SiPM and CMOS SPAD characterization at liquid nitrogen temperatures

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Overview

- Background
  - future RICH detectors present high photodetector requirements
- spadRICH project
  - developing rad-hard digital analog SiPM
- CMOS SPADs characterization results
  - Previous results (180 nm, 55 nm SPADs)
  - Cryogenic characterization setup
  - Preliminary results for 10 SPAD samples
    - 55 nm (irradiated), 110 nm (non irradiated)
- Summary

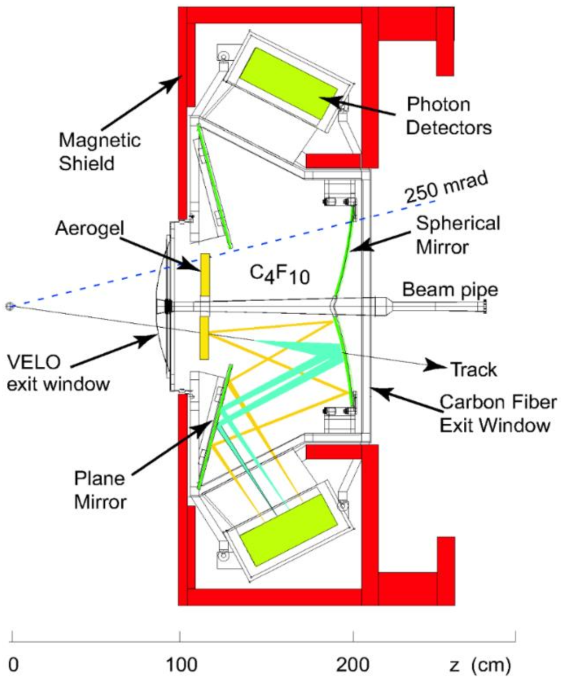
Abbreviations:

SPAD: single photon avalanche photodiode
SiPM: silicon photomultiplier
Vbr: breakdown voltage
OV: over-voltage, excess bias
DCR: dark count rate
PDP: photon detection probability
PDE: photon detection efficiency (=PDP * geometric efficiency)

Background

- Planned upgrades of Ring Imaging Cherenkov (RICH) detectors
  - **LHCb**, Belle II, ALICE3
- High performance requirements for photodetectors
- **Silicon Photomultiplier (SiPM)**
  - main candidate
  - main issue: **neutron radiation damage**

LHCb RICH1:



LHCb RICH Upgrade II Photodetector Requirements	
Radiation hardness	**2 x 10^{13} neutron eq/cm^2** 12 kGy TID 1 x 10^{13} HEH (>20 MeV)/cm^2
Timing	**100 ps FWHM SPTR** few ns gate / 25 ns (40 MHz bunch-crossing)
Maximum occupancy	**30%** 1-photon hit probability / mm^2 /25 ns
Total area	1.5 m^2 + 2 m^2
Granularity	1.4x1.4 mm^2 / 2.8x2.8 mm^2
PDE	50% @ 400 nm
DCR	~100 kHz – 1 MHz/mm^2
Cooling	100K (liquid nitrogen cooling) considered as an option
Annealing	In situ annealing considered

spadRICH Project

- Develop radiation-hard photosensor optimized for RICH application
- Based on SiPMs including reconfigurable electronics → **digital analog SiPM**

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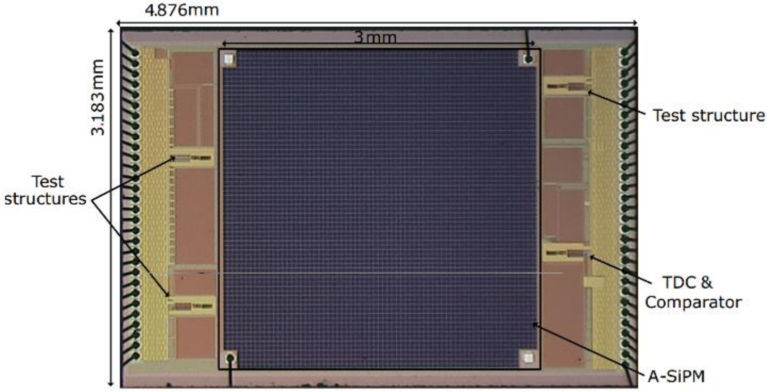
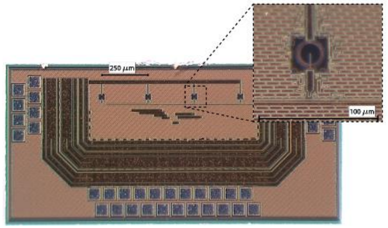


- Radiation hardness achieved by means of:
  - rad-hard design techniques at transistor and SPAD level
  - integrated compensating electronics → switch off noisy SPADs, employ active recharge and custom hold-off times
  - microlenses → smaller SPADs

- Possible SPAD/architecture optimizations in a RICH detector scenario:
  - limited photon angular acceptance (NA) → reduce SPAD size (DCR↓), compensate with microlenses
  - timing resolution, gated operation → reduce DCR and data rates
  - cryogenic (liquid nitrogen) operation → reduce DCR, but potential increase in afterpulsing (irradiated samples)

Previous Results - 180 nm CMOS SPADs

- SPADs: 25 µm diameter, passively quenched/actively recharged
- Neutron irradiated at JSI TRIGA reactor up to 10^{12} 1-MeV neutron equivalent/cm^2



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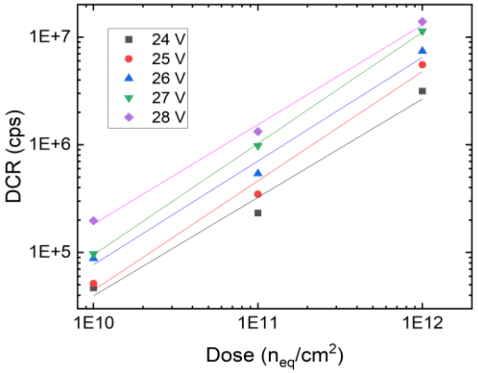
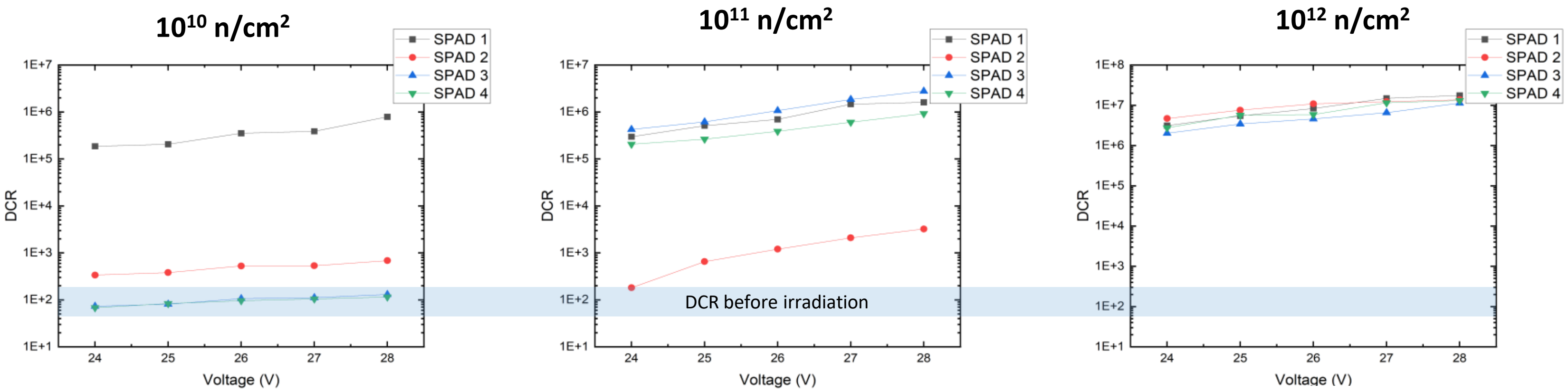
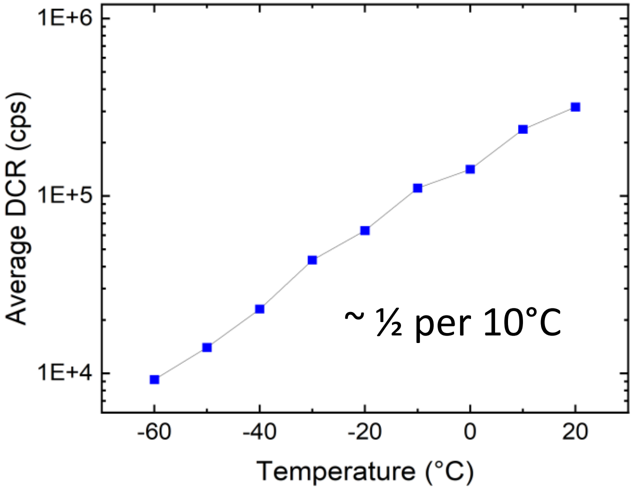
DOI: 10.3390/s22082919
IEEE NSS/MIC 2023 N-01-135

Dark count rate (DCR) of 4 SPADs/chip:

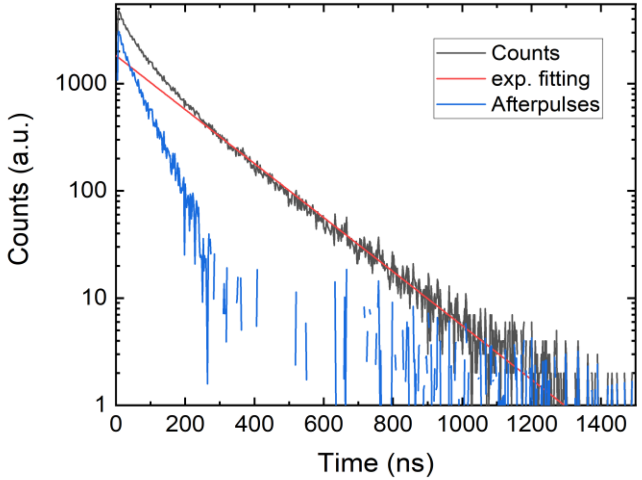




Cooling (10^{11} n/cm^2, average, after 2w RT annealing):



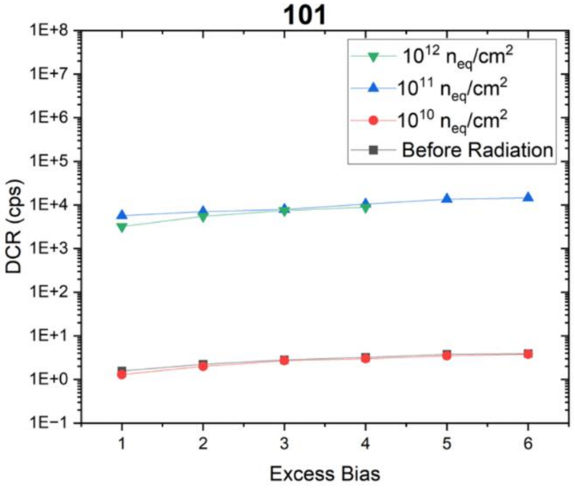
Afterpulsing probability: (10^{12} n/cm^2)

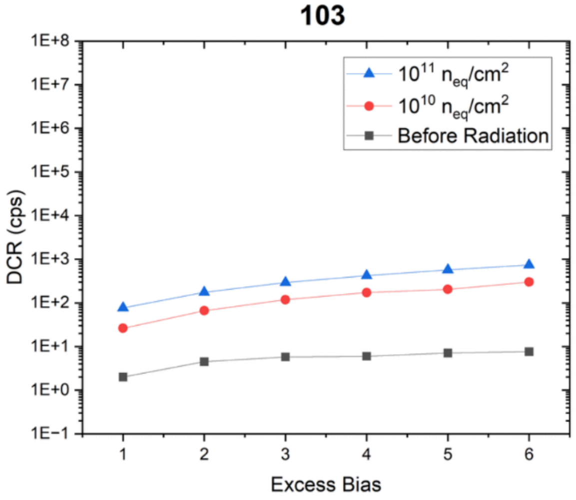


Previous Results - 55 nm CMOS SPADs

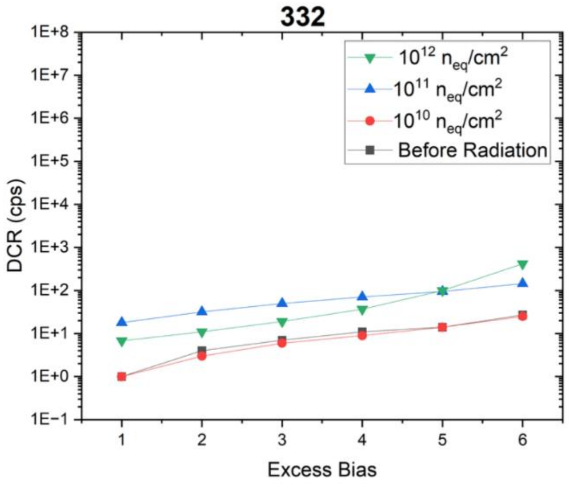
Total SPAD diameter: 8 µm | 9 µm | 10 µm | 12 µm

