Cryogenic operation of neutron-irradiated SiPM arrays from FBK and Hamamatsu

Esteban Currás Rivera

Laboratoire de Physique des Hautes Energies

École Polytechnique Fédérale de Lausanne

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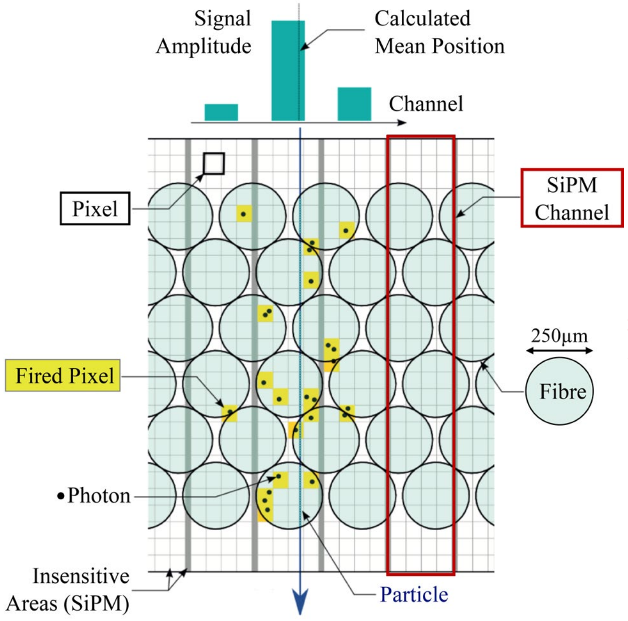
Outlook

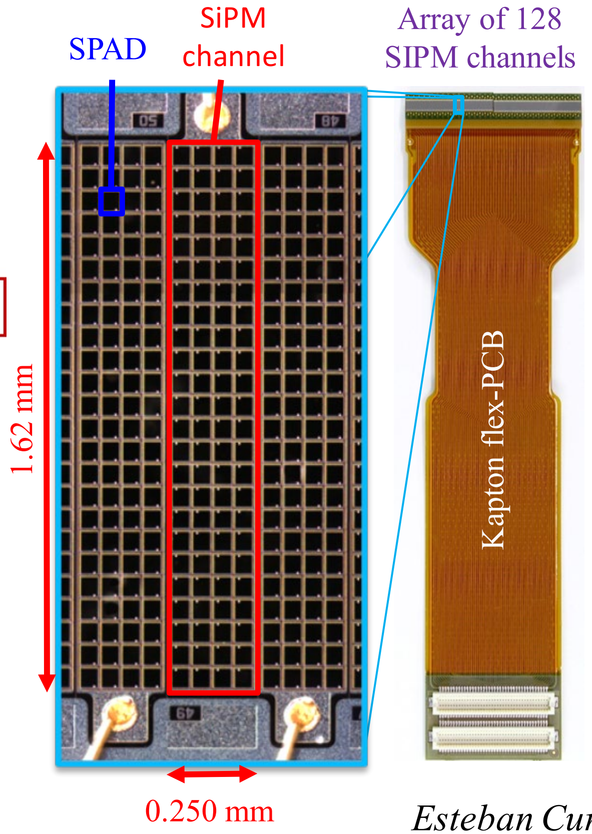
- Introduction and motivation
- Silicon PhotoMultiplier (SiPM) modules under study and neutron irradiation
- Measurement in the cryostat setup
  - Breakdown voltage (V_{bd}) → irradiated
  - Quenching resistor (R_q) and recovery time (T_r) → unirradiated
  - Photo Detection Efficiency (PDE) → unirradiated
  - Gain (G) and Direct Crosstalk Probability (DCP) → unirradiated
  - Dark Count Rate (DCR) based on dark current measurements → irradiated
  - Signal correlated noise (measured only at 100 K) → irradiated
  - Annealing studies at high temperature (measured only at 100 K) → irradiated
- Summary and conclusions

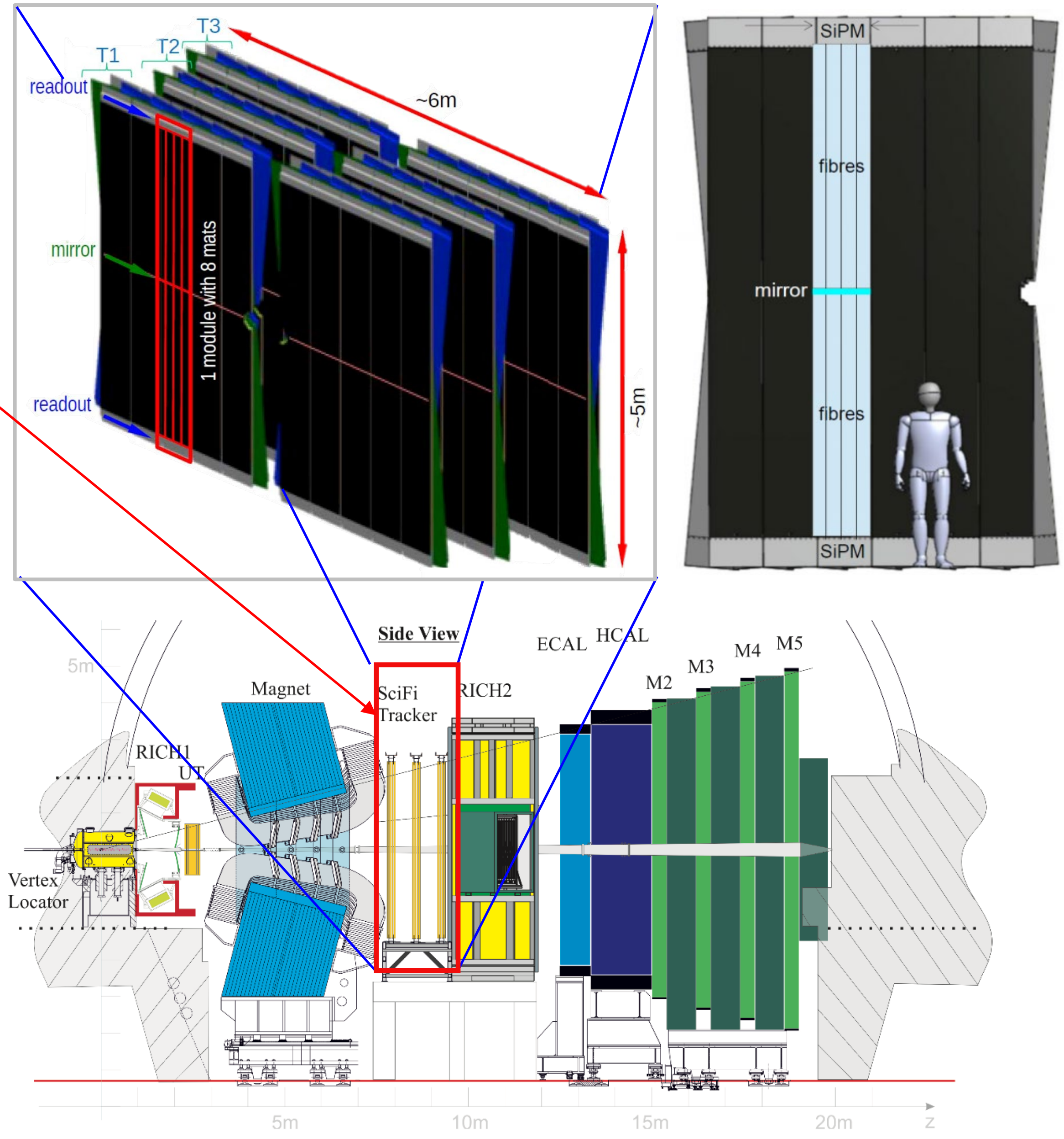
LHCb upgrade I (2019-2021)

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 multi-channel SiPMs



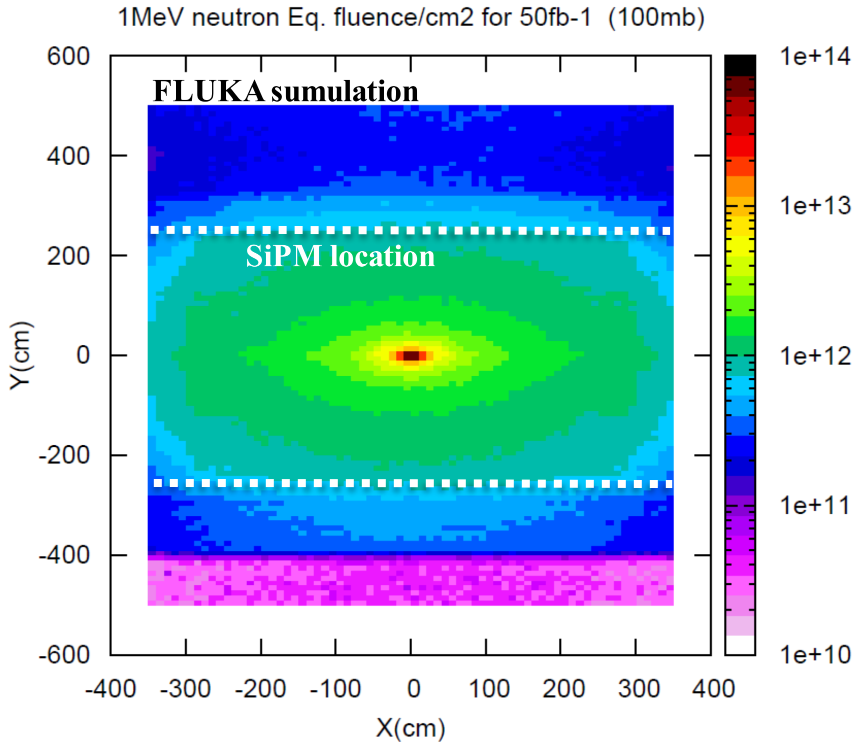


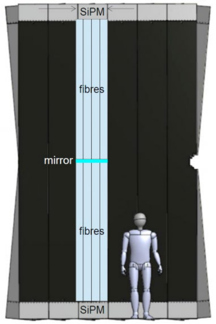


LHCb experiment upgrade (side view)

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.

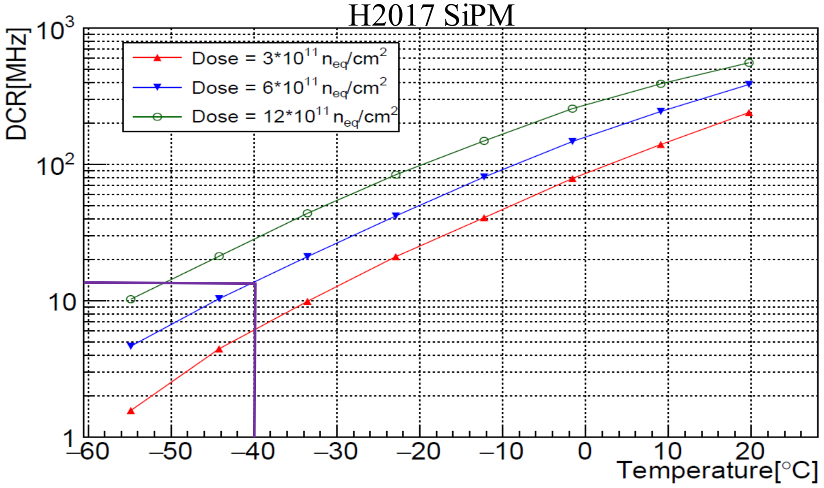
The SiPMs are positioned far from the beam center.

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.

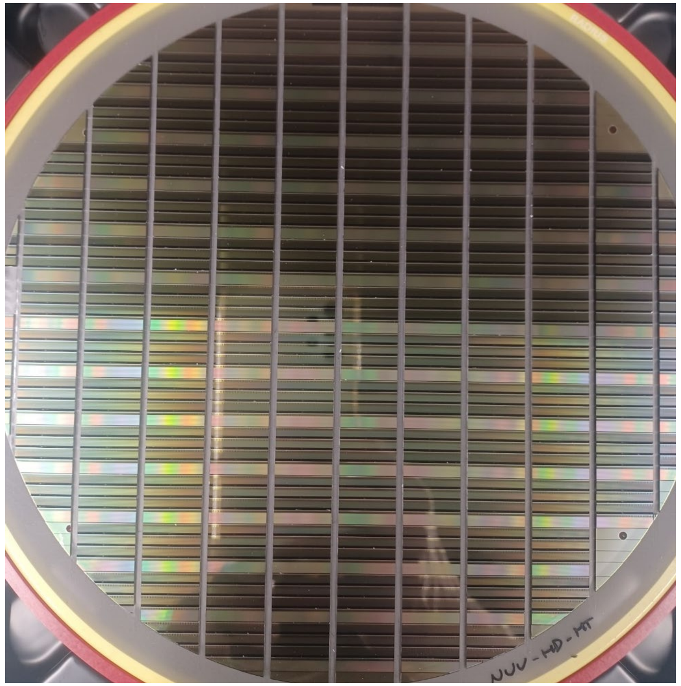
DCR ($6 \cdot 10^{11}$ n_{eq}/cm^2 @ -40 °C): 14 MHz.



