SciFi SiPMs irradiation study

Monitoring of the radiation damage induced aging of the LHCb SciFi tracker SiPMs during Run 3

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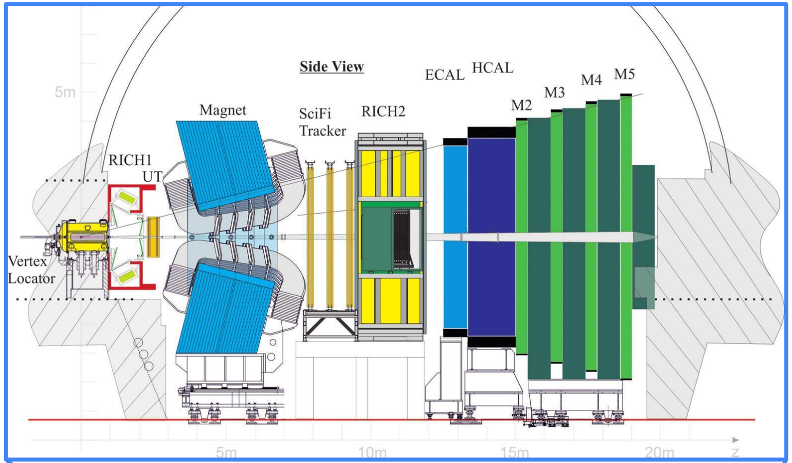
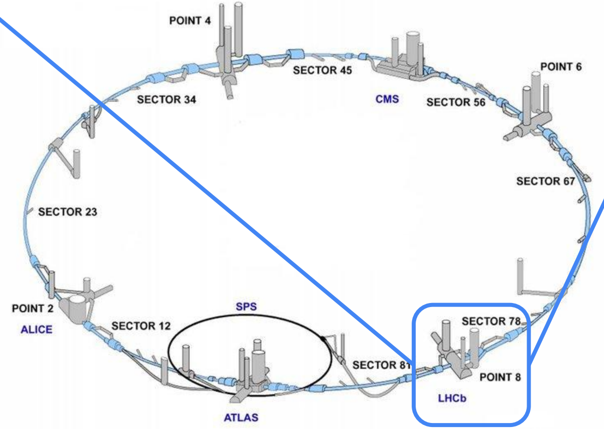
The LHCb experiment @ CERN

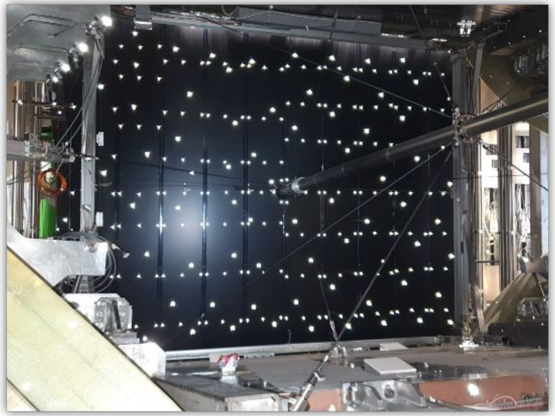
- **Particle physics experiment** at the Large Hadron Collider (LHC) @ CERN
- Studies **CP symmetry violation** in heavy flavour hadrons decay by proton-proton collisions
- In 2018-2021 → major upgrade (**LHCb Upgrade I**)
  - **Complete new tracking system**
  - Update of the RICH systems
  - New readout electronics

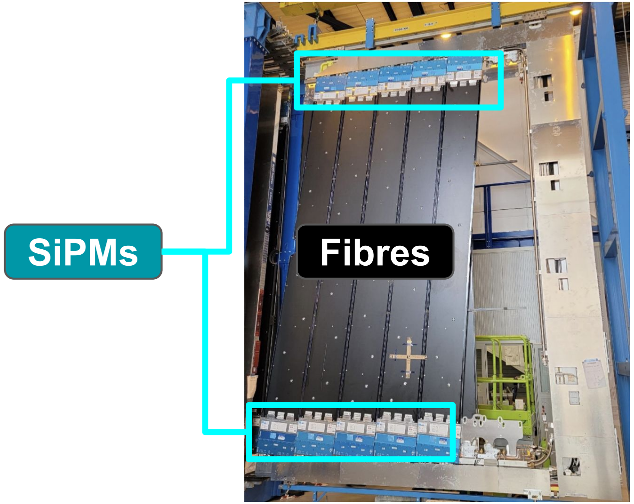




The LHCb SciFi tracker

- 250 µm ∅ Scintillating Fibres grouped in mats
- Fibre mats readout by SiPM arrays
- 12 layers → 6 x 5 m^2 each for a total of 340 m^2
- 1 layer = 0.1% X_0
- Spatial resolution < 100 µm
- > 500’000 channels readout at 40 MHz
- All cooling and readout electronics located outside the acceptance
- SiPMs cooled @-40°C

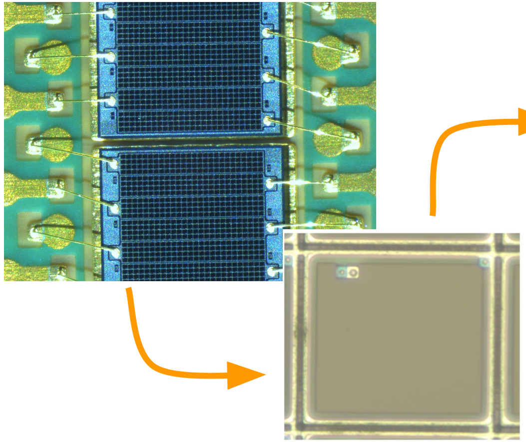


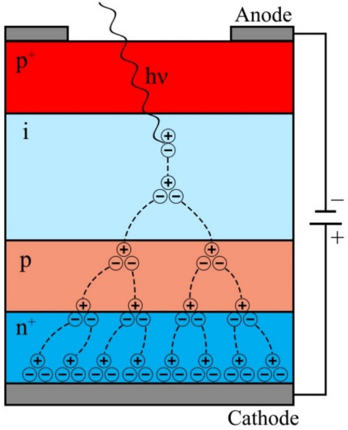


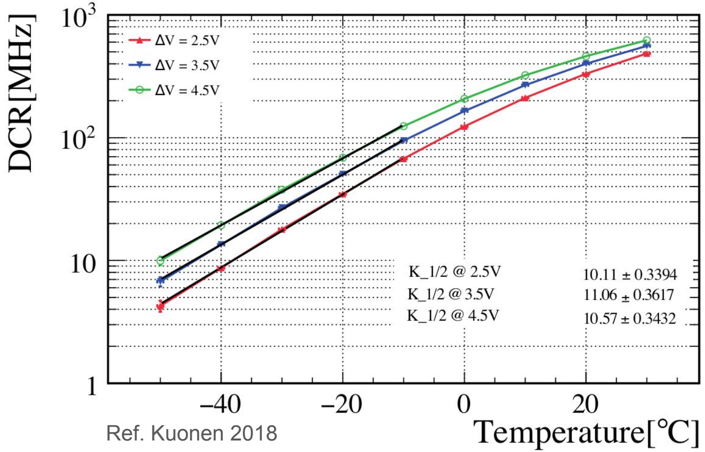
Introduction: SiPMs and Dark Count Rate (DCR)

Silicon PhotoMultipliers are **solid state photodetectors** made of several avalanche photodiodes operating in Geiger mode

Light →Avalanche → Signal





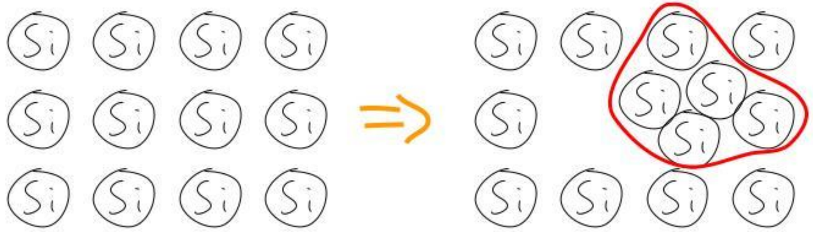


Ref. Kuonen 2018

Avalanches can be generated also thermally → **main source of noise = DCR**

$$\mathrm{DCR}(T) = \mathrm{DCR}(T_0) \cdot 2^{\frac{T-T_0}{K_T}}$$

Radiation damages and annealing

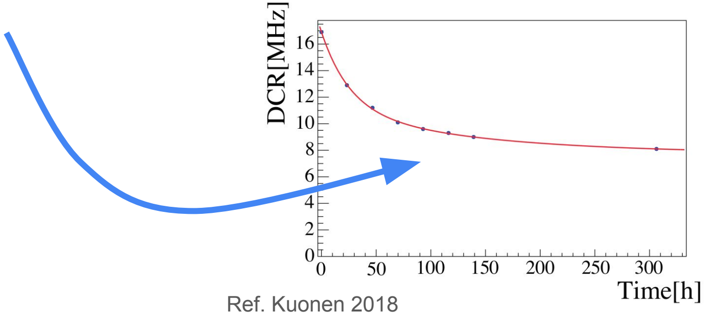


- Radiation provokes **displacements of Si atoms** → imperfections in the lattice
- **Increase of the DCR**
- Higher thresholds required leading to lower hit detection efficiency

