Phose2023 - Workshop on "Photodetectors and sensors for particle identification and new physics searches"

Jožef Stefan Institute, Ljubljana, Slovenija

SiPMs for Belle II ARICH

D. Consuegra Rodríguez[1], R. Dolenec[1,2], P. Križan[1,2], S. Korpar[1,3], A. Seljak[1], R. Pestotnik[1]

[1] Experimental particle physics department, Jozef Stefan Institute (JSI) , Ljubljana, Slovenia
[2] University of Ljubljana, Faculty of Mathematics and Physics, Ljubljana, Slovenia
[3] University of Maribor, Faculty of Chemistry and Chemical Engineering, Maribor, Slovenia

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Outline

- Motivation / Objectives / Specific task
- SiPM characterization before irradiation
- SiPM characterization after irradiation
- Annealing studies after irradiation
- Conclusions

Acknowledgments:

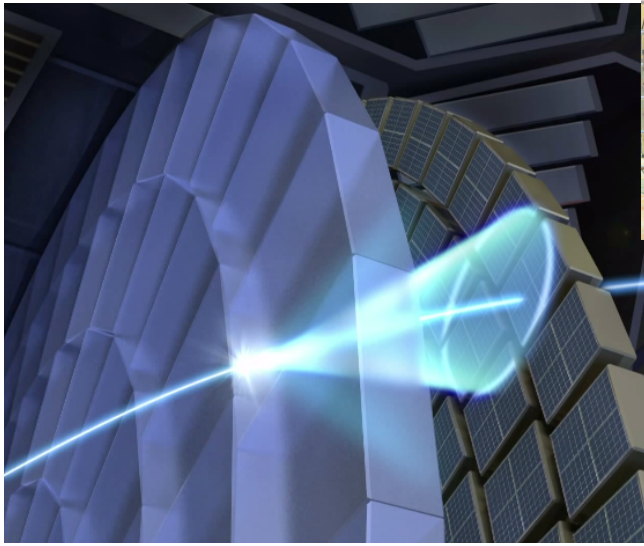
We would like to thank A. Gola, S. Merzi, and M. Penna from Fondazione Bruno Kessler for providing the photodetector samples and all the other support.
We would like to thank A. Verdir, A. Jazbec, and S. Rupnik for the help with sample irradiation at JSI TRIGA reactor.

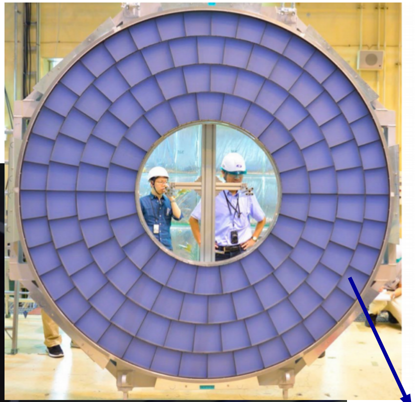
Author contact: dania.consuegra@ijs.si

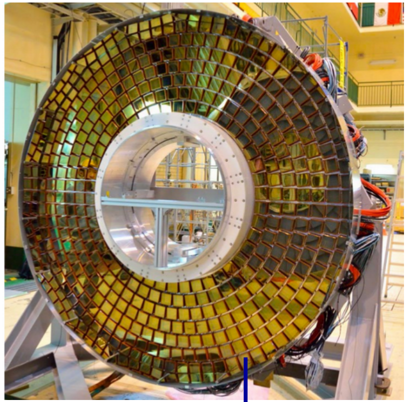
Motivation

State-Of-The-Art

Belle II ARICH



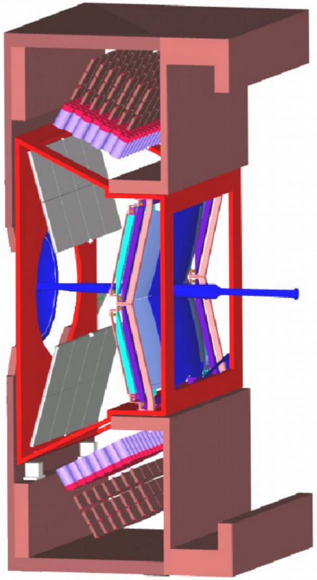




Aerogel radiator

420 Hybrid Avalanche Photodetectors (HAPD)

LHCb RICH1



Belle III ARICH ~ 2035

- Proposal: Increase the luminosity
- Higher backgrounds
- HAPD will not be able to operate

Research and Development

- Search for new technologies
- Photodetectors with sufficient performance during a few years of data-taking, despite the accumulation of radiation damage.

neutron radiation hardness (3 x 10^{12} neq/cm^2 by detector end-of-life)

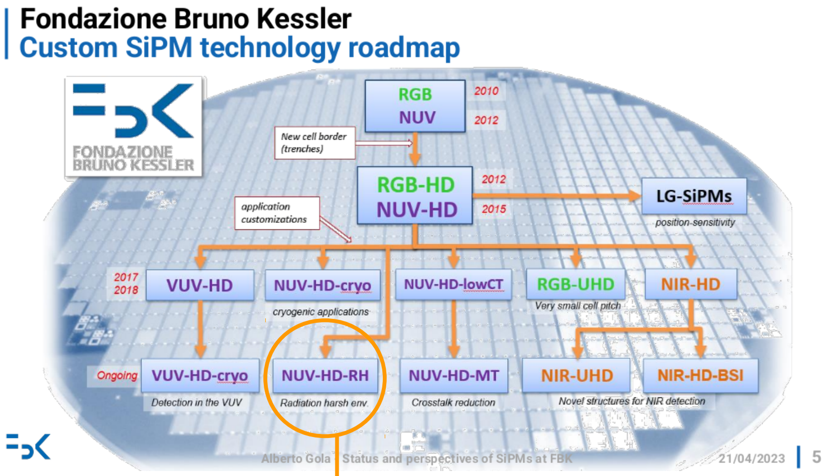
[M.Fiorini. The upgrade of the LHCb RICH detectors, NIMA 2020]

- Candidates: MCP-PMT & SiPMs

Objectives

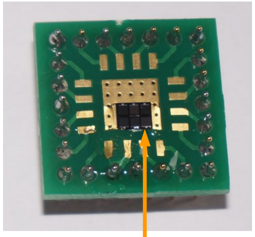
- Develop a setup for **SiPM characterization** at room temperature and at different controlled temperature steps down to liquid nitrogen before and after irradiation.
    - Current-voltage characteristics (I-V curve)
    - Threshold scan (Dark count rate)
    - Waveform analysis
        - Signal shape
        - Pulse height distribution
        - Charge distribution
        - Single photon timing resolution (SPTR)
- Carry out preliminary annealing studies after irradiation.

Specific task



UHD-DE

1 x 1 mm²
15 µm



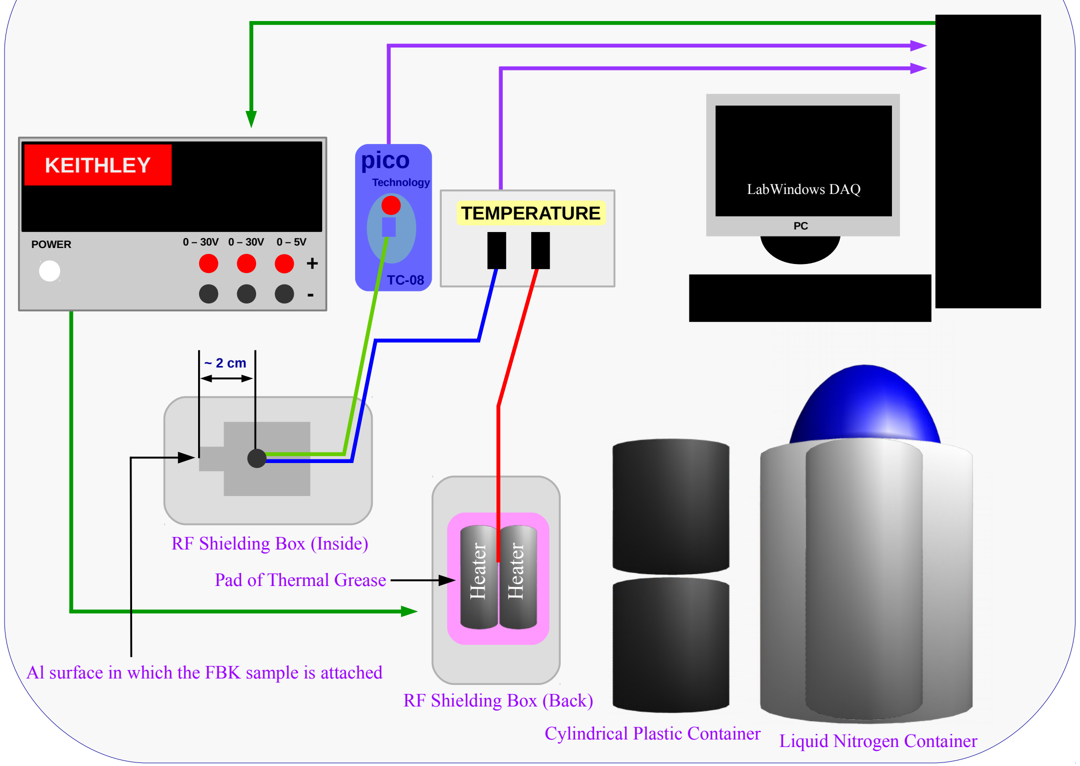
Characterization of 6 Samples (**NUV-HD-RH**) developed by FBK

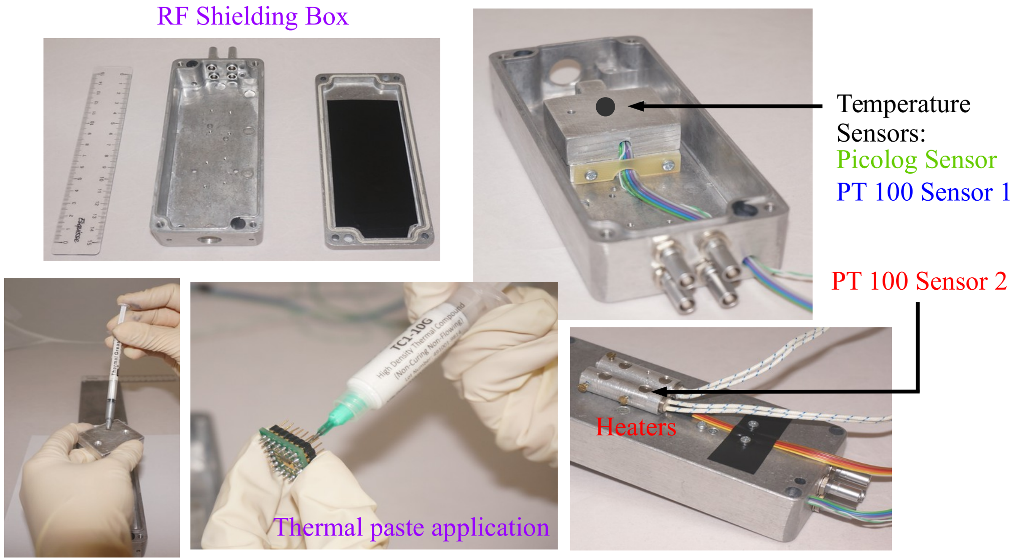
TOTAL: 18 **SiPMs** (Presenting results for 6 **UHD-DE SiPMs**)

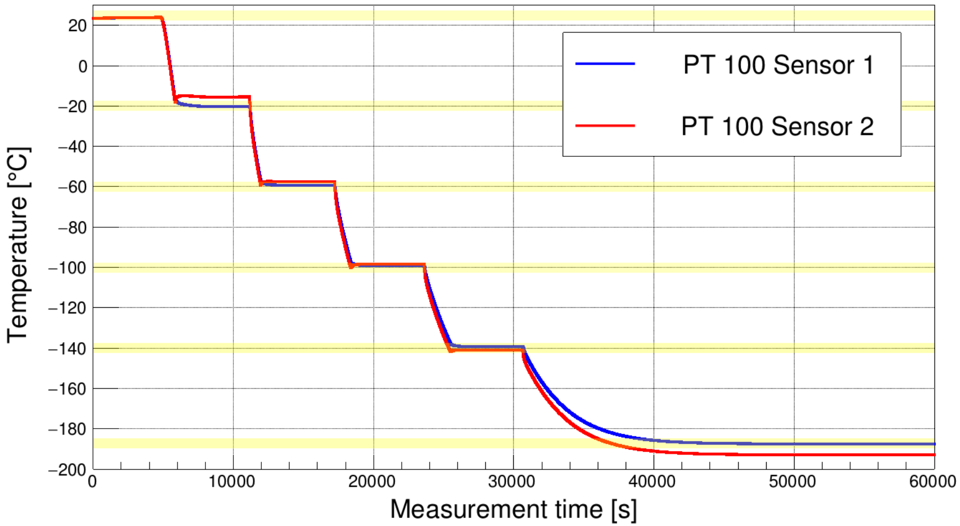
Temperature stabilization

How to stabilize the SiPM temperature ?

Schematic temperature stabilization







- The temperature can be stabilized between 25 ^{0}C and -187 ^{0}C.
- Temperature stabilization inside better than ± 5 ^{0}C of the set temperature.

