SiPM photosensors for RICH

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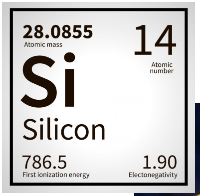
SiPM option for RICH optical readout

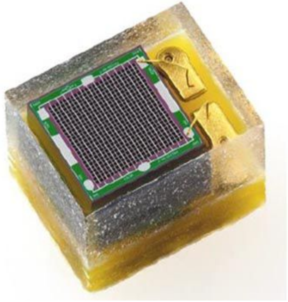
- **pros**
  - cheap
  - high photon efficiency
  - excellent time resolution
  - insensitive to magnetic field

- **cons**

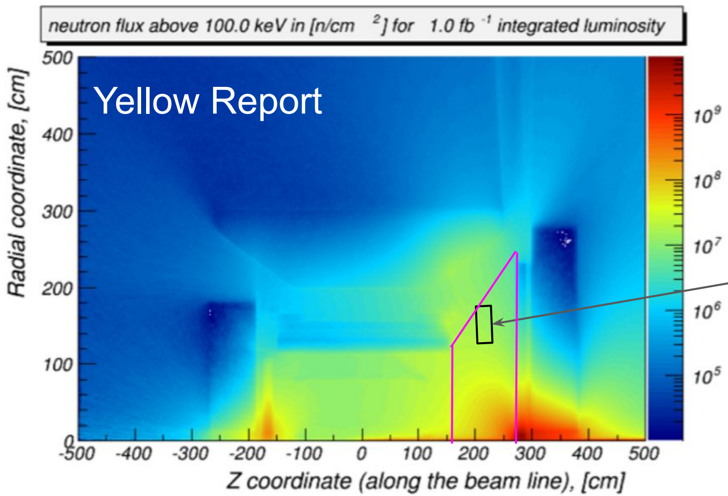
large dark count rates

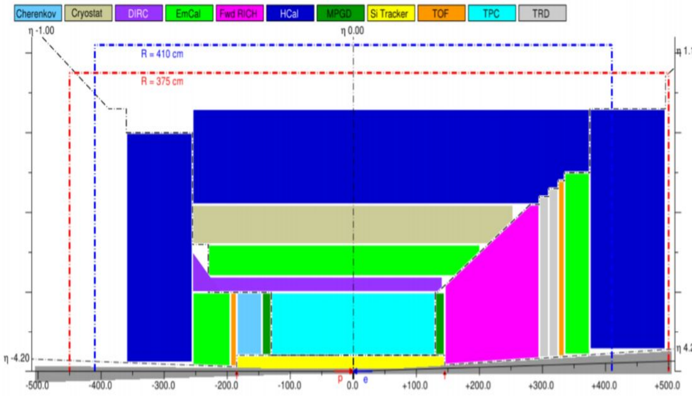
not radiation tolerant





Neutron fluxes and SiPM radiation damage





Most of the key physics topics discussed in the EIC White Paper [2] are achievable with an integrated luminosity of 10 fb^{-1} corresponding to 30 weeks of operations. One notable exception is studying the spatial distributions of quarks and gluons in the proton with polarized beams. These measurements require an integrated luminosity of up to 100 fb^{-1} and would therefore benefit from an increased luminosity of $10^{34}\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$.

possible location of dRICH photosensors
neutron fluence for 1 fb^{-1} → 1-5 10^7 n/cm^2 (> 100 keV ~ 1 MeV n_{eq})

- radiation level is moderate
- magnetic field is high(ish)

R&D on SiPM as potential photodetector for dRICH, main goal
study SiPM usability for Cherenkov up to 10^{11} 1-MeV n_{eq}/cm^2

notice that 10^{11} n_{eq}/cm^2 would correspond to 2000-10000 fb^{-1} integrated $\mathcal{L}$
quite a long time of EIC running before we reach there, if ever
it would be between 6-30 years of continuous running at $\mathcal{L} = 10^{34}\ \mathrm{s}^{-1}\ \mathrm{cm}^{-2}$

→ better do study in smaller steps of radiation load

10^9 1-MeV n_{eq}/cm^2	*most of the key physics topics*
10^{10} 1-MeV n_{eq}/cm^2	*should cover most demanding measurements*
10^{11} 1-MeV n_{eq}/cm^2	*possibly never reached*

SiPM radiation damage and mitigation strategies

Radiation damages increase currents, affects V_{bd} and increase DCR
With very high radiation loads can bring to baseline loss, but…
does not seem to be a problem up to 10^{11} n_{eq}/cm^2 (if cooled, T = -30 C)

If the baseline is healthy, single-photon signals can be be detected
one can work on reducing the DCR with following mitigation strategies:

- Reduce operating temperatures (**cooling**)
- Use **timing**
- High-temperature **annealing** cycles

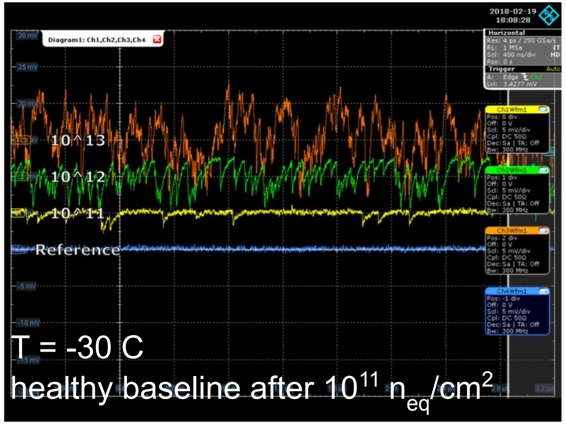
Key point for R&D on RICH optical readout with SiPM:

- demonstrate capacity to measure Single Photon
- keep DCR under control (ring imaging background)

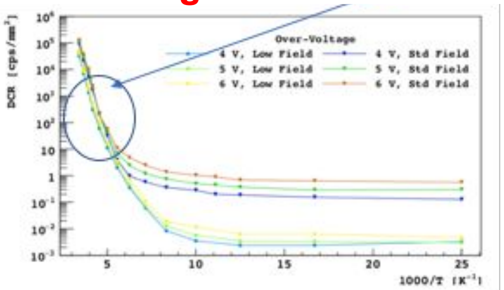
despite radiation damages

Calvi, NIM A 922 (2019) 243

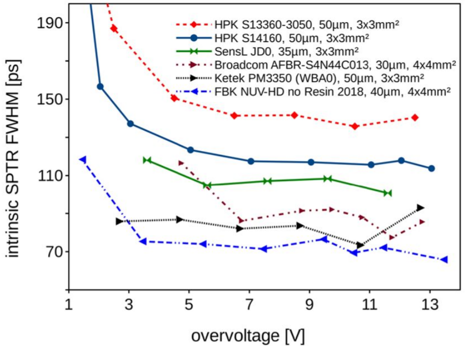
10^{11}

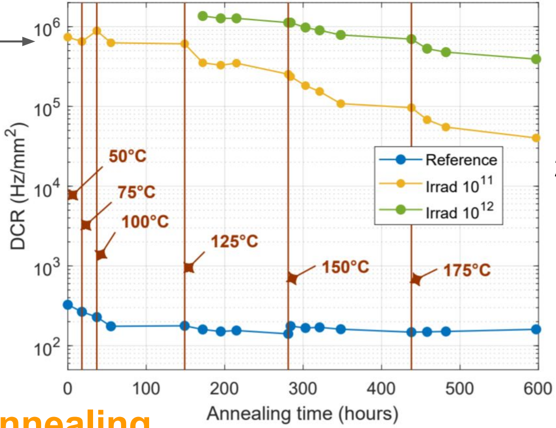


cooling



timing





200x less DCR

annealing

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- Use timing
- High-temperature annealing

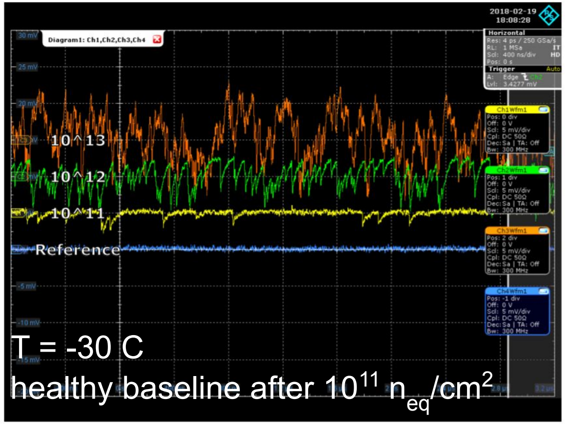
Key point for R&D on RICH optica...
- demonstrate capacity to mea...
- keep DCR under control (rin...

despite radiation damages

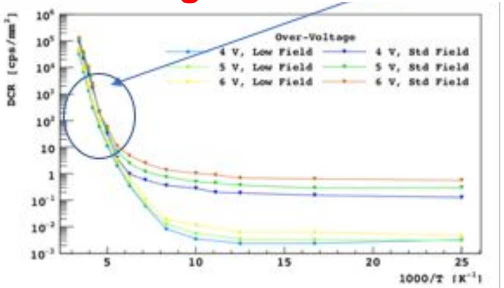
true for the sensors of Calvi which are 1.3 x 1.3 mm^2

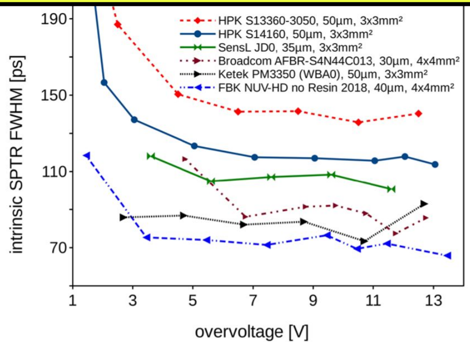
for 3 x 3 mm^2 sensors the story is a bit different as we will see later
same DCR/mm^2
5x larger DCR/pixel

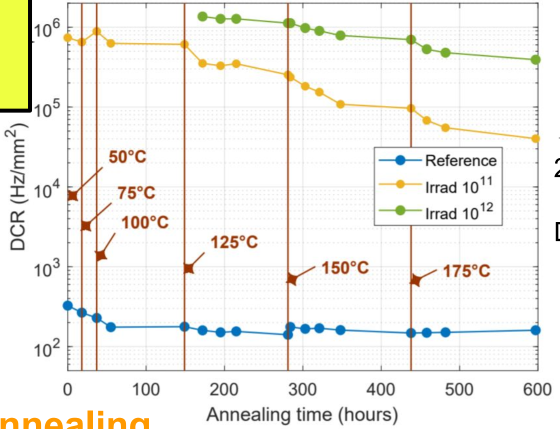
Calvi, NIM A 922 (2019) 243



cooling







200x less DCR

annealing

SiPM R&D program

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- **born within the forward RICH proposal for EIC**
  - proof of feasibility of SiPM for Cherenkov application at colliders, this requires
    - single-photon counting capabilities (SiPM can do it)
    - reasonable dark-count rates (low-temperature operation, time resolution)
    - radiation tolerance (small SPAD cells, high-temperature annealing)
  - SiPM readout with dedicated readout electronics
    - ALCOR front-end ASIC (Torino)
    - streaming (aka continuous) readout DAQ
- **two main phases in 2021**
  - characterisation of the sensors before and after irradiation
  - use of the sensors (with/without irradiation) in dRICH prototype at test beam
- **can have direct applications in multiple cases, i.e.**
  - other EIC detectors looking for B-tolerant photon counters
  - the Aerogel-RICH proposal for ALICE3

this R&D is 100% synergic with ALICE3

Electronics equipment

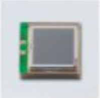
acquisition of commercial and prototype (FBK) SiPM sensors
design and production of dedicated electronics boards

- **SiPM carrier boards (BO)**
  - host SiPM matrix: designed with irradiation, annealing and testbeam in mind
  - one form factor, different layout for different SiPM family
- **SiPM adapter boards (FE)**
  - couples the SiPM carrier board with readout system (oscilloscope, ALCOR)
    - IV-base adapter (for SiPM IV and DCR characterisation)
    - mini-adapter (for ALCOR-TEST board)
    - adapter-CA (for ALCOR-FE board)
- **ALCOR FrontEnd board (TO)**
  - hosts ALCOR frontend ASIC
- **FireFly breakout board (ARCADIA)**
  - links ALCOR I/O to FPGA
    - ALCOR configuration and readout

the list does not stop here, these are the main equipment boards

Commercial SiPM sensors

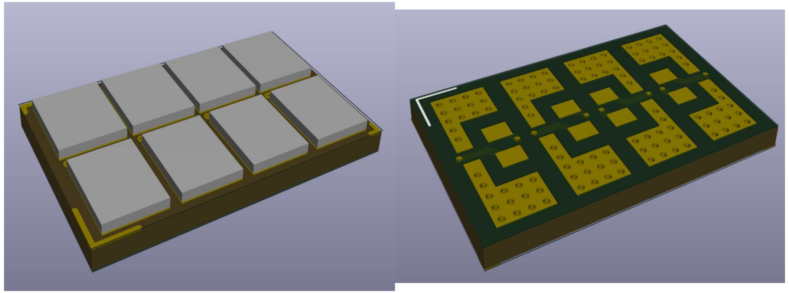


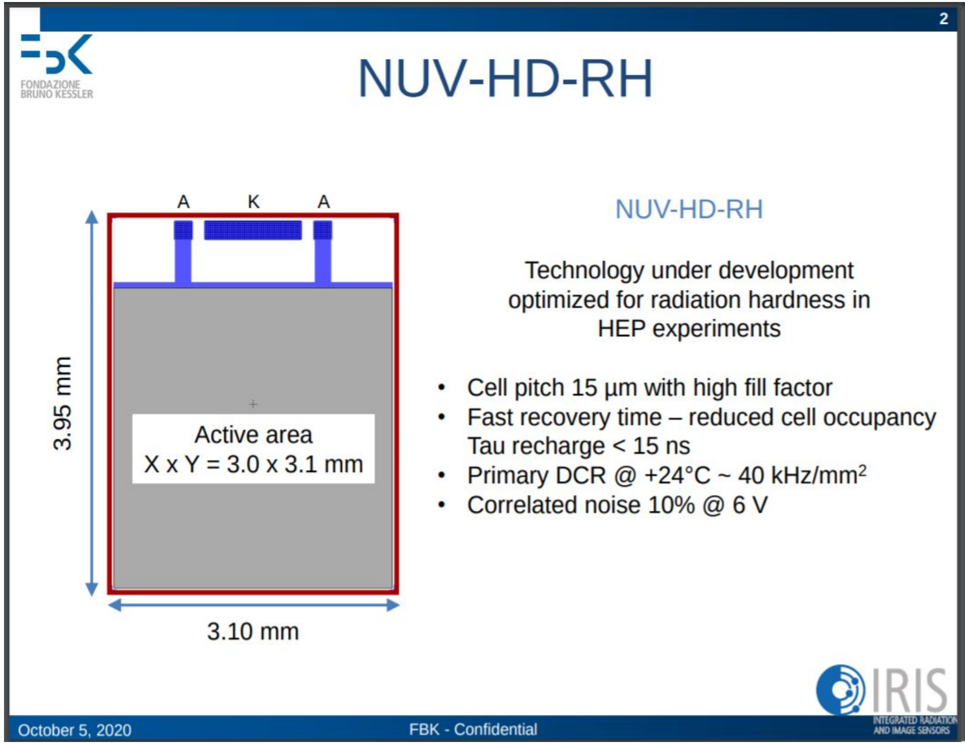


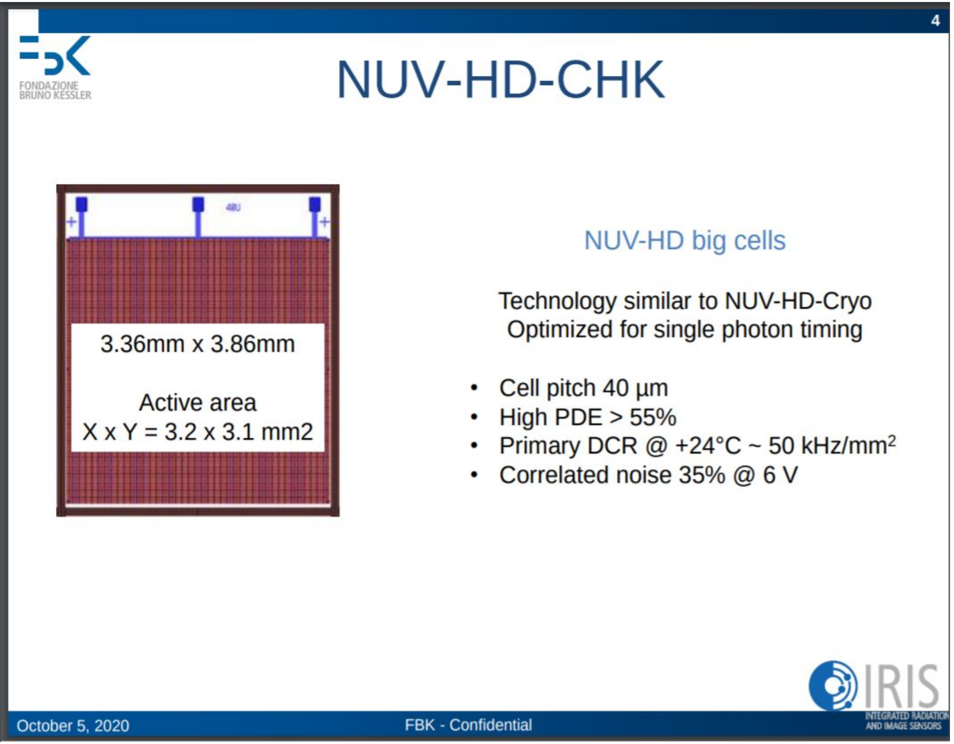
board	sensor	uCell (µm)	V_{bd} (V)	PDE (%)	DCR (kHz/mm^2)	window	notes
HAMA1	S13360 3050VS	50	53	40	55	silicone	legacy model Calvi et. al
HAMA1	S13360 3025VS	25	53	25	44	silicone	legacy model smaller SPAD
HAMA2	S14160 3050HS	50	38	50		silicone	newer model lower V_{bd}
HAMA2	S14160 3015PS	15	38	32	78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

and FBK prototype sensors wire bonded on custom mini-tiles

FBK has developed for us custom mini-tiles hosting 2x4 prototypes each

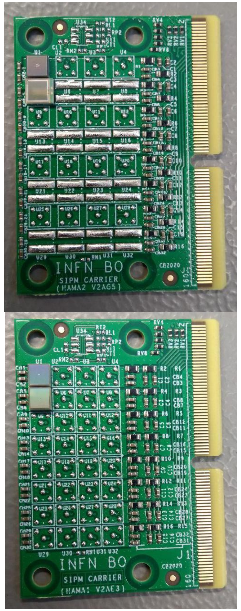




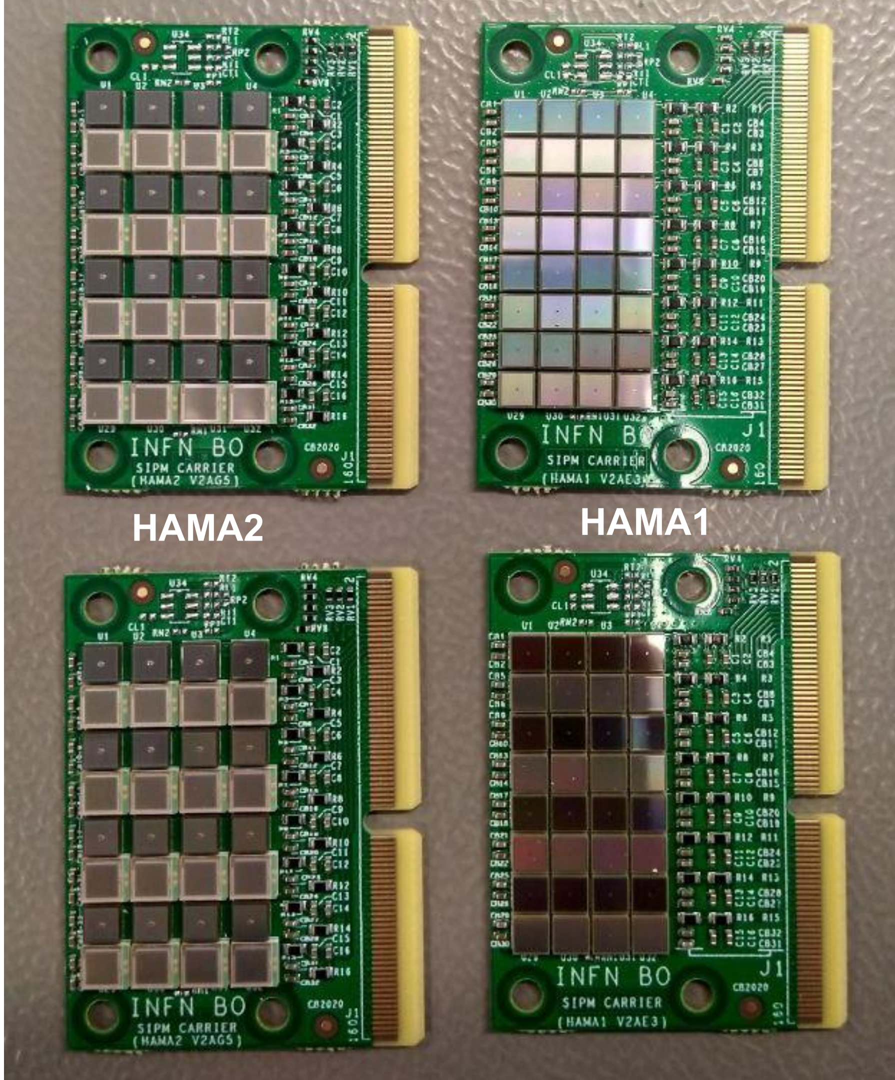


Schede SiPM carrier

- **SENSL**
  - 2 schede FULL
  - 3 schede LIGHT
- **BCOM**
  - 4 schede FULL
  - 2 schede LIGHT
- **HAMA1**
  - 2 schede FULL
  - 3 schede LIGHT
- **HAMA2**
  - 2 schede FULL
  - 3 schede LIGHT
- **FBK**
  - 4 schede FULL



schede LIGHT



schede FULL

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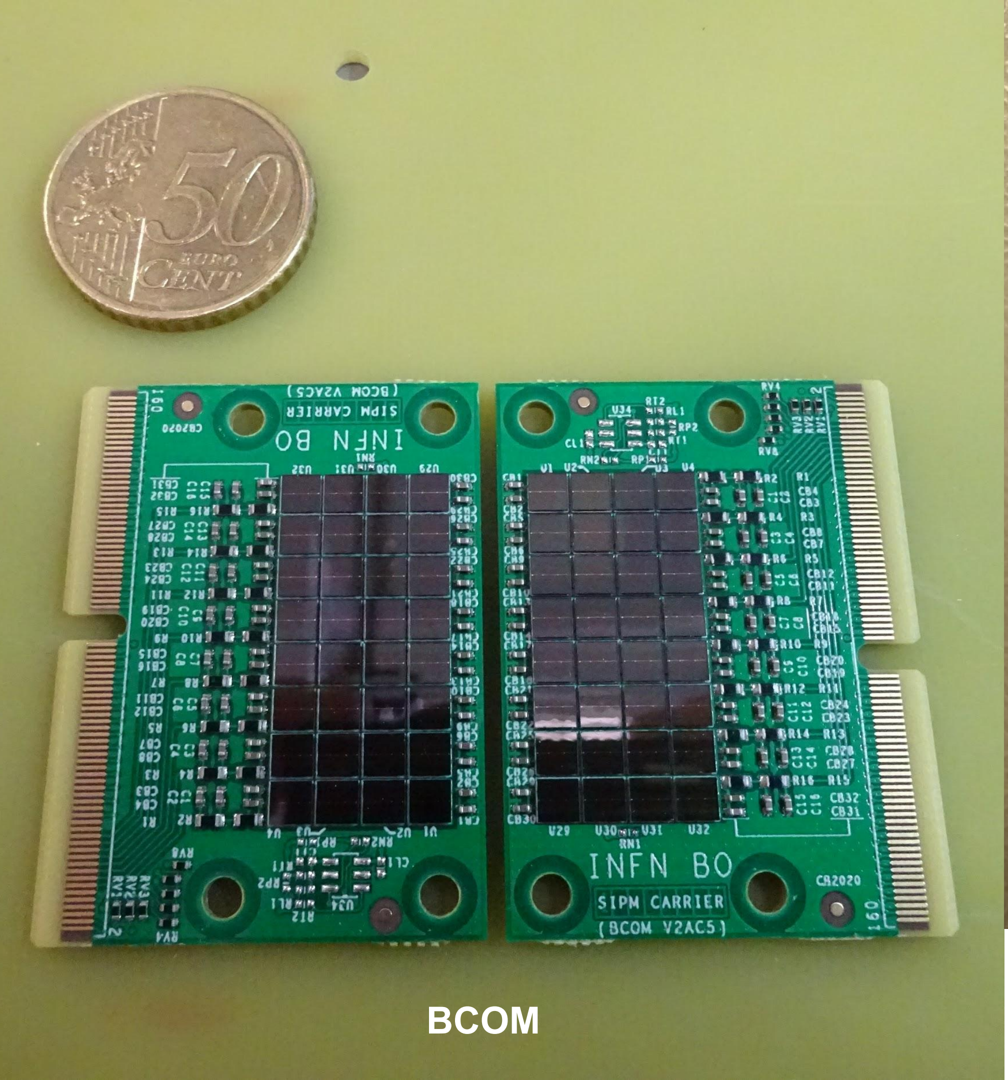

