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

EPFL

Esteban Currás Rivera

Laboratoire de Physique des Hautes Energies

École Polytechnique Fédérale de Lausanne

6th International Workshop on new Photon-Detectors (PD24)

19 – 21 November 2024, Vancouver

LHCb

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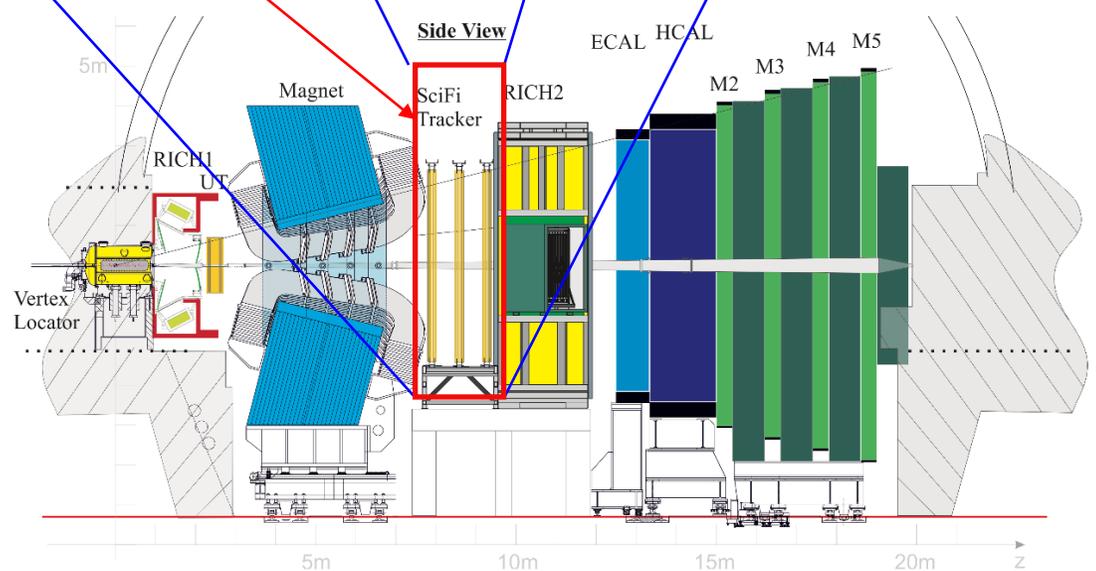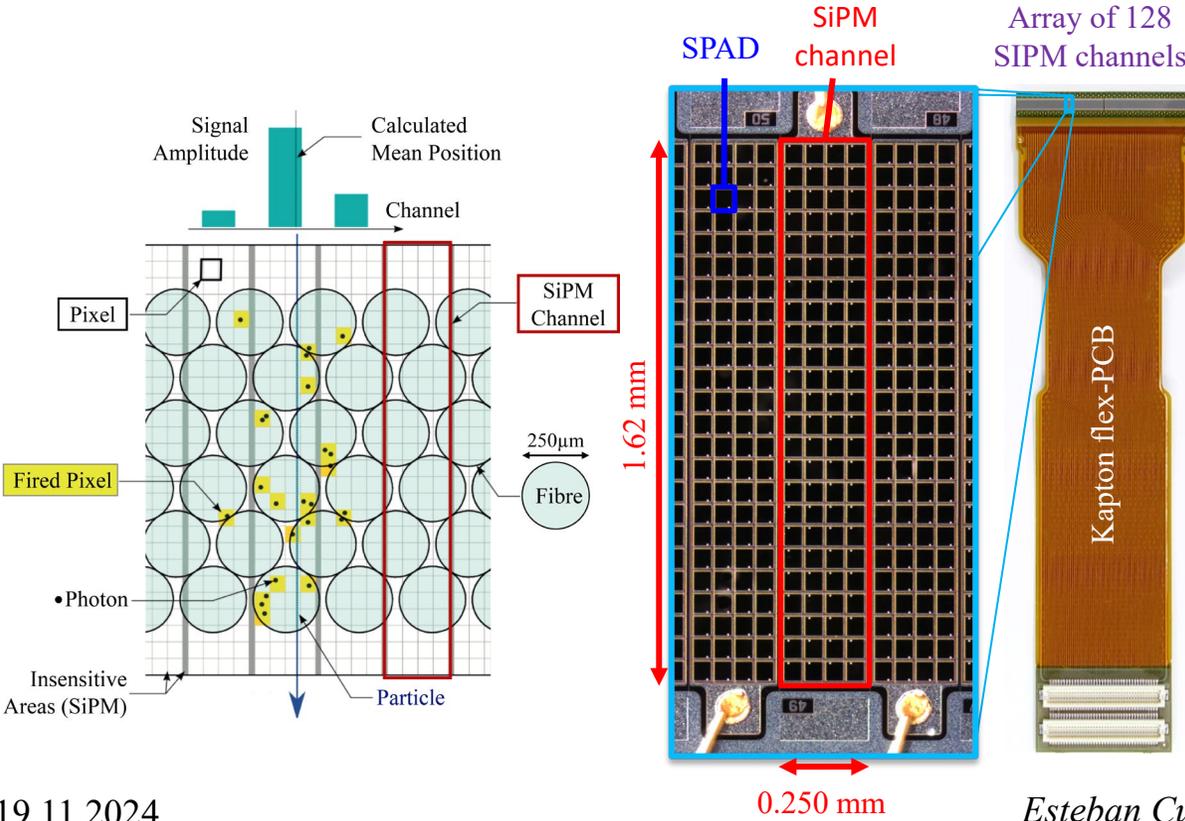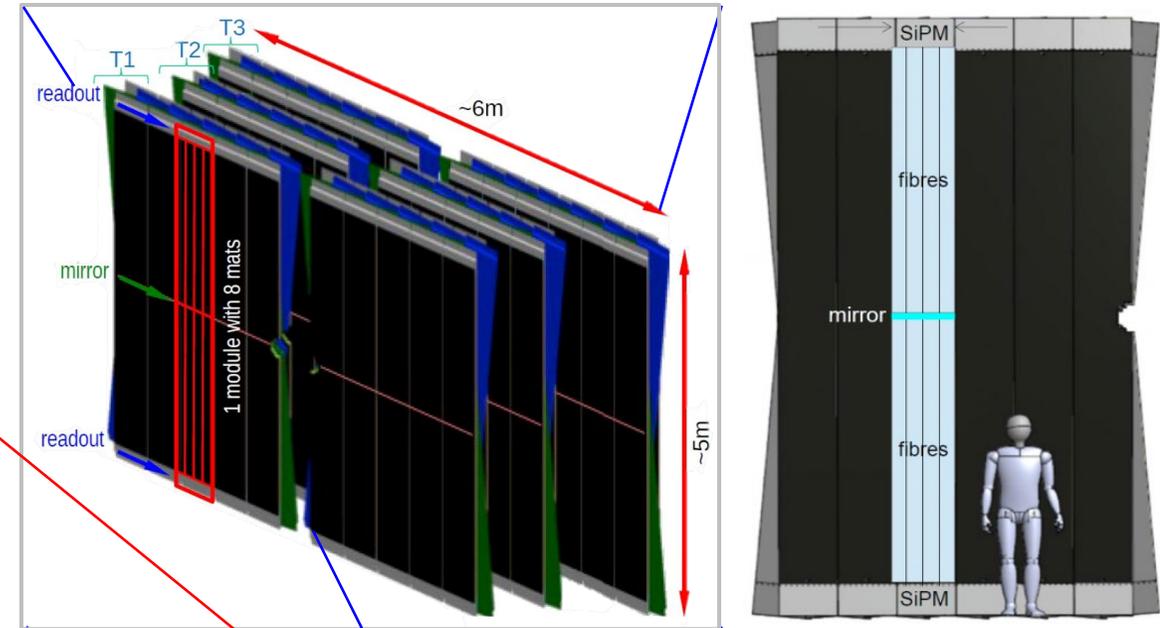FOR ACCELERATOR
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Outlook

- 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

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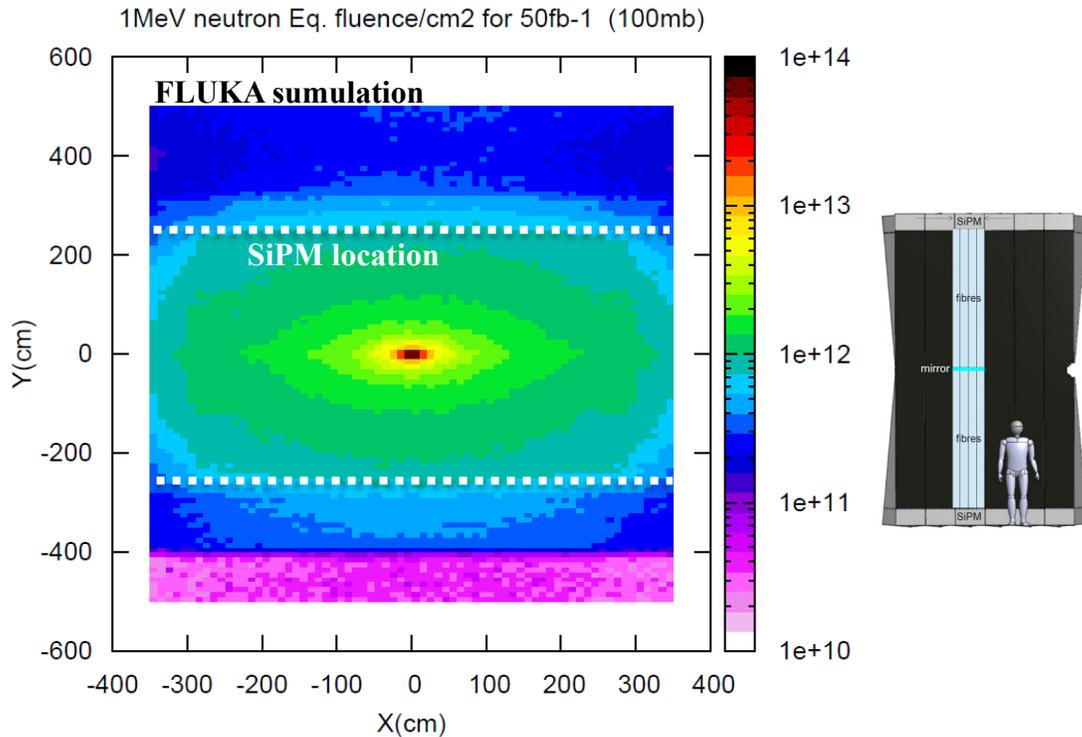# LHCb upgrade I (2019-2021)
The new SciFi detector

- 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)

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SiPM challenges for the LHCb Upgrade II (2033)

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

1MeV neutron Eq. fluence/cm2 for 50fb-1 (100mb)

FLUKA sumulation

SiPM location

Goal: cooling with liquid nitrogen at ~100 K

Learned from Upgrade I

Dark count rate per SiPM channel (DCR)

DCR (not irradiated): 0.04 MHz.

DCR is increasing with neutron radiation.

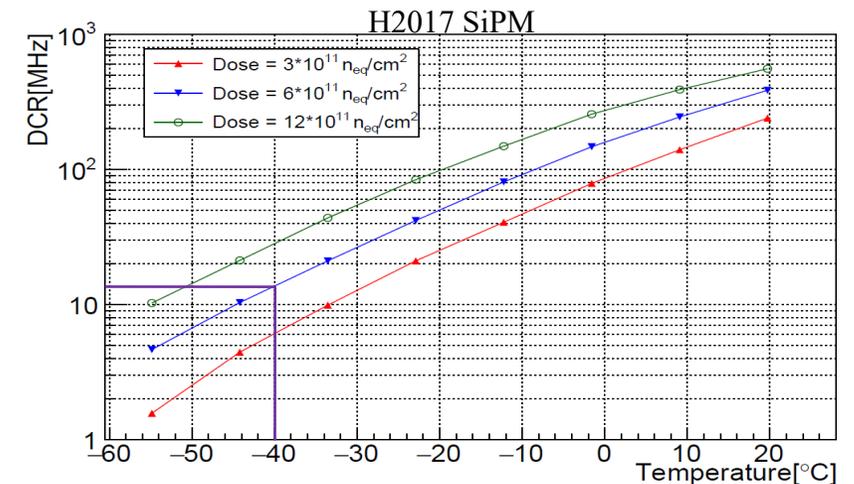The SiPMs are positioned far from the beam center.

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.

