detector upgrade

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).

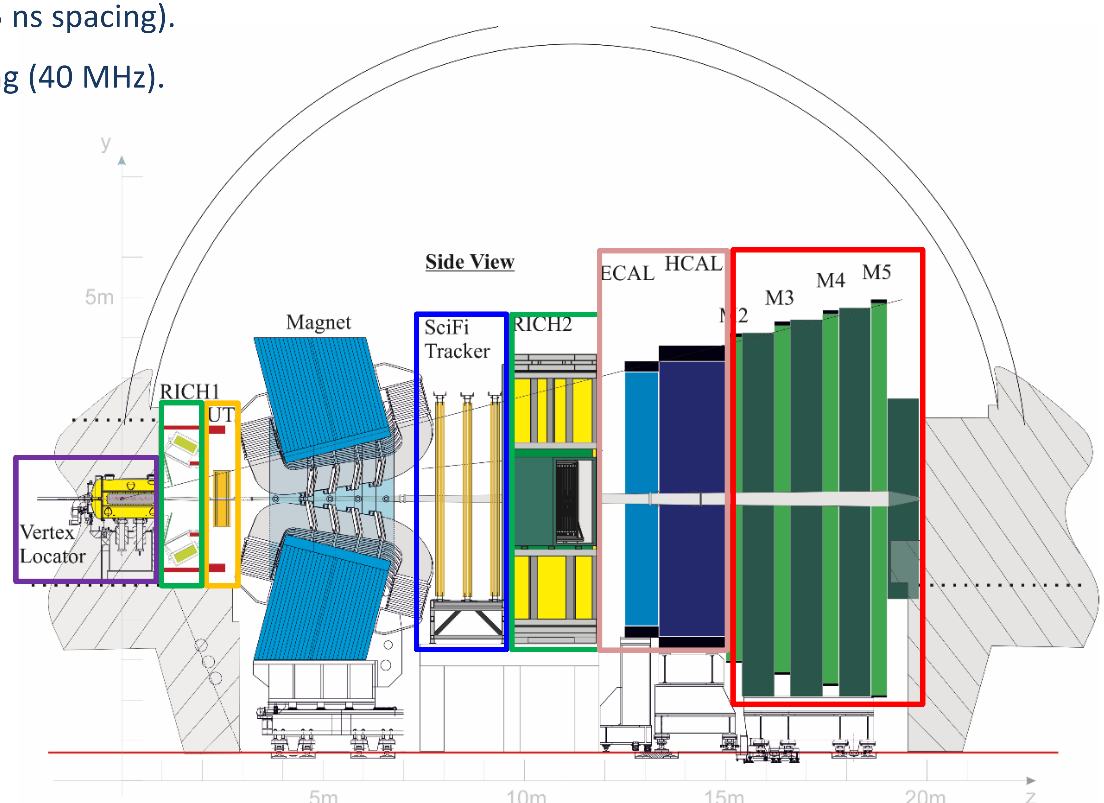


Full replacement of all trackers:

- 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 %.

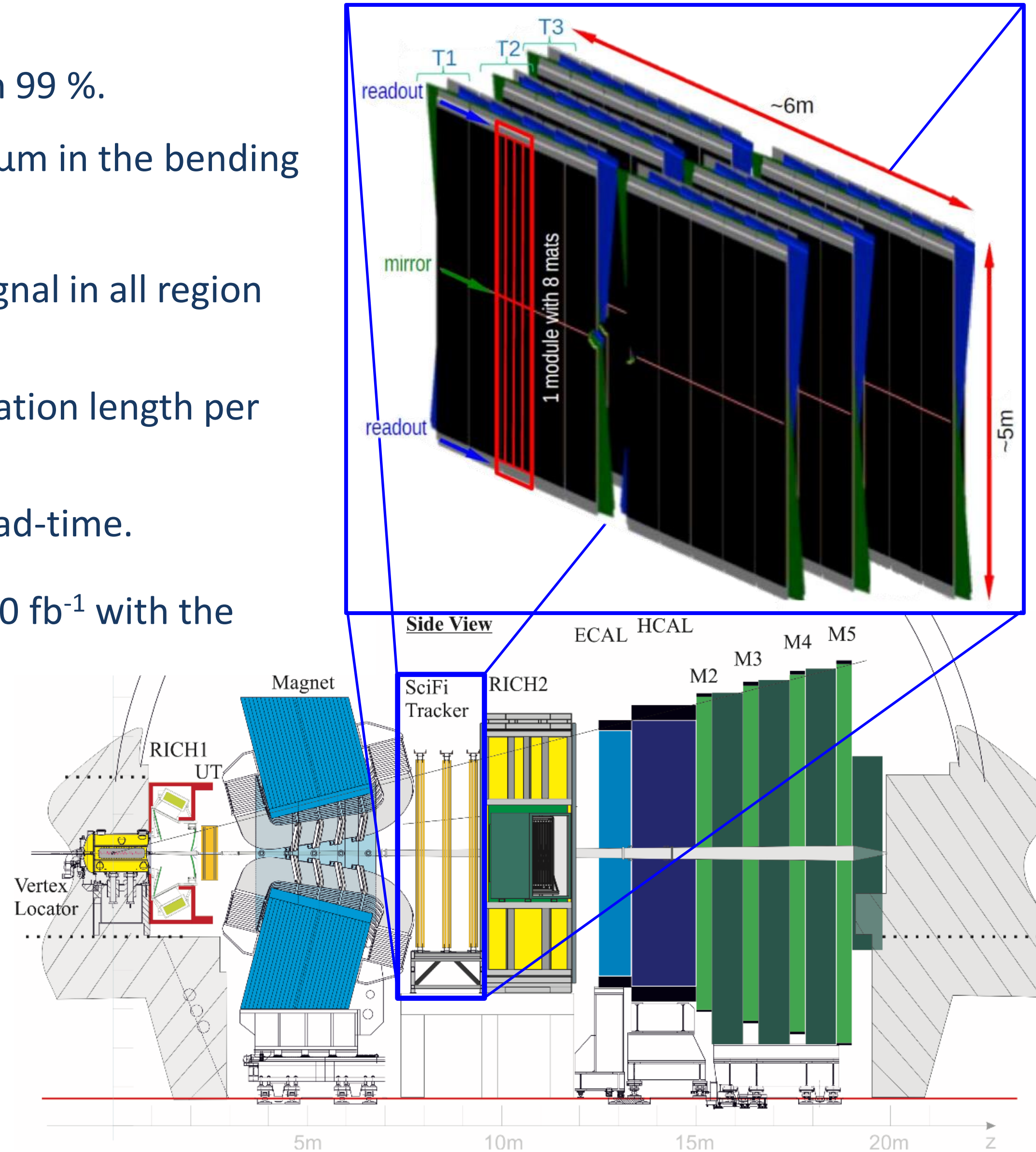
3) **Spatial resolution:** Better than 100 µm in the bending plan of the magnet (vertical).

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.

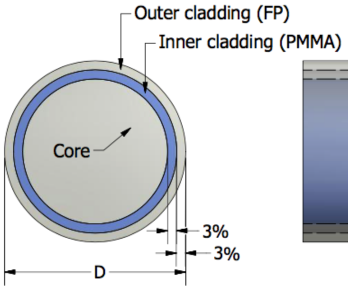
7) **Life time:** Integrated luminosity of 50 fb^{-1} with the above specified performance.

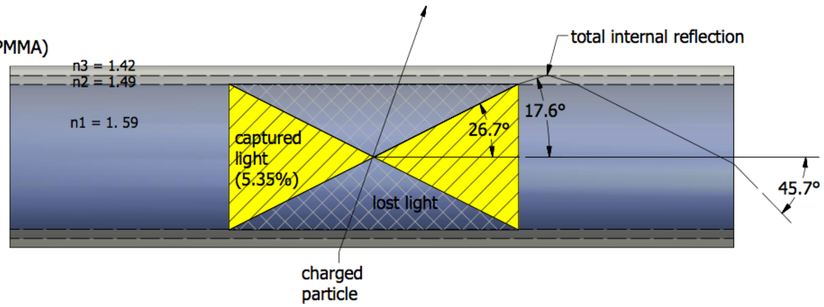


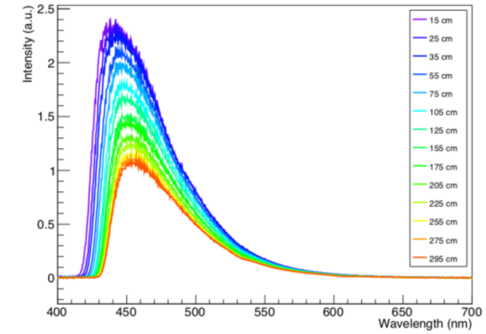
Technology and production

Scintillating fibers

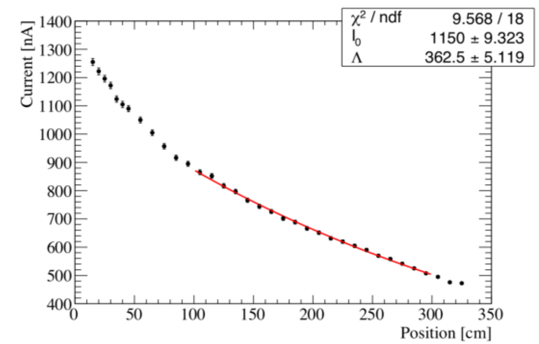
Double cladded round fibres Ø 250 µm (Kuraray SCSF-78MJ) was selected:





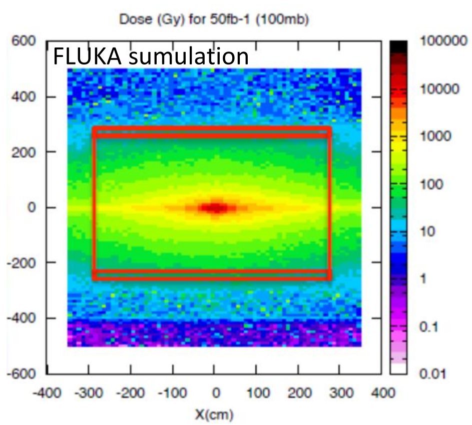


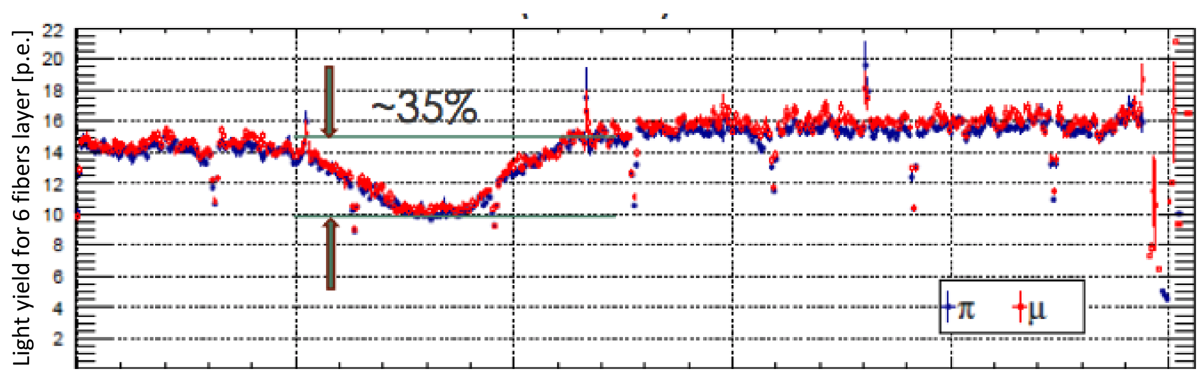
- About 300 photons/MIP
- 3-4 p.e. detected @ 240 cm for a single fiber (trapping fraction, attenuation and PDE of Silicon photomultiplier)
- Emission peak ~450 nm
- Attenuation length ~3.5 m



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).

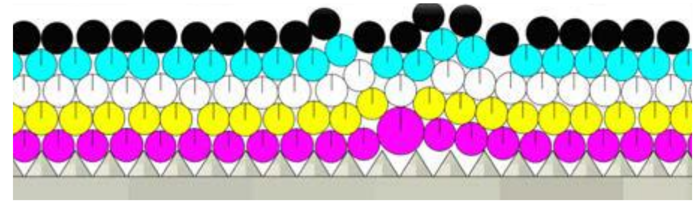
Scanning for diameter anomalis (bumps).

Removal of big bumps (ΔD > 100 µm) without cutting/gluing the fiber.

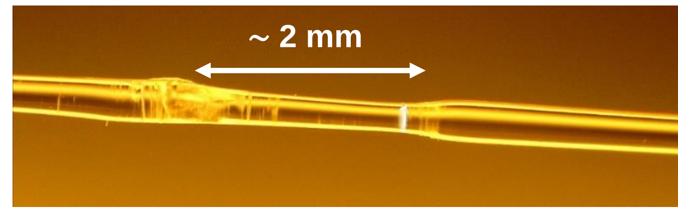
The light yield suffers at the removed bumps, but with 6 fibers in a mat it is tolerable.

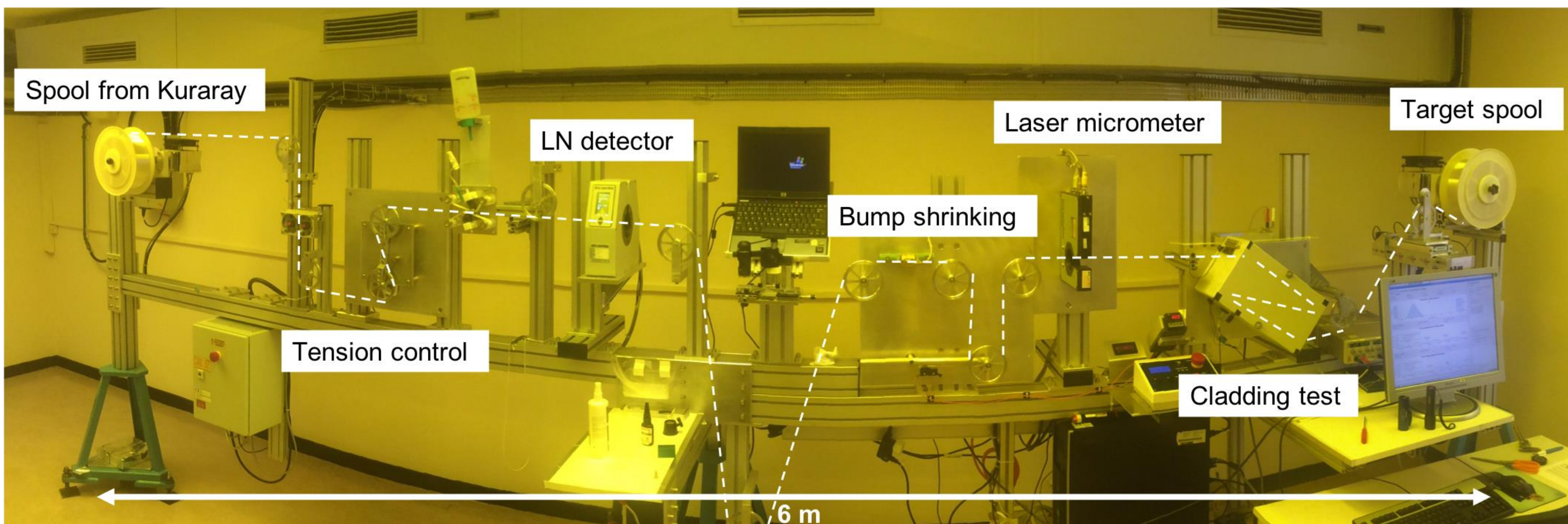
Verification of cladding integrity.

Problem if there is a bump on a fiber



Bump after shrinking





Fiber mat production

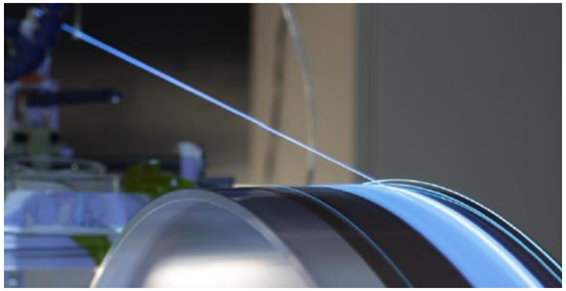
Custom winding machine (Ø = 80 cm wheel with fine thread).

