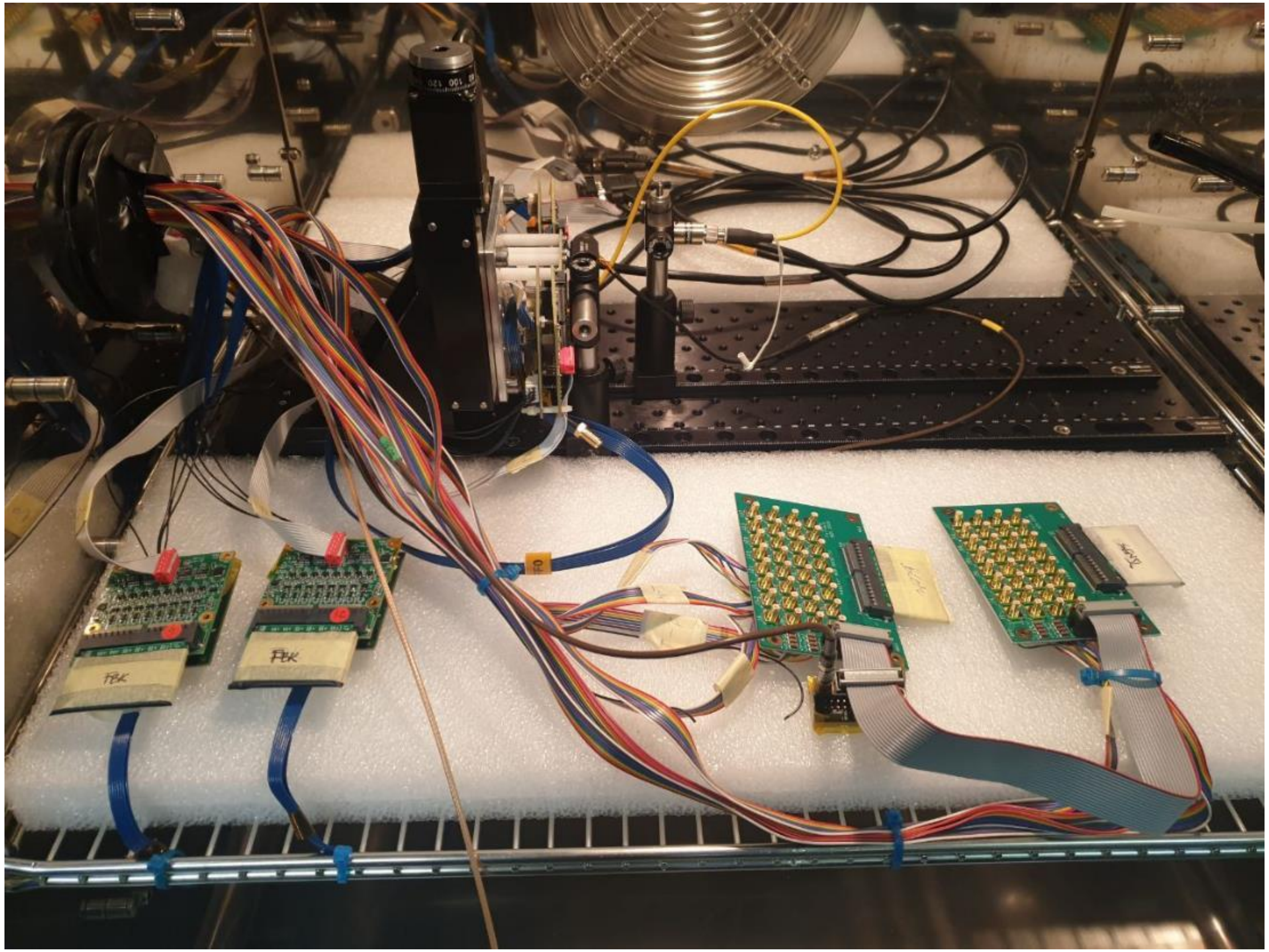
SiPM: irradiation and annealing campaign

Giornata nazionale EIC_NET 2022
Luigi Rignanese rignanes@bo.infn.it

Outline

- Introduction
- Characterization setup
- Irradiation and annealing campaign
- Results



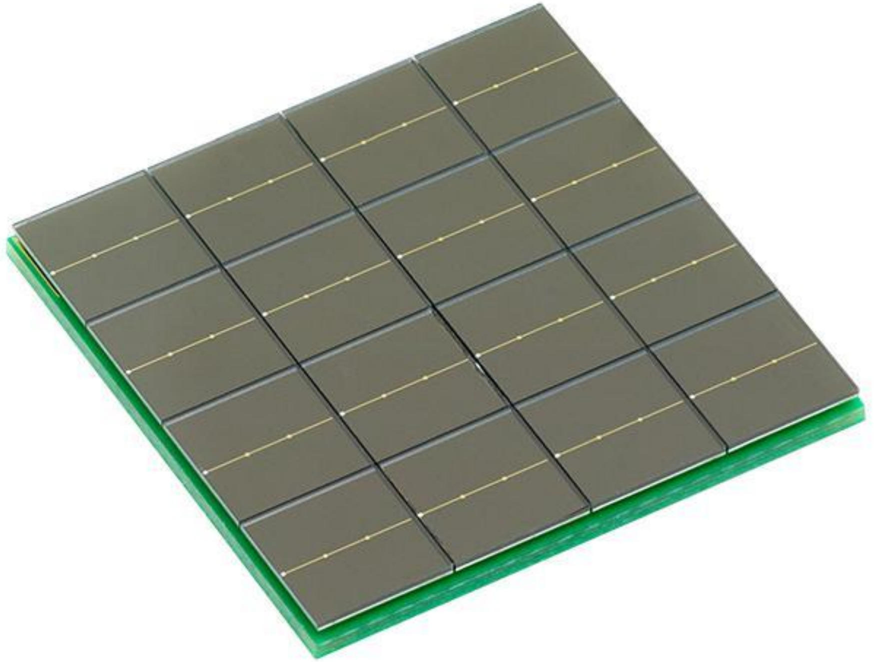
Introduction

SiPMs are a valuable option for the **Dual Rich** optical readout:

- **Cheap**
- **Low voltage** operation
- Excellent **time resolution**
- **Single photon** detection
- **Insensitive** to **magnetic field**
- High **spatial resolution**

But:

- Large **Dark Count Rate**
- Prone to **radiation damage**.



Introductio

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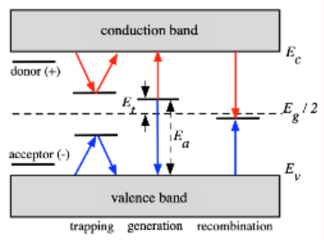
DCR reduction by operating at **low temperatures** (≈-30°C)

Radiation damage by Non-ionizing Energy Loss (**NIEL**) leads to **displacement** damages and build up of **crystal defects** that results in:

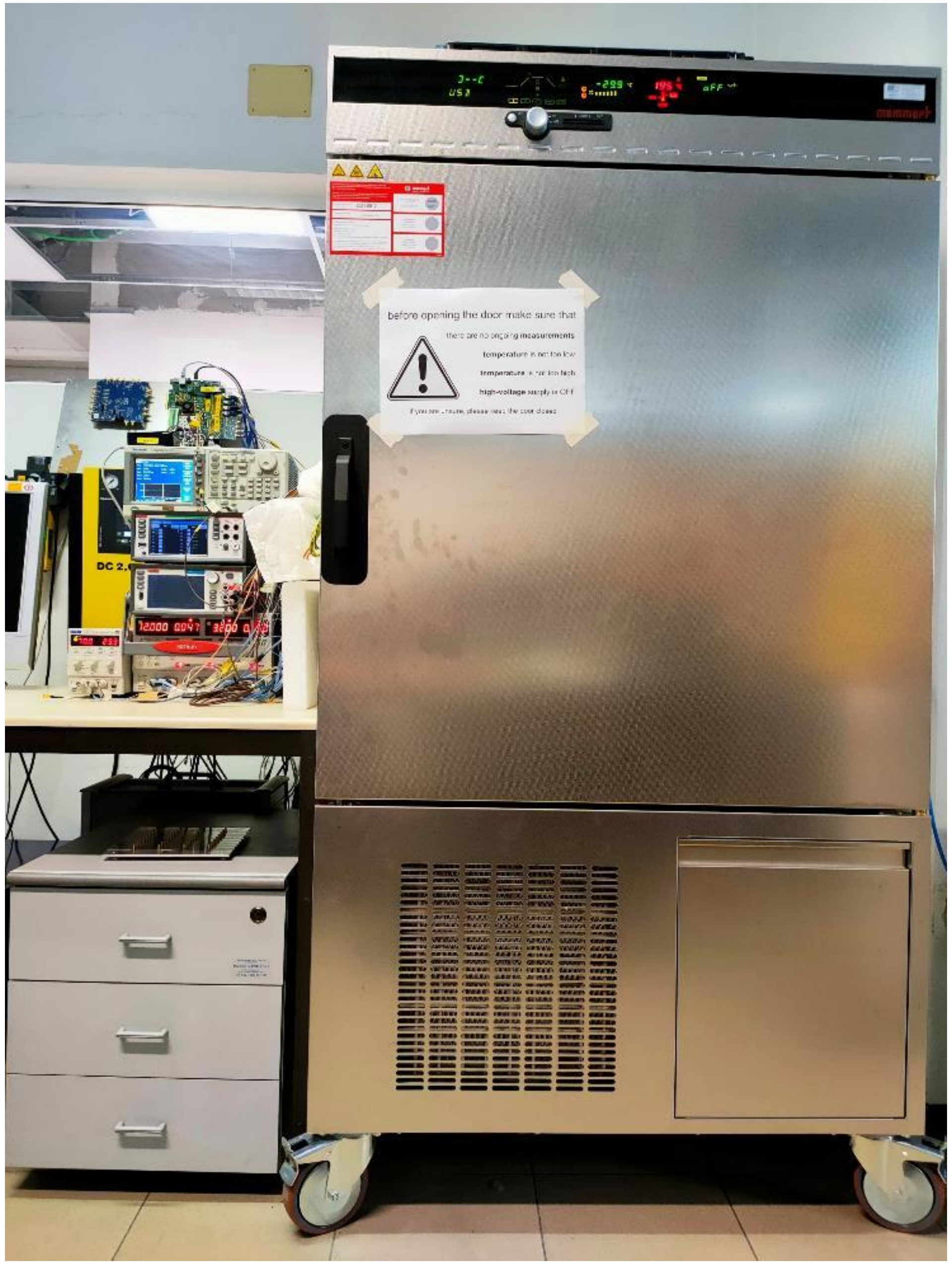
- Increased **DCR**
- Increased **AP**
- Change in **charge collection**



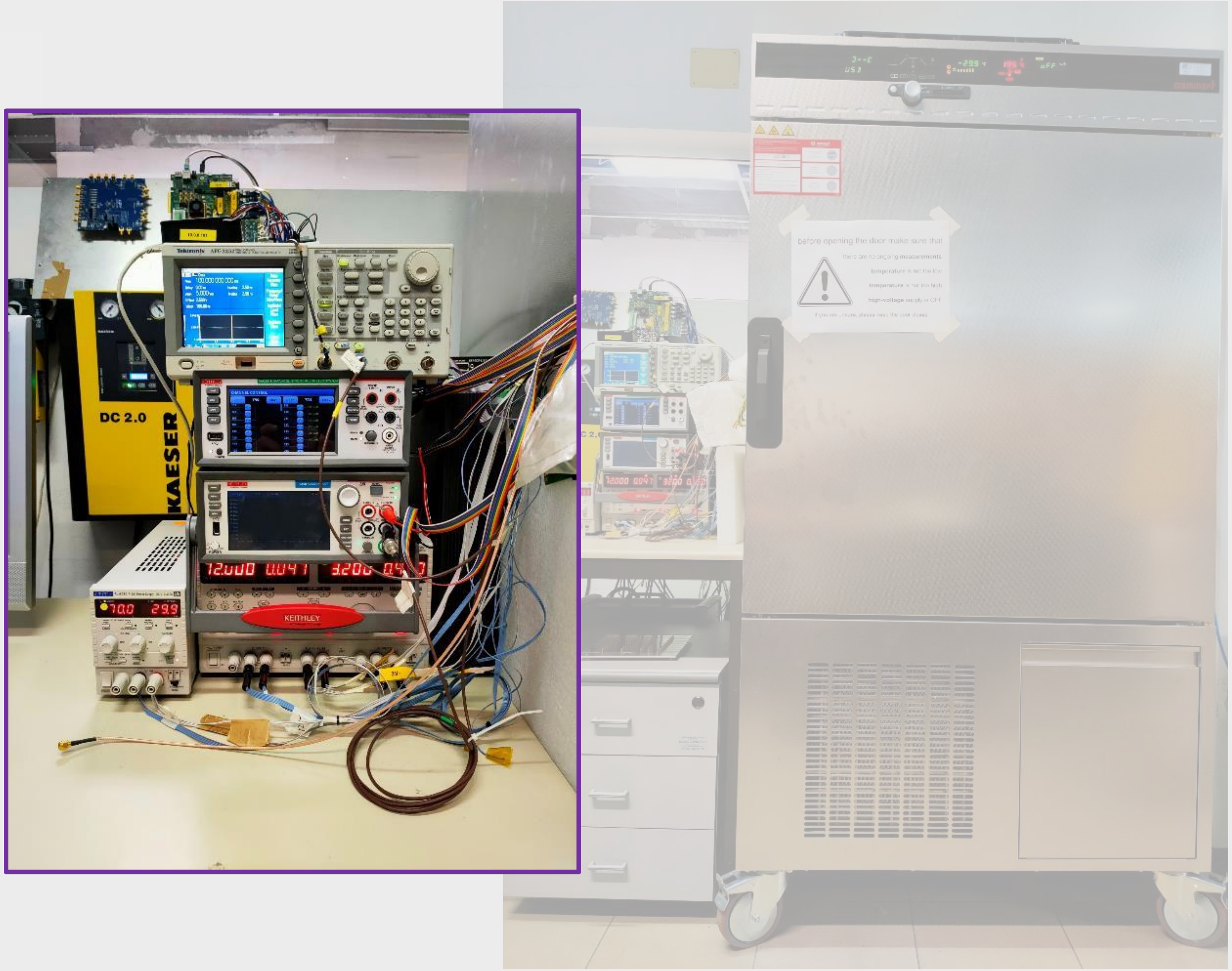
Performance can be recovered by using annealing techniques
(https://arxiv.org/pdf/1805.07154.pdf, https://www.osti.gov/pages/servlets/purl/1477958, https://ieeexplore.ieee.org/document/9059772, https://arxiv.org/abs/1804.09792 ...)

Setup

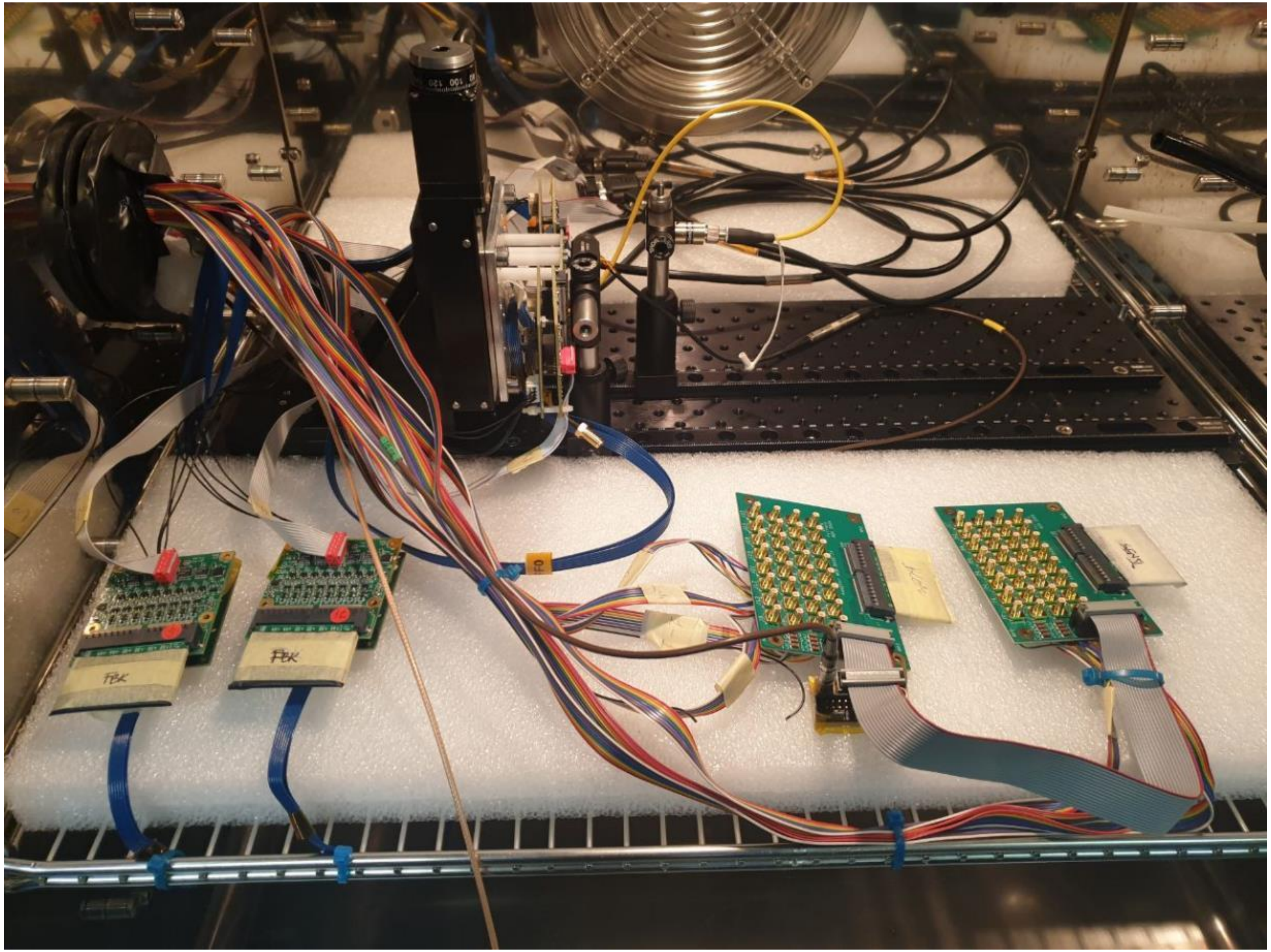
Memmert climatic chamber to mimic the operative conditions: -30°C