H2017 SiPM

Dose = $3*10^{11}$ n_{eq}/cm^2
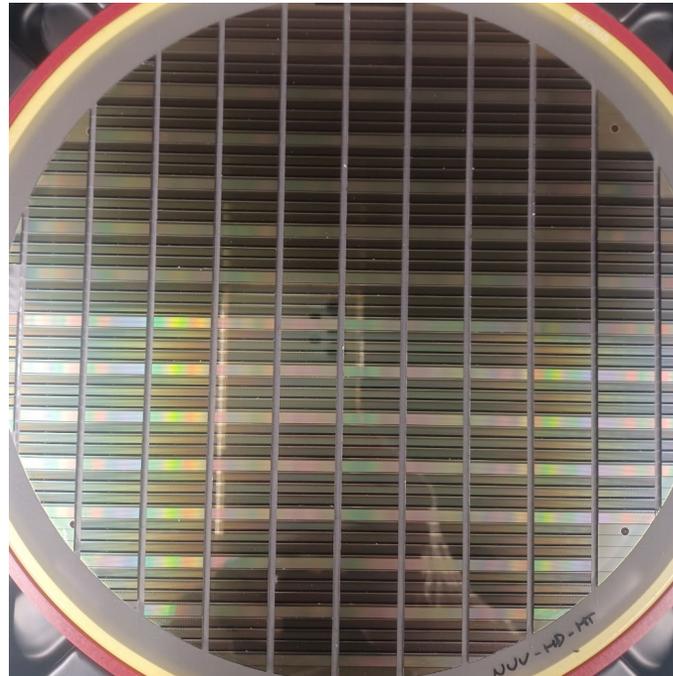Dose = $6*10^{11}$ n_{eq}/cm^2
Dose = $12*10^{11}$ n_{eq}/cm^2

1st set of SiPM modules for the testing

Produced by **FBK** in 2022

Wafer layout

NUV-HD-MT

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

+ Gain −

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

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

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Cryogenic setup

Helium cryocooler (25K up to RT)

DAO

Cryostat

4 SiPM modules

Illumination source

Compressor

T^{ra} sensor

50W heaters under the support

Pump for the vacuum
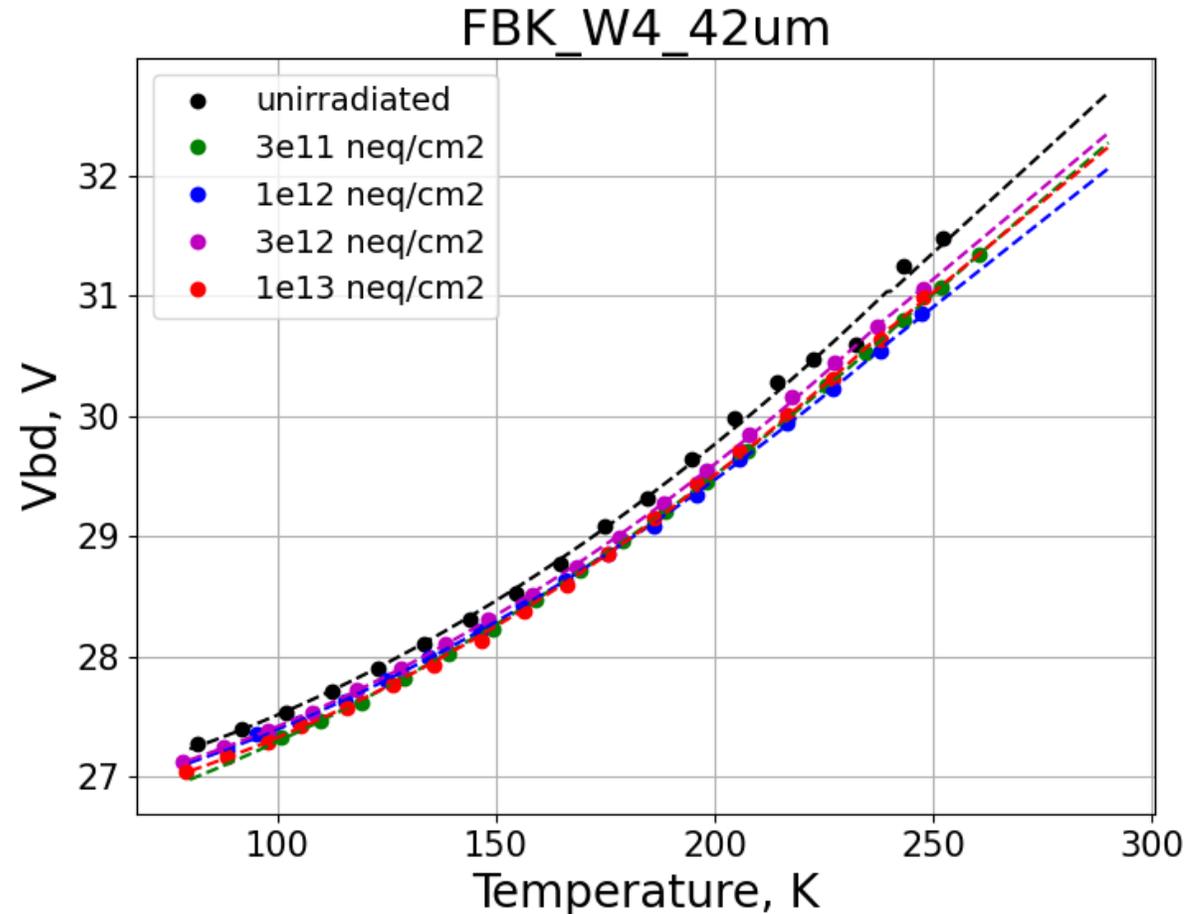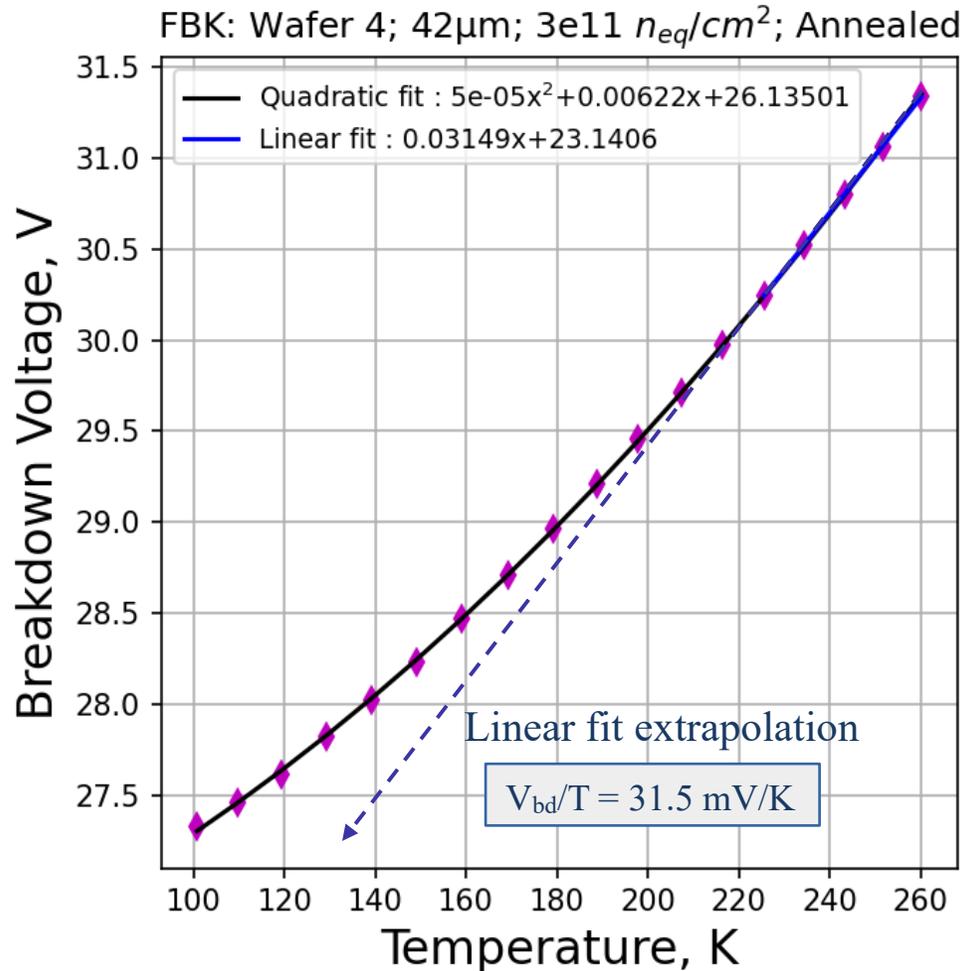
Expander (Cryocooler)

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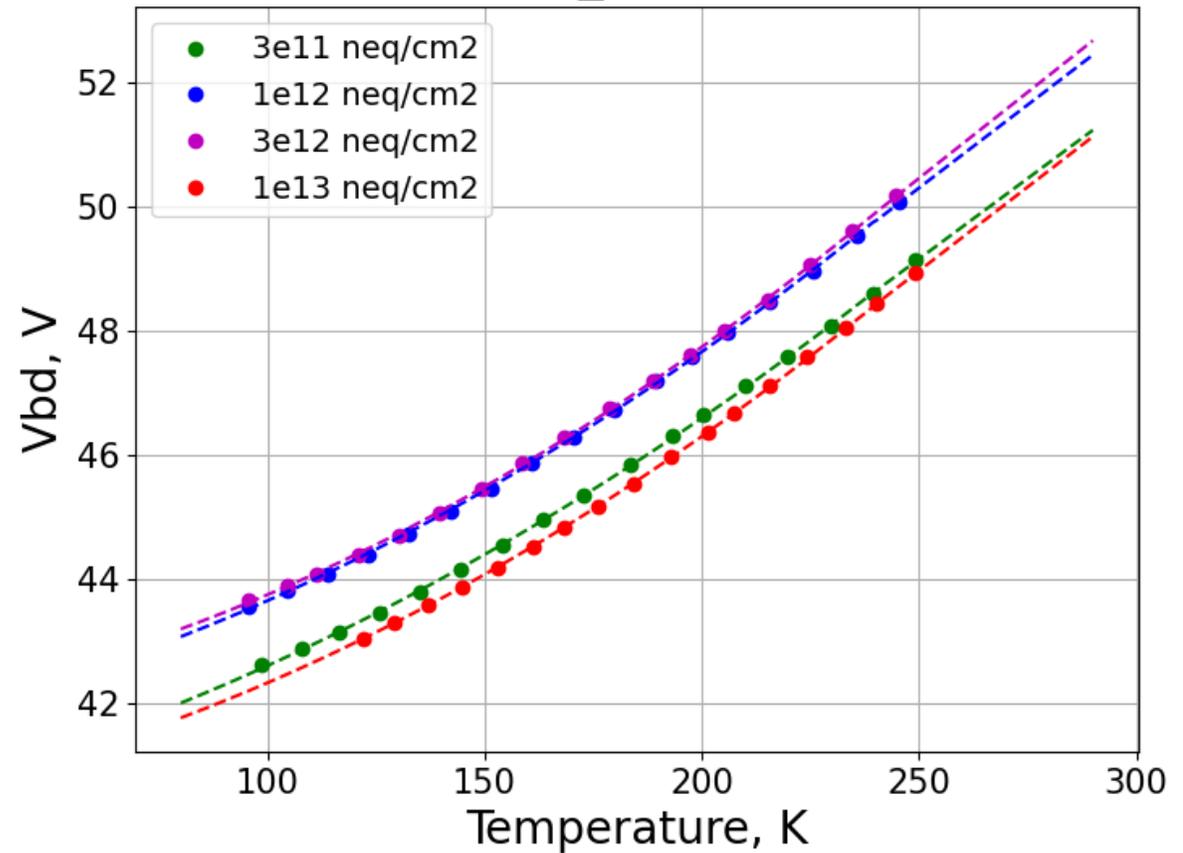# FBK SiPMs: V_{bd} vs temperature

EPFL

Breakdown voltage as a function of the temperature

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

FBK: Wafer 4; 42μm; 3e11 n_{eq}/cm^2; Annealed

Quadratic fit : $5e-05x^2+0.00622x+26.13501$
Linear fit : $0.03149x+23.1406$

Linear fit extrapolation

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

FBK_W4_42um

- unirradiated
- 3e11 neq/cm2
- 1e12 neq/cm2
- 3e12 neq/cm2
- 1e13 neq/cm2

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HPK SiPMs: V_{bd} vs temperature

