Cryogenic Characterization of Neutron-Irradiated SiPMs in view of the LHCb Upgrade II

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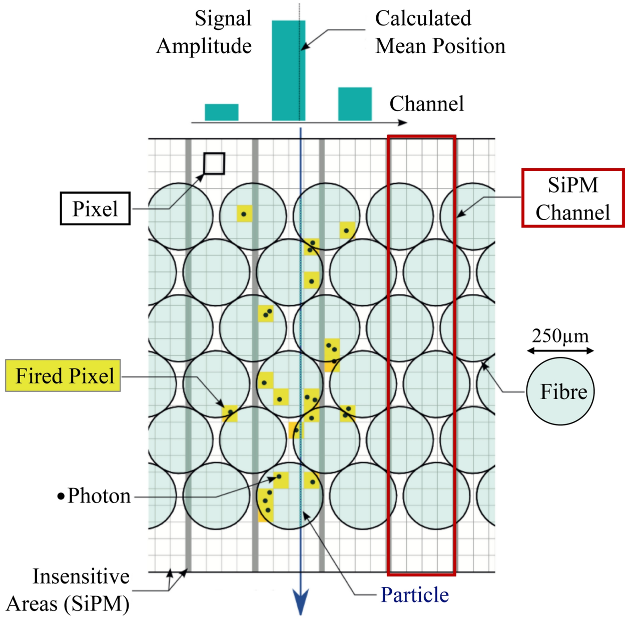
Outlook

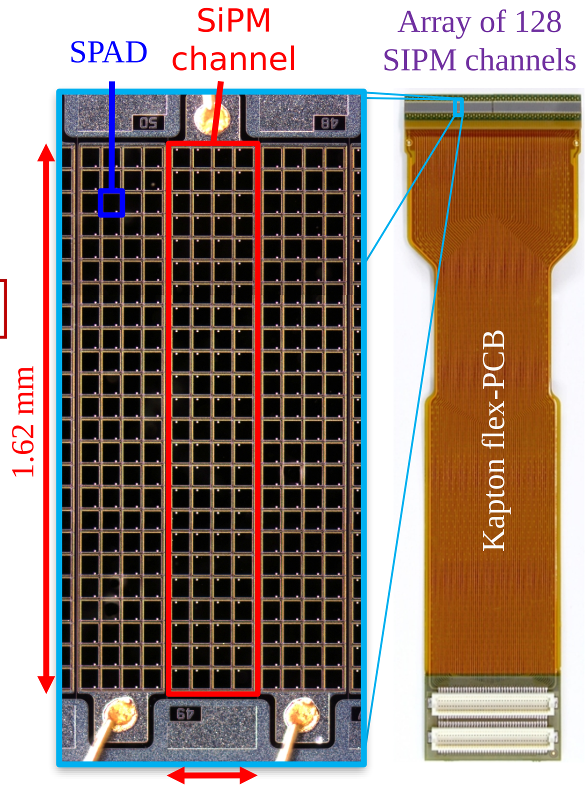
- Introduction and motivation
- Silicon PhotoMultiplier (SiPM) modules under study and neutron irradiation
- Measurement in the cryostat setup
    - Breakdown voltage (V_{bd}) calculation
    - Dark Count Rate (DCR) based on dark current measurements
    - Annealing studies at high temperature (measured only 100 K)
- Summary and next steps

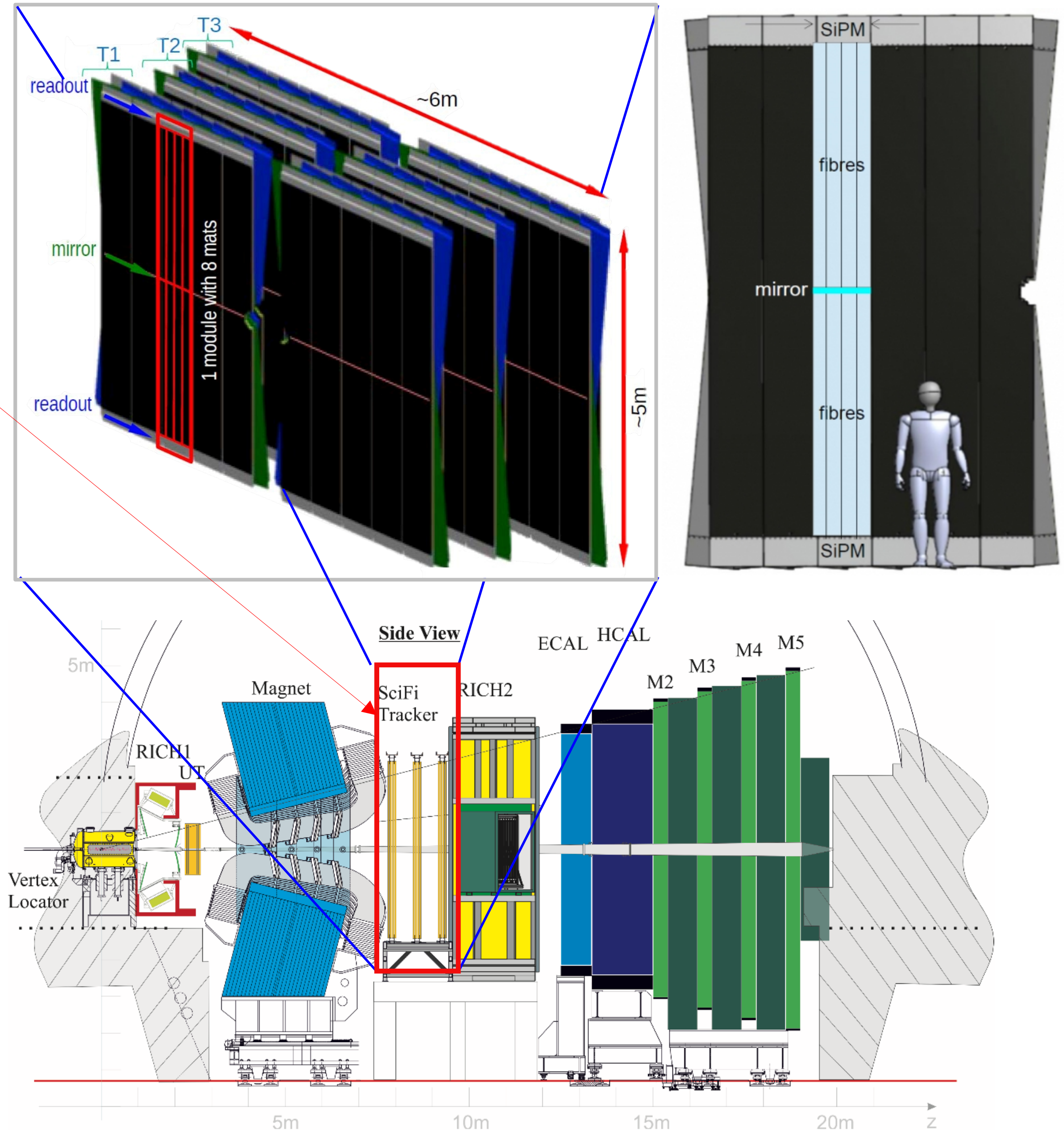
LHCb upgrade I (2019-2021)

The new SciFi detector

- Scintillating Fibre Tracker is installed in the tracking stations located downstream of the LHCb dipole magnet (highlighted in red).
- The scintillation light is recorded with arrays of state-of-the-art multi-channel SiPMs.