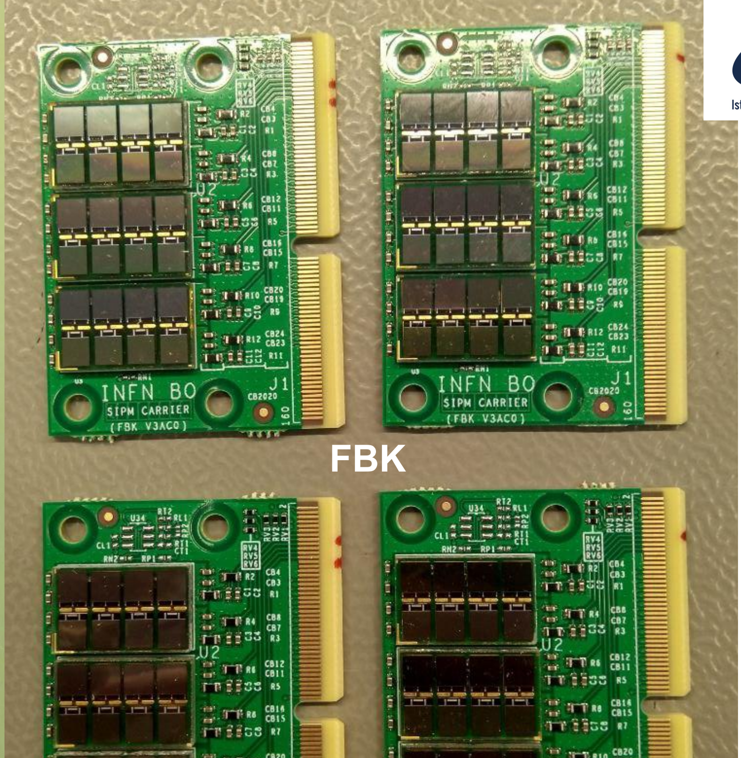

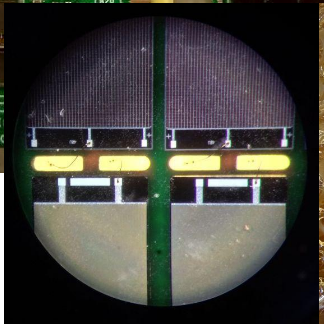

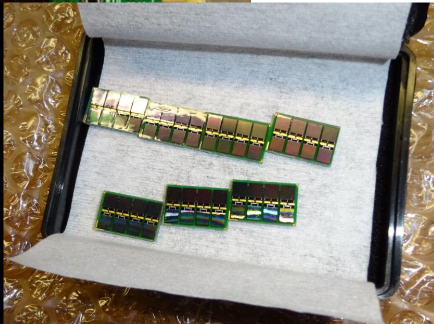

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Schede adapter

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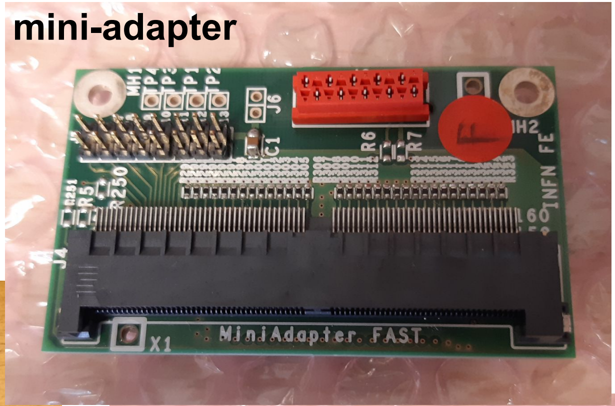
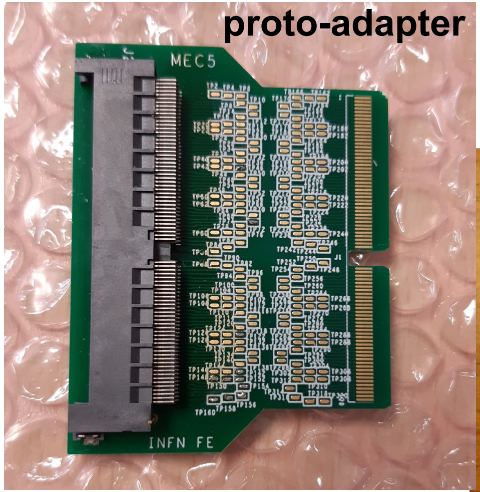
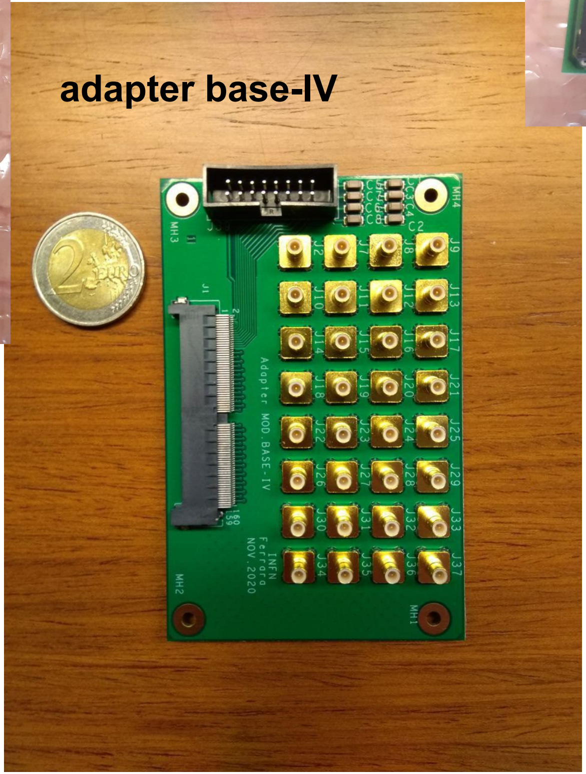
mini-adapter



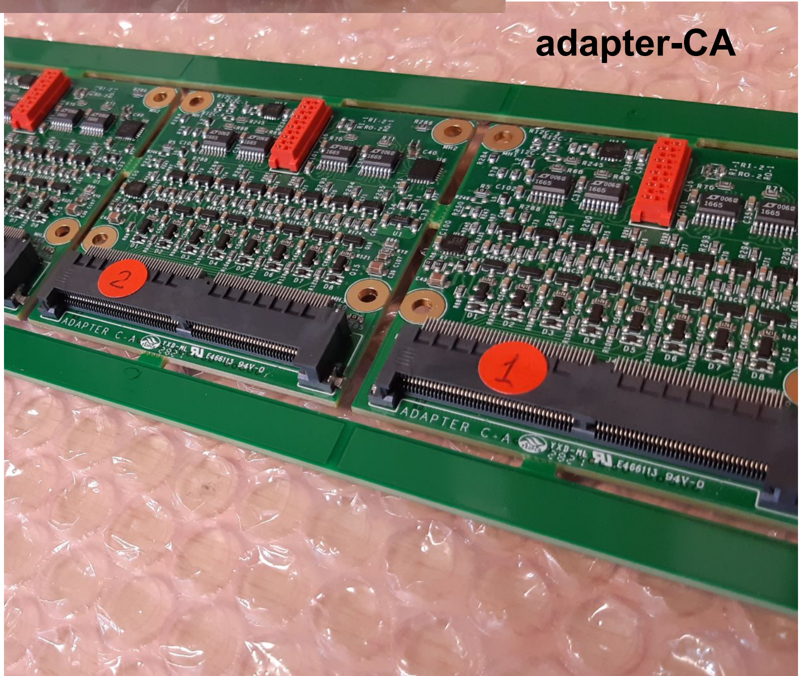
proto-adapter



adapter base-IV



adapter-CA

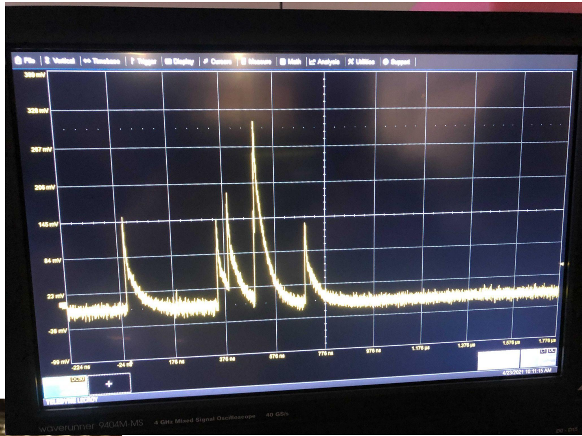


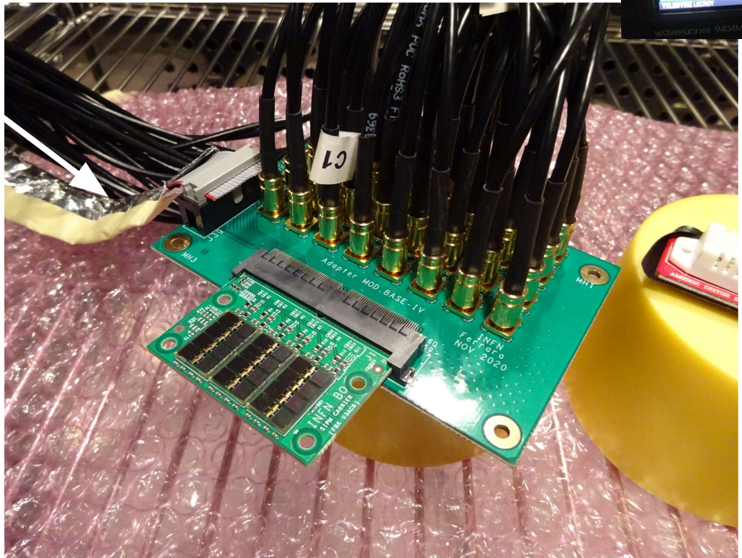
SiPM characterisation @ BO

I-V curves and DCR at different temperatures

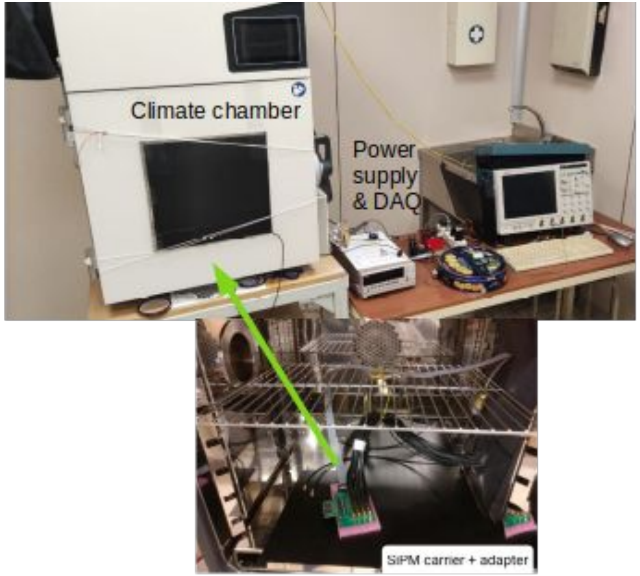
+20 C −10 C −30 C

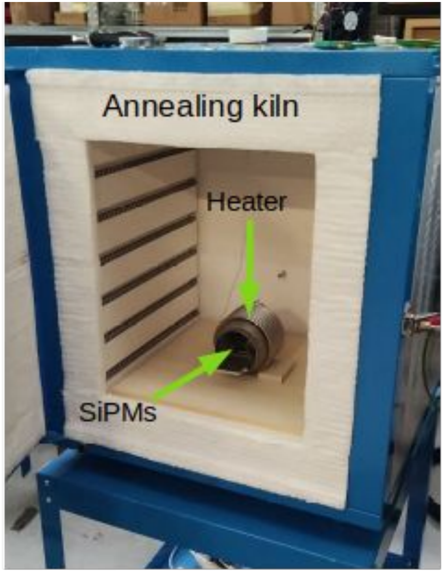
- Memmert climatic chamber
- Keithley source meter
- Keysight power supply
- Cividec amplifier
- Lecroy oscilloscope



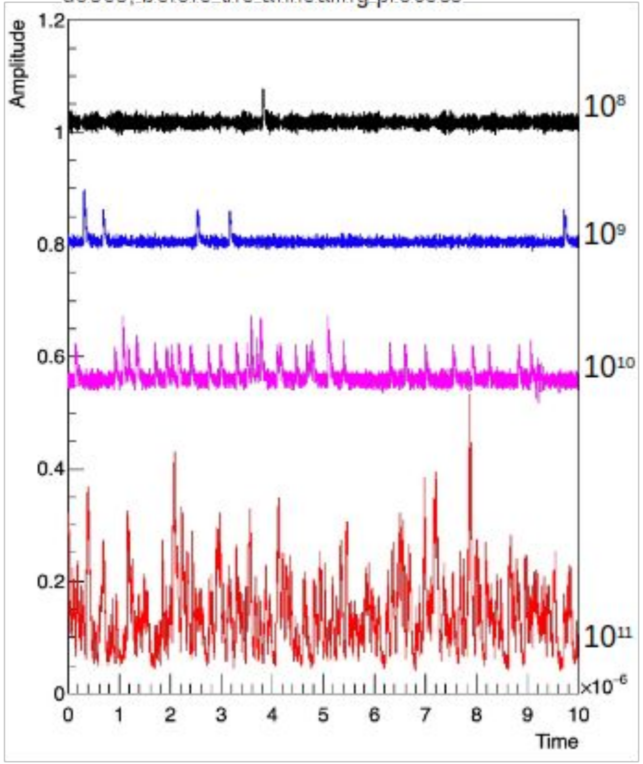


SiPM characterisation @ FE

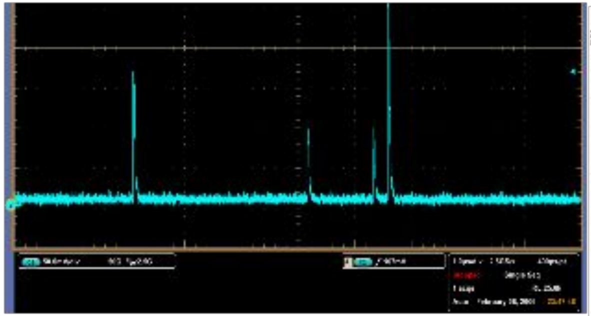


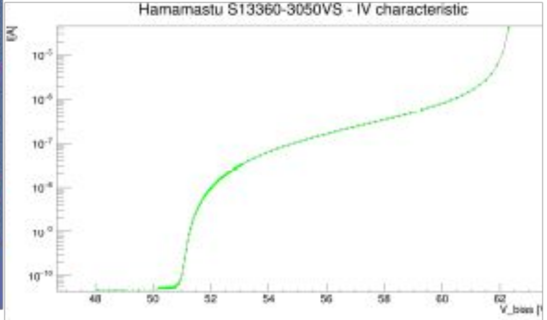


Signals of SiPMs irradiated with different doses, before the annealing process



Not irradiated SiPMs, room temperature, signal and IV characteristic



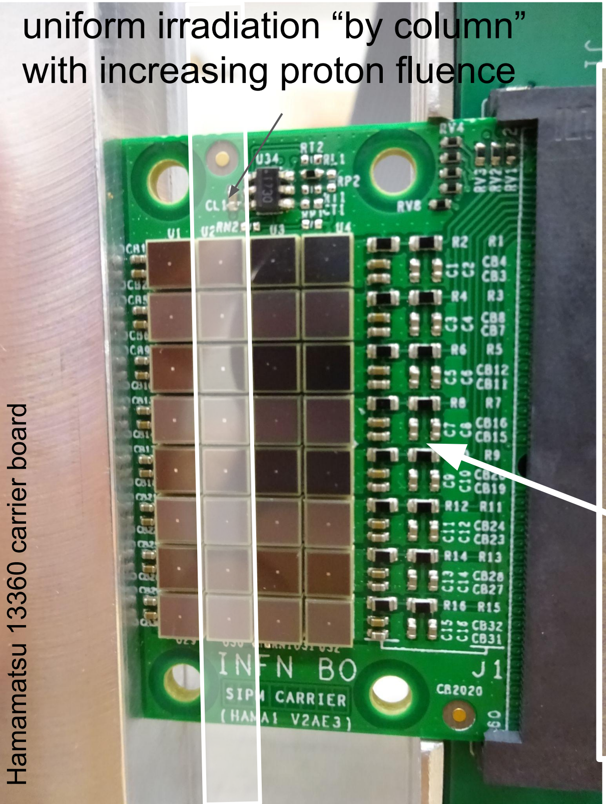


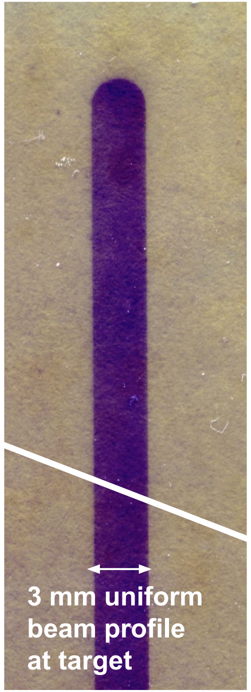
1st irradiation round in May

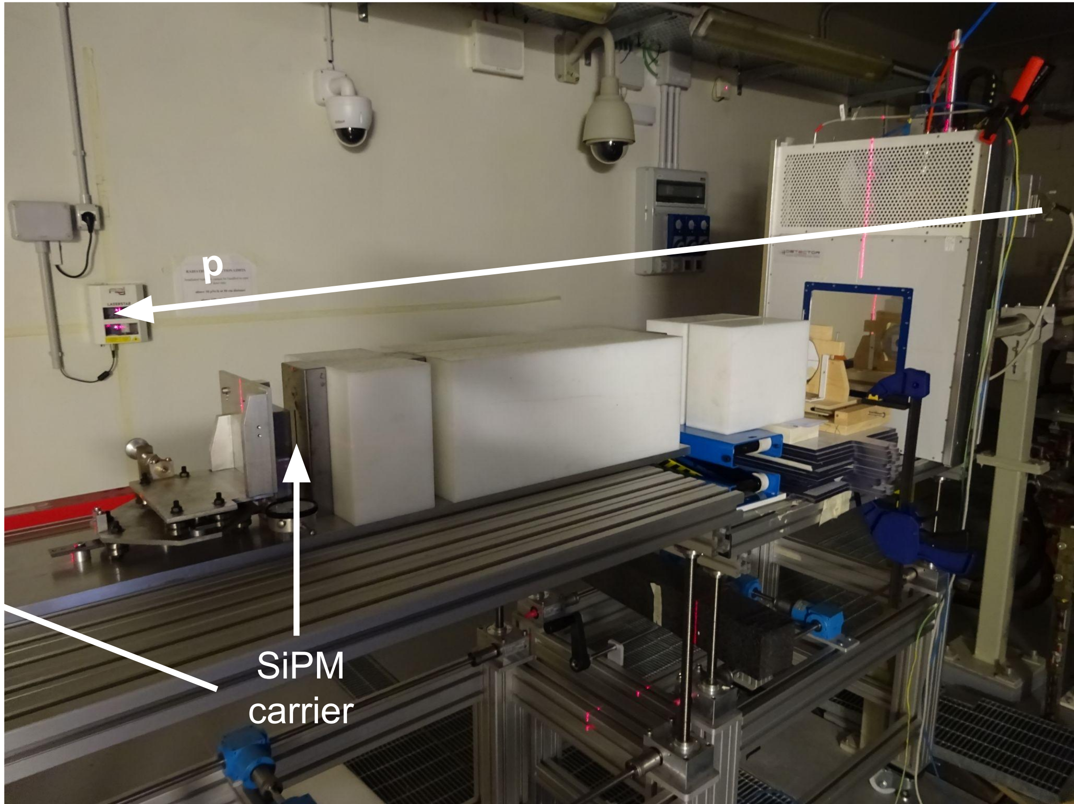
3x3 mm^2 SiPM sensors
4x8 “matrix” (carrier board)

multiple types of SiPM: **Hamamatsu** commercial (13360 and 14160)
FBK prototypes (rad.hard and timing optimised)

148 MeV protons → scattering system → collimation system → carrier board



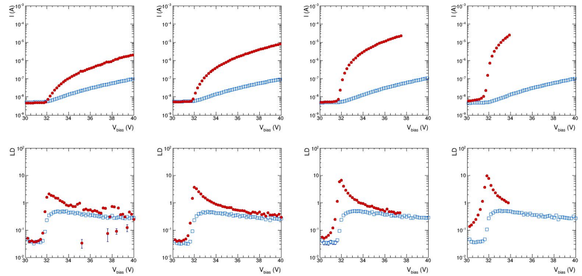


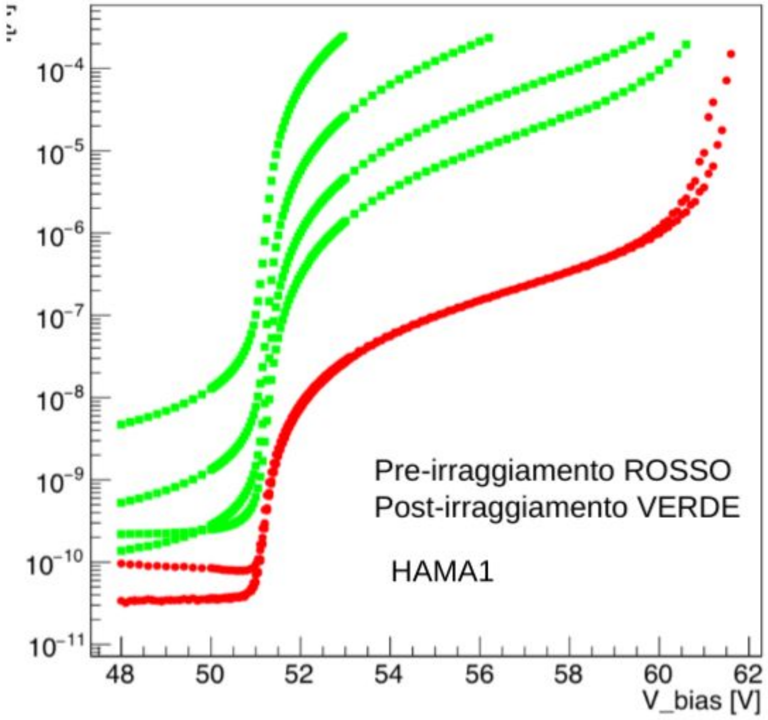


Post-irradiation characterisation

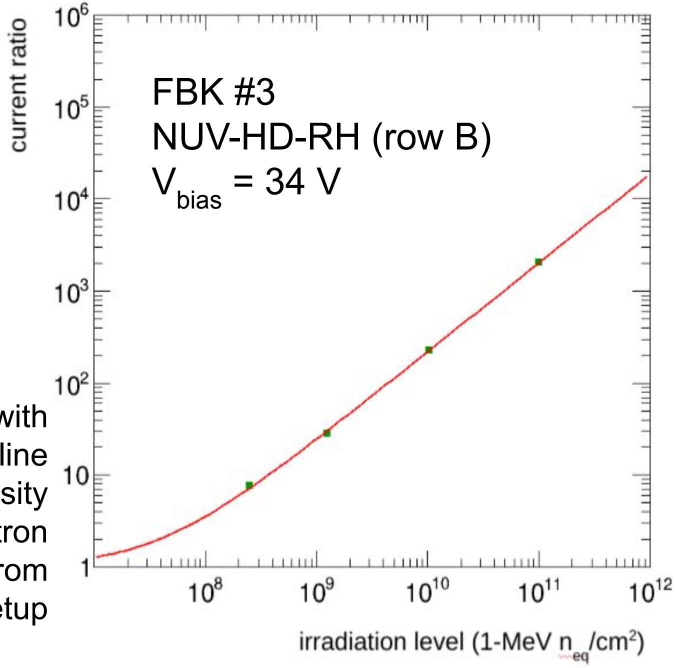
measured also right after irradiation in TIFPA bunker and ~10 days later when TIFPA released the SiPM

after
before

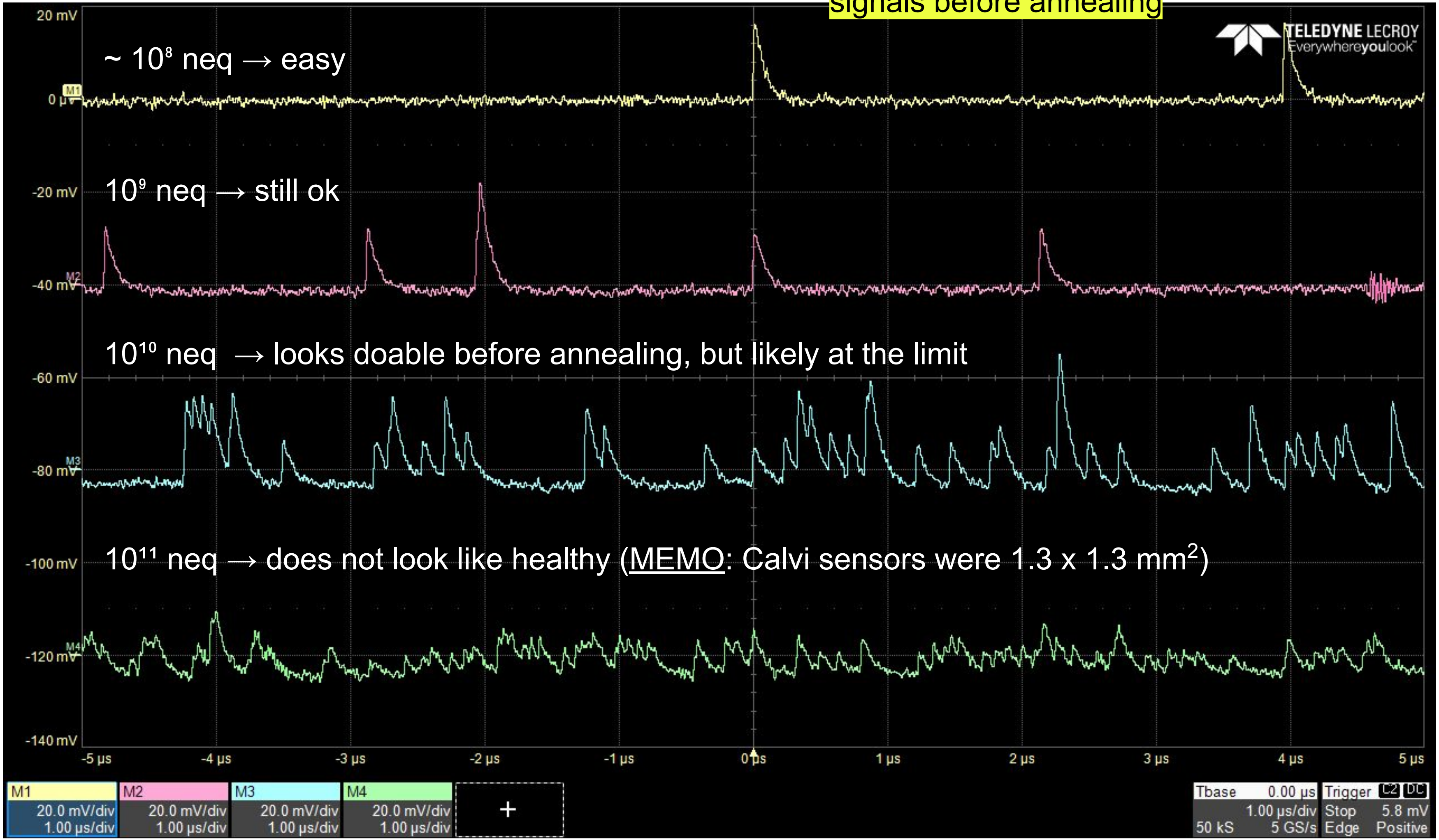




current increases with irradiation level in line with proton intensity calibration + neutron background from simulations of the setup



