Readout Electronics of the LHCb SciFi Tracker

Jahrestreffen der deutschen LHCb-Gruppen

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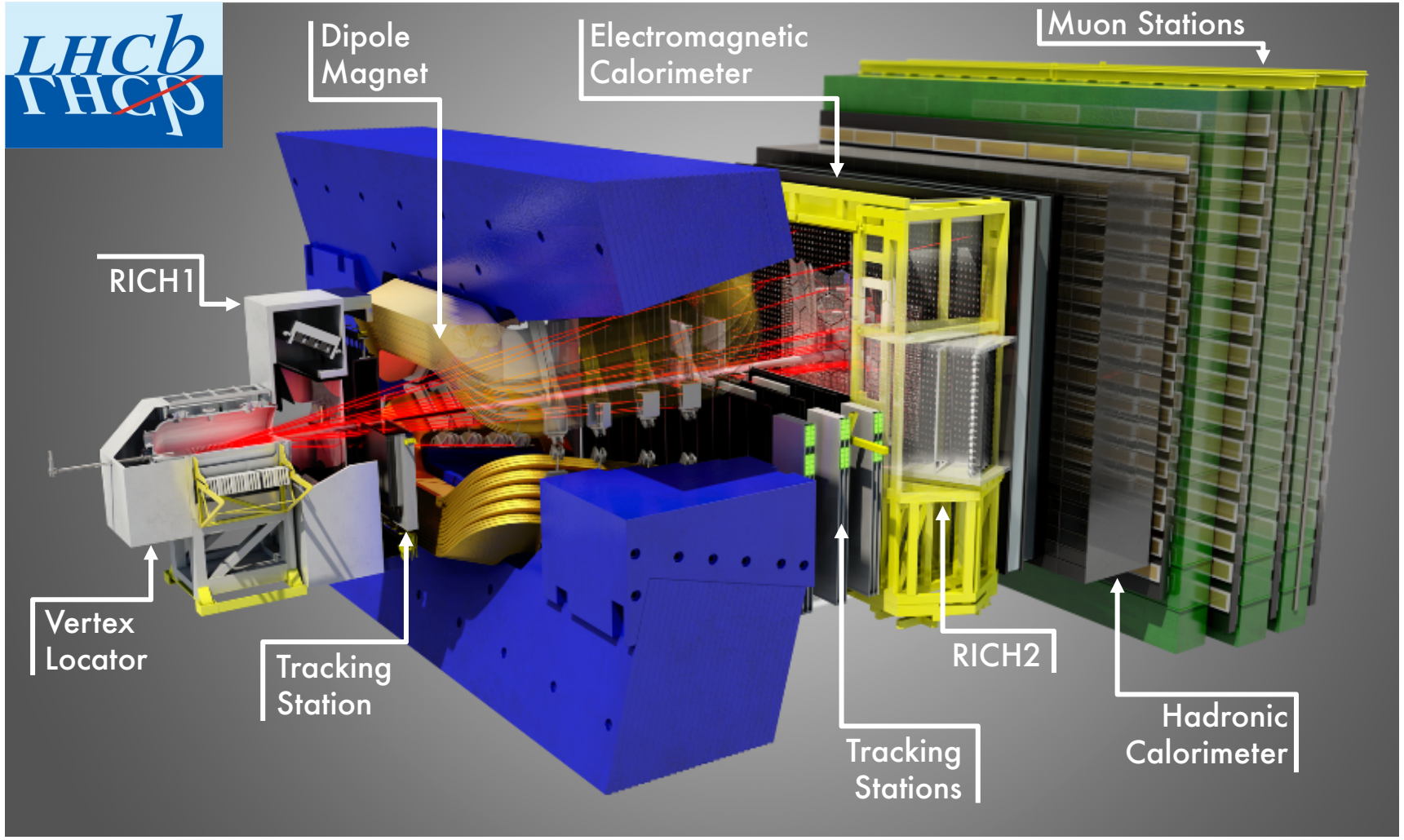
LHCb Detector

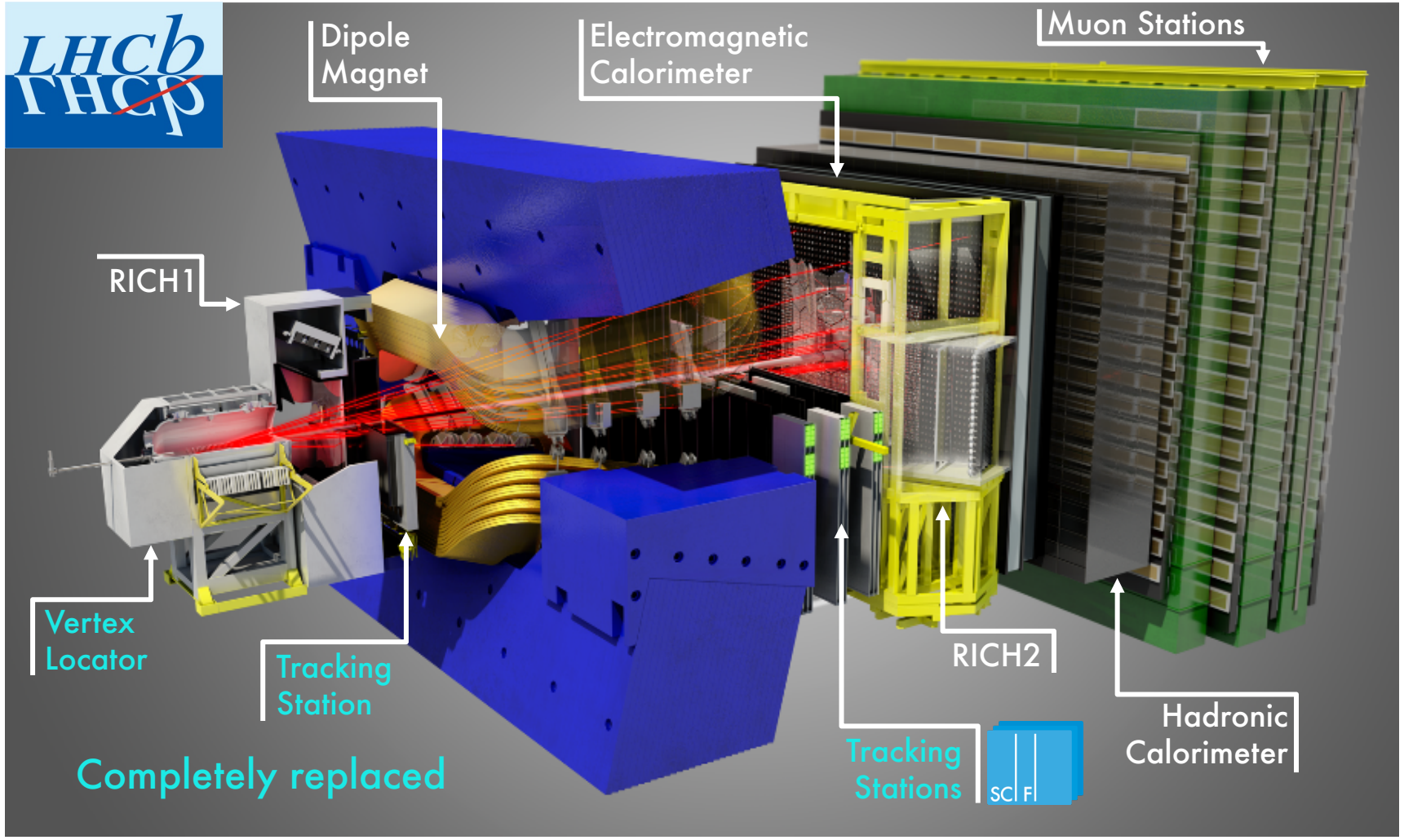
Phase-I



- Single-arm forward spectrometer $2 < \eta < 5$
- Instantaneous Luminosity $\mathcal{L}_{\text{inst}} = 4 \cdot 10^{32}\,\text{cm}^{-2}\text{s}^{-1}$
- Detector readout rate $R = 1\,\text{MHz}$

LHCb Detector

Phase-I Upgrade



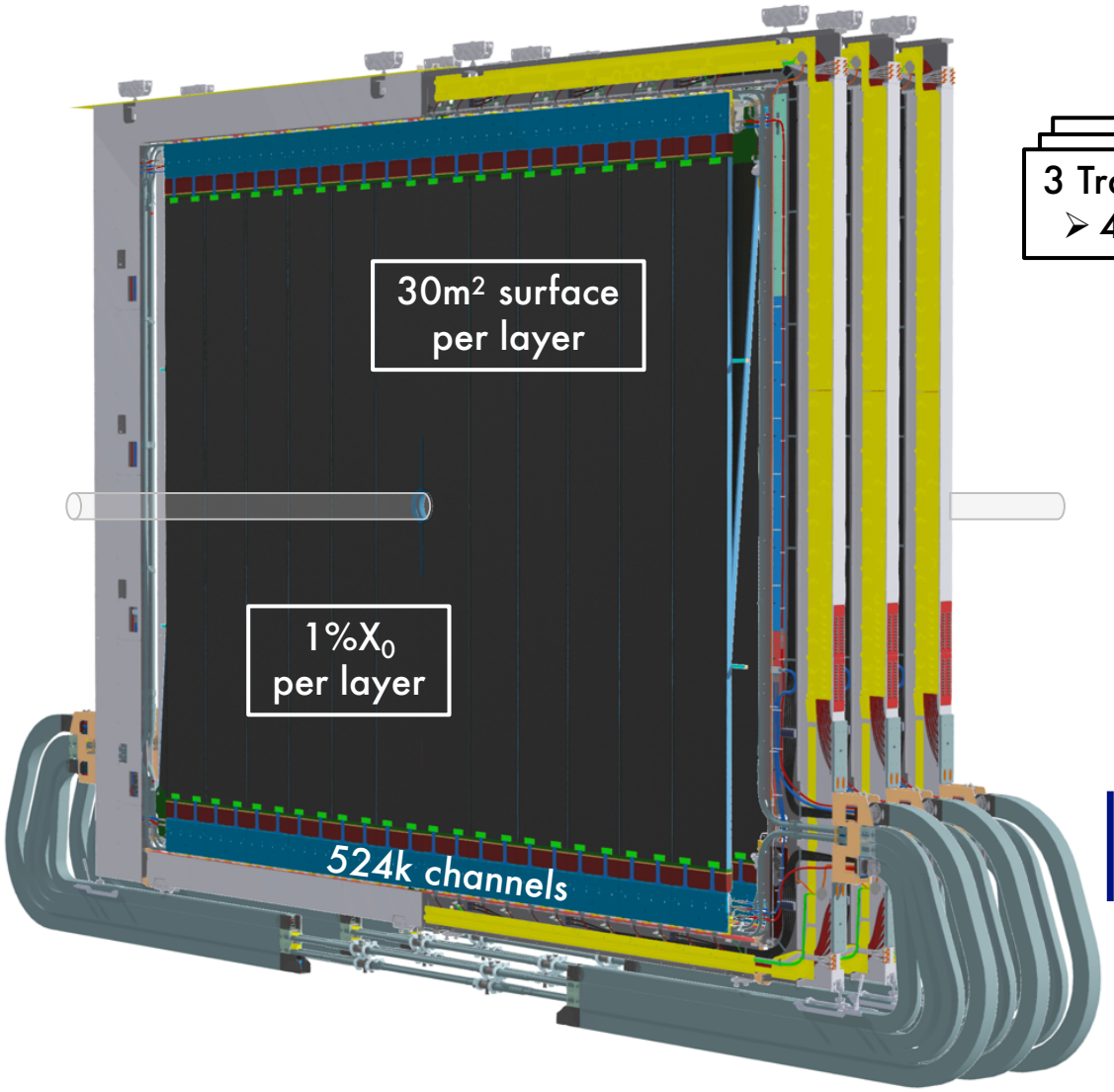
- Single-arm forward spectrometer $2 < \eta < 5$
- Instantaneous Luminosity $\mathcal{L}_{\text{inst}} = \frac{\cancel{4}}{20} \cdot 10^{32}\,\text{cm}^{-2}\text{s}^{-1}$
- Detector readout rate $R = \frac{\cancel{1}}{40}\,\text{MHz}$
- Replacement of
  - » Front- and back-end electronics
  - » Vertex Locator
  - » Tracking Stations
    - » SciFi
    - » Upstream Tracker

Scintillating Fibre Tracker

Core Characteristics

Detector performance

- Hit efficiency ≈ 99%
- Hit resolution < 100μm
- Noise cluster rate < 10%



3 Tracking Stations
➢ 4 Layers each

Data rate: 20 Tb/s* through optical fibres

*40% of LHCb data rate

Scintillating Fibre Tracker

Core Characteristics

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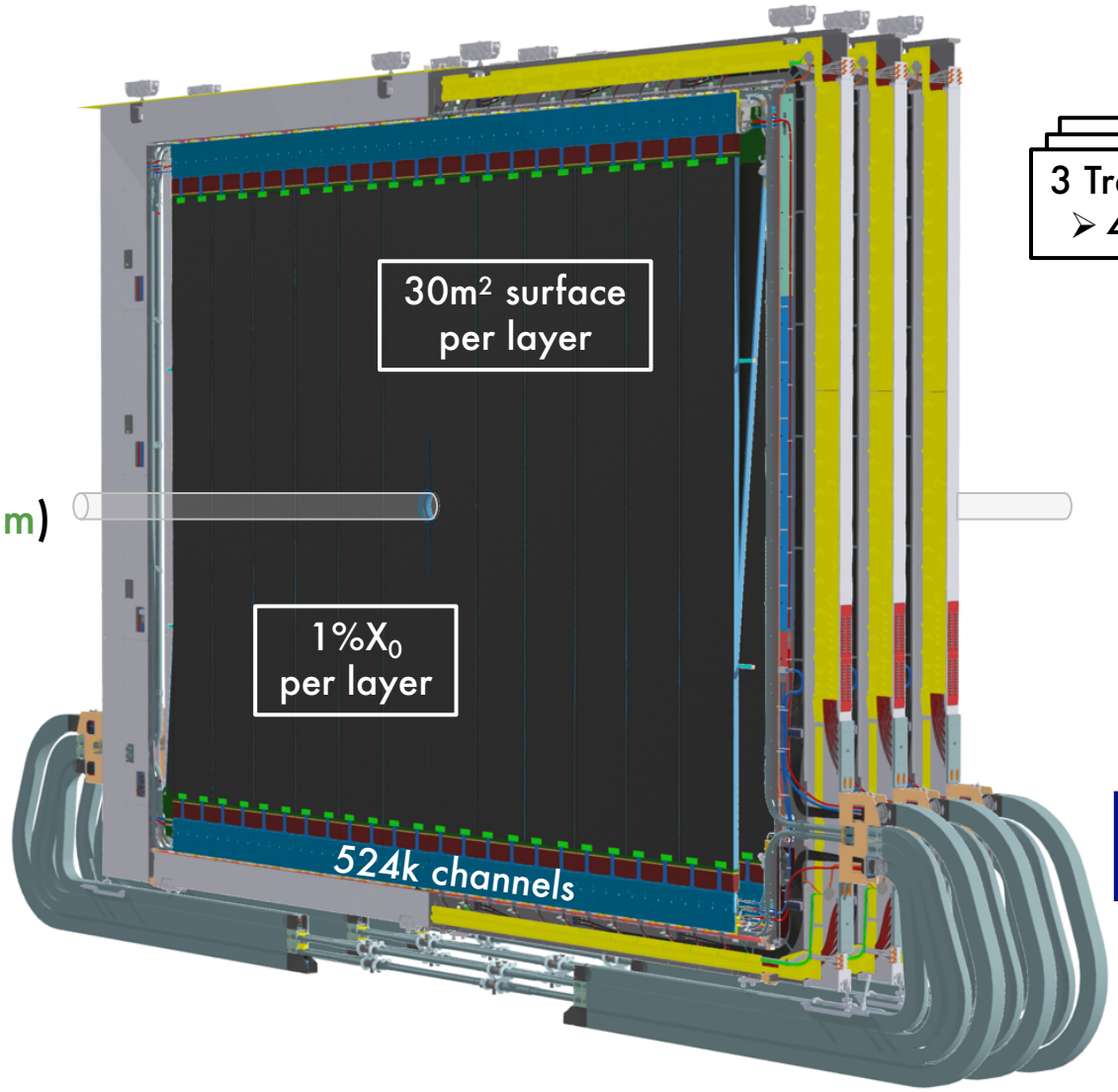
- Hit resolution < 100μm (65μm)
- Noise cluster rate < 10%