Overview of the setup

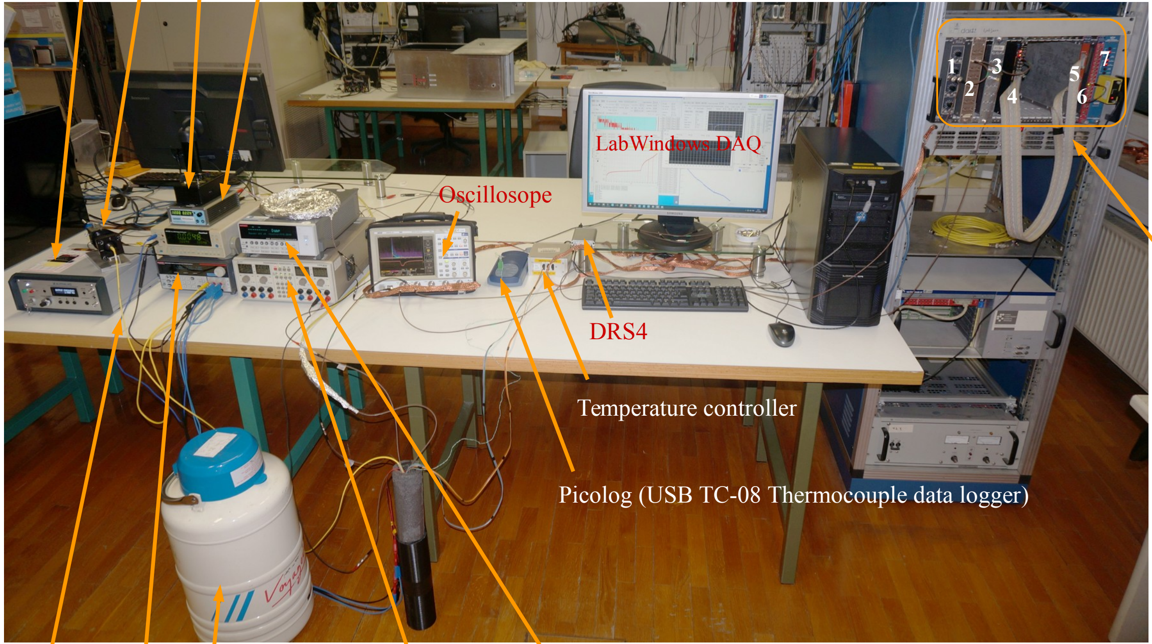
ALPHALAS (Picosecond Laser Diode Driver PLDD – 20 M)

Laser shutter

Laser shutter controller (Melles Girot electronic shutter controller)

GOPHER power supply for the laser shutter controller

Modular electronics



Modular electronics

Optical fiber

Liquid Nitrogen Container

KEITHLEY 6517B ELECTROMETER

HAMEG power supply for the pre-amp of the custom electronics board

KEITHLEY power supply for the heaters

1. Philips Quand rotary Attenuator Model 804
2. ORTEC Octal Fast Timing Amplifier Model FTA820
3. Octal divider
4. Phillips Scientific 16 Channel discriminator latch CAMAC Model 7106
5. C.A.E.N 16 Ch ECL Scaler MOD C 257
6. C.A.E.N: 16 Ch Universal Programmable I/O register MOD C 219
7. Lecroy PC interface

Measurement protocol

M: manual

A: automatic

M | **FBK NUV-HD-RH Sample X**

Oscilloscope screen-shot

M | **UHD-DE**

A | RT

- * I-V scan → ~ 20 min
- * Threshold scan (Laser OFF): 3 OV, 5 OV, 7 OV, 9 OV, 11 OV, 13 OV → ~ 23 min
- * Timing - DRS4 (Laser ON): 3 OV, 5 OV, 7 OV, 9 OV, 11 OV, 13 OV → ~ 36 min

~ 1 h 20 min

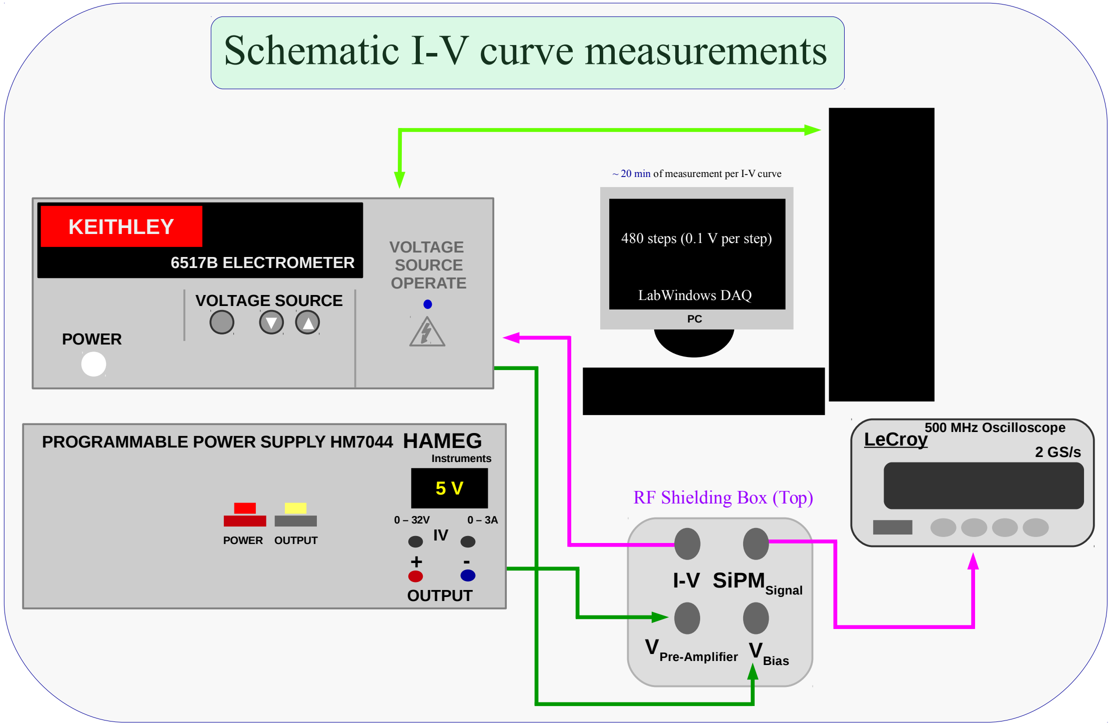
M | Setup into the liquid nitrogen container !!!

A | LN

- Stabilize the temp (~1h)
- - 20 ^{0}C: **~ 1 h 20 min**
- Stabilize the temp (~1h)
- - 60 ^{0}C: **~ 1 h 20 min**
- Stabilize the temp (~1h)
- - 100 ^{0}C: **~ 1 h 20 min**
- Stabilize the temp (~1h)
- - 140 ^{0}C: **~ 1 h 20 min**
- Stabilize the temp (~1h)
- LN: **~ 1 h 20 min**

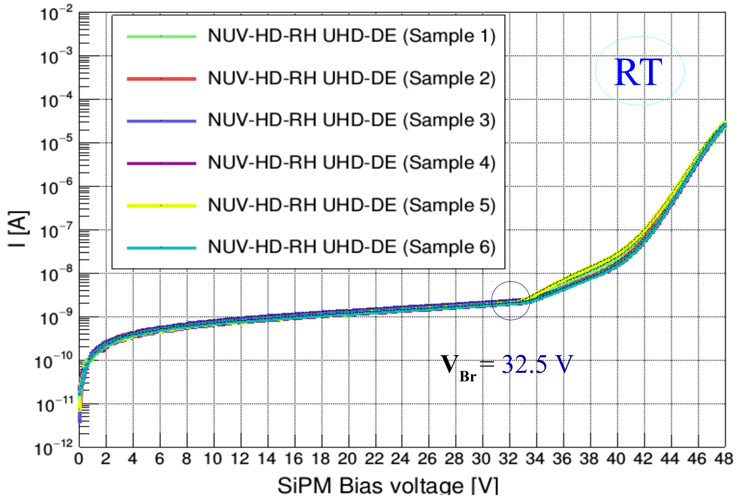
~ 14 h of RAW data per SiPM

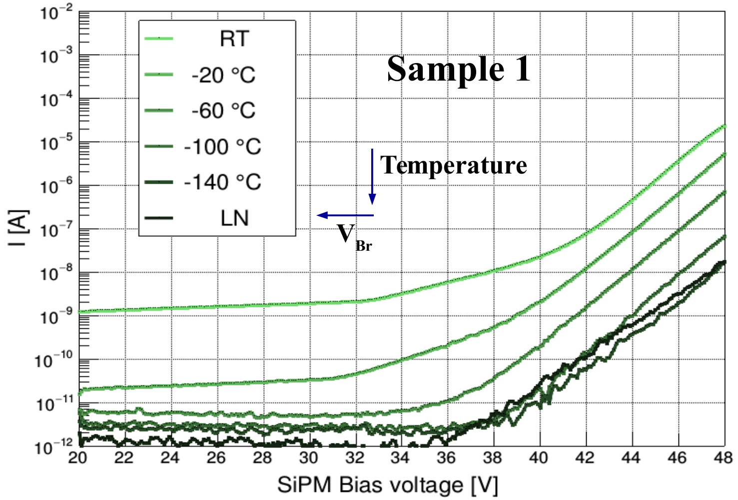
Current-voltage characteristics (I-V curve)



- **6 NUV-HD-RH UHD-DE SiPMs** were characterized.
- The expected $\mathbf{V_{Br}}$ = 32.5 V at RT was observed.
- The I decreases with the decrease in temperature.
- The $\mathbf{V_{Br}}$ slowly shifts to lower values with the decrease in temperature.

SiPM characterization before irradiation

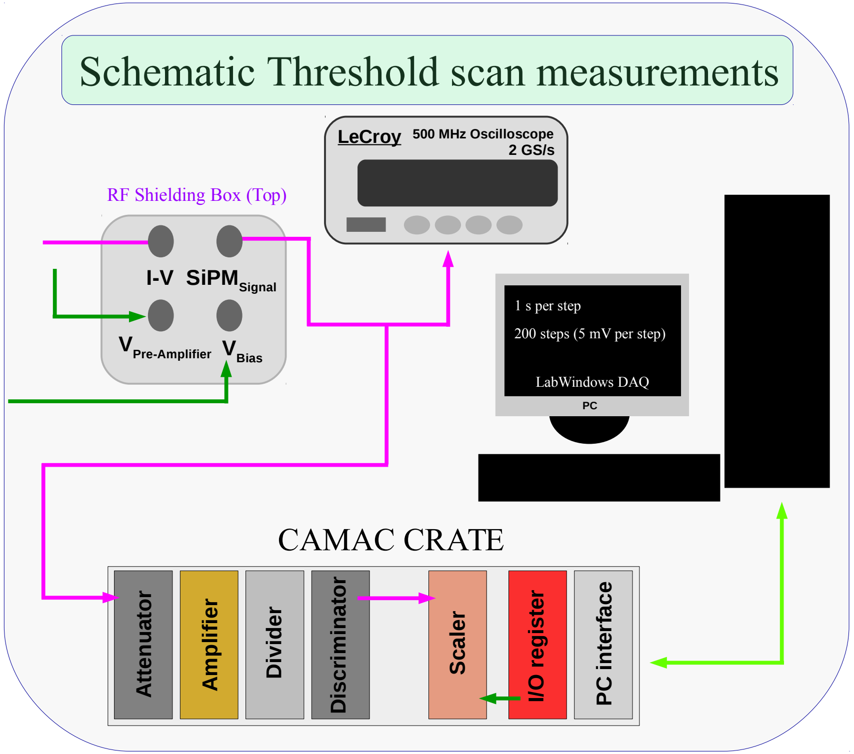


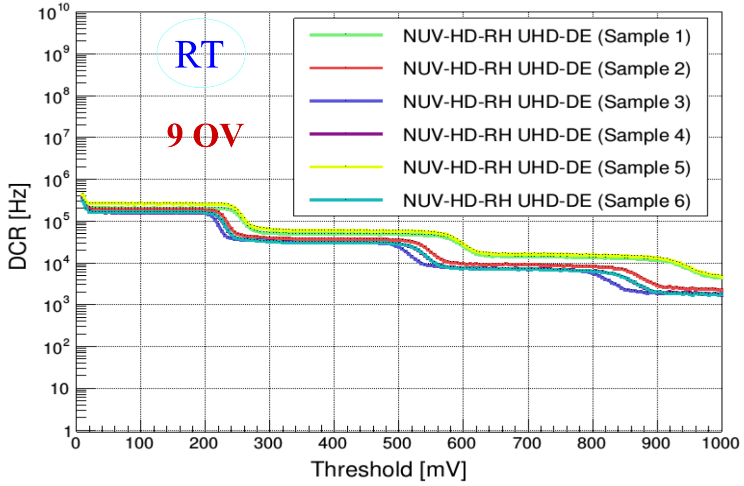


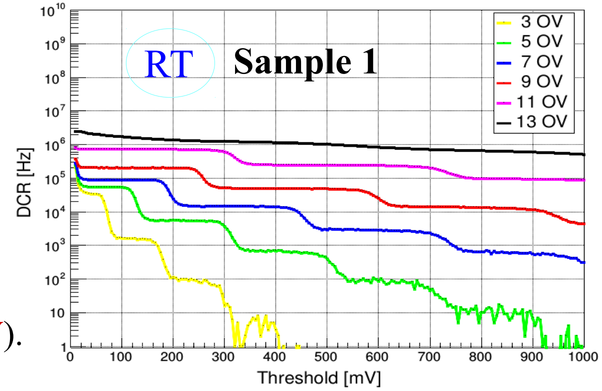
Results shown for Sample 1 are representative for the other 5 Samples

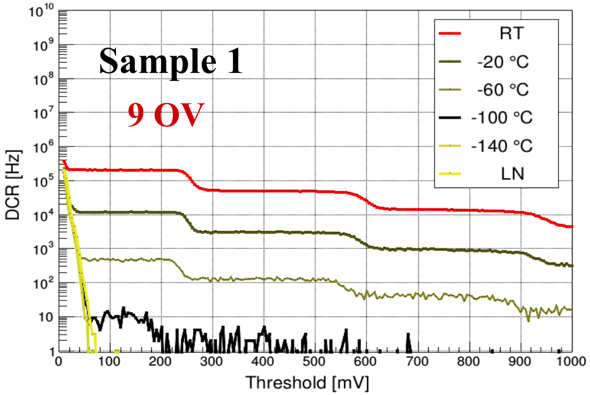
Threshold scan (Dark count rate)

SiPM characterization before irradiation







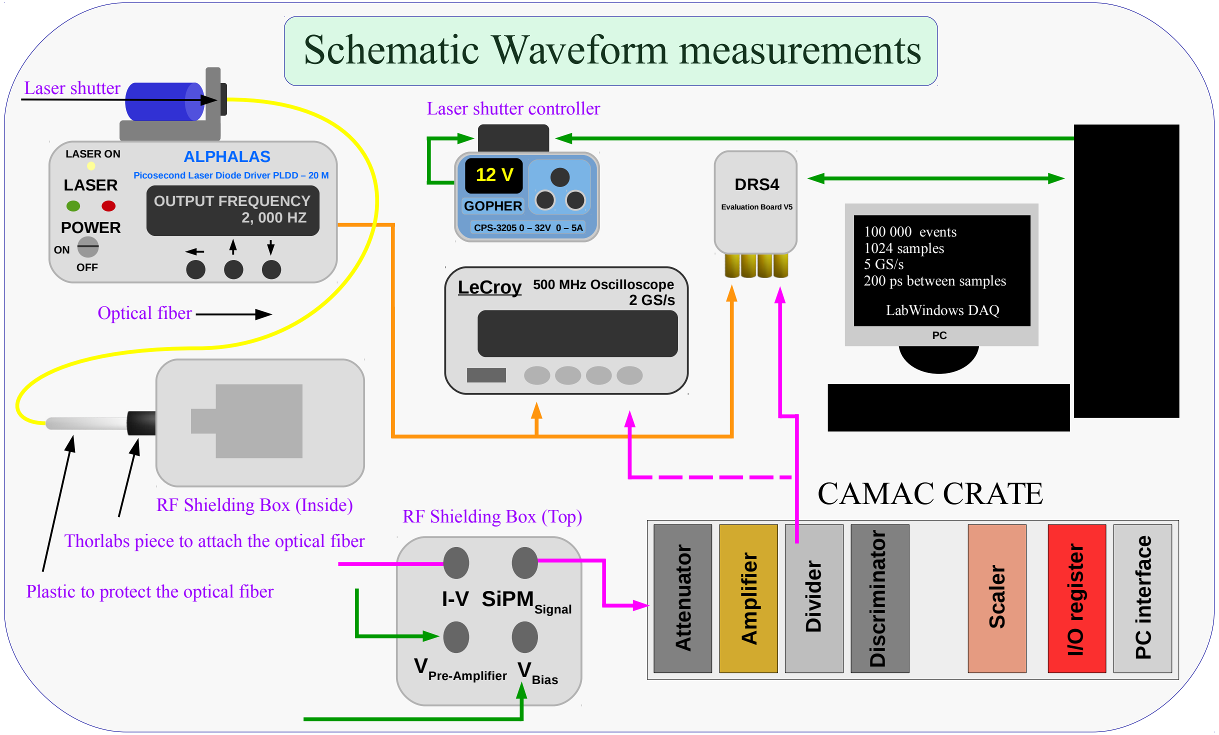


- 6 **NUV-HD-RH UHD-DE SiPMs** were characterized.
- The DCR increases with the increase in the overvoltage (**OV**).
- The DCR decreases with the decrease in temperature.