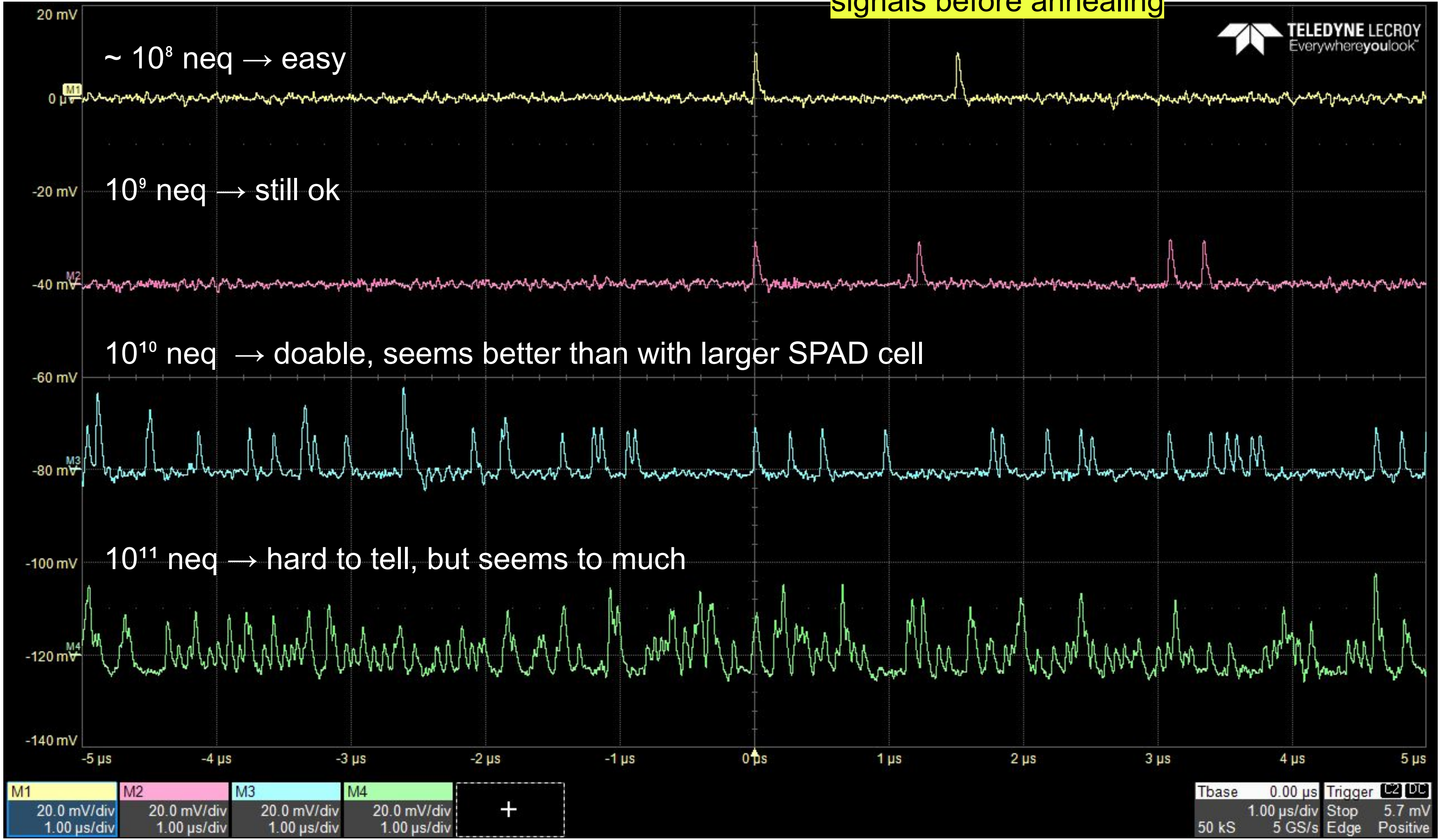
signals before annealing

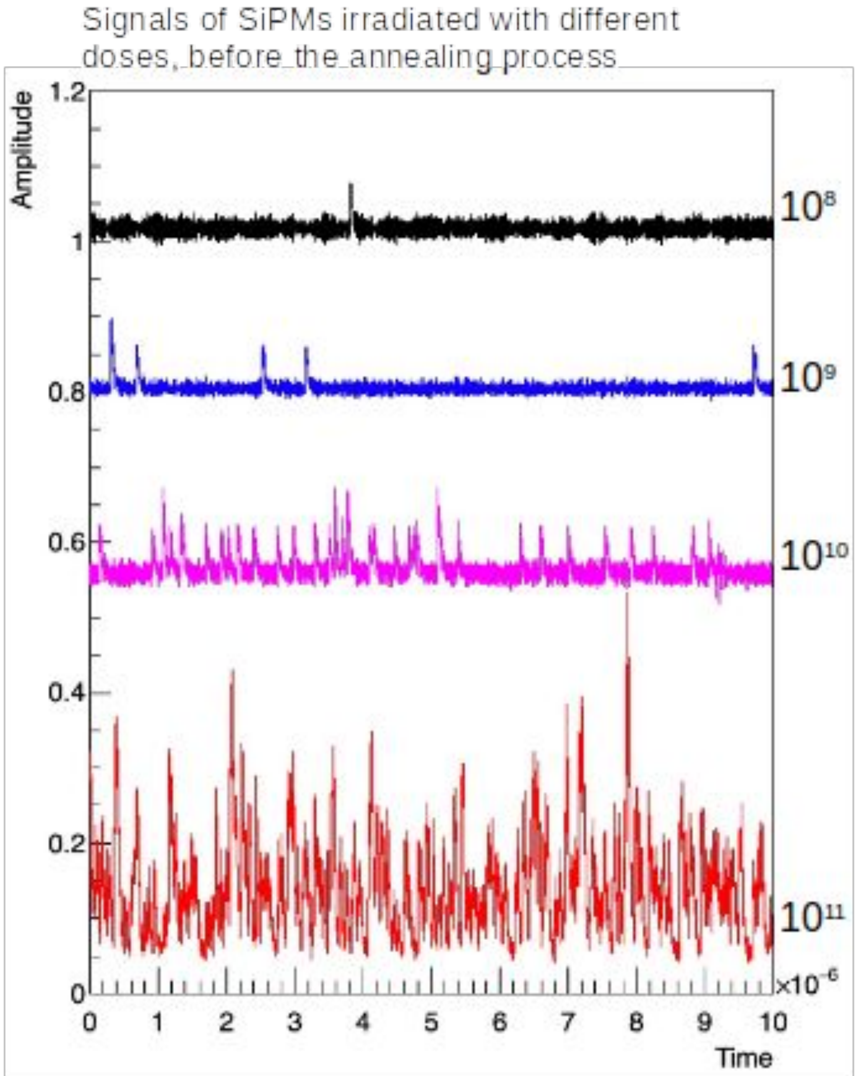


FBK #3 (T = -30 C)
NUV-HD-CHK (row A)

signals before annealing

FBK #3 (T = -30 C)
NUV-HD-RH (row B)

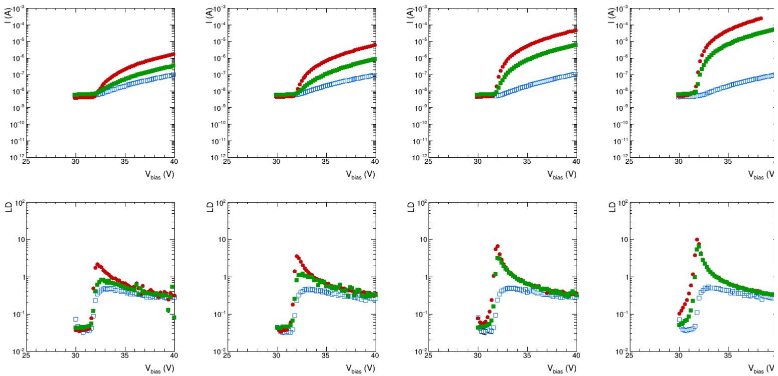


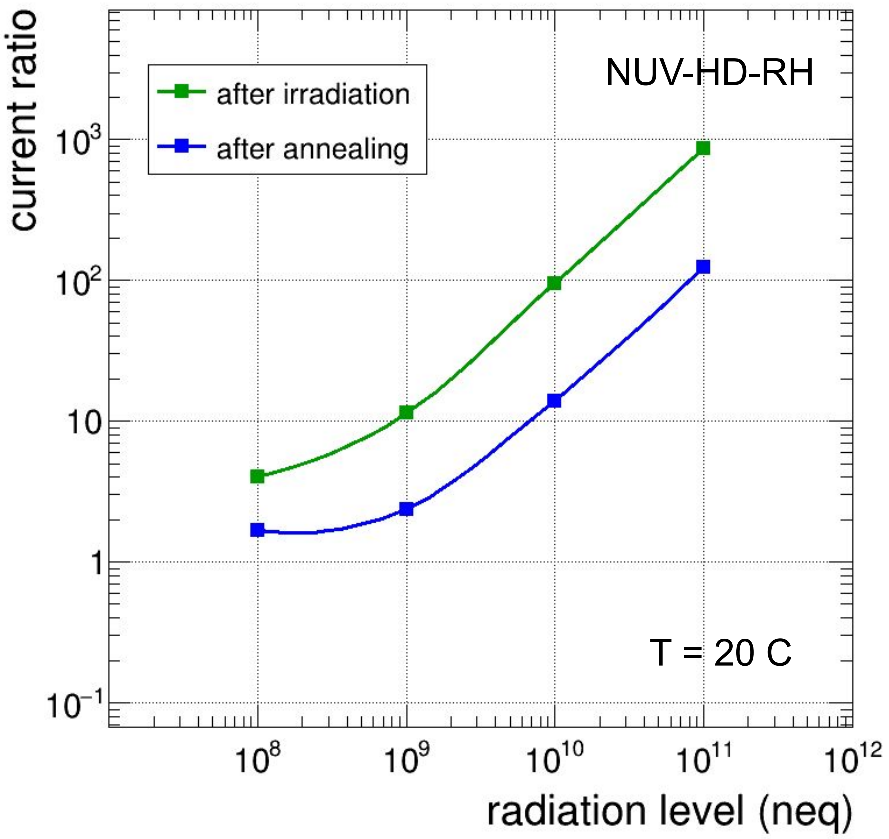


also Hamamatsu sensors seem to be doing ok up to 10^{10} neq

FBK characterisation after 1 week of annealing at T = 125 C

new
irradiated
annealed





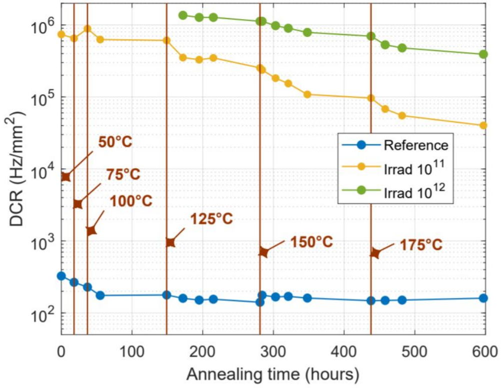
annealing reduced dark current by a factor of ~5-10, in line with expectations

SiPM irradiated up to 10^{11} now behave like if they were irradiated by 10^{10}

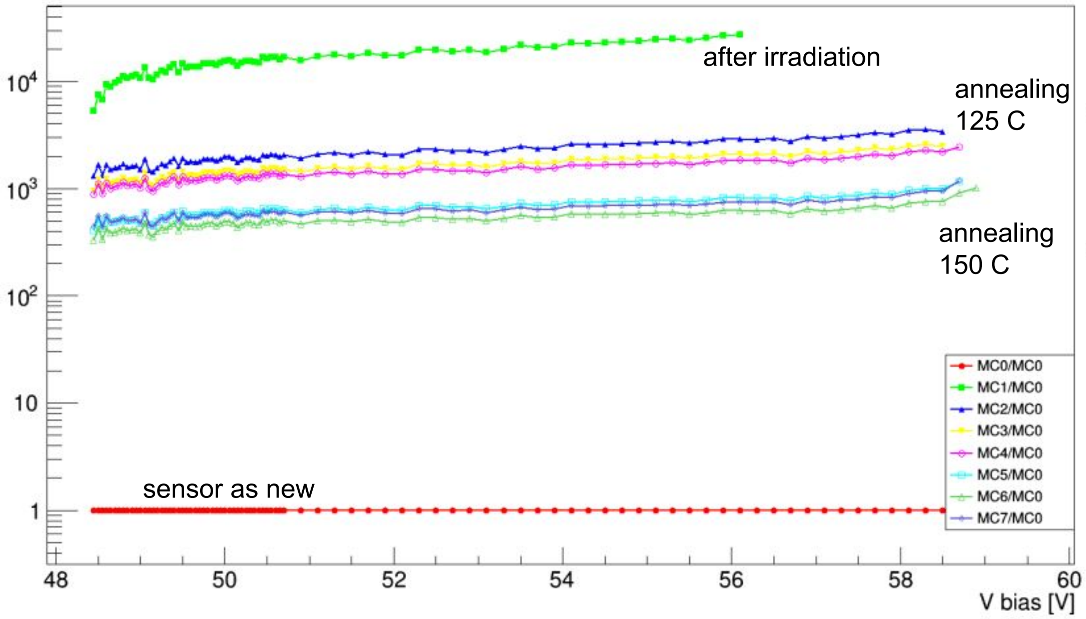
FBK annealing stopped at 125 C at the time
little issue related to the solder paste used during assembly (T = 138 C) did not allow to reach T = 175 C
→ needed reworking of the carrier boards
→ reworked boards back from company a few days ago

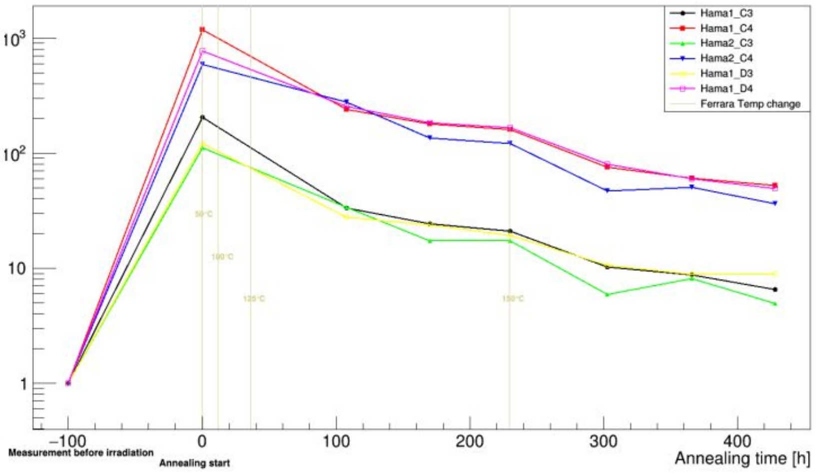
Hamamatsu annealing up to T = 150 C completed

behaviour in line with literature (Calvi et al)



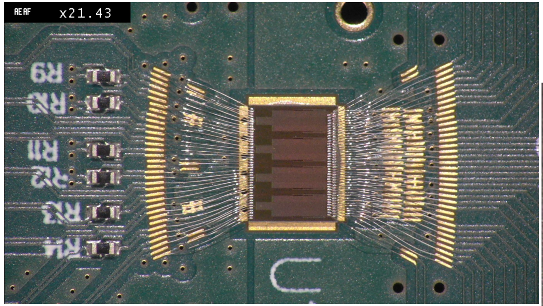
current ratio wrt. before irradiation

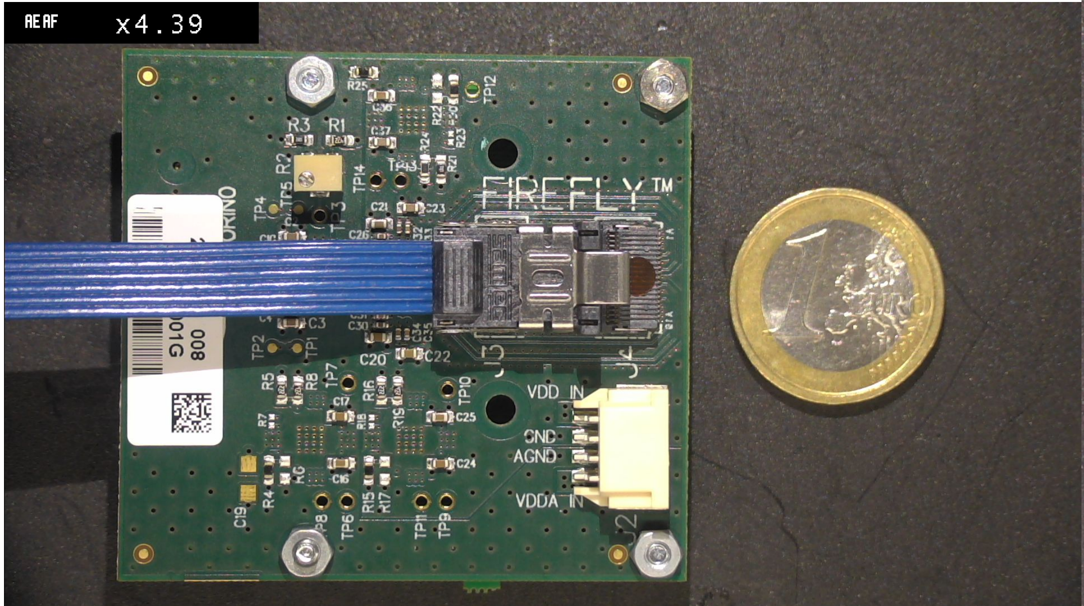




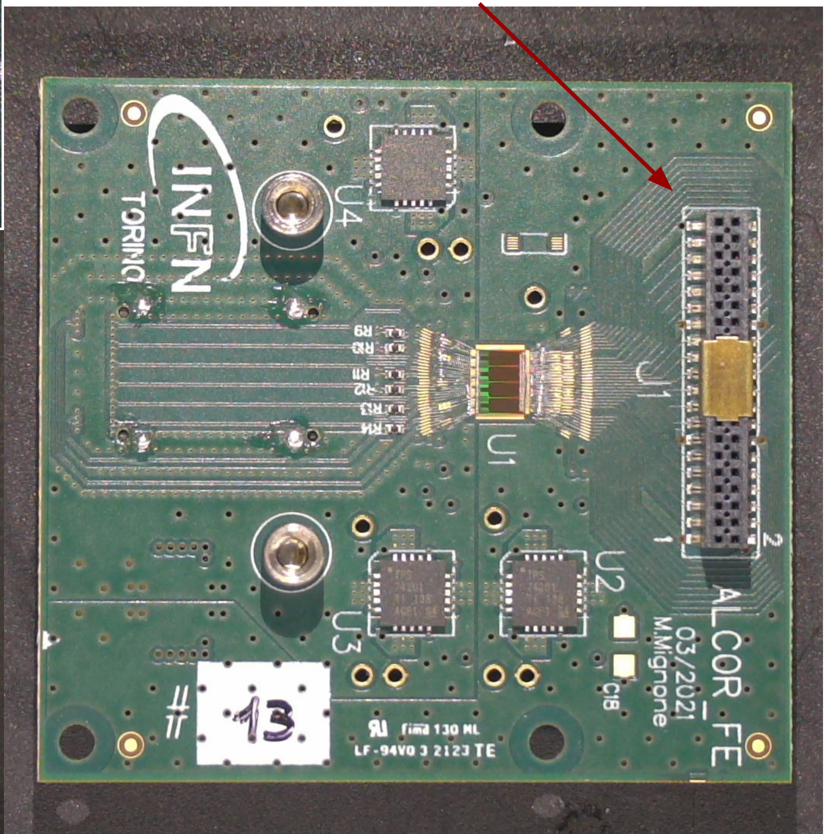
ALCOR – A Low Power Chip for Optical sensor Readout

ALCOR-FE frontend board for testbeam with bonded ALCOR chip and FireFly cable





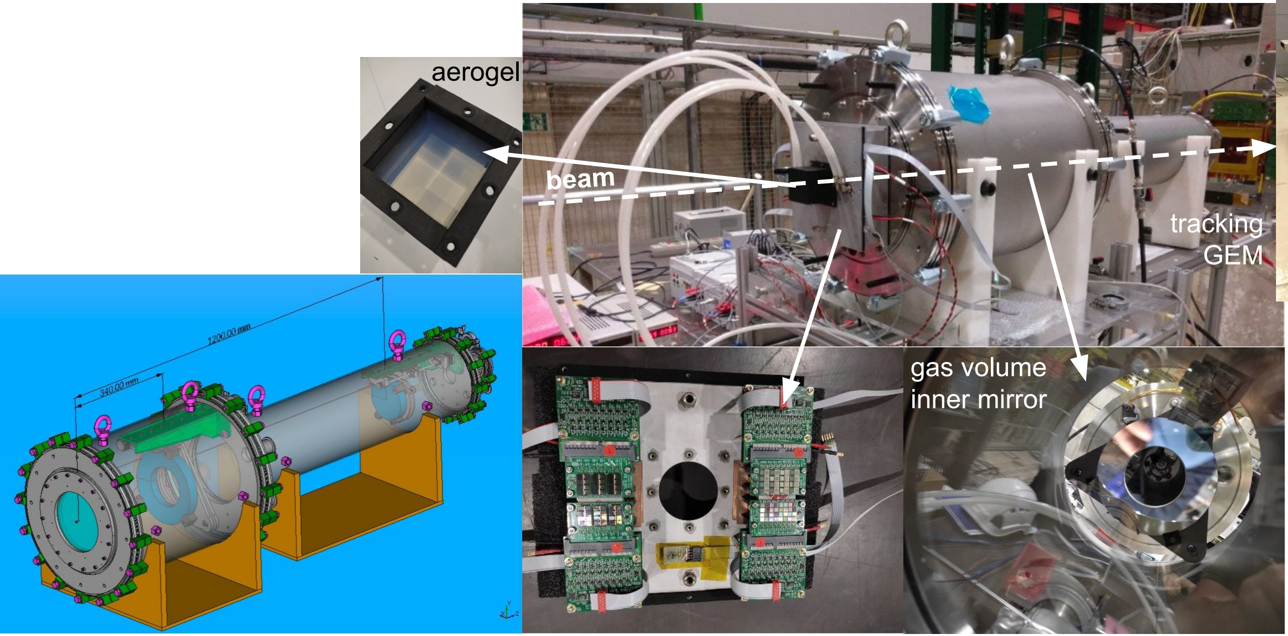
connector to adapter-CA board



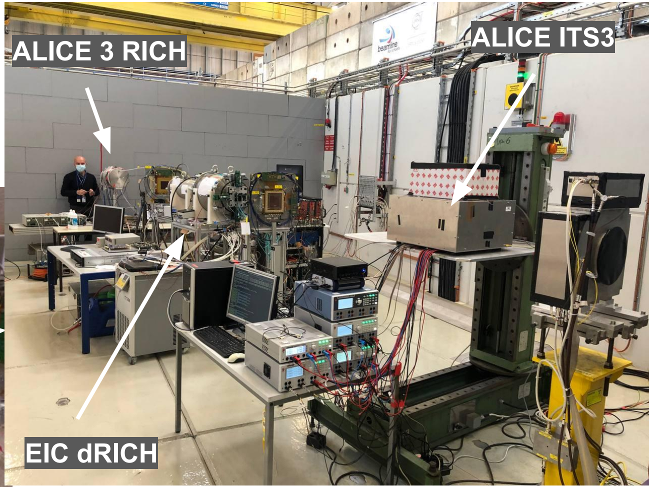
SiPM tested with beams at CERN

first test-beams in September (SPS) and October 2021 (PS, in synergy with ALICE) at CERN

dRICH prototype @ CERN-SPS

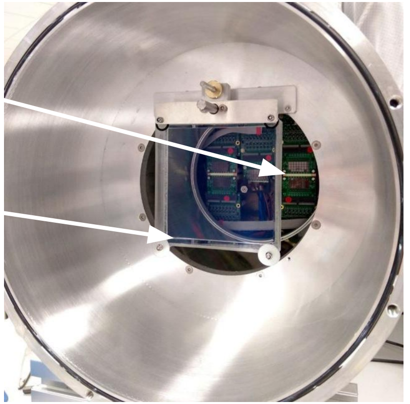


ALICE and EIC at CERN PS T10 October 2021



EIC SiPM with ALCOR readout

ALICE 3 aerogel Chiba sample

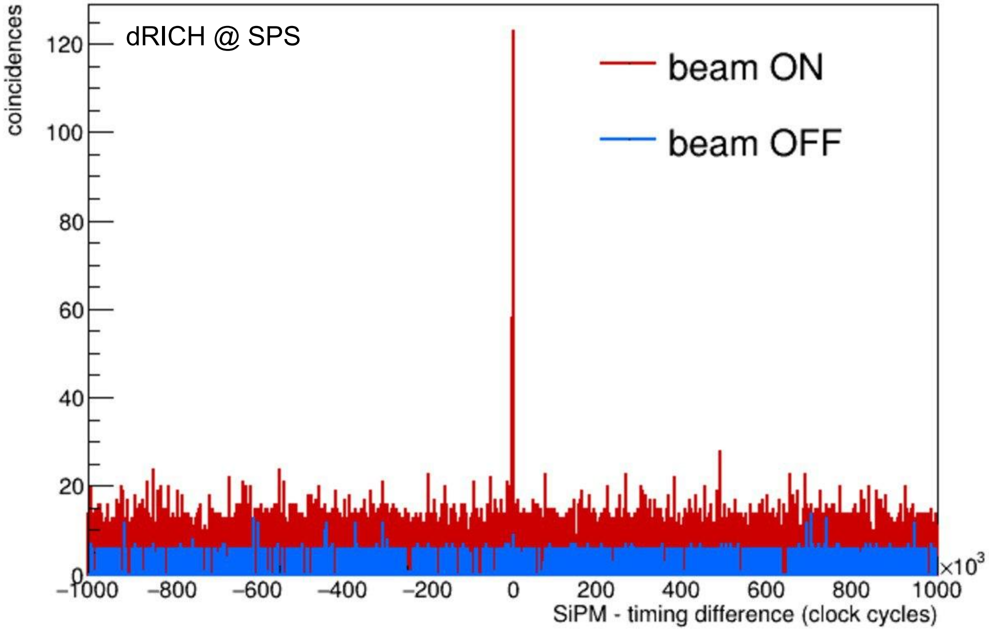


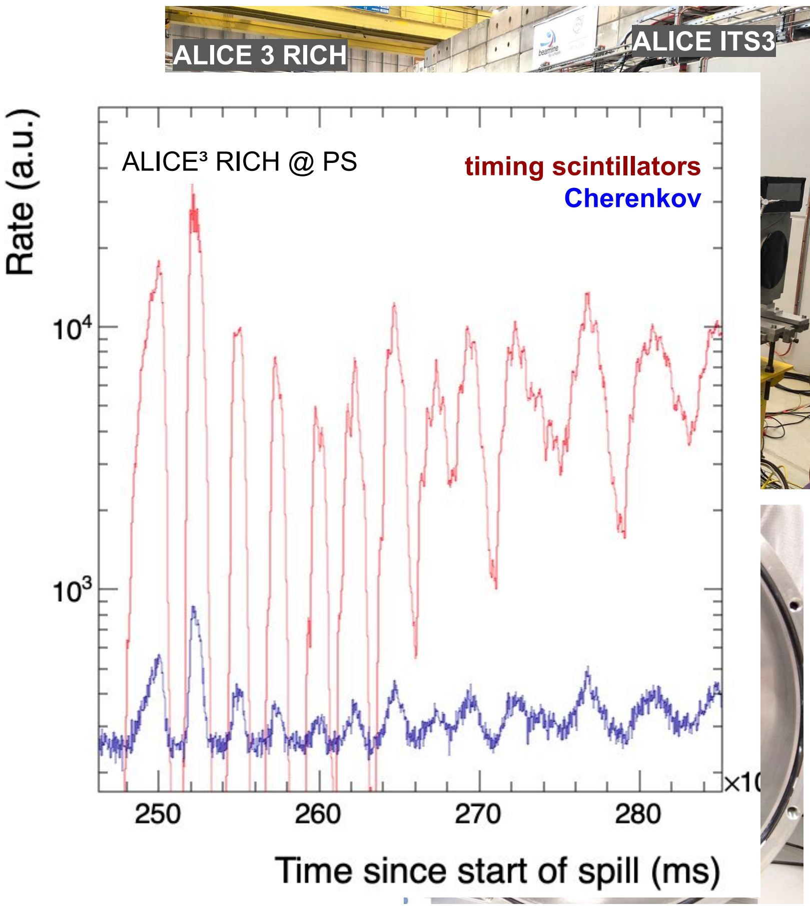
perhaps too optimistic / ambitious for the program of 2021
some troubles with electronics, not really a successful beam test for the SiPM readout
but we have anyway learned something, stay positive for 2022!

