SiPM photosensors for RICH

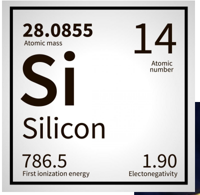
SiPM option for RICH optical readout

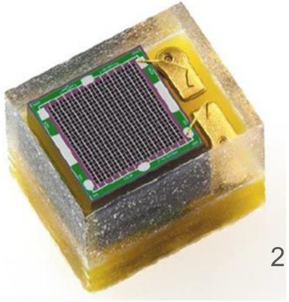
- **pros**
  - cheap
  - high photon efficiency
  - excellent time resolution
  - insensitive to magnetic field

- **cons**

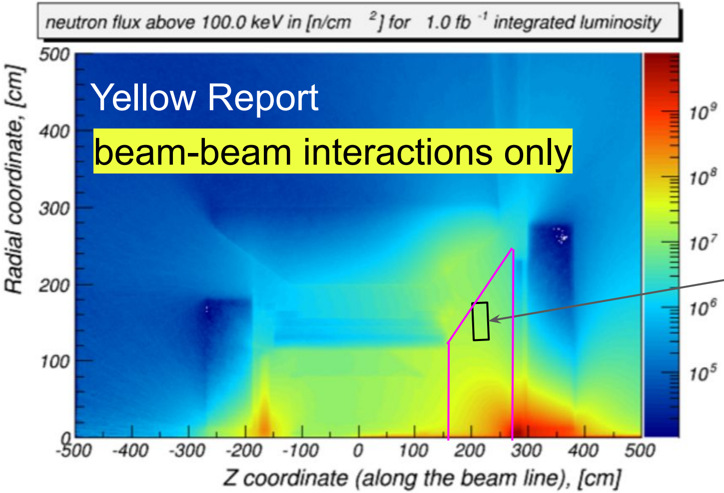
  large dark count rates

  not radiation tolerant





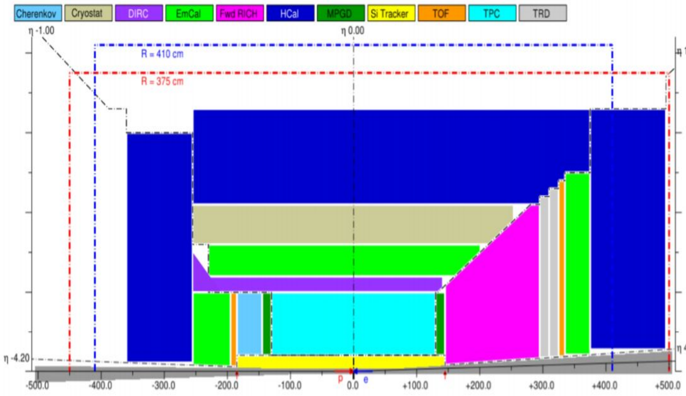
Neutron fluxes and SiPM radiation damage



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*

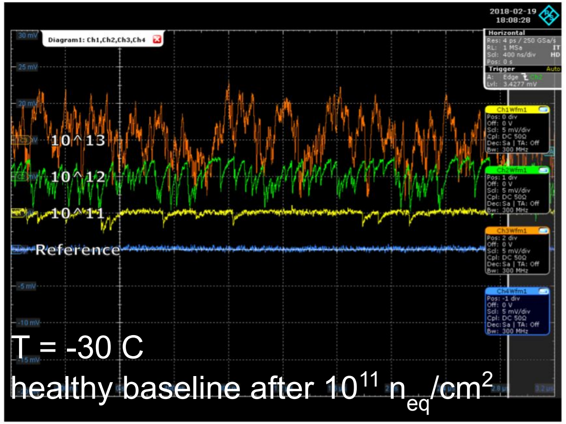
Updated radiation load studies from ATHENA are in backup

10^{11} 1-MeV n_{eq}/cm^2 at dRICH sensor location is reached after 10 years of operations running at the maximum interaction rate (500 kHz)

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)

Calvi, NIM A 922 (2019) 243



10^{11}

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

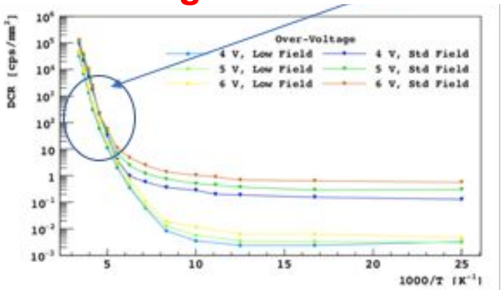
- Reduce operating temperatures (**cooling**)
- Use **timing**
- High-temperature **annealing** cycles

<u>Key point for R&D on RICH optical readout with SiPM</u>:

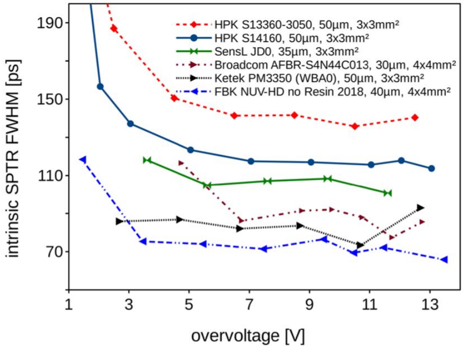
- demonstrate capacity to measure Single Photon
- keep DCR under control (ring imaging background)

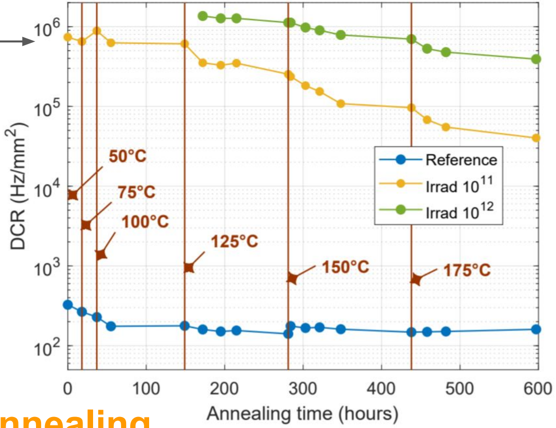
despite radiation damages

cooling



timing





20x less DCR

annealing

SiPM radiation damage and mitigation strategies

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- Use **timing**
- High-temperature **annealing**

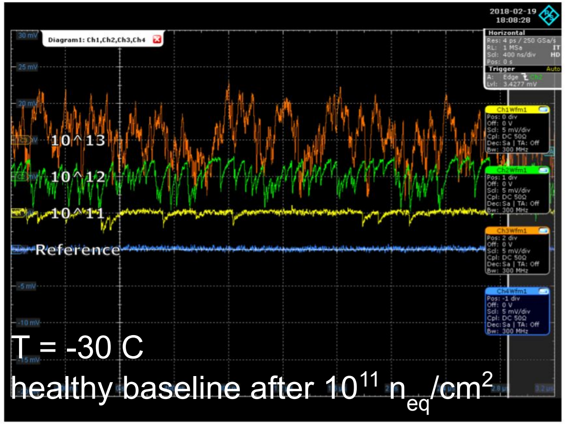
Key point for R&D on RICH optica…
- demonstrate capacity to mea…
- keep DCR under control (rin…

despite radiation damages

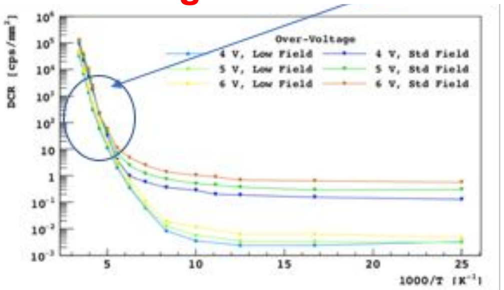
true for the sensors of Calvi which are 1.3 x 1.3 mm^2

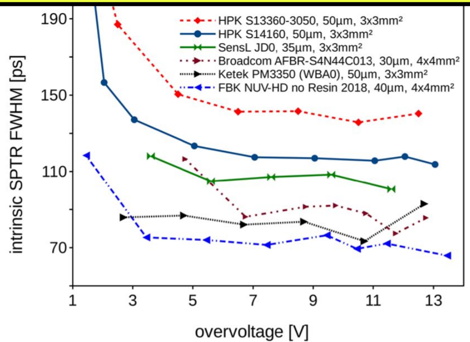
for 3 x 3 mm^2 sensors the story is a bit different as we will see later
same DCR/mm^2
5x larger DCR/pixel

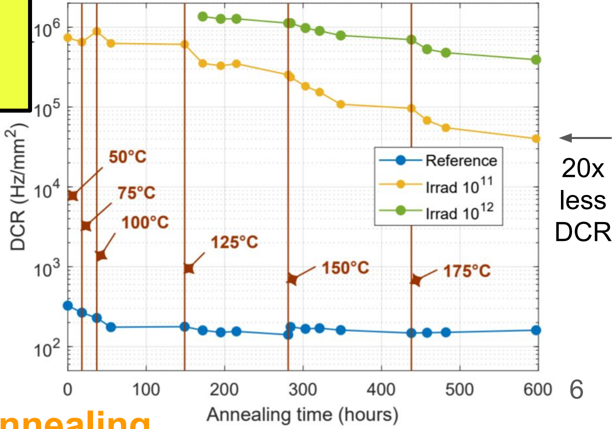
Calvi, NIM A 922 (2019) 243



cooling







annealing

where we are

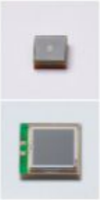
Garutti et al: “Due to the increased DCR, the single photoelectron separation from noise is lost already at relatively low fluences Φ_{eq} ~ 10^{10} cm^{-2}. This limit depends on many factors related to the SiPM design and the operation conditions, so <u>it should be tested for each specific application.</u>“

this is what we are doing for the dRICH SiPM option

- **acquired multiple SiPM samples**
  - from different manufacturers
  - and of different types
- **developed electronic boards**
  - SiPM carrier boards
  - adapter boards
  - ASIC readout board
- **first irradiation campaign**
  - FBK prototypes
  - Hamamatsu sensors
  - NIEL: ~ 10^8 10^9 10^{10} and 10^{11}
- **high-temperature annealing**
  - Hamamatsu up to T = 150 C
  - FBK up to T = 125 C
- **characterisation and operation**
  - I-V characteristics
  - DCR and signal sampling
  - low temperature operation
  - with ALCOR ASIC readout

Commercial SiPM sensors

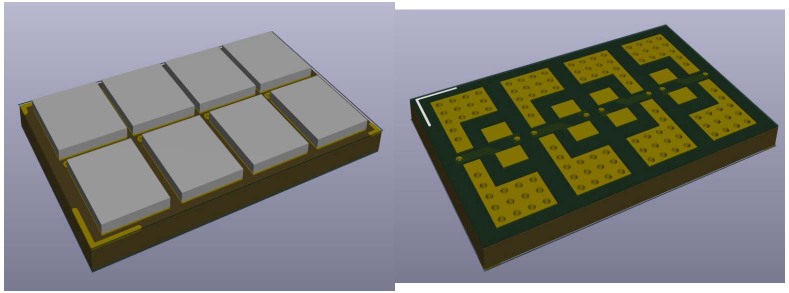
Istituto Nazionale di Fisica Nucleare



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

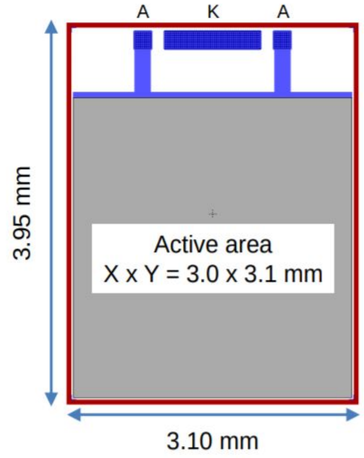
and FBK prototype sensors wire bonded on custom mini-tiles

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



FONDAZIONE BRUNO KESSLER

NUV-HD-RH



NUV-HD-RH

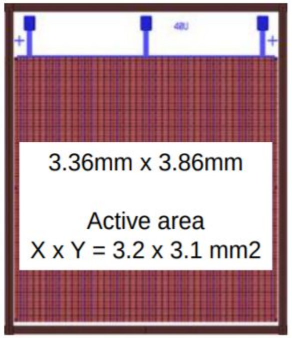
Technology under development optimized for radiation hardness in HEP experiments

- Cell pitch 15 µm with high fill factor
- Fast recovery time – reduced cell occupancy Tau recharge < 15 ns
- Primary DCR @ +24°C ~ 40 kHz/mm²
- Correlated noise 10% @ 6 V

IRIS INTEGRATED RADIATION AND IMAGE SENSORS

FONDAZIONE BRUNO KESSLER

NUV-HD-CHK



NUV-HD big cells

Technology similar to NUV-HD-Cryo
Optimized for single photon timing

- Cell pitch 40 µm
- High PDE > 55%
- Primary DCR @ +24°C ~ 50 kHz/mm²
- Correlated noise 35% @ 6 V

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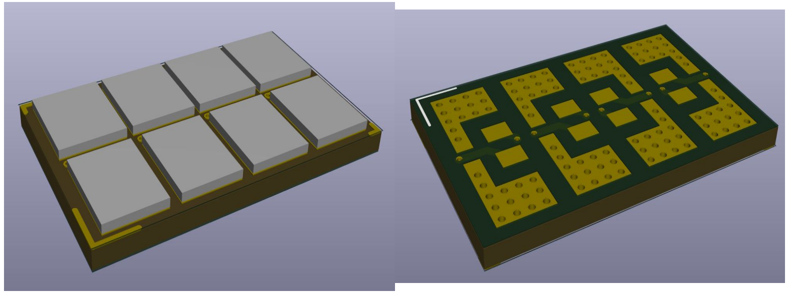
IRIS INTEGRATED RADIATION AND IMAGE SENSORS

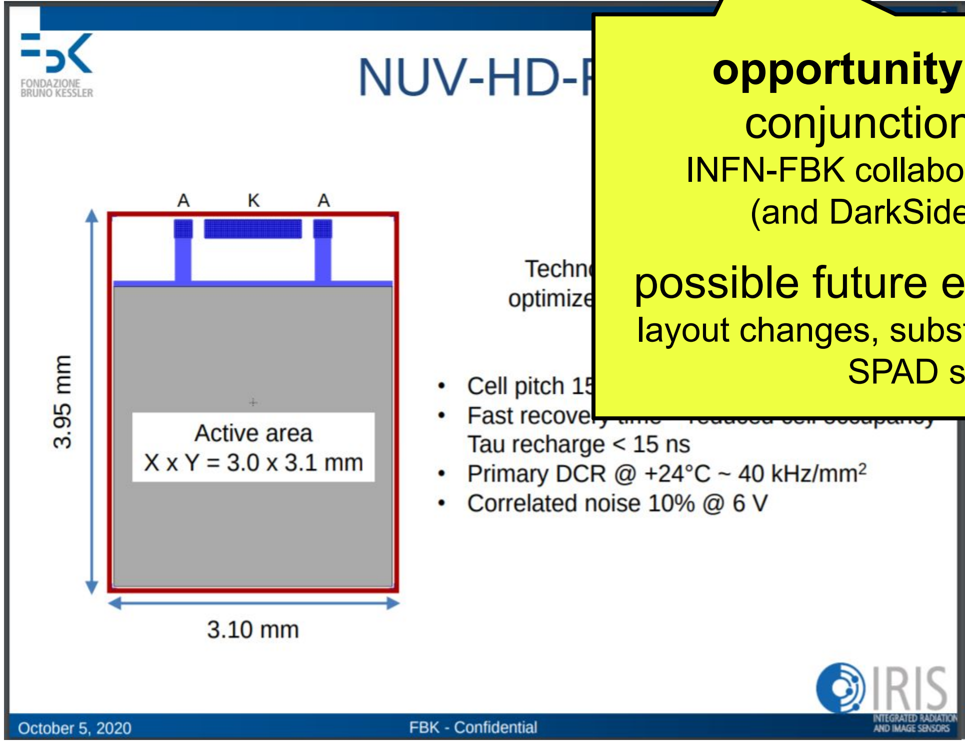
and FBK prototype sensors wire bonded on custom mini-tiles

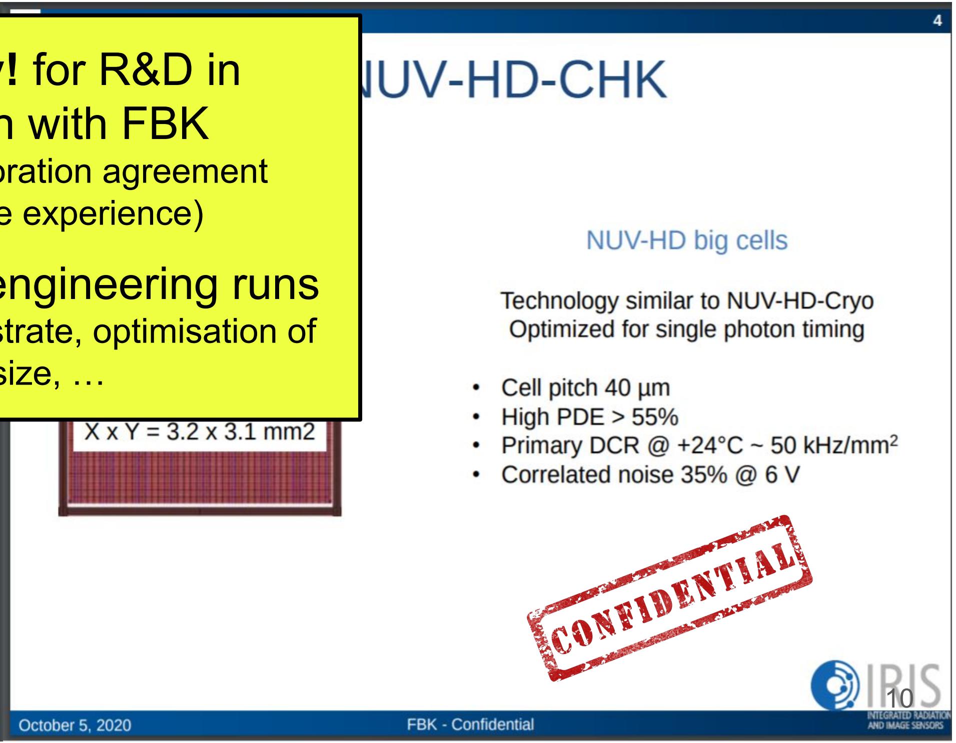


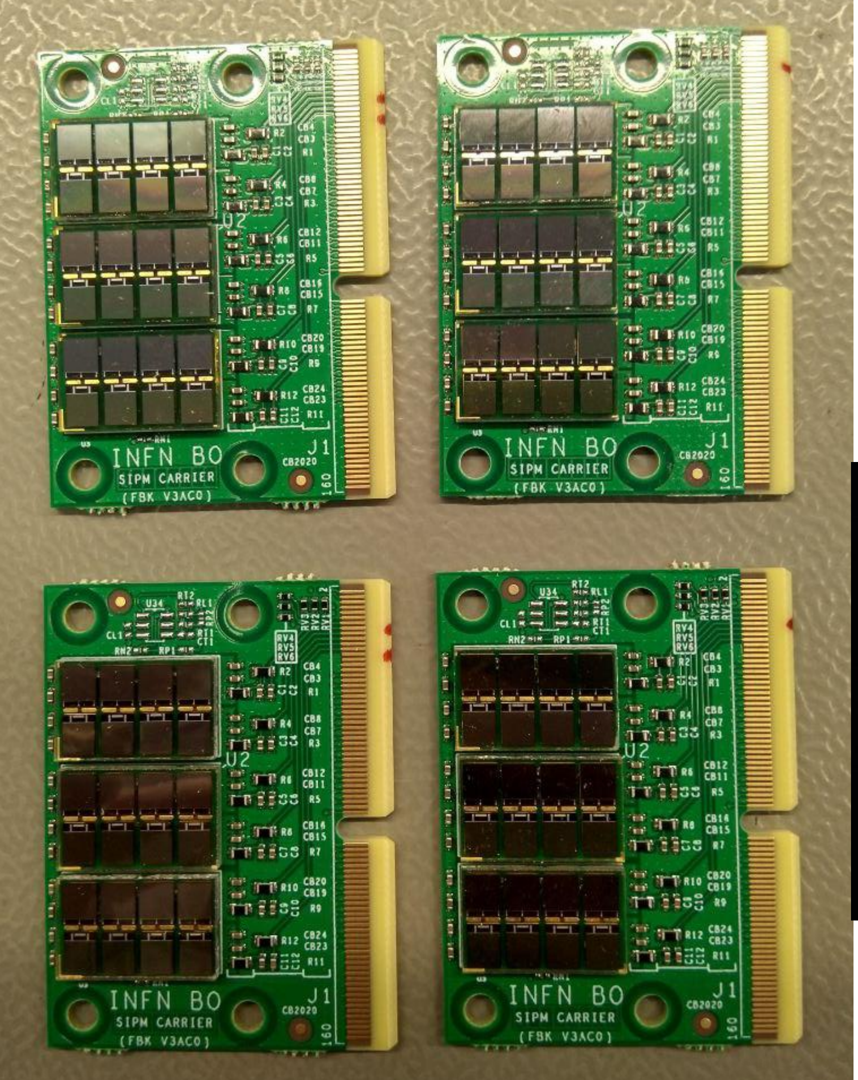
FBK has developed for us custom mini-tiles hosting 2x4 prototypes each

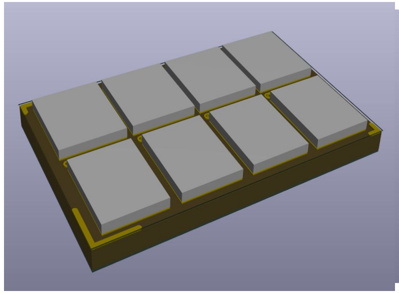
opportunity! for R&D in conjunction with FBK
INFN-FBK collaboration agreement
(and DarkSide experience)

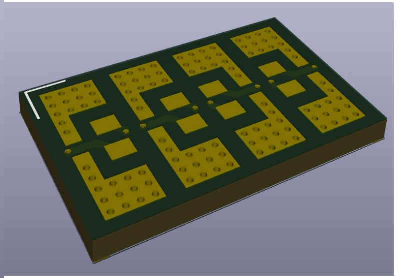
possible future engineering runs
layout changes, substrate, optimisation of SPAD size, …

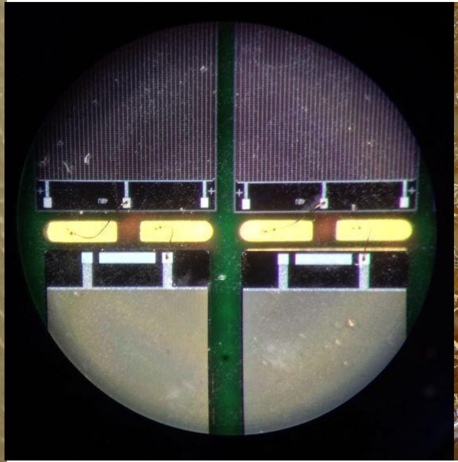


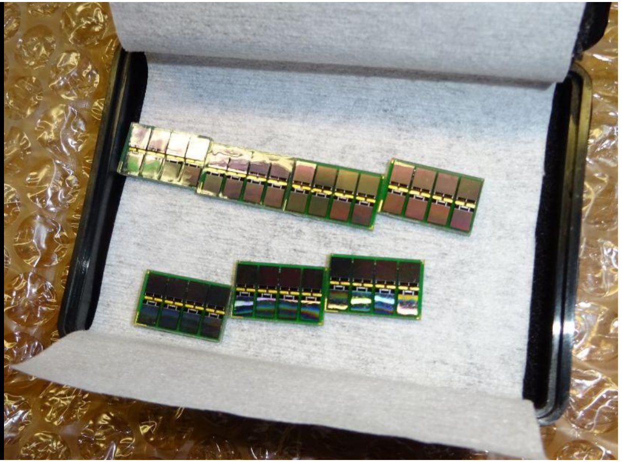



INFN BO
SIPM CARRIER
(FBK V3AC0)







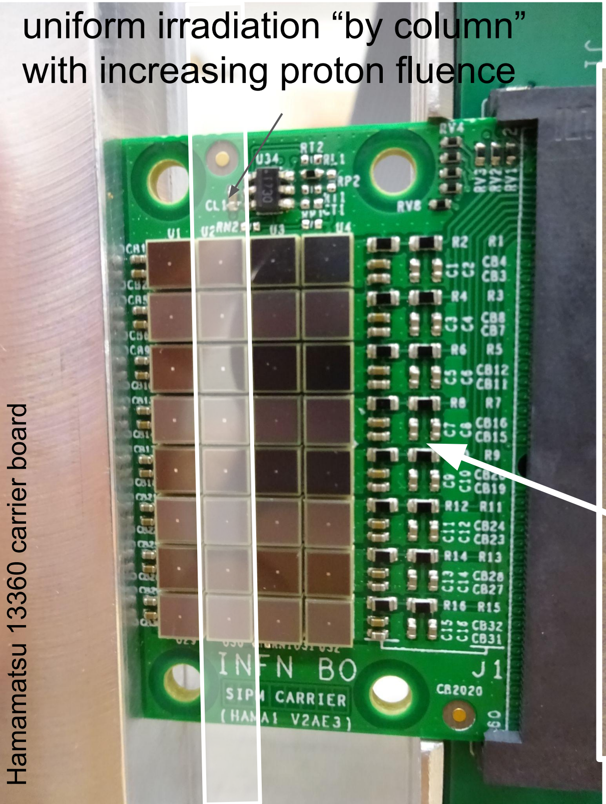


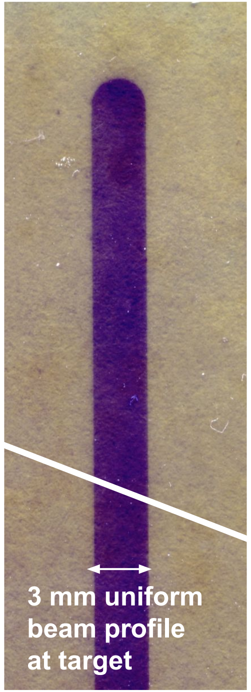
1st irradiation round in May

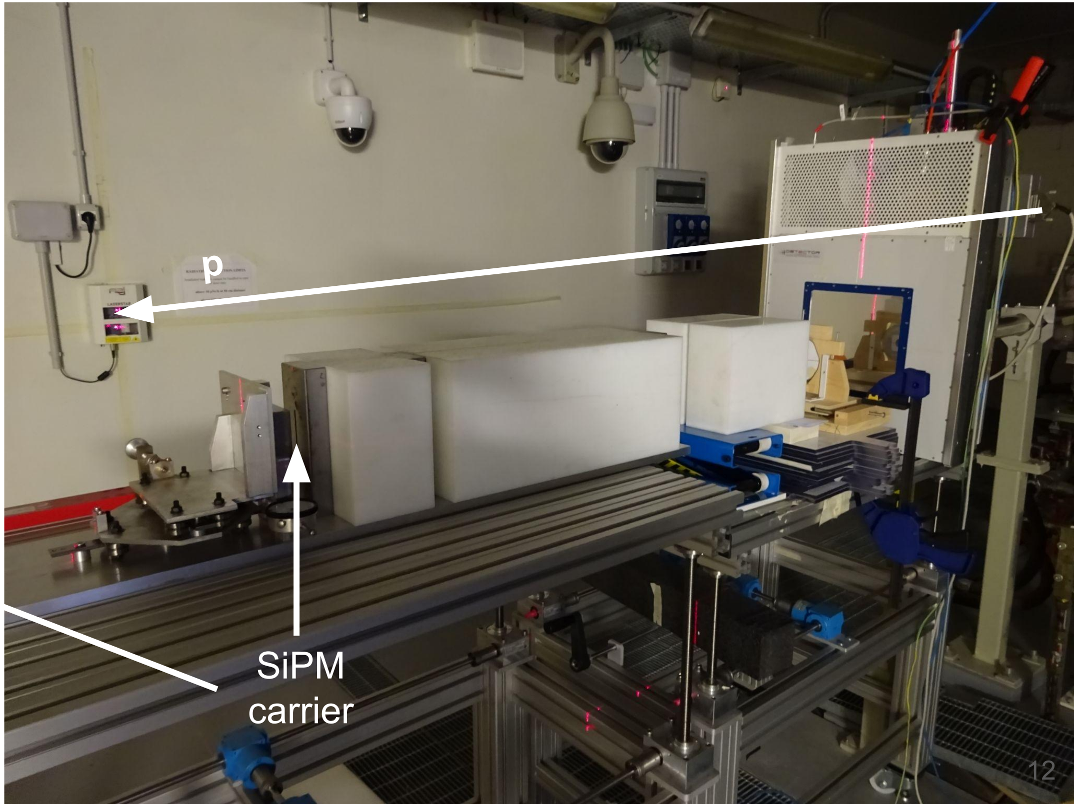
3x3 mm^2 SiPM sensors
4x8 “matrix” (carrier board)

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

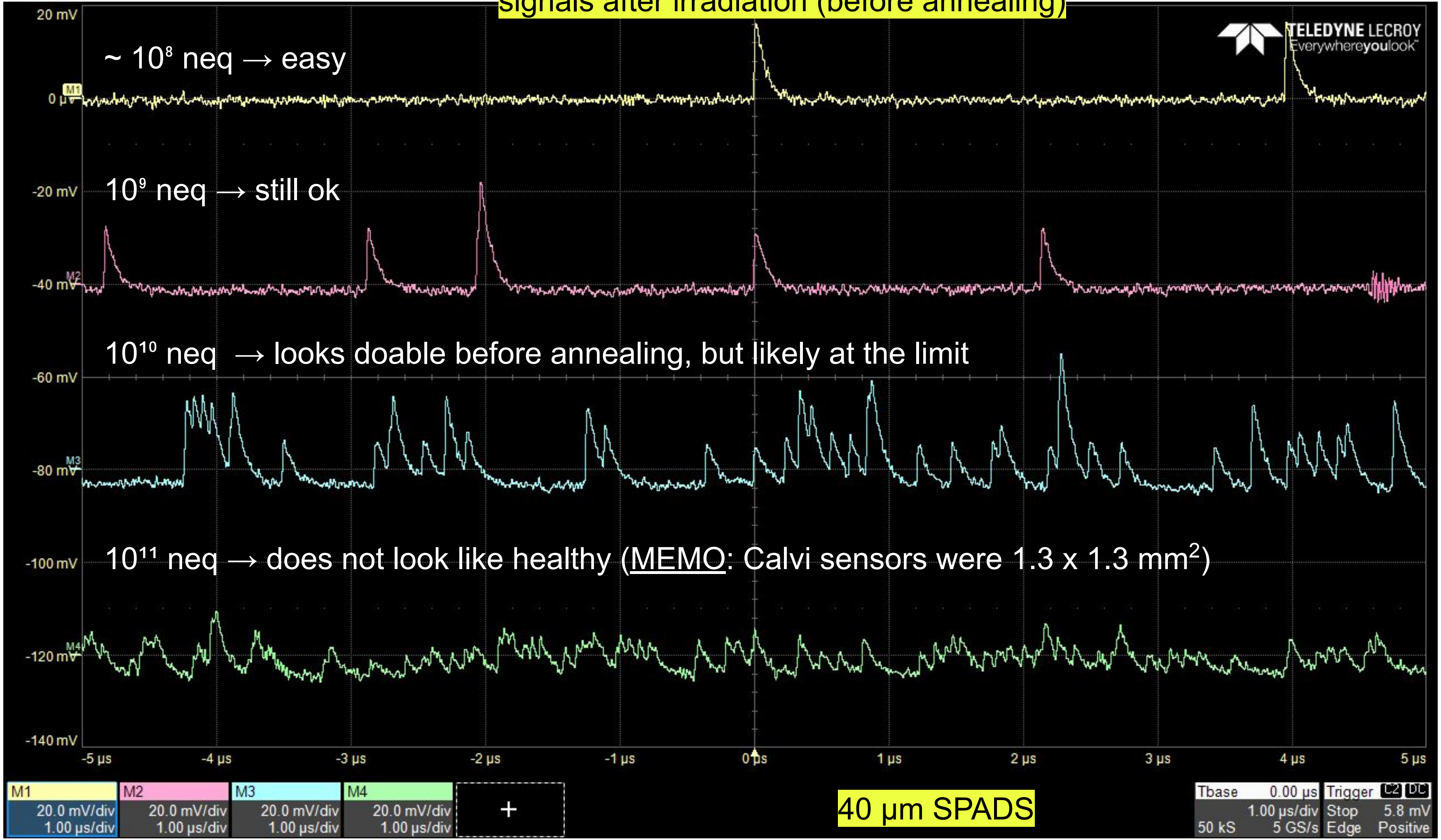
148 MeV protons → scattering system → collimation system → carrier board