Breakdown voltage as a function of the temperature
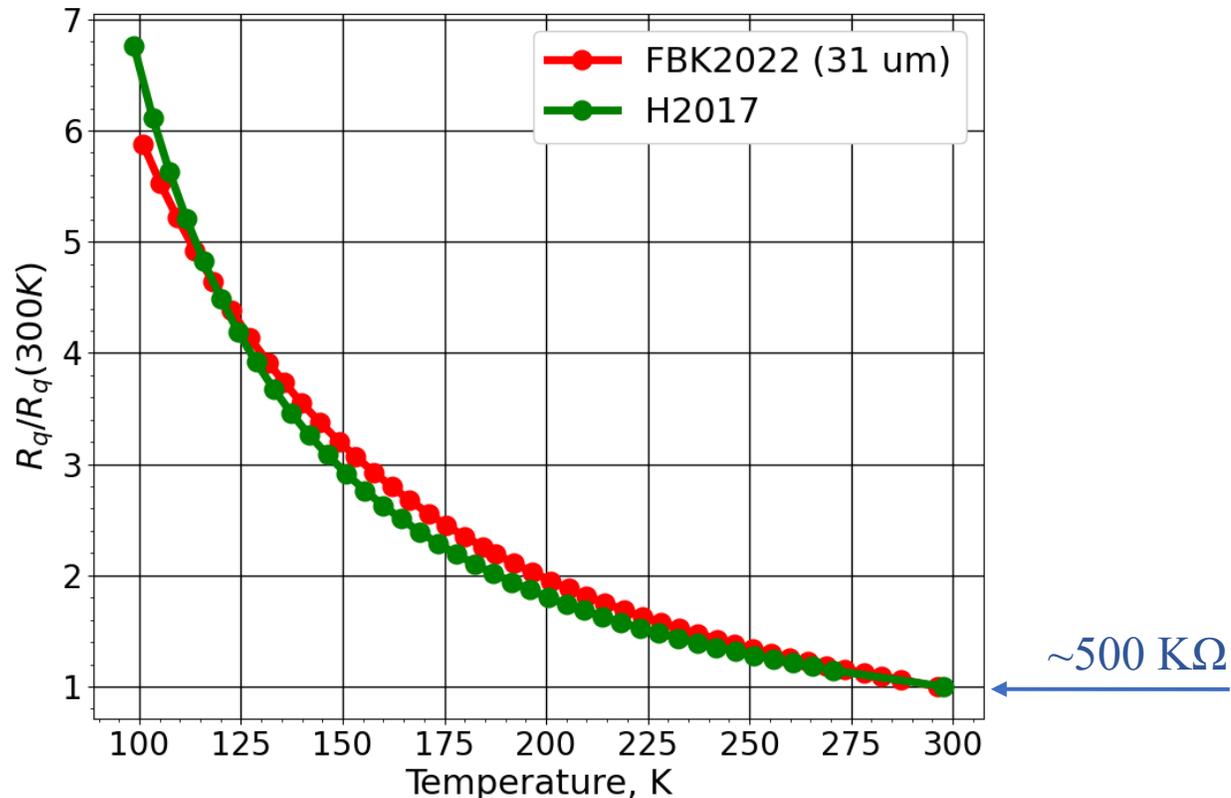
We do not observe any variation with the irradiation fluence (bigger dispersion between different modules ~ 1.0V)

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

Quadratic fit : 8.13e-05x^2+0.0155x+40.24837
Linear fit : 0.05183x+36.20519

Linear fit extrapolation

V_{bd}/T = 51.8 mV/K

H2017_62x57um^2

- 3e11 neq/cm2
- 1e12 neq/cm2
- 3e12 neq/cm2
- 1e13 neq/cm2

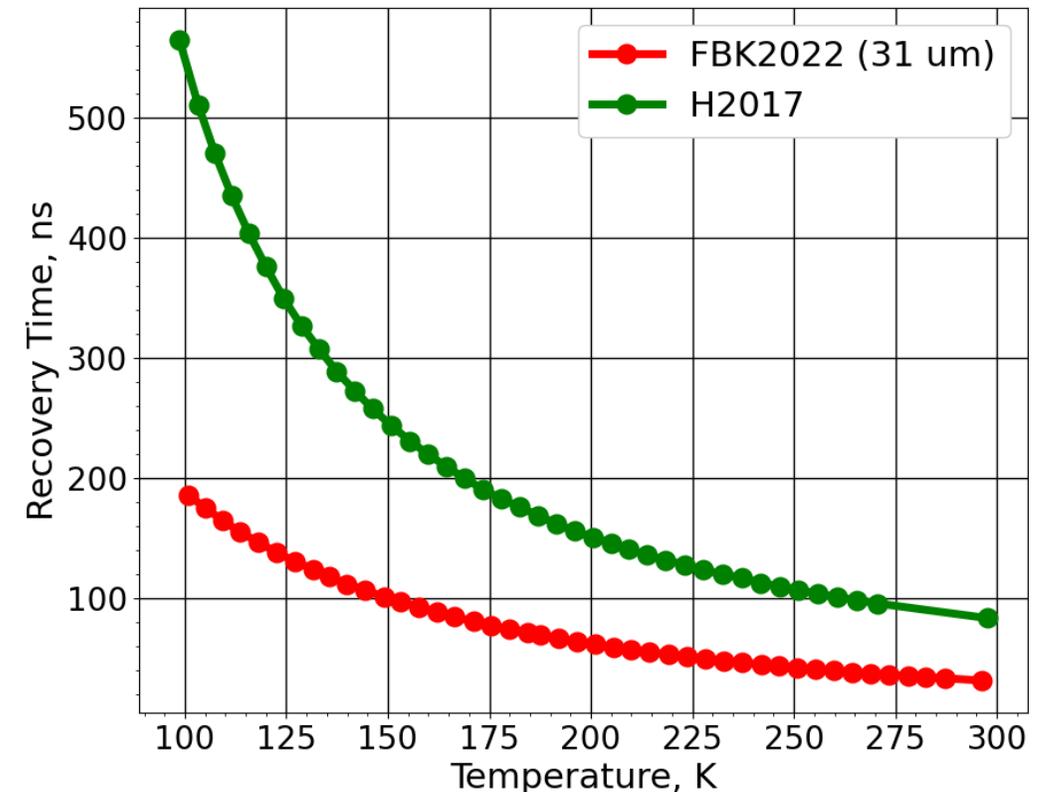*Esteban Currás Rivera (EPFL)*

SiPMs: R_q & T_r vs temperature (unirradiated)

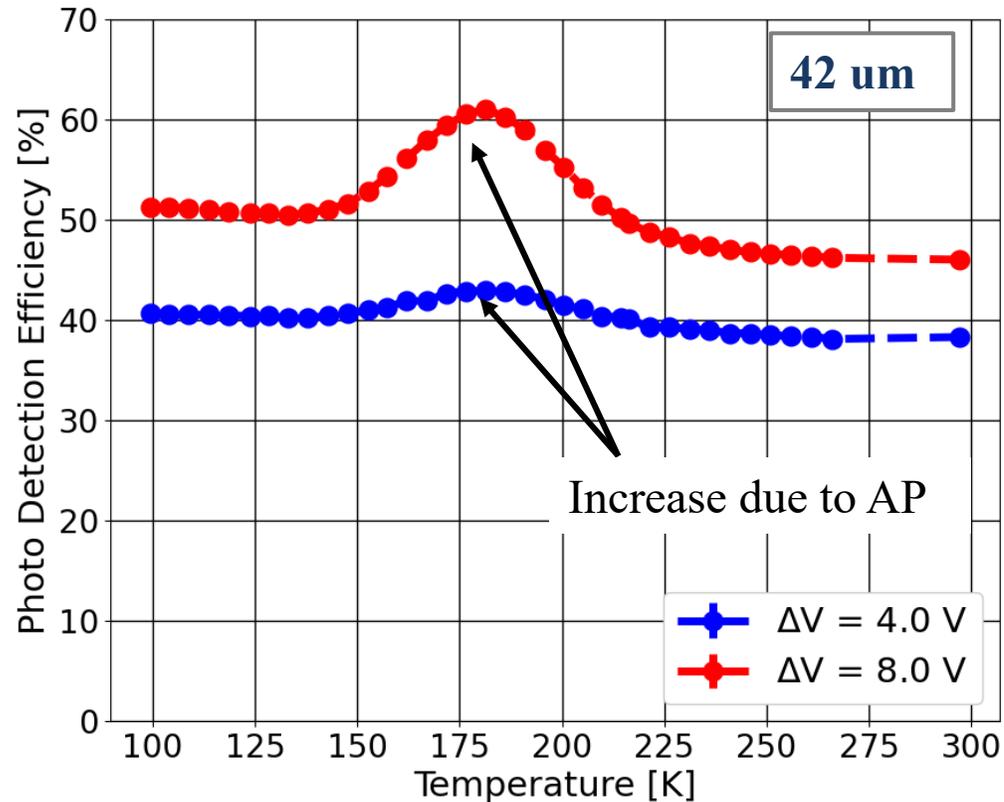**Quenching resistor vs temperature**

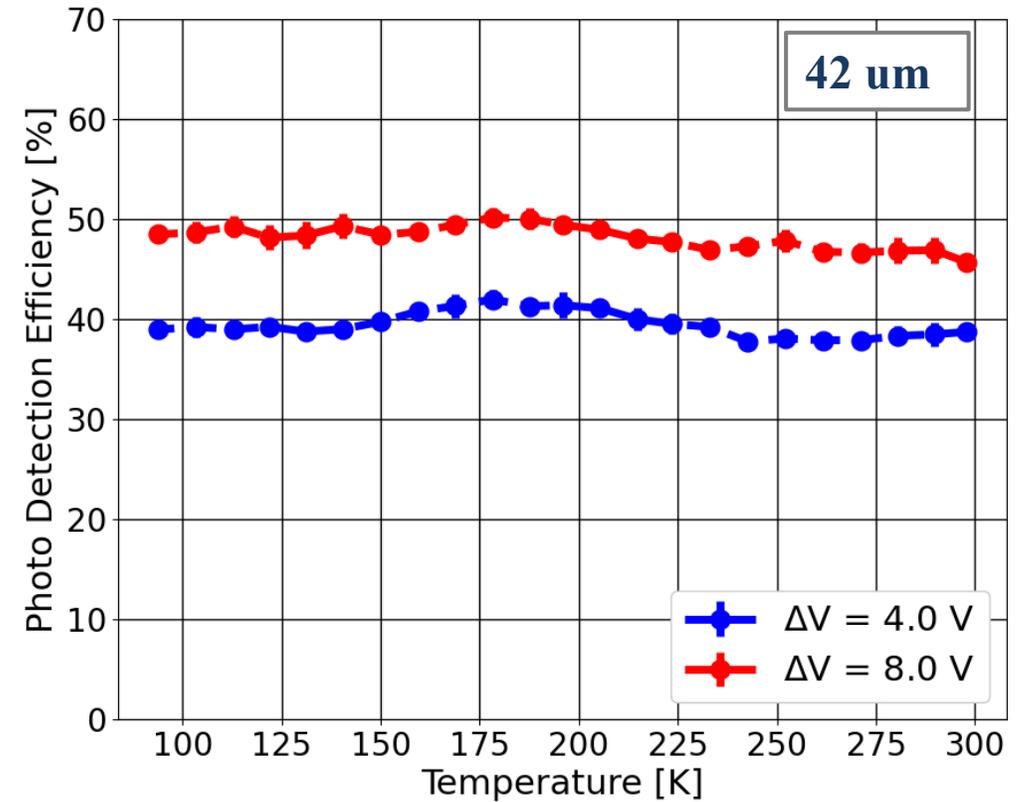**Recovery time vs temperature**

- 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

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FBK SiPMs: PDE vs temperature (unirradiated)

EPFL

Illumination: Monochromator (λ = 450 nm)

42 um

Increase due to AP

Photo Detection Efficiency [%] vs Temperature [K]