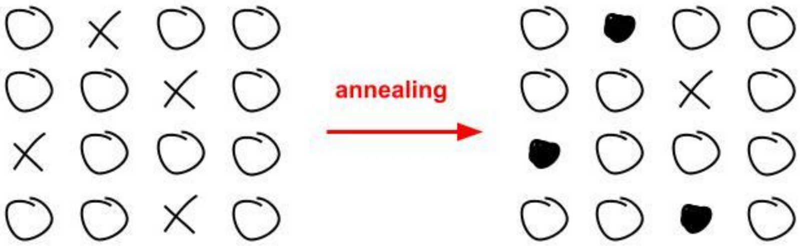
→**PROBLEMS FOR TRACKING!**

BUT! We can **recover** from radiation damages **heating up** the detectors

Thermal annealing



Ref. Kuonen 2018



X → damage or not recovered
● → recovered by annealing

LHCb high radiation environment

- The SciFi is affected by both ionising and non-ionising radiation-induced damage

Ionising:

- Mainly affects **fibres** (close to the beam pipe)
- Expected dose of **35 kGy** after 50 fb^{-1} integrated luminosity

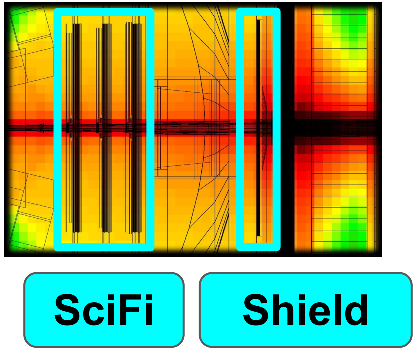
→ decrease of the **fibre attenuation length** by **40%** and so decrease in fibre **Light Yield (LY)**

Non-ionising:

- Mainly affects **SiPMs**
- Due to back-splashed **neutrons** from downstream calorimeters
- Expected neutron fluence after 50 fb^{-1} integrated luminosity:
  - **4.1 x 10^{11}** 1MeV n_{eq}/cm^2 @ T3
  - **3.2 x 10^{11}** 1MeV n_{eq}/cm^2 @ T1

→ SiPM **DCR** is expected to increase up to ~ **10 MHz** per channel in the innermost part of T3

Values from **FLUKA simulation**:
- At end-of-life conditions → **50 fb^{-1}**
- Assuming E_{CM} = **14 TeV**
- Assuming σ_{pp} = **84 mb**
- With neutron **shield** installed

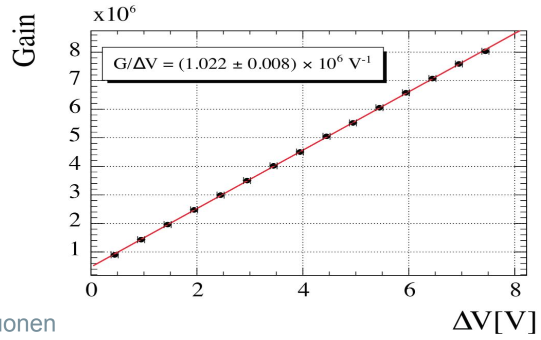


Dark Count Rate (DCR)

- 512 = number of SiPM channels in one HV line (1 sub-module)
- **Imat**: current measured by one CAEN channel
- **G** from gain measurement (R&D)

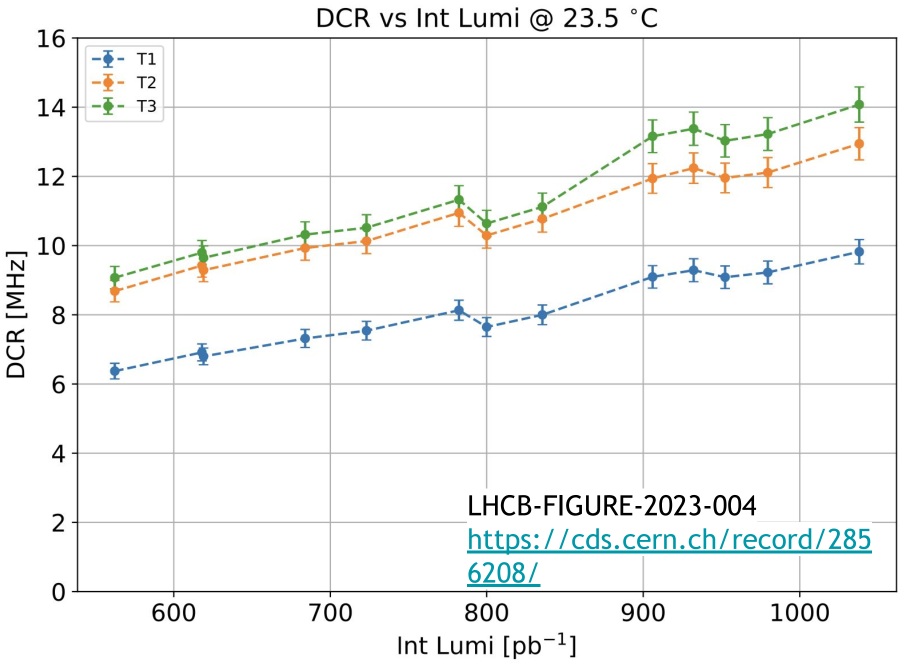
$$\mathbf{Imat = DCR \cdot G \cdot 512 \cdot e}$$

We measure the average DCR per channel based on the measurement of the current of each mat



source: Kuonen

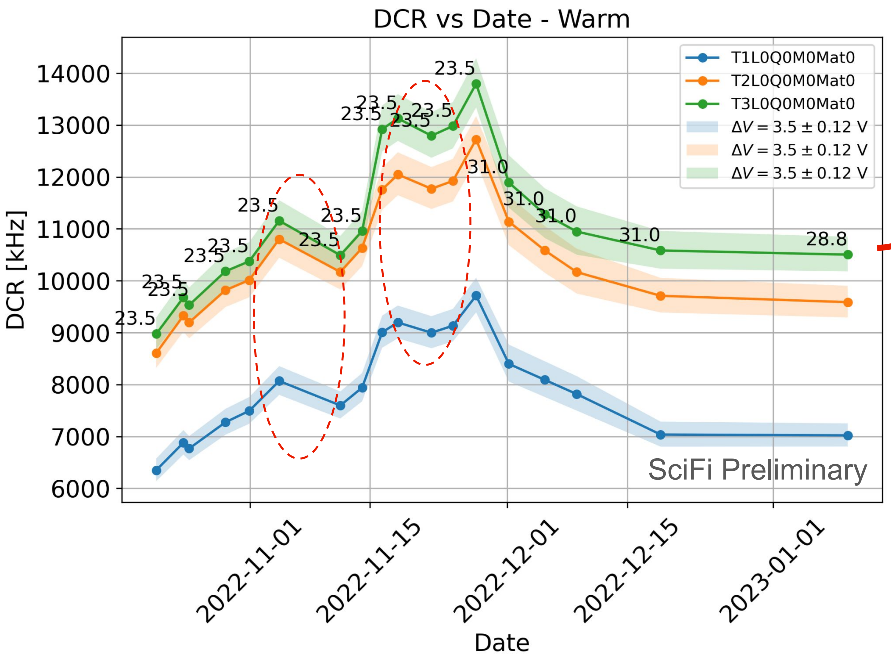
DCR WARM

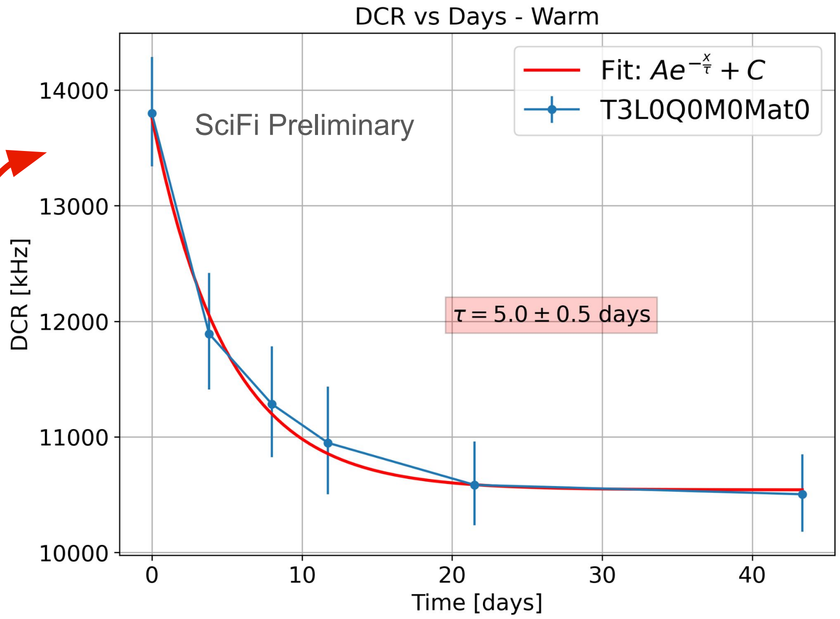


- Warm detector = **end-of-life conditions → 14 MHz DCR x channel**
- First effects of **annealing**
- From 21 October to 28 November 2022