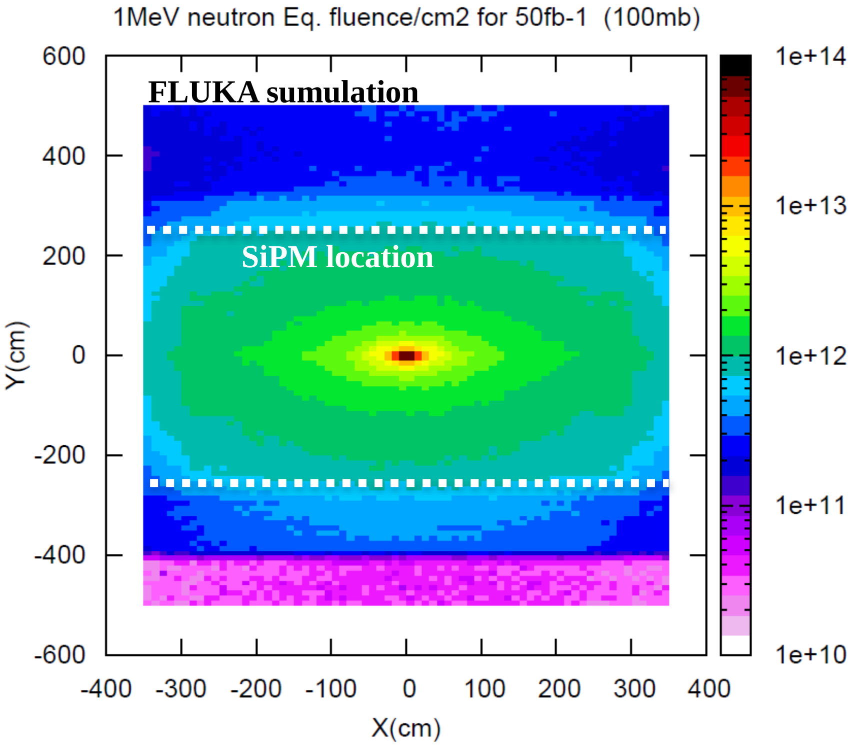


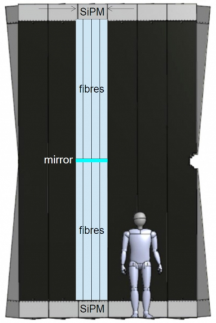


LHCb experiment upgrade (side view)

SiPM challenges for the LHCb Upgrade II (2033)

- More challenging radiation environment
- Mainly dominated by **neutrons:**
  - Neutron radiation expected: **$3\text{x}10^{12}$ n_{eq}/cm^2 (5x Upgrade I)**





Goal: cooling with liquid nitrogen at ~100 K

Dark count rate per SiPM channel (DCR)

Learned from Upgrade I

DCR (not irradiated): 0.04 MHz.

DCR is increasing with neutron radiation.

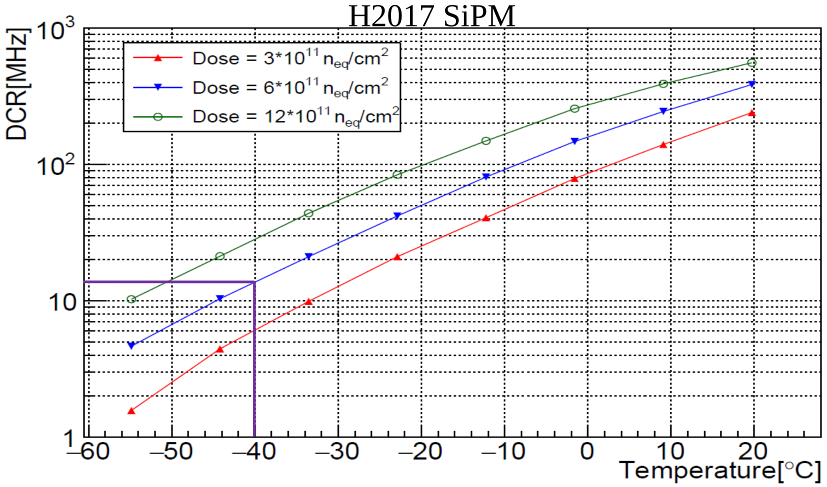
The SiPMs are positioned far from the beam center.

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

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

The DCR can be reduced by cooling the SiPM.

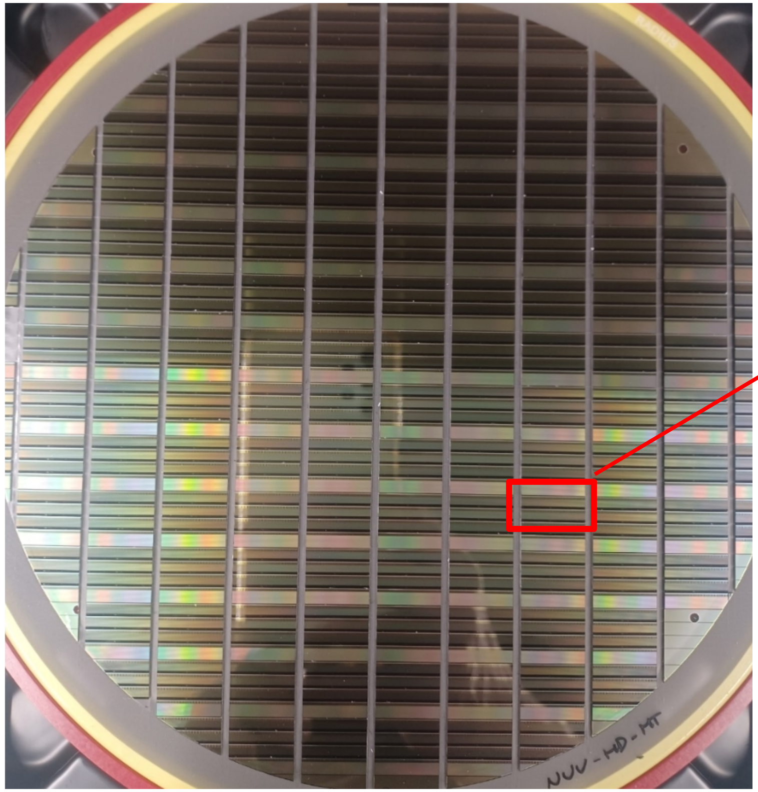
DCR ($6 \cdot 10^{11}$ n_{eq}/cm^2 @ -40 °C): 14 MHz.



1^{st} set of SiPM modules for the testing

Produced by **FBK** in 2022

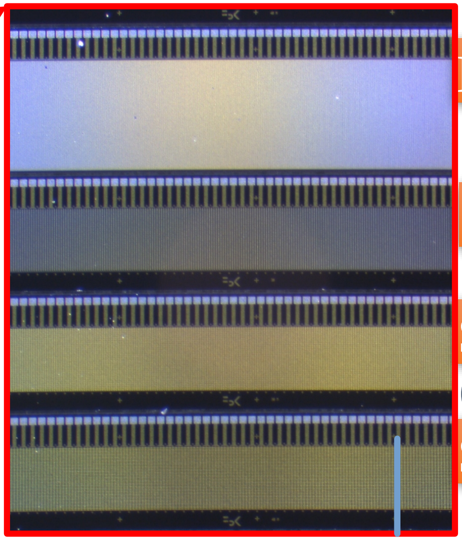
Wafer layout



NUV-HD-MT

Wafer n.	Layout
1	EPFL
4	EPFL
7	EPFL
9	EPFL
11	EPFL

+ Gain -



ECAL
15.65 µm cell, standard pulse shape

SciFi A
31.3 µm cell, standard pulse shape

SciFi B
(M) **31.3 µm cell**, fast pulse shape

SciFi C
41.733 µm cell, fast pulse shape

Also, as a reference: HPK SiPMs (H2017 with 62 µm x 57 µm cell)

Irradiated with **neutrons** in Ljubljana (summer 2023)

