Construction of the Scintillating Fibre Tracker

Challenges and lessons learned

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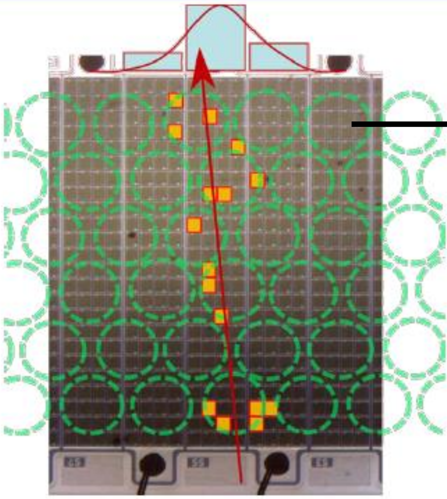
Heidelberg University
Krakow 26/09/2022

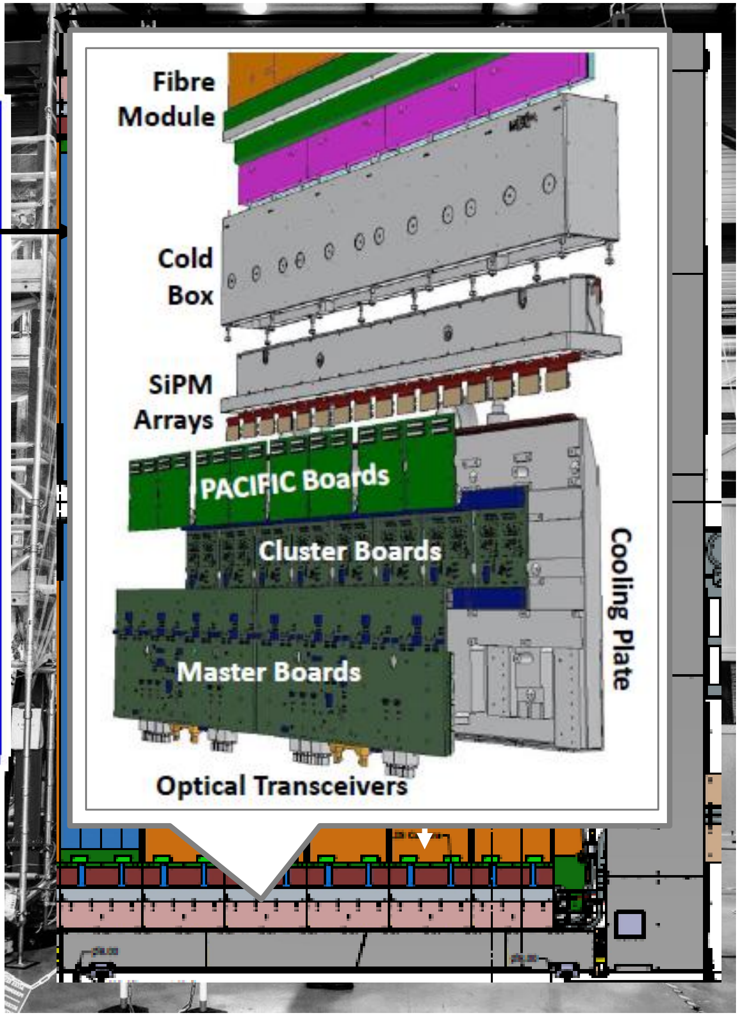
SciFi Overview



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

11,000 km fibre

3 m



12 layers w/ $3 \times 5\ m^2$
$\rightarrow$ 340 m^2 active area

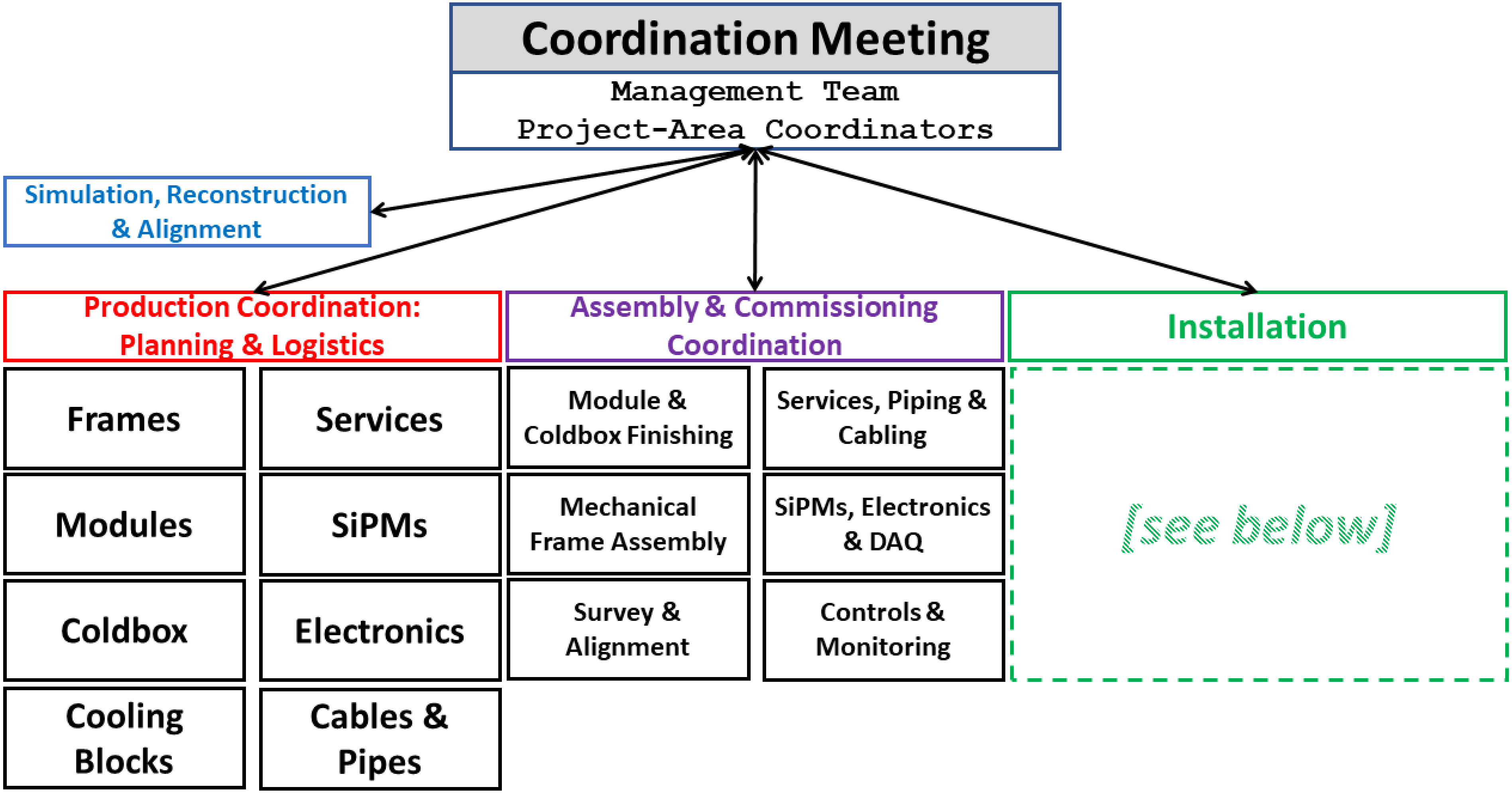
12 C-frames
w/ 2 layers (x+u/v)
each w/ 12 (10) mod.
$\rightarrow$ 128 modules

528k channels
4096 optical links

2.3 TB/s (~40% LHCb)

Modular design (mechanics, modules, electronics) – very successful

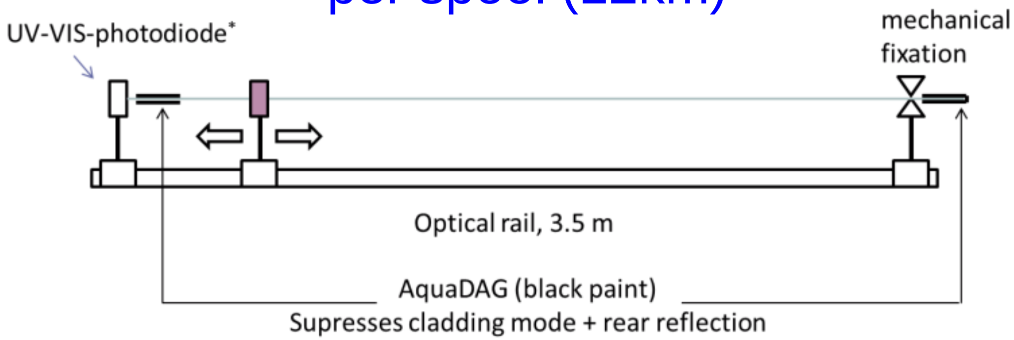
The Project Organisation (Production)



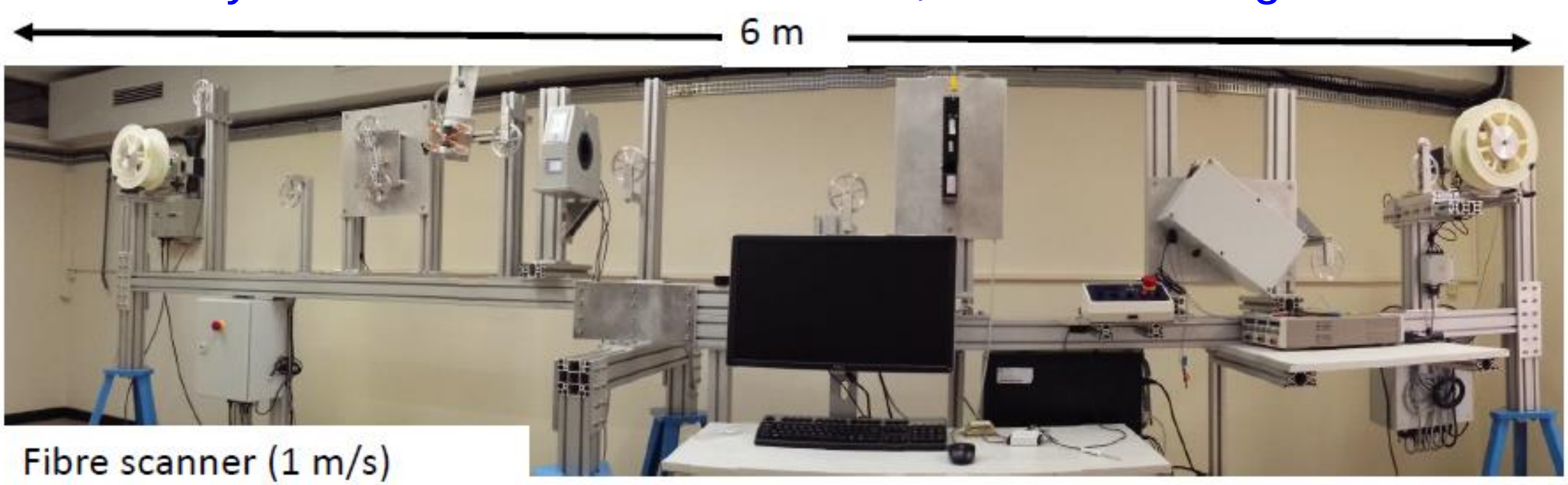
Scintillating Fibre – industrial supplier

Challenges:
11000 km
Radiation hardness of fibres
Light-yield & attenuation length
Homogenity
Cladding
Production & price

Measure light yield and attenuation per spool (12km)

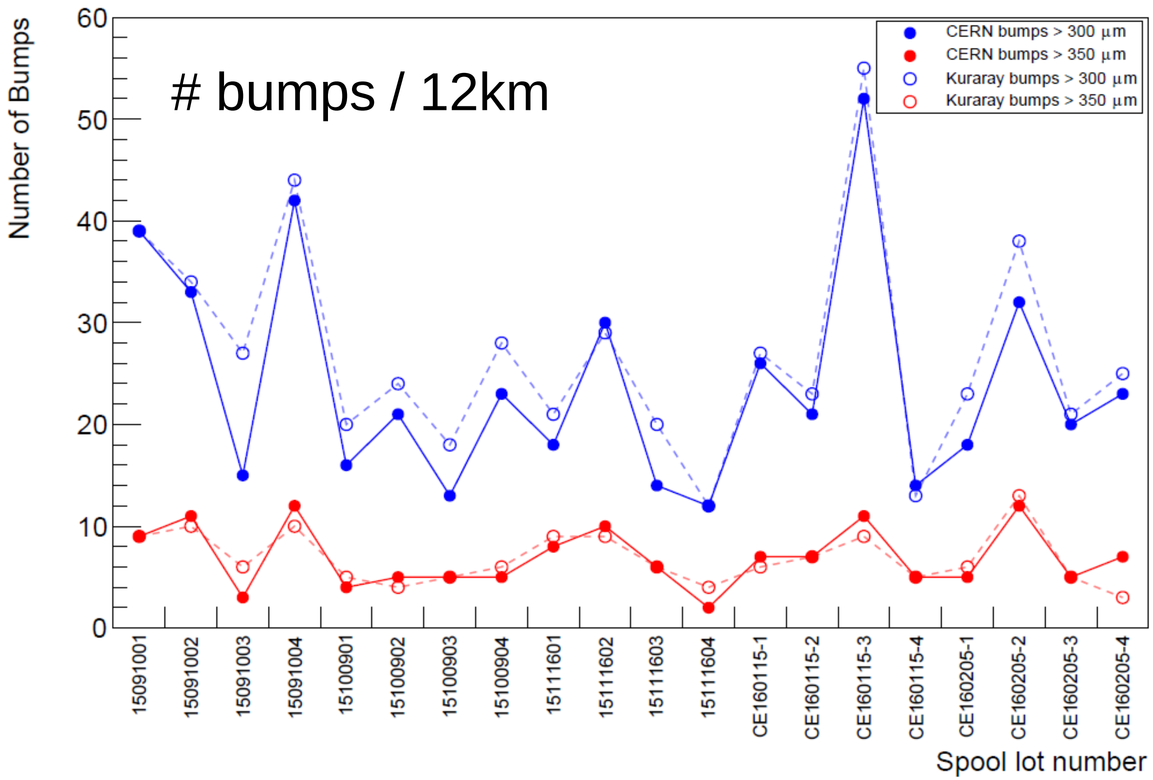


Scan every milimeter: measure diameter, check cladding.



Fast acceptance check of all fibres by one lab (CERN) was important!

Biggest Problem: Bumps



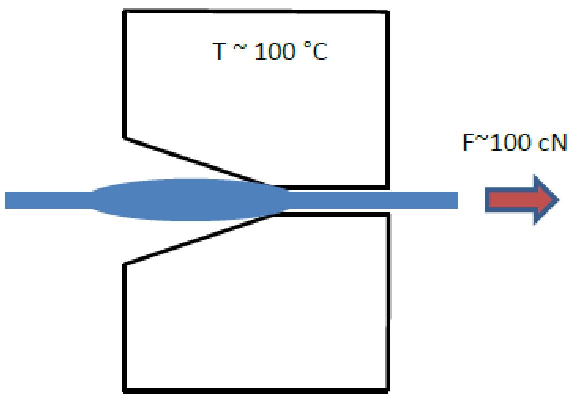
Significant number of „bumps“ >350 µm: destroy winding pattern of mats.

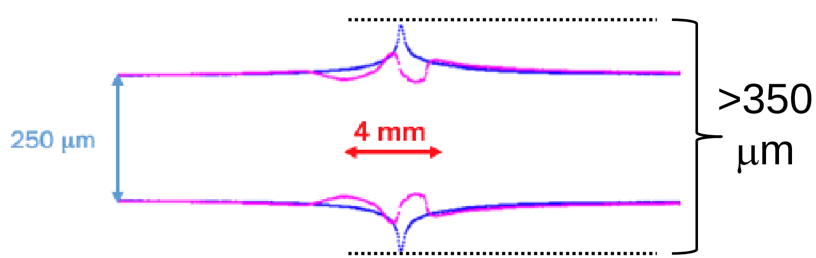
→ even w/ optimization of production process producer was unable to eliminate the “big” bumps (had to accept in average 8 bumps per 12 km)

Even experienced producers cannot always provide flawless products.

Bump Removal

Automatic bump shrinkage using a “hot drawing” tool. Applied routinely.

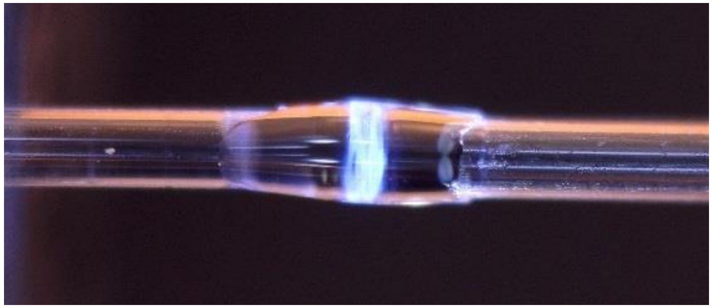




Caveat:
1-2 bumps per spool are larger than 500 mm → shrinking fails.

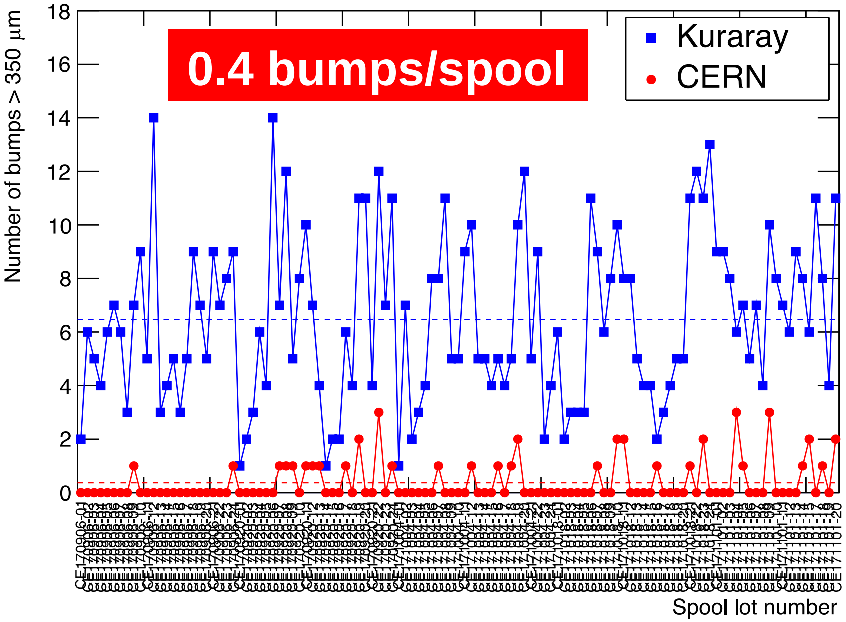
Those were manually removed by cutting & gluing.

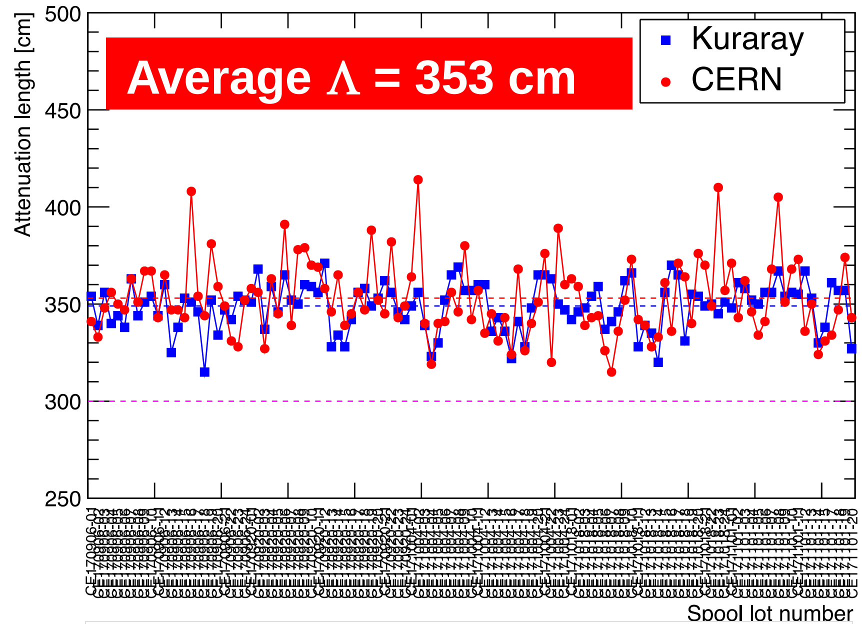
UV curing glue: t = 10-15s per bump.