- ΔV = 4.0 V
- ΔV = 8.0 V

Illumination: Laser (λ = 450 nm)
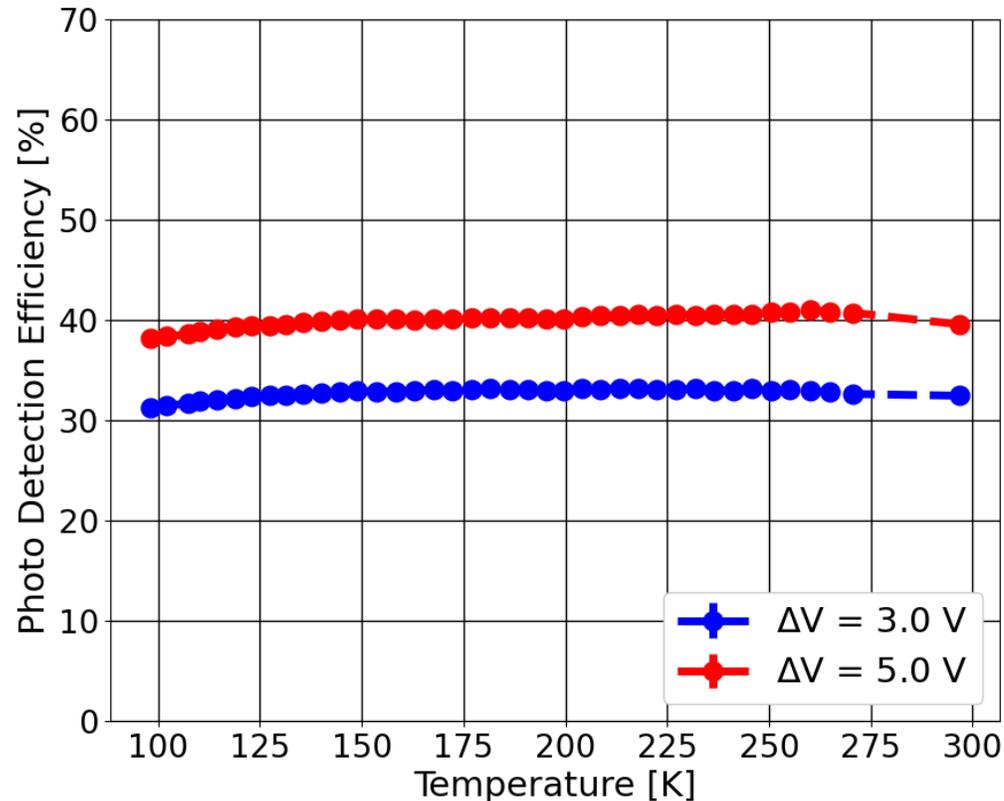

42 um

Photo Detection Efficiency [%] vs Temperature [K]
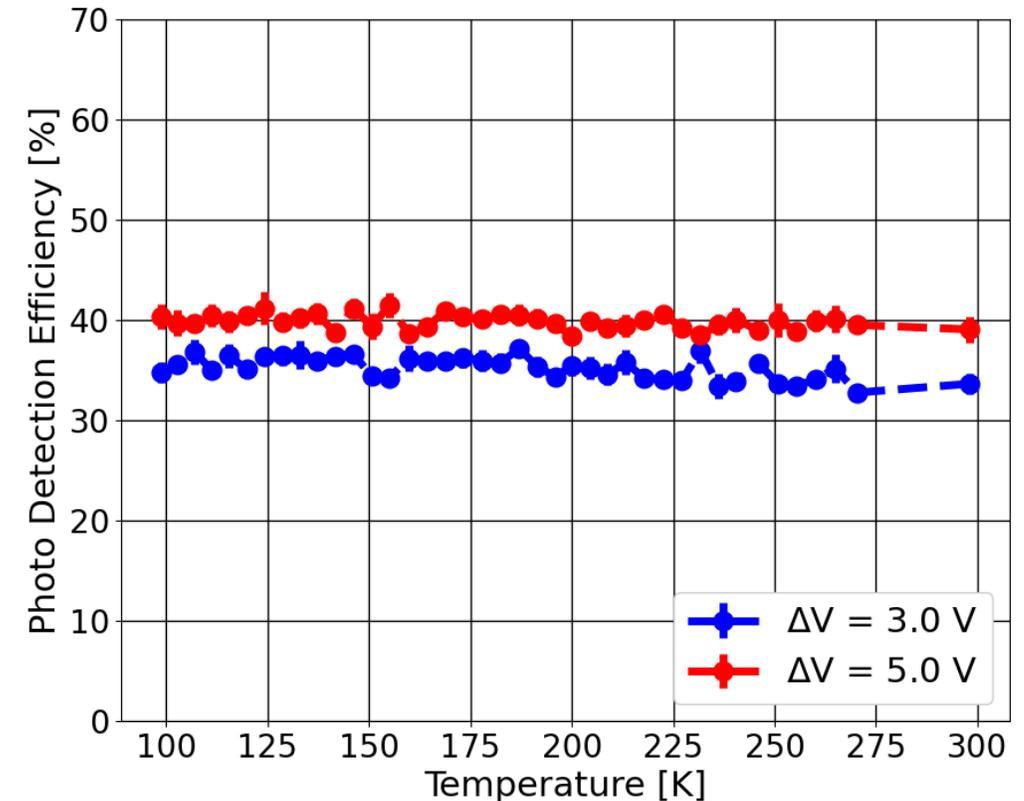
- ΔV = 4.0 V
- ΔV = 8.0 V

- 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)
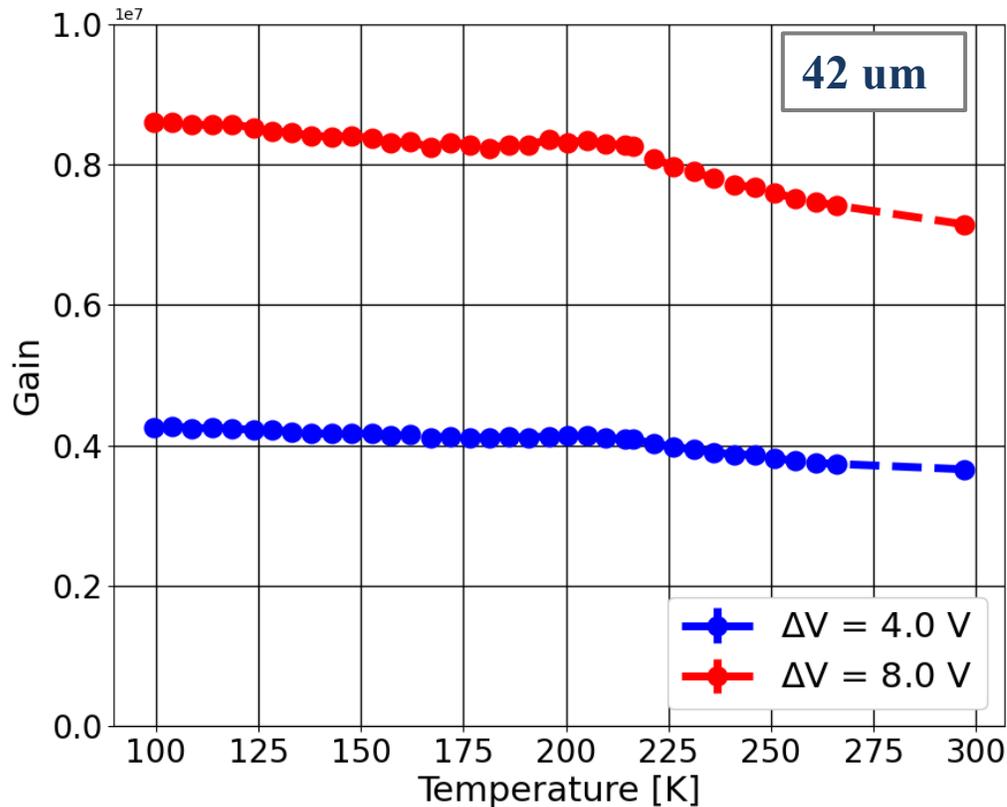
Illumination: Monochromator (λ = 450 nm)
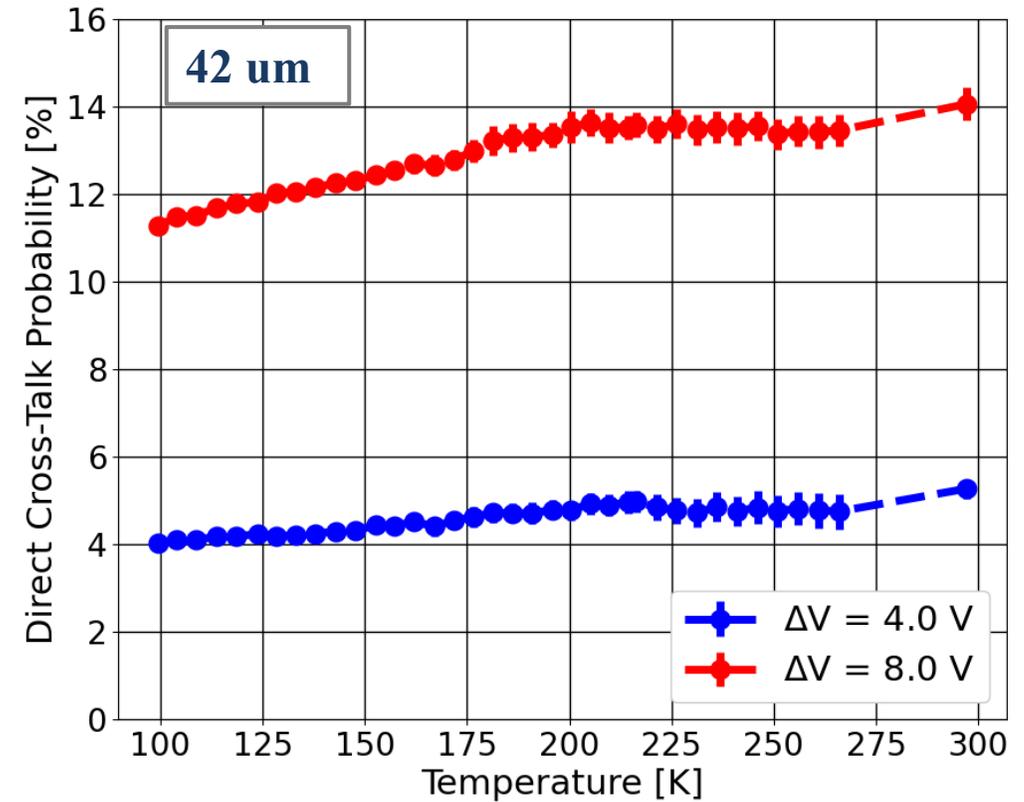
Illumination: Laser (λ = 450 nm)

- 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

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FBK SiPMs: G & DCP vs temperature (unirradiated)