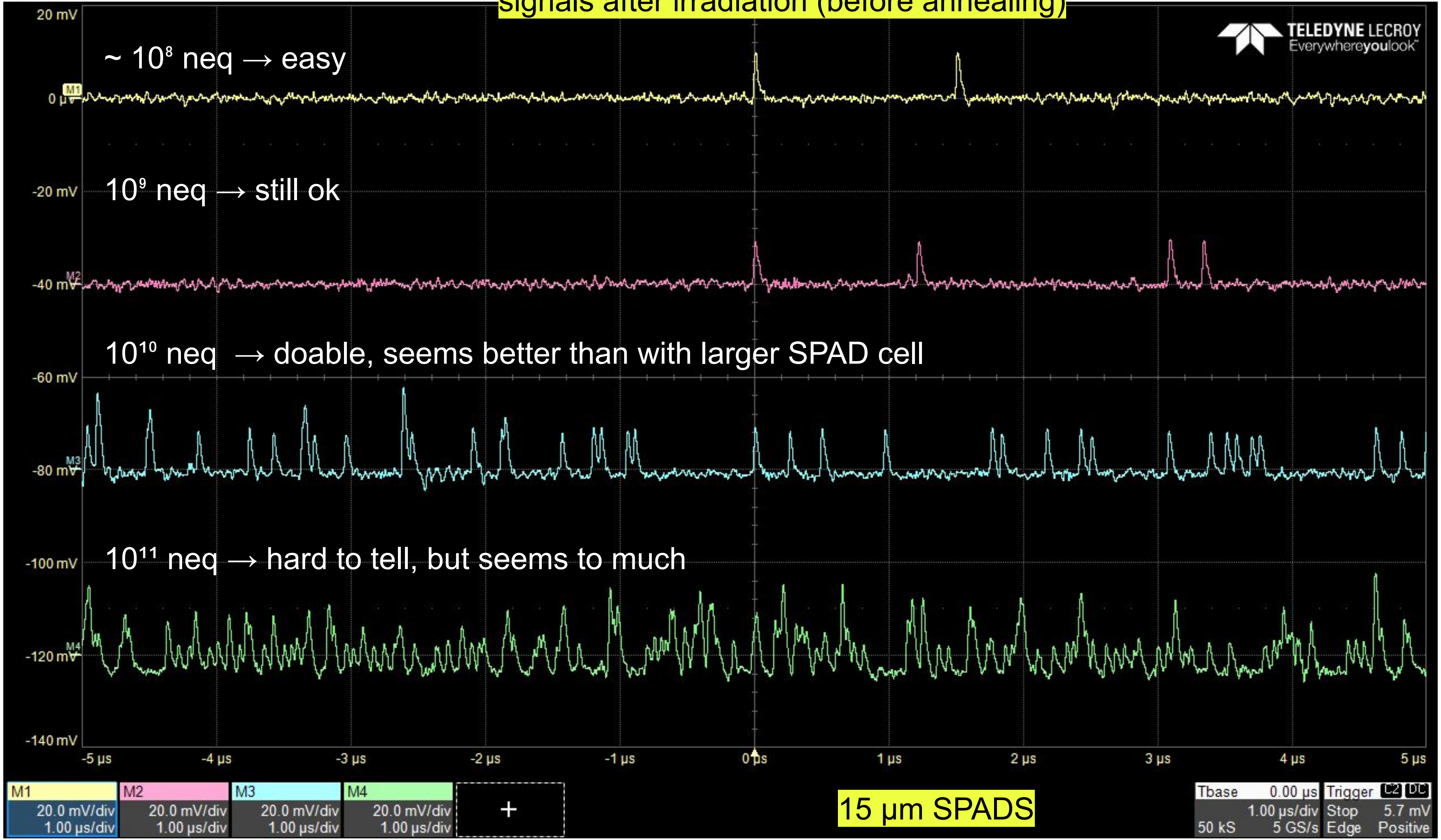
signals after irradiation (before annealing)



FBK #3 (T = -30 C)

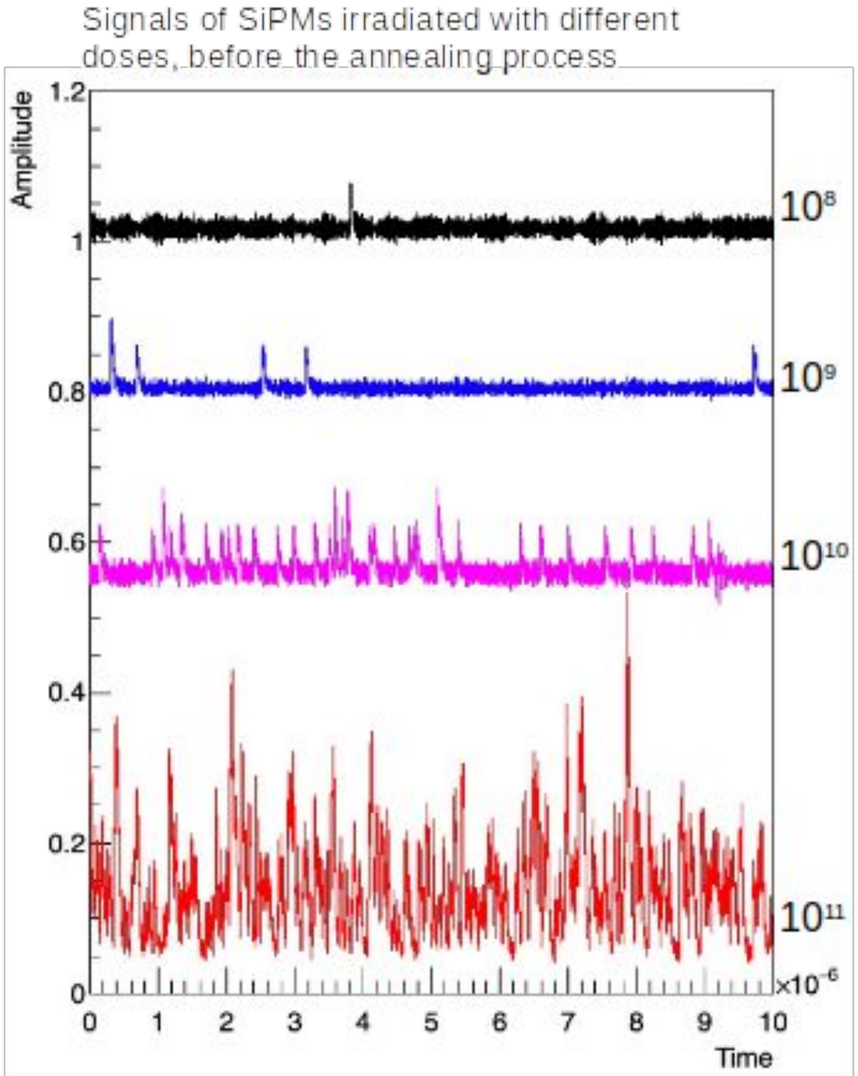
NUV-HD-CHK (row A)

signals after irradiation (before annealing)



FBK #3 (T = -30 C)

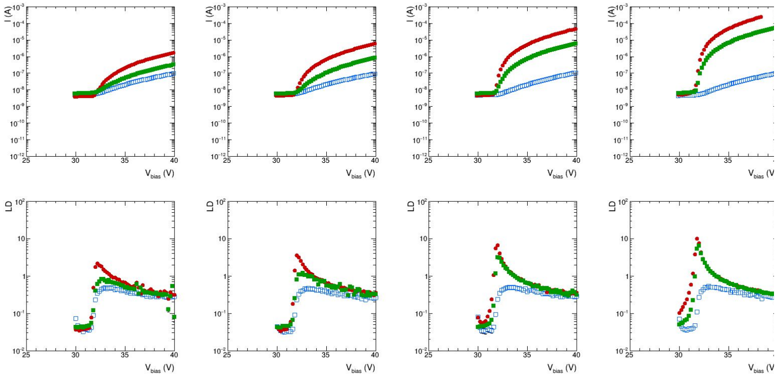
NUV-HD-RH (row B)

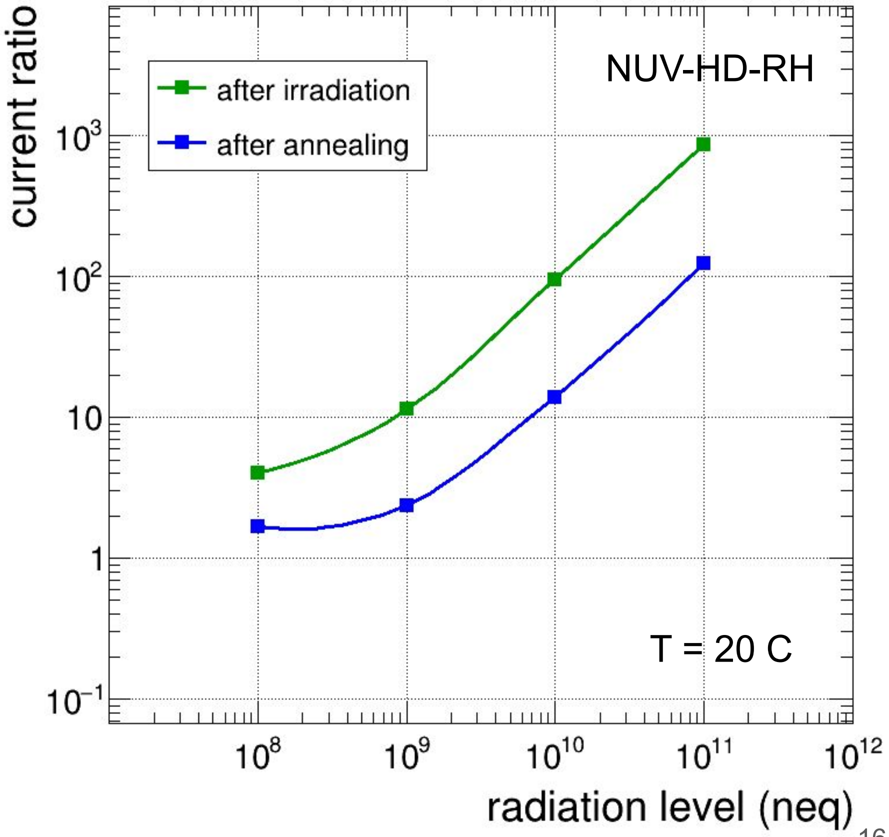


also Hamamatsu sensors seem to be doing ok up to 10^{10} neq

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

new
irradiated
annealed





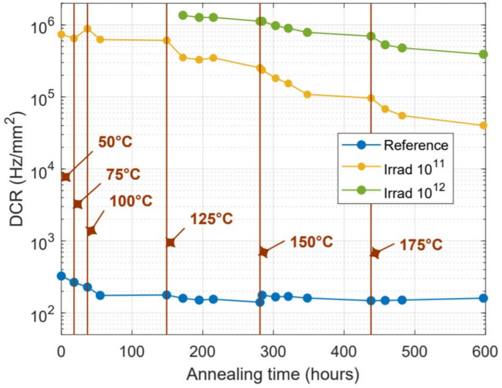
annealing reduced dark current by a factor of ~5-10, in line with expectations

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

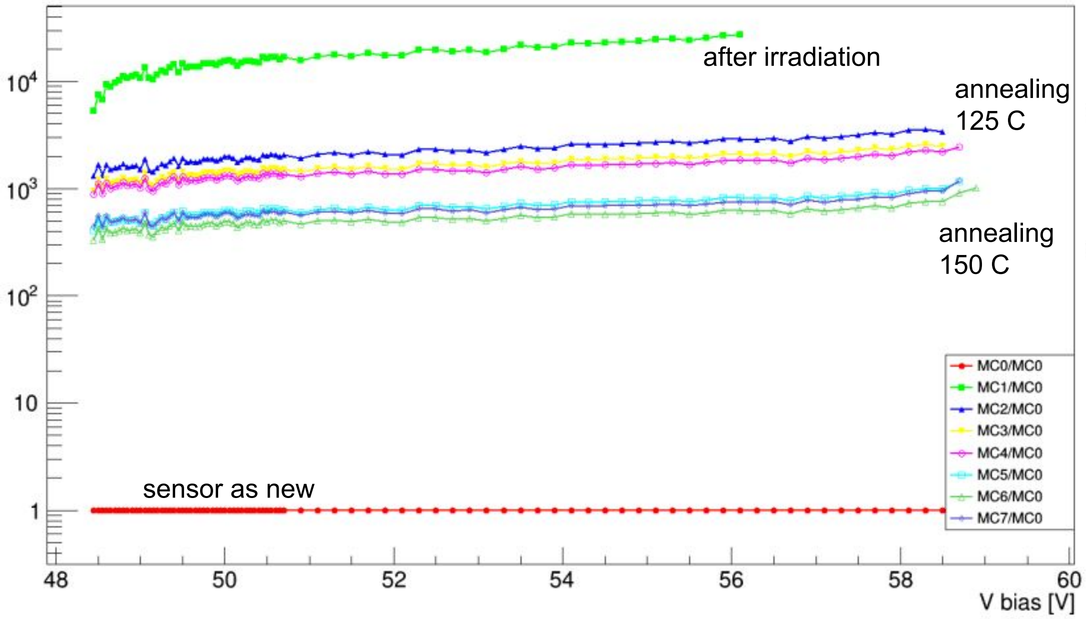
FBK annealing stopped at 125 C at the time
little issue related to the solder paste used during assembly (T = 138 C) did not allow to reach T = 175 C
→ needed reworking of the carrier boards
→ reworked boards back from company a few days ago

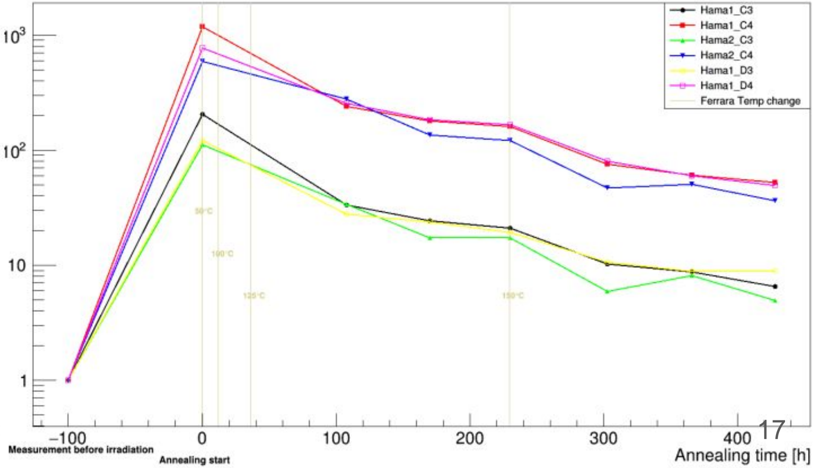
Hamamatsu annealing up to T = 150 C completed

behaviour in line with literature (Calvi et al)



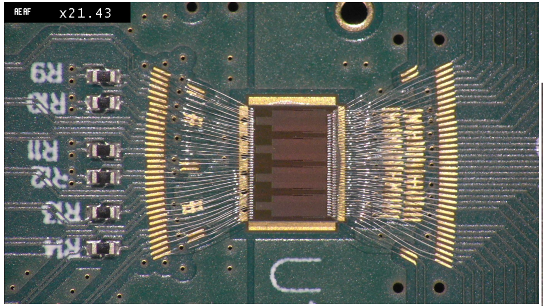
current ratio wrt. before irradiation

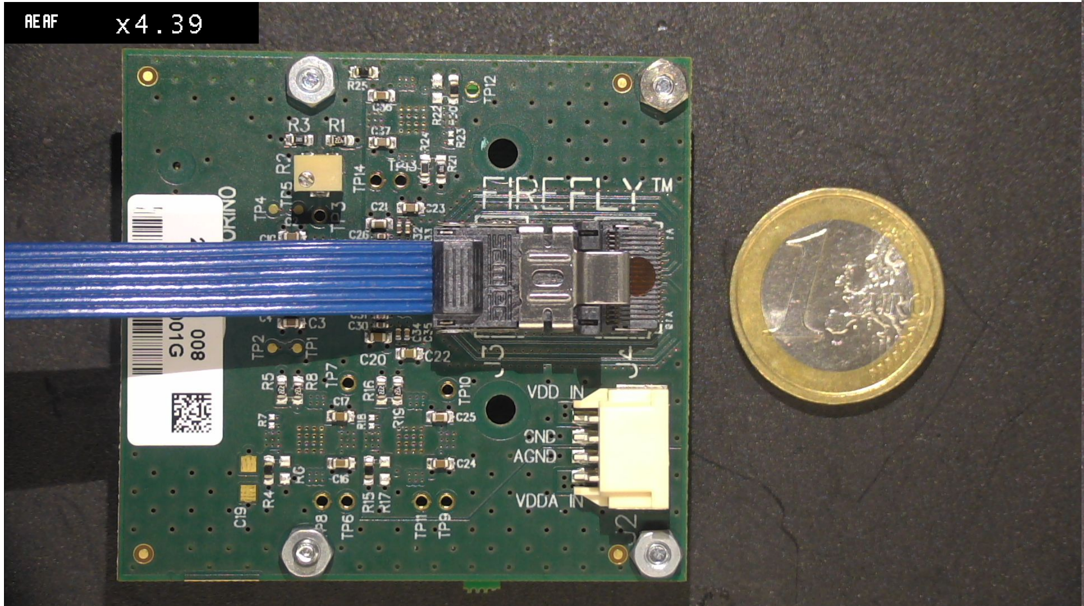




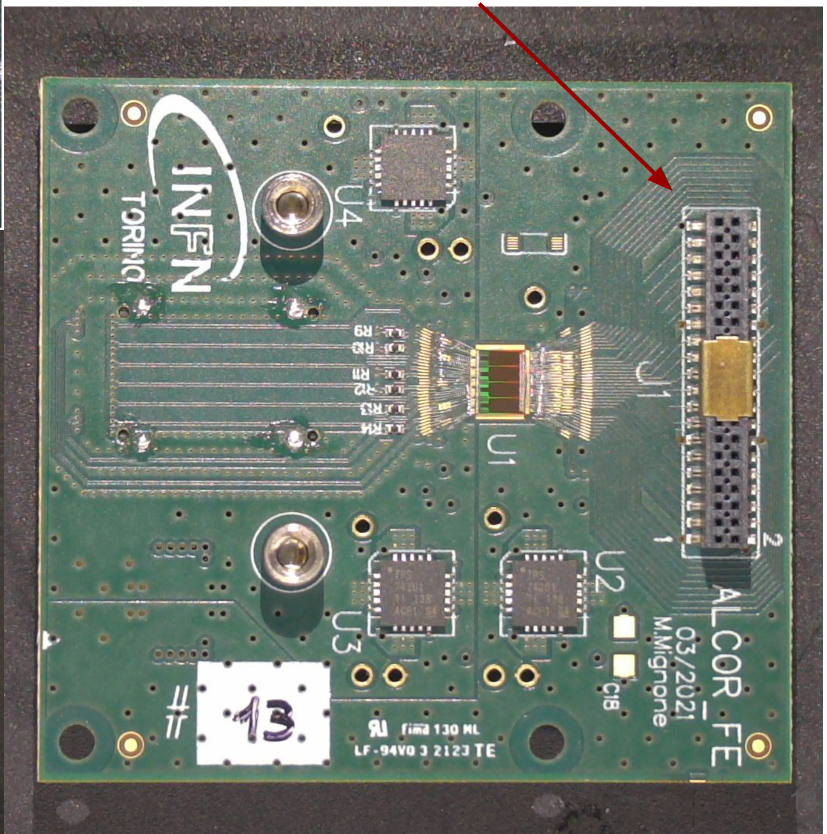
ALCOR – A Low Power Chip for Optical sensor Readout

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



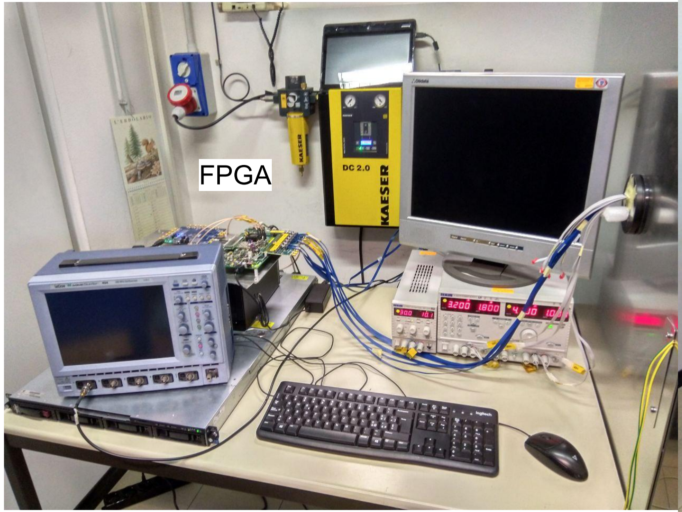


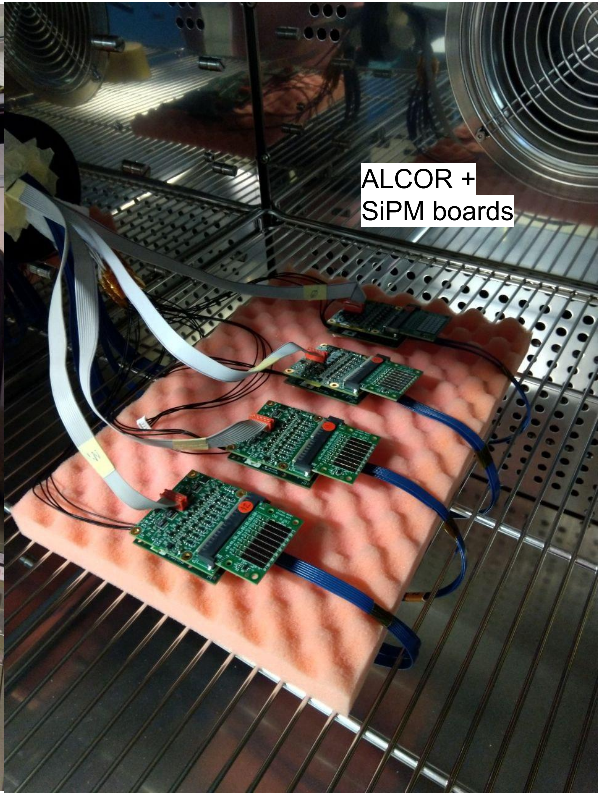
connector to adapter-CA board



SiPM+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!





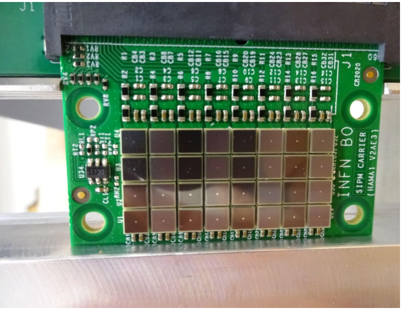
plan to add laser diode (or LED) soon
illuminate SiPM inside chamber
measure correlation on top of DCR

the following results have been obtained with this setup

Hamamatsu (HAMA1 #2) threshold scans

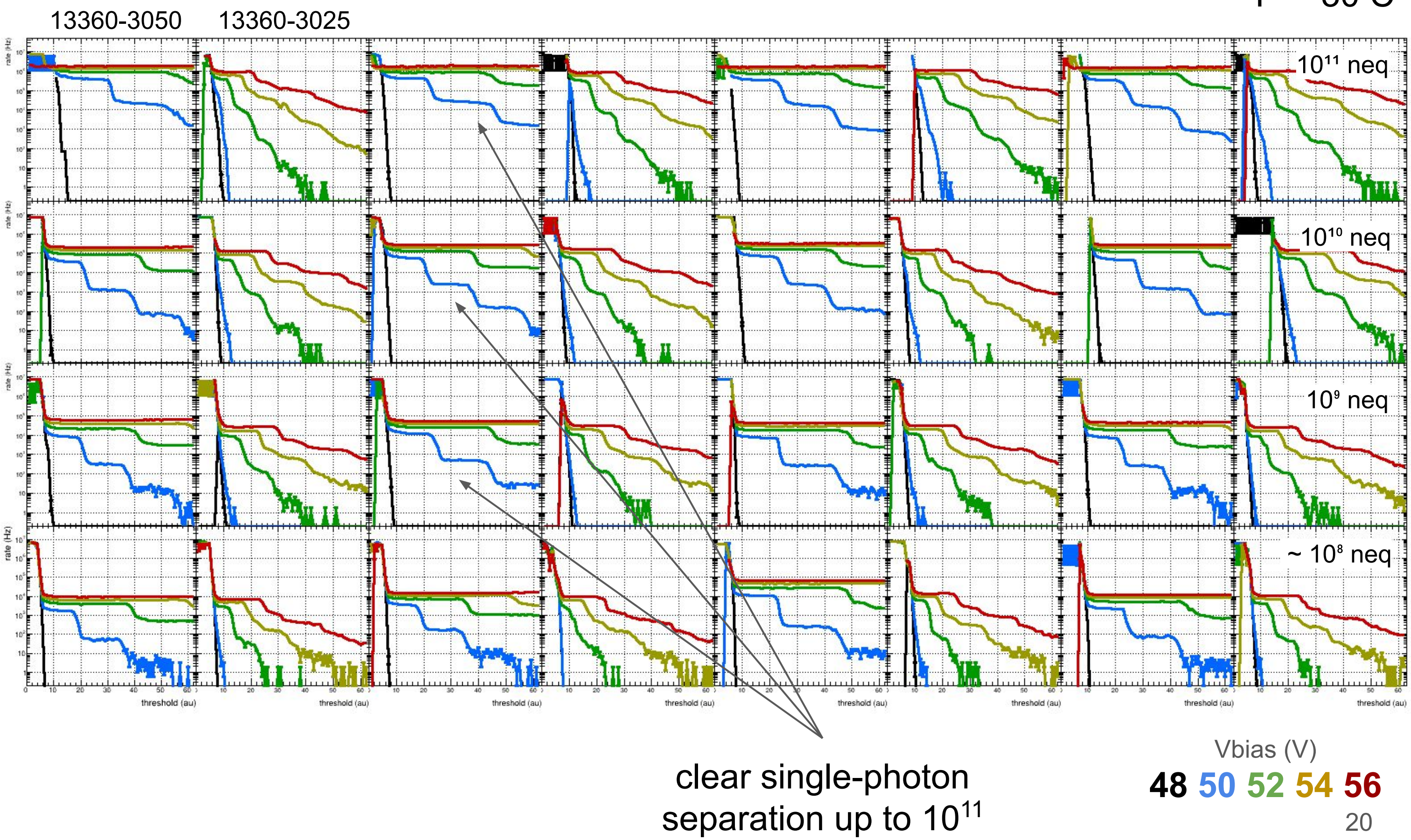
PRELIMINARY

T = -30 C



irradiated board after annealing

still working!

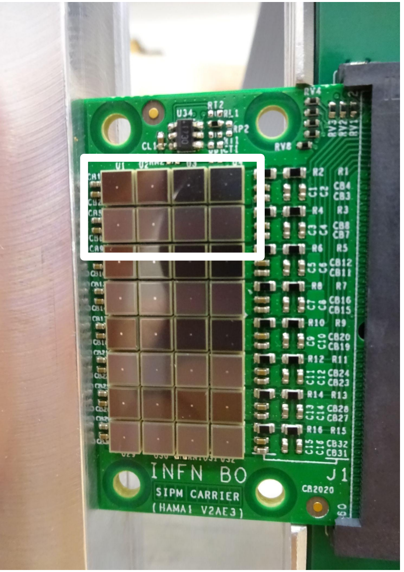


Hamamatsu (HAMA1) grand comparison

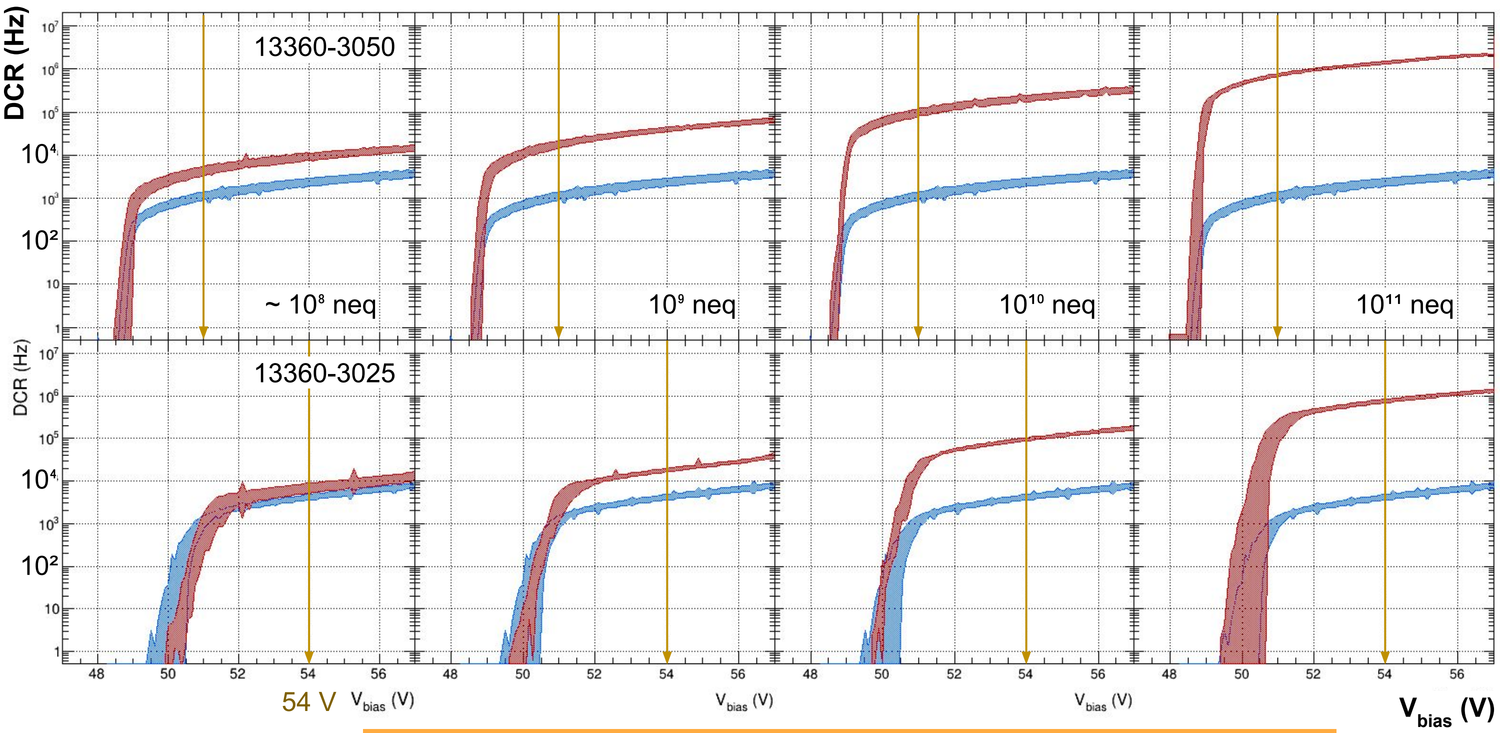
PRELIMINARY

T = -30 C

not irradiated board



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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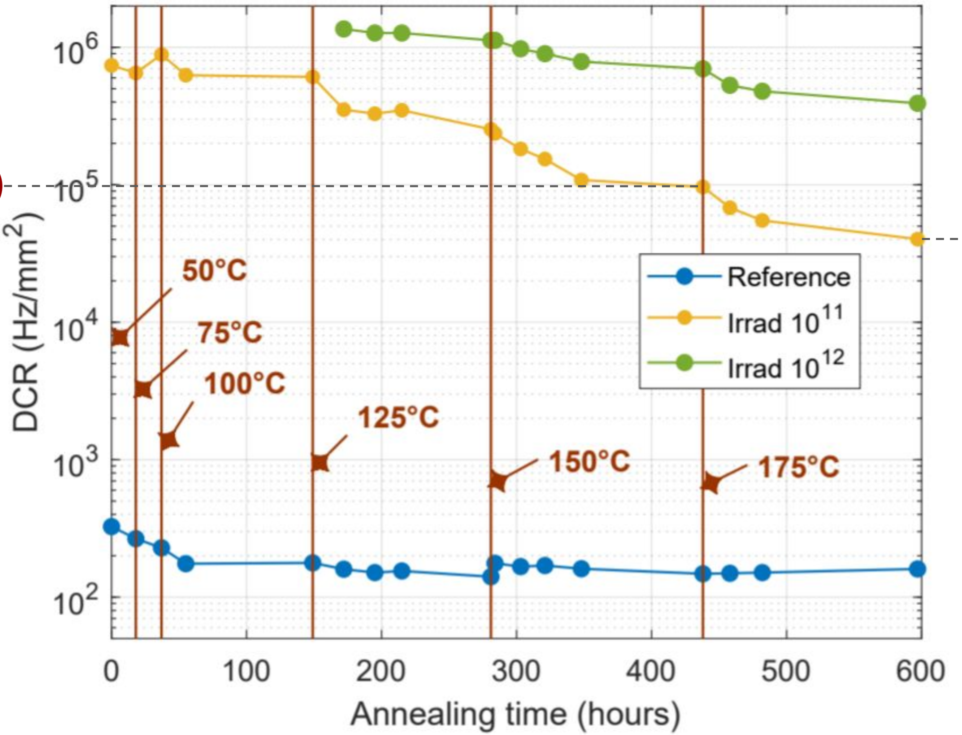
Hamamatsu (HAMA1) grand comparison

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 2(4)x factor
operating at T = -40(-50) C
we know DCR decreases by 2x every 10 C