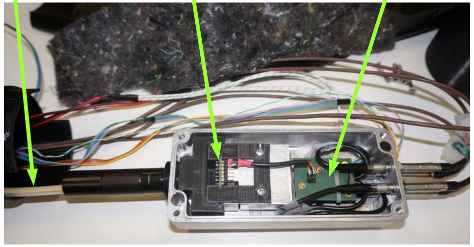
Results shown for Sample 1 are representative for the other 5 Samples

Waveform analysis

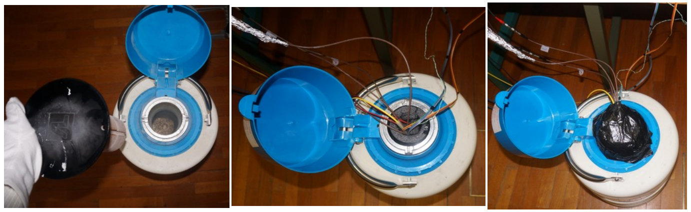
SiPM characterization before irradiation



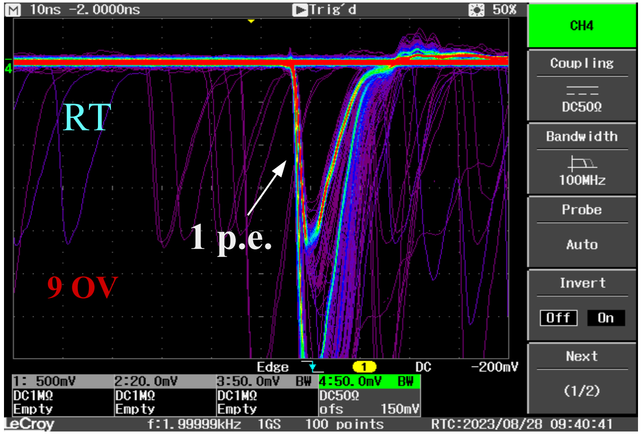
Optical fiber NUV-HD-RH UHD-DE SiPM Custom electronic board

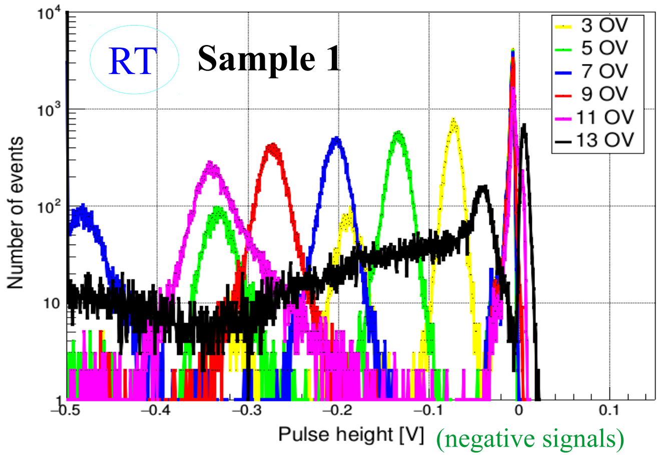


Setup into the liquid nitrogen container



Signal shape & Pulse height distribution





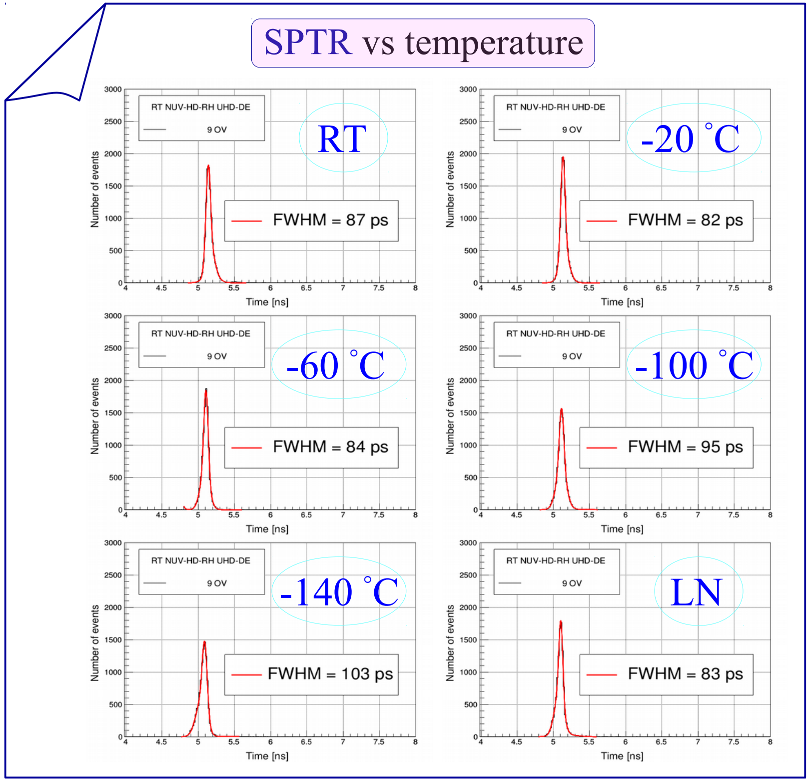
(negative signals)

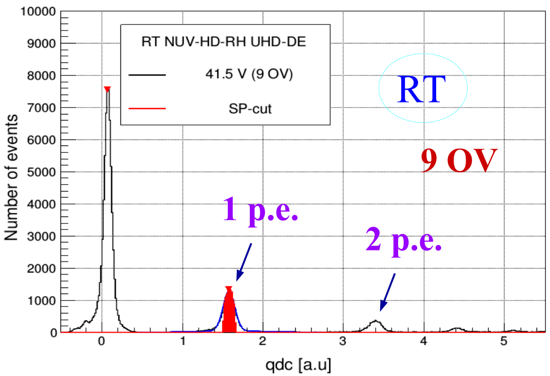
Results shown for Sample 1 are representative for the other 5 Samples

Waveform analysis

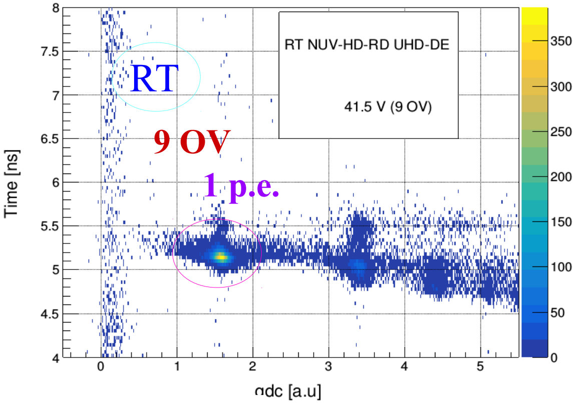
SiPM characterization before irradiation

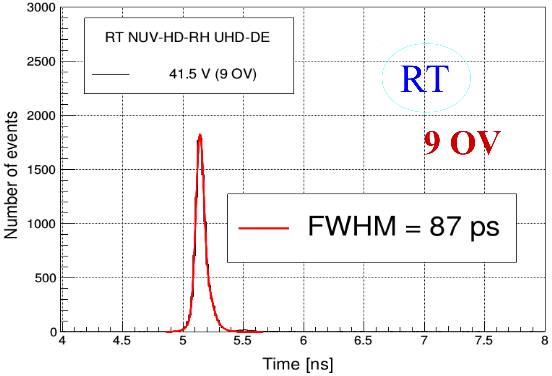
Charge distribution & Single photon timing resolution (SPTR)





Correlation plot





- The SPTR [FWHM] values has no temperature dependence.
- The shape of the timing distribution is not always symmetric. Noise contribution could not be completely removed and it moves relative to the main peak randomly (in regards to temperature, Sample, and time).

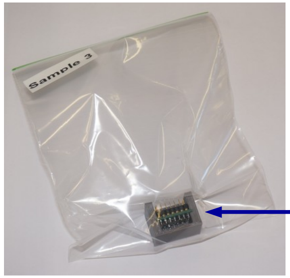
- Single photon cut in the qdc distributions was always applied.
- An SPTR < 100 ps [FWHM] was measured.

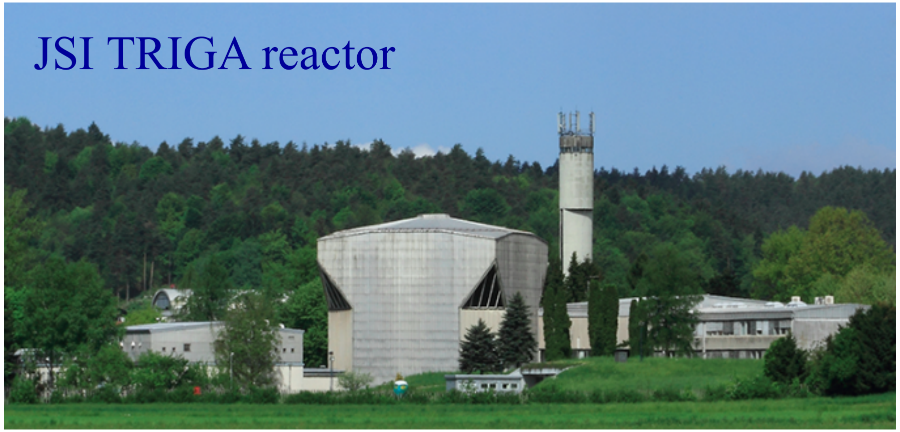
Results shown for Sample 1 are representative for the other 5 Samples

Irradiation of the Samples

Preparing the Samples

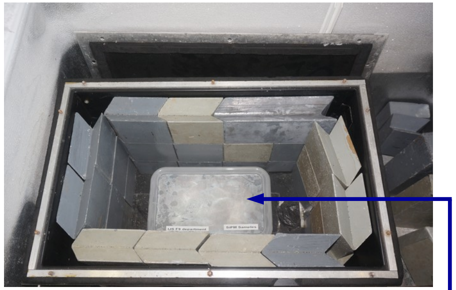
The Samples were protected, avoiding contact between the SiPMs structures and the plastic bag.





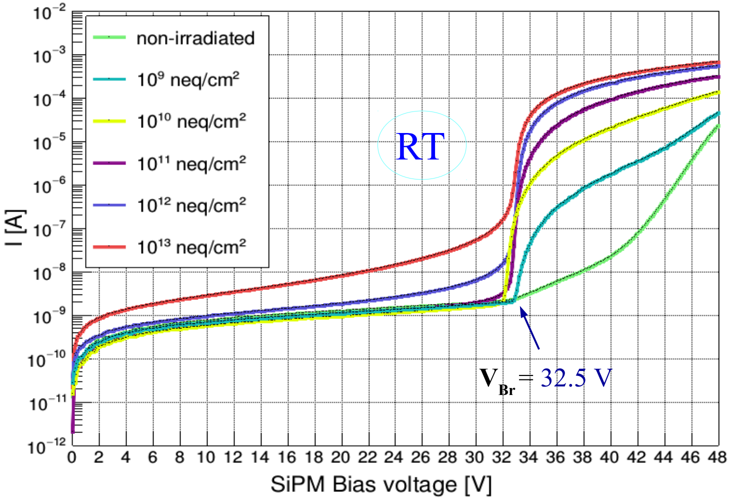
Irradiation 2/10/2023

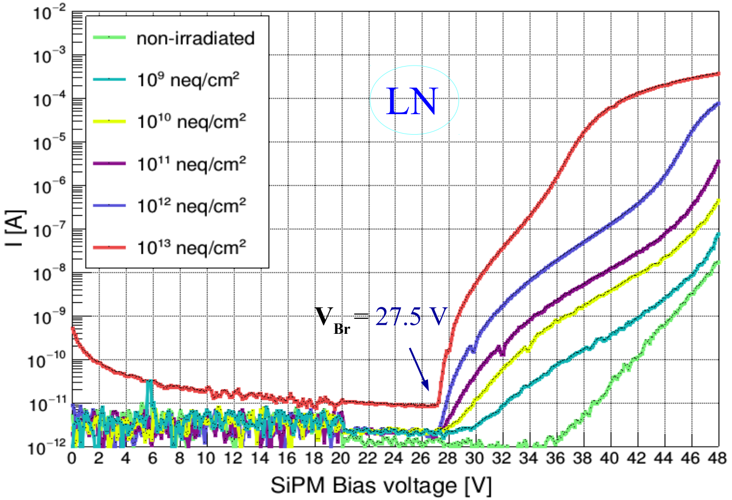
Target [neq/cm^2]	Sample
10^9	6
10^{10}	5
10^{11}	4
10^{12}	3
10^{13}	2
Non-irradiated	1



While waiting for re-characterization after irradiation, the Samples were placed inside a freezer (~ -25 ^{0}C).

Current-voltage characteristics (I-V curve)

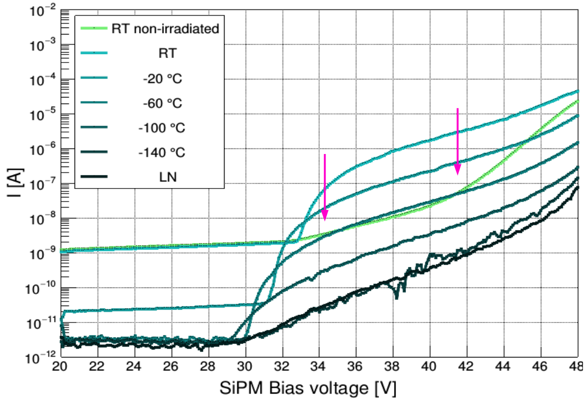




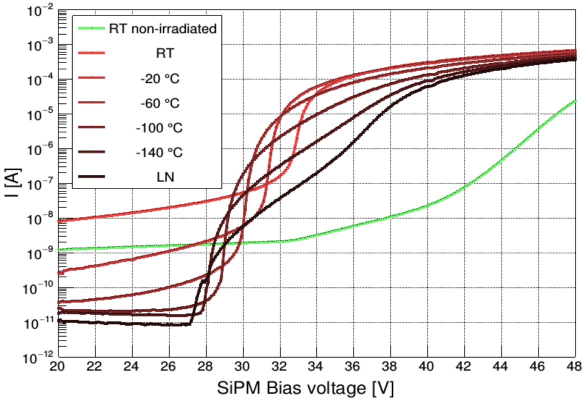
- **5 NUV-HD-RH UHD-DE SiPMs** were characterized.
- The shape of the I-V curves depends on the irradiation level at any temperature step.
- The $\mathbf{V_{Br}}$ at RT remained at 32.5 V.
- The $\mathbf{V_{Br}}$ shifts to lower values with the decrease in temperature.
- The $\mathbf{V_{Br}}$ in LN is at 27.5 V.
- Cooling irradiated **SiPMs** can match the I before irradiation until **10^{12} neq/cm²**.