√ Verified in test beams



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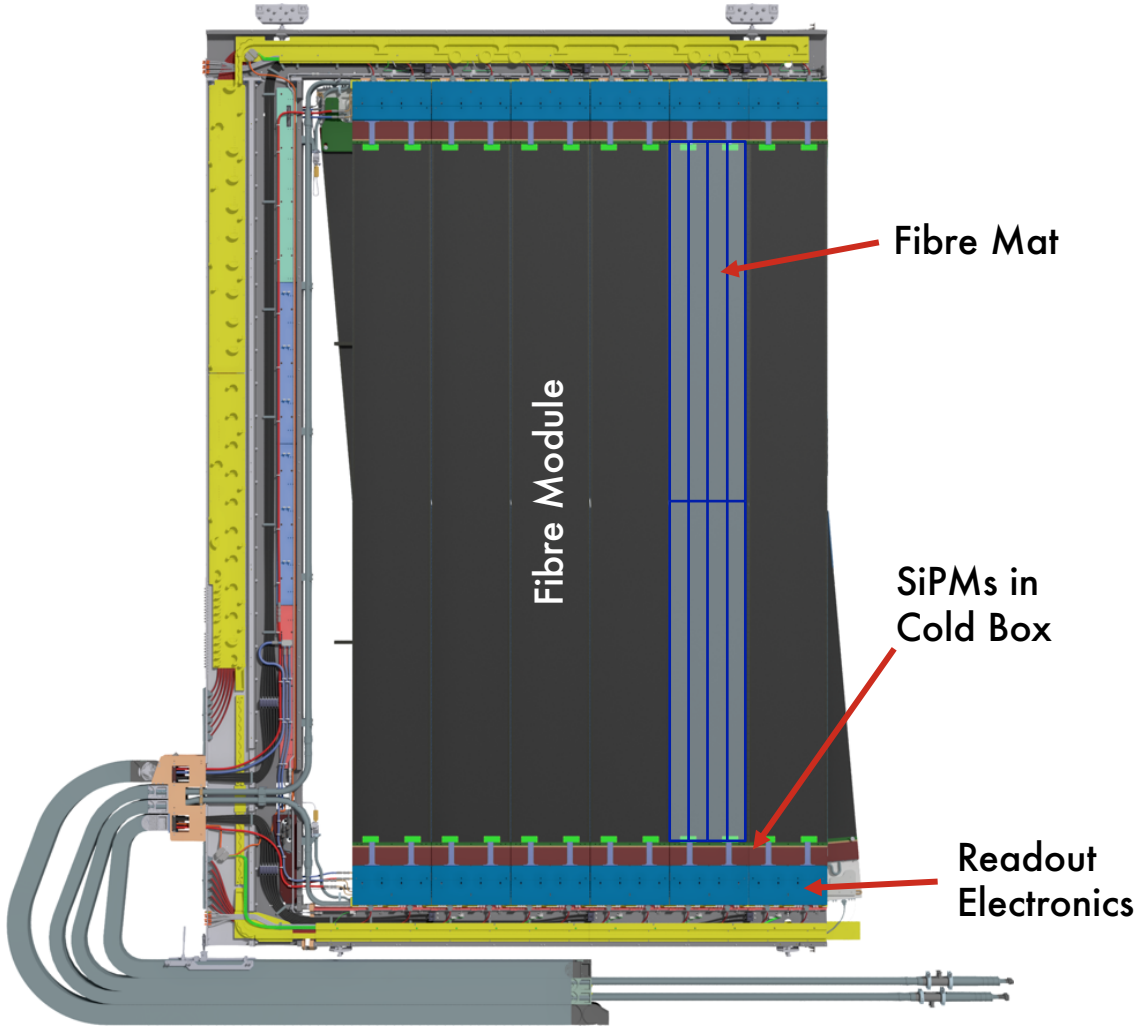
*40% of LHCb data rate

Scintillating Fibre Tracker

C-Frame Design



- C-Frame ≙ 1/12 of the final detector
- Assembly & Commissioning above ground
- Mechanical support for fibre modules & *services*
  - » Low-voltage for readout electronics
  - » High-voltage for SiPM readout
  - » Water cooling of readout electronics → 20°C
  - » NOVEC cooling of SiPMs → −40°C
    - » Vacuum, Dry-Gas
  - » Optical links for control and data transmission

C-Frame Design

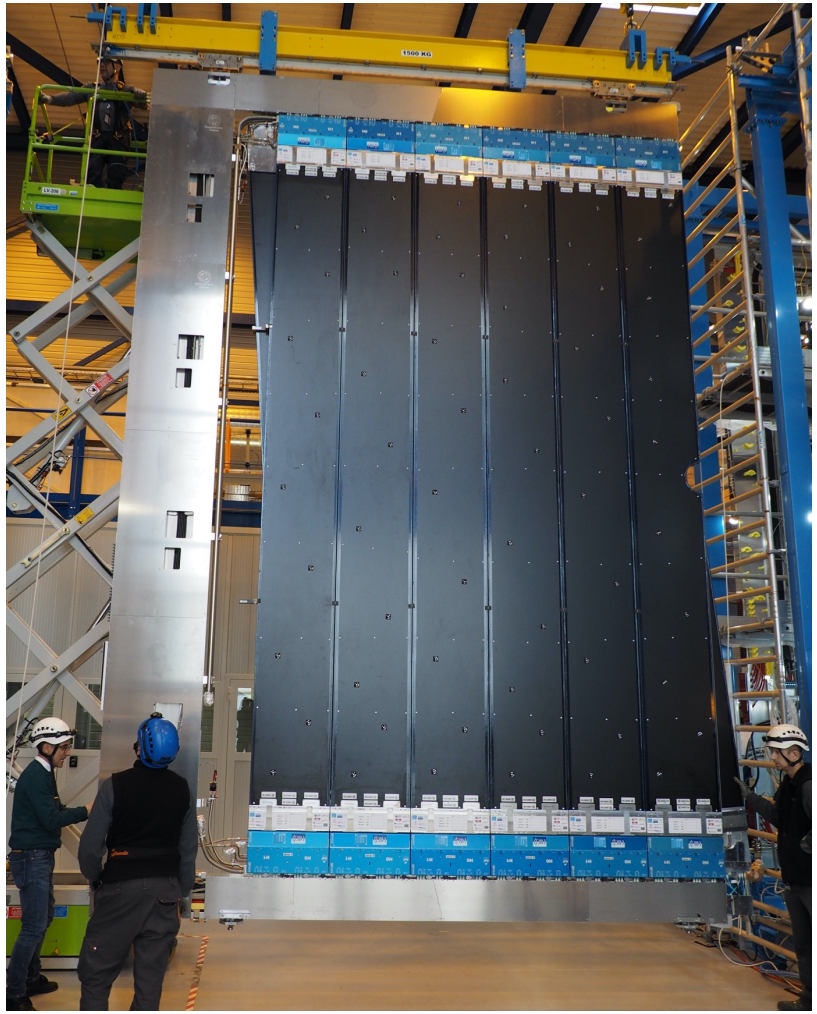


Photo of first assembled C-Frame

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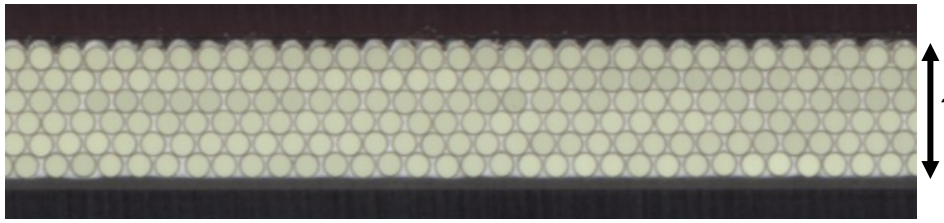
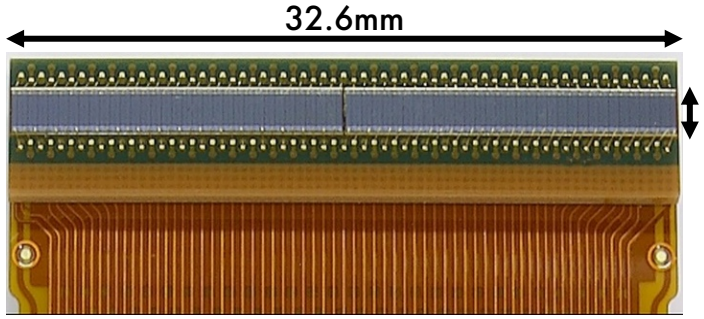
Scintillating Fibre Tracker

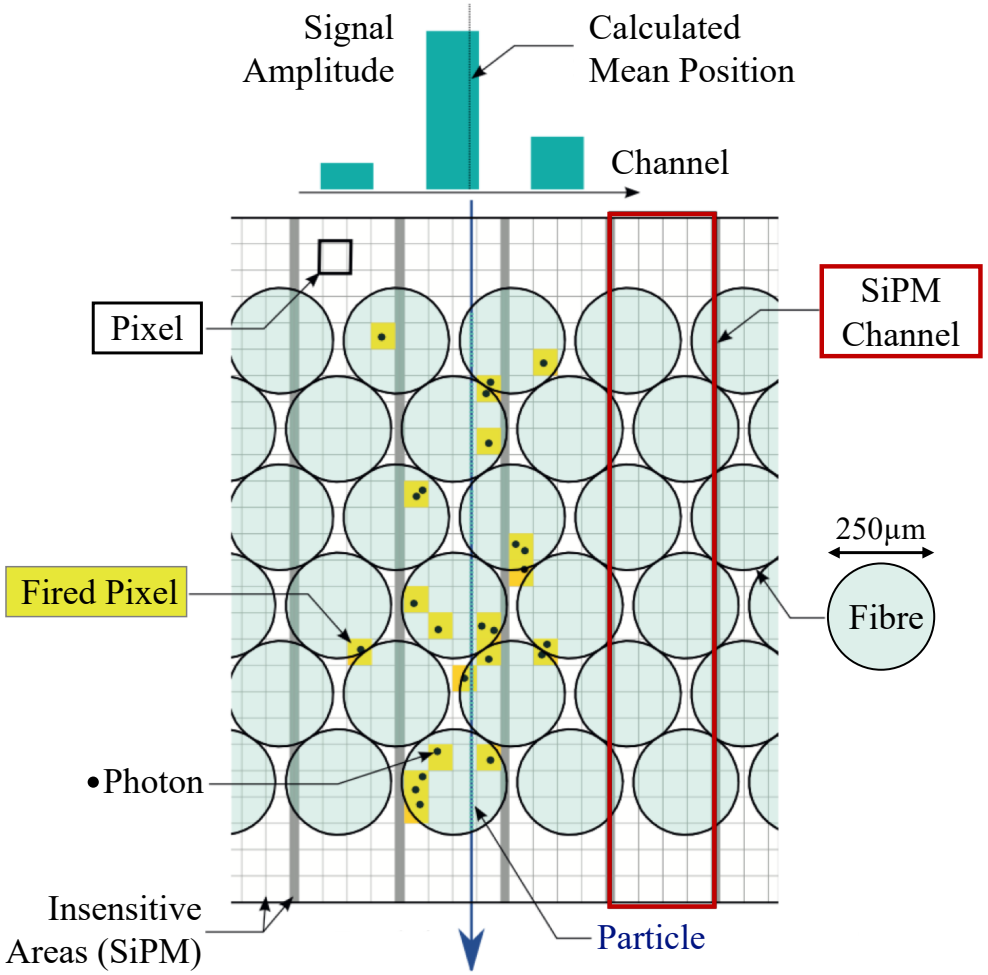
Working Principle

Cross-sectional view on scintillating fibre mat
- 6 staggered layers of 250µm scintillating fibres
- 2.5m long
- Mirror on the other end





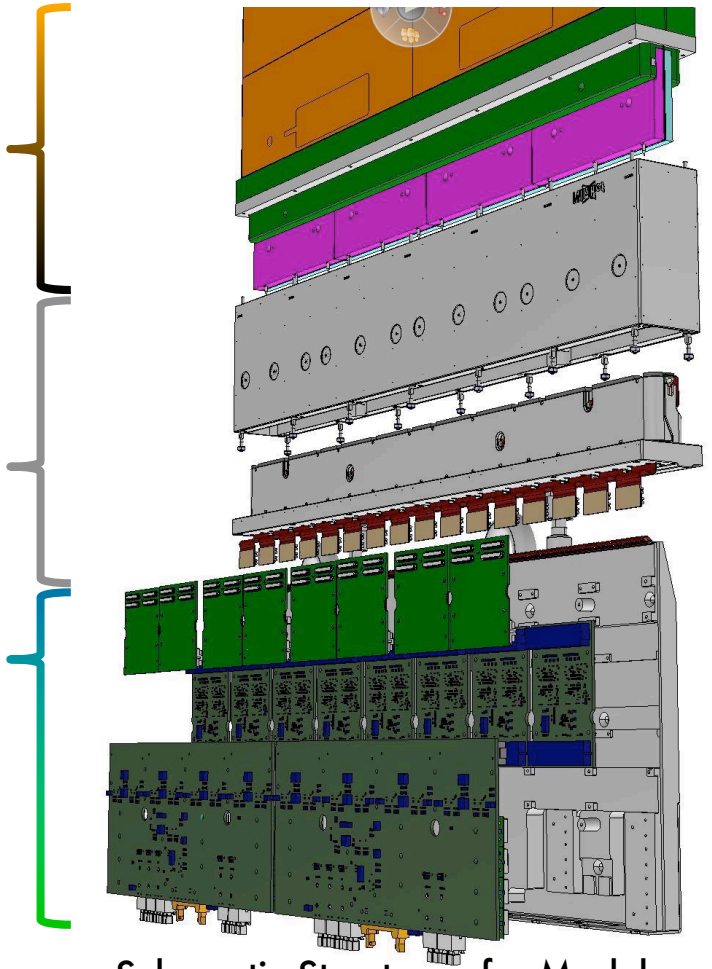
Hamamatsu H2017 SiPM array
- 128 channels
- 104 pixels per channel
- Cooled to −40°C



Scintillating Fibre Tracker

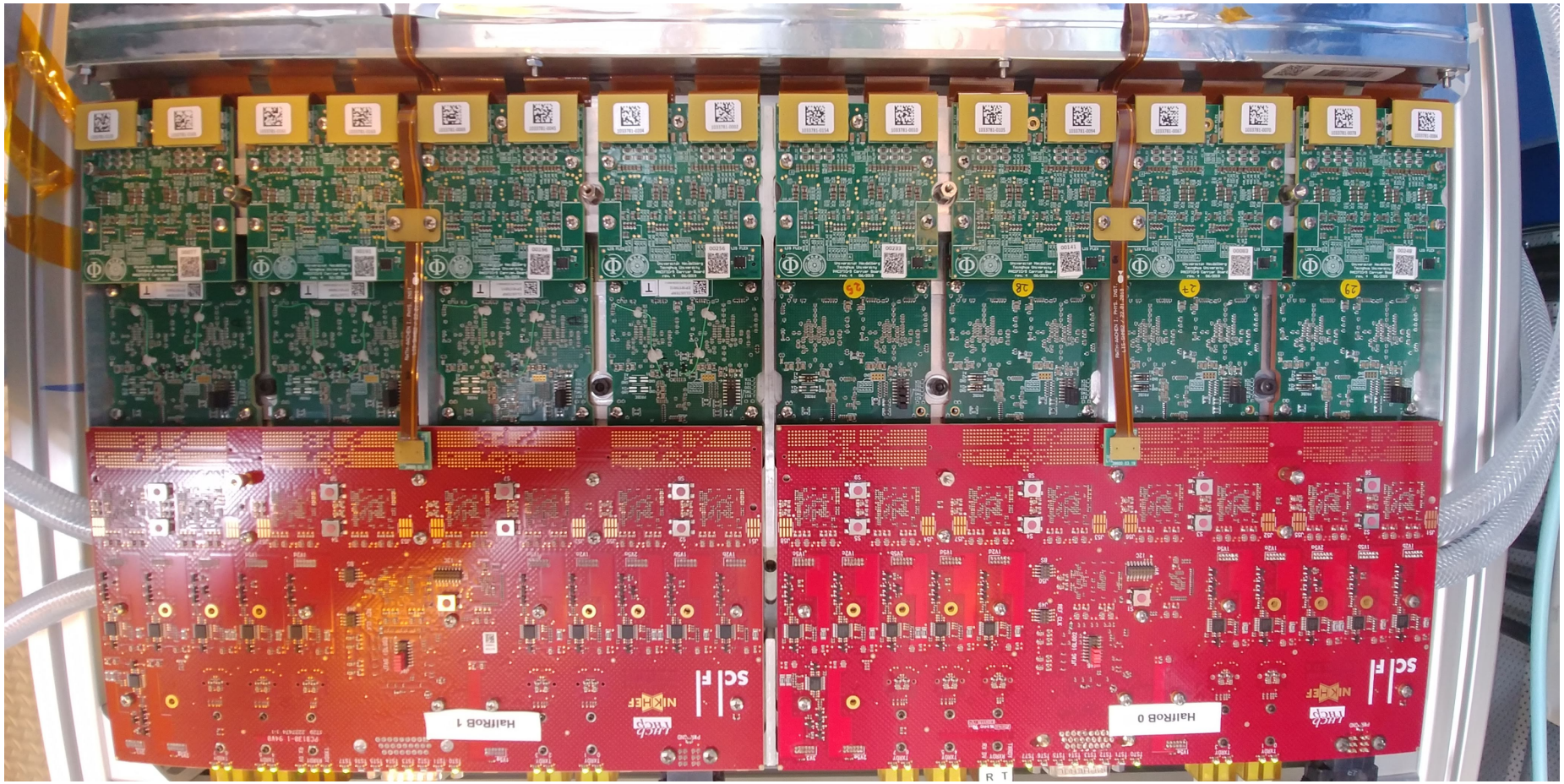
Readout Boxes

Readout Boxes assembled on C-Frame



Schematic Structure of a Module and Readout Box (w/o blue cover)