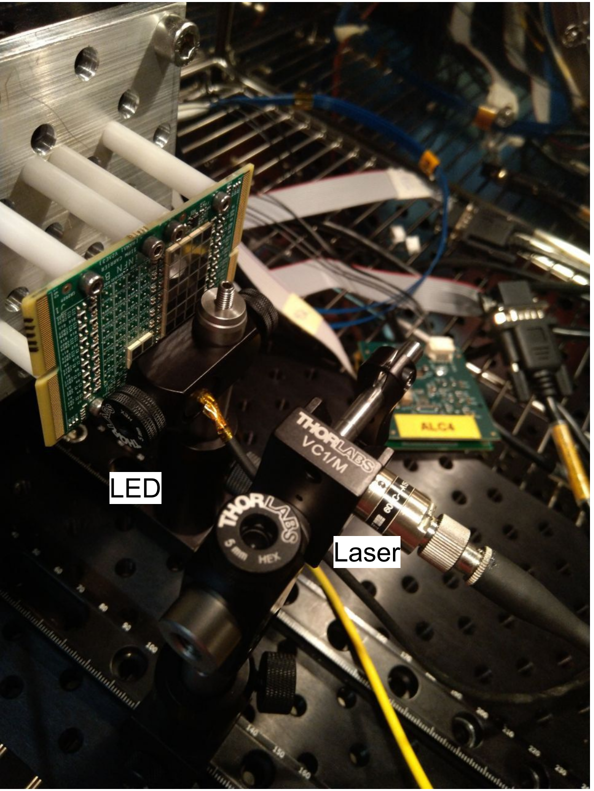
900 kHz
in 3x3 mm^2

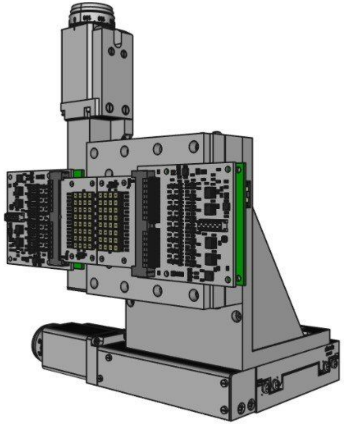


350 kHz
in 3x3 mm^2

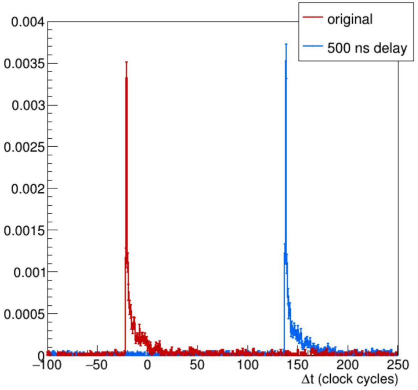
values at the indicated Vbias	new	~ 10^8 neq	10^9 neq	10^{10} neq	10^{11} neq
13360-3050	1.1 kHz	4.4 kHz	18 kHz	100 kHz	730 kHz
13360-3025	2.4 kHz	7.0 kHz	18 kHz	95 kHz	770 kHz

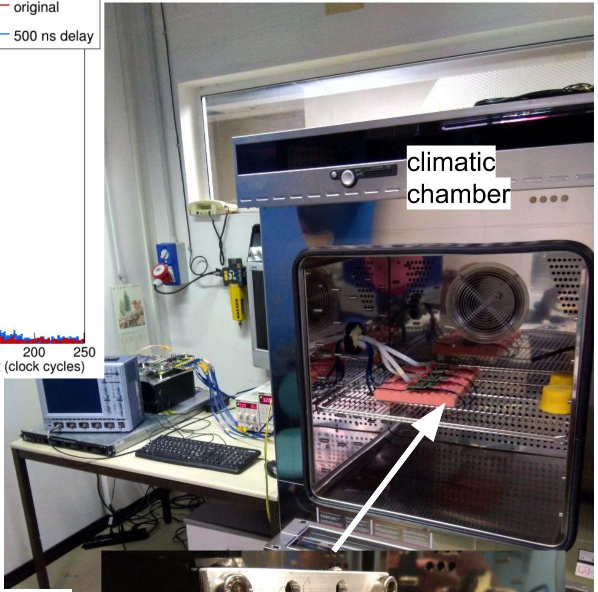
SiPM+ALCOR setup in Bologna



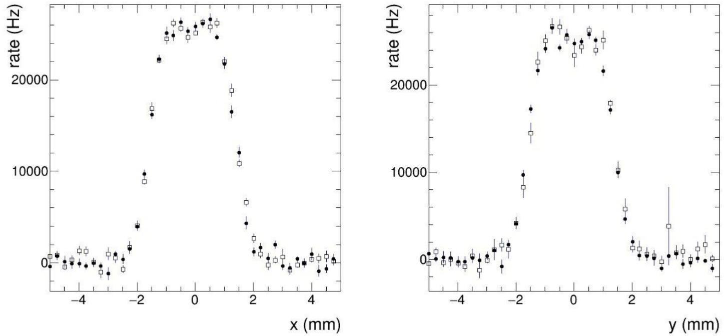


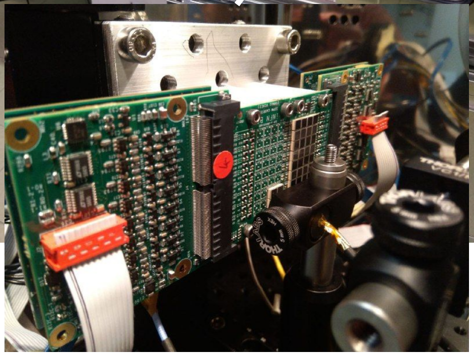
time correlations





position scan



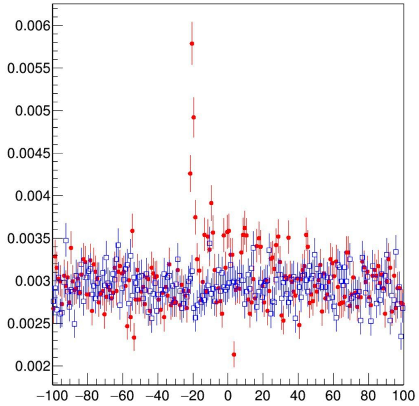


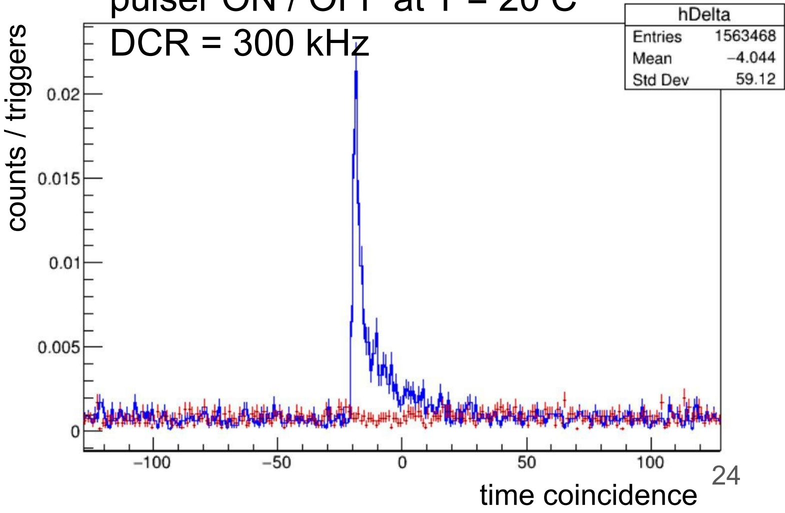
Bologna setup is **being upgraded** in these day with LED, laser and movimentation in climatic chamber

SiPM + ALCOR response with light

- **use the complete electronics built in 2021 for laboratory tests**
  - SiPM carrier + adapter + ALCOR + readout
  - mount everything in the climatic chamber
  - with an LED / laser in front of the sensor
  - plus movimentation to inspect all sensors
- **study response of SiPM to pulsed light**
  - pulsed LED / laser
  - measure increase of rates
  - measure time coincidences
  - compare sensors with different NIEL
- **system is being setup in Bologna**
  - the goal is to have it as a permanent test bench
  - to be used to test SiPM response for 2022 irradiation plan
    - ie. relative variation of PDE
  - to be used to get ready for test beam

NIEL received 10^{11} + annealing





PRELIMINARY

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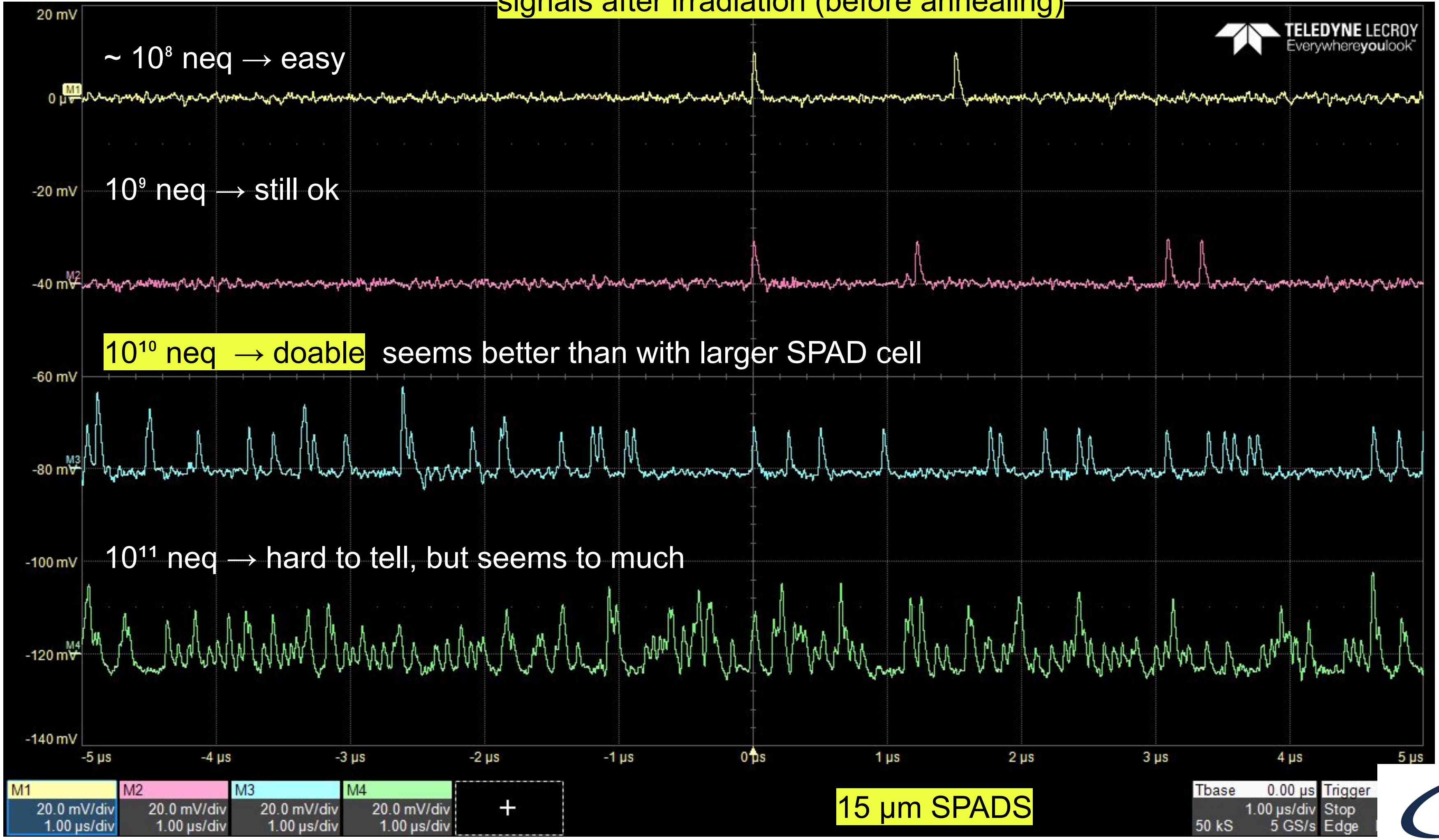
how often do we need to do annealing?

signals after irradiation (before annealing)



~ 10^8 neq → easy

10^9 neq → still ok

10^{10} neq → doable seems better than with larger SPAD cell

10^{11} neq → hard to tell, but seems to much

15 µm SPADS

FBK #3 (T = -30 C)

NUV-HD-RH (row B)

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How often to do annealing

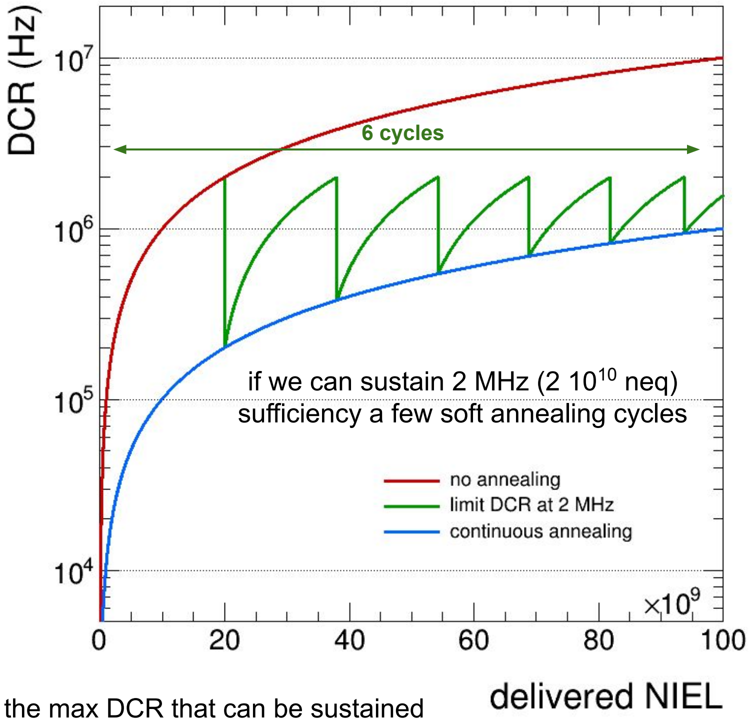
assumptions

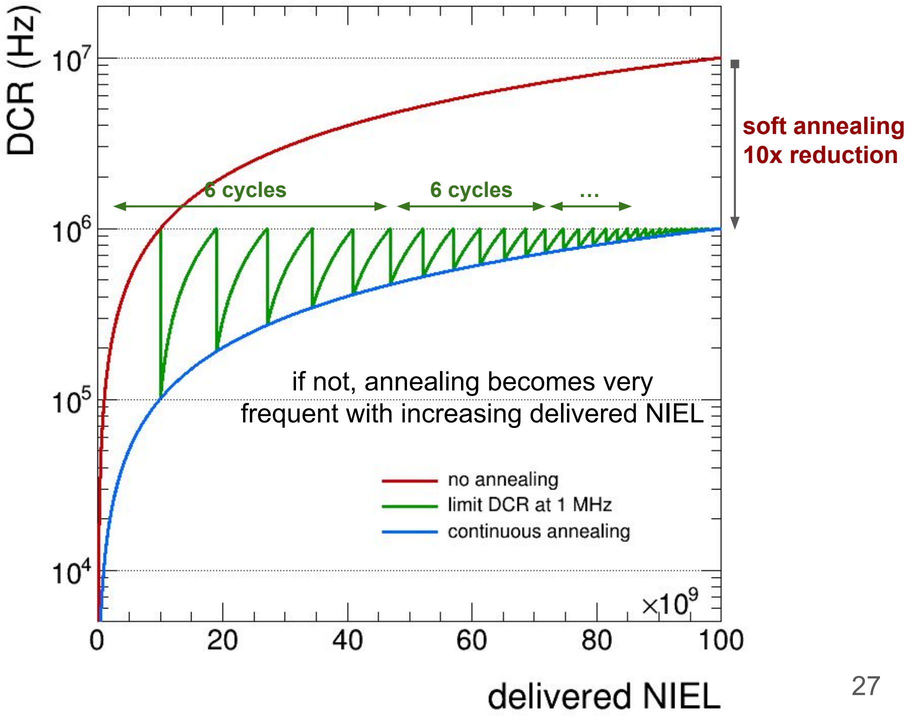
- NIEL = 10^{11} neq/cm^2 ⇒ DCR = 10 MHz
- DCR increases proportionally to NIEL
- annealing always cures same fraction of damage caused by NIEL
  - constant fraction of new damage, regardless total damage

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

How often to do annealing

EXAMPLE

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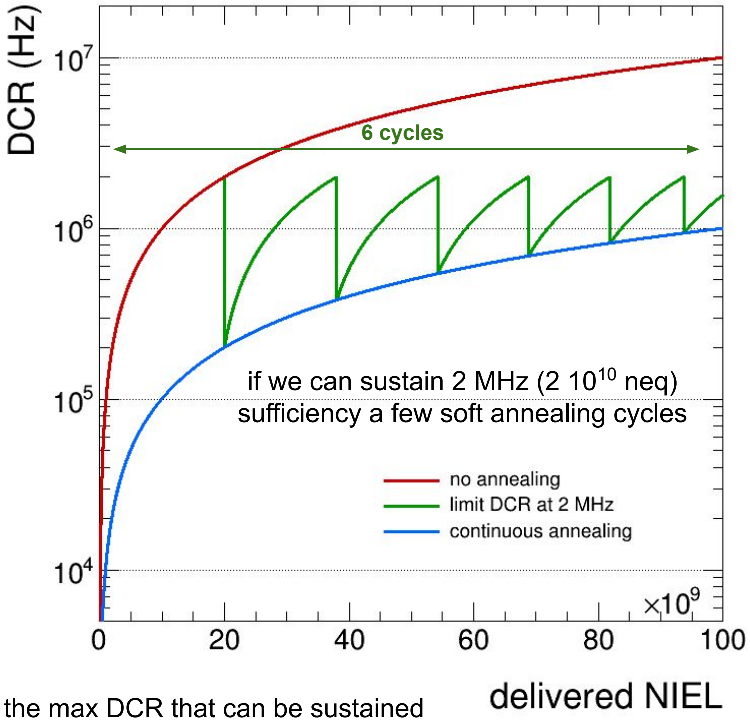
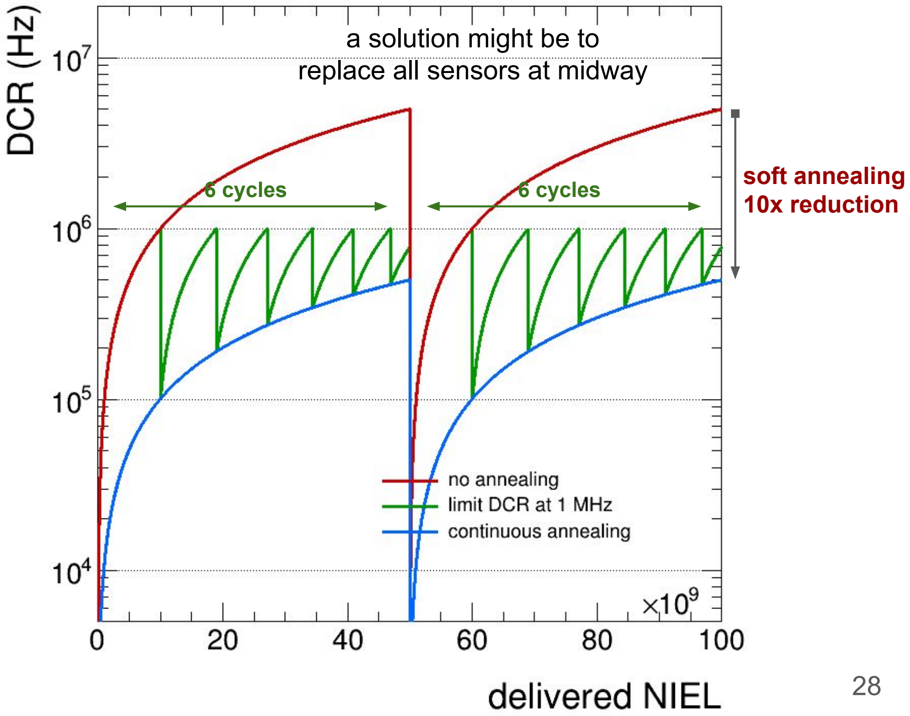
10^{10} neq





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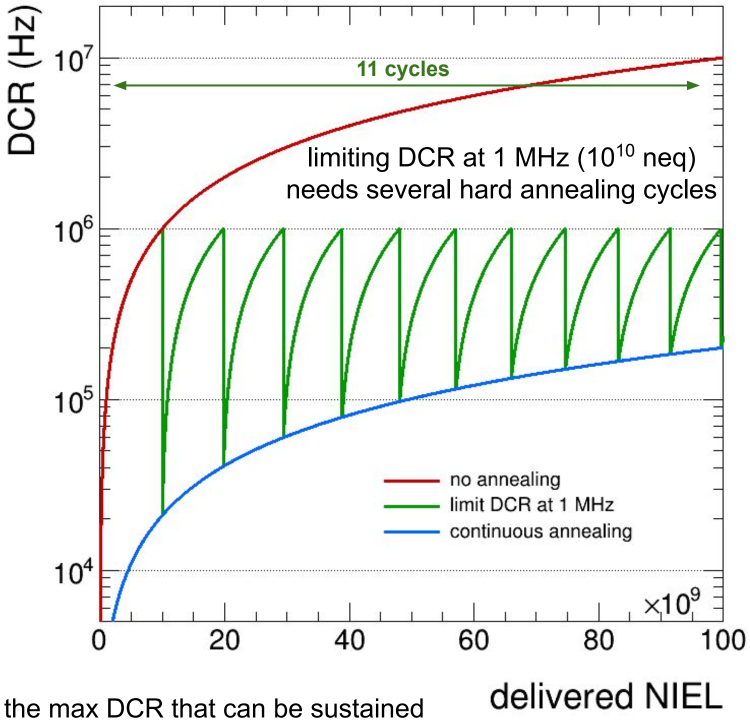
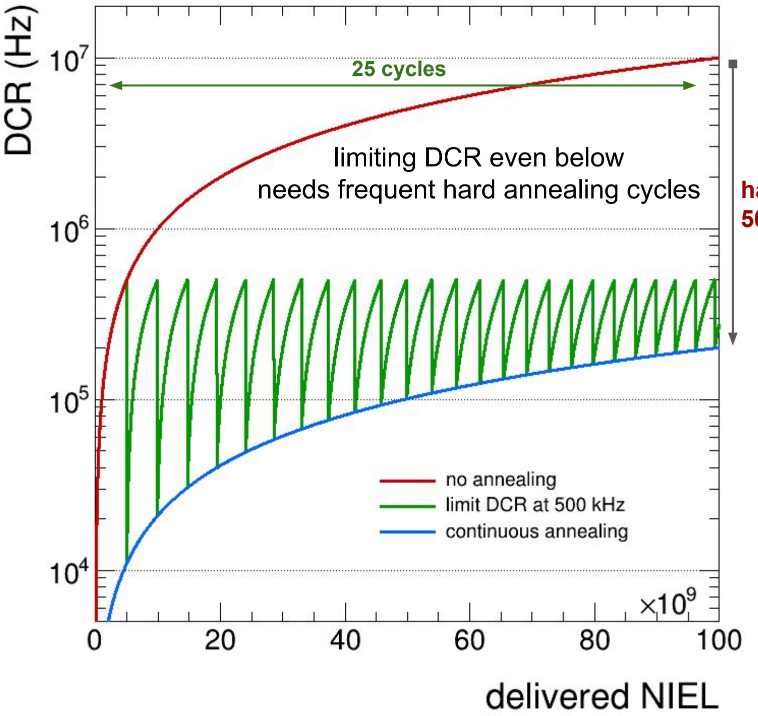
EXAMPLE

10^{10} neq





hard annealing
50x reduction

it depends on the max DCR that can be sustained

How often to do annealing

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- NIEL = 10^{11} neq/cm^2 ⇒ DCR = 10 MHz
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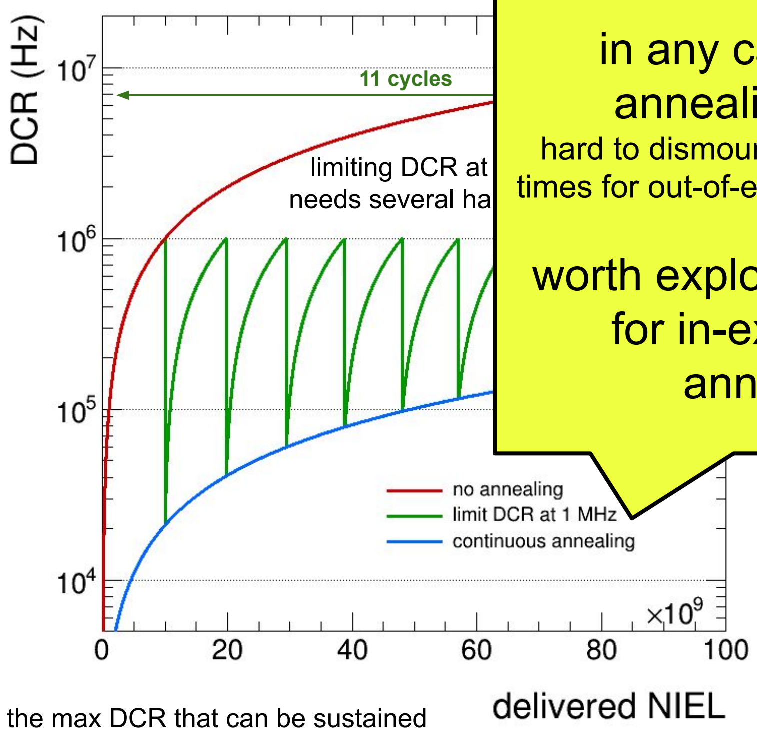
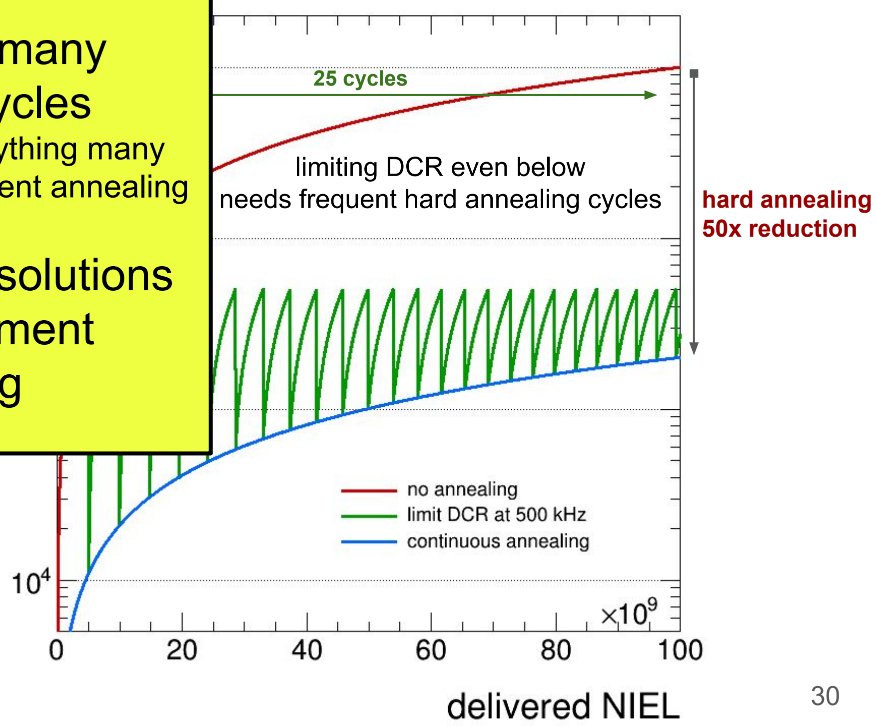
10^{10} neq





in any case, many annealing cycles

hard to dismount everything many times for out-of-experiment annealing

worth exploring solutions for in-experiment annealing

it depends on the max DCR that can be sustained

2022 irradiation proposal

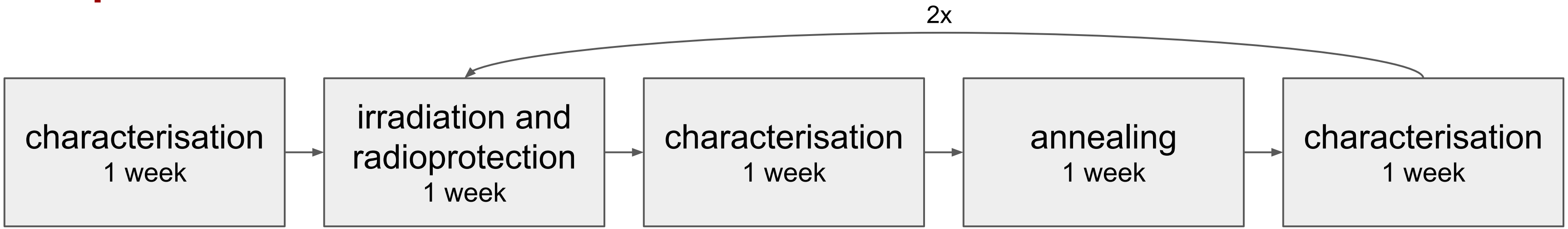
test SiPM performance and annealing with increasing integrated NIEL

simulate a more realistic experimental situation

irradiate full SiPM carrier boards with flat proton field

no collimators, his will make life much easier and very efficient use of beam

- **3 short accesses at TN protontherapy centre (TIFPA) in spring**
  - ideally 4 hours on Saturdays, should be sufficient time to setup and fire the beam
  - tentative dates: 30 April, 28 May and 25 June
  - one access every 4 weeks: allow time for radioprotection, characterisation and annealing
  - small NIEL integration steps, perhaps: 1 10^9 , 2 10^9 , 4 10^9
- **plus 1 more access in fall**



Summary

- **SiPM as photosensors for RICH applications**
  - many pros
  - a few cons
- **R&D program has started**
  - well linked with ASIC development
  - from first irradiation results, SiPM look a very promising option
    - soon correlation/efficiency studies with laser/LED on irradiated SiPM
    - test if we can efficiently distinguish the signal from the DCR
  - next irradiation campaign in 2022
    - test SiPM performance and annealing with increasing integrated NIEL
    - simulate in a more realistic way operation in experimental environment
  - approaches and discussions for sensor development
    - develop radiation harder SiPMs
    - opportunities to exploit INFN-FBK collaboration experience and agreements
- **further engineering needs for SiPM operation in experiment**
  - DAQ system must be able to sustain rate
    - there are handles for that (staging + interaction signal, …)
  - bring cooling, down to -30 C (or perhaps even -50 C)
    - LHCb experience with SiPM cooling
  - 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

Where we are

- **several reference publication on SiPM radiation damage / recovery**
  - review on radiation damage of SiPM
    - https://inspirehep.net/literature/1694163
  - Calvi et al studies on annealing
    - https://inspirehep.net/literature/1674007
  - also studies on annealing with forward bias current
- **main messages**
  - single-photon detection possible with low-T operation and annealing
    - up to ~ NIEL 10^{11}
  - main SiPM characteristics / parameters do not change up to ~ NIEL 10^{12}
  - limits depend on many factors related to the SiPM design and the operation conditions
    - it should be tested for each specific application.
- **several directions for development of radiation harder SiPMs**
  - see following slides

Approaches to develop radiation harder SiPMs

Approaches to develop radiation harder SiPMs

- **as outlined in Garutti et al. “Radiation damage of SiPMs”**
  - https://inspirehep.net/literature/1694163
- **dark noise reduction**
  - optimizing the field in the depletion region through field shaping, by
    - reducing the thickness of the depleted region
    - reducing trap-assisted tunneling by reducing the peak electric field in the SiPM p–n-junction.
  - unfortunately these two approaches contradict each other
    - careful R&D has to be performed to find an optimum compromise
- **we selected commercially-available SiPM to study radiation response**
  - different V_{bd} characteristics and likely different substrate doping / technology
  - thickness of the depleted region can be measured in laboratory
- **discussion with producers / R&D facilities (FBK)**
  - will help finding the direction for the optimisation required for EIC

Approaches to develop radiation harder SiPMs

- **as outlined in Garutti et al. “Radiation damage of SiPMs”**
  - https://inspirehep.net/literature/1694163
- **cell occupancy reduction**
  - the cell occupancy reduction can be achieved by
    - reducing the cell active volume (smaller cell size)
    - and cell recovery time
  - however SiPMs with high cell density have large non-sensitive zone areas
    - occupied by polysilicon quenching resistors which are almost opaque
  - the solution to this problem can be the use of
    - very thin trenches (<0.5 μm) separating cells
    - the use of metal film resistors with high transparency to visible light
- **FBK NUV-HD technology uses trenches**
  - we acquired commercial and prototype FBK NUV-HD sensors
    - also with very small SPADs developed for radiation hardness
- **discussion with producers / R&D facilities (FBK)**
  - will help finding the direction for the optimisation required for EIC

Approaches to develop radiation harder SiPMs

- **as outlined in Garutti et al. “Radiation damage of SiPMs”**
  - https://inspirehep.net/literature/1694163
- **reduction of the damage in SiPM entrance window**
  - the SiPM entrance window material has to be chosen appropriately
    - avoiding materials with hydrogen or boron content
  - thickness of the SiO2 layer has to be properly adjusted taking into account surface effects
  - thickness of the non-depleted region near the SiPM entrance window has to be minimized
- **effects of high-temperature annealing on the SiPM entrance window**
  - material has to be chosen appropriately also for that
    - avoid material that become opaque to light in the wavelength of interest
- **discussion with producers / R&D facilities (FBK, Hamamatsu)**
  - we acquired samples of entrance windows from Hamamatsu
    - detailed studies of transparency and modifications with radiation + annealing
  - FBK prototype sensors we acquired
    - packaged for us with special resin to resist radiation high-T annealing e radiation