I vs temperature

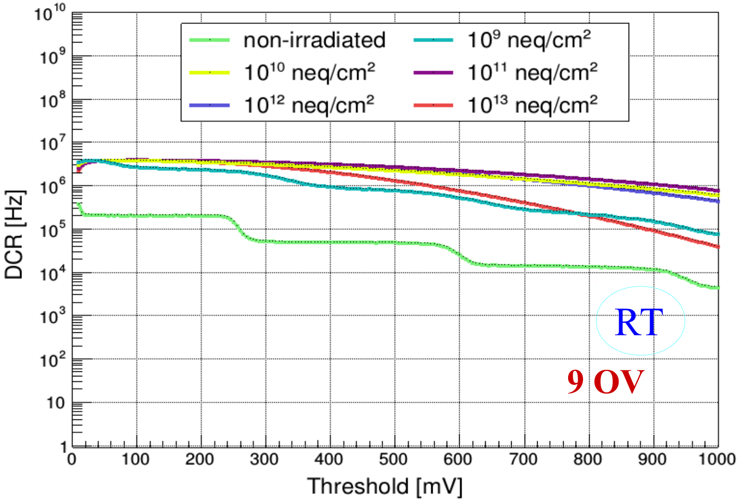
10^9 neq/cm²

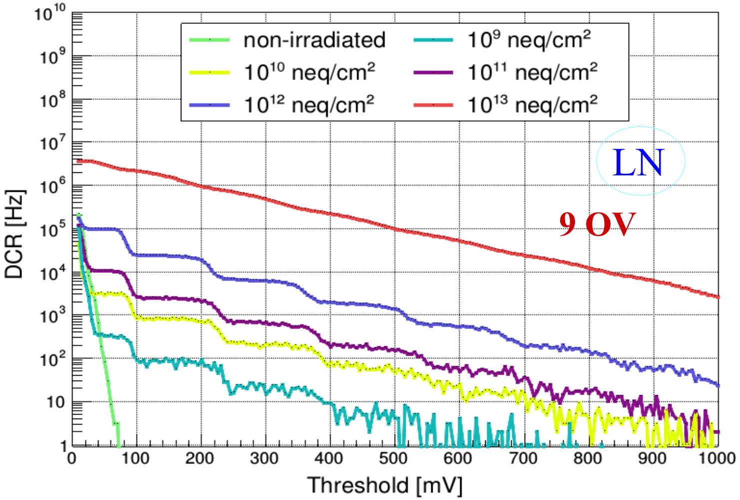


10^{13} neq/cm²



Threshold scan (Dark count rate)

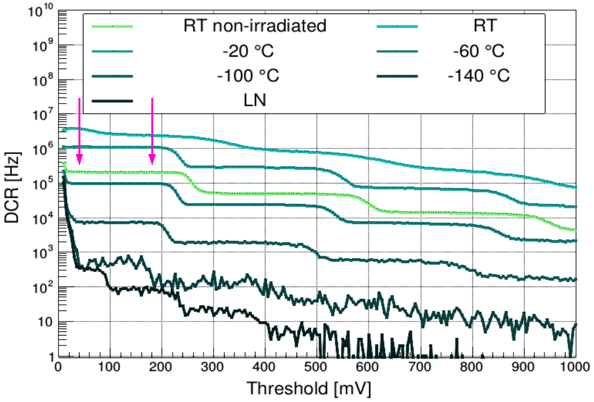




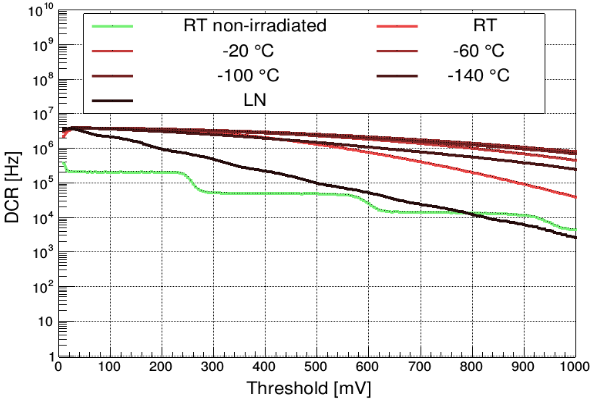
- **5 NUV-HD-RH UHD-DE SiPMs** were characterized.
- The shape of the threshold scans in LN are fully dependent on the irradiation level.
- Cooling irradiated **SiPMs** can match the DCR before irradiation until **10^{12} neq/cm²**.

DCR vs temperature

10^{9} neq/cm²



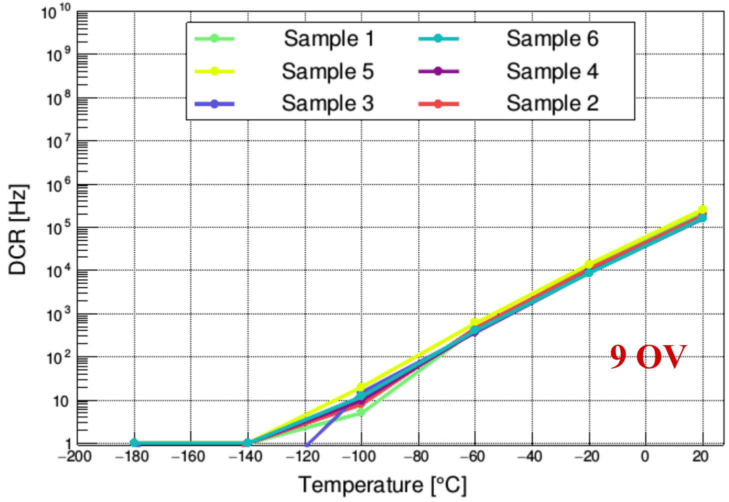
10^{13} neq/cm²



Threshold scan (Dark count rate)

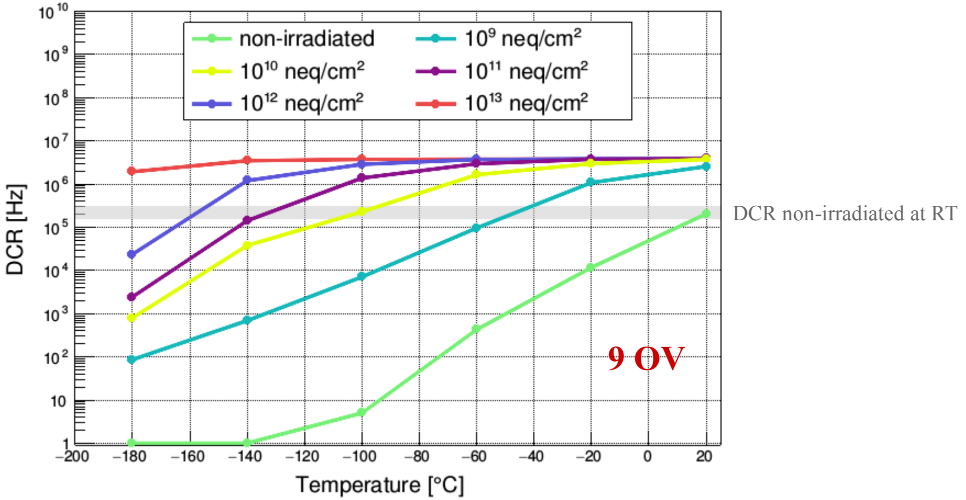
- DCR was measured at single photon level (0.5 p.e.).

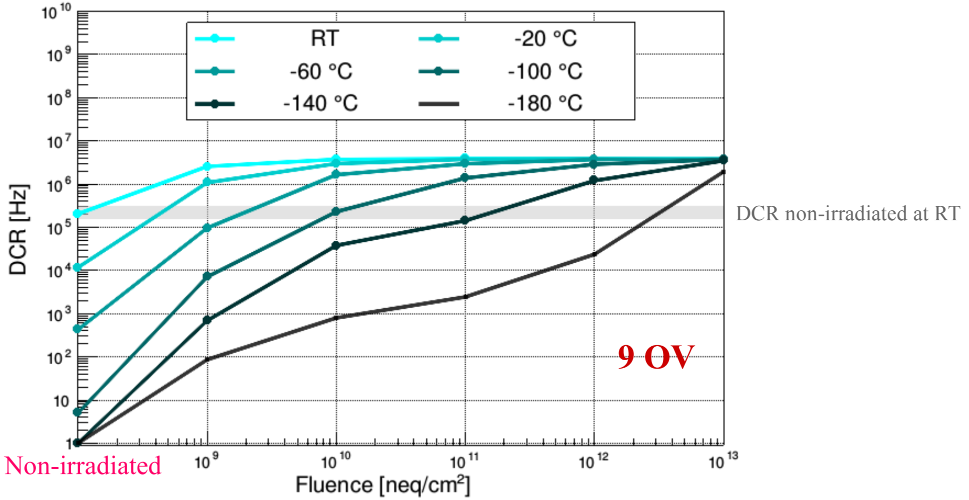
SiPM characterization before irradiation



- Before irradiation DCR of all **6 NUV-HD-RH UHD-DE SiPMs** decreases with temperature.
- Plot of DCR vs temperature at different fluences shows how much cooling is needed to get the same DCR as RT no-irradiated.
- Plot of DCR vs fluences at different temperatures shows how is the maximum fluence possible at certain cooling level.

SiPM characterization after irradiation



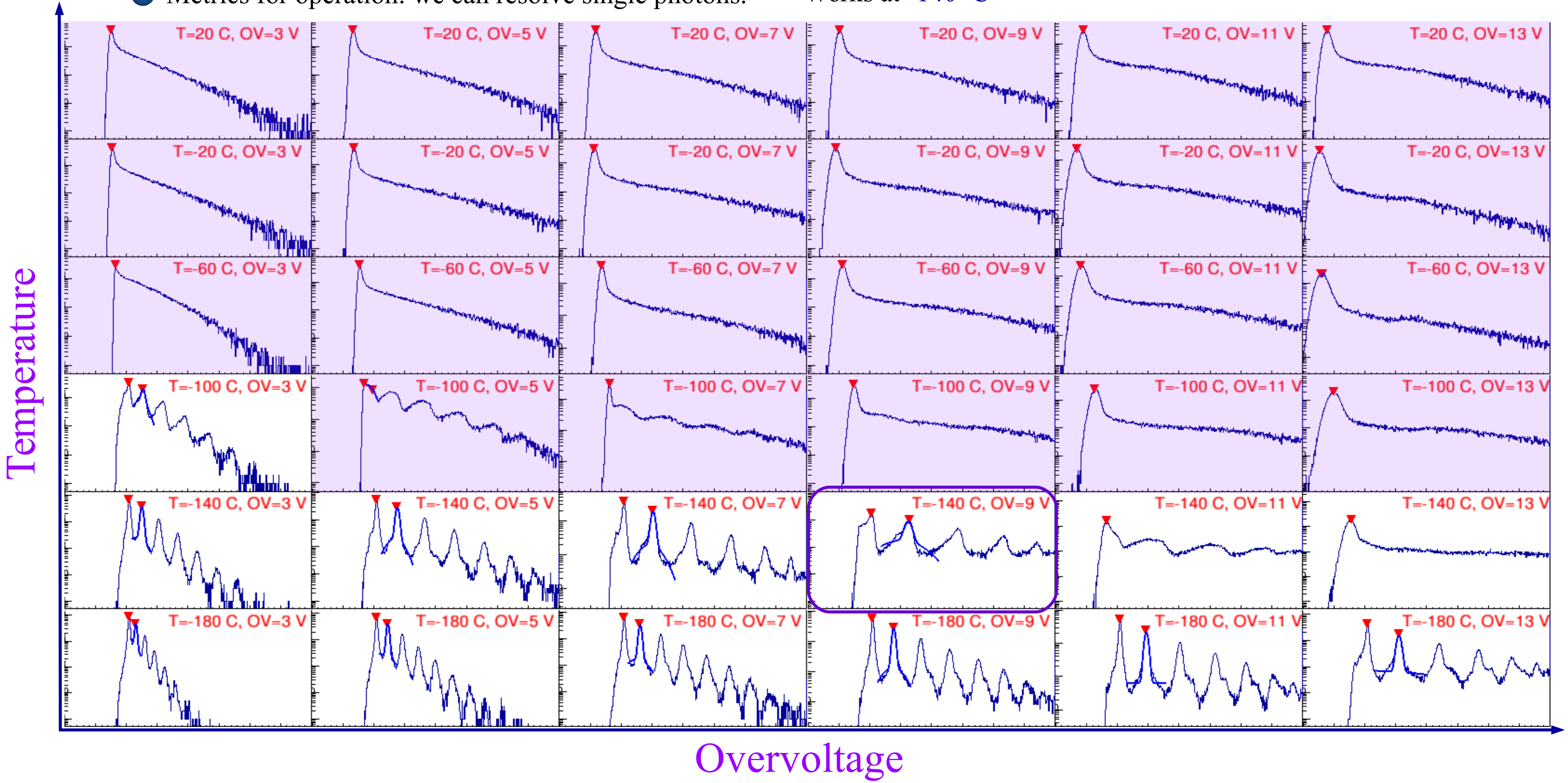


Waveform analysis

SiPM characterization after irradiation

qdcs at 10^{12} neq/cm^2

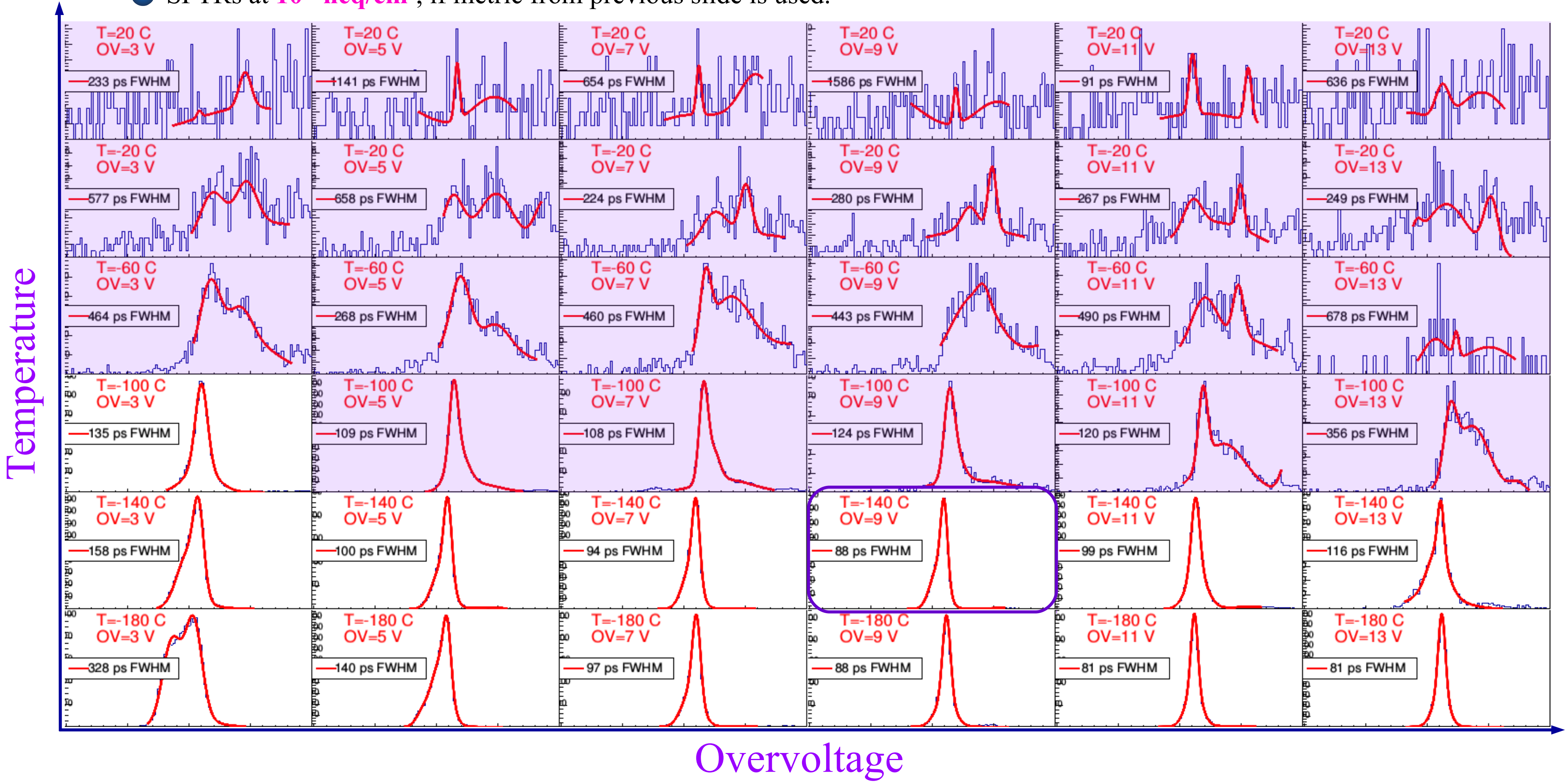
- Metrics for operation: we can resolve single photons. → Works at -140 ^{0}C