Readout Box Components

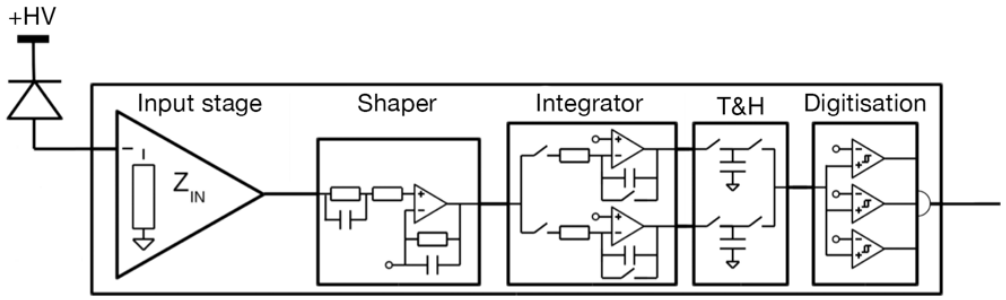


Open Readout Box consisting of two identical halves (*HalfROBs*)

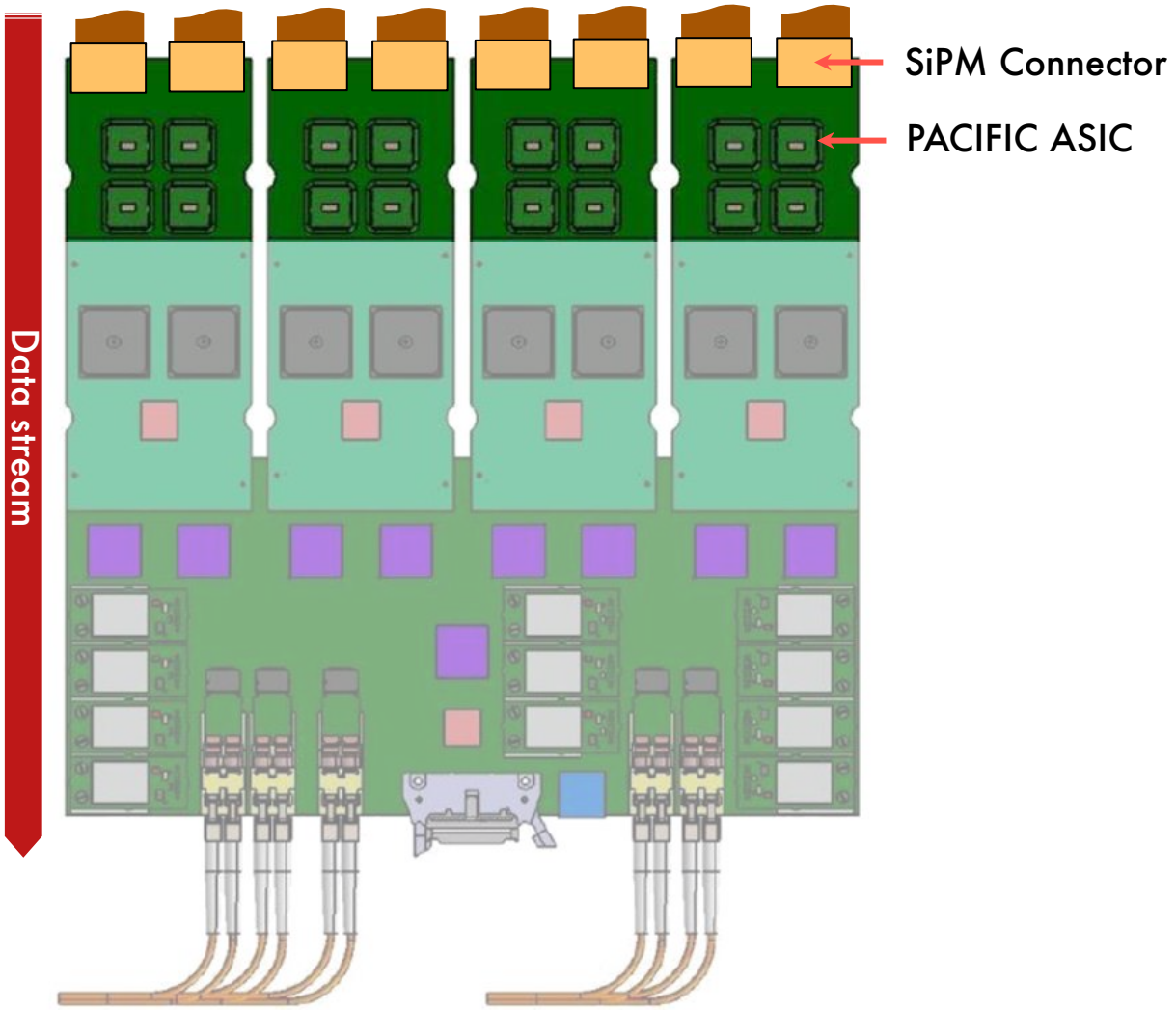
Readout Electronics

Readout Box Components

- PACIFIC Board
  - » Carrier for 4 PACIFIC ASICs
- PACIFIC ASIC
  - » 64 channels (2 ASICs per SiPM)
  - » Analogue processing of SiPM signals
  - » Digitisation into 2 bits per channel
    - » 3 tuneable thresholds



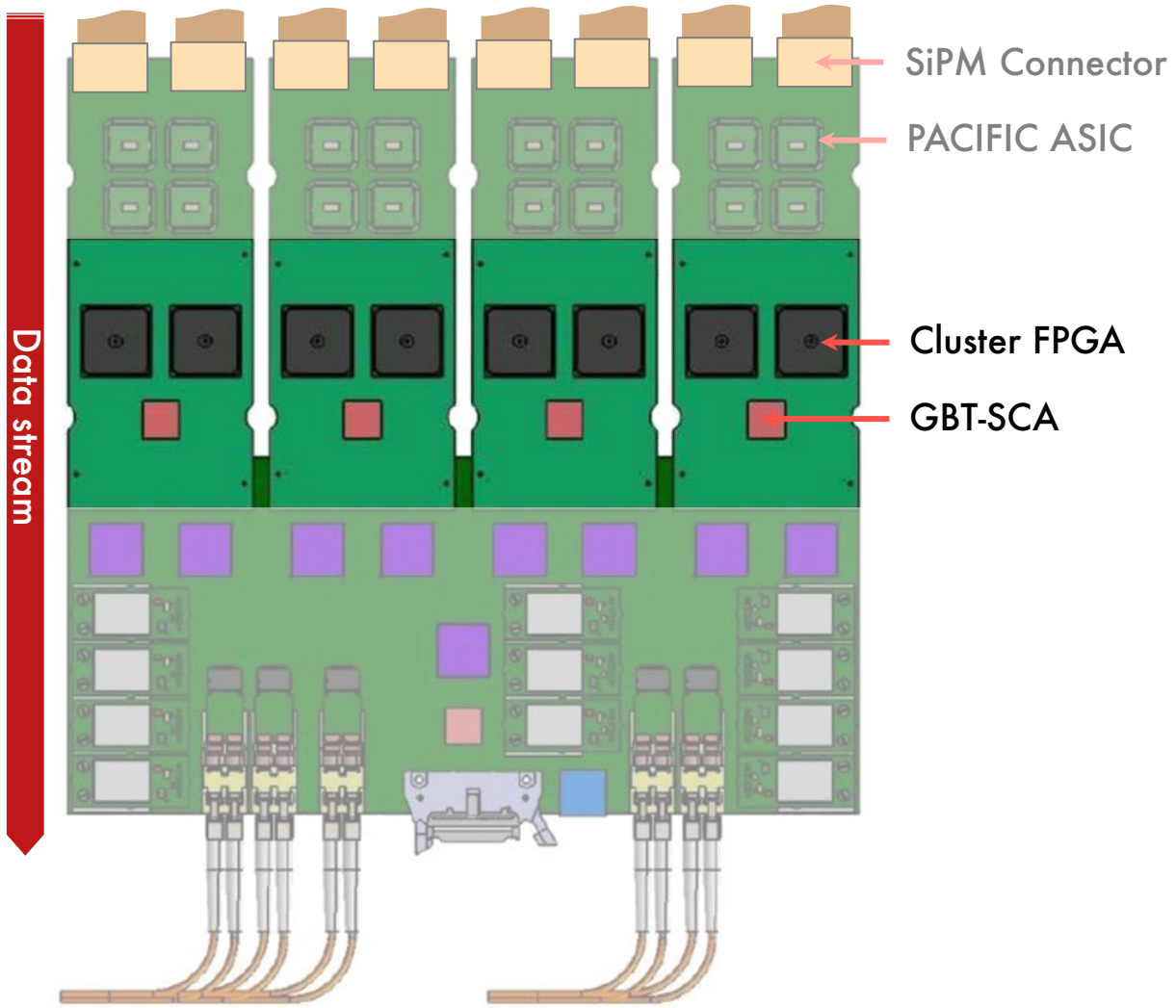
PACIFIC ASIC Channel: Analog processing & digitisation



Readout Electronics

Readout Box Components

- Cluster Board
  - » Carrier for 2 Cluster FPGAs
  - » 1 GBT-SCA
- Cluster FPGA
  - » Hit reconstruction
  - » Noise suppression
- GBT-SCA
  - » Dedicated Slow Control Adapter
  - » Control of PACIFIC ASICs and Cluster FPGAs
    - » I^2C, JTAG, GPIO
  - » ADC to monitor temperatures and voltages

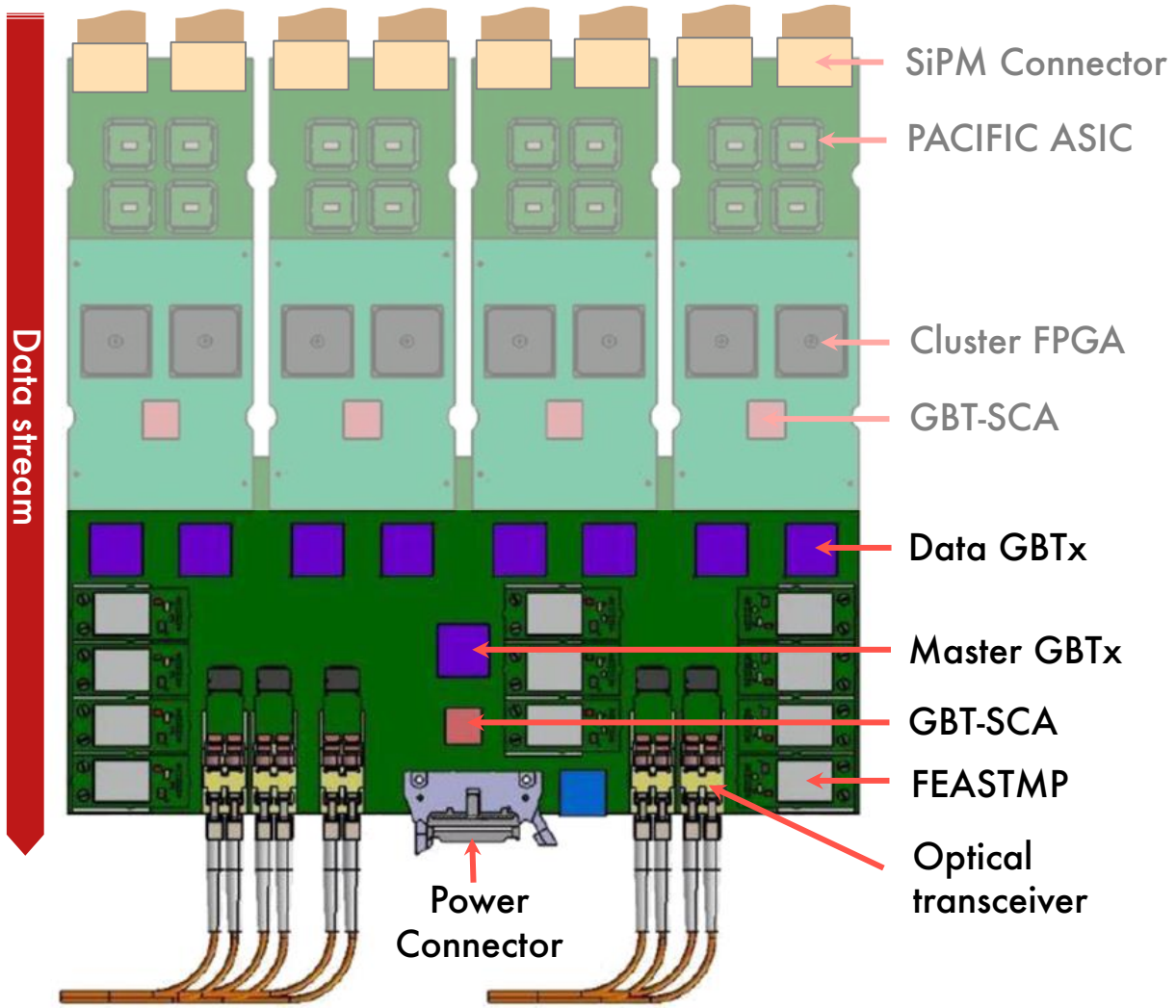


Readout Electronics

Readout Box Components

- Master Board
  - 1 GBT-SCA
  - FEASTMP DC-DC converters
  - 8 optical links for data transmission
  - 1 bidirectional optical link for control
  - 8+1 GBTx ASICs

- GBTx ASIC
  - Implements 4.8 Gb/s optical links
  - Usable as unidirectional transmitter (data) or bidirectional transceiver (control)
  - Distribution of 40MHz reference clock



C-Frame Assembly

Assembly Hall

Assembly of the C-Frames in dedicated hall on the LHCb site (LHC Point 8)

Assembly Hall at night
4 C-Frames can be assembled at the same time

C-Frame Assembly

Status

C-Frame	C1	C2	C3	C4	C5	C6	C7
Mechanics							
Water-Cooling							
NOVEC-Cooling							
Dry-Gas							
Cabling							
Modules							
Heating Wires							
Electronics							
Optical Fibres							
Commissioning							

Legend: Completed | In Progress | Open

C-Frame Assembly

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Mechanics							
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Heating Wires							
Electronics							
Optical Fibres							
Commissioning							

Legend: Completed | In Progress | Open

Electronics Commissioning

- Step-by-step verification of each component
- Ranges from basic functional to full system tests
- Results are presented in *Commissioning Reports* and stored in database
- Full procedure takes about 2 weeks per C-Frame