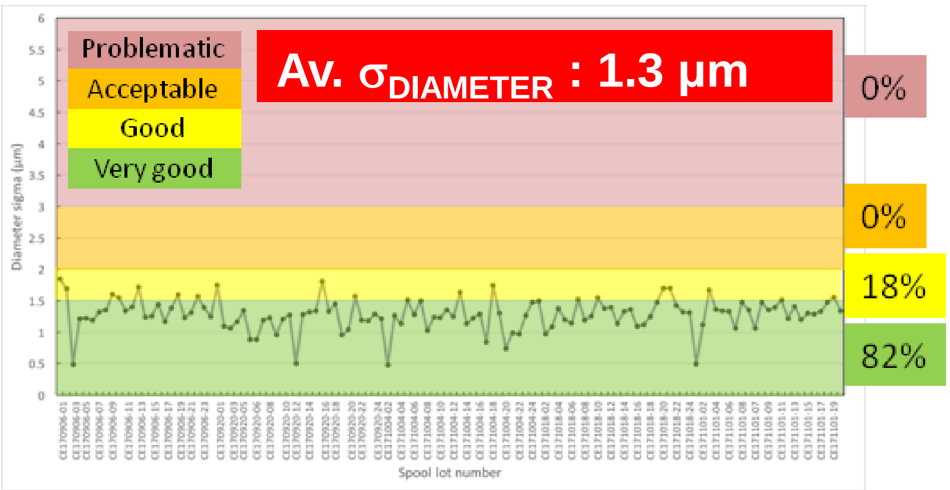


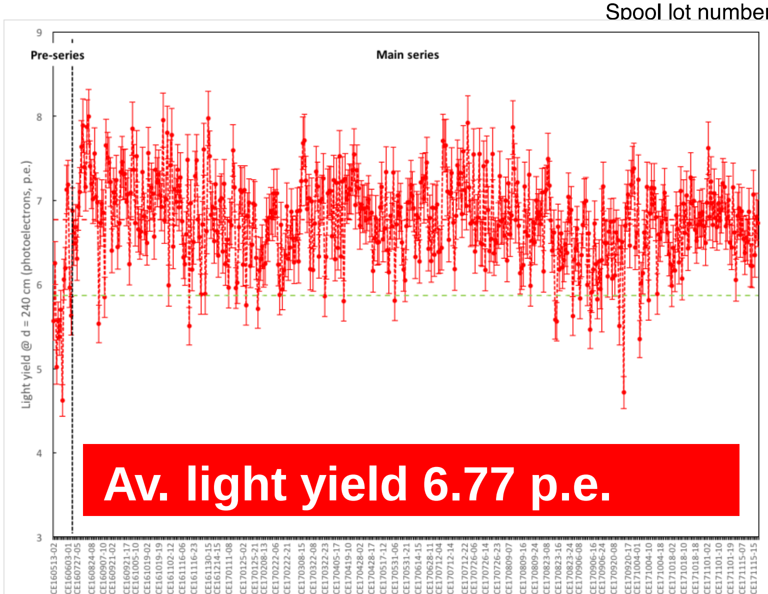
Production quality was excellent

– also as result of our fast feedback.



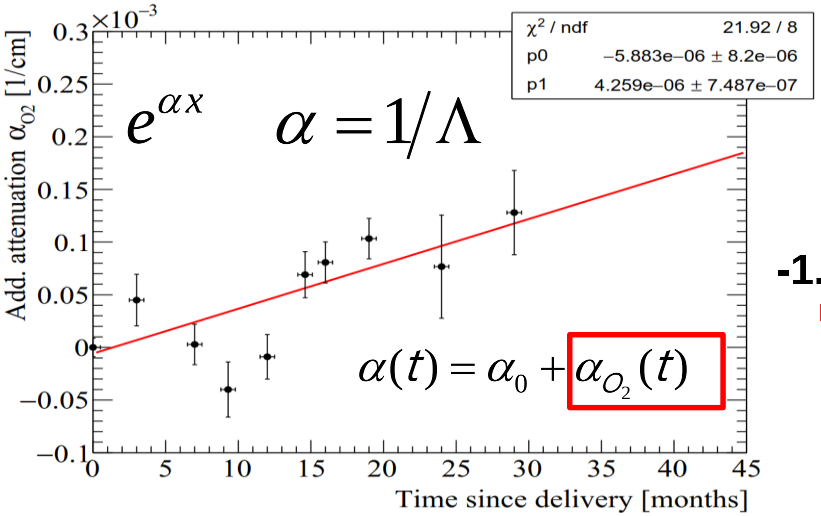






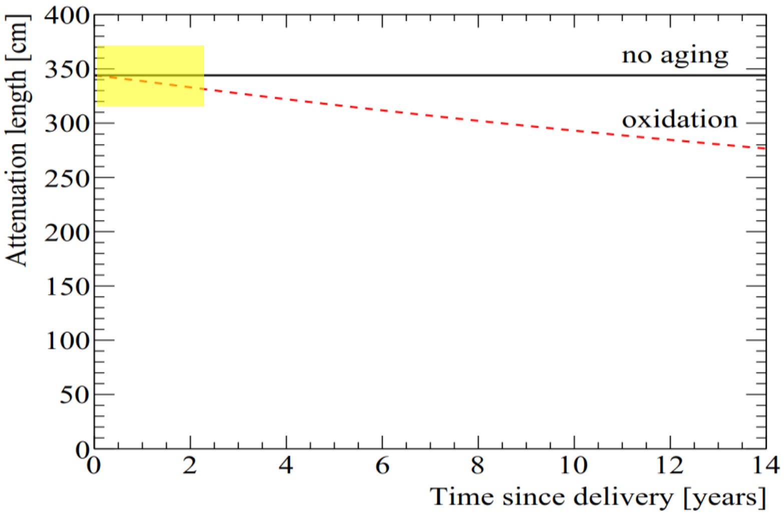
Monitoring revealed another problem

Stored reference samples show a slight decrease of the attenuation length over time due to oxidation.



-1.4%/year

Extrapolation to 14 years:



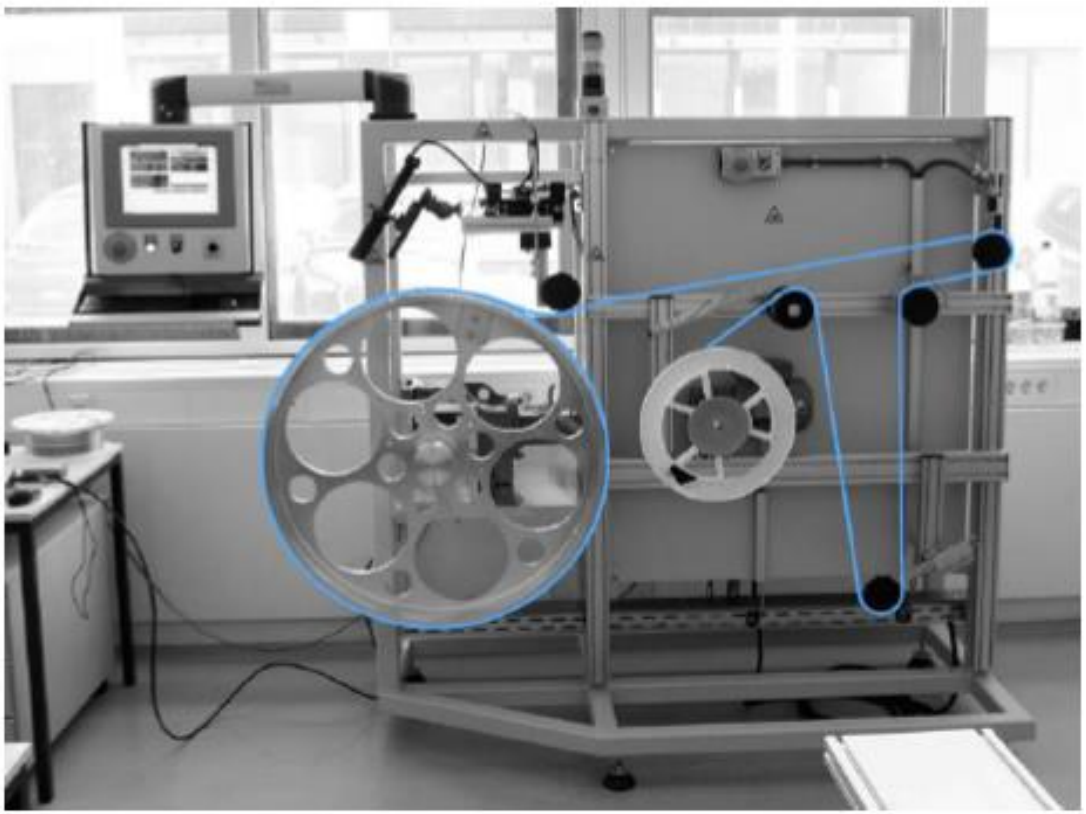
Observed already before by producer and others.
Surprising for us. Not critical for the operation of SciFi.

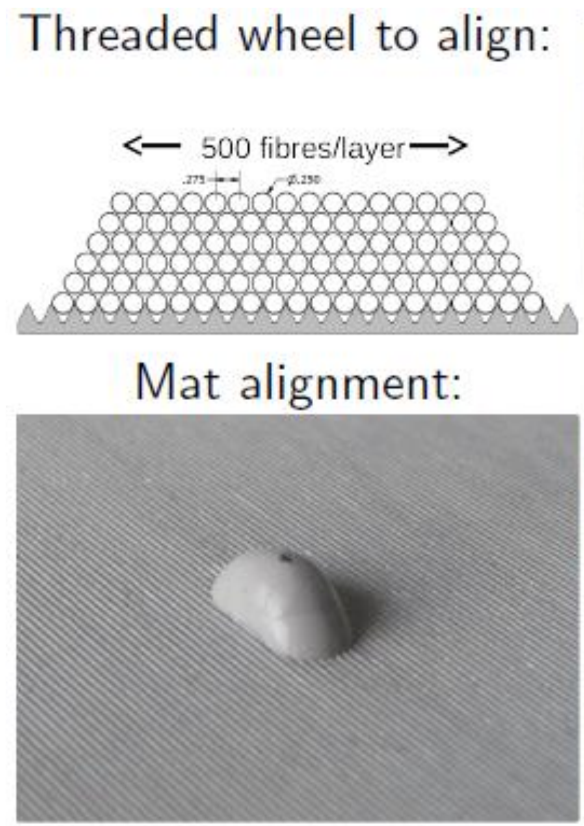
The more you check the more problems you find!

Fibre Mat Production

About 1100 + spares mats (130 mm × 2.5 m) needed → 4 production centres

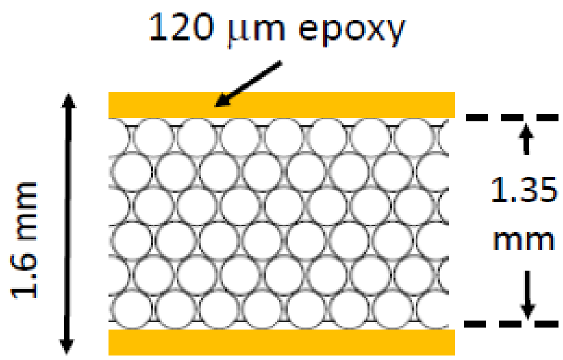
Four equal winding machines prodcued in industry:

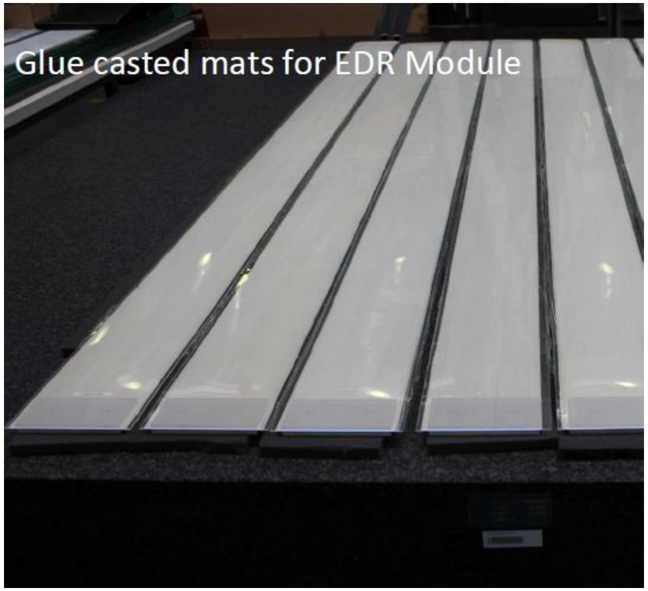




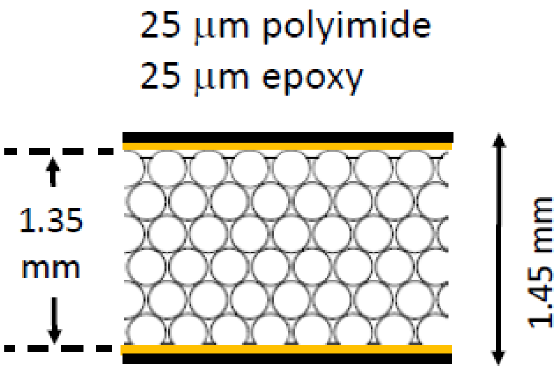
Optimization of Mat Production

TDR design: Glue casting



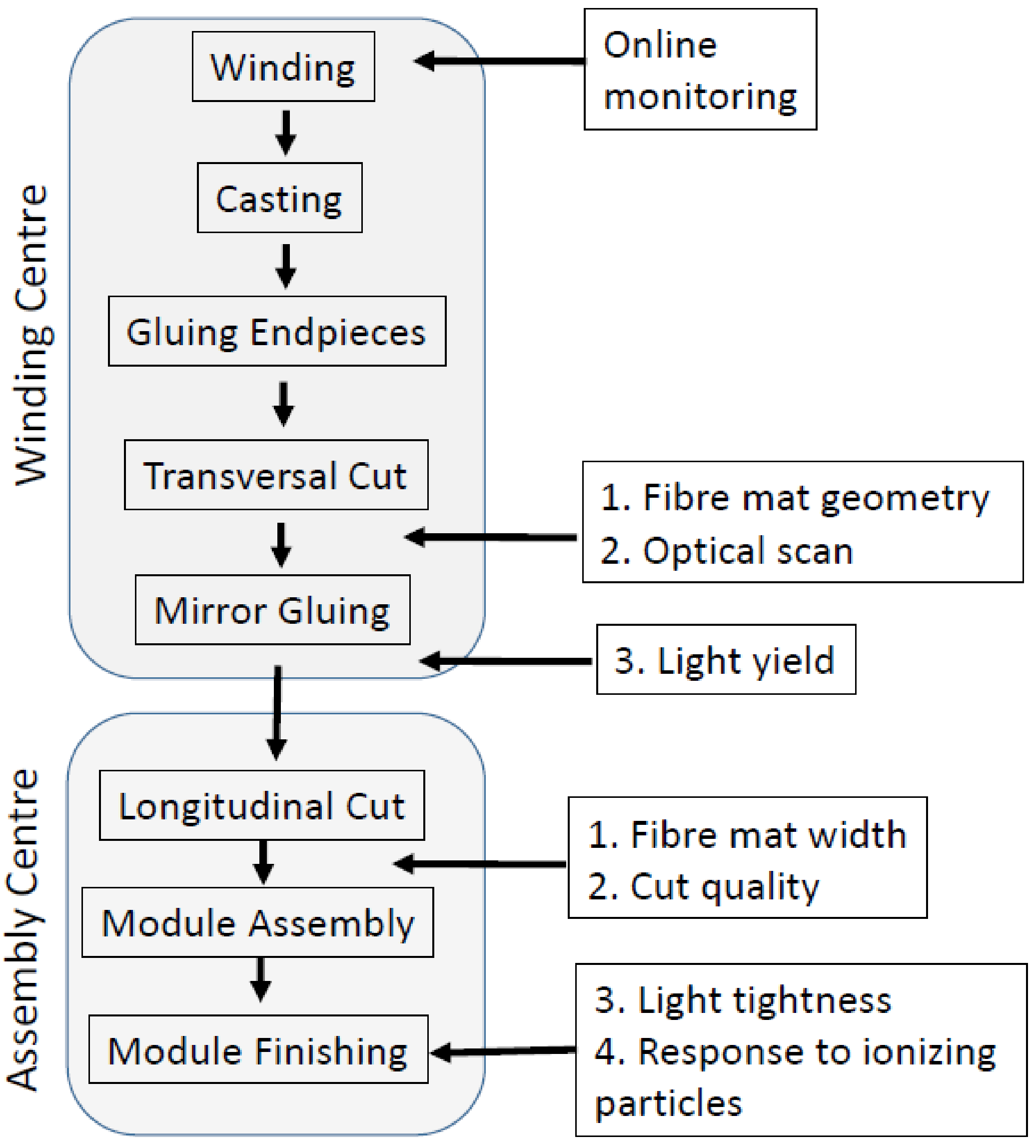


Production: Foil lamination



Be open for optimization steps even if they deviate from TDR design.

Production Organigramm

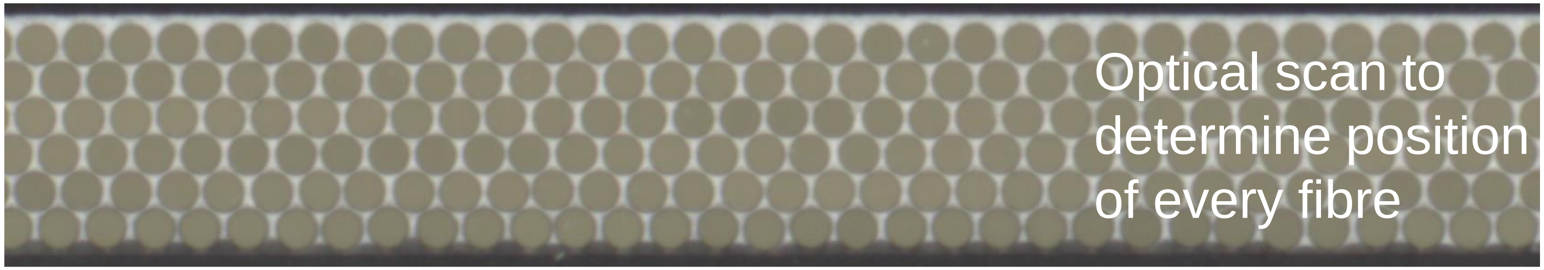


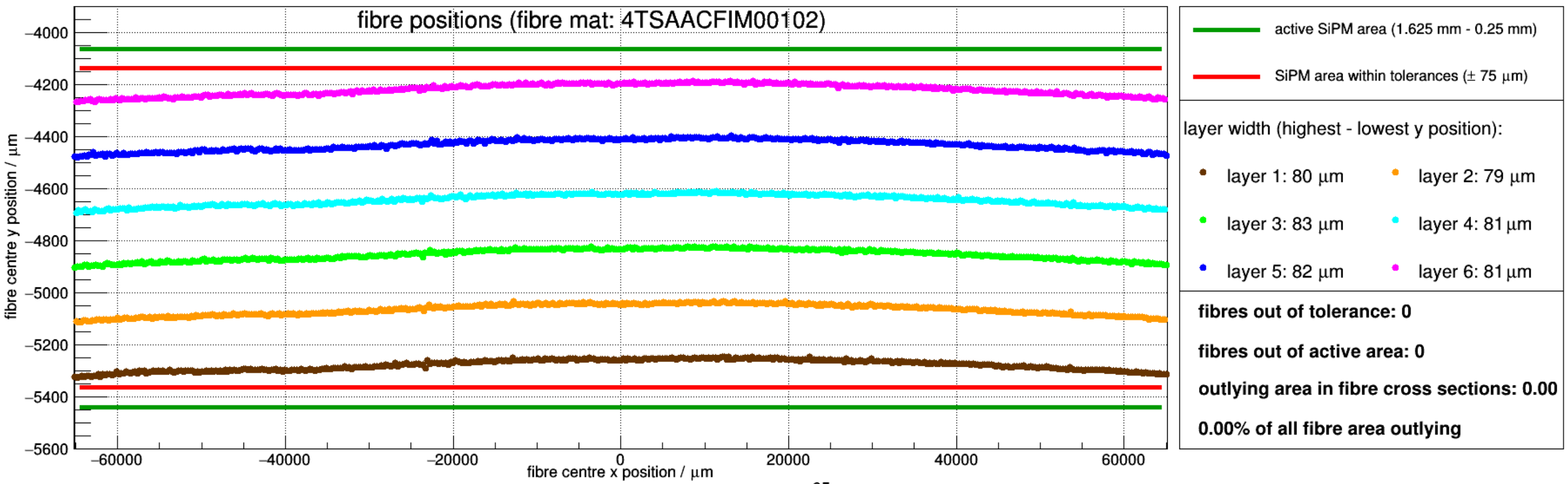
Aachen
EPFL
Dortmund
Kurchatov

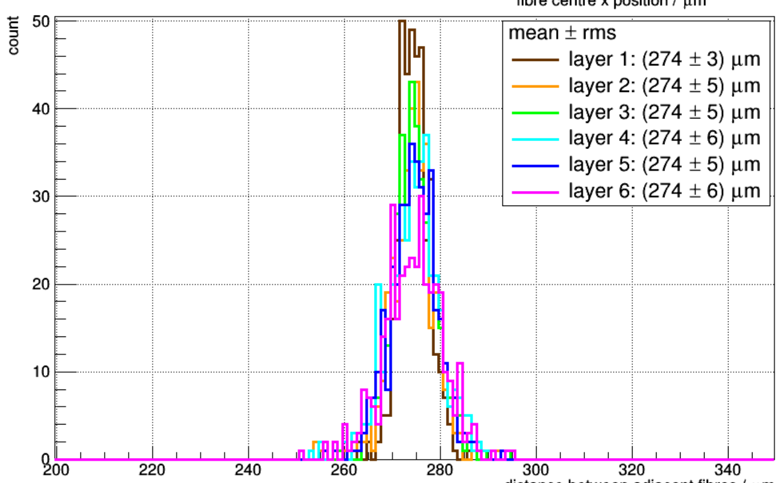
To ensure the same quality of all production sites we used excatly the same tools, procedures and test stands (we verified test results by exchanging mats).
This sounds much easier than it was!