SiPM characterization after irradiation

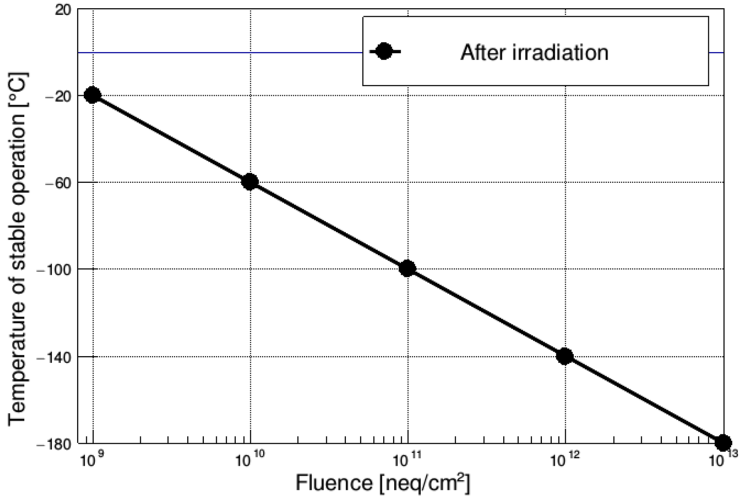
SPTRs at 10^{12} neq/cm^2

- SPTRs at 10^{12} neq/cm^2, if metric from previous slide is used.



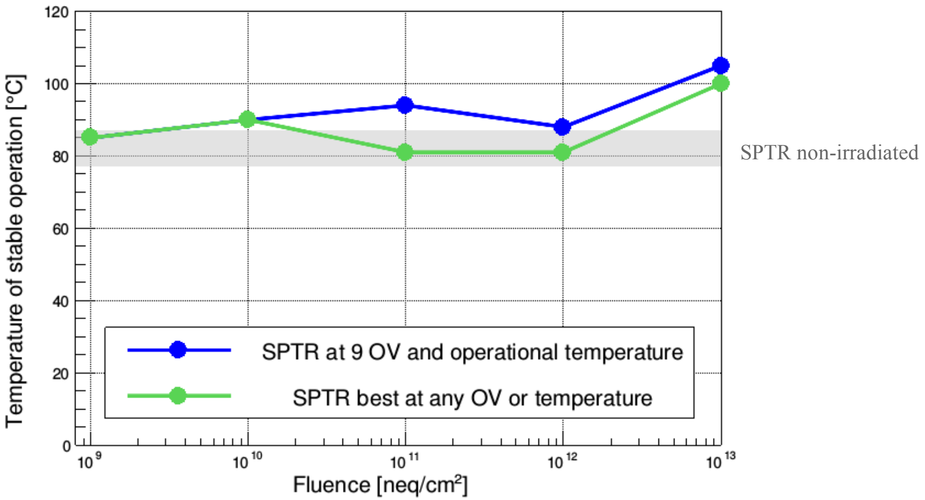
SiPM characterization after irradiation

- The temperature of stable operation for the **SiPMs** after irradiation was defined to be when single photon cut is possible at **9 OV**.



- By **10^{13} neq/cm^2** colling to LN is necessary.

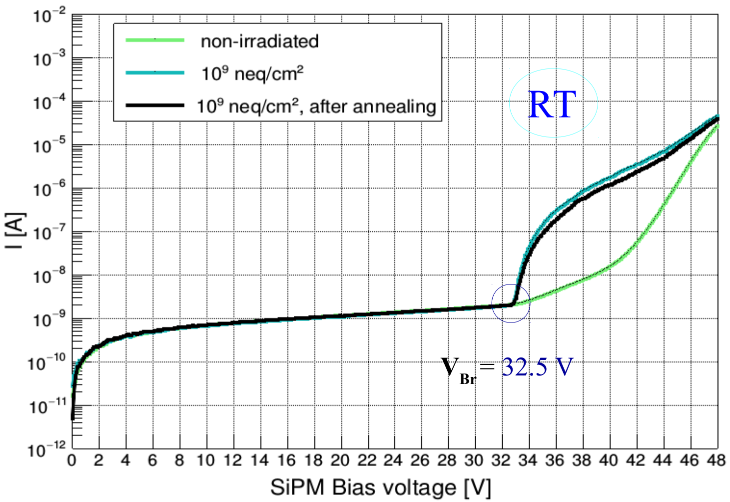
- SPTR [FWHM] of the **SiPMs** after irradiation.
- Best SPTR [FWHM] at any **OV** or temperature is also shown.

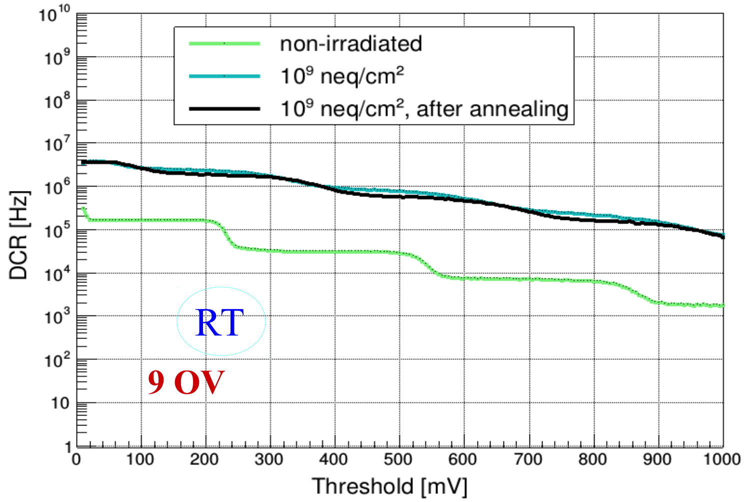


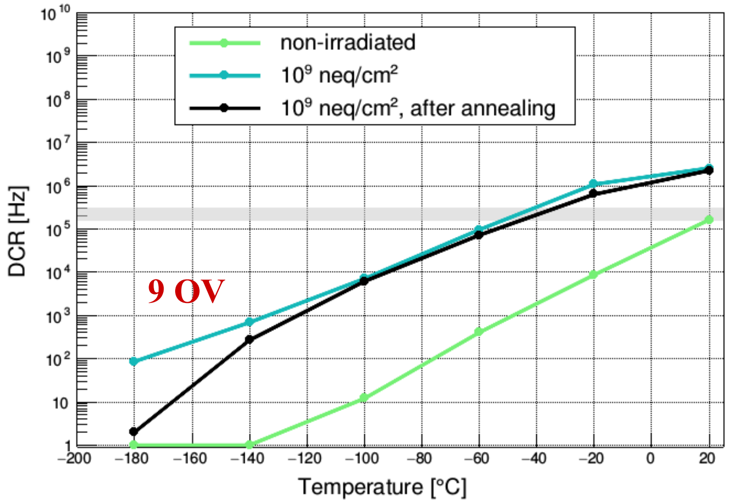
- SPTR [FWHM] does not seem to be affected by irradiation as long as single photon cut is possible, at least until **10^{13} neq/cm^2**.

Annealing studies after irradiation

Sample 6 was annealed at **RT for 1 month**







- After annealing Sample 6 for 1 month at RT, very small improvement was observed.
- SPTR [FWHM] was not changed.
- Next step: Annealing at high temperature.

Conclusions

- **6 NUV-HD-RH UHD-DE SiPMs** were characterized before and after irradiation up to **10^{13} neq/cm^2**.
- DCR increased with irradiation level.
- SPTR not degraded by irradiation, as long as single photons could be resolved.
- Cooling to certain level allowed irradiated **SiPMs** to operate well again.
- By **10^{13} neq/cm^2**, cooling to ± 180 ^{0}C needed.
- Annealing at room temperature for 1 month only slightly improved performance (only sample irradiated at **10^9 neq/cm^2** measured so far).

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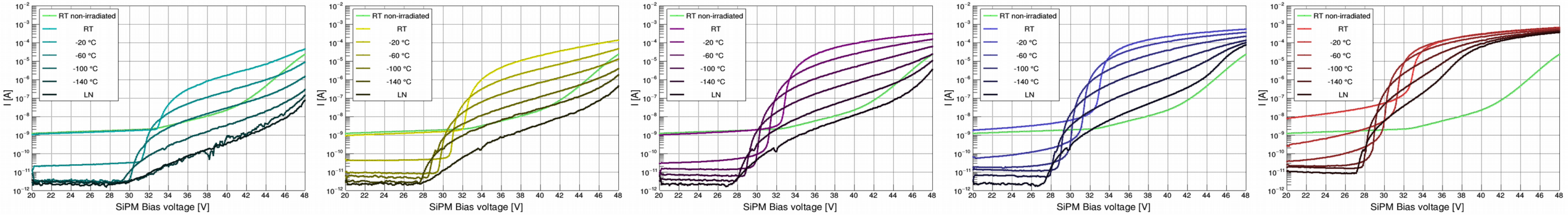
We would like to thank A. Verdir, A. Jazbec, and S. Rupnik for the help with sample irradiation at JSI TRIGA reactor.

SiPM characterization after irradiation

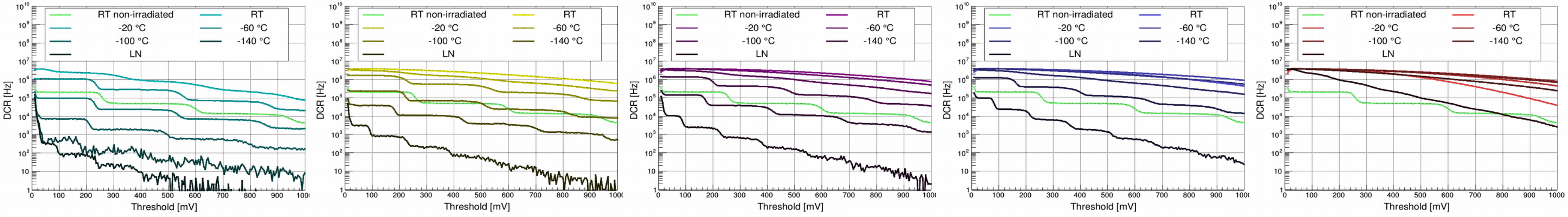
I vs temperature

10^{9} neq/cm^{2} | 10^{10} neq/cm^{2} | 10^{11} neq/cm^{2} | 10^{12} neq/cm^{2} | 10^{13} neq/cm^{2}



DCR vs temperature

10^{9} neq/cm^{2} | 10^{10} neq/cm^{2} | 10^{11} neq/cm^{2} | 10^{12} neq/cm^{2} | 10^{13} neq/cm^{2}

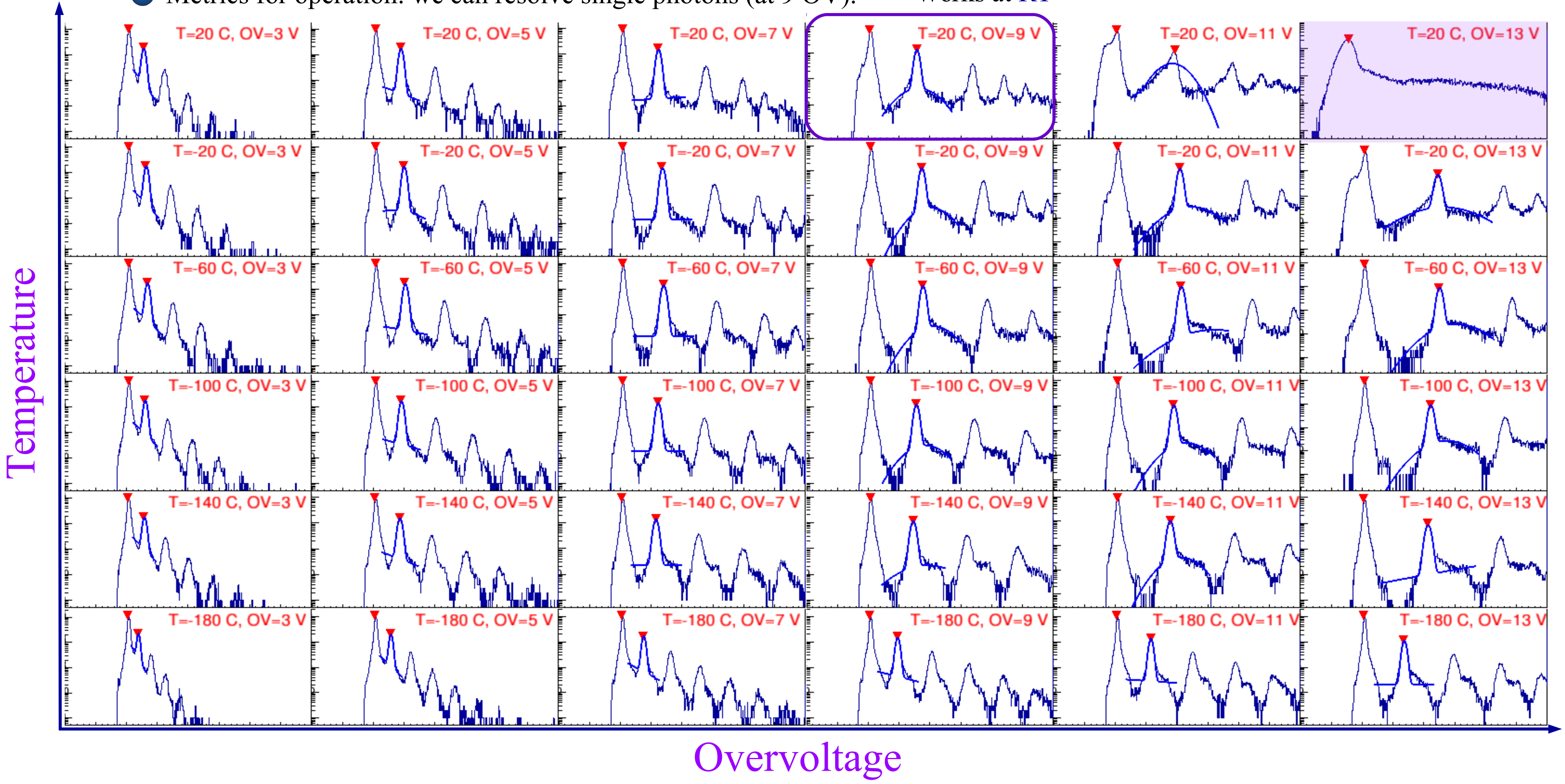


- Cooling irradiated **SiPMs** can match the I and DCR before irradiation until 10^{12} neq/cm^{2}.