Annealing at room temperature

- Detector at ~30°C in december
- REMEMBER: the annealing started as soon as the detector was warmed up
- Temperatures in plot are in °C

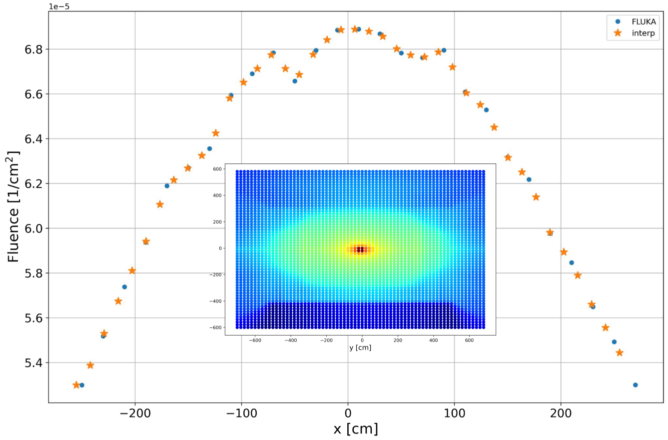


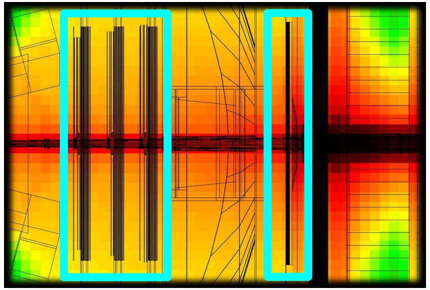


Annealing during YETS

FLUKA simulation comparison

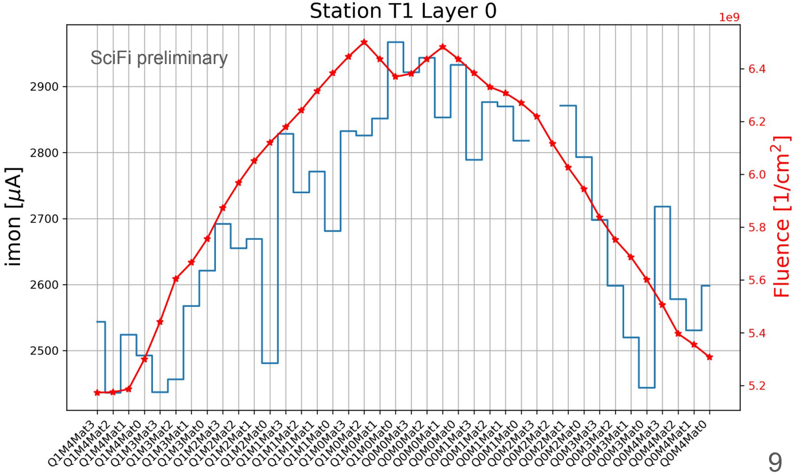
- **FLUKA simulation** datapoints by Matthias Karacson
- Each bin is 20x20x20 cm^3 in xyz extracted for 3 z positions
- **Interpolation** of points in the center of every Mat
- Scaling for 1.058 fb^{-1}
- Comparison between ratios of fluence at T1 and T3 and averaged currents in one layer



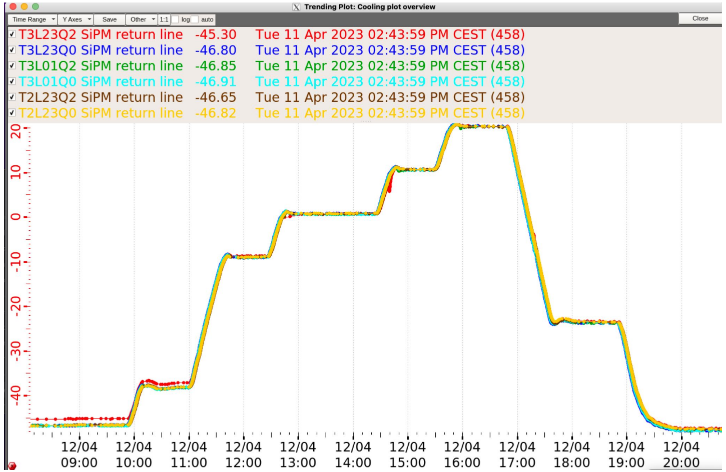


SciFi Shield

	T1/T3
FLUKA no shield	0.58
FLUKA w shield	0.74
SciFi (27/11/22)	0.70 ± 0.05
SciFi (22/02/23)	0.68 ± 0.04

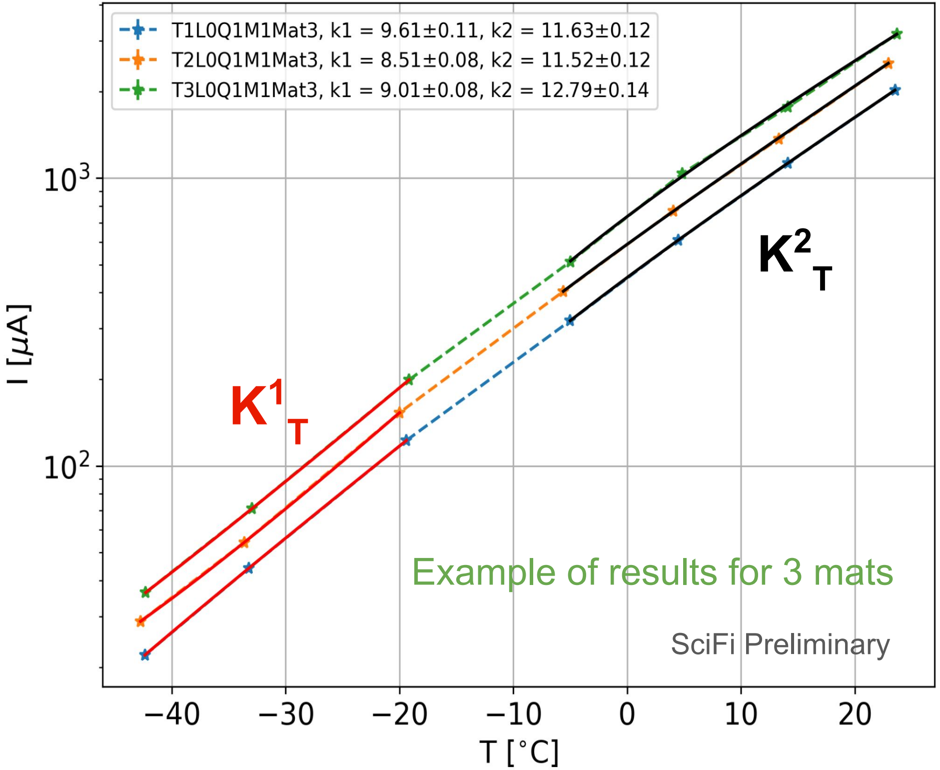


Temperature scan



Remember: T is the temperature averaged over 4 SiPM

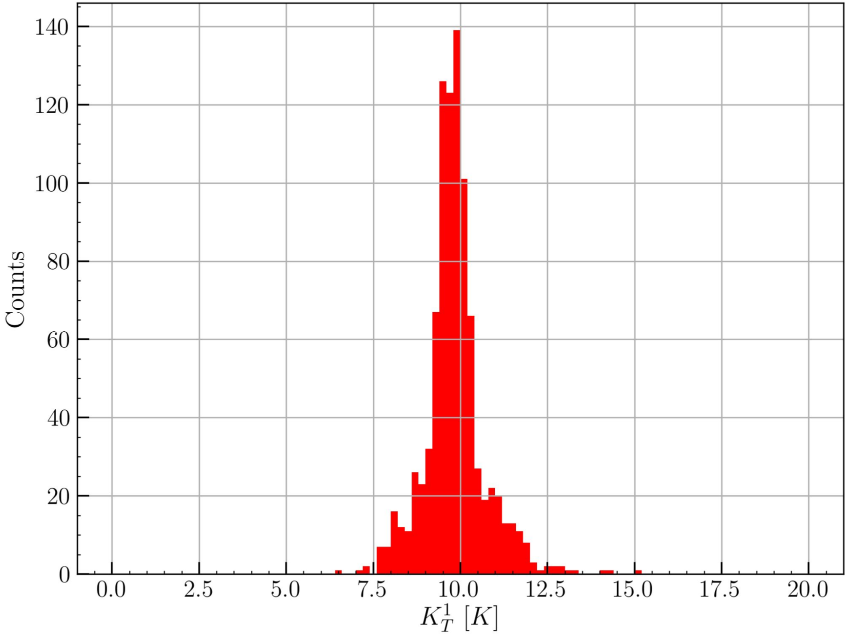
$$I(T) = I(T_0) \cdot 2^{\frac{T-T_0}{K_T^{1,2}}}$$