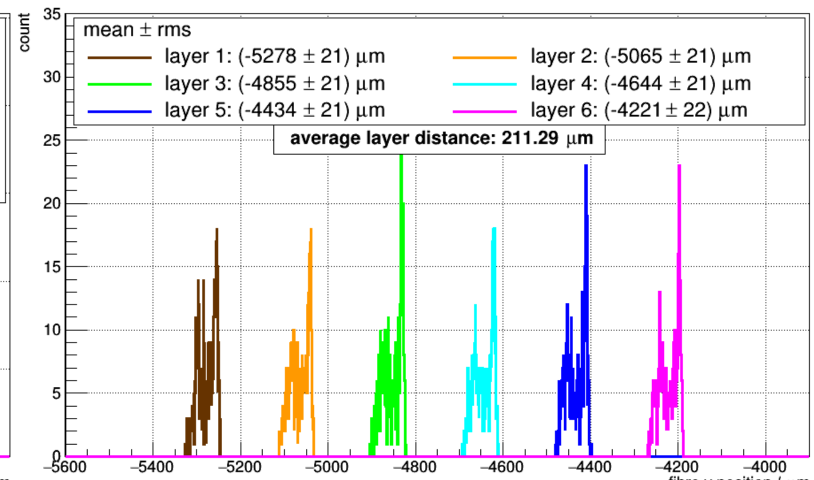
Heidelberg
Nikhef

Quality Assurance: Winding Pattern



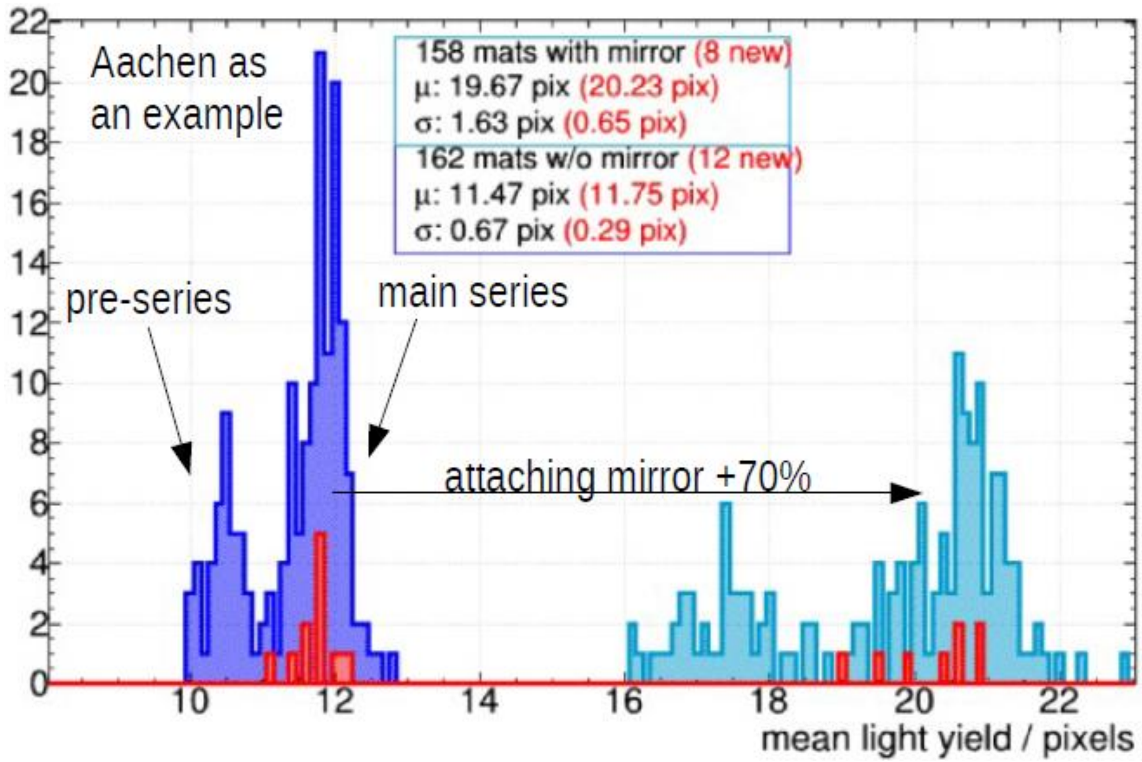


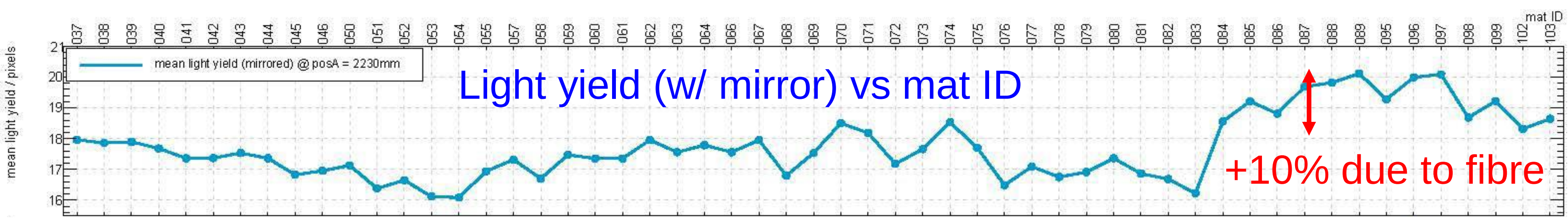




Light Yield & Mirror Reflectivity

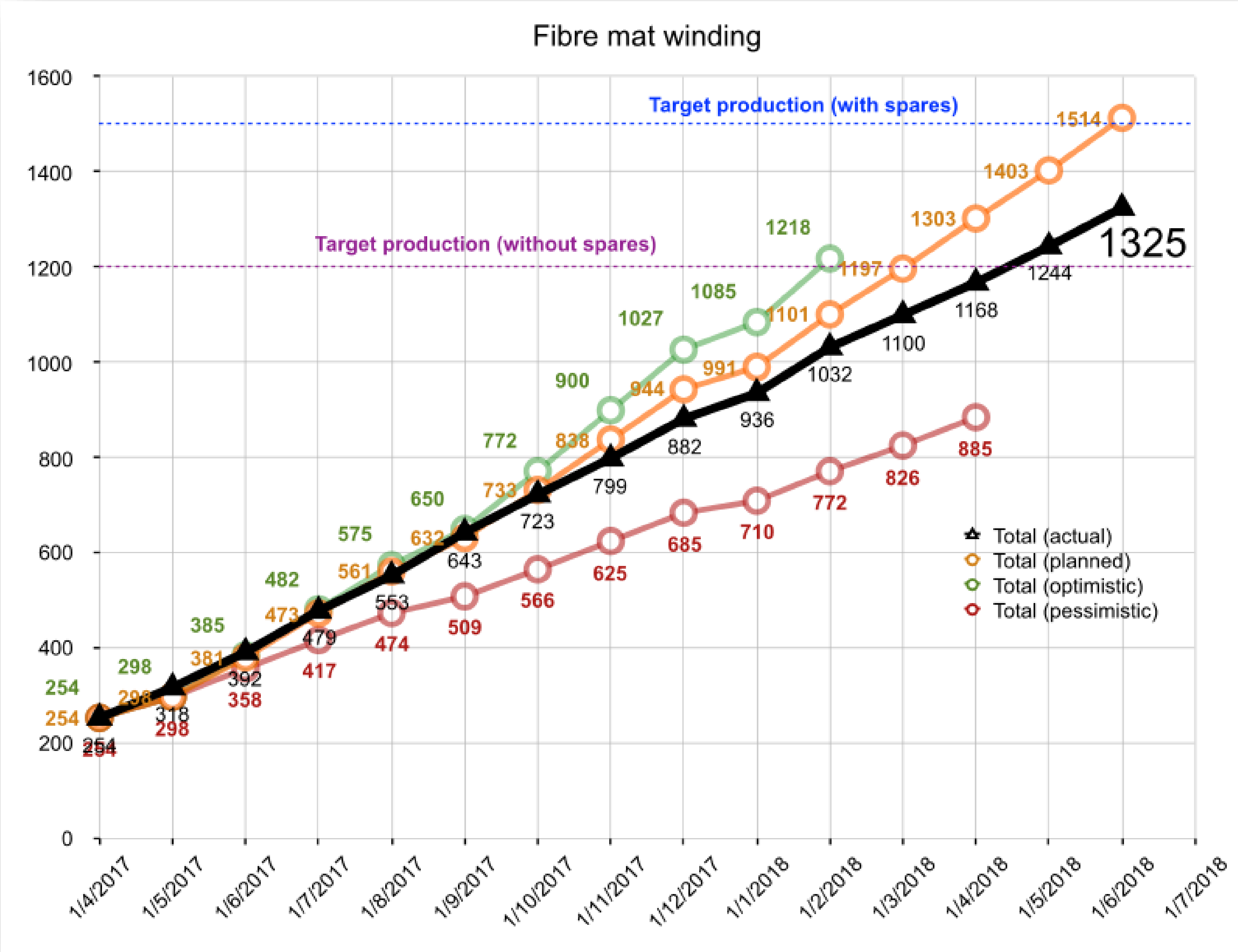
For every mat: light yield before and after mirrow glueing



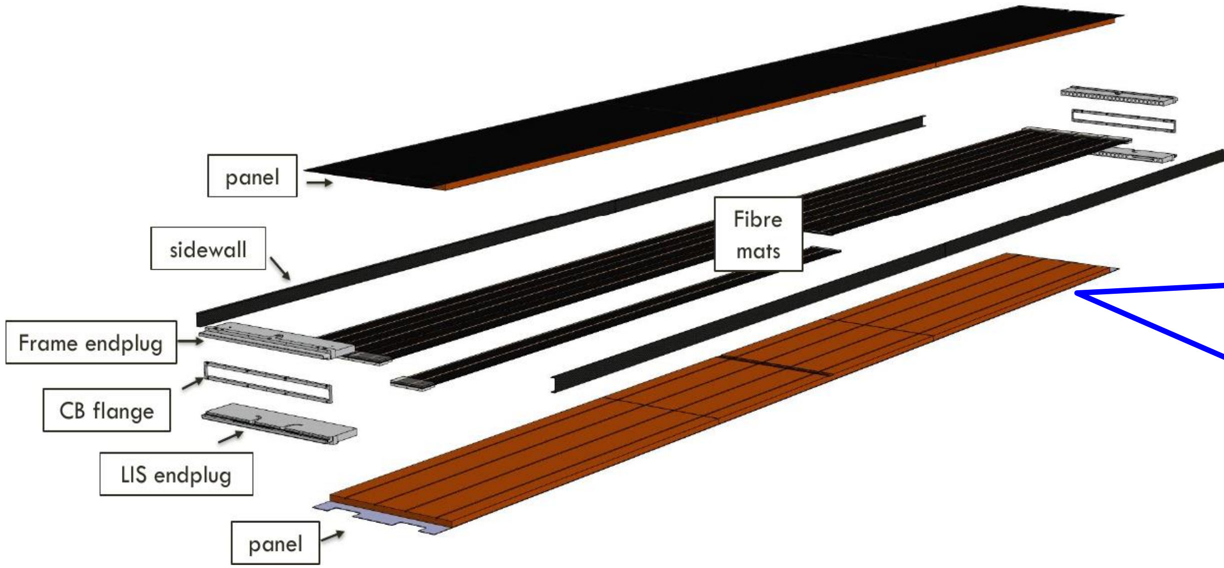


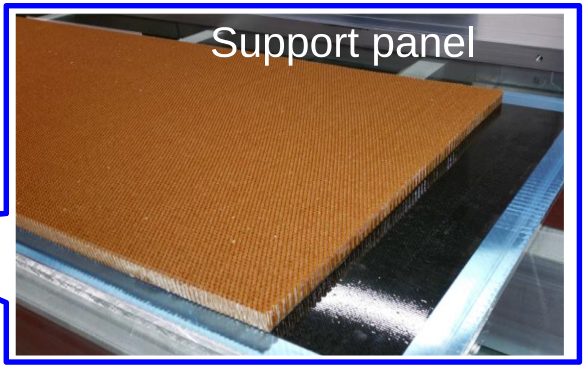
Pre series → | ← main series

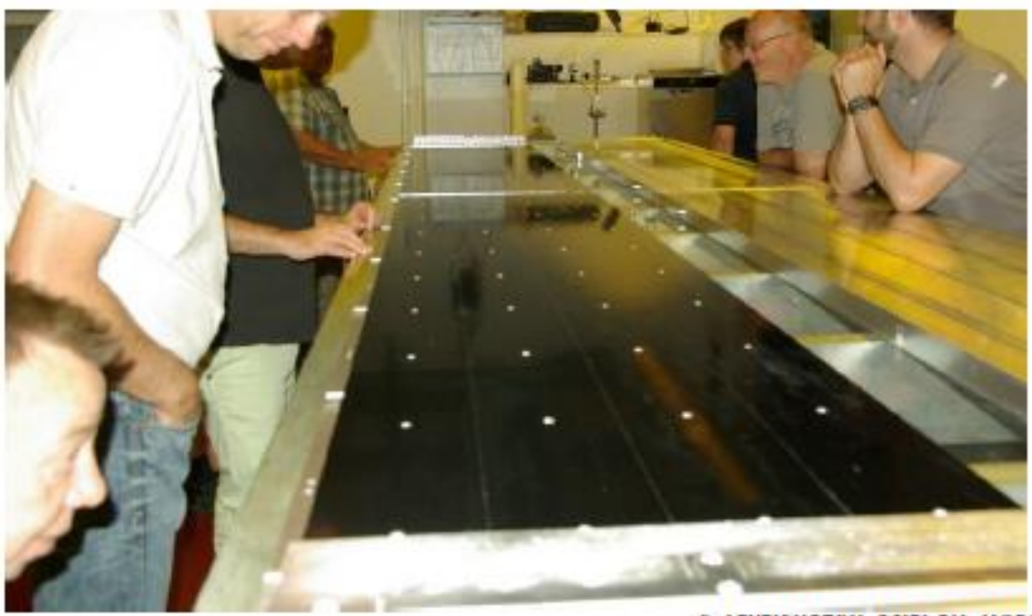
Production Schedule



Module Production







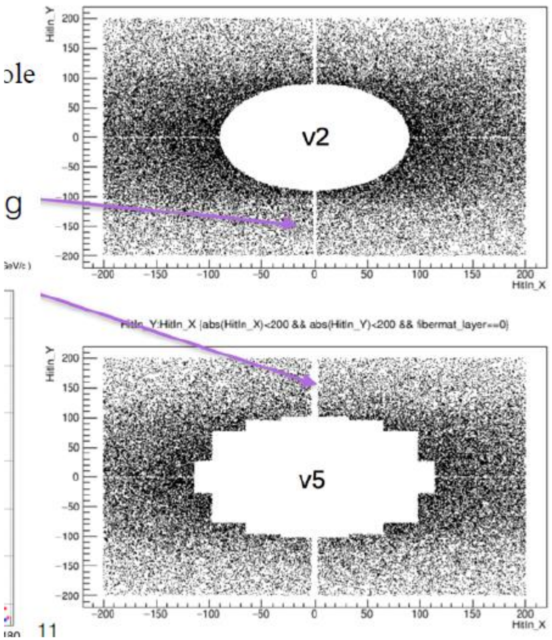
Initial problems:

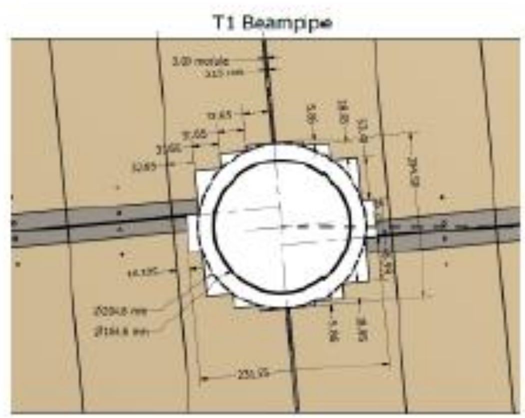
- Lateral bending of mats
- Shrinkage of fibre mats
- alu endplugs incorrect

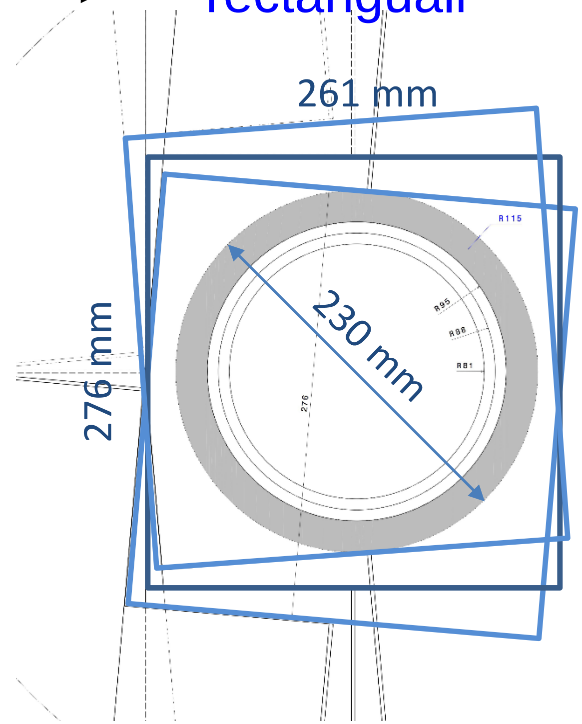
→ immediate feedback
to winding centres

„Academic“ TDR Design: beam-pipe cut-out

round → polygone → rectangualr





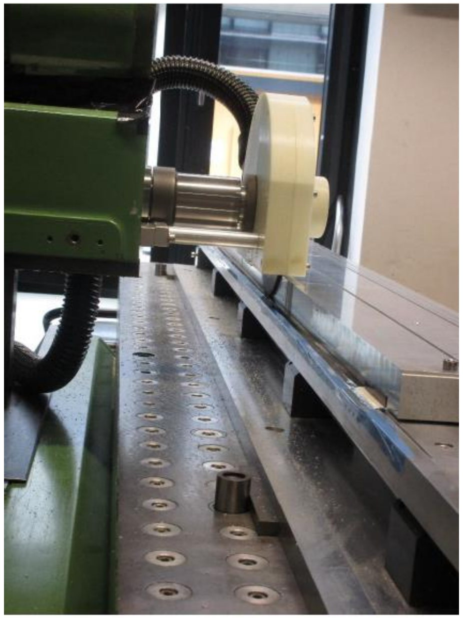


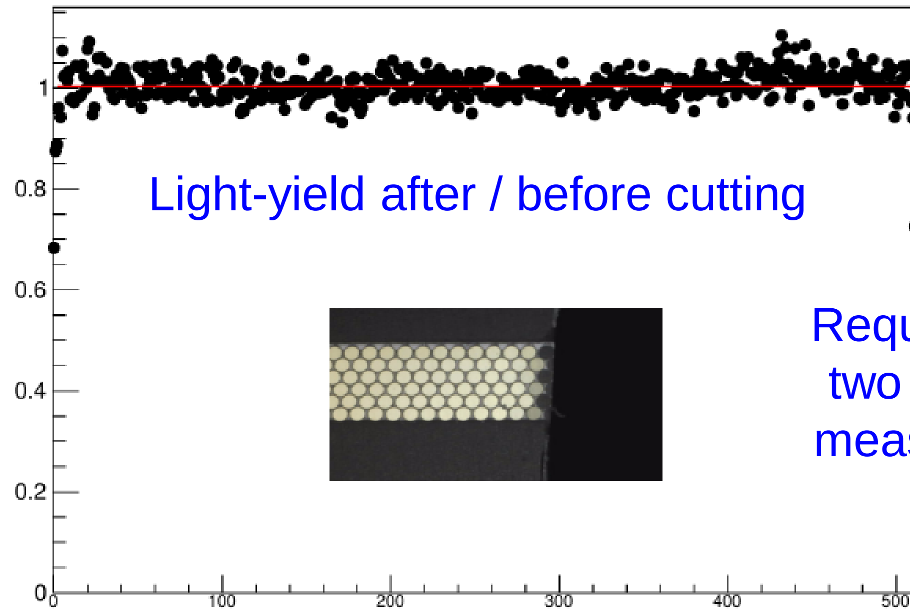
From round - ideal but unfeasible - to rectangular and identical for all layers

Review the TDR design with a critical eye!