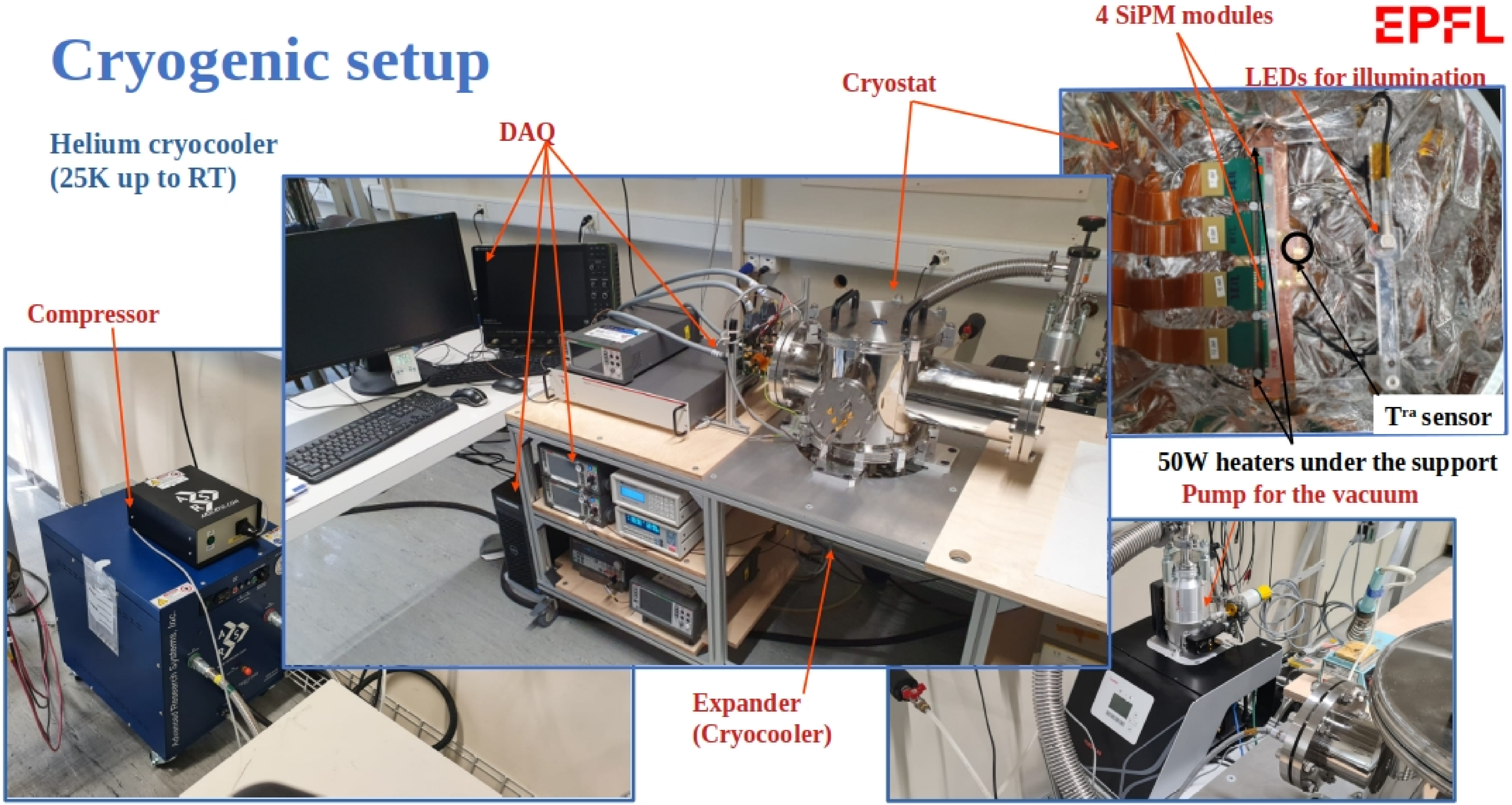
→ $3\text{x}10^{11}\ n_{eq}/cm^2$
→ $1\text{x}10^{12}\ n_{eq}/cm^2$
→ $\mathbf{3x10^{12}\ n_{eq}/cm^2}$
→ $1\text{x}10^{13}\ n_{eq}/cm^2$

After irradiation, a thermal annealing was performed:

→ Detectors kept at 30°C for 2 weeks inside an oven.

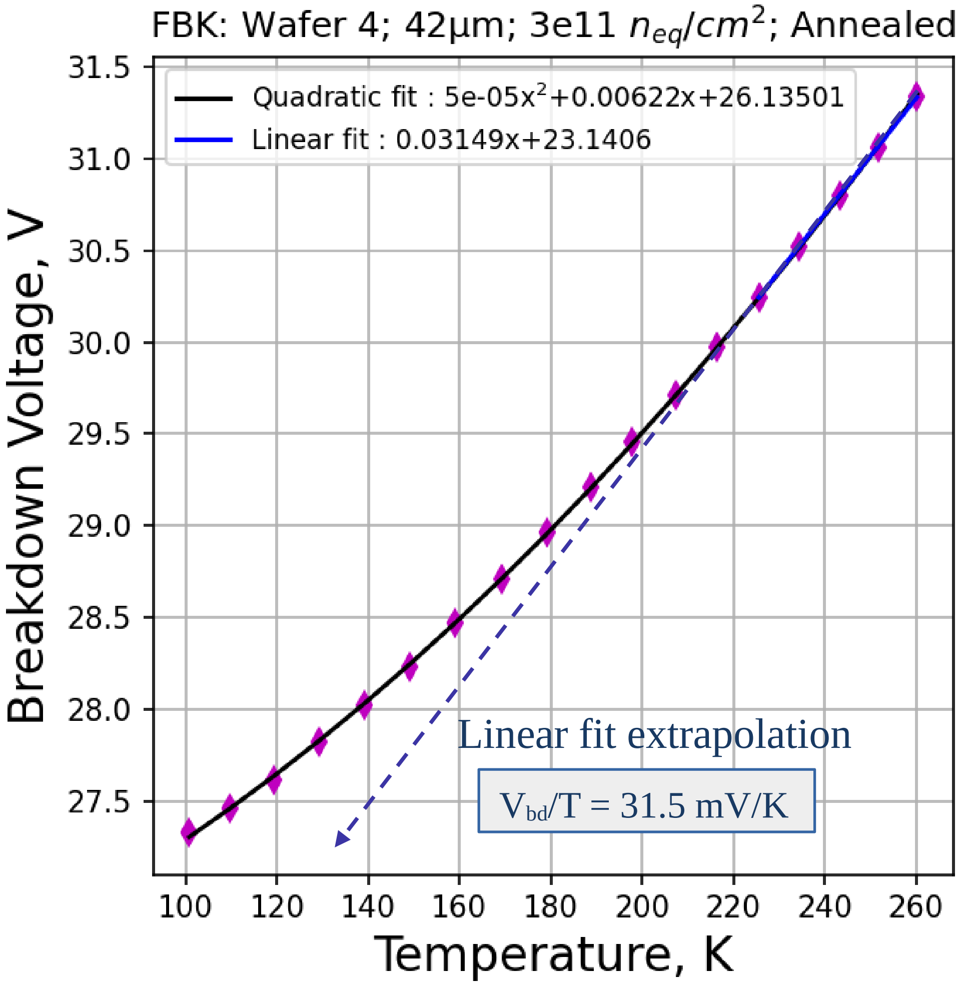
Cryogenic setup

Helium cryocooler
(25K up to RT)