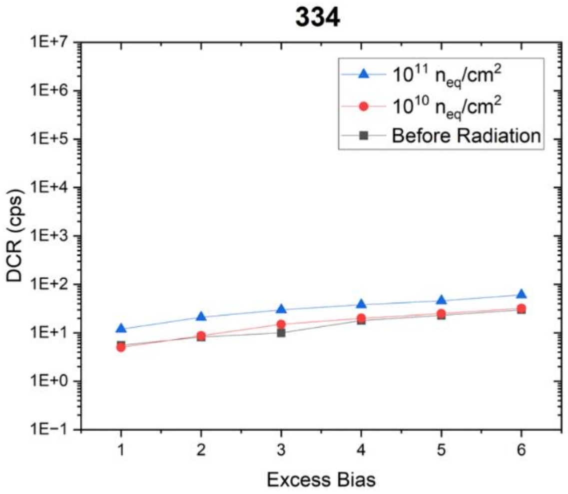
PN junction

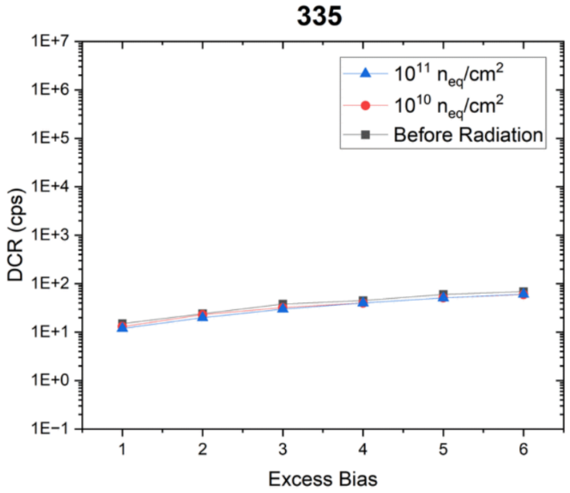




NP junction







NB: active area changes between samples

Cryogenic SPAD characterization

- Study different SiPM technologies (SPADs, micro-lenses, electronics…)
  - Before and after neutron irradiation
  - At stabilized temperatures between room temperature (RT) and liquid nitrogen (LN) temperatures

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- Can measure
  - IV curves
  - Threshold scans (rate vs. threshold) → This presentation
  - Waveform analysis (DRS4 chip)

Poster: Radiation hardness and annealing study of neutron-irradiated silicon photomultipliers

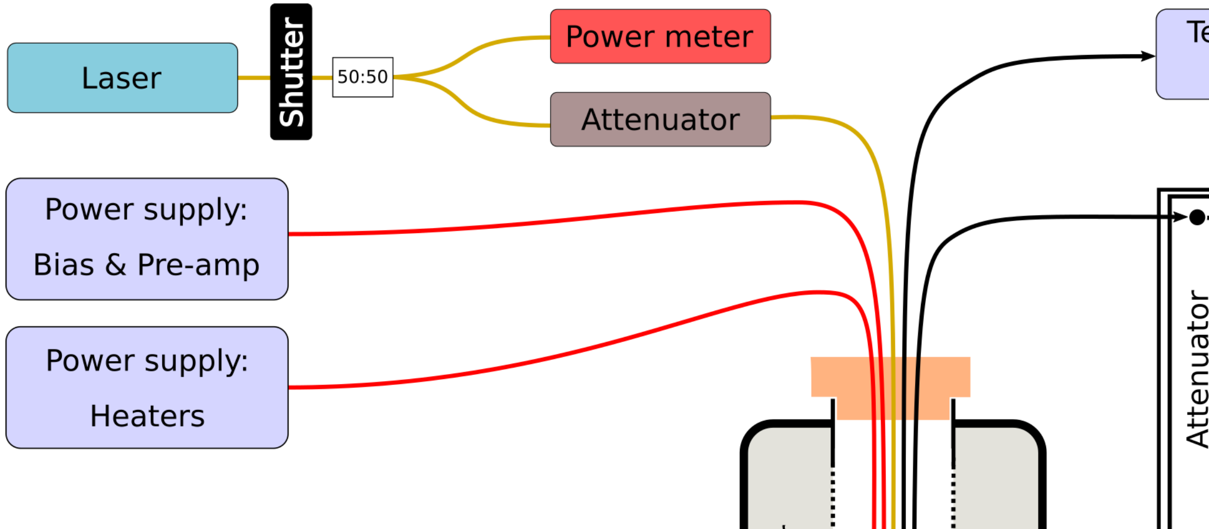
- Limitations:
  - Measurement time: max. 2 SPADs/day
  - Lowest measurable DCR: individual count measurement of 1 s
  - PDP results affected by optical fiber movements (when moving into LN after RT measurement)

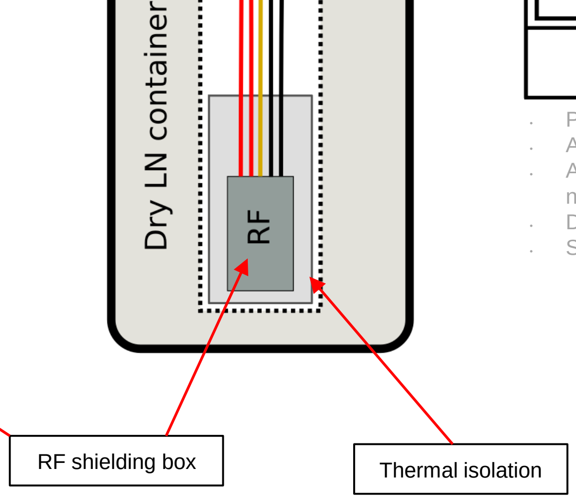
Experimental setup

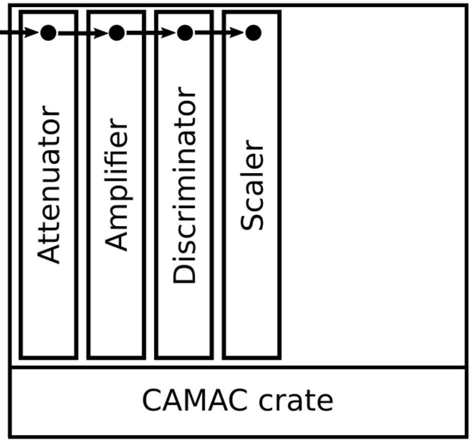
- SPAD samples:

Technology	Label	Junction	Diameter [mum]	# of samples
55 nm	101	PN	5	3
	102	PN	5	
	103	PN	7	
	104	PN	7	
	331	NP	2	
	332	NP	2	
	333	NP	4	
	334	NP	4	
	335	NP	5	
	336	NP	5	
110 nm	523	N+	10	3
	524	N+	10	
	523005	N+	5	
	523025	N+	25	
	527	N+	10	
	405	N+	10	
	406	N+	10	
	13	N+	10	
	107	P+	10	
	108	P+	10	
	115	P+	10	
	108005	P+	5	
	115005	P+	5	

- Laser: ALPHALAS Picosecond Laser Diode PLDD-20 M (**405 nm**)
- Optical power meter: Thorlabs S150C + PM101A (350 -1100nm, 100 pW - 5 mW)
- Optical splitter: Thorlabs TM200R5F1A (50:50 split, 200 mum, 0.22NA multimode fibers)
- Optical attenuation: ND filters + Thorlabs VOAMMF variable optic attenuator

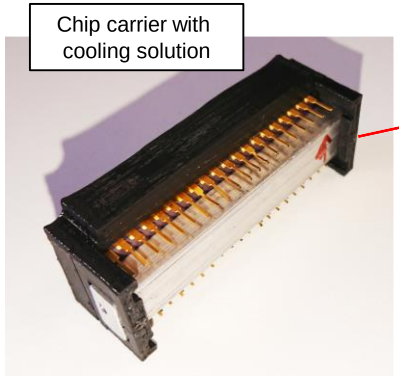


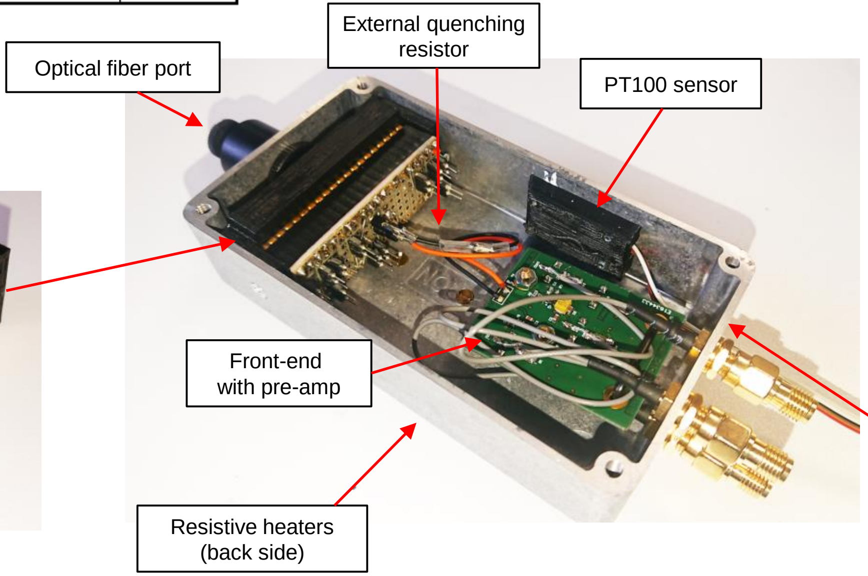




- Pre-amp: NEC muPC2710TB (1GHz bandwidth, 33dB)
- Attenuator: Phillips Scientific 804
- Amplifier: ORTEC FTA820 (350MHz bandwidth, 200x, inverting or non-inverting)
- Discriminator: Phillips Scientific 7106 (140MHz frequency
- Scaler: CAEN C 257 (24 bit counter, 100 MHz frequency)

- SPAD samples wire bonded on chip carrier

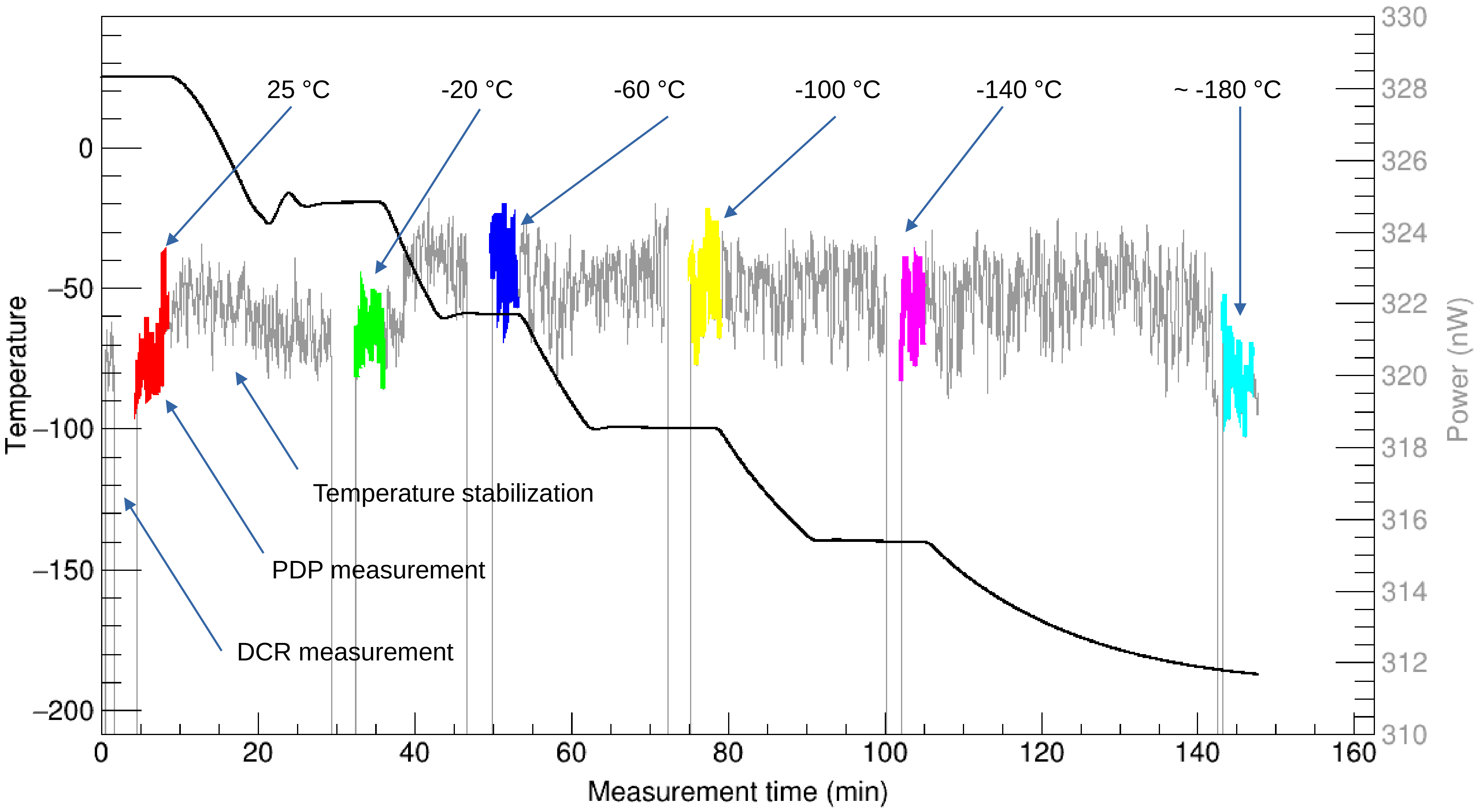




- Optical attenuation adjusted so laser @ 100 kHz rate results in ~1kHz SPAD rate above DCR
- PC controlled shutter for DCR measurements
- Scaler settings: 1 s count time, 10 mV threshold steps
- BR and temperature coefficient estimated on-the-fly
- Measurement started 10 min after temperature stabilized (distance between PT100 and SPAD)