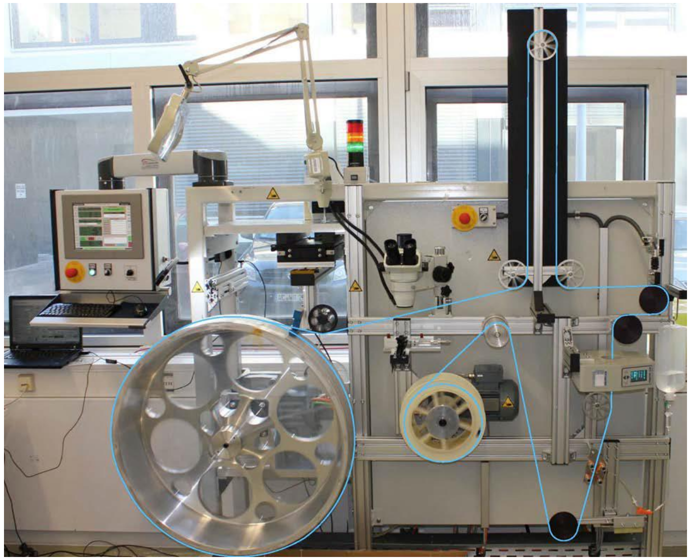
Mat size: 2650 mm x 140 mm.

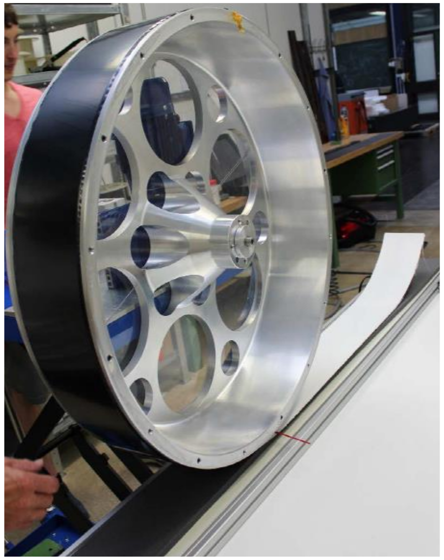
1500 mats produced at 4 sites (incl. spares).

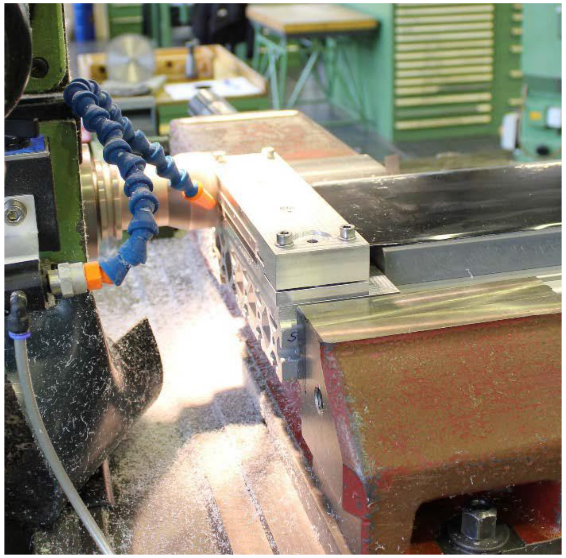
The ends of the fiber mats were milled to optical quality.

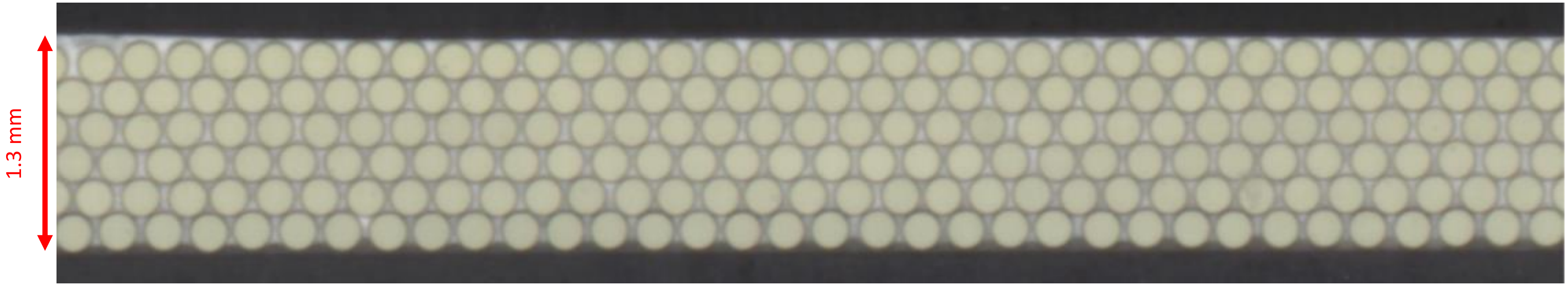
One fiber mat end gets a mirror glued onto it.











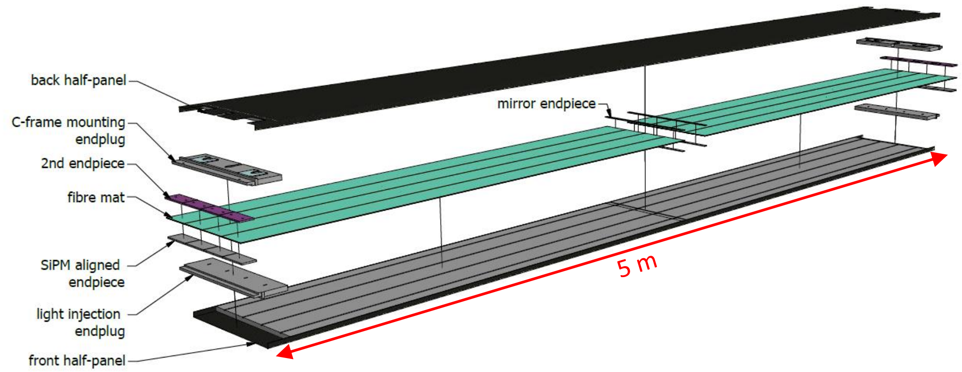
Fiber module production

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.

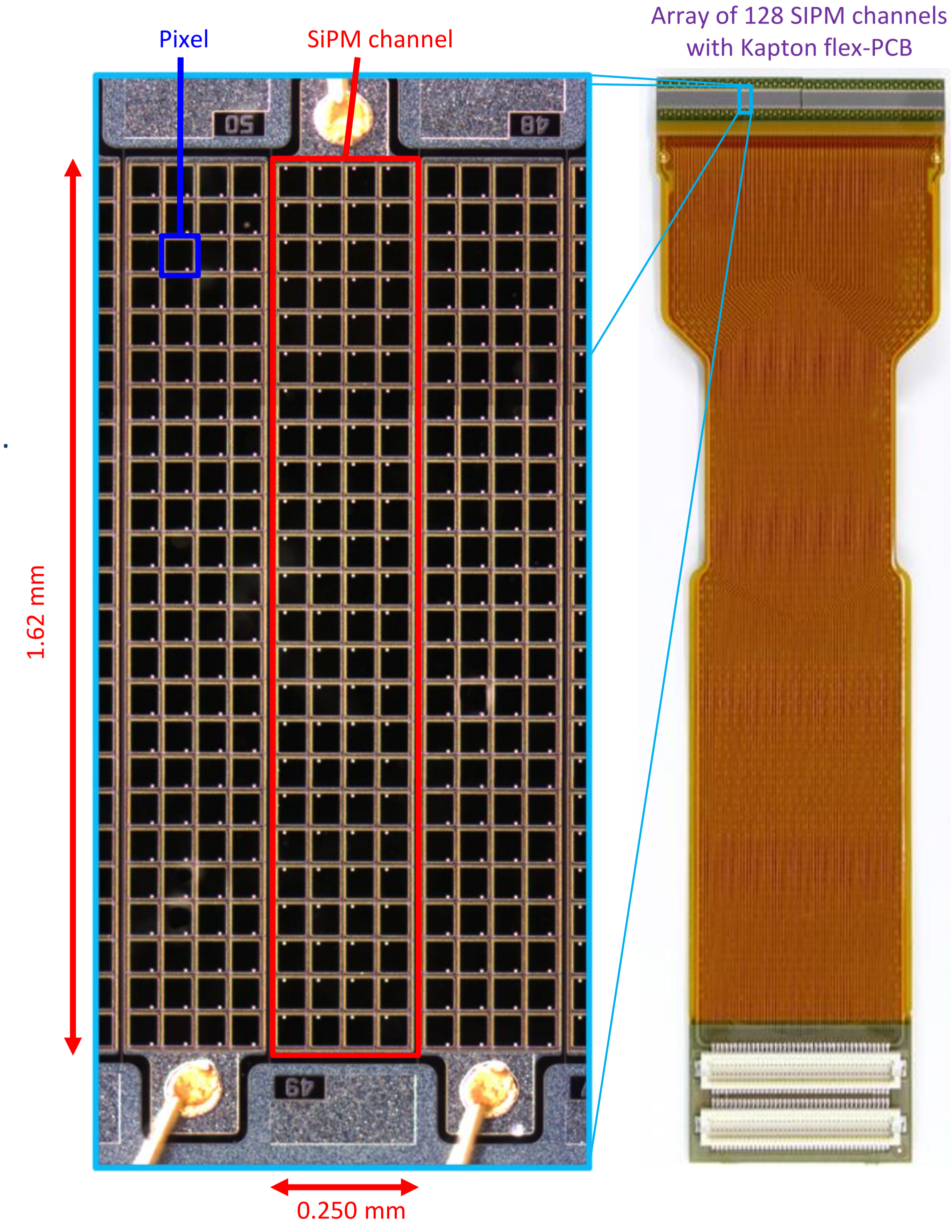
Array model: Hamamatsu MPPC S13552 – H2017.

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

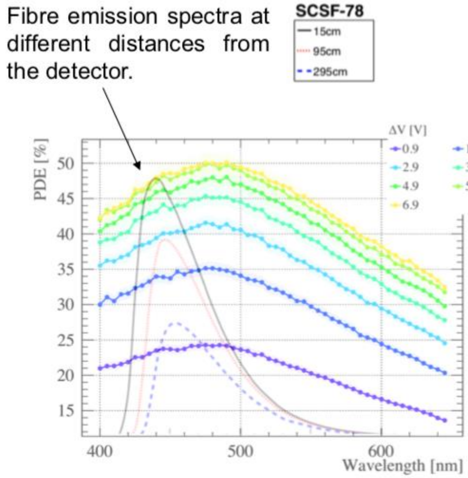
Peak Photon Deletion Efficiency (PDE): 45 % (at over-votlage ΔV = 3.5 V).

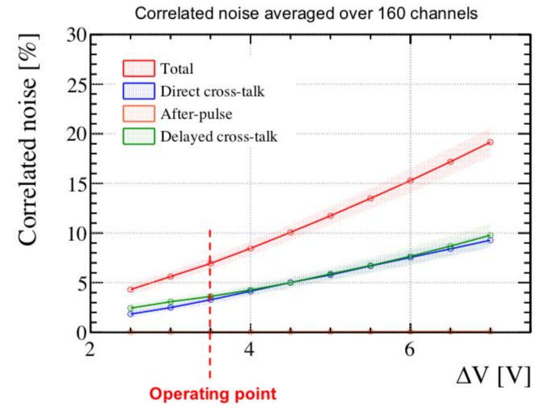
After-pulse < 0.1%.

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.

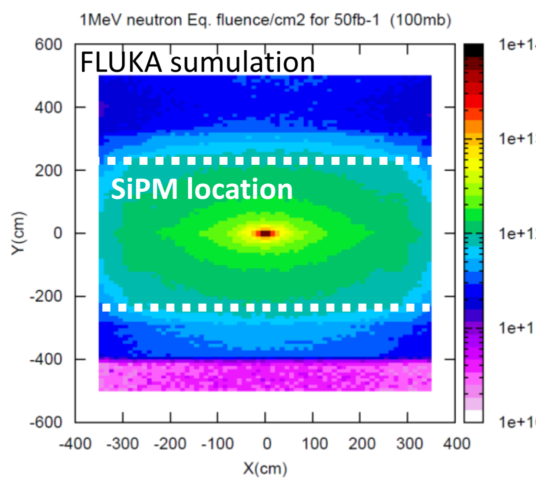
The SiPMs are positioned far from the beam center.

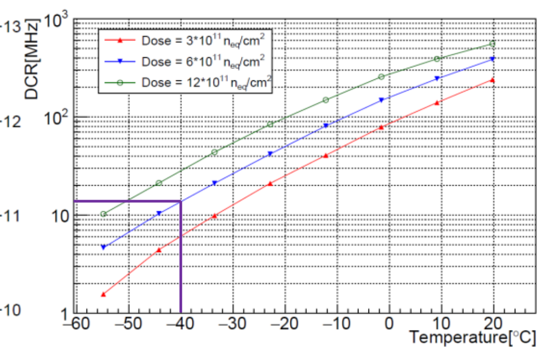
Neutron radiation expected: $6 \cdot 10^{11}$ n_{eq}/cm^2.

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.





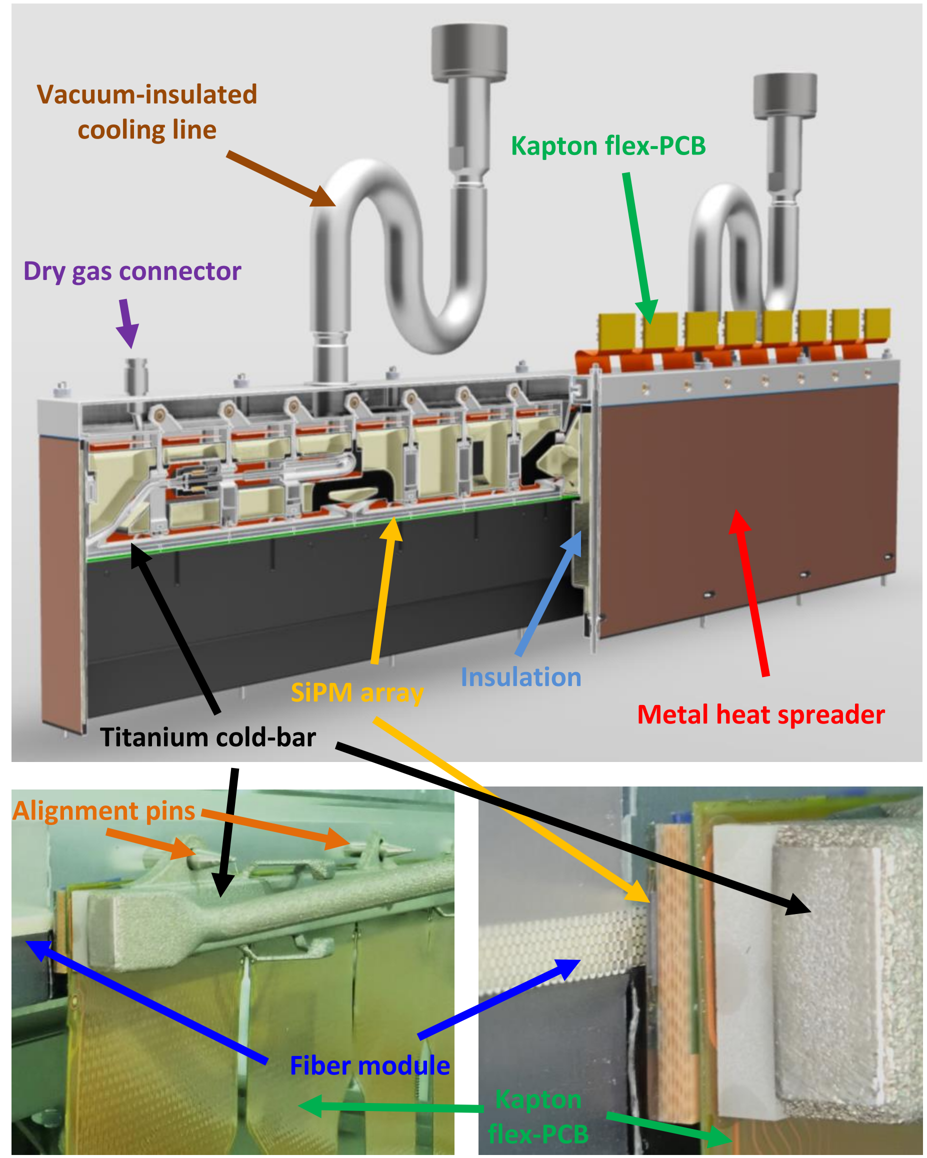
Silicon Photomultipliers cooling

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.