FPGA board
Pulser
Multiplexer
Source meter
Power supplies
PC



3 setups for a full characterization of the detectors



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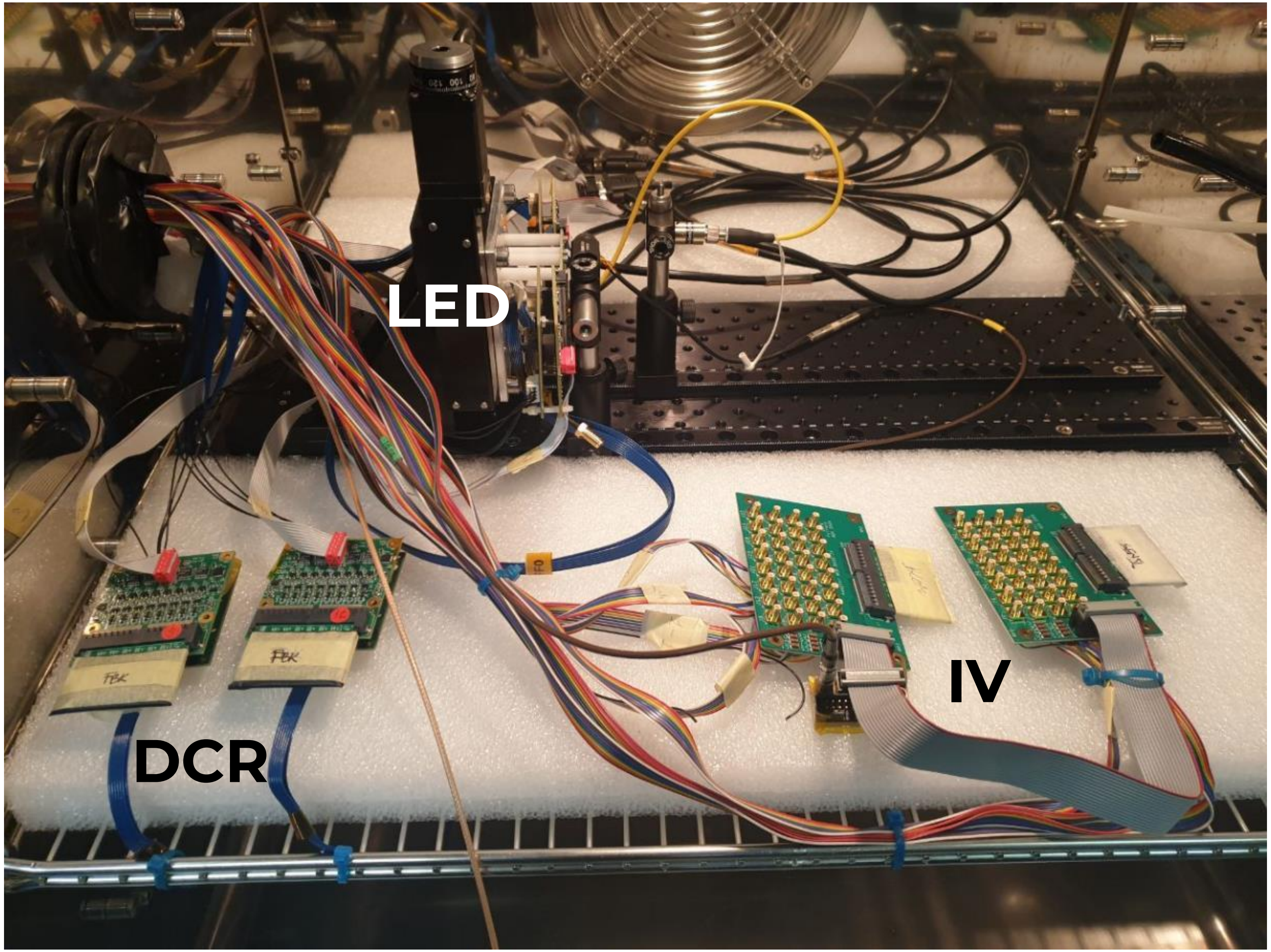
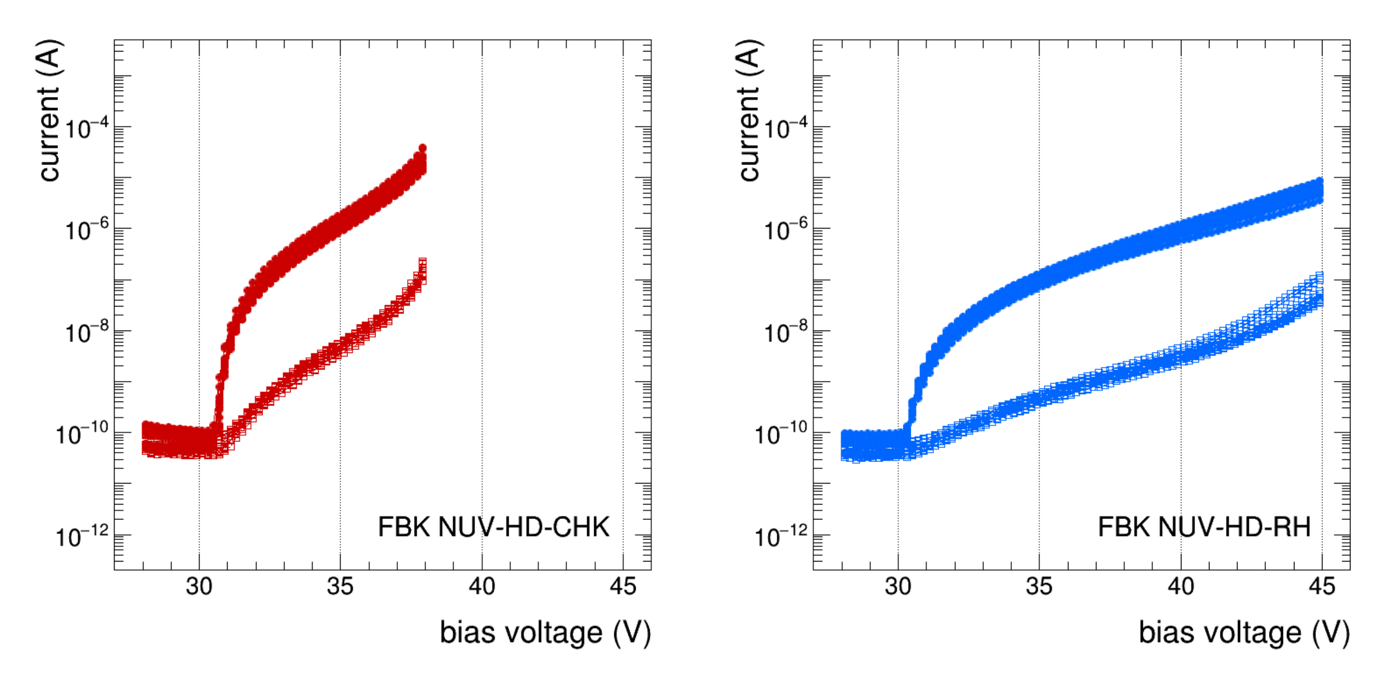
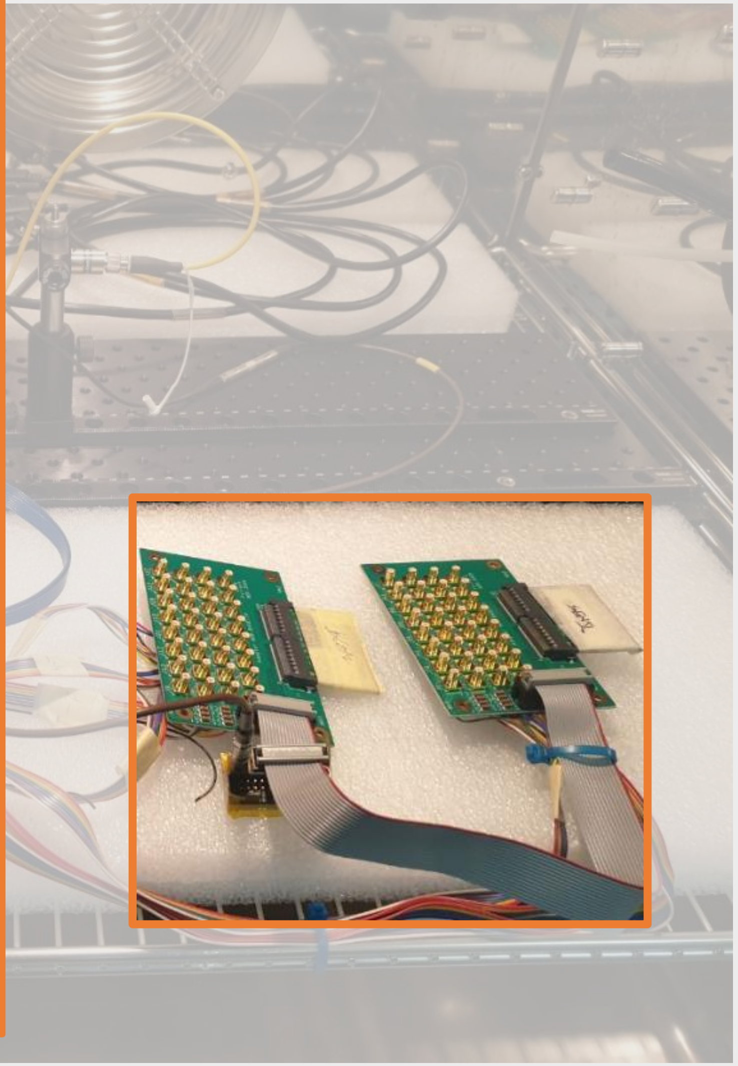


IV setup: Dark Current - V_{BD}

Keithley 2450 SMU (10 fA resolution)
Keithley 7702 40 ch Mux
Up to 32 SiPMs (2 boards) automated measurement





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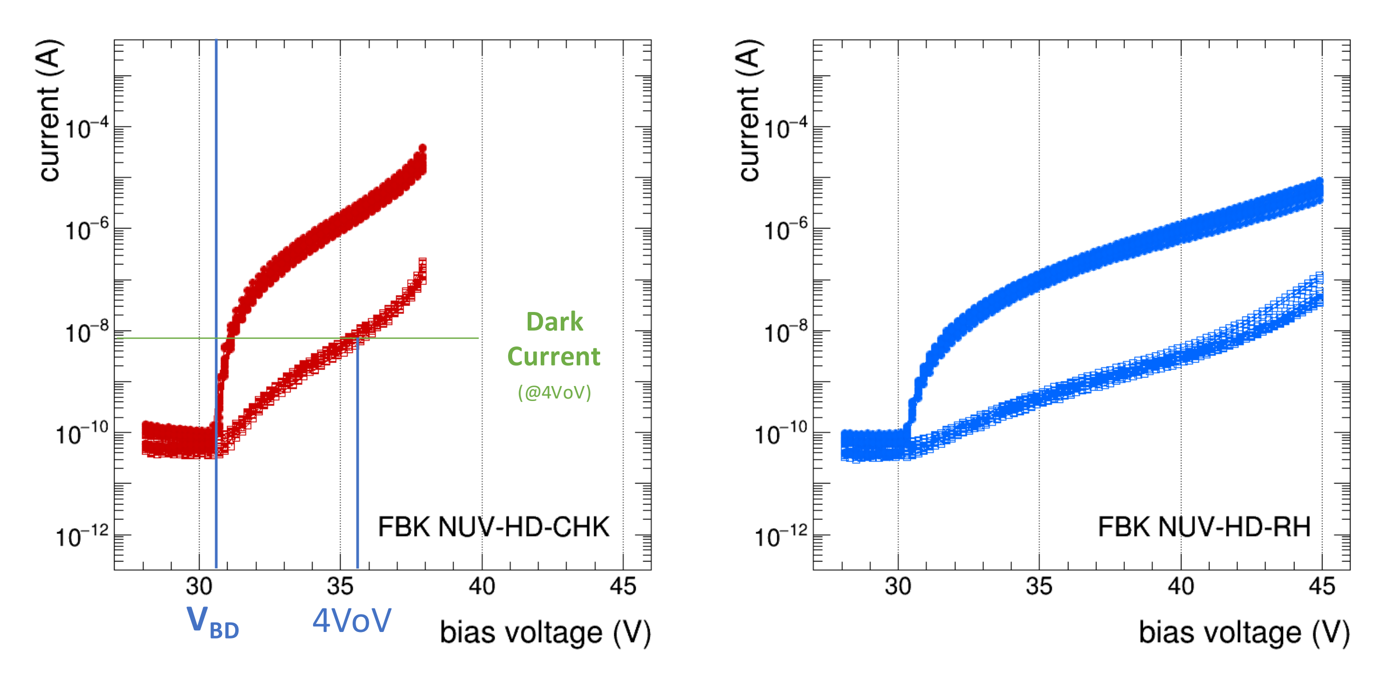
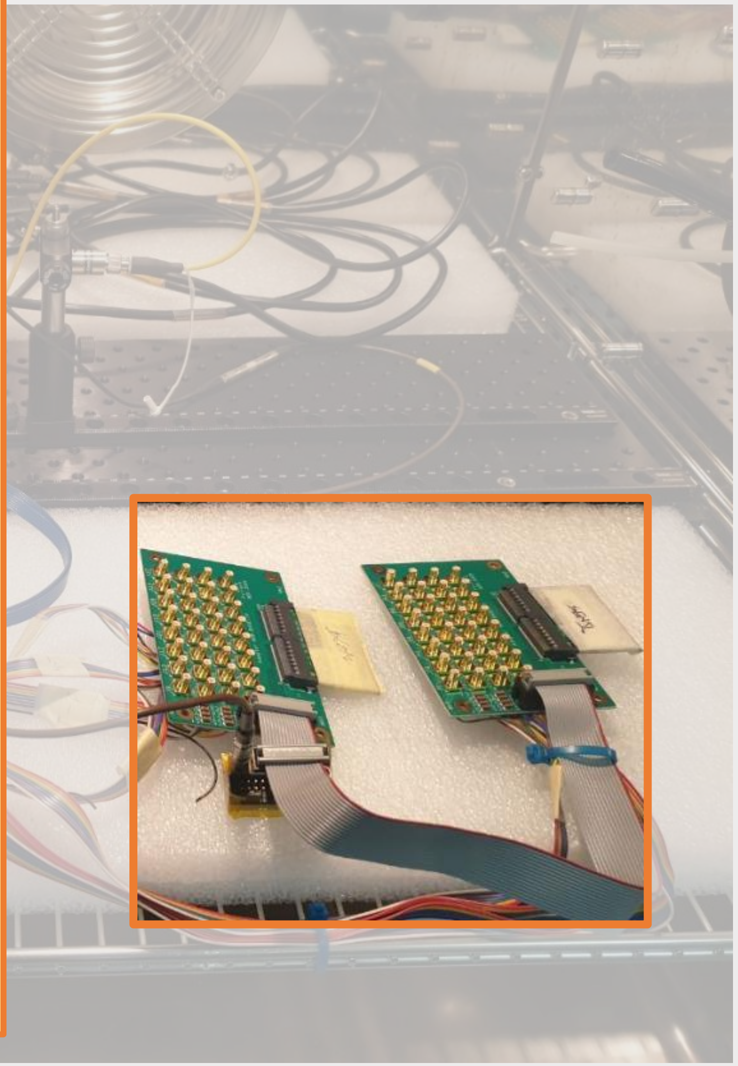
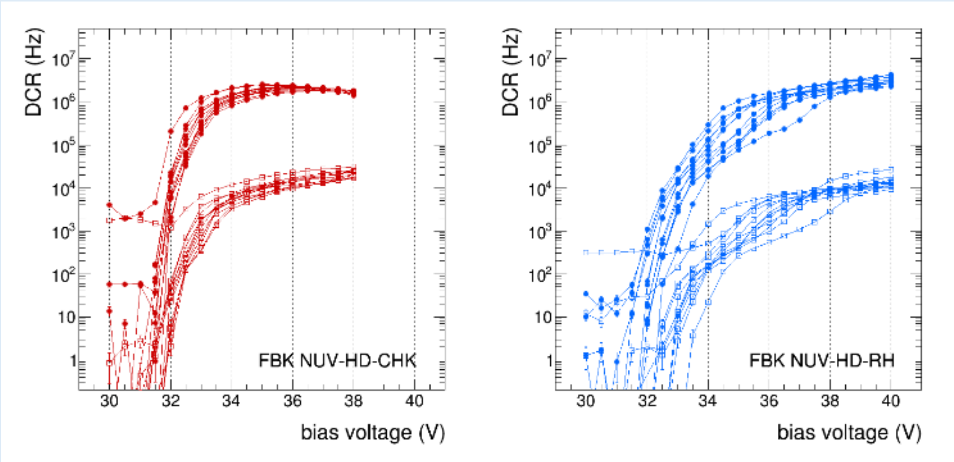
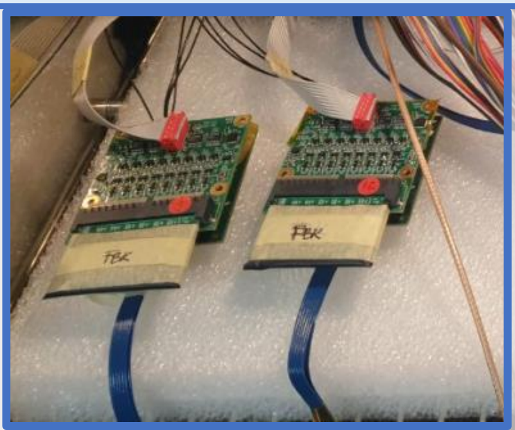




DCR

Full dressed readout:
- **ALCOR** ASIC (To)
- **Bias** distribution (Fe)
- **FPGA** (Bo)





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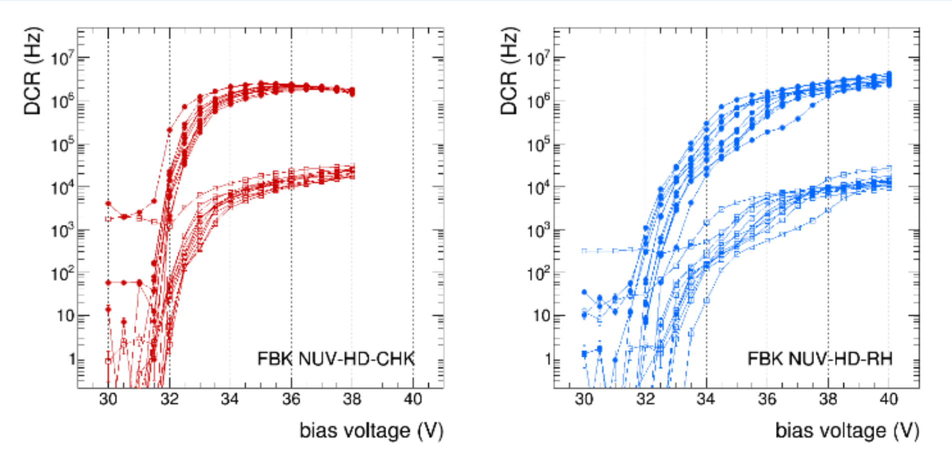
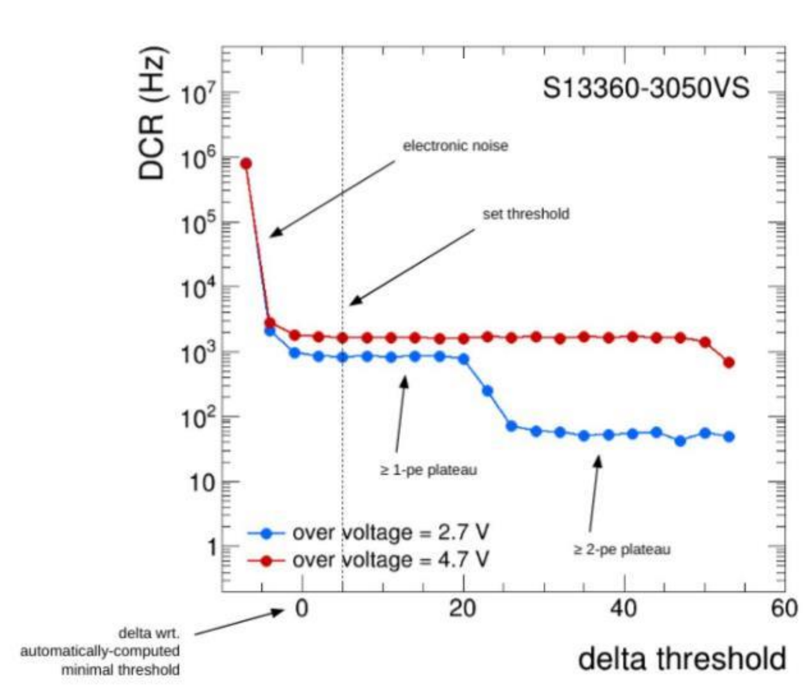
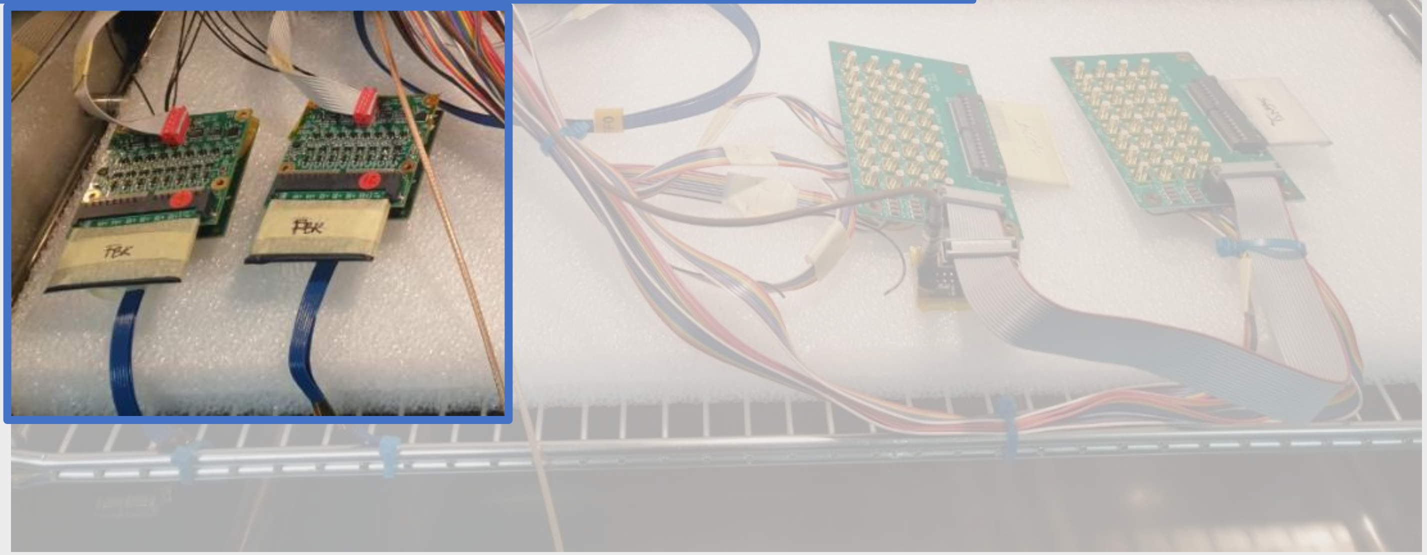