Every step was monitored for every module

Cutting of fibre mats to the correct widths → damage fibres

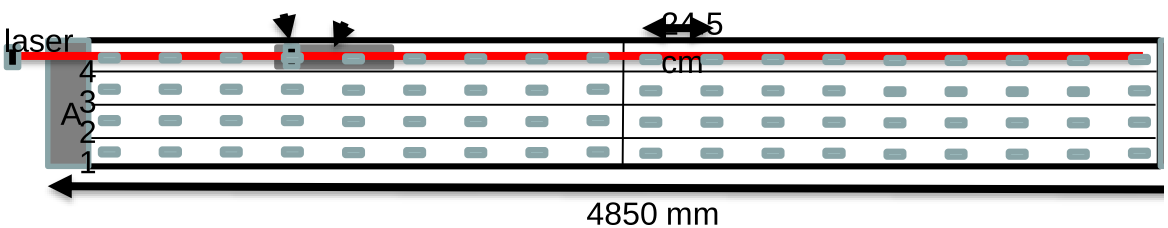


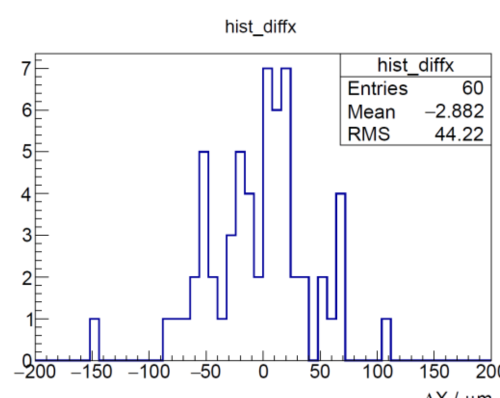


channels

Requires again two light yield measurements

Straightness of the mats after first gluing:



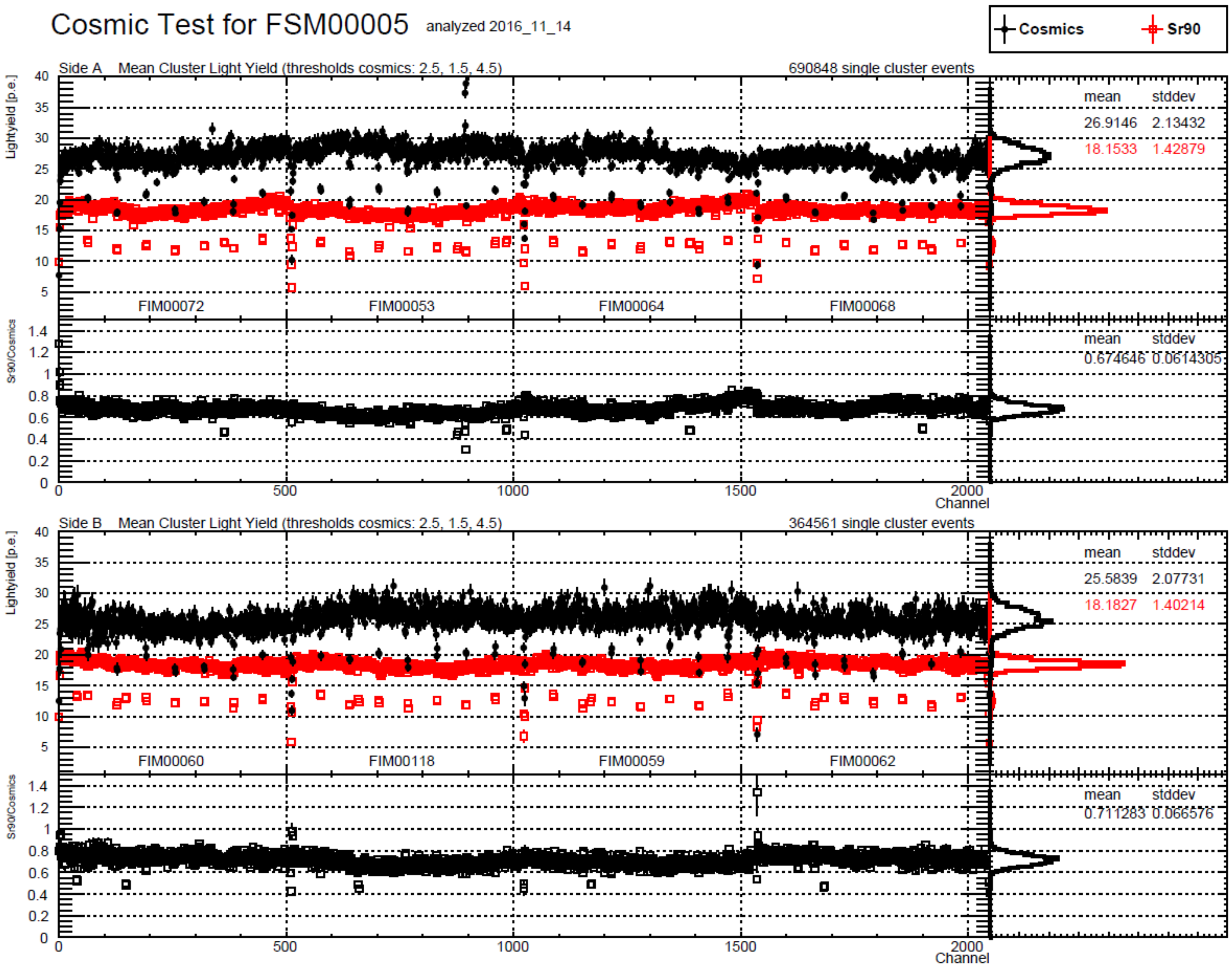


Cosmic test of all modules

Another light yield test – complete module

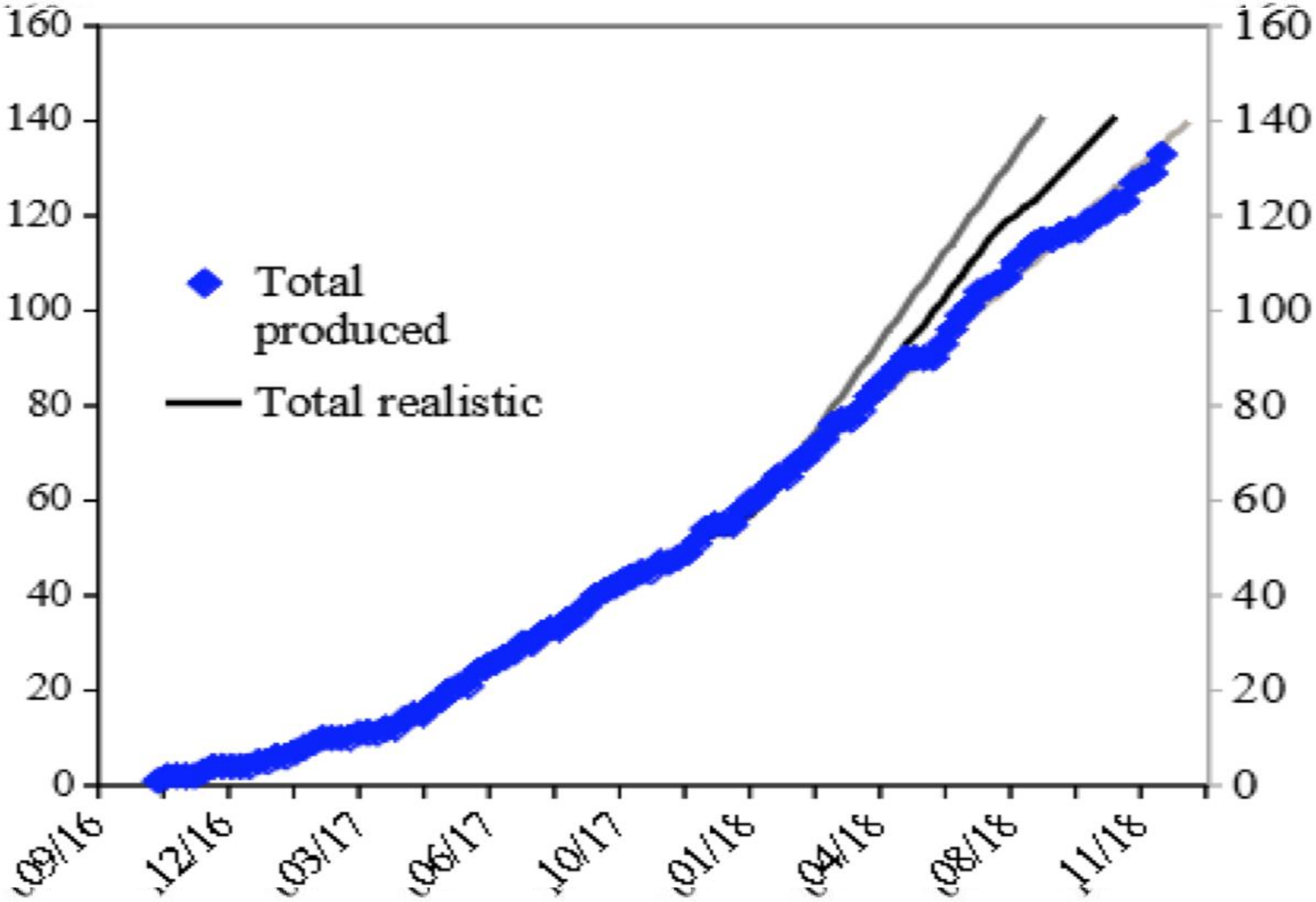
Cosmics

Sr-90



Module Production Schedule

Module production parallel to mat winding!



Production Database

SciFi DB serves four tasks:

Stock control

Inventory	Origin	Serial	Date Bond	T	rH	Mat A1	Mat A2	Mat A3	Mat A
FSM00017	PI	*	2017-04-26	22	23	FIM00227	FIM00316	FIM00126	FIM003
FSM00019	PI	*	2017-05-03			FIM00296	FIM00293	FIM00258	FIM003

Inventory	Origin	ID	Arrived	Tested	Component status
Hide filter	Any	Any	- - - / - - -	- - - / - - -	On FB
EPB00046	Tsinghua University	50c81a0000ad	2018-09-18	2019-04-09	On FEB
EPB00068	Tsinghua University	61c81a00008c	2018-09-18	2019-04-09	On FEB
EPB00076	Tsinghua University	51c81a00009a	2018-09-18	2019-04-09	On FEB
EPB00109	Tsinghua University	bbc91a0000cd	2018-09-18	2019-04-09	On FEB

View Fibre mat

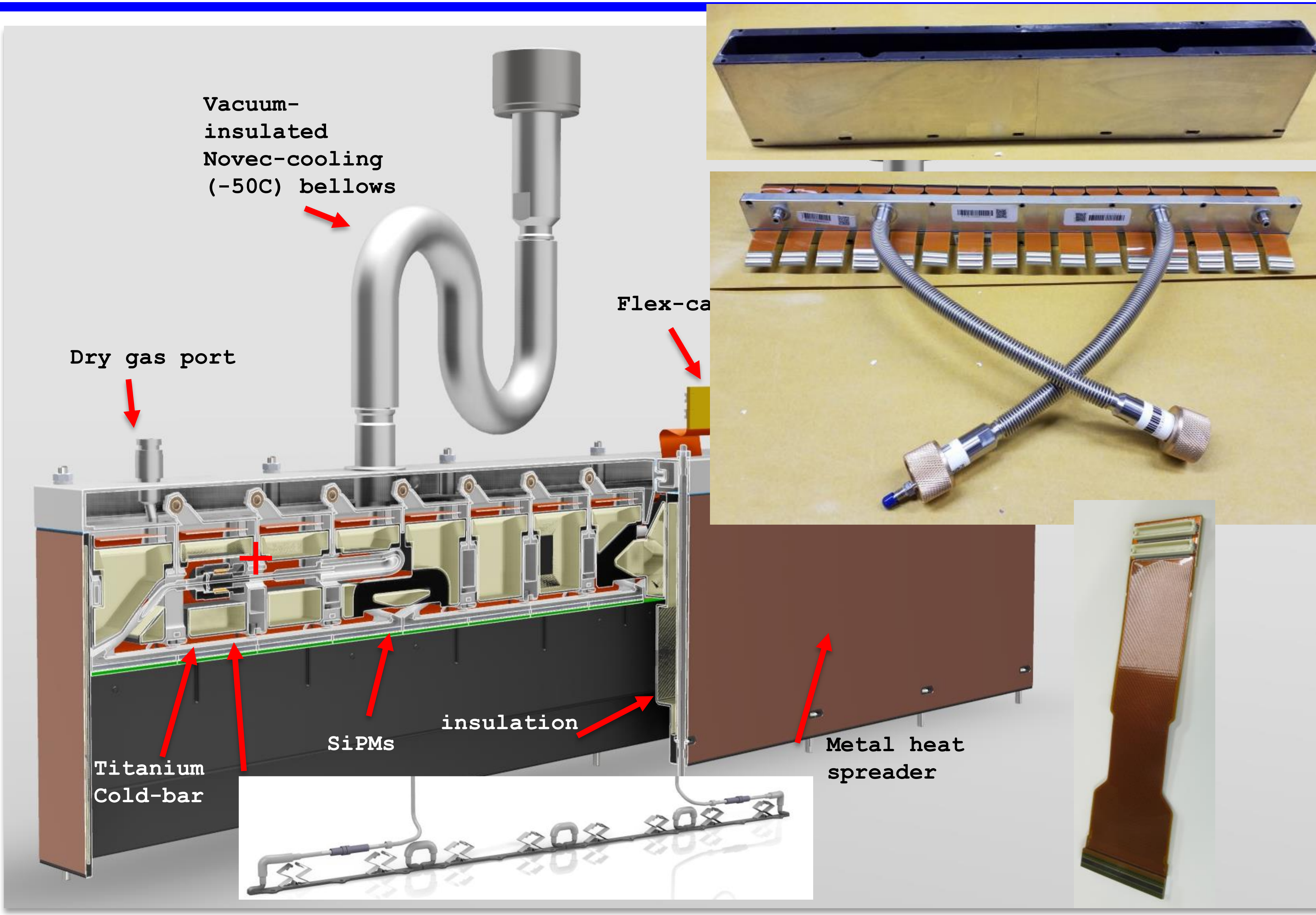
Origi	
Intenal nam	
Beam pipe	
light yield after long. cu	
Number of photo-electron	
Broken channels after long. cu	
Commer	

View PACIFIC Board

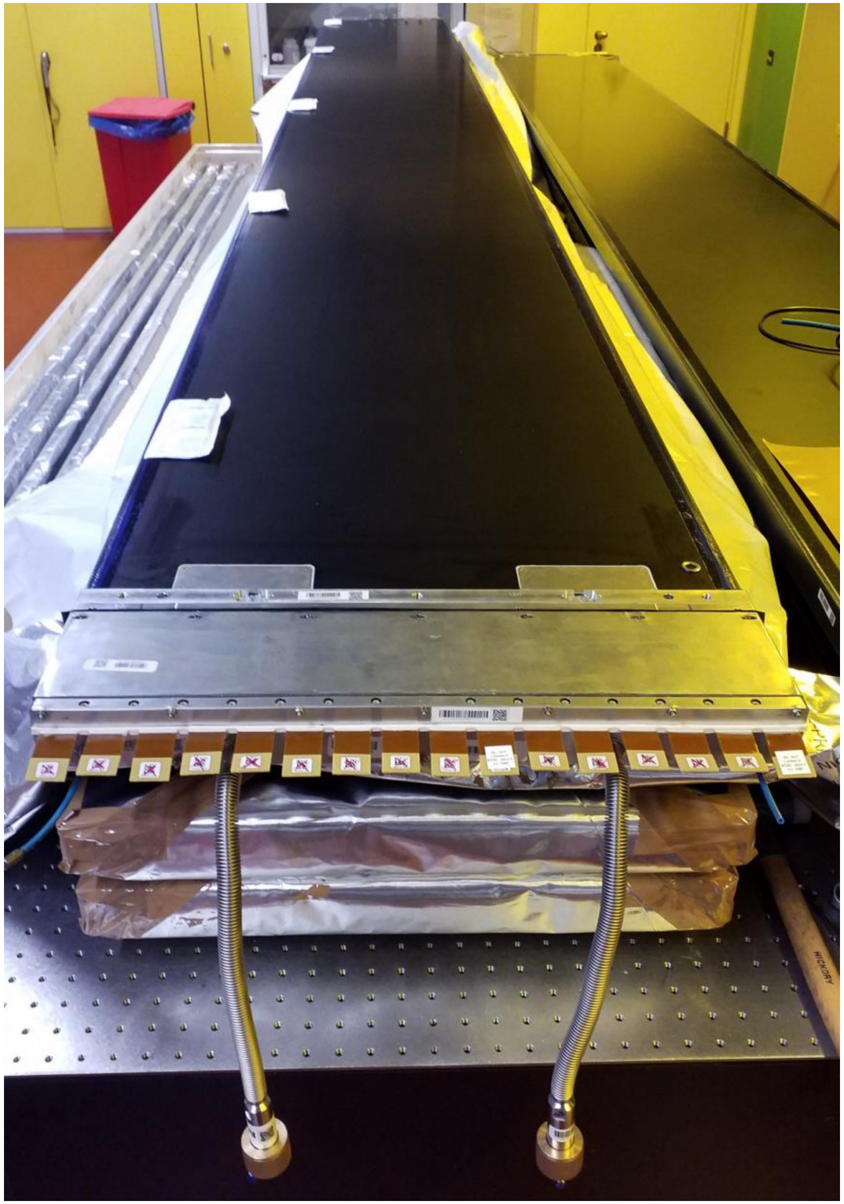
Origin	Tsinghua University
ID	51c81a00009a
Arrived	2018-09-18
Tested	2019-04-09
Component status	On FEB
Dimensions [mm x mm x mm]	60x65x1.6
Weight [kg]	0.0235
Material composition	TU-862HF
Comment	kept in HD, need to retune;sent back to Tsinghua to retune Jan
Full ID	00001ac85118
Initial current [mA]	1617
Configured current [mA]	2047
Board failure	Working
Number of untrimmed channels ASIC0	0
Number of untrimmed channels ASIC1	0
Number of untrimmed channels ASIC2	0
Number of untrimmed channels ASIC3	0
max_abs(T-B) ASIC0	1.8
max_abs(T-B) ASIC1	1.7
max_abs(T-B) ASIC2	1.9
max_abs(T-B) ASIC3	1.6
ideal_ASIC0 [charge1_DClevel]	70
ideal_ASIC1 [charge1_DClevel]	74
ideal_ASIC2 [charge1_DClevel]	78
ideal_ASIC3 [charge1_DClevel]	78
Number of uniform channels ASIC0	47
Number of uniform channels ASIC1	52
Number of uniform channels ASIC2	46
Number of uniform channels ASIC3	53
THOFF	90
Config [.aconf]	PB_4TSTHUEPB00076.conf
Raw data [.root]	rawData_BoardQA_testsystem23_Board_4TSTHUEPB00076.root
Summary report [.pdf]	4TSTHUEPB00076.pdf
ASIC 0	EPA00661
ASIC 1	EPA00426
ASIC 2	EPA00557
ASIC 3	EPA00436

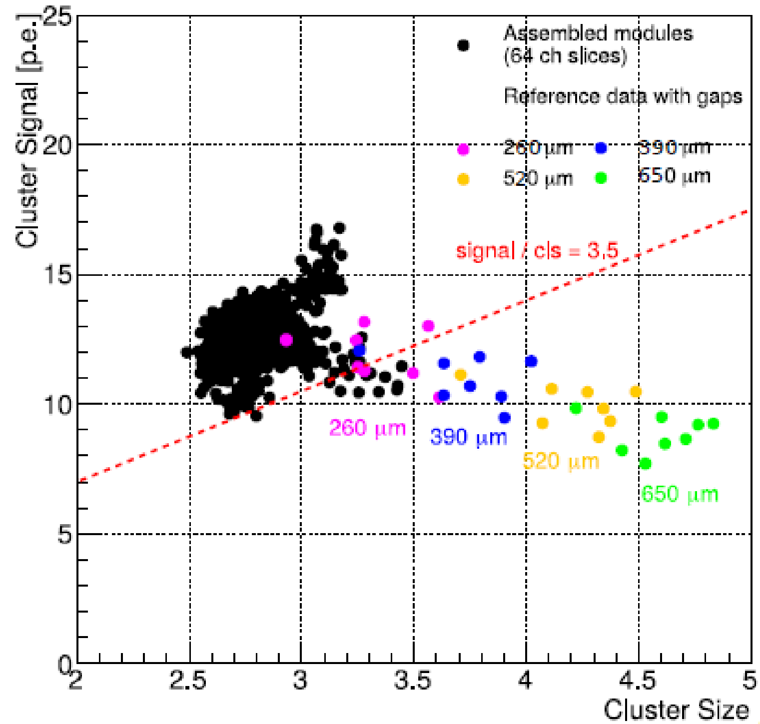
Same database was used for production and assembly of all components: modules, electronics, coldboxes and final C-frames. This paid off!

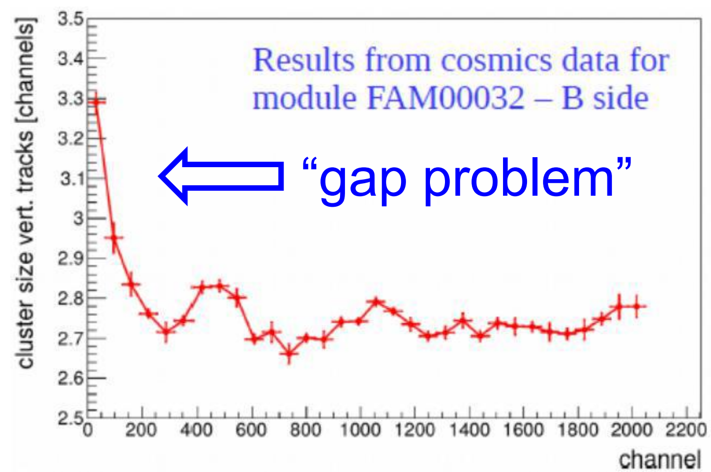
Coldboxes


Vacuum-
insulated
Novec-cooling
(-50C) bellows
Dry gas port
Flex-ca
Titanium
Cold-bar
SiPMs
insulation
Metal heat
spreader

Module Finishing & QA w/ Cosmics







Electronics Readout

SiPM 128 channels

⇩

2 PACIFICs

⇩ 10.24 Gb/s

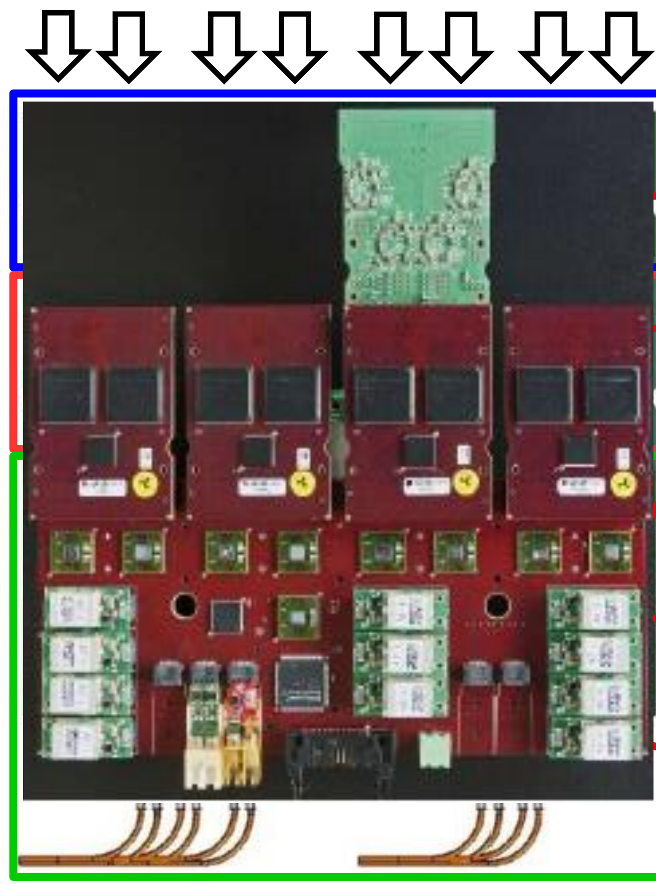
Clusterization FPGA

⇩ max. 4.48 Gb/s

Master GBT

⇩ max. 4.48 Gb/s

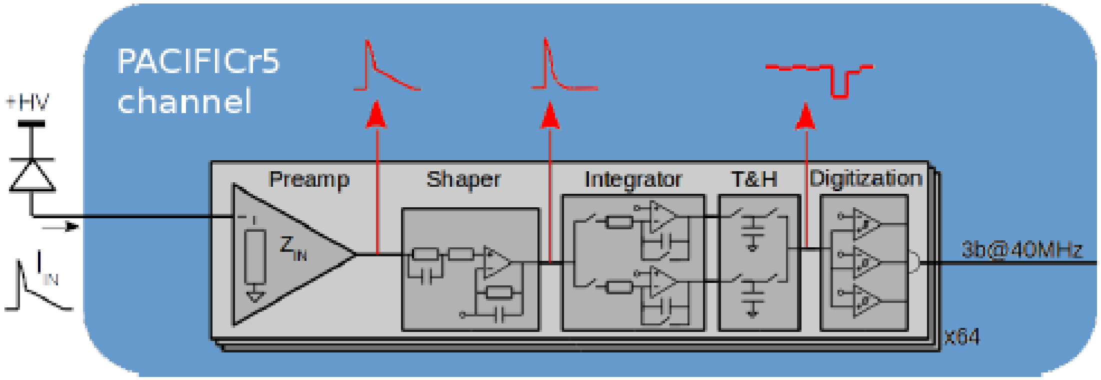
DAQ

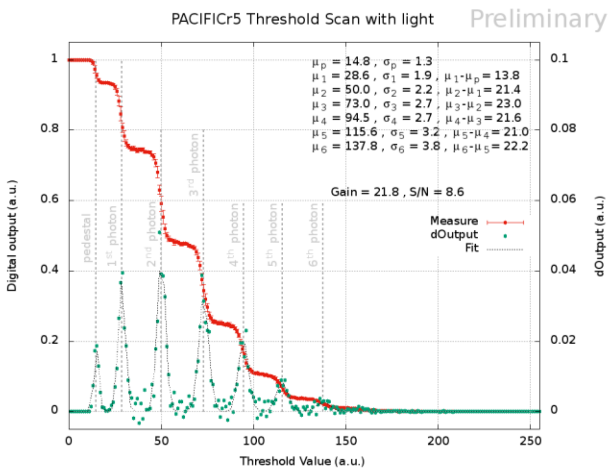


SciFi (528k channels) – 4096 GBT links (max. 2.3 TB/s)

Correct modularity important: yield versus number of connections!