1st set of SiPM modules for the testing

Produced by **FBK** in 2022

Wafer layout



NUV-HD-MT

\+

Gain

\-

Wafer n.	Layout	Epi Thickness	DI energy	DI dose	Note	Note
1	EPFL	Thin	LF	D3	Cryo	Metal In Trench
4	EPFL	Thin	LF	D2	Cryo	Metal In Trench
7	EPFL	Thin	ULF	D3	Cryo	Metal In Trench
9	EPFL	Thin	ULF	D2	Cryo	Metal In Trench
11	EPFL	Thin	ULF	D1	Cryo	Metal In Trench

This study will focused on:

- FBK2022 modules of two different pixel size → **31.3x31.3 μm² (FBK 31 um)** / **41.7x41.7 μm² (FBK 42 um)**
- HPK2017 modules with a pixel size of → **62.0x57.0 μm² (H2017)**

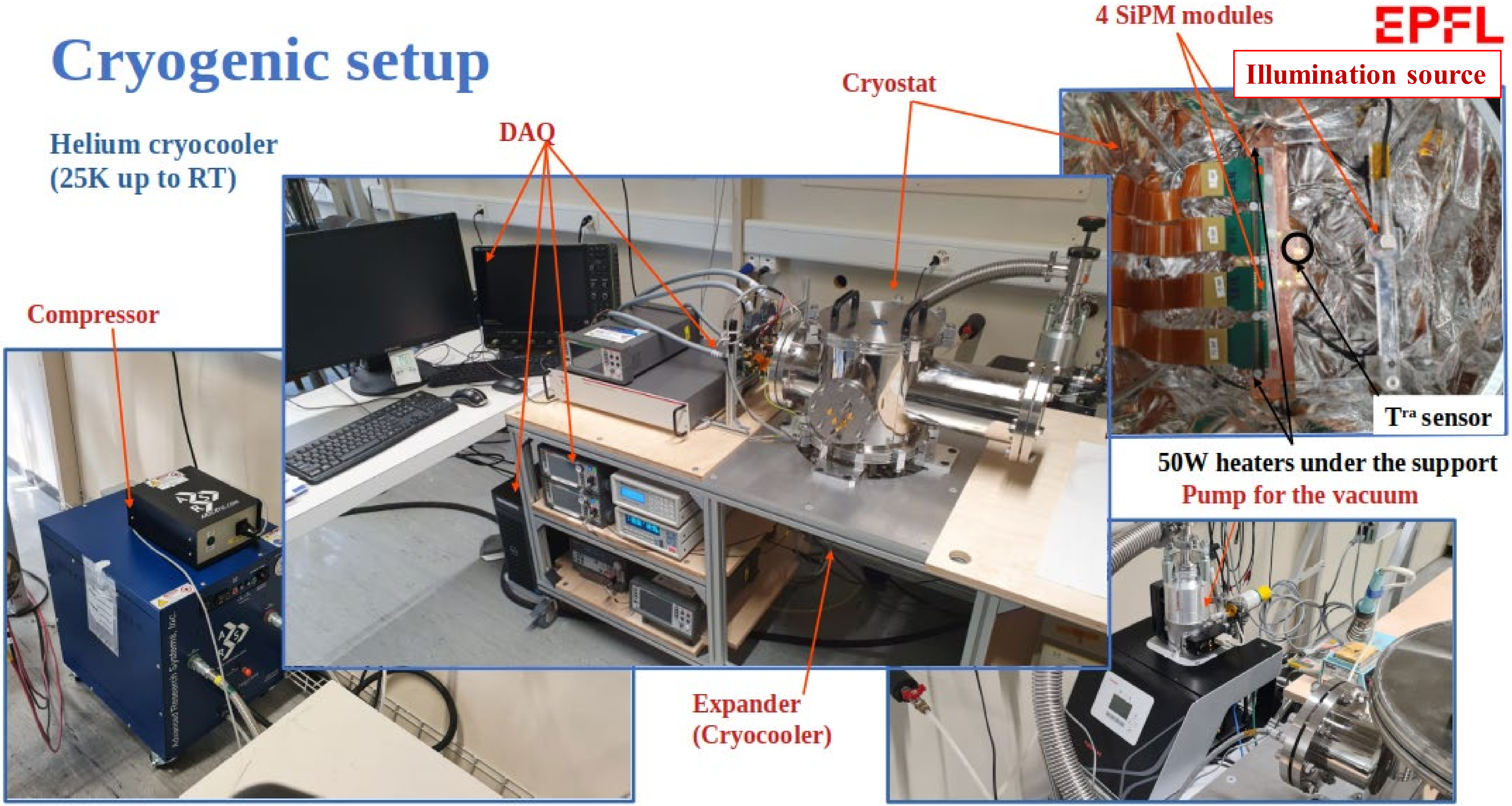
Irradiated with **neutrons** in Ljubljana (2023)

- $3\text{x}10^{11}\ n_{eq}/cm^2$
- $1\text{x}10^{12}\ n_{eq}/cm^2$
- **$3\text{x}10^{12}\ n_{eq}/cm^2$** (nominal fluence)
- $1\text{x}10^{13}\ n_{eq}/cm^2$

After irradiation, a thermal **annealing of 2 weeks at 30°C** was performed

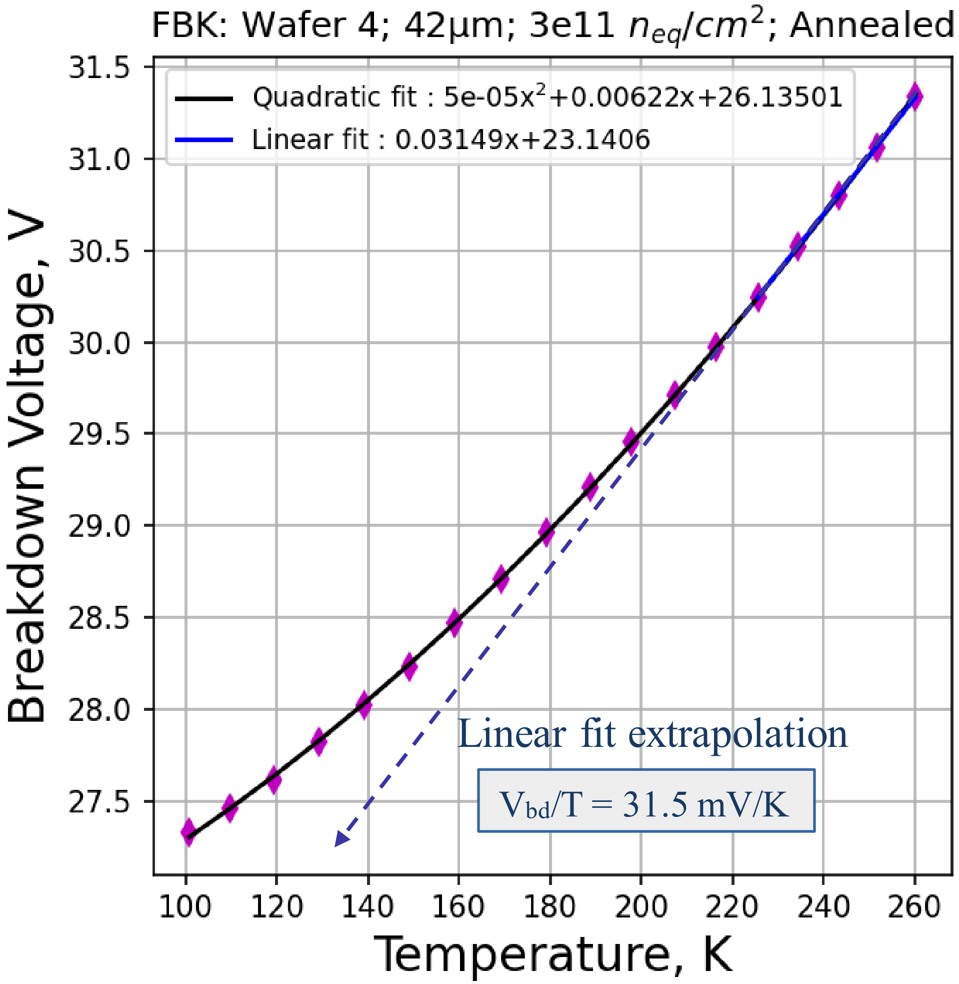
Cryogenic setup

Helium cryocooler
(25K up to RT)



FBK SiPMs: V_{bd} vs temperature

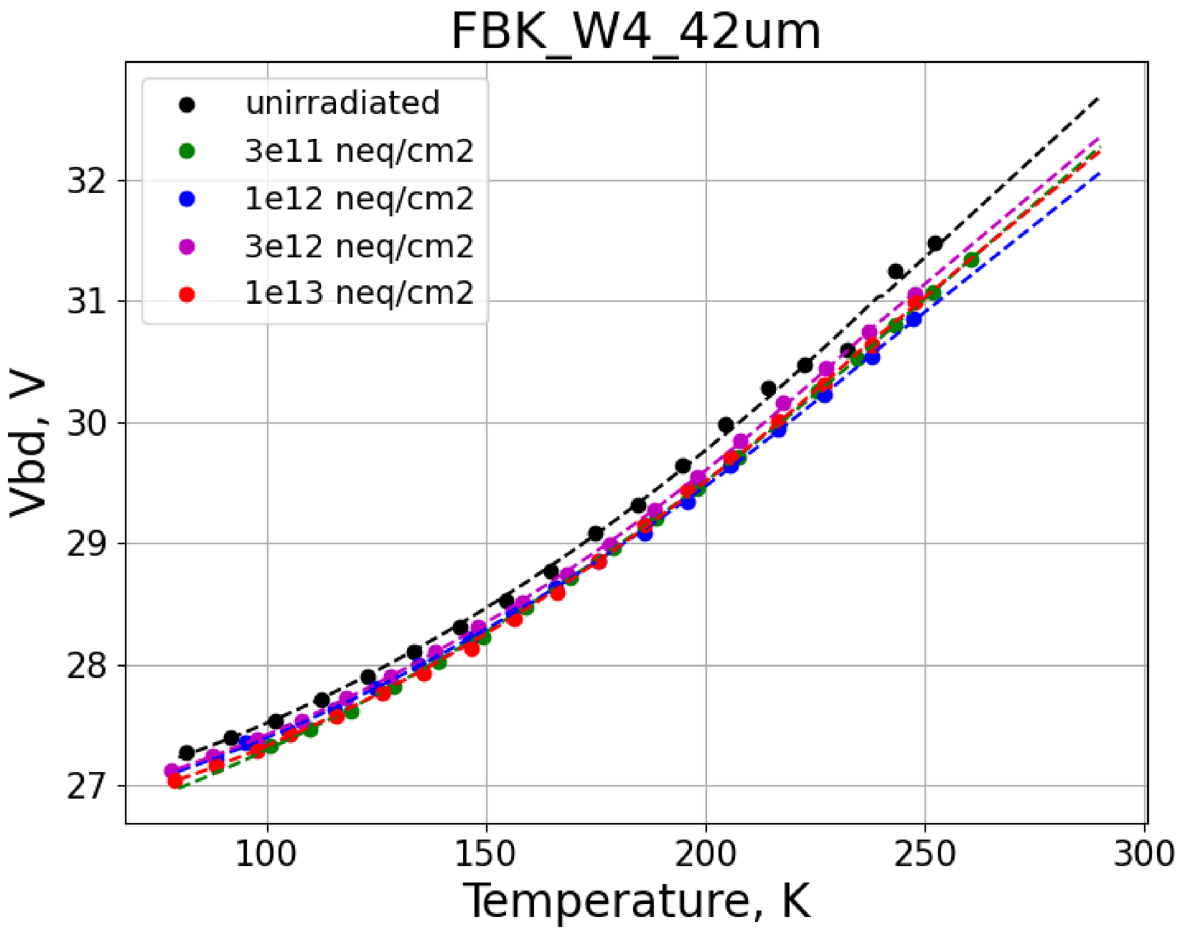
Breakdown voltage as a function of the temperature



Linear fit extrapolation

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

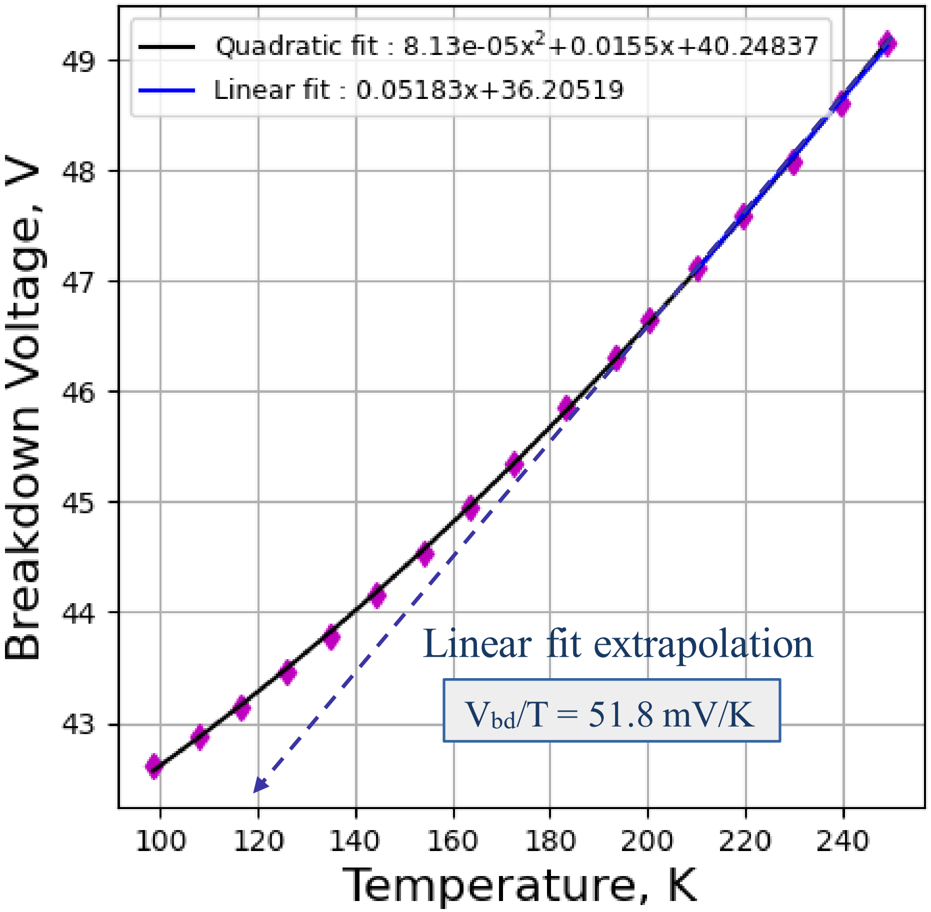
We do not observe any variation with the irradiation fluence (dispersion between different modules ~ 0.5V)



