dRICH photosensors status and risk mitigation

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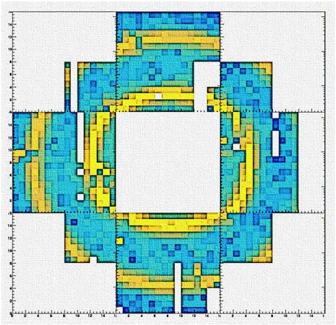
on behalf of the dRICH Collaboration



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TIC meeting, 6 November 2023

dRICH SiPM are part of the SiPM Long-Lead Procurement
on 14 September 2023 dRICH SiPM reviewed at the

Final Design Review for SiPM applications in ePIC detector sub-systems

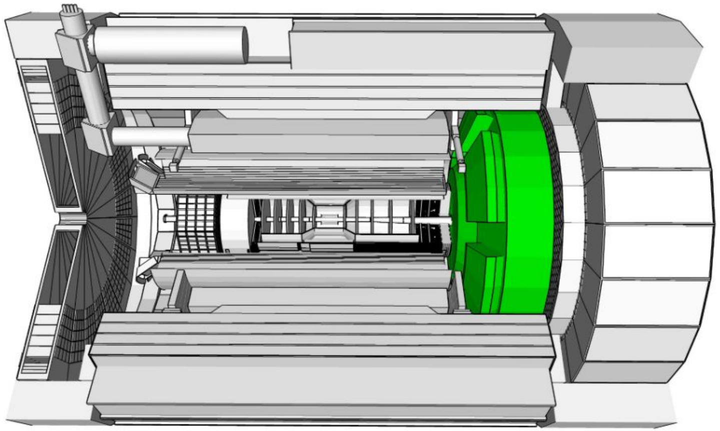
positive feedback from reviewing committee
recommendation to commence SiPM procurement
no further recommendation

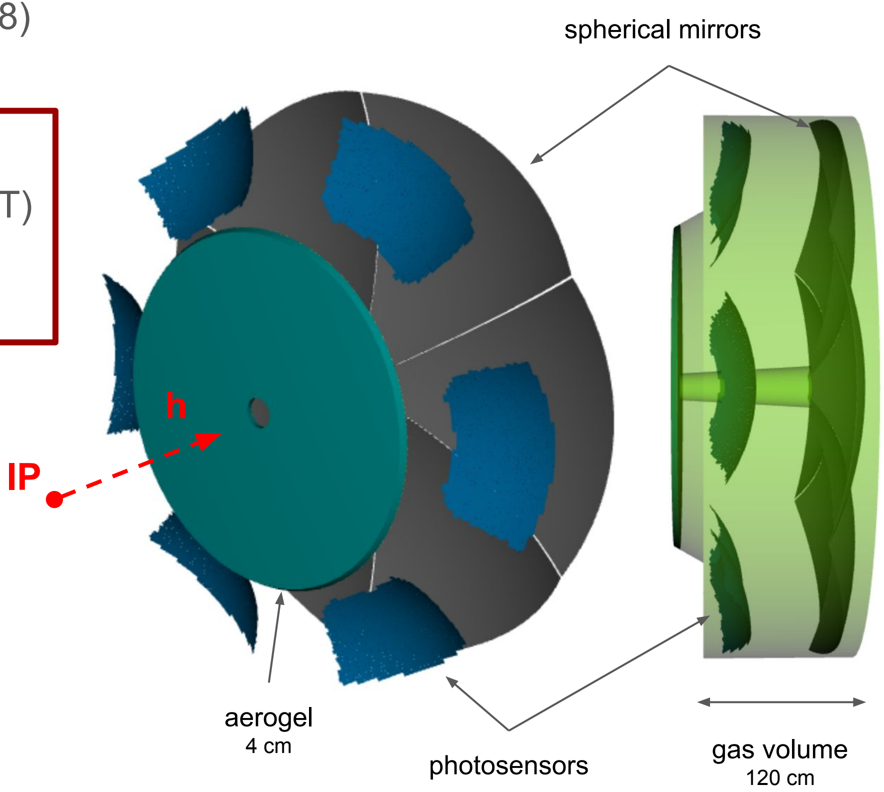
The dual-radiator (dRICH) for forward PID at EIC

compact and cost-effective solution for broad momentum coverage at forward rapidity

p = [3.0, 50] GeV/c
η = [1.5, 3.5]
e-ID up to 15 GeV/c

- **radiators:** aerogel (n ~ 1.02) and C_2F_6 (n ~ 1.0008)
- **mirrors:** large outward-reflecting, 6 open sectors
- **sensors:** 3x3 mm^2 pixel, 0.55 m^2 / sector
  - single-photon detection inside high B field (~ 1 T)
  - outside of acceptance, reduced constraints
  - SiPM optical readout

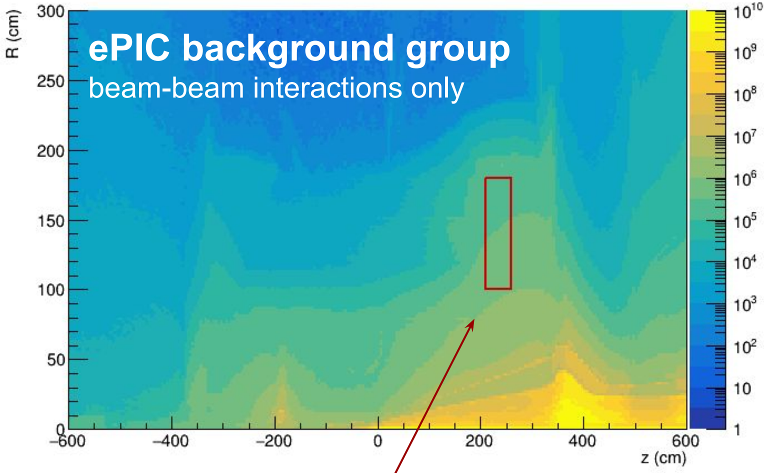




Environment

radiation damage estimates

1-MeV neutron equivalent fluence (1 fb^{-1} ep running)



location of dRICH photosensors

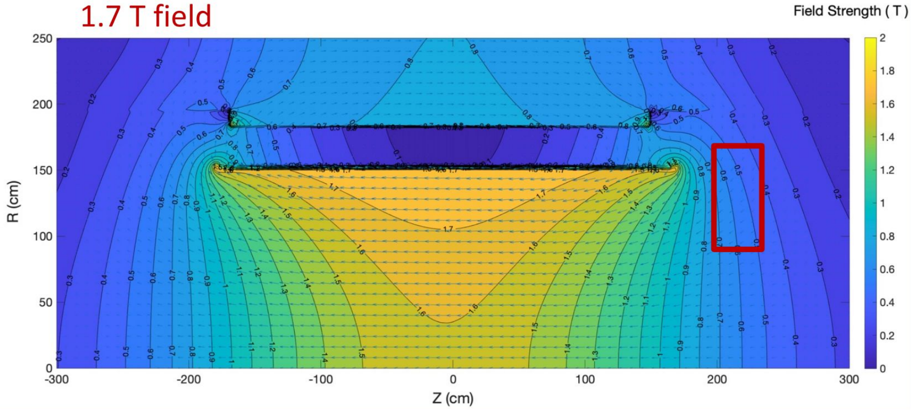
assume fluence: ~ 10^7neq / cm^2 / fb^{-1}

conservatively assume max fluence and 10x safety factor

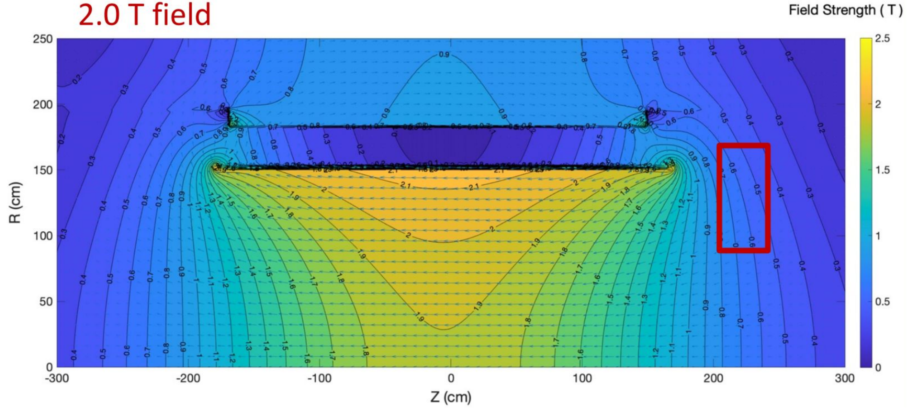
moderate radiation, 1000 fb^{-1} integrated ℒ corresponds to ~ 10^{10} n_{eq}/cm^2