Measurement protocol and monitoring

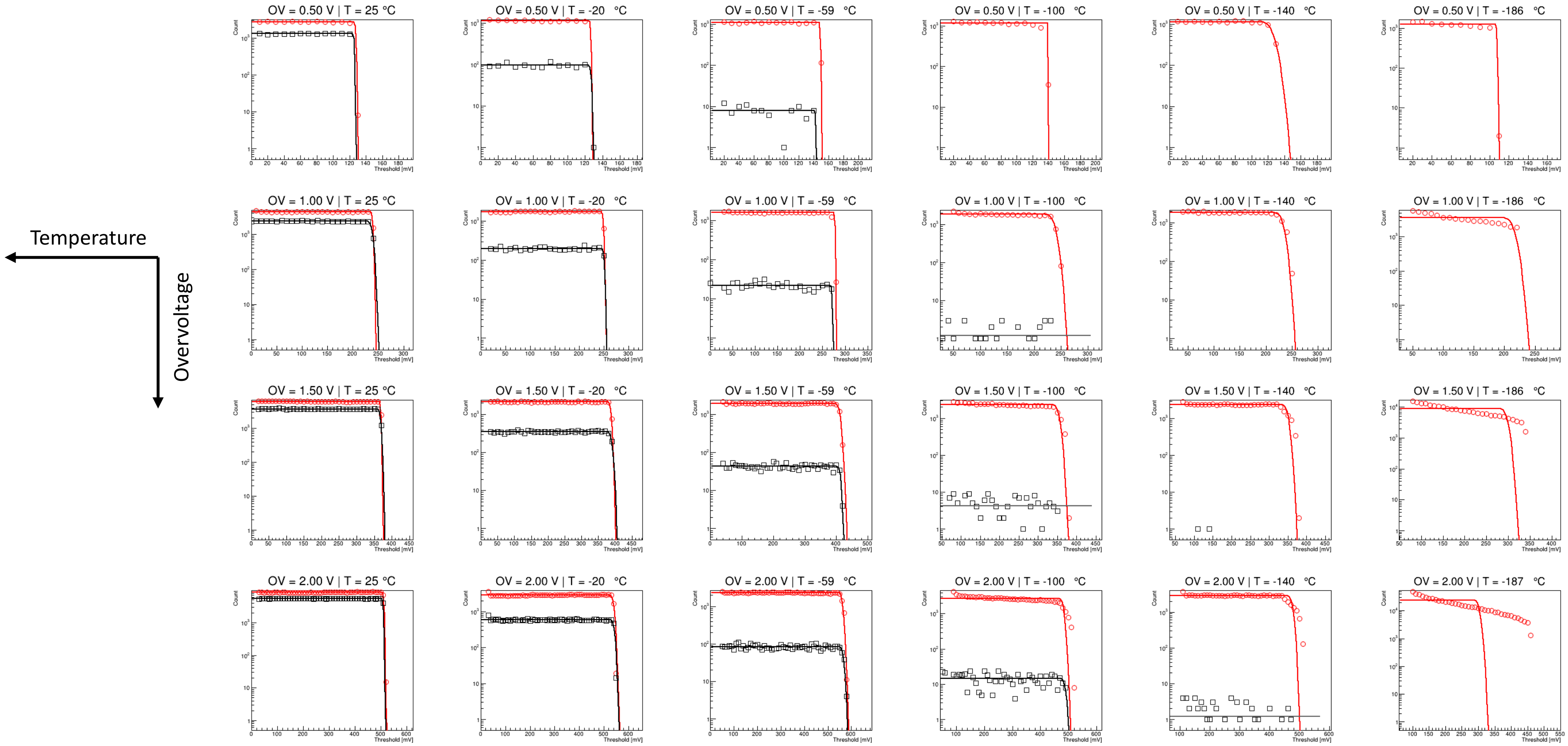
- Temperature and laser optical power monitored
- Temperature stabilized at predetermined steps



Threshold scans

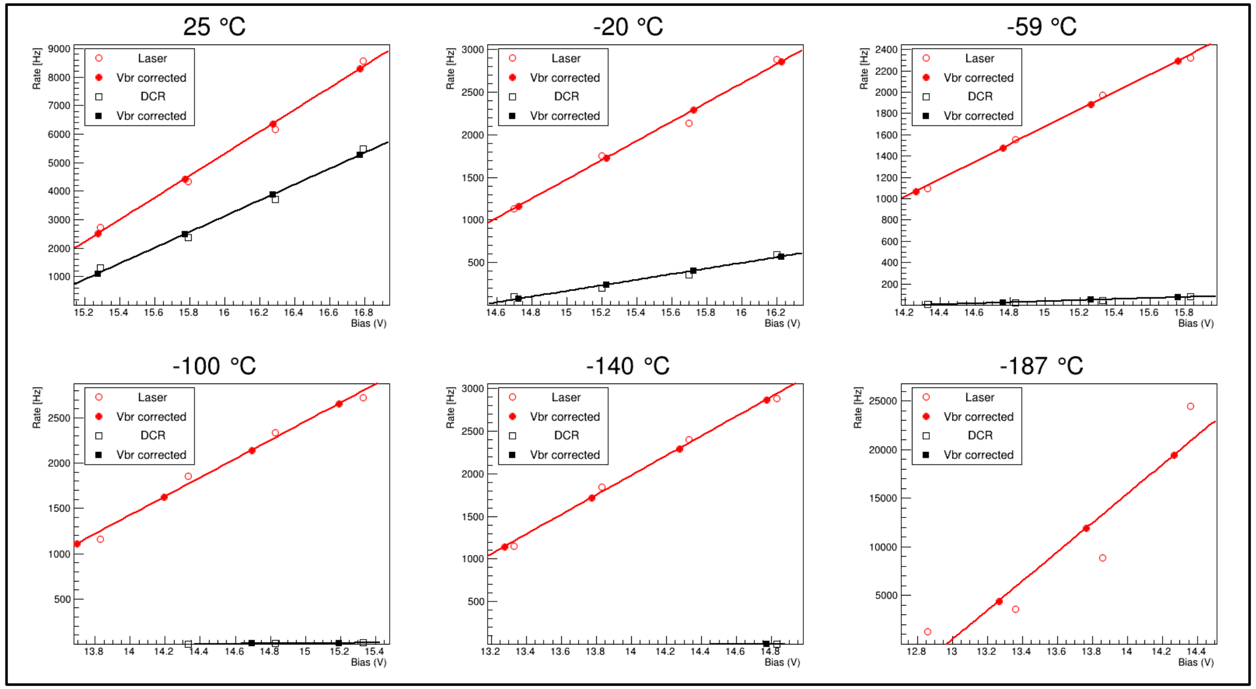
- rates with laser (○) - rate & pulse height estimated from fitted with error function
- dark counts (□) - when very low: rate from average of counts

Sample 527 (110 nm, 10 μm/N+)

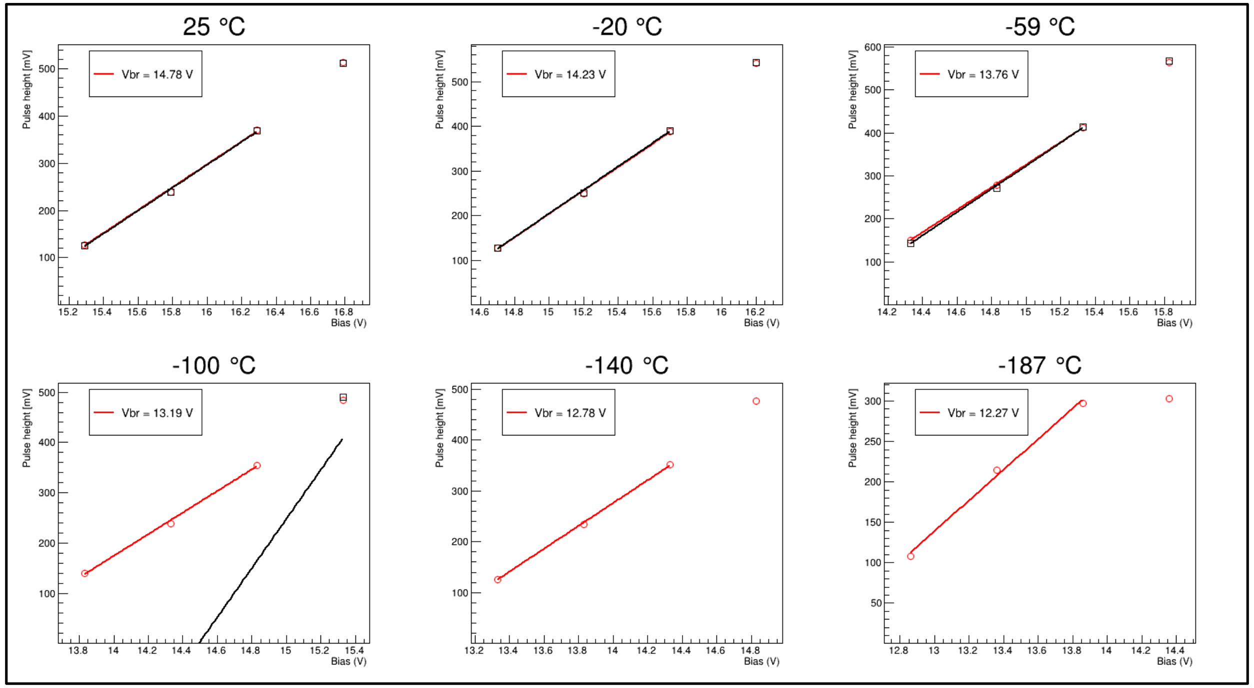


Data analysis

- Rate vs. bias voltage (incl. correction for on-the-fly estimated Vbr)



- Pulse height vs. bias voltage → Vbr



Sample 527 (110 nm, 10 µm/N+)

Results

- 10 SPAD samples measured so far:

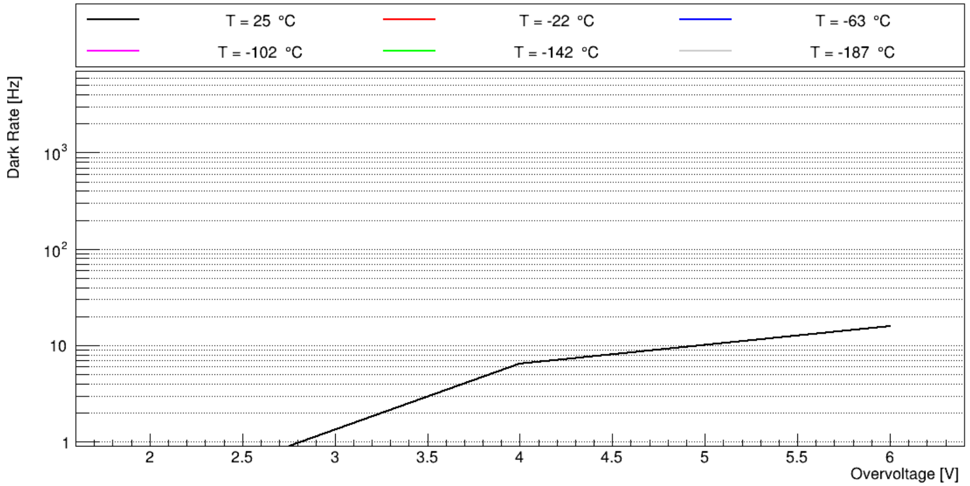
Technology	Label	Junction	Diameter [µm]	Dose [n/cm²]	Breakdown [V] @ RT	Temp. Coefficient [mV/K]	DCR [Hz] @ RT	Rate with laser Trend RT → LN	
55 nm	101	PN	5	10^{10}	19.4	22.2	<1	0%	
				10^{11}	19.4	22.1	10^3	+ 20%	
				10^{12}	-	-	-	-	(1)
	335	NP	5	10^{10}	31.0	27.4	10	+ 350%	
				10^{11}	30.9	27.2	10	+ 400%	
				10^{12}	-	-	-	-	(2)
110 nm	115005	P+	5	-	20.8	27.6	10	+ 40%	
	523005	N+	5	-	18.4	16.2	10^2	- 10%	(3)
	527	N+	10	-	14.8	12.2	10^3	+ 20%	(3)
	523025	N+	25	-	17.7	13.9	10^3	+ 10%	(3)

(1) No signal (not due to irradiation, wire bond broken?)
(2) Extreme radiation damage: constant discharges, Vbr shift
(3) Excessive rates at LN (afterpulsing, carrier freezout?)