HPK SiPMs: V_{bd} vs temperature

Breakdown voltage as a function of the temperature

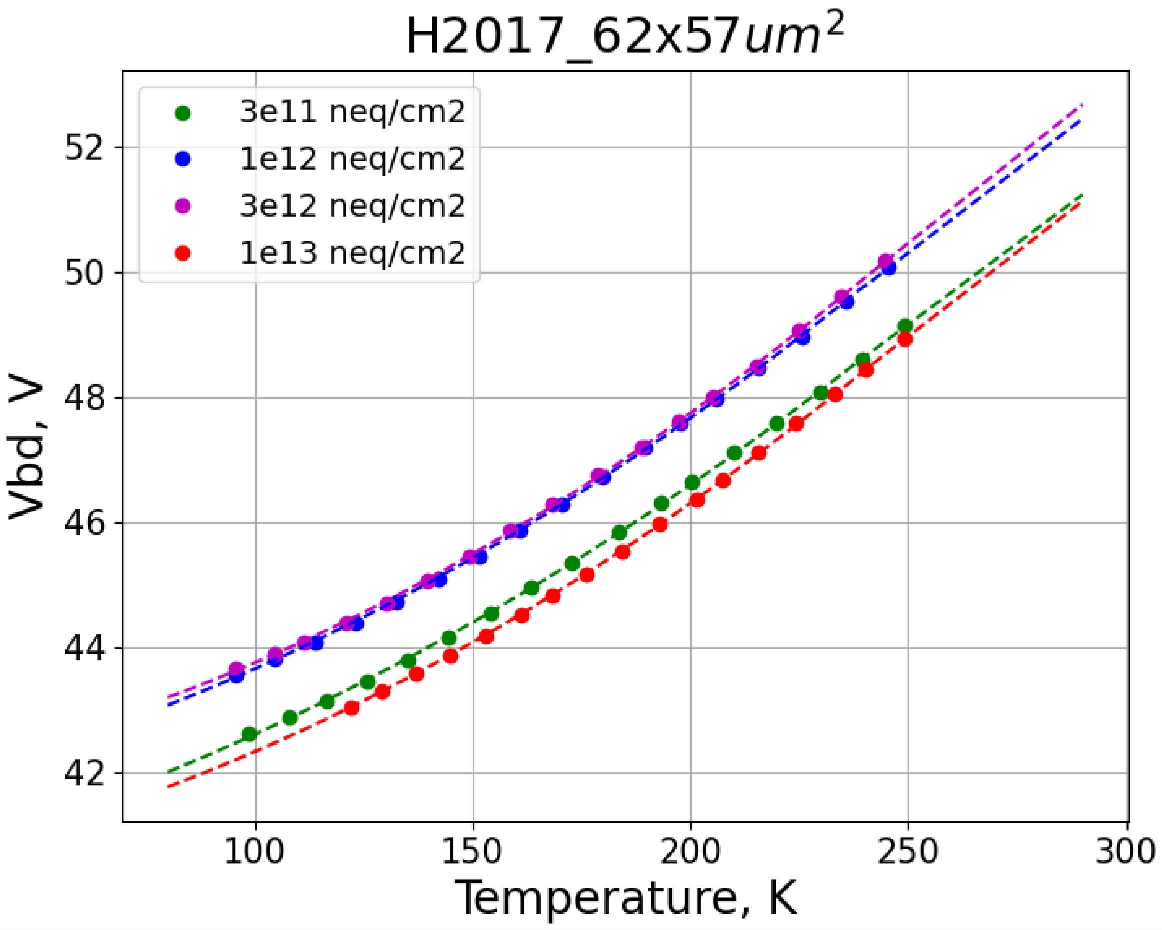
H2017: 3e11 n_{eq}/cm^2; Annealed



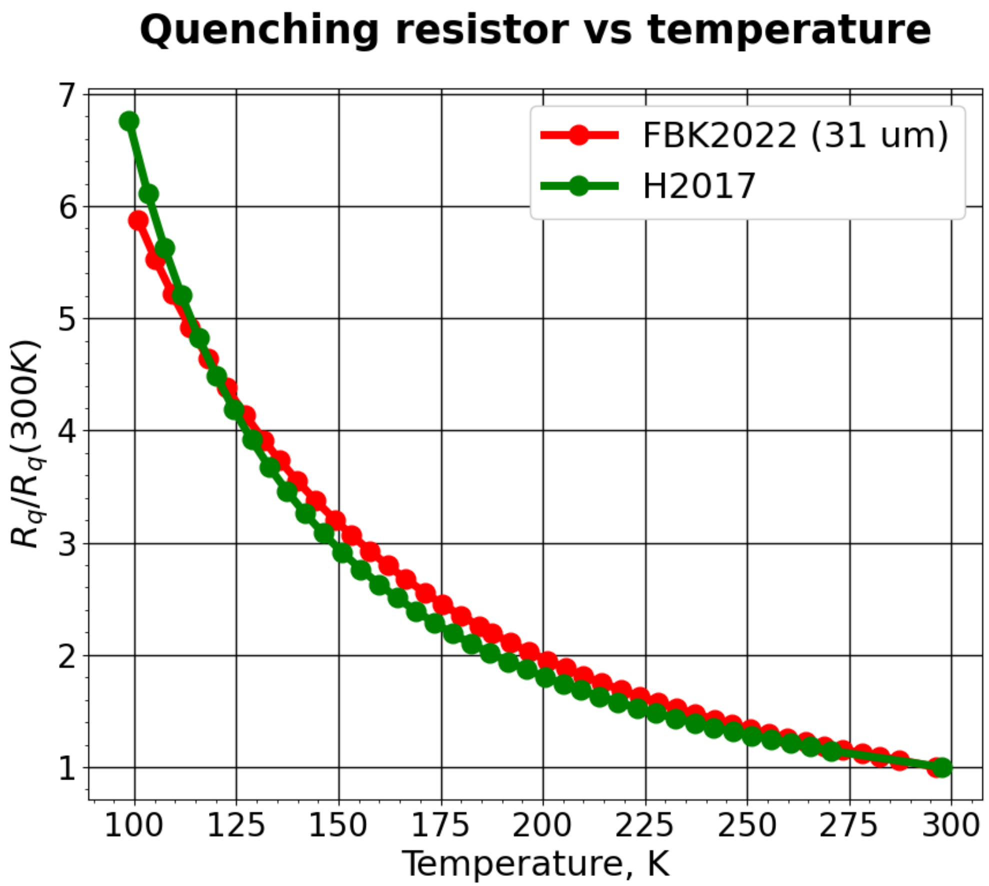
Linear fit extrapolation

$V_{bd}/T = 51.8$ mV/K

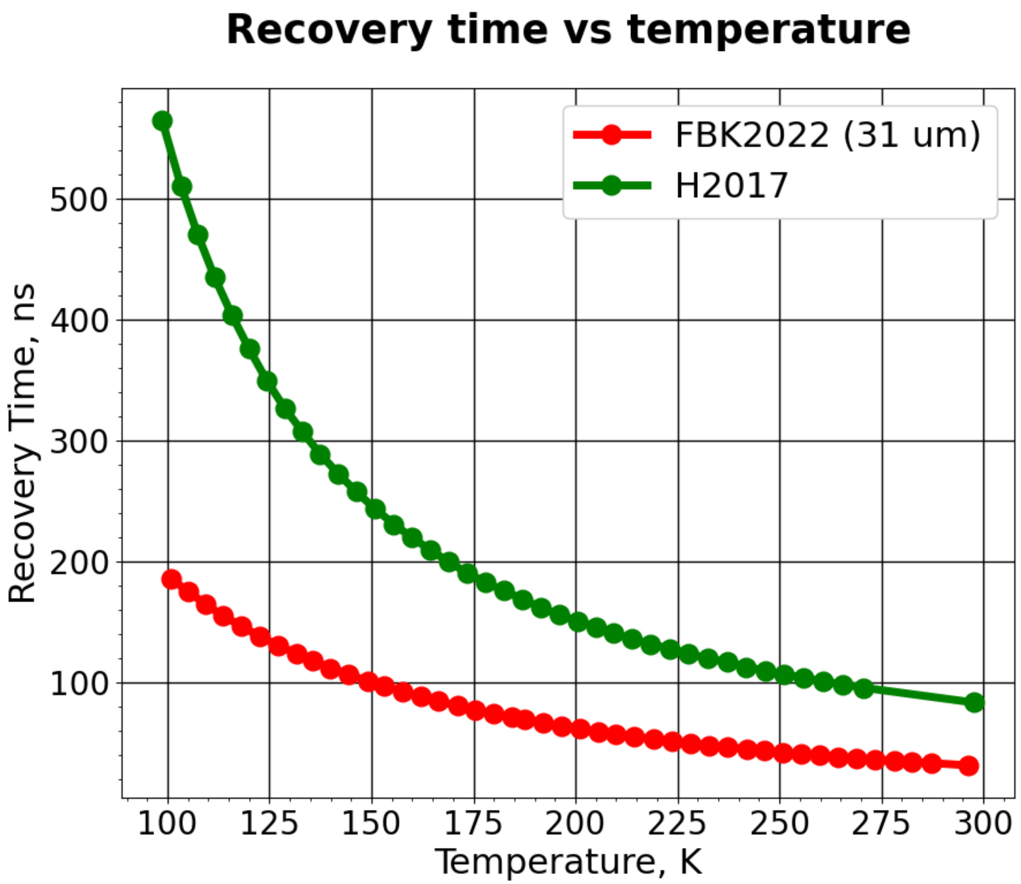
We do not observe any variation with the irradiation fluence (bigger dispersion between different modules ~ 1.0V)



SiPMs: R_q & T_r vs temperature (unirradiated)



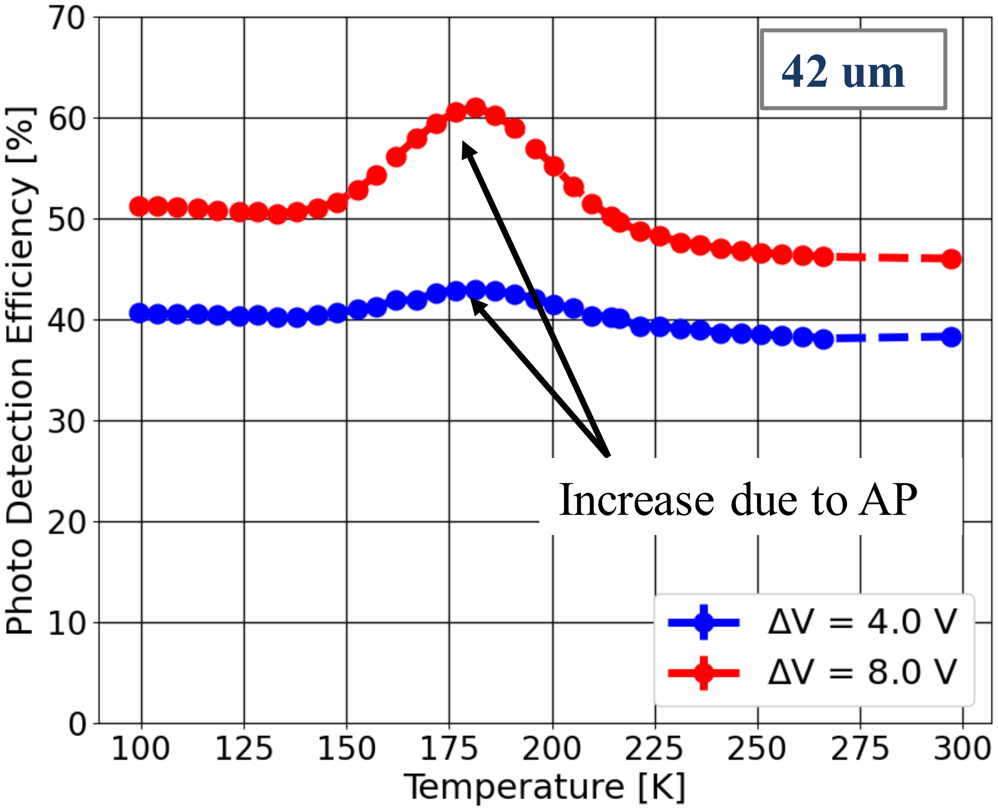
~500 KΩ



- The quenching resistor value at 100 K is a factor of 6-7 higher than at room temperature
- The target recovery time for the experiment should be around 200 ns:
  - Shorter recovery times are better to increase the detector efficiency
  - Longer recovery times are better to minimize the impact of AP

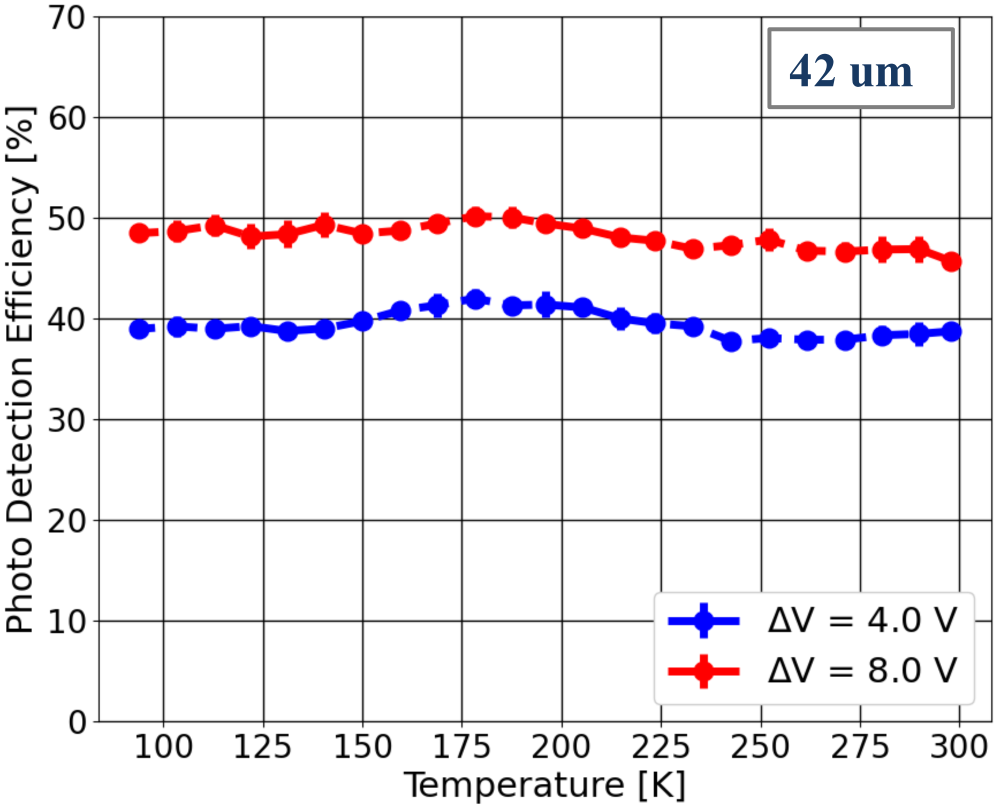
FBK SiPMs: PDE vs temperature (unirradiated)

Illumination: Monochromator (λ = 450 nm)