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):

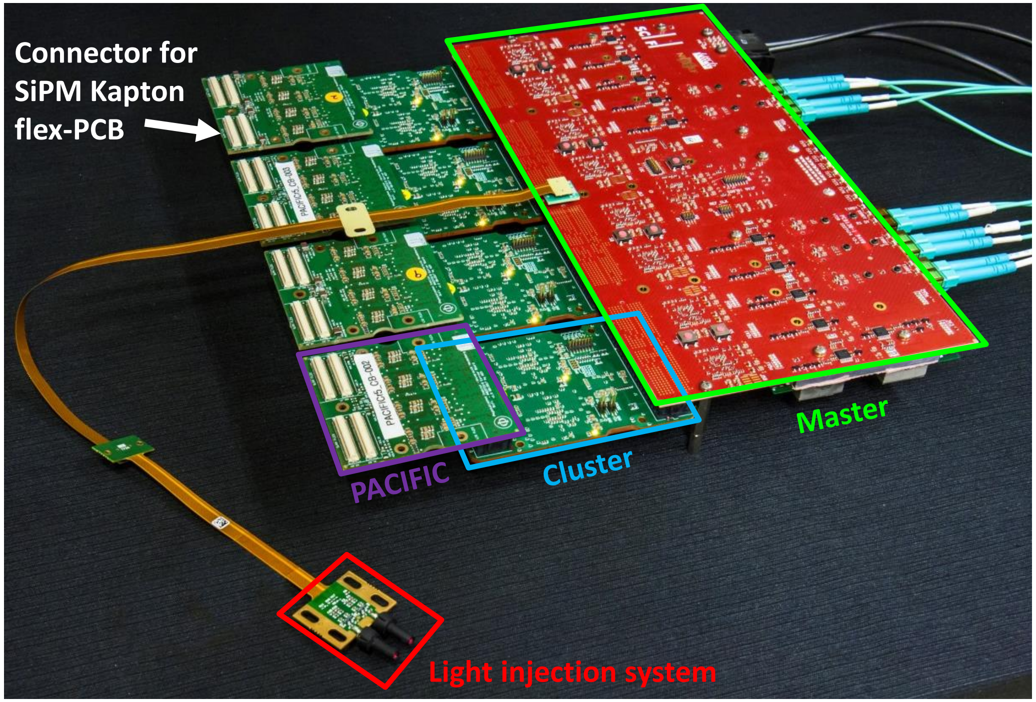
- FGPA (antifuse) based clustering and zero suppression.

Master board (512 needed):

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

Light injection system:

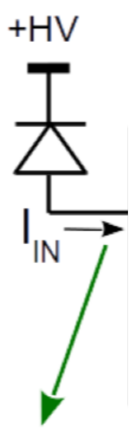
- Generate light pulses for SiPMs for calibration.



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.

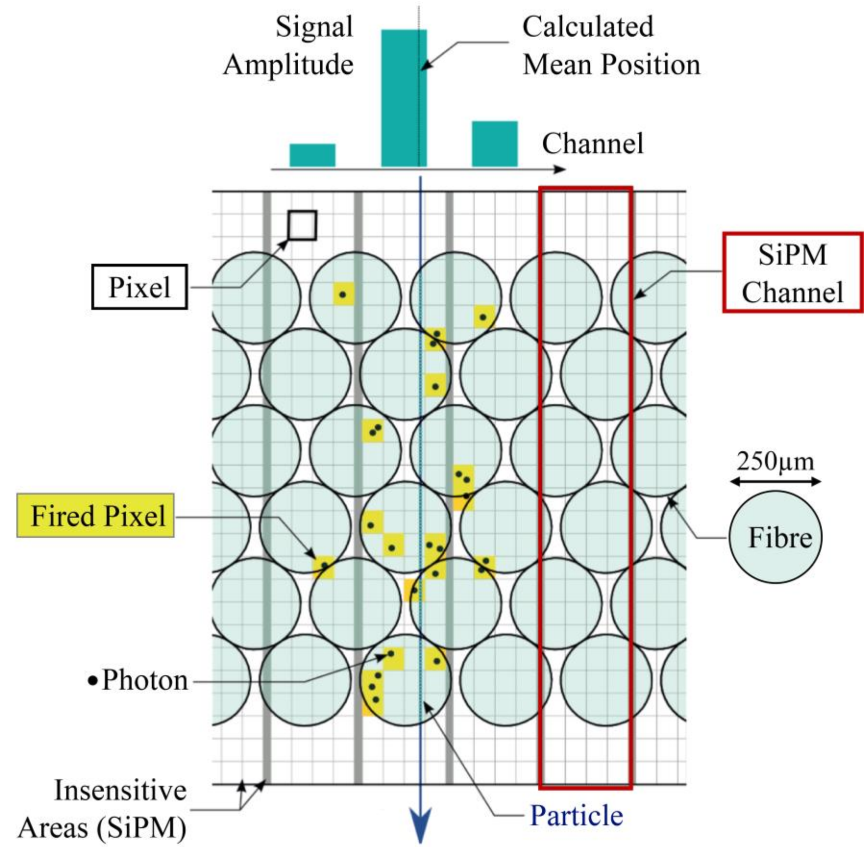
Throughput at 40 MHz.

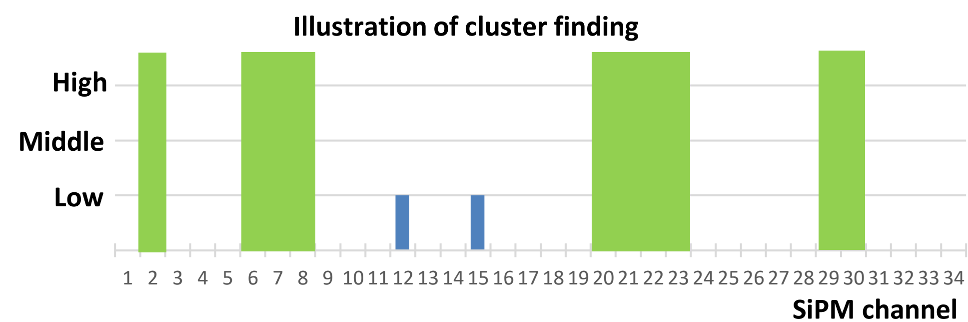
Performance (at full irradiated detector):

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:

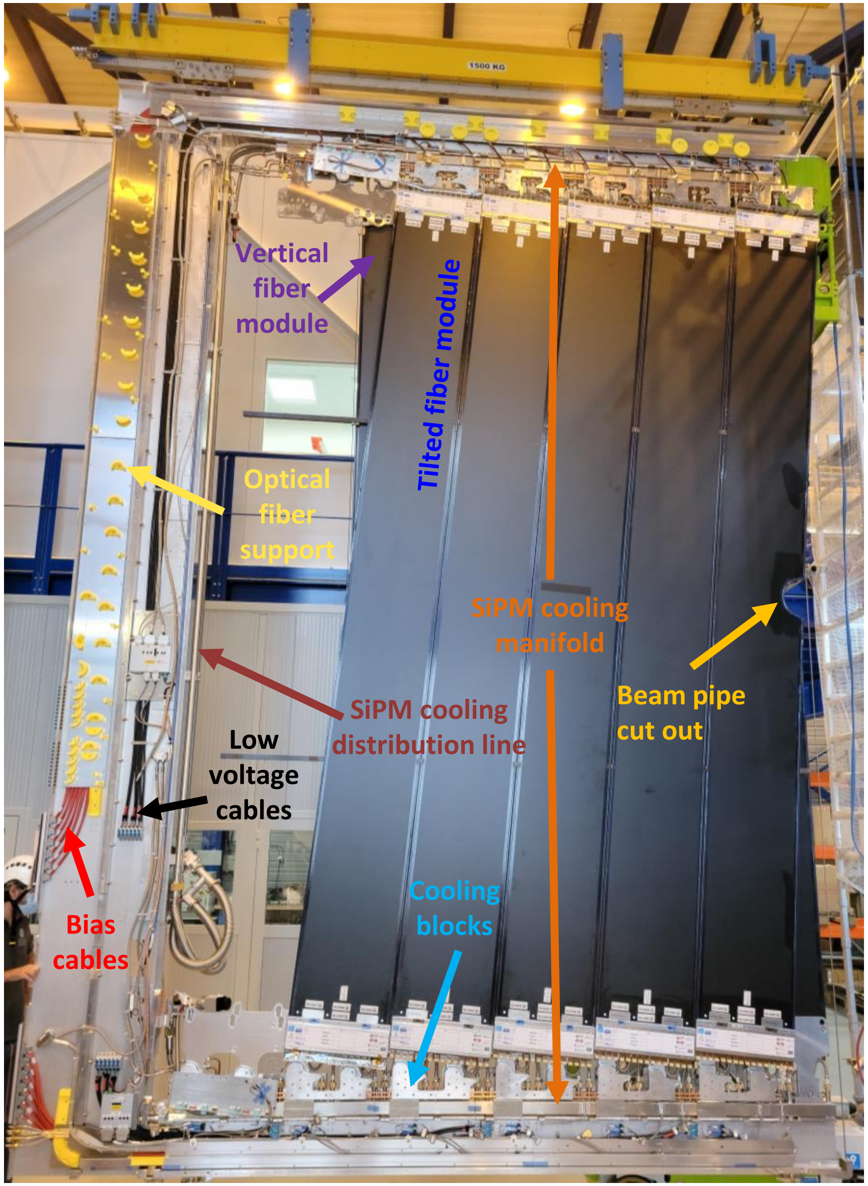
- All optical fibers has identical length to equalize timing, so the optical fiber slag is to be rolled up.

Manifold for SiPM cooling liquid.

- Vacuum insulated.

Distribution lines for SiPM cooling liquid.

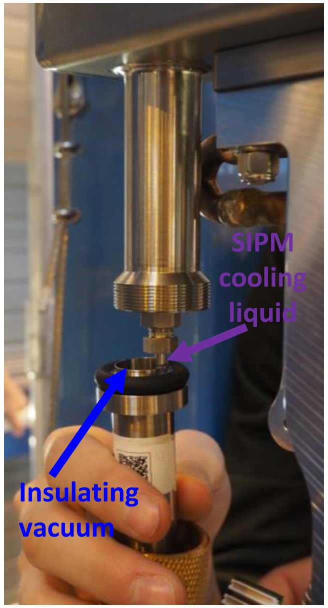
- Vacuum insulated.



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.

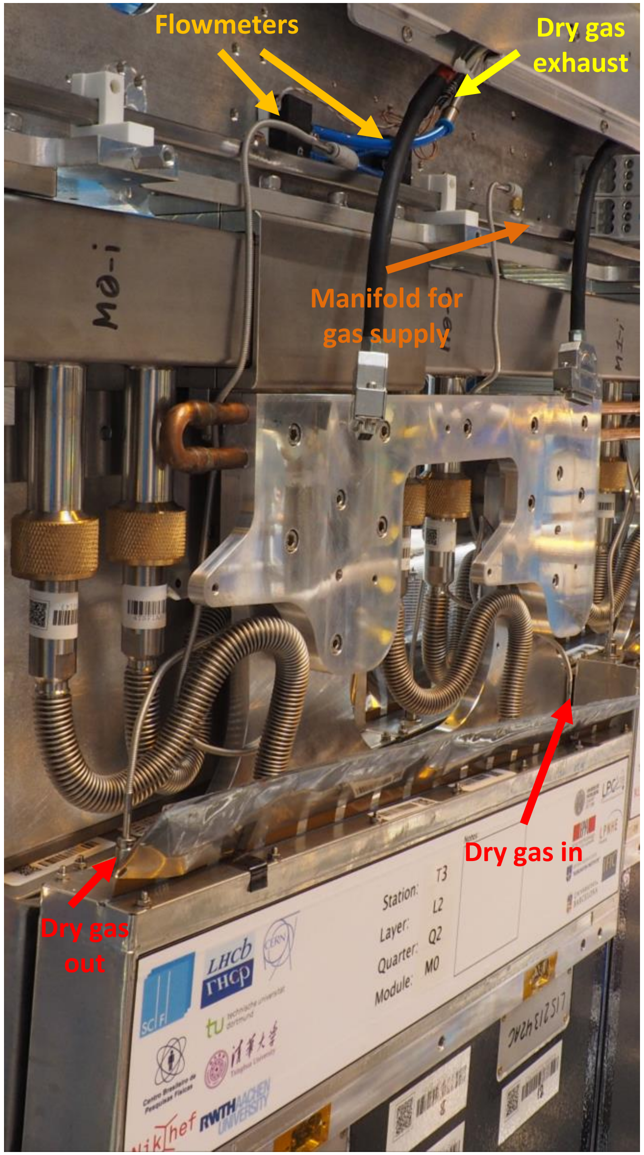


2 Pirani vacuum sensors per C-frames

- 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

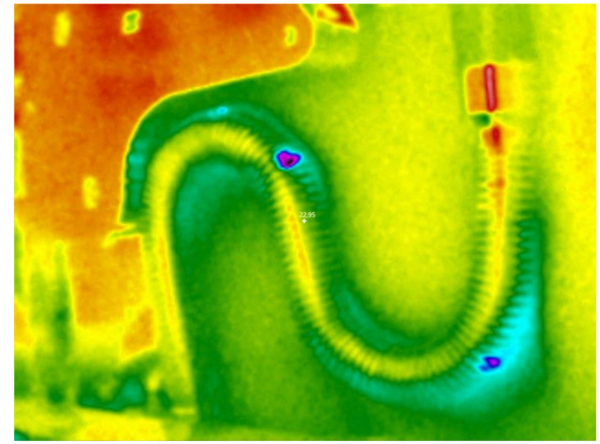
During assembly testing a major problem was discovered:

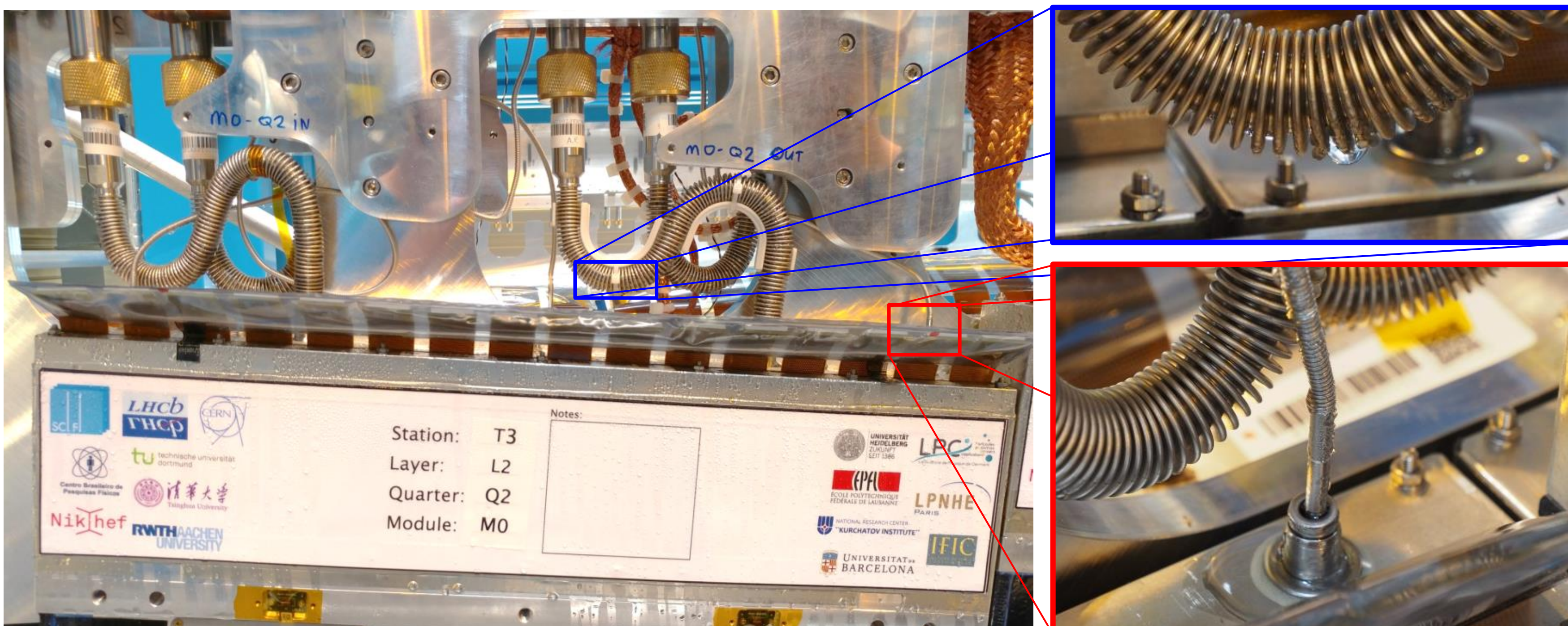
- Condensation observed on the first assembled C-frame (July 2019).