TDC threshold computed automatically over the **baseline**

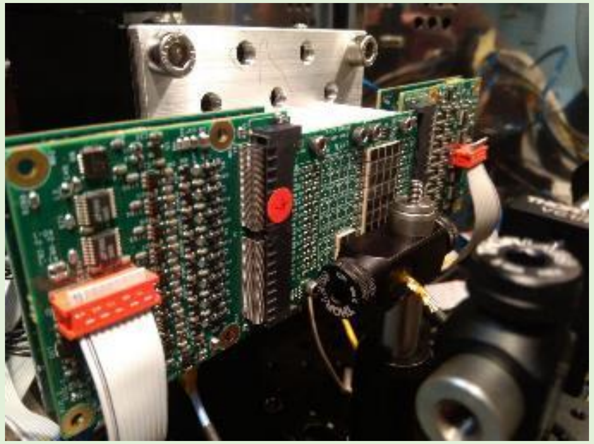


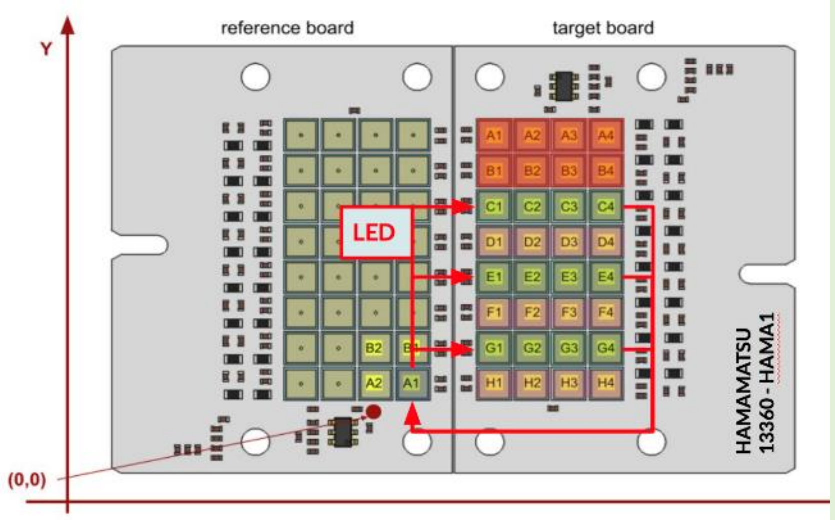


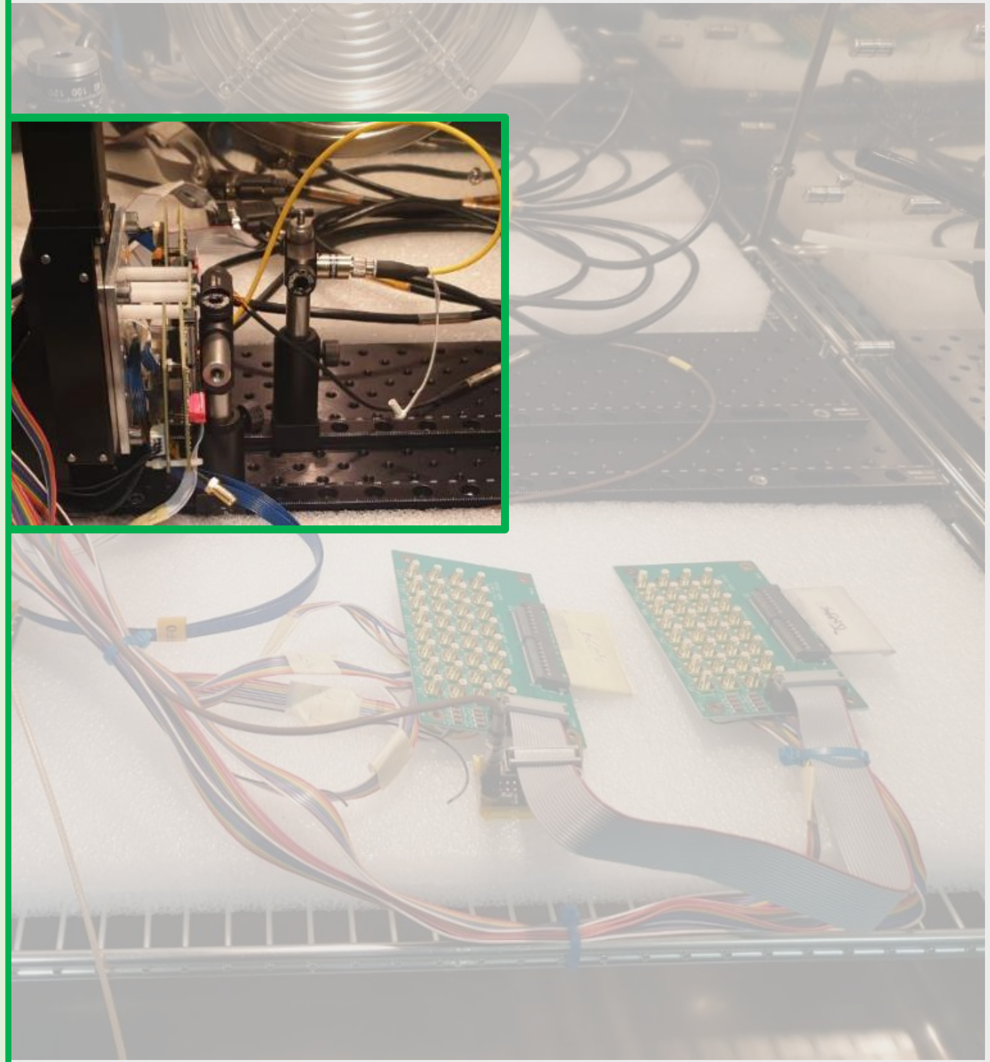
LED optical bench – PDE

Full **ALCOR readout**.

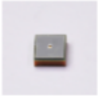
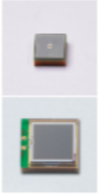
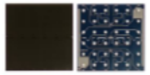
Linear stage move the sensor **matrix** in front of the **LED**.
LED driven by a high precision **pulser**.
The same pulse is sent to the **FPGA** to perform **coincidences**.
At the beginning of each line, a **reference sensor** is measured.







The sensors


board	sensor	uCell (µm)	V_{bd} (V)	PDE (%)	DCR (kHz/mm^2)	window	notes
HAMA1	S13360 3050VS	50	53	40	55	silicone	legacy model Calvi et. al
	S13360 3025VS	25	53	25	44	silicone	legacy model smaller SPAD
HAMA2	S14160 3050HS	50	38	50		silicone	newer model lower V_{bd}
	S14160 3015PS	15	38	32	78	silicone	smaller SPADs radiation hardness
SENSL	MICROFJ 30035	35	24.5	38	50	glass	different producer and lower V_{bd}
	MICROFJ 30020	20	24.5	30	50	glass	the smaller SPAD version
BCOM	AFBR S4N33C013	30	27	43	111	glass	commercially available FBK-NUVHD

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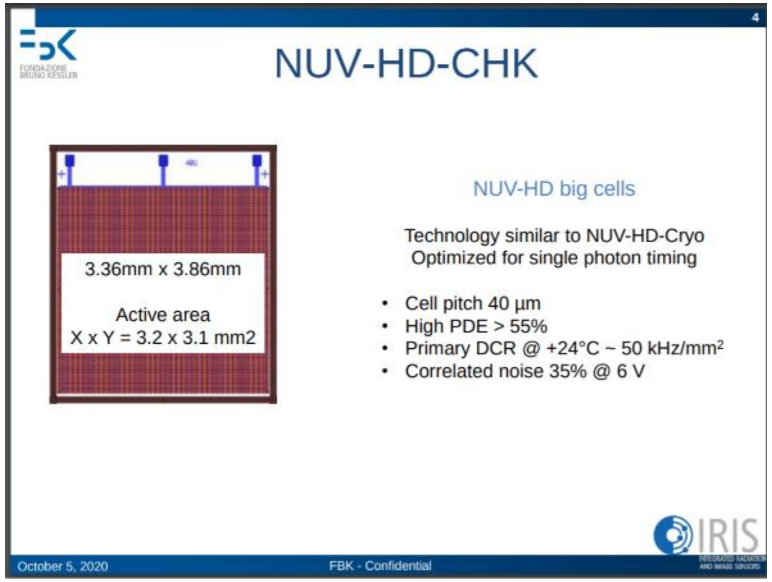

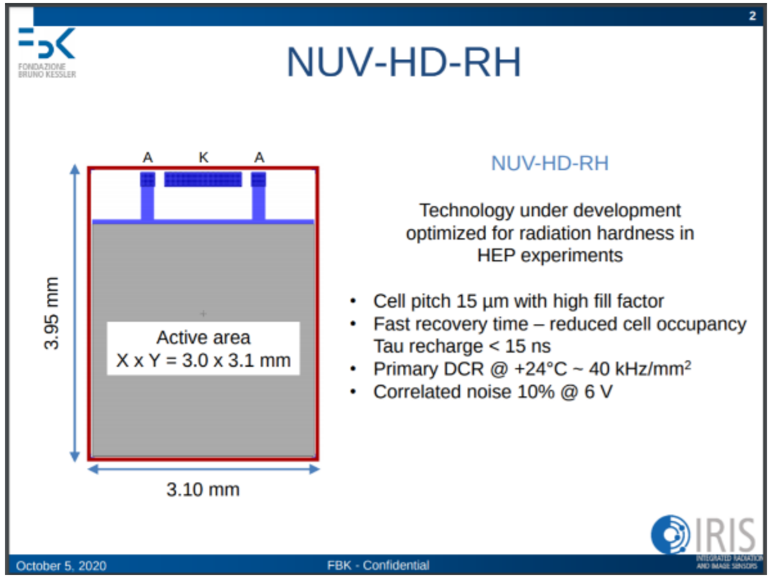

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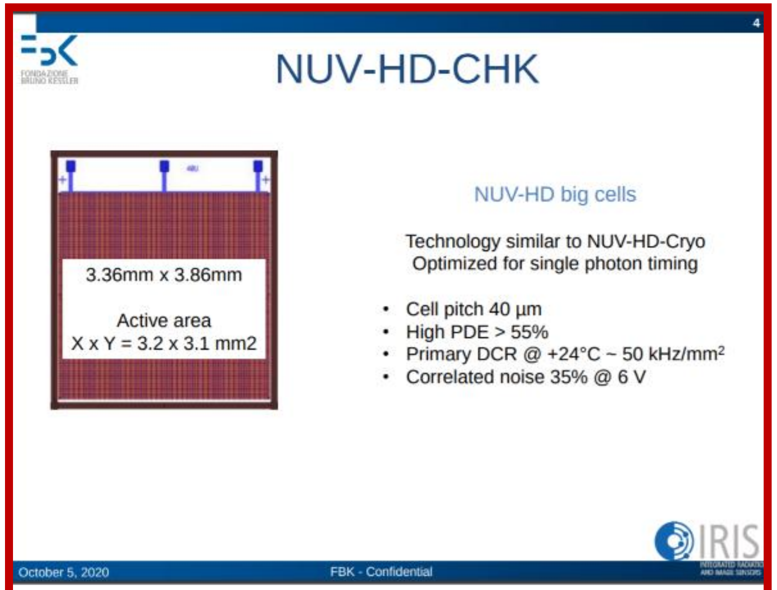

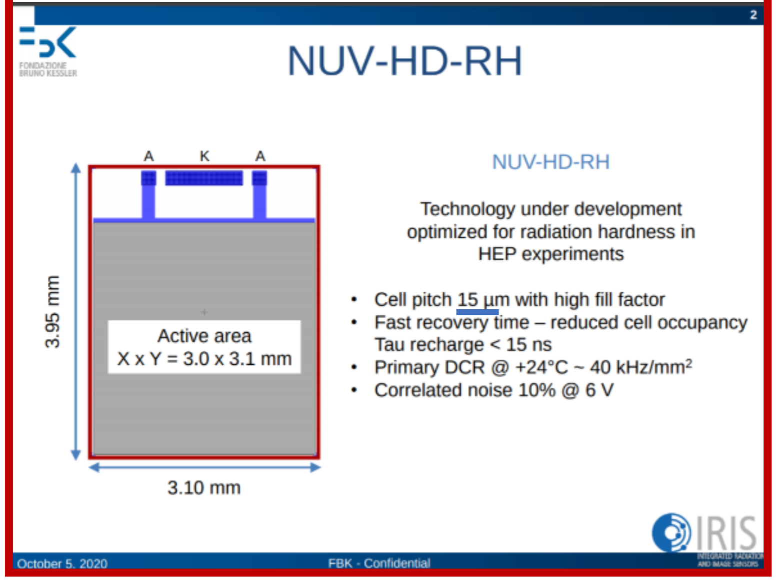

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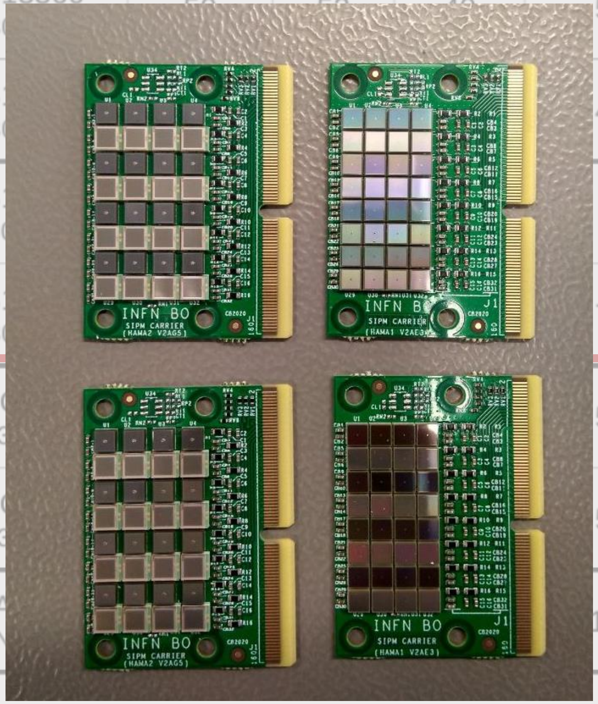

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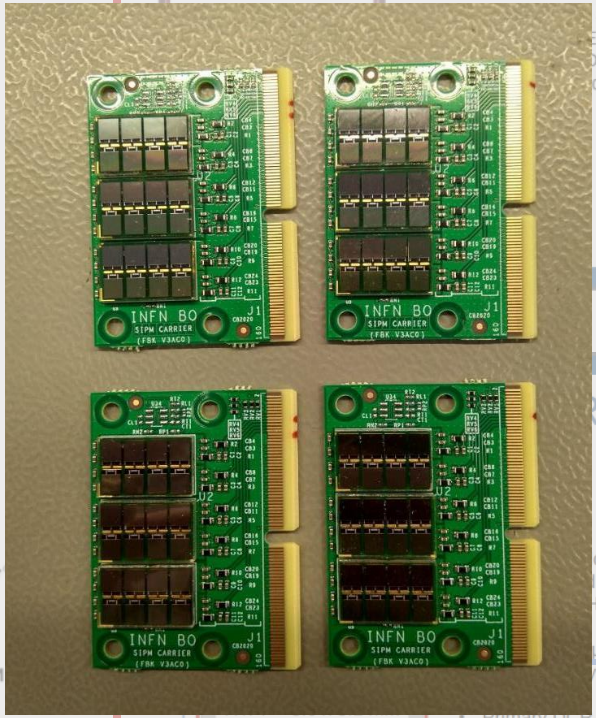


Measuring plan

	DCR		IV		LED	
	CHIP2	**CHIP3**	**MUX1**	**MUX2**	**CHIP0**	**CHIP1**
1	FBKa	FBKb	HAMA1	HAMA2	not running	
2	HAMA1	HAMA2	SENSL	HAMA1L	not running	
3	SENSL	HAMA1L	FBKa	FBKb	not running	
4	not running		not running		HAMA1	reference

Operators needed at the **start** of each run to place the correct **devices** and **start** the acquisition.
After that, the characterization is fully **automated**.
Reports are sent via **email** to the operator's group to check the **status** of the run and give a **quick-look** of the measures

Irradiation and annealing campaigns

2021

Matrixes were irradiated at **different levels** of radiation **10^8-10^{11}** (1MeV) n_{eq}/cm^2

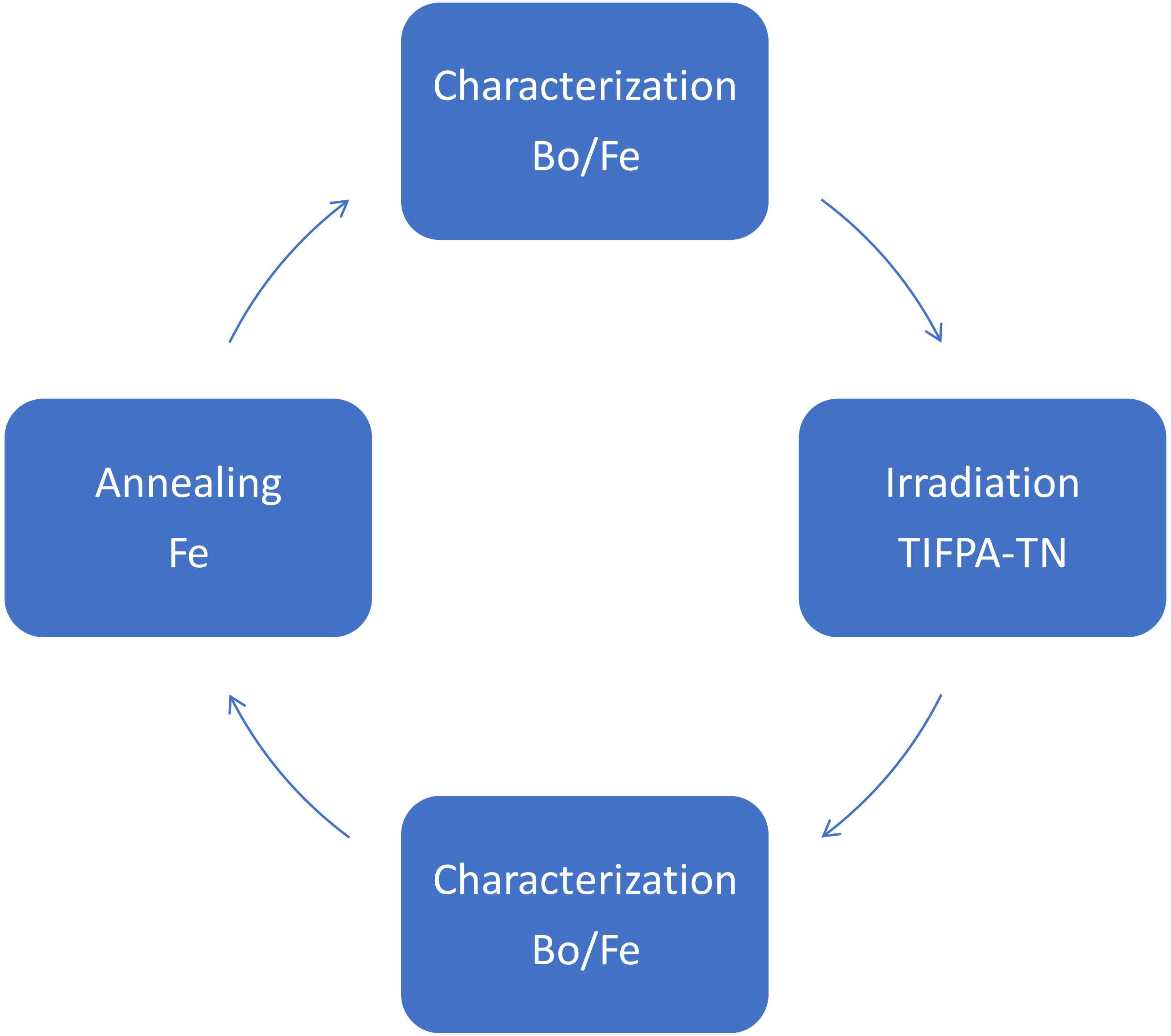
2 subsequent oven **annealing**:

- **200** hours **@120°C**

  +

- **200** hours **@150°C**

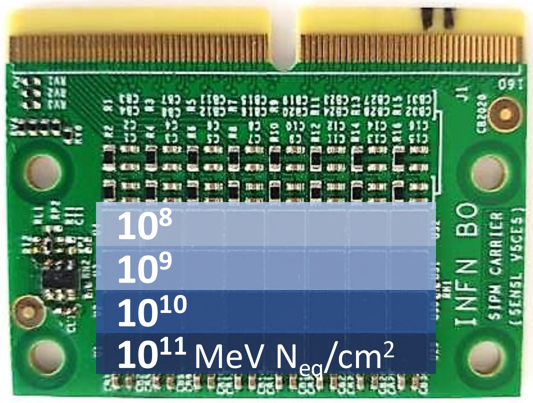
Characterization

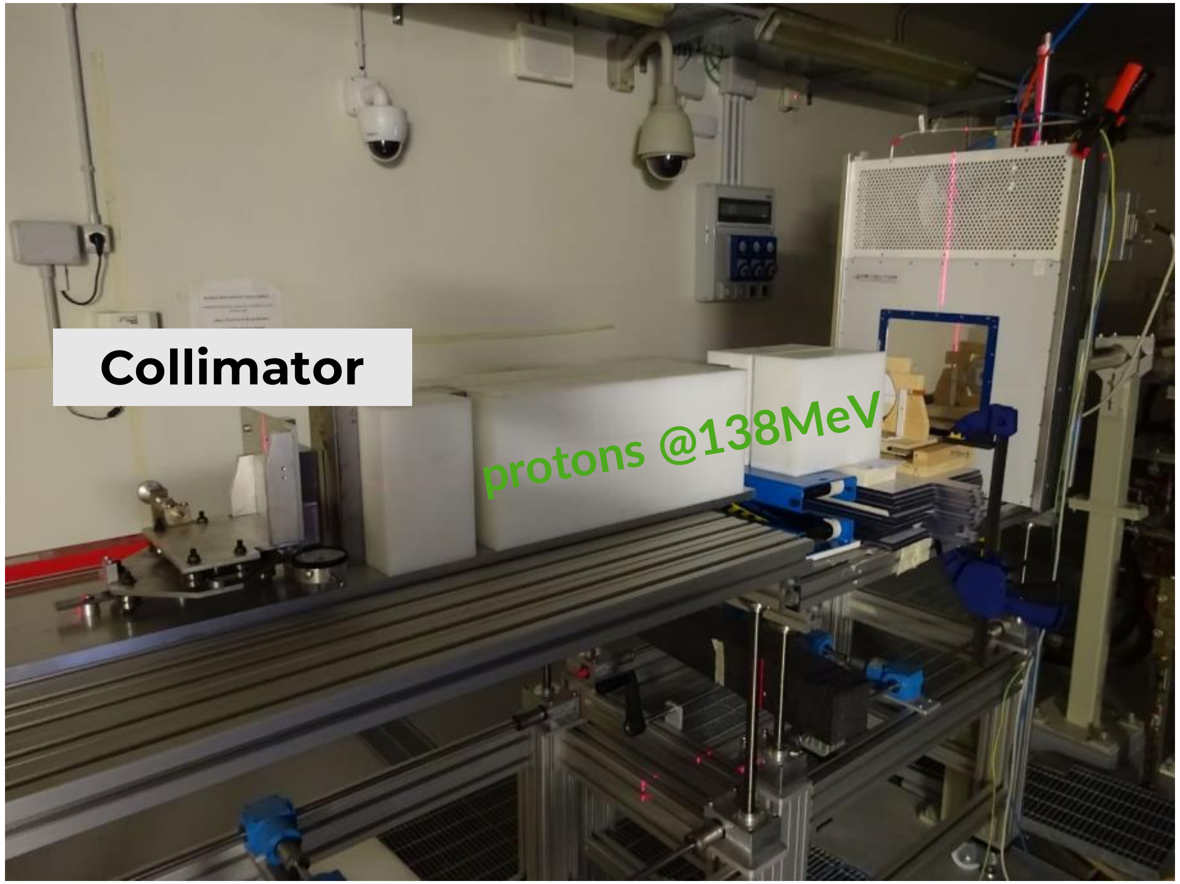


2021 campaign

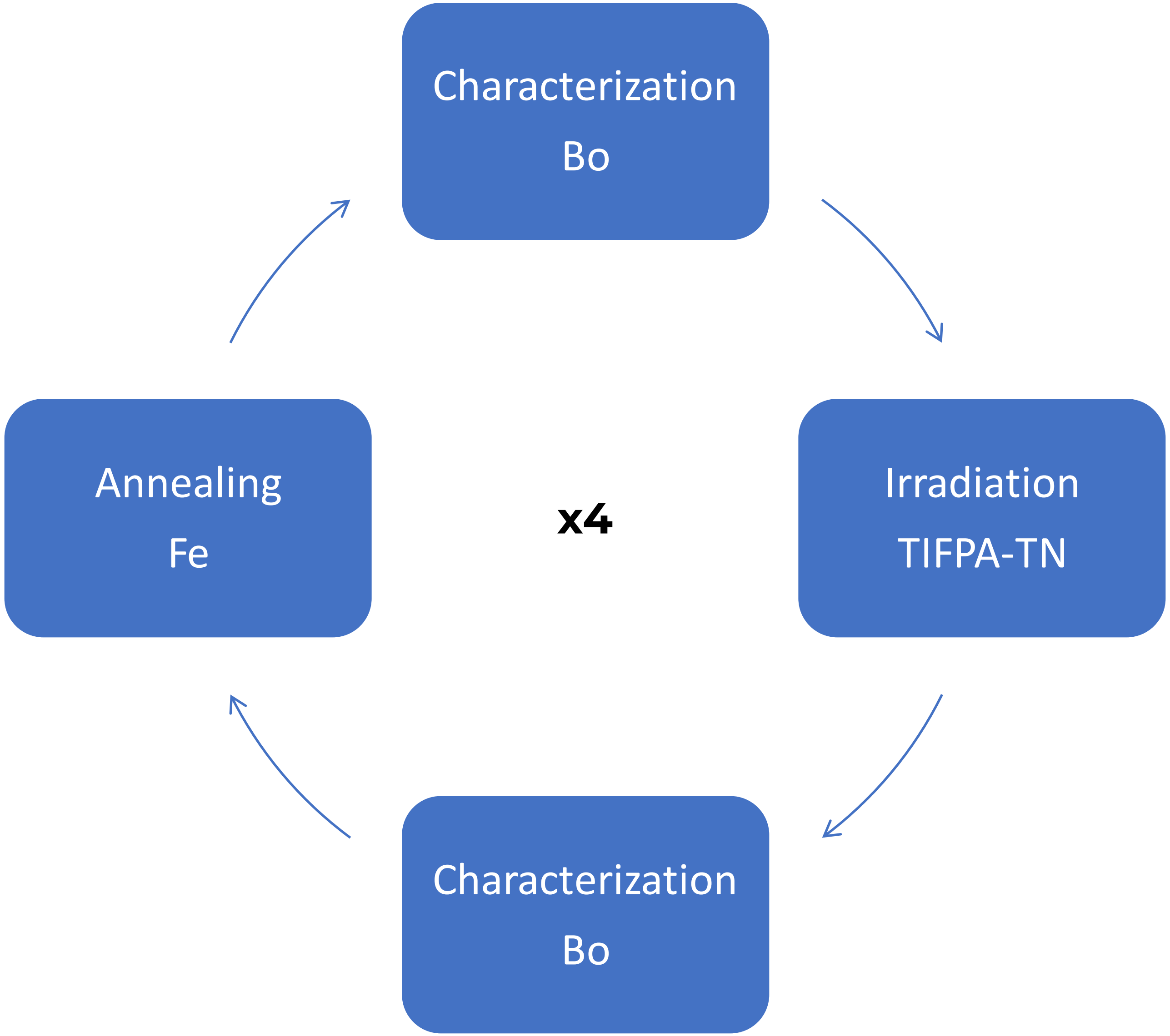
Trento Institute for Fundamental Physics and Applications

HAMA1
HAMA2
FBK NUV-HD-CHK
FBK NUV-HD-RH
SENSL
BCOM





Irradiation and annealing campaigns



2022

4 steps irradiation scheme with increasing cumulative fluence:

1. **$1x10^9$** 4/6/22
2. **$2x10^9$** 16/7/22
3. **$3x10^9$** August/22
4. **$4x10^9$** December/22

2 kind of annealing:

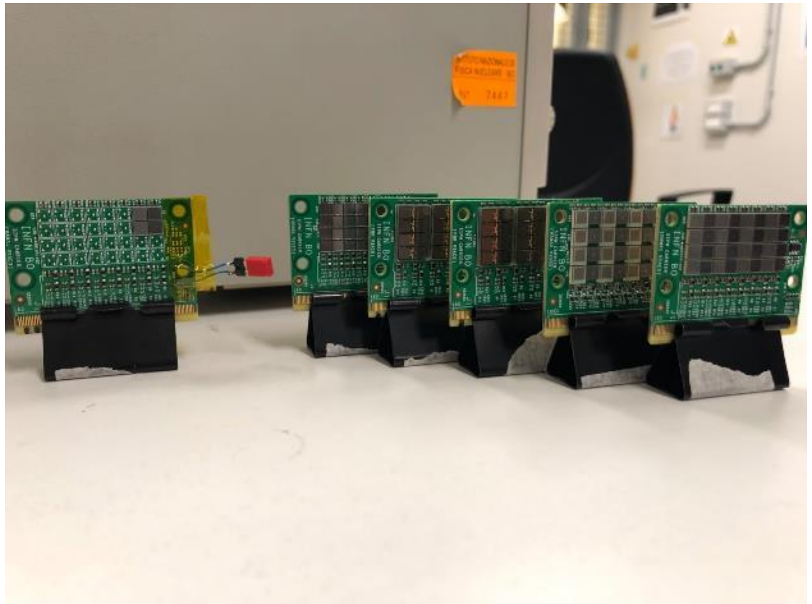
- **Oven** annealing **150** hours **@150°C**
- **Direct current** annealing

Characterization

2022 campaign

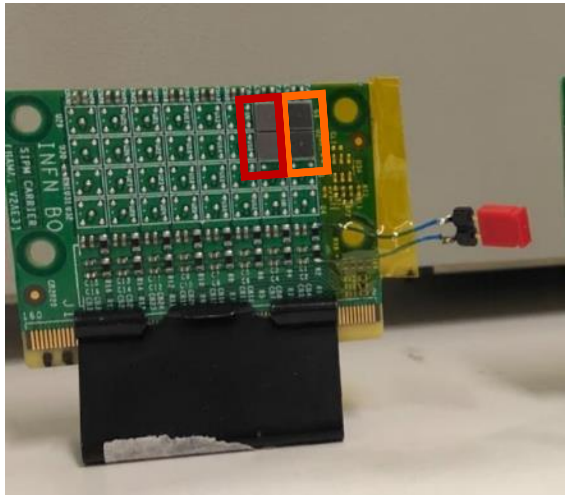
Trento Institute for Fundamental Physics and Applications

HAMA1
HAMA2
FBK NUV-HD-CHK
FBK NUV-HD-RH
HAMA1L



Direct current annealing

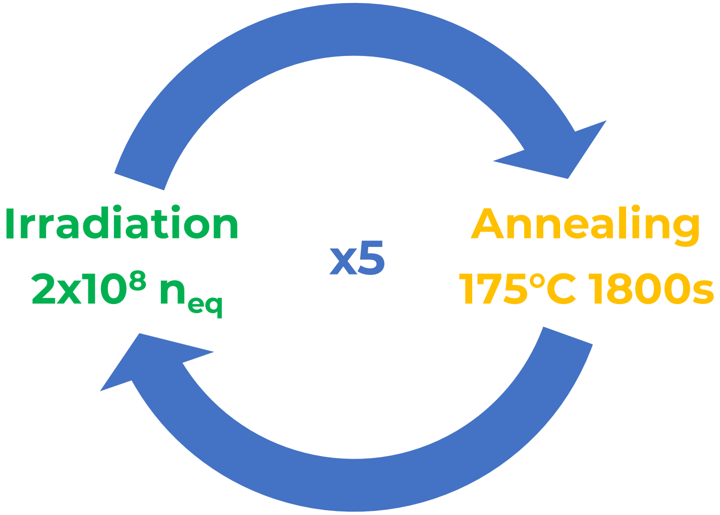
HAMA1L board equipped with **Hamamatsu S13360** irradiated for a total of **10^9 n_{eq}**



2 kind of direct current annealing:

- **Online** for the **3050** (50um spad)
- **Offline** for the **3025** (25um spad)

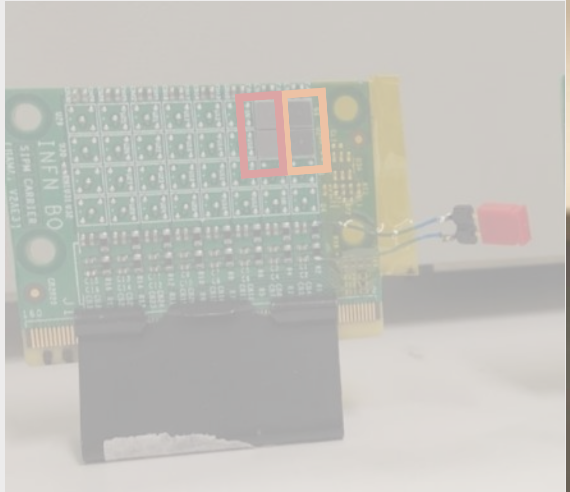
Online: irradiation divided in **5** cycles interleaved by direct current annealing **@175°C** for 30 min (**2.5h** total)



Offline: two phase annealing in Bologna. **@175°C** for 30 min and 175°C for 2 h (**2.5h** total)

UPDATE on Direct current annealing

HAMA1L board equipped with **HP**
irradiated for a total of **10^9**



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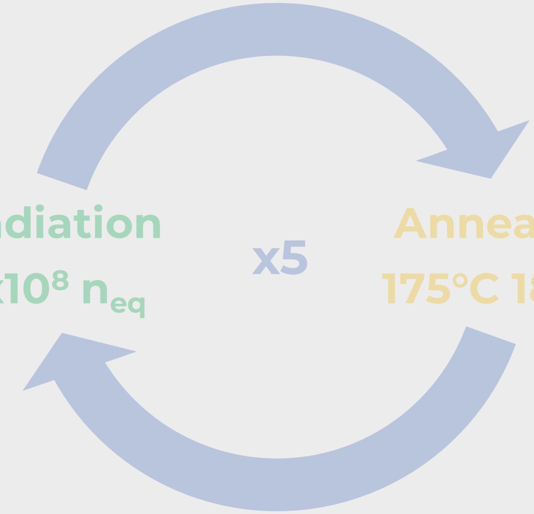
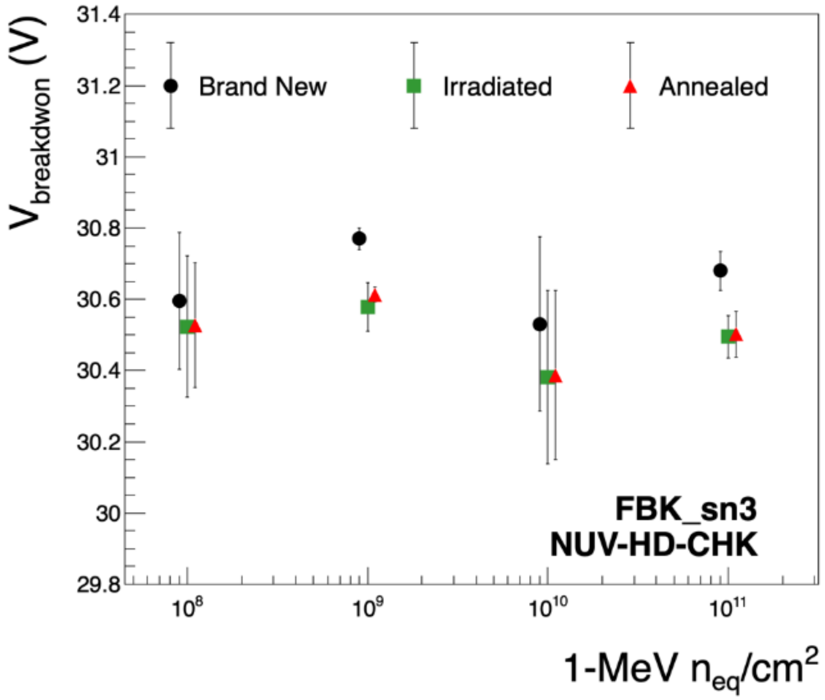


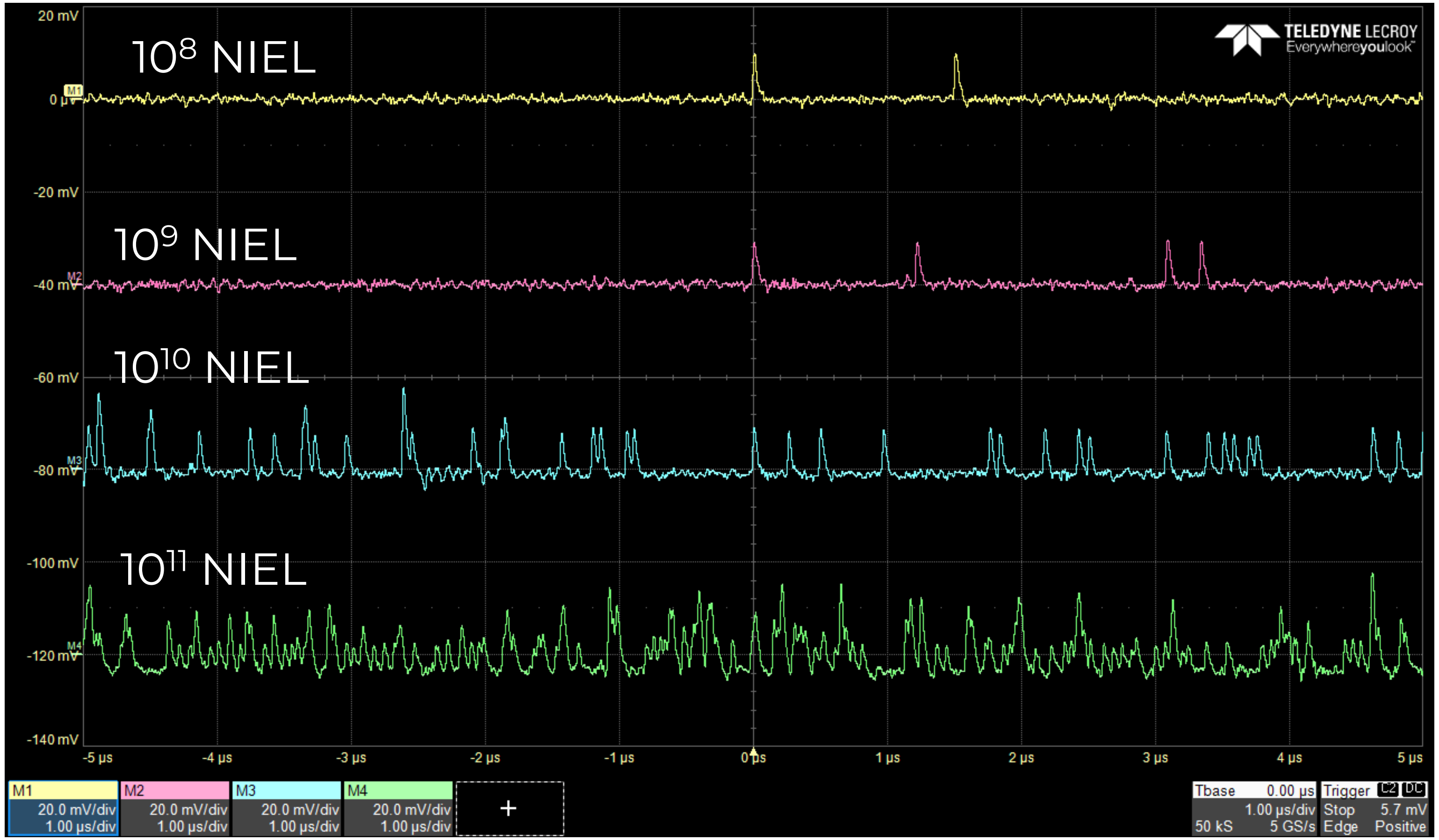
o phase annealing in Bologna. @**175°C**
for 30 min and 175°C for 2 h (**2.5h** total)

Temperature monitored via a FLIR thermo-camera calibrated with Luca Barion
2% uncertainty

Results

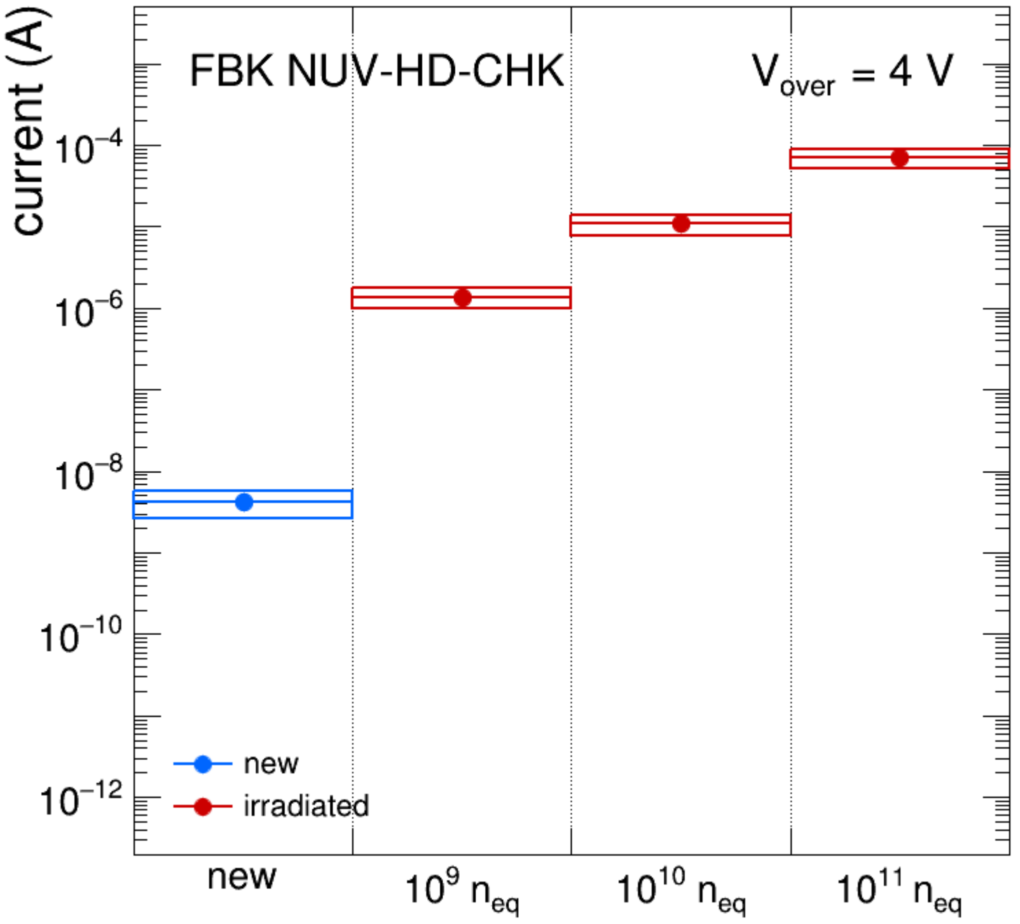
SiPMs remain **functional** even at **10¹¹** NIEL.
No relevant **changes** in **VBD** after **irradiation** and/or annealing





Results: Dark Current vs NIEL (2021)