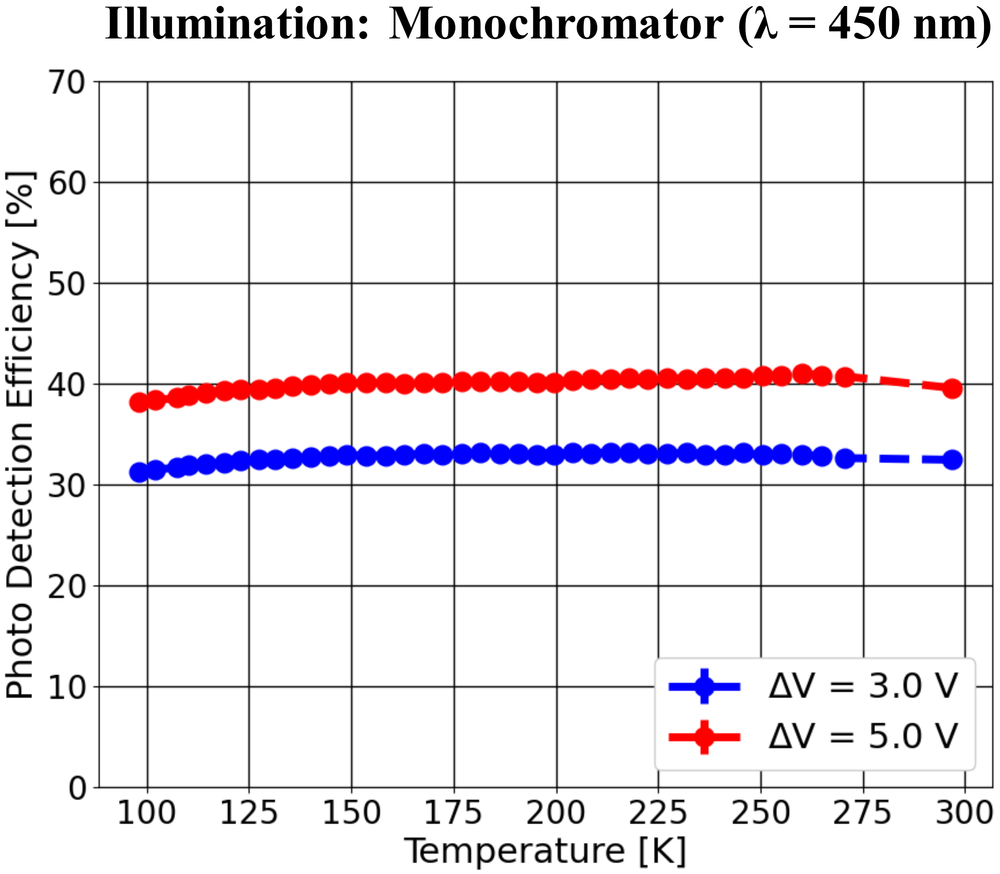
Increase due to AP

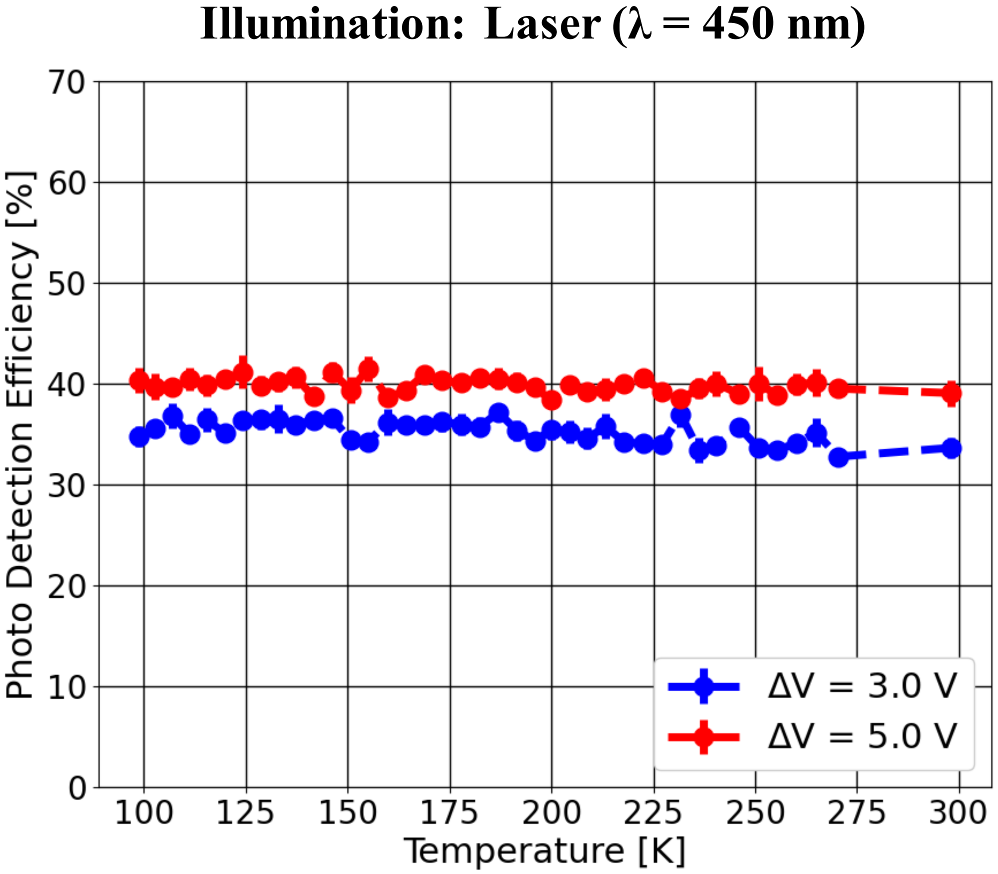
Illumination: Laser (λ = 450 nm)



- The PDE does not change with temperature significantly
- Big presence of AP due to probably material impurities around 180 K
  - Monochromator: the AP noise is not filtered as there is not trigger signal
  - Laser: the AP noise is filtered, data taking is synchronize with the laser trigger

HPK SiPMs: PDE vs temperature (unirradiated)

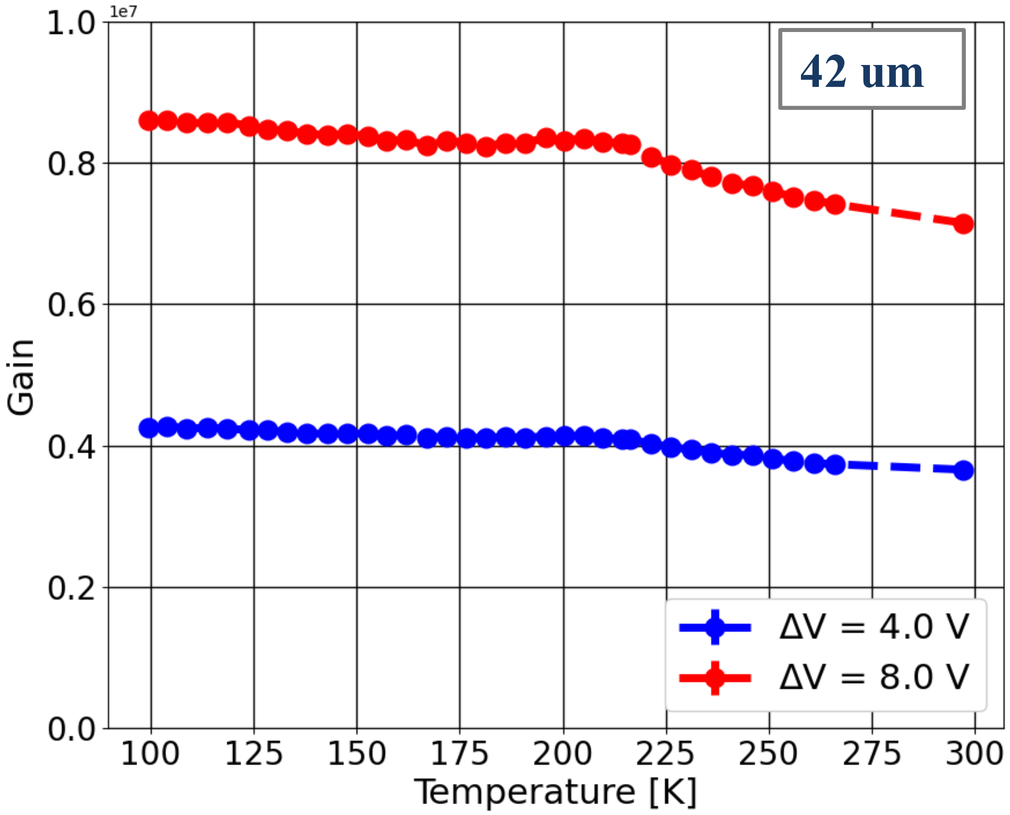




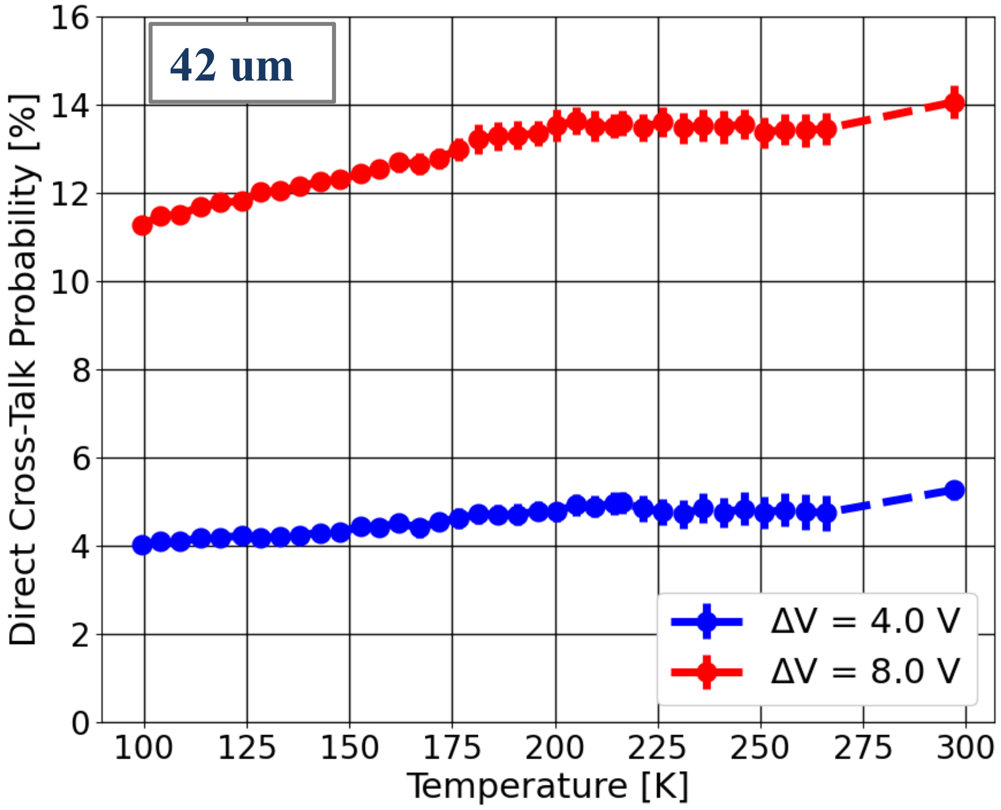
- The PDE does not change with temperature significantly
- No AP measured, less presence of impurities compared with FBK
  - Monochromator: the AP noise is not filtered as there is not trigger signal
  - Laser: the AP noise is filtered, data taking is synchronize with the laser trigger

FBK SiPMs: G & DCP vs temperature (unirradiated)

Illumination: Monochromator (λ = 450 nm)



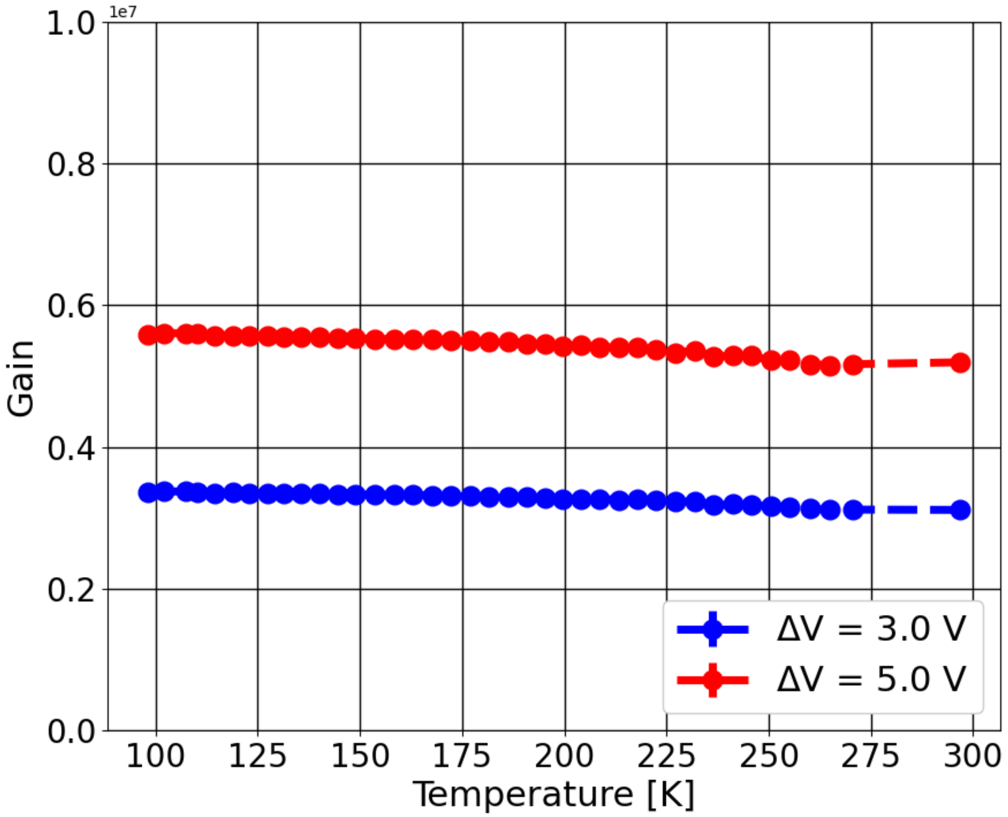
Illumination: Laser (λ = 450 nm)