MARCO magnetic field maps

1.7 T field



2.0 T field



non-uniform, strong magnetic field ~ 0.7 T

field lines ~ parallel to photodetector surface

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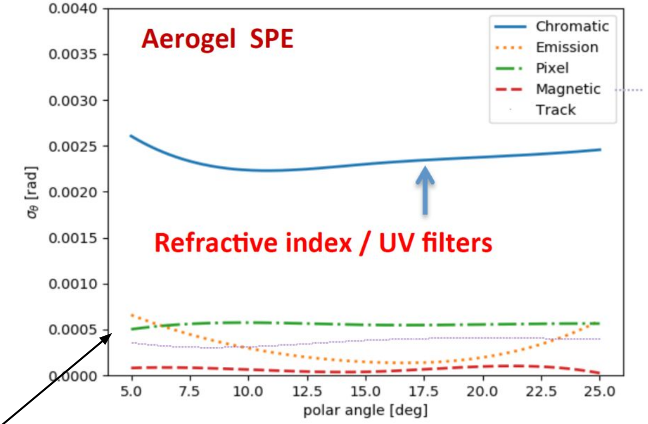
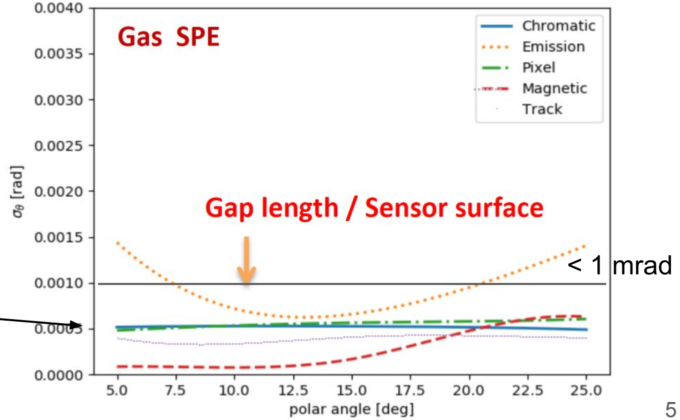
3x3 mm² pixel size optimises performance and number of SiPM / electronics readout channels

not the dominant contribution to the resolution
→ will not benefit from smaller size pixels
→ performance requirements already met
bigger pixel size will have impact on gas
→ will start becoming dominant contribution





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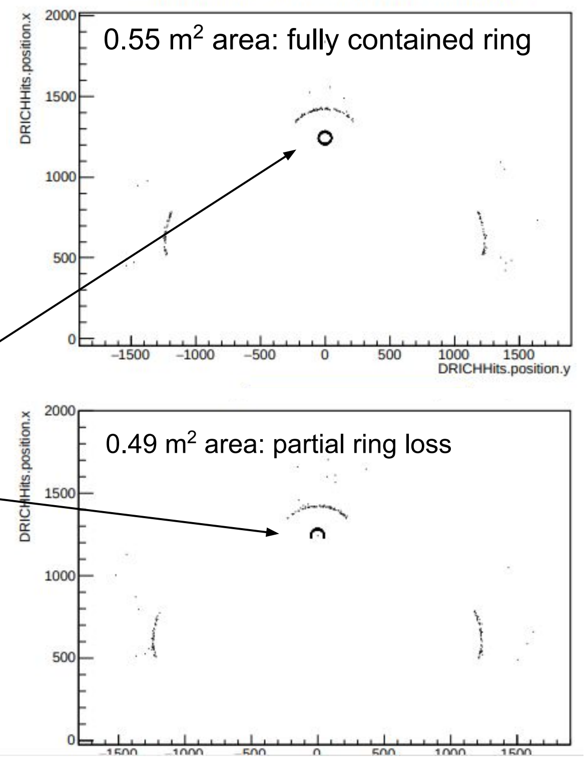
readout surface area of ~ 0.55 m^2 / sector required to fully contain rings at extreme pseudorapidities

high eta = most demanding for PID
→ large number of photons
→ no acceptance losses

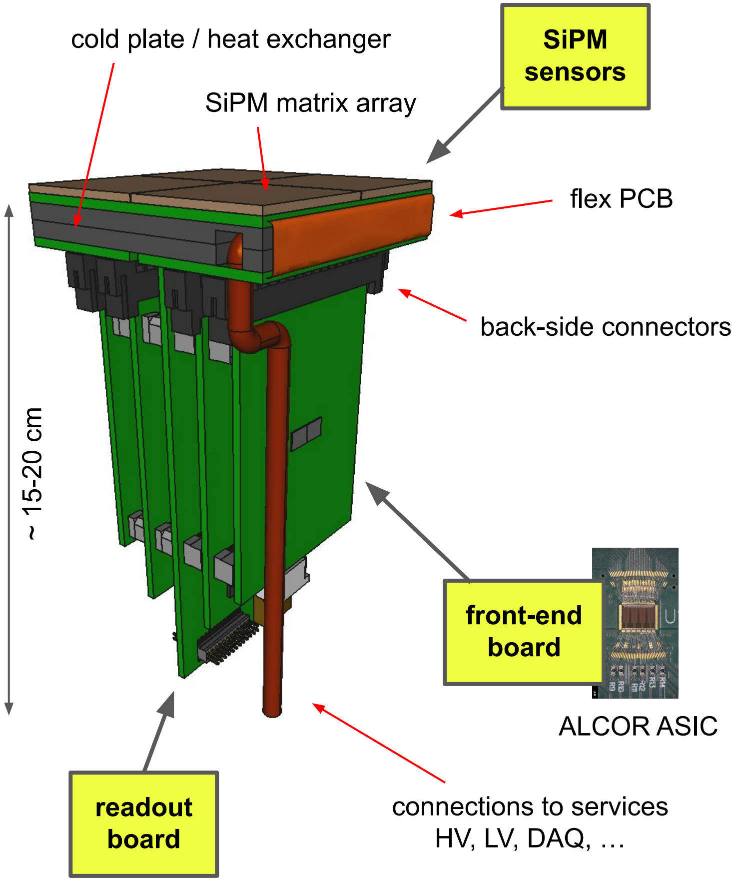
0.55 m^2 / sector x 6 sectors (3x3 mm^2 pixels)
→ 3.3 m^2 of instrumented area (~ 317 k SiPM channels)