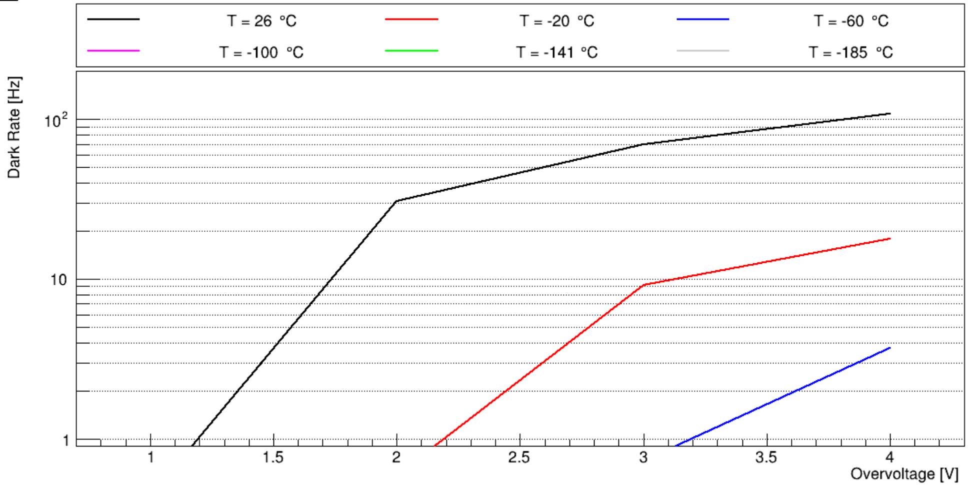
Results - DCR

110 nm

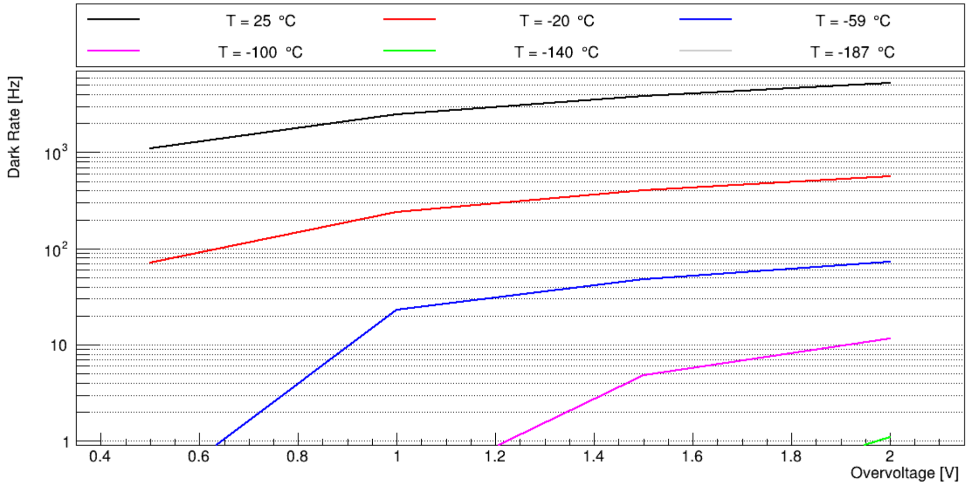
5 µm/P+



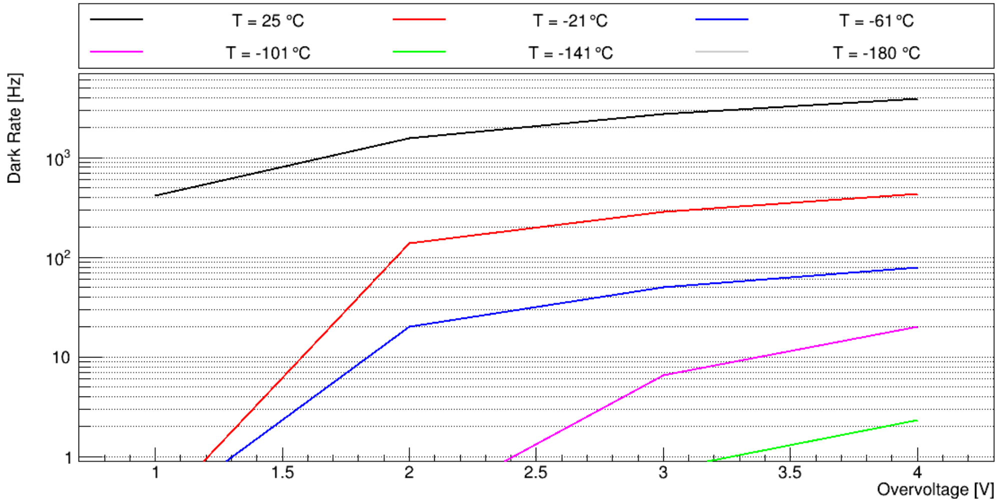
5 µm/N+



10 µm/N+



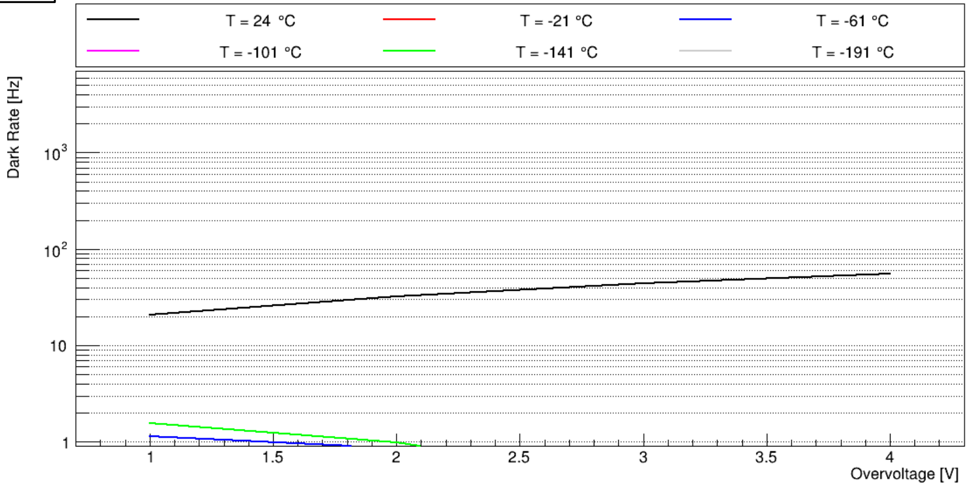
25 µm/N+



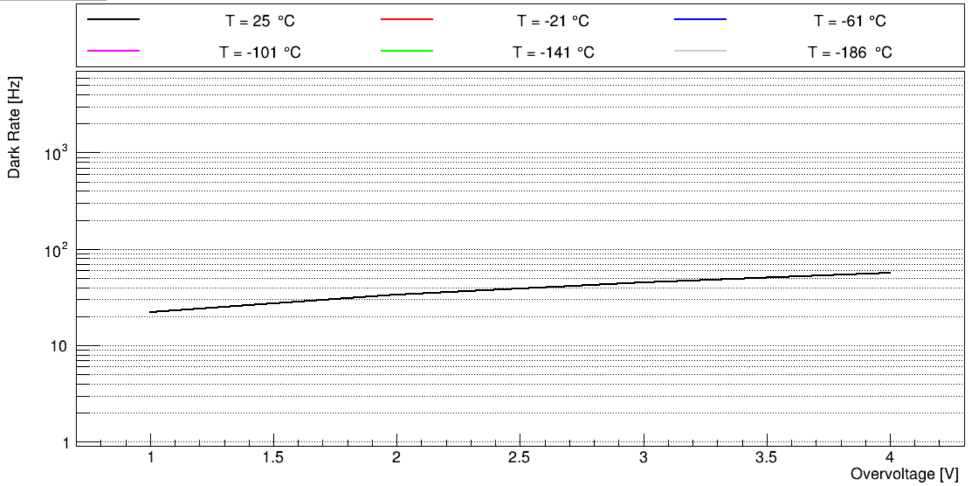
Results - DCR

55 nm

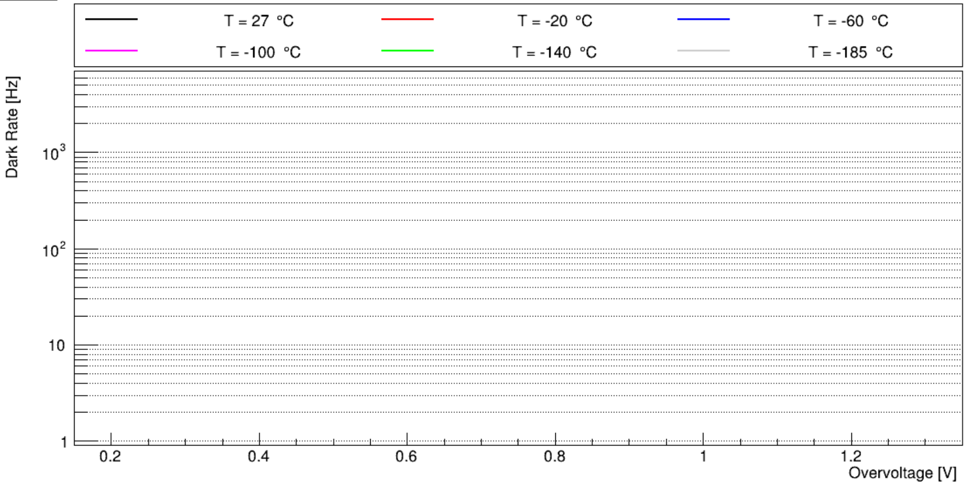
NP/10^{10} n cm^{-2}



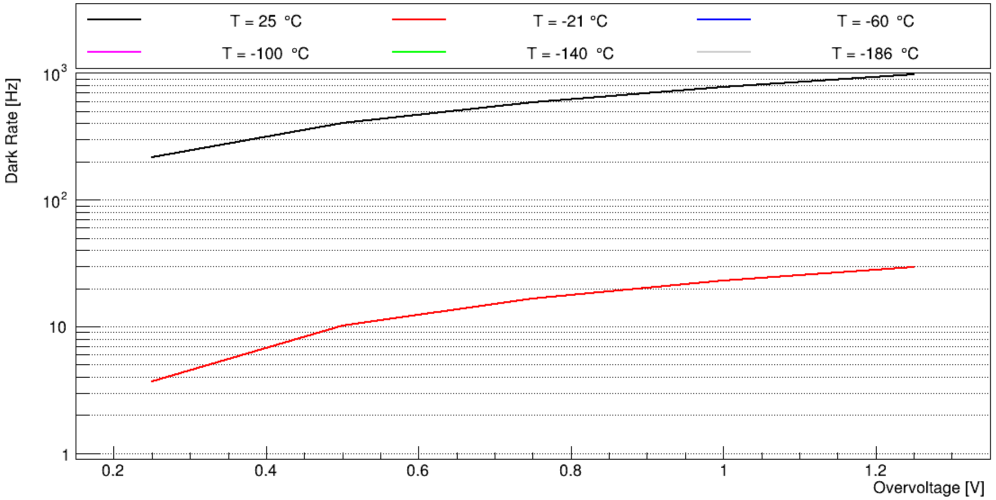
NP/10^{11} n cm^{-2}



PN/10^{10} n cm^{-2}



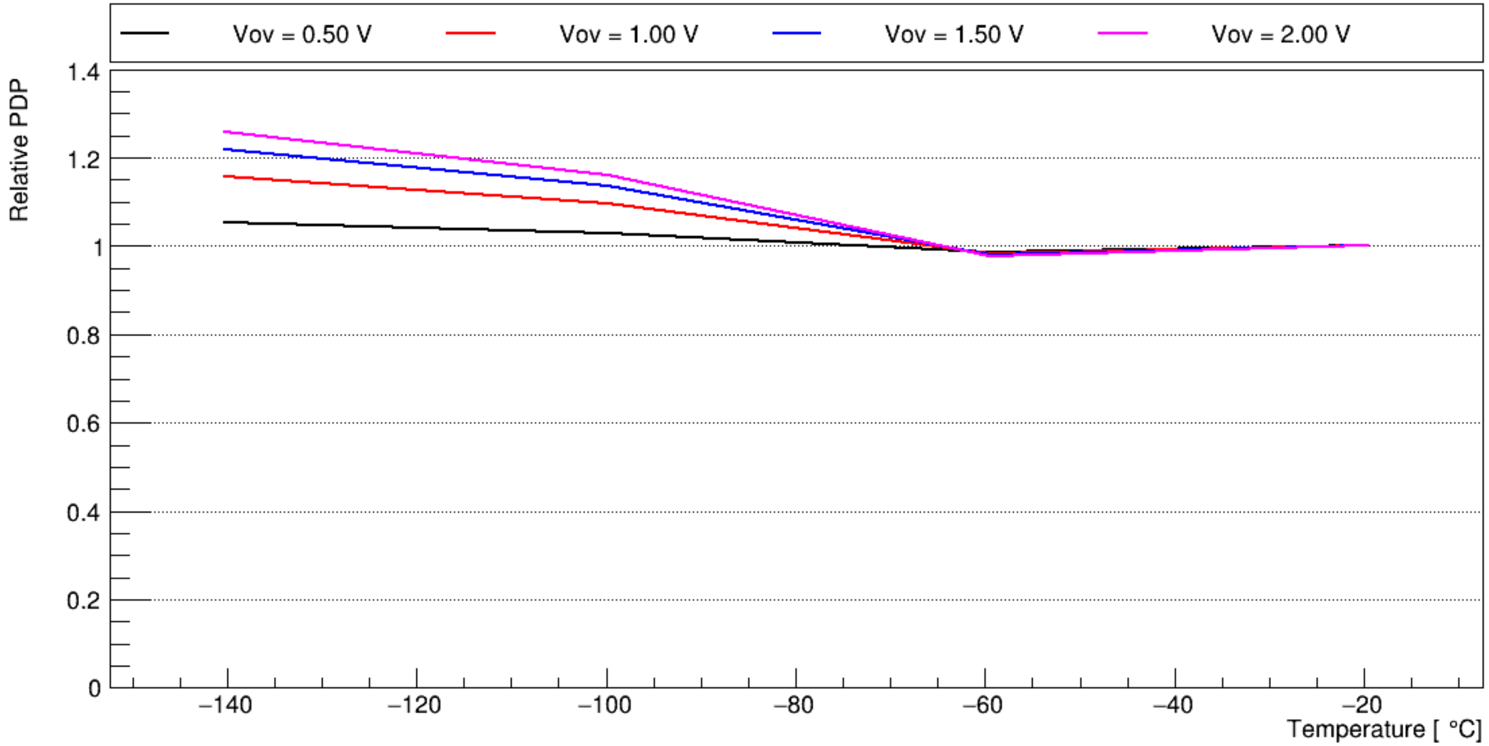
PN/10^{11} n cm^{-2}



Data analysis - Relative Photon Detection Probability

- Rates measured with 405 nm laser
  - Laser trigger rate @ 100 kHz
  - Light attenuated so SPAD detection rate ~ 1 kHz
- DCR subtracted
- Relative PDP (normalized to -20°C point, for each OV)
- <u>Afterpulsing etc. included</u>