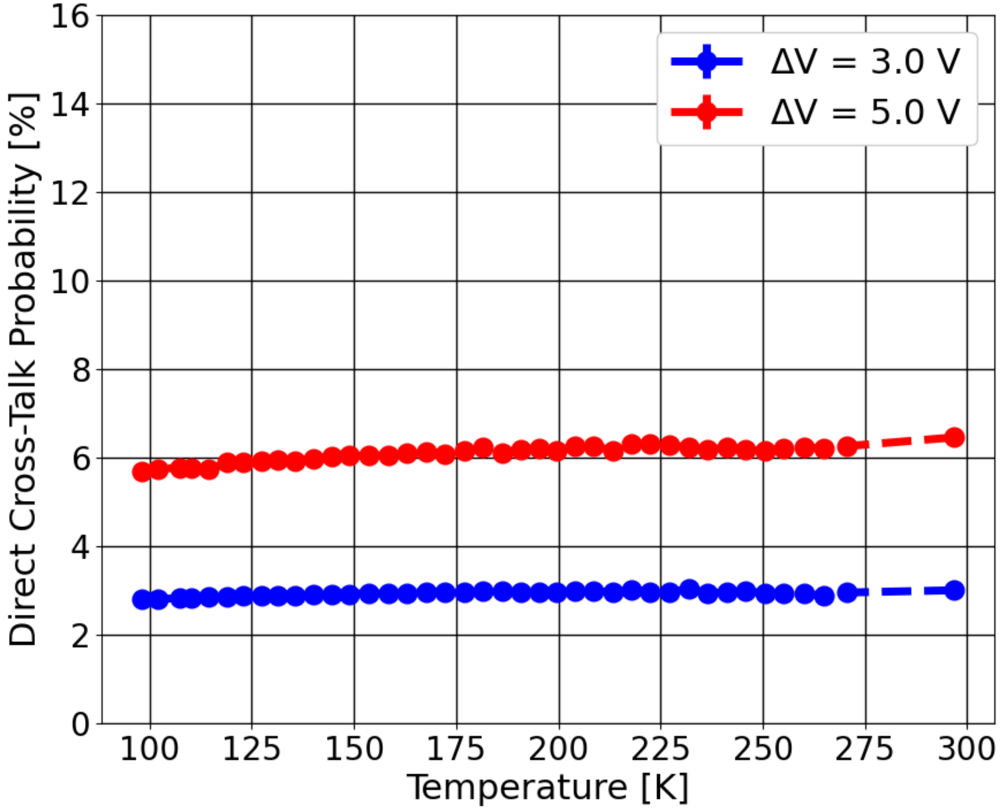
- The gain slightly increases with cooling
- The direct cross talk probability slightly decreases with cooling

HPK SiPMs: G & DCP vs temperature (unirradiated)

Illumination: Monochromator (λ = 450 nm)



Illumination: Laser (λ = 450 nm)

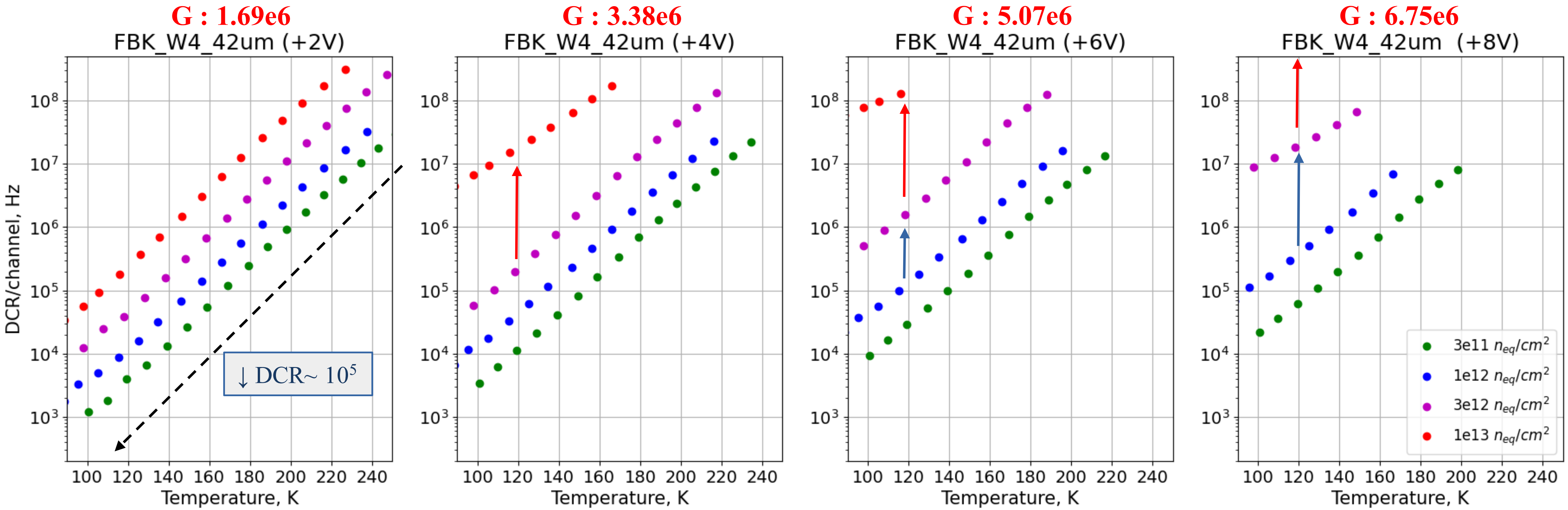


- The gain slightly increases with cooling
- The direct cross talk probability slightly decreases with cooling

FBK SiPM 42 um: DCR irradiated

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

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



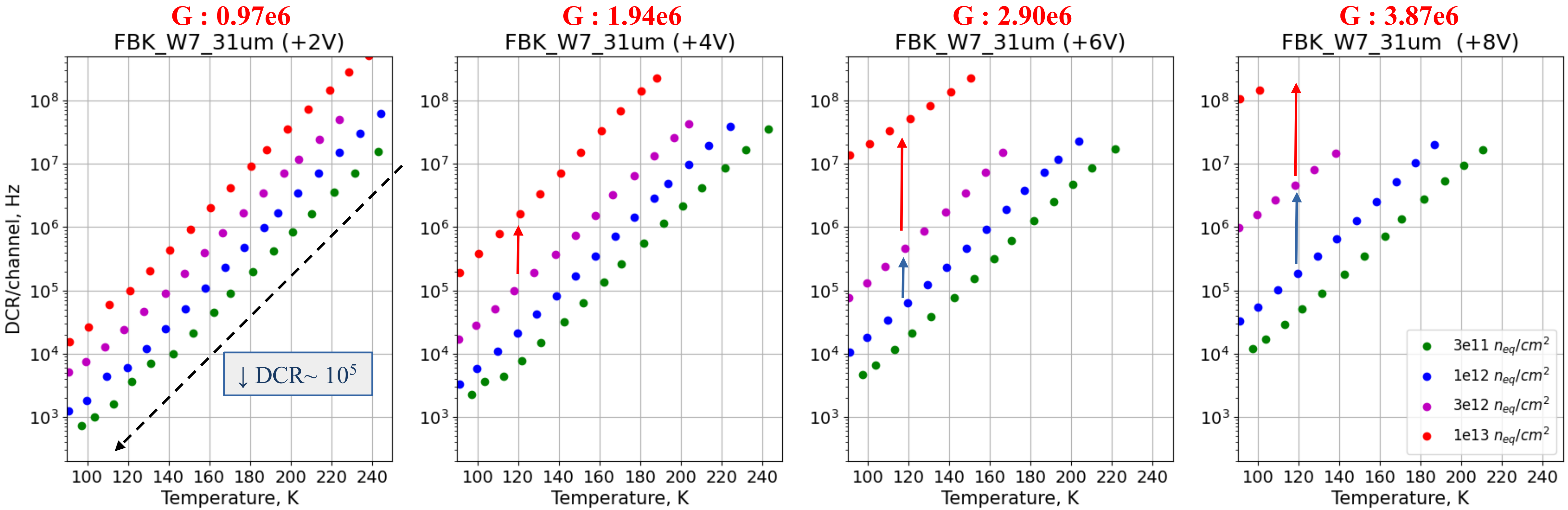
↓ DCR~ 10^5

- 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

FBK SiPM 31 um: DCR irradiated

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

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

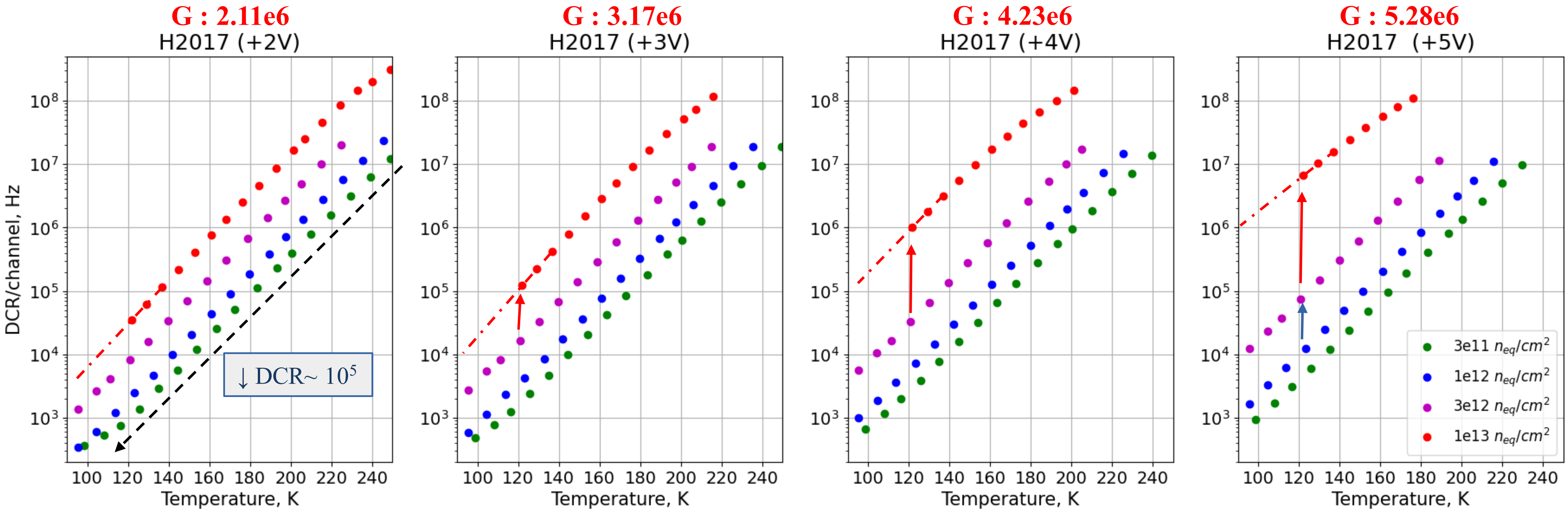


- Same as for 42µm pixel size but NIEL hypothesis valid up to ~3×10^{12} n_{eq}/cm^2
- For the same over-voltage shows lower DCR (smaller pixel size == lower gain)

HPK SiPM: DCR irradiated

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

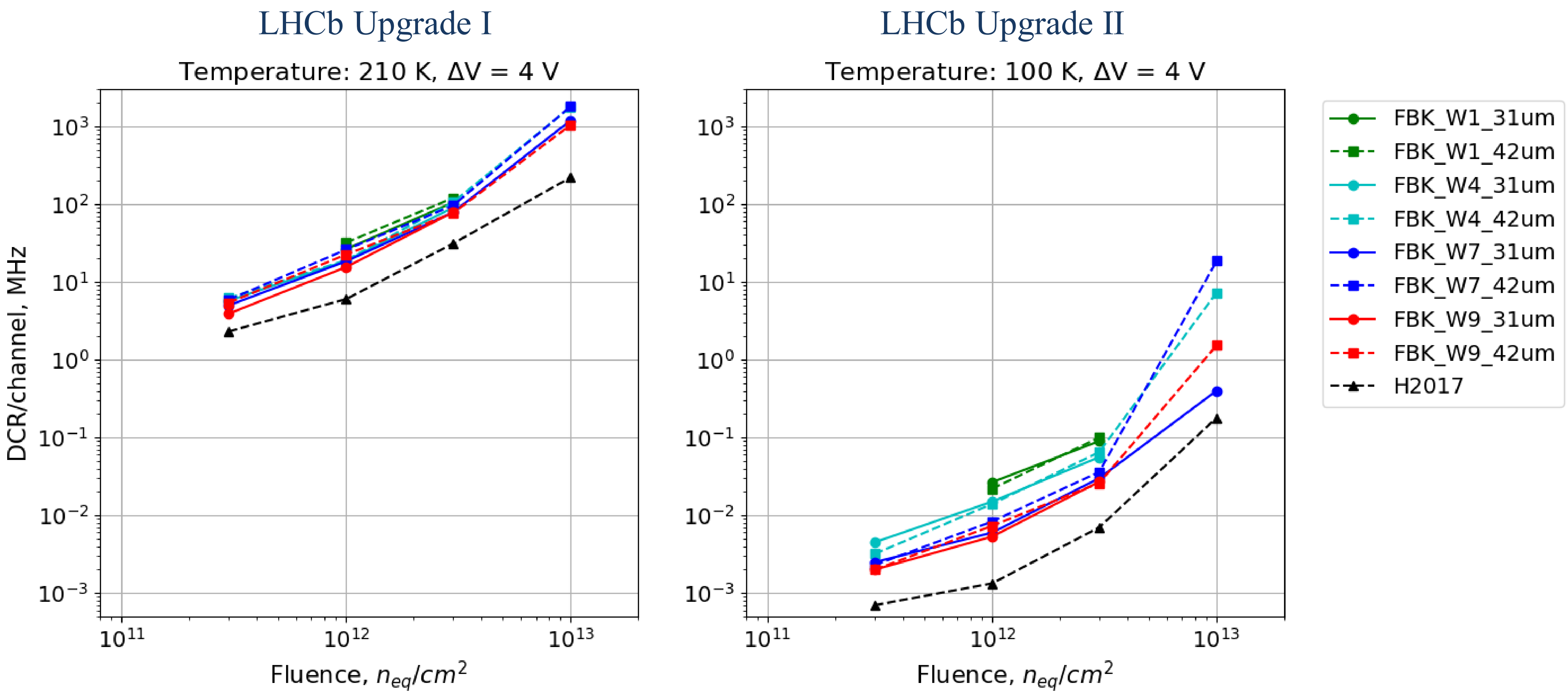
DCR as a function of the temperature for different over-voltages:



Note: values for the fluence of 1×10^{13} extrapolated down to 100K (last measured point at 120 K)