SiPM tested with beams at CERN

ALICE and EIC at CERN PS T10 October 2021

first test-beams in September (SPS) and October





signals from SiPM + ALCOR system could be seen

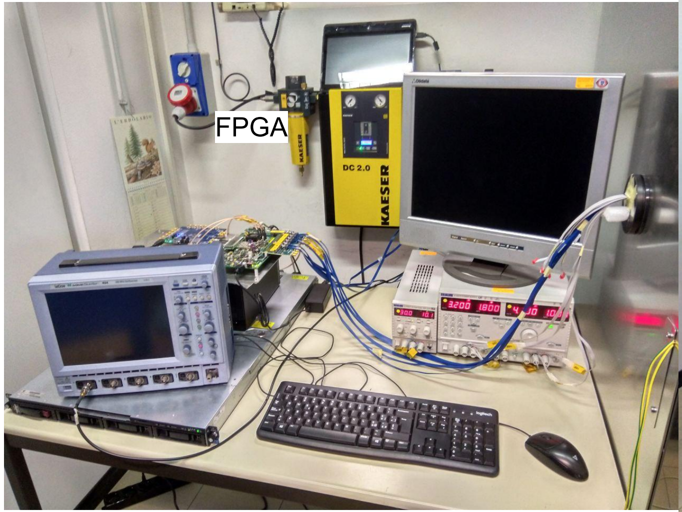
pe

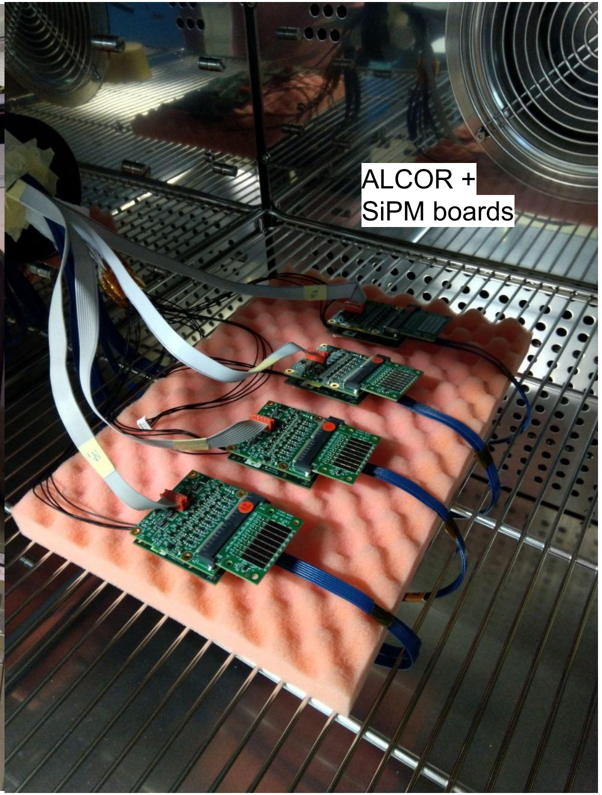
some troubles with electronics, not really a successful beam test for the SiPM readout

but we have anyway learned something, stay positive for 2022!

SiPM+ALCOR setup in Bologna

permanent EIC SiPM setup in the INFN Bologna Silicon Labs
characterisation of performance of SiPM with full (ALCOR) readout system
measure many SiPM in one go!





plan to add laser diode (or LED) soon
illuminate SiPM inside chamber
measure correlation on top of DCR

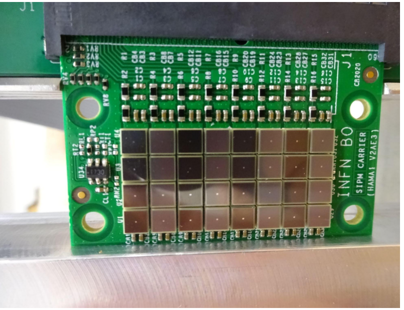
the following results have been obtained with this setup a look into the operation of a complete SiPM readout

Hamamatsu (HAMA1 #1) threshold scans

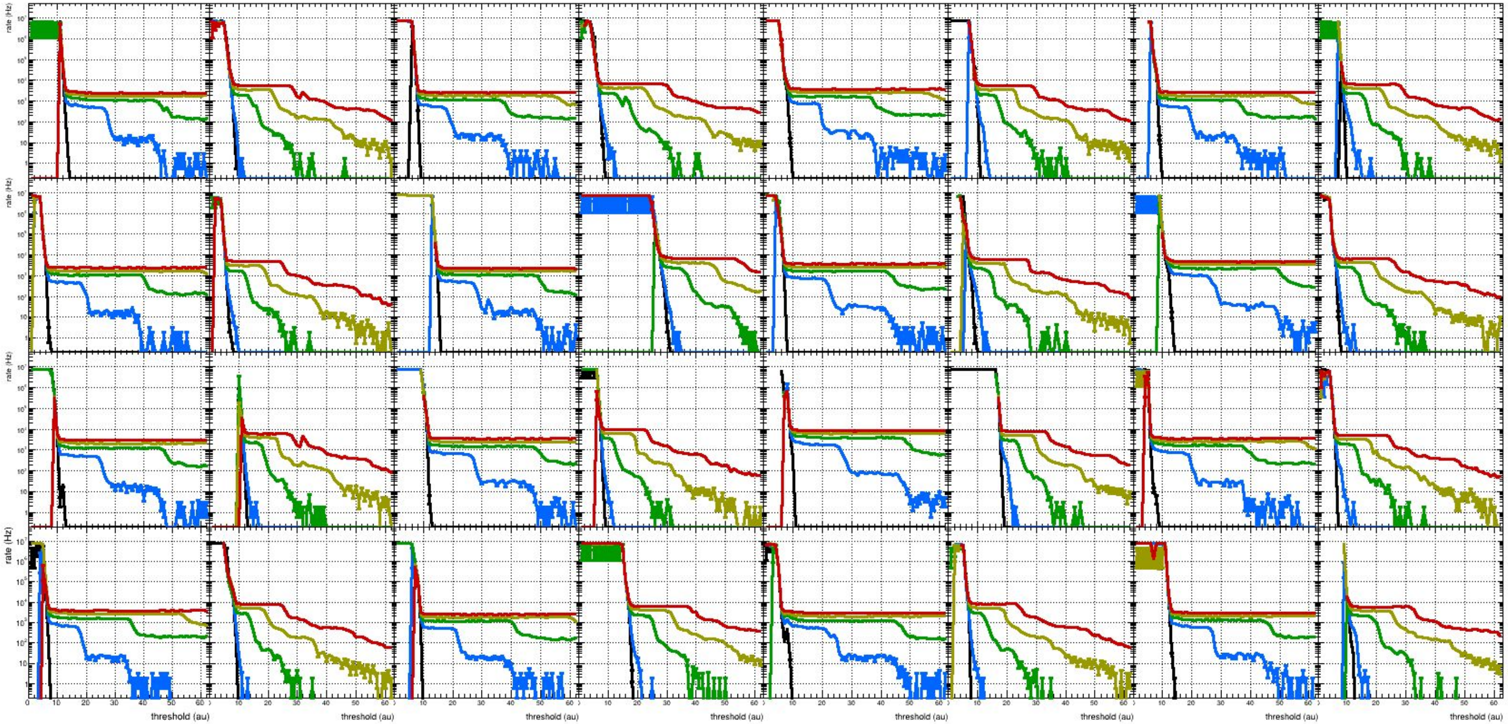
PRELIMINARY

T = -30 C

not irradiated board



13360-3050 13360-3025



Vbias (V)
48 50 52 54 56

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Hamamatsu (HAMA1 #2) threshold scans

PRELIMINARY

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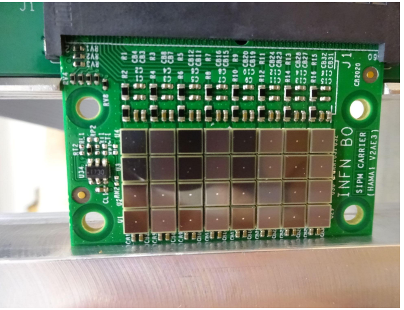

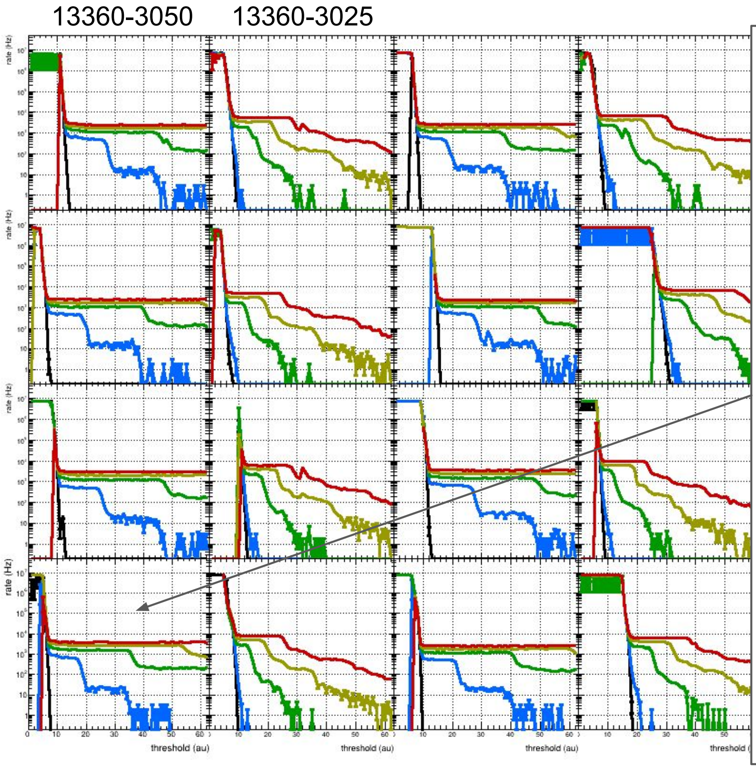

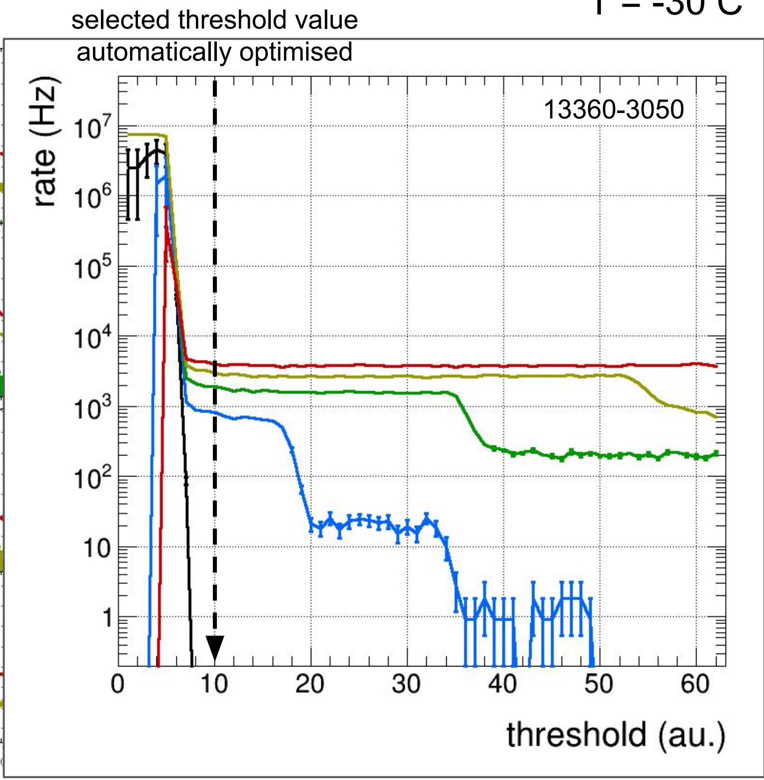

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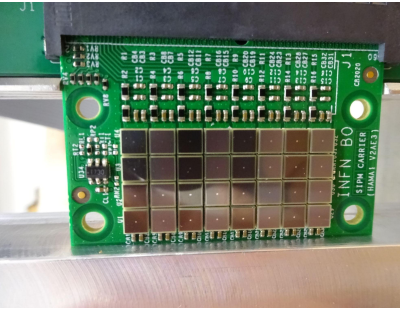
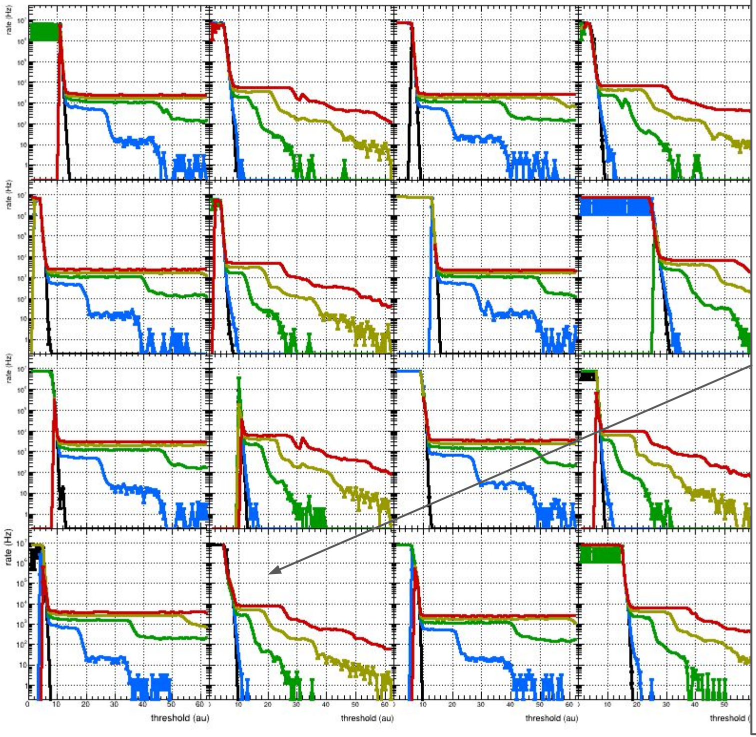
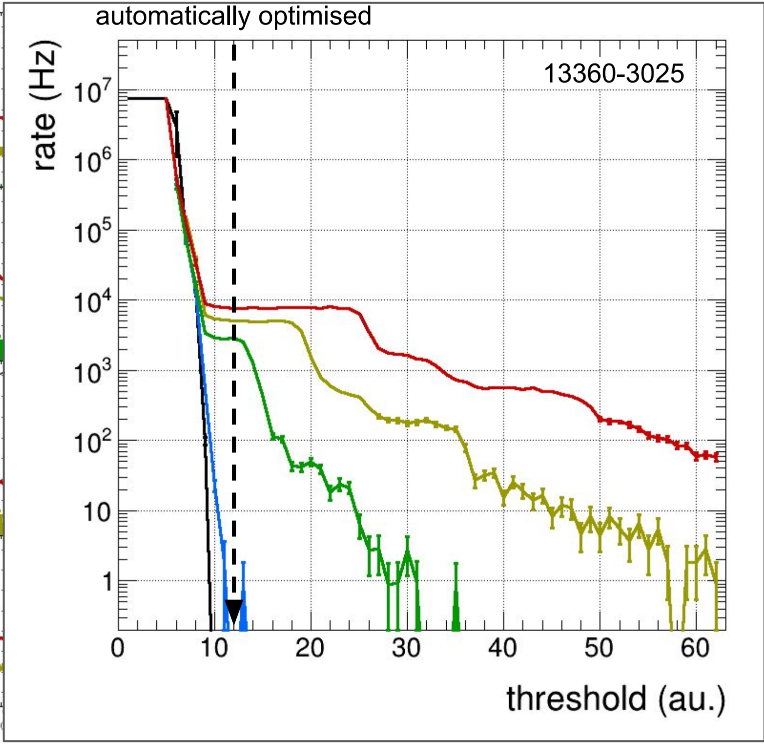




selected threshold value automatically optimised



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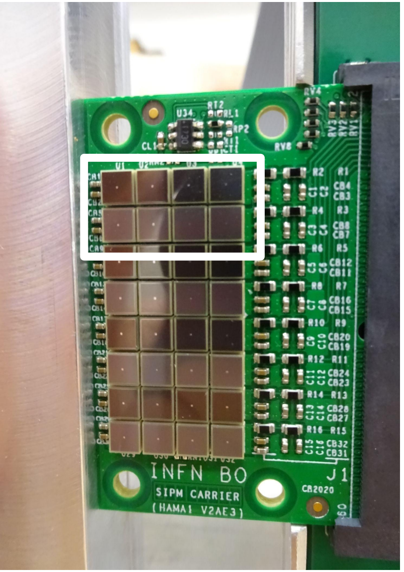

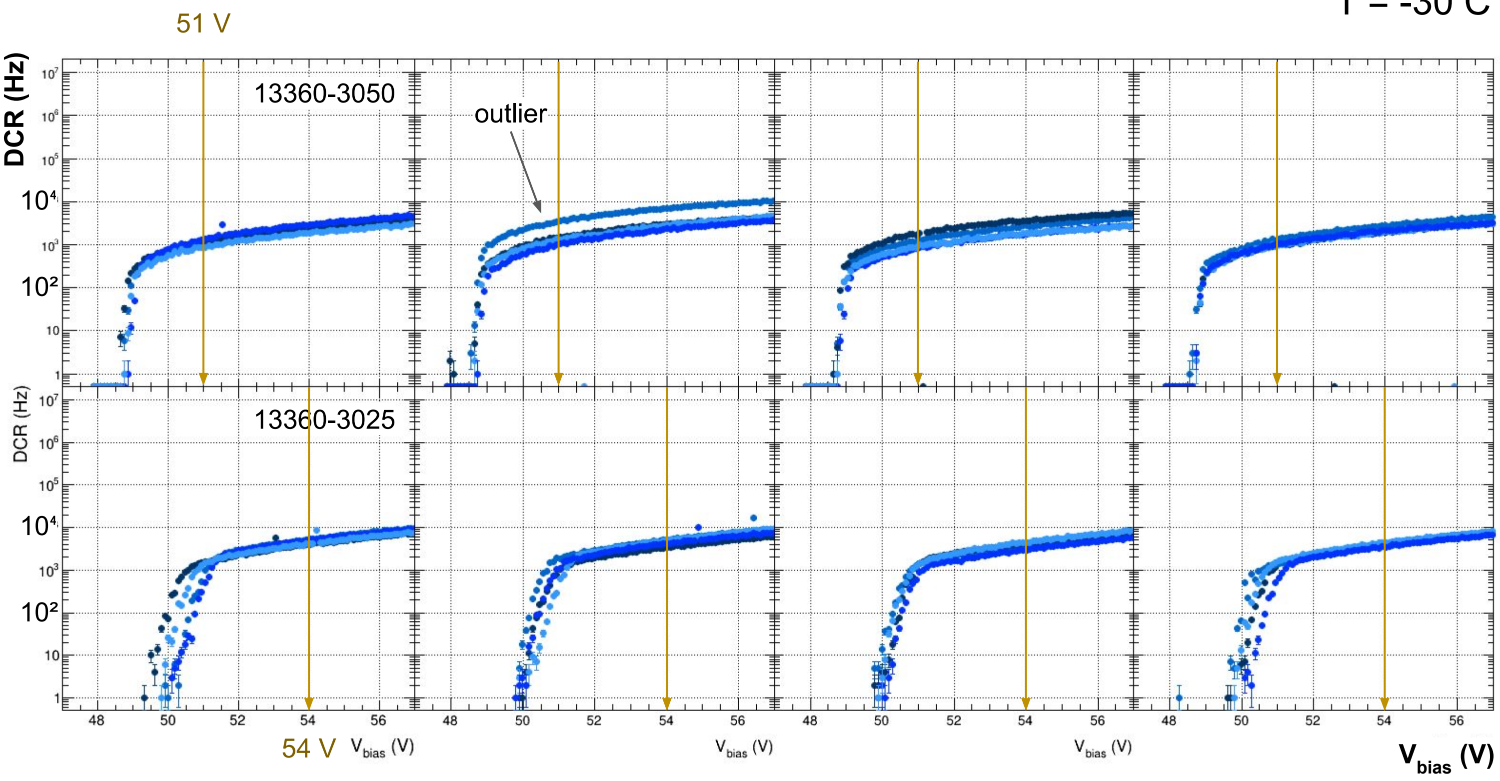

very uniform performance (besides one outlier) when signal above threshold

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Hamamatsu (HAMA1 #1) Vbias scans

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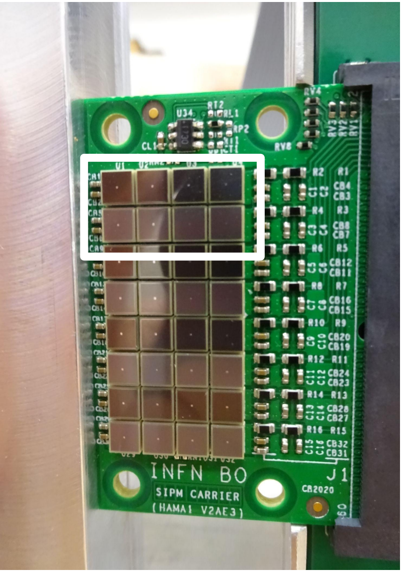

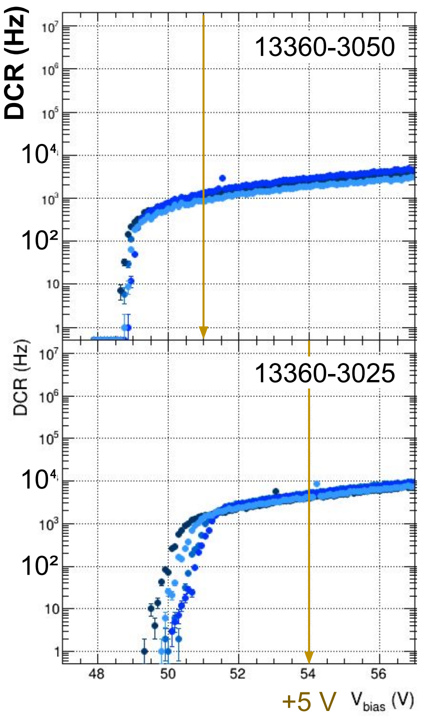

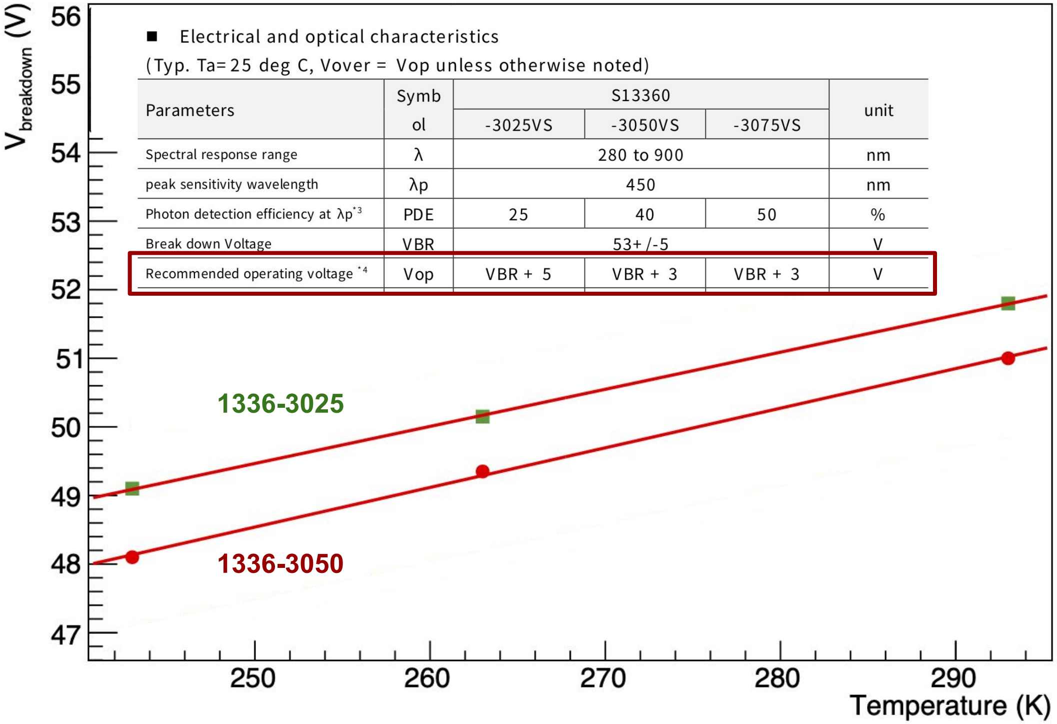

■ Electrical and optical characteristics

(Typ. Ta= 25 deg C, Vover = Vop unless otherwise noted)