SiPM characterization after irradiation

qdcs, **non-irradiated**

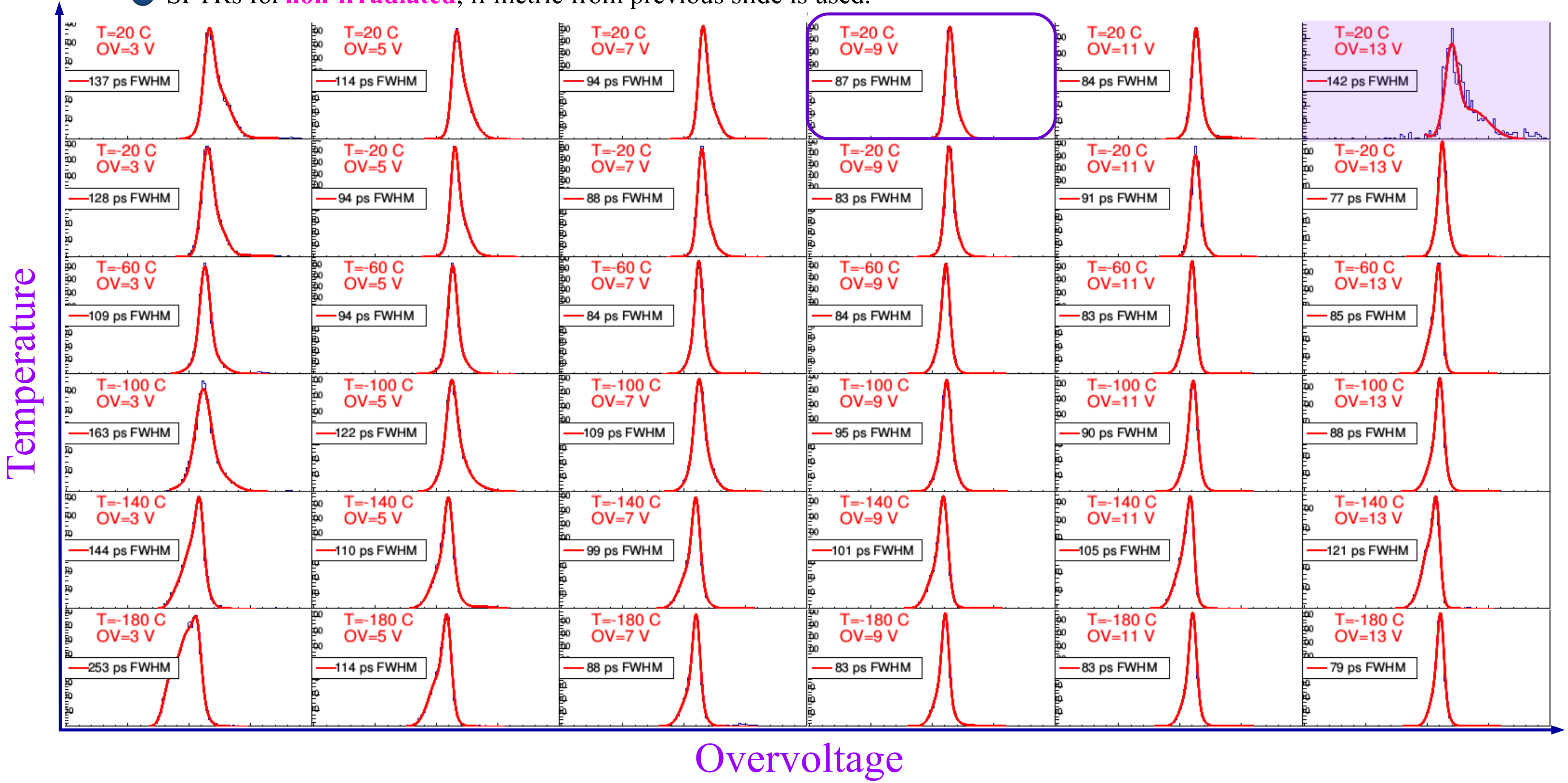
- Metrics for operation: we can resolve single photons (at 9 OV). → Works at RT



SiPM characterization after irradiation

SPTR, **non-irradiated**

- SPTRs for **non-irradiated**, if metric from previous slide is used.

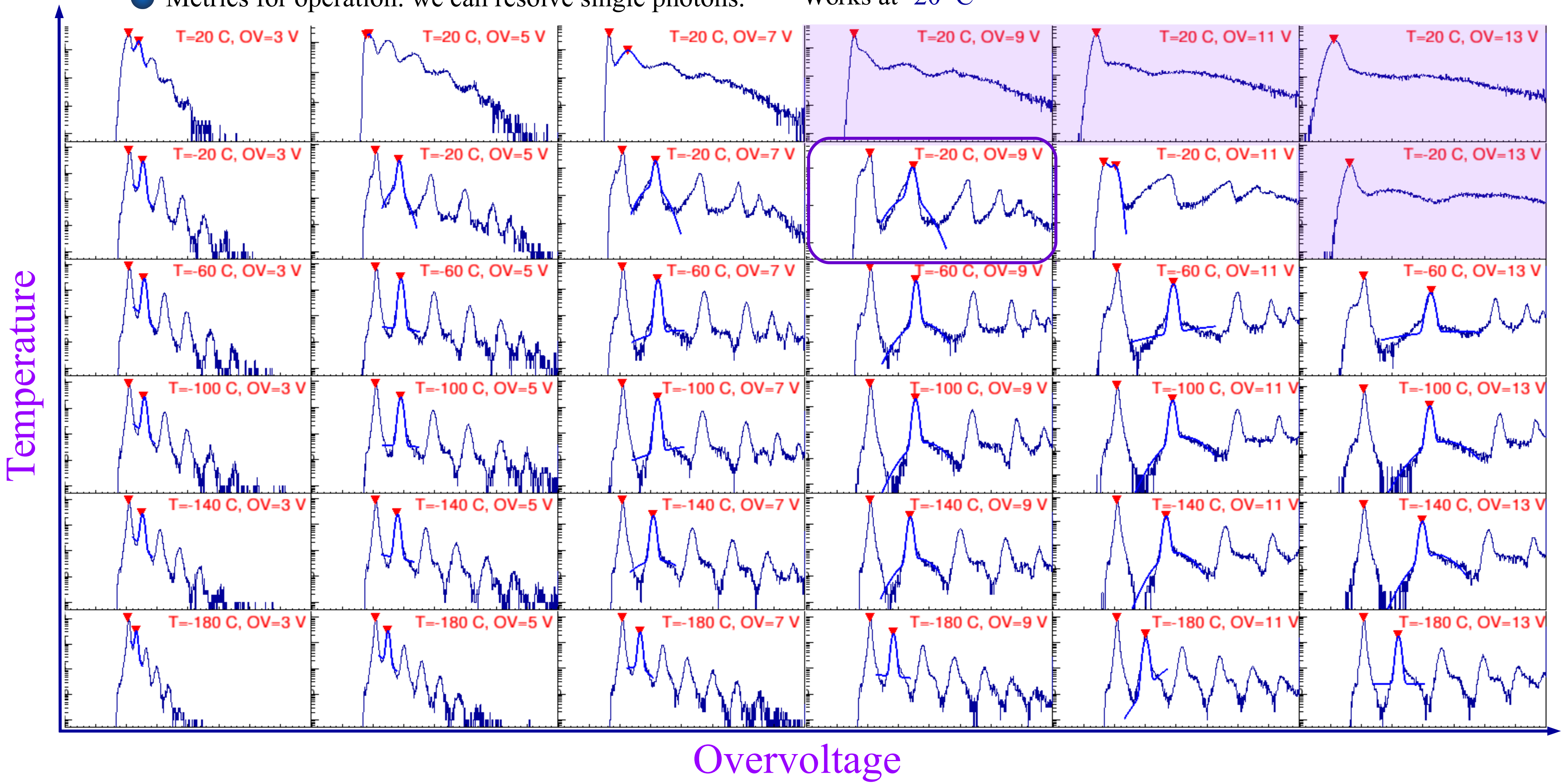


Backup

SiPM characterization after irradiation

qdcs at 10^9 neq/cm^2

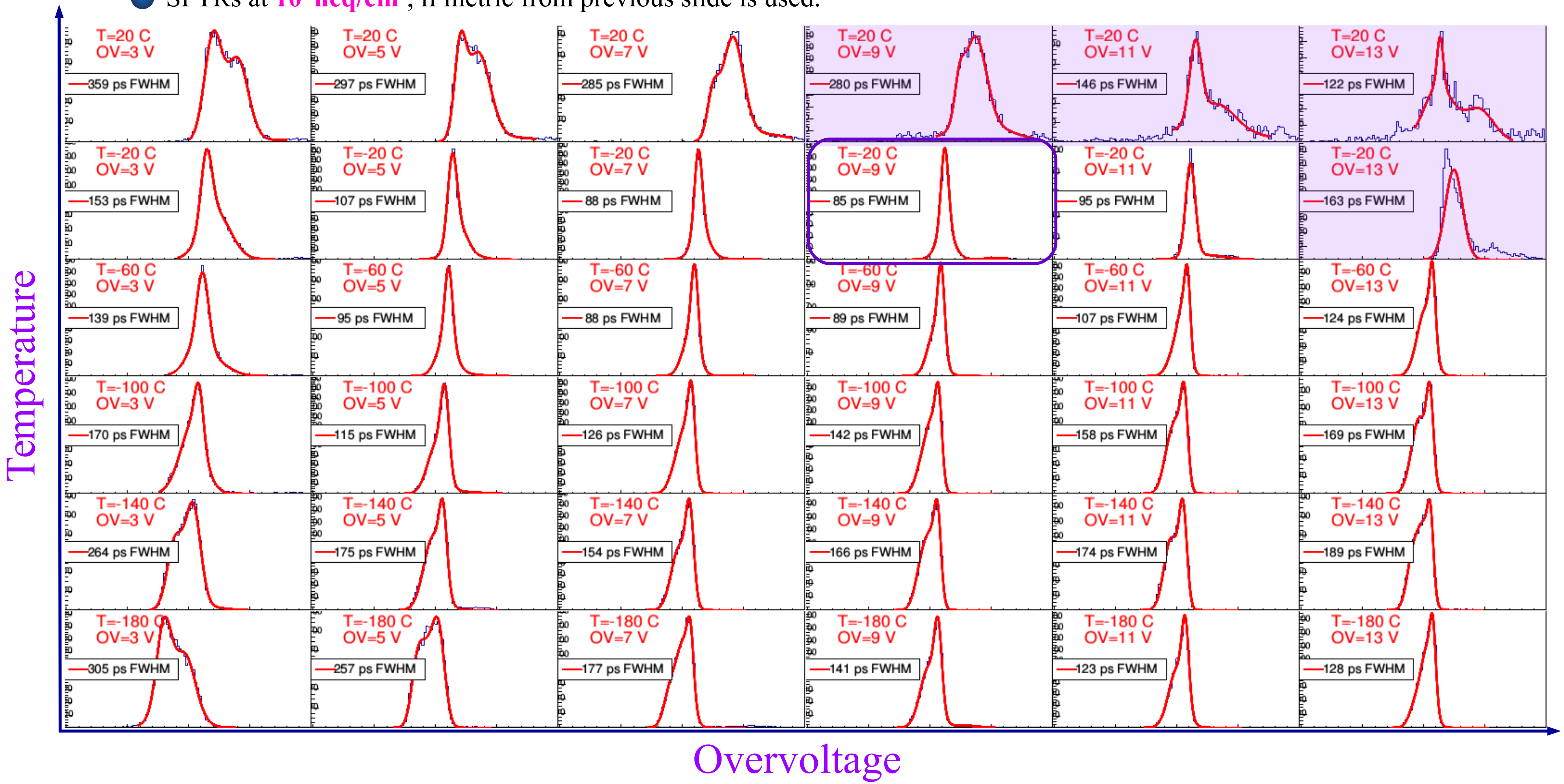
- Metrics for operation: we can resolve single photons. → Works at -20 ^{0}C



SiPM characterization after irradiation

SPTR at 10^9 neq/cm^2

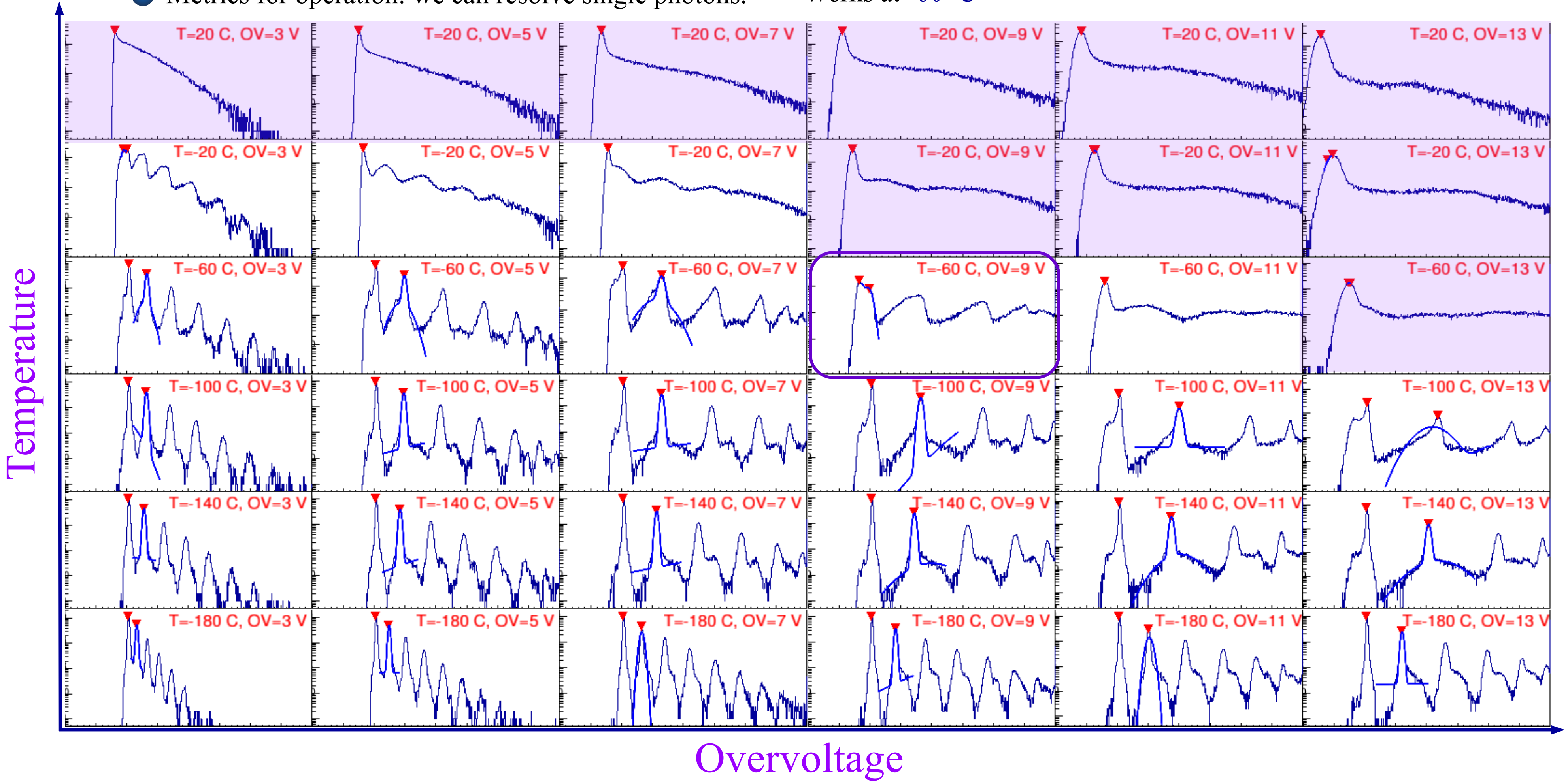
- SPTRs at 10^9 neq/cm^2, if metric from previous slide is used.