- 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^{13} n_{eq}/cm^2

Comparison all SiPMs: DCR vs fluence

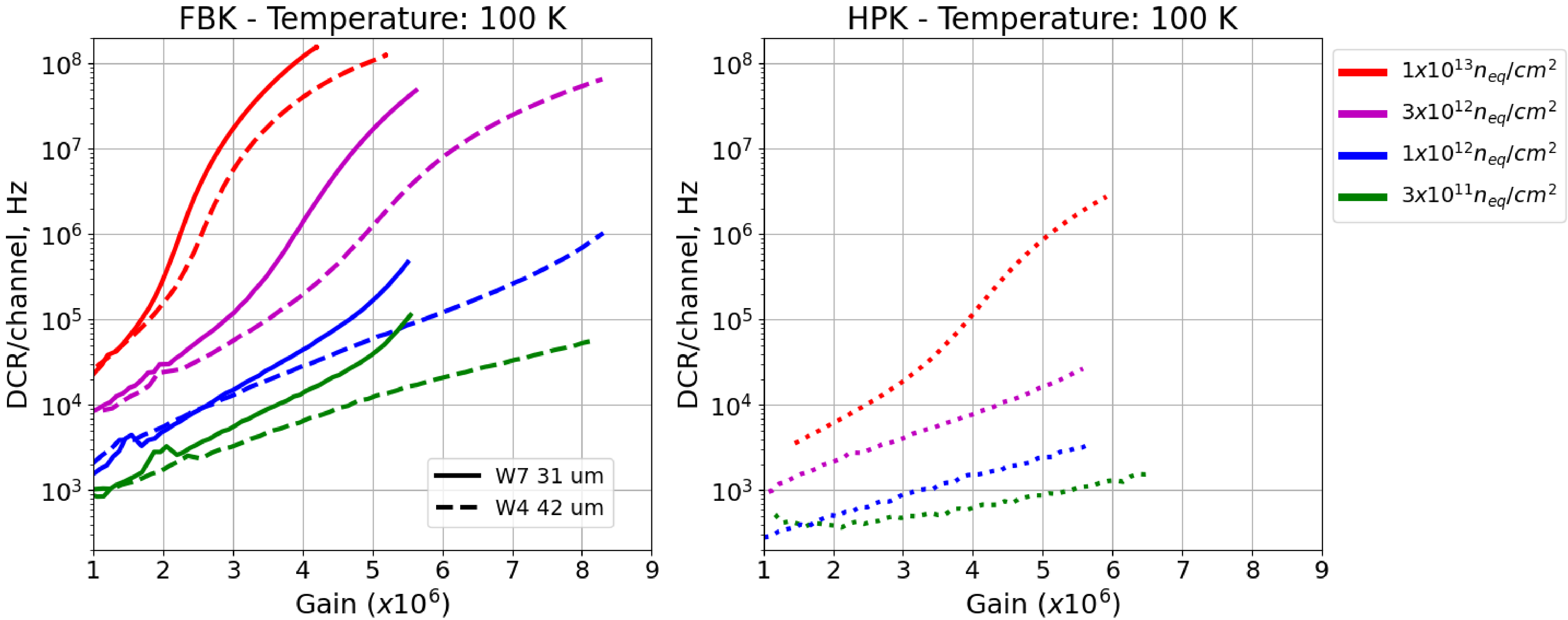


LHCb Upgrade I

LHCb Upgrade II

- 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 $3 \times 10^{12}\ n_{eq}/cm^2$
- Smaller pixels can be operated at higher fluence!

Comparison all SiPMs: DCR vs G

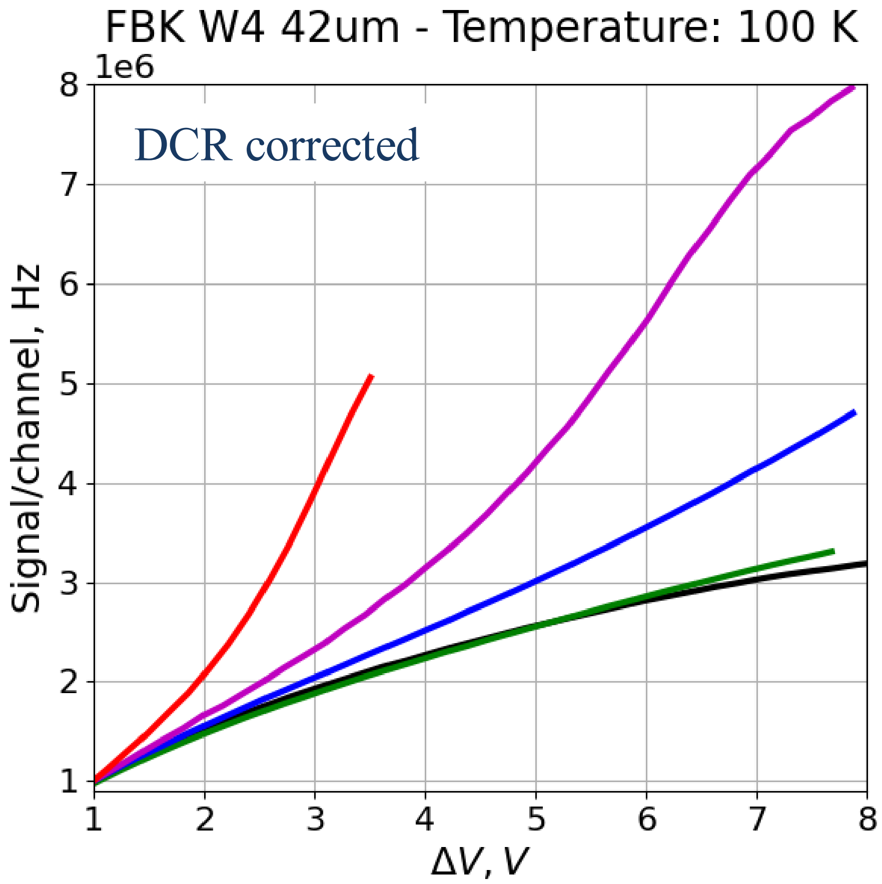


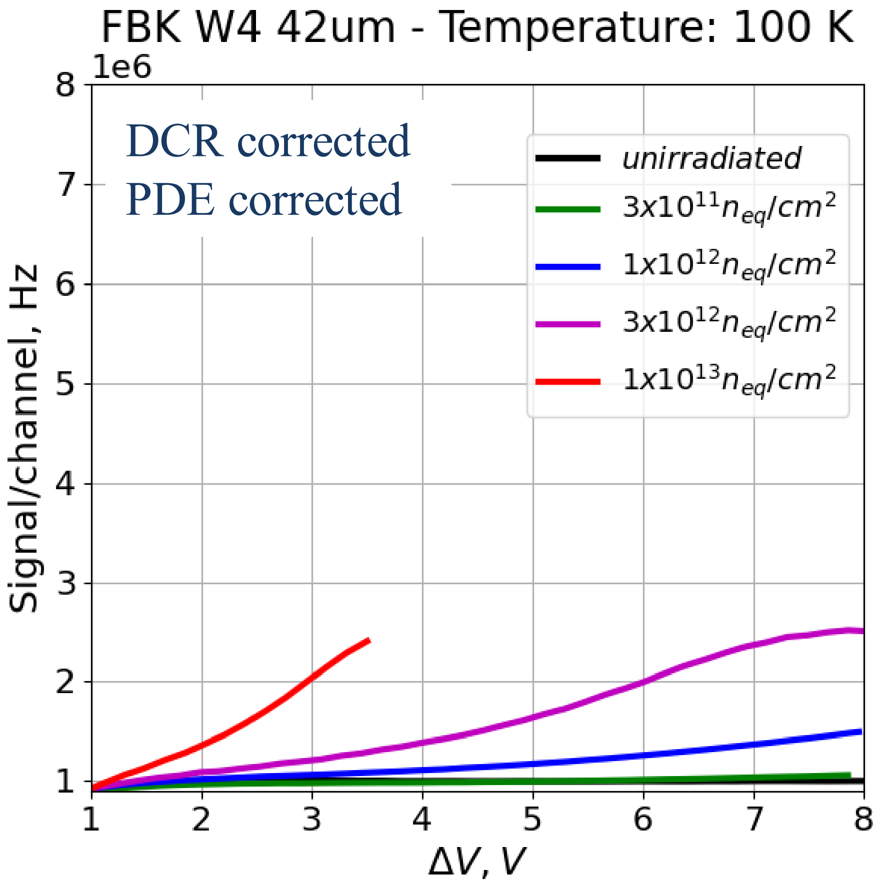
FBK - Temperature: 100 K

HPK - Temperature: 100 K

- Better performance of HPK when comparing DCR in terms of gain
- Similar performance of the FBK 42 um and FBK 31 um in terms of gain but, FBK 42 um is better at higher gains
- Beside the difference in the Si wafers (FBK vs HPK), there are difference in the gain layer electric field in all devices

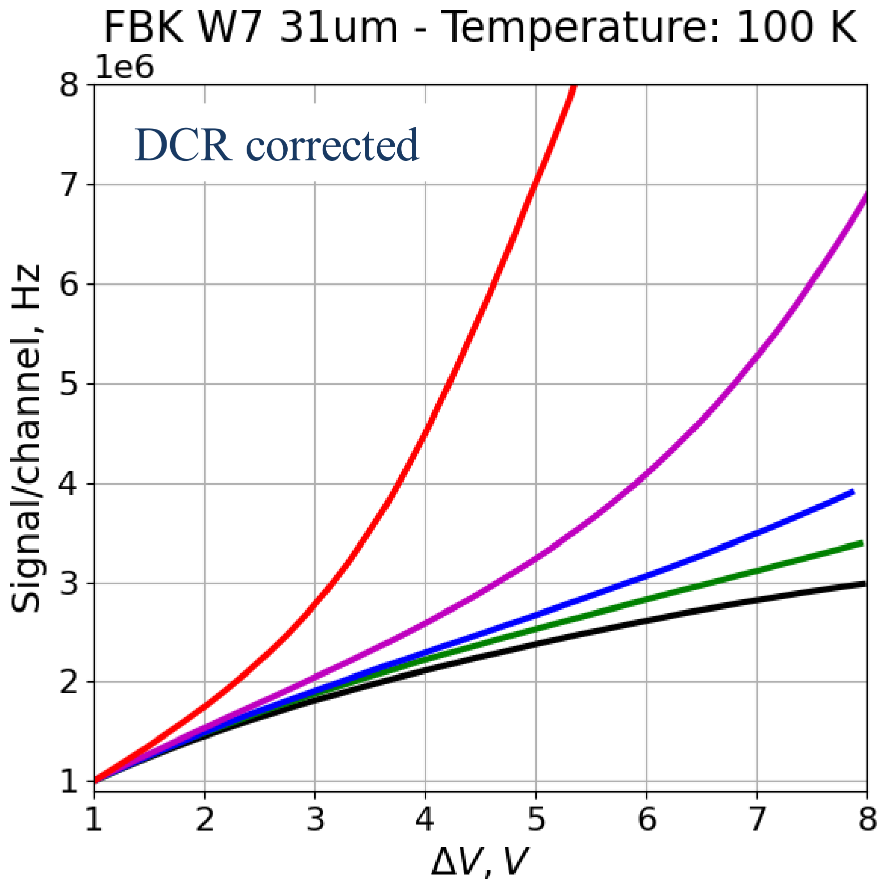
FBK SiPM 42 um: Signal vs ΔV at 100 K

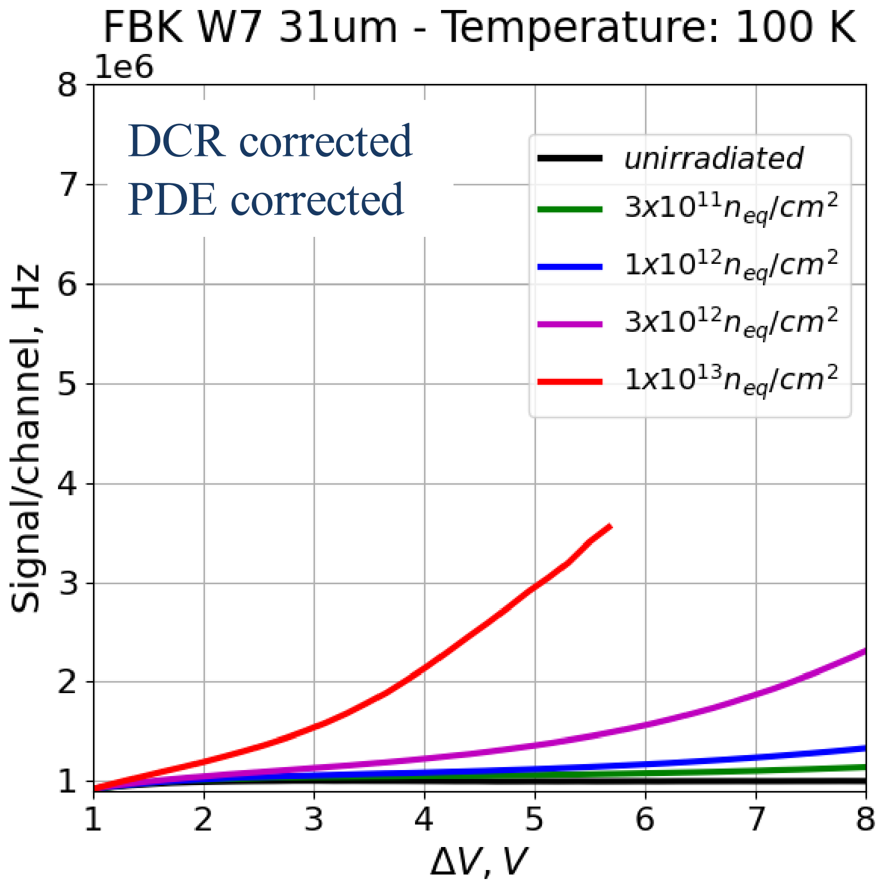




- Laser illumination (450 nm) to get a signal rate around 1 MHz/channel
  - All data normalized to 1 MHz/channel for ΔV = 1V.
- After DCR and PDE correction, it is observe an increase in the correlated noise for fluences higher that $1 \times 10^{12}\ n_{eq}/cm^2$.