C-Frame Commissioning

Test Setup

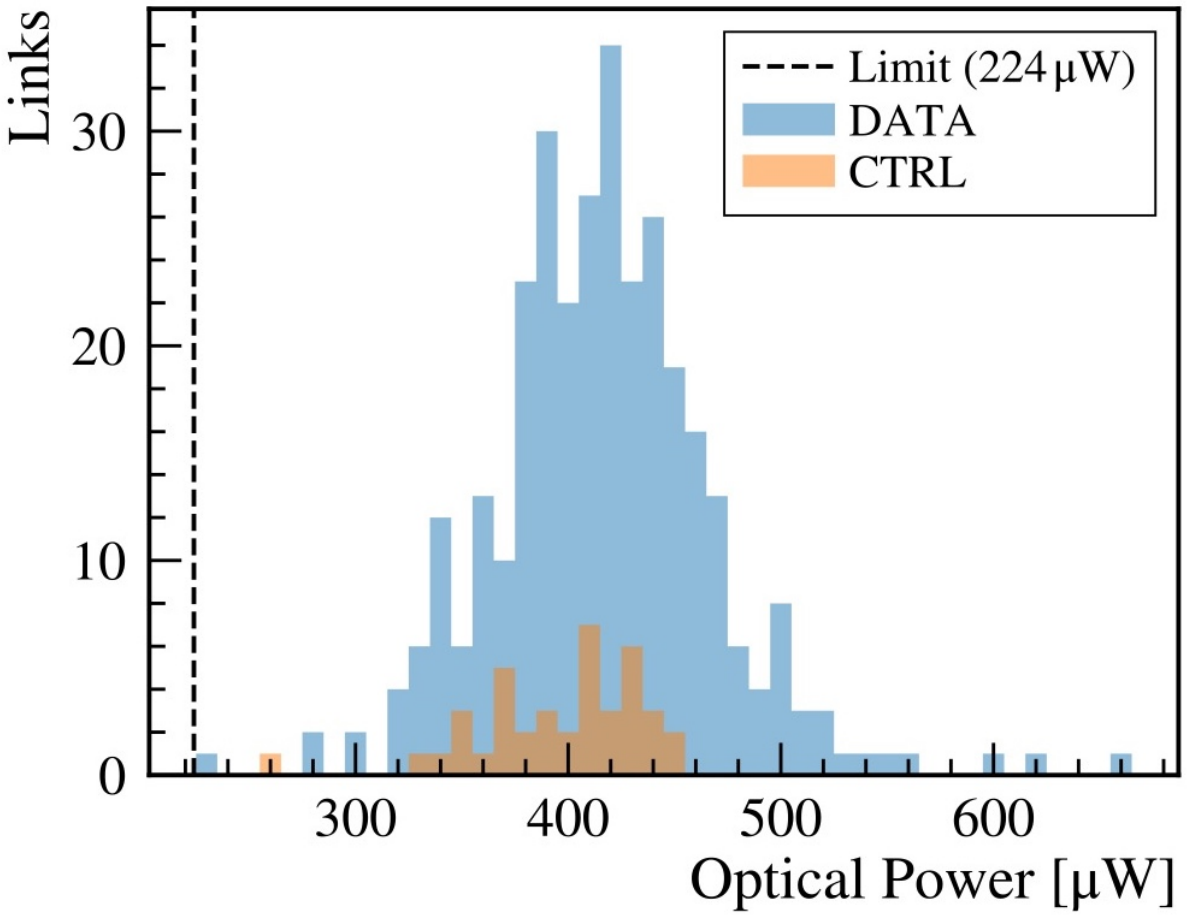
C-Frame to be commissioned

~15+60m optical fibres

DAQ Server

Optical Power Measurement

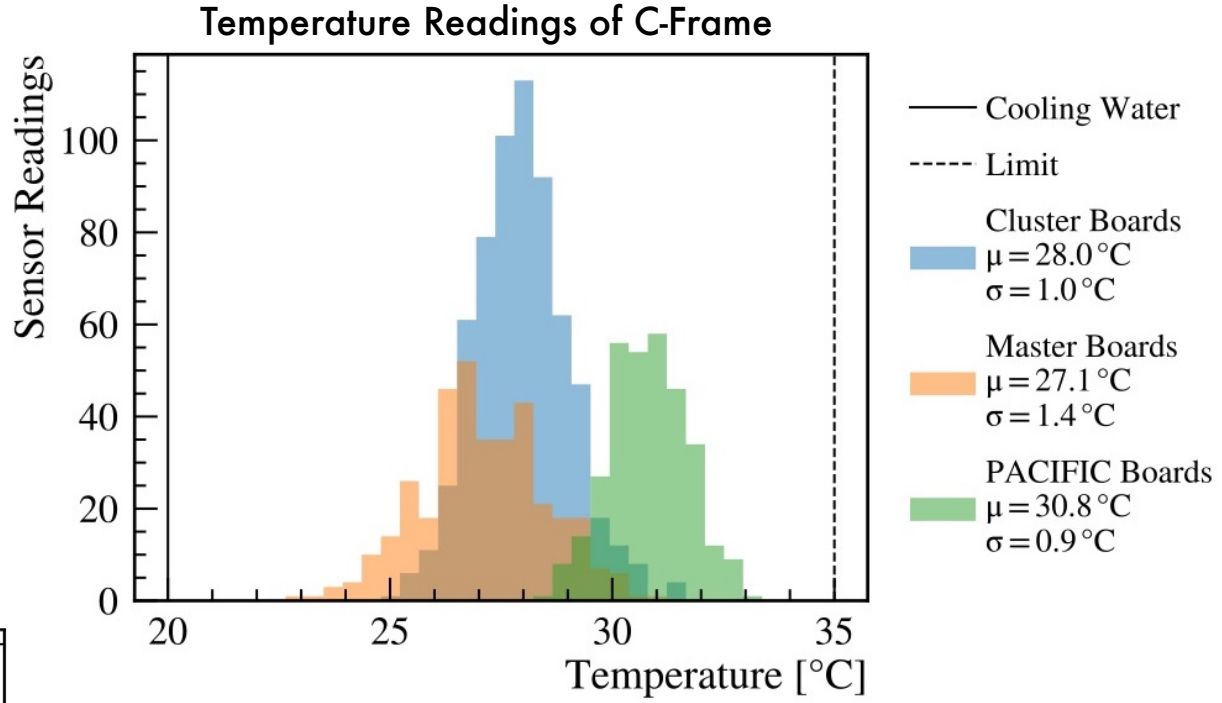
- Measure power of optical transmitters arriving at the DAQ server
- Crucial measurement to ensure stable connection in final setup underground with ~300m optical fibres and additional patch panels
- Not much margin for some optical links
  - » Careful treatment and cleaning of fibres and lenses

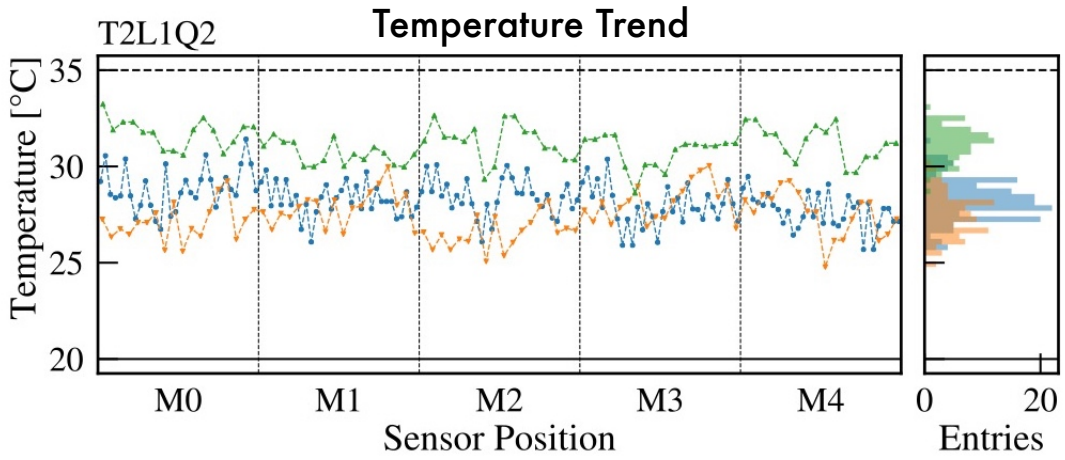


C-Frame Commissioning

Temperature Sensor Readings

- 82 temperature sensors per Readout Box
- Ensure functioning of all sensors
- Locate bad thermal connections



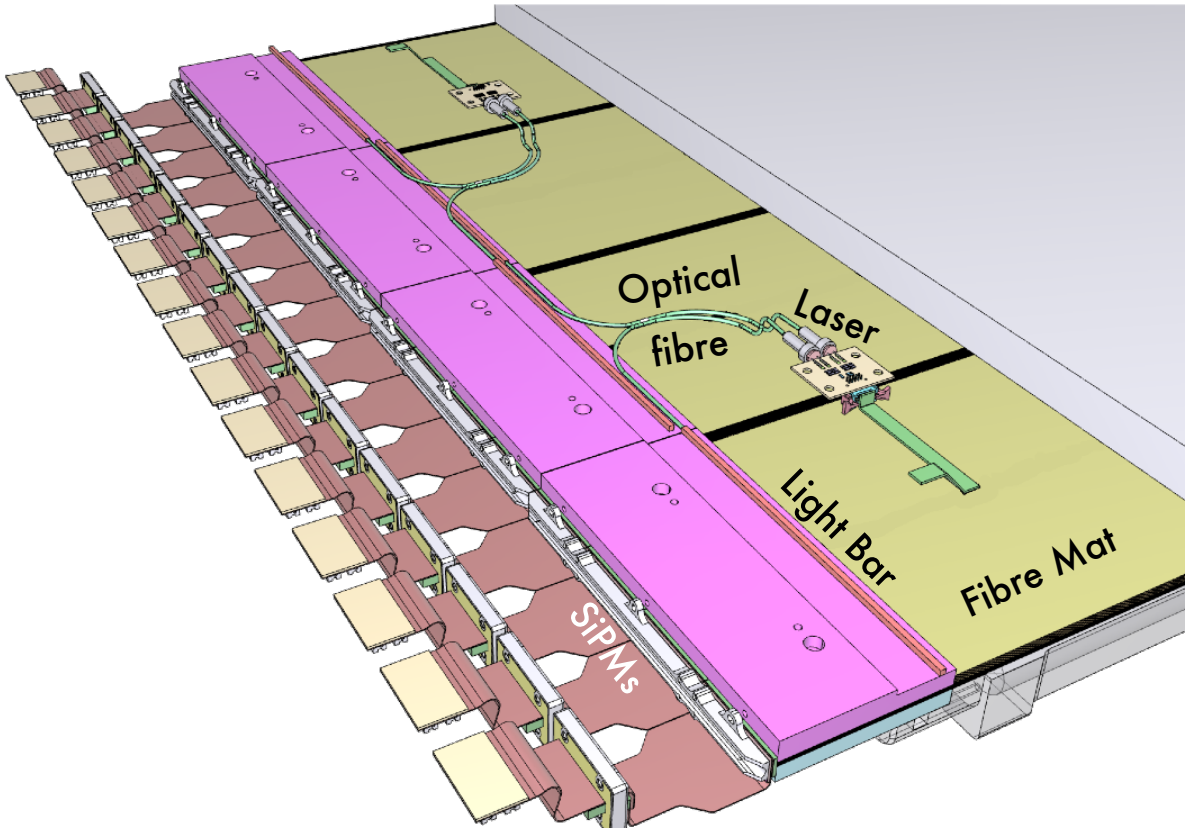


C-Frame Commissioning

Full System Test

- Dedicated light injection system
  - » Illuminate SiPMs with pulsed light
- Commissioning: Test for dead channels without the need of particles

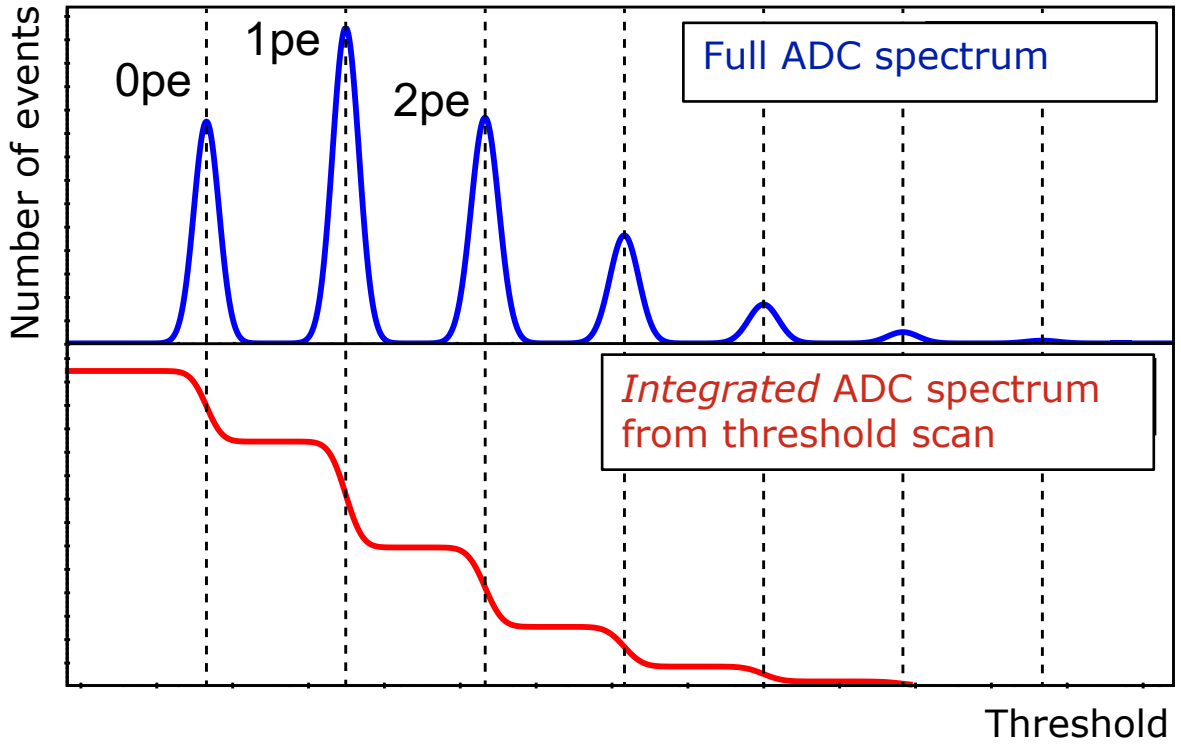
Schematic Layout of the SciFi Light Injection System



C-Frame Commissioning

Full System Test

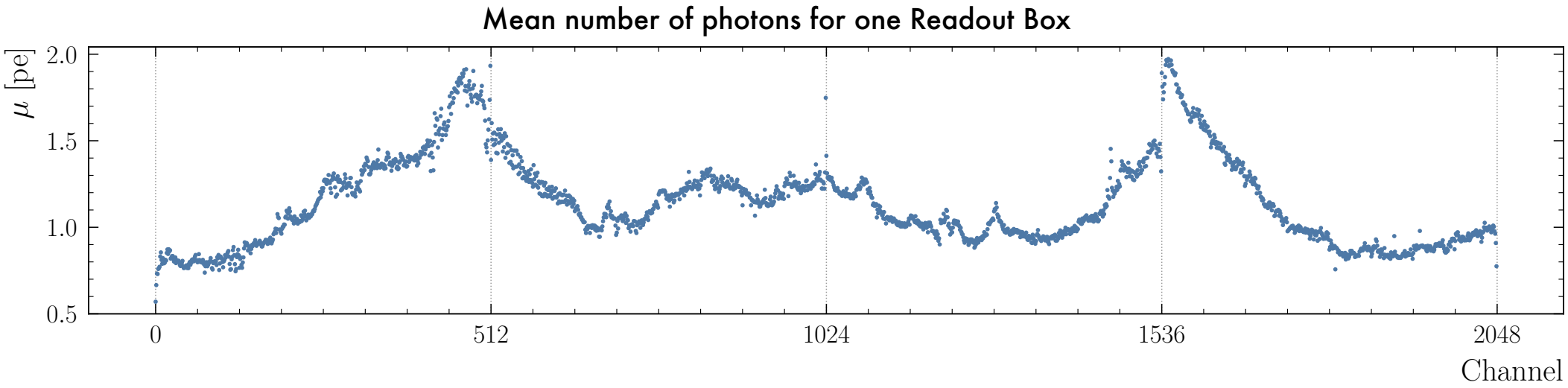
- Dedicated light injection system
  - » Illuminate SiPMs with pulsed light
- Commissioning: Test for dead channels without the need of particles
- PACIFIC: Can only measure integrated ADC spectrum by scanning thresholds through dynamic range
  - » Extract parameters like mean number of photons or gain by fitting the curve



C-Frame Commissioning

Full System Test

- Verify that all ~50k channels of a C-Frame detect light (μ > 0)
- Structure originates from light distribution of the light injection system
  - » Light bars are handmade



Summary & Outlook

- 3 (out of 12) C-Frames have been fully assembled and commissioned to date
  - » Commissioning of 4th C-Frame ongoing
  - » Assembly of 3 other C-Frames ongoing

- Delayed due to pandemic
  - » Scientists and technicians from different countries involved in assembly and commissioning
  - » Commissioning can be continued remotely and with people already on site
  - » Situation in the near future unclear

- Gained a lot of experience along the way
  - » Developing tools and software
  - » Operate the detector and process the large amount of data