FBK SiPMs: V_{bd} vs temperature

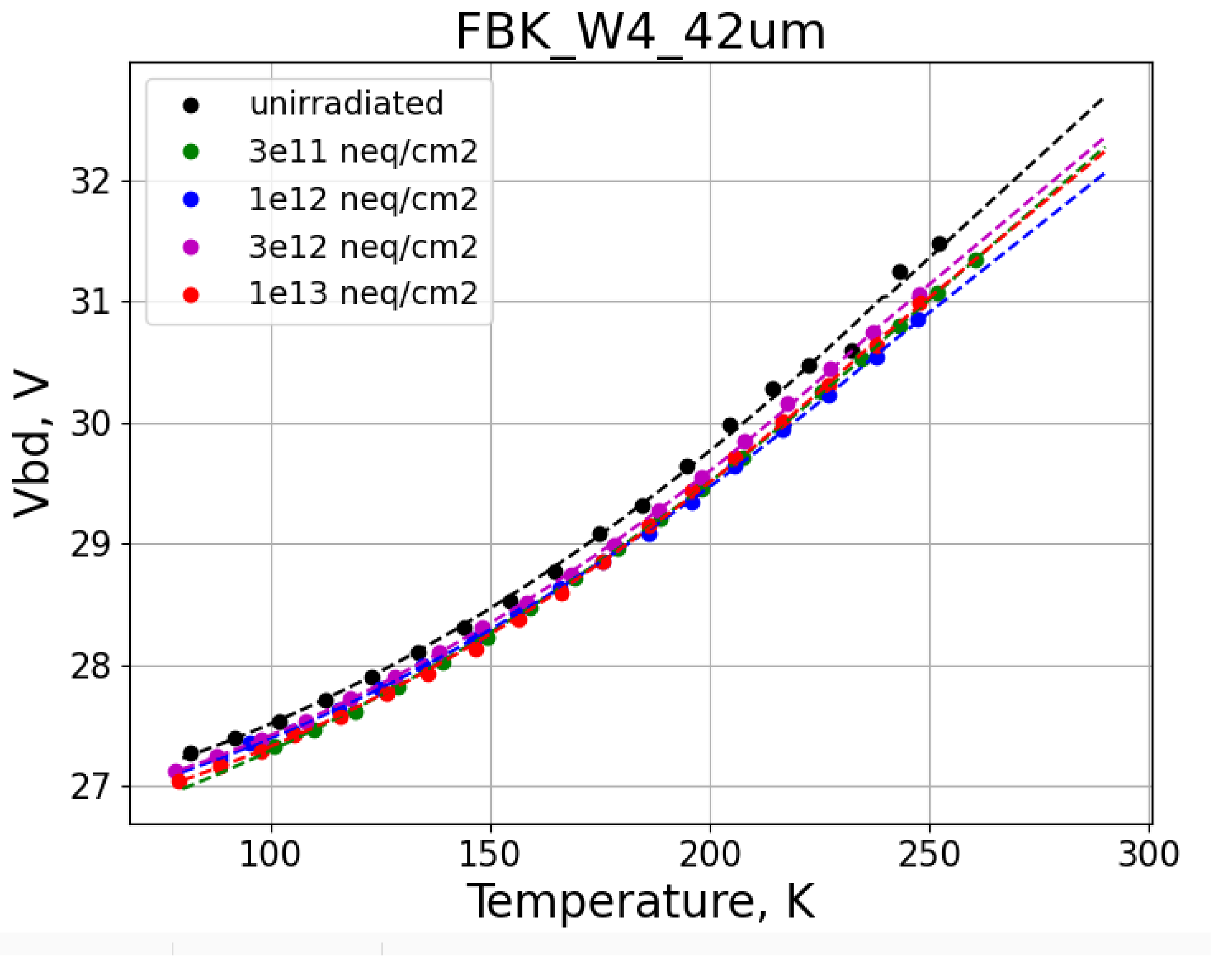
Breakdown voltage as a function of the temperature



Linear fit extrapolation

$V_{bd}/T = 31.5$ mV/K

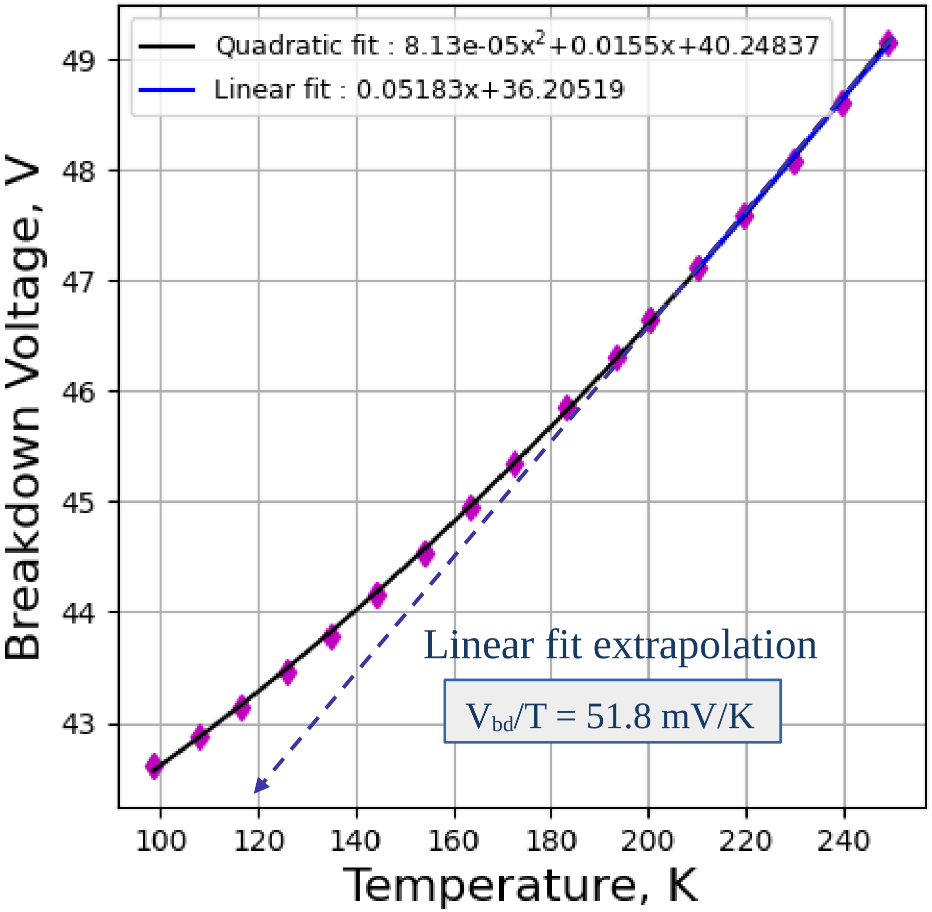
We do not observe any variation with the irradiation fluence (dispersion between different modules ~ 0.5V)