ePIC GEANT4 simulation

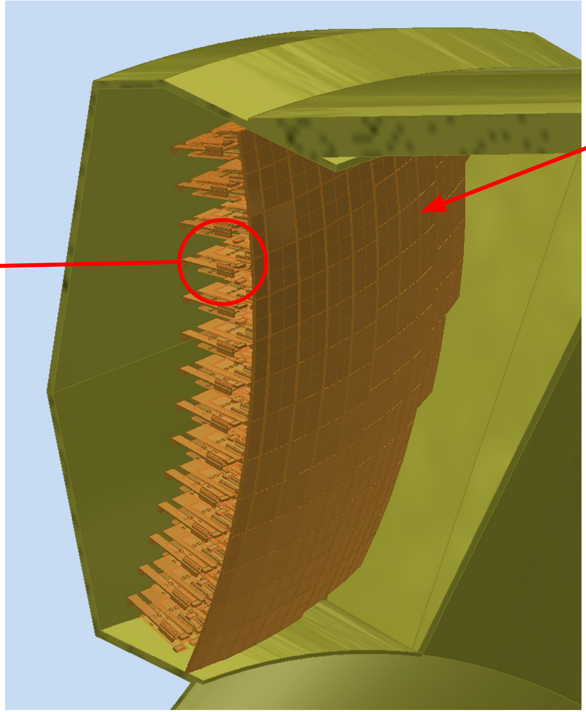
Photodetector unit

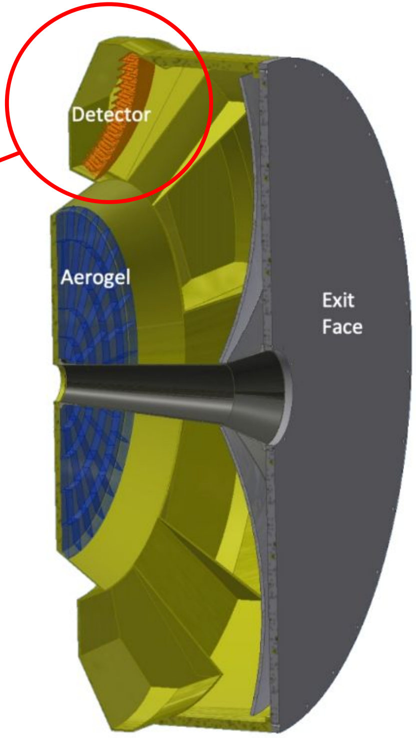
conceptual design of final layout



SiPM sensor matrices mounted on carrier PCB board

- 4x 64-channel SiPM array device (256 channels) for each unit
  - need modularity to realise curved readout surface
- 1240 photodetector units for full dRICH readout
  - 4960 SiPM matrix arrays (8x8)
  - 317440 readout channels





SiPM technical specs

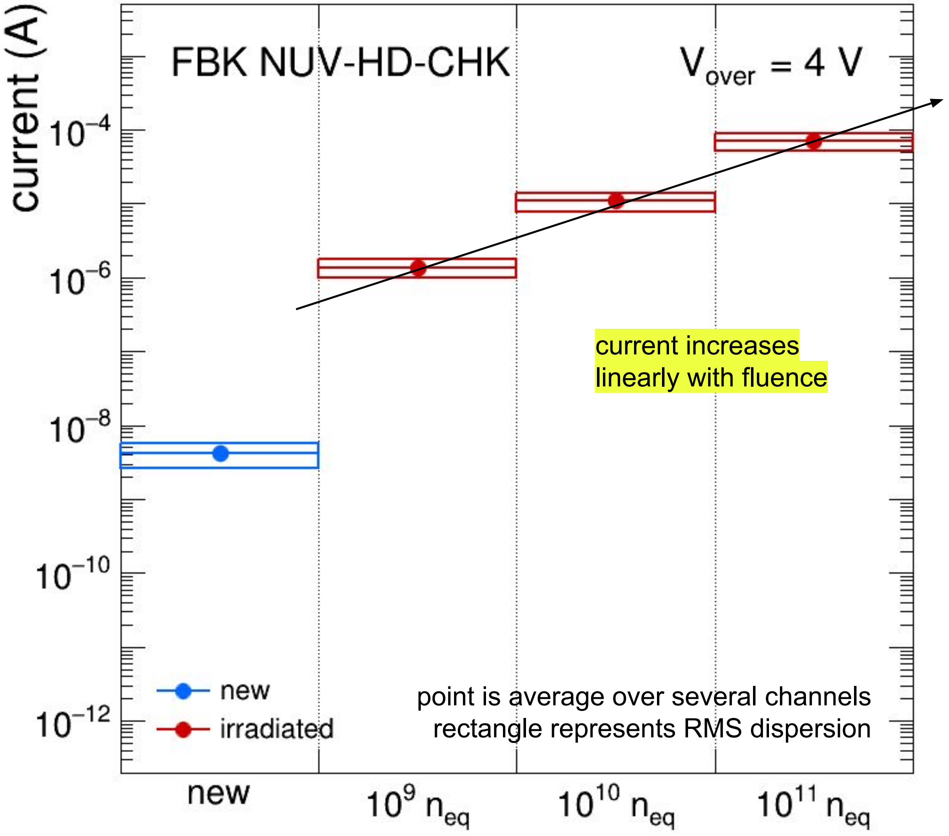
baseline sensor device
64 (8x8) channel SiPM array
3x3 mm^2 / channel

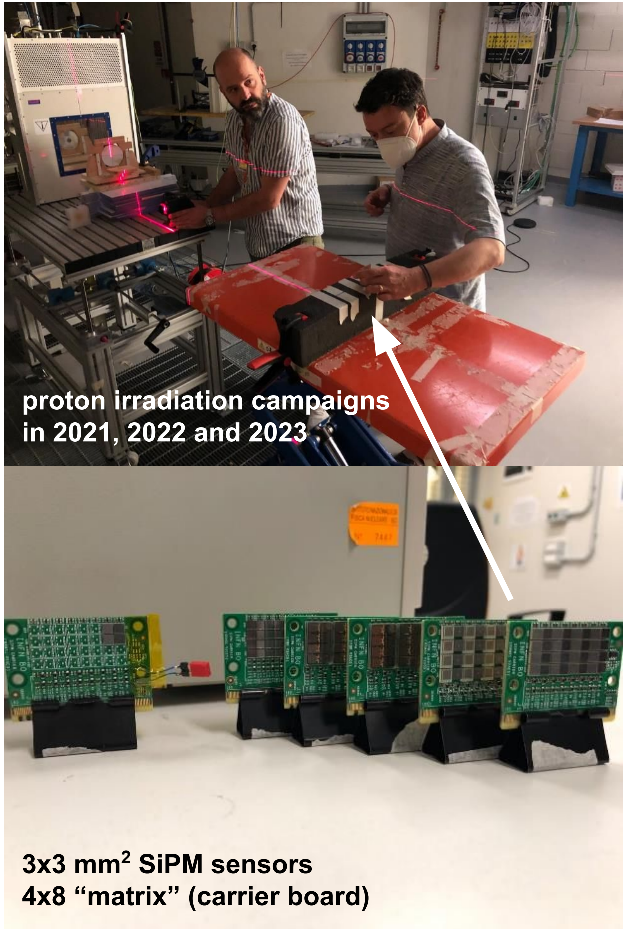
Parameters	Value	Notes (all parameters at the recommended operating voltage and T = 25 C, unless specified)
Device type	SiPM array	
Number of channels	64	8 x 8 matrix
Active Area	3 x 3 mm^2	active area of one channel, total active area is 64 x 3 x 3 mm^2
Device Area	< 28 x 28 mm^2	device area should be small such as to have > 75% fraction of active area over device total area
Pixel Size	40 - 80 um	pitch of the microcell SPAD
Package Type	surface mount	
Operating voltage	< 64 V	
Peak Sensitivity	400 - 450 nm	
PDE	> 35%	at peak sensitivity wavelength
Gain	> 1.5 10^6	
DCR	< 1.5 MHz	
Temperature coefficient of Vop	< 60 mV / C	
Direct crosstalk probability	< 10%	
Terminal capacity	< 600 pF	
Packing granularity		
Vop variation within a tray	< 300 mV	Vop variation between channels in one device
Recharge Time	< 100 ns	ctau recharge time constant
Fill Factor	> 70%	
Protective Layer	silicone resin (n = 1.5 - 1.6)	radiation resistant, heat resistant (up to T = 180 C)
DCR at low temperature	< 10 kHz	at T = -30 C
DCR increase with radiation damage	< 1 MHz / 10^9 neq	at T = -30 C, after a radiation damage corresponding to 10^9 1-MeV neutron equivalent / cm^2 (neq)
Residual DCR after annealing	< 25 kHz / 10^9 neq	at T = -30 C, after a radiation damage of 10^9 neq and a 150 hours annealing cycle at T = 150 C
Single photon time resolution	< 200 ps FWHM	corresponding to < 85 ps RMS