Where else the technology has to improve

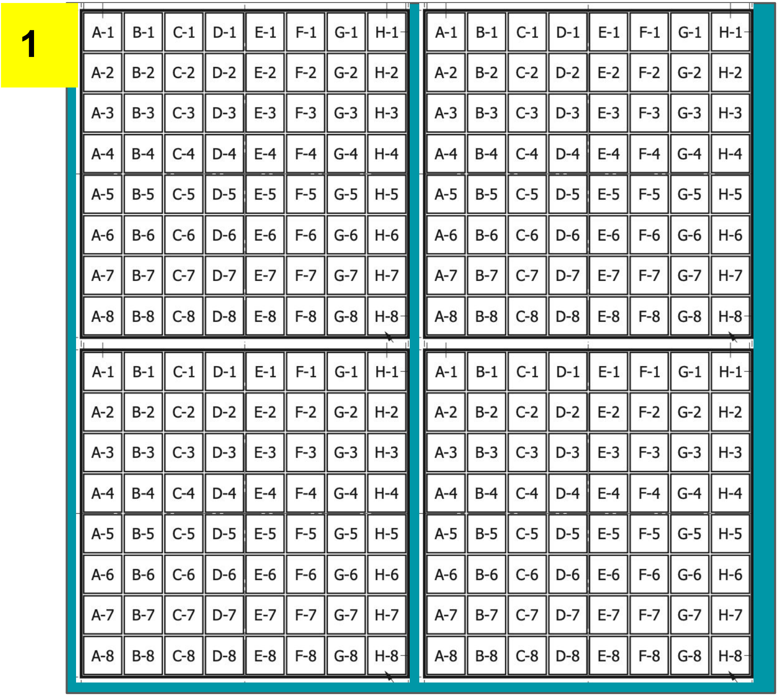
- **where else the technology has to improve**
  - SiPMs need electronics capable to sustain the high DCR rates after radiation
    - ASIC
    - DAQ system + strategies to efficiently / cleverly deal with it
    - see following slides on DAQ and readout considerations
- **what the prospects are**
  - in year 2022: consolidate on SiPMs as a viable option for dRICH
  - in following 2-3 years (TDR): demonstrate SiPM capability to work within EIC specs
    - both sensors and electronics
  - on a longer timescale we expect further optimisation of the sensors
- **where we can benefit from synergies**
  - LHC studies (LHCb RICH upgrade, a group in Ferrara)
  - INFN-FBK collaboration agreement
  - further developments within INFN (DarkSide, ARCADIA, ….)
  - furter synergies / collaboration with US groups interested on SiPMs for calorimetry
- **what do we need to focus on**
  - develop instrumentation and test-bench setups
  - establish status of commercial SiPM and manufactures
  - develop protocols for cooling and annealing
  - engineering problems for a large low-T ~ 100% coverage SiPM array for EIC

DAQ and readout considerations

dRICH readout current scheme (I)

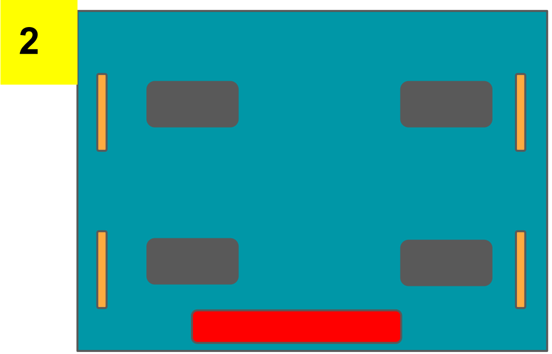
current scheme: caveat: used for proposal/costing not necessarily the final one. A lot of work ahead, but useful to focus on requirements

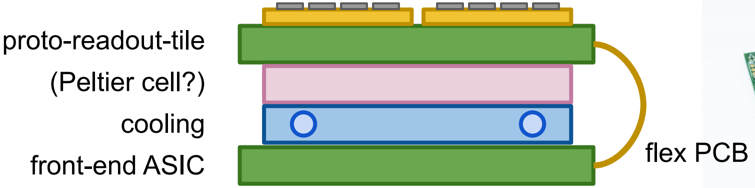
dRICH tile: 1024 x 3x3 mm^2 SIPM sensors

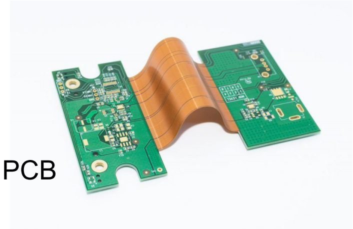


dRICH tile 5.6 x 5.6 cm^2

FEB: Front-End board with ALCOR ASIC (64 ch)



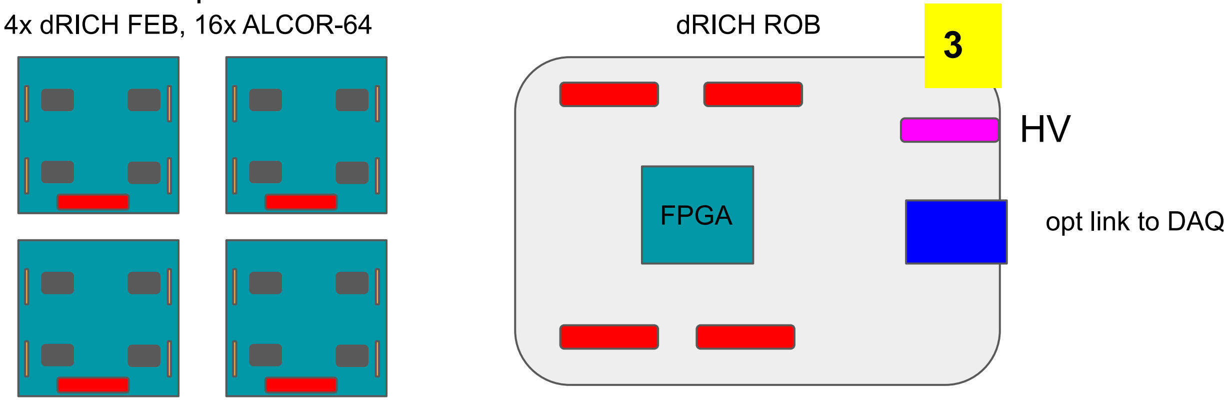




- Note cooling performance is critical (factor 2 less in DCR every 10 C)
- LHCb SciFi cooling system for SIPM expected to work at T=-50 C → factor 4 less in DCR

dRICH readout scheme (II) ROB (read-out board)

- based on readout/throughput considerations 4 dRICH FEB (1024 ch) should be read-out by 1 dRICH ROB (4096 channels)
- ROB acts as concentrator + data reduction (BC timing) (factor 3-5: EIC 1 BC every 9.6 ns: just get a fraction (like 2 ns of window of interest or possibly less: potential spread is 150 ps but bunch length 0.3-0.4 ns!). In current estimate applied only a factor 3 reduction (could be 5)
- ROB potential area 10x10 cm^2



current scheme assume ATLAS FELIX board on PC
+ lpGBT link on ROB

- This choice for throughput modelling keeps bandwidth on opt link to DAQ < 10 Gbps (current limitation)
- On each FEB-ROB bus expected throughput at 4 Gbps (at maximum damage from rad before annealing) if no veto on ALCOR is possible
- On each opt-link (after data reduction via timing): 5.9 Gbps

Throughput considerations & SIPM

SIPM radiation damage will increase DCR. Total throughput for a dRICH-class detector ($3x10^5$ channels - sensor area 3x3 mm^2), assuming an average 300 kHz DCR/sensor goes to 1.8 Tbps

Note: available on the market SIPMs, operated at T=-30 C, have DCR at 3 kHz -> At “turn on” day dRICH will have 18.0 Gbps throughput

The average limit of 300 KHz was assumed because:
it is where Hamamatsu irradiated at 10^11 1 MeV-neq were brought back in DCR after annealing (“worst case”)
it allows one to keep a manageable number of optical links (310 (assumed limited at 10 Gbps as per current Felix board) and Felix boards

→ Therefore, 300 KHz is currently the average DCR/sensor that triggers “annealing” when reached

However:

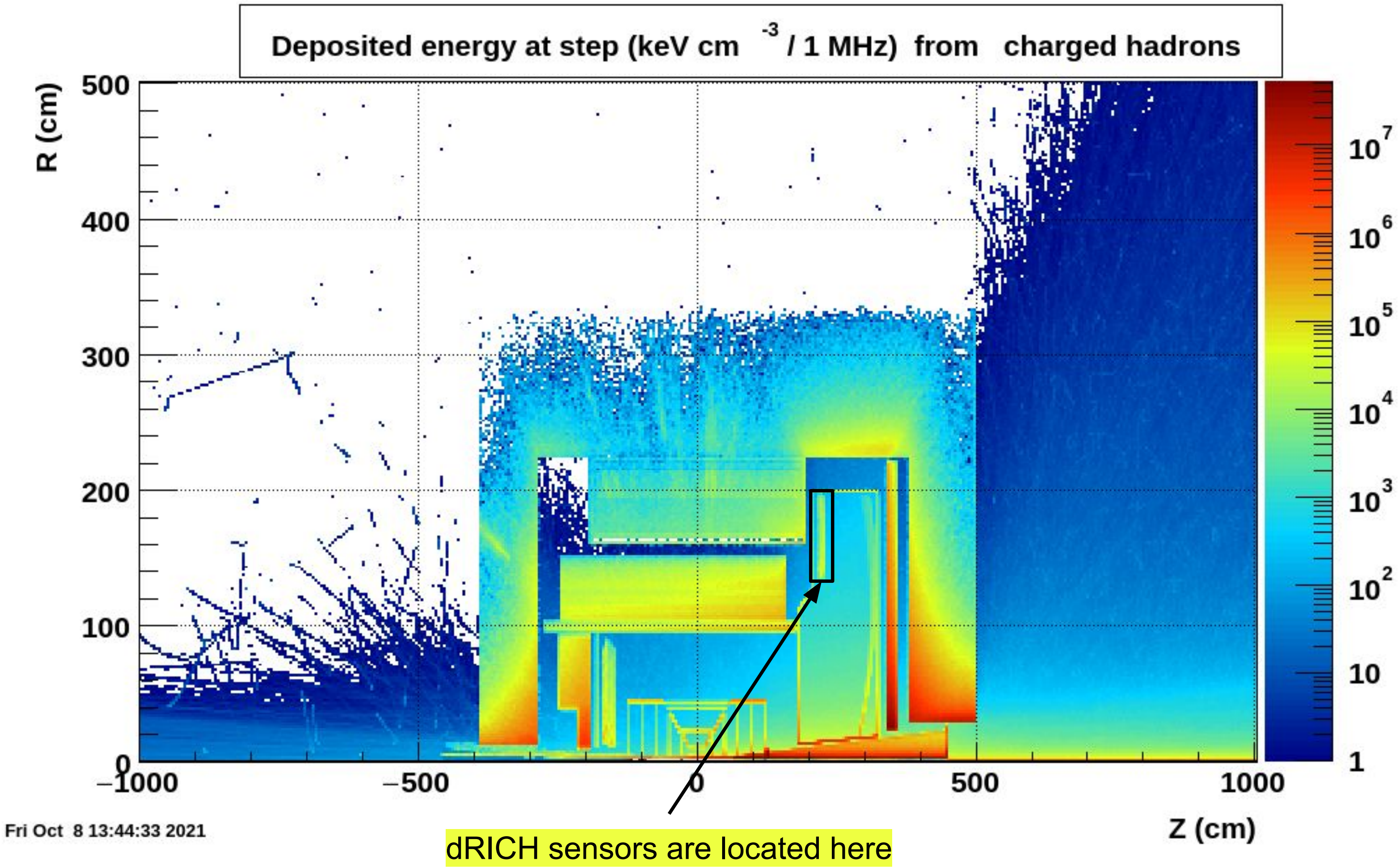
- already available on the market high-end switches (as ARISTA R3 series offer links at 400 Gbps single link and are capable of managing 200 Tbps input rate). The 10 Gbps limitation will certainly go
- if we give up TOT information throughput will decrease by a factor 2
- if we have a MB pre-trigger (GEM/rWell close to dRICH) distributed to our ROB cards (or to a central switch) with sufficient small latency (note ARISTA R3 switches have 24 GB buffers on each port) we could reduce by a factor 200

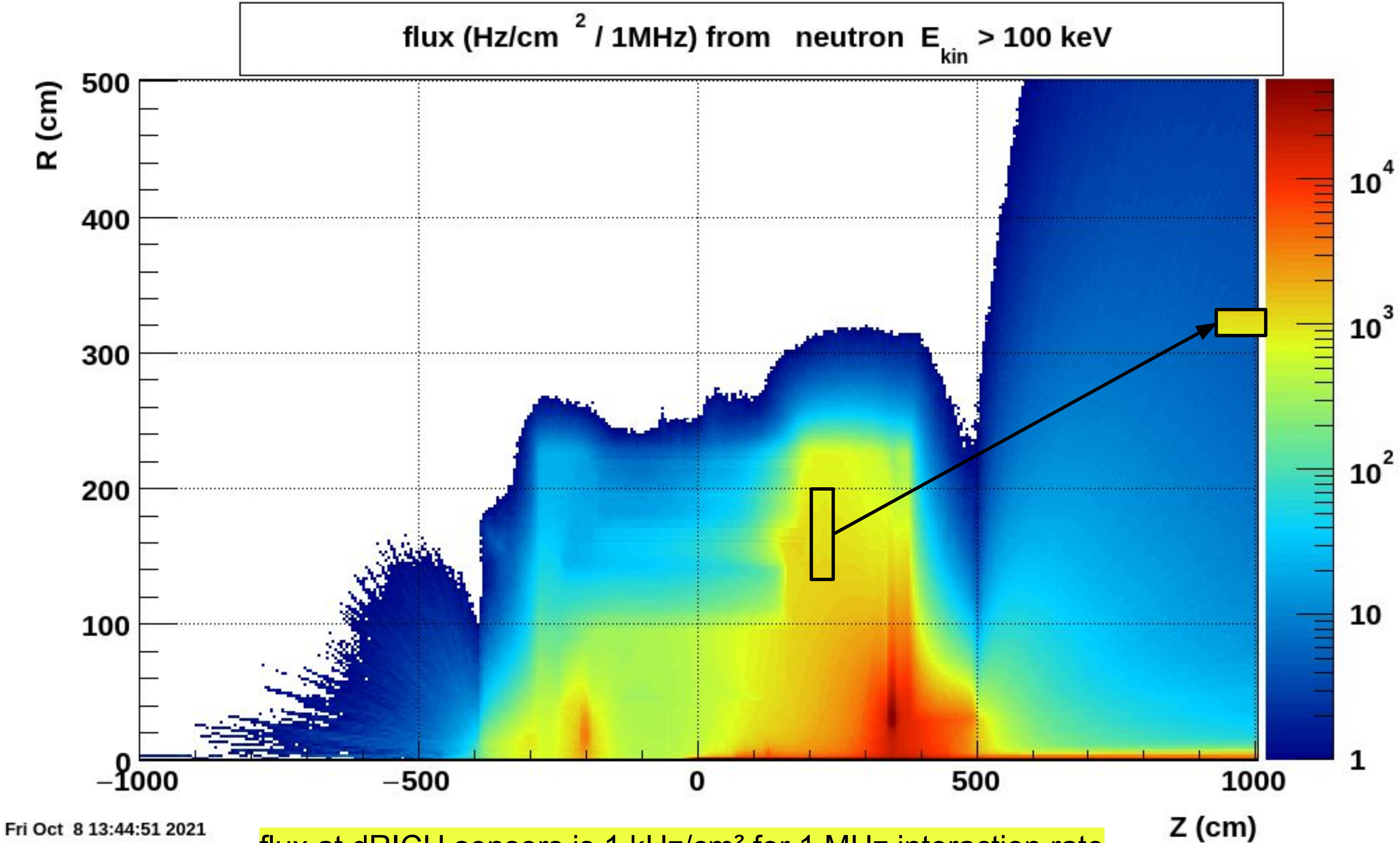
So the threshold to trigger annealing will likely become ALCOR maximum rate (probably few MHz, may be 10 including BC sub-windows)

- if we lower temperature to -50 C, DCR will decrease by a factor 4 the “threshold for annealing”

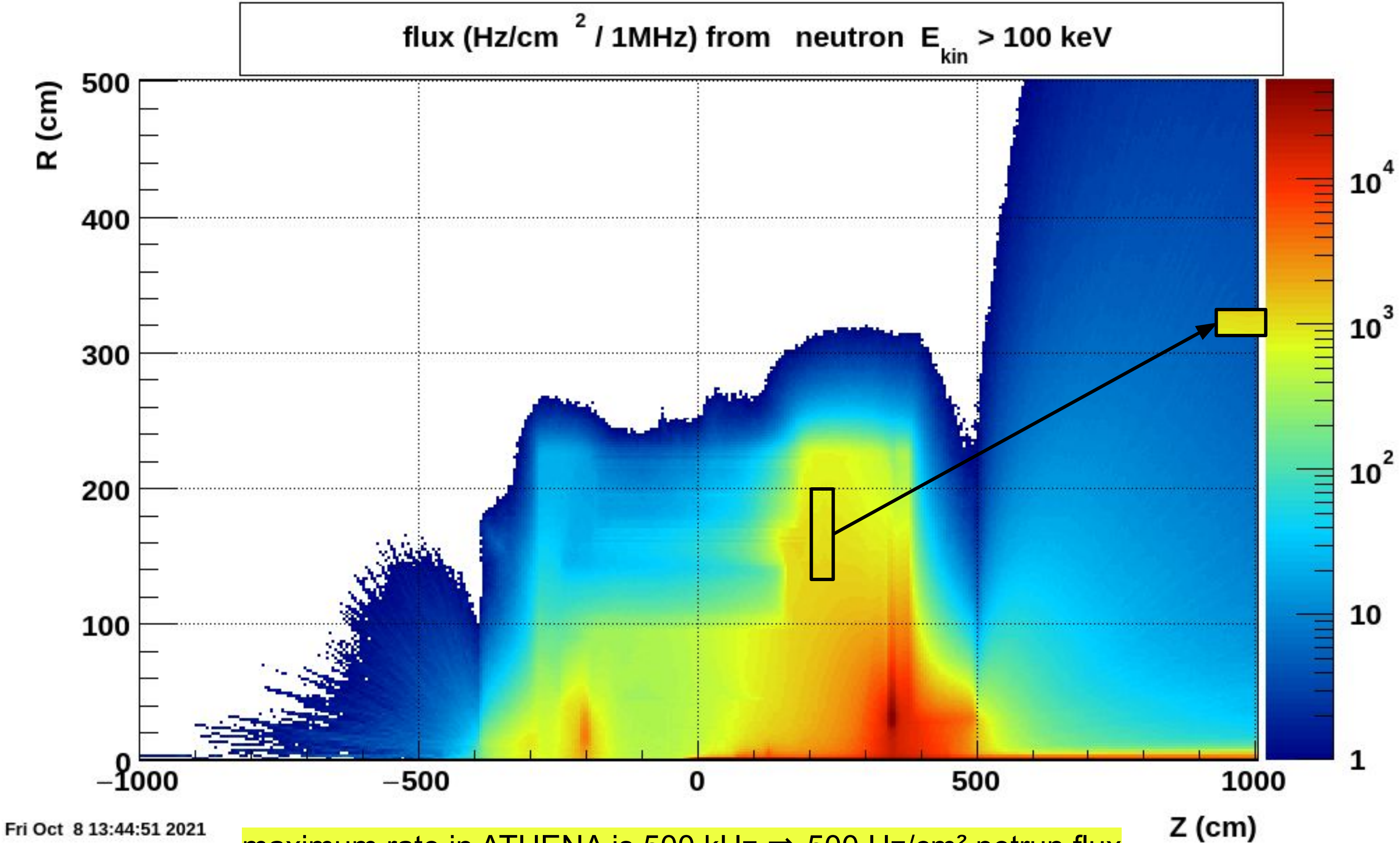
Updated radiation load studies from ATHENA in backup

10^{11} 1-MeV n_{eq}/cm^2 at dRICH sensor location is reached
after 10 years of running at the maximum (500 kHz) interaction rate

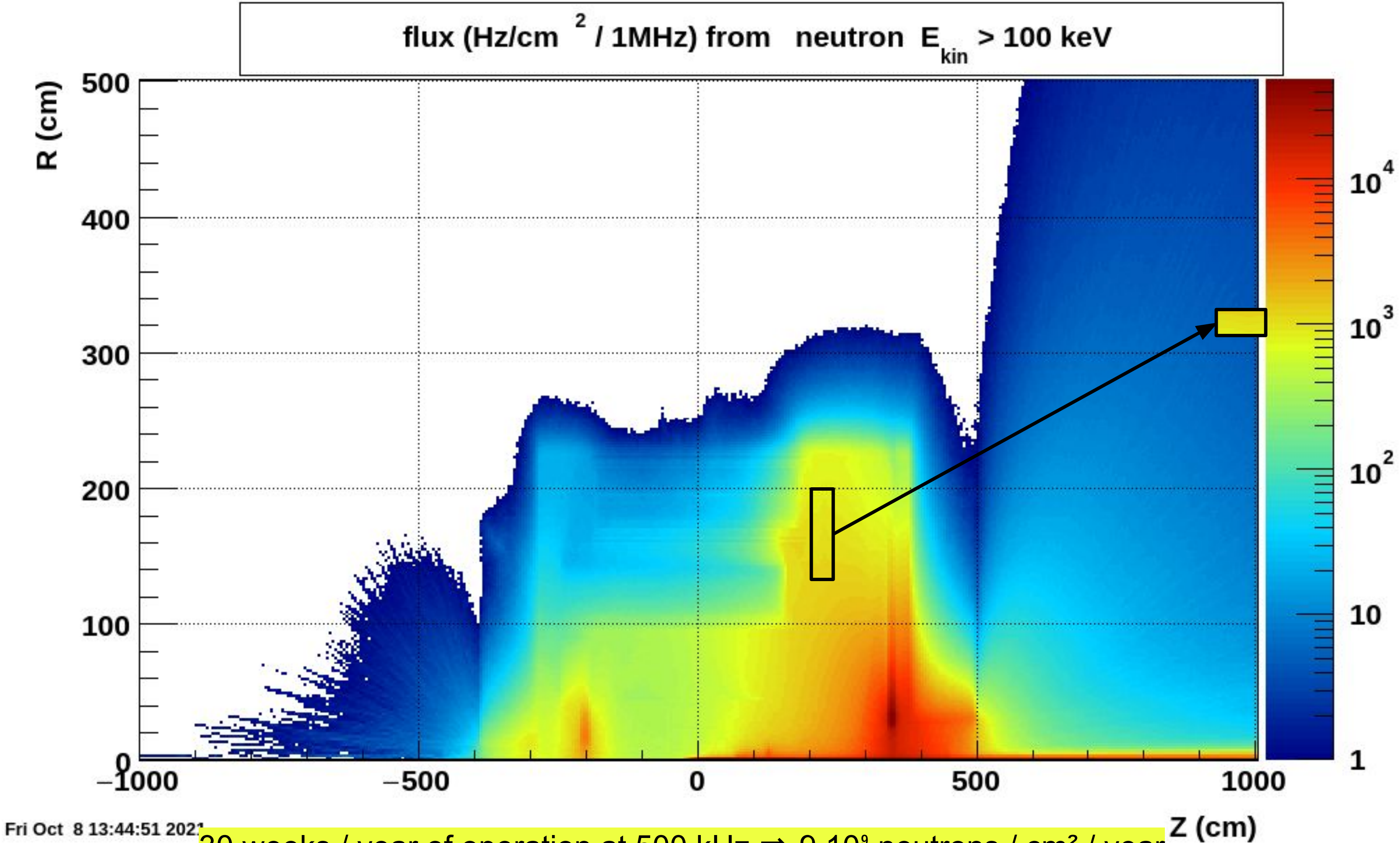

Deposited energy at step (keV cm^{-3} / 1 MHz) from charged hadrons
R (cm)
500
400
300
200
100
0
−1000
−500
0
500
1000
Z (cm)
10^7
10^6
10^5
10^4
10^3
10^2
10
1
Fri Oct 8 13:44:33 2021
dRICH sensors are located here



flux at dRICH sensors is 1 kHz/cm² for 1 MHz interaction rate



maximum rate in ATHENA is 500 kHz ⇒ 500 Hz/cm² netrun flux



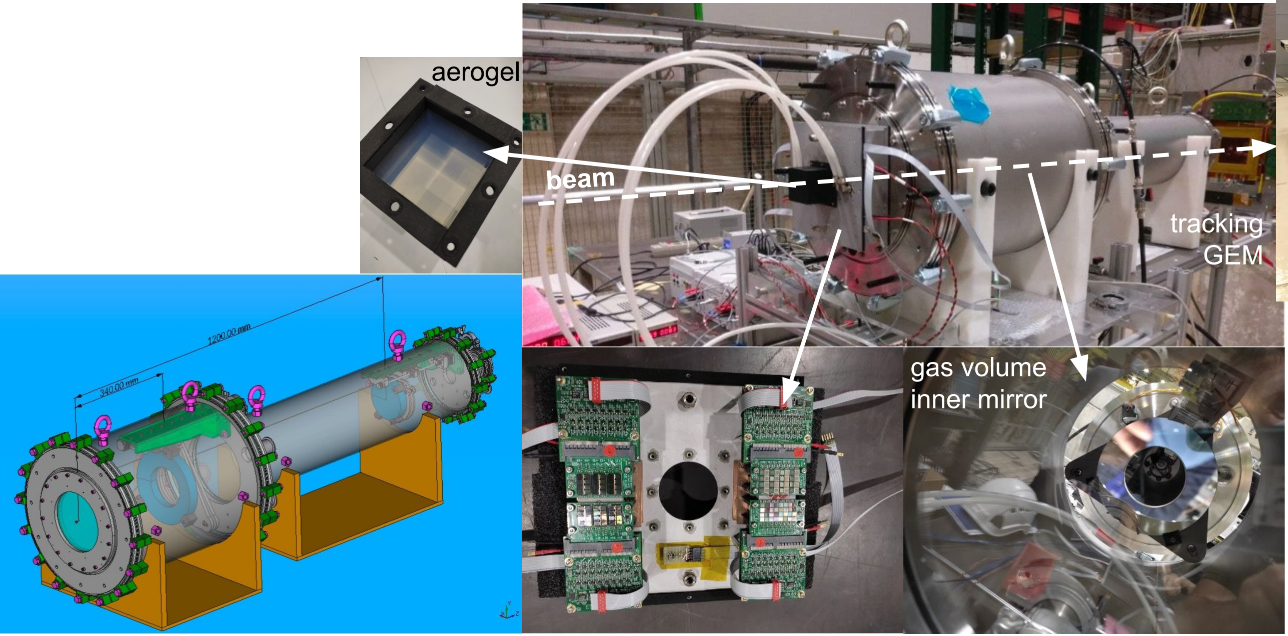
30 weeks / year of operation at 500 kHz ⇒ 9 10^9 neutrons / cm² / year

more spare slides

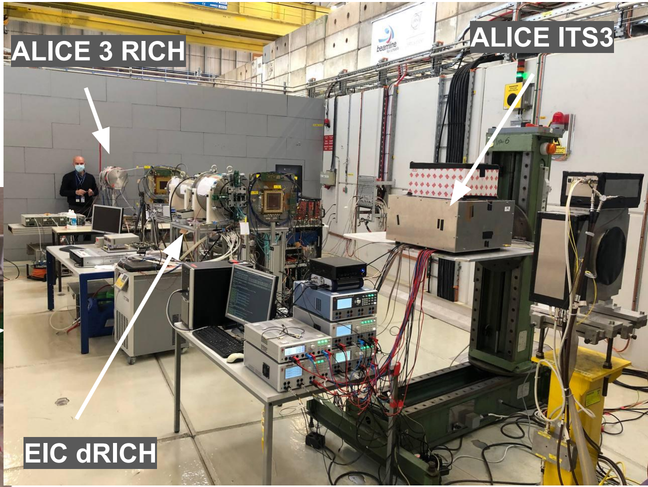
SiPM tested with beams at CERN

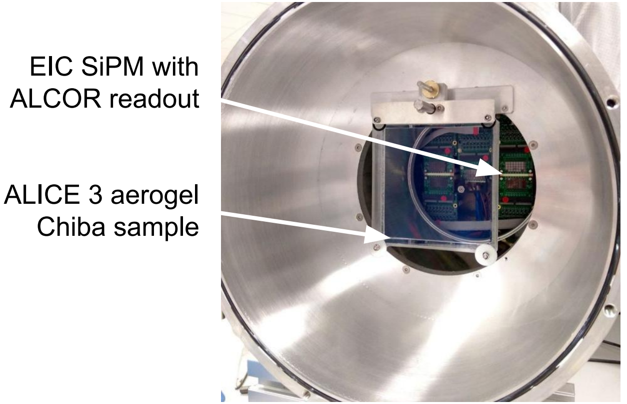
first test-beams in September (SPS) and October 2021 (PS, in synergy with ALICE) at CERN

dRICH prototype @ CERN-SPS



ALICE and EIC at CERN PS T10 October 2021



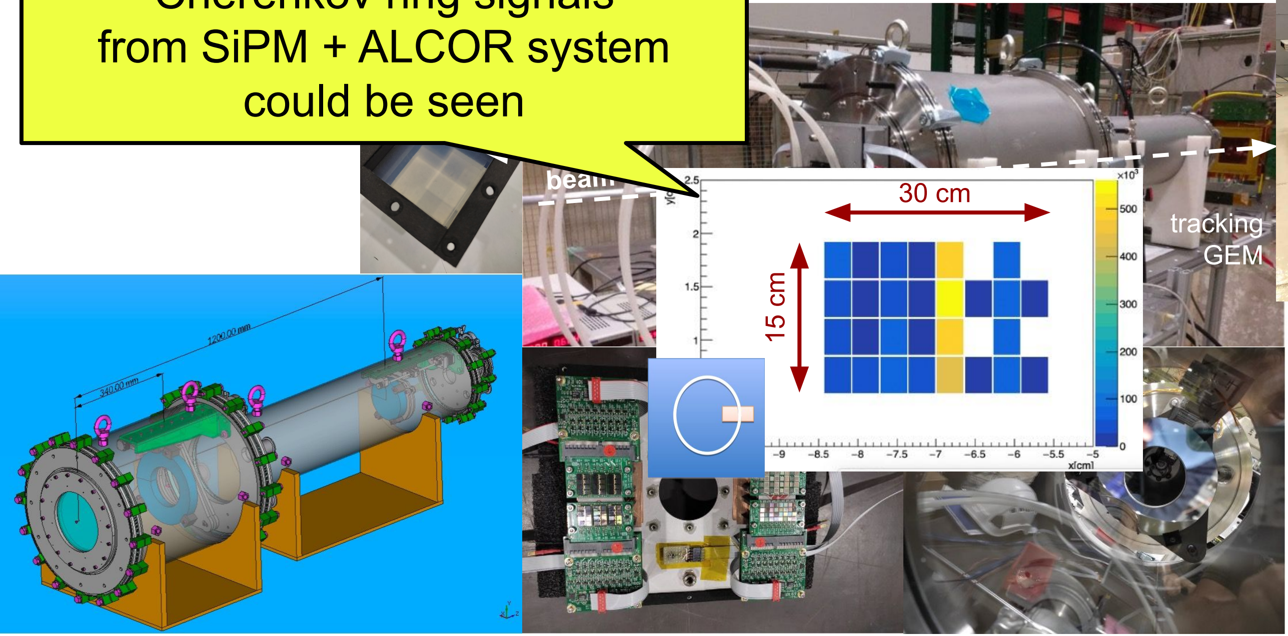


SiPM tested with beams at CERN

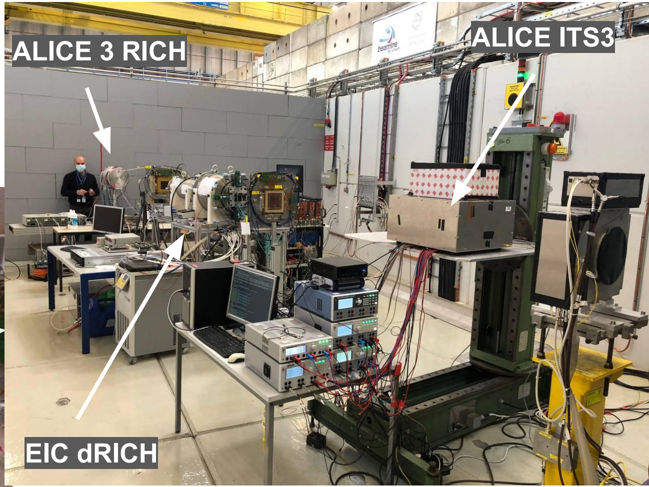
first test-beams in September (SPS) and October 2021 (PS, in synergy with ALICE) at CERN

Cherenkov ring signals from SiPM + ALCOR system could be seen

@ CERN-SPS

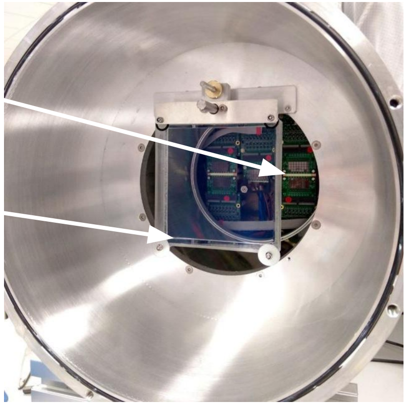


ALICE and EIC at CERN PS T10 October 2021



EIC SiPM with ALCOR readout

ALICE 3 aerogel Chiba sample



SiPM R&D program

- **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

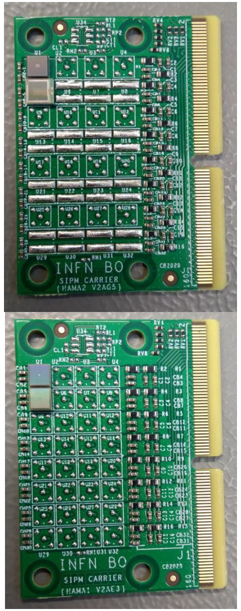
acquisition of commercial and prototype (FBK) SiPM sensors
design and production of dedicated electronics boards