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.

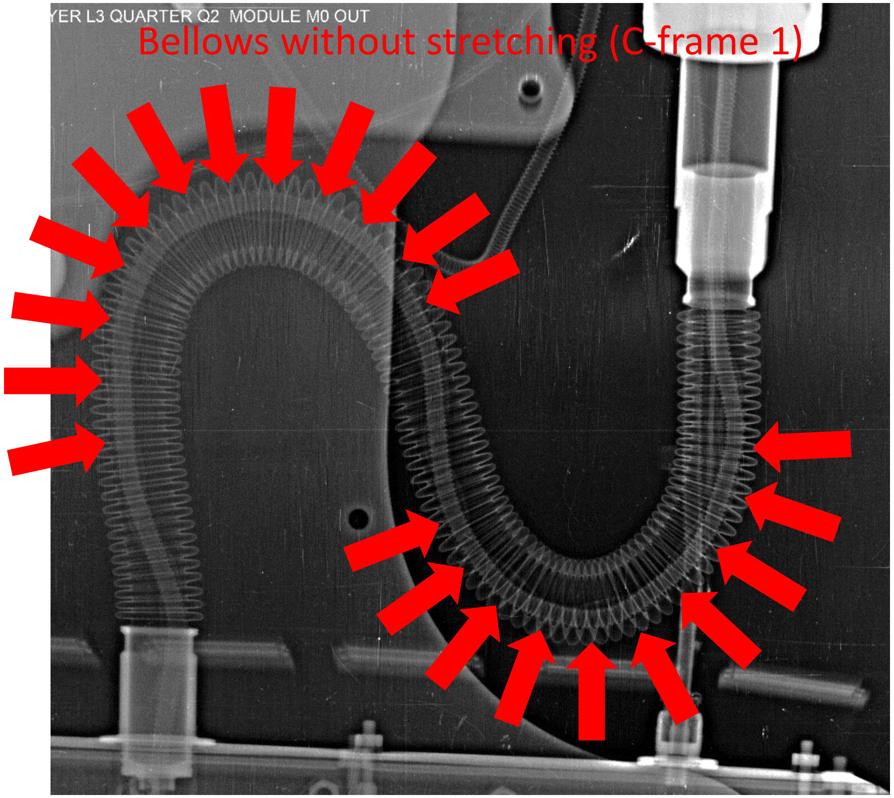


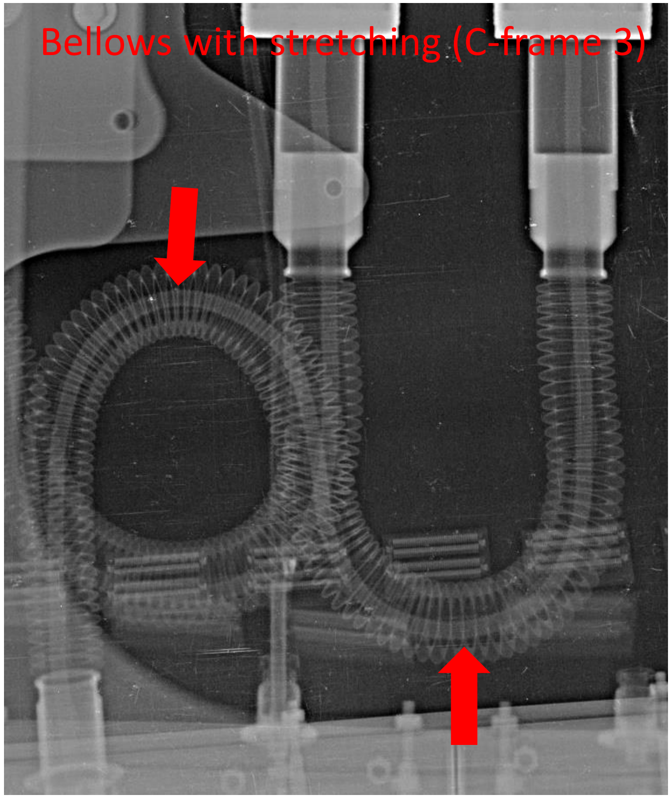


Condensation problem – Solution part 1

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.

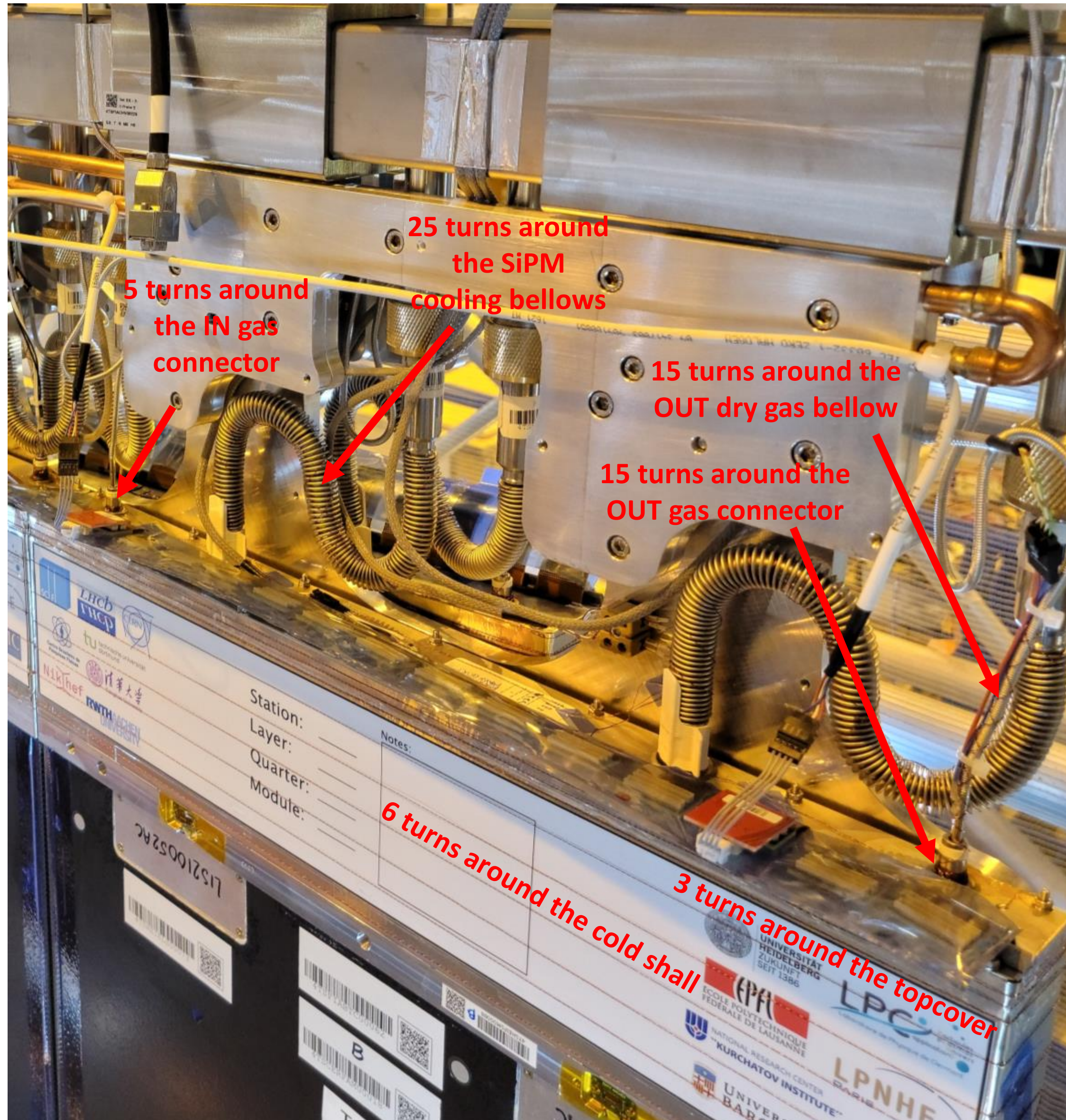
The most effective solution was active heating using an heating wire:

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.

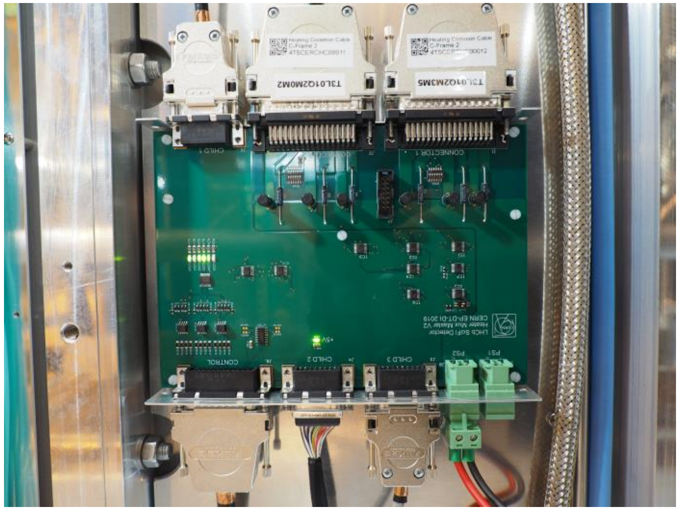
The wire is actually a twisted pair with current in opposite direction to avoid introducing a magnetic field.



Condensation problem – Solution part 2 continued

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

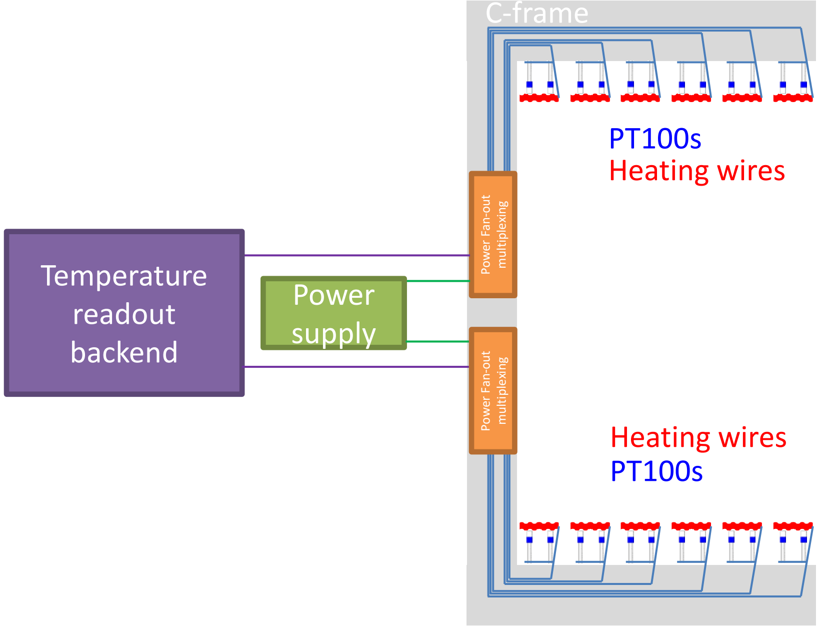
Custom made radiation tolerant multiplexing board for the PT100 readout was integrated on the C-frame.



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.



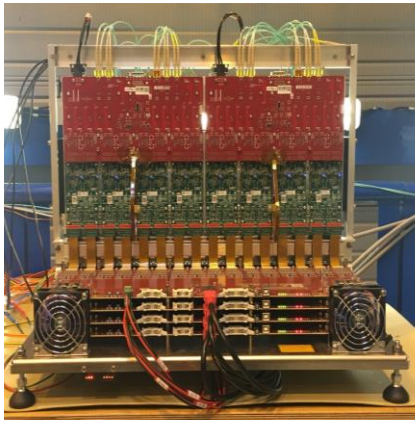
C-frame assembly – The last bit

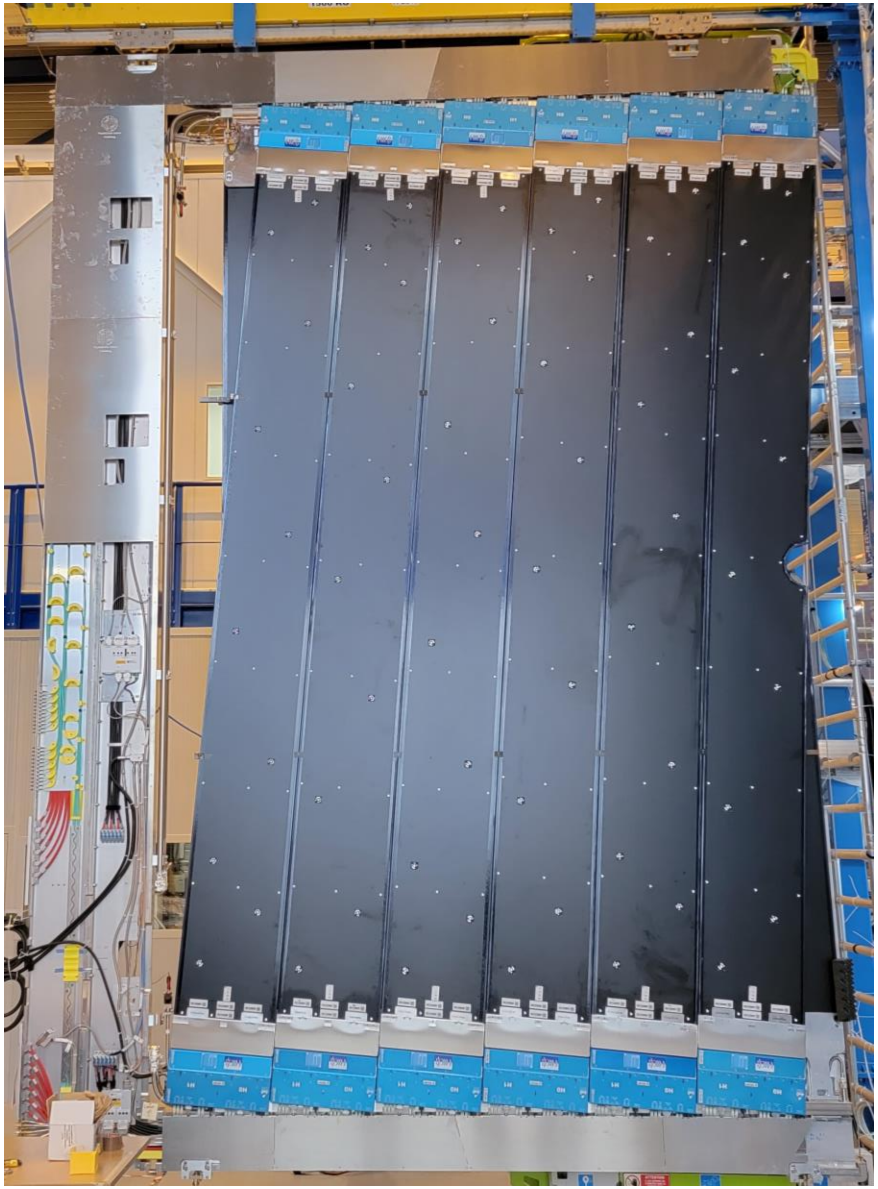
All Front-End electronic was thoroughly tested on 2 dedicated test benches by providing input signals to all channels and measuring the optical output.