Parameters	Symbol	S13360			unit
		-3025VS	-3050VS	-3075VS	
Spectral response range	λ	280 to 900			nm
peak sensitivity wavelength	λp	450			nm
Photon detection efficiency at λp*3	PDE	25	40	50	%
Break down Voltage	VBR	53+/-5			V
Recommended operating voltage *4	Vop	VBR + 5	VBR + 3	VBR + 3	V

very uniform performance (besides one outlier) when signal above threshold

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Hamamatsu (HAMA1 #1) Vbias scans

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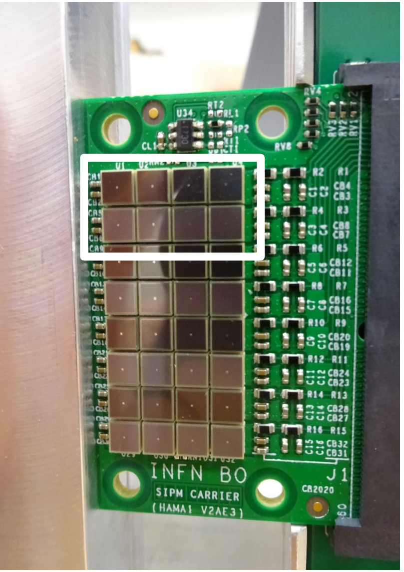
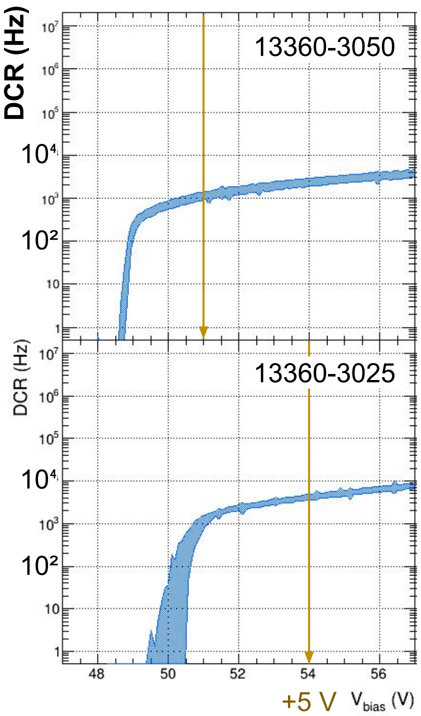
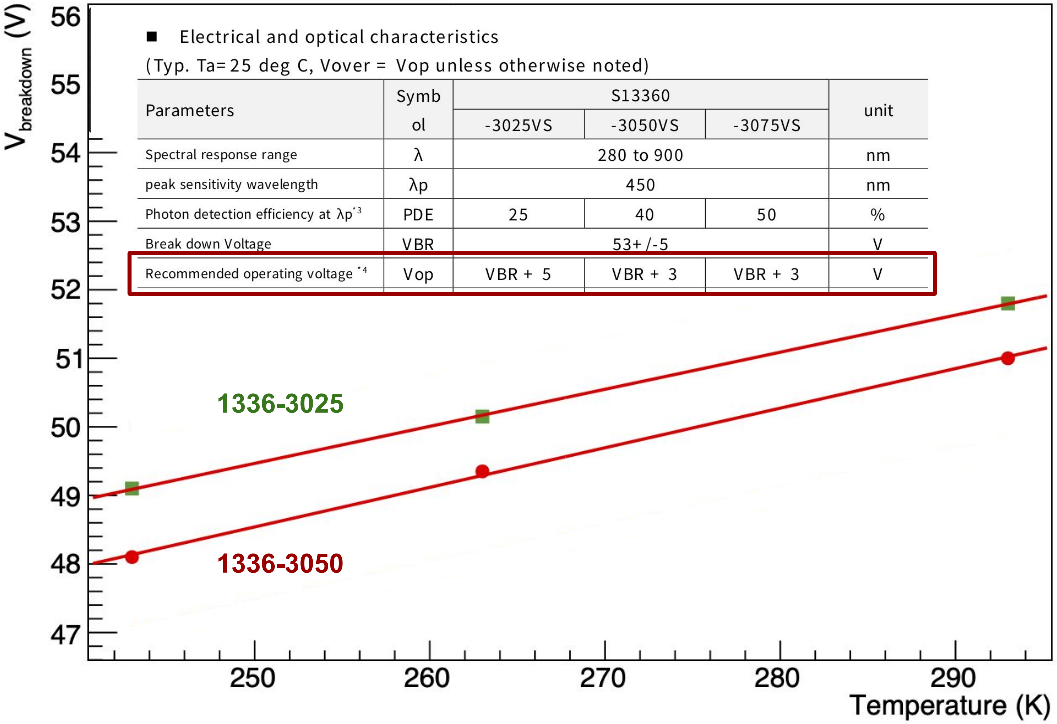


51 V





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Recommended operating voltage [*4]	Vop	VBR + 5	VBR + 3	VBR + 3	V

average of the various SiPM sensors, band indicates ± RMS

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Hamamatsu (HAMA1 #2) threshold scans

PRELIMINARY

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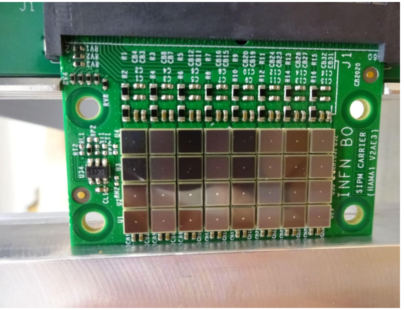
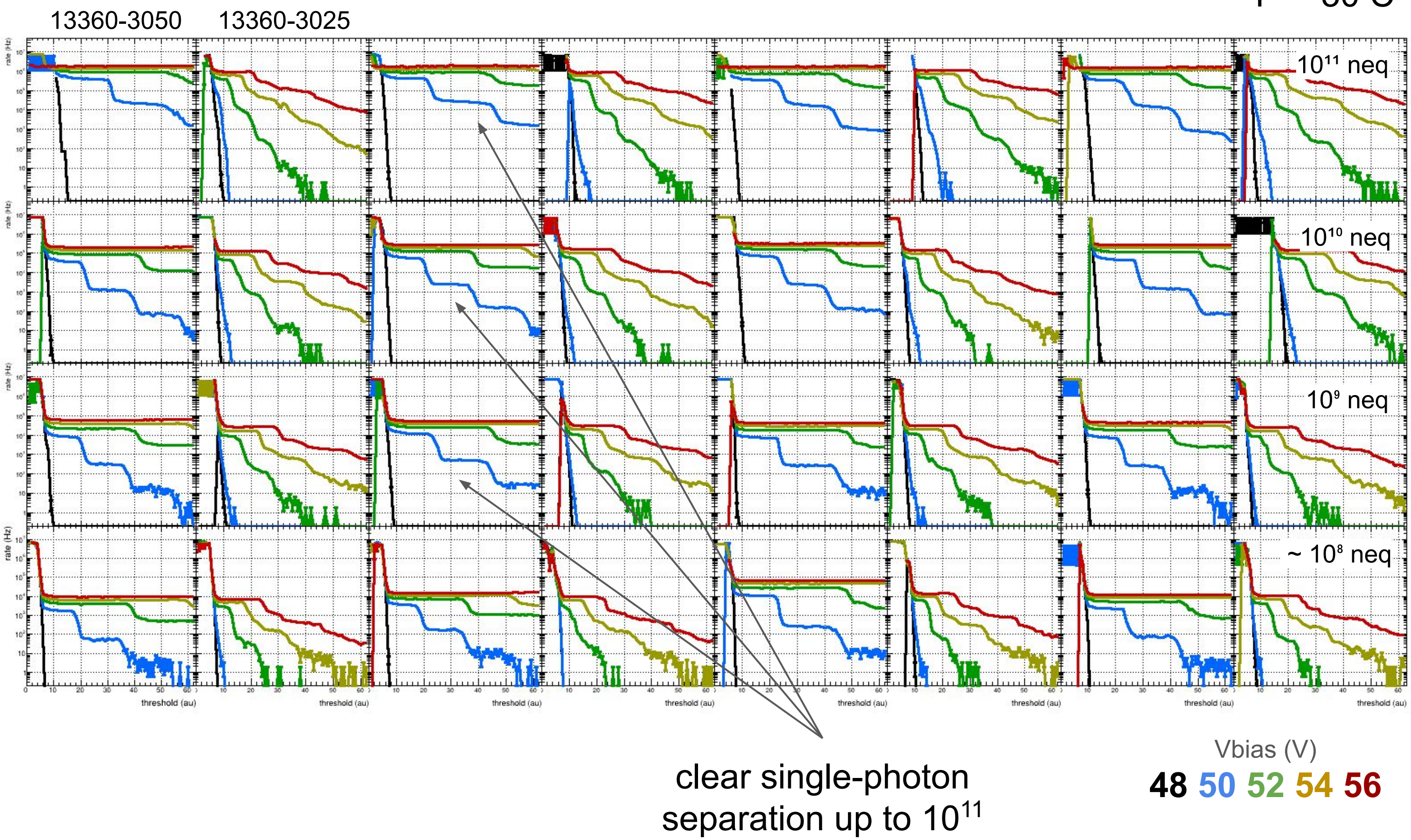


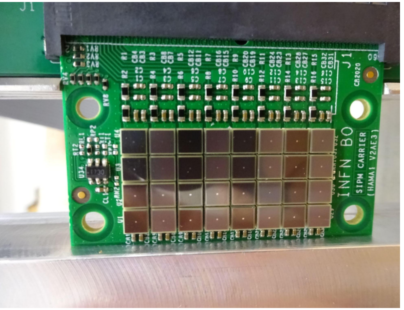
irradiated board after annealing

still working!



Hamamatsu (HAMA1 #2) threshold scans

T = -30 C



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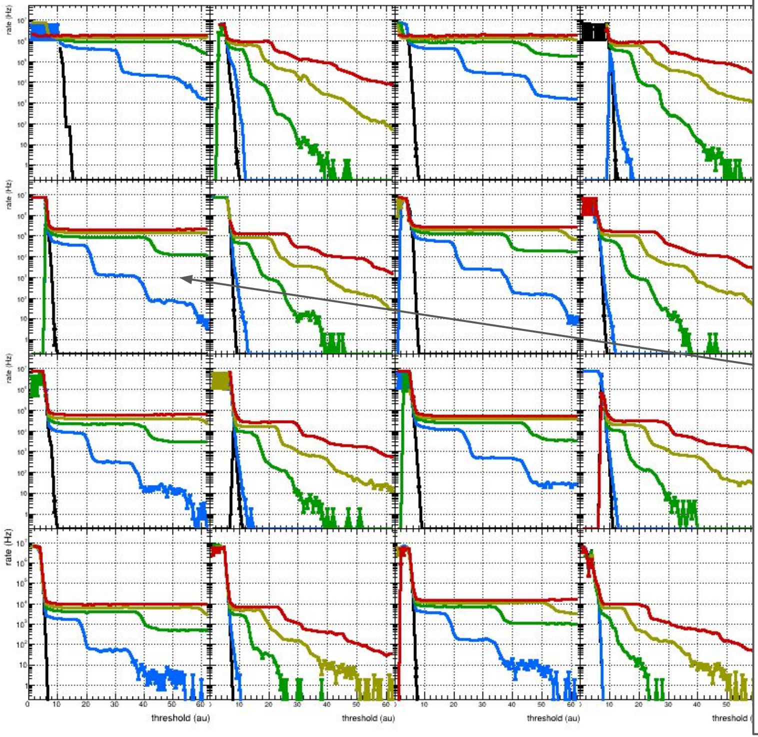
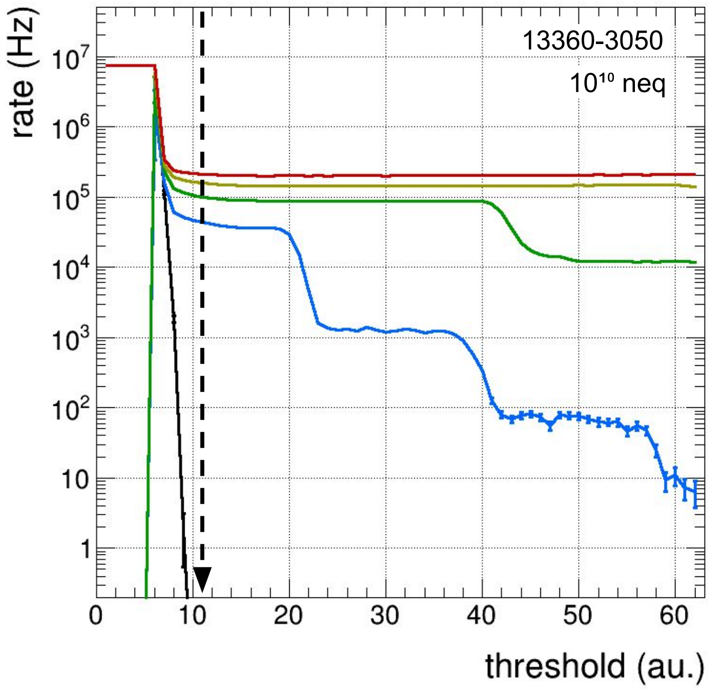


selected threshold value automatically optimised



Vbias (V)

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Hamamatsu (HAMA1 #2) threshold scans

PRELIMINARY

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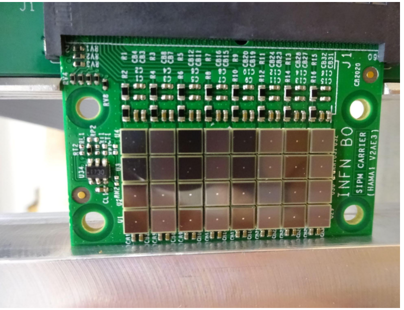

irradiated board after annealing

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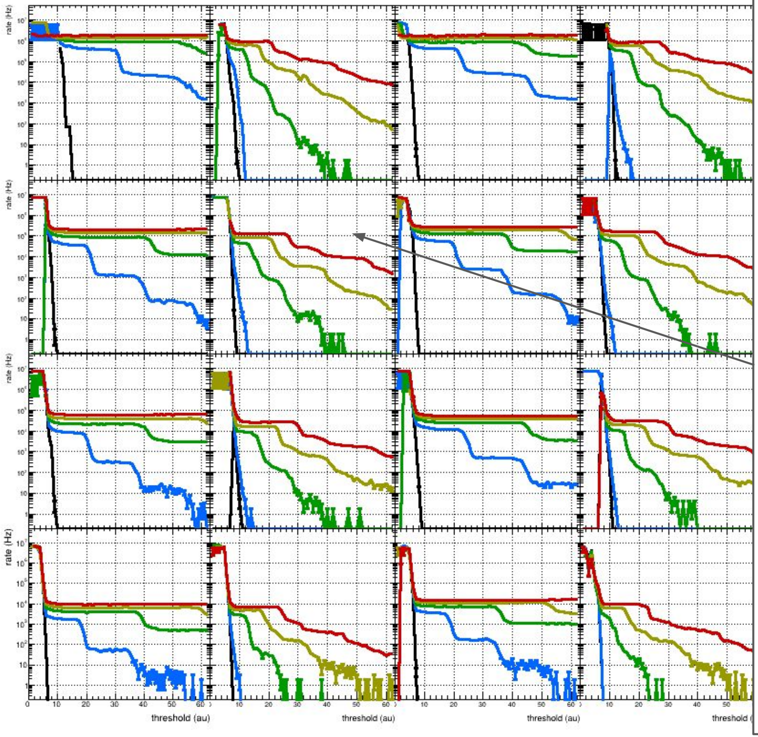
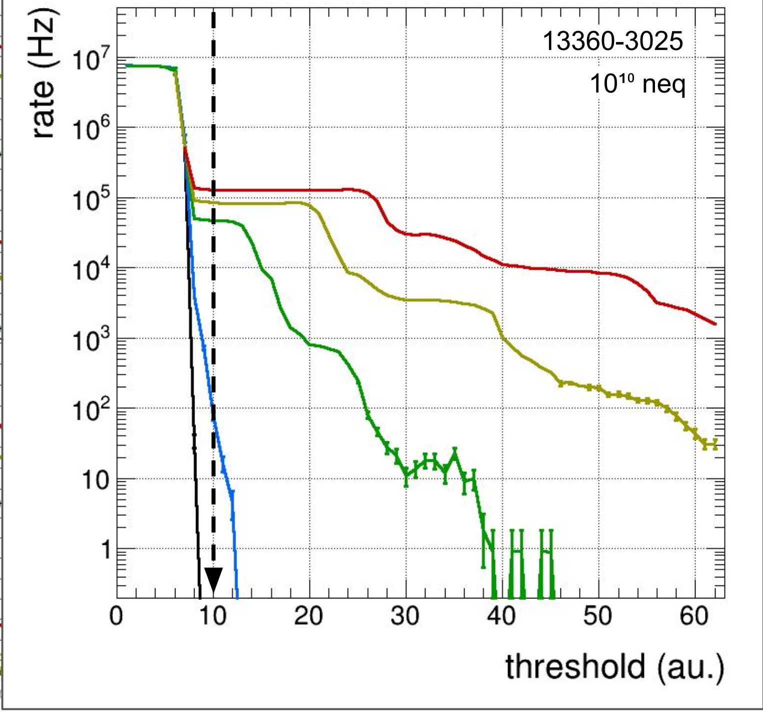
13360-3050 13360-3025



selected threshold value
automatically optimised



Vbias (V)

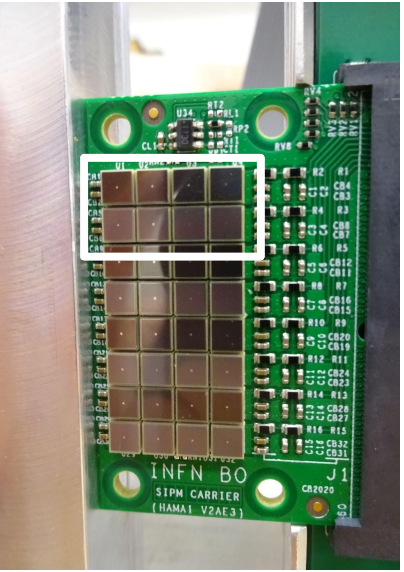
48 50 52 54 56

let’s look into the irradiated board

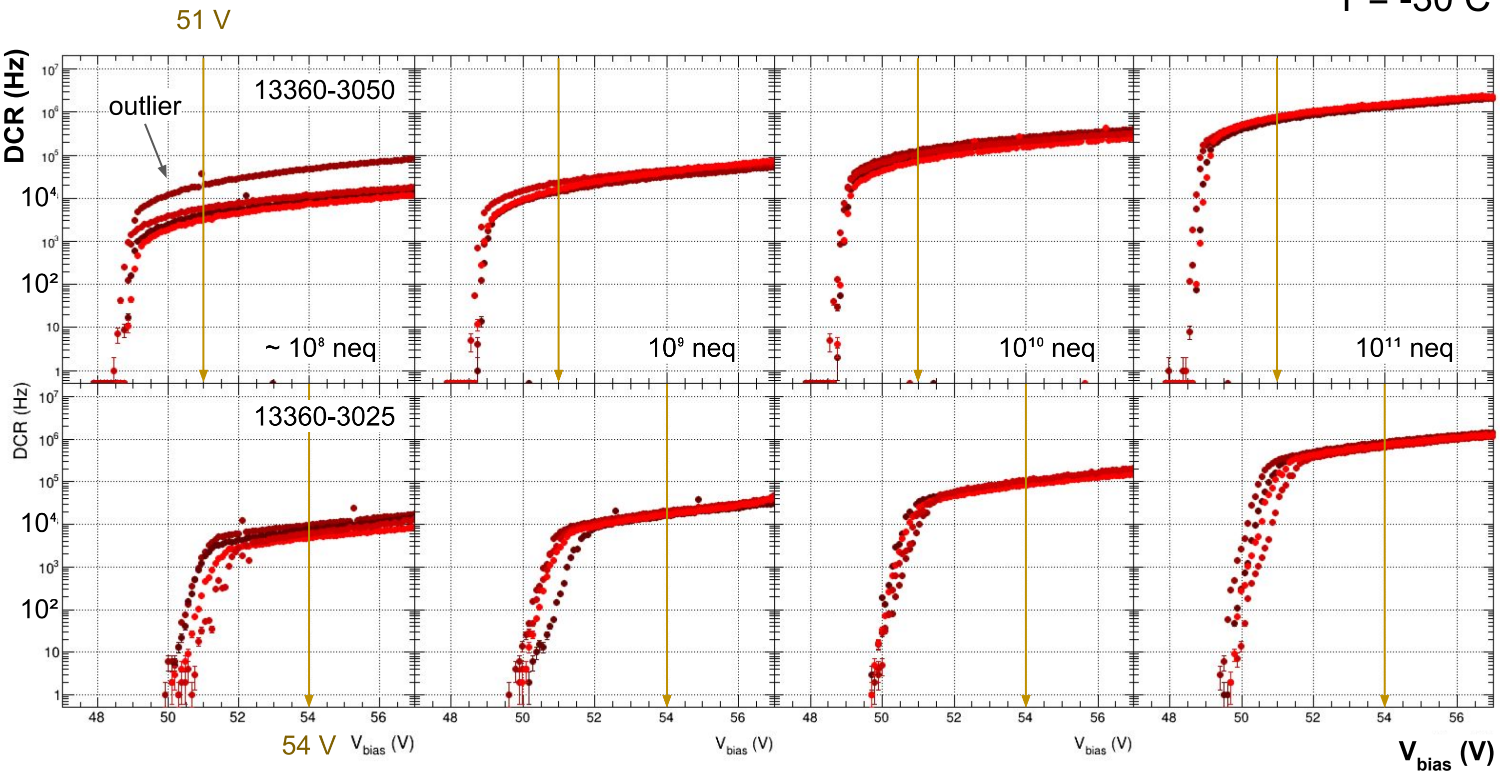
Hamamatsu (HAMA1 #2) Vbias scans

PRELIMINARY

T = -30 C



irradiated board after annealing



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Hamamatsu (HAMA1 #2) Vbias scans

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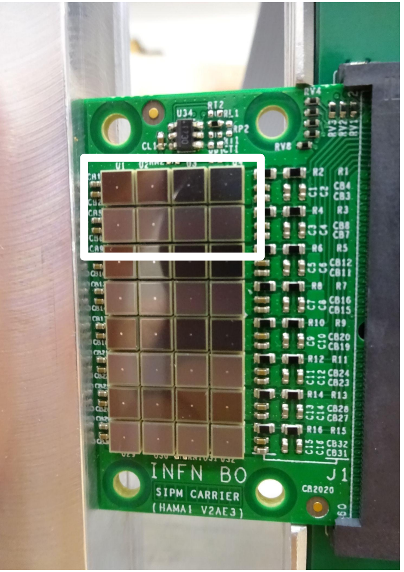

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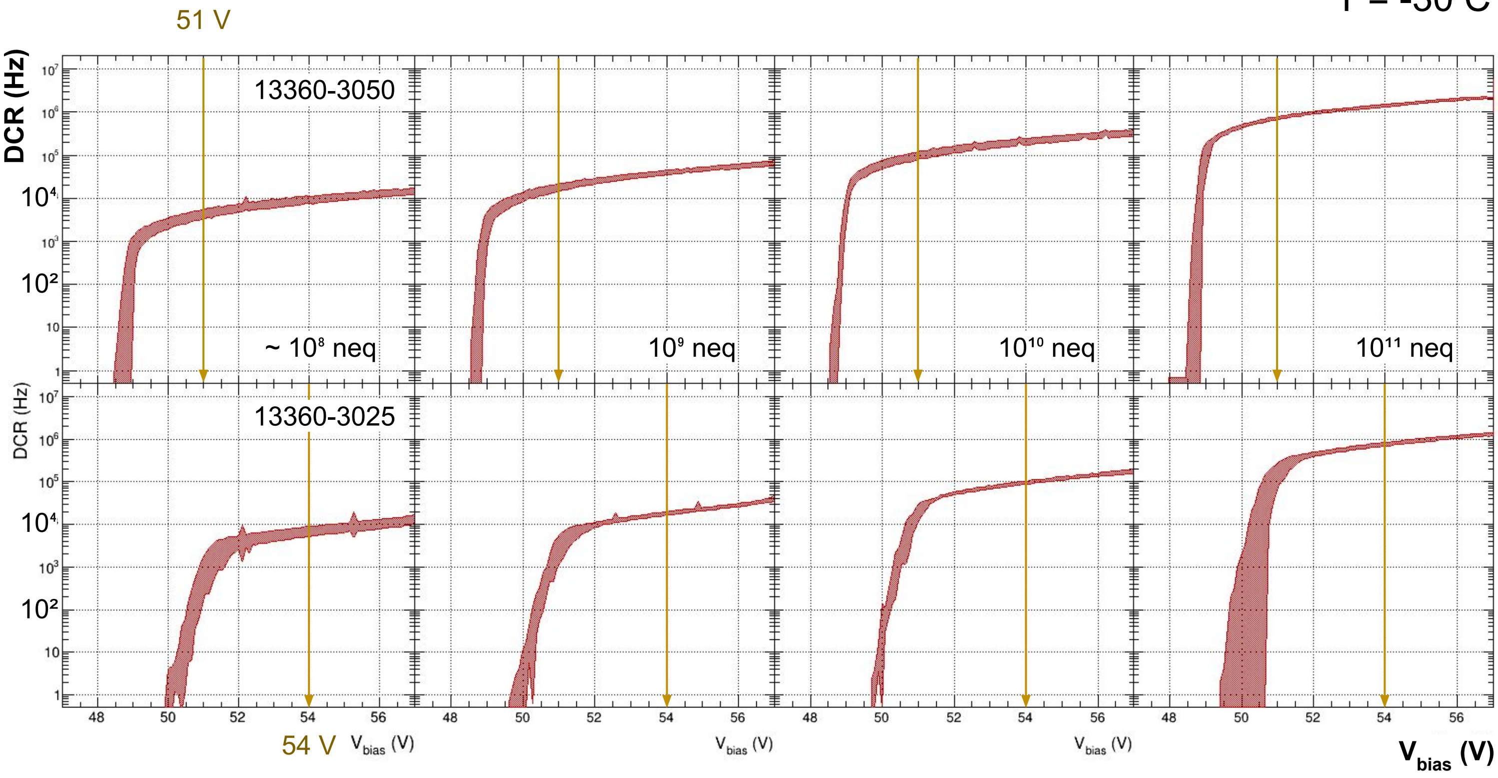

average of the various SiPM sensors, band indicates ± RMS

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Hamamatsu (HAMA1) grand comparison