HPK SiPMs: V_{bd} vs temperature

Breakdown voltage as a function of the temperature

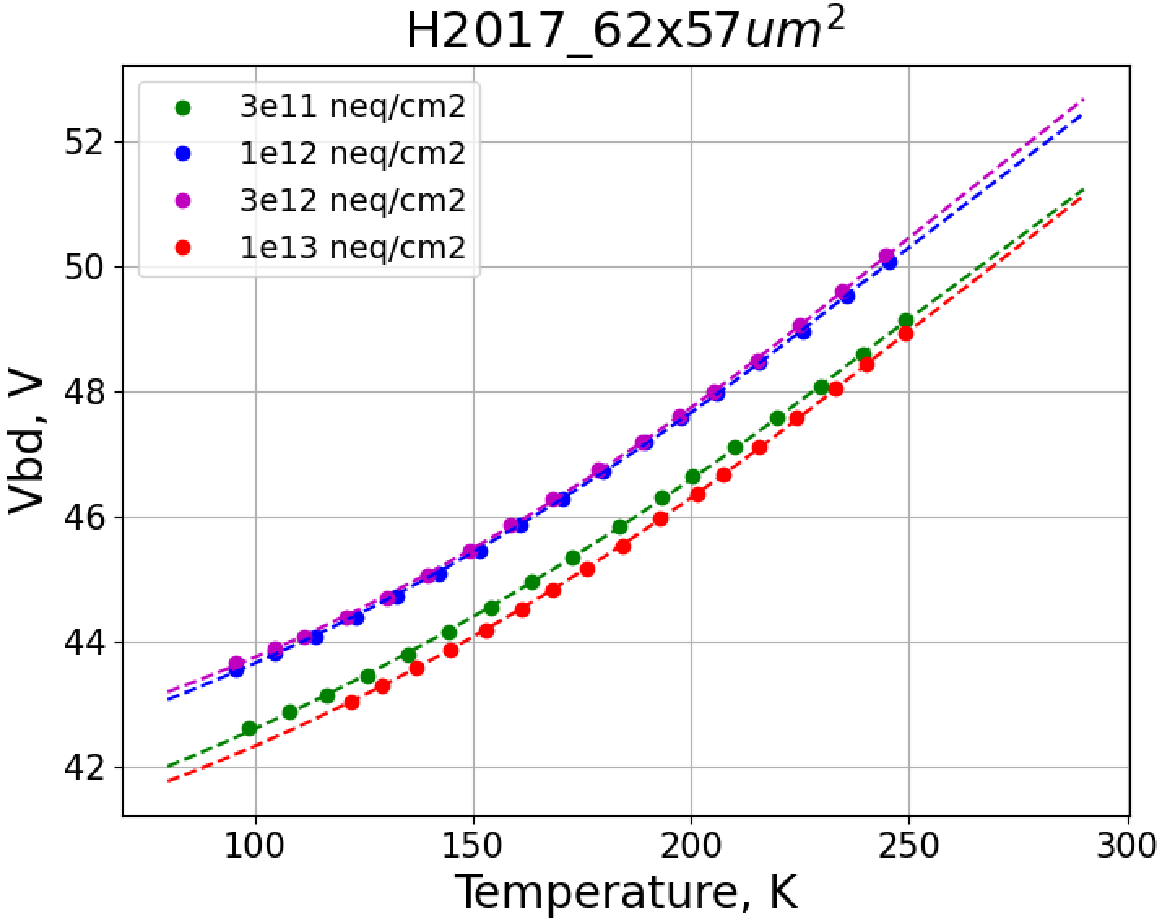
H2017: 3e11 n_{eq}/cm^2; Annealed



Linear fit extrapolation

V_{bd}/T = 51.8 mV/K

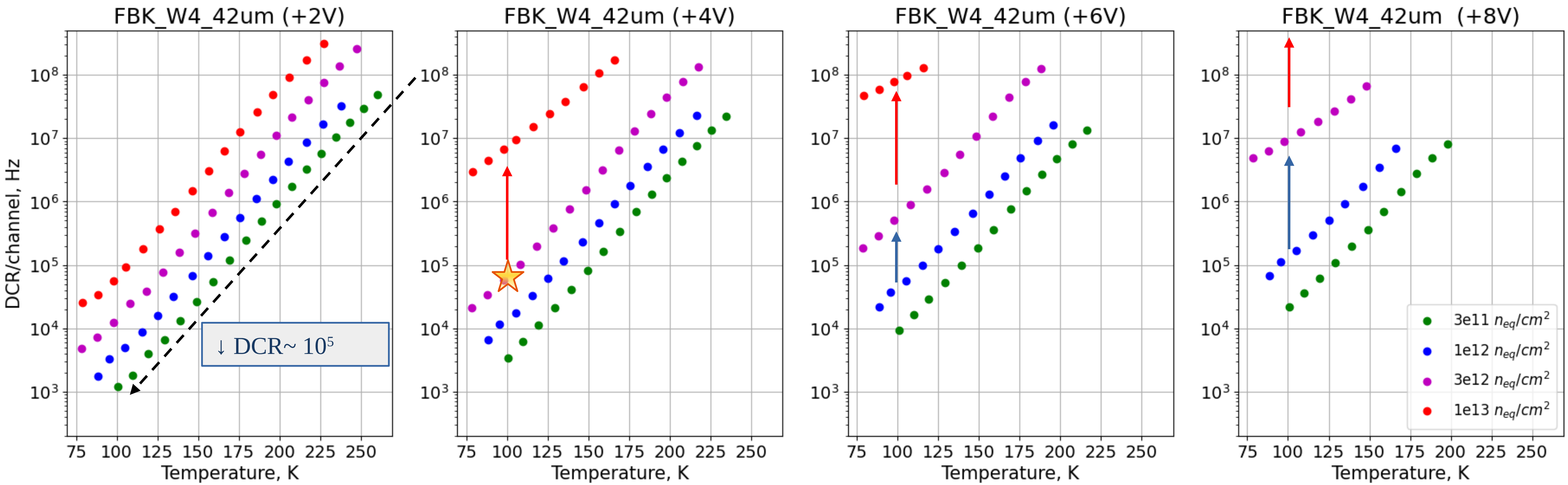
We do not observe any variation with the irradiation fluence (bigger dispersion between different modules ~ 1.0V)



FBK SiPM 42 um: DCR

$$DCR = \frac{I_{dark}}{e \times Gain}$$

DCR as a function of the temperature for different over-voltages:



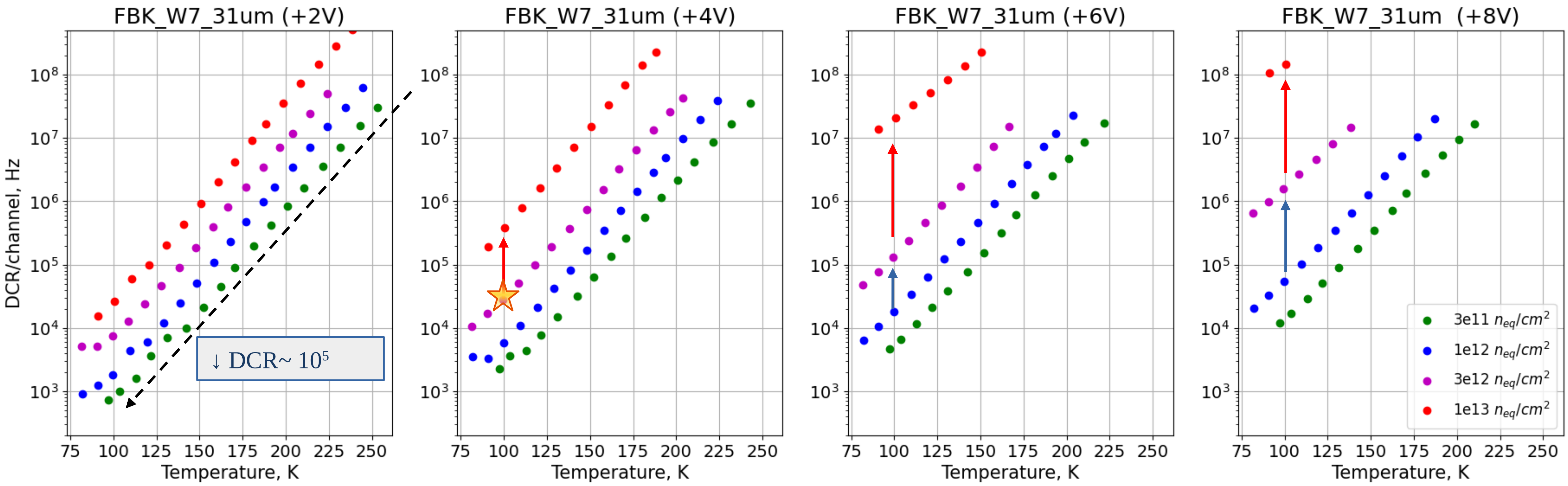
- DCR decreases with cooling, ~10^5 from room temperature down to 100K ($K_{1/2}$ = 10.1 K slope).
- DCR increase proportional with fluence (NIEL hypothesis) only up to ~1×10^{12} n_{eq}/cm^2 .