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.

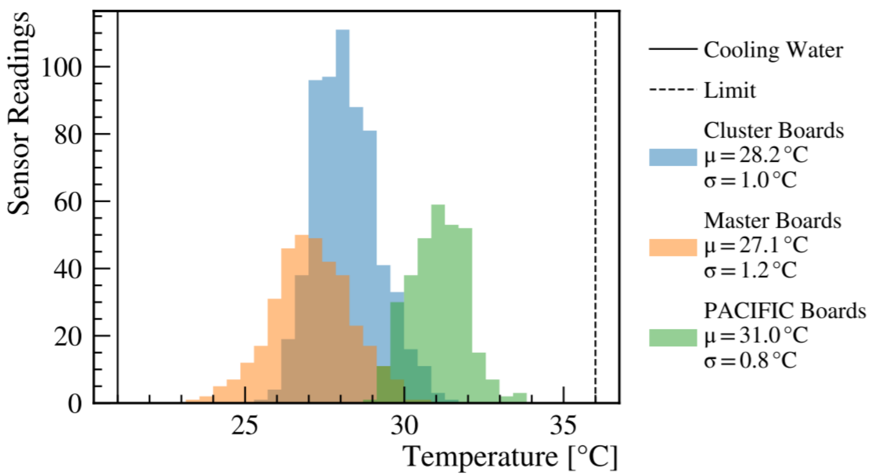




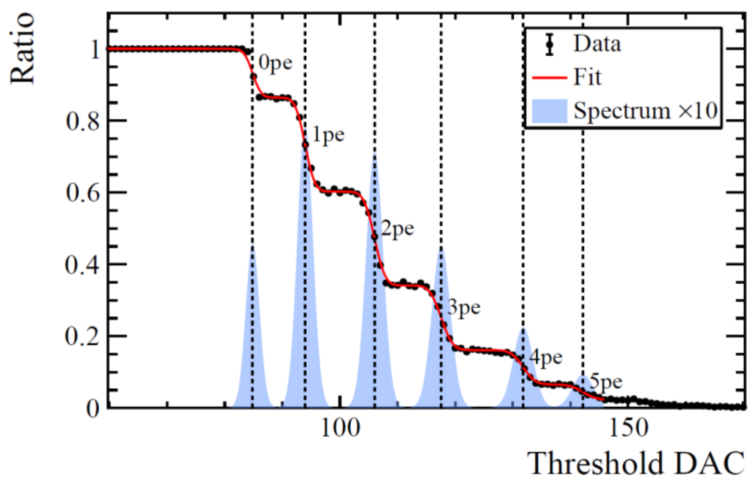
Testing of full C-frames – Front-End electronics

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.

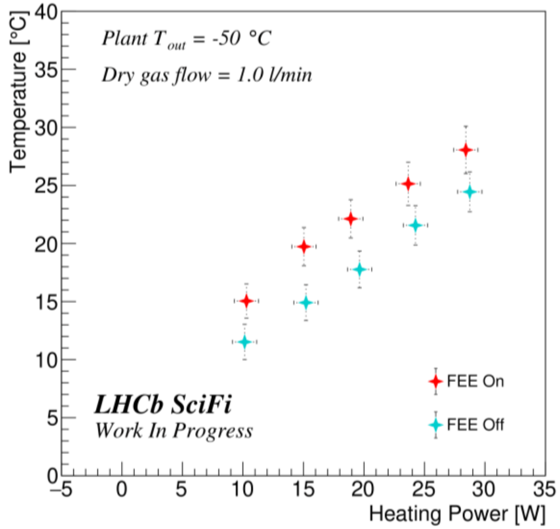
Helium leak test on all SiPM cooling and vacuum circuits.

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

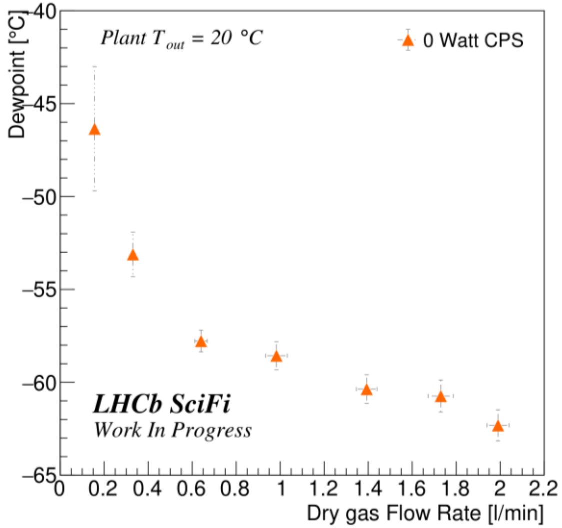
Results used to select operation parameters.

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

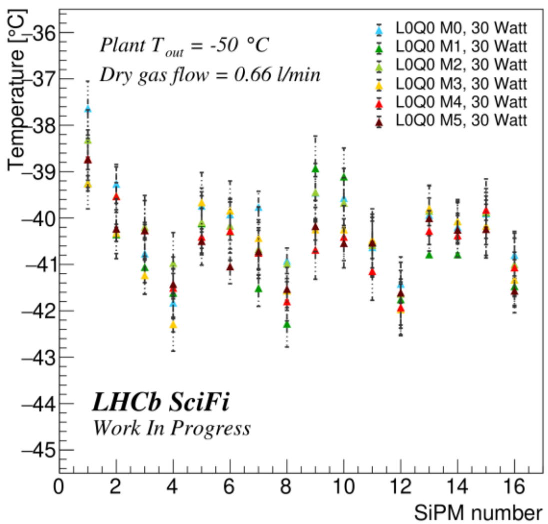
Gas connector temperature vs heating wire power



Dew point AFTER coldbox vs flow



Temperature distribution in coldboxes – systematic same pattern in all



C-frame assembly – Survey of the detector

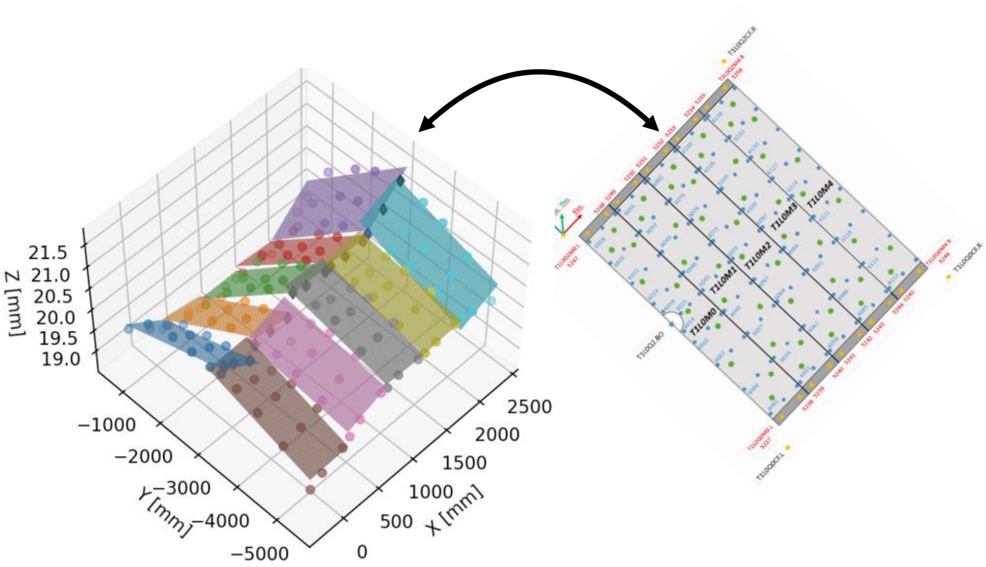
The detector was hang on a dedicated installation frame and reflective stickers installed on the modules.

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

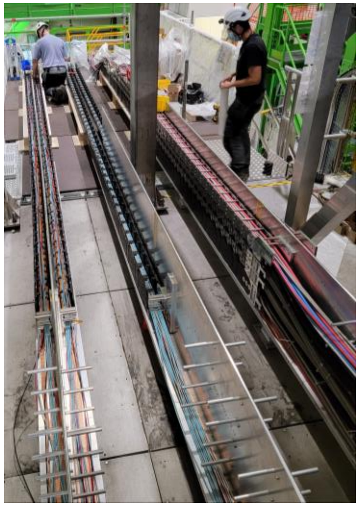
- 4 cable chains are needed for all the cables and services for a C-frame.

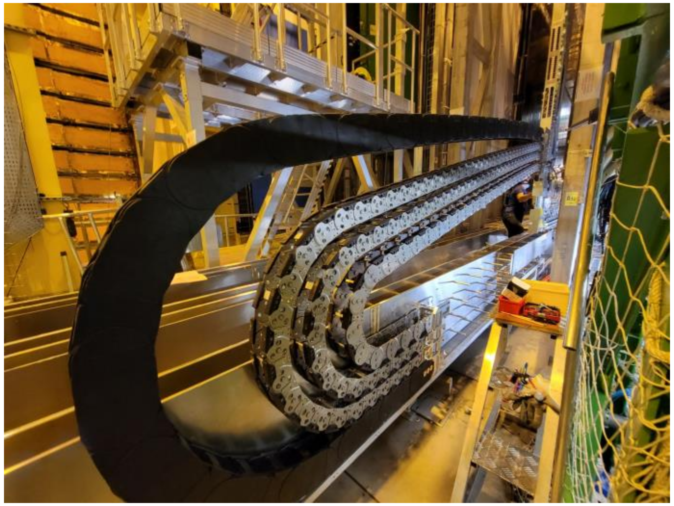
The chains were filled with cables before the C-frames were installed.

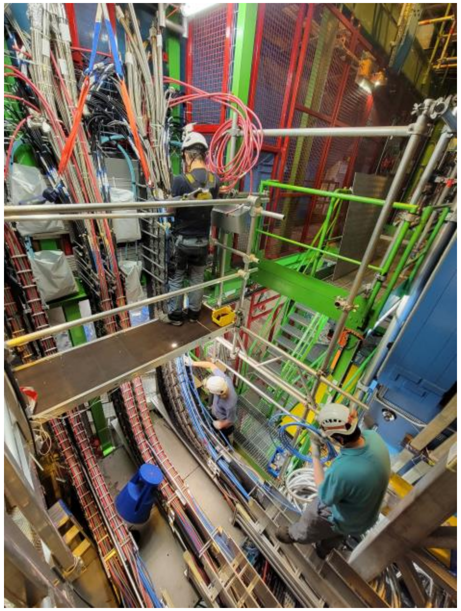
- A-side: Easy, the chains could by laid flat.
- C-side: Difficult, the chains had to be filled hanging on the wall due to space constrains.

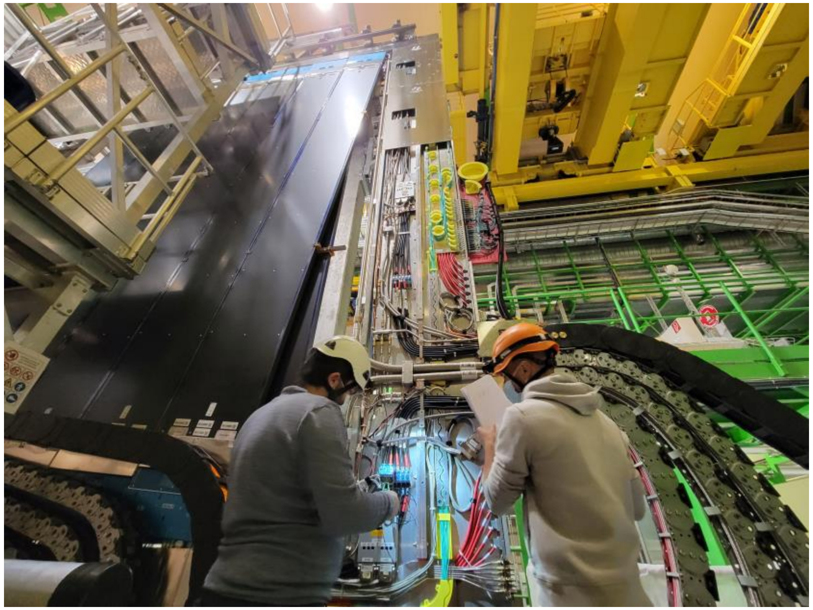
Connection of chains to C-frame.

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.

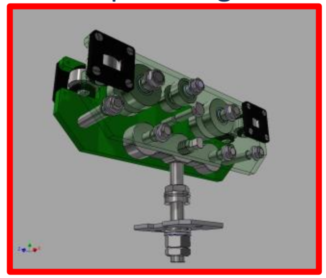
Main priorities of alignment:

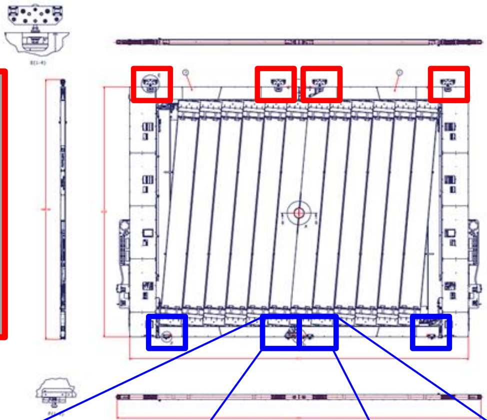
- Adjust such that the cut-out fits around the beam pipe.
- A-side and C-side C-frames can overlap without touching.
- Check reproducibility (important after interventions where the C-frames needs to be open).
- Provide a starting point for track based alignment.

Movement and securing of C-frame:

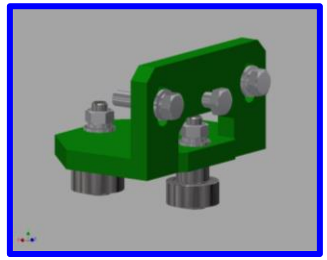
- Far from the beam pipe, the C-frames are moved by hand.
- The last ~2 m movement are done with a threaded rod.
- The system also keeps the C-frame in the desired position.
- Precision toward beam pipe by mechanical stopper.