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

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HPK SiPMs: G & DCP vs temperature (unirradiated)
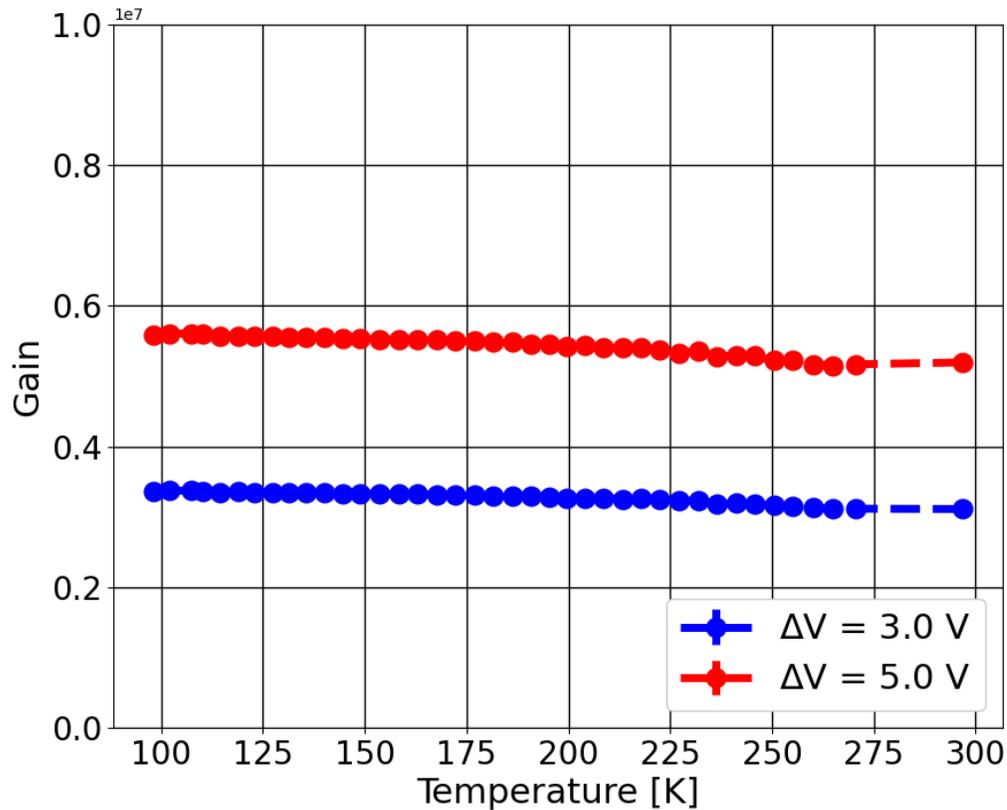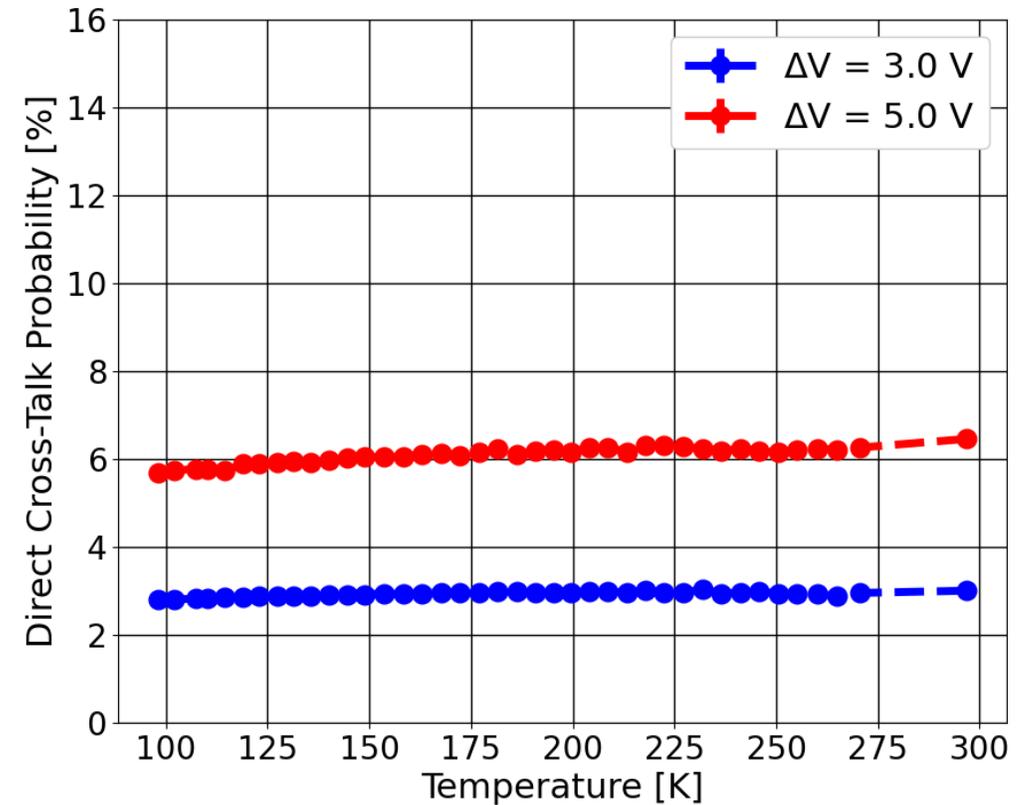
Illumination: Monochromator (λ = 450 nm)
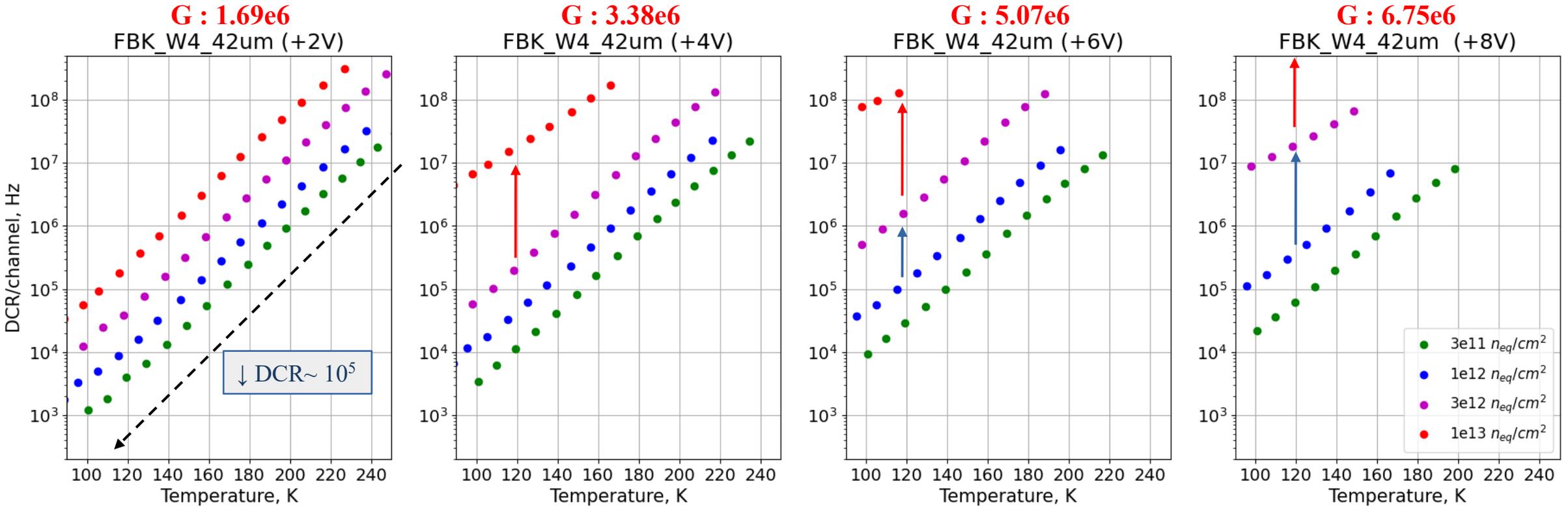
Illumination: Laser (λ = 450 nm)

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

FBK SiPM 42 um: DCR irradiated

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

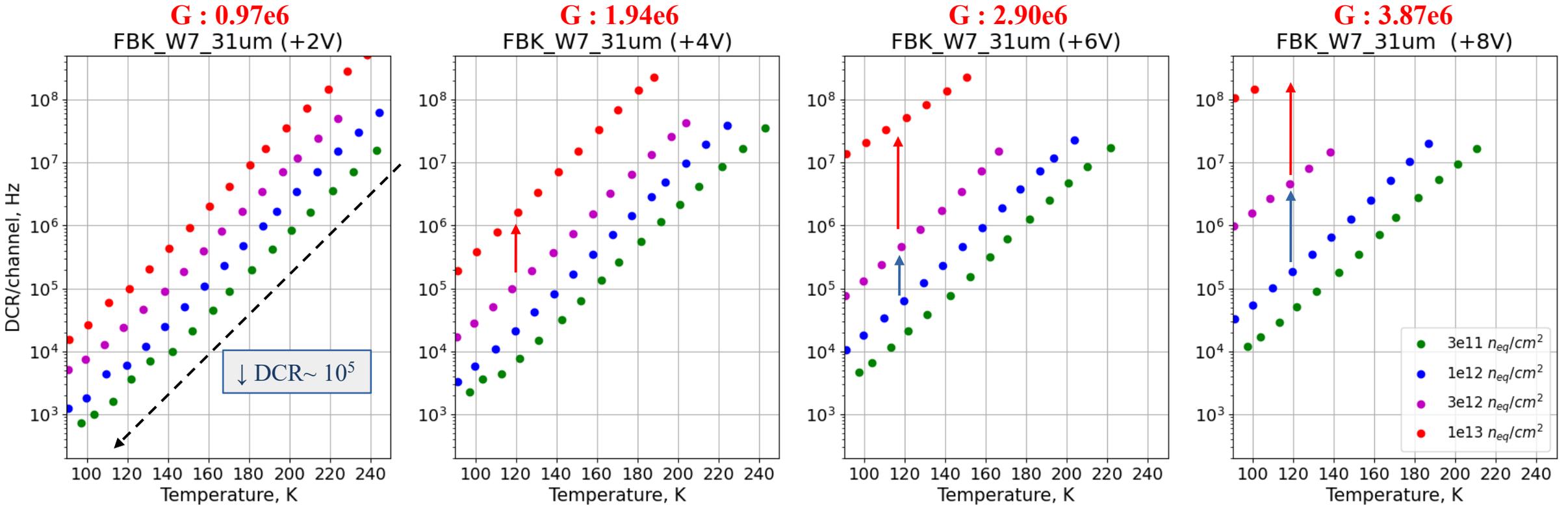DCR as a function of the temperature for different over-voltages:

- DCR 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

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FBK SiPM 31 um: DCR irradiated

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

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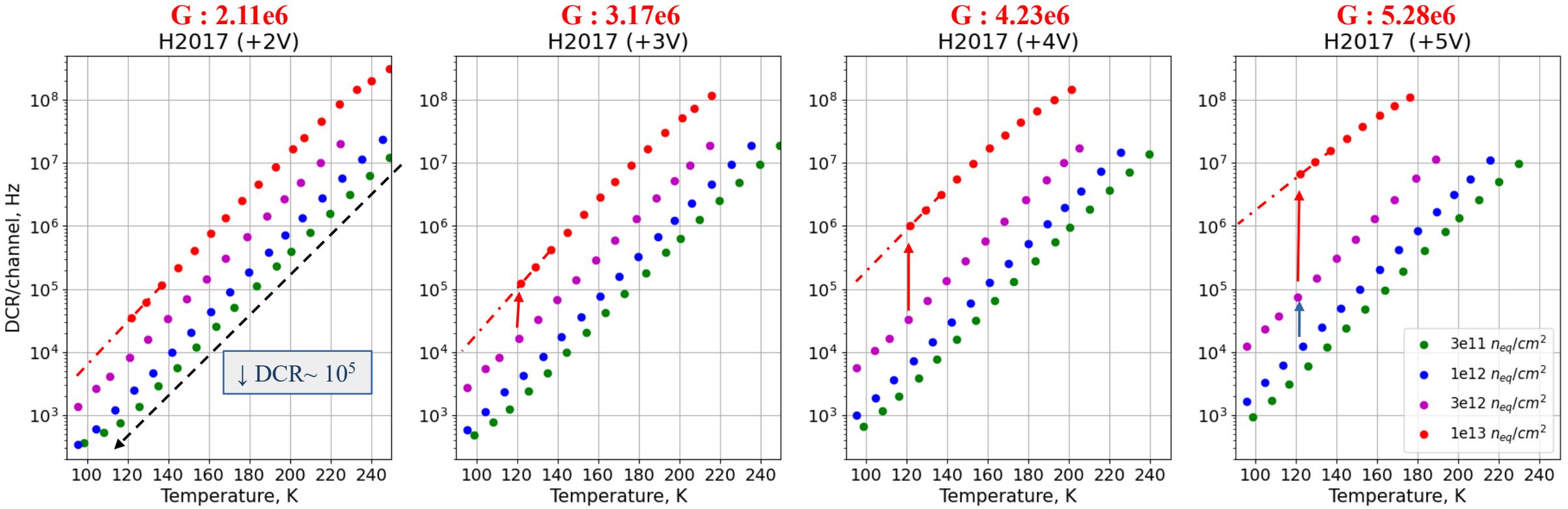

- Same as for 42μm pixel size but NIEL hypothesis valid up to $\sim 3 \times 10^{12}\ n_{eq}/cm^2$
- For the same over-voltage shows lower DCR (smaller pixel size == lower gain)