The **dark current increases linearly** with the **level** of **irradiation**



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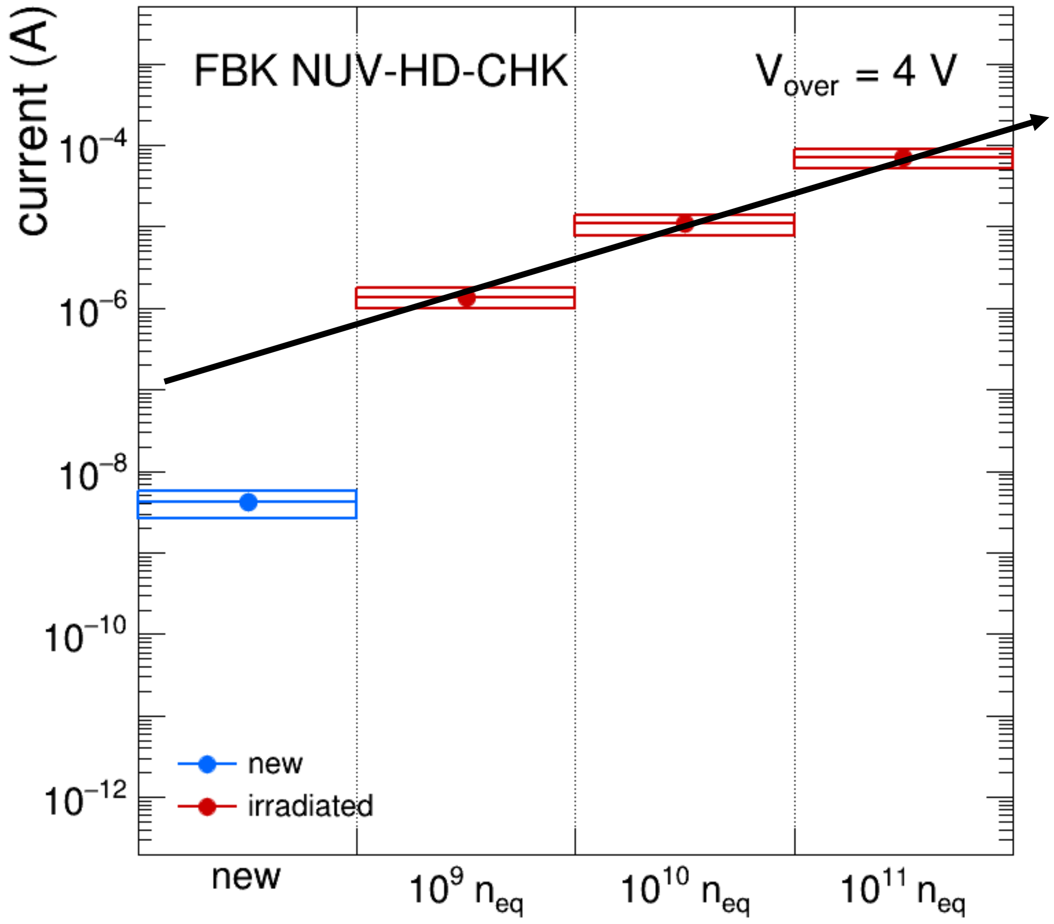
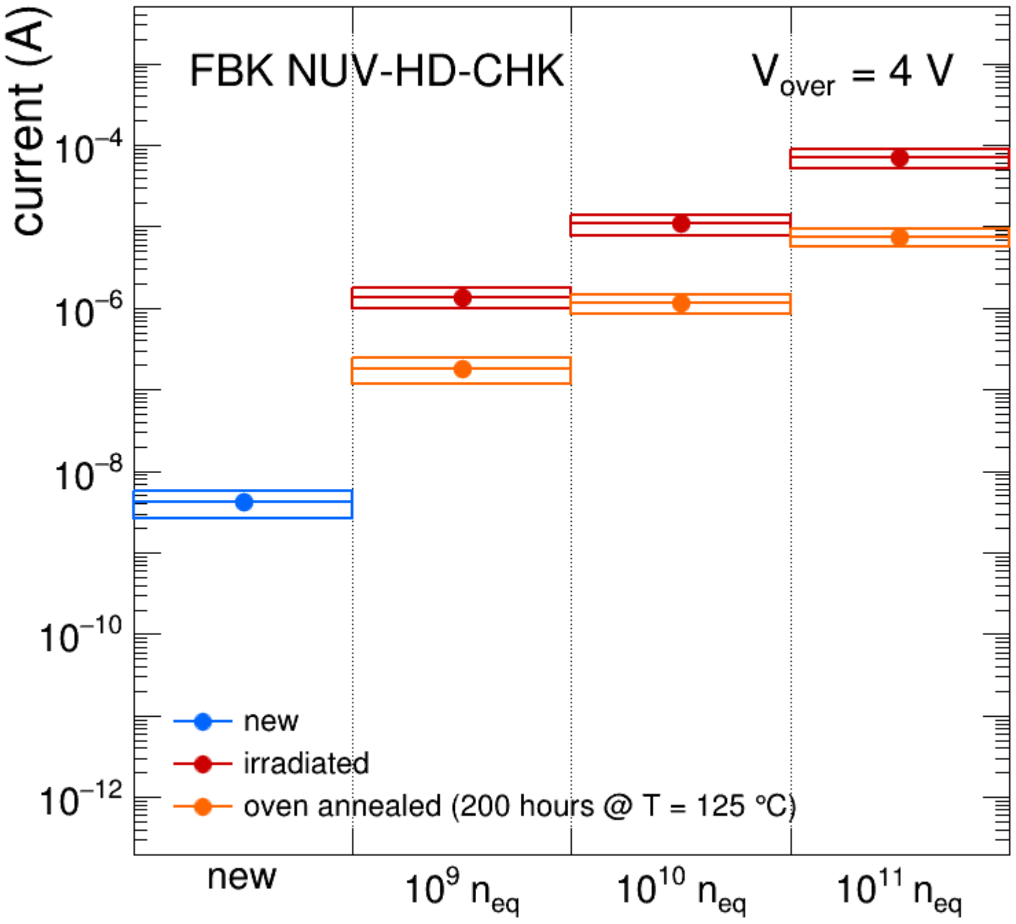


Results: Dark Current vs NIEL (2021)

200 hours @ 125°C oven annealing reduces the **dark current** by a factor **≈ ≈10**



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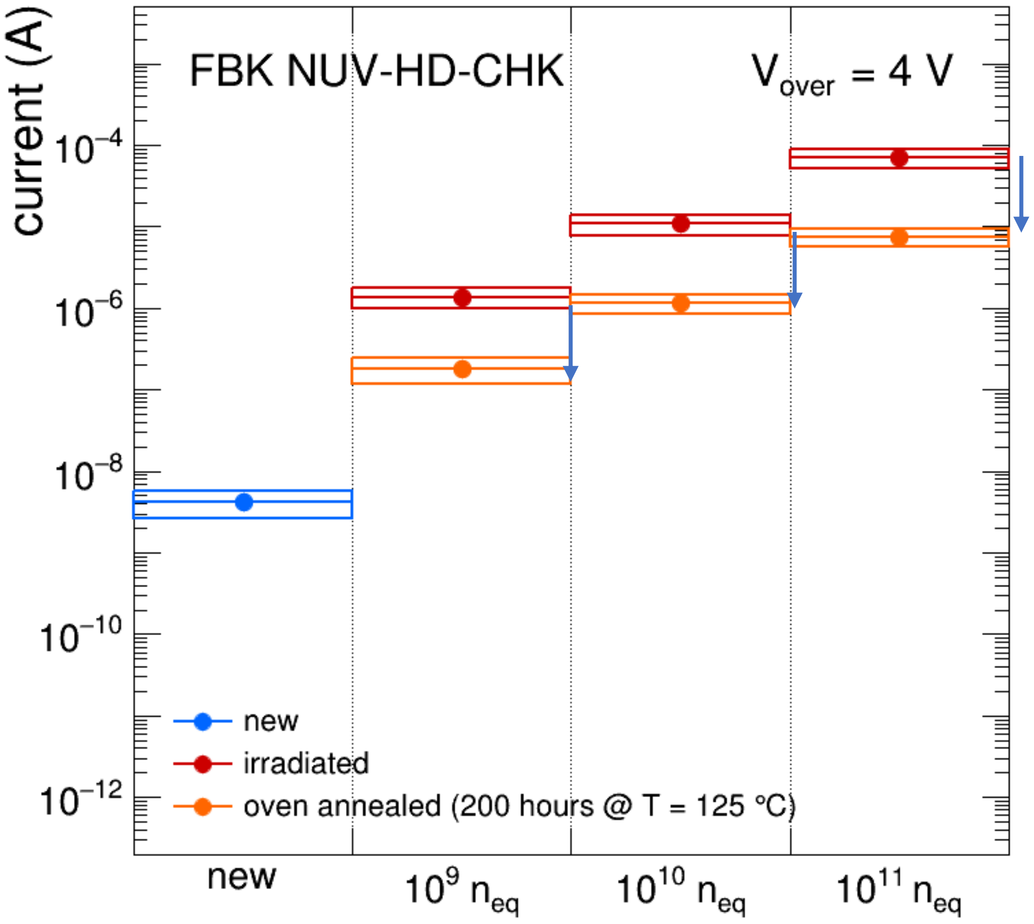
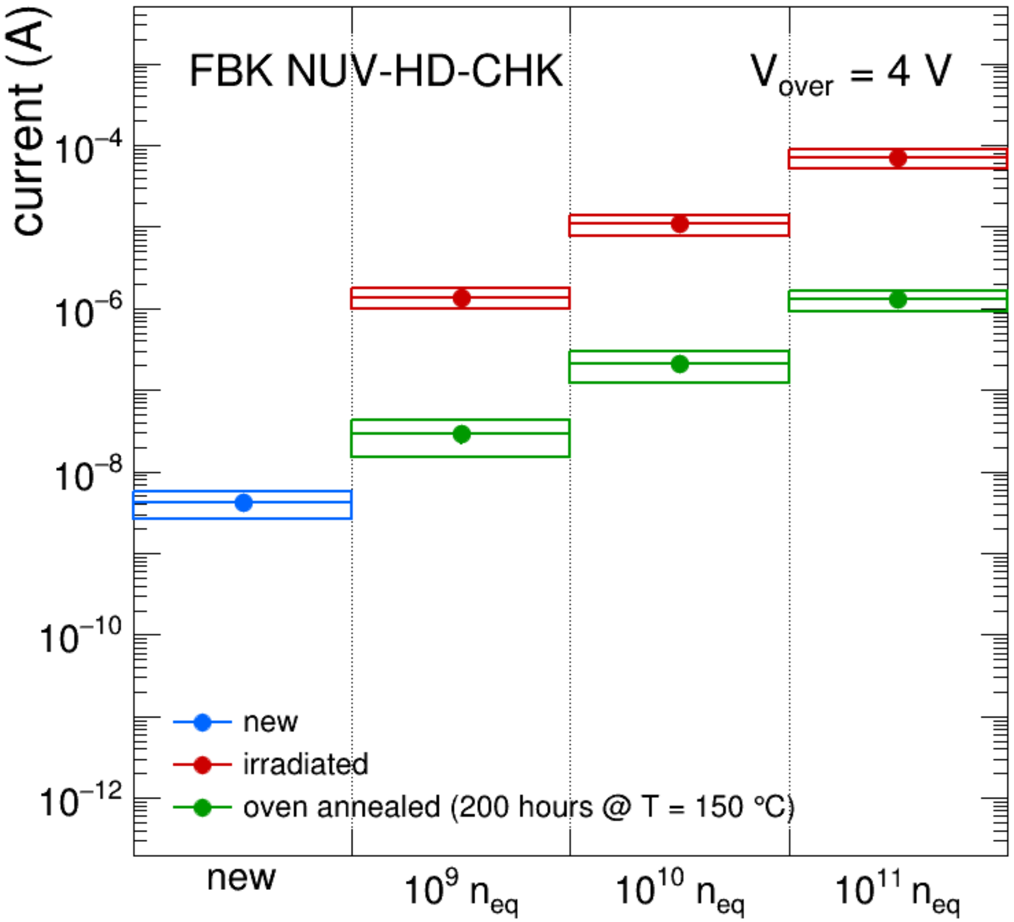


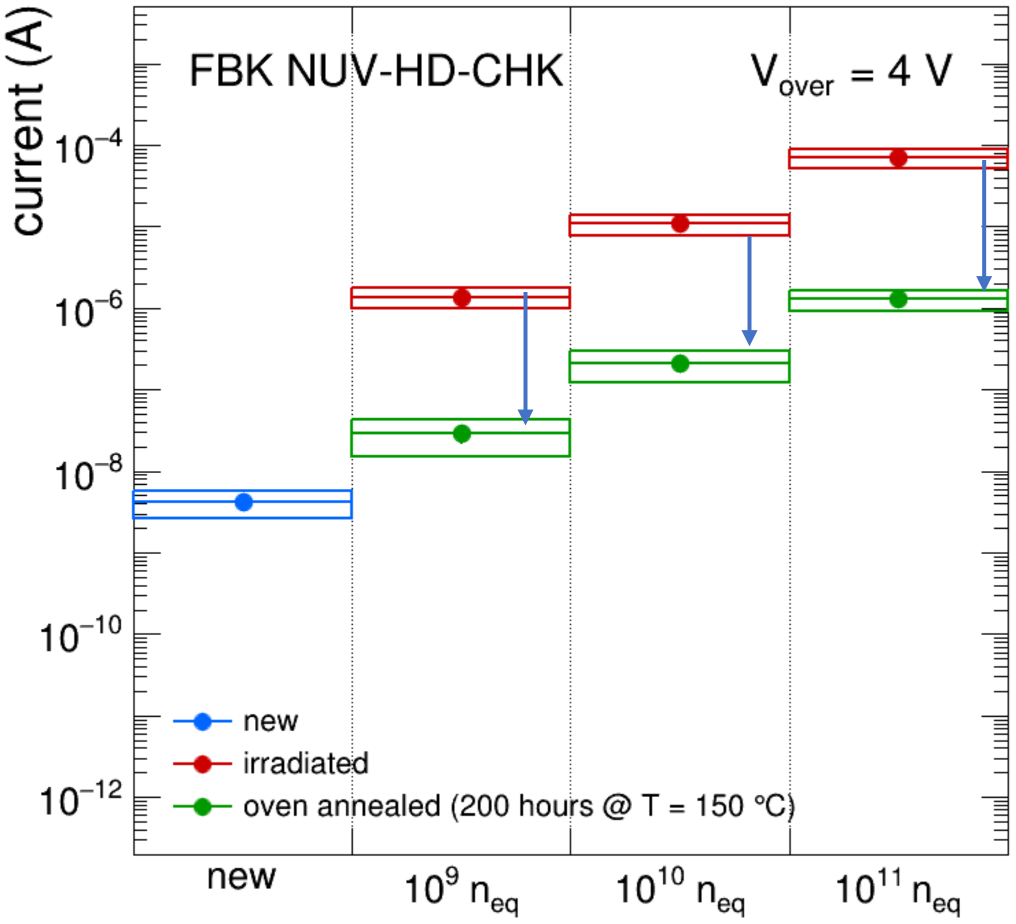
Results: Dark Current vs NIEL (2021)

200 hours @ 150°C oven annealing reduces the **dark current** by a factor **≈100**.

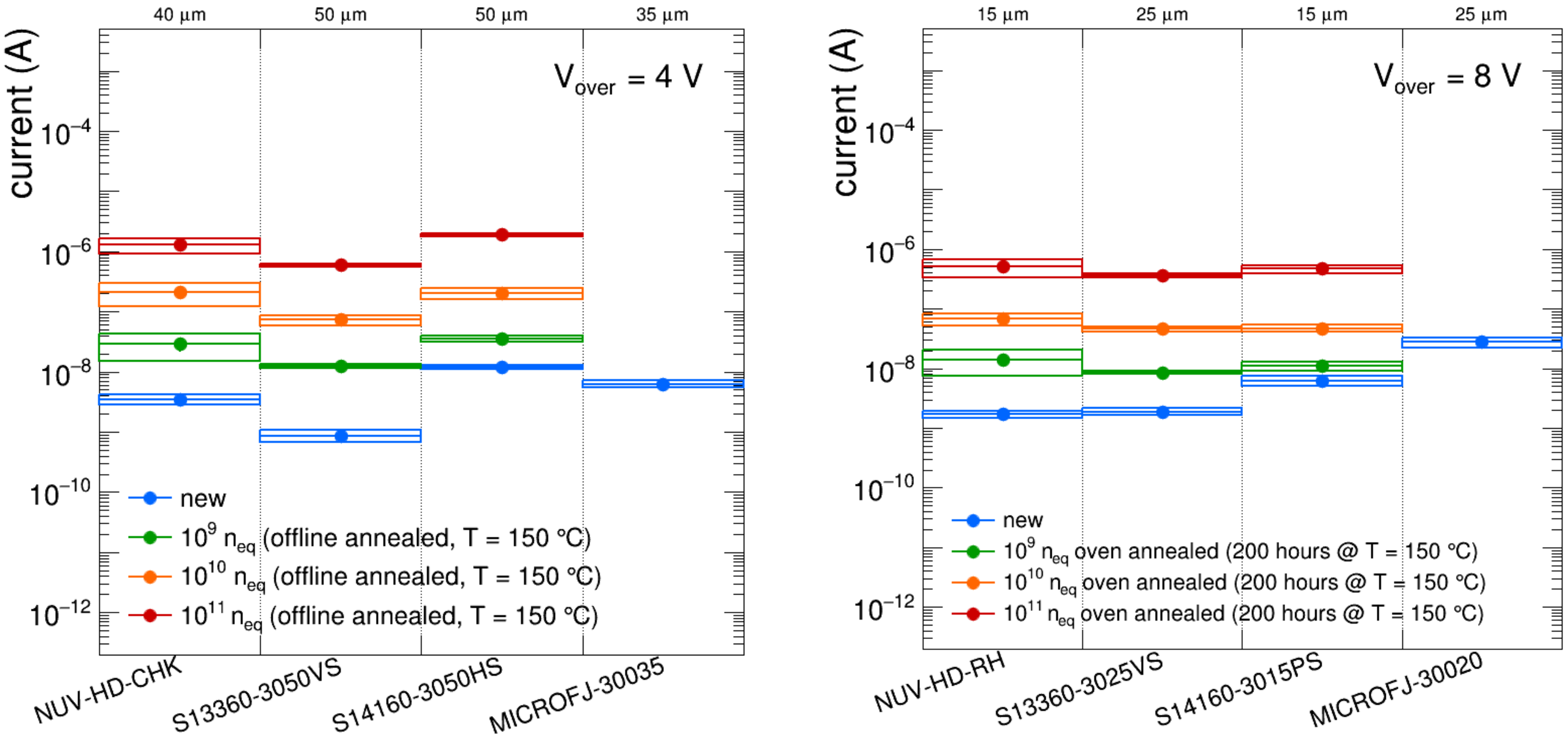


Results: Dark Current vs NIEL (2021)

200 hours @ 150°C oven annealing reduces the **dark current** by a factor **≈100**.