C-Frame test transport to the LHCb cavern

BACKUP

Test Beam

Setup

SPS north area H8 beam line

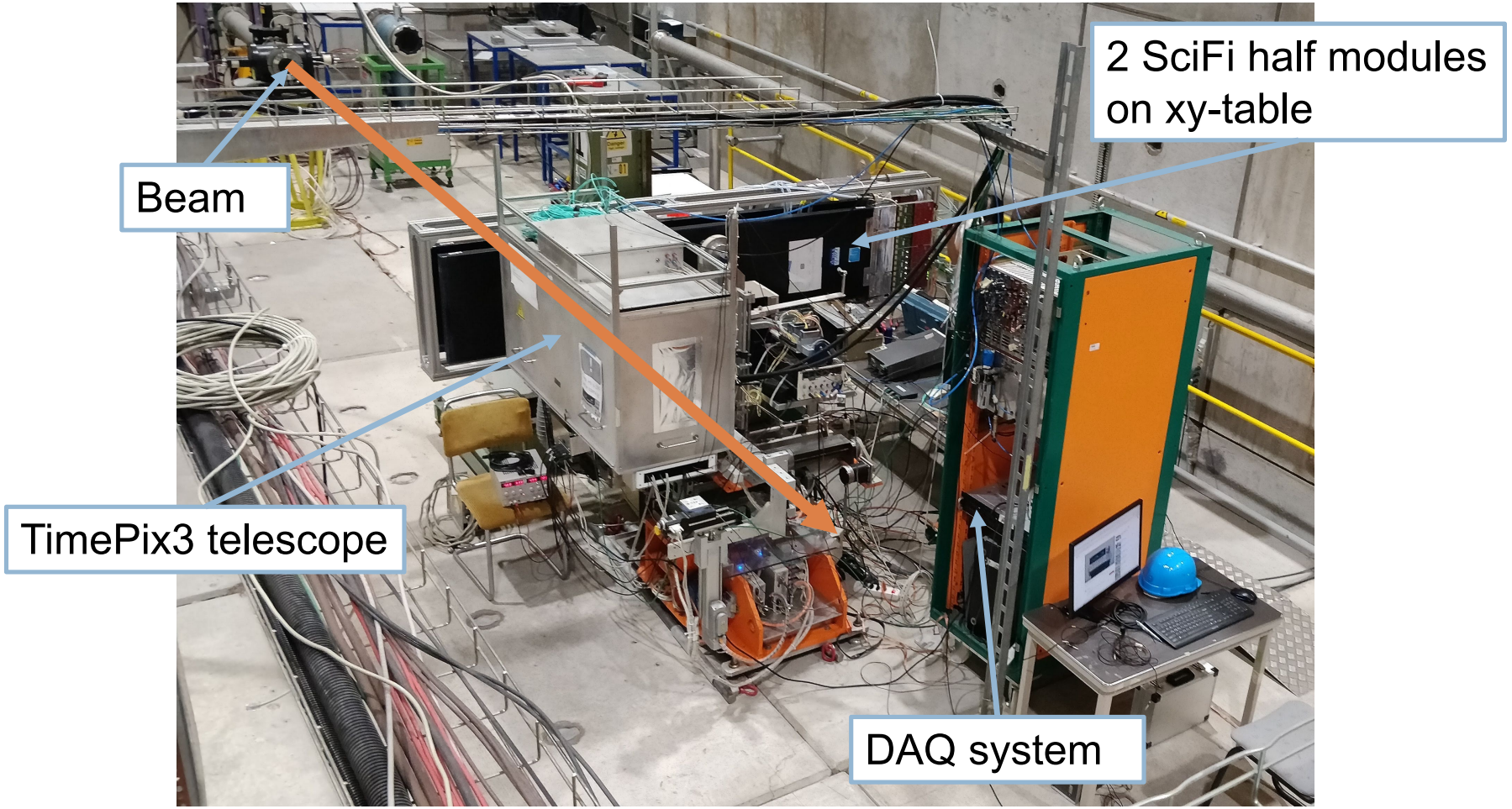
- 180GeV protons/pions
- 1cm beam width
  - Needed large translation table for module (50×250cm^2) scans
- Beam asynchronous to our 40MHz readout
  - Required additional timestamps to select in-time events offline
- Recorded ~500k events/spill, only need 2 spills to get enough statistics
  →Short runs, nice for shifters

TimePix3 telescope

- Tracks for efficiency & resolution measurements
- Provided trigger + fine timestamps for offline selection
  - Synchronised to our DAQ

Test Beam

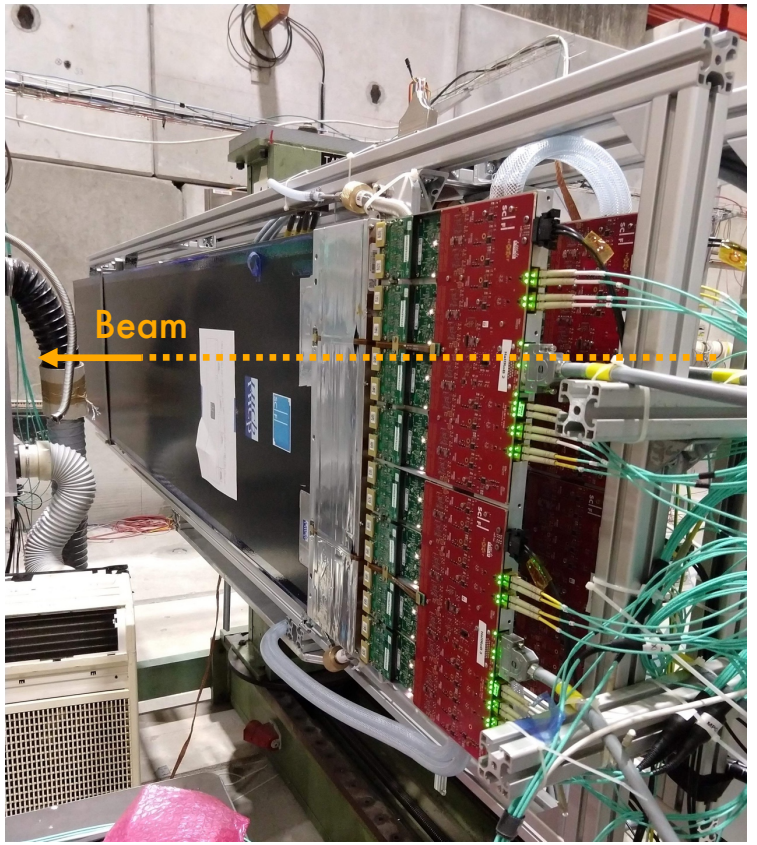
Setup



Results from Test Beam

July 2018 @ SPS

- First time
  - » Putting all detector components of 2 ROBs together
  - » Reading out 32 data links @ 40 MHz
  - » Calibrating 4k channels
    - » 12k configurable thresholds



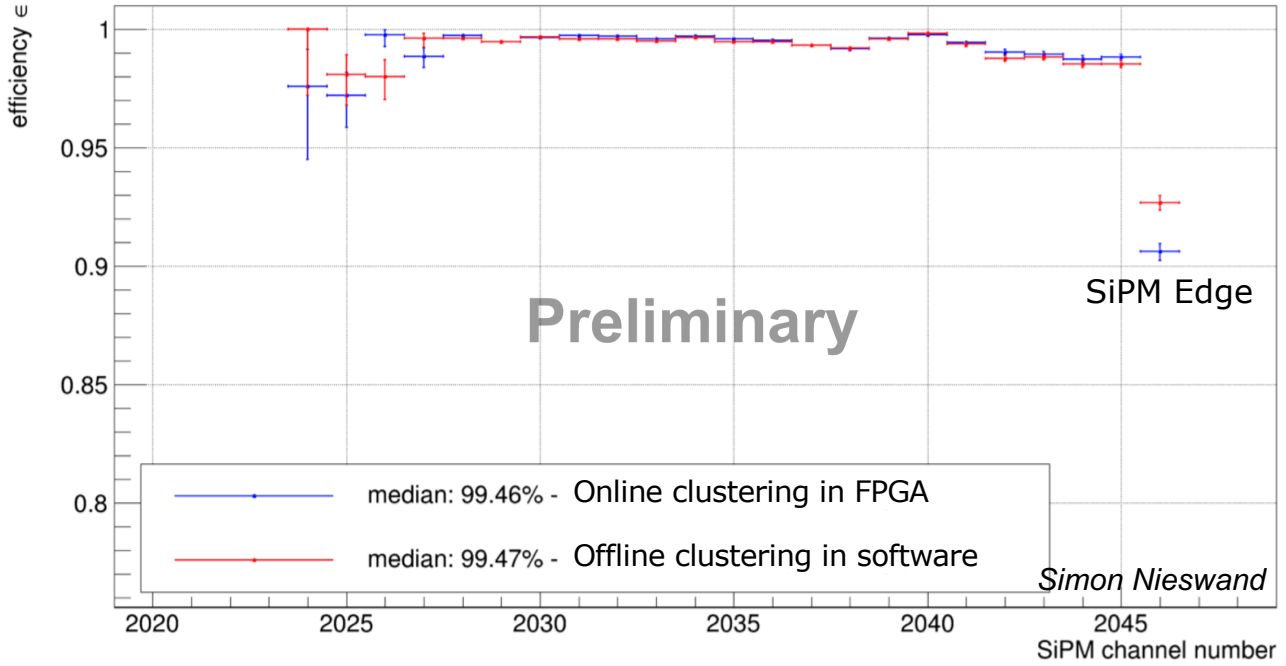
Test Beam Setup
with 2 Readout Boxes

Results from Test Beam

July 2018 @ SPS

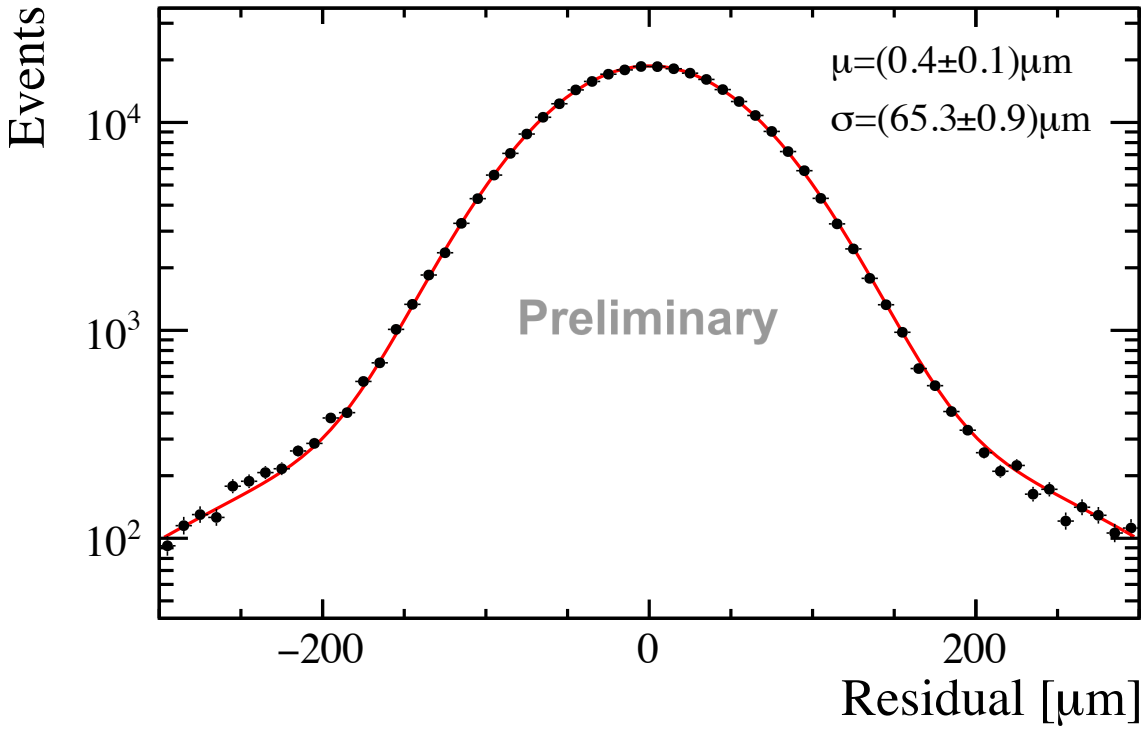
- First time
  - » Putting all detector components of 2 ROBs together
  - » Reading out 32 data links @ 40 MHz
  - » Calibrating 4k channels
    - » 12k configurable thresholds

- **Target performance parameters fulfilled!**
  - » Hit efficiency: 99.47%
  - » Correlated noise cluster rate: 2%
  - » Hit resolution: 65µm
- Online clustering verified



More details from my colleague Lukas Witola:
Tomorrow at 17:45 in S01 (T 90.8)

Spatial Resolution



- Resolution ~65μm for both modules
- ✓ Better than required (≤100μm)

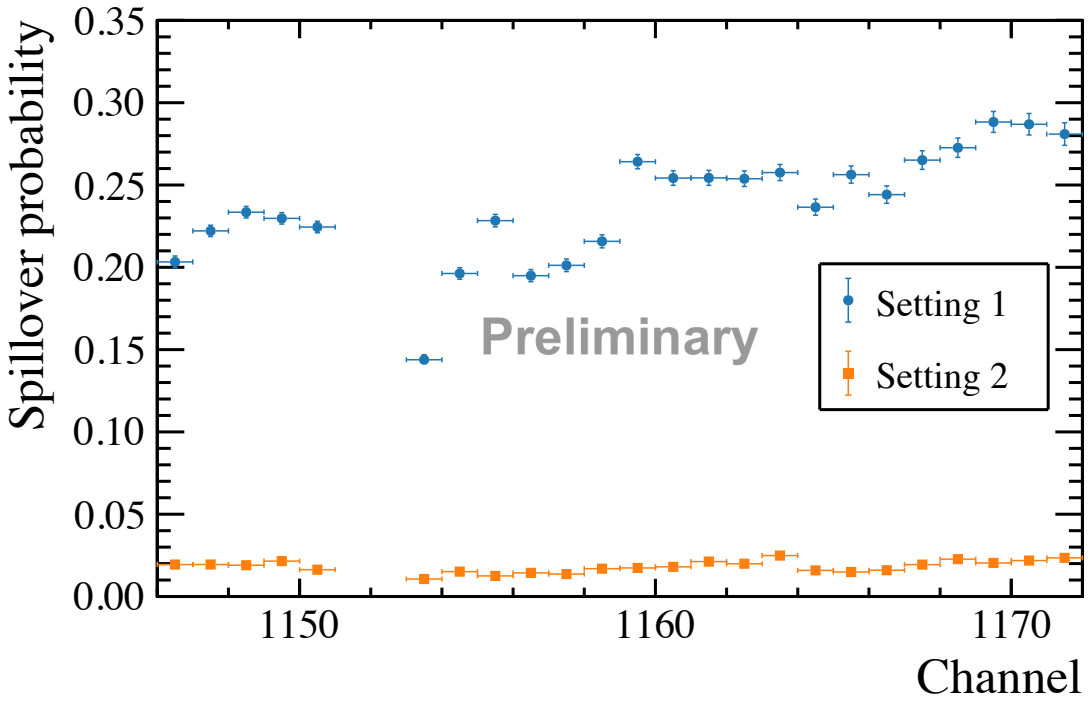
Spillover = Correlated Noise Clusters

Probability to find a cluster from BX_n in BX_{n+1} at the same position

- Shaper settings have great influence
- Two settings:
  1. More undershoot
  2. Less undershoot & wider