- **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

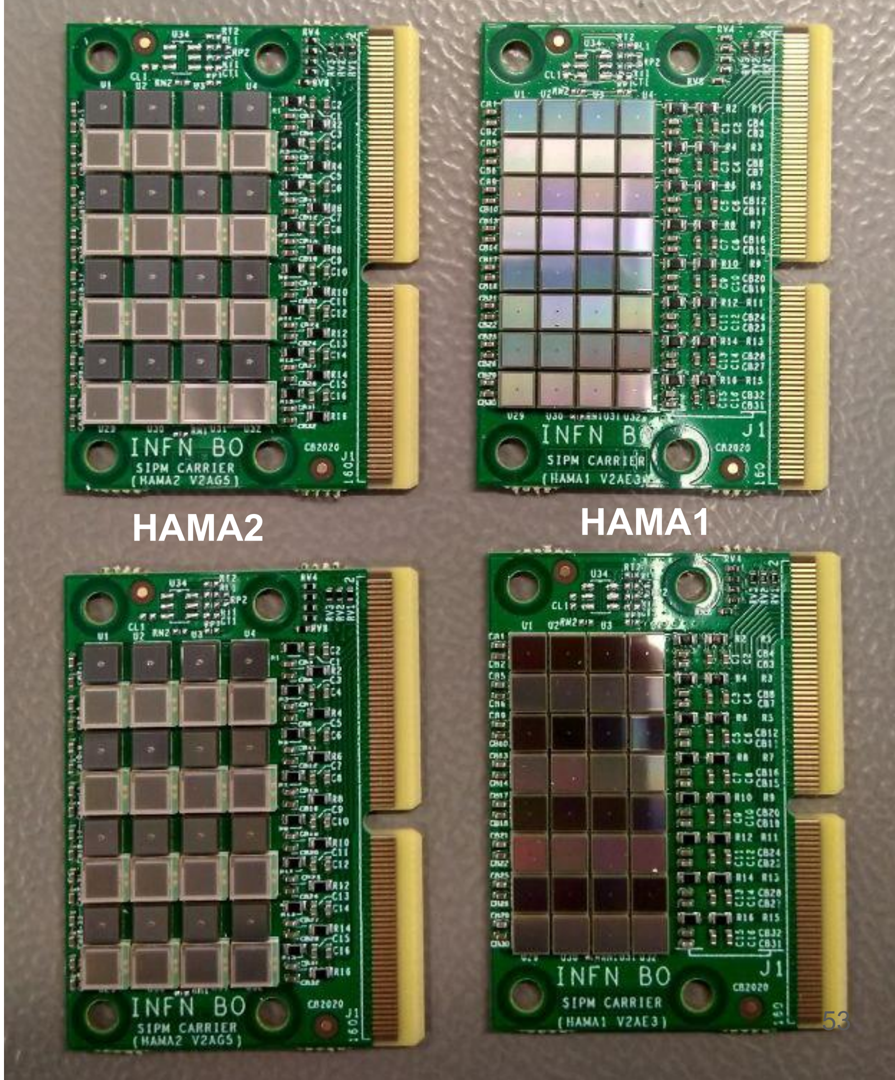
the list does not stop here, these are the main equipment boards

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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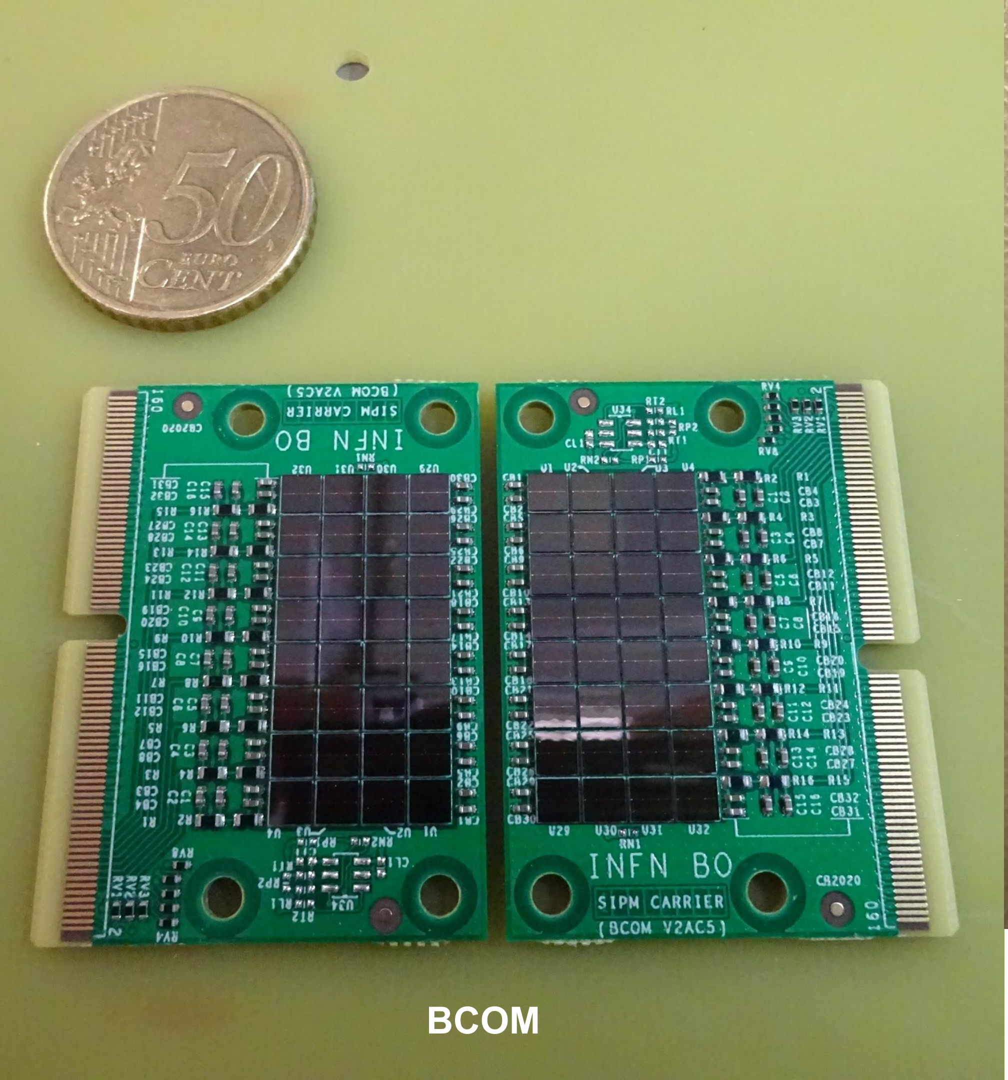
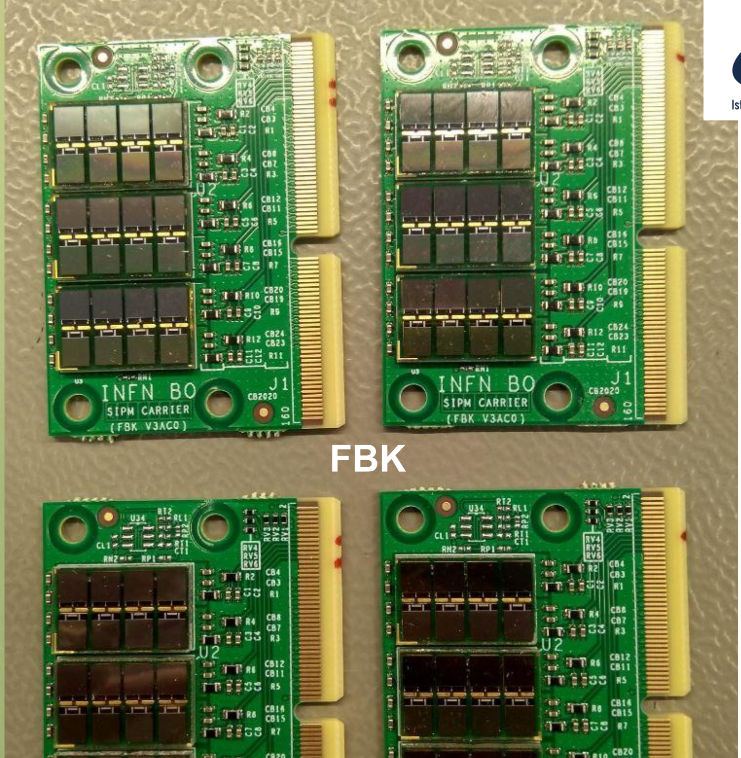
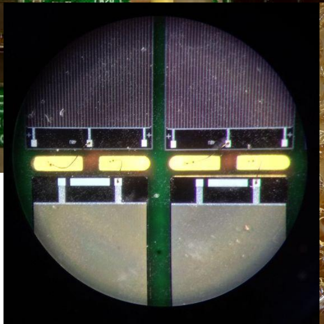
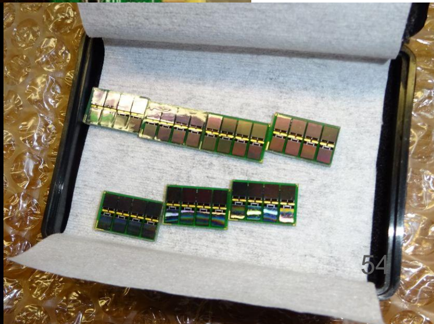


BCOM

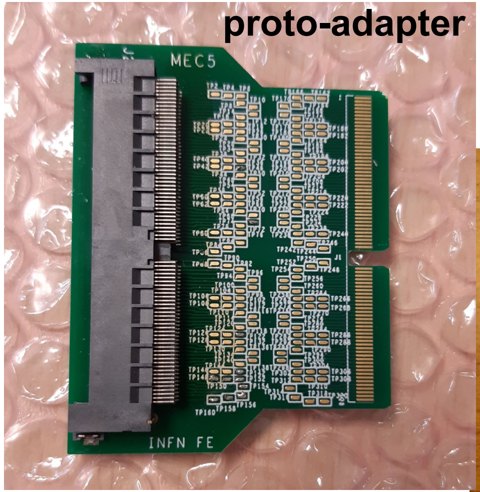


FBK

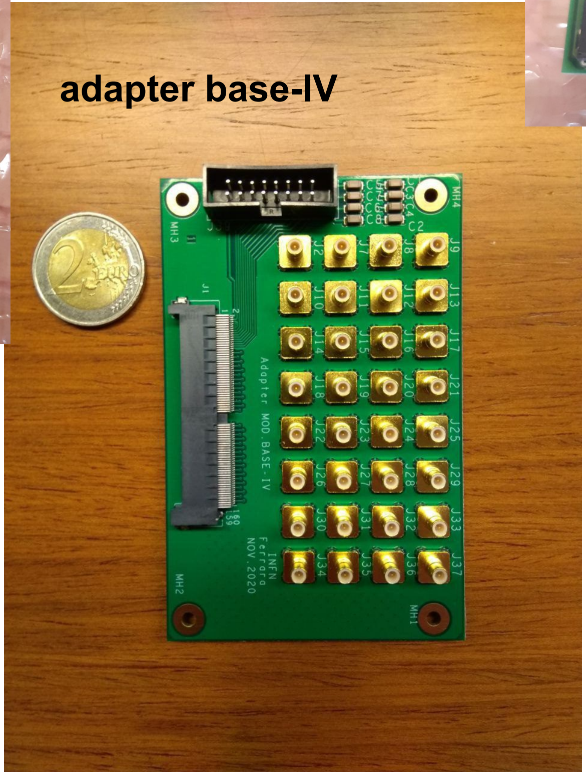




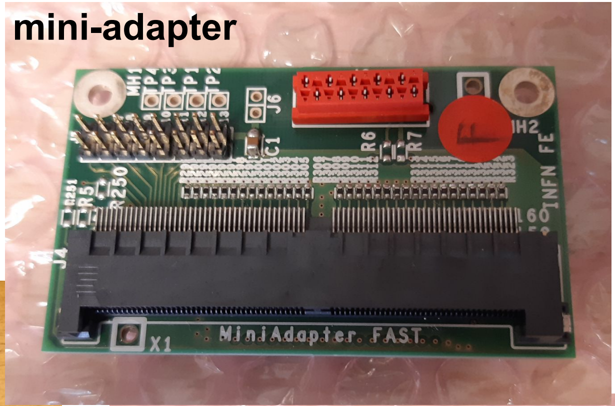
Schede adapter



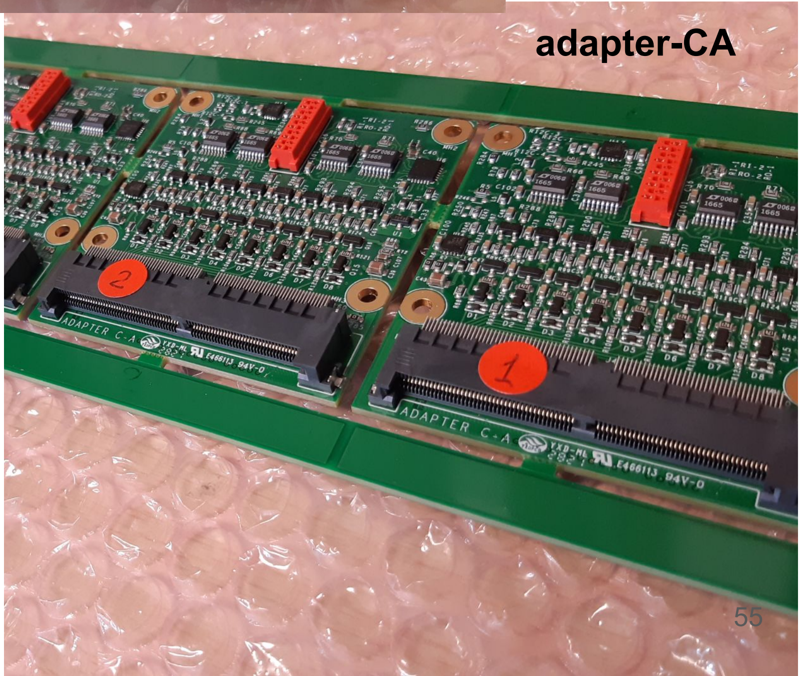
proto-adapter



adapter base-IV



mini-adapter



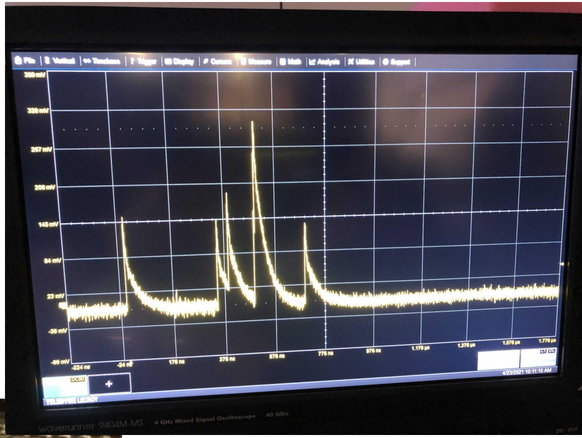
adapter-CA

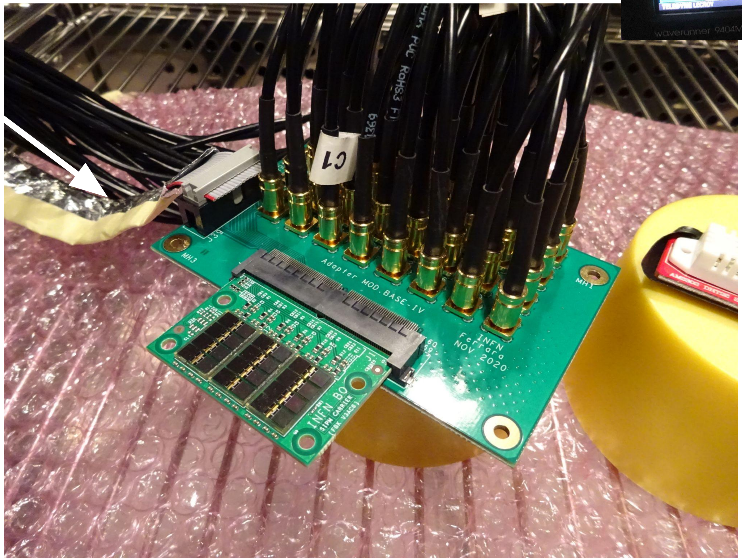
SiPM characterisation @ BO

**I-V curves and DCR
at different temperatures**

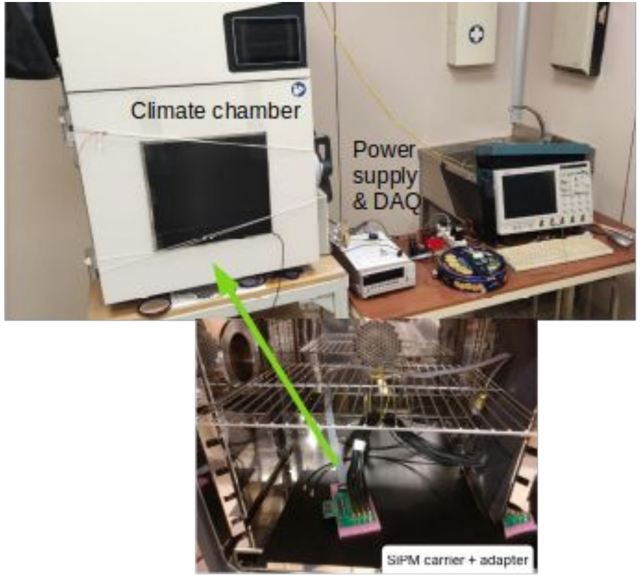
+20 C −10 C −30 C

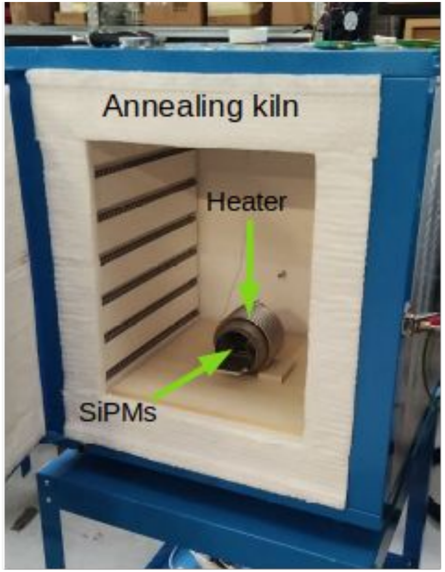
- Memmert climatic chamber
- Keithley source meter
- Keysight power supply
- Cividec amplifier
- Lecroy oscilloscope



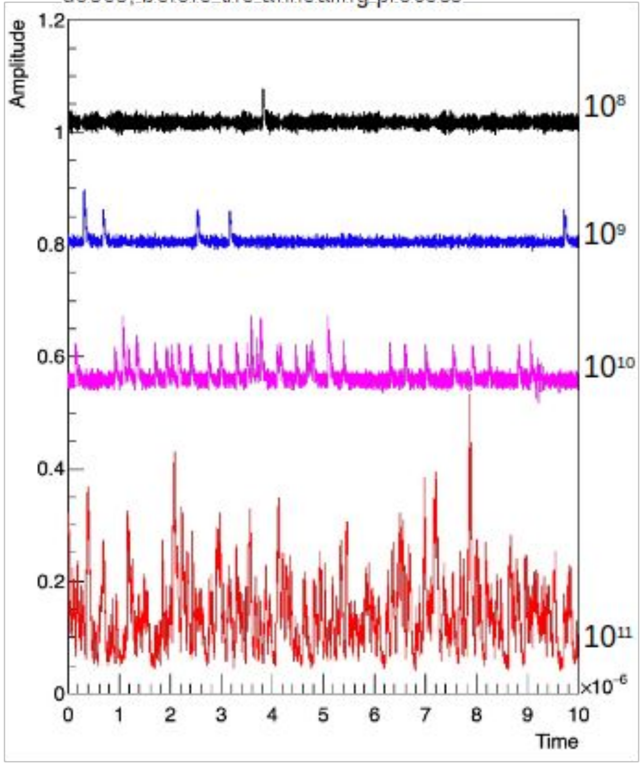


SiPM characterisation @ FE

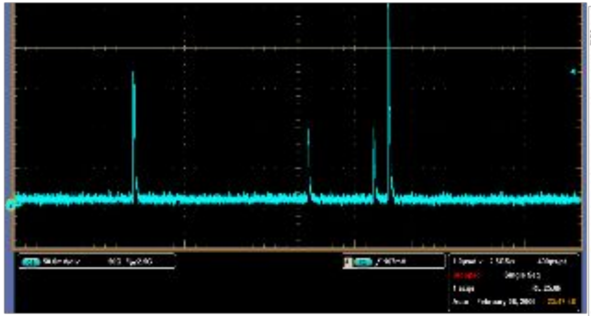


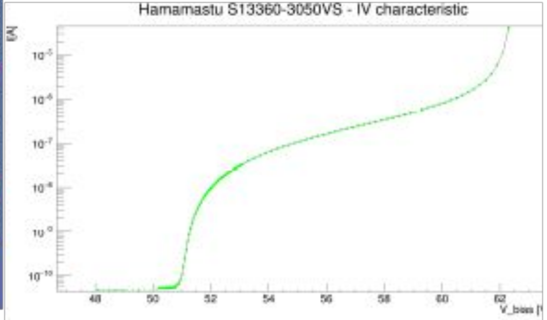


Signals of SiPMs irradiated with different doses, before the annealing process



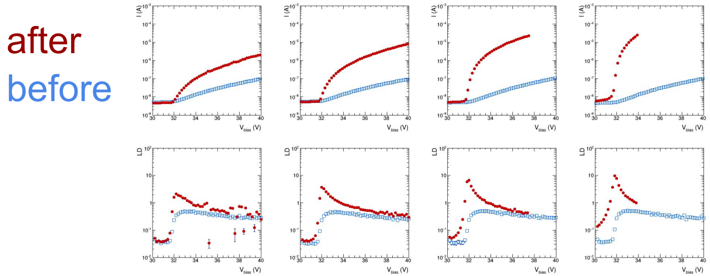
Not irradiated SiPMs, room temperature, signal and IV characteristic

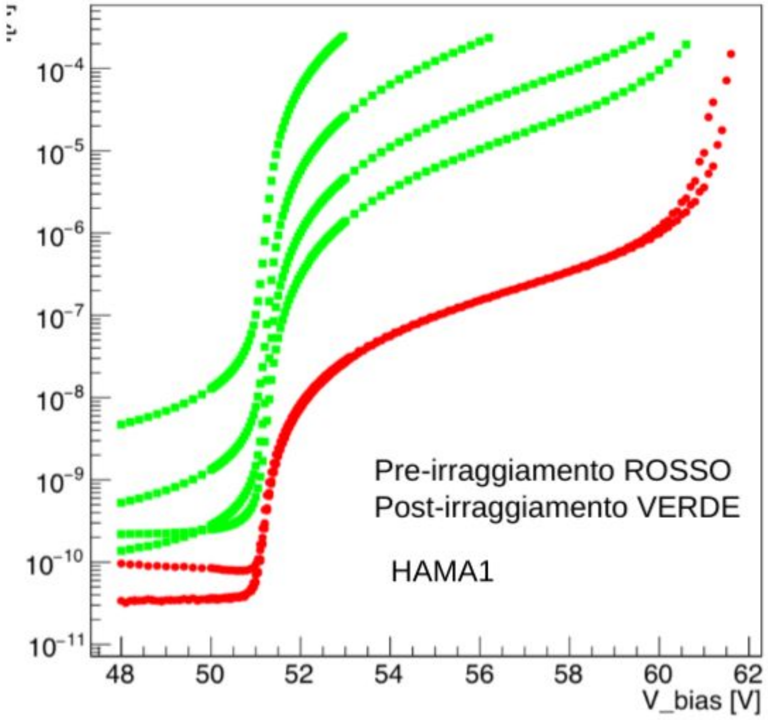




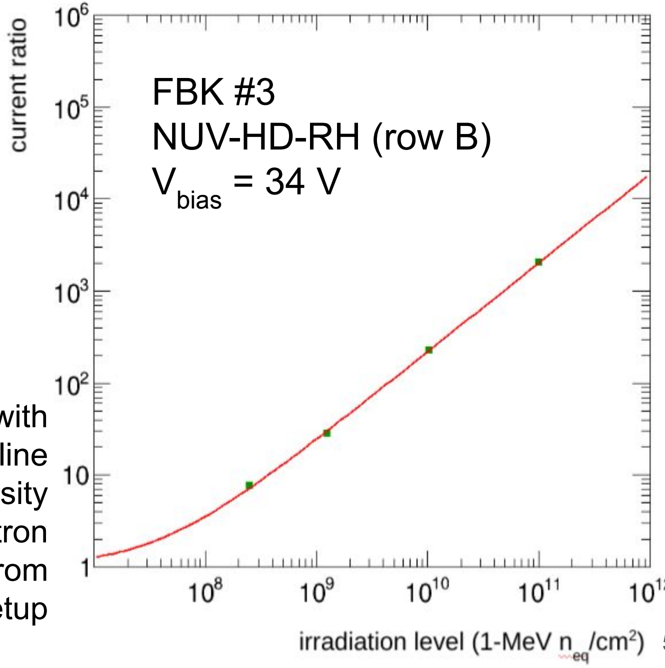
Post-irradiation characterisation

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

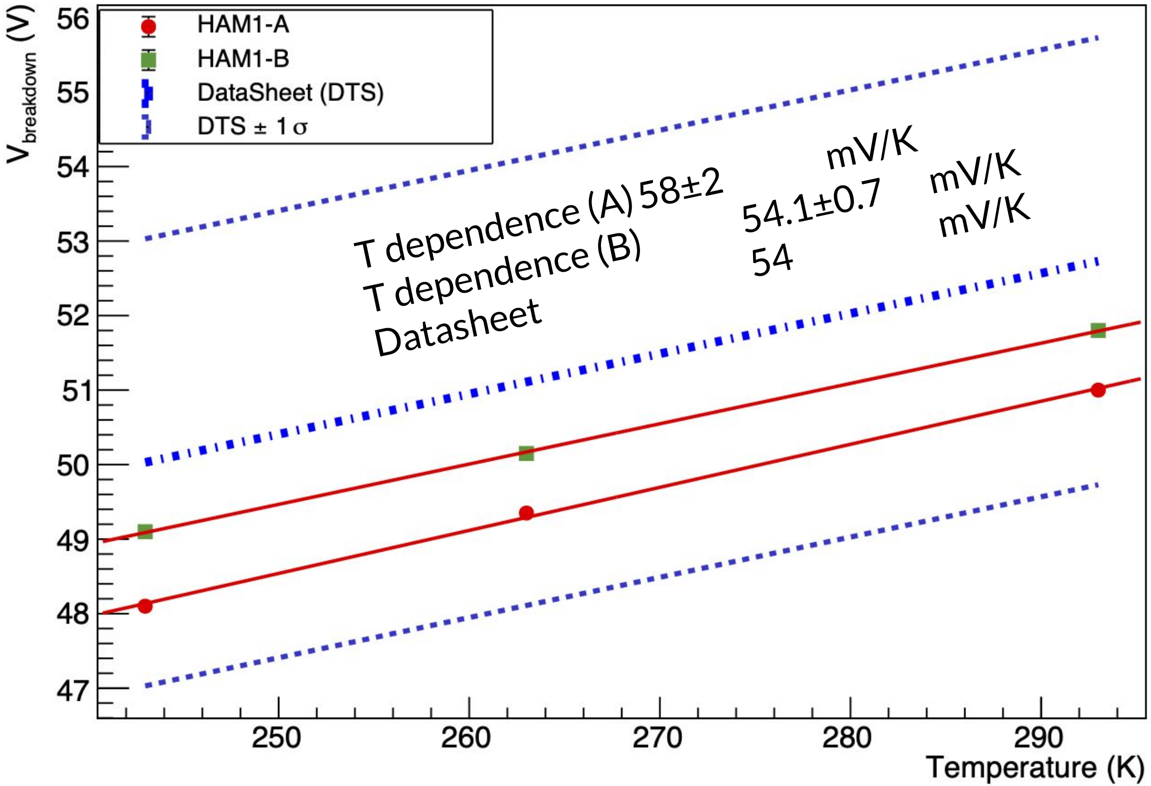




current increases with irradiation level in line with proton intensity calibration + neutron background from simulations of the setup

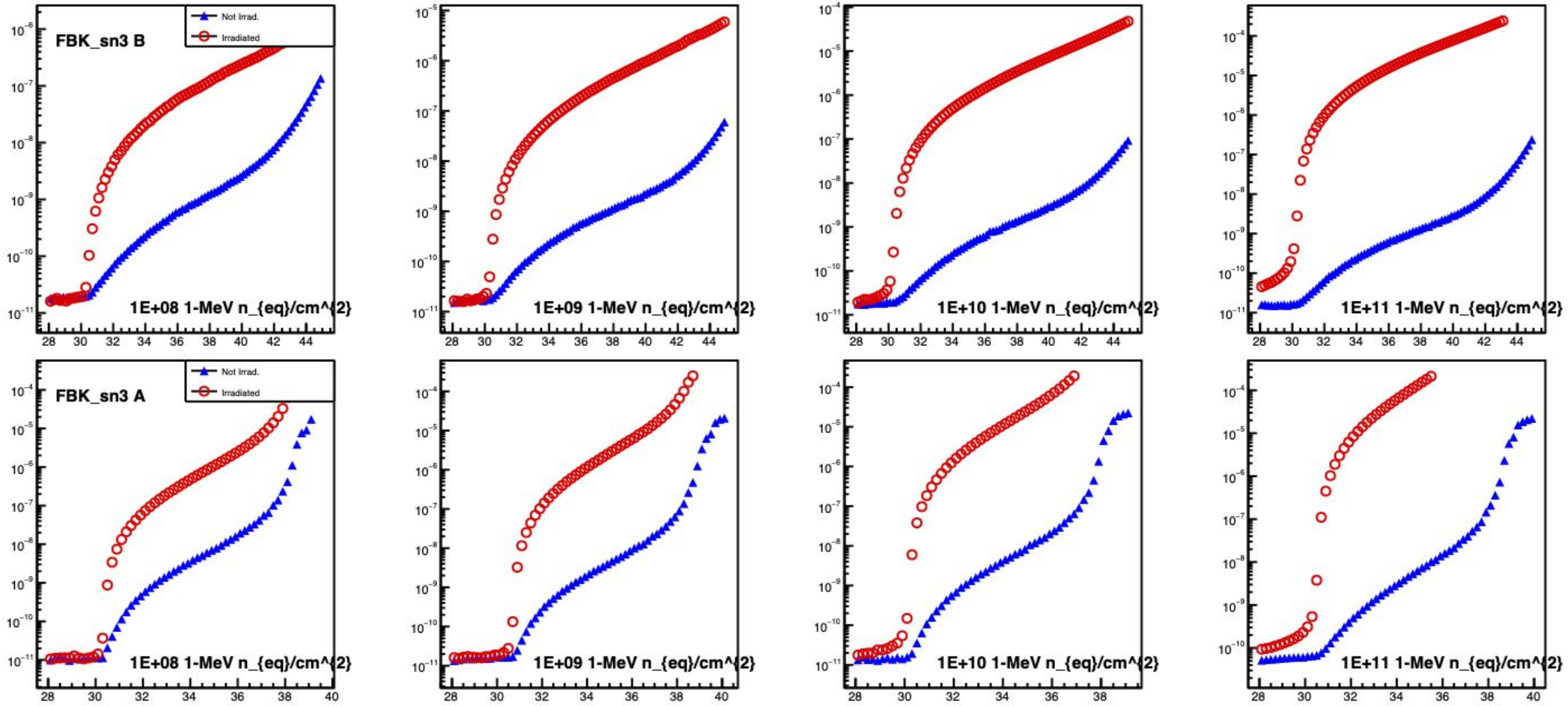


Breakdown Voltage estimation (HAM1-A & -B)

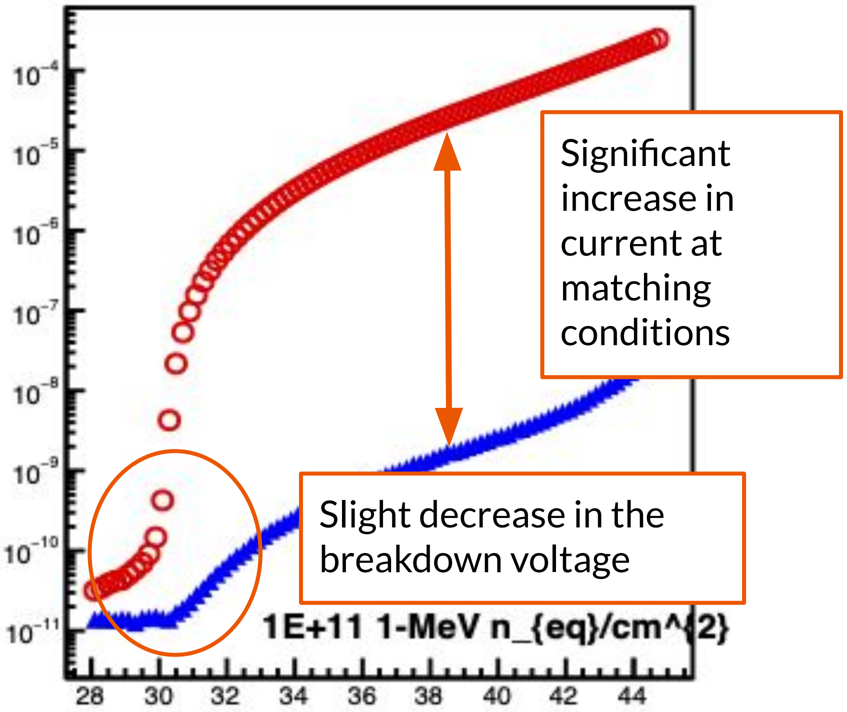


The curve seems consistent with what is reported on the Datasheet.