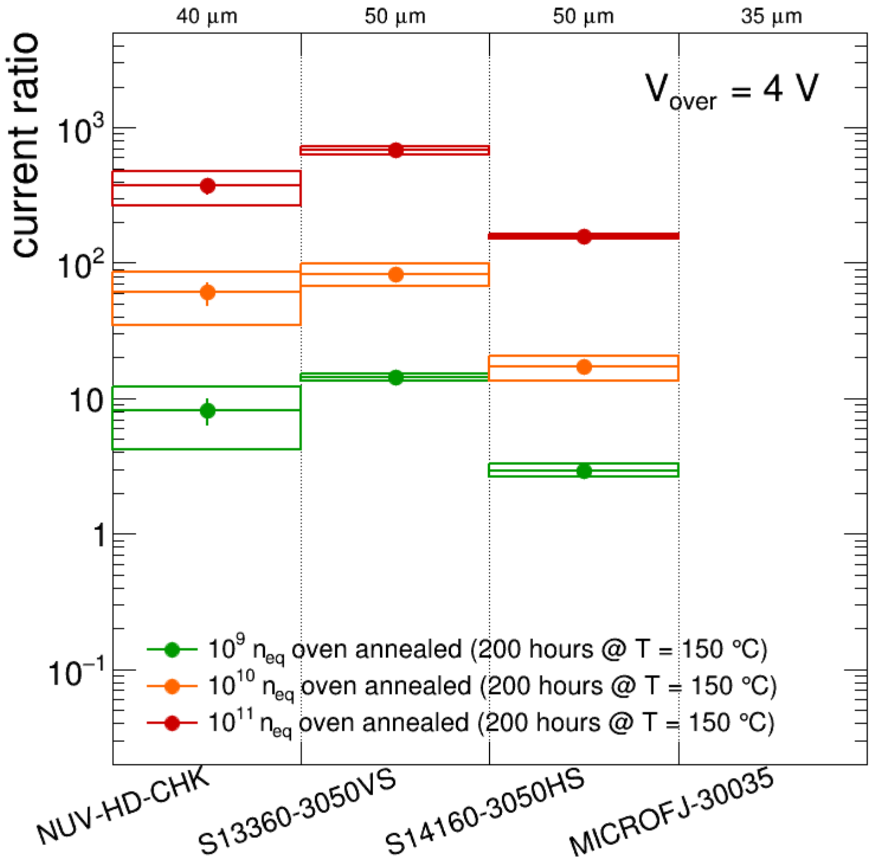


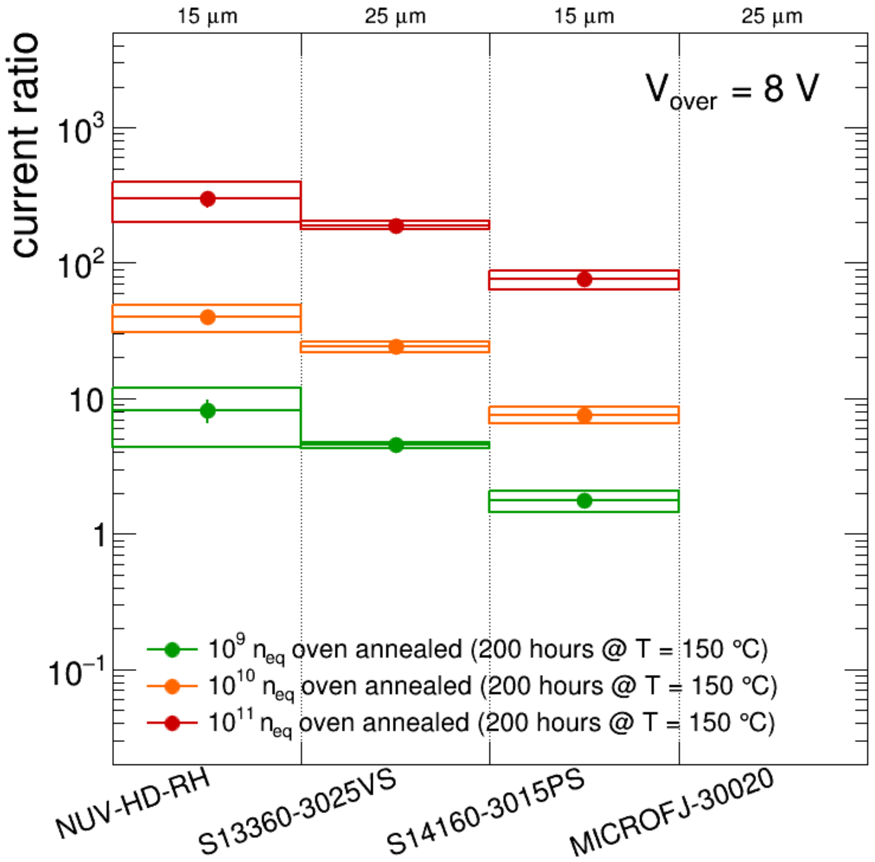
Results: Dark current



Common behavior along all the samples

Results: Dark Current ratio to new





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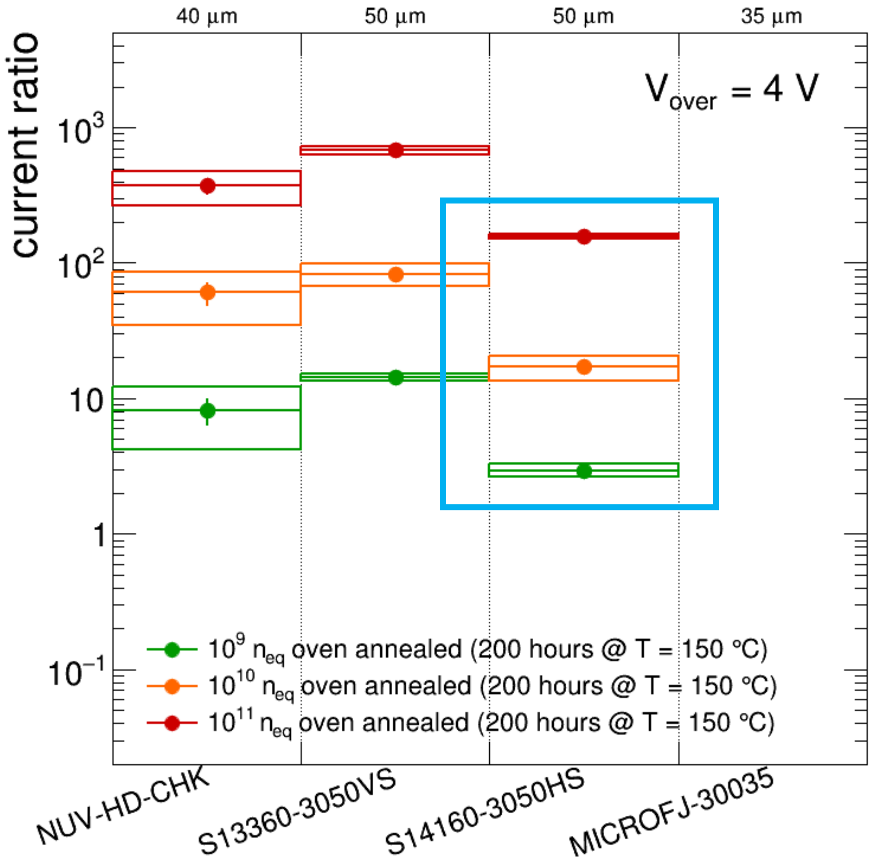
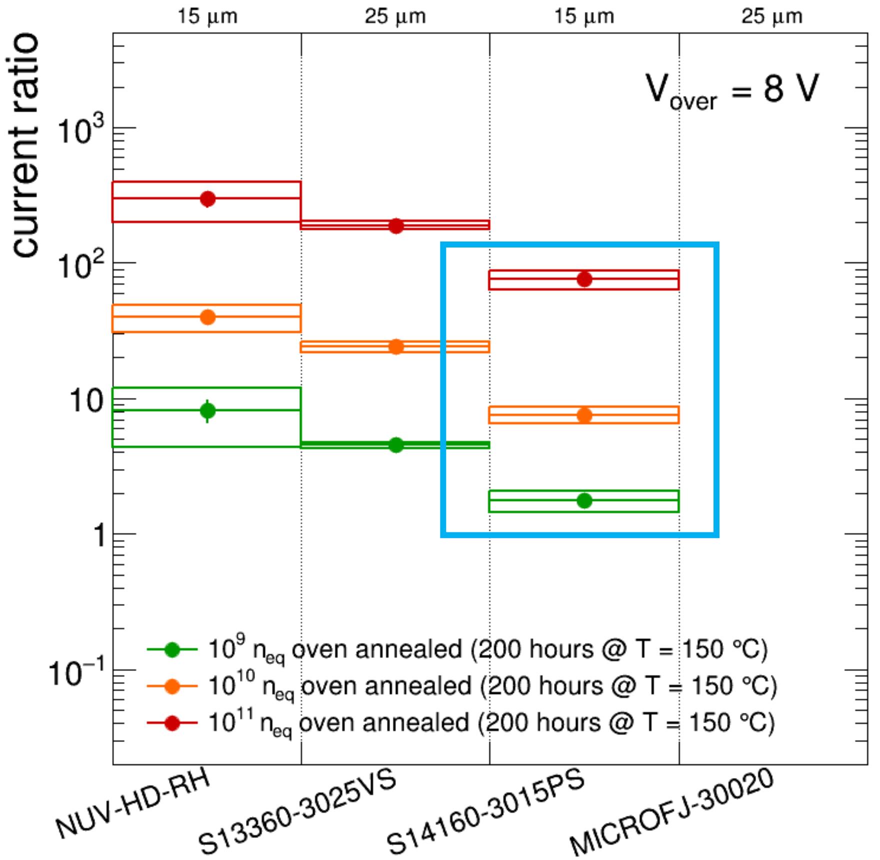
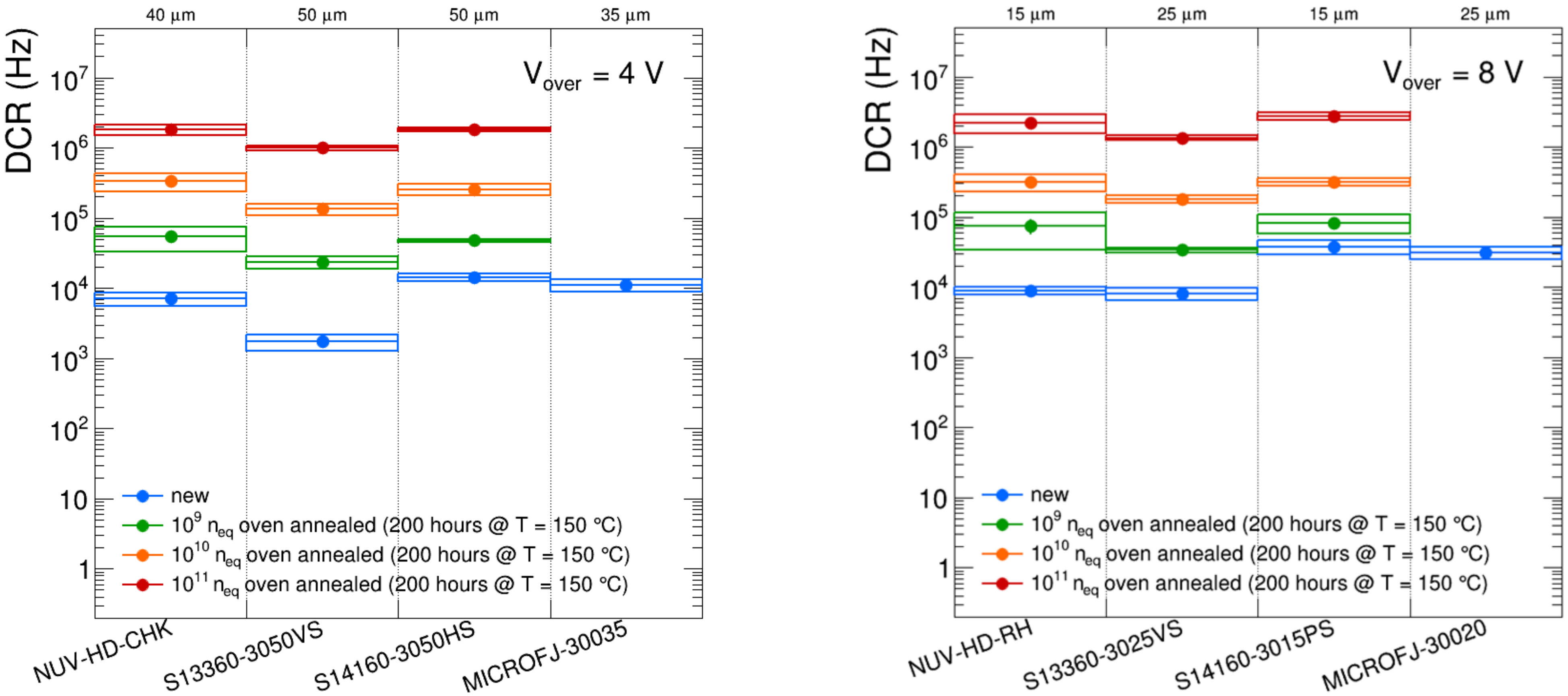




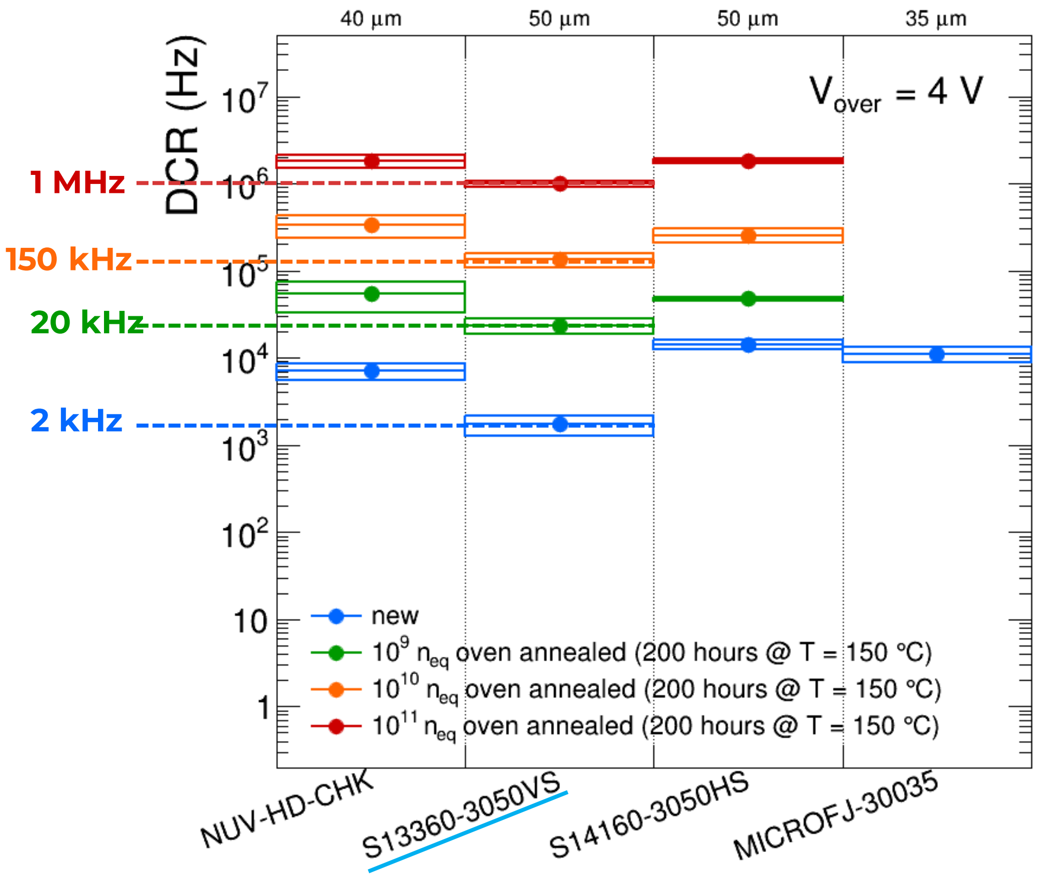
Hamamatsu S14160 series show a better recovery with the annealing

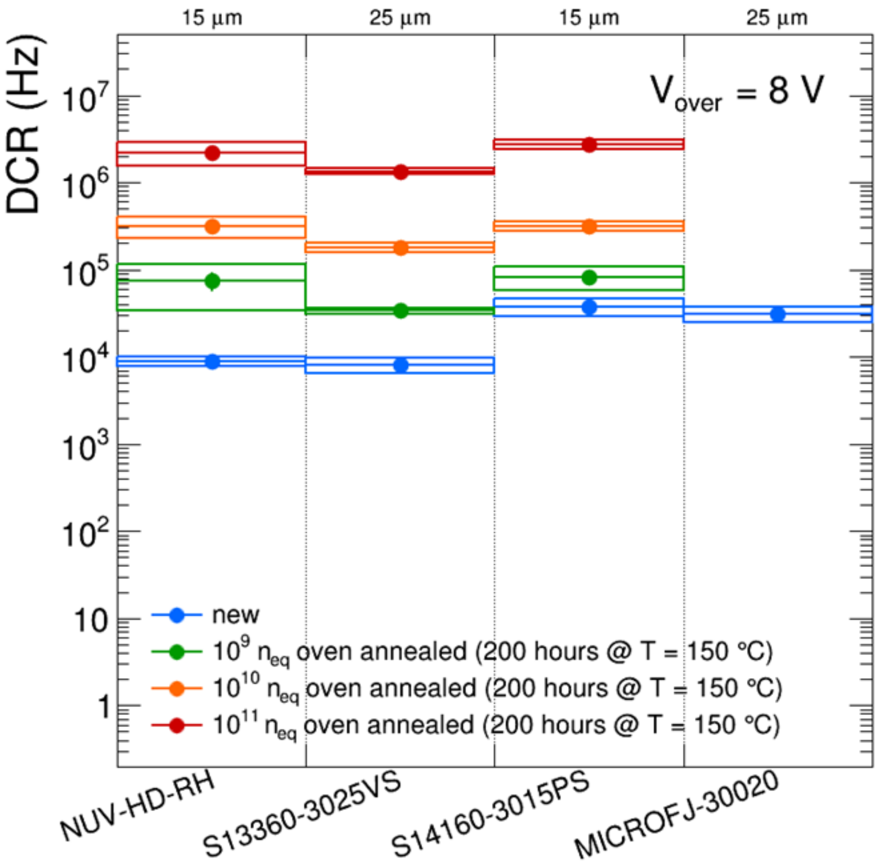
Results: DCR



DCR is a better **figure of merit** respect to **Dark Current**

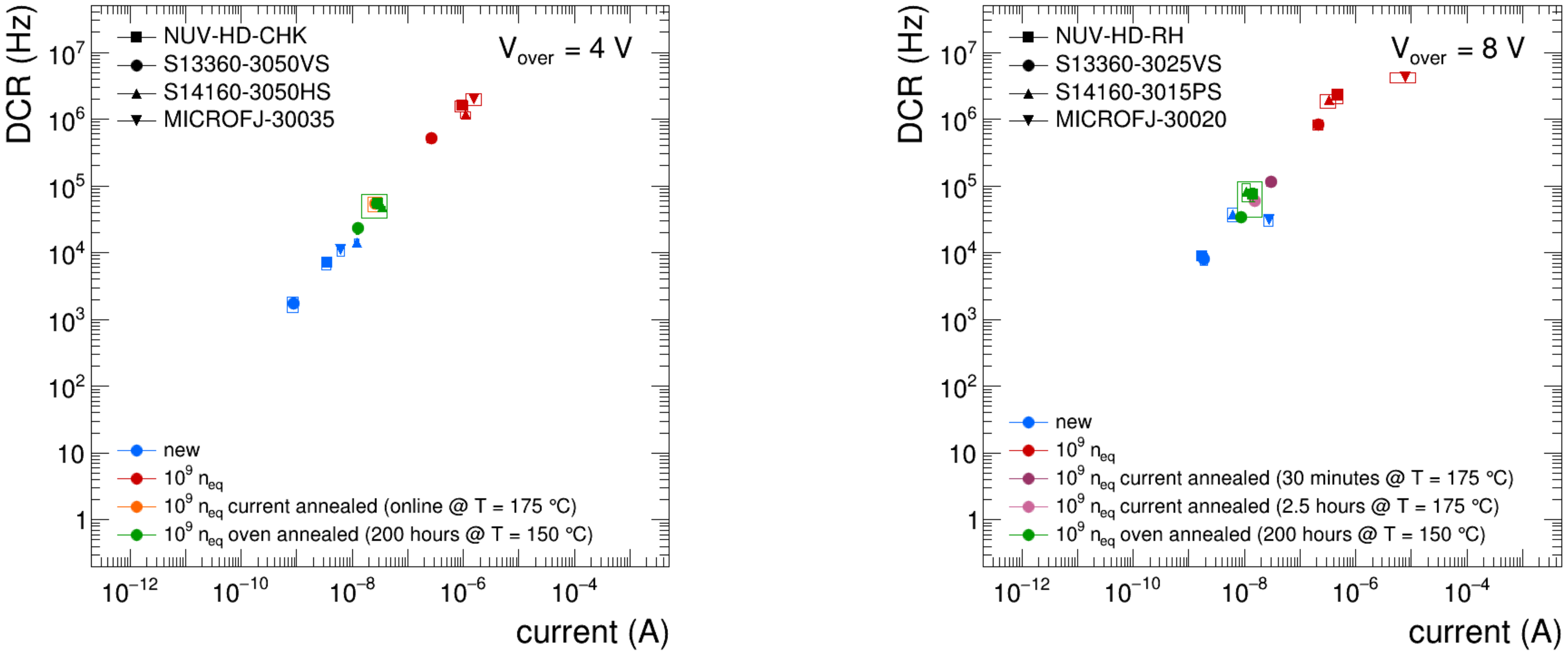
Results: DCR





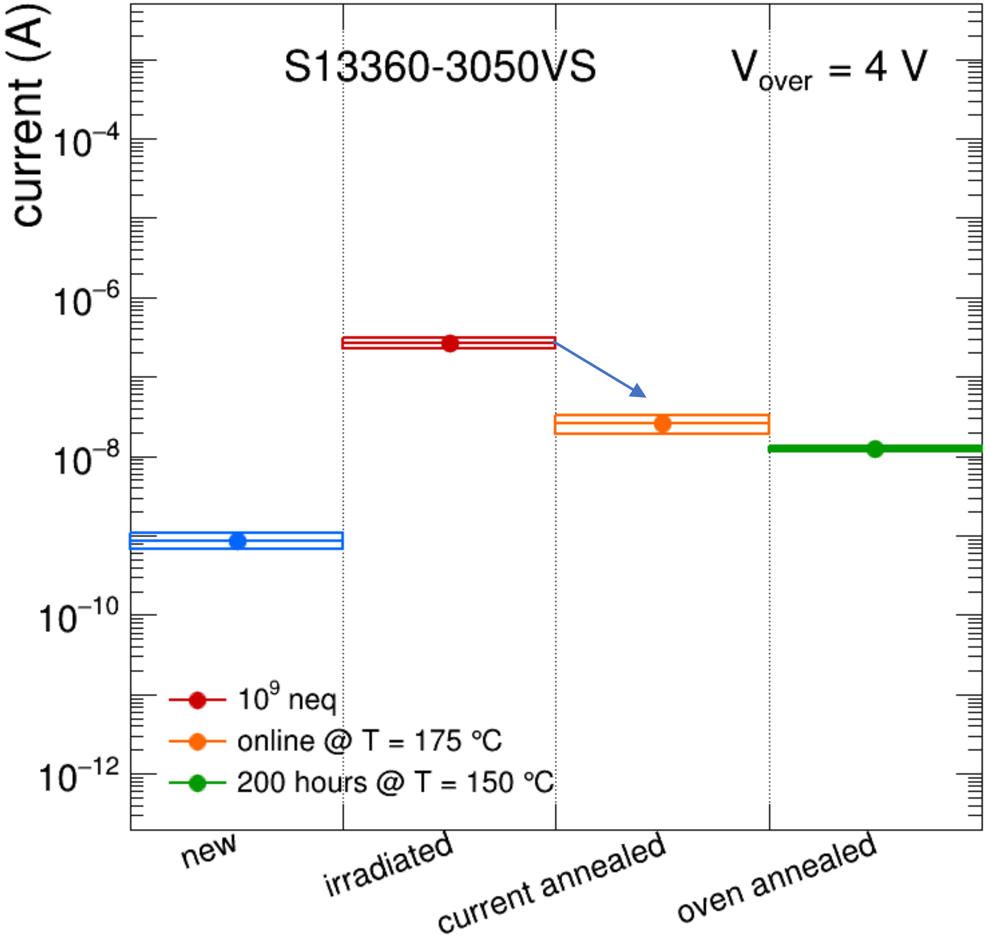
Hamamatsu S13360-3050 shows **less DCR** at **any irradiation/annealing level**