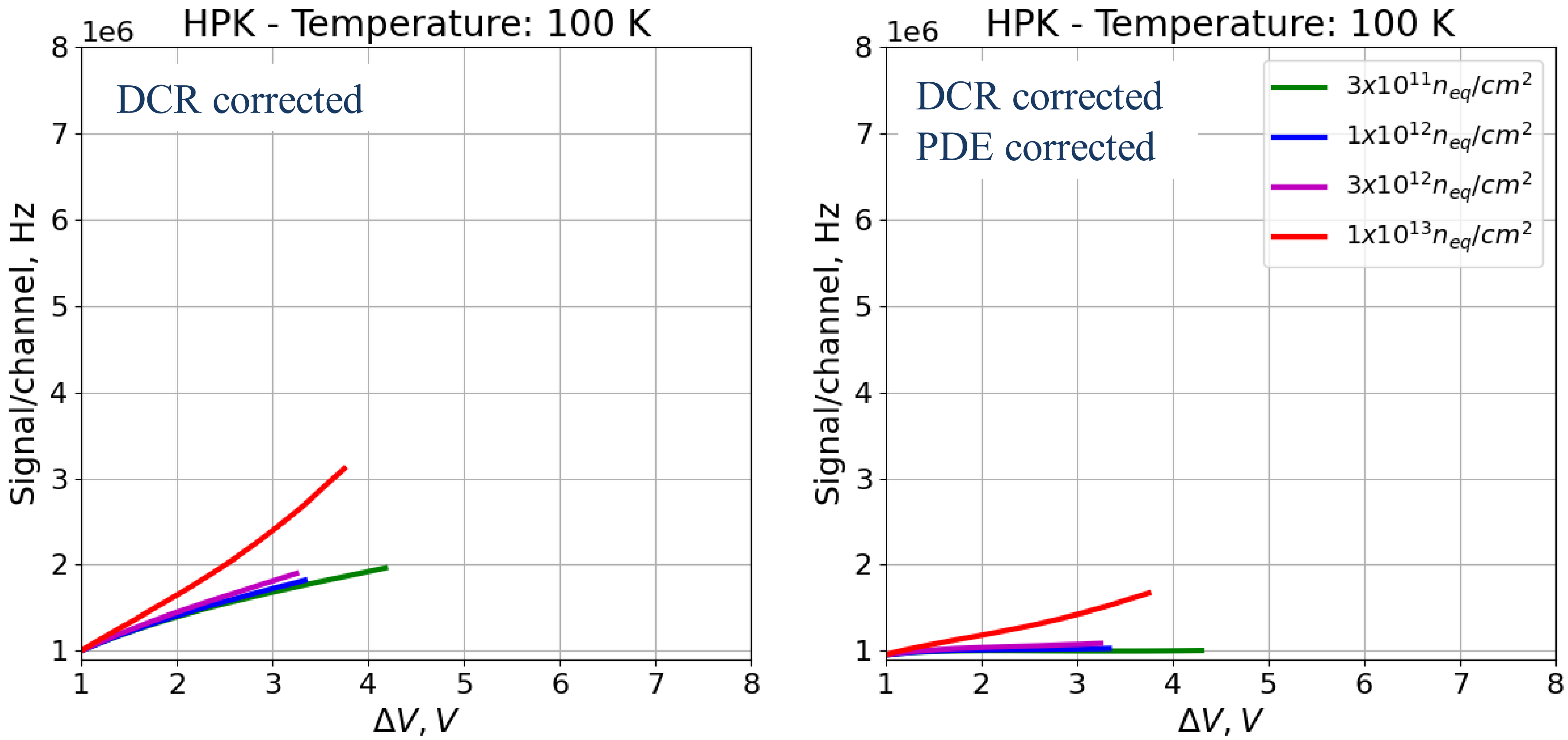
FBK SiPM 31 um: Signal vs Δ V at 100 K





- Laser illumination (450 nm) to get a signal rate around 1 MHz/channel
  - All data normalized to 1 MHz/channel for ΔV = 1V
- After DCR and PDE correction, it is observe an increase in the correlated noise for fluences higher that 1×10^{12} n_{eq}/cm^2

HPK SiPM: Signal vs Δ V at 100 K

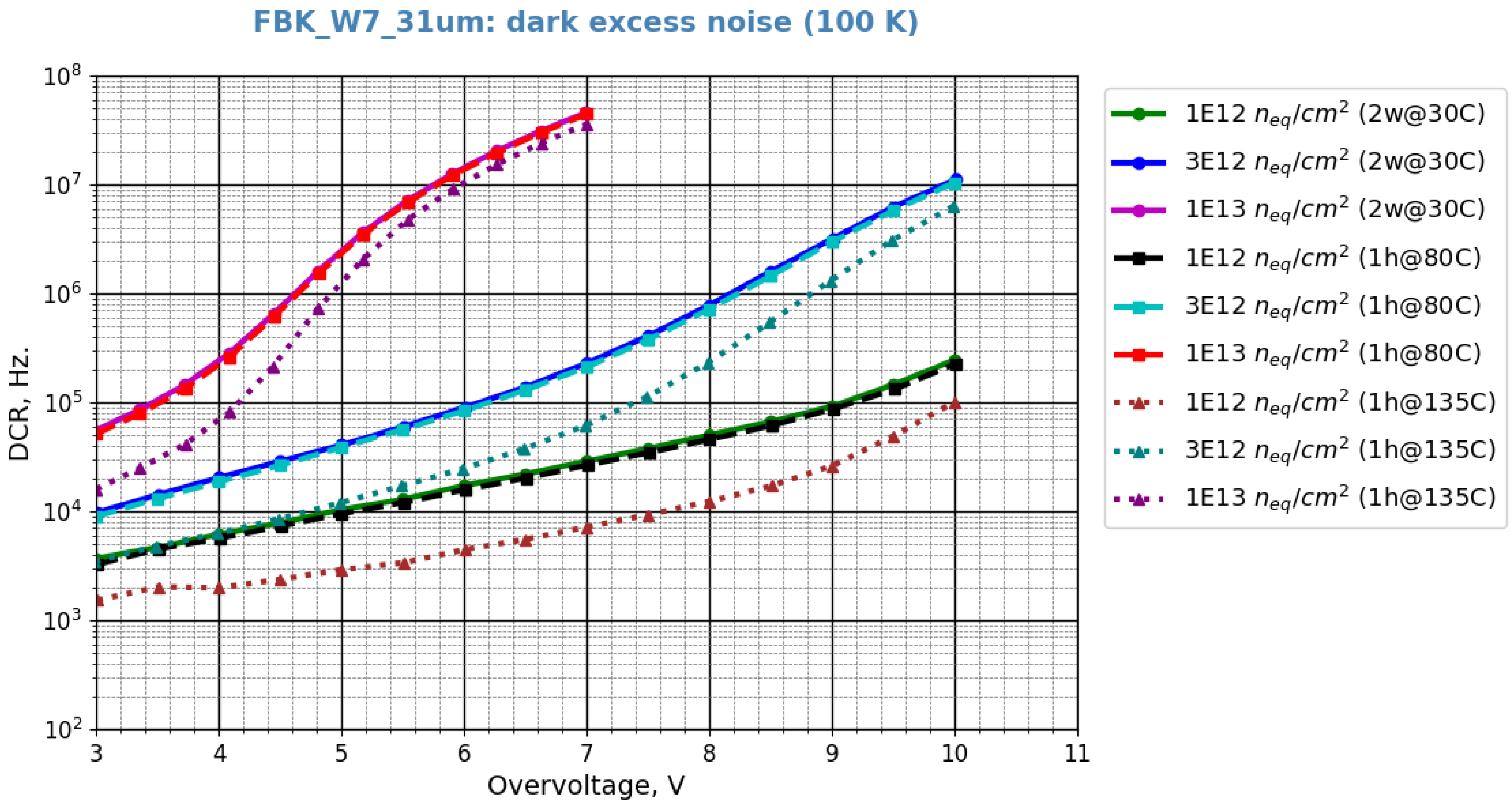


DCR corrected

DCR corrected
PDE corrected

- Laser illumination (450 nm) to get a signal rate around 1 MHz/channel
  - All data normalized to 1 MHz/channel for ΔV = 1V
- After DCR and PDE correction, it is observe an increase in the correlated noise for fluences higher that 3×10^{12} n_{eq}/cm^2

FBK SiPM 31 um: Annealing (measured at 100 K)



- 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 and conclusions:

- Breakdown voltage as a function of the temperature not linear (visible at cryogenic temperatures)
- R_q and T_r increase with cooling, a factor 6-7 from 300 K down to 100 K
- Gain slightly increases with cooling, direct crosstalk slightly decreases with cooling and PDE does not change
- DCR reduced by $\sim 10^3$ for operation (100 K and 4 V) compared to Upgrade I operation (210 K)
  - **This leads indeed to an almost noise free detector!**
- Large DCR increase beyond fluences of $\sim 1\text{x}10^{12}$ n_{eq}/cm^2 and signal correlated noise increase beyond fluences of $\sim 3\text{x}10^{12}$ n_{eq}/cm^2
- Small pixel size (low gain) and low ΔV (low gain) are better at high fluences
  - HPK SiPM modules less affected
  - The effect of the gain layer doping profile and wafer quality needs to be better understood
- Annealing at high temperatures (> 80°C) helps to reduce DCR

Back up

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°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

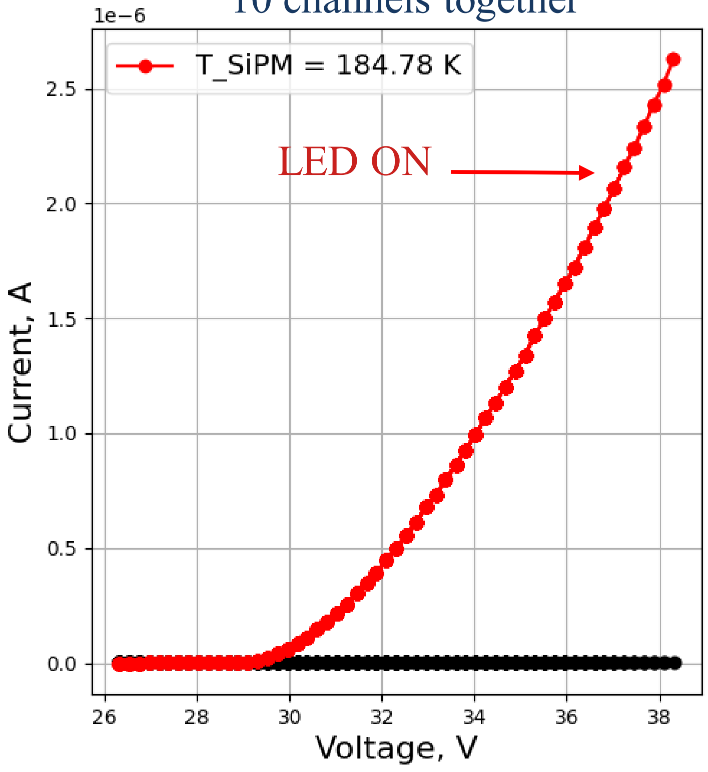
Measurement campaign: V_{bd}

Extracting the breakdown voltage

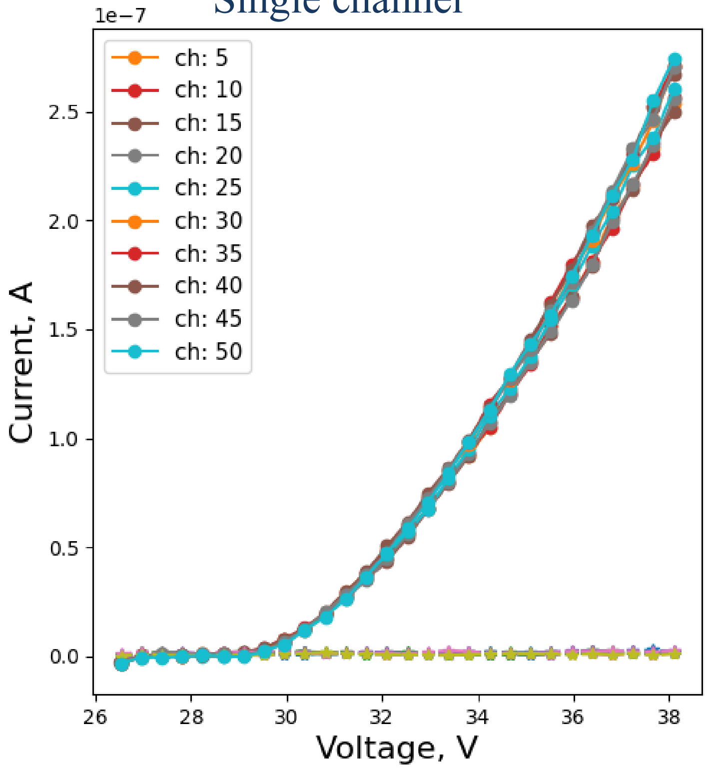
Method of Inverse Logarithmic Derivative (ILD)

E.g.: FBK_W4_42um (unirradiated)

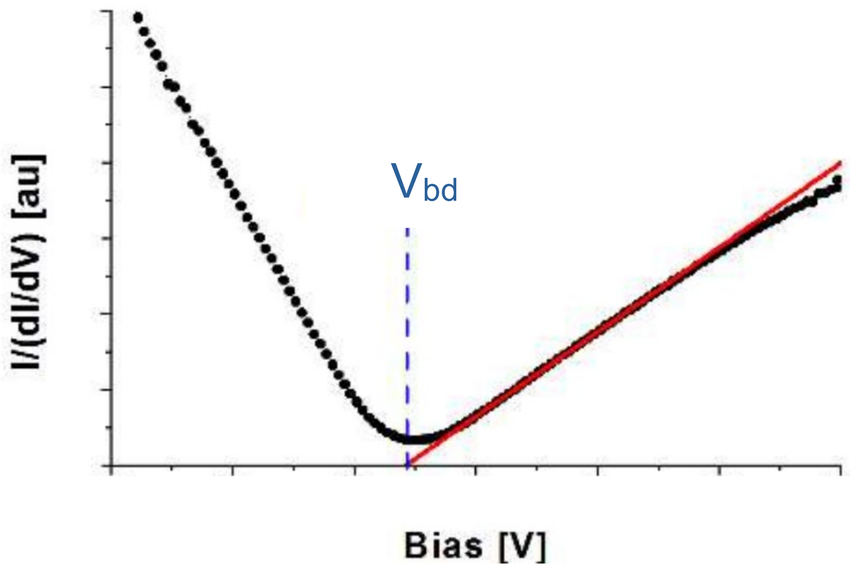
10 channels together



Single channel



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

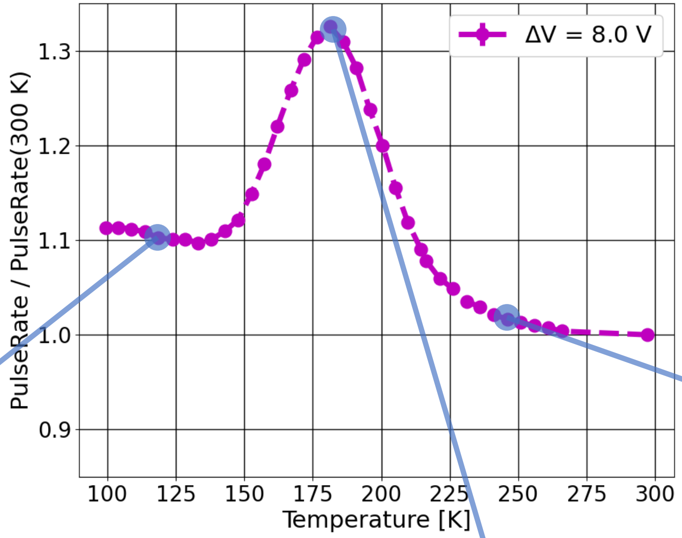


Detector: FBK_W3_42um_003_Flat

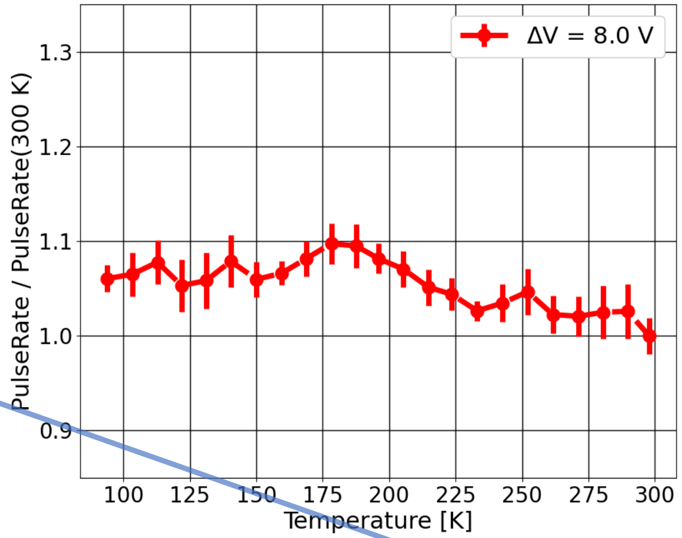
Laser CH81:

- Intensity set for 1 pe.
- Wavelength: 450 nm
- Laser rate: 500 KHz
- **Over-voltage: 8.0 V**
- 1 pe amplitude: 260 mV
- Threshold for AP: 130 mV
- Excluded all peaks with amplitude higher than 1 pe.