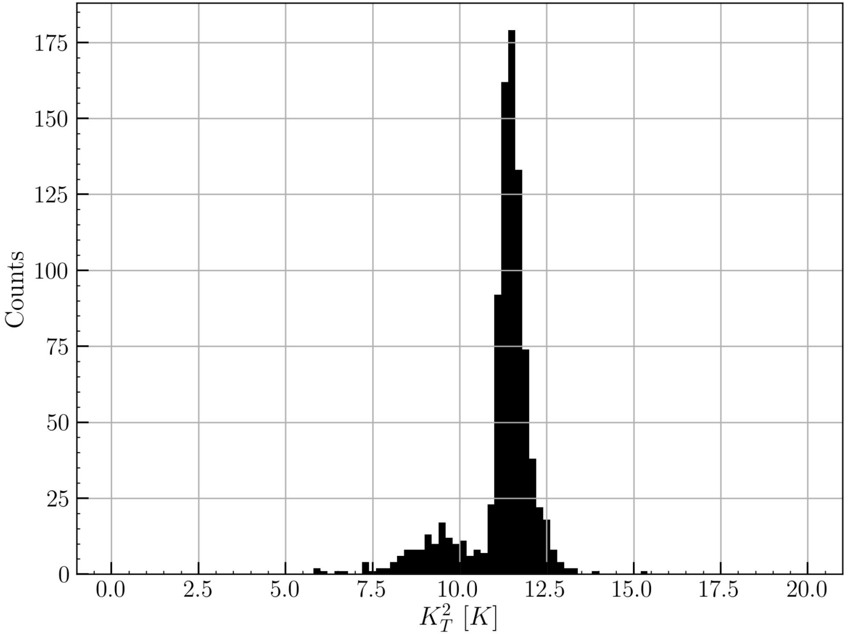


2 behaviours at low and high temperatures → in warm, loss of linearity

→ 2 different fits (<-10°C and >-10°C)

Temp scan: k^1_T and k^2_T measured over the whole detector





Avg = 9.84 K
Std = 0.89 K

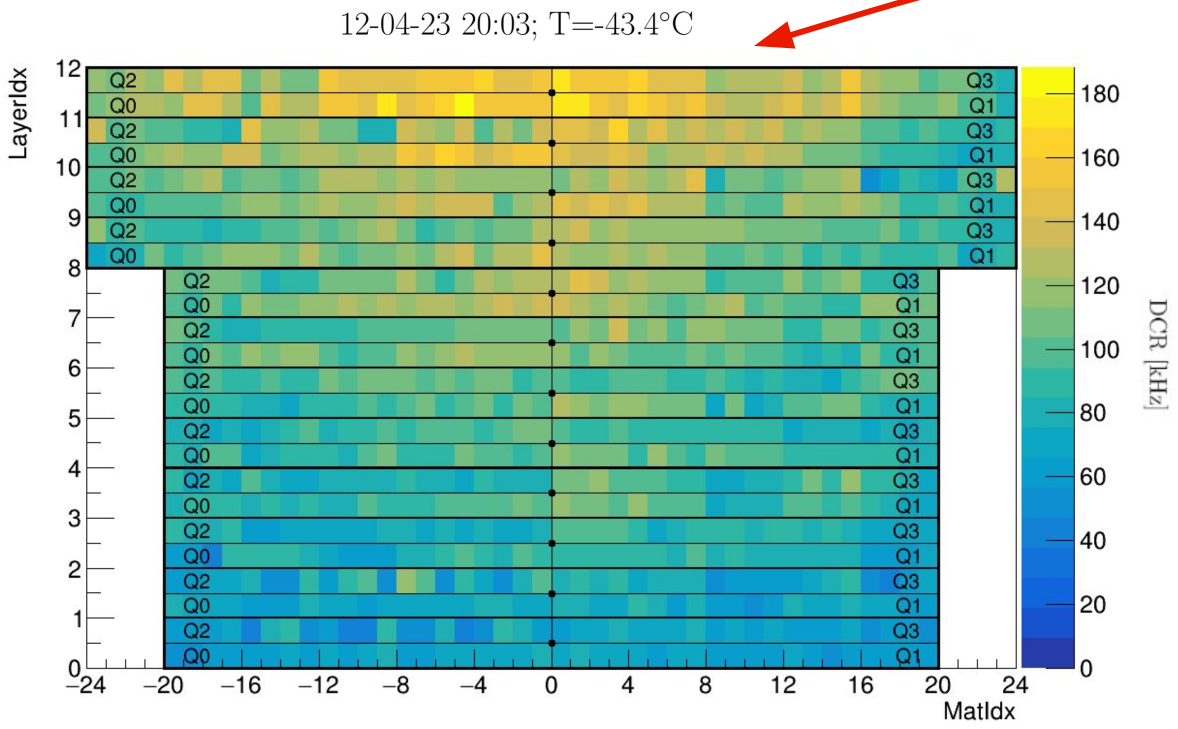
Good agreement with R&D results!

Avg = 11.21 K
Std = 1.02 K

R&D K_T value = 11.06 ± 0.36 K

Ref. Kuonen 2018

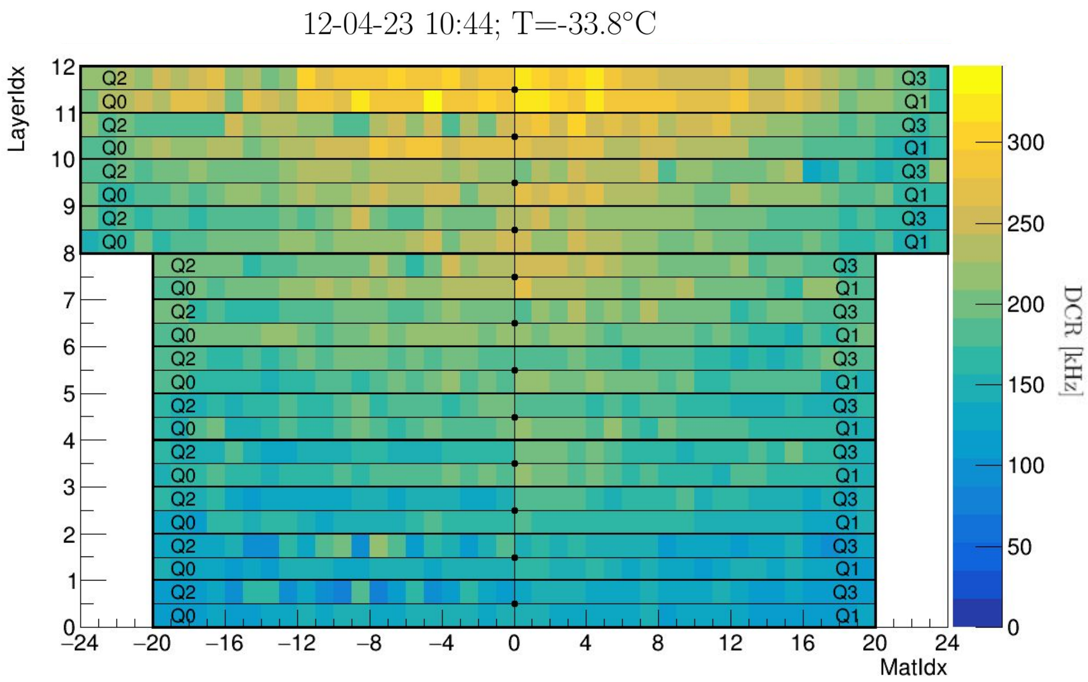
DCR @ -43.4°C measured during T scan



Average over few channels in T3

DCR @ -43.4°C → inner part of T3 ~ 143 ± 15 kHz

DCR @ -33.8°C measured during T scan



Average over few channels in T3

DCR @ -33.8°C → inner part of T3
~ 273 ± 17 kHz

Temperature scaling
→ scaled using k^1_T to -43.4°C: ~ **139 kHz**, compatible with measurement shown above

Int lumi scaling
→ scaled from 1.058 fb^{-1} to 50 fb^{-1}:
~ 13 MHz @ -33.8°C

Conclusions

- The study of the **aging** of the SciFi SiPMs is ongoing:
  - **Currents and DCR monitored** in cold and warm periods
  - Observation of **annealing effect** during warm period
- We compared the **FLUKA simulation** of the radiation environment with data from the detector
  - **Good agreement** between expectations and measurements for the **neutron shield effectiveness**
  - Comparison between FLUKA and SciFi DCR profiles is ongoing
- We performed a **temperature scan** changing temperatures between 20°C and -50°C
  - **DCR measurement** at two operation points (-50°C and -40°C)
  - **Temperature constant $K_{T1/2}$** measurement in warm and cold regimes