PACIFIC Frontend Chip (40 MHz)





<u>Minimal ASIC functionality:</u>

- No ADC – 3 thresholds to access the pulse height
- No digital data-processsing → use FPGA
- 338 registers (8 bits) for chip configuration

<u>History:</u>

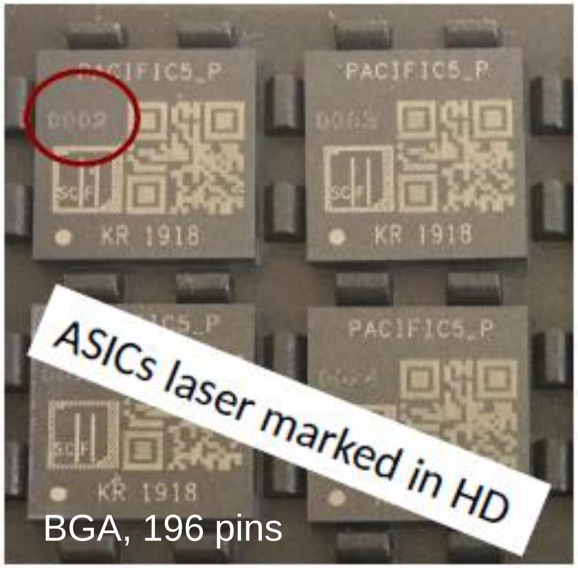
May 2013: PACIFICr0 (preamp)
Nov 2013: PACIFICr1 (analog FE)
Aug 2014: PACIFCr2 (8 chan analog)
Jul 2015: PACIFICr3 (full 8 chan, 130nm)
Sep 2016: PACIFICr4 (opimization)
Mar 2017: PACIFCr5 (production, different)

Test beams

If possible keep the ASIC simple. Chip designer should be involved in testing, the development of the carrier boards and in test beam studies!

ASIC Production and Carrier Board

Packaging of preseries:



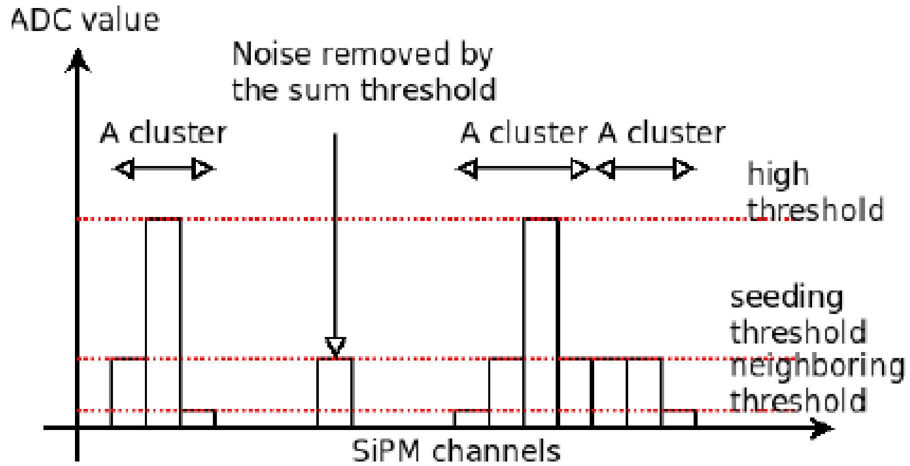
Company made mistake with unique QR codes in first batch: all chips are "Ser.No. 1", human readable number missing → laser etched chip numbers in Heidelberg instead

Anything than can go wrong will go wrong.

- All chips have been tested and qualified (tuning parameters measured).
- Carrier boards have been developed and produced in parallel
- Carrier boards have undergone again a similar test as the chips.

Cluster Boards using antifuse FPGA

Clustering for noise supression and data compression (→ ×0.5):



Use antifuse FPGA (Microsemi IGLOO2)

(expected radiation dose ~100 Gy 10krad)

Remark:
CERN studies showed that these FPGAs still work at that level. Studies reported „problems w/ progammability“

→ our owvn test at CERN‘s irradiation facility:
programmability can be lost after 1krad (~1 year)

FPGA Purchase Process (example)

5100 FPGAs needed → international tendering required

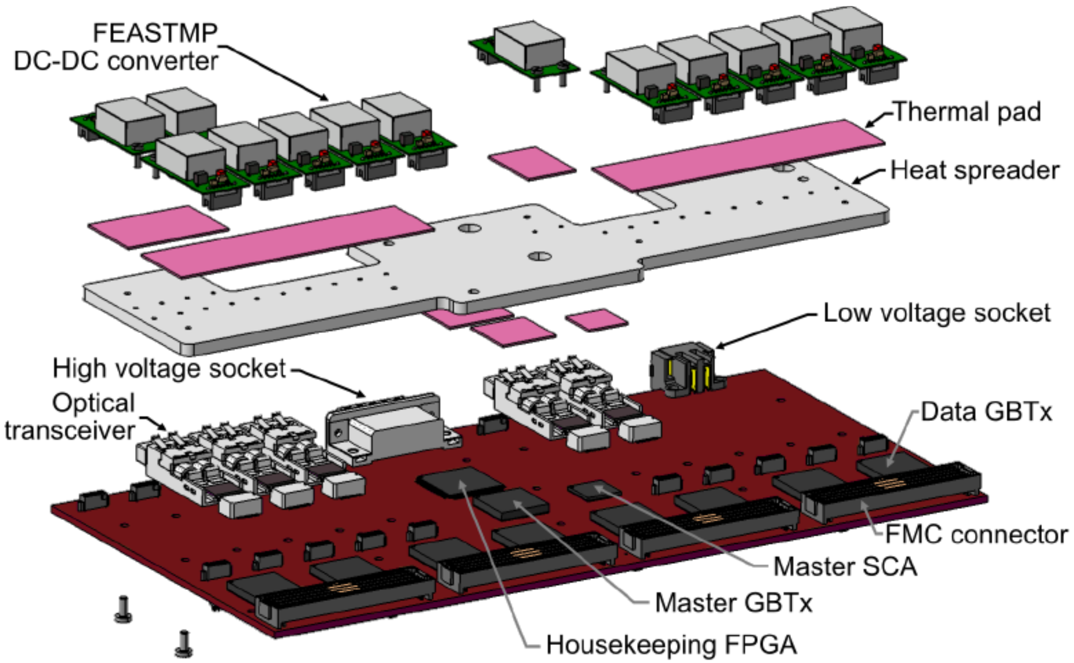
Tendering procedure via CERN (VAT):

- ~4 month of preparation with the CERN purchaser officer to agree on the "best" procedure and produce all the documents.
- 1 month for the publication
- 1.5 month between the opening of the offers and the sending of the order (price negotiation, etc.) and not smooth at all!

Oder submitted: 25/07/2019
1st batch delivery: 25/10/2019
2nd batch delivery: 21/11/2019

Purchase process of expensive parts can easily take ~1 year.

Master Board



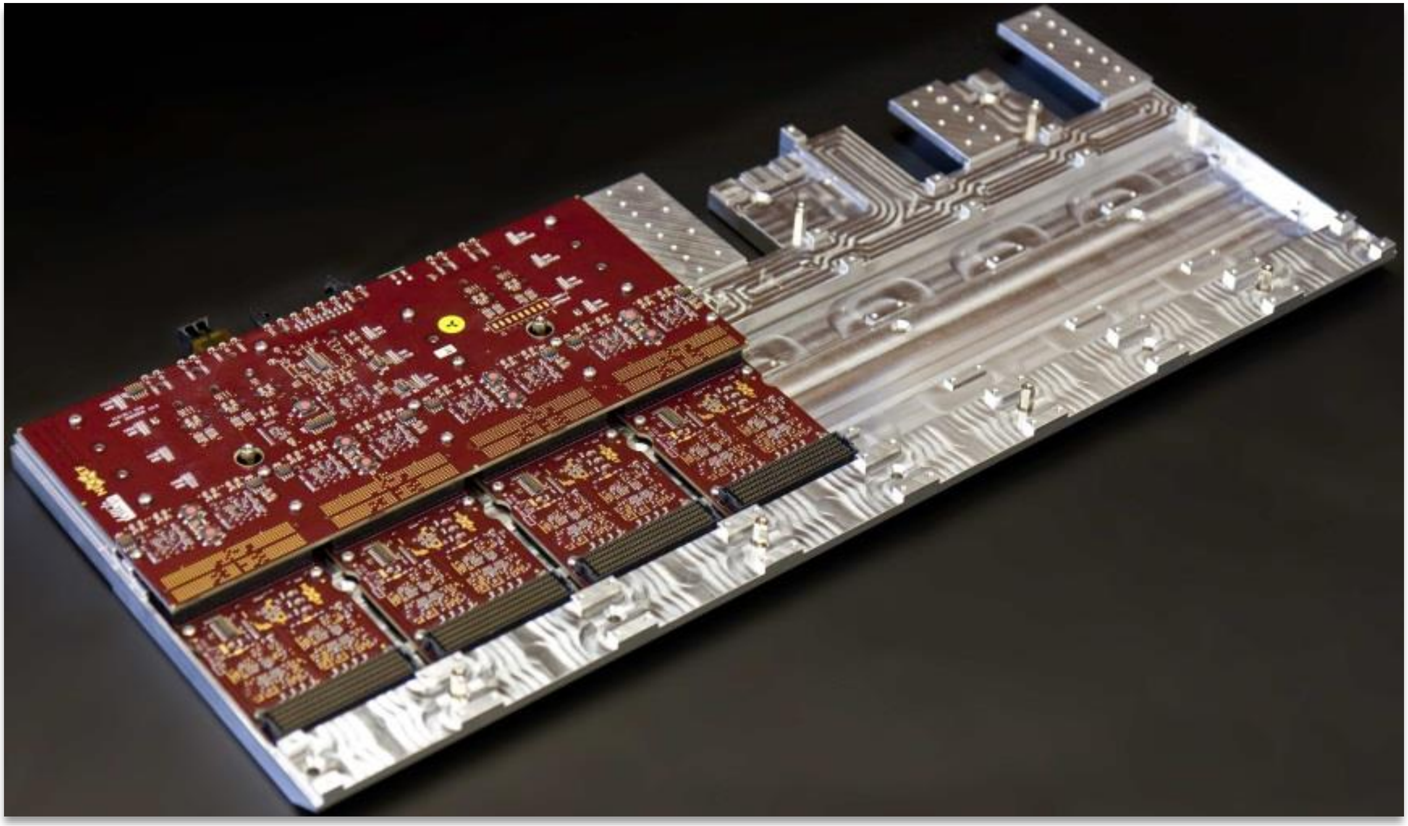
<u>Provide connections:</u>
LV Power
HV (SiPM)
Optical transceivers:
Slow/Fast crtl, data links
DC-DC power converter
House-keeping FPGA

Many connectors!

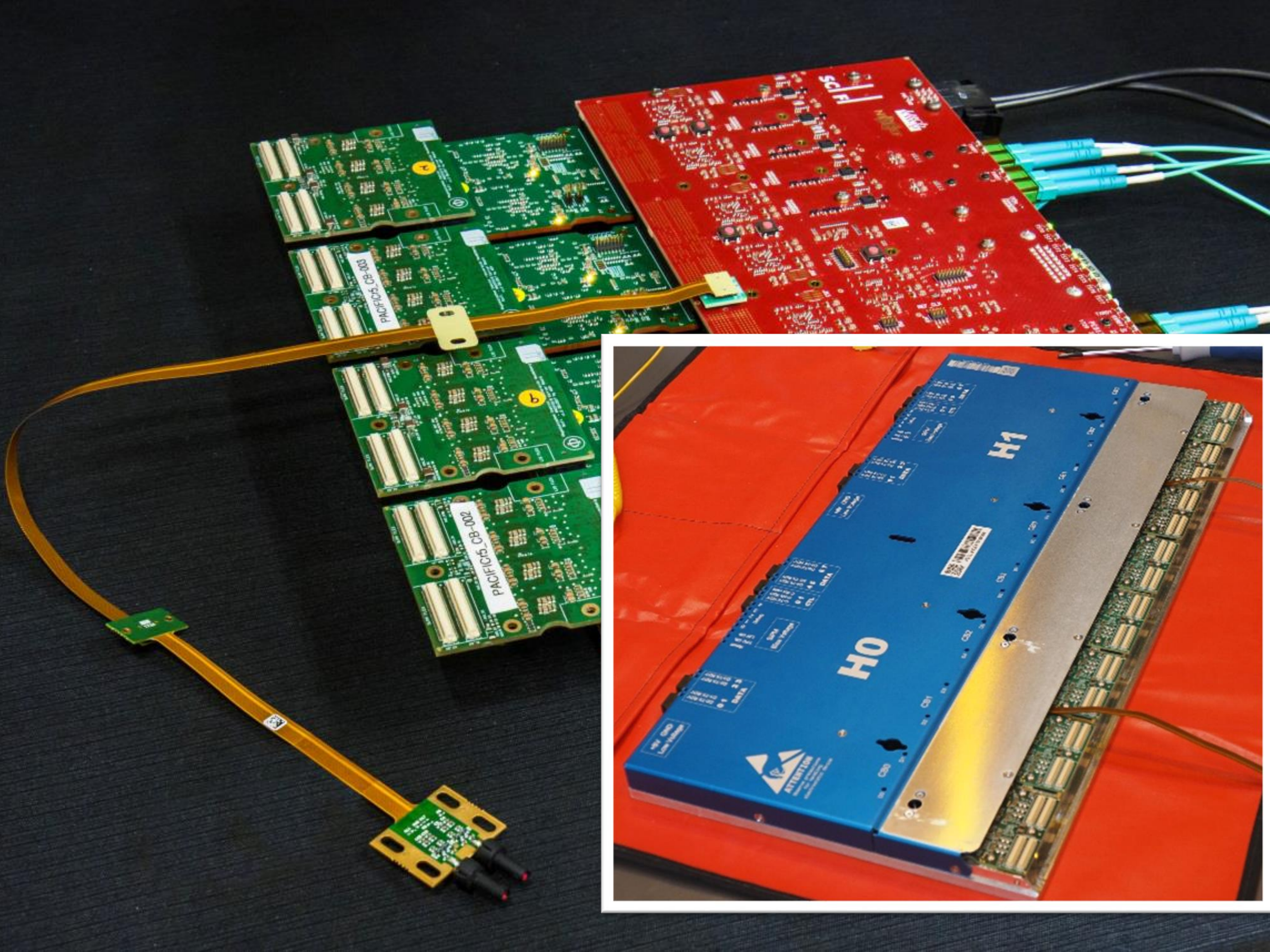
Mechanically and electrically very demanding board!

Electronics Cooling

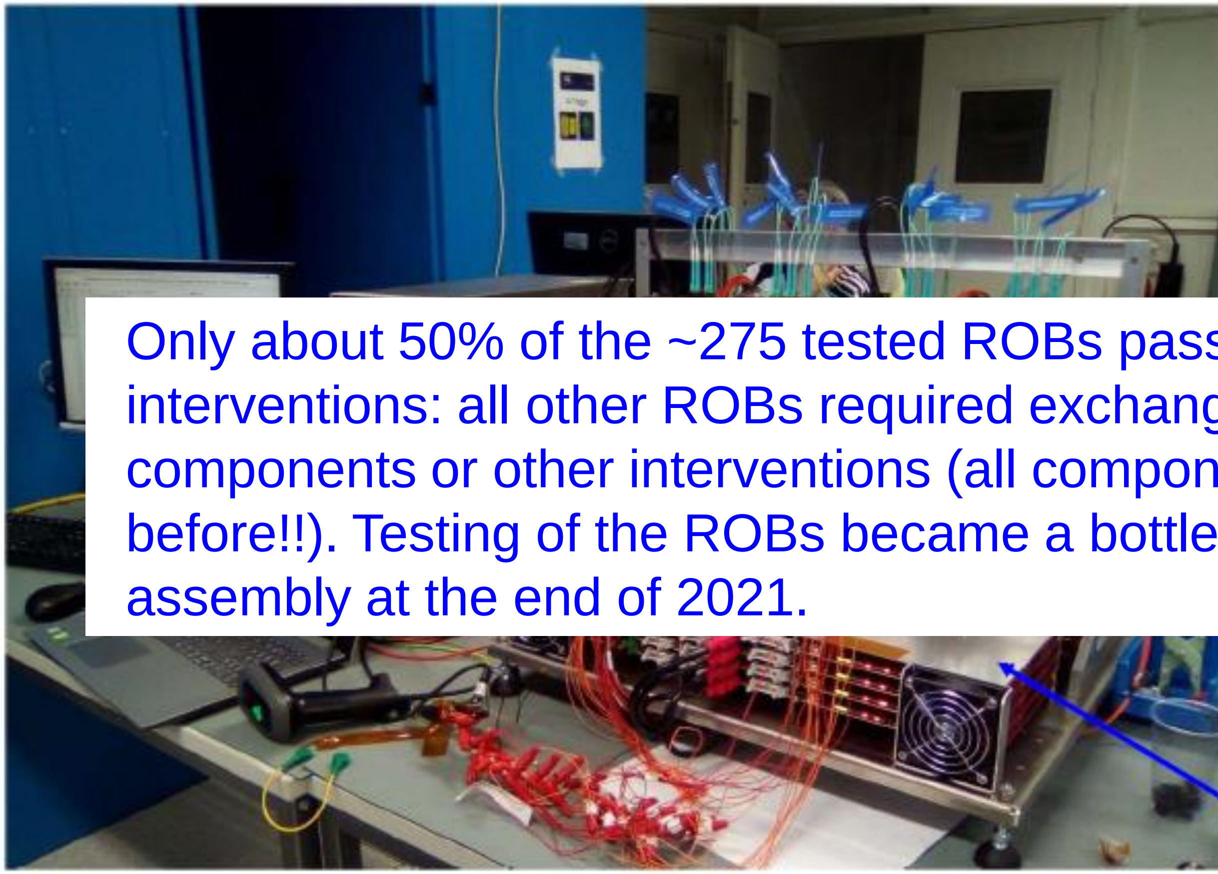
Power dissipation of full Readout Box: 120 W → 30 KW SciFi
Water cooling necessary – integrated in the mounting structure.
Cooling structure connected to water cooled cooling-plates.