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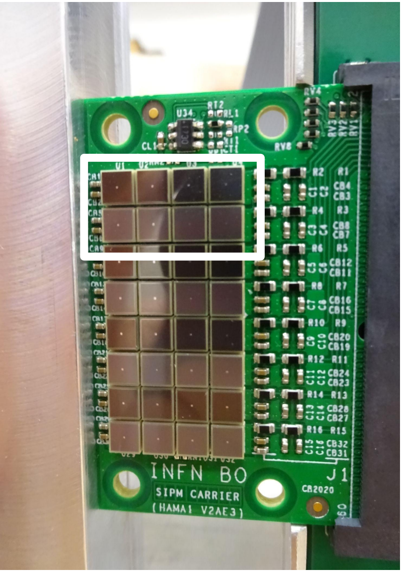
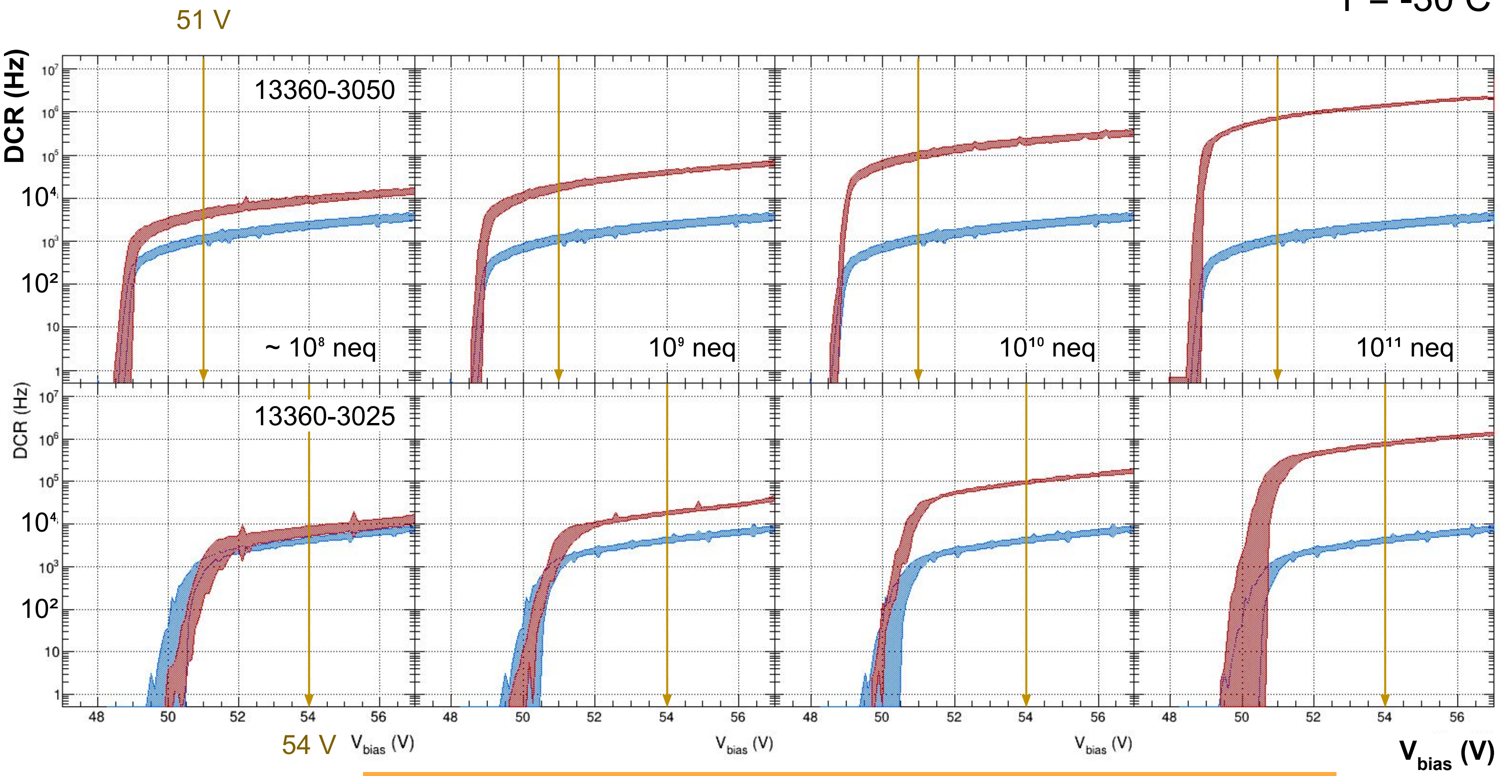


irradiated board after annealing



values at the indicated Vbias	new	~ 10^8 neq	10^9 neq	10^{10} neq	10^{11} neq
13360-3050	1.1 kHz	4.4 kHz	18 kHz	100 kHz	730 kHz
13360-3025	2.4 kHz	7.0 kHz	18 kHz	95 kHz	770 kHz

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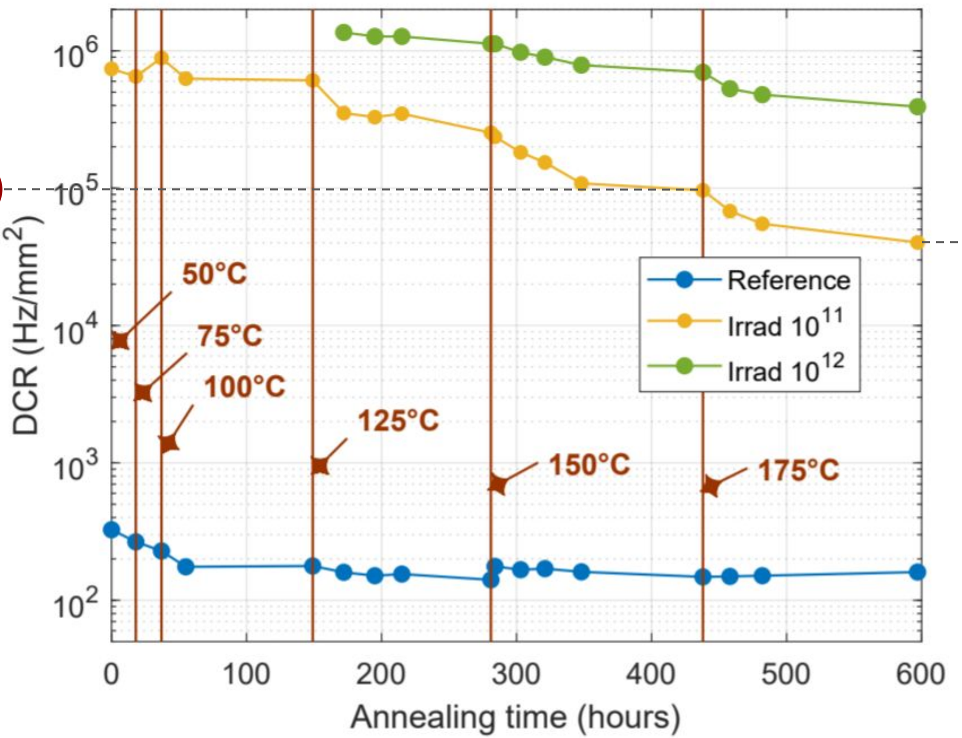
Hamamatsu (HAMA1) grand comparison

measured ~ 750 kHz DCR
after 10^{11} neq dose
and T = 150 C annealing
in line with Calvi

could reduce by another 3x factor
with T = 175 C annealing
if we believe in Calvi (we do)

could reduce by a further 2x factor
operating at T = -40 C
we know DCR decreases by 2x every 10 C

900 kHz
in 3x3 mm²



350 kHz
in 3x3 mm²

values at the indicated Vbias	new	~ 10^8 neq	10^9 neq	10^{10} neq	10^{11} neq
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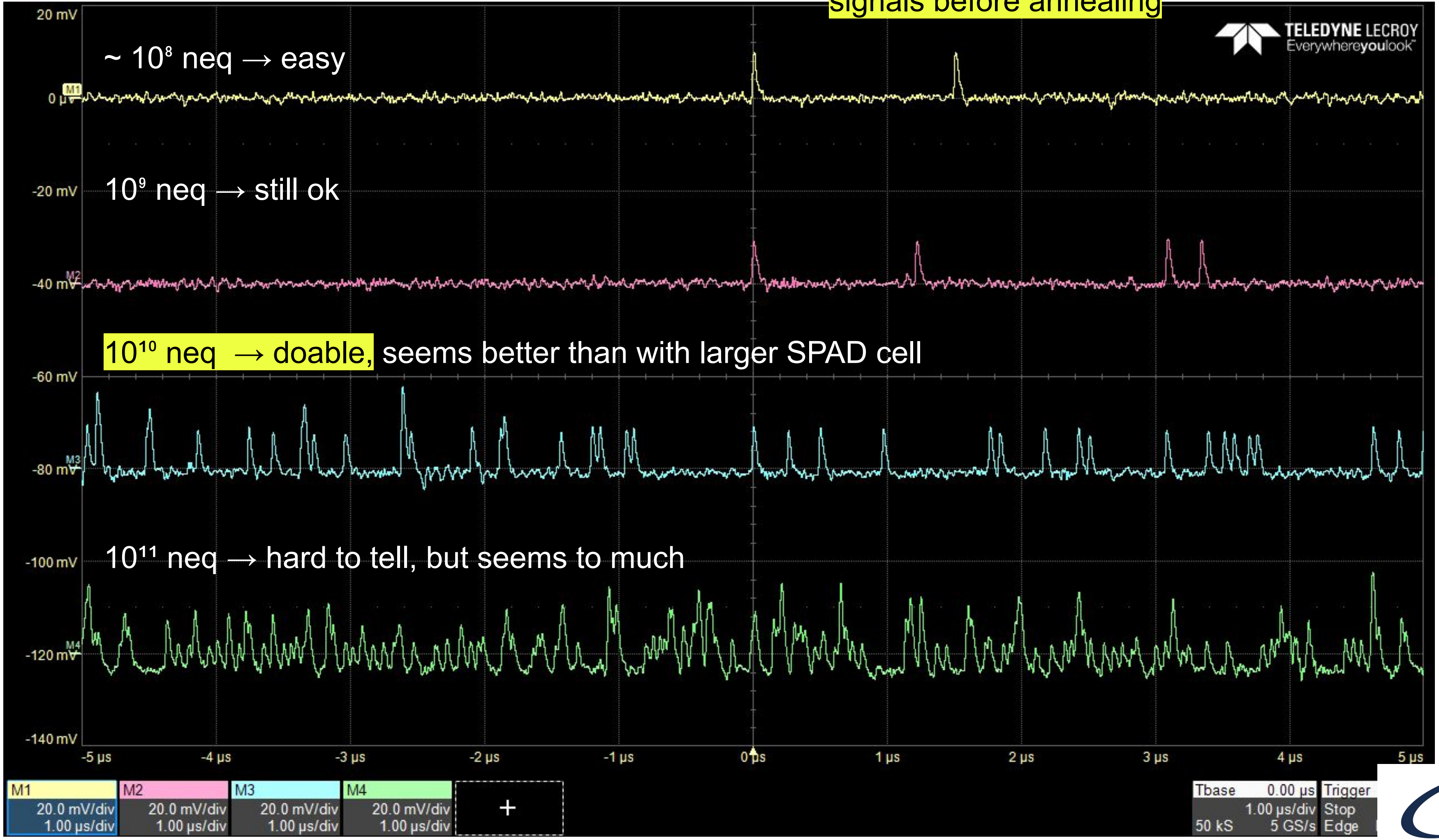
how often do we need to do annealing?

signals before annealing

FBK #3 (T = -30 C)
NUV-HD-RH (row B)



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How often to do annealing

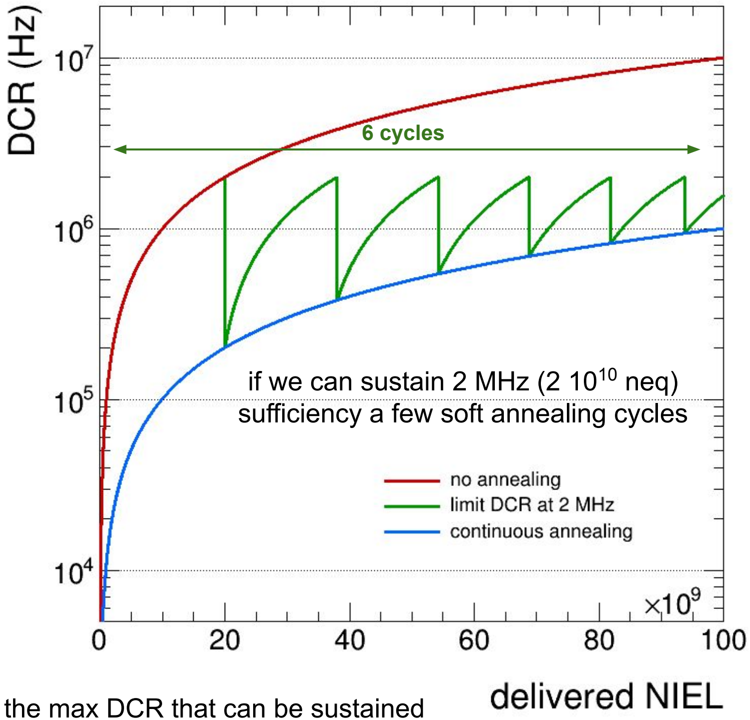
assumptions

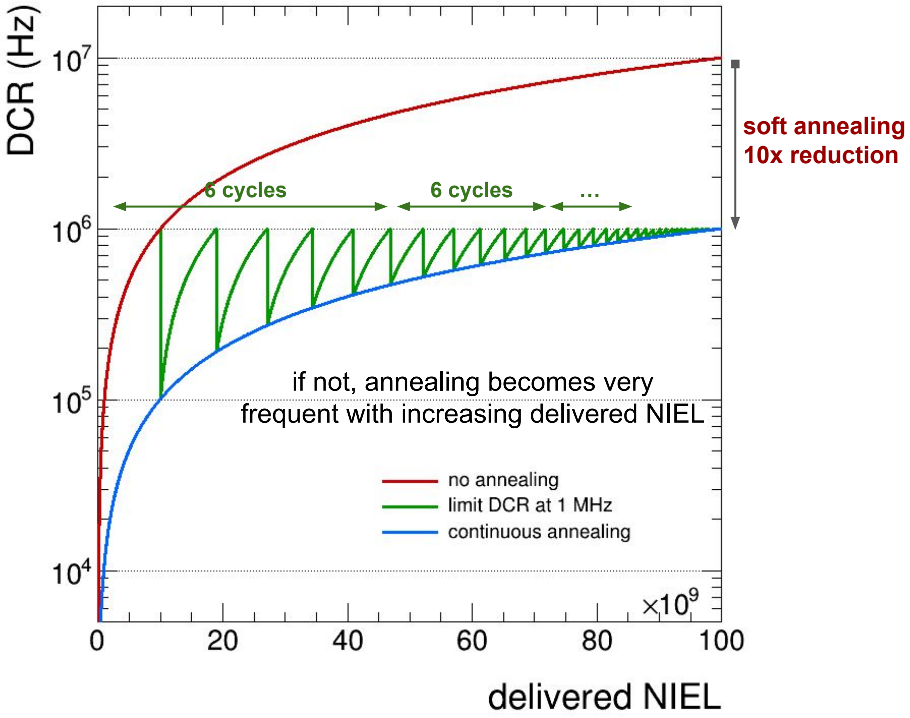
- NIEL = 10^{11} neq/cm^2 ⇒ DCR = 10 MHz
- DCR increases proportionally to NIEL
- annealing always cures same fraction of damage caused by NIEL
    - constant fraction of new damage, regardless total damage

example

- delivered 10^{10} ⇒ DCR = 1 MHz
- annealing, cures 90% of damage ⇒ DCR = 0.1 MHz
- delivered another 10^{10} ⇒ DCR = 1.1 MHz
- annealing, cures 90% of new damage ⇒ DCR = 0.2 MHz

10^{10} neq





it depends on the max DCR that can be sustained

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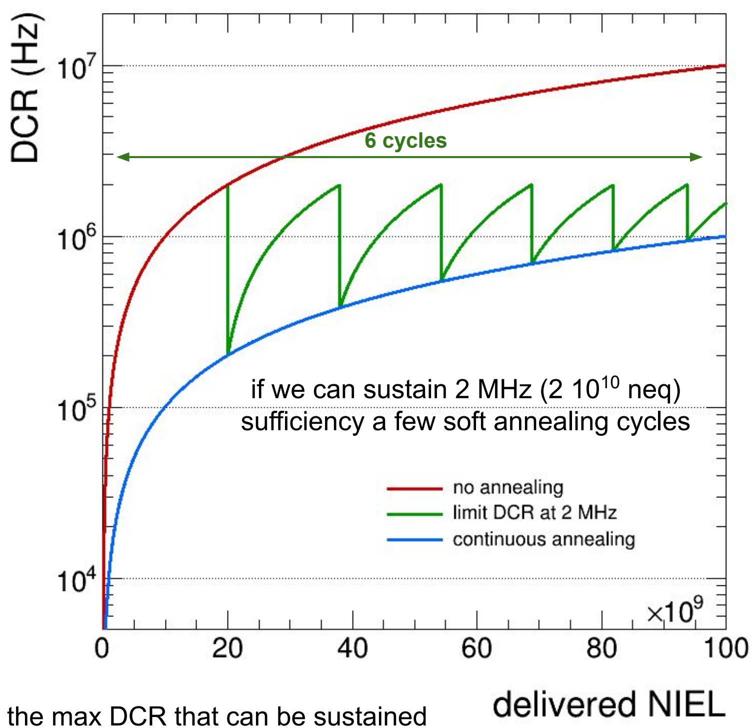

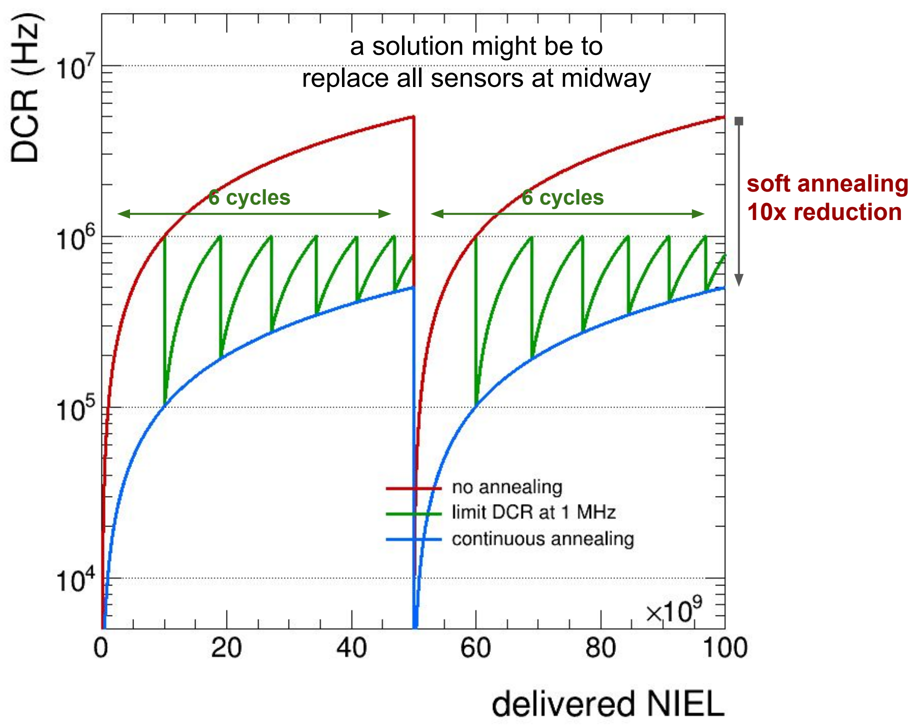

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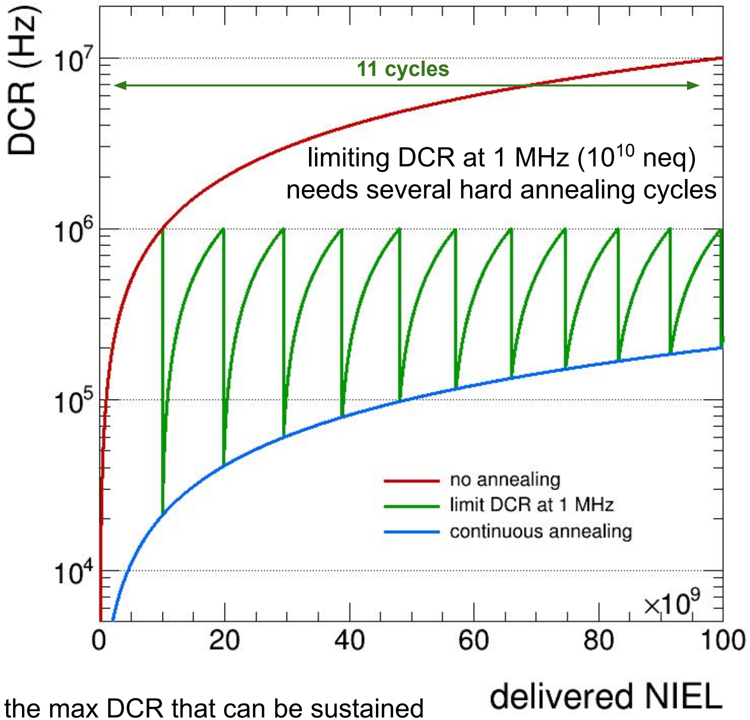

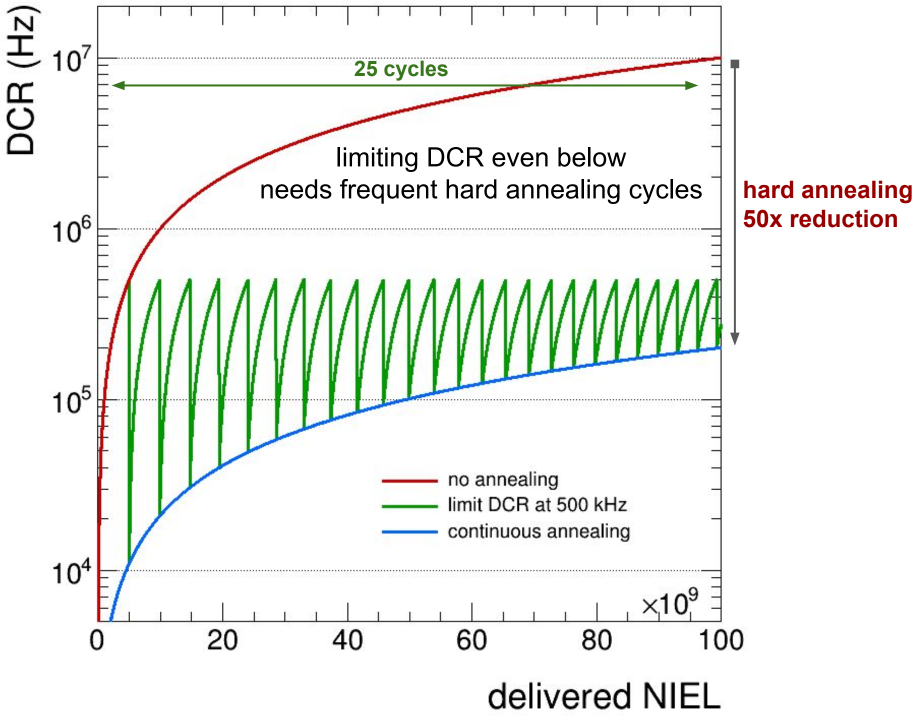

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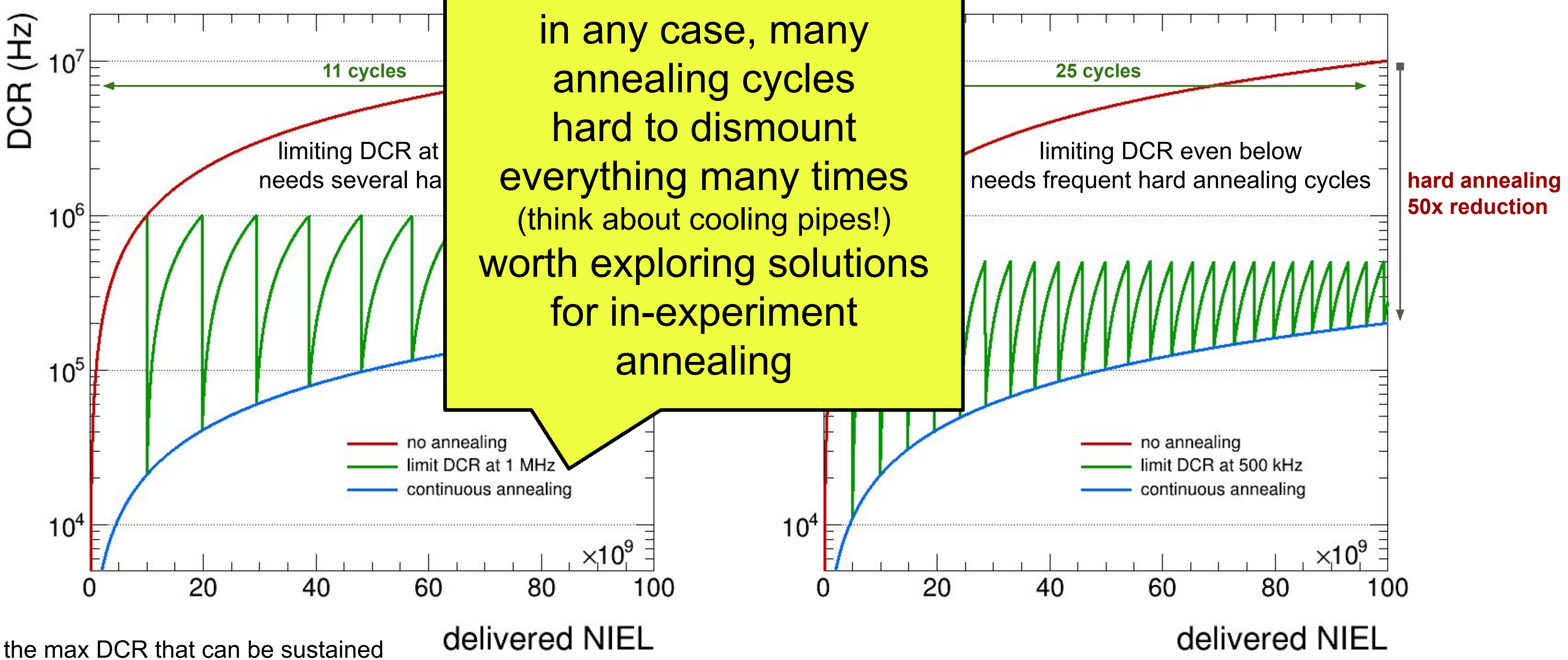


in any case, many annealing cycles
hard to dismount everything many times
(think about cooling pipes!)
worth exploring solutions for in-experiment annealing