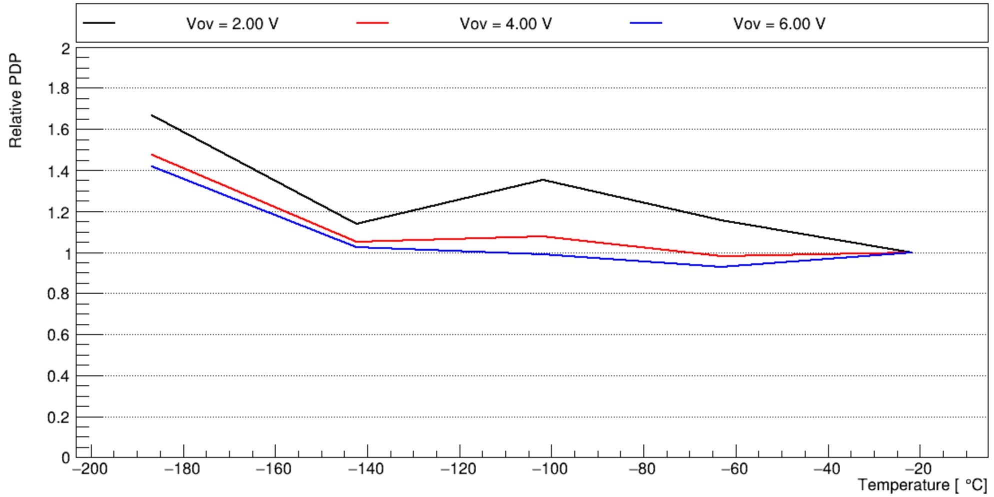
Sample 527 (110 nm, 10 μm/N+)