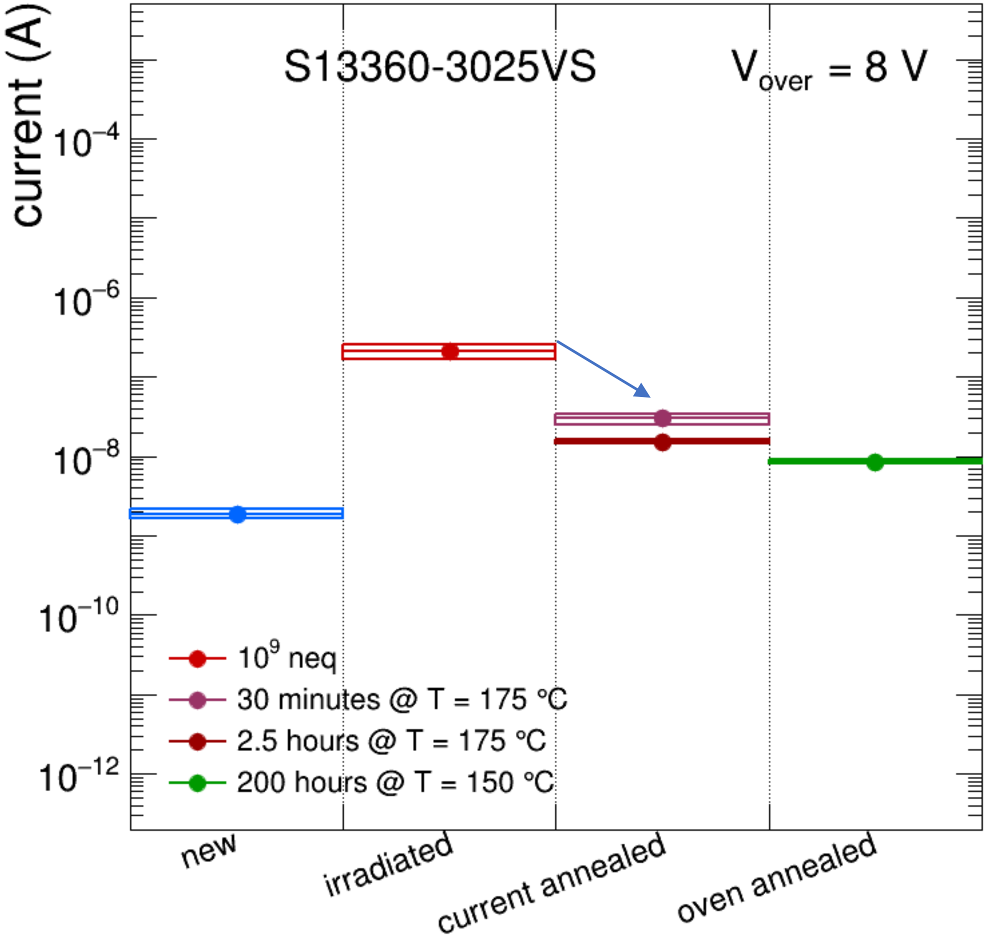
Results: DCR vs. Dark Current



Correlation between the two measurement. The **slope** represents the **GAIN** of **SiPMs** that remains **constant** at all the different **irradiation/annealing levels**

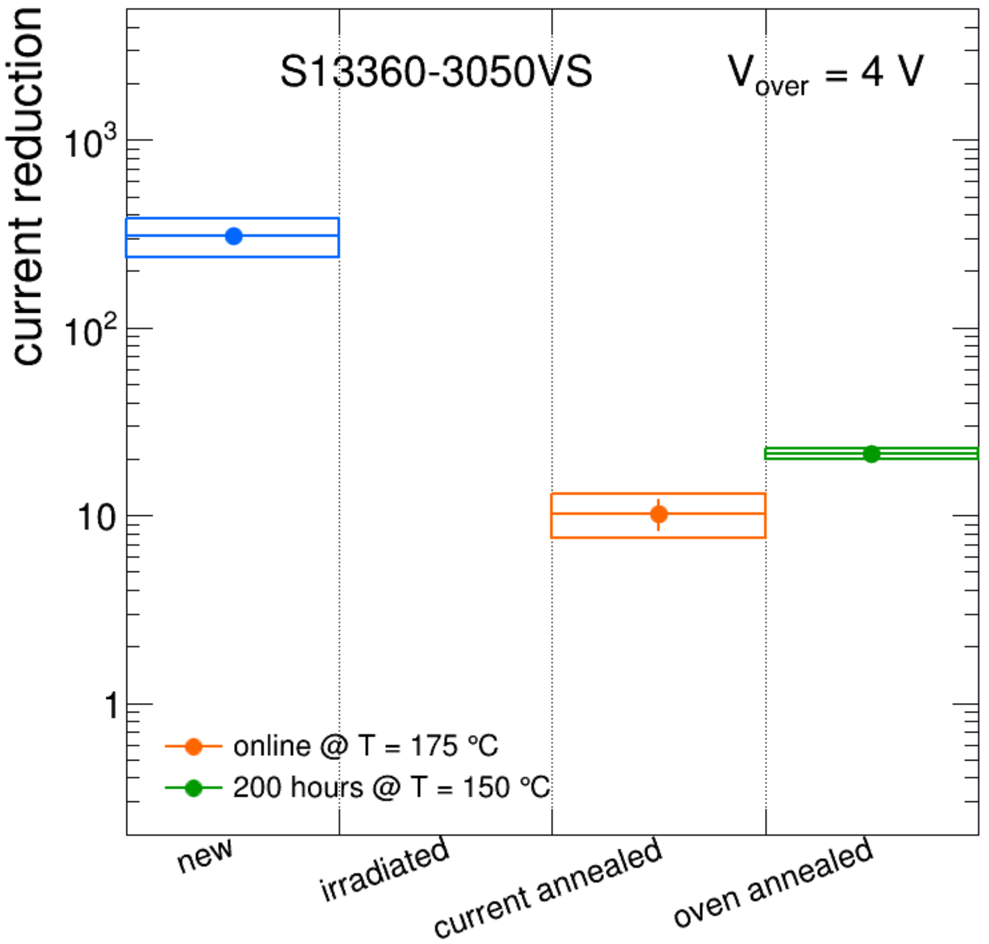
Results: Direct Current Annealing (Dark current)

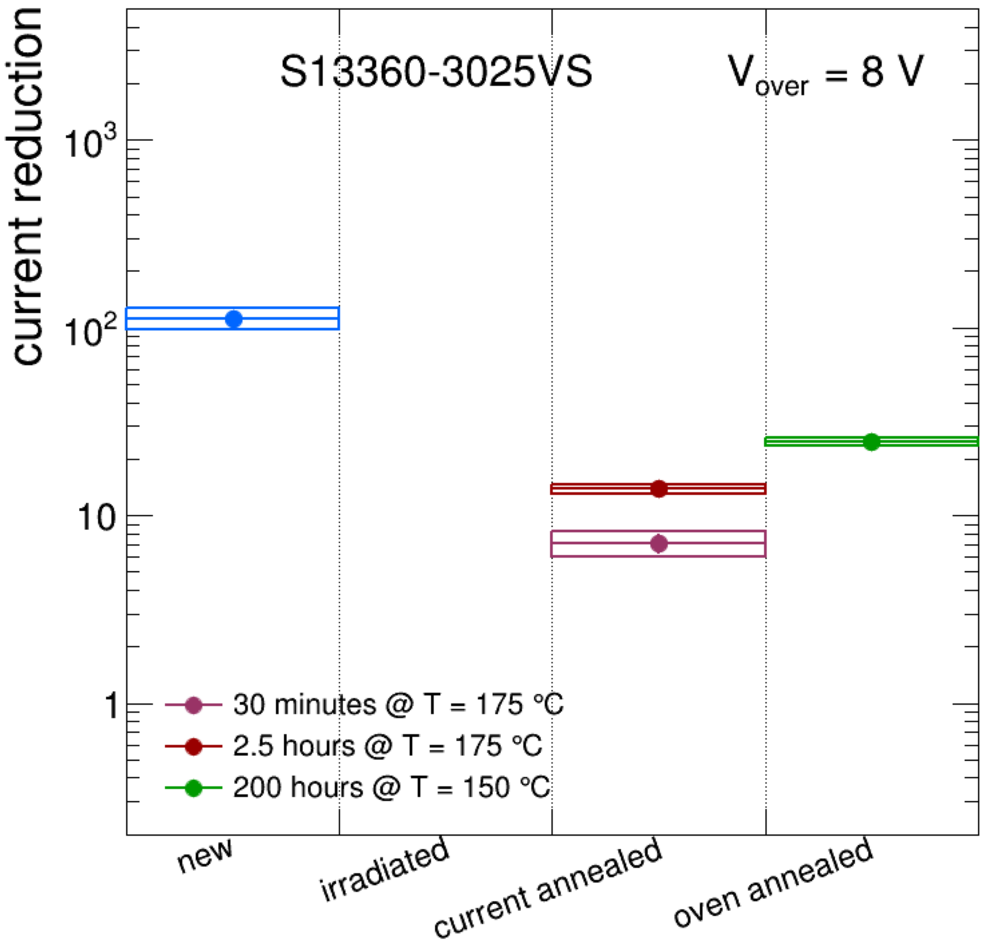




Dark current decreases in both the methods but without reaching the oven but in 1/10 of the annealing time.

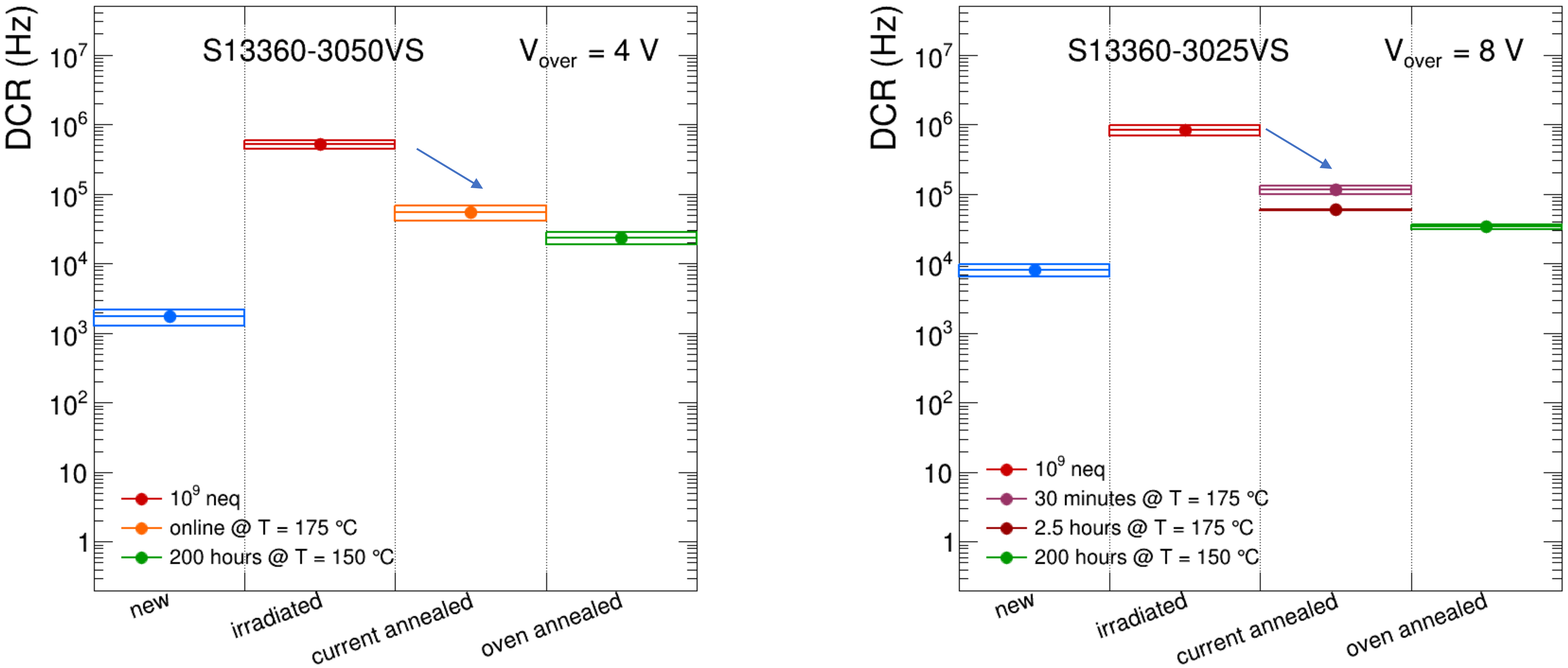
Results: Direct Current Annealing (Current reduction)





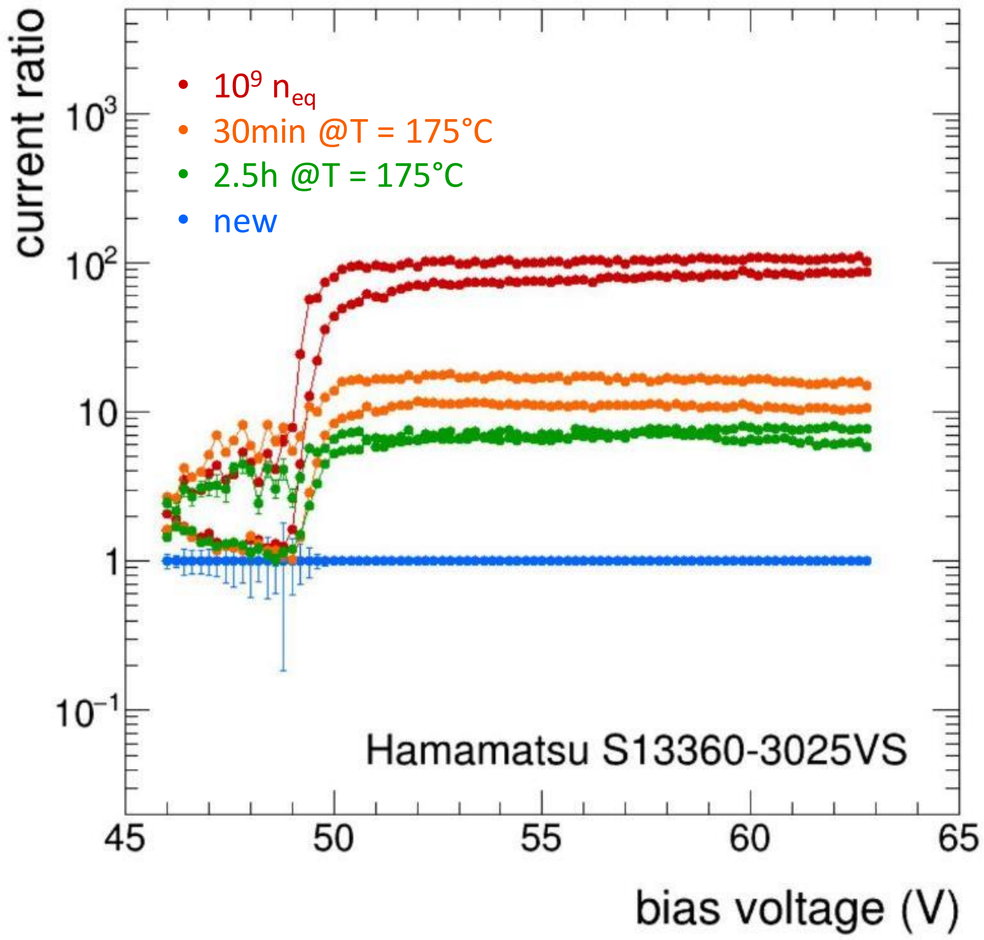
The Dark Current reduction.

Results: Direct Current Annealing (DCR)



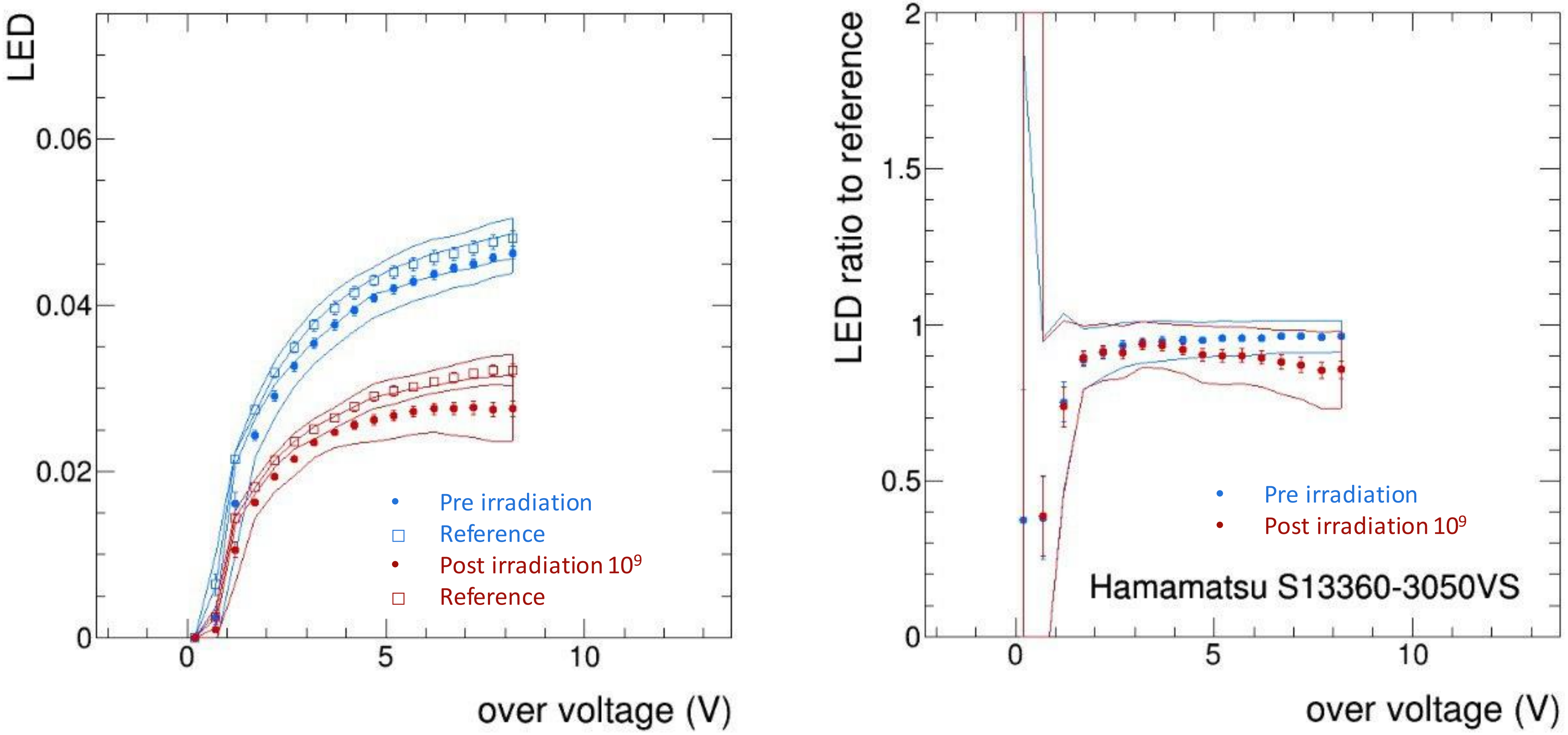
DCR scales accordingly

Results: Direct Current Annealing 3025 offline



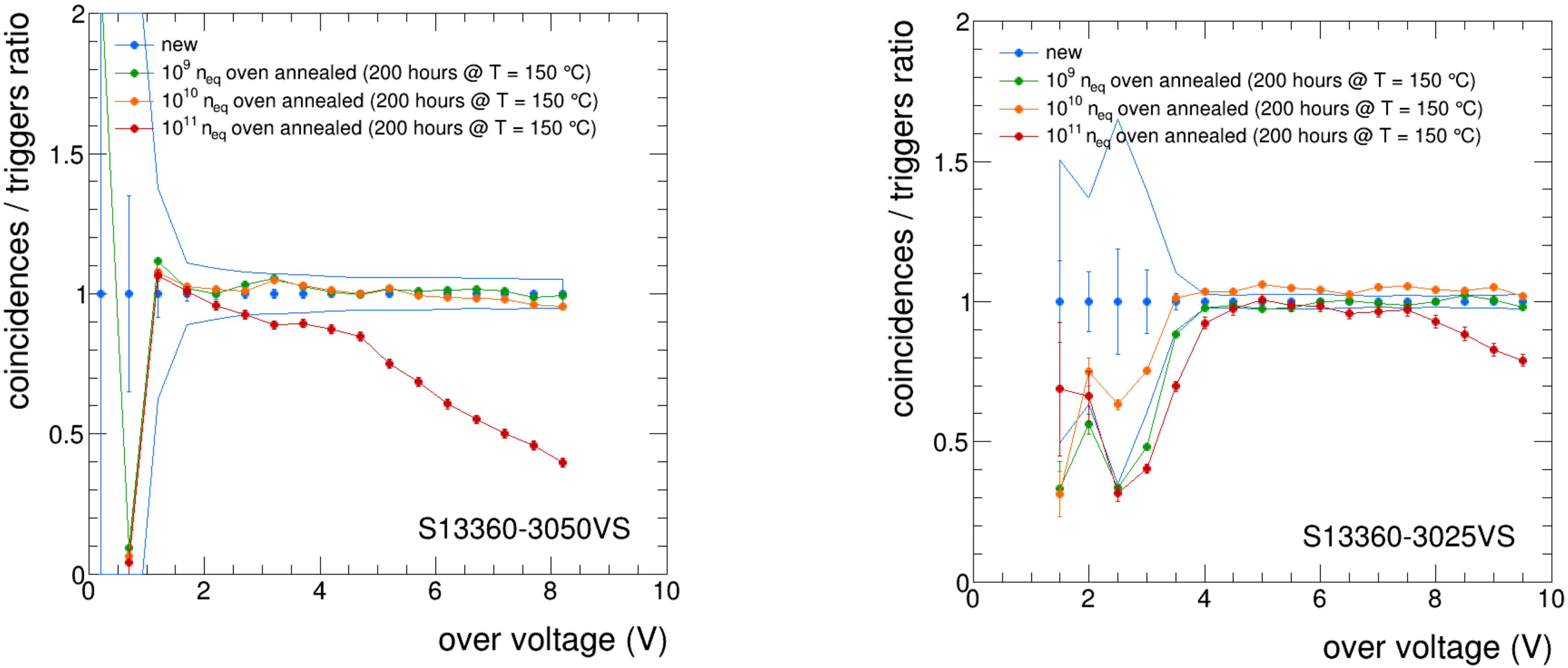
In the first 30 min of annealing, a factor ≈**7** of dark current is recovered. In the next 2 hours, only a factor ≈**2** is recovered but the homogeneity is far better.