SiPM characterization after irradiation

qdcs at 10^{10} neq/cm^2

- Metrics for operation: we can resolve single photons. → Works at -60 ^{0}C

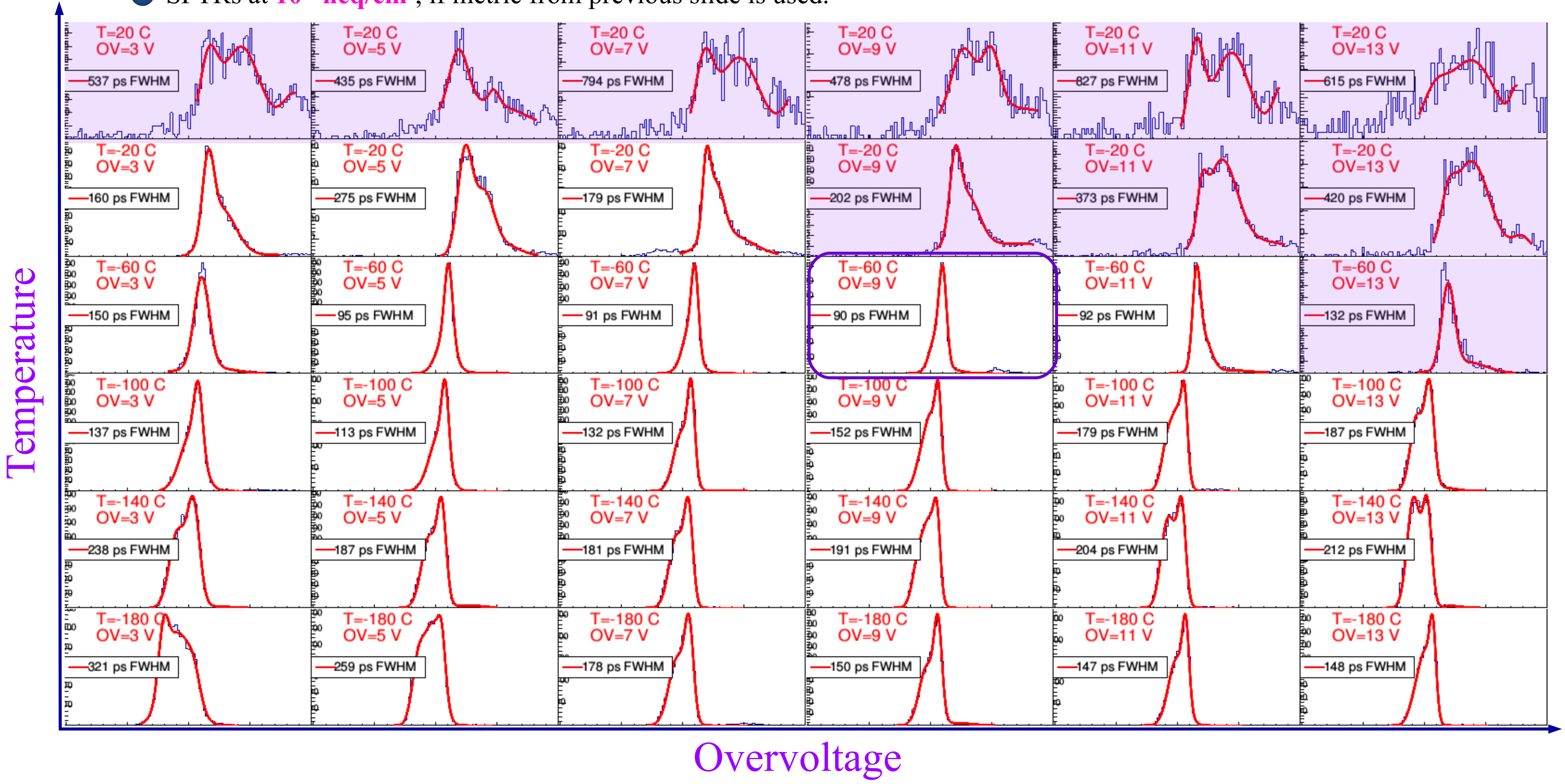


Backup

SiPM characterization after irradiation

SPTR at 10^{10} neq/cm^2

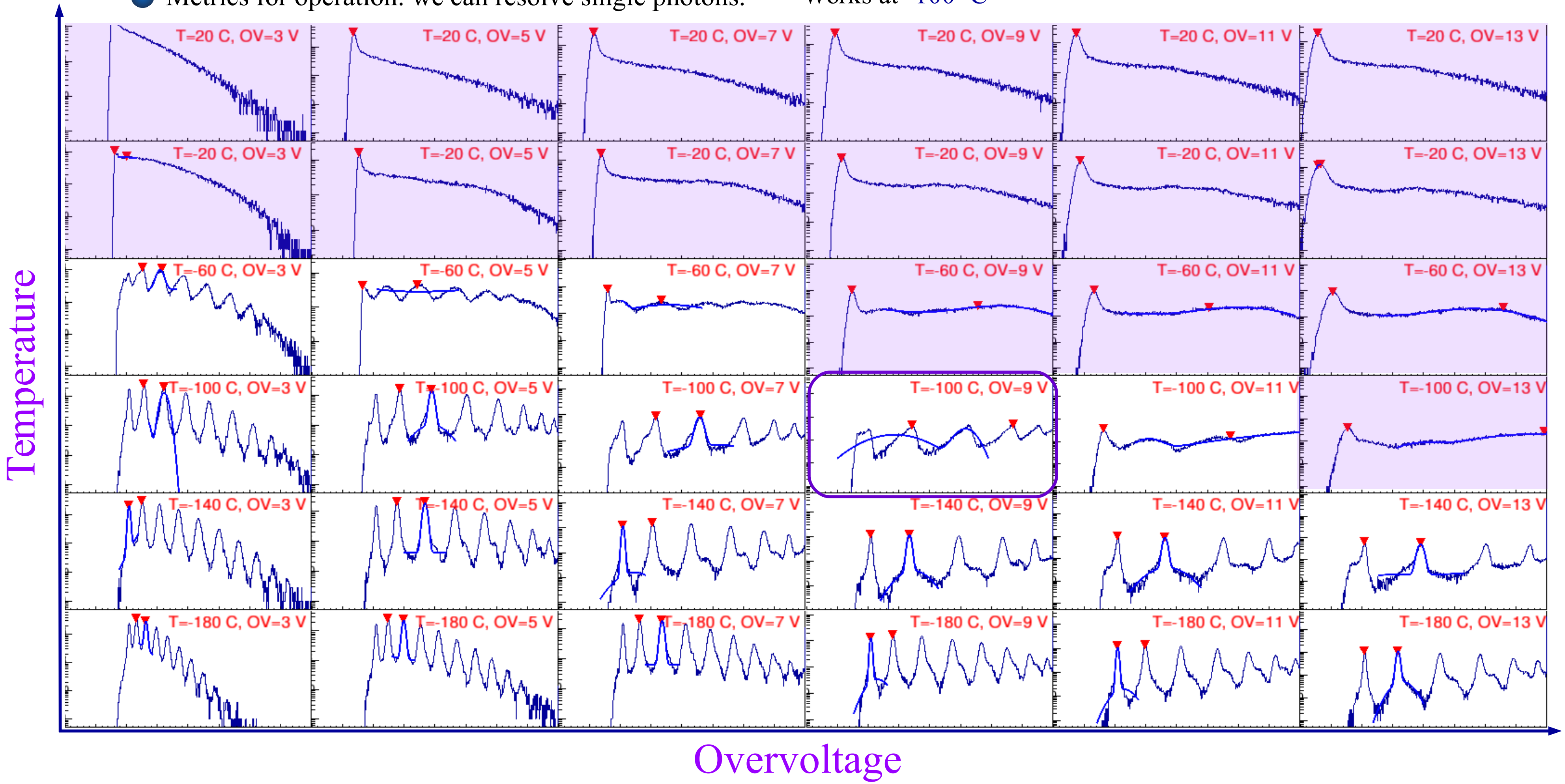
- SPTRs at 10^{10} neq/cm^2, if metric from previous slide is used.



SiPM characterization after irradiation

qdcs at 10^{11} neq/cm²

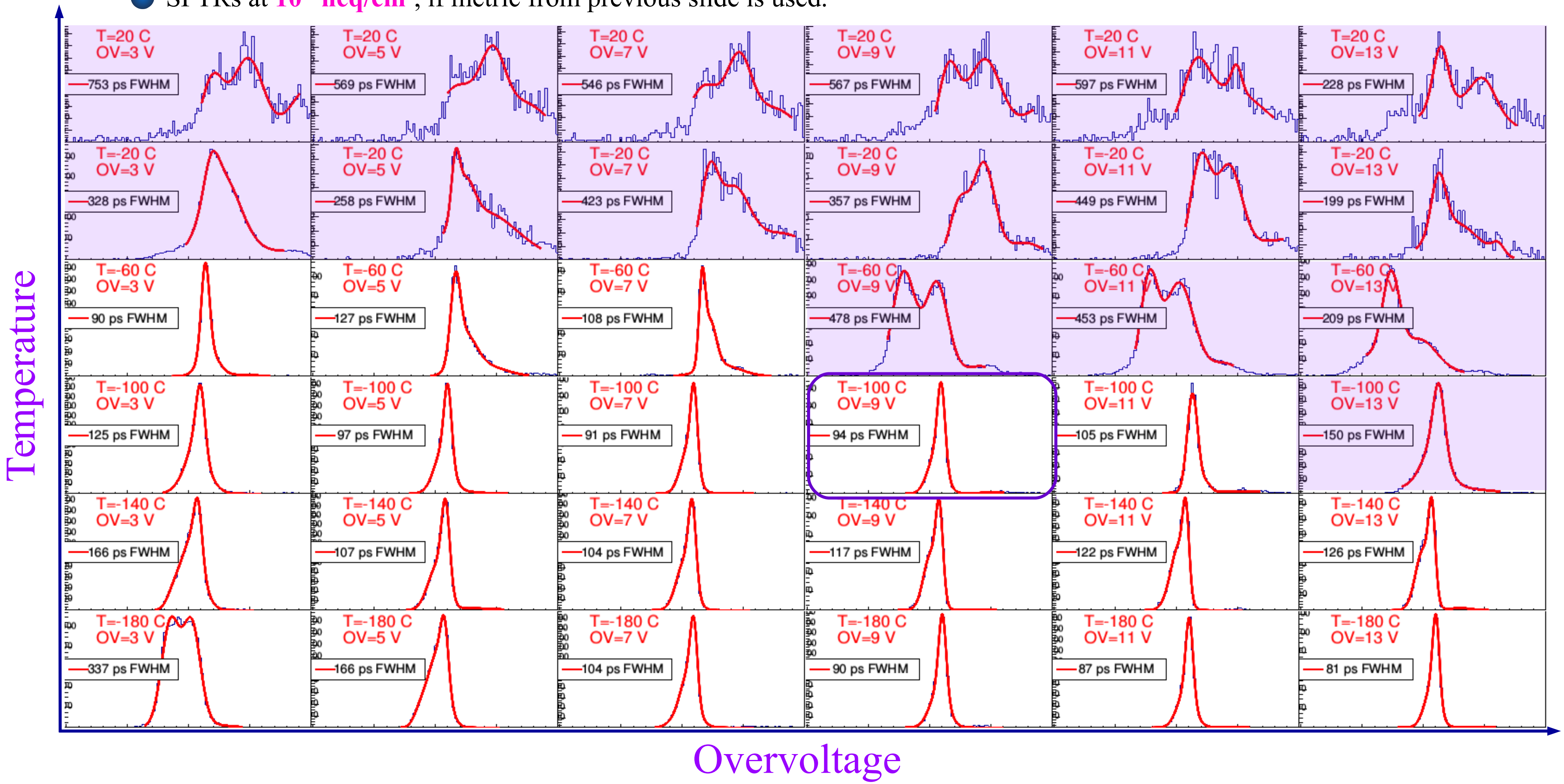
- Metrics for operation: we can resolve single photons. → Works at -100 ^{0}C