very important parameters to ensure detector performance over the years

we will evaluate as part of QA, testing sensor samples in received batches

Studies of radiation damage on SiPM

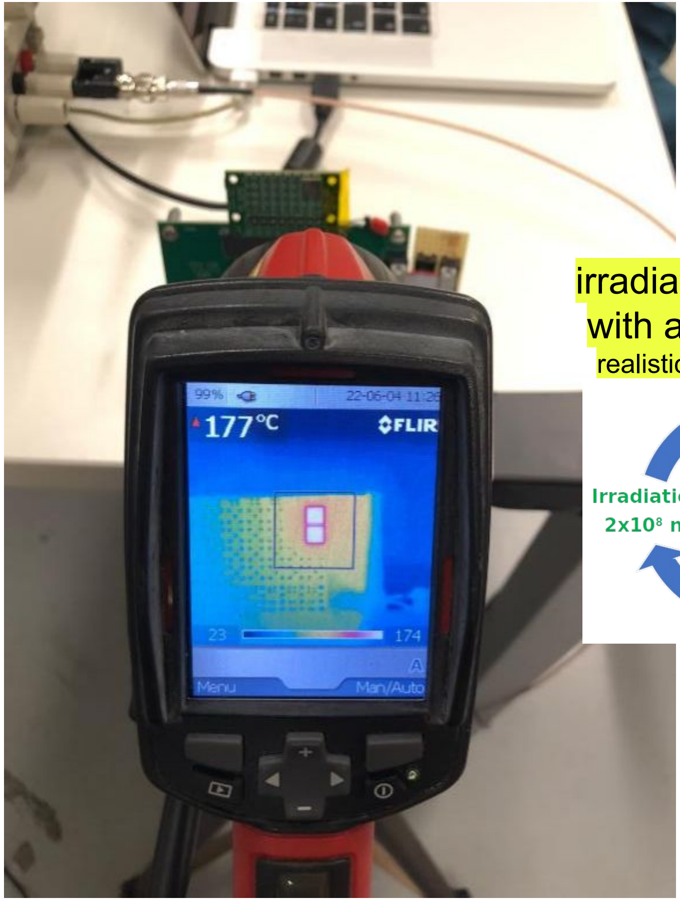




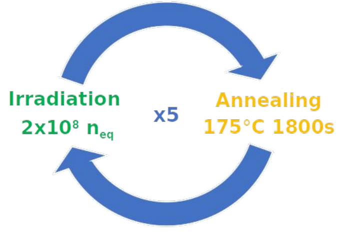
all results are reported at T = -30 C

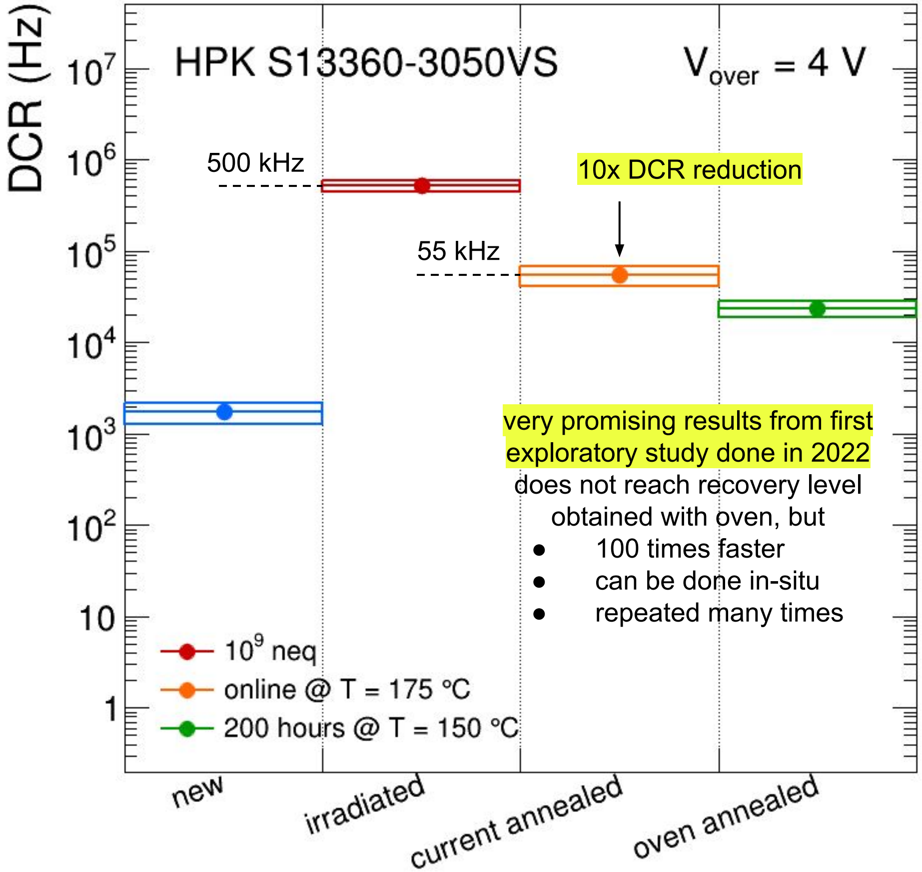
“Online” self-induced annealing

studies for “in-situ” SiPM recovery
multiple cycles: 30 minutes at 175 C
~ 1 W power/sensor delivered with forward bias voltage



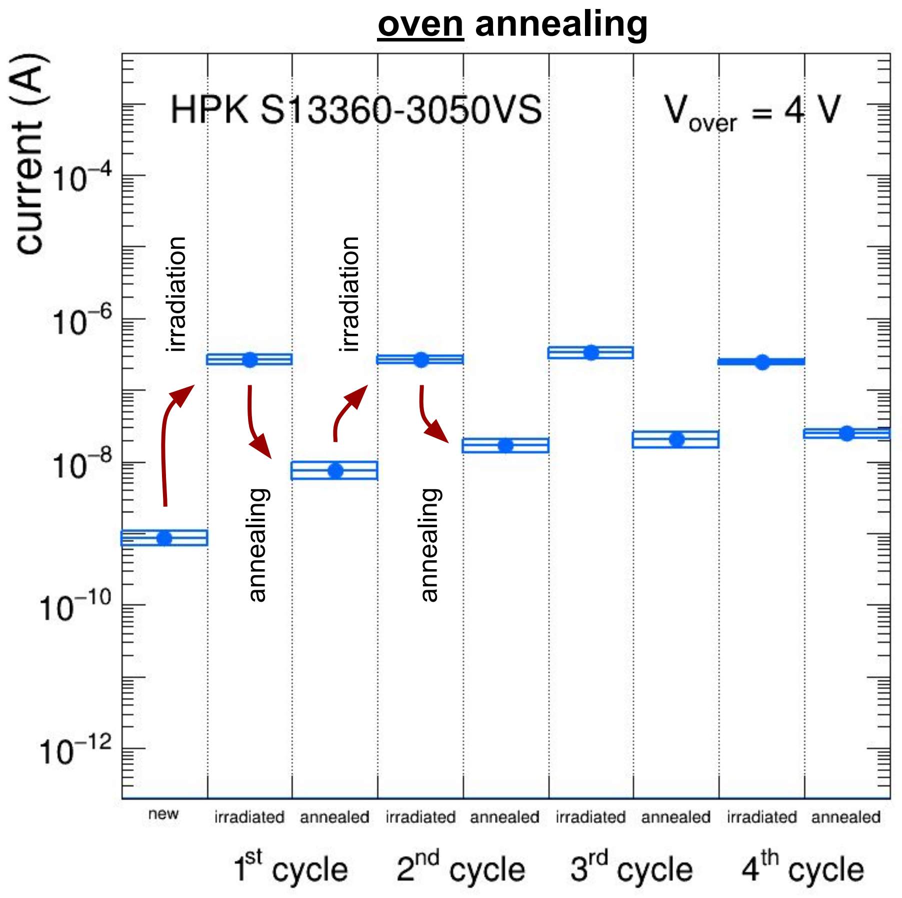
irradiation interleaved with annealing cycle
realistic experimental case