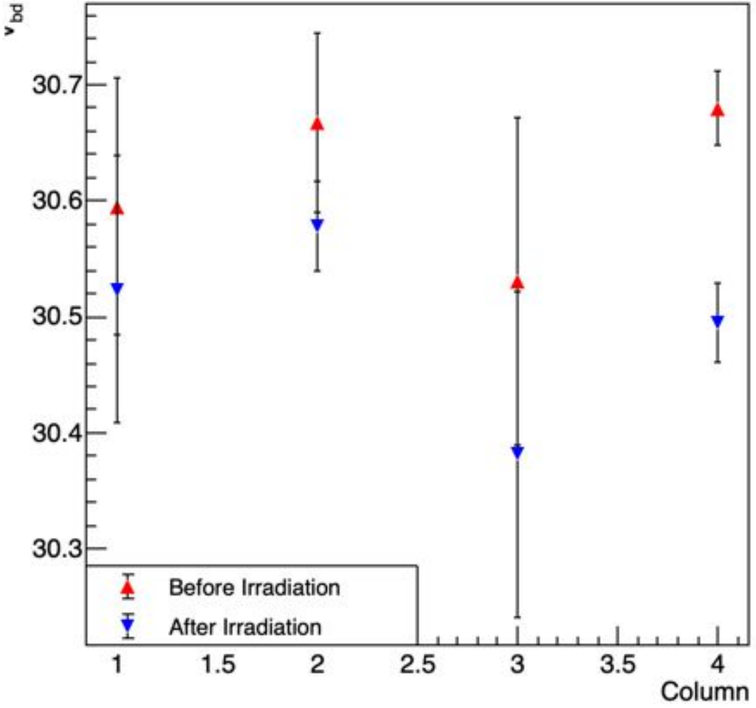
Current comparison @243K for FBK3-(C)(R)

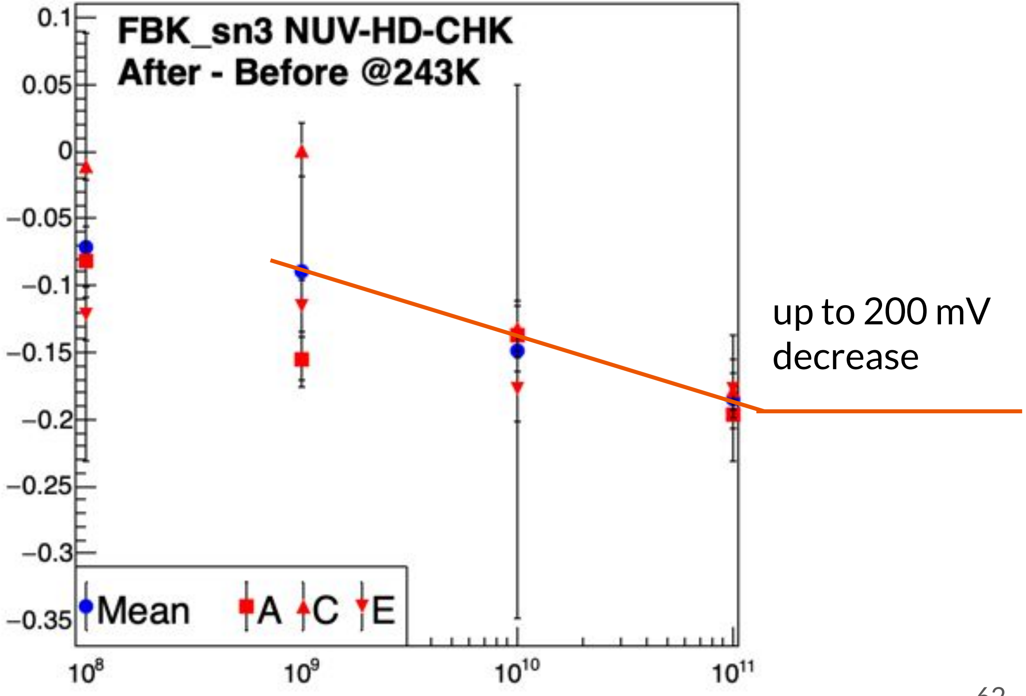


Current comparison



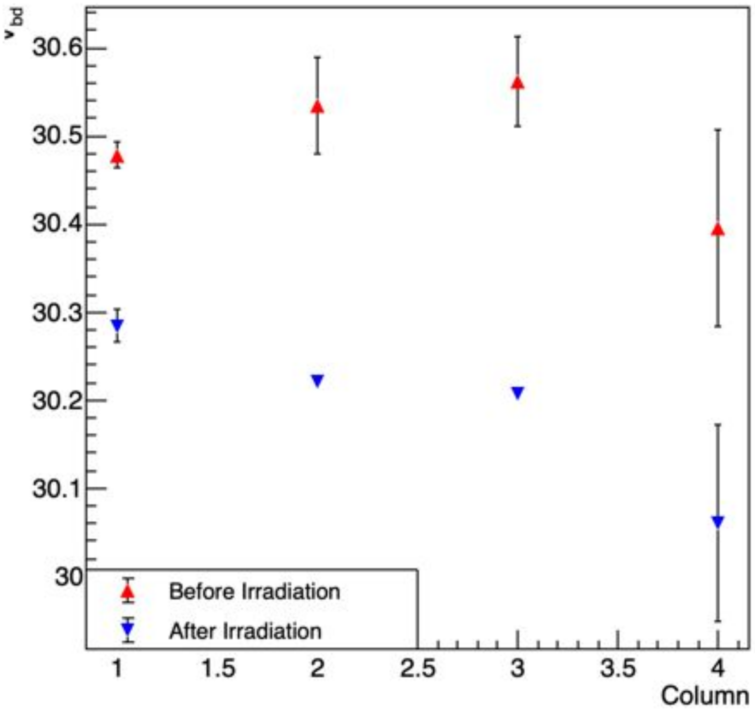
V_{BD} estimation @243K for FBK3-C

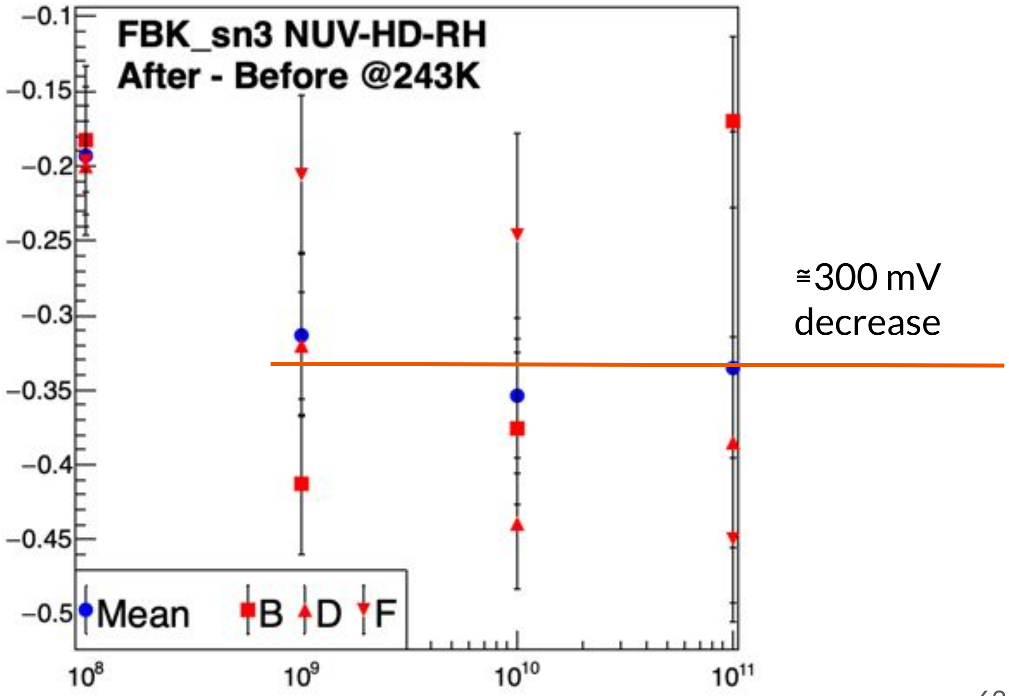




up to 200 mV decrease

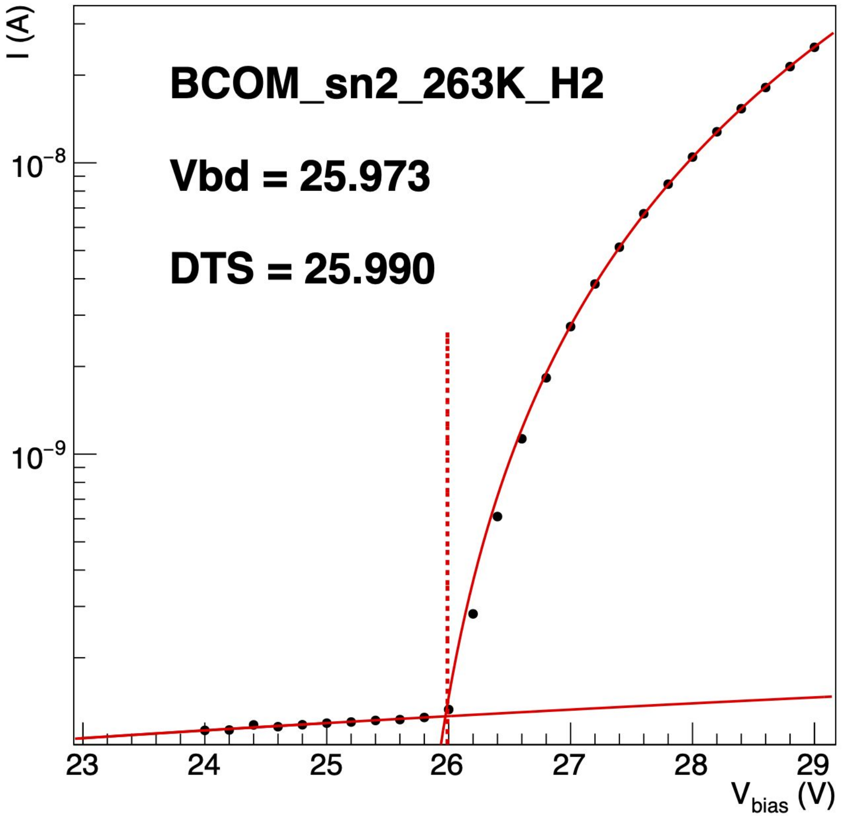
V_{BD} estimation @243K for FBK3-R





≅300 mV decrease

Breakdown Voltage Estimation



Breakdown Voltage estimation

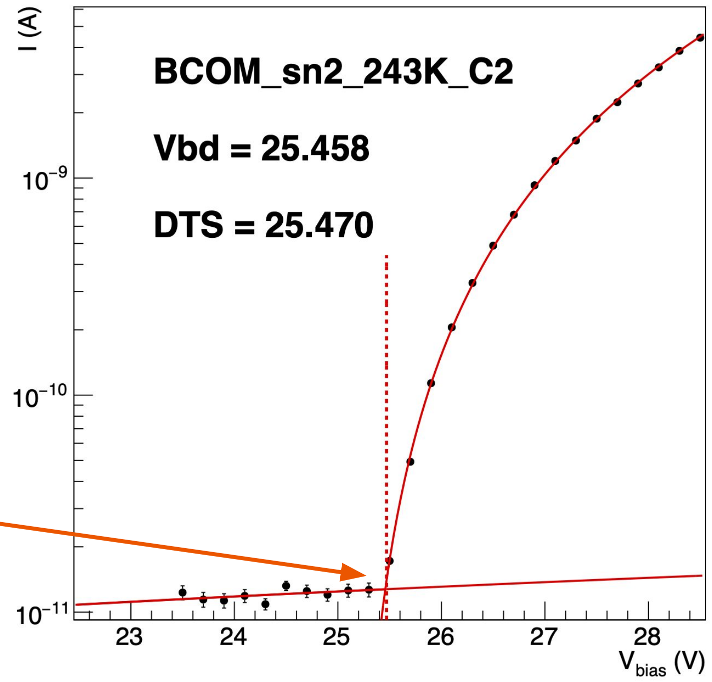
6. A second order polynomial, fitted to $I(V_{bias})$ above V_{bd} after surface-current subtraction, crosses the V_{bias} axis.

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

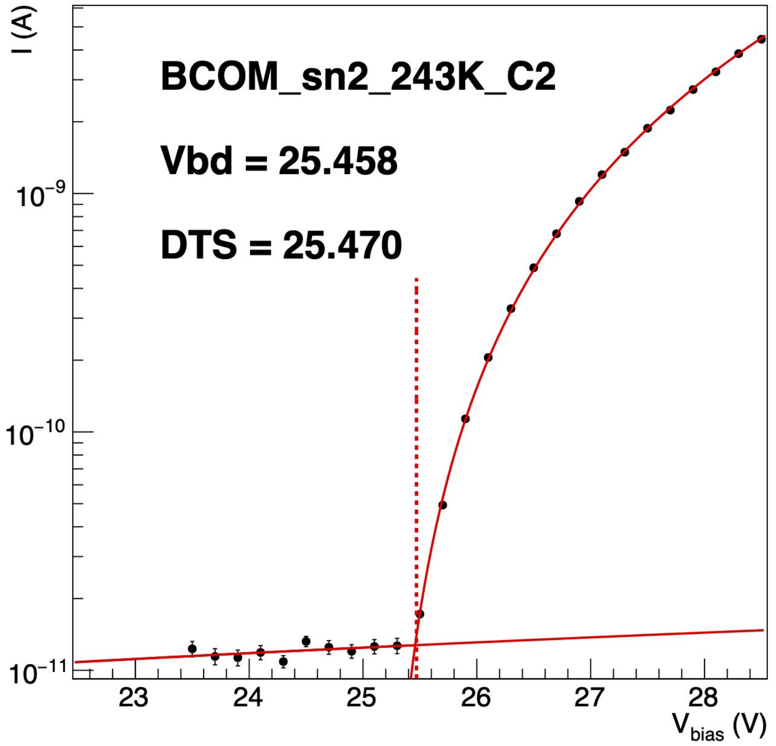
Procedure:

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

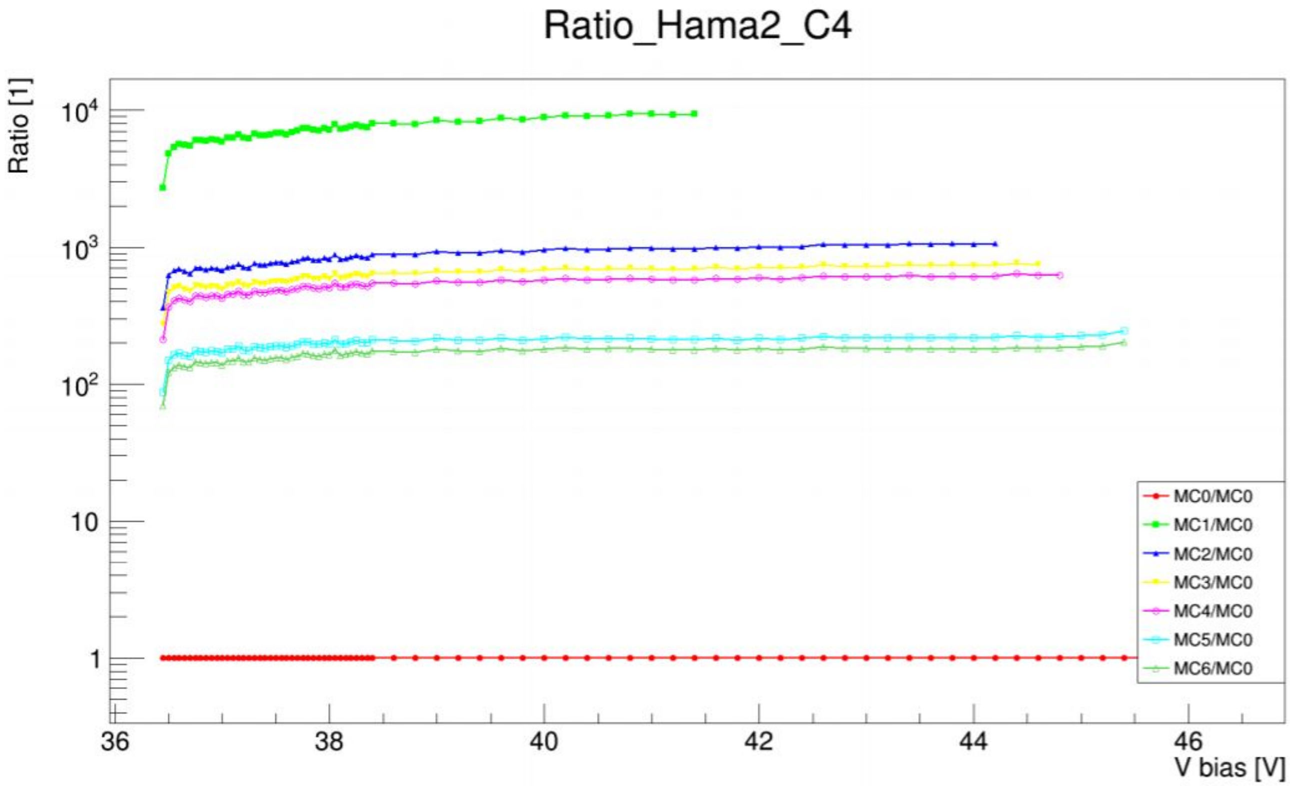
4. Steps 2 and 3 are repeated until the difference between the new guess and the previous guess is less than 1.e-5



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)

S.Vallarino

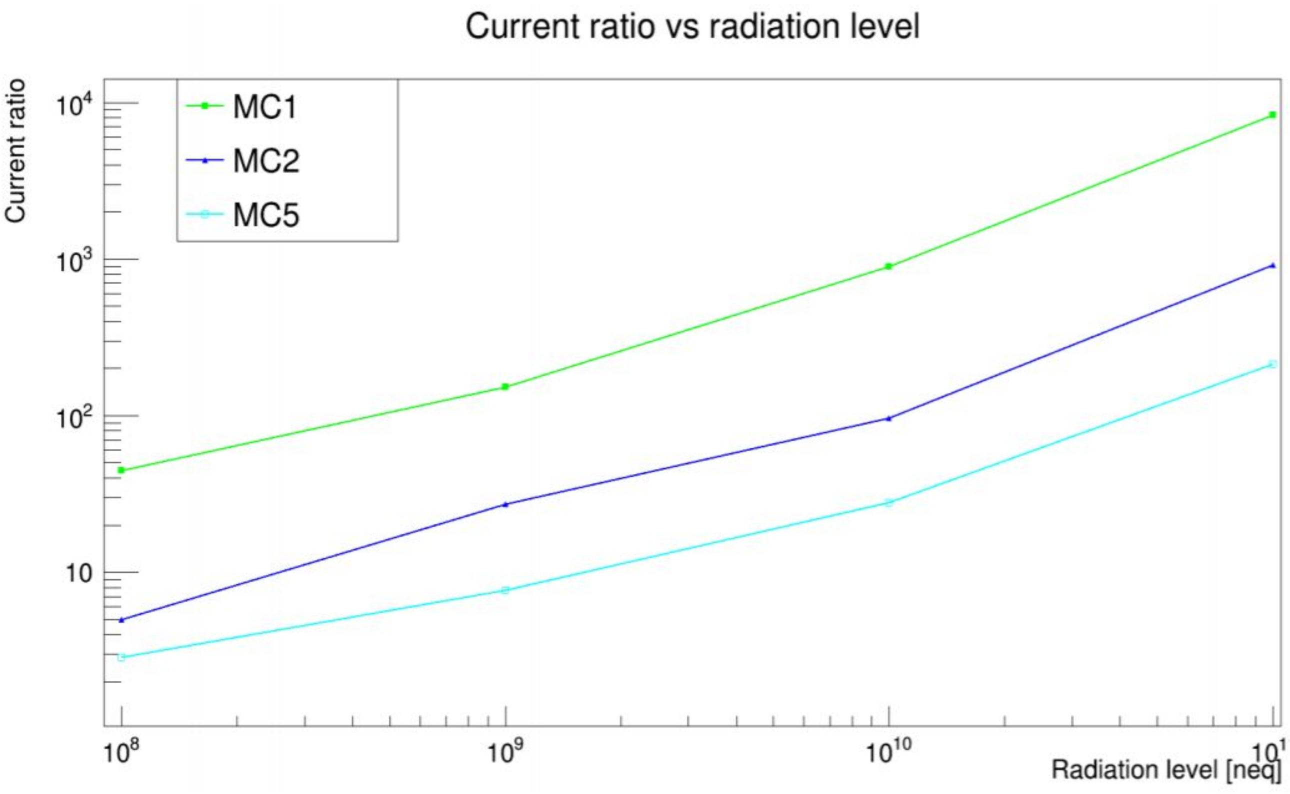
VI characteristic – ratio with respect to MC0



- 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.

S.Vallarino

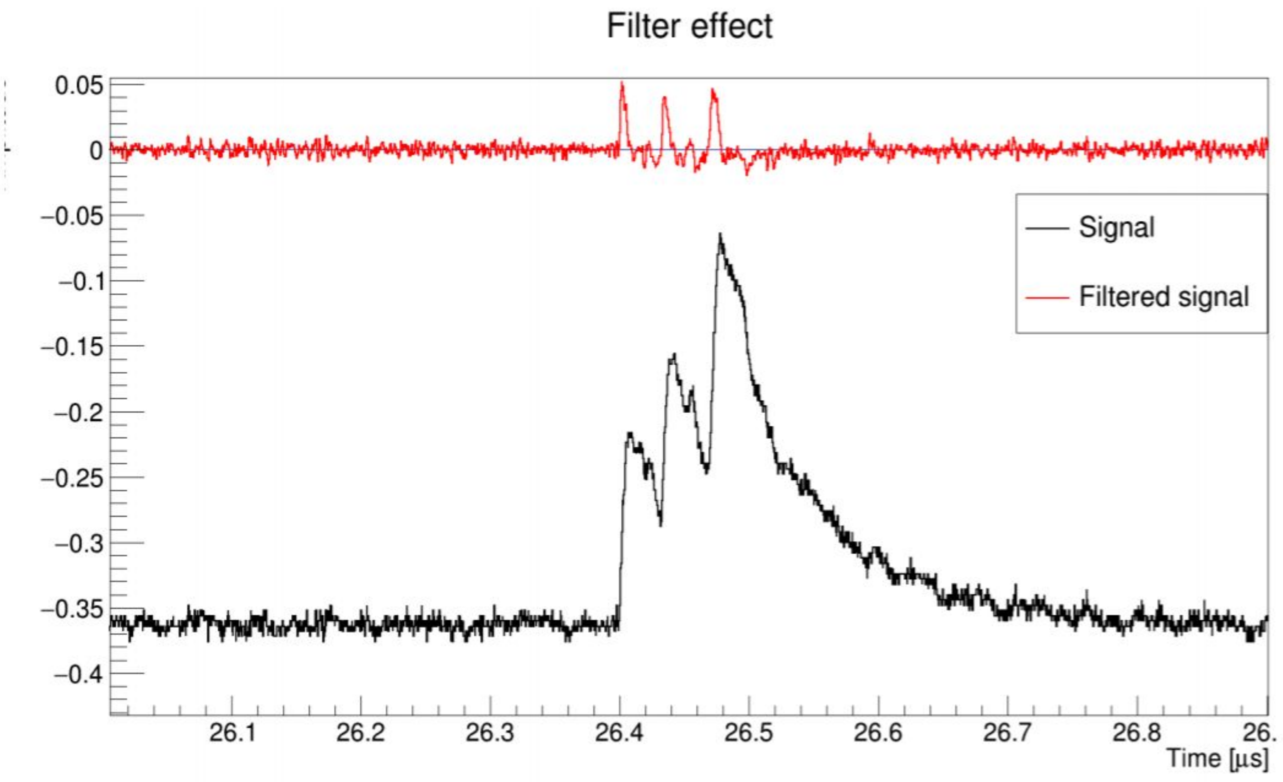
Current ratio to the recommended operating voltage



- 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.

S.Vallarino

Filter effect



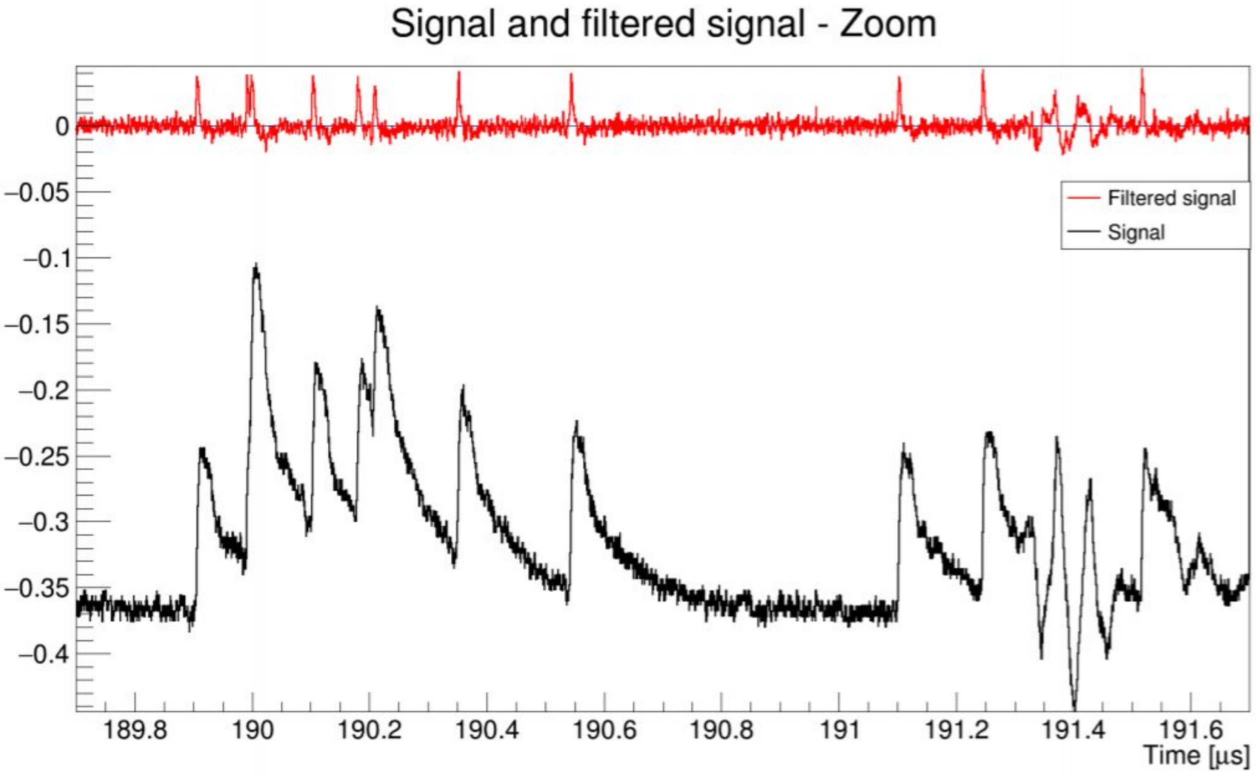
The plot shows the effect of filter.

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

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

S.Vallarino

Filter effect



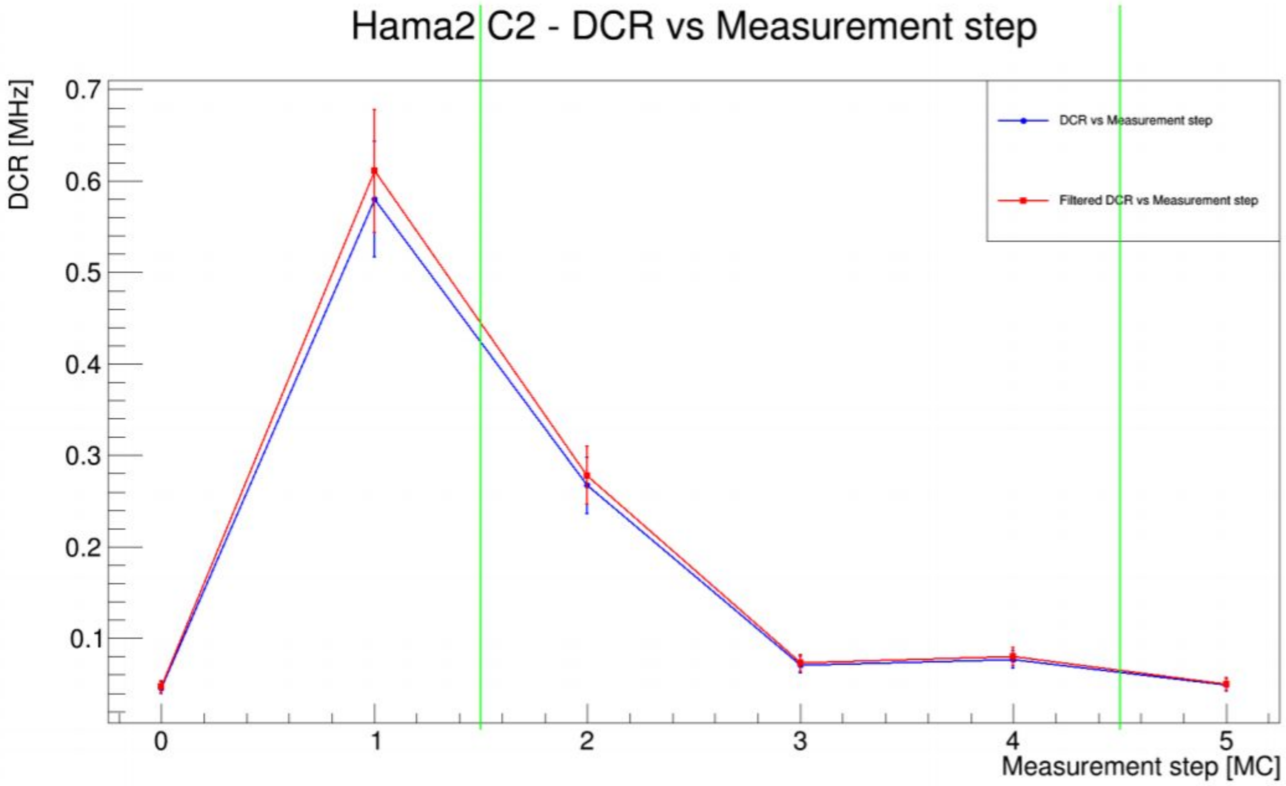
The plot shows the effect of filter.

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



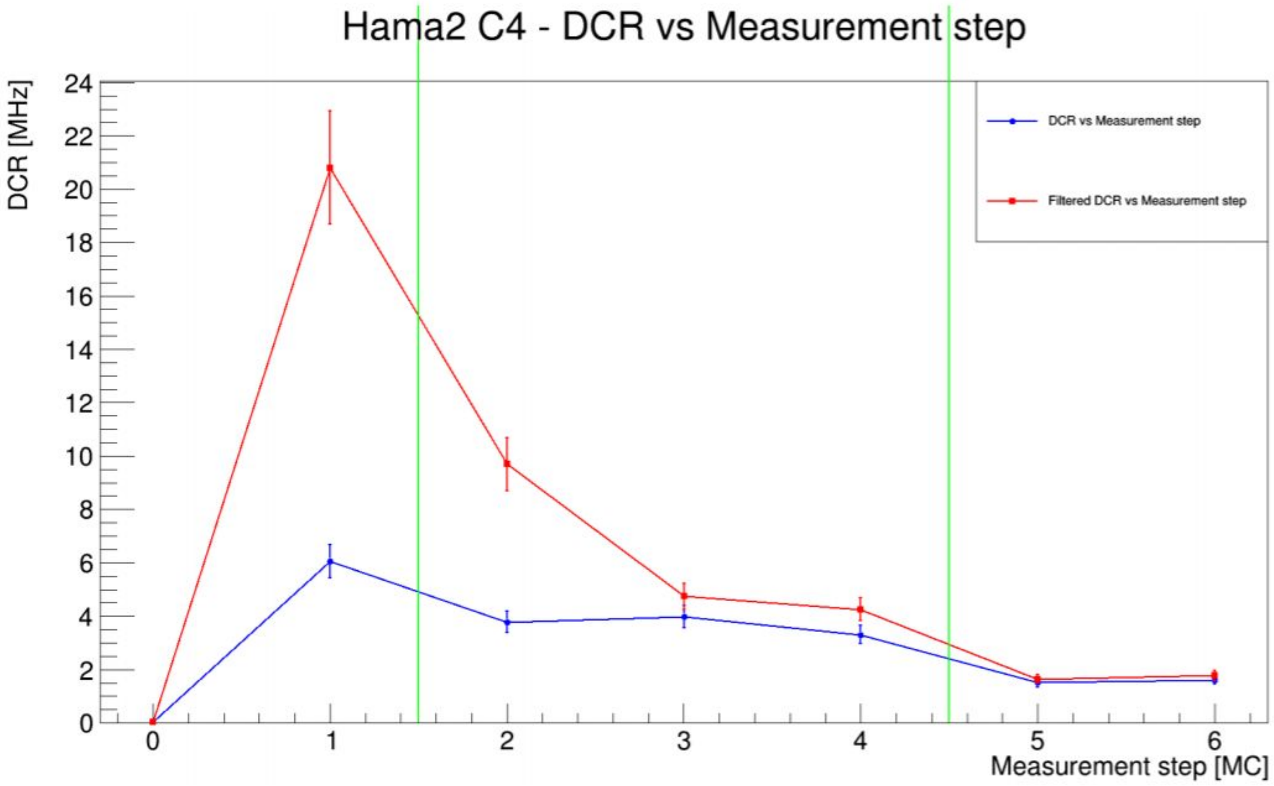
The plot shows the DCR vs the measurement for a 50µm-cell SiPM wich has received a low dose (10^9), with or without filtering.
The DCR is quiet low, this allows to obtain it even without the filter.
The vertical green lines marks the different annealing temperature steps:

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

As expected, the DCR decreases while the annealing proceeds

S.Vallarino

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.