HPK SiPM: DCR irradiated

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

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

- 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

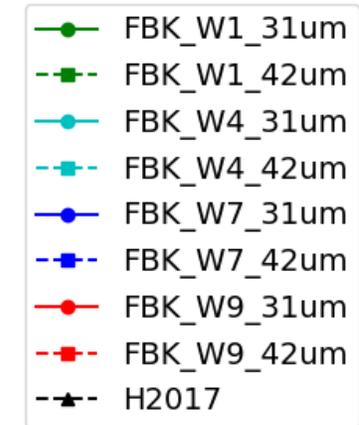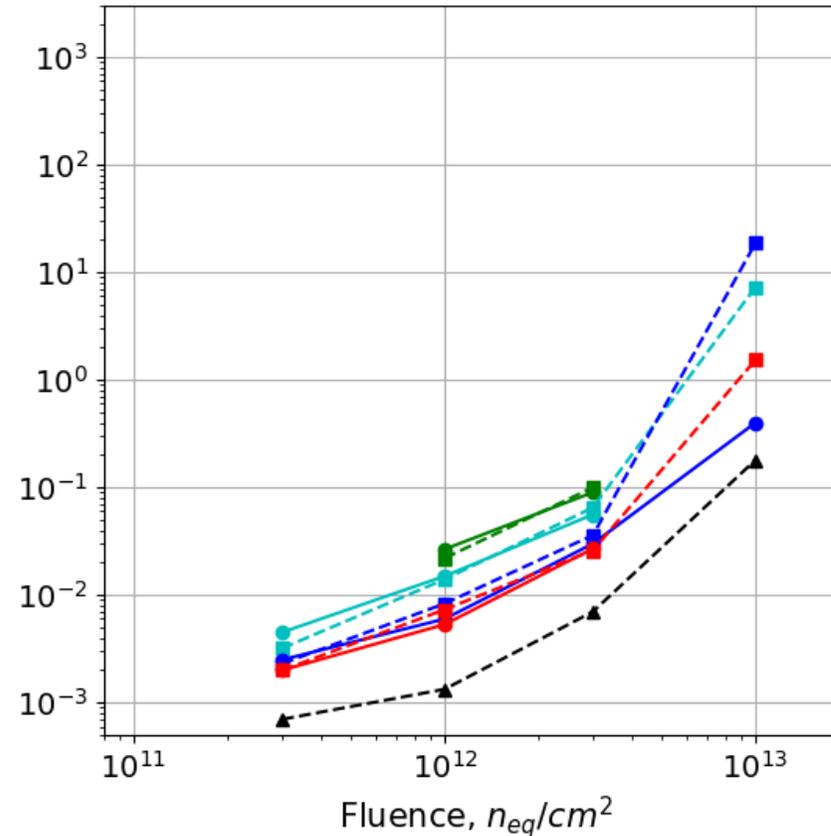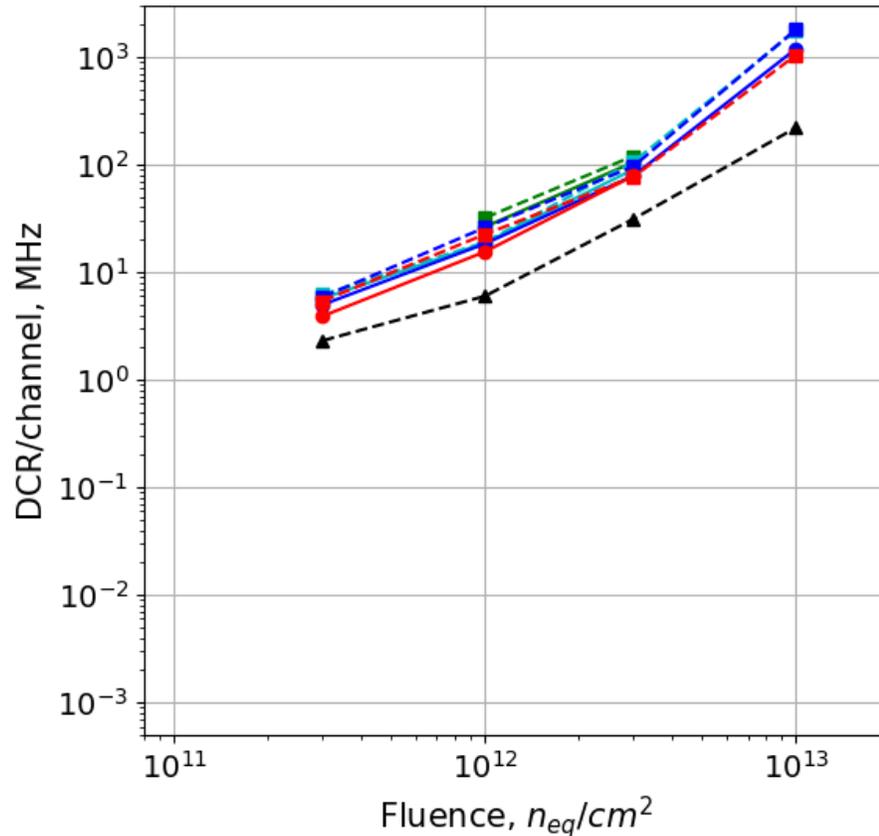Note: values for the fluence of 1×10^{13} extrapolated down to 100K (last measured point at 120 K)

Comparison all SiPMs: DCR vs fluence

LHCb Upgrade I — Temperature: 210 K, ΔV = 4 V

LHCb Upgrade II — Temperature: 100 K, ΔV = 4 V

Legend: FBK_W1_31um, FBK_W1_42um, FBK_W4_31um, FBK_W4_42um, FBK_W7_31um, FBK_W7_42um, FBK_W9_31um, FBK_W9_42um, H2017

- 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!
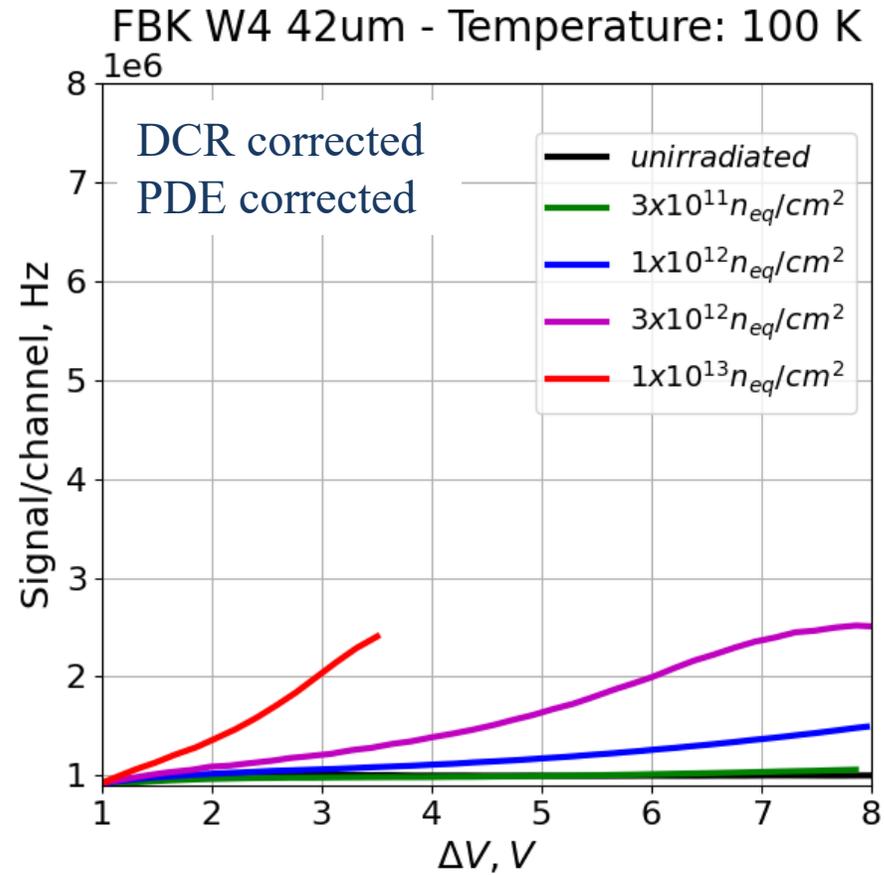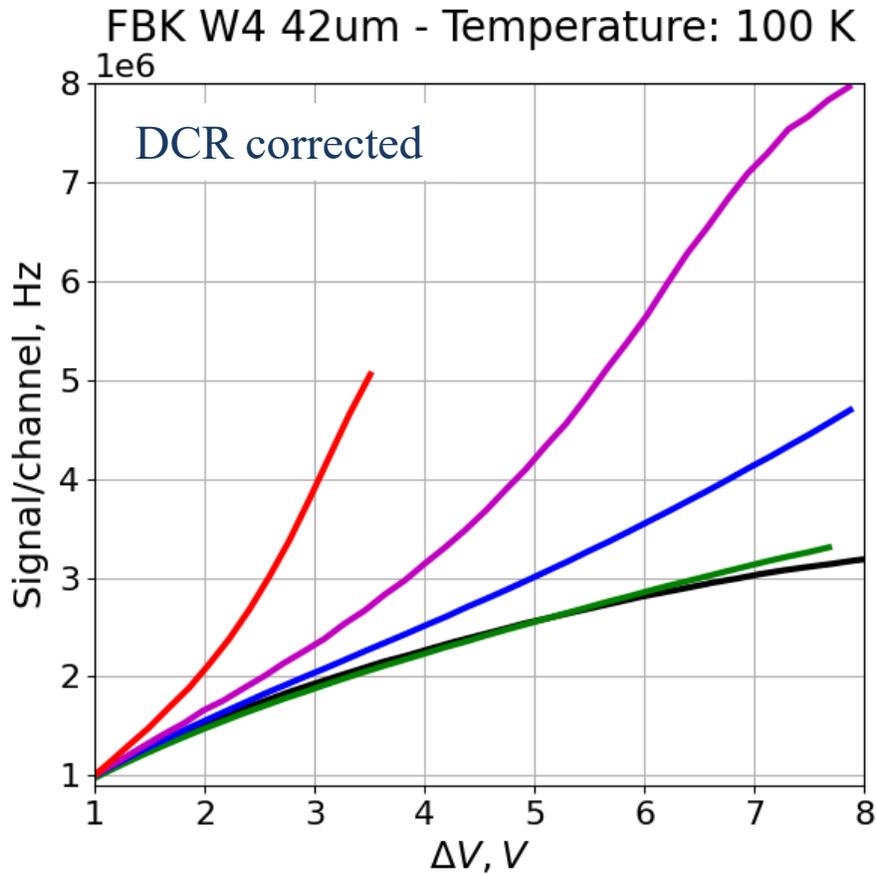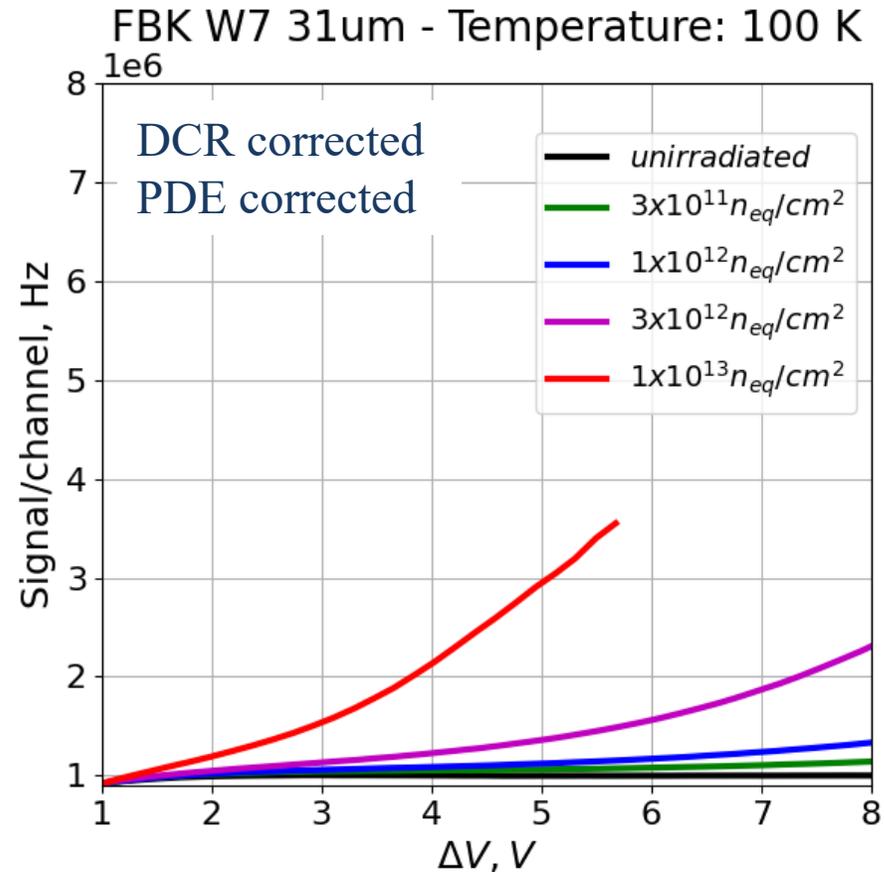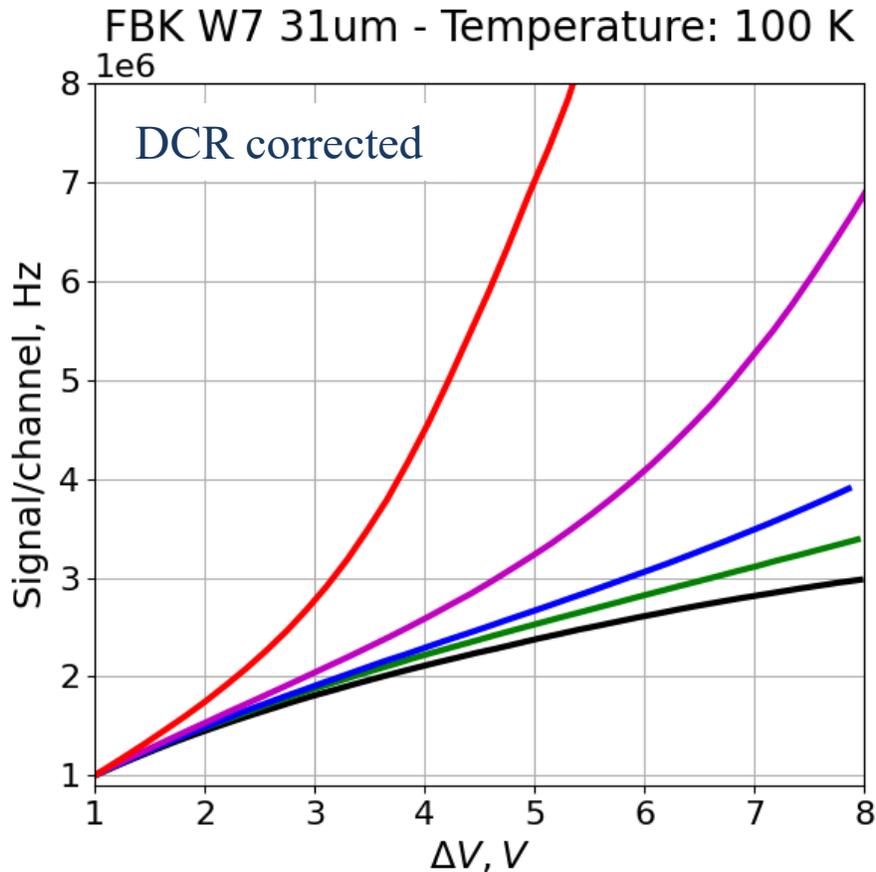
Comparison all SiPMs: DCR vs G