very promising results from first exploratory study done in 2022
does not reach recovery level obtained with oven, but
- 100 times faster
- can be done in-situ
- repeated many times

Repeated irradiation-annealing cycles



test reproducibility of repeated irradiation-annealing cycles

simulate a realistic experimental situation

- consistent irradiation damage
  - DCR increases by ~ 500 kHz (@ Vover = 4)
  - after each shot of 10^9 n_{eq}
- consistent residual damage
  - ~ 15 kHz (@ Vover = 4) of residual DCR
  - builds up after each irradiation-annealing

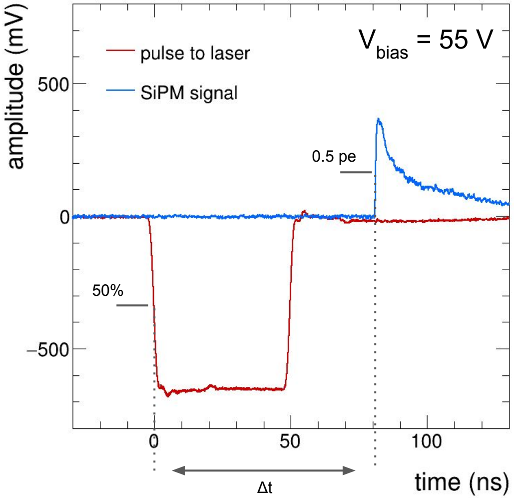
annealing cures same fraction of newly-produced damage

~ 97% for HPK S13360-3050 sensors

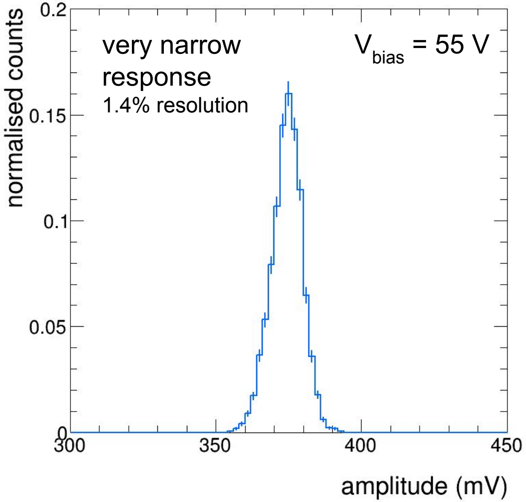
Laser timing measurements with oscilloscope

Hamamatsu S13360-3075

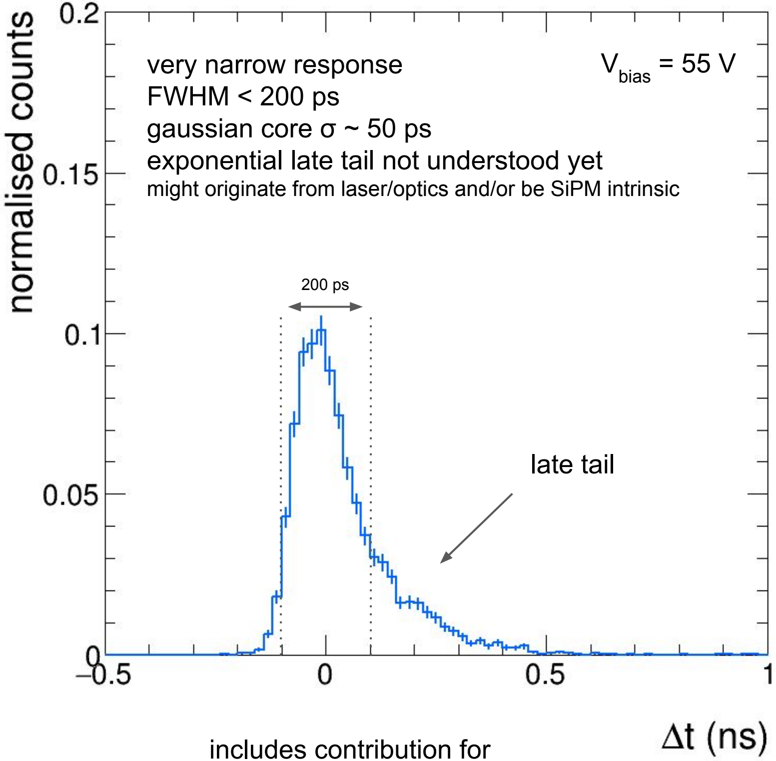
acquired oscilloscope traces



SiPM signal amplitudes (1pe)



laser-SiPM correlations (time-walk corrected)



includes contribution for laser-oscilloscope synchronization
measured to be σ_{sync} = 30 ps

measurements performed at T = -30 C with

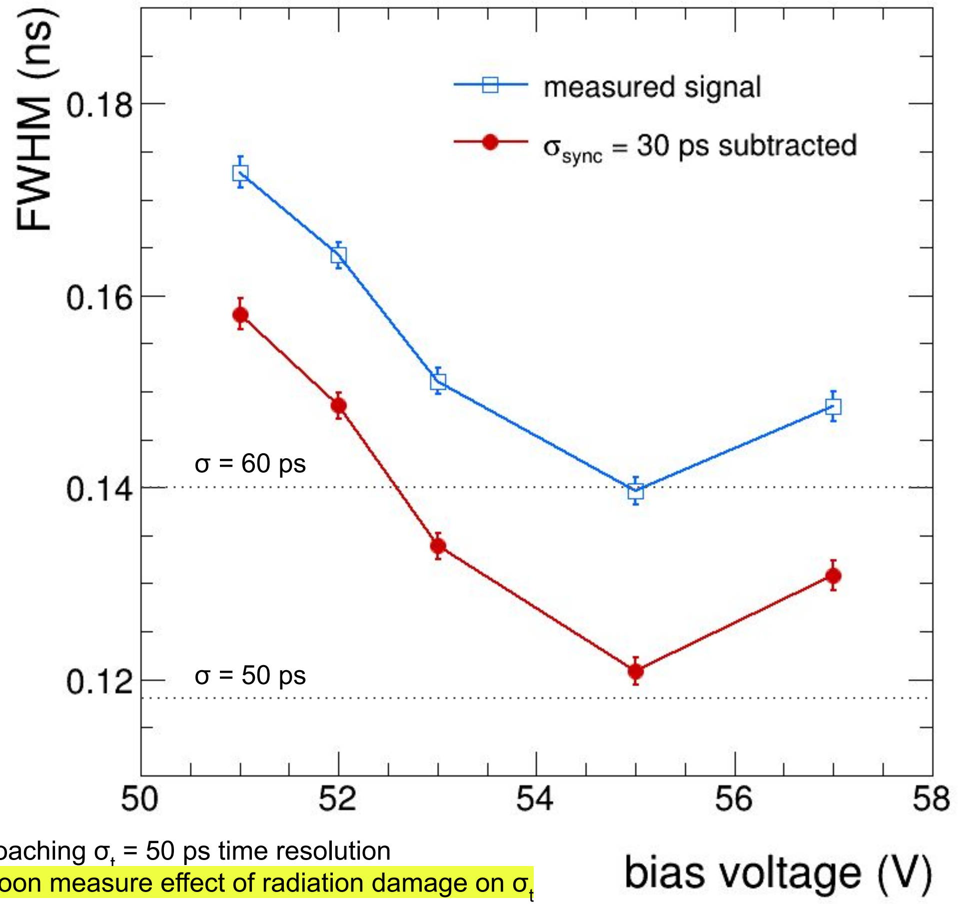
- Lecroy Waverunner 40186 oscilloscope
- Cividec Broadband amplifier (40 db)