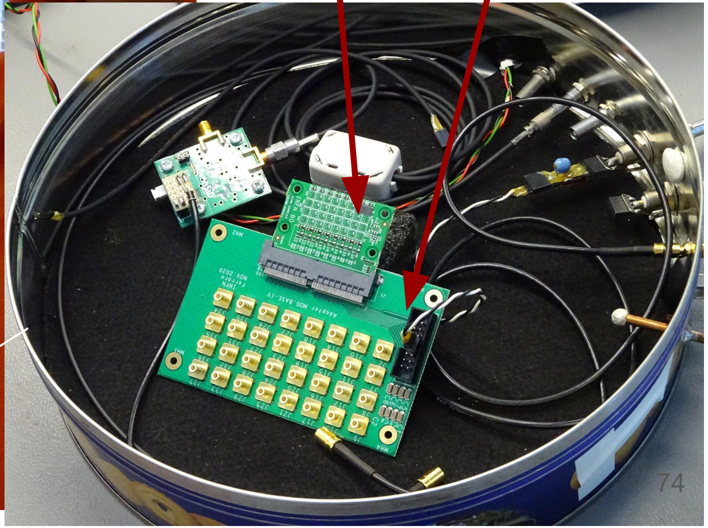
When the DCR increases, the analisys without filter fails to identify nearby peaks.

in azienda durante produzione schede SiPM

segnali dai SiPM !

SiPM carrier LIGHT

SiPM adapter Base-IV



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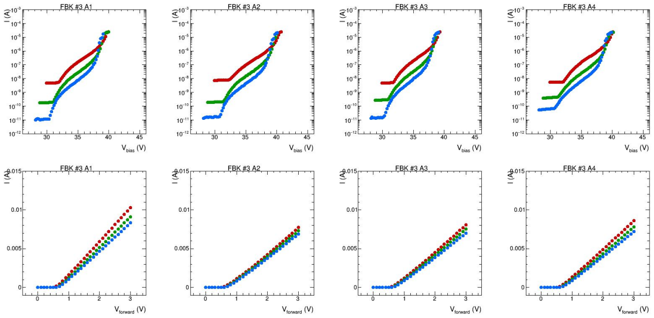
SiPM characterisation

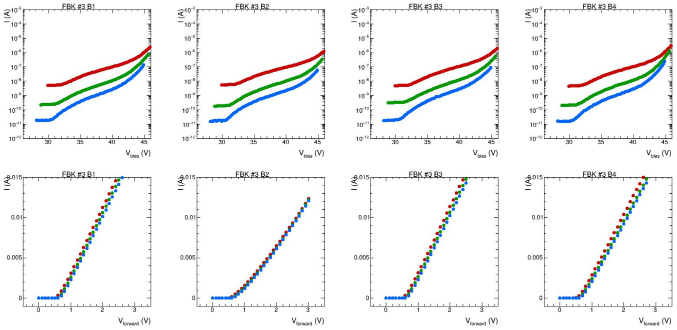
IV characteristics at different T

+20 C
−10 C
−30 C

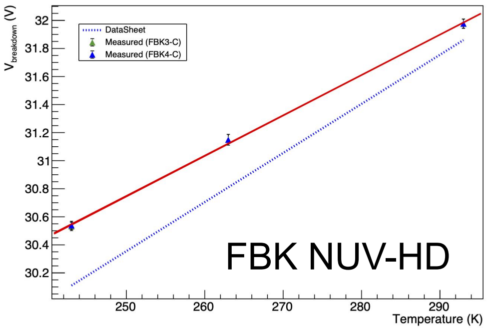
FBK NUV-HD-CHK

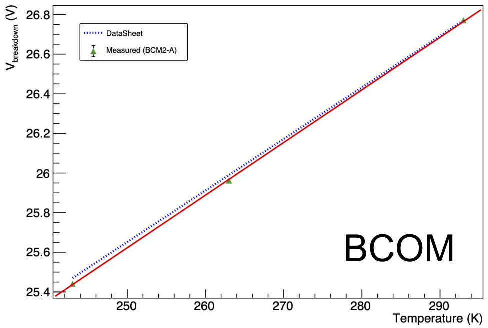


FBK NUV-HD-RH

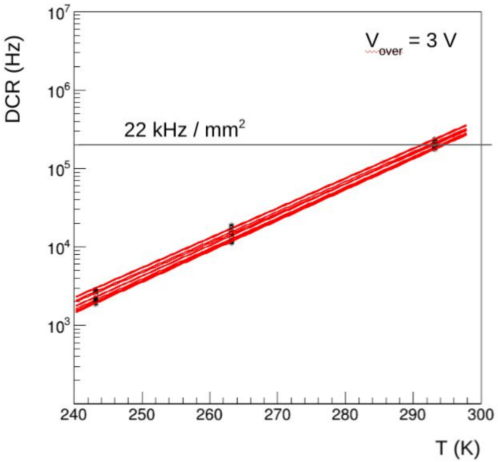


breakdown voltage vs. temperature



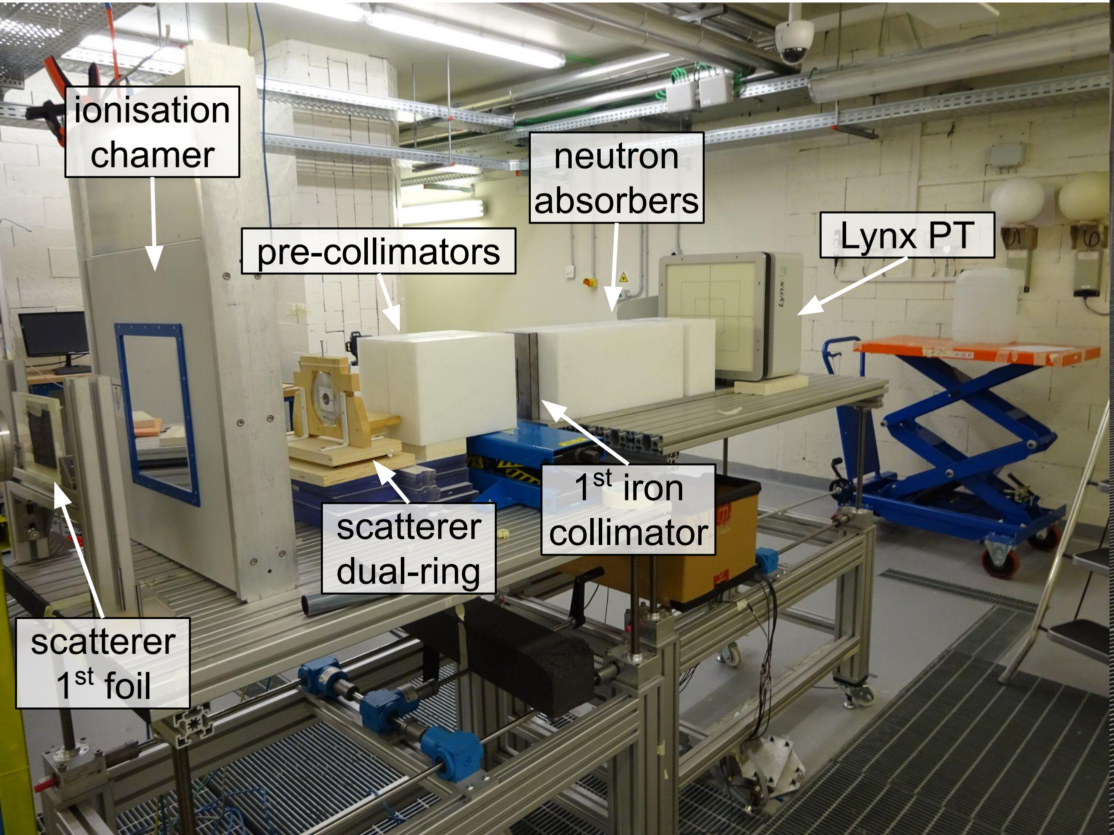


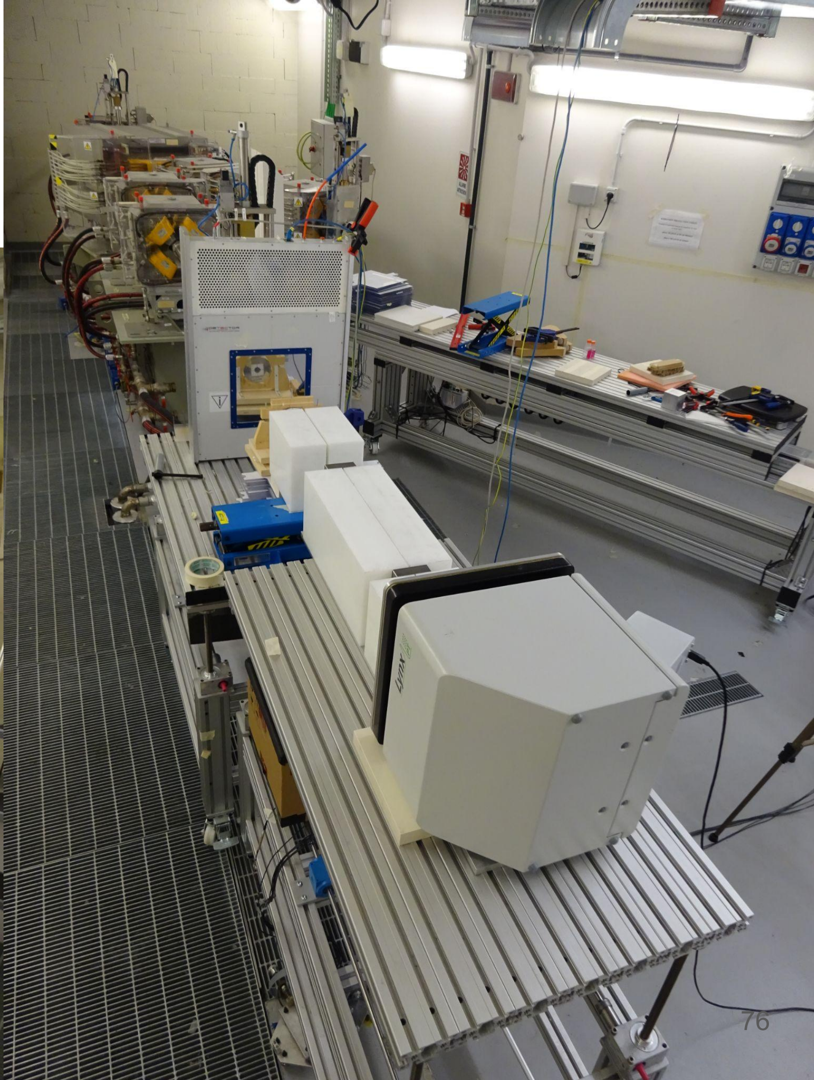
dark count rate vs. temperature



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

Collimator setup: intensity calibration





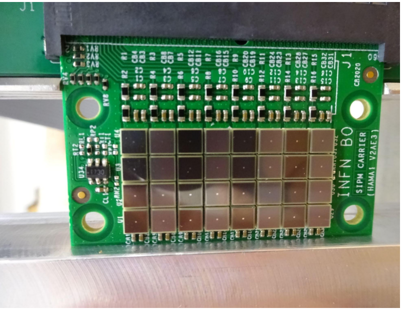
a look into the operation of a complete SiPM readout

Hamamatsu (HAMA1 #1) threshold scans

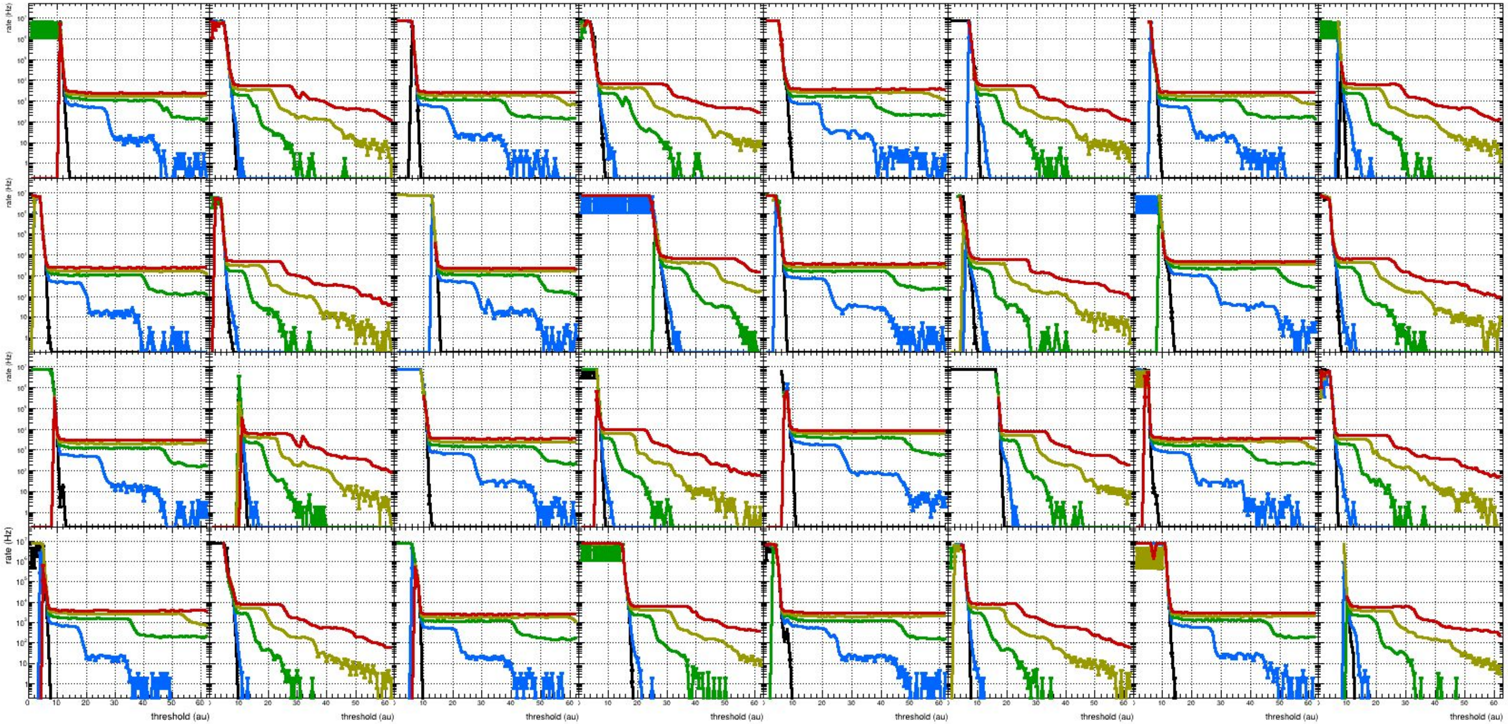
PRELIMINARY

T = -30 C

not irradiated board



13360-3050 13360-3025



Vbias (V)

48 50 52 54 56

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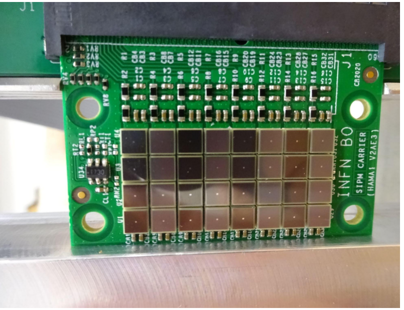
Hamamatsu (HAMA1 #2) threshold scans

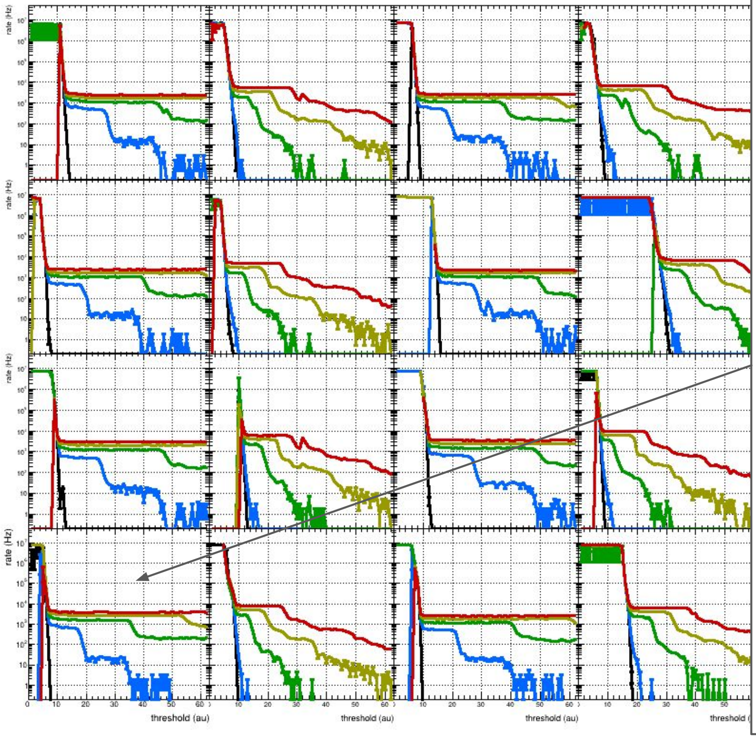
PRELIMINARY

T = -30 C

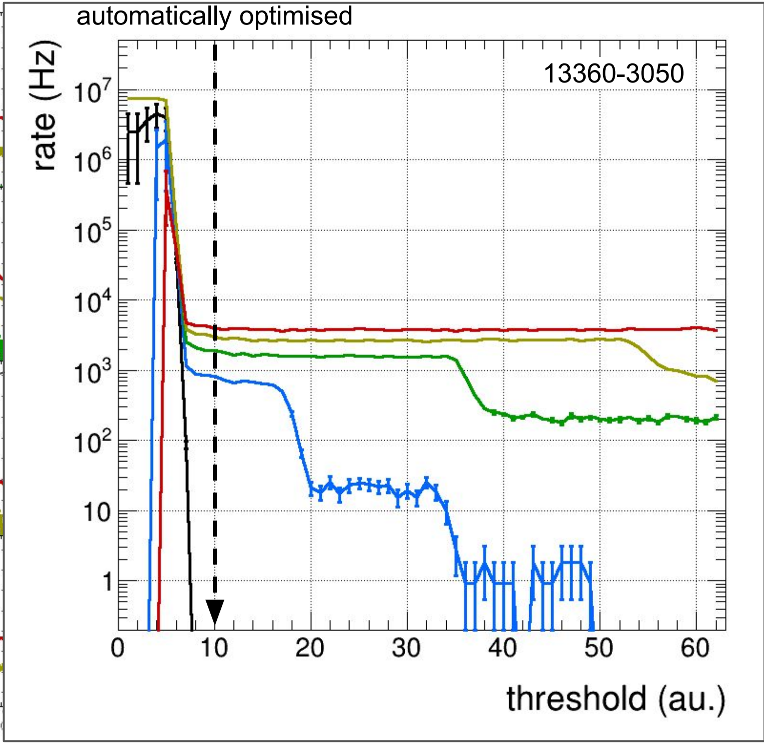
not irradiated board



13360-3050 13360-3025



selected threshold value
automatically optimised



Vbias (V)

48 50 52 54 56

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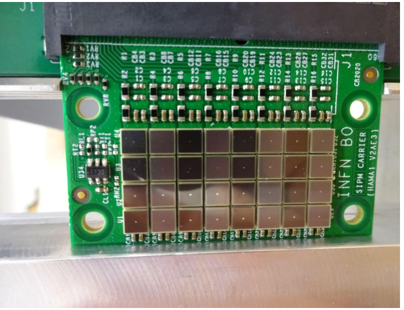
Hamamatsu (HAMA1 #1) threshold scans

PRELIMINARY

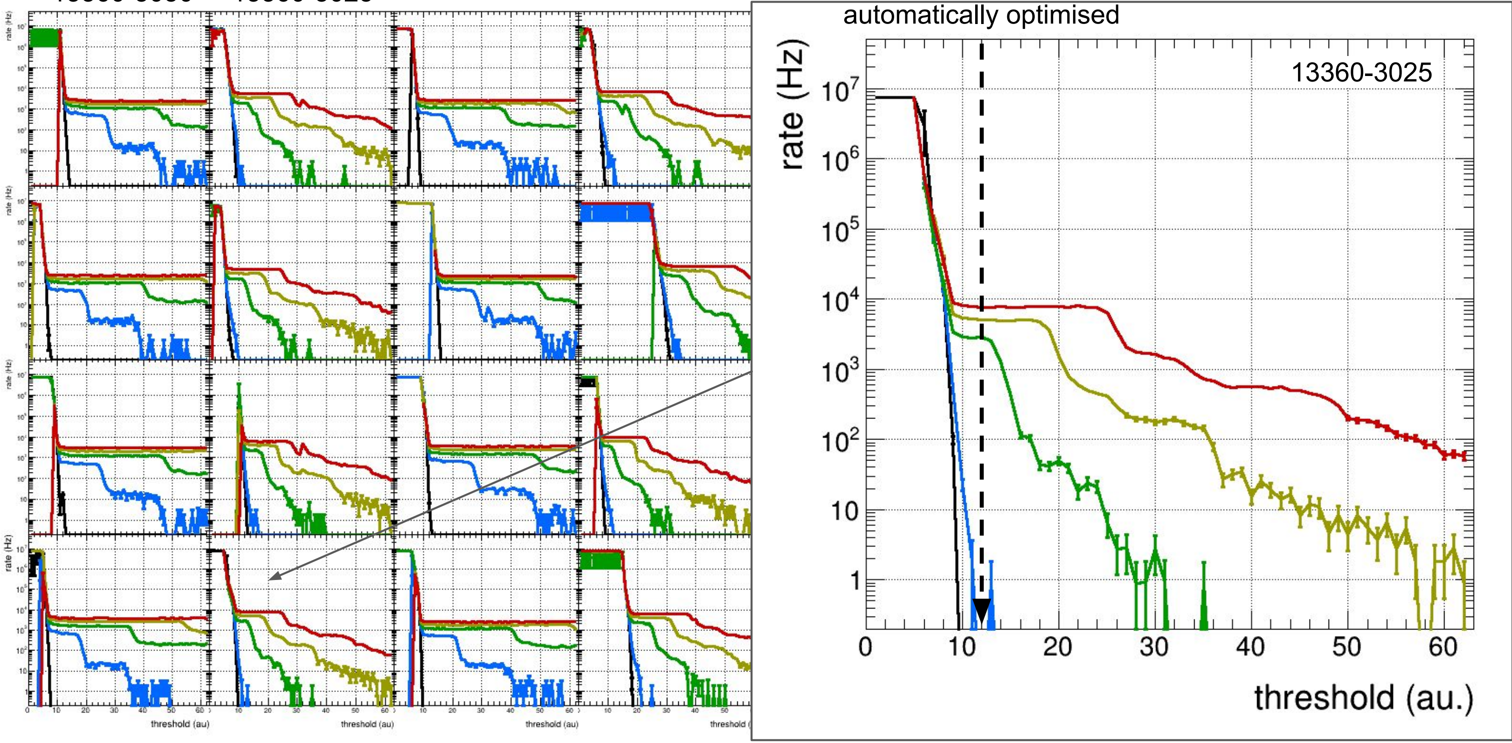
T = -30 C

not irradiated board



13360-3050 13360-3025

selected threshold value
automatically optimised



Vbias (V)

48 50 52 54 56

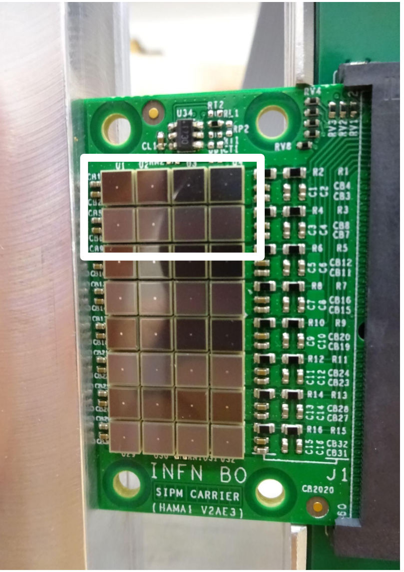
Istituto Nazionale di Fisica Nucleare

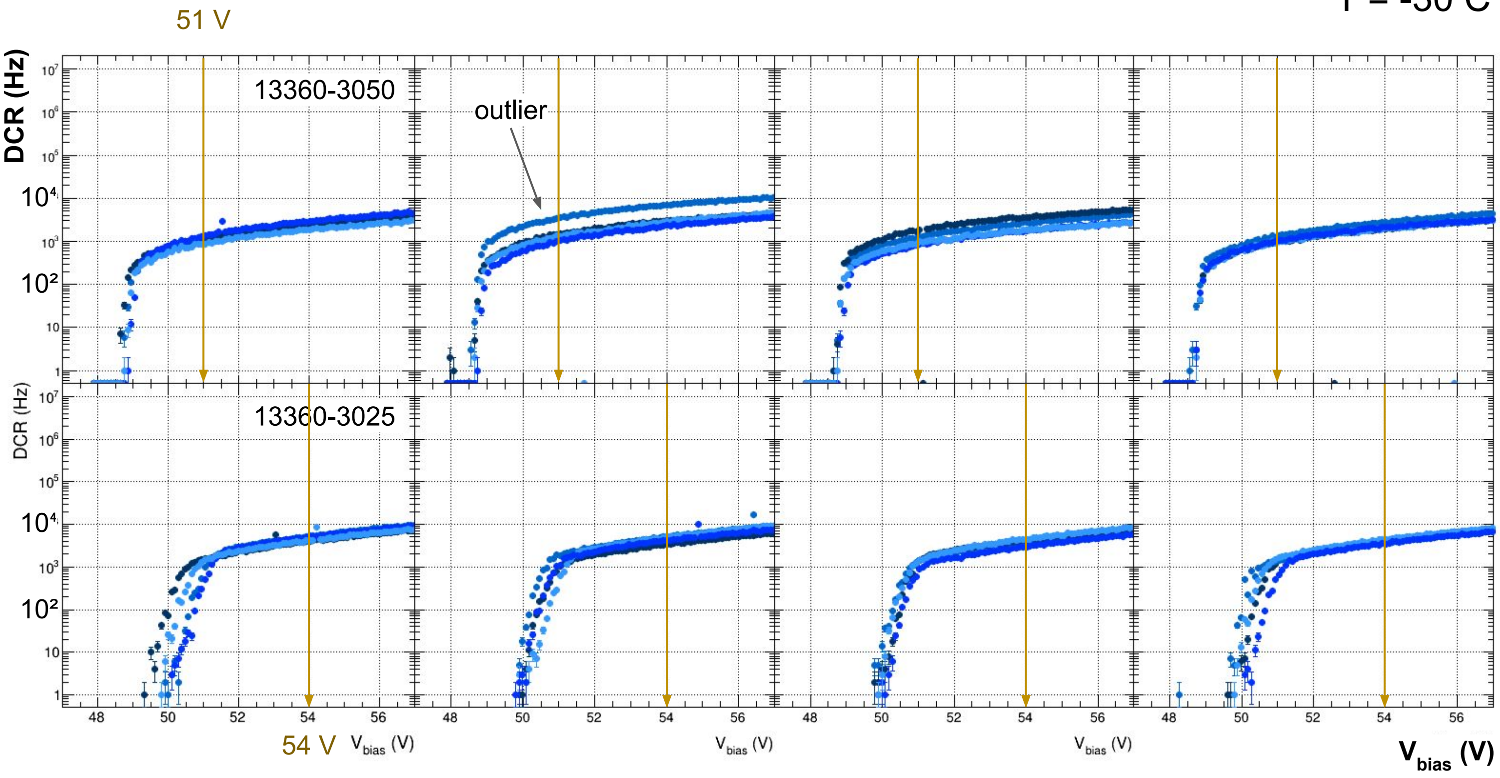
Hamamatsu (HAMA1 #1) Vbias scans

PRELIMINARY

T = -30 C

not irradiated board





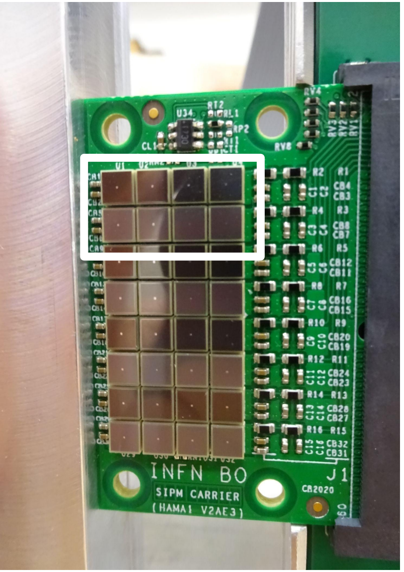
very uniform performance (besides one outlier) when signal above threshold

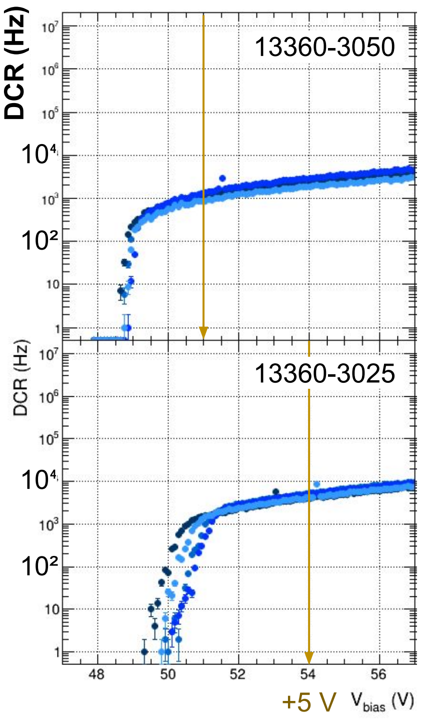
Hamamatsu (HAMA1 #1) Vbias scans

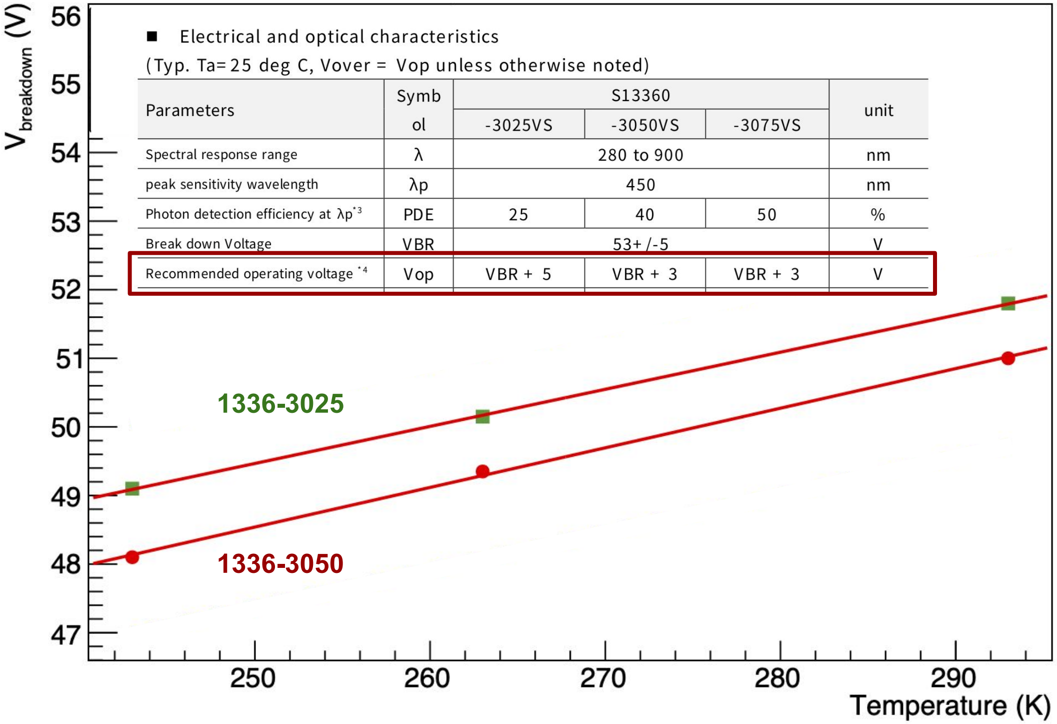
PRELIMINARY

T = -30 C

not irradiated board







■ 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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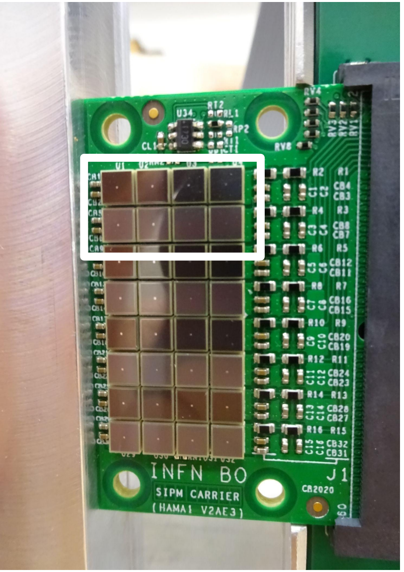
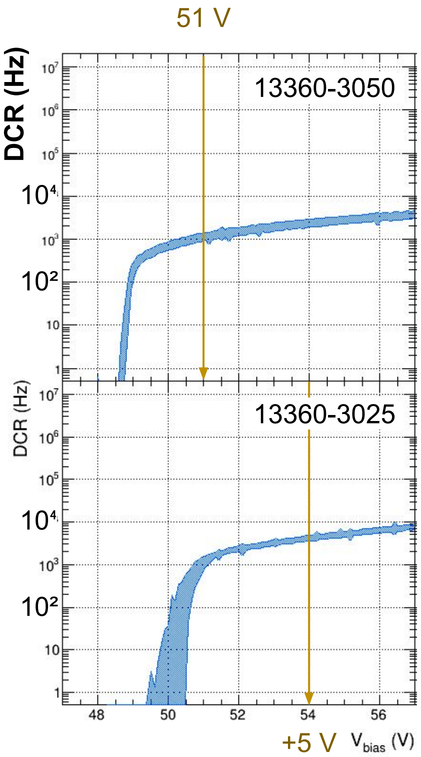
Hamamatsu (HAMA1 #1) Vbias scans