Setting 1: 24%

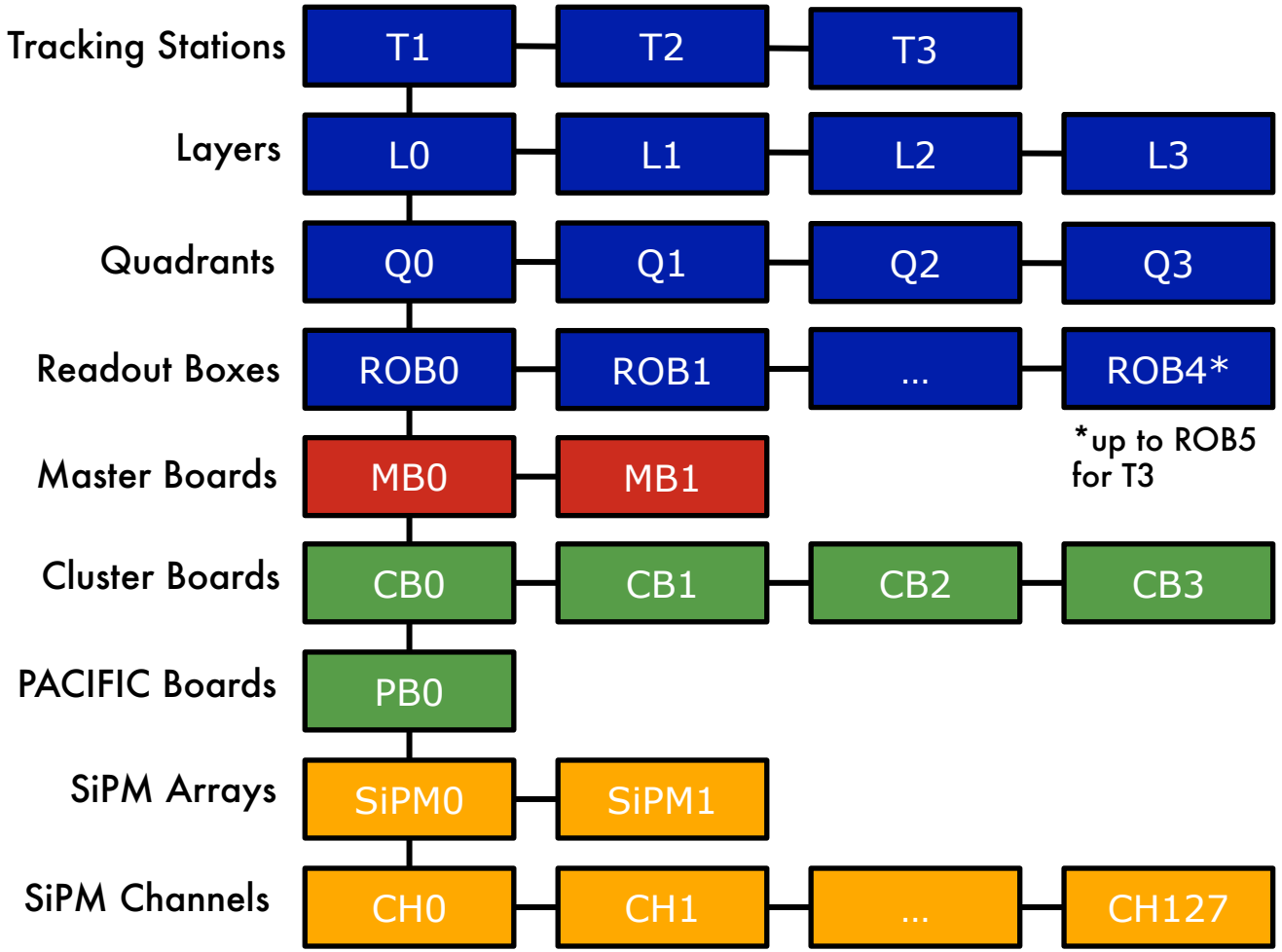
Setting 2: 2%



Spillover with production version PACIFIC

SciFi Readout Electronics

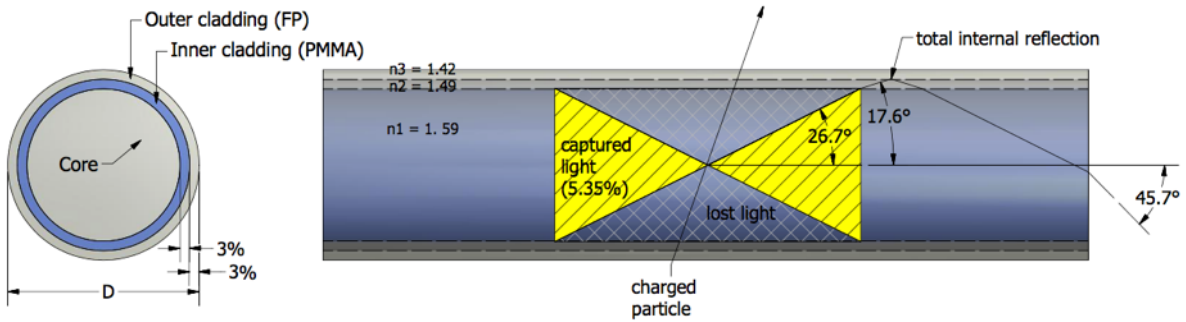
In Numbers

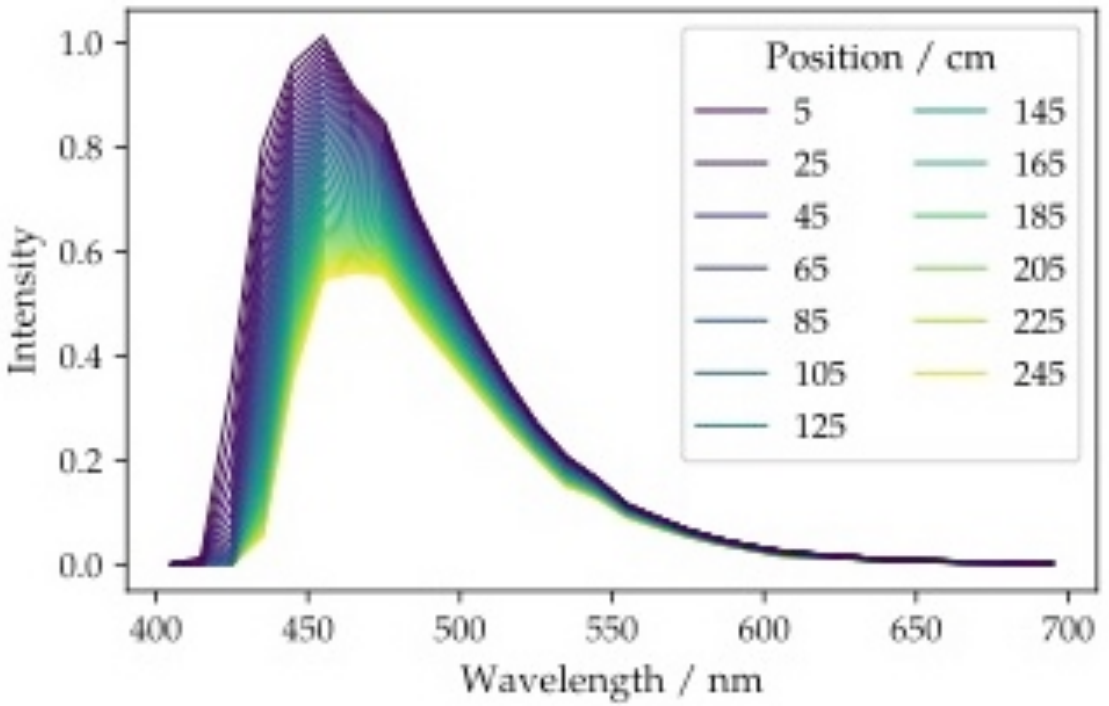


- 256 Readout Boxes
- 524k channels
- 1.6M configurable PACIFIC thresholds
- 4k data links
- Data rate ≈ 20Tb/s

More than any other LHCb subsystem

Scintillating Fibres



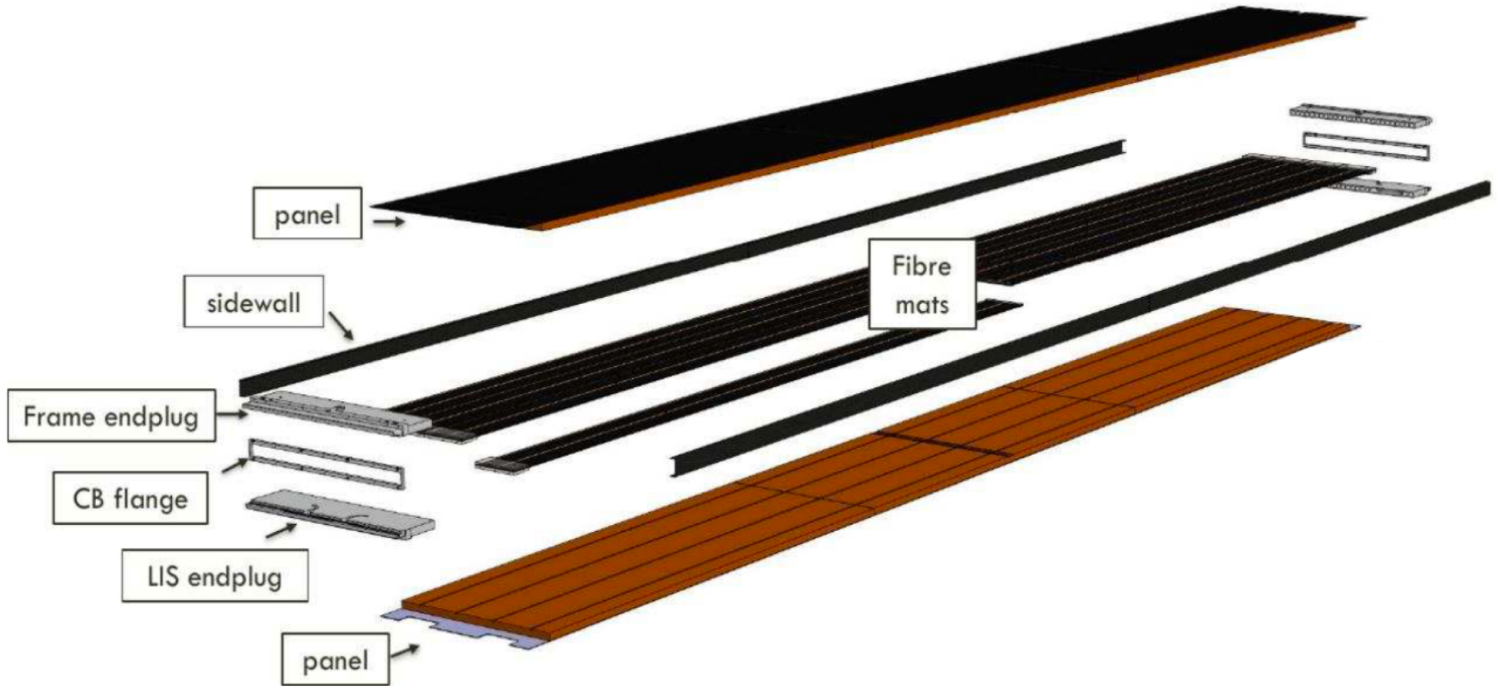


PS: Polystyrene
PMMA: Polymethylmethacrylate
FP: Fluorinated polymer

Spectrum of a scintillating fibre
$\tau = 2.8ns$
Attenuation length: ~5m

Fibre Modules

- 8 fibre mats per module
- Light yield:
  - » Unirradiated: 20pe
  - » After 10 years in hottest area: 12pe
- Support structure
  - » 200µm carbon
  - » 20mm honeycomb
- Alignment precision of 50µm over 5m
- Production finished



SiPM

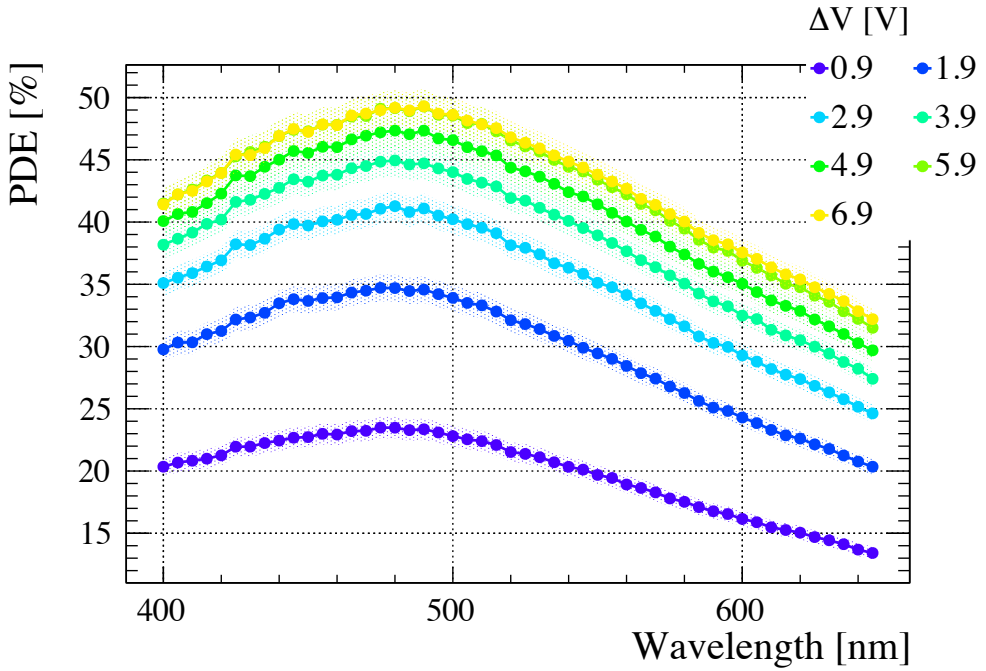
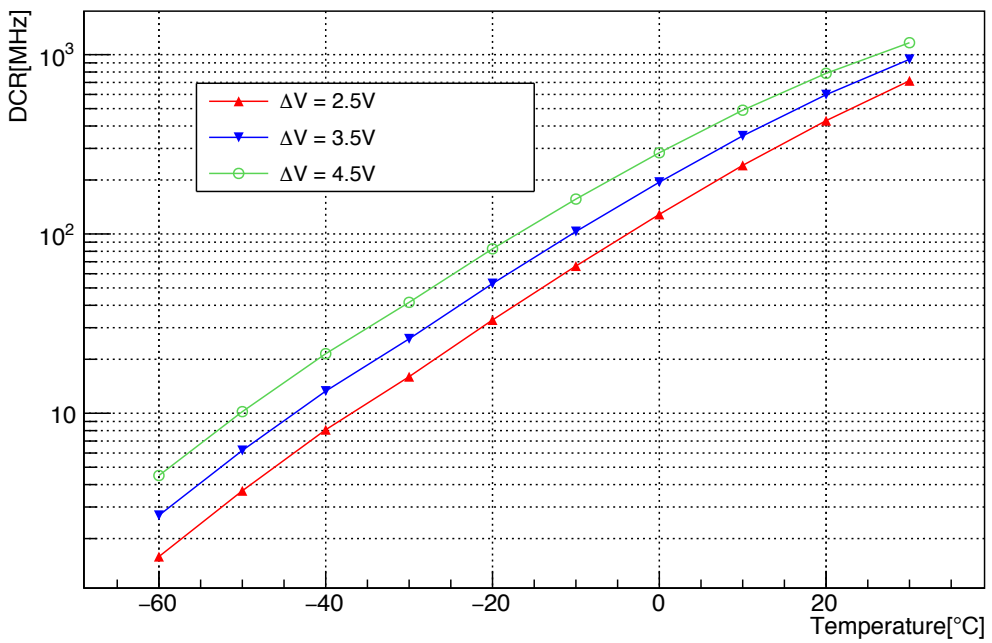


Photo detection efficiency for different over-voltages

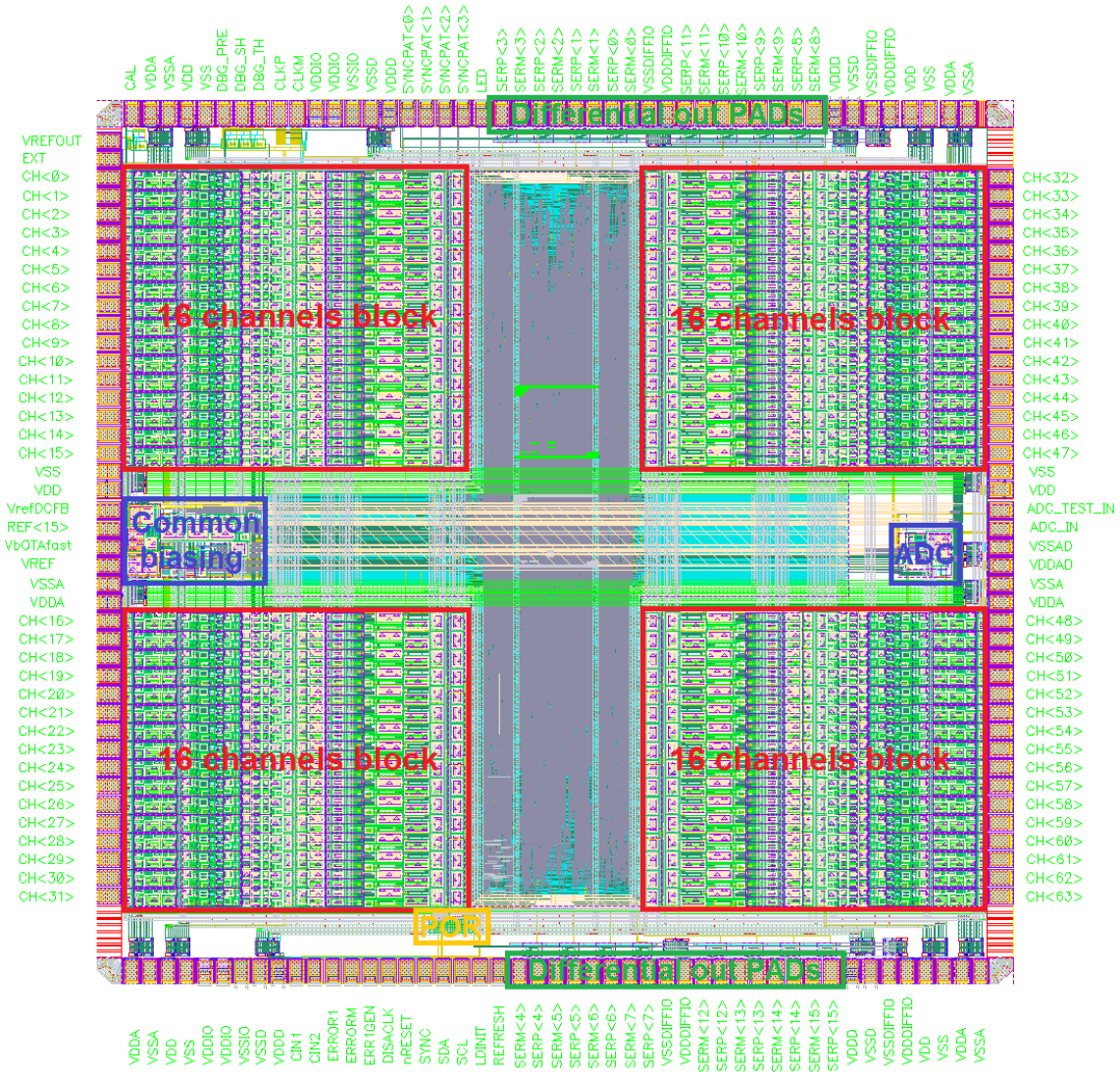


Dark count rate for irradiated detector for different over-voltages

DCR was shown to be the only parameter affected by radiation!