timing defined with fixed thresholds

- laser pulse at 50% of signal
- SiPM signal at 0.5 pe (average amplitude)

time-amplitude correlation (walk) corrected

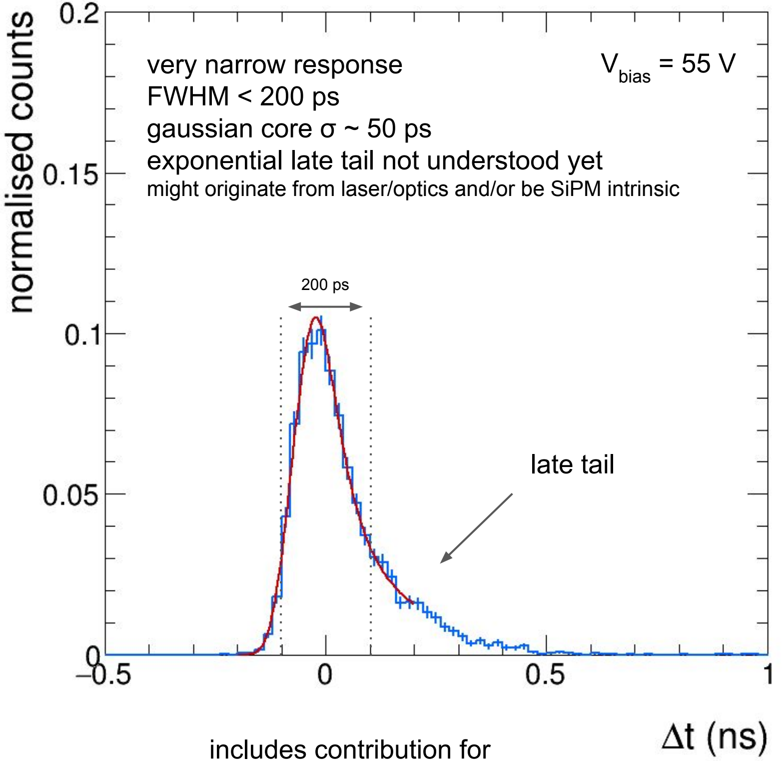
Laser timing measurements with oscilloscope



approaching σ_t = 50 ps time resolution

will soon measure effect of radiation damage on σ_t

laser-SiPM correlations (time-walk corrected)

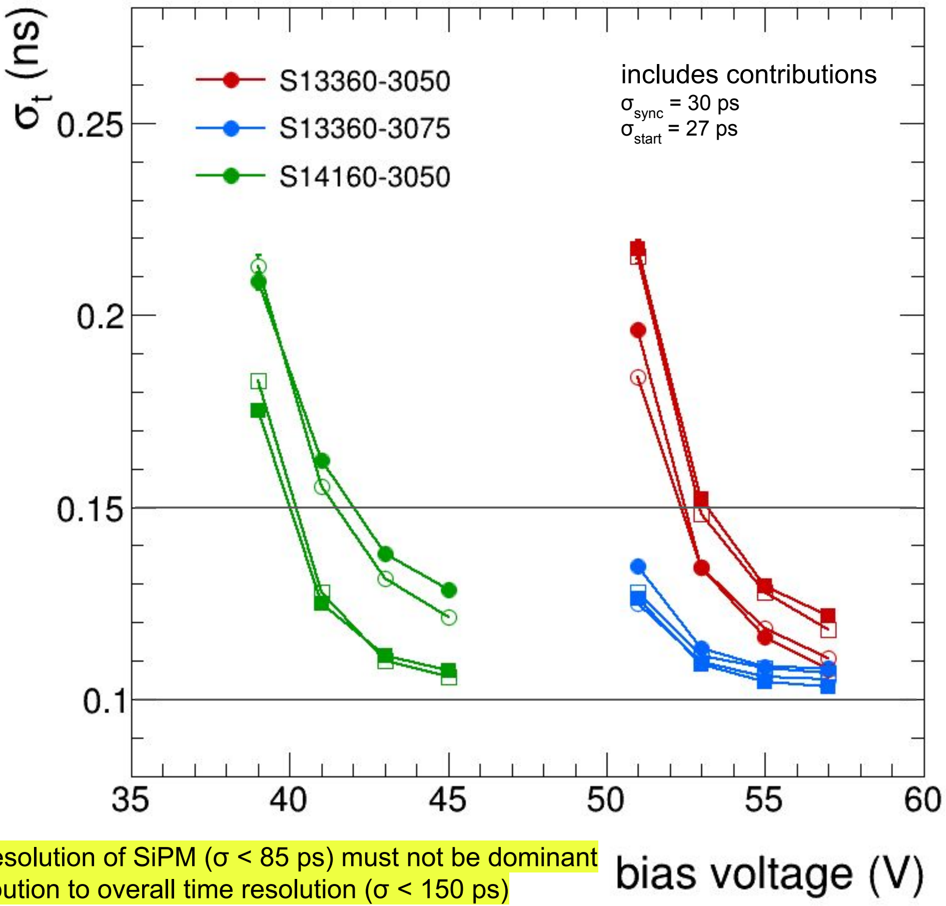


includes contribution for
laser-oscilloscope synchronization
measured to be σ_{sync} = 30 ps

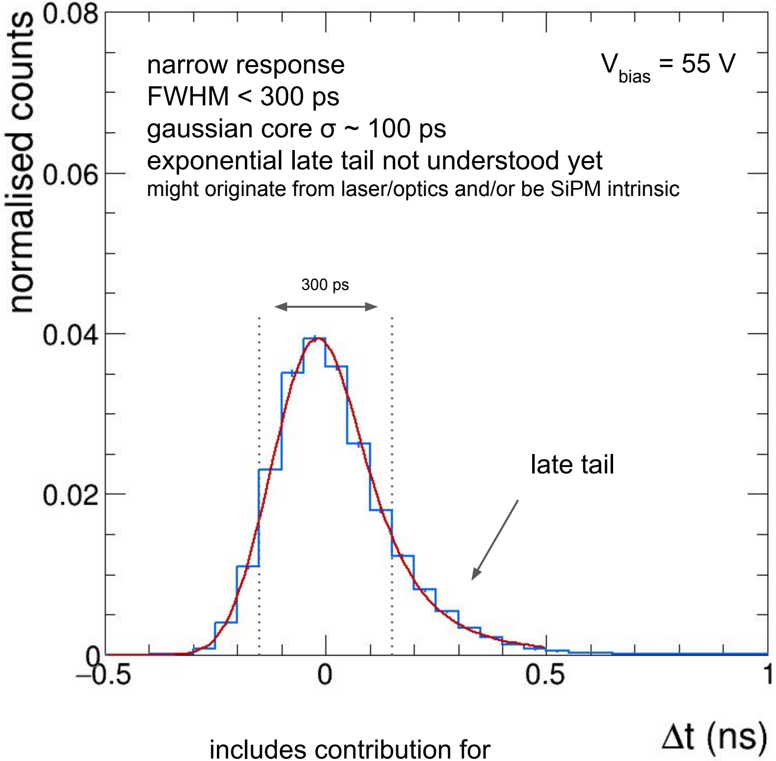
Timing performance measurements with ALCOR