- 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

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FBK SiPM 42 um: Signal vs ΔV at 100 K

FBK W4 42um - Temperature: 100 K

DCR corrected

FBK W4 42um - Temperature: 100 K

DCR corrected
PDE corrected

Legend:
- unirradiated
- $3 \times 10^{11} n_{eq}/cm^2$
- $1 \times 10^{12} n_{eq}/cm^2$
- $3 \times 10^{12} n_{eq}/cm^2$
- $1 \times 10^{13} n_{eq}/cm^2$

- Laser illumination (450 nm) to get a signal rate around 1 MHz/channel
  - All data normalized to 1 MHz/channel for $\Delta V = 1V$.
- After DCR and PDE correction, it is observe an increase in the correlated noise for fluences higher that $1 \times 10^{12} n_{eq}/cm^2$.
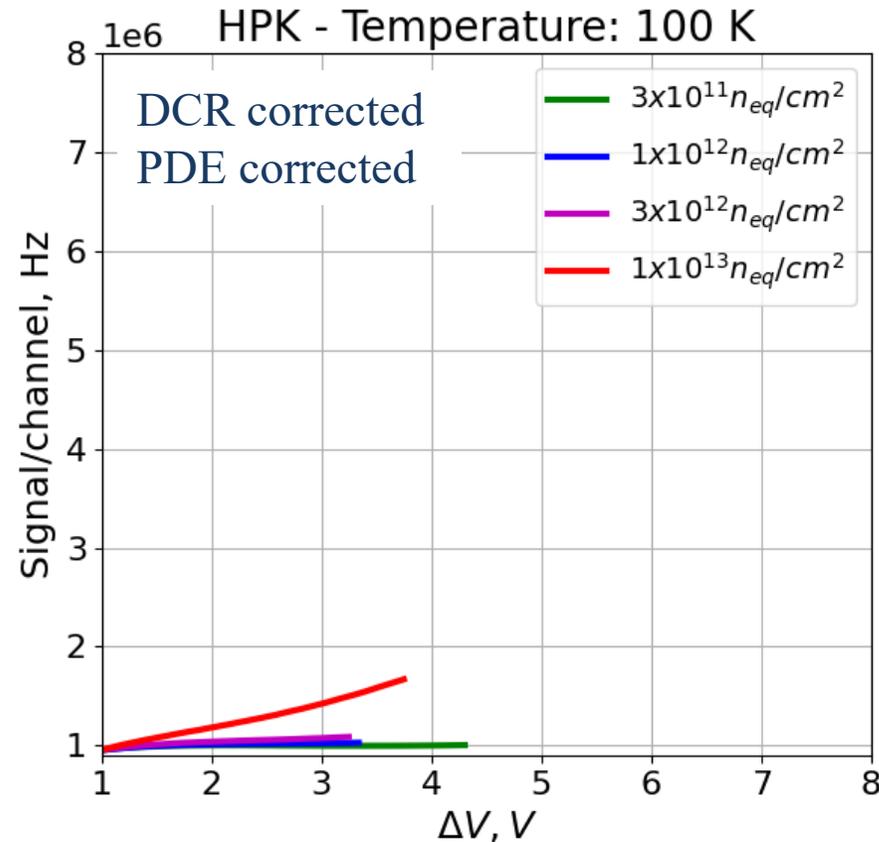
FBK SiPM 31 um: Signal vs Δ V at 100 K

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

HPK SiPM: Signal vs Δ V at 100 K
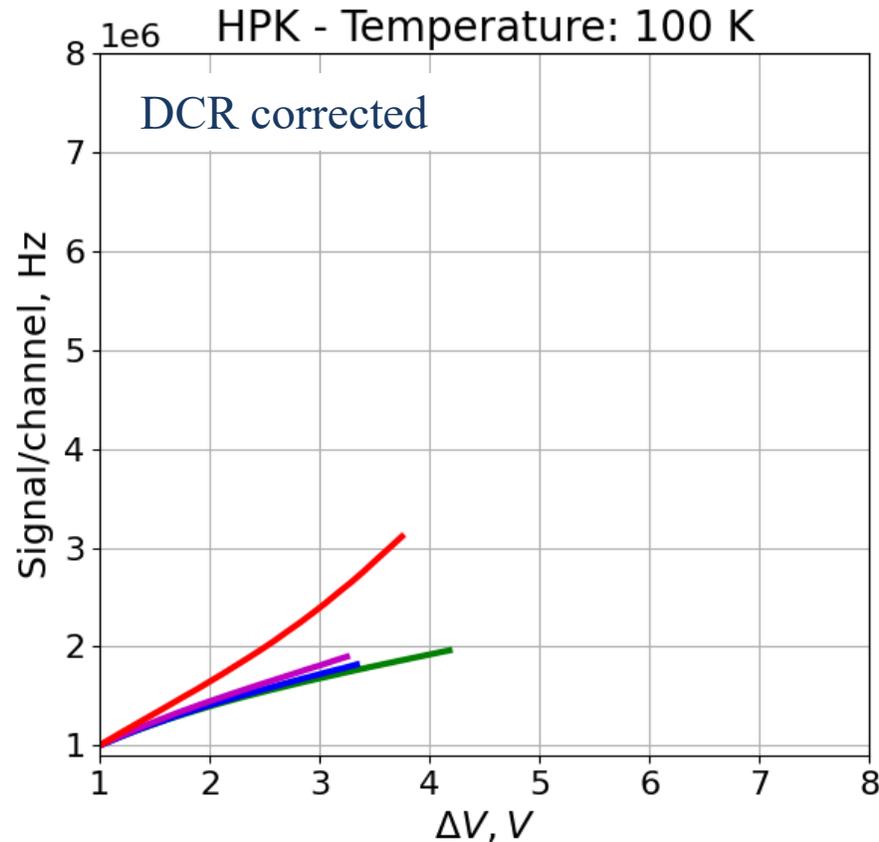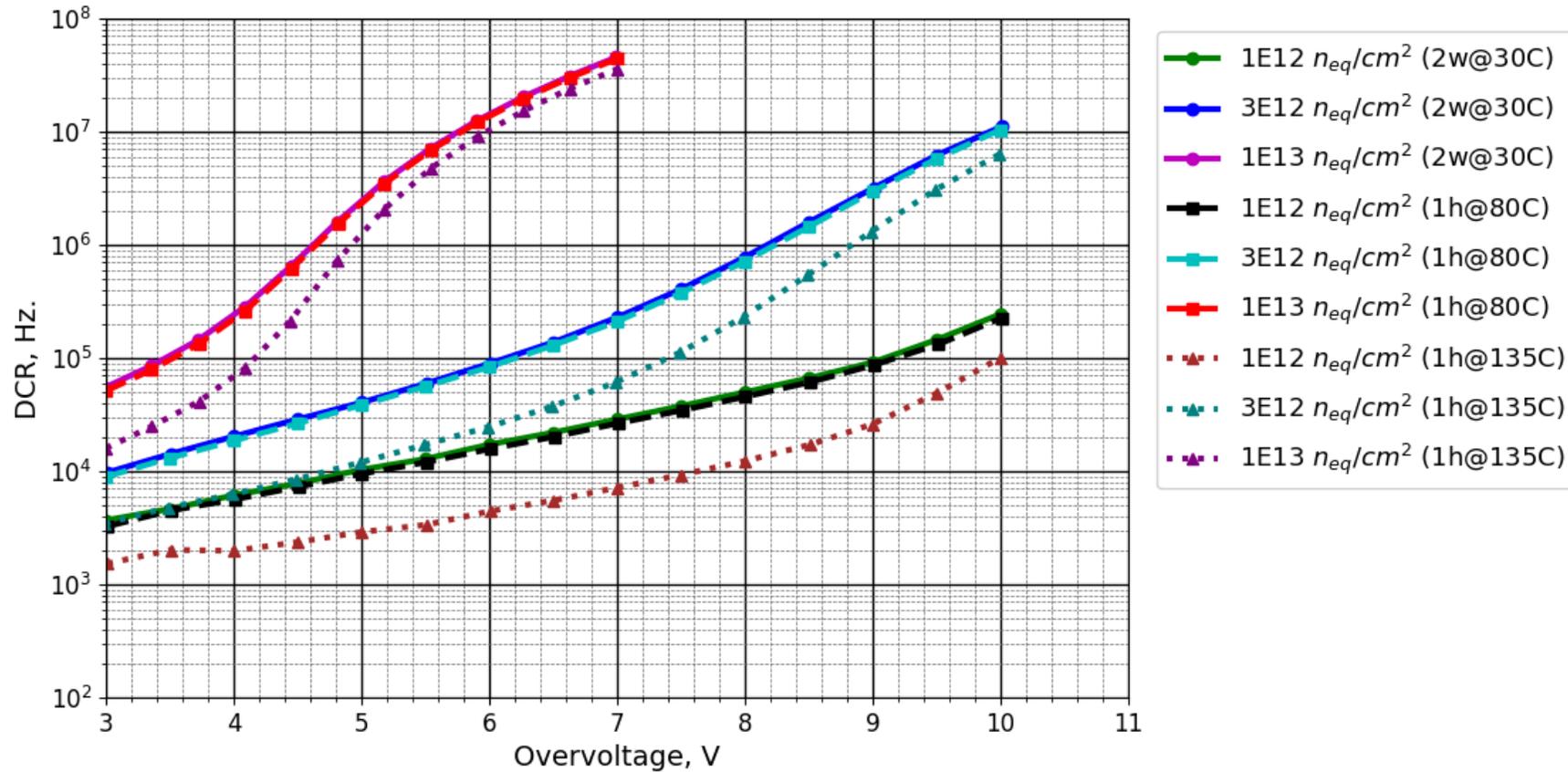
- Laser illumination (450 nm) to get a signal rate around 1 MHz/channel
  - All data normalized to 1 MHz/channel for ΔV = 1V
- After DCR and PDE correction, it is observe an increase in the correlated noise for fluences higher that $3 \times 10^{12}\, n_{eq}/cm^2$

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

FBK_W7_31um: dark excess noise (100 K)