☆ End-life expected working conditions (100K and 4V: ~5×10^4 Hz/ch)

FBK SiPM 31 um: DCR

$$DCR = \frac{I_{dark}}{e \times Gain}$$

DCR as a function of the temperature for different over-voltages:



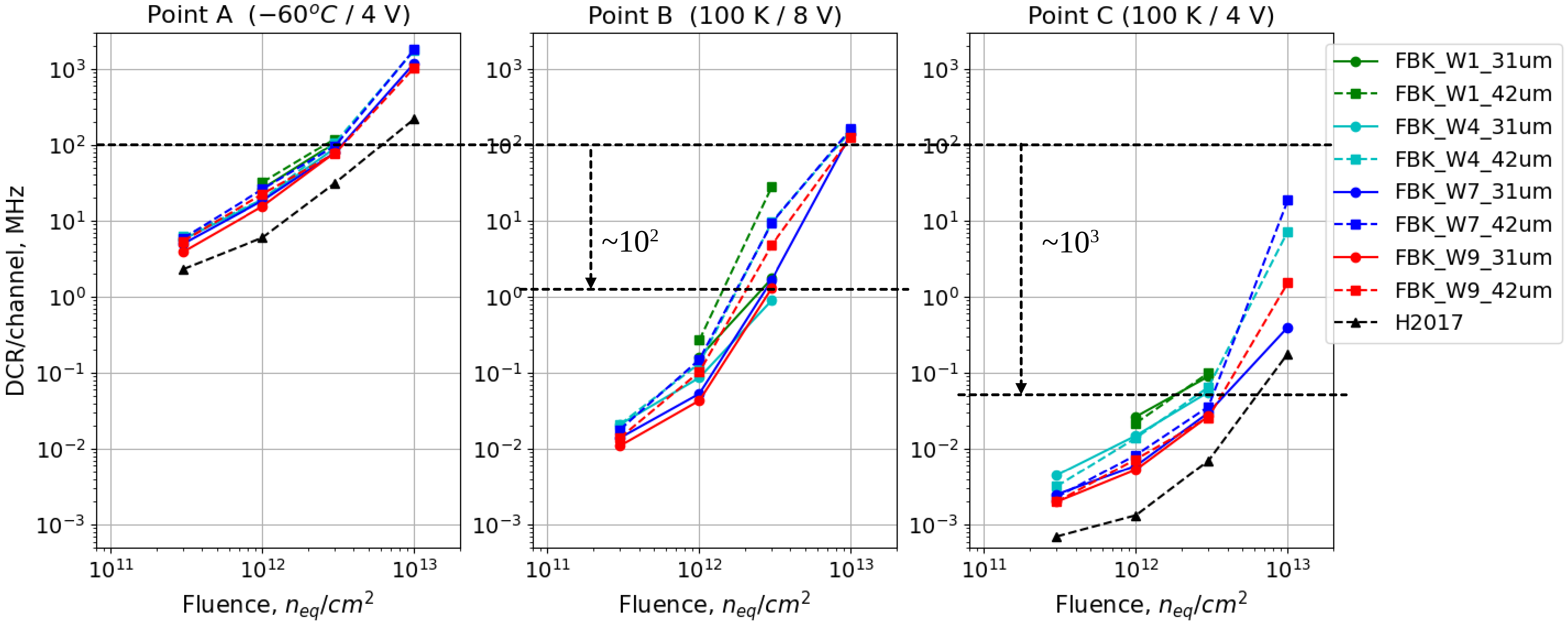
- Same as for 42µm pixel size but NIEL hypothesis valid up to ~3×10^{12} n_{eq}/cm^2 .
- For the same over-voltage shows lower DCR (smaller pixel size == lower gain).

☆ End-life expected working conditions (100K and 4V: ~$3\text{x}10^4$ Hz/ch)

Comparison all SiPMs

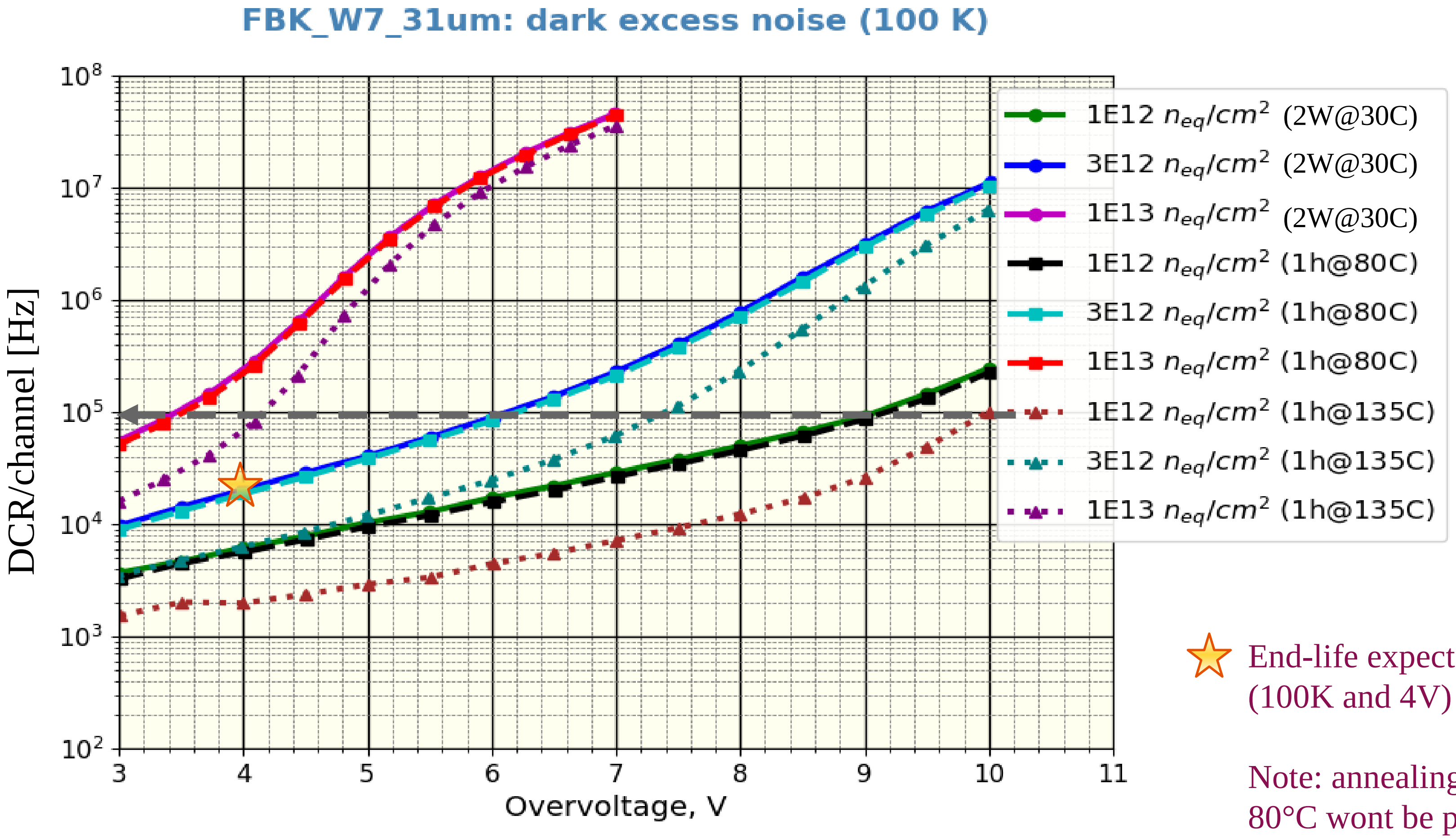
Benchmark points

A	Upgrade I (FBK &H2017)	@ -60°C and 4V
B	Upgrade II (FBK)	@ 100 K and 8V
C	Upgrade II (FBK & H2017)	@100 K and 4V



- Best FBK performance in terms of DCR is W9_31um (lower gain), while the worse is W1_42um (highest gain)
- H2017 has lower DCR than the latest technology from FBK but also large increase above 3×10^{12} n_{eq}/cm^2
- Smaller pixels can be operated at higher fluence!