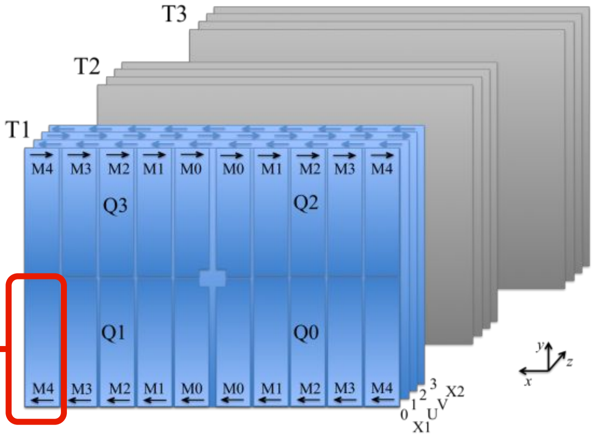
Thanks for the attention

Backup slides

CAEN channels

- Each CAEN channel provides the bias (Vbias) to **4 SiPM arrays** in a SciFi Mat
- Vbias is 3.5 V above the SiPM breakdown → **averaged Vbd(T)** over 4 SiPM arrays

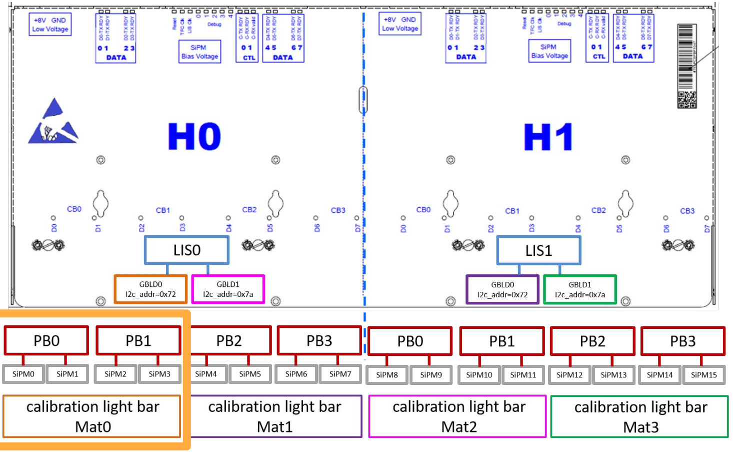
$$\Delta V = V_{bias} - V_{BD}(T)$$



1 Module = 1 FE box

→ 4 Mats

1 CAEN channel = 1 Mat = 4 SiPMs



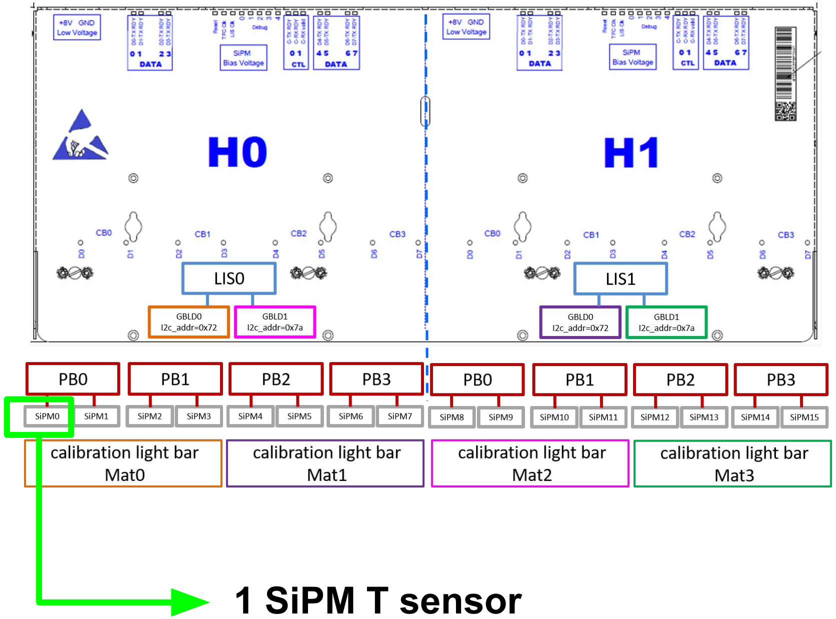
What do we measure?

1 current

1 Vbias voltage

4 temperature

SiPMs temperature measurement



For 1 Mat (1 CAEN channel)→ 4 T sensors

- PT1000 sensor readout with a 0.5 °C precision
- T variation:
  - **Space** → differences between 4 SiPMs of same mat, dependence seen (pattern for 16 SiPMs seen by Jan already)
  - **Time** → variation of T during time, expected to be small (precision of the sensor) in short periods

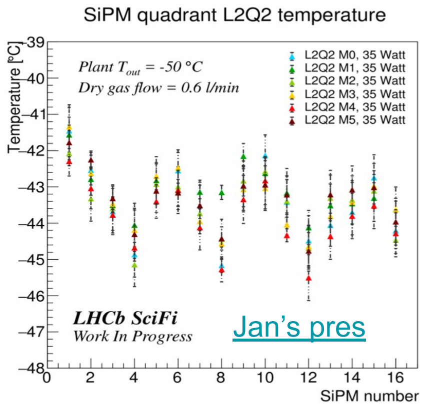


Figure 13: Temperature dispersion comparison for modules of quadrant L2Q2.

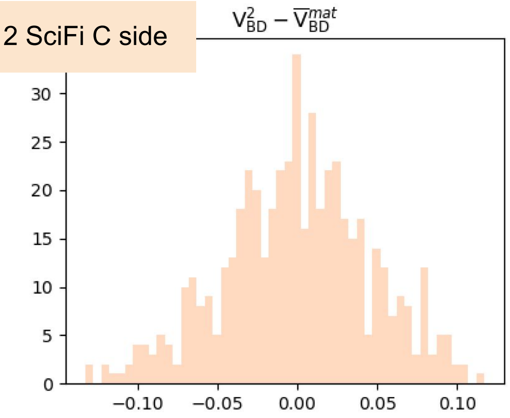
Breakdown voltage spread

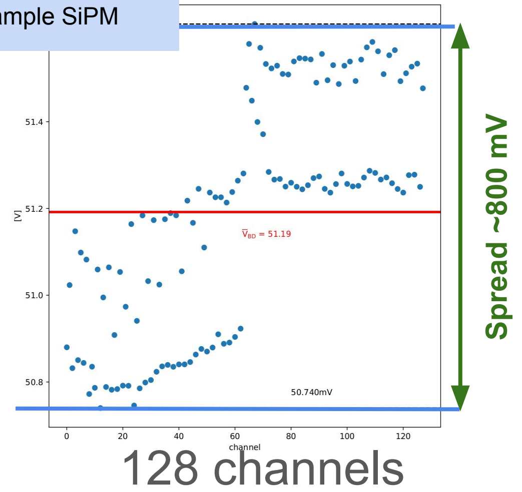
- Vbd spread among SiPMs within one Mat (4 SiPMs) is well contained in **50 mV**

  → with respect to the **avg Vbd** value of the 4 SiPMs in one mat

- Spread within the 128 channels of one SiPM can reach up to **400 mV** deviation from the average

  → can be corrected in the PACIFIC (up to ±250 mV)