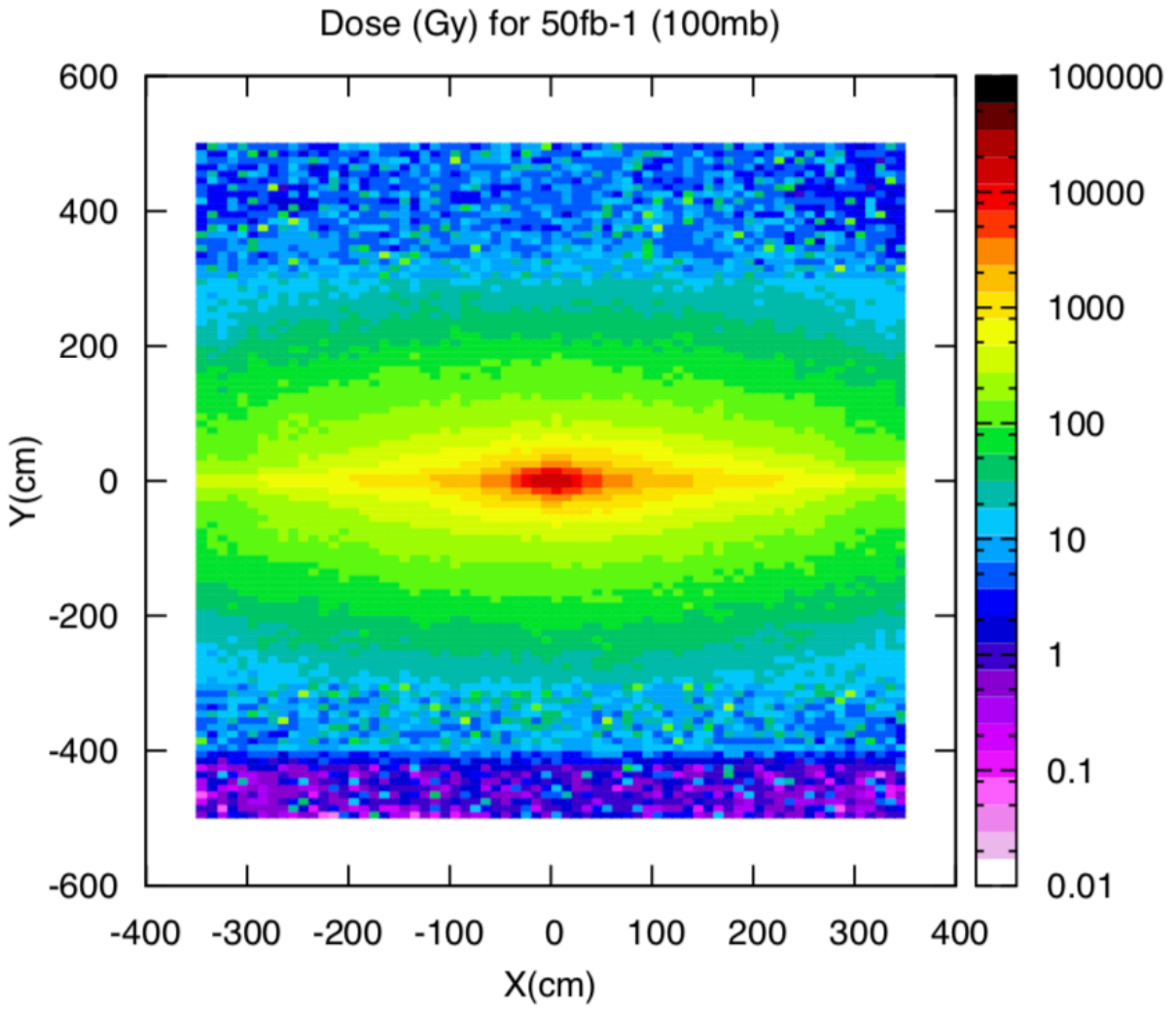
PACIFIC

- Low Power ASIC for Scintillating Fibre Tracker
  - » < 12mW per channel
- Hamming encoding of configuration registers
  - » Correct single bit flip on the fly
  - » Detect multi bit flip an raise error



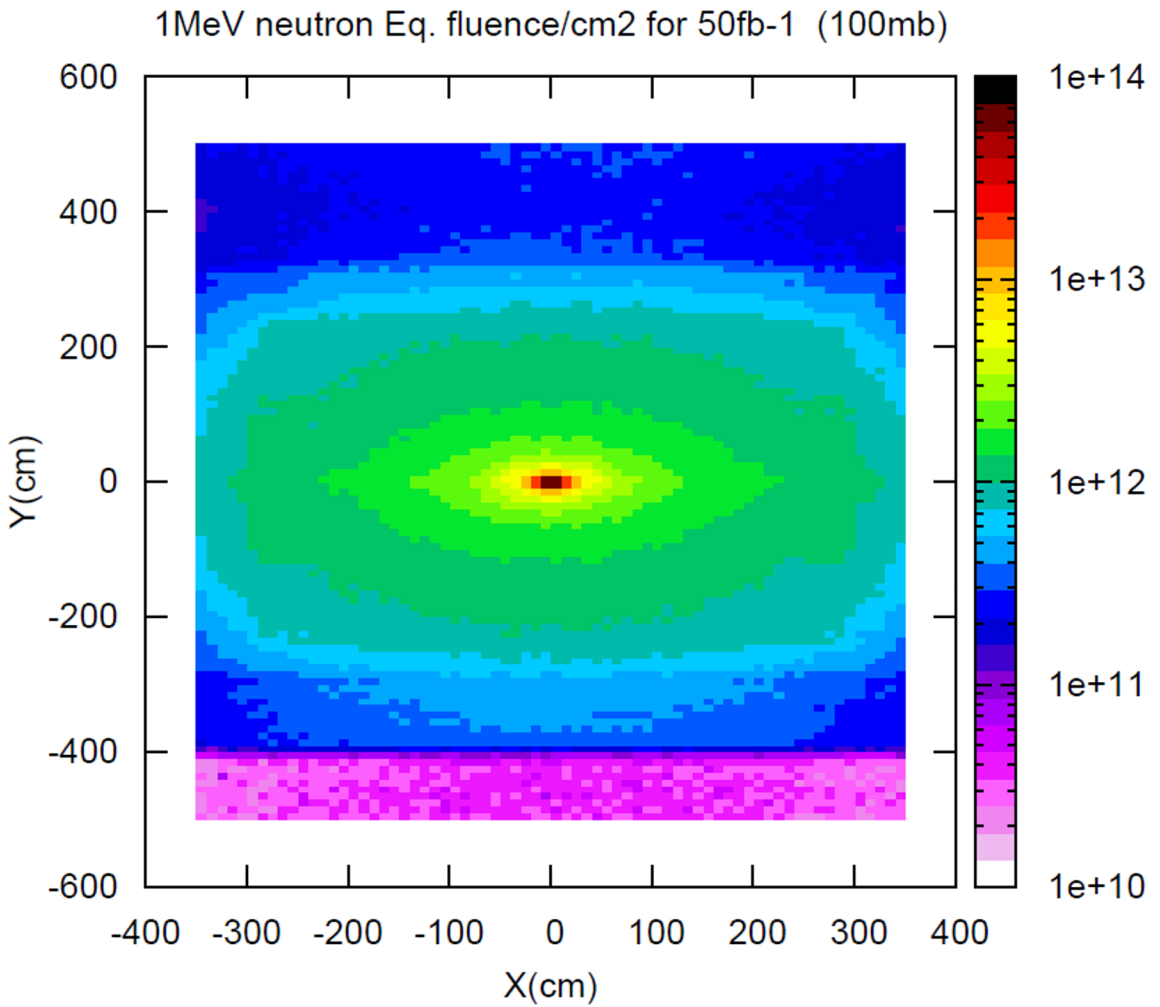
Radiation Environment

35 kGy in the hottest region around the beam pipe



Radiation Environment

$6 \cdot 10^{11}$ $n_{eq}cm^{-2}$ at the SiPM location (2.5m)

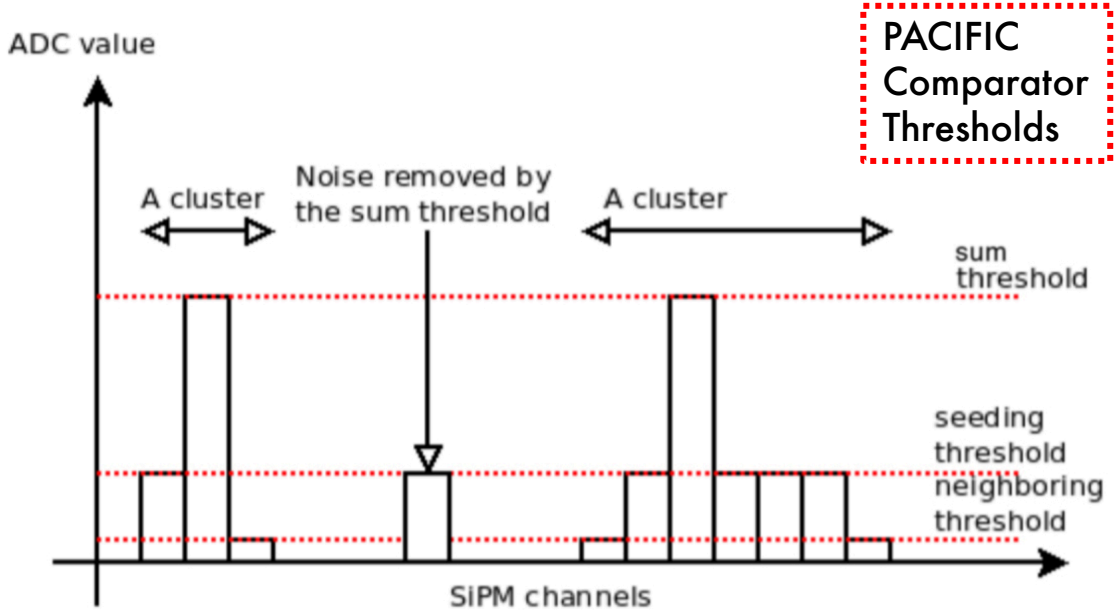


Clustering

Algorithm

- Making use of 3 comparators

1. Low threshold
   - » Just above dark noise rate
2. Middle threshold (“seed”)
   - » Slightly above low threshold
   - » Starting point for a cluster
3. High threshold
   - » Significantly larger
   - » Accept high signal single channel clusters



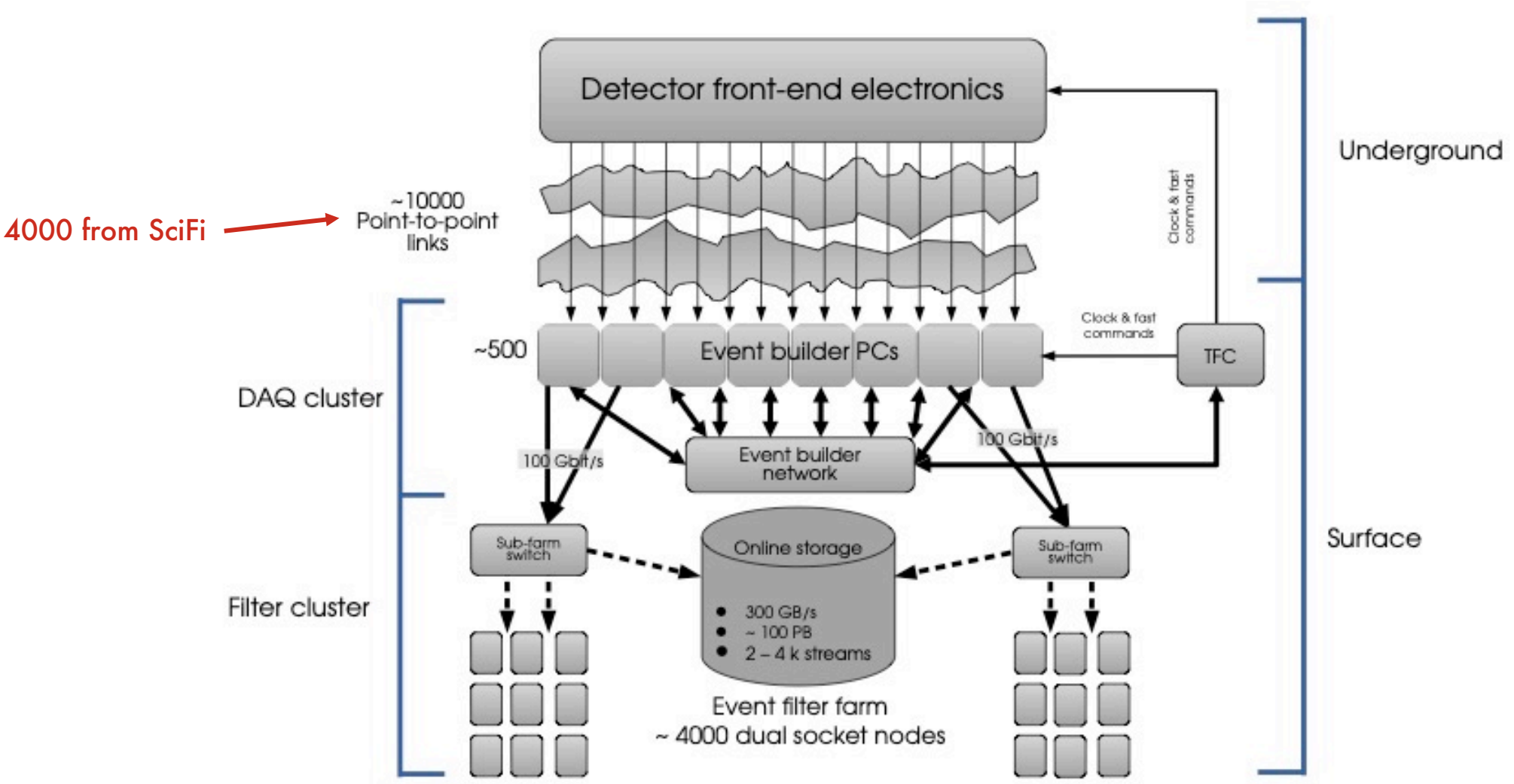
Cluster FPGA building clusters from 128 SiPM channels