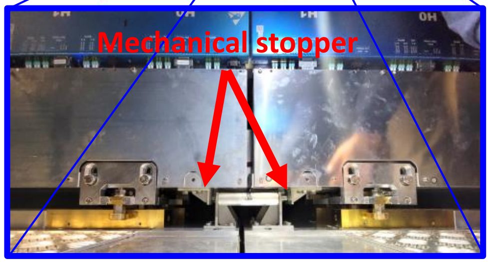
Top carriage

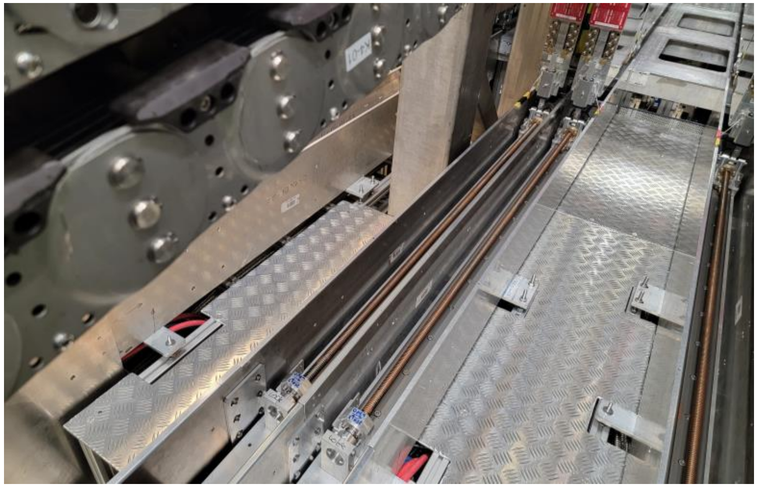


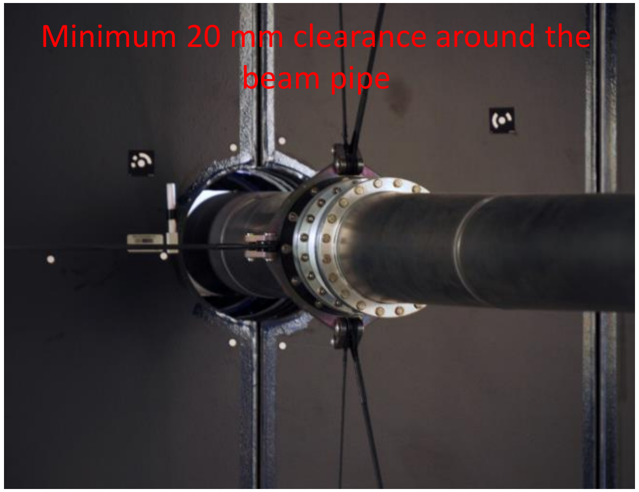


Bottom carriage

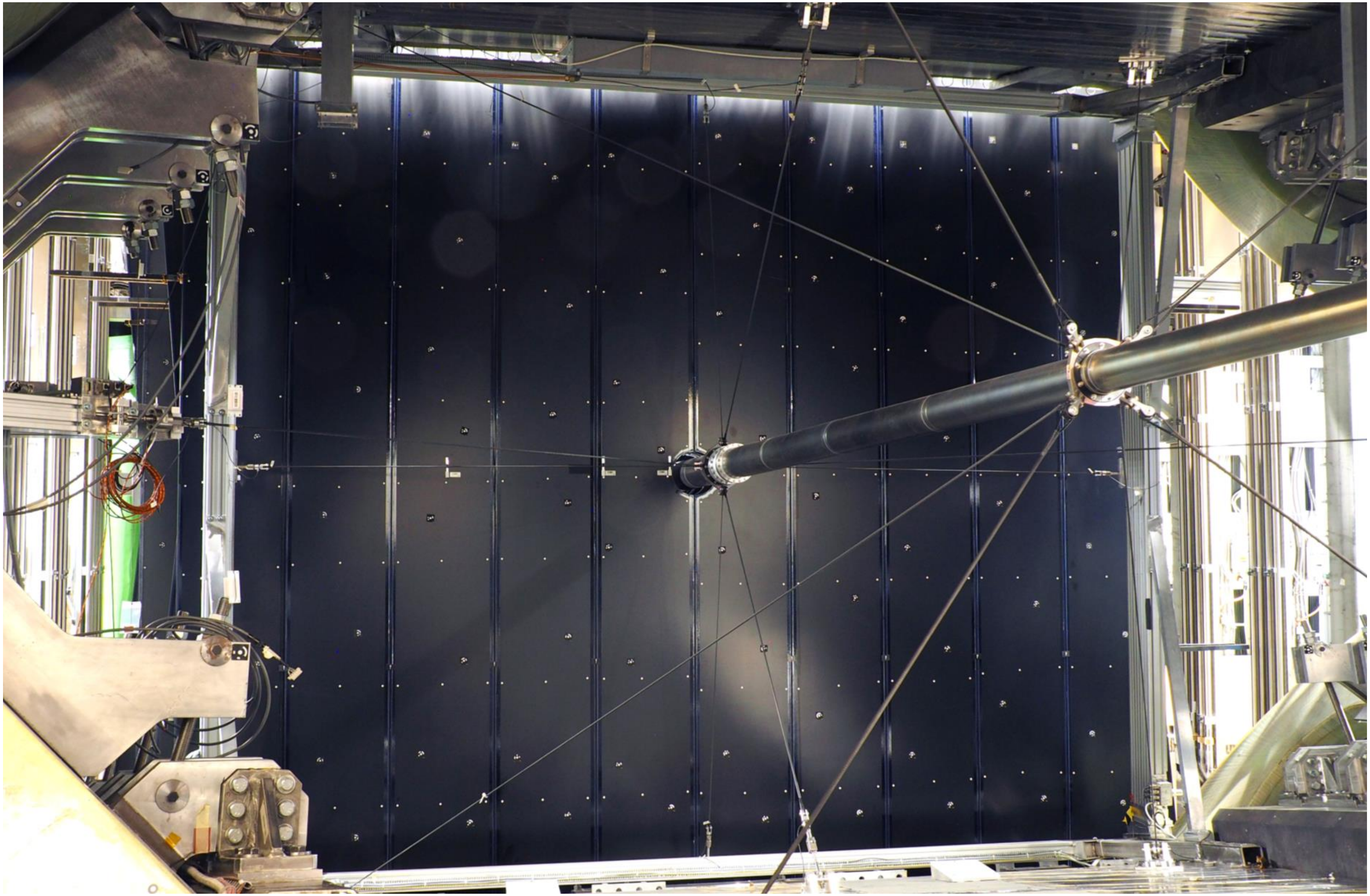








The closed SciFi detector seen from the magnet



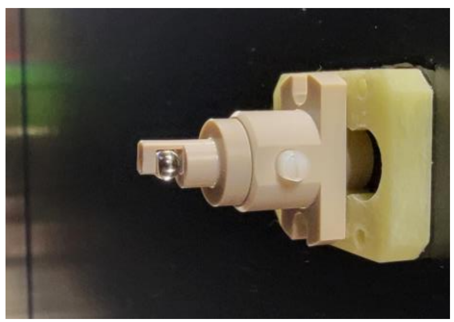
Monitoring of position over time – BCAM system

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:

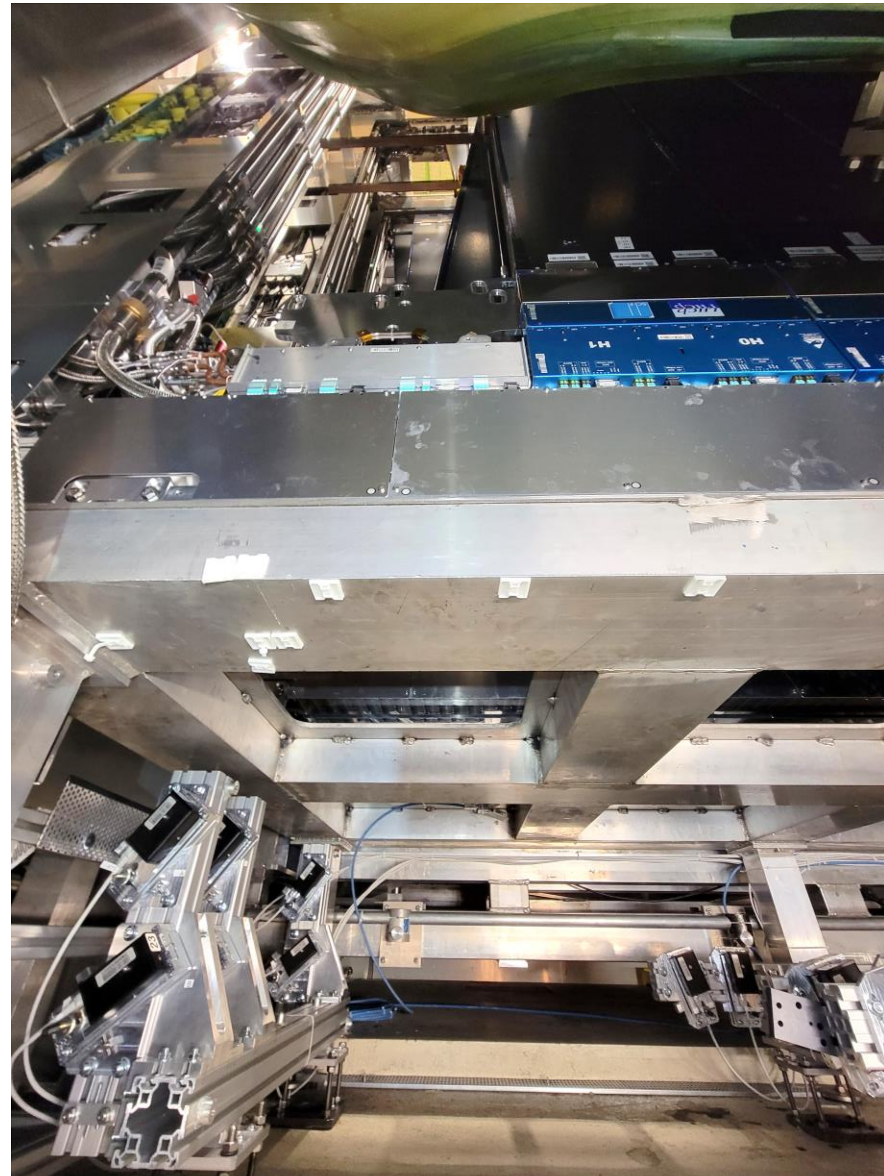
- 24 cameras are installed under the floor of SciFi.
- 42 targets (ø4-6 mm high index glass balls) are installed on the C-frames.



- 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.

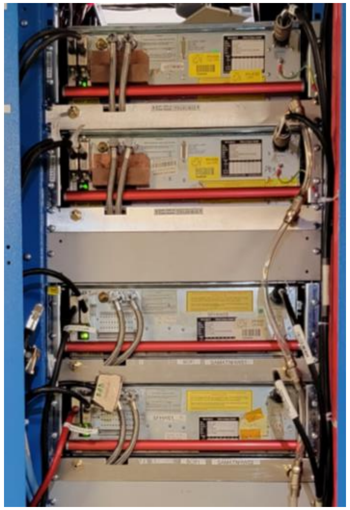


Low voltage and bias voltage

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).

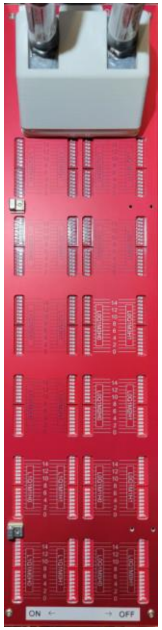
MARATON rack



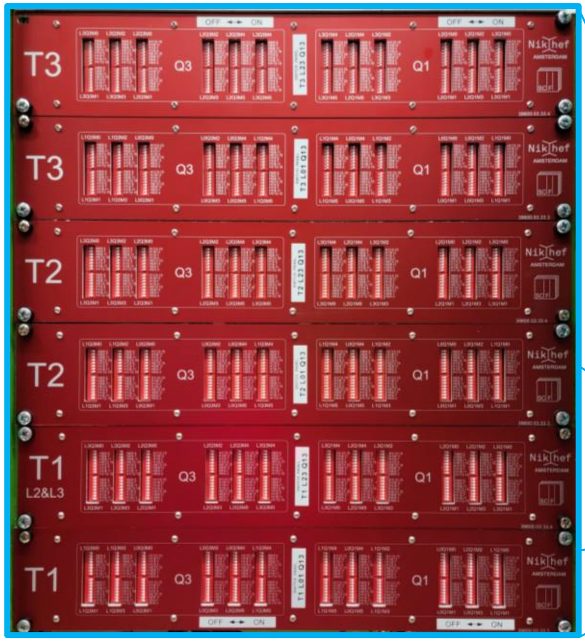
The bias voltage power supplies are installed in a zone with permanent access and about 80 m (cable length) from the detector (as very low current is required).

- 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

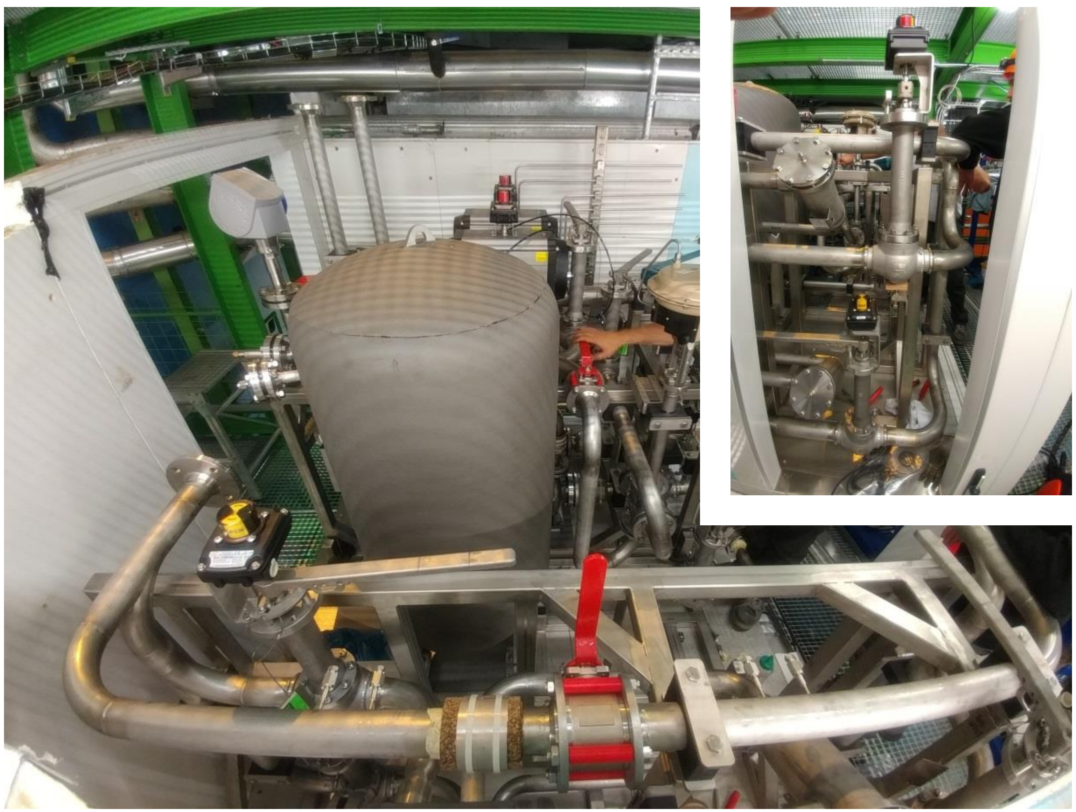
The cooling plant for the SiPMs are build at CERN.

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).

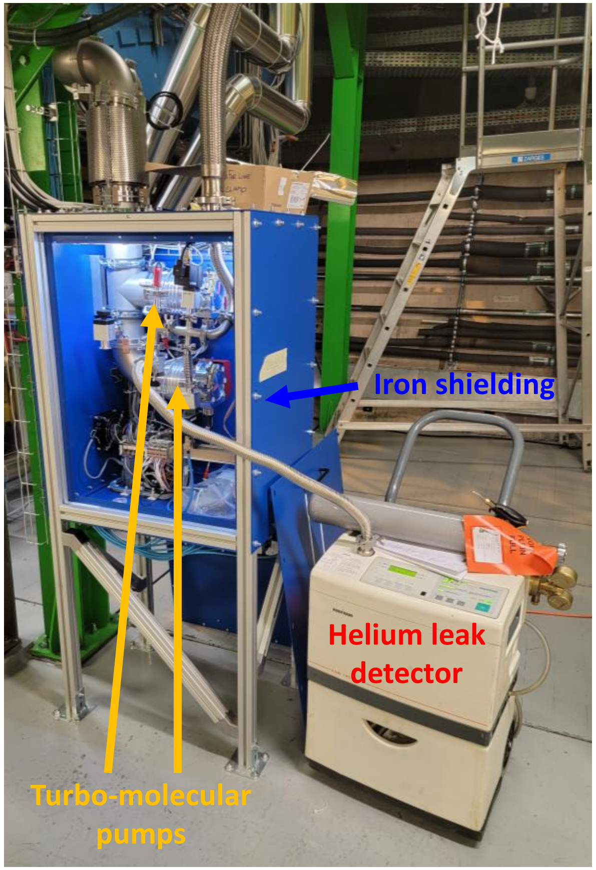
The turbo-molecular pumps are housed in a shielding cabinet consisting of to layers of iron for magnetic shielding.