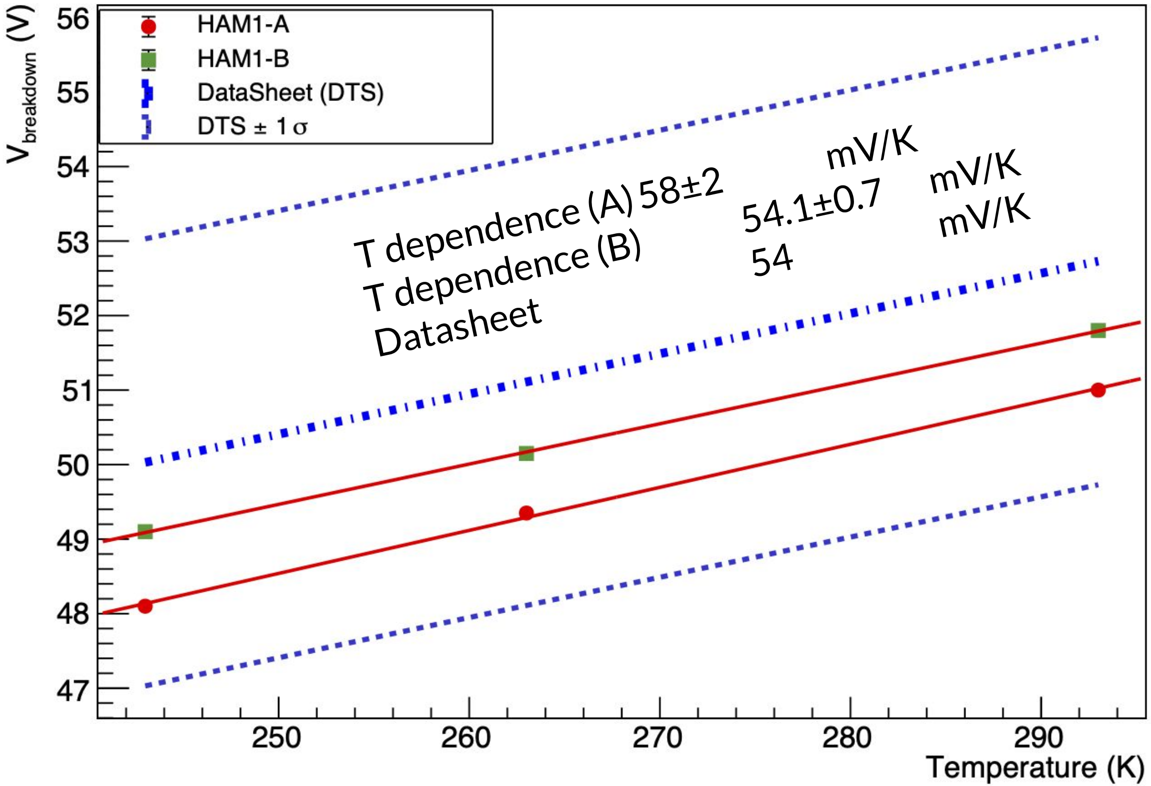
it depends on the max DCR that can be sustained

Summary

- **SiPM as photosensors for RICH applications**
  - many pros
  - a few cons
- **R&D program has just started**
  - well linked with ASIC development
  - from first irradiation results, SiPM look a very promising option
    - soon correlation/efficiency studies with with laser/LED on irradiated SiPM
    - can we distinguish the signal from the DCR ?
  - test beam was unfortunately not brilliant
    - signals could be seen, experience gained
  - stay tuned for the next irradiation campaign
    - 2022 might be decisive on choice of photosensors
- **engineering needs for SiPM operation in experiment**
  - bring cooling, down to -30 C (or perhaps even -50 C)
  - think about how to do annealing on-site
    - warm SiPM with forward bias (Joule effect)
    - design cooling plant to be a warming plant as well
  - cable routing, cooling, piping, connections while keeping ~ 100% active area

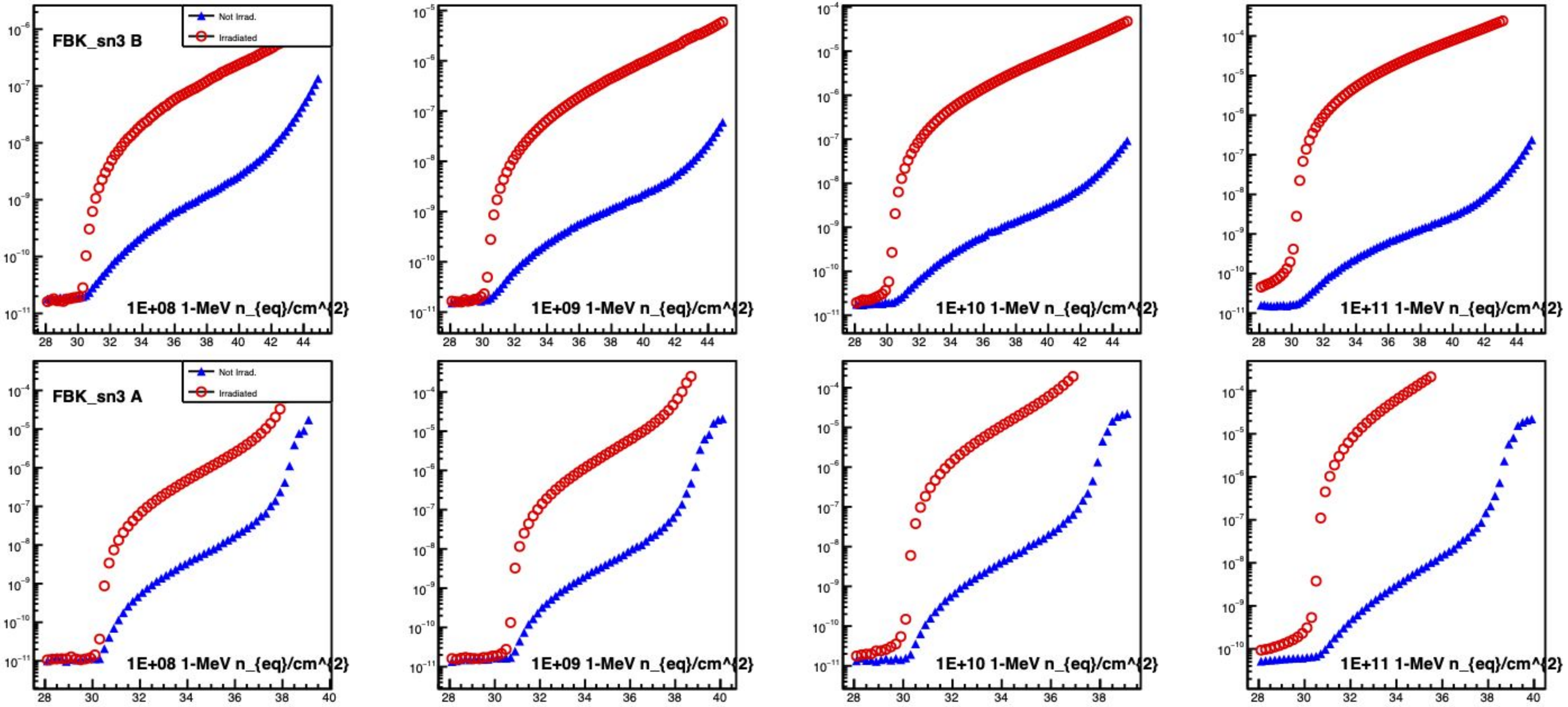
thanks to all people involved

Breakdown Voltage estimation (HAM1-A & -B)

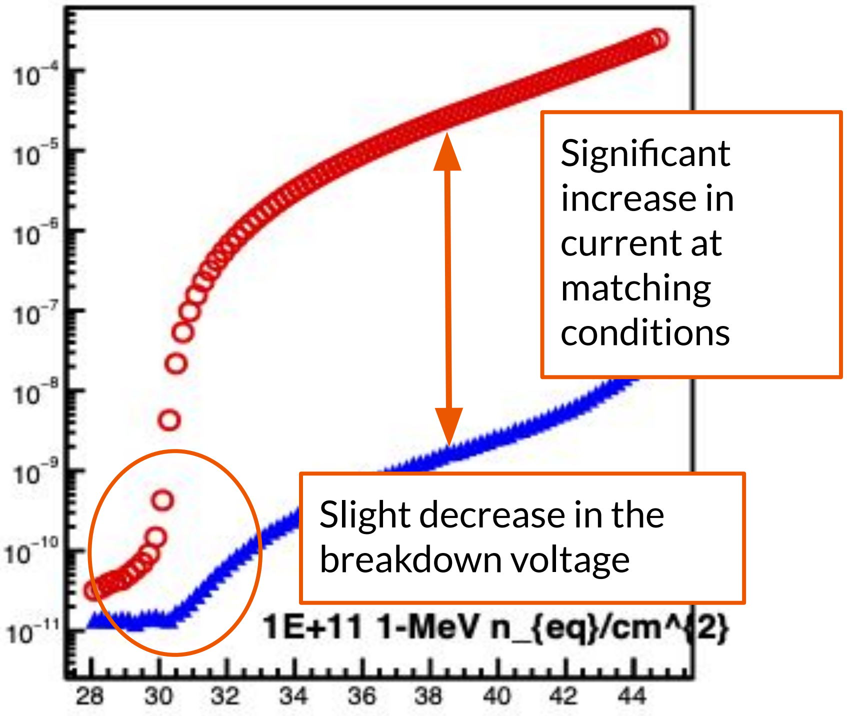


The curve seems consistent with what is reported on the Datasheet.

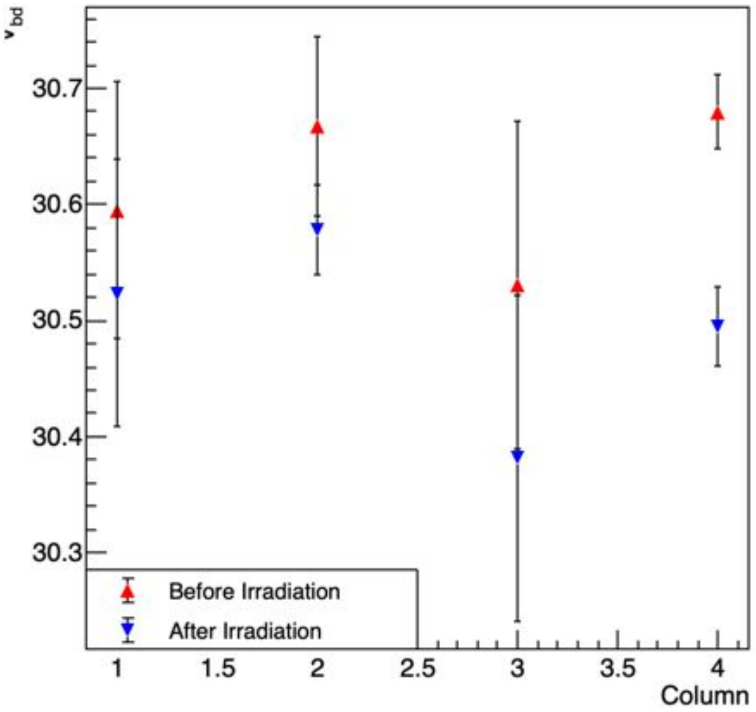
Current comparison @243K for FBK3-(C)(R)

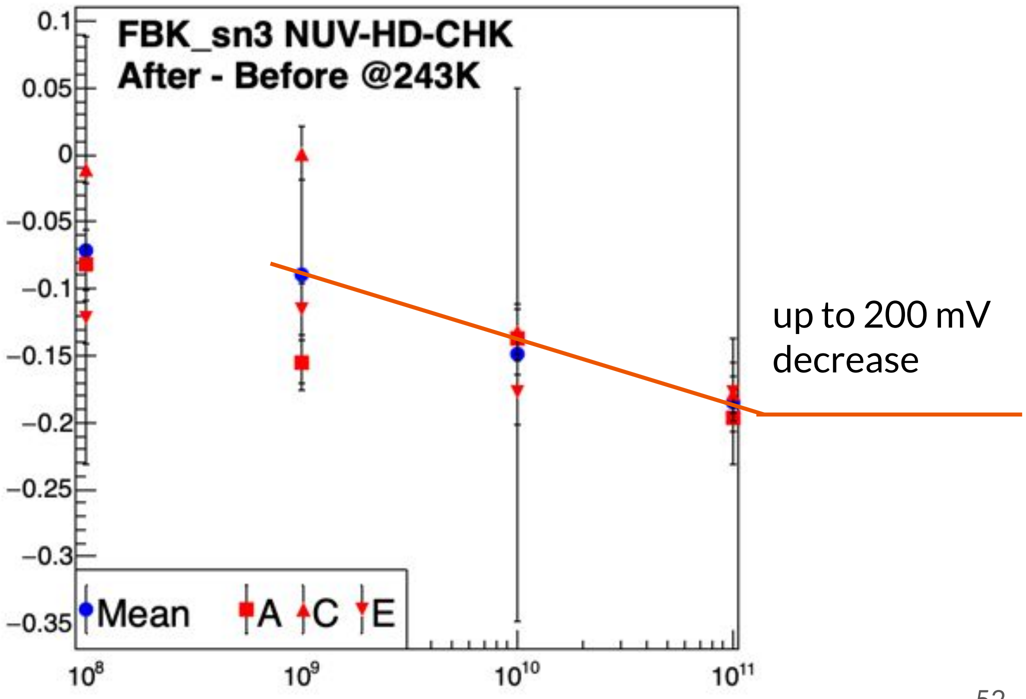


Current comparison



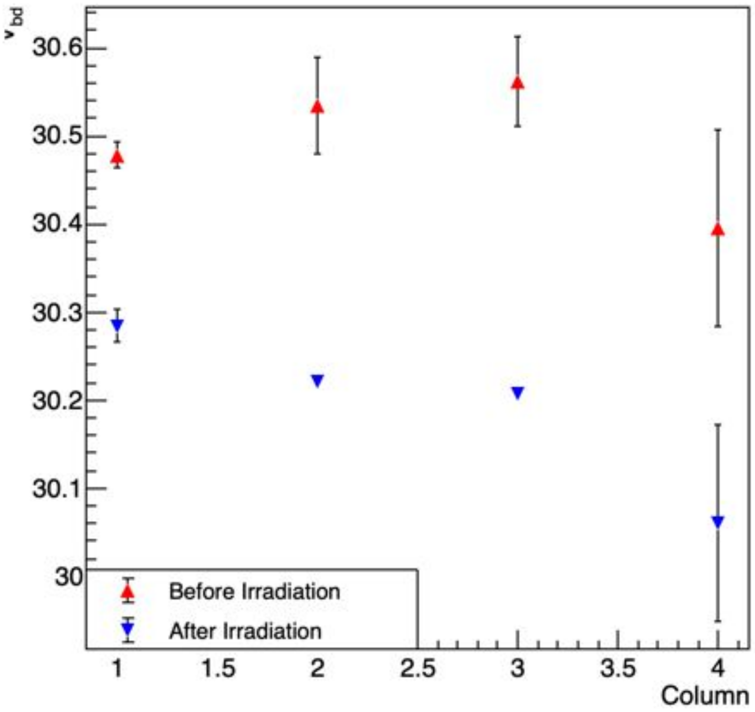
V_{BD} estimation @243K for FBK3-C

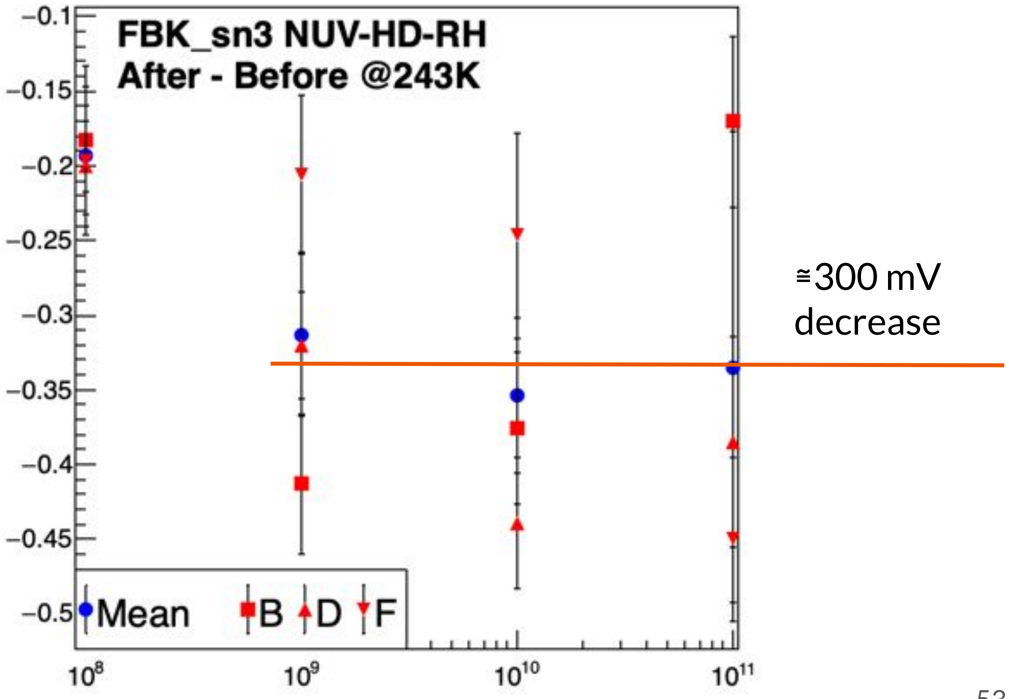




up to 200 mV decrease

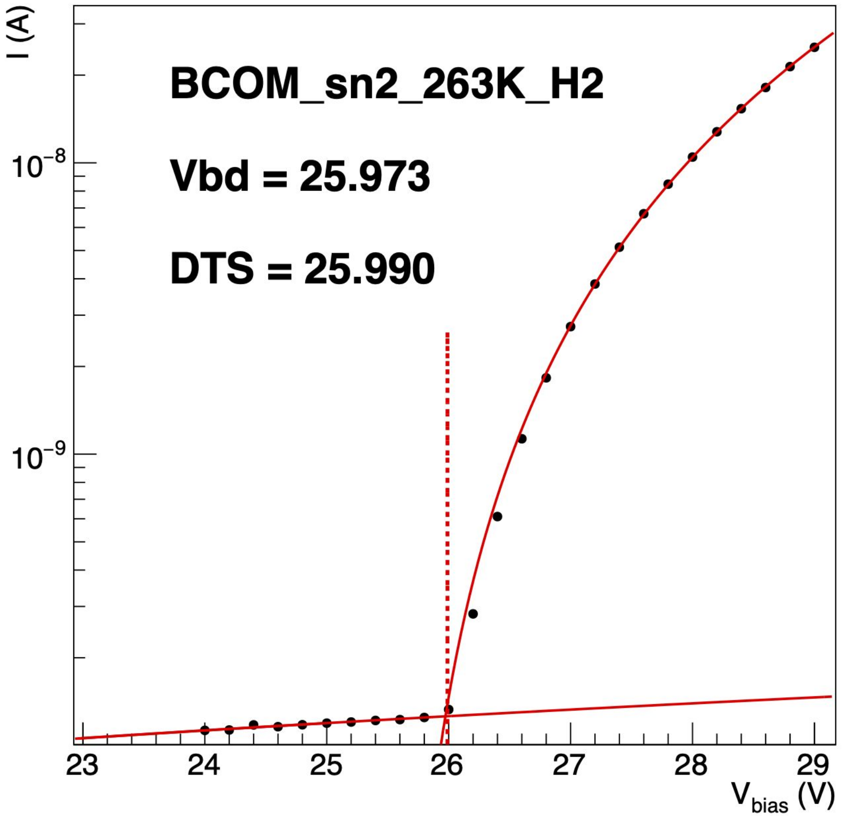
V_{BD} estimation @243K for FBK3-R





≅300 mV decrease

Breakdown Voltage Estimation



Breakdown Voltage estimation

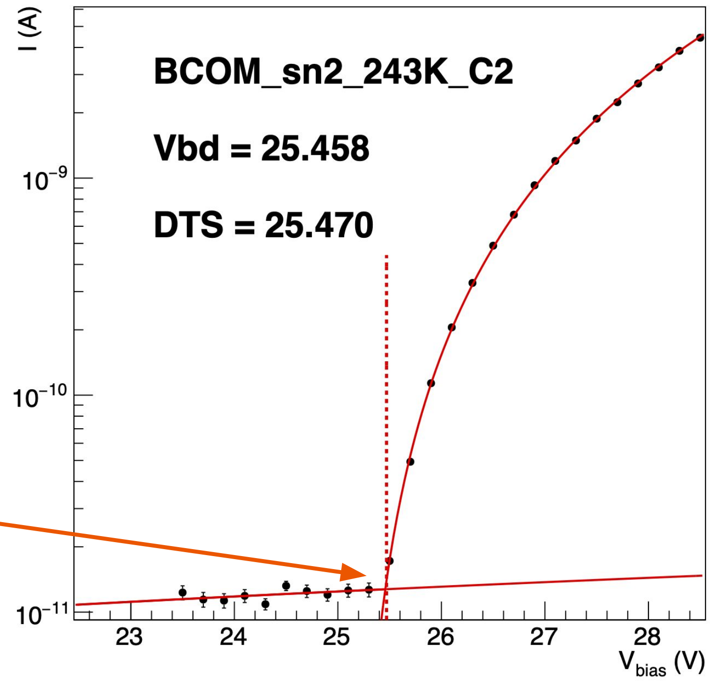
6. A second order polynomial, fitted to $I(V_{bias})$ above V_{bd} after surface-current subtraction, crosses the V_{bias} axis.

https://arxiv.org/pdf/1809.04346.pdf

We fit the I-V curve for V > V_{BD} with a power function:
[0]*(x - [1])^[2]
(Generalising the second order polynomial)

We fit the I-V curve for V < V_{BD} with a linear function:
[0] + x*[1]
(Acting as the surface current subtraction)

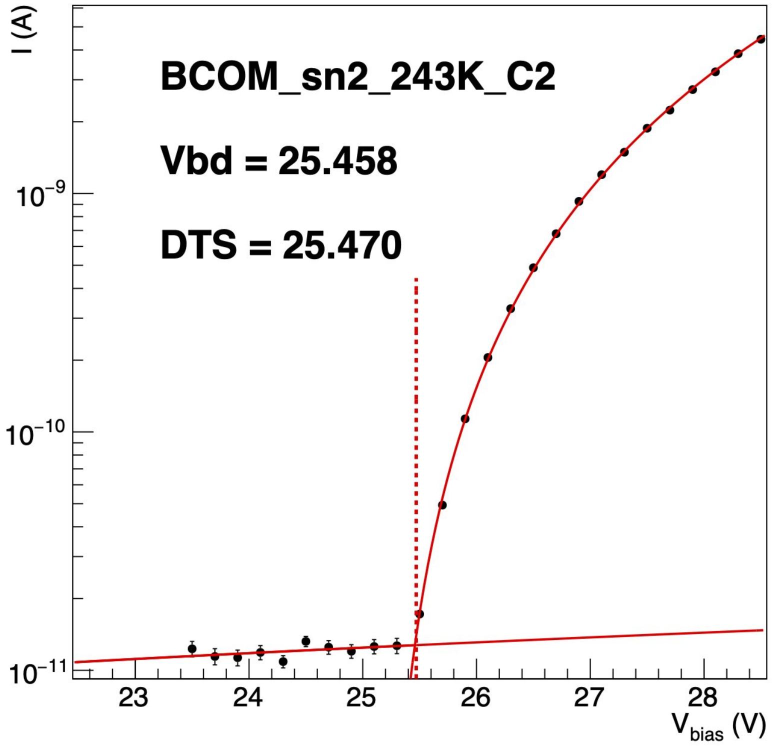
The crossing of the two functions will give us the Breakdown voltage



Breakdown Voltage estimation

Procedure:

1. We Fit the two functions in the range: [V_{BD}-4;V_{BD}-1] and [V_{BD}+1;V_{BD}+4] respectively, where V_{BD} is an initial guess.
2. The two function crossing is found and taken as the new V_{BD} guess
3. We Fit the two functions in the range: [V_{BD}-4;V_{BD}] and [V_{BD};V_{BD}+4] respectively
4. Steps 2 and 3 are repeated until the difference between the new guess and the previous guess is less than 1.e-5



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Measurement	MC0	MC1	MC2	MC3	MC4	MC5	MC6
Annealing step	Before irradiation	After irradiation	1st ann. @125°C	2nd ann. @125°C	3rd ann. @125°C	1st ann. @150°C	2nd ann. @150°C
Duration (tot)	N/A	N/A	12h @50°C 24h @100°C 72h @125°C	62h @125°C (134h)	60h @125°C (190h)	73h @150°C (73h)	63h @150°C (136h)

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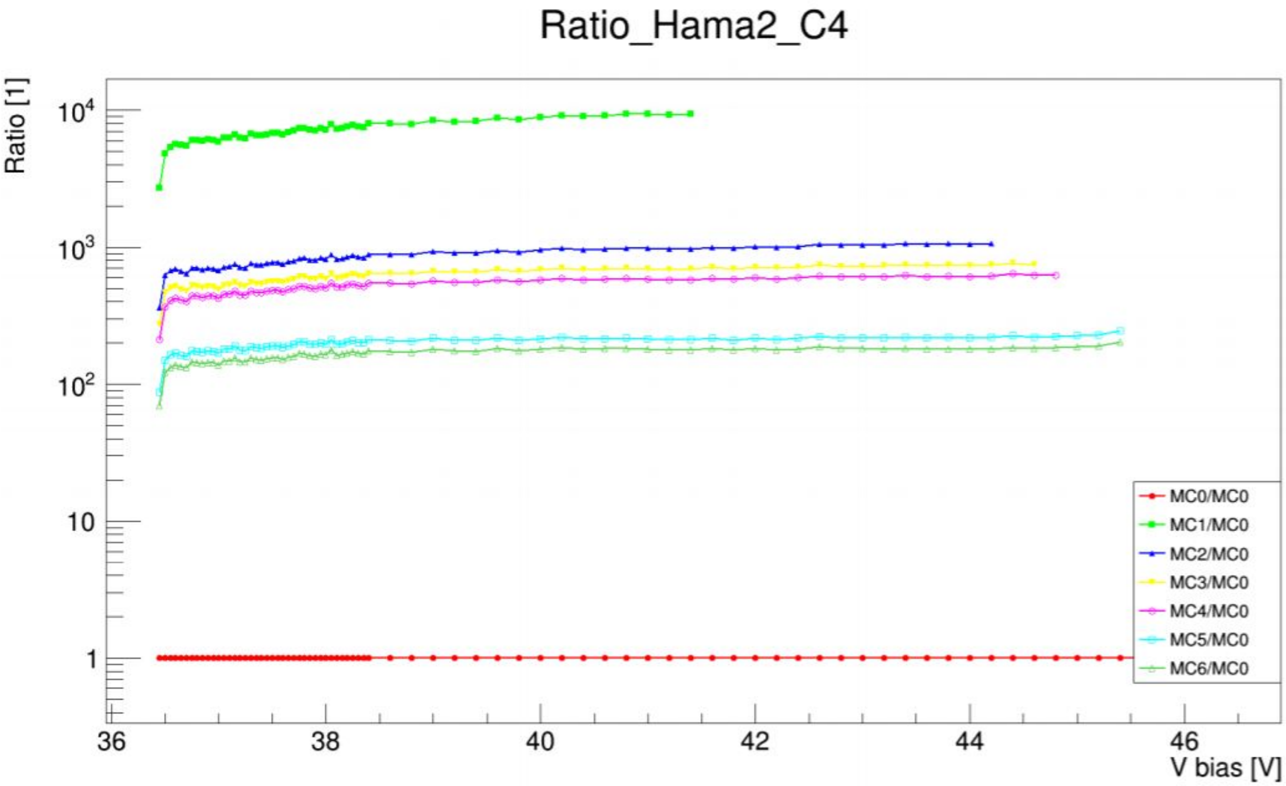
VI characteristic – ratio with respect to MC0



- VI characteristic ratio with respect to MC0
- 2 major gaps corresponding to increasing temperature
- The effect of the second and (probably) third annealing steps is significantly lower than the first.