Results: LED tests



It seems that there is a **lost** in **efficiency** in the light collection, but the **ratio respect** the **reference** sensor shows that the efficiency is maintained.

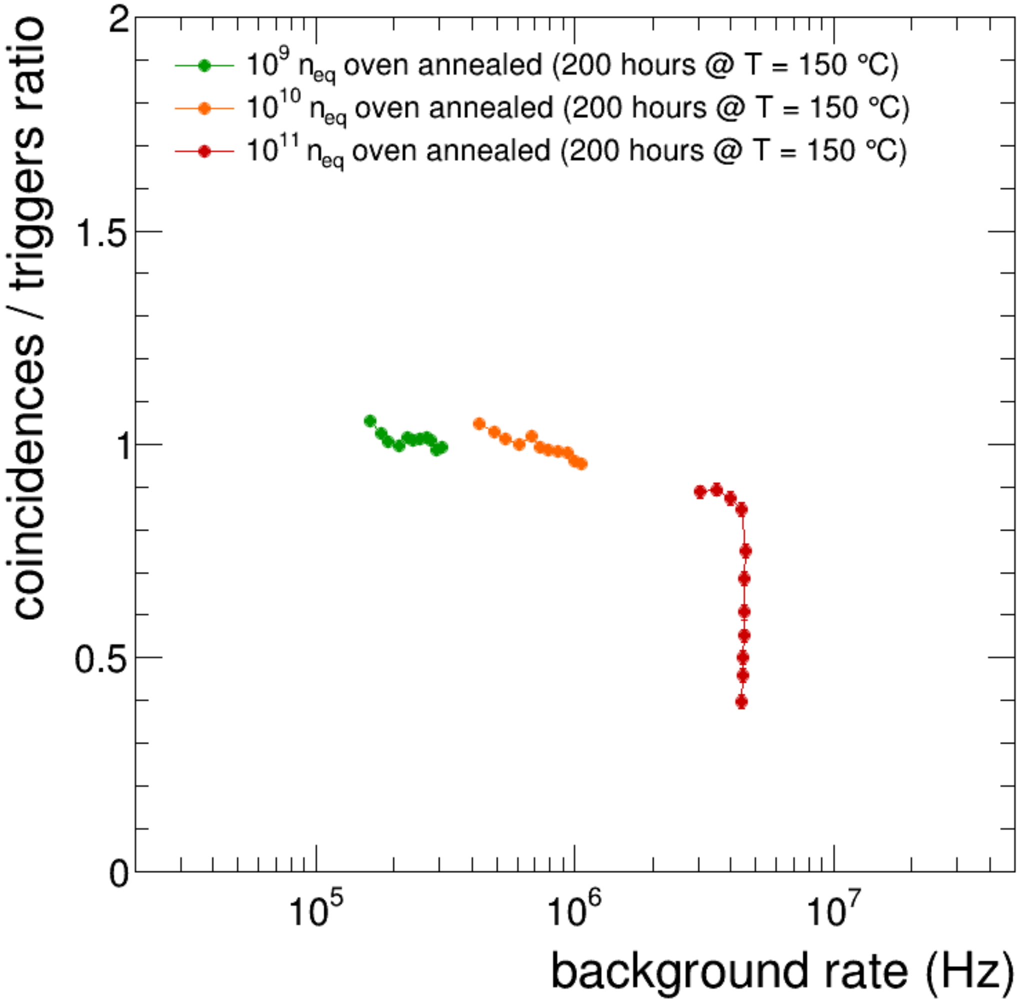
Results: LED tests



With the irradiation and annealing up to 10^{10} n_{eq} there are **no damage** to the **optical window** or in the **photon-ions conversion**.

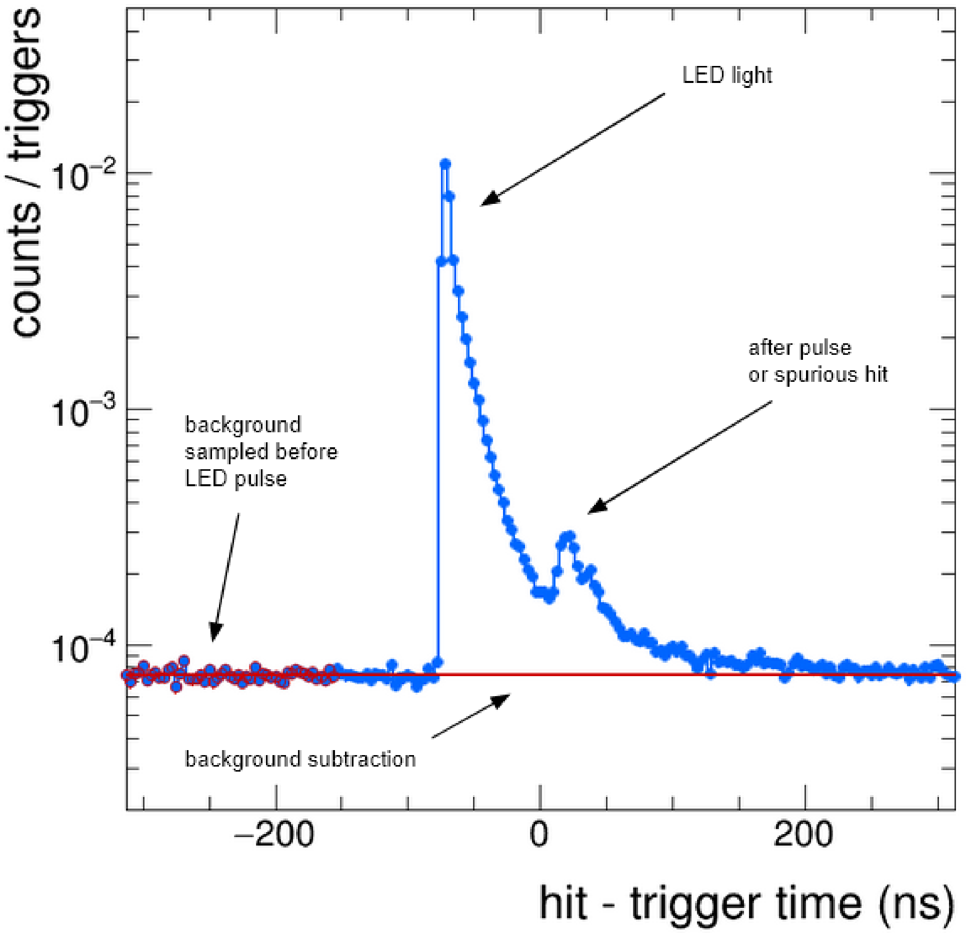
At 10^{11} n_{eq} and higher OV we see some problems that are compatible with a saturation in ALCOR

Results: LED tests



@4 MHz efficiency loss.

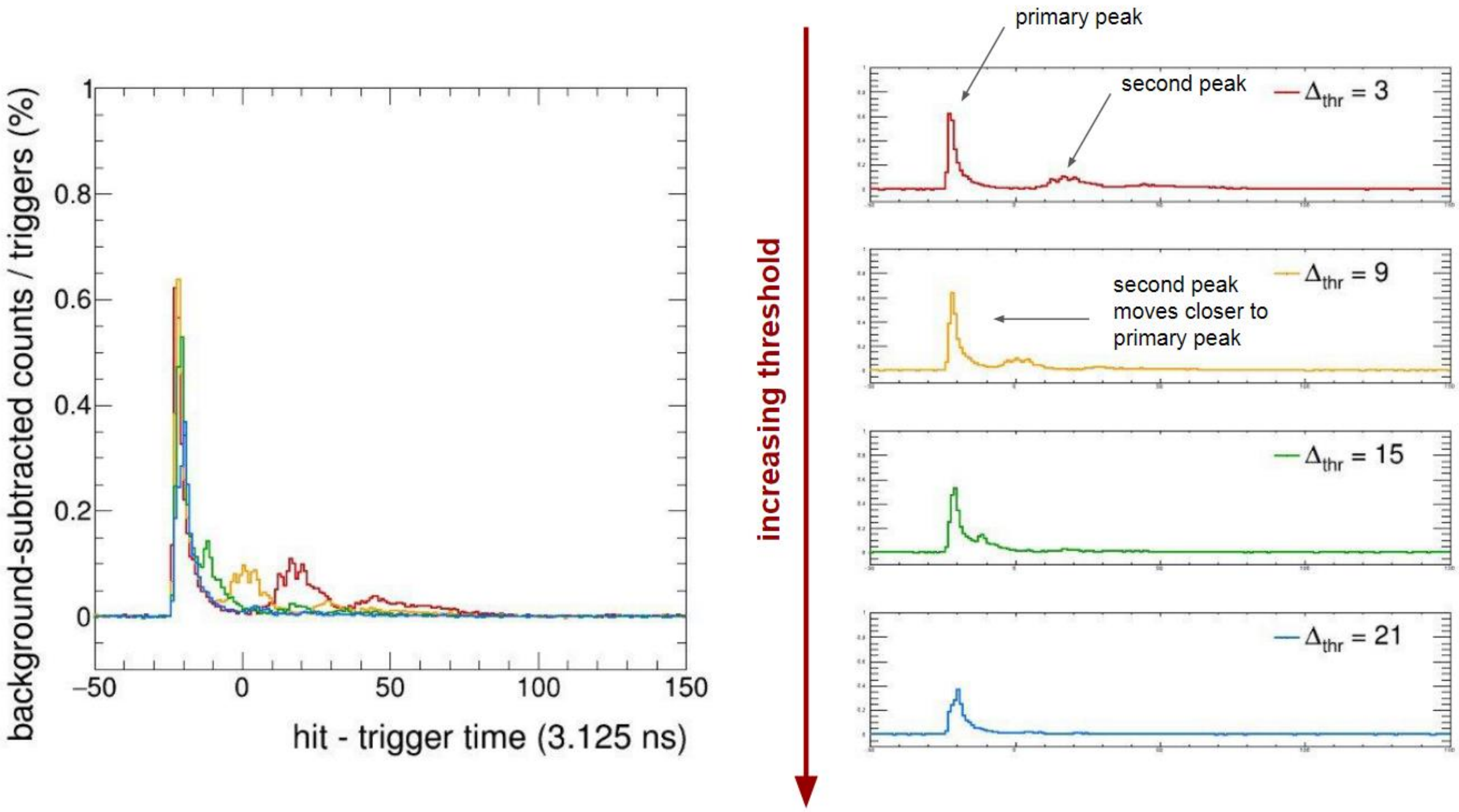
Results: LED tests



SiPMs – Alcor FE

Coupling issues

Results: LED tests



SiPMs – Alcor FE

Coupling issues

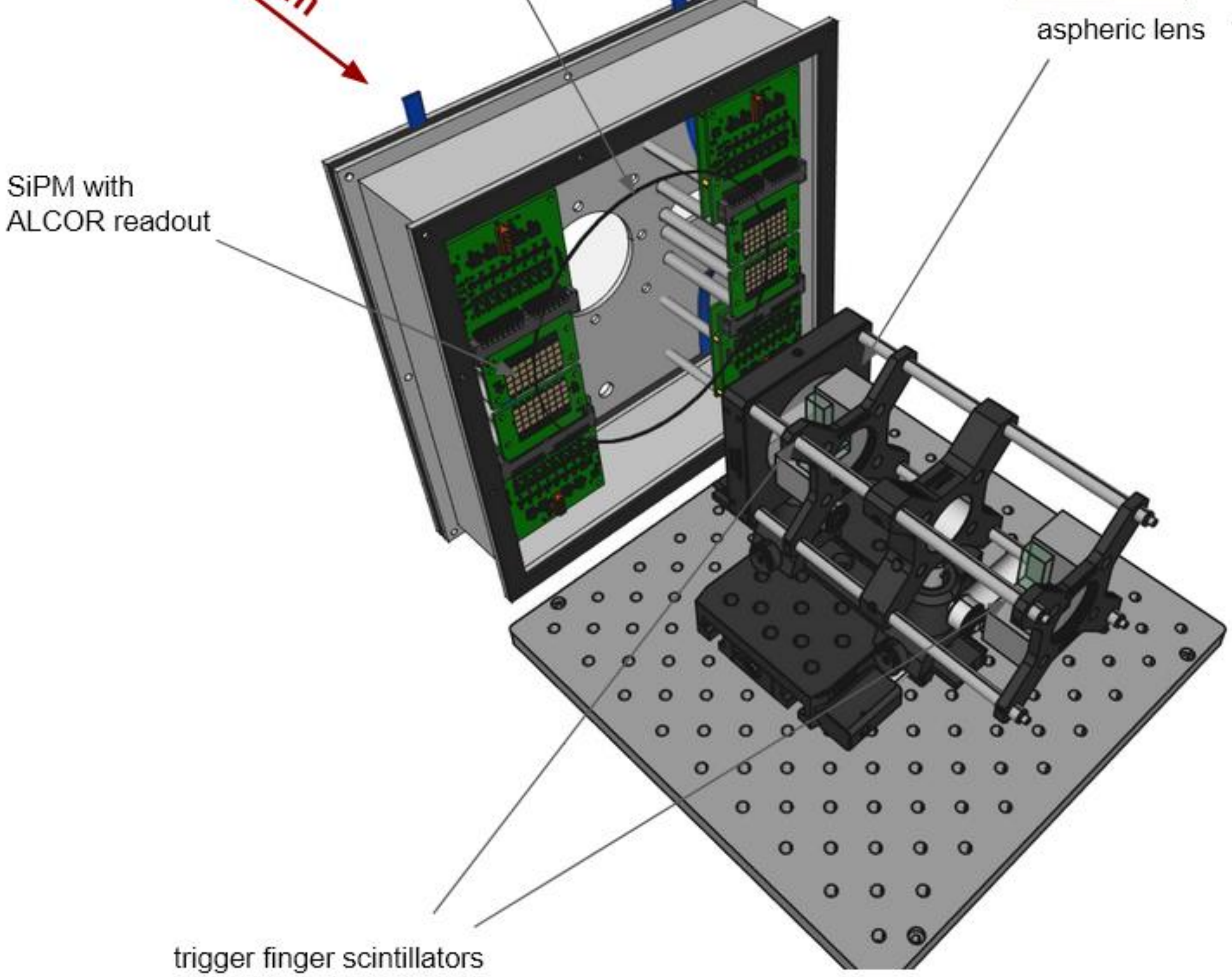
Conclusion

We developed an automated setup for SiPMs characterization, and the first results are shown.

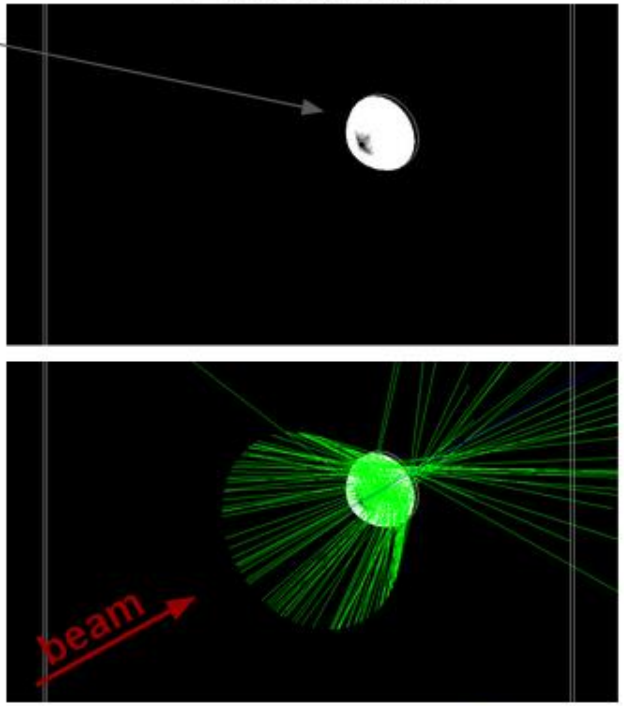
We are assessing commercial and prototypes SiPMs performance after irradiation and annealing.

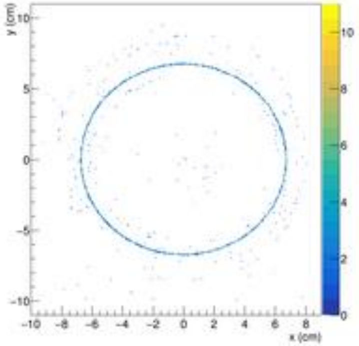
We are working on a standard (oven) and alternative (direct current) annealing protocols.

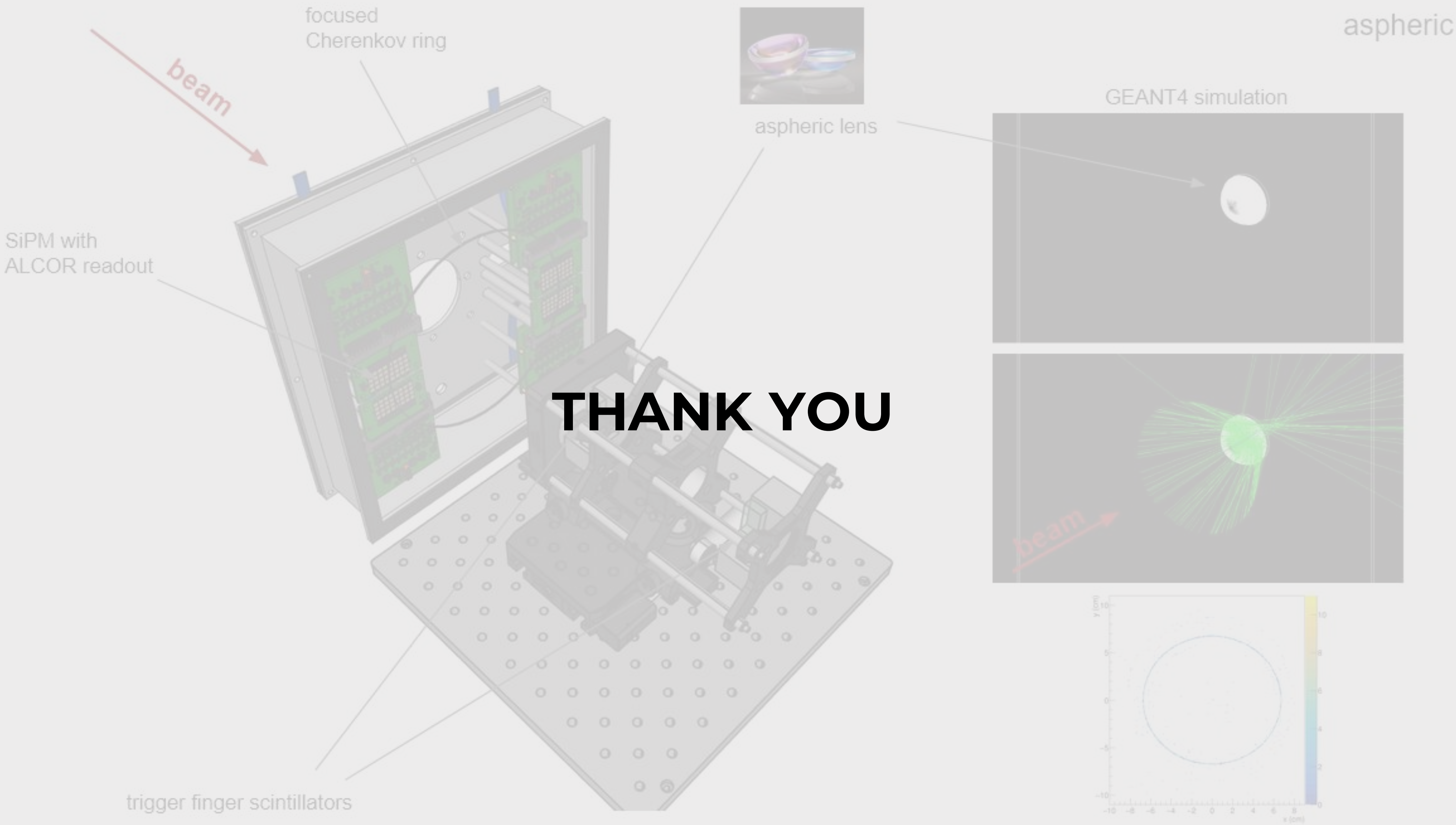
aspheric



GEANT4 simulation







THANK YOU

Luigi Rignanese rignanes@bo.infn.it