SiPM characterization after irradiation

SPTR at 10^{11} neq/cm^2

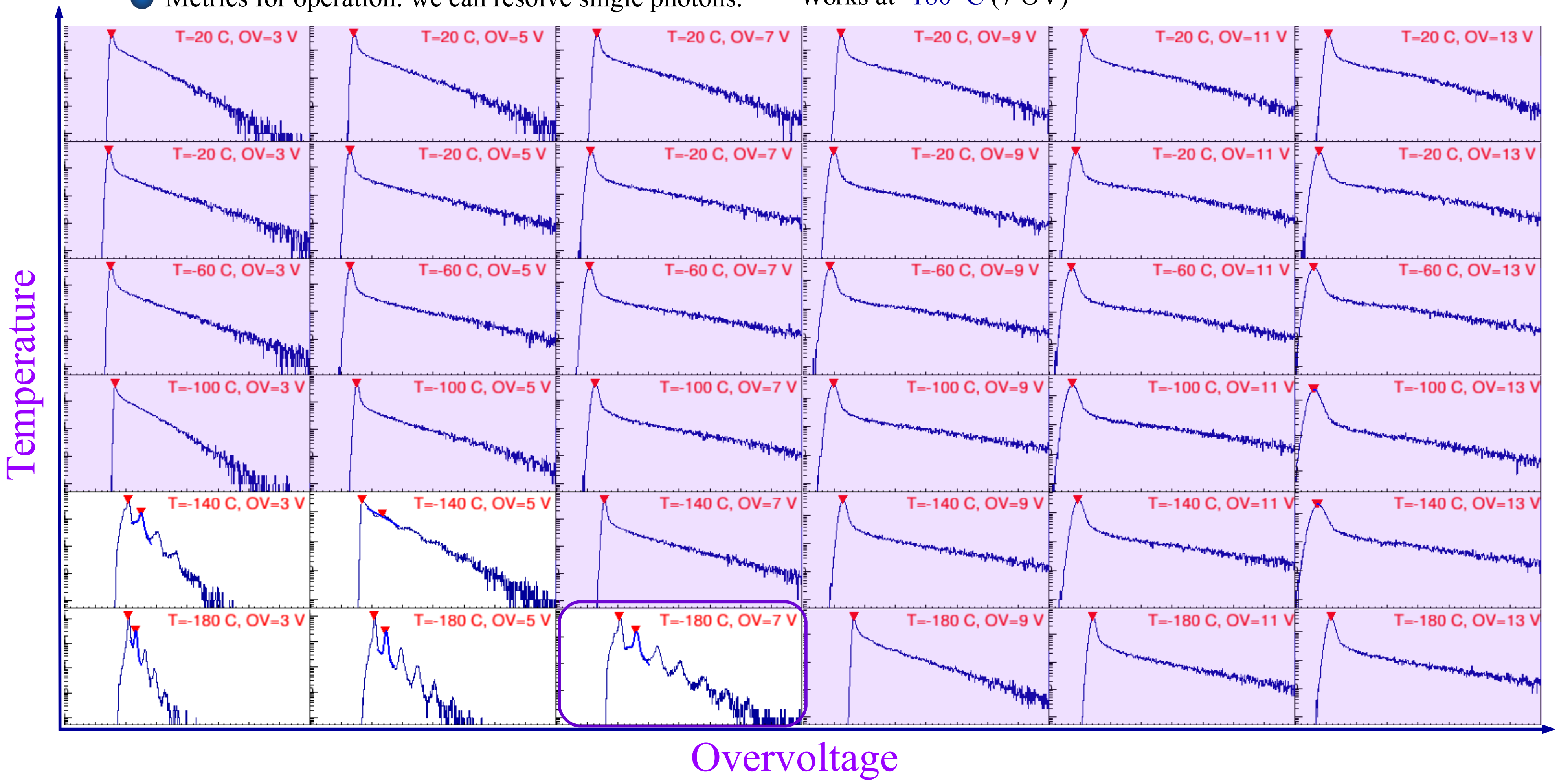
- SPTRs at 10^{11} neq/cm^2, if metric from previous slide is used.



SiPM characterization after irradiation

qdcs at 10^{13} neq/cm^2

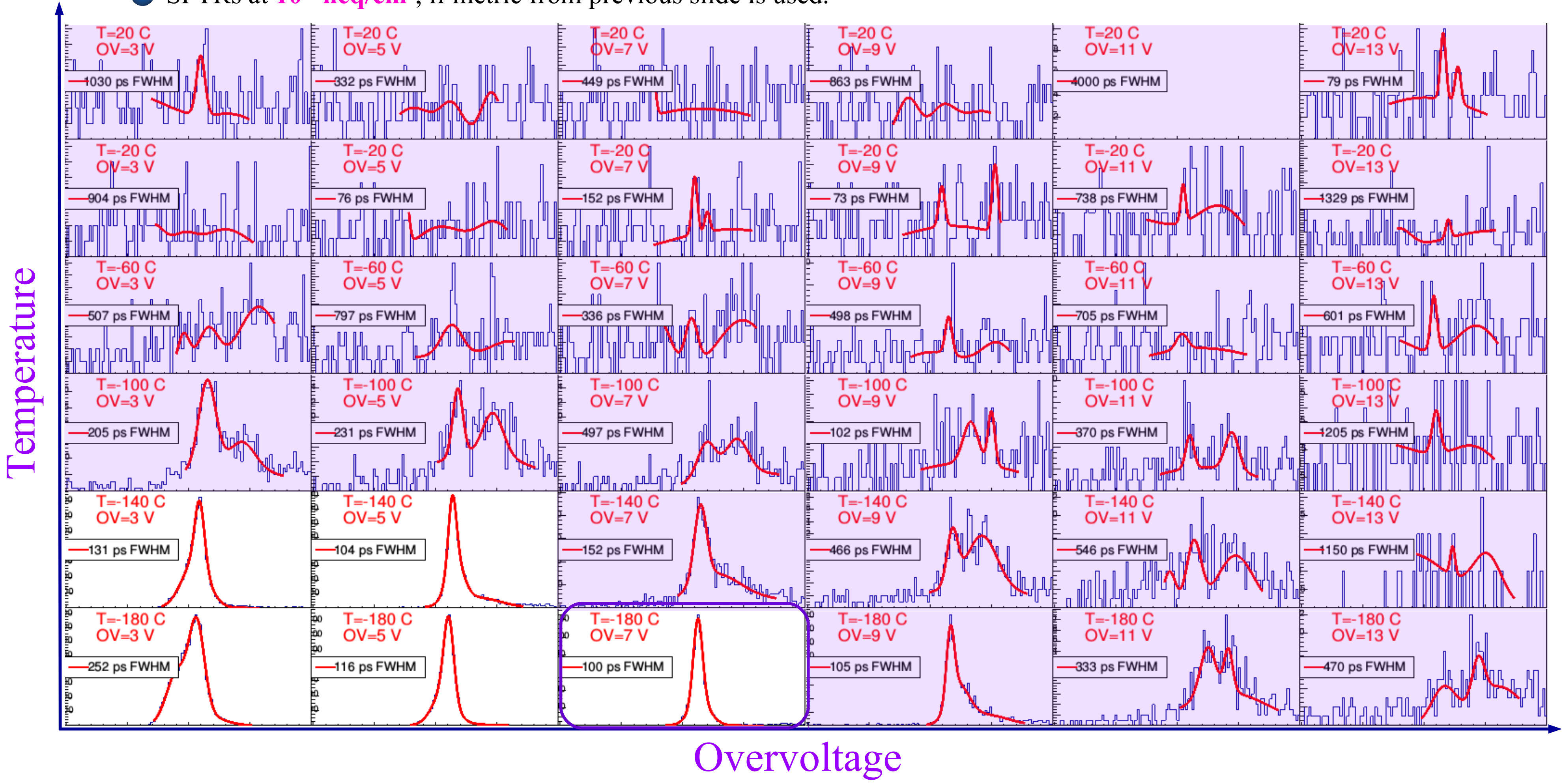
- Metrics for operation: we can resolve single photons. → Works at -180 ^{0}C (7 OV)



SiPM characterization after irradiation

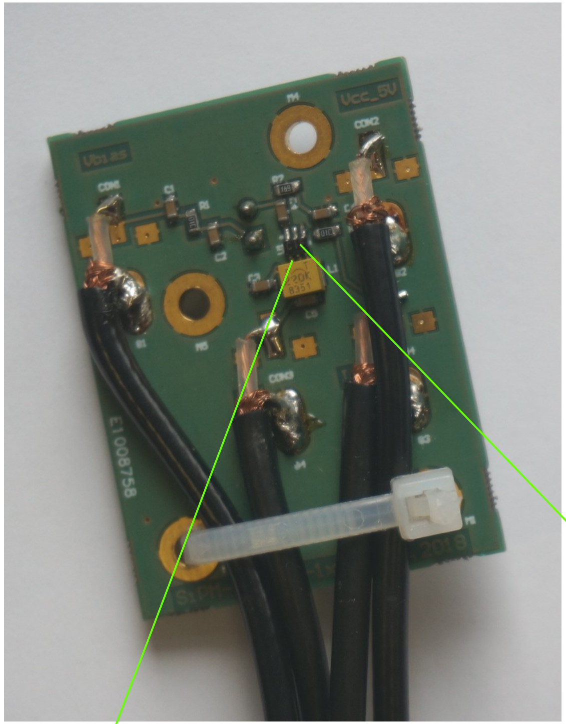
SPTR at 10^{13} neq/cm^2

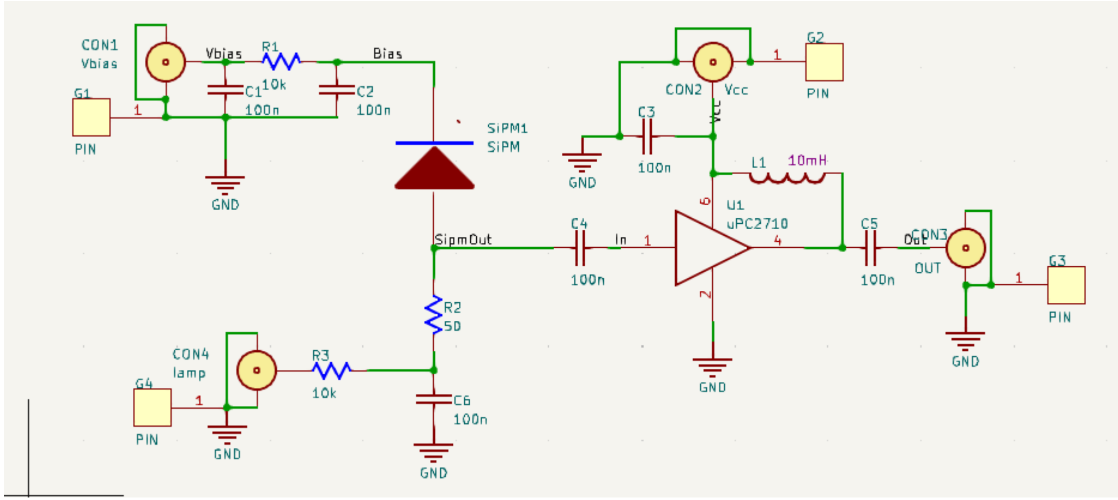
- SPTRs at 10^{13} neq/cm^2, if metric from previous slide is used.



Backup

Custom electronic board used for these measurements





NEC

DATA SHEET

BIPOLAR ANALOG INTEGRATED CIRCUIT

μPC2710TB

5 V, SUPER MINIMOLD SILICON MMIC
MEDIUM OUTPUT POWER AMPLIFIER

DESCRIPTION

The μPC2710TB is a silicon monolithic integrated circuit designed as PA driver for 900 MHz band cellular telephone tuners. This IC is packaged in super minimold package which is smaller than conventional minimold.

The μPC2710TB has compatible pin connections and performance to μPC2710T of conventional minimold version. So, in the case of reducing your system size, μPC2710TB is suitable to replace from μPC2710T.

This IC is manufactured using NEC's 20 GHz fT NESAT™ III silicon bipolar process. This process uses silicon nitride passivation film and gold electrodes. These materials can protect chip surface from external pollution and prevent corrosion/migration. Thus, this IC has excellent performance, uniformity and reliability.

FEATURES

- High-density surface mounting : 6-pin super minimold package
- Wideband response : f_u = 1.0 GHz TYP. @ 3 dB bandwidth
- Medium output power : $P_{O(sat)}$ = +13.5 dBm TYP. @ f = 500 MHz with external inductor
- Supply voltage : V_{CC} = 4.5 to 5.5 V
- Power gain : G_P = 33 dB TYP. @ f = 500 MHz
- Port impedance : input/output 50 Ω

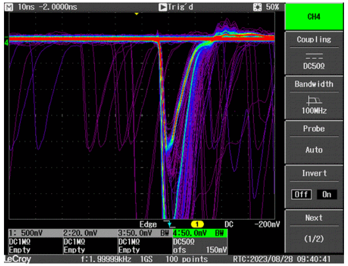
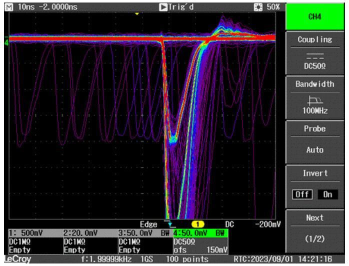
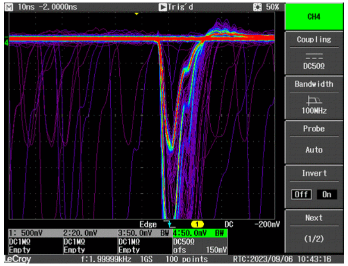
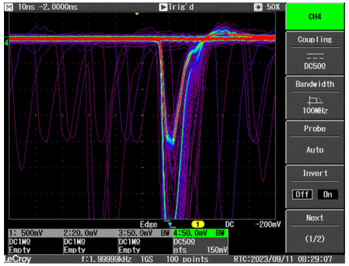
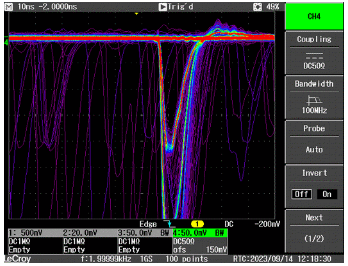
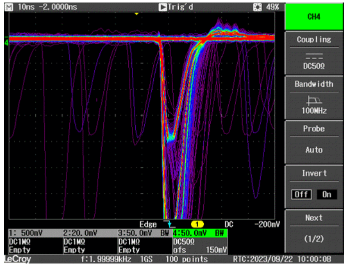
The pre-amplifier is on the board itself.

Backup

6 SiPMs before irradiation

9 OV

RT

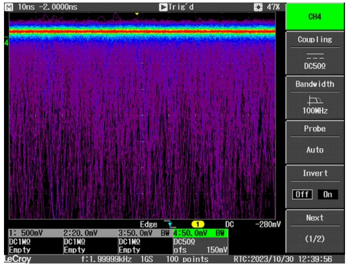
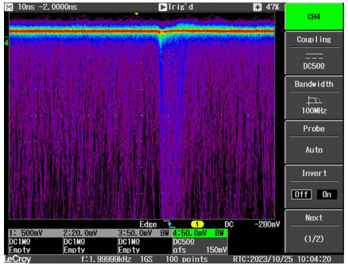
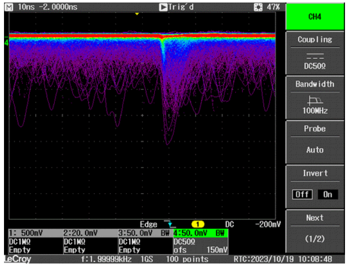
10^{13} neq/cm^2

10^{12} neq/cm^2

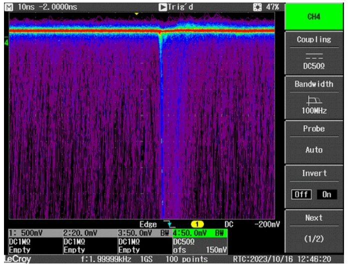
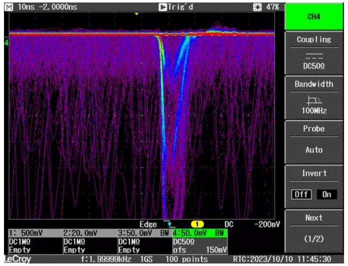
10^{11} neq/cm^2

10^{10} neq/cm^2

10^{9} neq/cm^2

Wrong OV

After annealing