Backend Electronics

PCIe40 card (so-called TELL40)
Up to 48 optical links

SuperMicro 4029GP-TRT server with 8 TELL40 cards and optical fibres connected

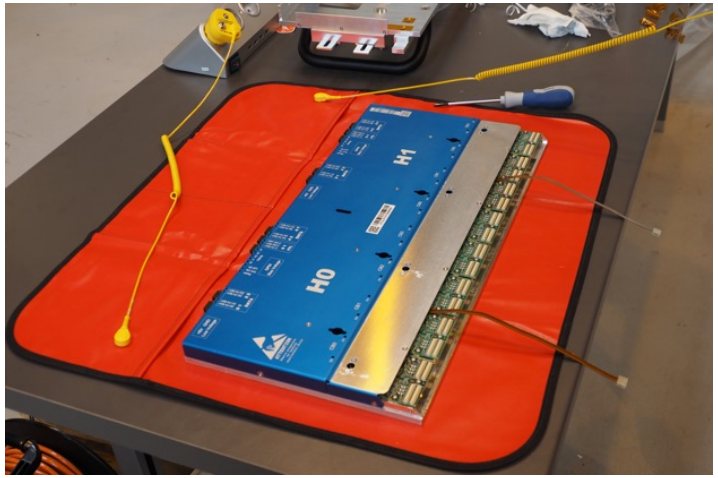
LHCb DAQ Network

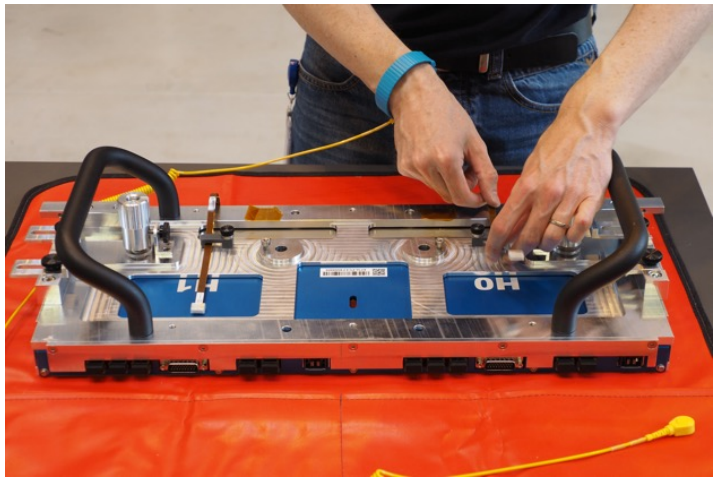


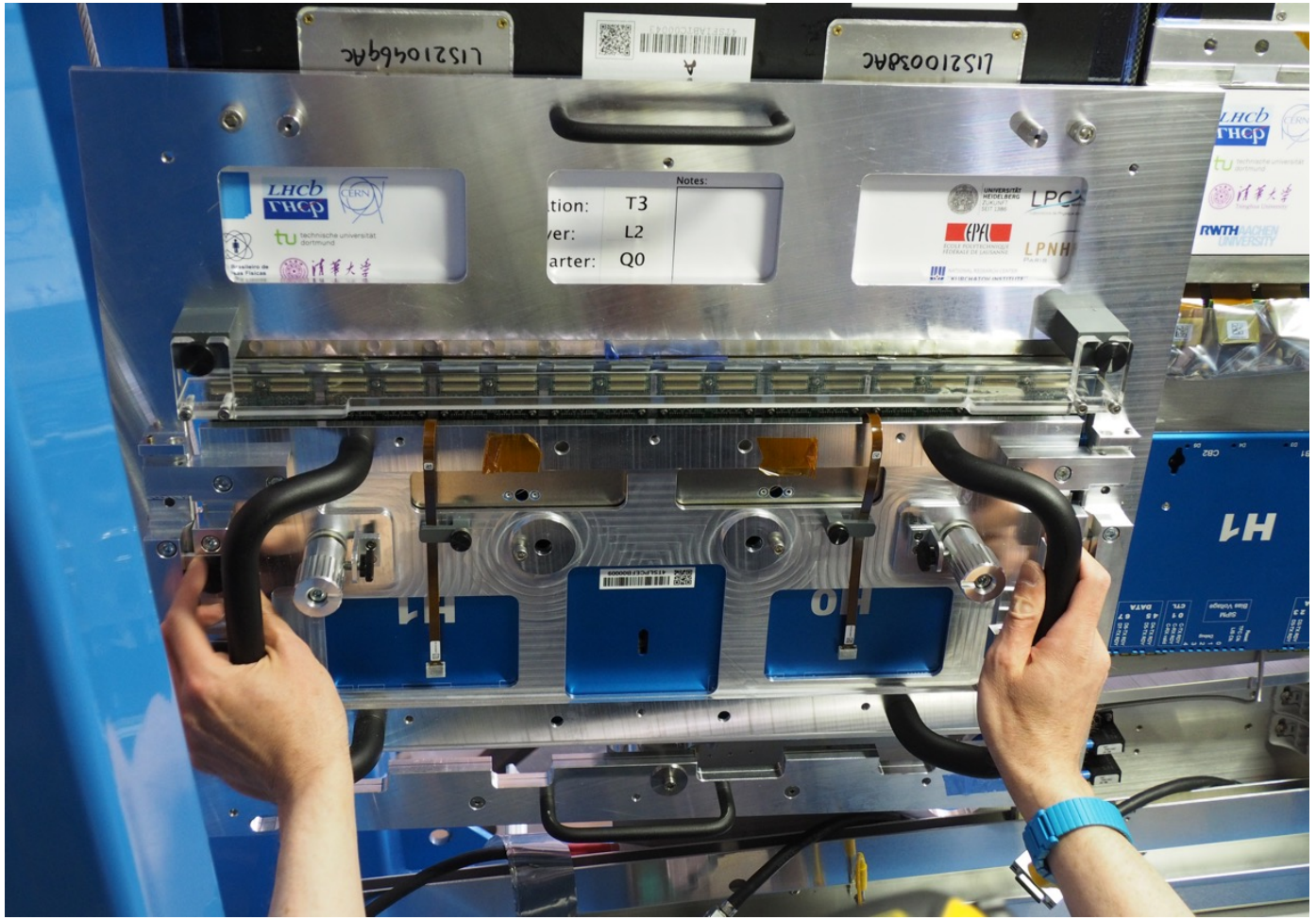
C-Frame Assembly

Module Installation

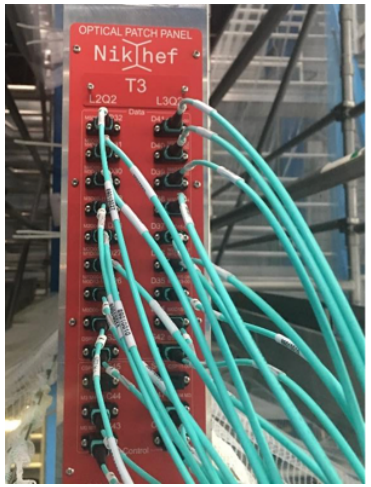
Readout Box Installation



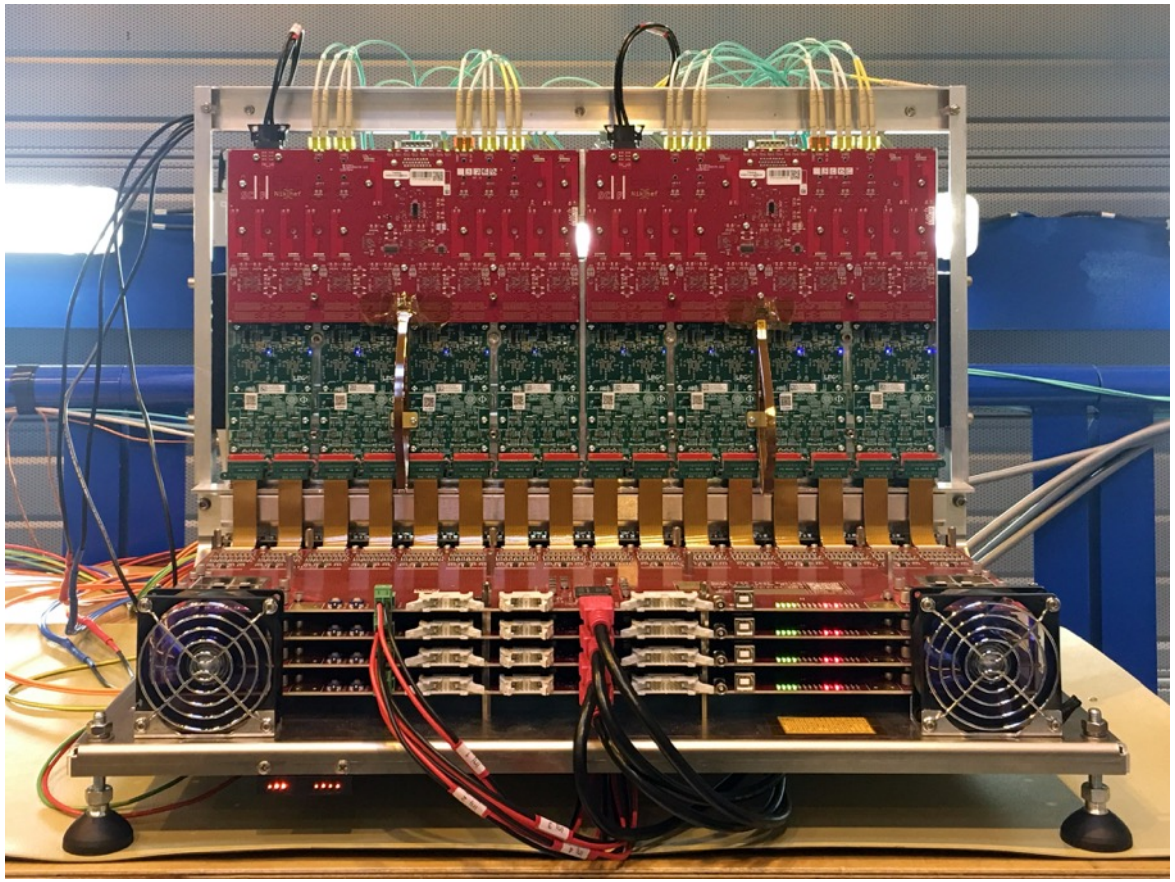




Cabling



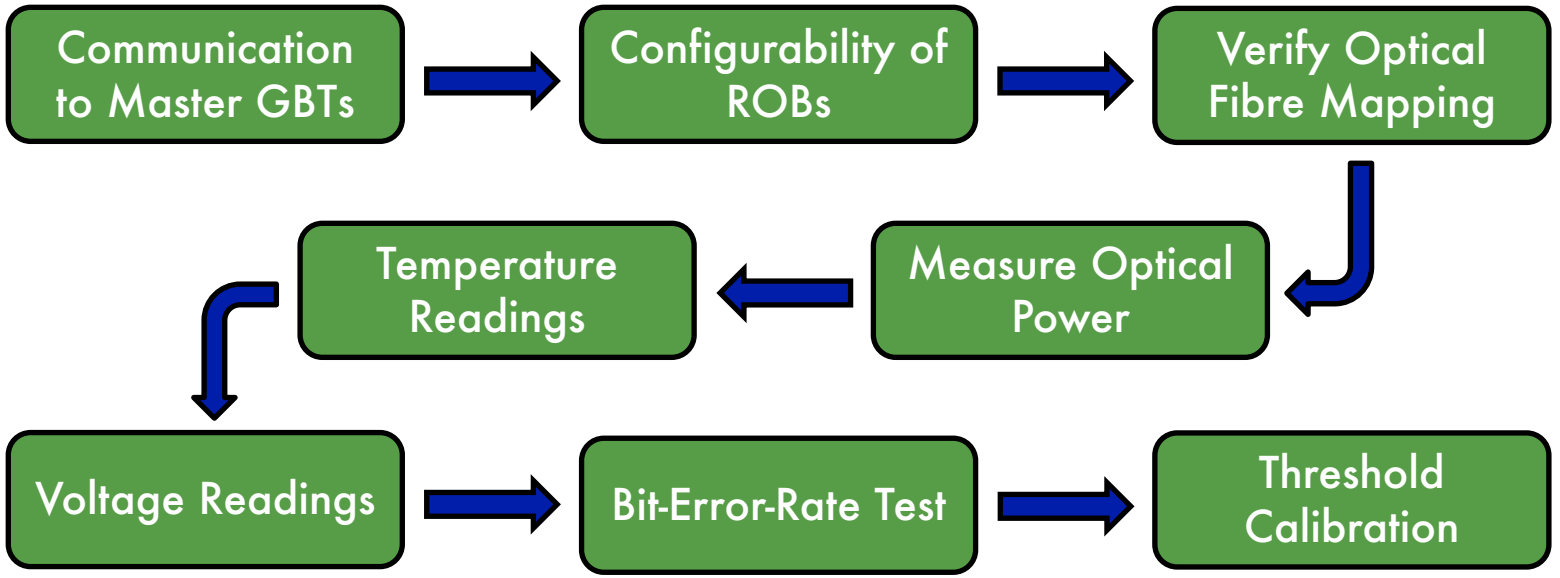
Readout Box QA



C-Frame Commissioning

Electronics Commissioning Procedure

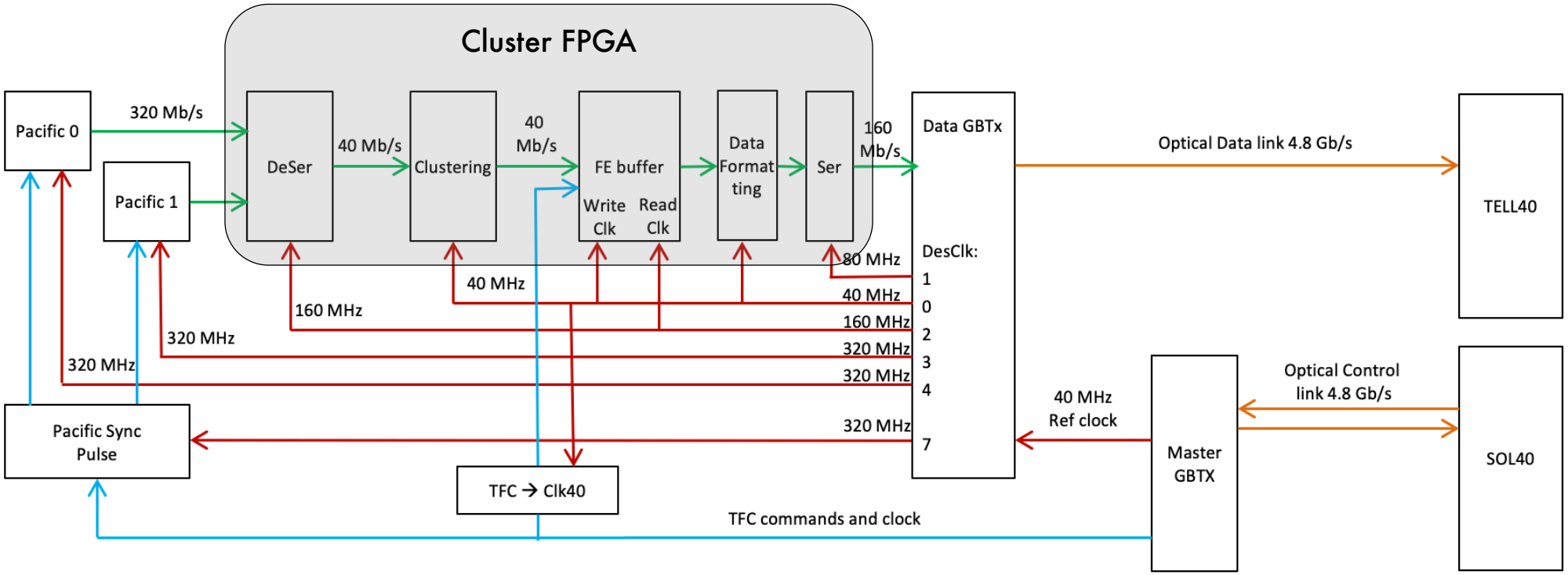
- Step-by-step verification of each component
- Ranges from basic functional to full system tests
- Results are stored in *Commissioning Reports*
- Full procedure takes about 2 weeks per C-Frame



Bit-Error-Rate Test (WIP)

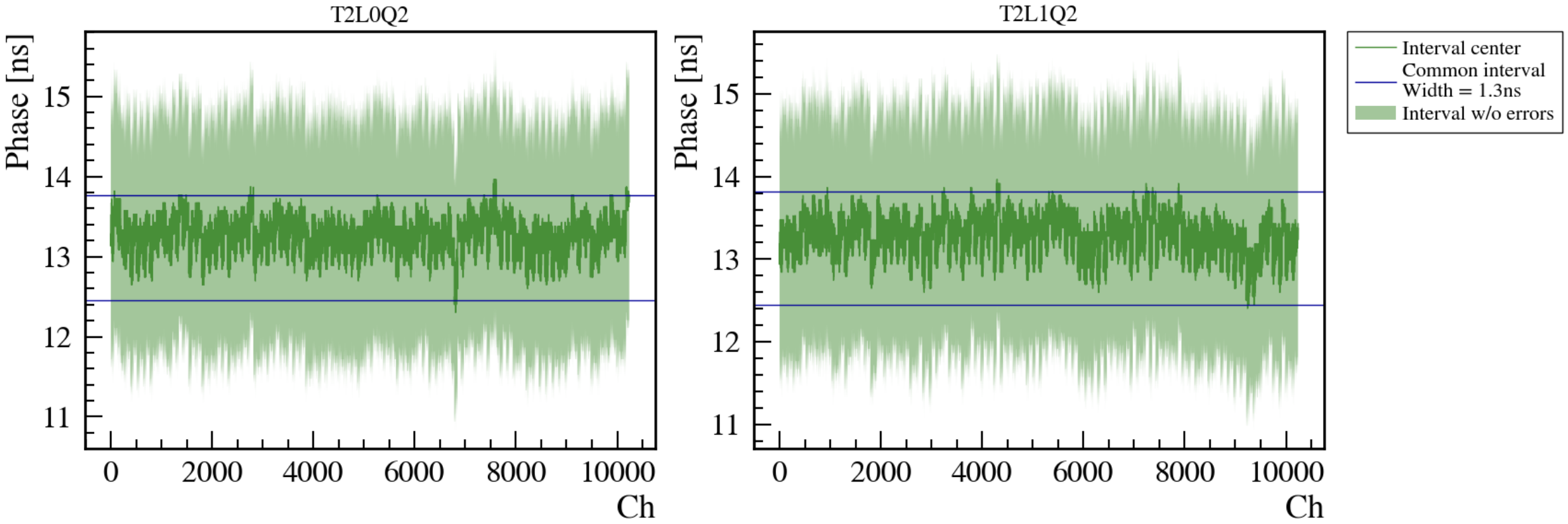
Difficulty: 6 clock phases have to be synchronised to each other to ensure a stable data transmission

- optical connections
- Data
- Fast control commands + clock
- clocks



4. PACIFIC Clock Scan

Using work-arounds



- No more interrupted intervals
- Common interval width = 1.3ns