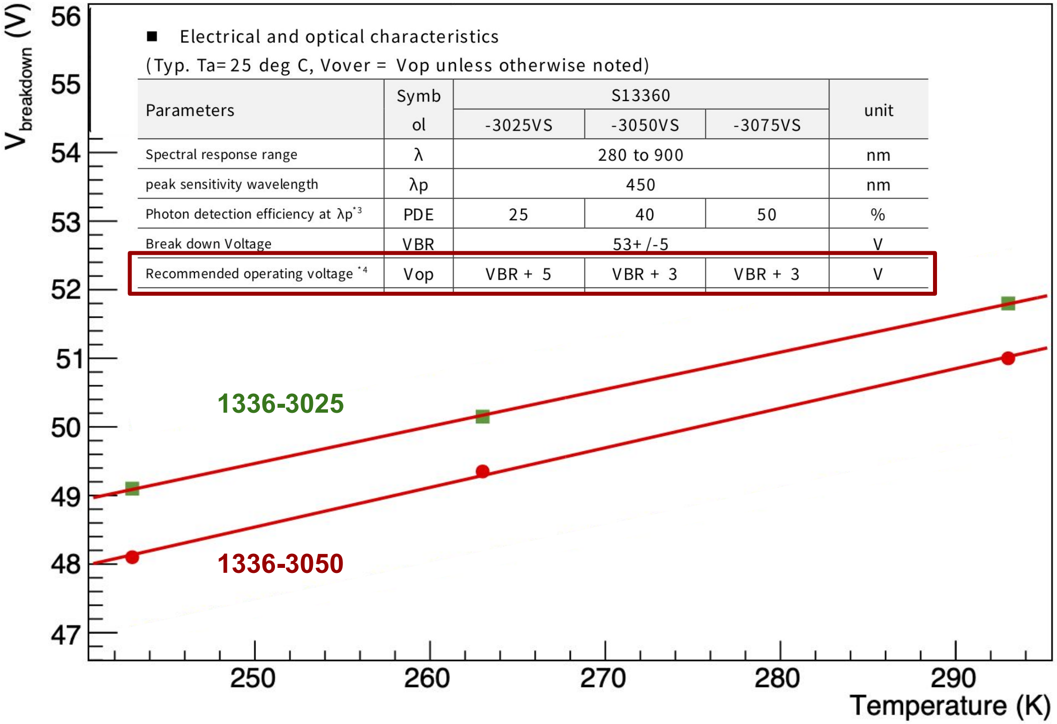
PRELIMINARY

T = -30 C

not irradiated board







■ 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

average of the various SiPM sensors, band indicates ± RMS

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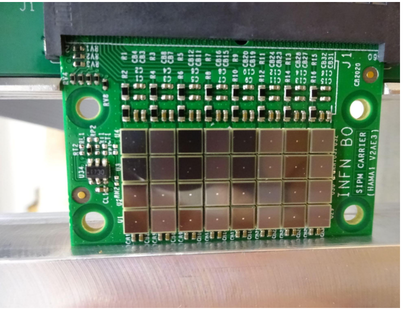
Hamamatsu (HAMA1 #2) threshold scans

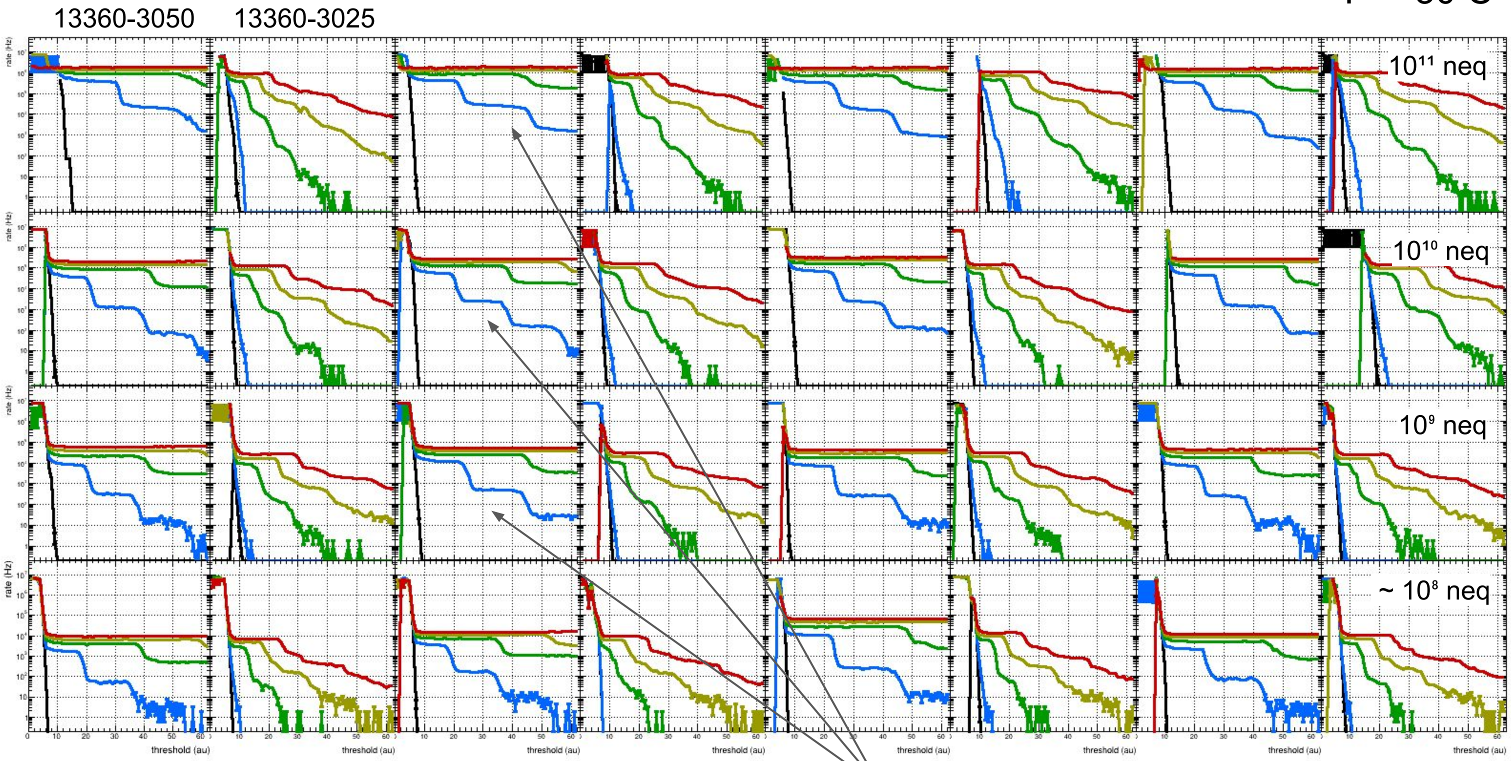
PRELIMINARY

T = -30 C



irradiated board after annealing

still working!



clear single-photon separation up to 10^{11}

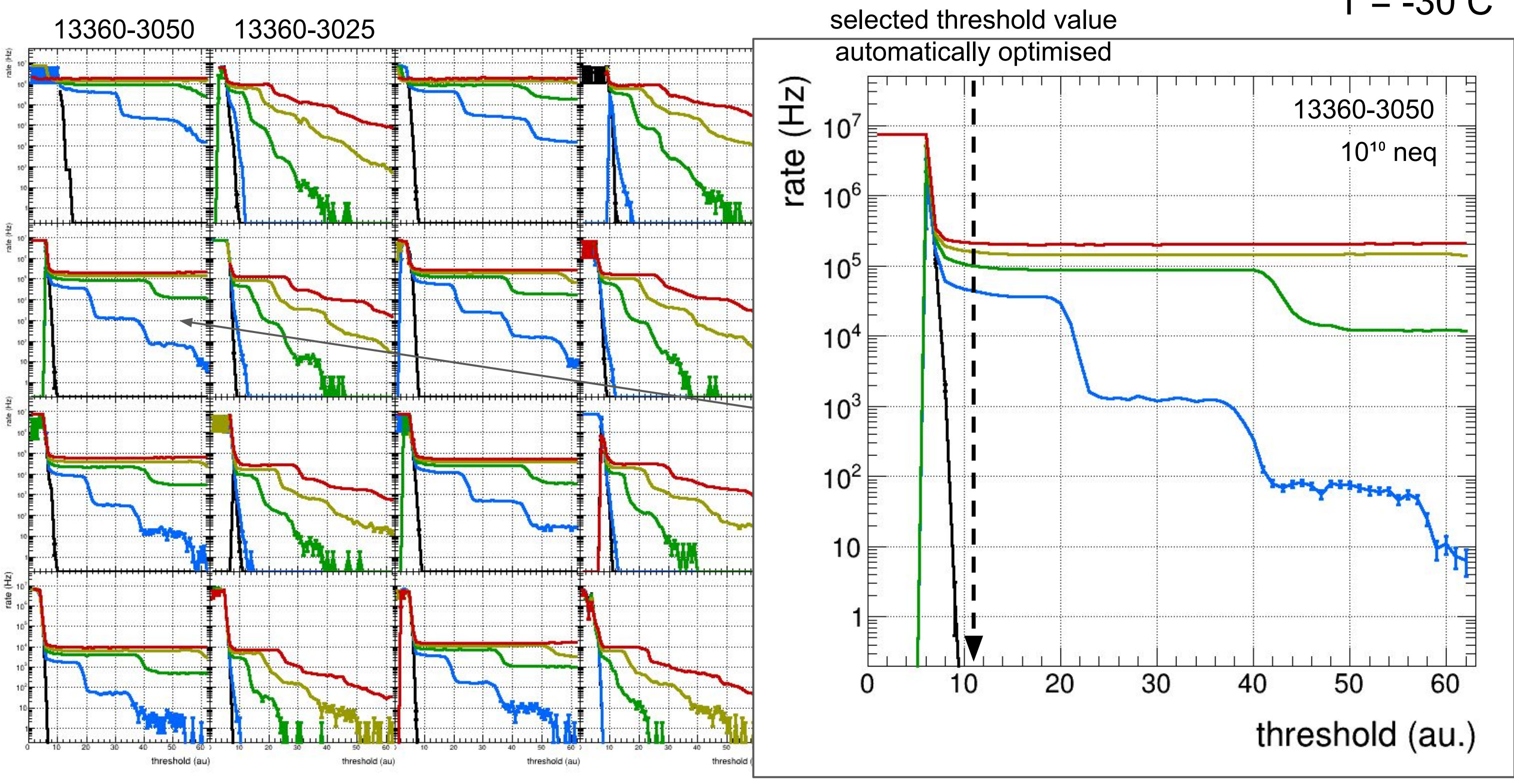
Vbias (V)

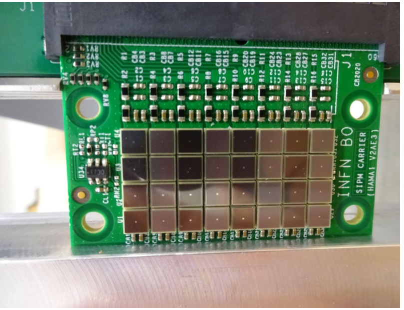
48 50 52 54 56

Hamamatsu (HAMA1 #2) threshold scans

PRELIMINARY

T = -30 C





irradiated board after annealing

still working!

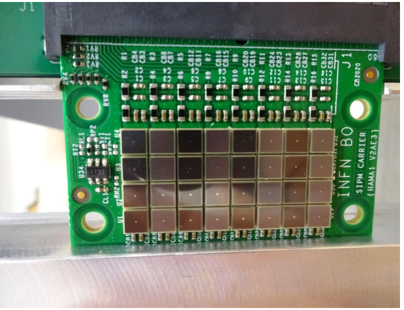
Vbias (V)

48 50 52 54 56

Hamamatsu (HAMA1 #2) threshold scans

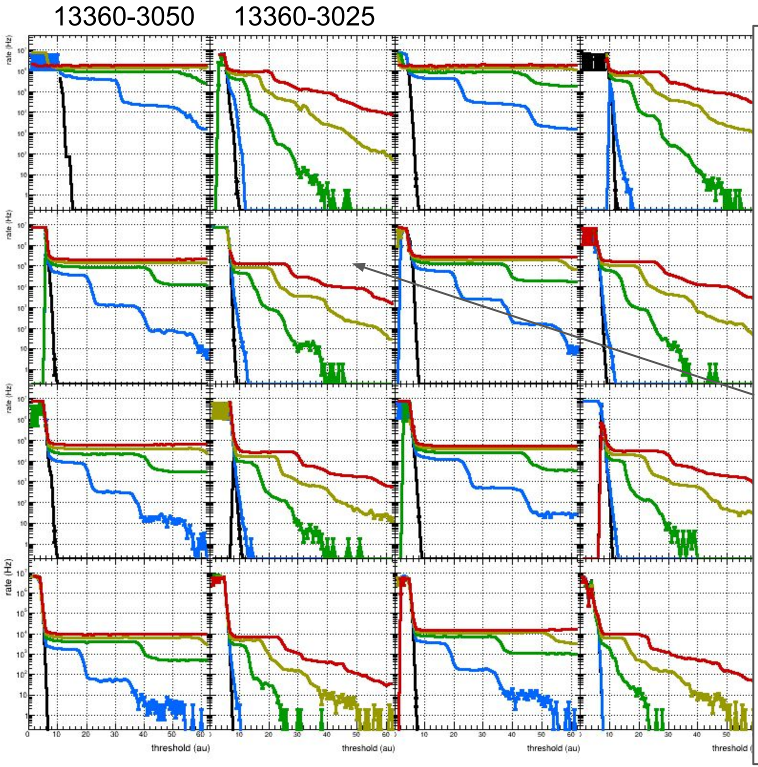
PRELIMINARY

T = -30 C

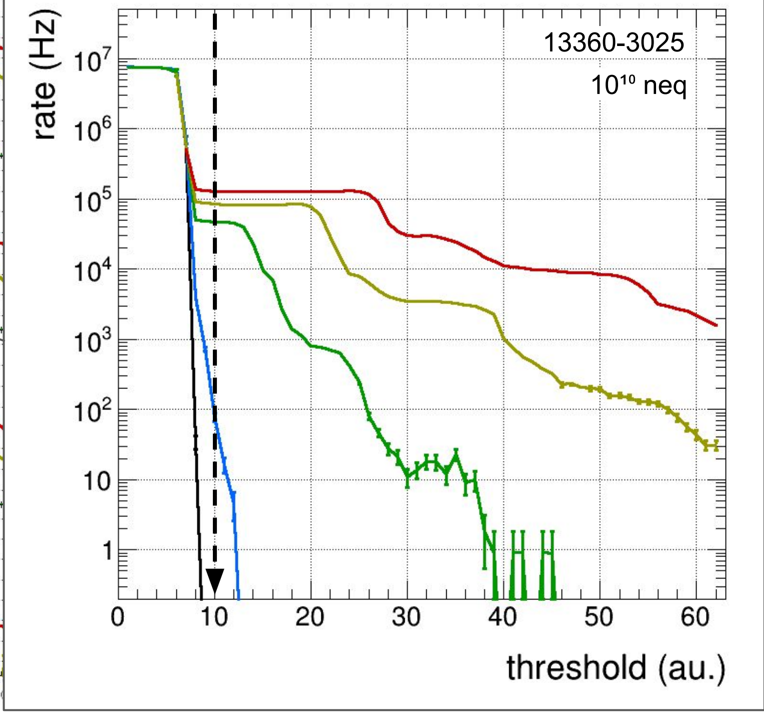


irradiated board after annealing

still working!



selected threshold value automatically optimised



Vbias (V)

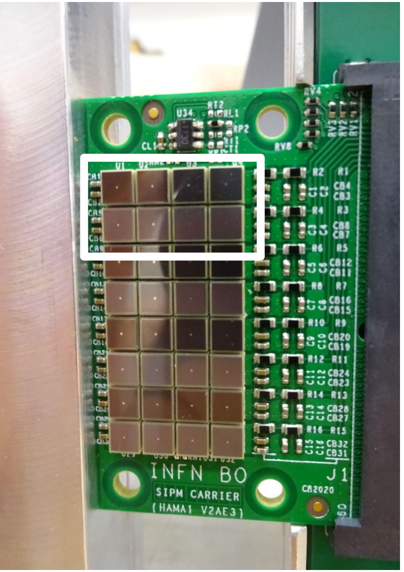
48 50 52 54 56

let’s look into the irradiated board

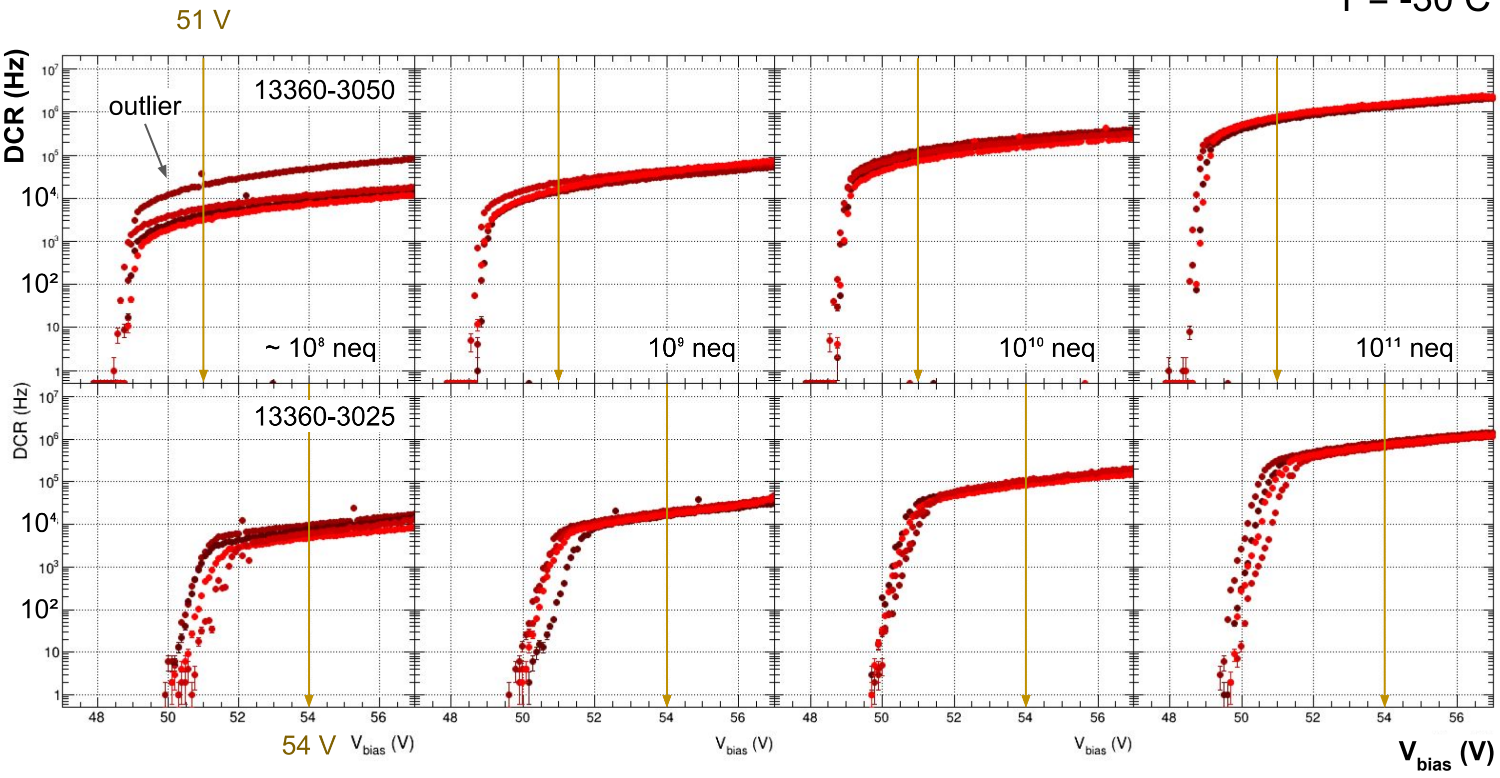
Hamamatsu (HAMA1 #2) Vbias scans

PRELIMINARY

T = -30 C



irradiated board after annealing



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

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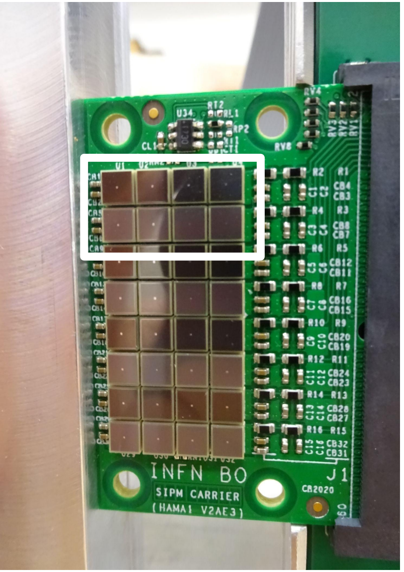
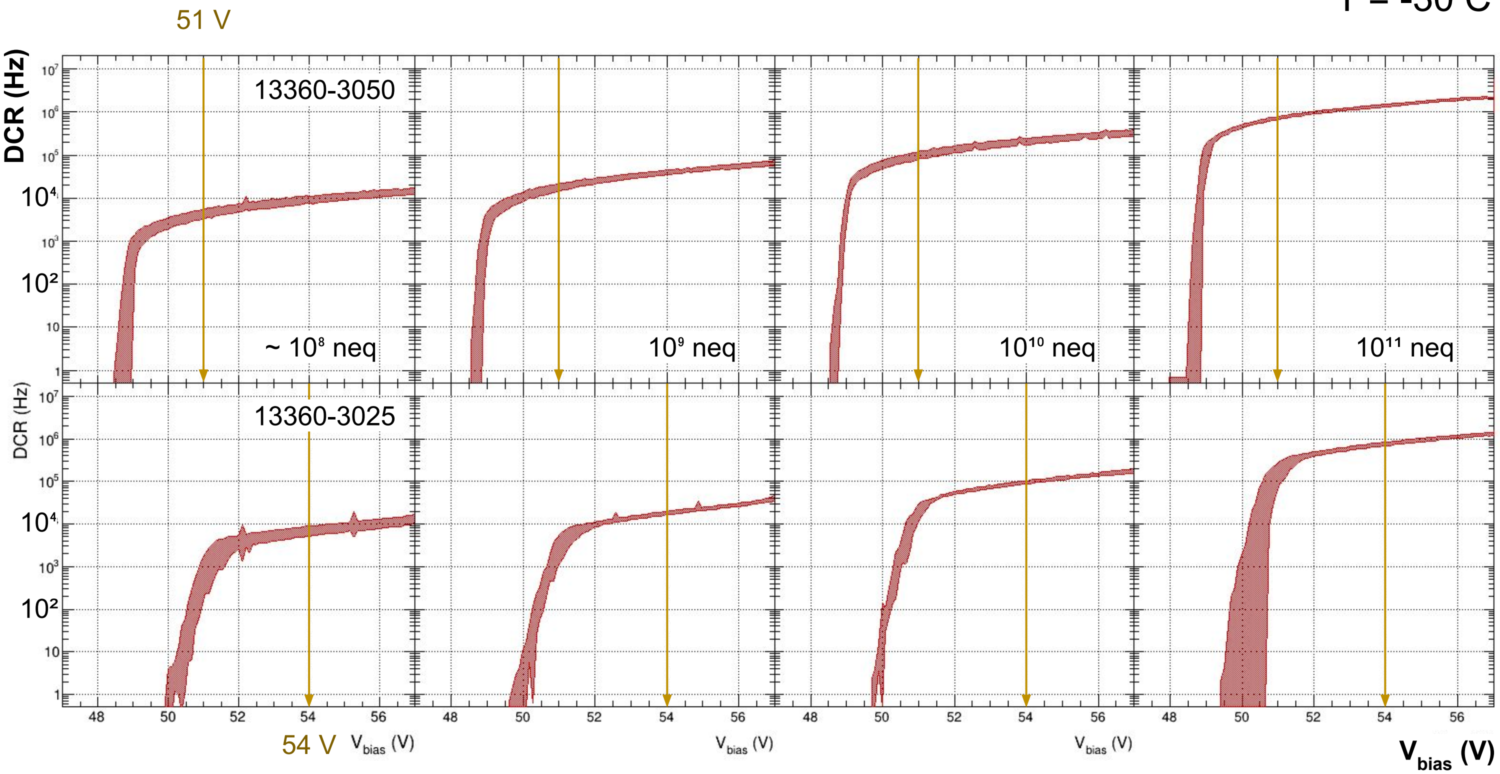
Hamamatsu (HAMA1 #2) Vbias scans

PRELIMINARY

T = -30 C



irradiated board after annealing



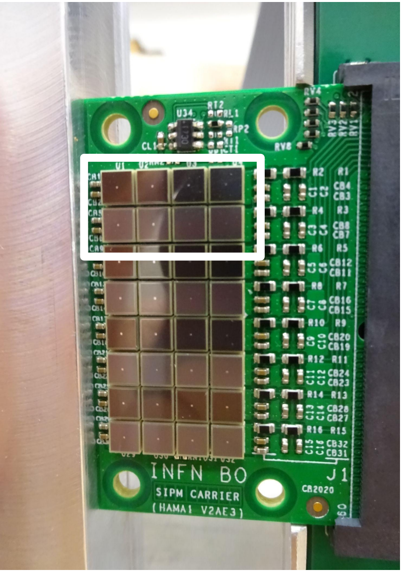
average of the various SiPM sensors, band indicates ± RMS

Hamamatsu (HAMA1) grand comparison

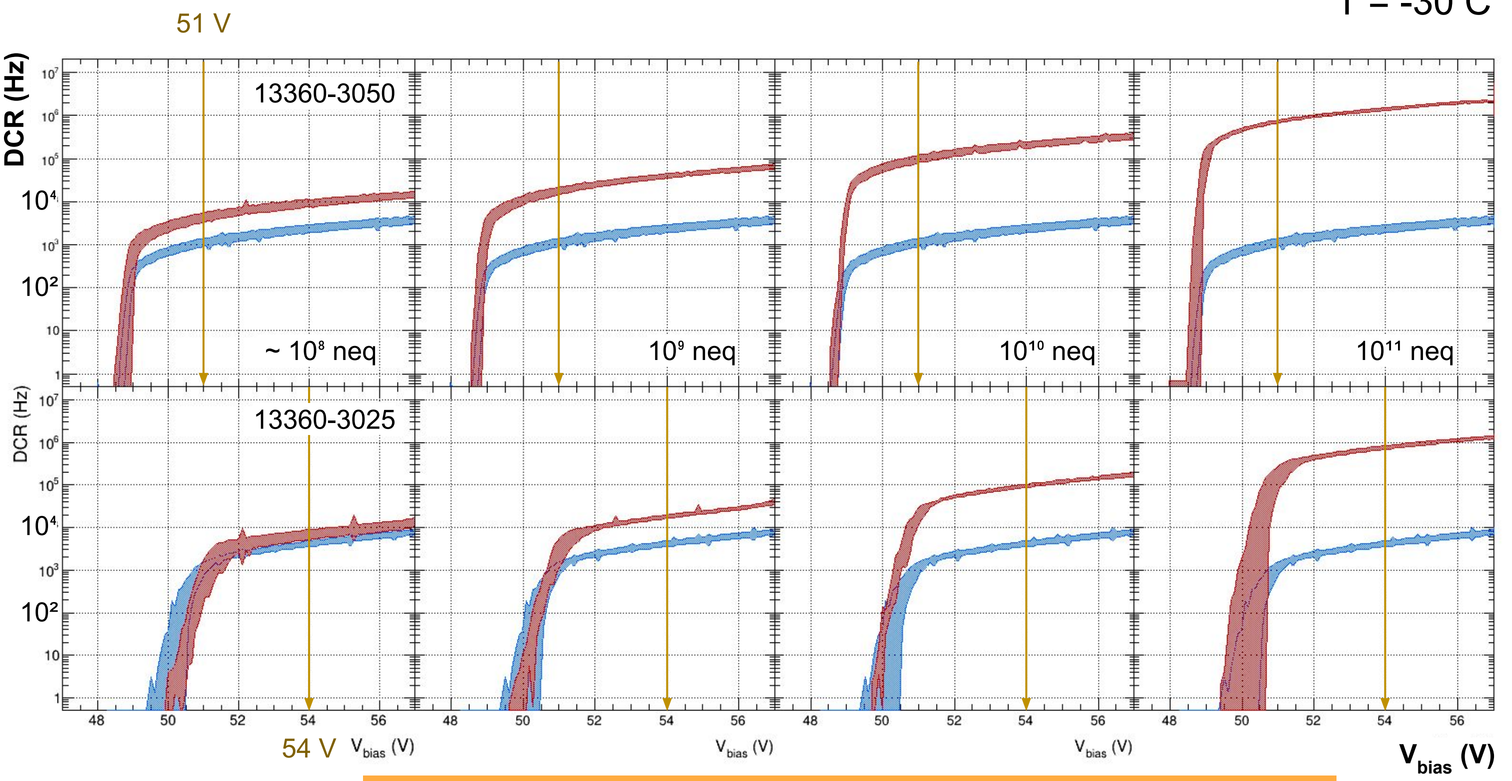
PRELIMINARY

T = -30 C

not irradiated board



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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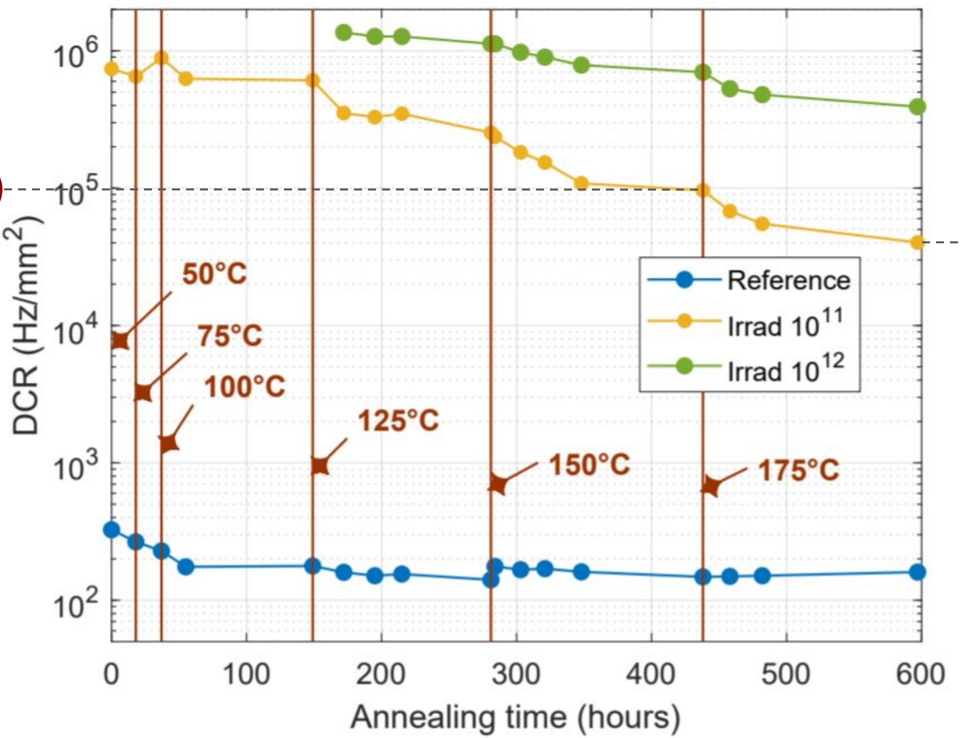
Hamamatsu (HAMA1) grand comparison

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 mm^2



350 kHz
in 3x3 mm^2

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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