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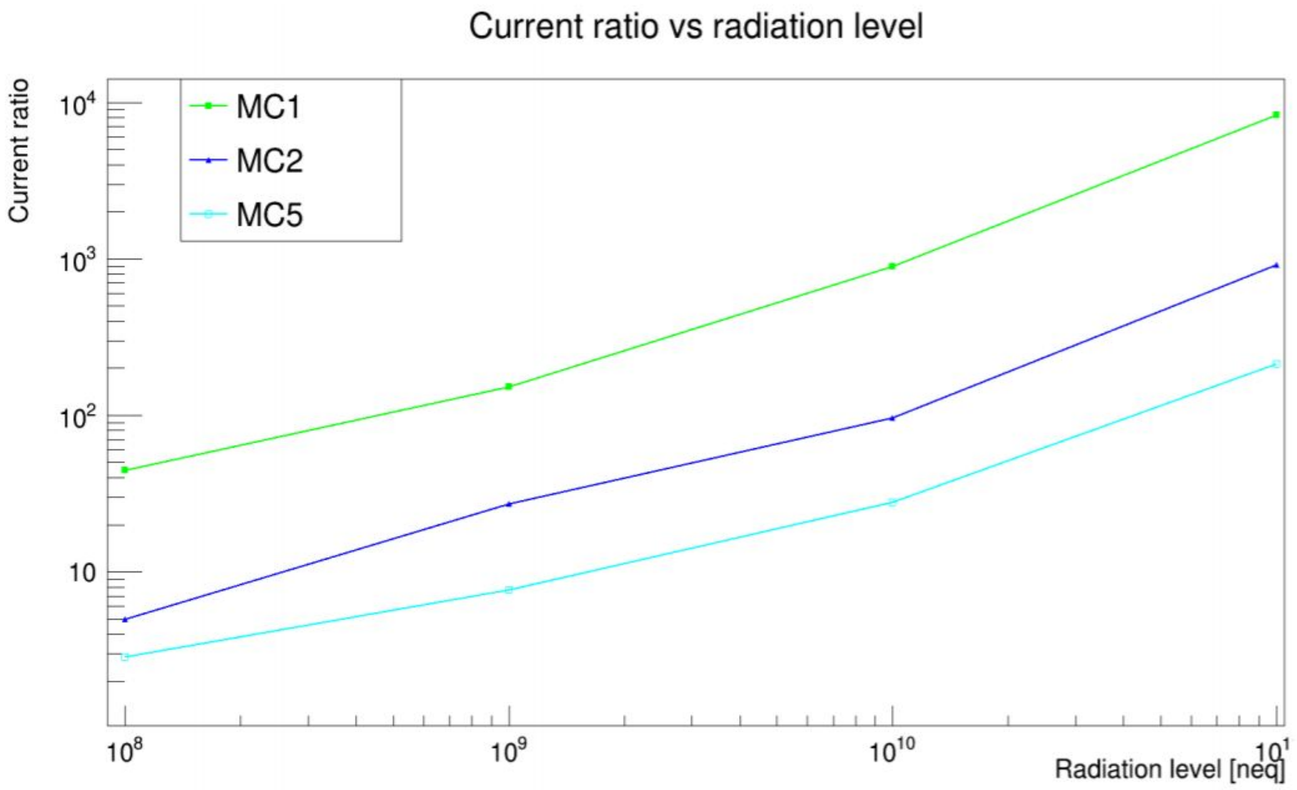
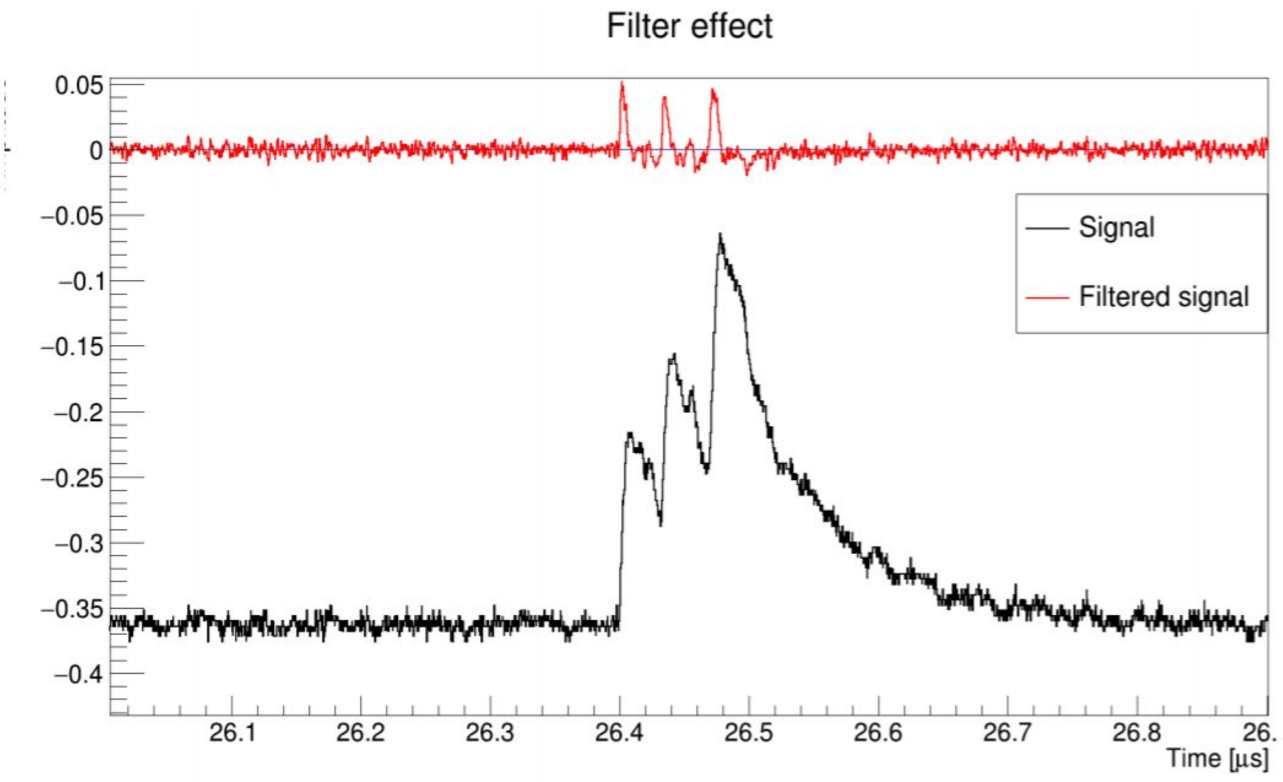
Current ratio to the recommended operating voltage



- Current ratio with respect to MC0 measured to the recommended operating voltage
- The plots shows the curves for the measurements before annealing and after the first annealing step at 125°C and 150°C.

Filter effect



The plot shows the effect of filter.

It allows to distinguish easily the three peaks (in this example)

$$V_i^{filtered} = V_i - \frac{1}{N}\sum_{j=1}^{N} V_{i-j} \cdot exp\left(-\frac{t_i - t_{i-j}}{\tau}\right)$$

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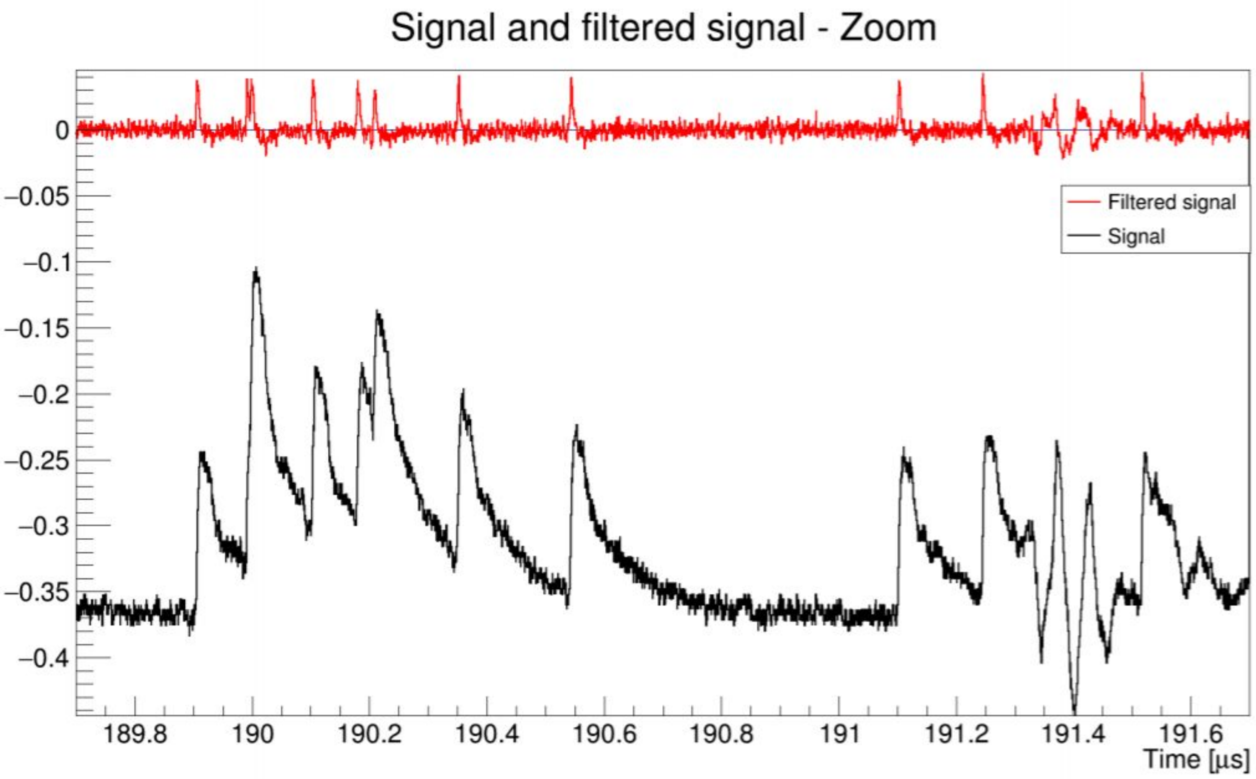
Filter effect



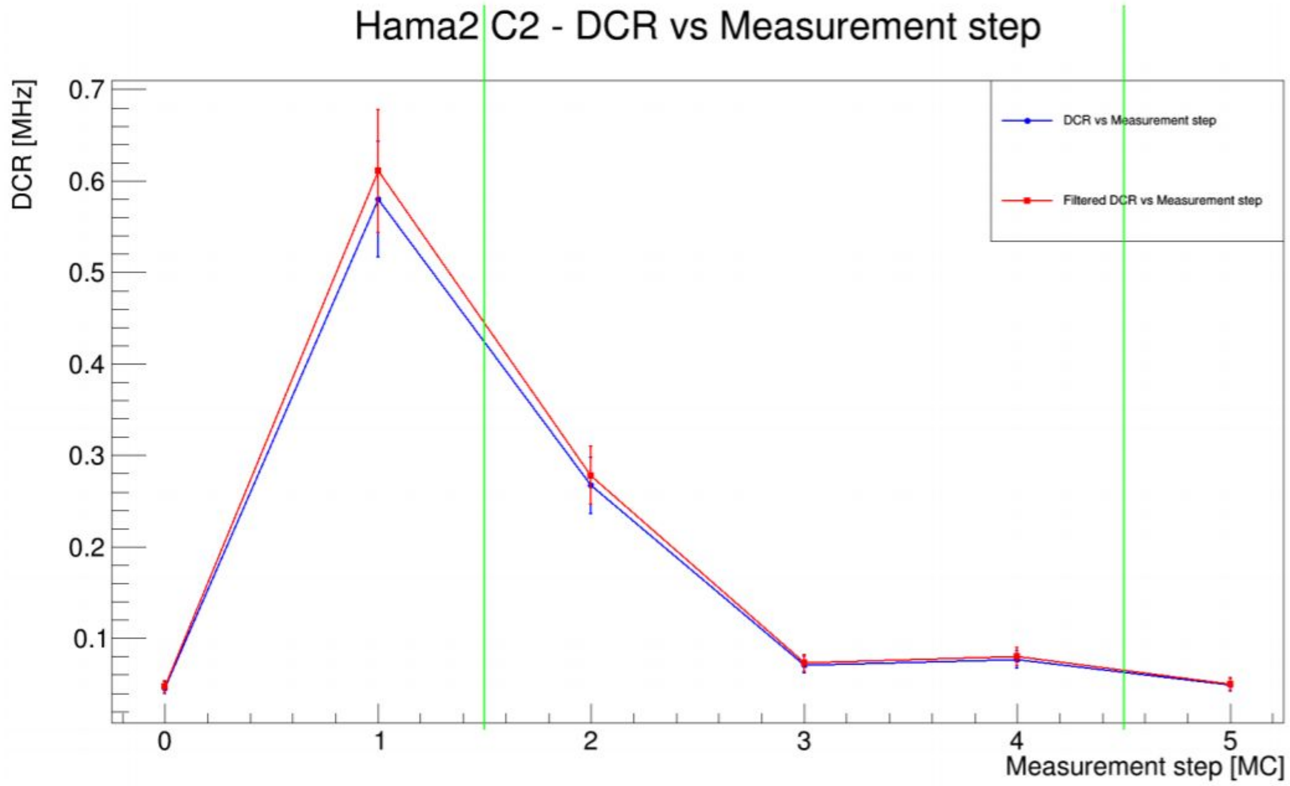
The plot shows the effect of filter.

It allows to distinguish easily the three peaks (in this example)

$$V_i^{filtered} = V_i - \frac{1}{N}\sum_{j=1}^{N} V_{i-j} \cdot exp\left(-\frac{t_i - t_{i-j}}{\tau}\right)$$

The time-over-threshold criteria to reject the noise appears still valid after filtering.

Dark Count Rate vs Measurement – Preliminary results



The plot shows the DCR vs the measurement for a 50µm-cell SiPM wich has received a low dose (10^9), with or without filtering.
The DCR is quiet low, this allows to obtain it even without the filter.
The vertical green lines marks the different annealing temperature steps:

- 125°C, between MC1 and MC2
- 150°C, between MC4 and MC5

As expected, the DCR decreases while the annealing proceeds

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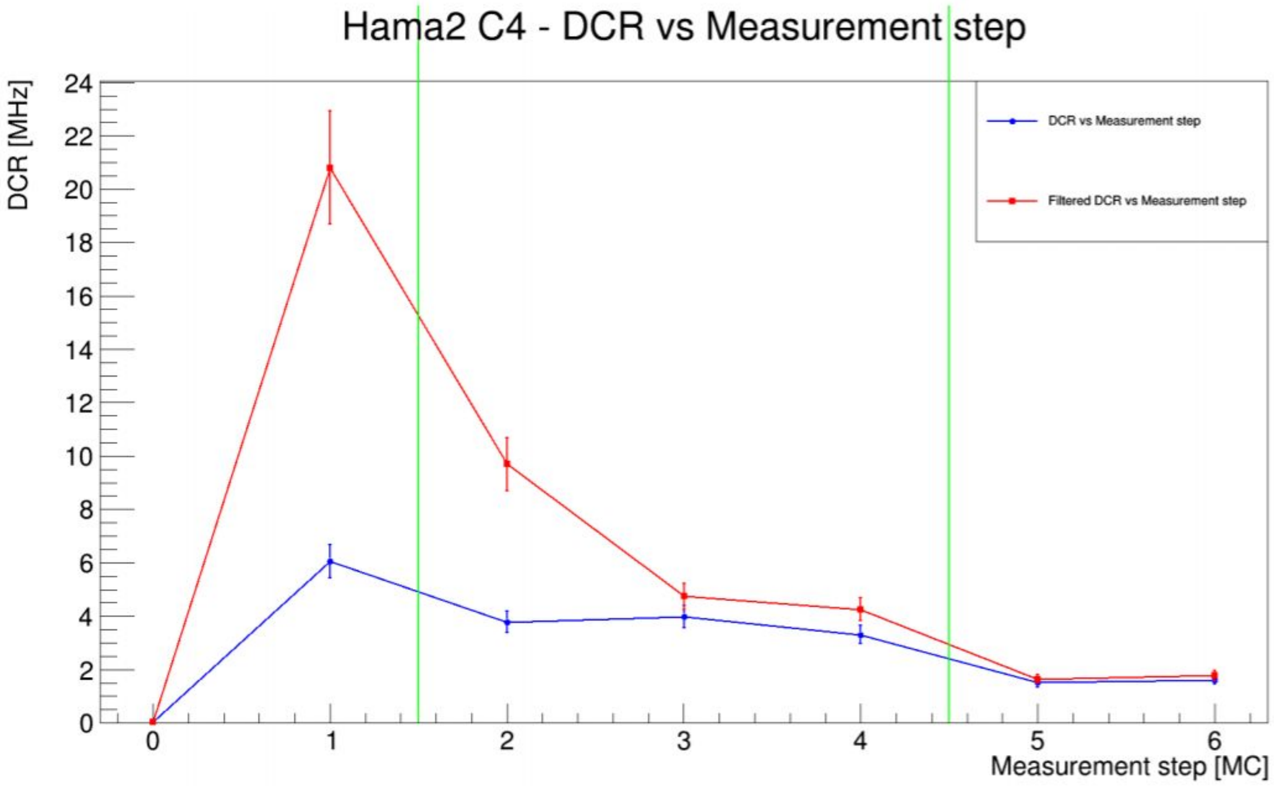
Dark Count Rate vs Measurement – Preliminary results



The plot shows the DCR vs the measurement for a 50µm-cell SiPM wich has received a high dose (10^{11}), with or without filtering.

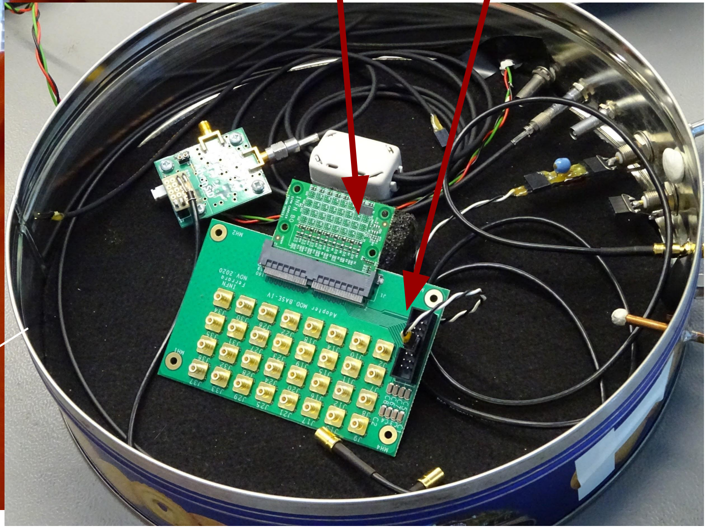
When the DCR increases, the analisys without filter fails to identify nearby peaks.

in azienda durante
produzione schede SiPM

segnali dai SiPM !

SiPM carrier LIGHT

SiPM adapter Base-IV



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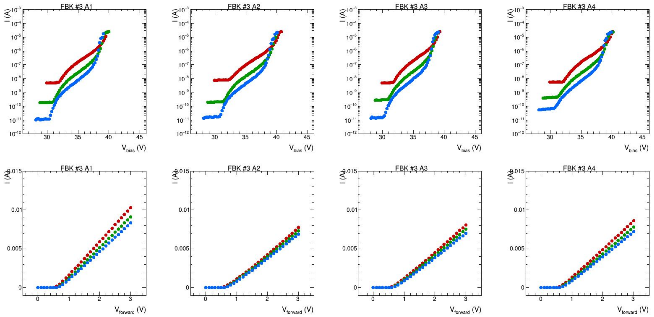
SiPM characterisation

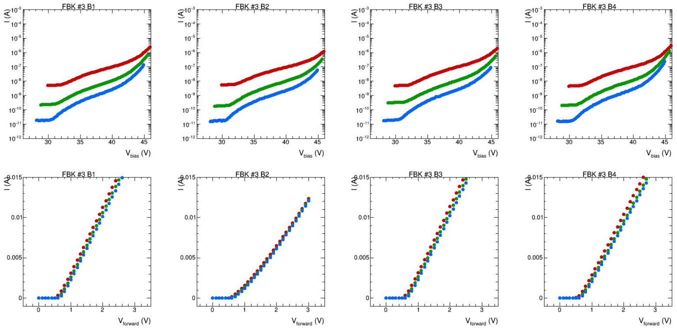
IV characteristics at different T

+20 C
−10 C
−30 C

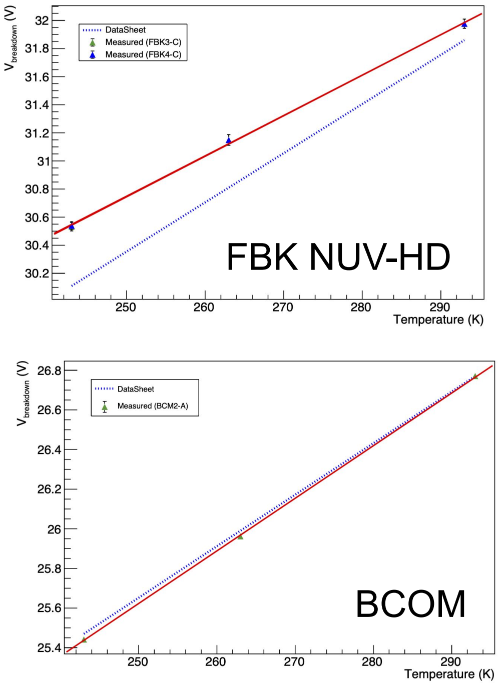
FBK NUV-HD-CHK



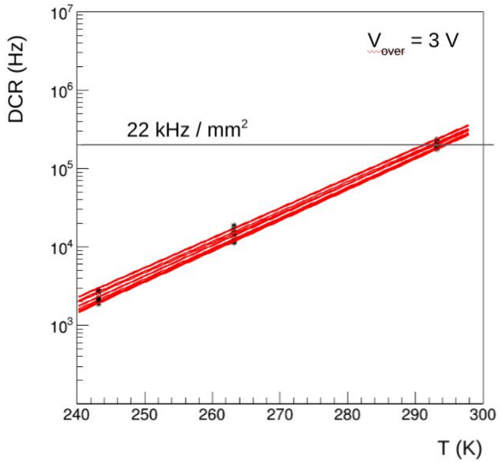
FBK NUV-HD-RH



breakdown voltage vs. temperature



dark count rate vs. temperature



only a little fraction of the large amount of data collected shown

Collimator setup: intensity calibration