Hamamatsu S13360-3075

standard ALCOR front-end bias configuration



laser-SiPM correlations (time-walk corrected)

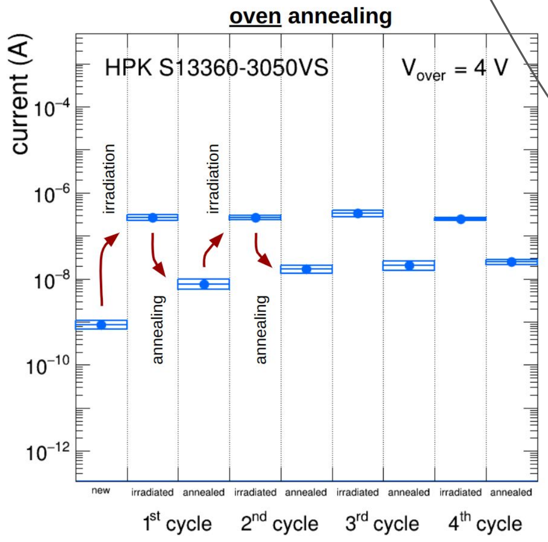


time resolution of SiPM (σ < 85 ps) must not be dominant contribution to overall time resolution (σ < 150 ps)

includes contribution for laser-ALCOR synchronization
measured to be σ_{sync} = 30 ps
and reference time resolution
measured to be σ_{start} = 27 ps

Ageing model

max acceptable DCR for
Physics performance
~ 10 noise hits / sector within 500 ps



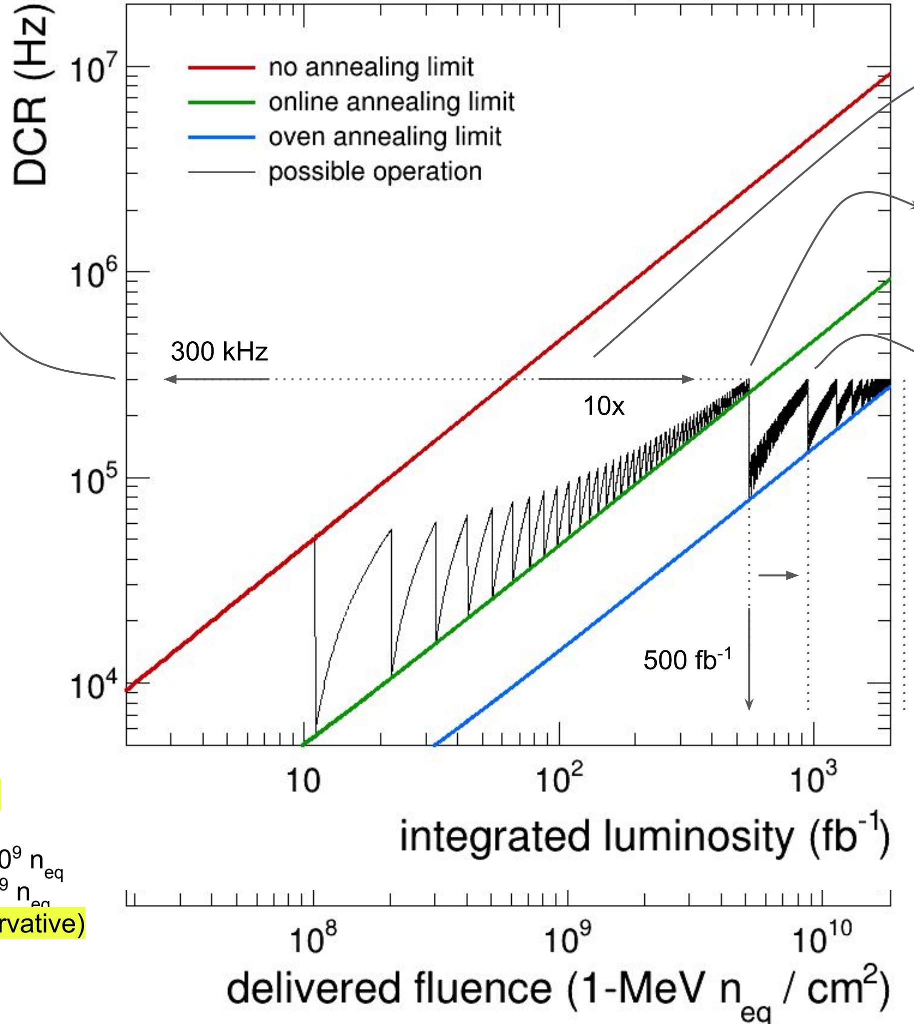
model input from R&D measurements (up to 2022)

- DCR increase: 500 kHz/10^9 n_{eq}
- residual DCR (online annealing): 50 kHz/10^9 n_{eq}
- residual DCR (oven annealing): 15 kHz/10^9 n_{eq}

1-MeV neq fluence from background group (conservative)

- 9 10^6 n_{eq} / fb^{-1}
- includes 10x safety factor

Hamamatsu S13360-3050 @ Vover = 4 V, T = -30 C



online annealing
extends SiPM
lifetime by ~ 10x

more aggressive
annealing needed here
might need to unmount SiPM (oven)

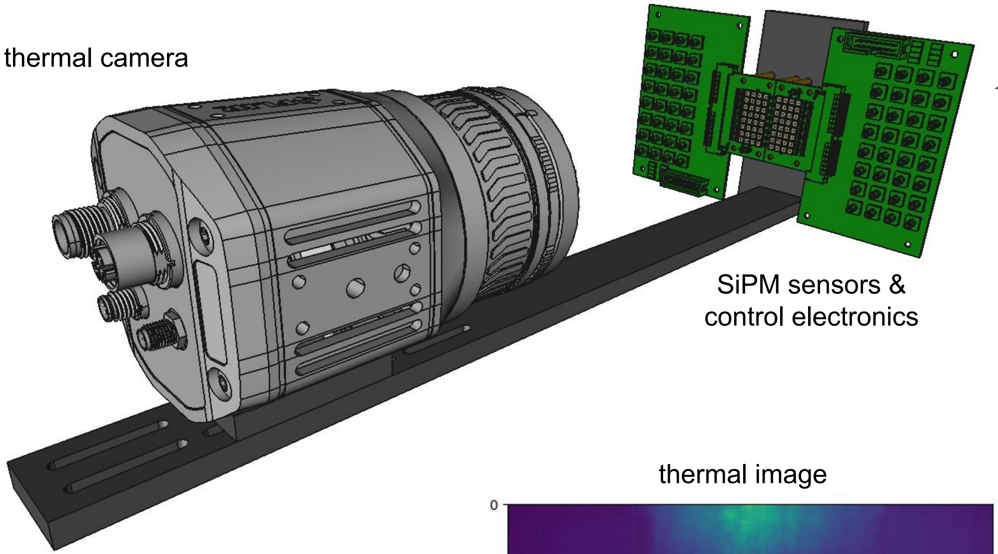
up to 1000 fb^{-1} with only
one oven annealing cycle
optimisation of online annealing
protocol could reach beyond that

these predictions are according to
present knowledge / tested solutions
there are more handles to
further mitigate DCR
lower Vover, 3V
lover T operation -40 C or below