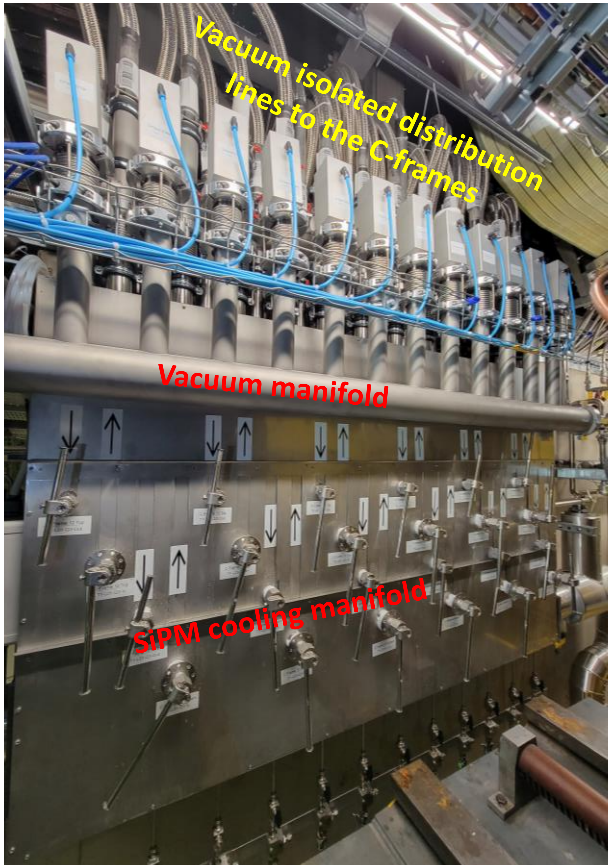
The vacuum manifold is located about 2 m from the turbo-molecular pumps.

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.

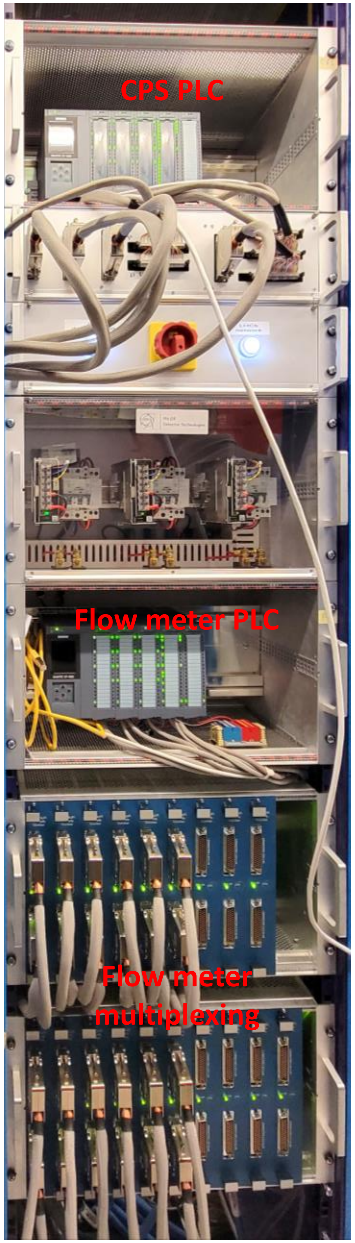
2 commercial dryers of model AtlasCopco CD65+ are used for redundancy.

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

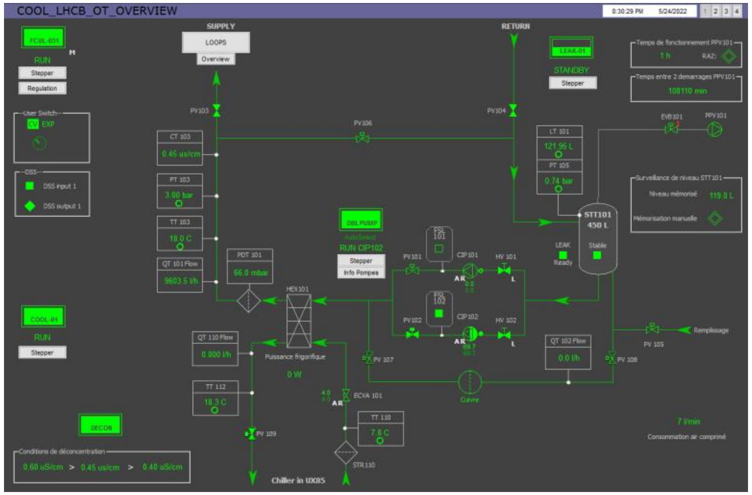
Low level UNICOS and high level LHCb Detector Control System (DCS) has been made to control and monitor the services.

Finite State Machine (FSM) made for all services.

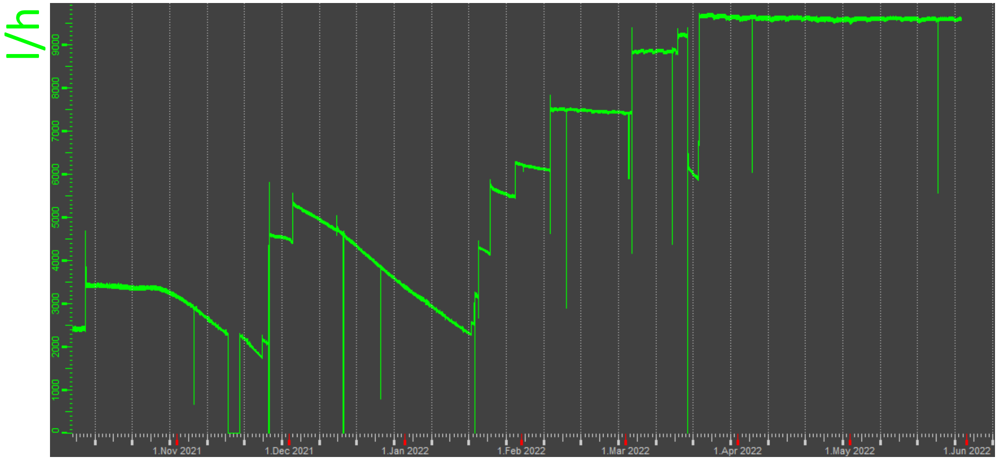
The Front-End cooling system has been fully commissioned.

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

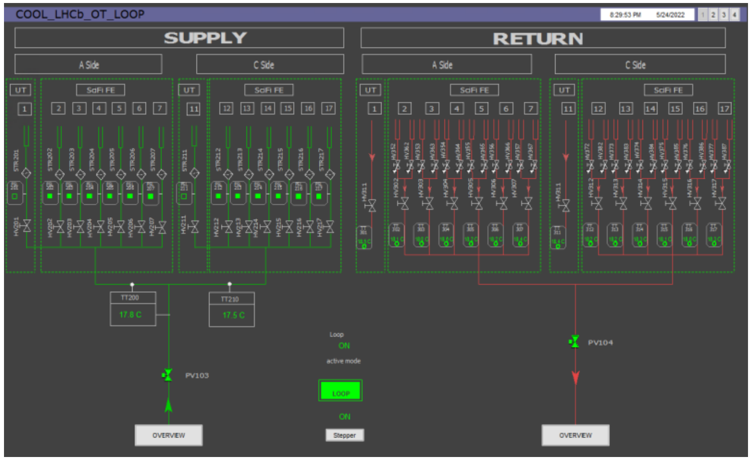
Plant



Overall flow during clogging problem after it was fixed



Manifolds



SiPM Cooling

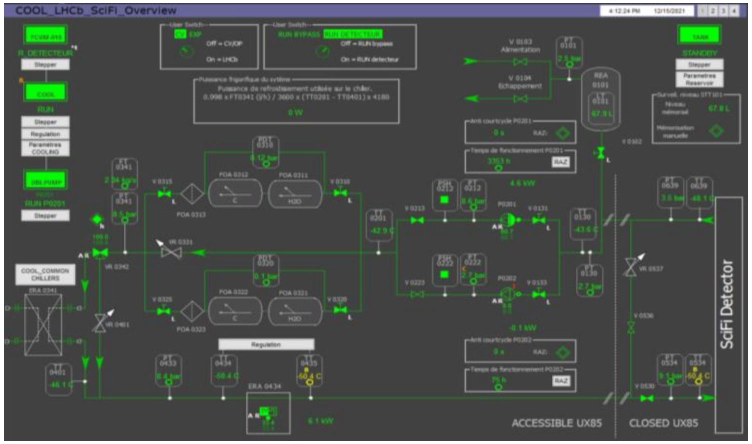
The SiPM cooling system has been fully commissioned.

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

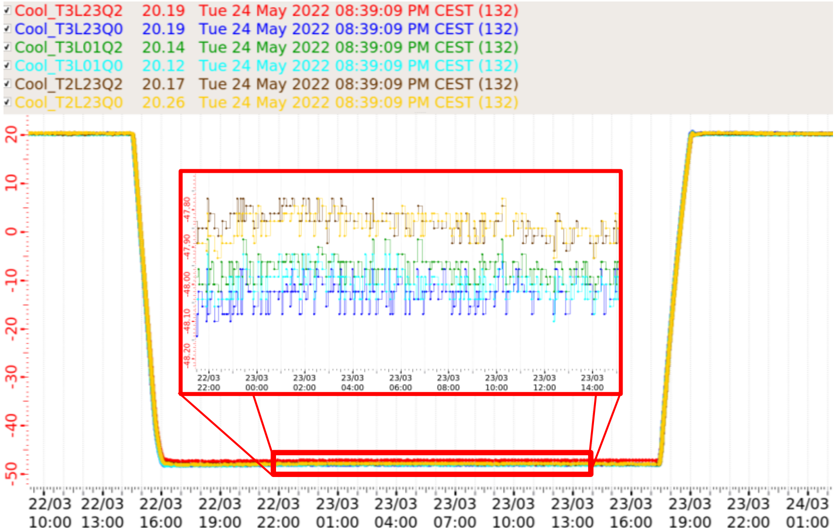
Temperature stability very good.

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

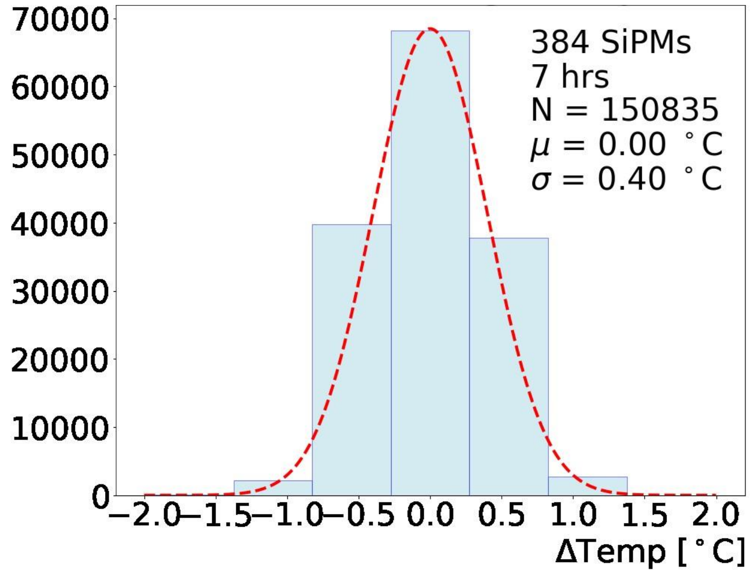
SiPM cooling plant



Temperatures on return lines



SiPM temperature stability for all SiPMs on a C-frame

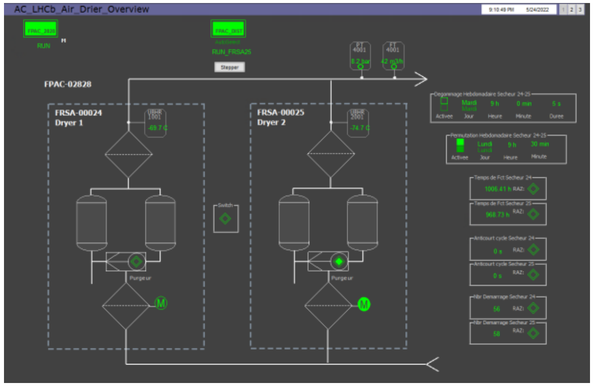


Dry gas

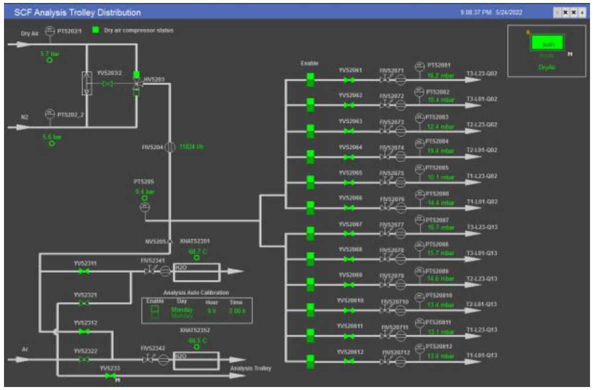
The dry gas system has been fully commissioned.
For one C-frame the dew point was measured with the external measurement device (dew point trolley).