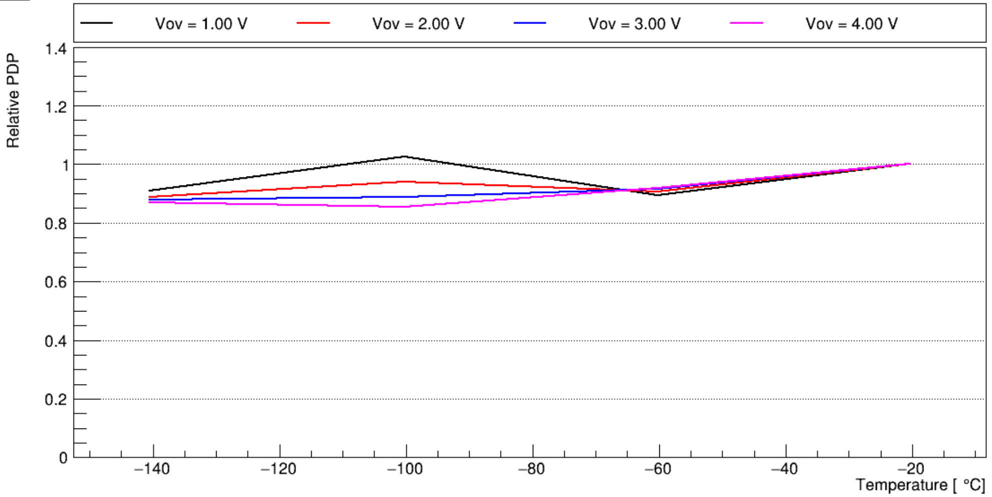
Results - PDP

110 nm

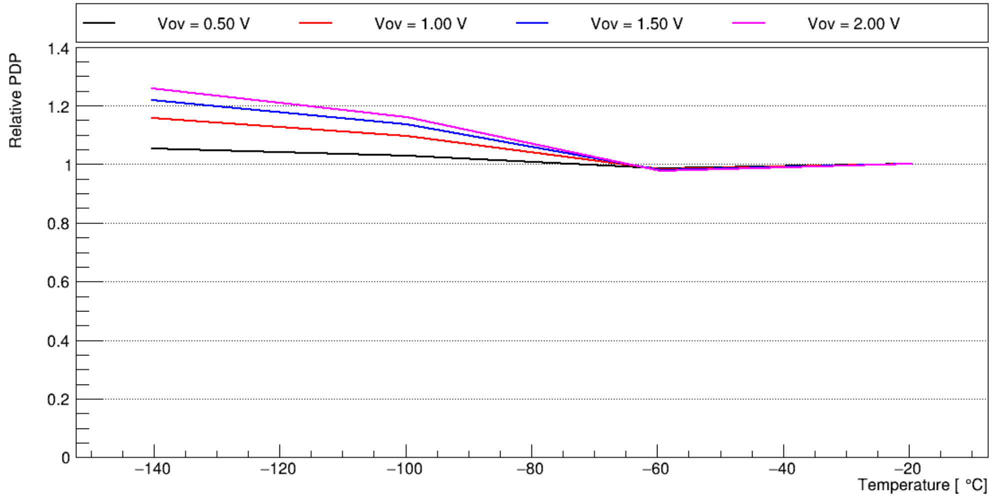
5 µm/P+



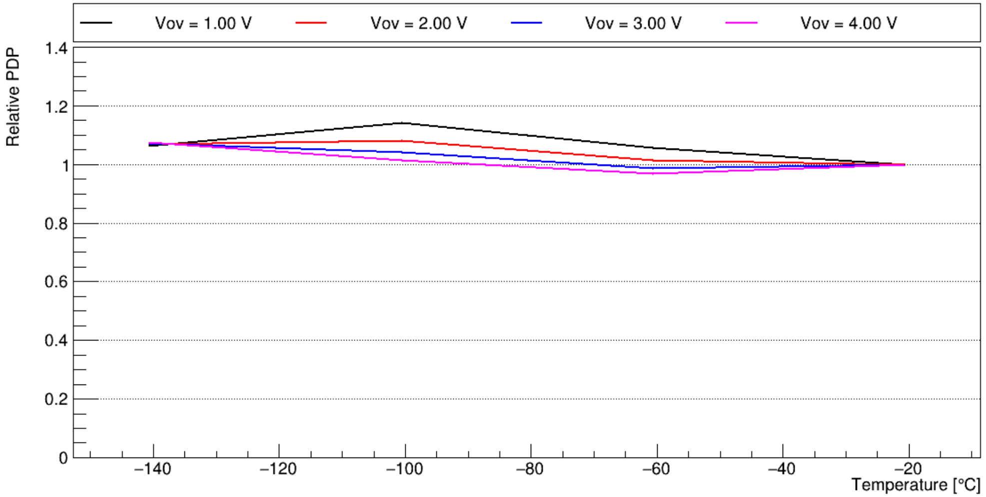
5 µm/N+



10 µm/N+

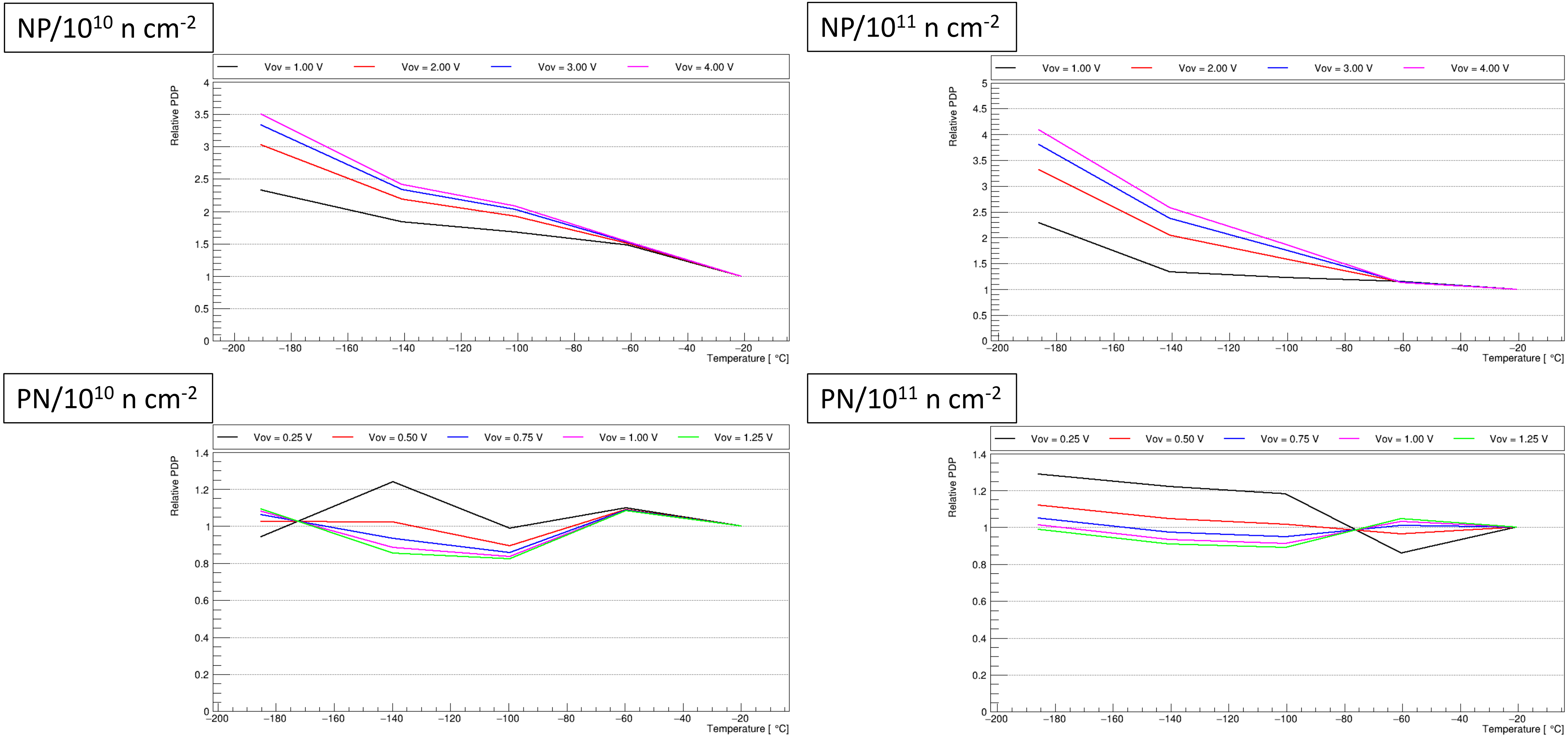


25 µm/N+



Results - PDP

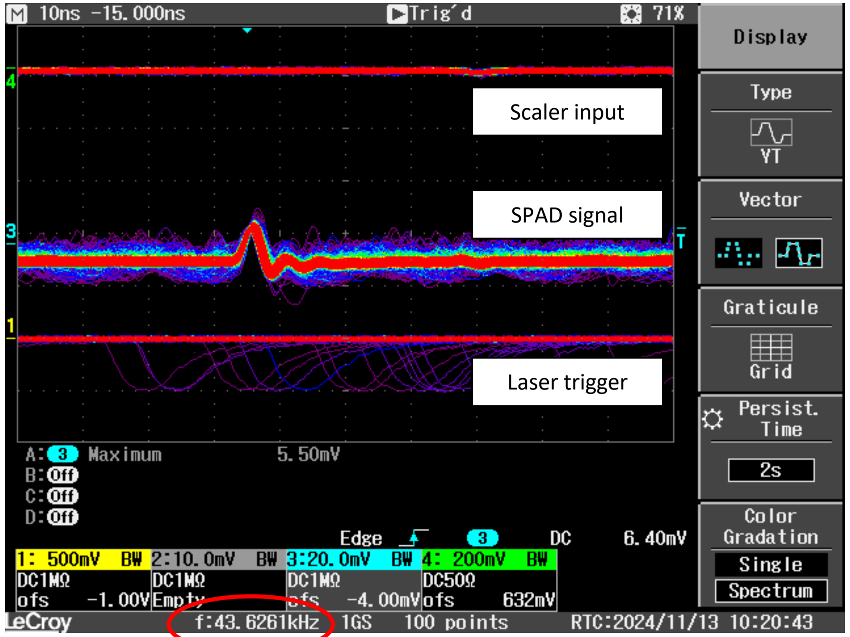
55 nm



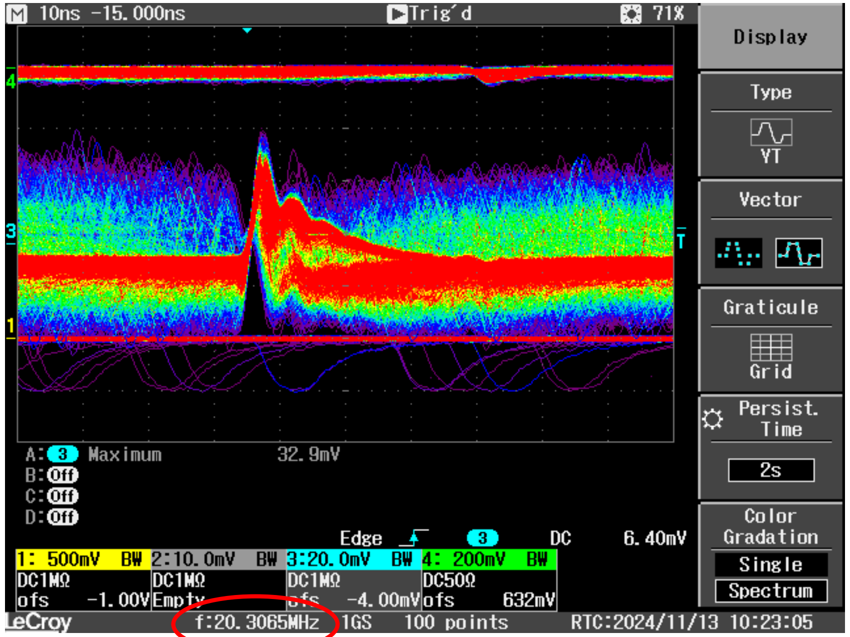
Case (2) Extreme radiation damage

Sample 335, NP/10^{12} n cm^{-2}

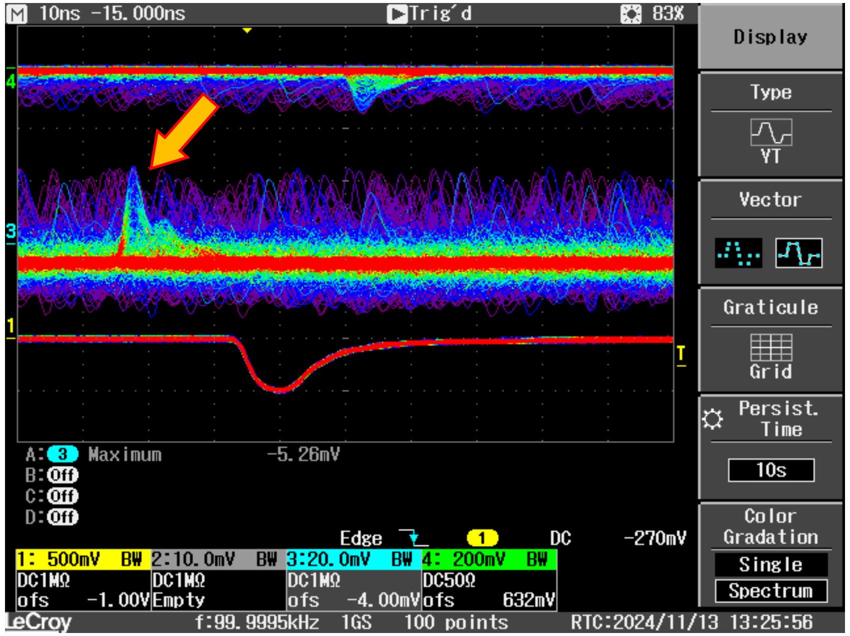
RT, Vbr – 4V	RT, Vbr	LN, Vbr – 1V, laser trigger



Discharges well below BR



Extremely high rate @ RT

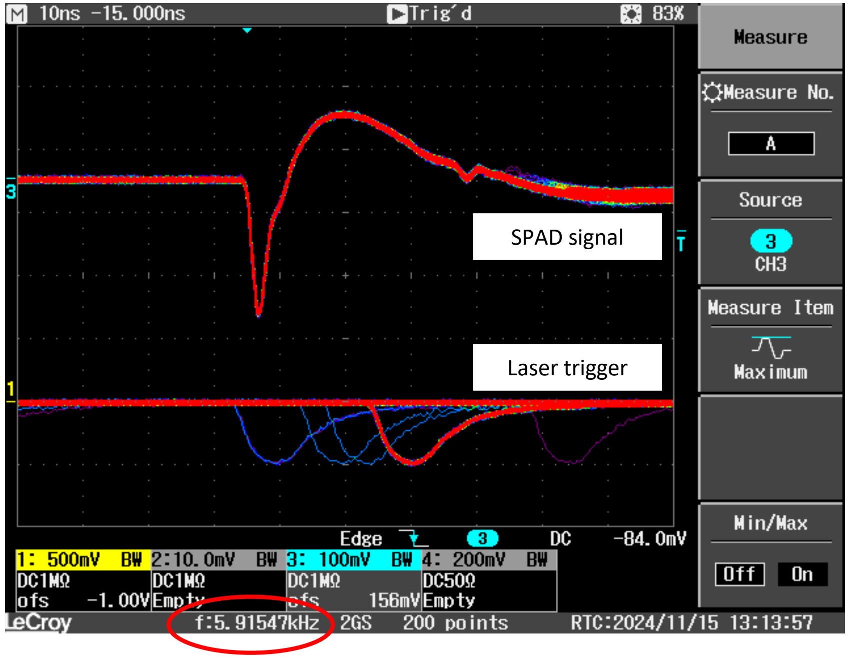


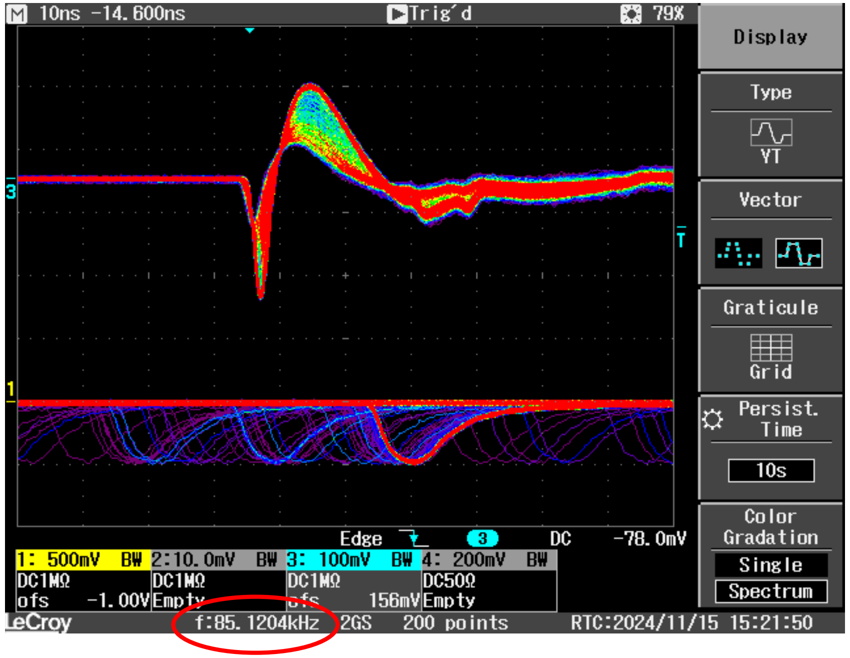
Some laser correlation regained at LN

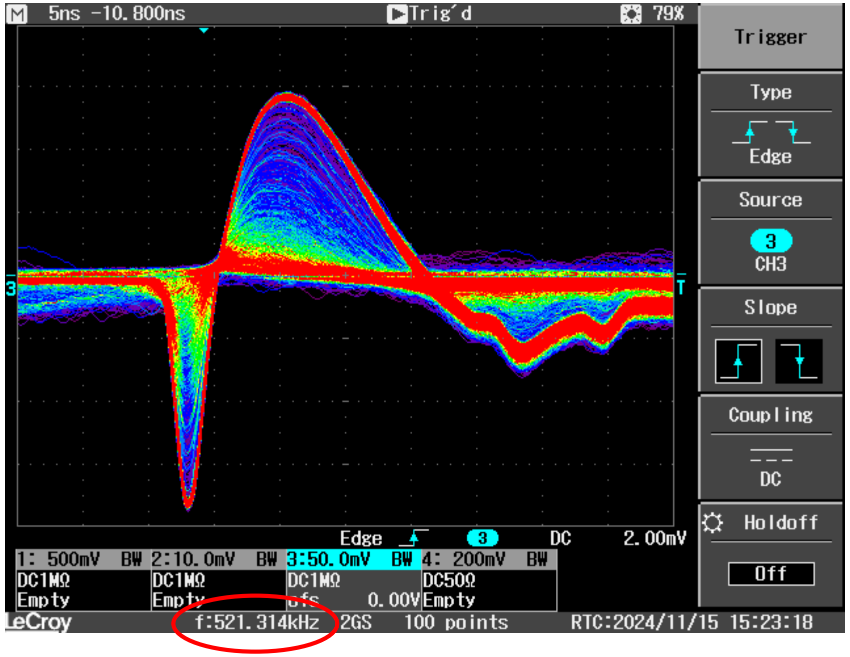
Case (3) Excessive rates at LN

Sample 527 (110 nm, 10 µm/N+)

RT	-190°C







RT: Discrete signals

LN: High rate,
continuum of signals

Closer look,
lower trigger

Summary

- Planned RICH detector upgrades → high photodetector requirements

- spadRICH project: monolithic dSiPM for future RICH detectors
    - SPADs samples (55 nm, 110 nm and 180 nm) for testing
    - Neutron irradiation up to 10^{12} neq/cm^2 @ JSI TRIGA
    - Cryogenic CMOS SPAD characterization ongoing
    - 10 SPAD samples measured so far

- Next steps
    - Measure afterpulsing → actual PDP
    - Study specific behavior of some SPADs at LN temperature
    - Micro-lenses: irradiation effects and cryogenic operation

spadRICH collaboration & Acknowledgements

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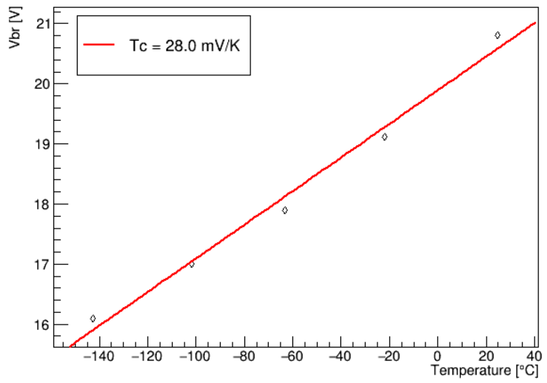
Backup