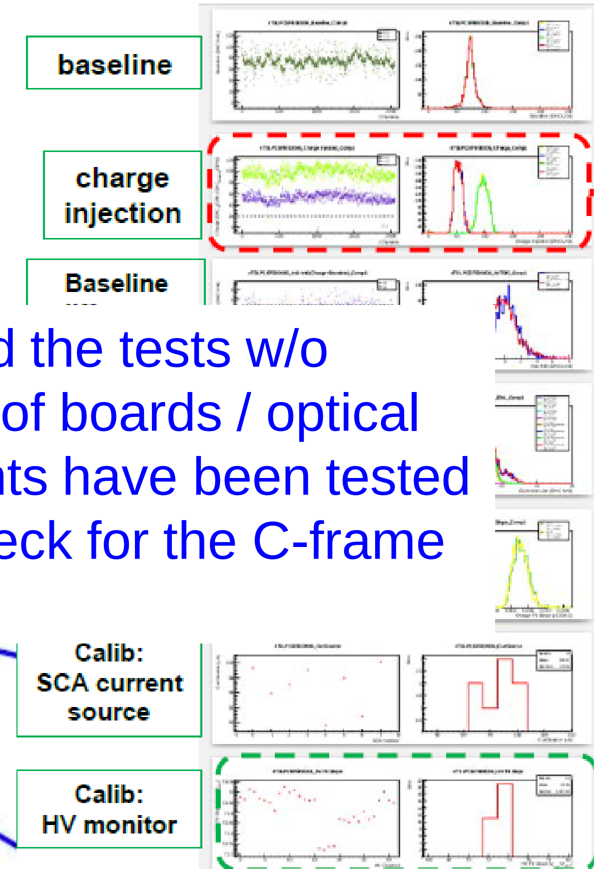


Cooling must be integral part of the front-end design!


PACIFICr5_CB-003
PACIFICr5_CB-002
H1
H0

Testing of finished Readout-Boxes



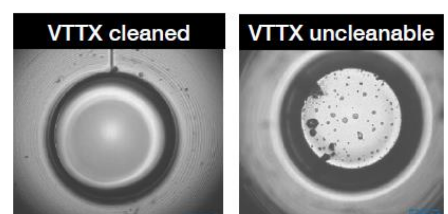


Only about 50% of the ~275 tested ROBs passed the tests w/o interventions: all other ROBs required exchange of boards / optical components or other interventions (all components have been tested before!!). Testing of the ROBs became a bottle neck for the C-frame assembly at the end of 2021.

All Readout Boxes have undergone a very detailed test (incl. bit error tests of all links).

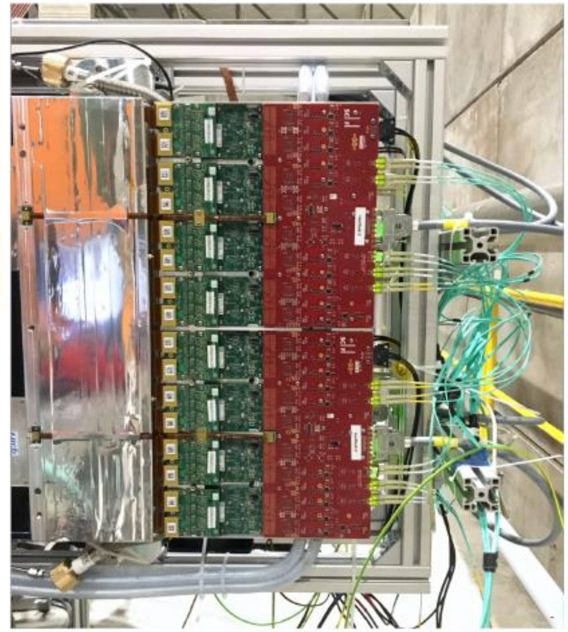
Very time consuming: Required lengthy cleaning of the optical transceivers and the optical connectors (delicate operation).

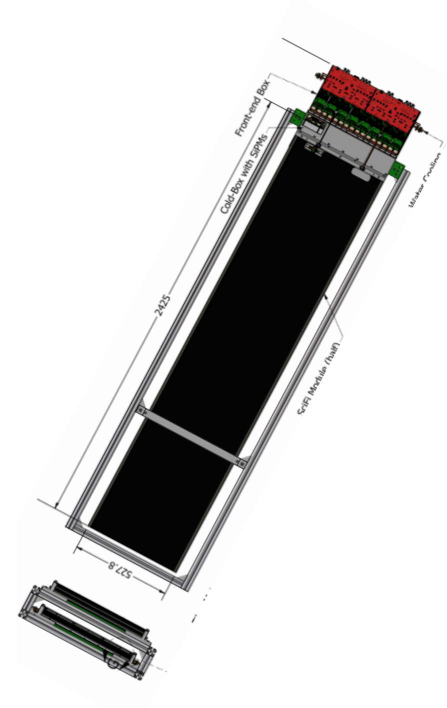
Test developed as result of commissioning.



„Slice test“ – test beam w/ full readout chain

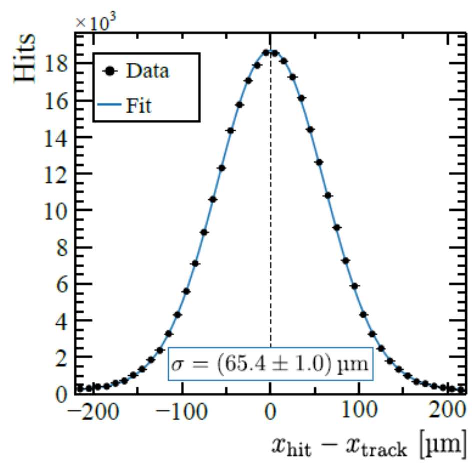
before launching serial production





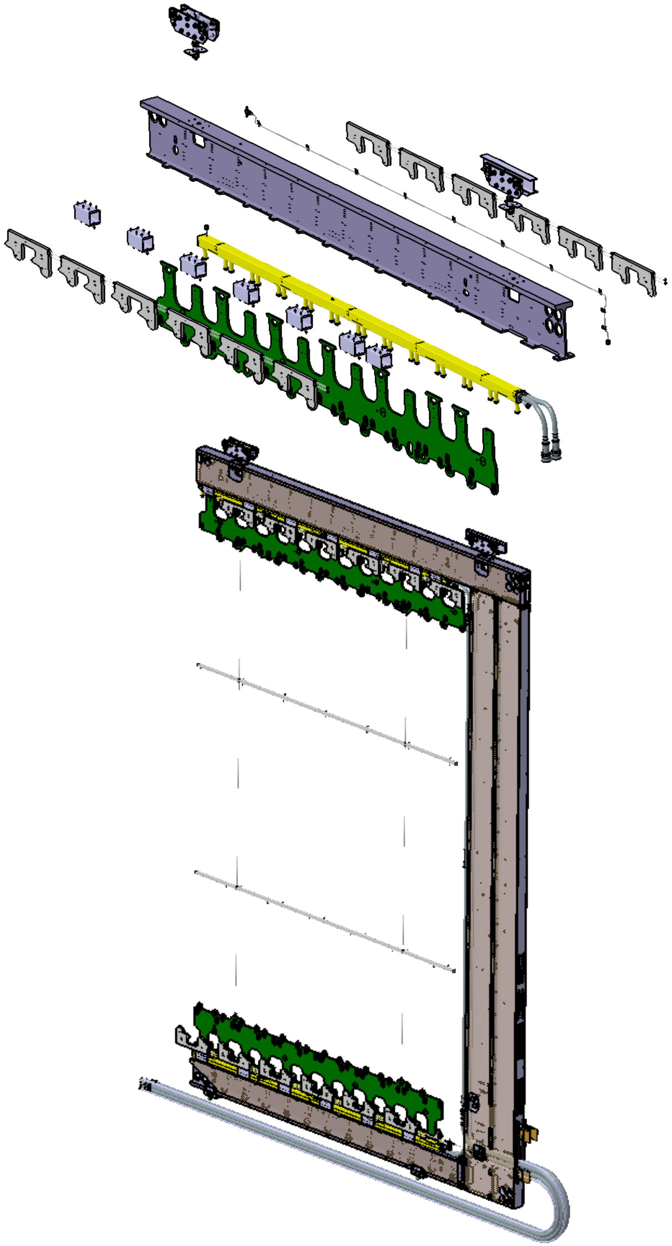
(Nearly) final readout electronics:
PACIFIC-5q boards
Master Boards (v3)
4 ×Cluster Boards (v2) + 12 (v3) w/ 2 different clustering algorithms
MiniDAQ2 (PCI40 1st version)

32 optical links,
4096 channels



$\sigma < 70\ \mu m$
$\varepsilon > 99\%$

Support Mechanics: C-Frames

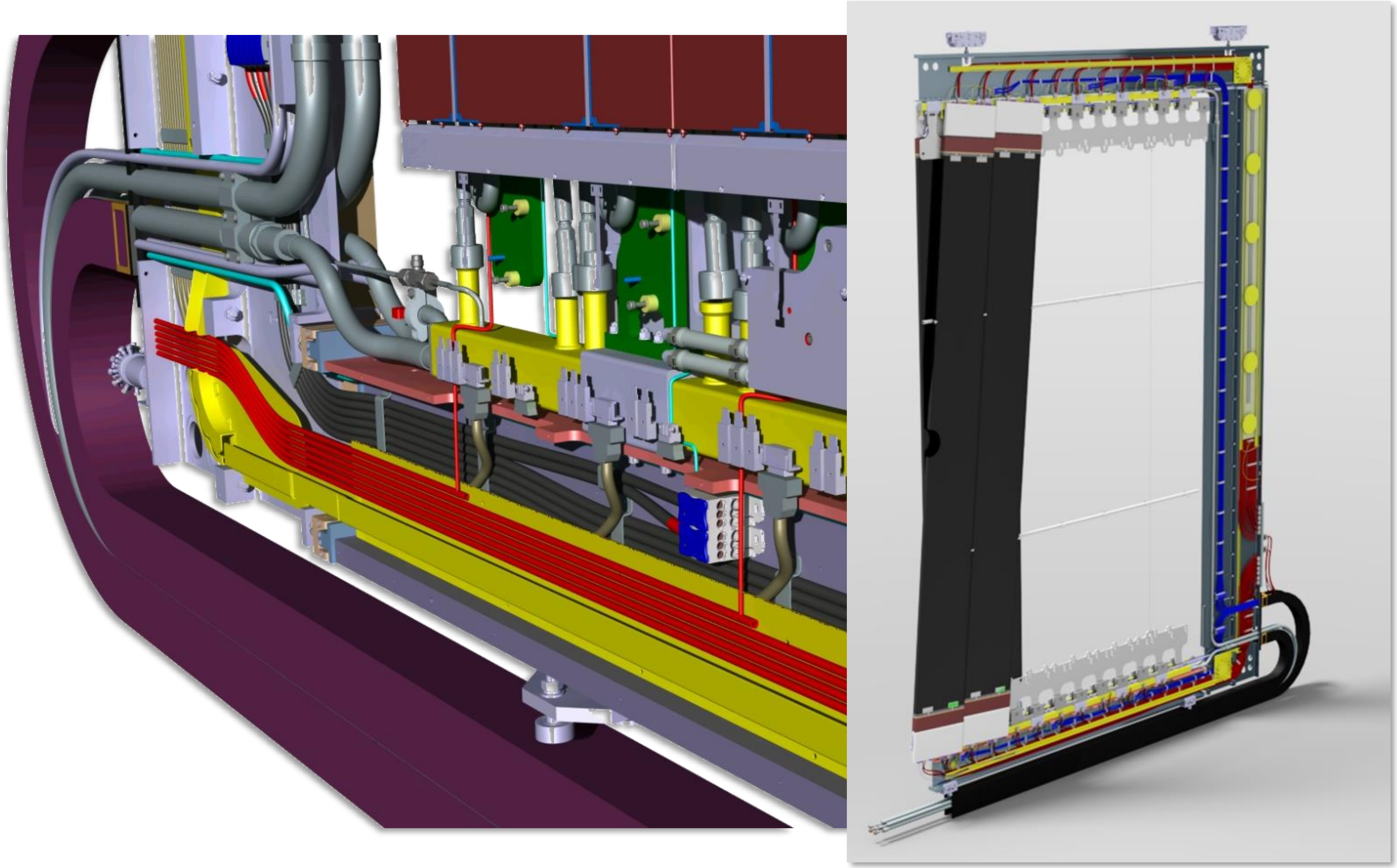


Extruded aluminum I-profiles:

Company (world leader) was a real pain!
Extrusion quality sometimes very bad!
Company unable to machine the profiles.
Delivery schedules completely unreliable.

Don’t rely on a single industrial producer!

Detailed 3D CAD-model of the C-frame

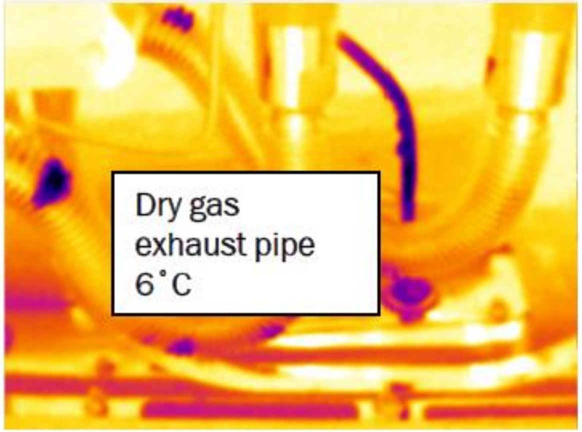


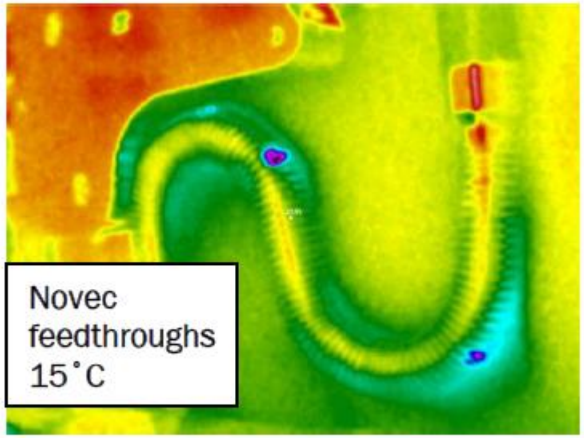
Integration of all services was very difficult! Prototype was vey helpful.

Full C-Frame Prototype (frame #0)

Fullsize prototype including services, electronics and modules etc.
Extremely useful to test mechanics, cabling paths, electronics readout …
Expensive but extremely valuable investment!

1st final C-frame (Jun 2019) – full operation

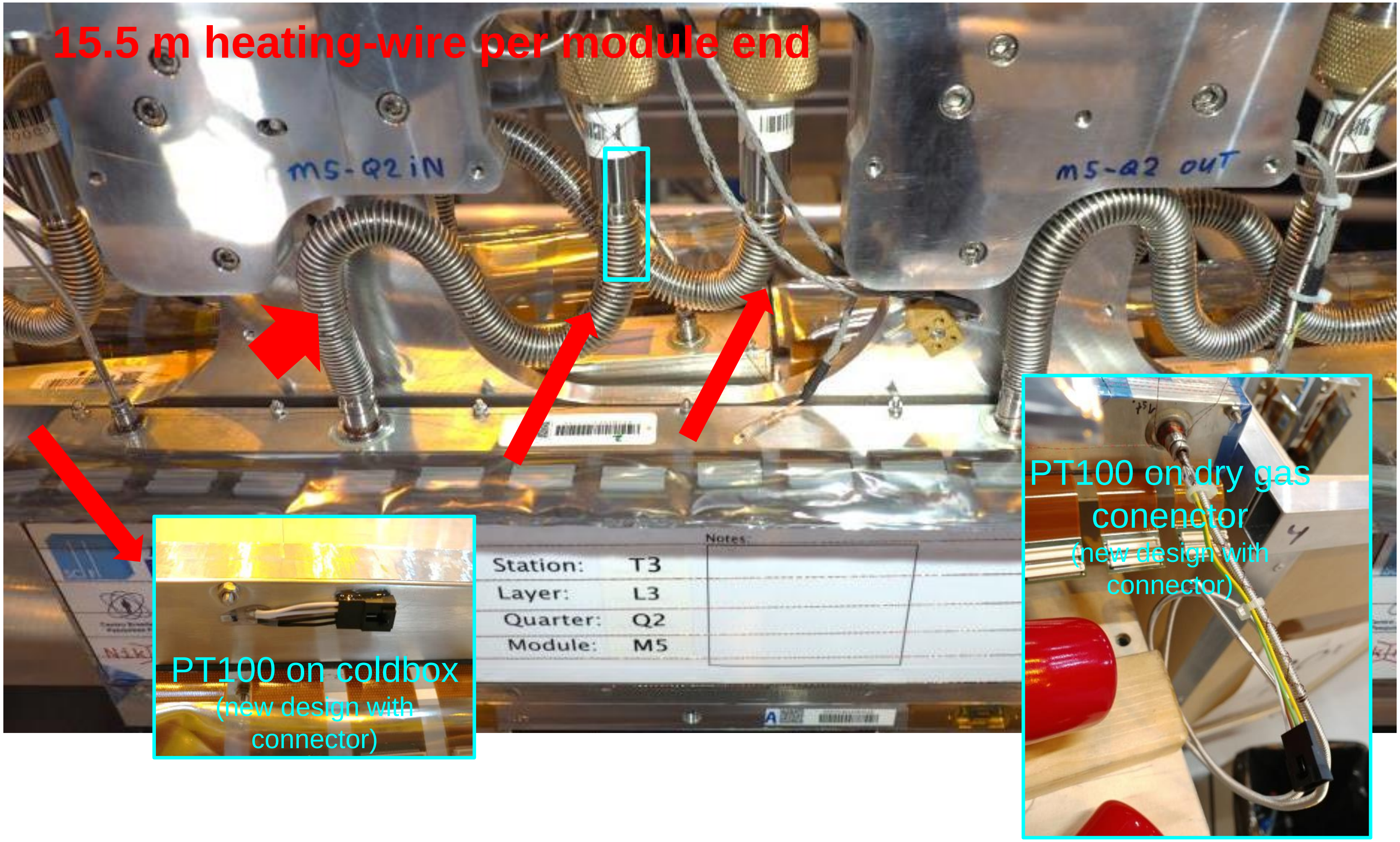




Condensation on vacuum insulated cooling pipes, cold-box, dry air exhaust.

Full commissioning and operation of the 1st C-frame revealed system problems which could not have not been before: noise on LV, condensation.

Mitigation of Condensation

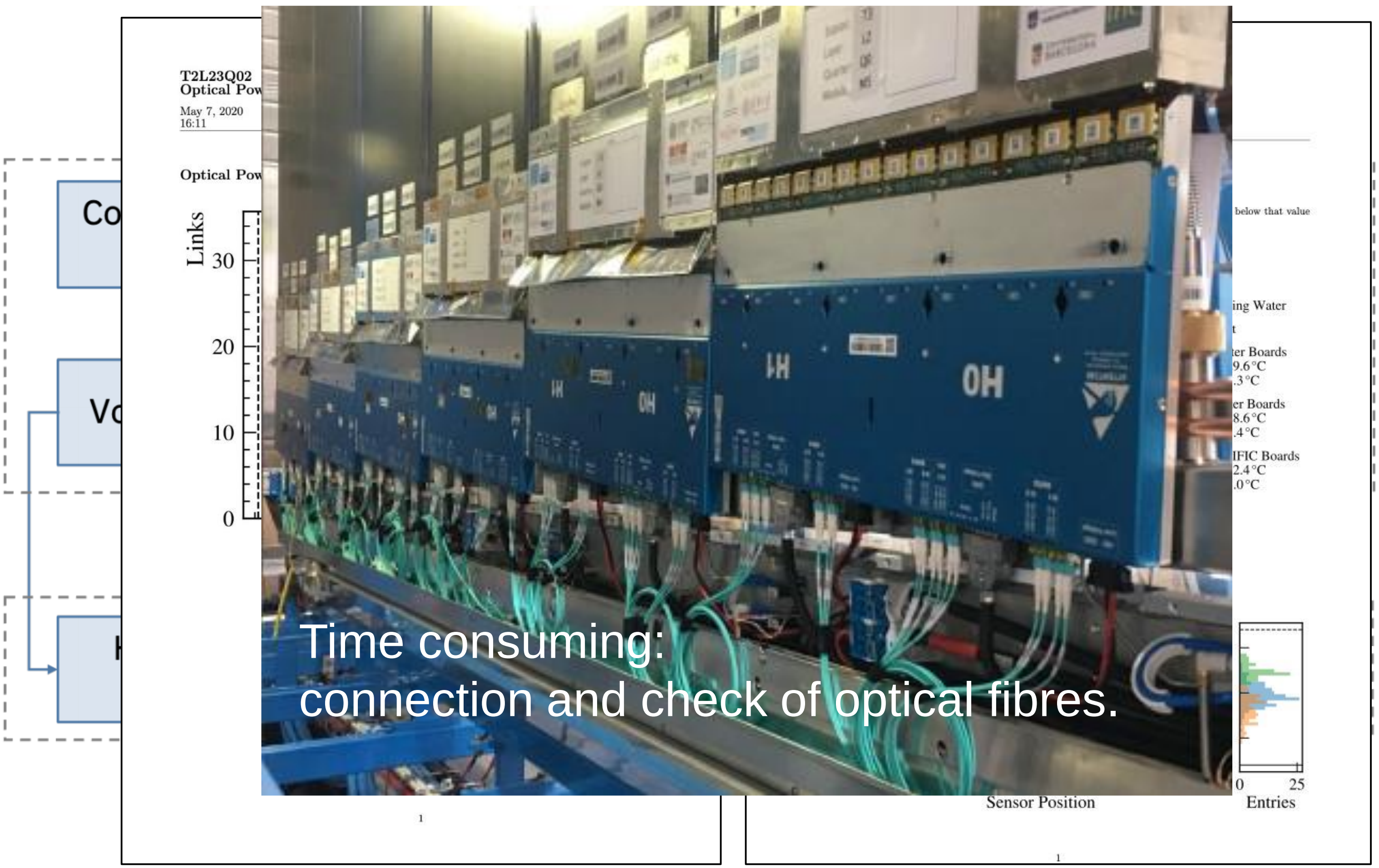


We launched a detailed study mitigate the problem using active heating → after review in Oct 2019 we continued with the assembly.