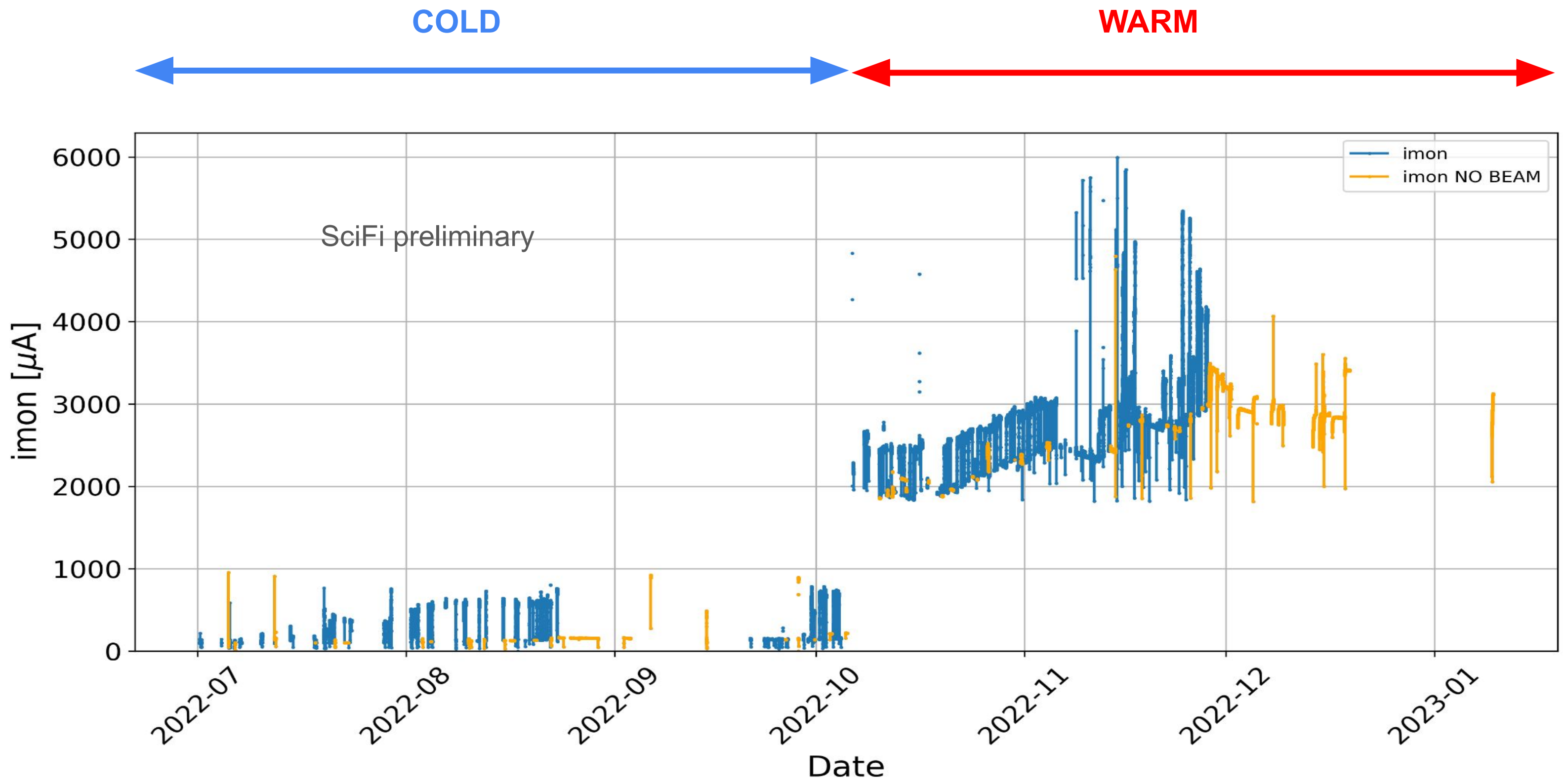


IMPORTANT NOTE

If T changes, Vbd changes as well → if we want ΔV=3.5V, **Vbias has to be updated**

$$V_{\text{bias}} = 3.5\,\text{V} + V_{\text{bd}} + 60\,\text{mV}\cdot(T - 25\,^{\circ}\text{C}) + V_{\text{offset}}$$

Snapshot of one Mat current July 2022 - January 2023

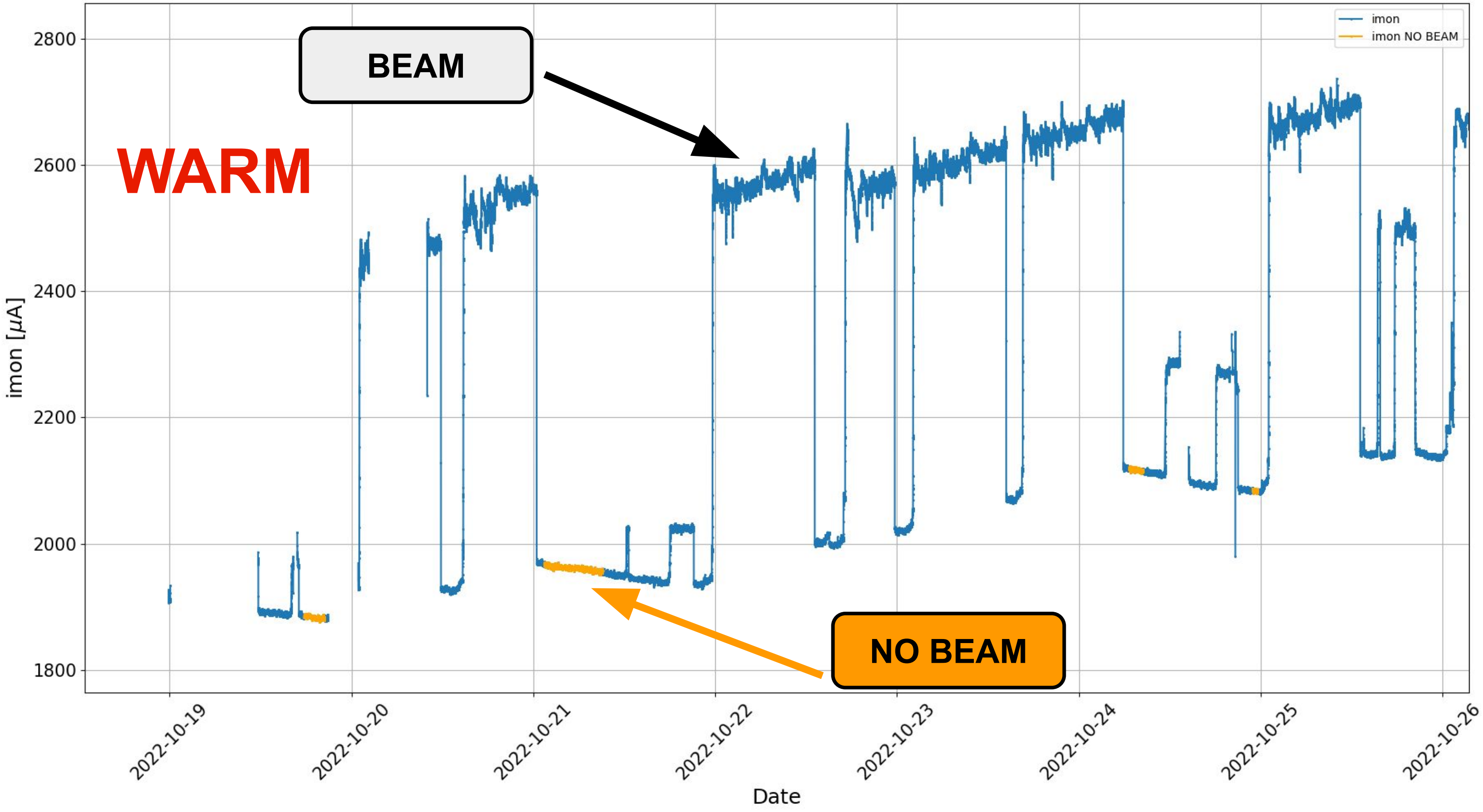


Channel T1L0Q0M0Mat0

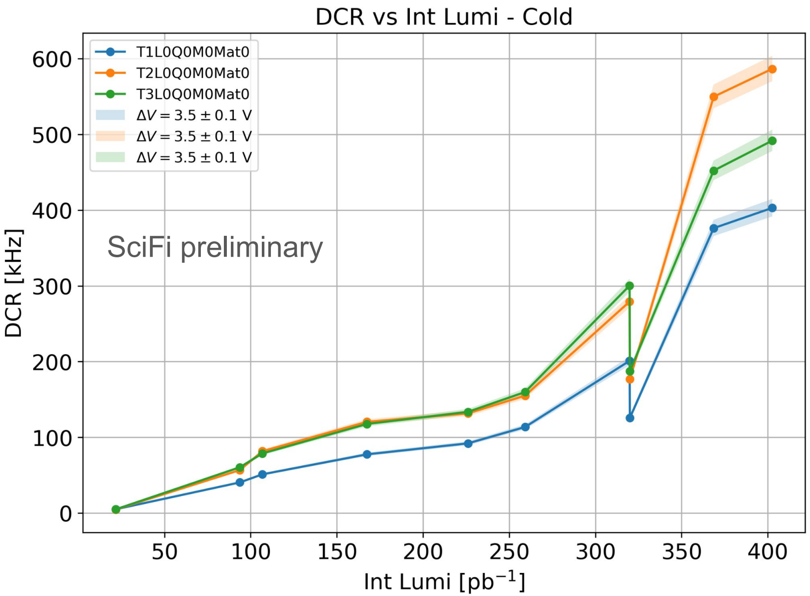
Reminder

→ DCR increases with radiation damage

→ DCR is T dependant

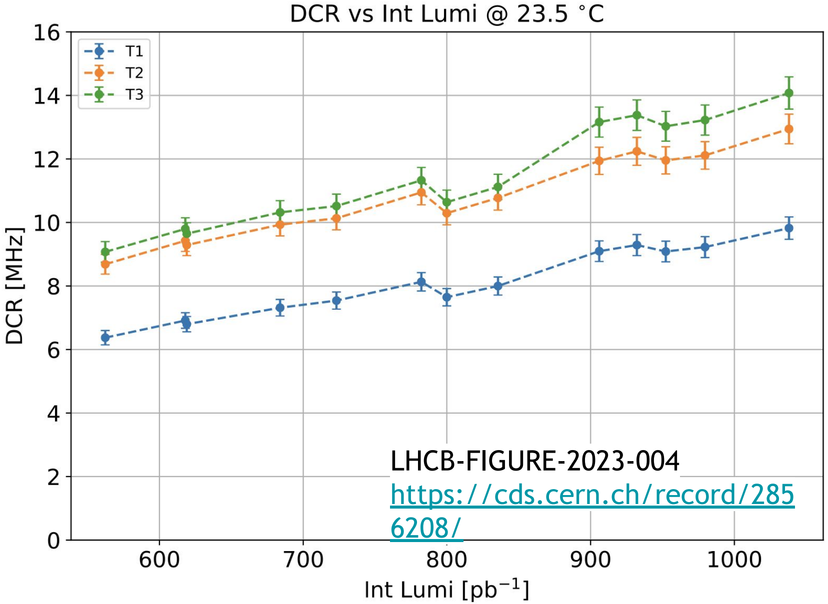

BEAM
WARM
NO BEAM
imon
imon NO BEAM
2800
2600
2400
2200
2000
1800
imon [μA]
2022-10-19
2022-10-20
2022-10-21
2022-10-22
2022-10-23
2022-10-24
2022-10-25
2022-10-26
Date