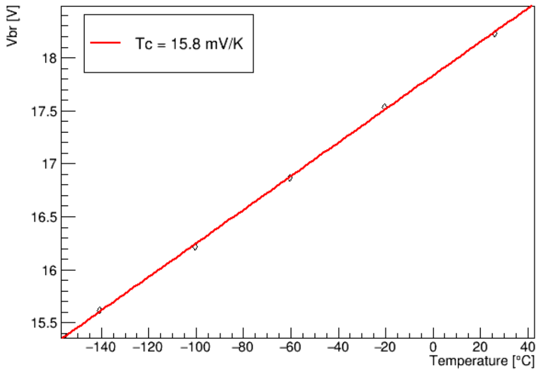
Results - Vbr temperature coefficient

110 nm		55 nm	

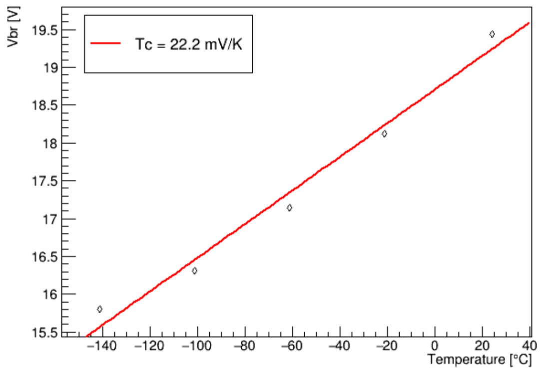
5 µm/P+



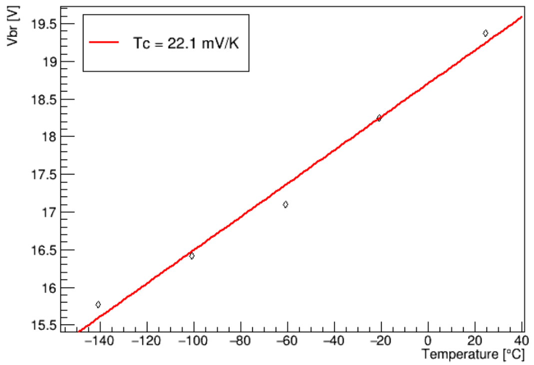
5 µm/N+



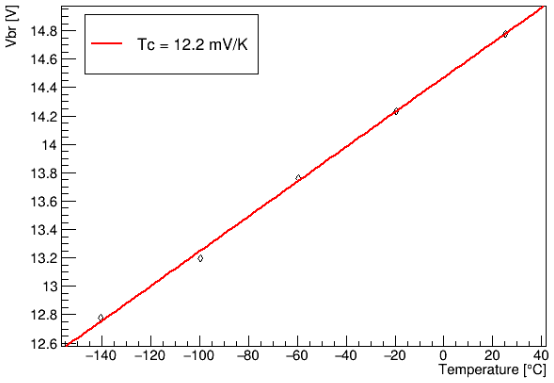
NP/10^{10} n cm^{-2}



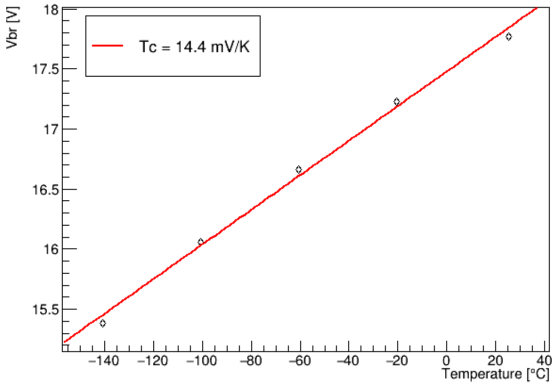
NP/10^{11} n cm^{-2}



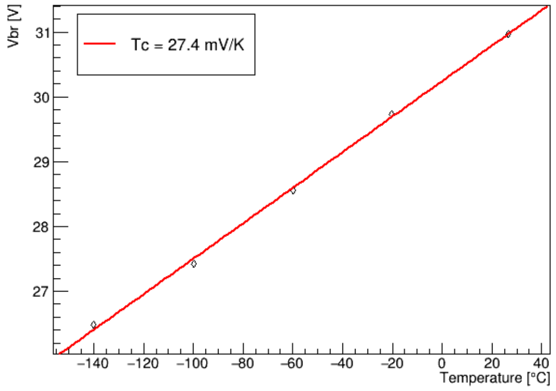
10 µm/N+



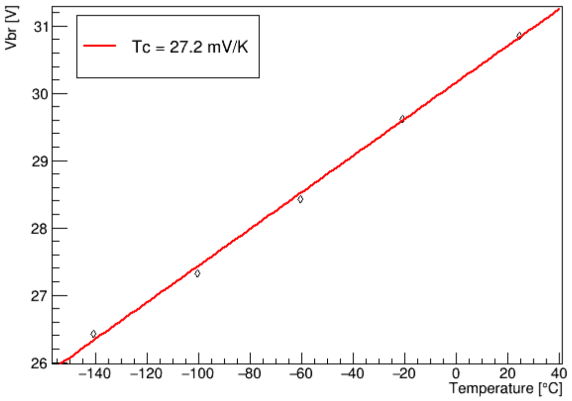
25 µm/N+

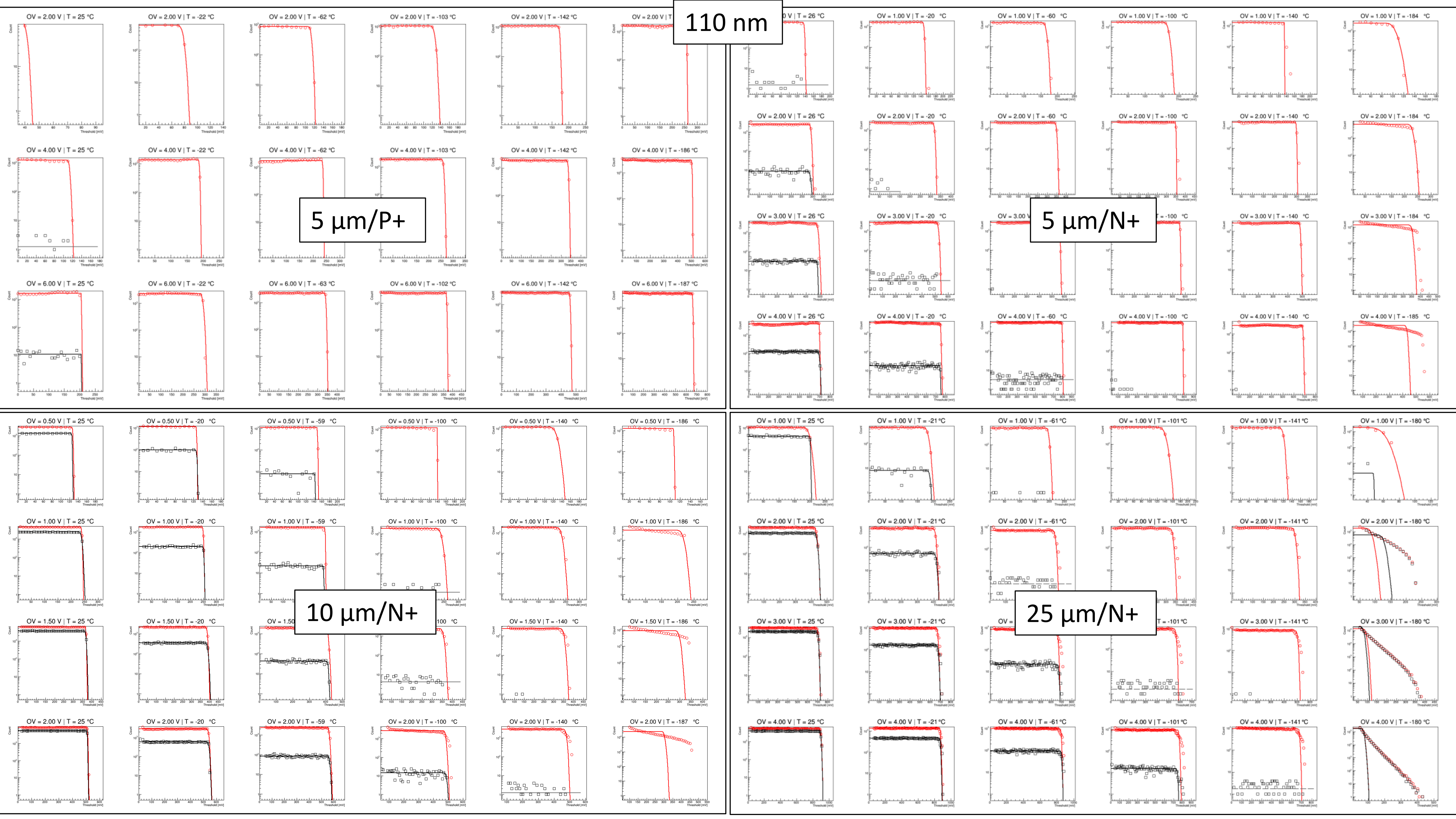


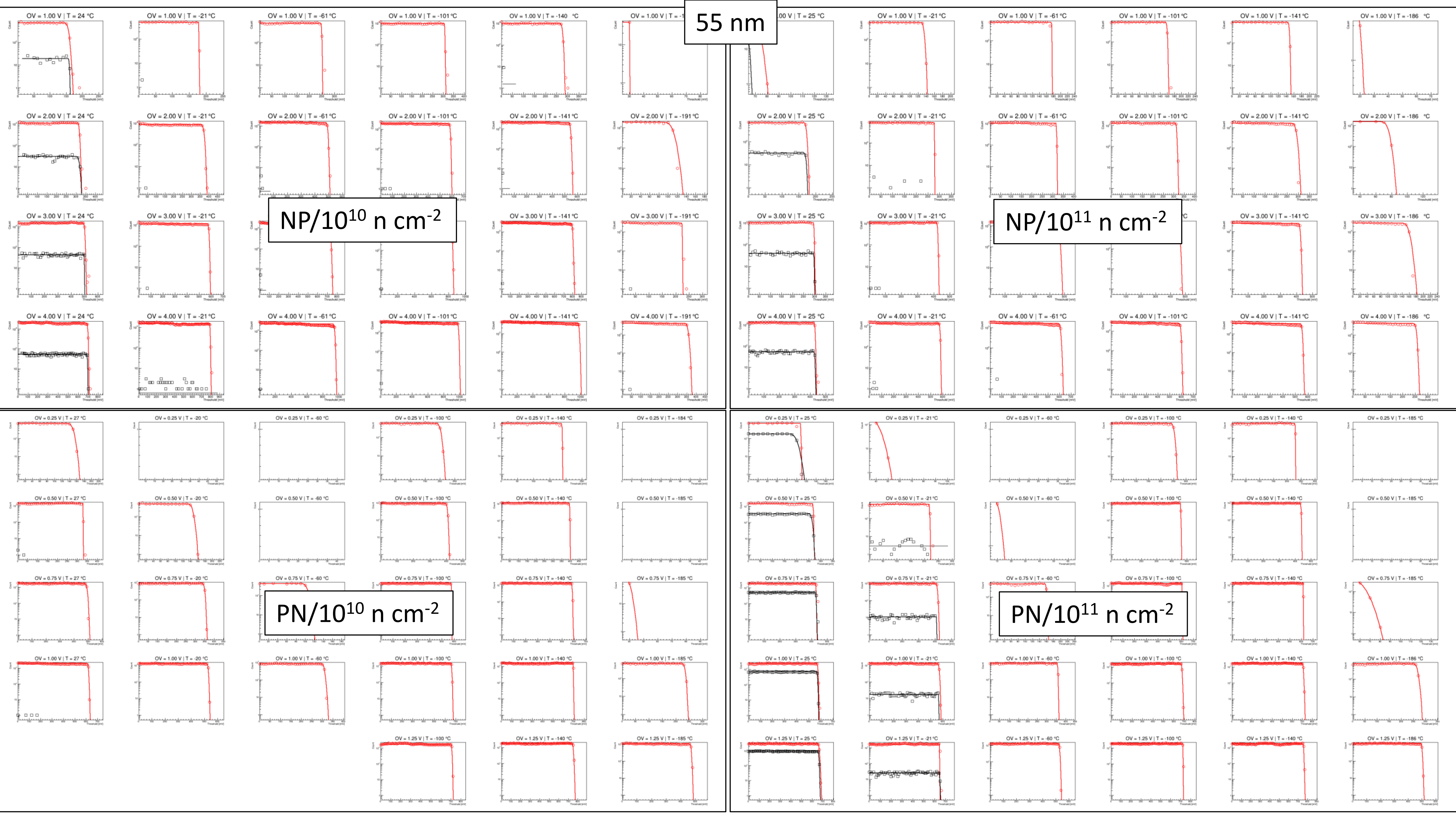
PN/10^{10} n cm^{-2}



PN/10^{11} n cm^{-2}



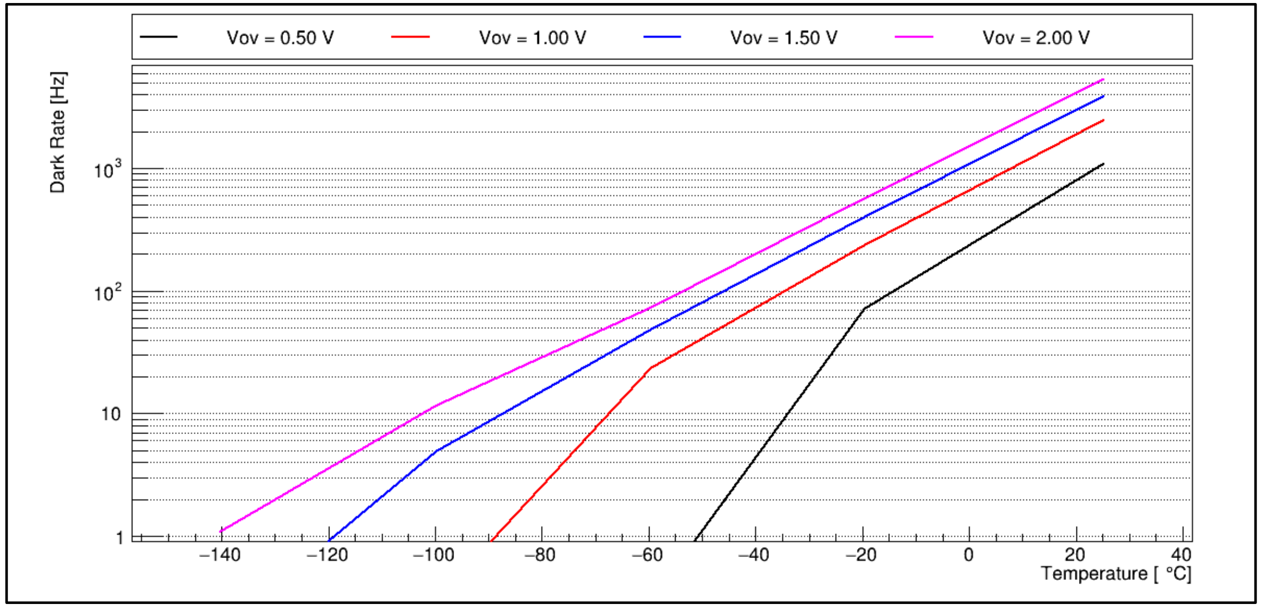

110 nm
5 µm/P+
5 µm/N+
10 µm/N+
25 µm/N+


55 nm
NP/10^10 n cm^-2
NP/10^11 n cm^-2
PN/10^10 n cm^-2
PN/10^11 n cm^-2

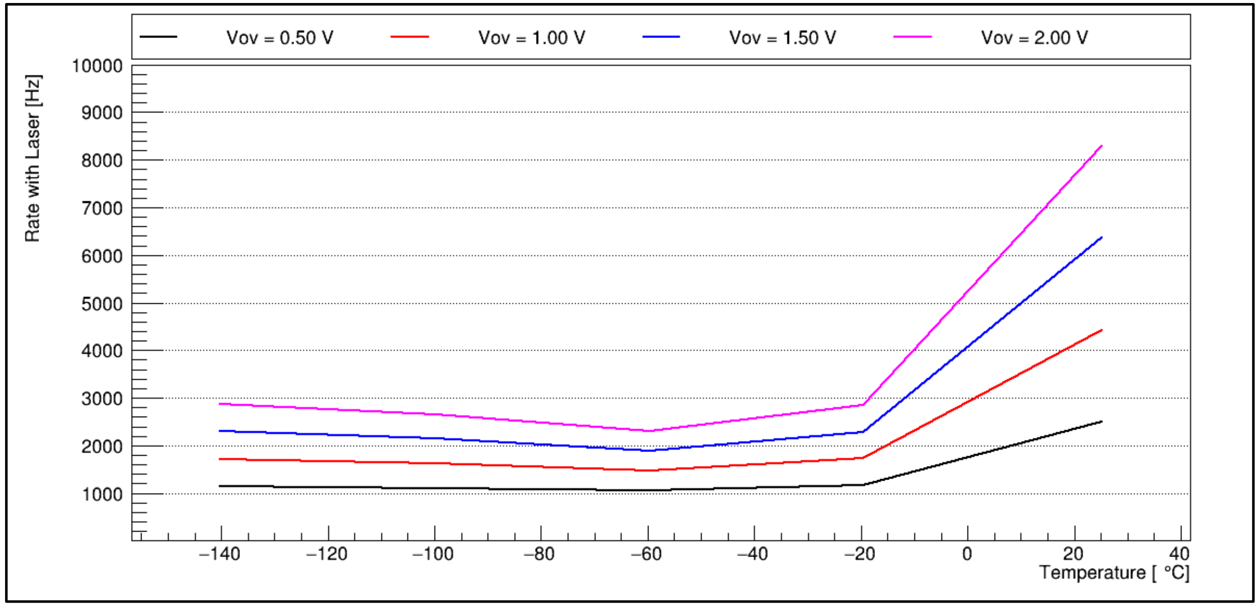
Data analysis

Sample 527 (110 nm, 10 µm/N+)

- Dark count rates



- Rates with laser

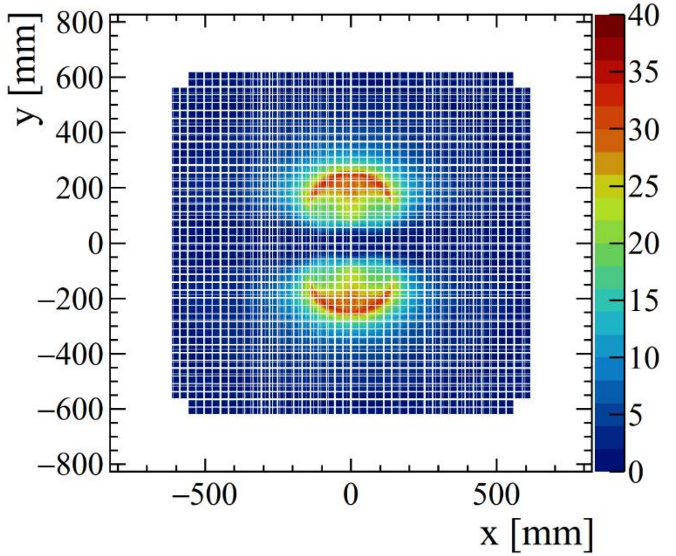


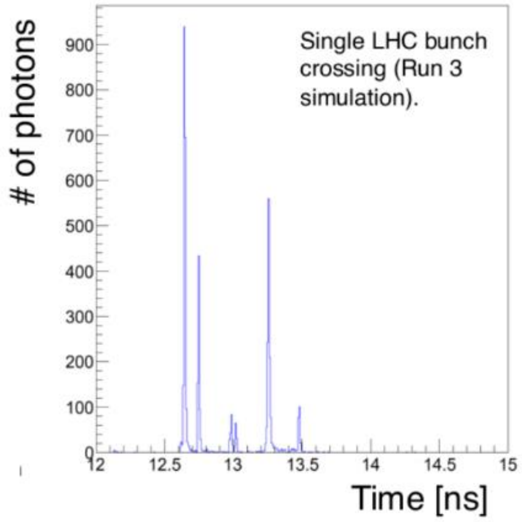
LHCb RICH upgrade photodetector requirements

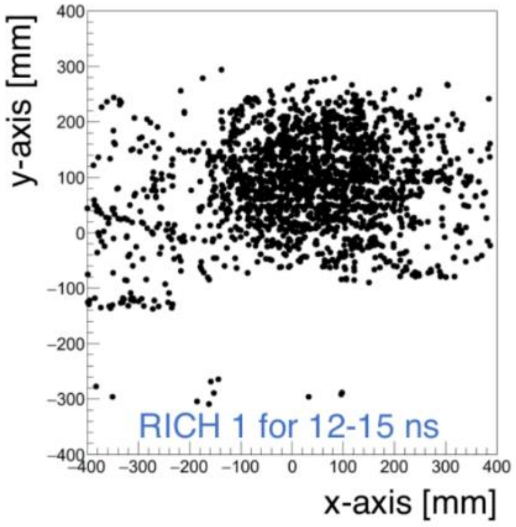