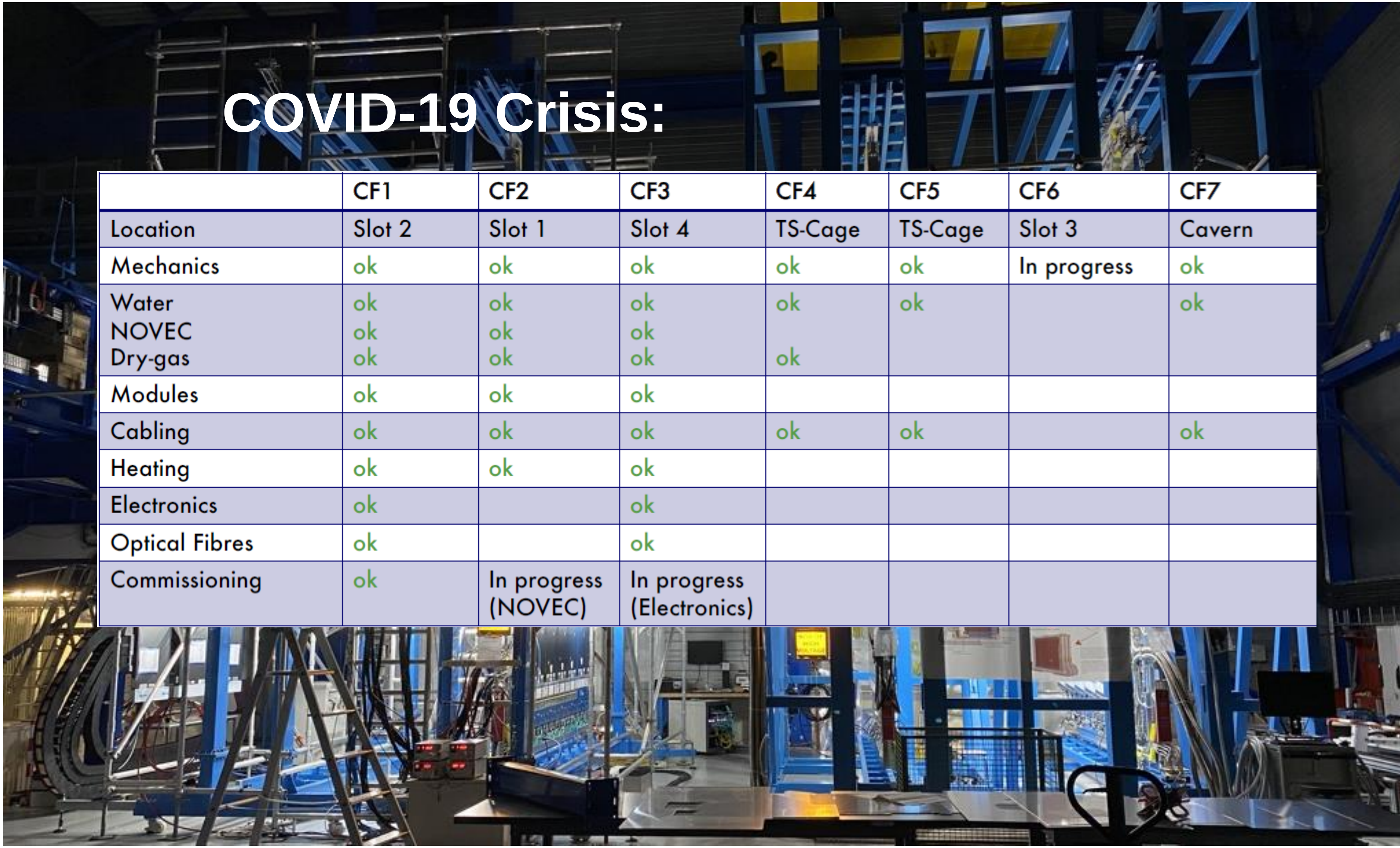
Be prepared for system effects which only show up with final detector.

Full Commissioning before Installation

Commissioning of all service systems and of Electronics:



C-frame Assembly & Commissioning at CERN

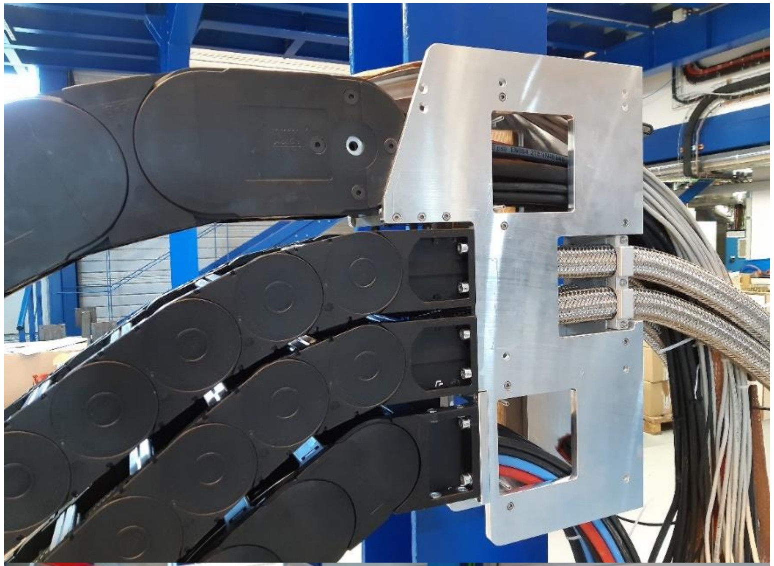


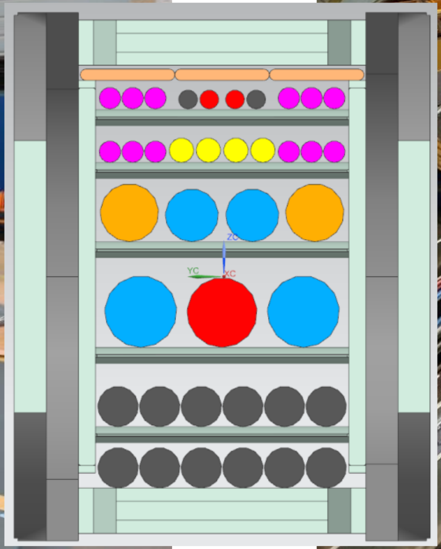
COVID-19 Crisis:

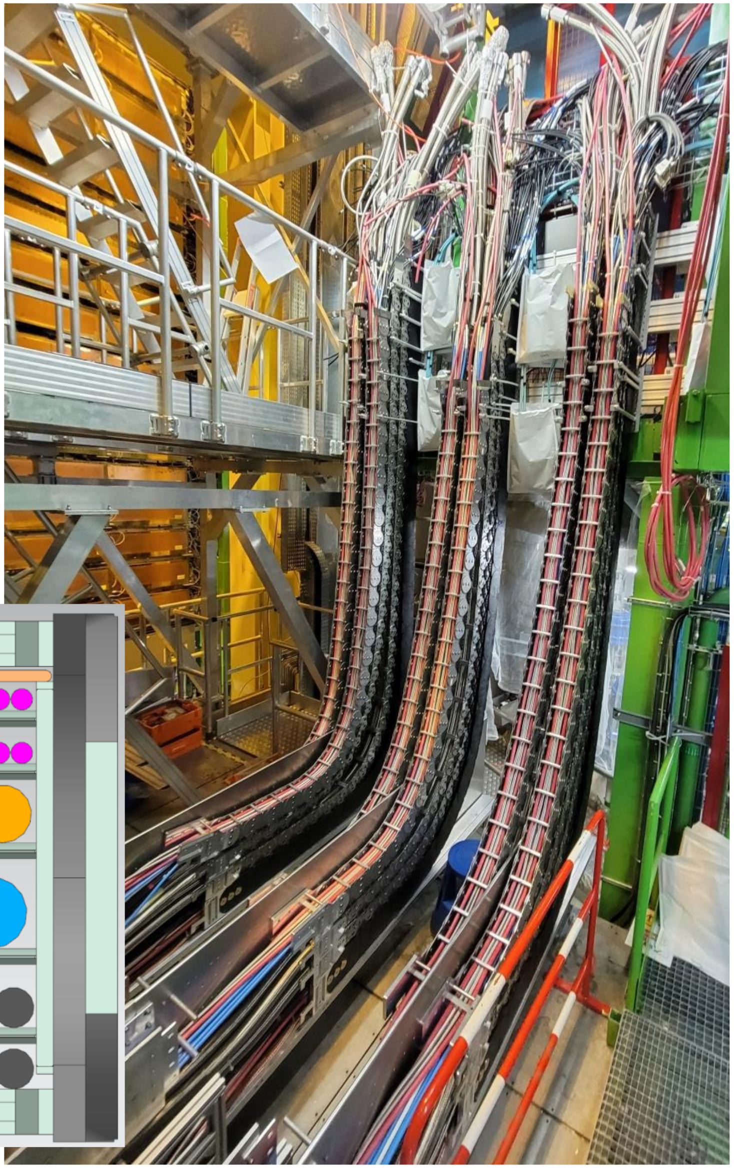
	CF1	CF2	CF3	CF4	CF5	CF6	CF7
Location	Slot 2	Slot 1	Slot 4	TS-Cage	TS-Cage	Slot 3	Cavern
Mechanics	ok	ok	ok	ok	ok	In progress	ok
Water	ok	ok	ok	ok	ok		ok
NOVEC	ok	ok	ok				
Dry-gas	ok	ok	ok	ok			
Modules	ok	ok	ok				
Cabling	ok	ok	ok	ok	ok		ok
Heating	ok	ok	ok				
Electronics	ok		ok				
Optical Fibres	ok		ok				
Commissioning	ok	In progress (NOVEC)	In progress (Electronics)				

In February 2020 all components at CERN, work on 4 frames in parallel …

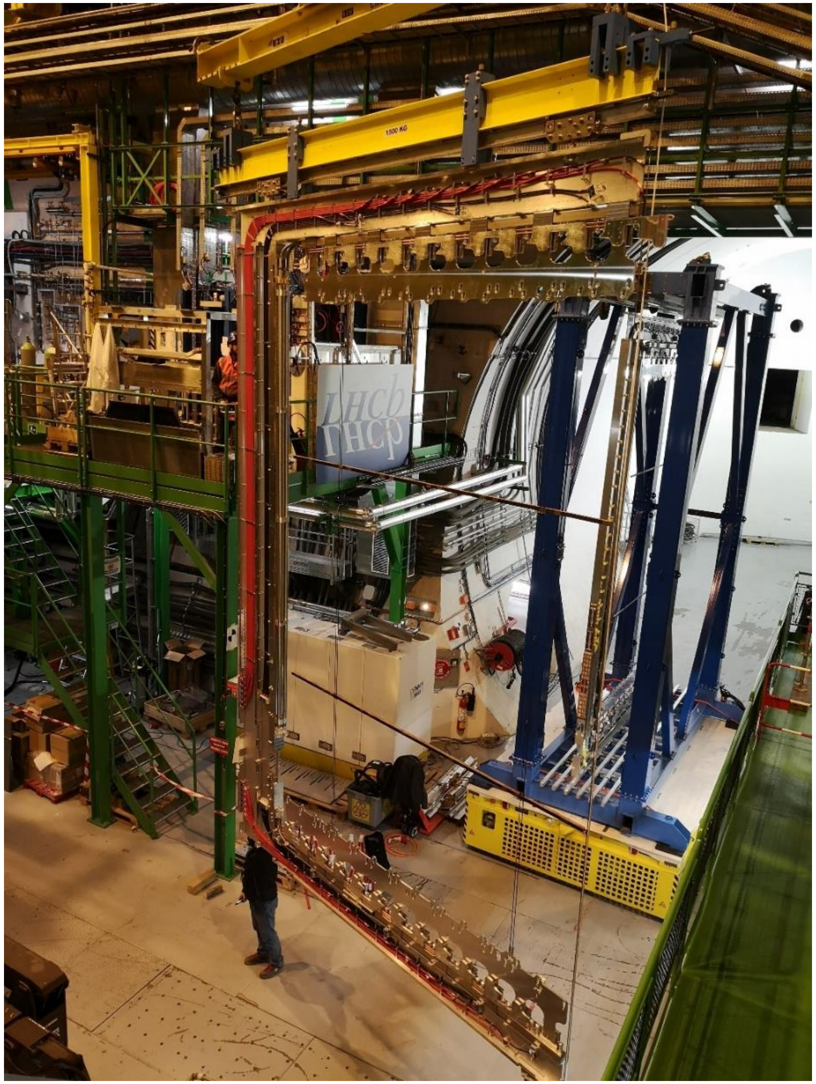
Installation - Prototyping







Test Installation of 2 empty frames

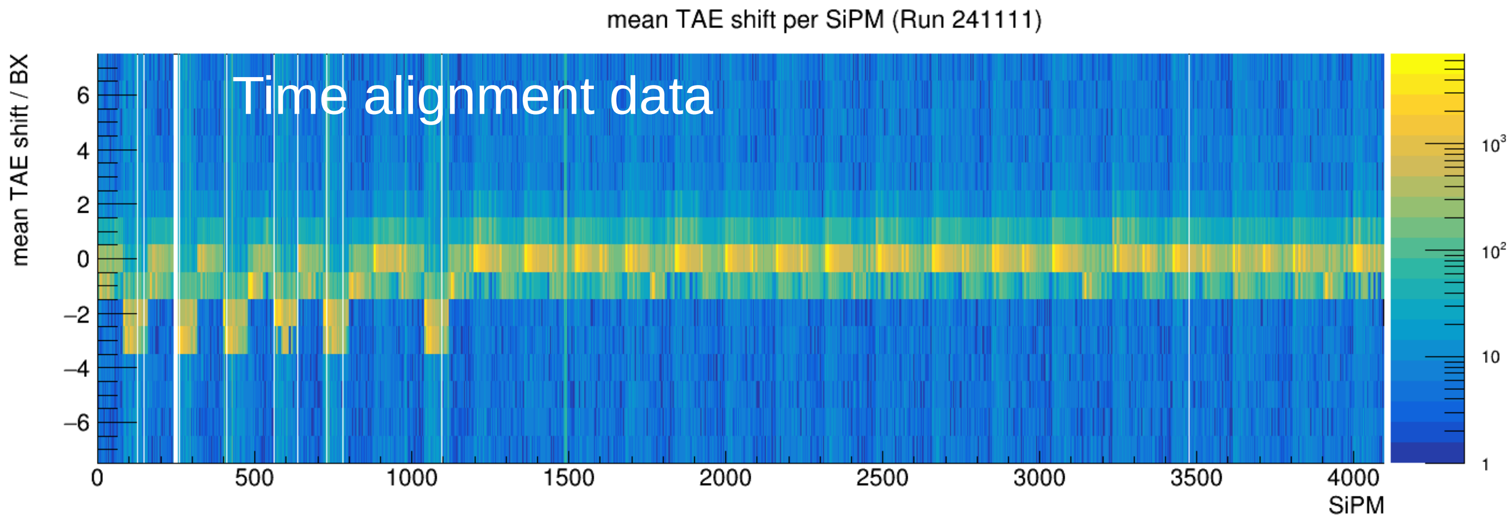


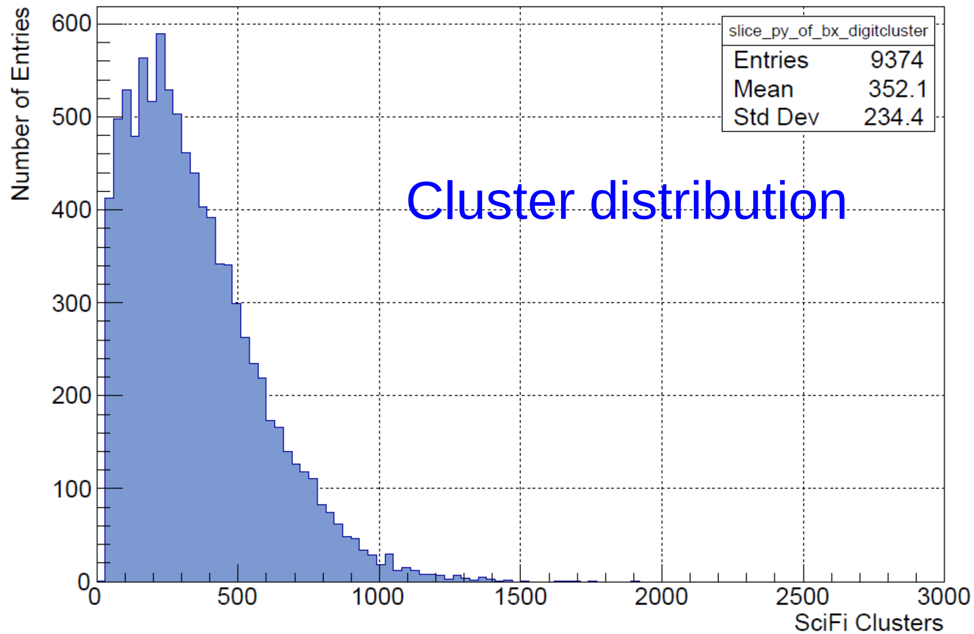
Installation of 1st 4 frames in May 2021

Installation and connection of C-frames went very smooth.

Most time consuming was the connection of the optical links.

First SciFi Data





Not working links:
0 / 1024 control links
~8 / 4096 data links

⇩

High functionality a result of the many tests that have been done

Conclusion

<u>My tips:</u>

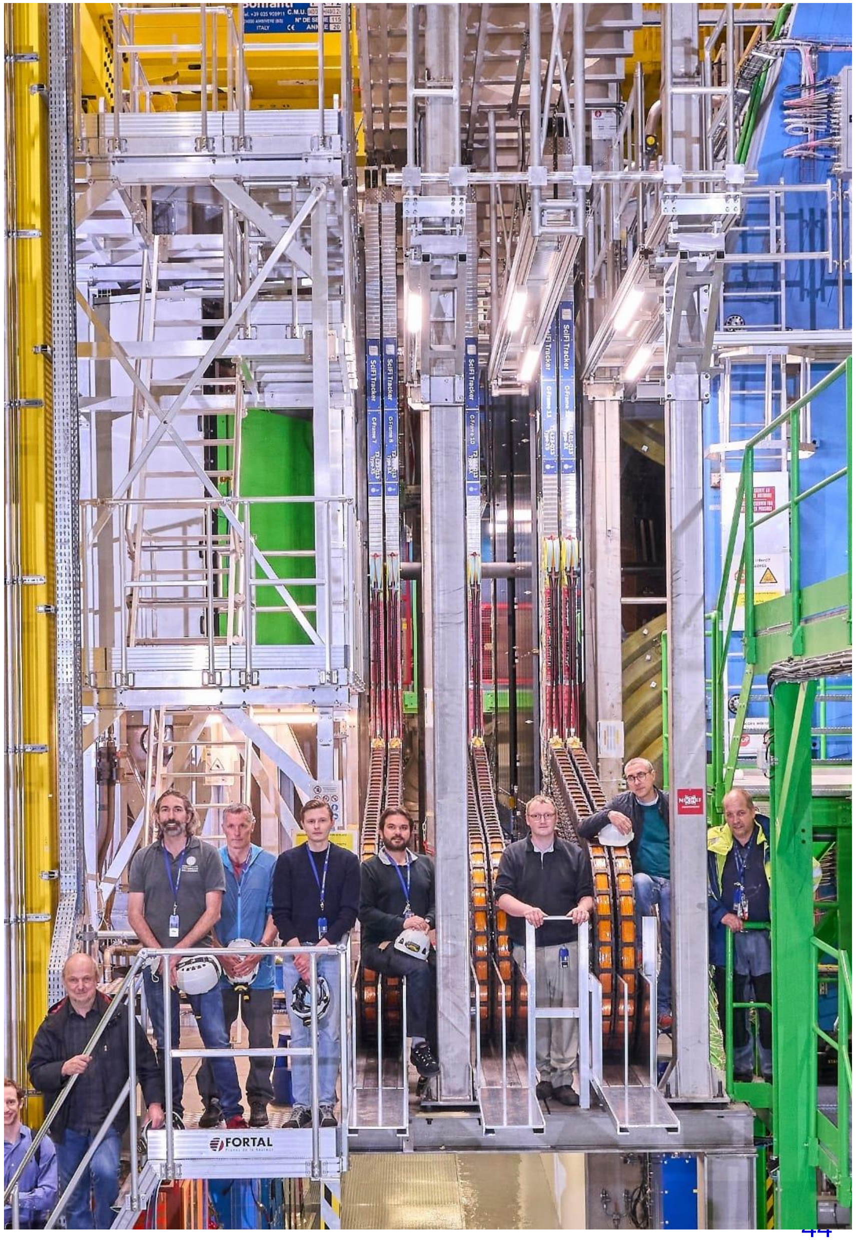
Dense QA for all components:
testing, testing, testing (many issues we had initially overlooked to monitor popped up during the many tests we were doing).

Early and full-size prototypes of all components: The knowledge gain easily balances the additional costs and efforts.