DCR COLD



- Start of the commissioning!
- Huge differences in temperature → difficulties to study the behaviour
- From 23 July 2022 to 5 October 2022

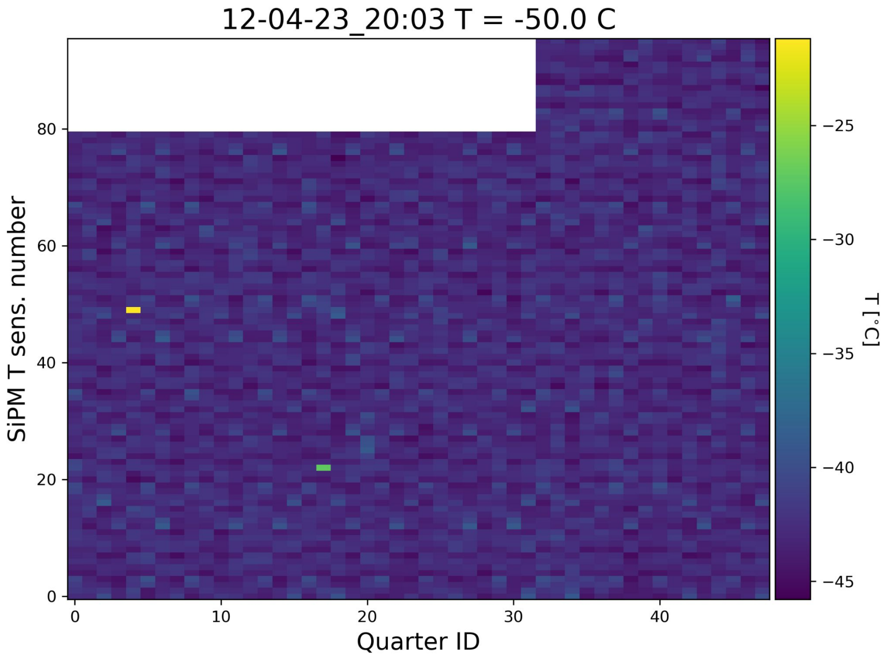
DCR WARM



- Warm detector = end of life conditions → 14 MHz DCR x channel
- First effects of annealing
- From 21 October to 28 November 2022

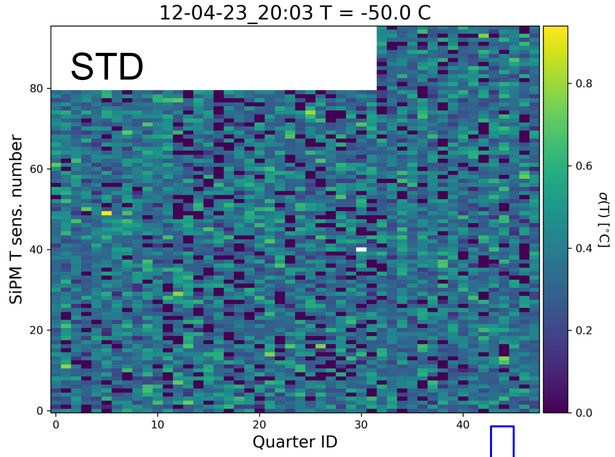
First look at temperatures stability:

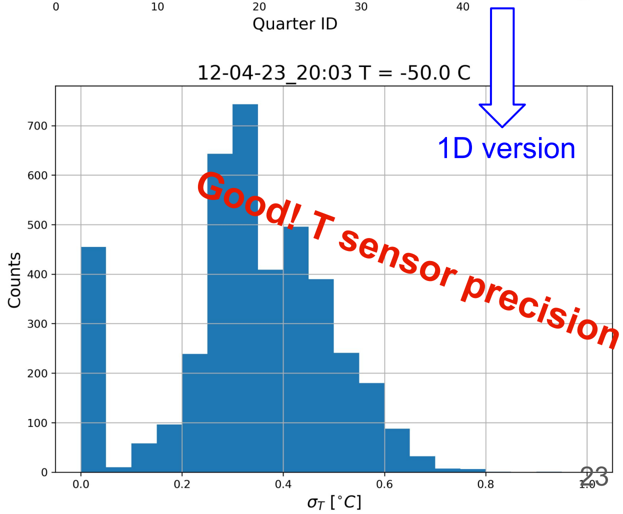
SiPM temperatures → Avg over 10 mins

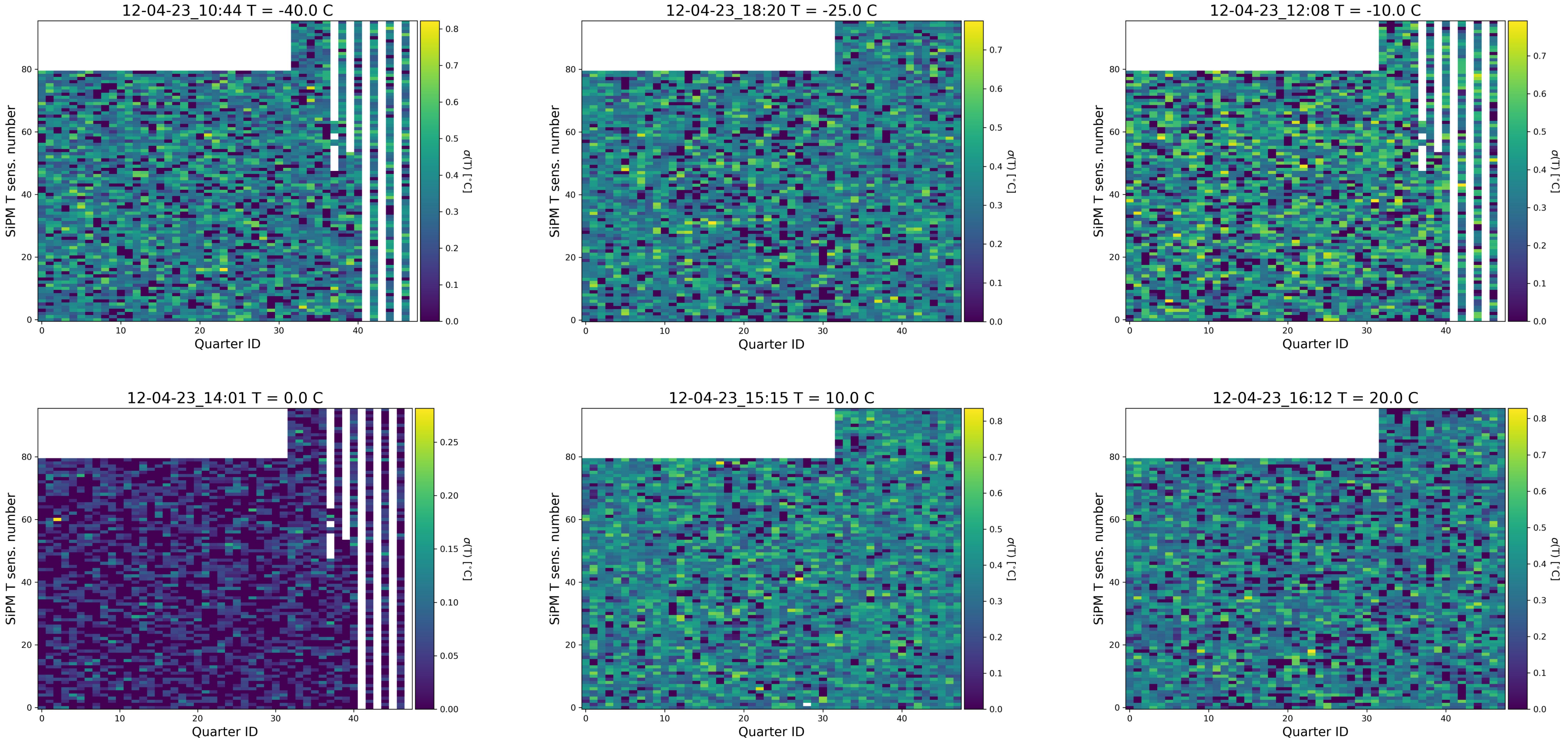


All SiPMs temperatures

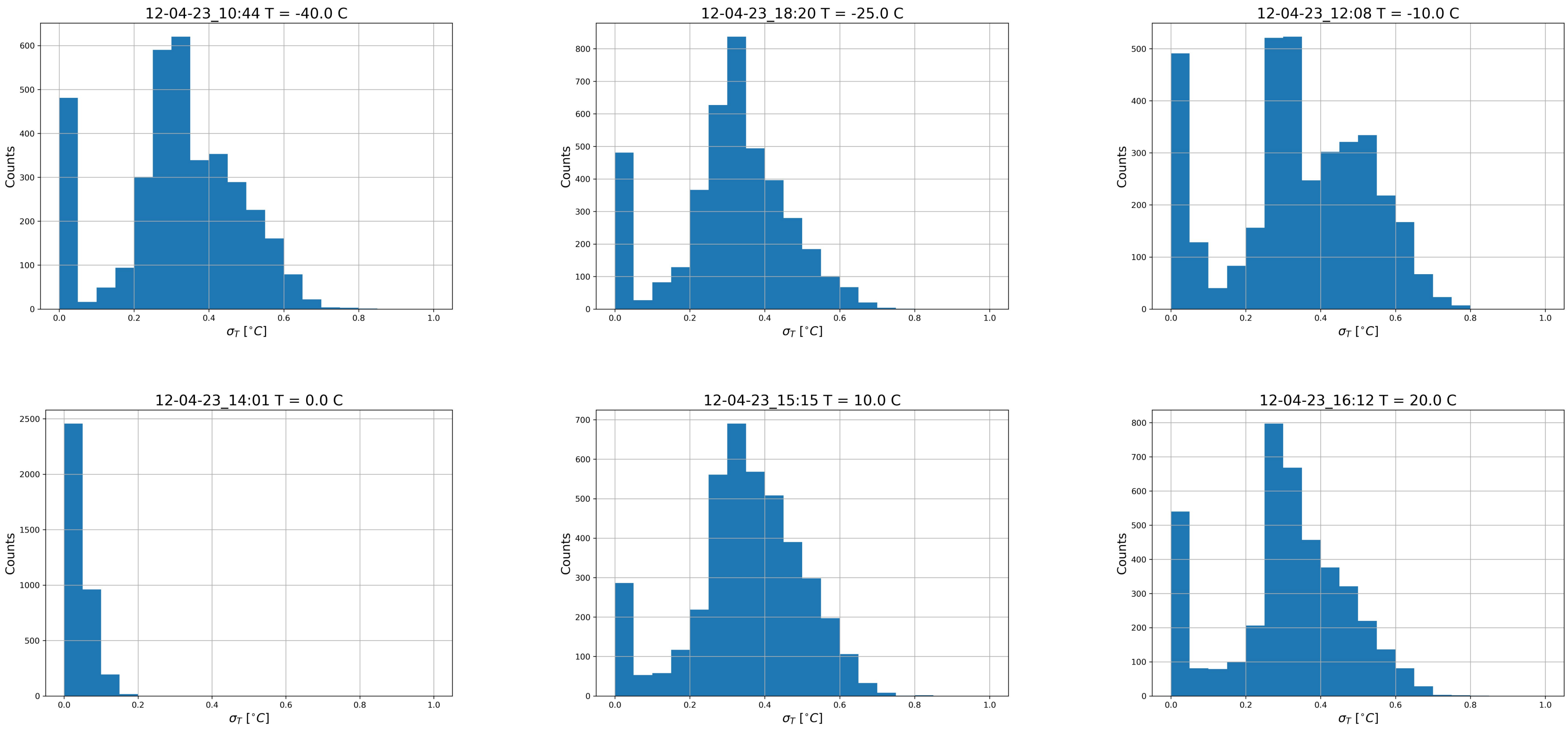
Variation in time (over 10 mins)







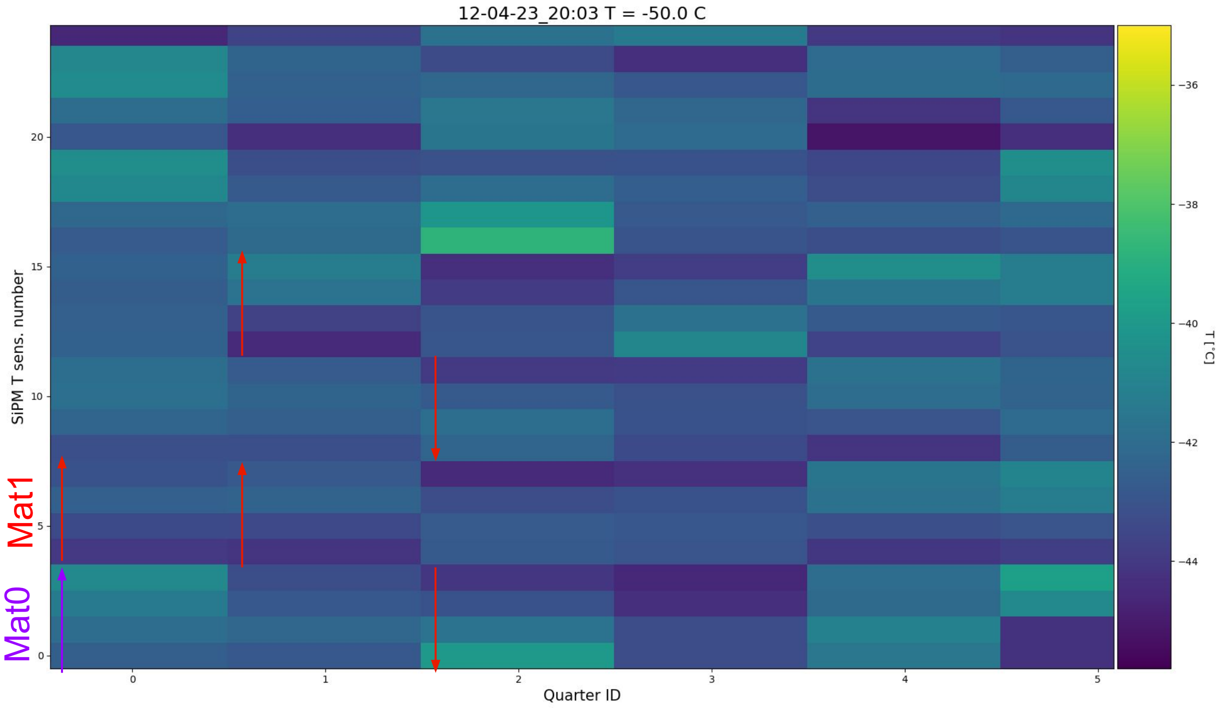
Temperature spread in time over 10 minutes

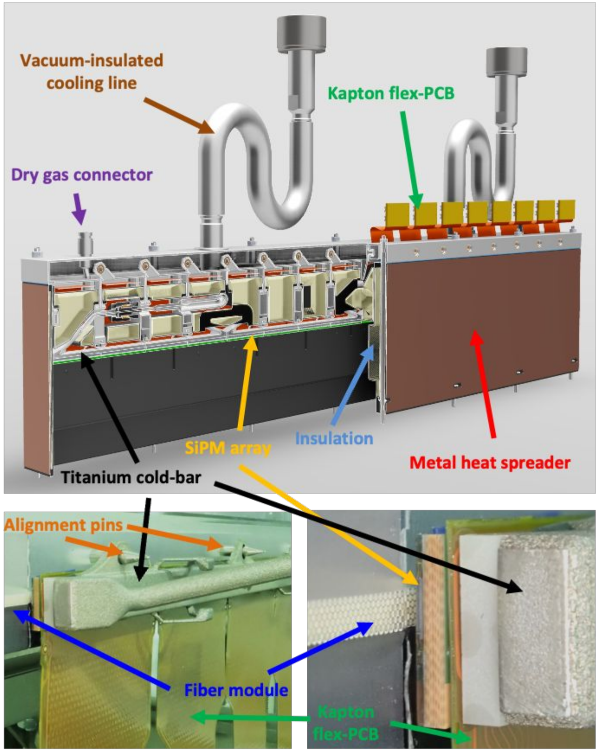


Temperature spread in time over 10 minutes

Temperature substructure?

A pattern can be spotted along SiPMs cooling lines





We compute the bias using the average of these 4 values: spread of 2 °C → to 120 mV spread in VBD

Systematics on DCR

Assumption: nearby mats have experienced the same irradiation → DCR values similar by few %

Relative DCR:

$$\text{rel\_DCR} = \frac{\text{DCR}(\text{Mat}_{n+1}) - \text{DCR}(\text{Mat}_n)}{\text{DCR}(\text{Mat}_n)}$$

Std 15% with larger outliers→ systematic effects due to temp dependencies discussed before

(yet under study)