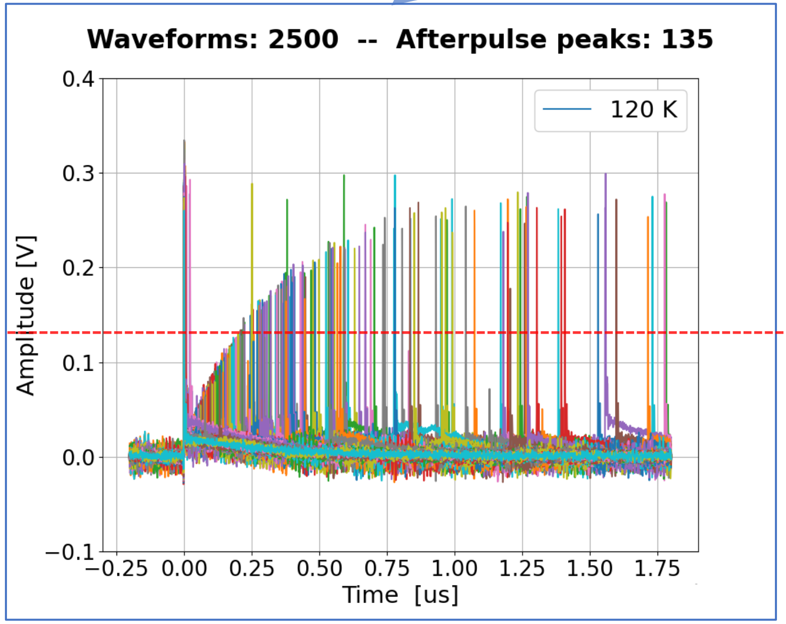
Illumination: Monochromator (λ = 450 nm)



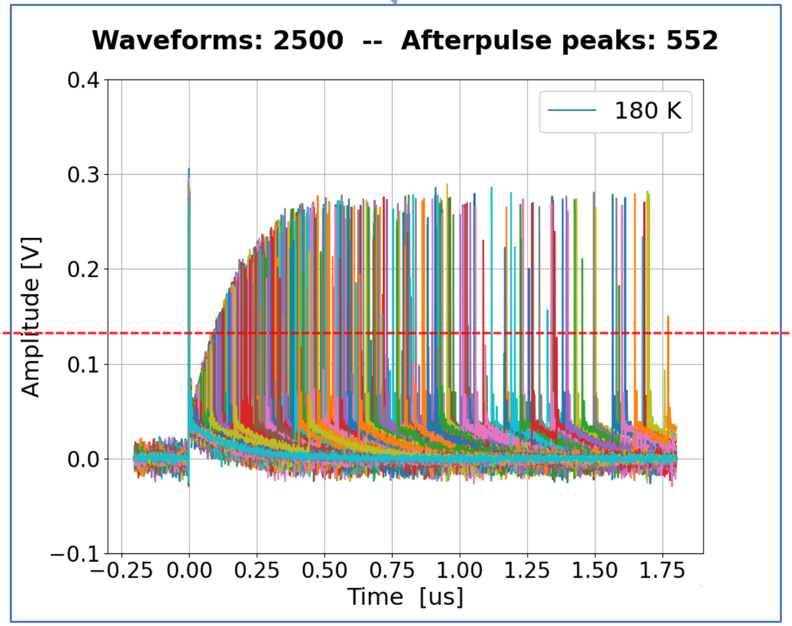
Illumination: Laser (λ = 450 nm)



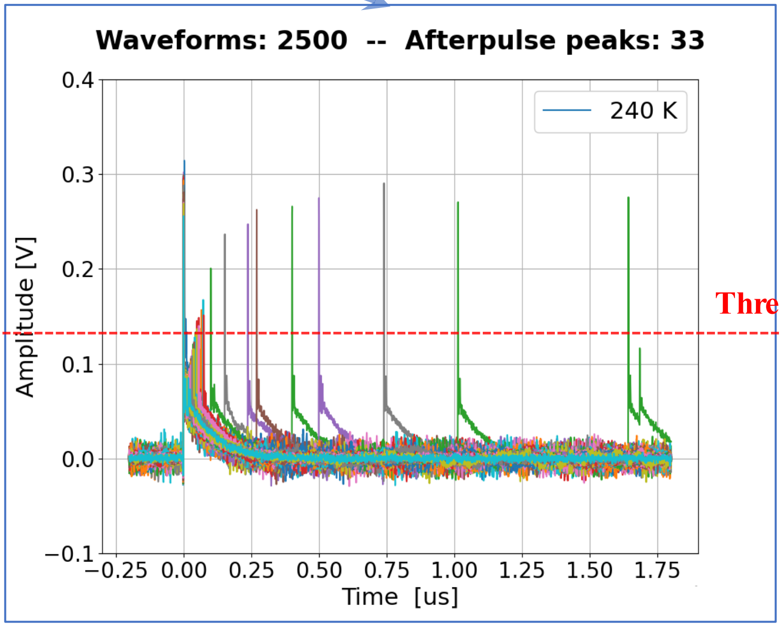
AP = 5.4%



AP = 22.1%



AP = 1.3%



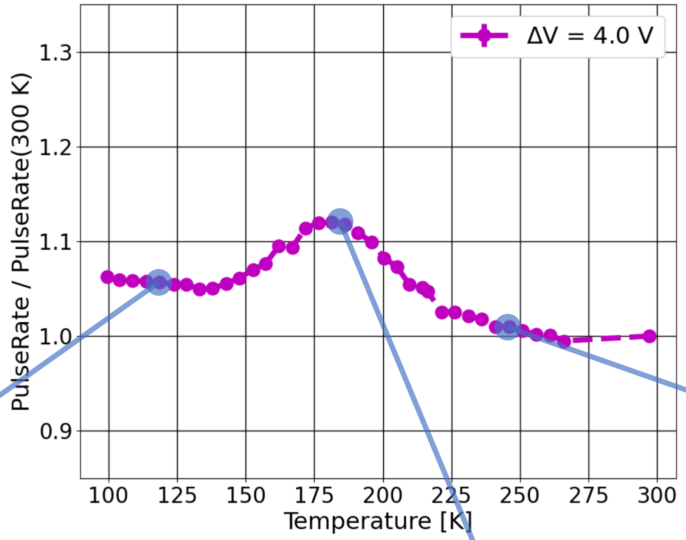
Threshold

Detector: FBK_W3_42um_003_Flat

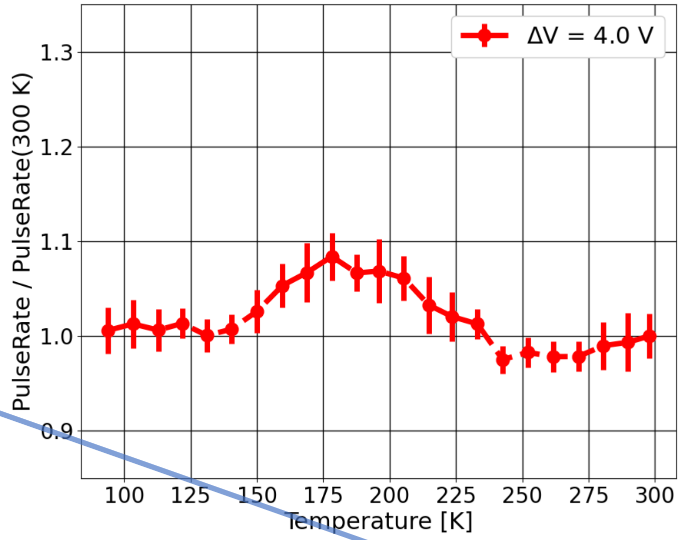
Laser CH81:

- Intensity set for 1 pe.
- Wavelength: 450 nm
- Laser rate: 500 KHz
- **Over-voltage: 4.0 V**
- 1 pe amplitude: 130 mV
- Threshold for AP: 65 mV
- Excluded all peaks with amplitude higher than 1 pe.

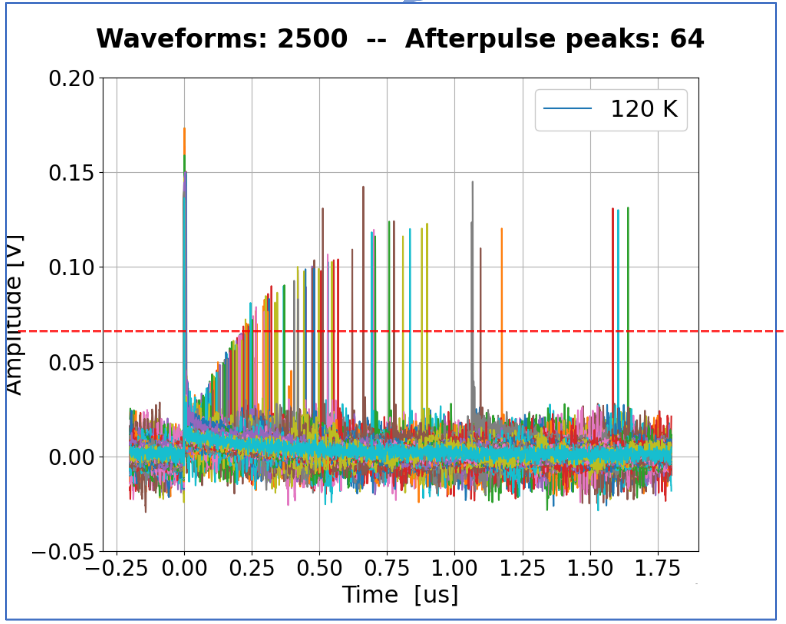
Illumination: Monochromator (λ = 450 nm)



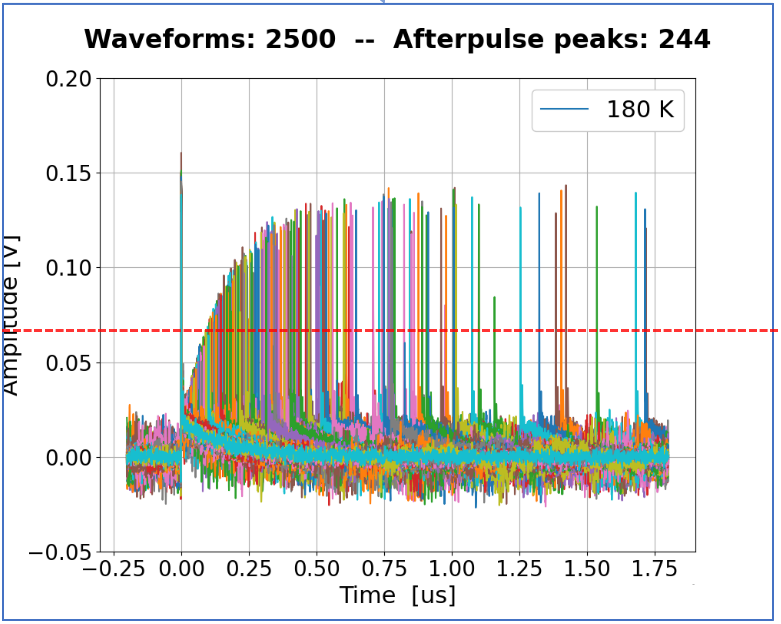
Illumination: Laser (λ = 450 nm)



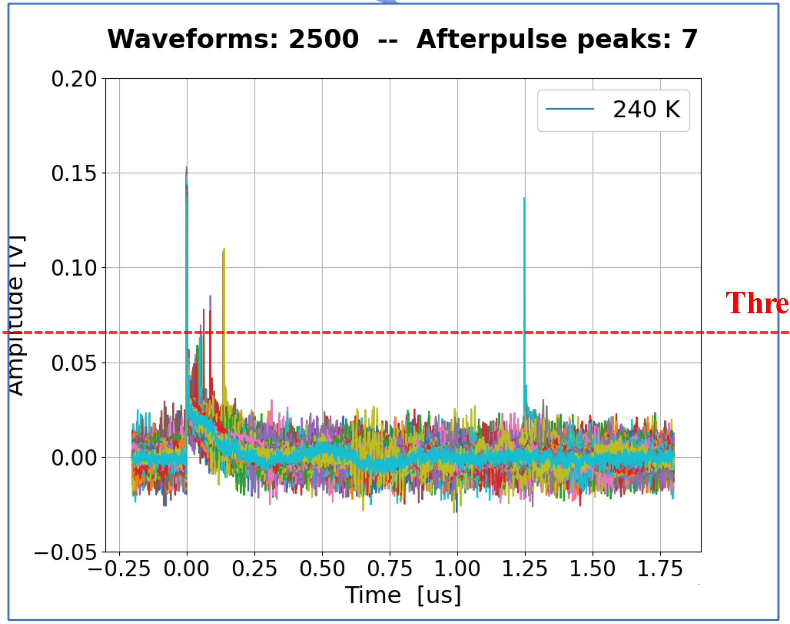
AP = 2.6%


Waveforms: 2500 -- Afterpulse peaks: 64

AP = 9.8%


Waveforms: 2500 -- Afterpulse peaks: 244

AP = 0.3%


Waveforms: 2500 -- Afterpulse peaks: 7

Threshold