Legend:
- 1E12 n_{eq}/cm^2 (2w@30C)
- 3E12 n_{eq}/cm^2 (2w@30C)
- 1E13 n_{eq}/cm^2 (2w@30C)
- 1E12 n_{eq}/cm^2 (1h@80C)
- 3E12 n_{eq}/cm^2 (1h@80C)
- 1E13 n_{eq}/cm^2 (1h@80C)
- 1E12 n_{eq}/cm^2 (1h@135C)
- 3E12 n_{eq}/cm^2 (1h@135C)
- 1E13 n_{eq}/cm^2 (1h@135C)

- 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

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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 ~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 ~1×10^{12} n_{eq}/cm^2 and signal correlated noise increase beyond fluences of ~3×10^{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

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Acknowledgments:

EPFL

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Back up

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SiPM modules irradiated at Ljubljana

EPFL

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

$\rightarrow 3\times10^{11}$ n_{eq}/cm^2, 1×10^{12} n_{eq}/cm^2, $\mathbf{3\times10^{12}}$ $\mathbf{n_{eq}/cm^2}$ and 1×10^{13} n_{eq}/cm^2

After irradiation, an annealing of 2 weeks at 30ºC 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

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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

$$ILD = \left(\frac{d\ln[I(V)]}{dV}\right)^{-1} \equiv \left[\frac{1}{I} \cdot \frac{dI(V)}{dV}\right]^{-1}$$
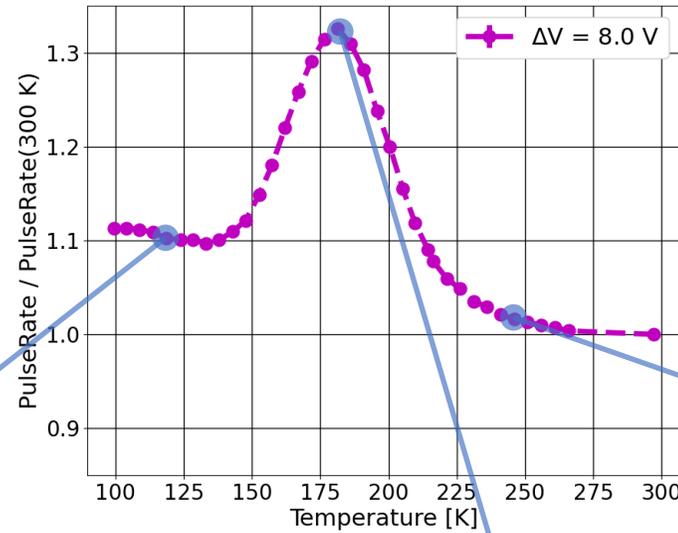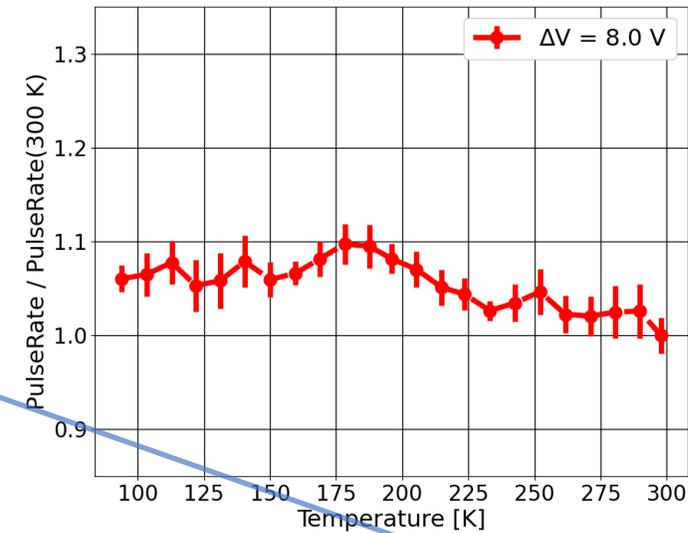
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Detector:
FBK_W3_42um_003_Flat

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.
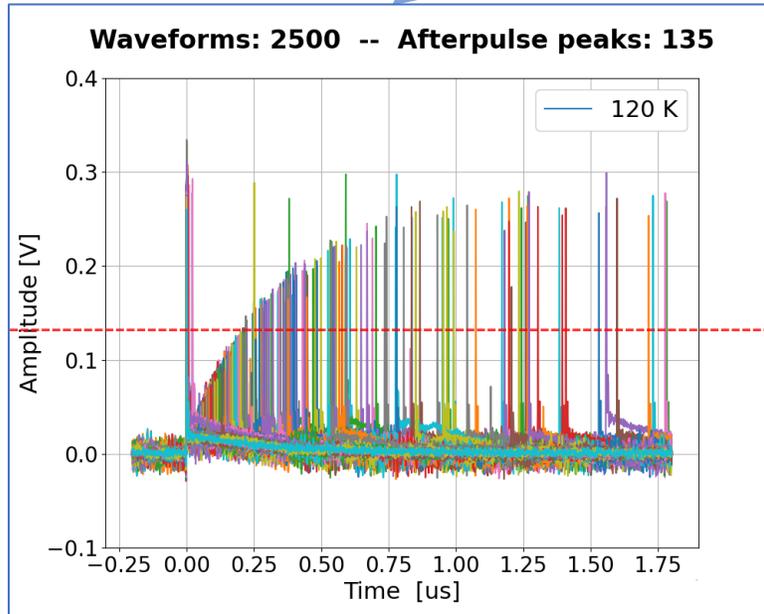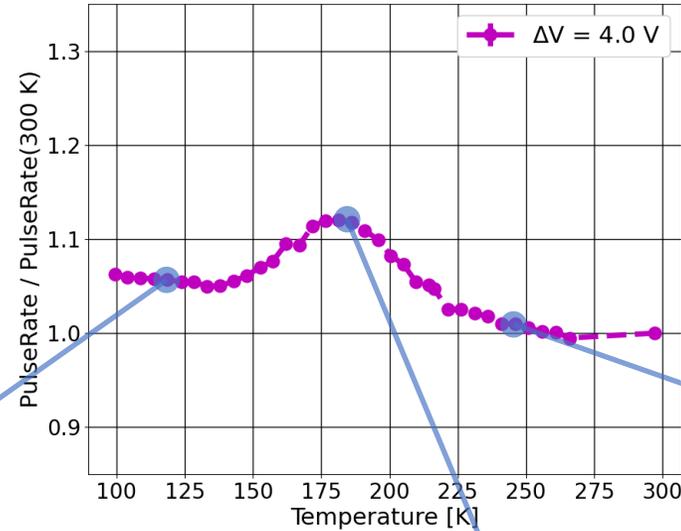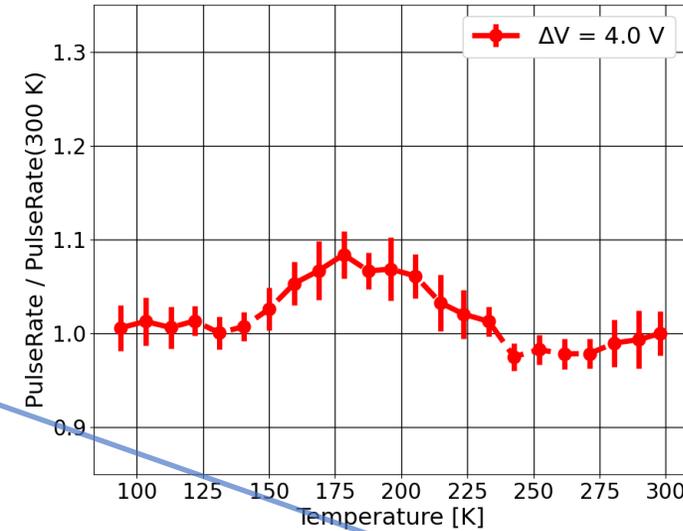

Illumination: Monochromator (λ = 450 nm)

Illumination: Laser (λ = 450 nm)

AP = 5.4%

AP = 22.1%

AP = 1.3%

Esteban Currás Rivera (EPFL)

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.
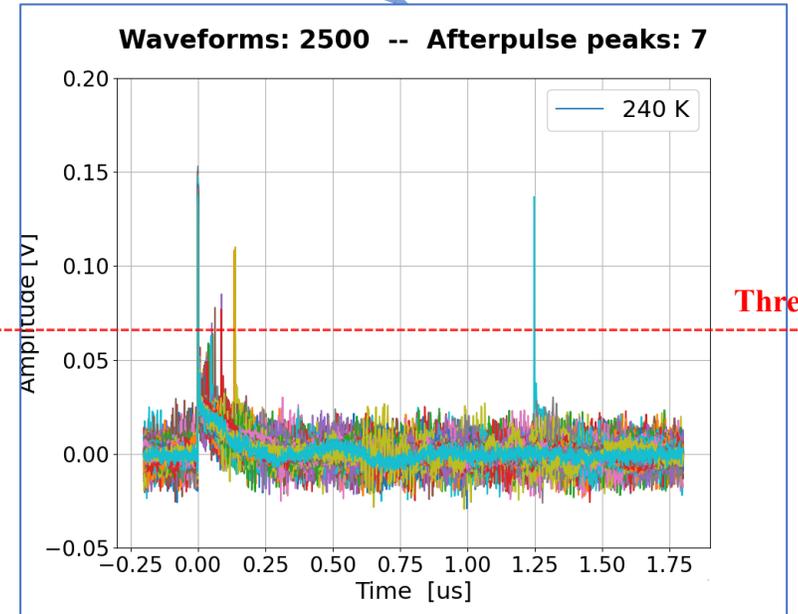

EPFL
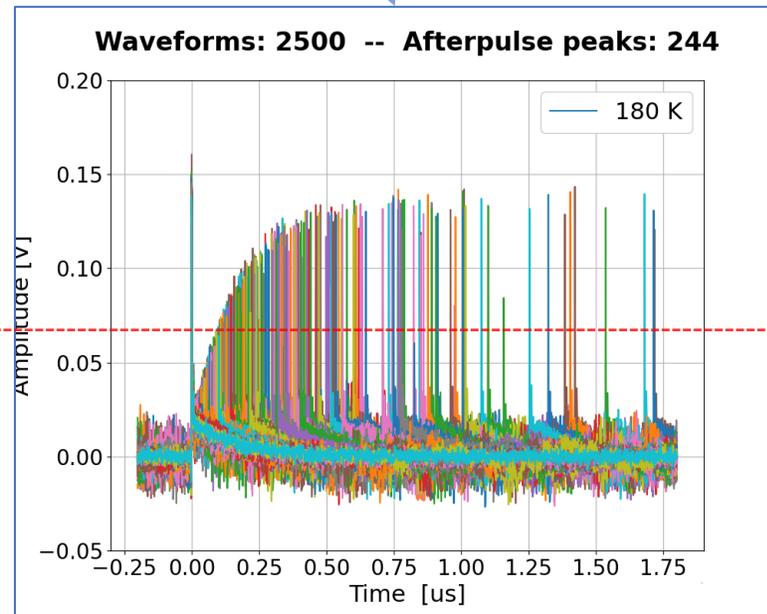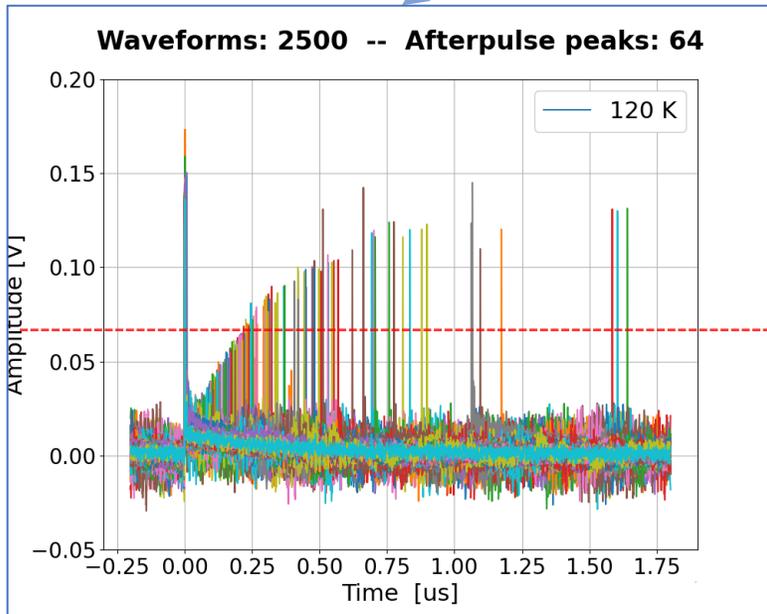
Illumination: Monochromator (λ = 450 nm)

Illumination: Laser (λ = 450 nm)

AP = 2.6%

AP = 9.8%

AP = 0.3%