FBK SiPM 31 um: Annealing



☆ End-life expected working conditions (100K and 4V)

Note: annealing at higher temperatures than 80°C wont be possible in the experiment.

- Initial annealing after irradiation of 2weeks@30°C.
- Further annealing at 80°C does not reduce the DCR further.
- Only annealing at high temperature (135°C) is reducing DCR.

Summary:

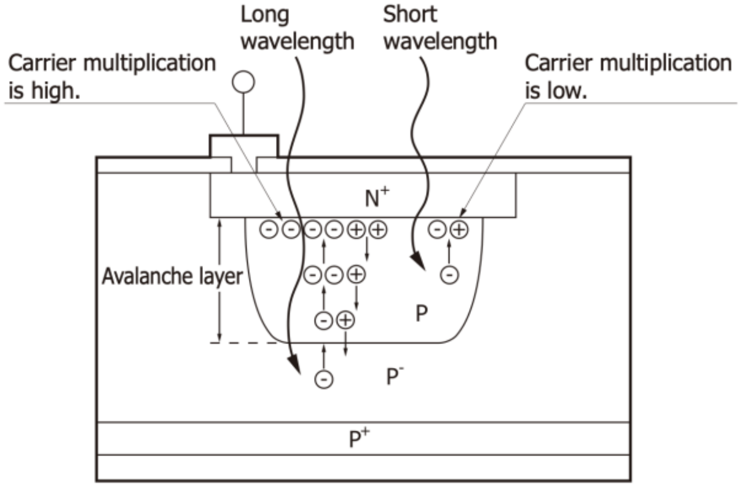
- Breakdown voltage as a function of the temperature not linear (visible at cryogenic temperatures)
- DCR reduced by ~10^3 for operation (100 K and 4 V) compared to Upgrade I operation (-60°C)
  - **This leads indeed to an almost noise free detector!**
- Large DCR increase beyond fluences of ~1×10^{12} n_{eq}/cm^2
- Small pixel size (low gain) and low ΔV (low gain) are better at high fluences
- Annealing at high temperatures ($> 80^{o}$C) helps to reduce DCR
  - For LHCb Upgrade II only possible low temperature annealing ($< 80^{o}$C)

Next steps:

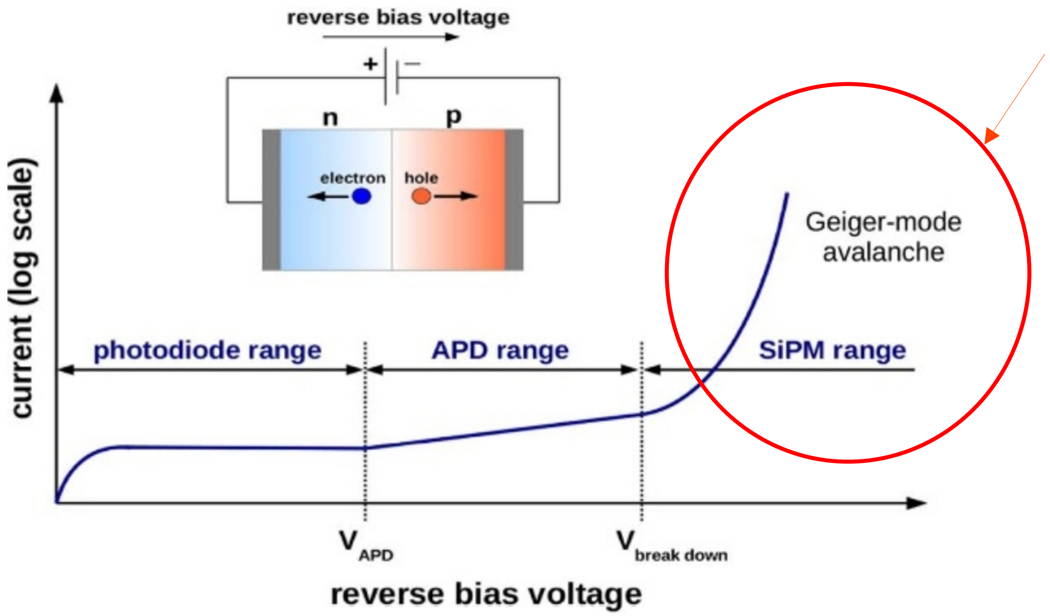
- A new irradiation campaign is undergoing
  - New H2024 SiPM modules received
  - Single FBK2022 cells to investigate the origin of excess DCR
- New FBK production:
  - Targeting better performance after irradiation: low DCR (low gain)

Back up

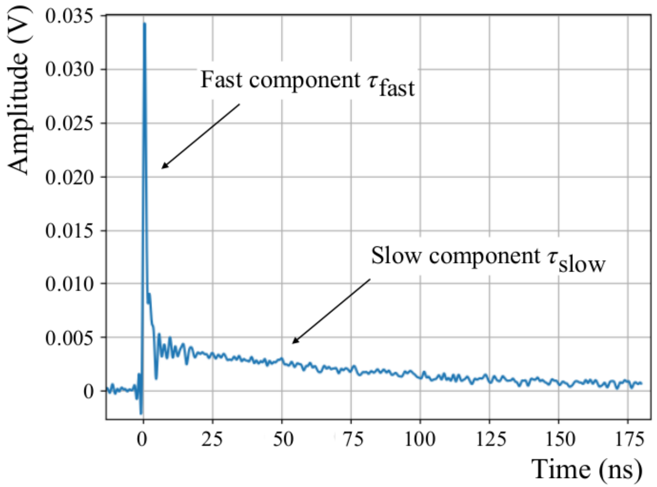
Single Photon Avalanche Diode (SPAD)



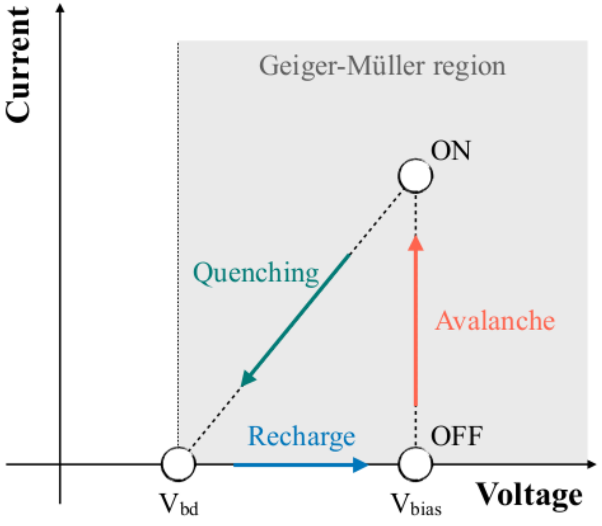
SPAD schematic cross section (not to scale)



SPAD working regime



Signal shape example



Quenching resistor needed to stop the avalanche breakdown

SiPM modules irradiated at Ljubljana

Irradiated with **neutrons** in Ljubljana (summer 2023)