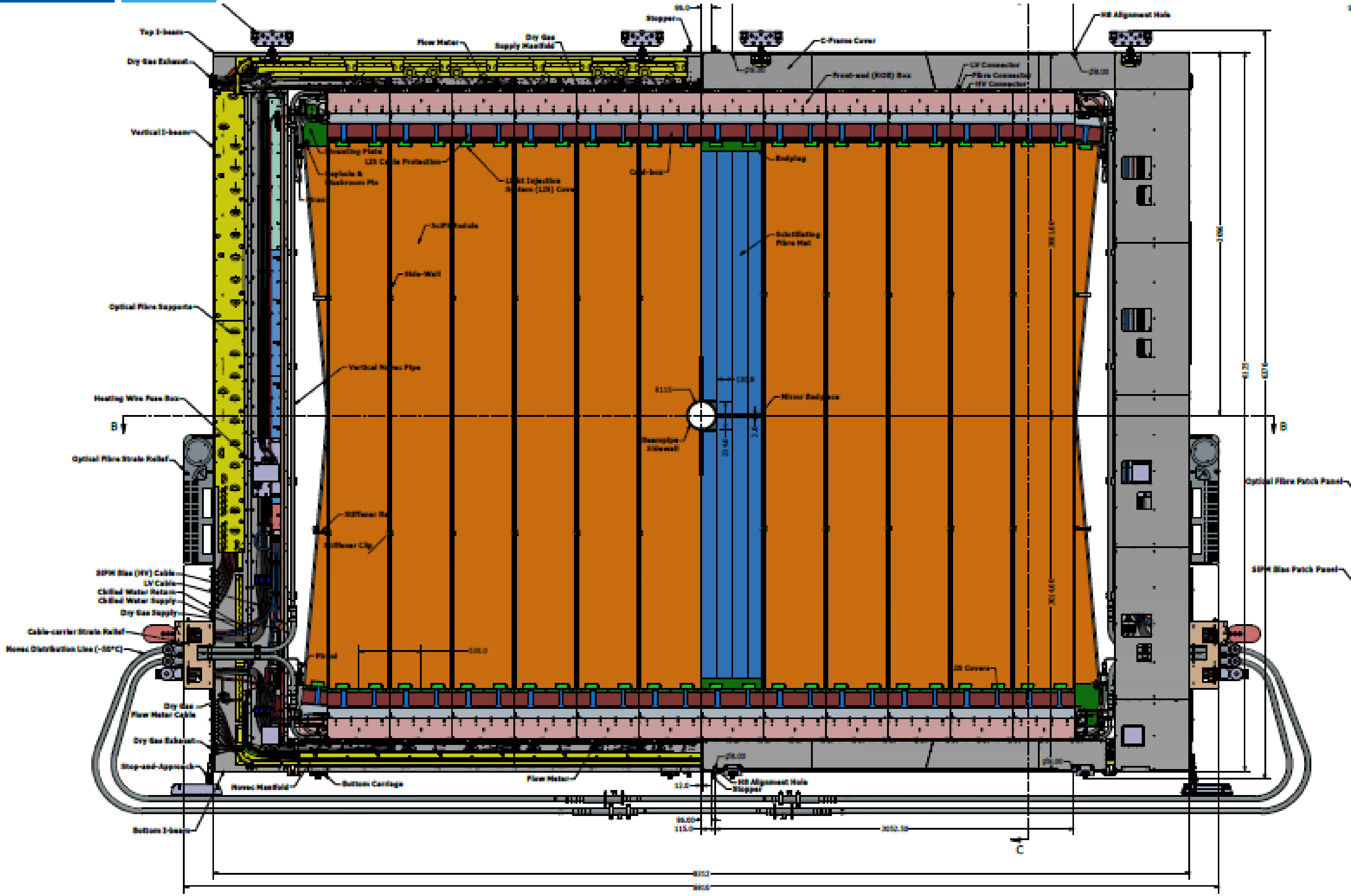
Electronics:
Full chain tests already w/ an early version of the electronics. Realistic "slice test" of a larger system before serial production is launched.

Take Engineering Design and Production Readiness Review serious.

Purchase of material takes time.
Don't trust quality of industrial suppliers..



Back-Up

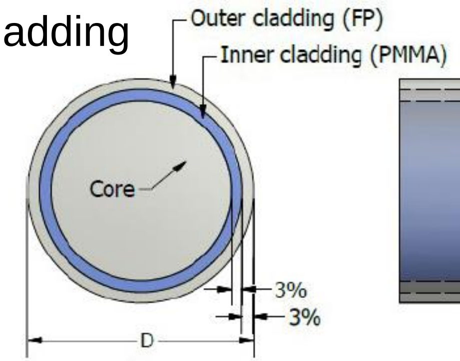

Top I-beam
Dry Gas Exhaust
Vertical I-beam
Optical Fibre Supports
Heating Wire Fuse Box
Optical Fibre Strain Relief
Flow Meter
Dry Gas
Supply Manifold
Stopper
C-Frame Cover
HB Alignment Hole
Front-end (ROB) Box
LV Connector
Fibre Connector
HV Connector
Mounting Plate
LIS Cable Protection
Light Injection
System (LIS) Cover
SciFi Module
Side-Wall
Vertical Novec Pipe
Endplug
Scintillating
Fibre Mat
Mirror Endpiece
Beampipe
Sidewall
Stiffener Clip
SiPM Bias (HV) Cable
LV Cable
Chilled Water Return
Chilled Water Supply
Dry Gas Supply
Cable-carrier Strain Relief
Novec Distribution Line (-50°C)
Dry Gas
Flow Meter Cable
Stop-and-Approach
Novec Manifold
Bottom Carriage
Bottom I-beam
Optical Fibre Patch Panel
SiPM Bias Patch Panel
LIS Covers
B
C

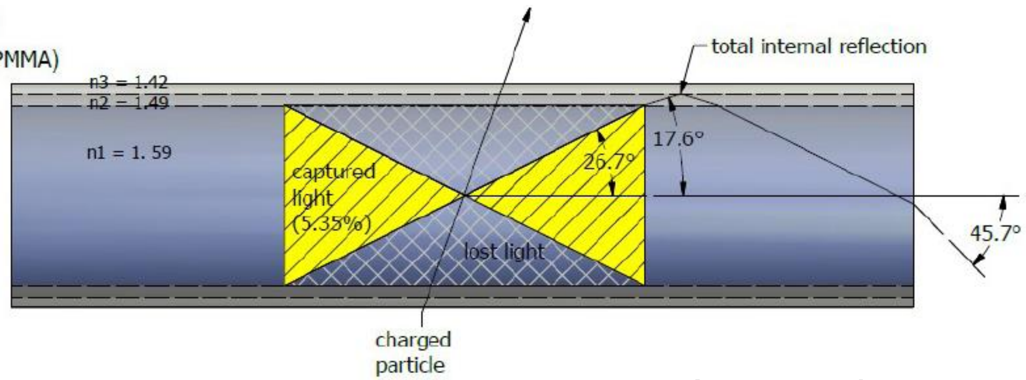
Scintillating Fibre

Kuraray SCSF-78

Double cladding

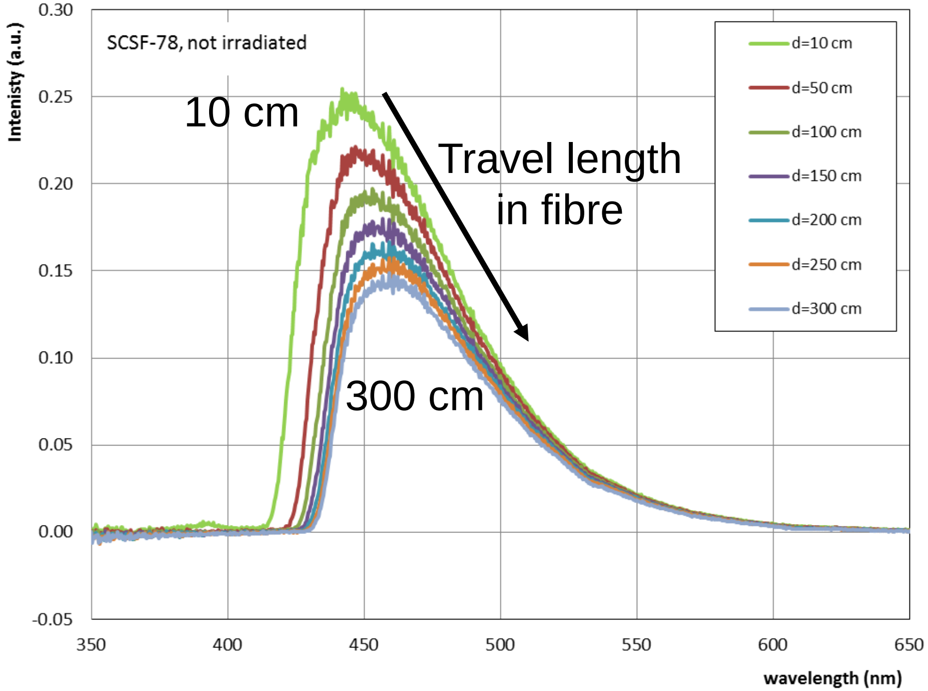
Core: Polystyrene + 2 dyes





~300 photons / MIP
(only 2×5% are captured)

CERN-LHCb-PUB-2015-011



Light emission peak 460 nm
Attenuation length ~3.5 m

Ionizing radiation degrades light transmission property:
50 fb^{-1} (35 kGy) $\rightarrow$ 40 % reduction for particles near the beam-pipe

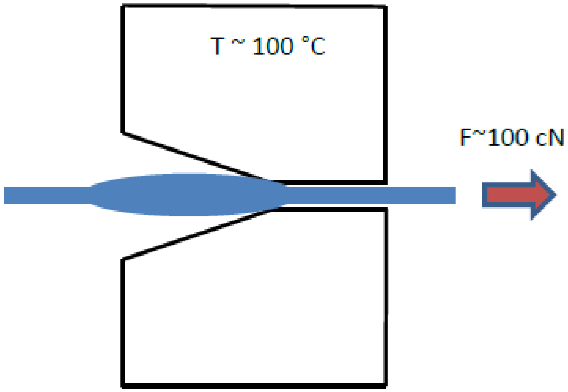
Fibre Quality Assurance

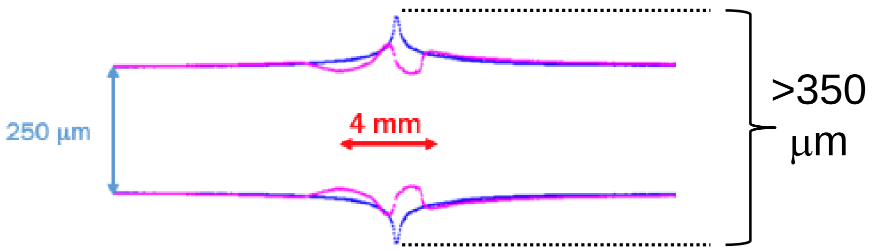
Kuraray SCSF-78

Fibre scanner, LHCb-PUB-2015-009

- All fibre spools scanned for mechanical defects and irregularities (so far ~6000 km scanned).
- We observe "bumps" = local increase of diameter.
- Bumps >350 μm (typ. ~8 per 12500 m) produce irregularities in winding pattern and must be removed.
- Automatic bump shrinkage using a "hot drawing" tool. Applied routinely.

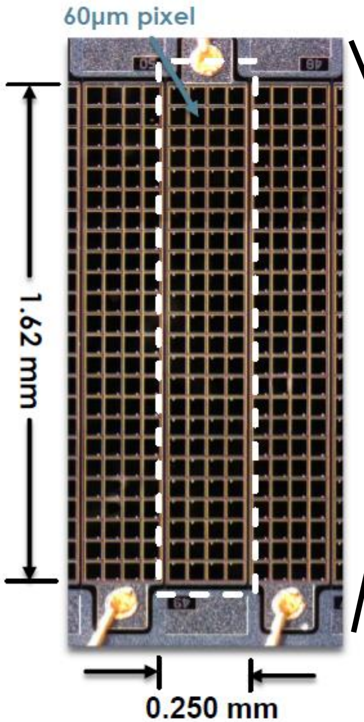
LHCb-PUB-2016-010



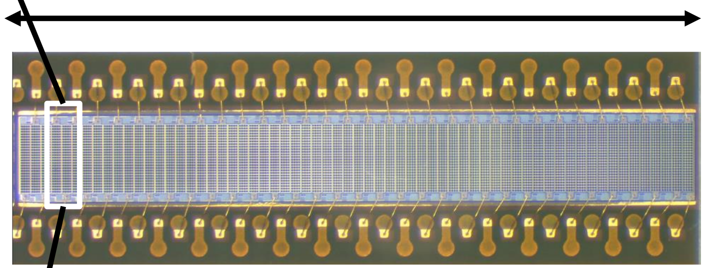


Silicon Photomultiplier

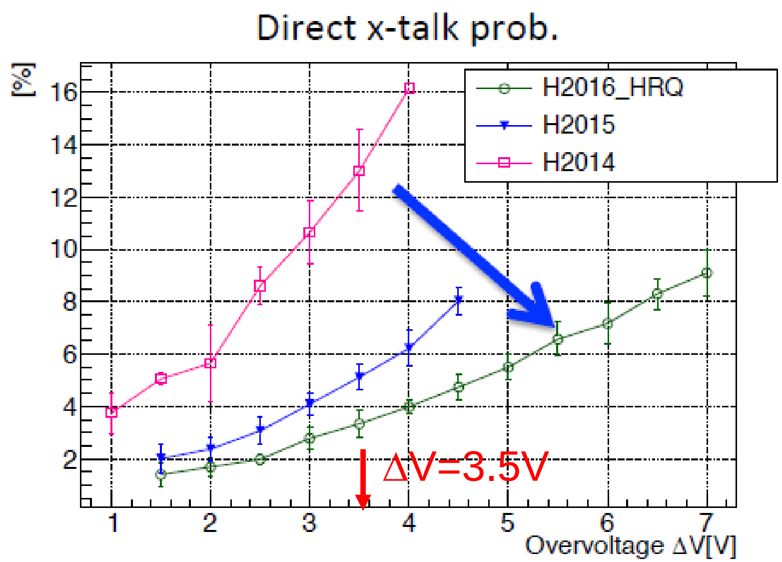
Hamamatsu, H2016-HRQ



1 die = 64 channels



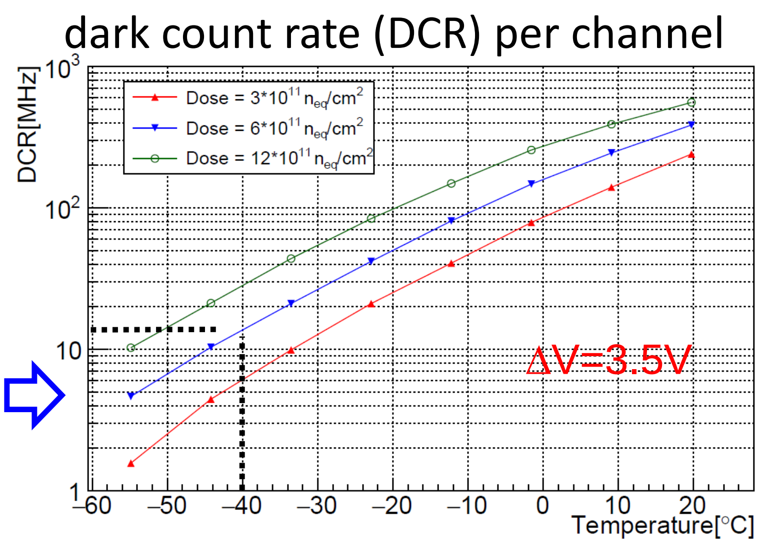
SiPM = 2 dies = 32 mm



Performance:

- peak PDE = 48% (at 3.5 V)
- direct cross-talk = 3 %,
- delayed cross-talk = 2.5%
- afterpulses < 0.1%.

Dark count rate per channel after neutron irradiation:

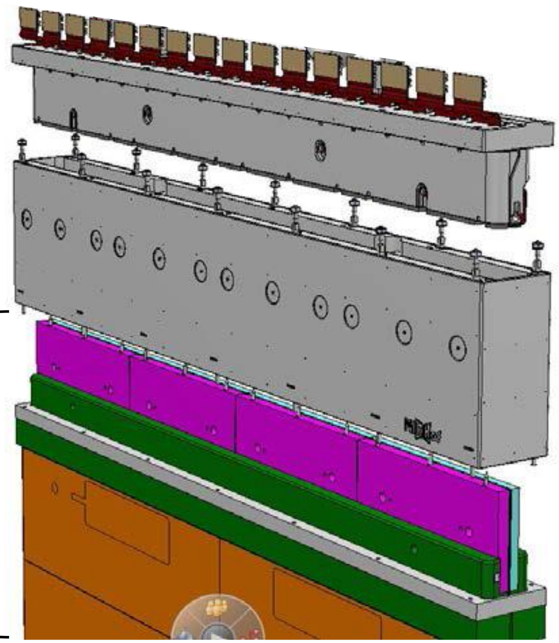


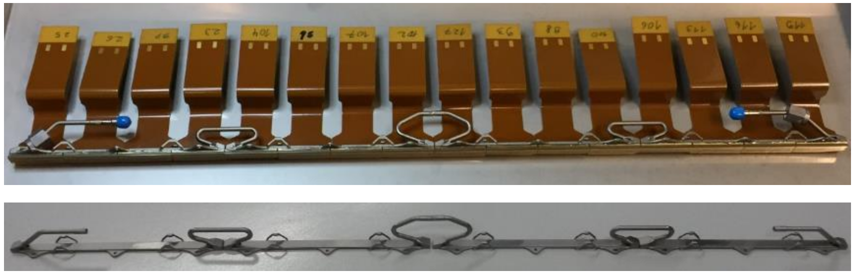
DCR halved every -10 K:

$\Phi = 6 \cdot 10^{11}\ n_{eq}/cm^2 \rightarrow 14$ MHz at -40C

[Characterisation of the Hamamatsu silicon photomultiplier arrays for the LHCb Scintillating Fibre Tracker Upgrade](), **Axel KUONEN, TIPP 2017**

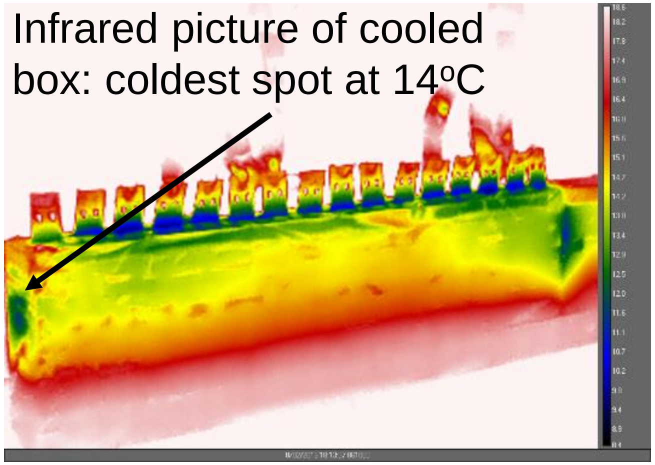
SiPM Cooling and Alignment - Coldbox





3D printed Ti cooling bar, carry/align 16 SiPMs

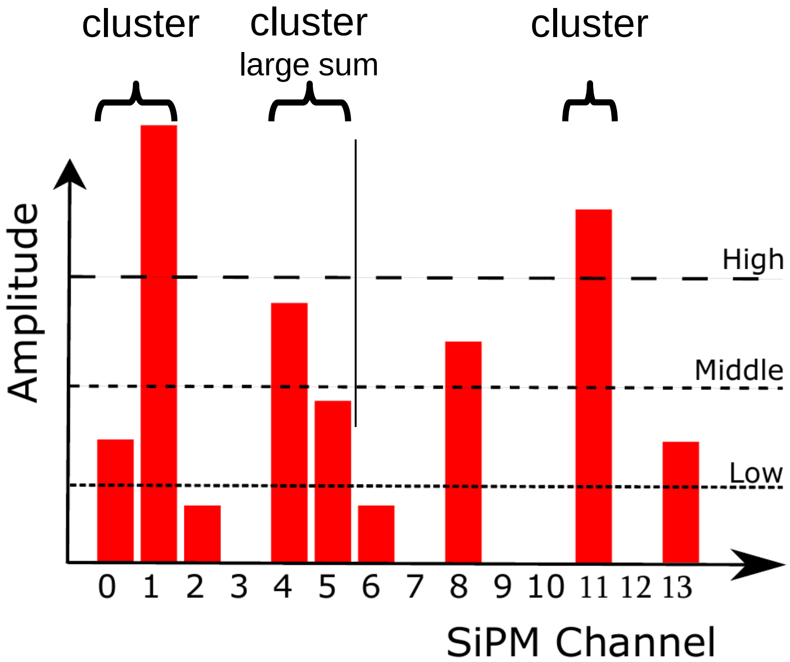
SiPM on flex print



Infrared picture of cooled box: coldest spot at 14°C

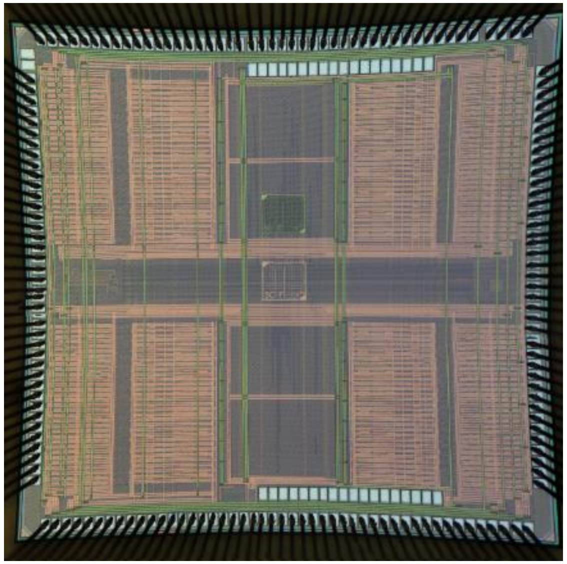
- Cold box (3D printed nylon) at each end of fibre module; houses 16 SiPMs at -40°C, aligned and in optical contact to fibre ends.
- **Challenges:** thermal insulation, humidity management inside box (total length 130m)
- Pre-series under production.

Clusterization



2 bit/channel
low, middle,
high threshold
passed

PACIFICr4 ASIC



A readout ASIC for the LHCb Scintillating Fibre (SciFi) tracker, **X. HAN at TIPP 2017**

Clustering = key to noise / data reduction:

Dark count rate w/ 6×10^{11} n_{eq} / cm^2
~14 MHz / channel

cluster rate 0.8 MHz / 128 channels
calculate x-position of clusters