- Fast timing
  - Nanosecond front-end gate – background and data throughput reduction
  - Picosecond hit timestamps – reduce combinatorial background
- Cherenkov angle resolution
  - High granularity ~1x1 mm^2 – also to reduce photon occupancy
  - Enhanced sensitivity in green – enable chromatic error reduction

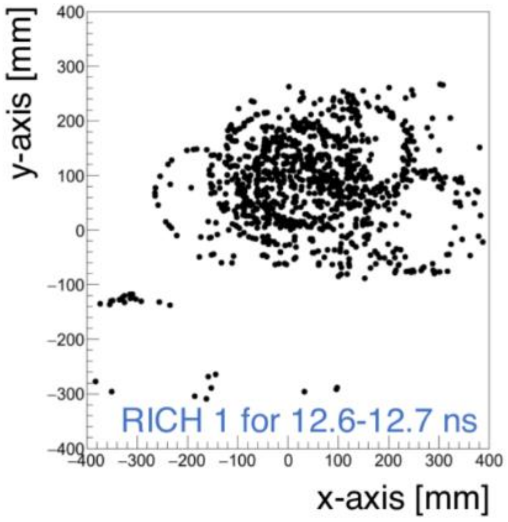
Occupancy: 1-photon hit probability/channel/bunch crossing (25 ns)

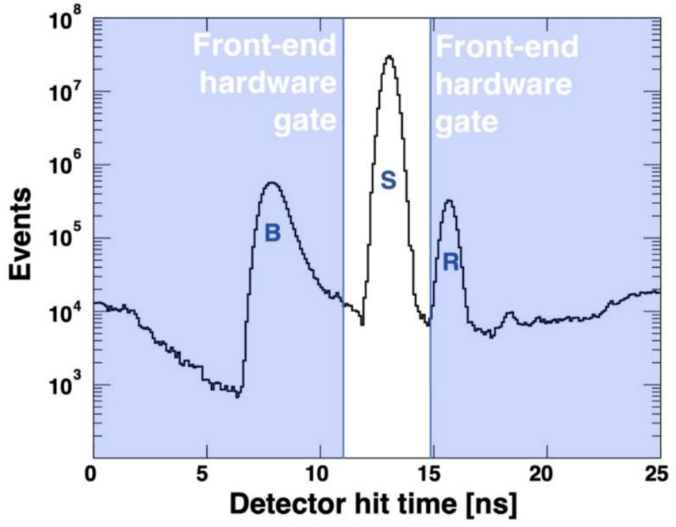
LHCb RICH occupancy (%)





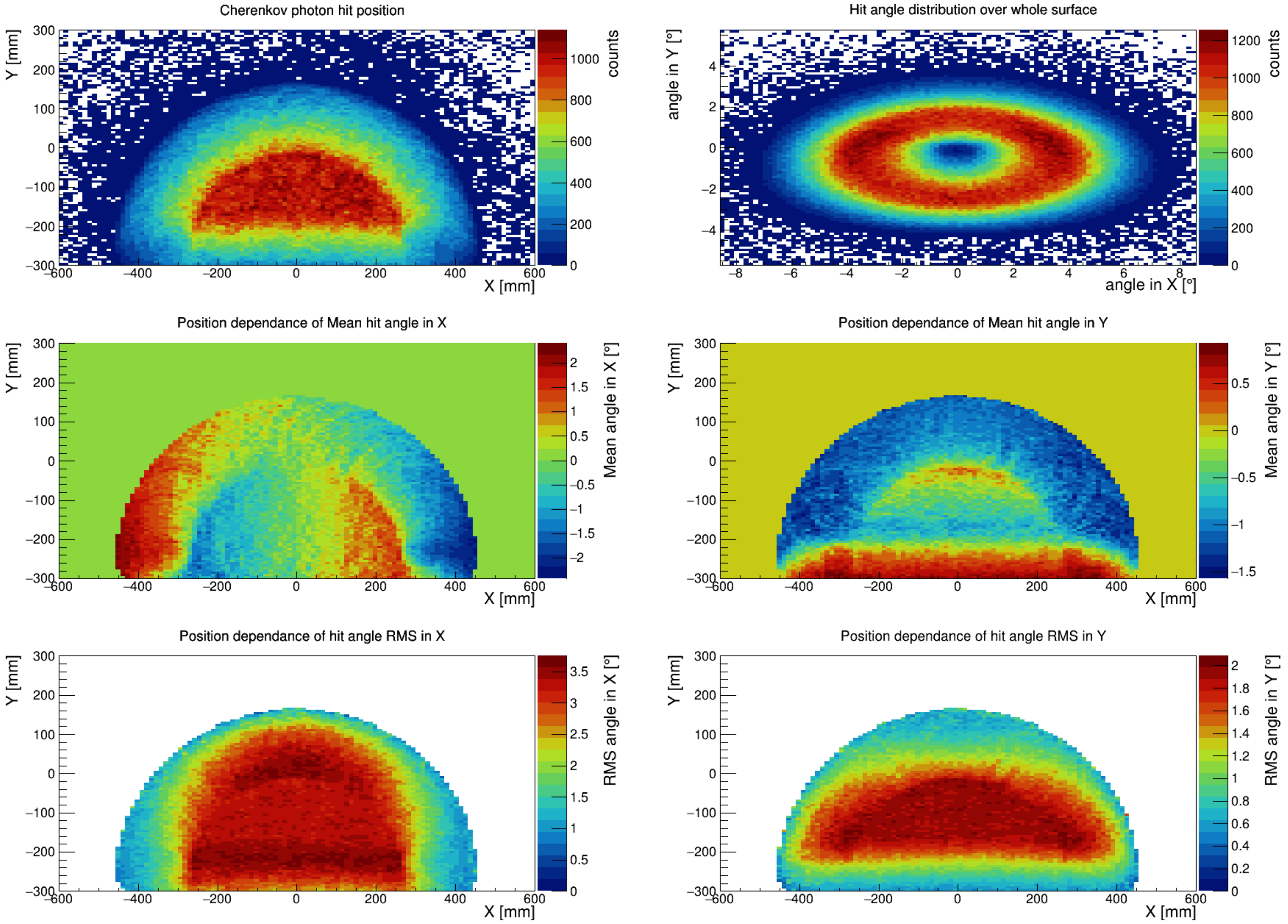






RICH specific optimizations: Micro-lenses

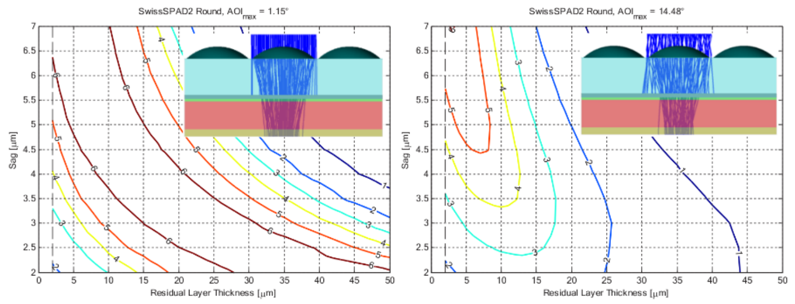
- Small SPAD area → improved radiation hardness, microlenses → recover effective active area
- Simulated photon hit distributions in LHCb RICH (upper detector):



→ Maximum required micro-lens acceptance half angle ≈ 6°

→ Relatively modest NA ≈ 0.1 / f ≈ 5

→ Good concentration factor possible



→ Possible position dependent optimization of microlenses to further improve concentration factors