→ $3x10^{11}\ n_{eq}/cm^2$, $1x10^{12}\ n_{eq}/cm^2$, **$3x10^{12}\ n_{eq}/cm^2$** and $1x10^{13}\ n_{eq}/cm^2$

After irradiation, an annealing of 2 weeks at 30^{o}C was performed

		Number of detectors irradiated				
		Fluence				
		A	B	C (ref)	D	
Type	Wafer #	1.00E+13	3.00E+12	1.00E+12	3.00E+11	Total
16	1	0	0	0	0	0
	4	1	1	1	1	4
	7	0	0	0	0	0
	9	1	1	1	1	4
	11	0	0	0	0	0
31	1	1	1	2	1	5
	4	1	1	2	1	5
	7	1	1	2	1	5
	9	1	1	2	1	5
	11	1	1	2	1	5
31m	1	0	0	0	0	0
	4	1	1	1	1	4
	7	1	1	1	1	4
	9	1	1	1	1	4
	11	1	1	1	1	4
42	1	1	1	2	1	5
	4	1	1	2	1	5
	7	1	1	2	1	5
	9	1	1	2	1	5
	11	1	1	2	1	5
H2017		1	1	1	1	4
Total		17	17	27	17	78

Detector #			
Fluence			
A	B	REF	D
1.00E+13	3.00E+12	1.00E+12	3.00E+11
#1	#2	#4	#5
#1	#2	#3	#5
#5	#6	#7, #8	#9
#1	#2	#3, #4	#5
#1	#2	#3, #4	#5
#1	#2	#4, #5	#6
#1	#2	#3, #5	#6
#1	#2	#3	#4
#1	#2	#5	#6
#2	#3	#4	#5
#1	#2	#3	#4
#2	#3	#5, #6	#8
#2	#3	#6, #8	#9
#1	#2	#3, #5	#6
#1	#2	#3., #4	#5
#1	#2	#3., #4	#5
#169	#205	#563	#1149

One set of H2017 SiPM modules were also included as a reference

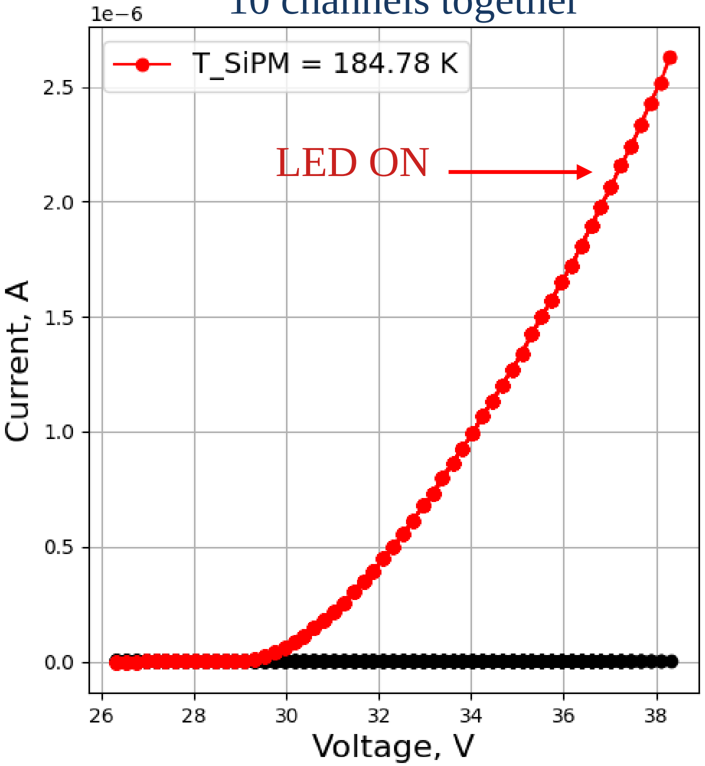
Measurement campaign: V_{bd}

Extracting the breakdown voltage

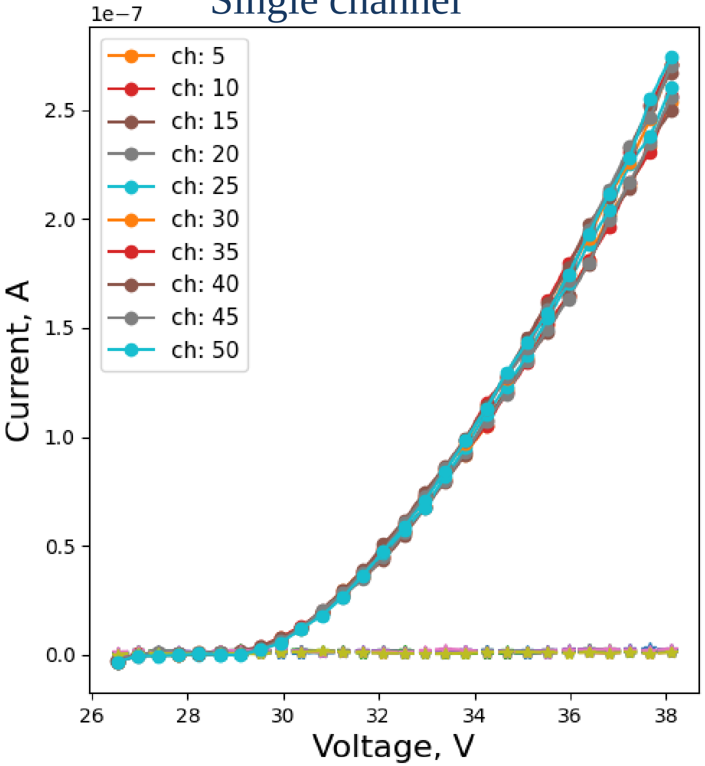
Method of Inverse Logarithmic Derivative (ILD)

E.g.: FBK_W4_42um (unirradiated)

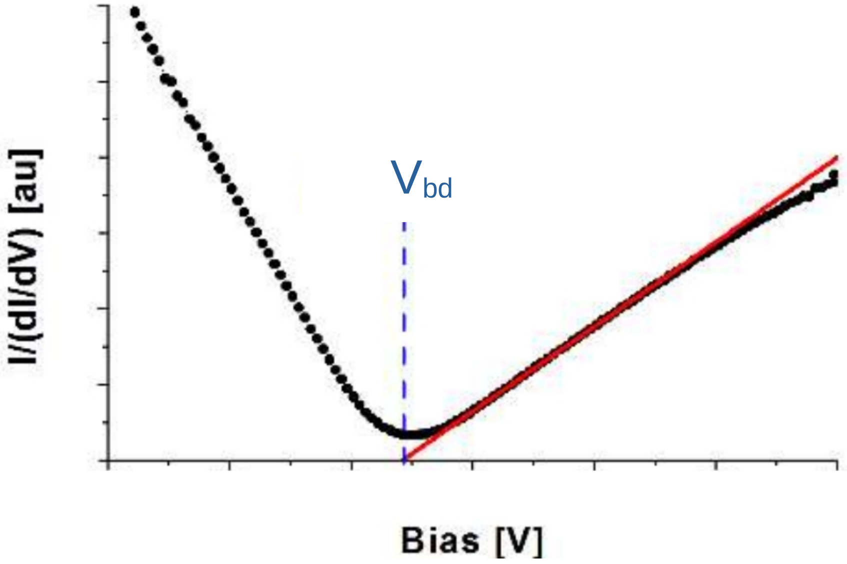
10 channels together



Single channel



$$ILD = \left(\frac{d\ln[I(V)]}{dV}\right)^{-1} \equiv \left[\frac{1}{I}\cdot\frac{dI(V)}{dV}\right]^{-1}$$



Quenching resistor and recovery time

FBK_W4_31um_028 (unirradiated)