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

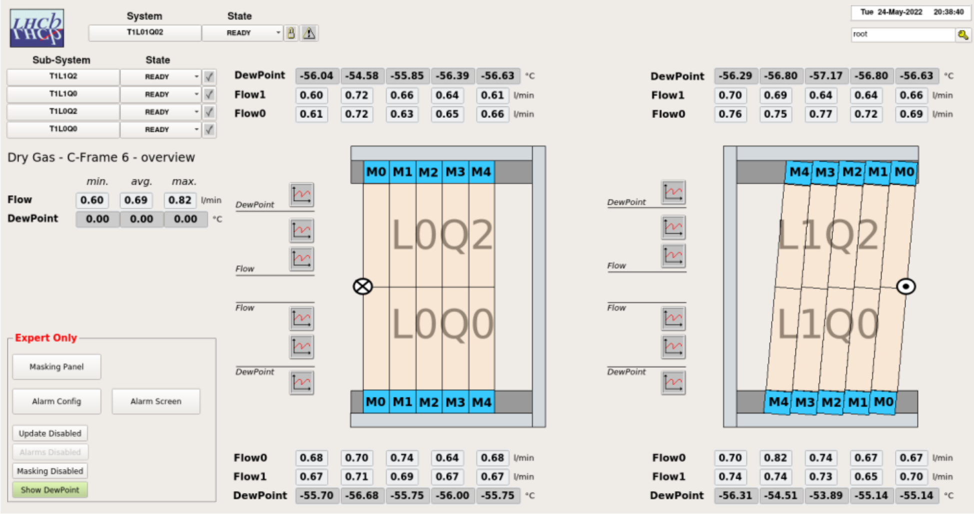
Dry gas supply



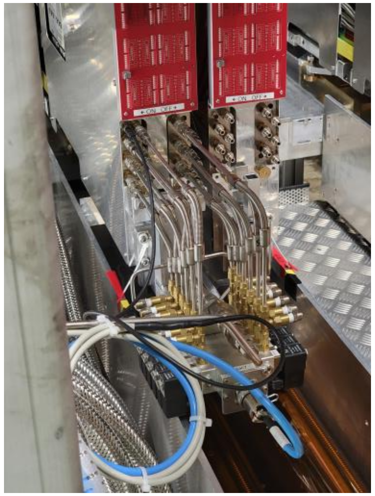
Dry gas distribution



Monitoring on C-frames

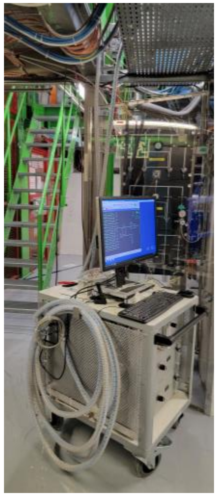


Bottom gas multiplexer



Top gas multiplexer

Dew point trolley



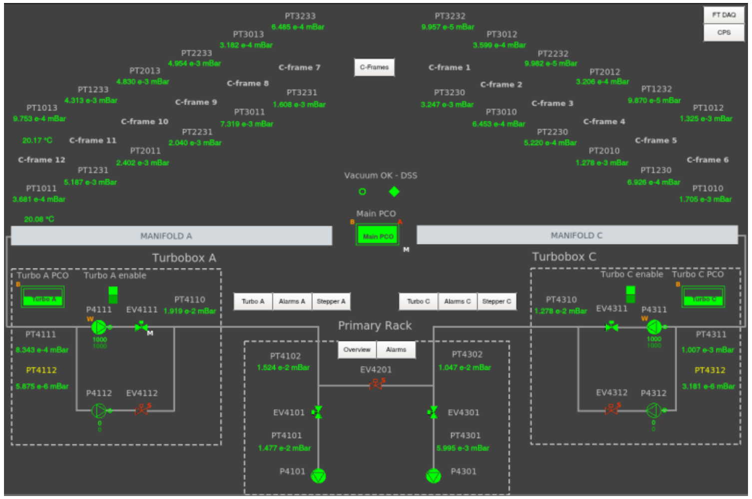
Vacuum and CPS

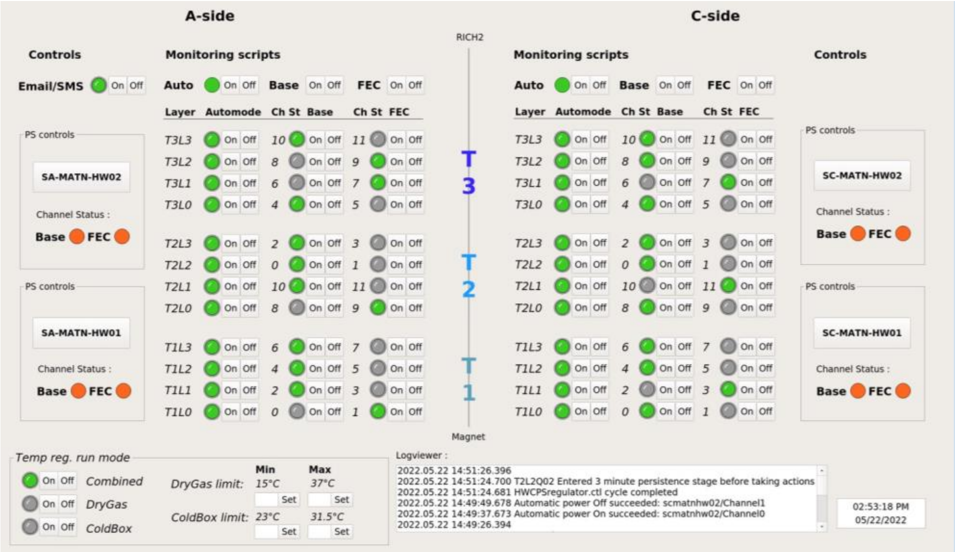
The vacuum system has been fully commissioned and is running with very stable.

The CPS system has been fully commissioned.

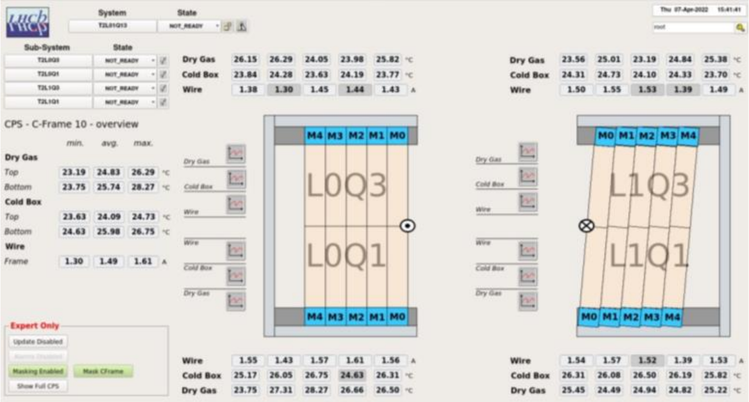
The CPS automatically power on/off MARATON channels to change the heating power depending on the measured temperatures.

Vacuum system





CPS for one C-frame



Controls and DAQ

Connection established to all Front-End electronics.

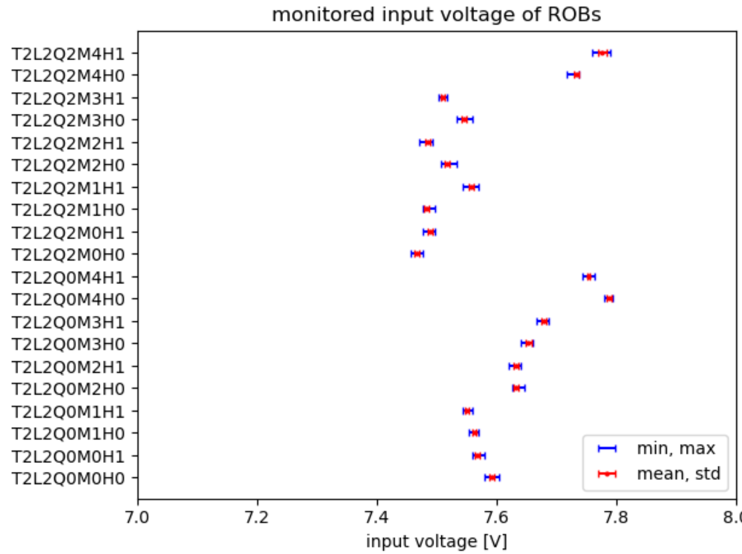
Basic monitoring of Front-End electronics.

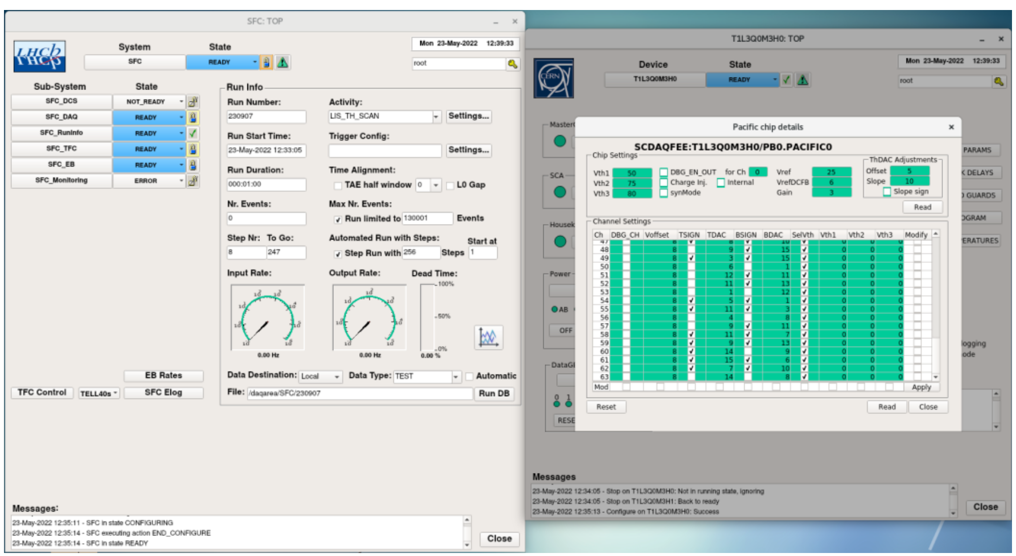
Monitoring of SiPM temperatures.

Standalone DAQ operational.

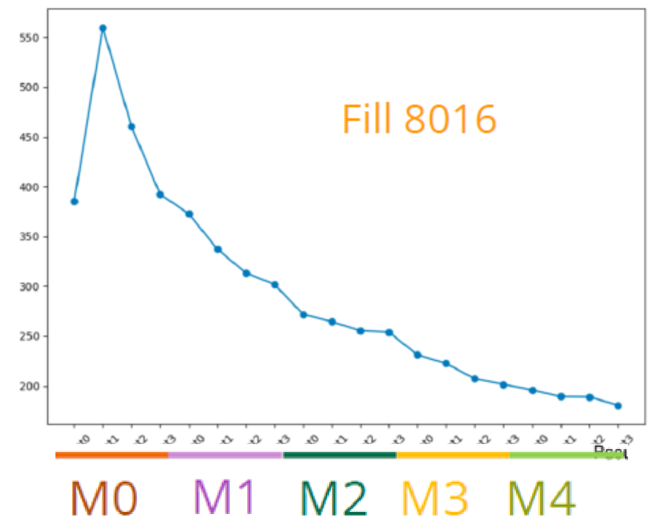
Current from SiPMs clearly scales with occupancy (and can likely be used a luminosity meter).

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





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

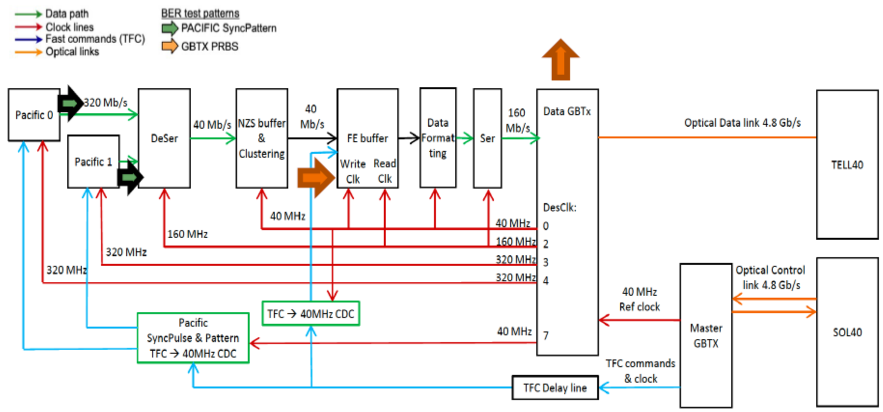


Timing in

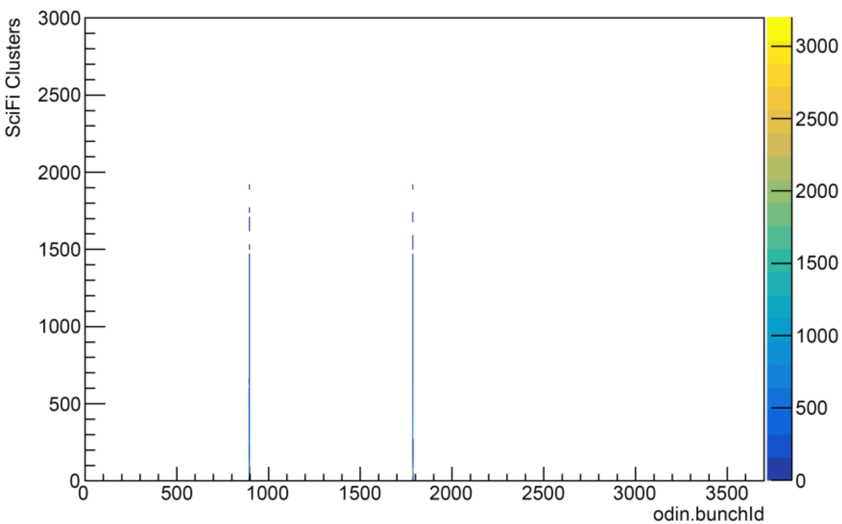
There are several level to time in for LHCb SciFi:

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.

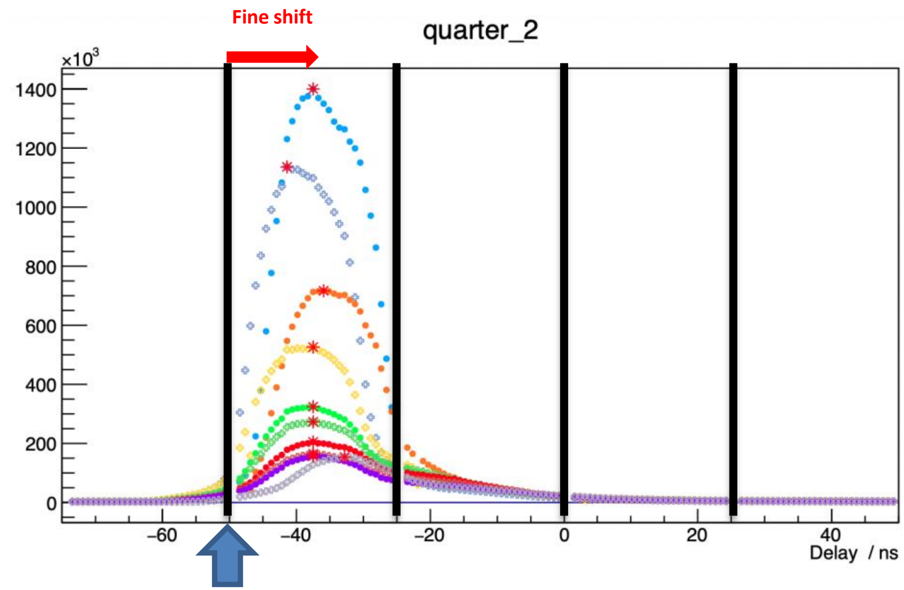
Overview of internal clocks



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.

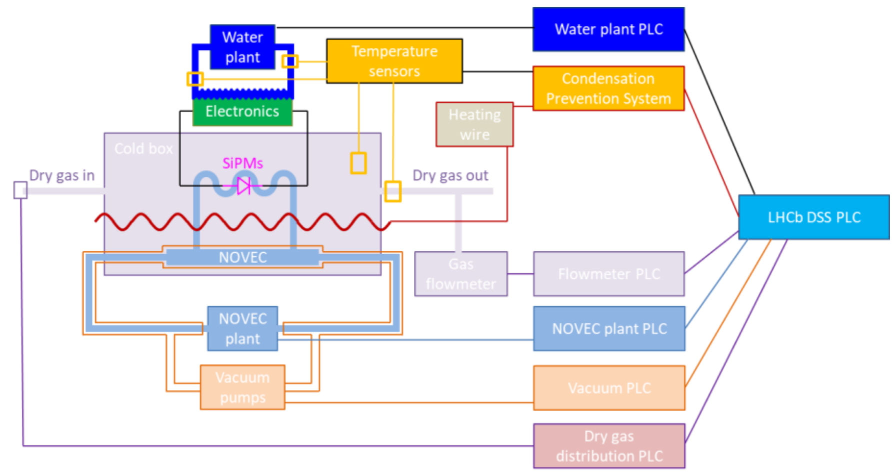
DSS is fully hardware based.

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.

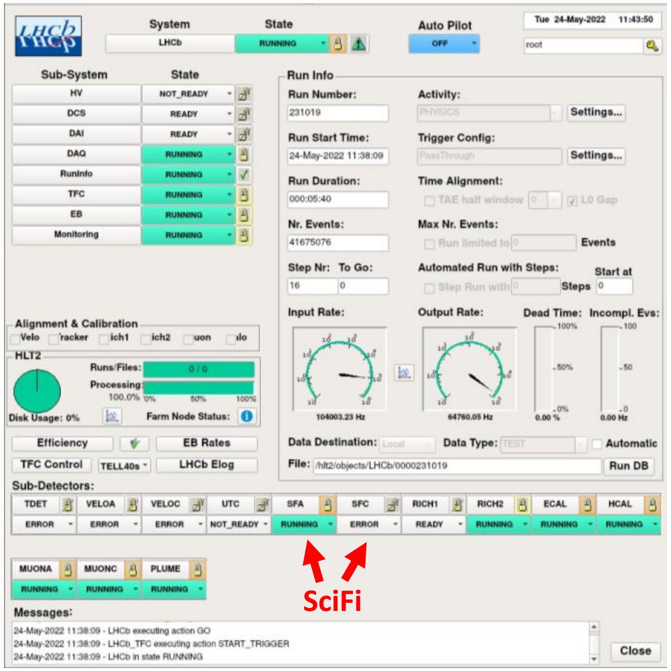
DSS overview



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