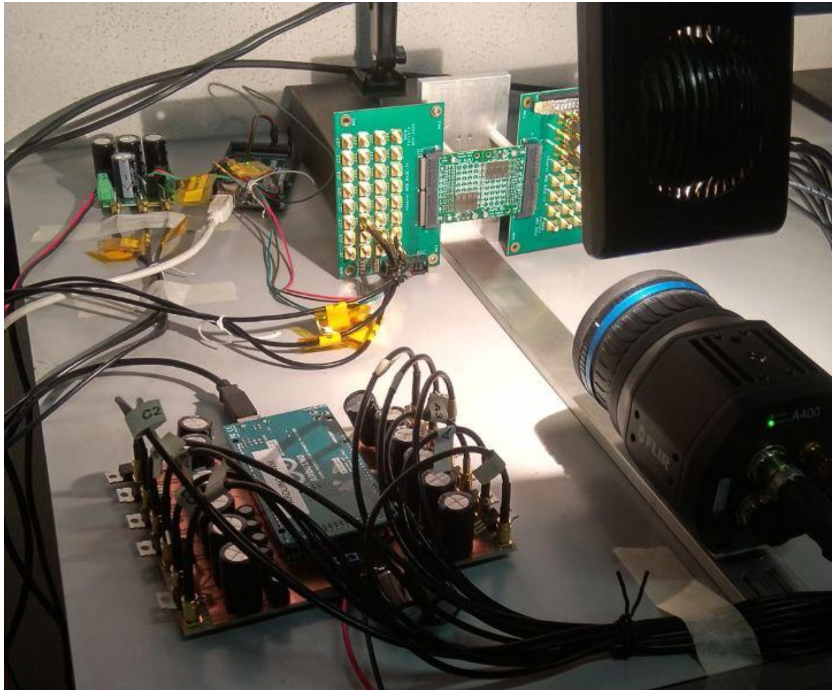
Automated multiple SiPM online self-annealing

system for online self-annealing with temperature monitor and control of each individual SiPM

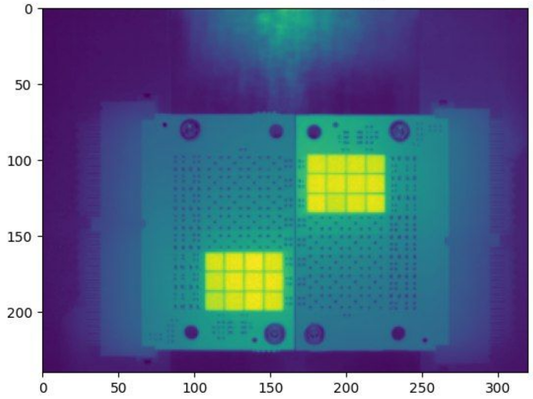
thermal camera



SiPM sensors & control electronics



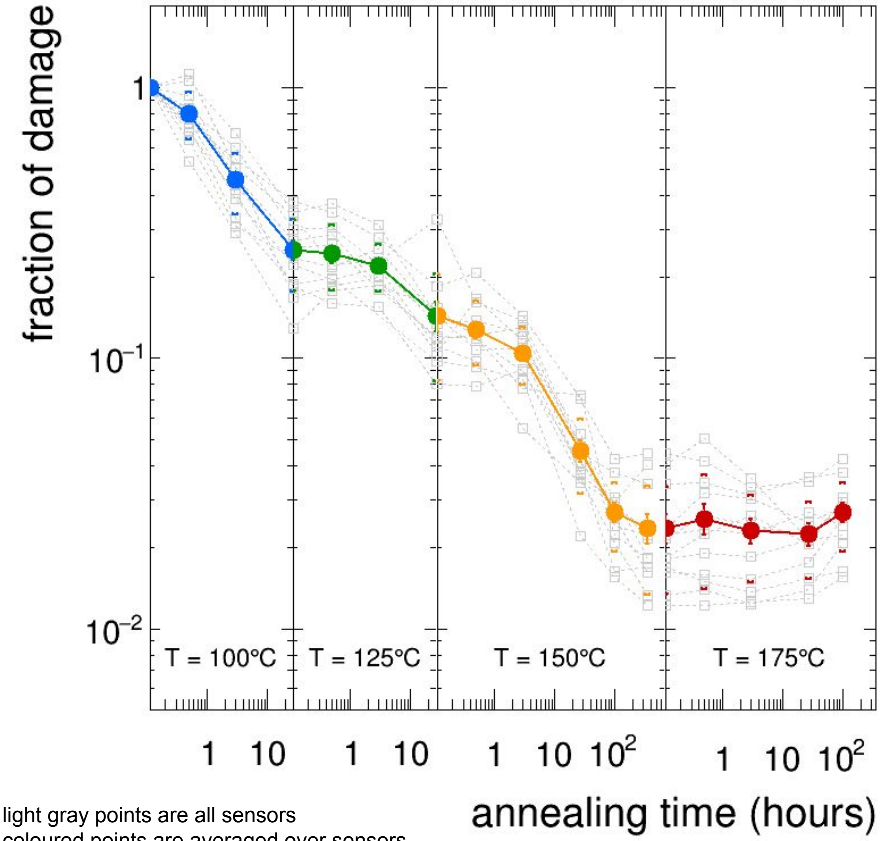
thermal image



monitor and logging system

Detailed studies of SiPM online self-annealing

online self-annealing with forward bias



light gray points are all sensors
coloured points are averaged over sensors
coloured brackets is the RMS

test on a large number of proton irradiated sensors how much damage is cured as a function of temperature and time

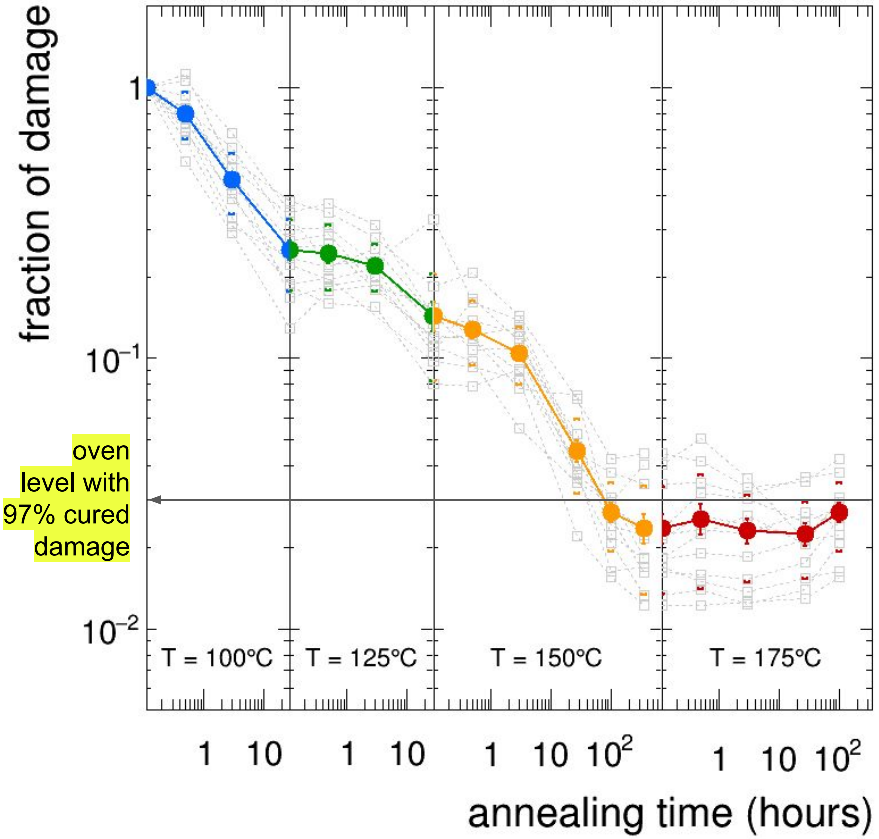
in this study, the same sensors have undergone self-annealing in increasing temperature steps and increasing integrated time steps

- started with T = 100 C annealing
  - performed 4 steps up to 30 hours integrated
- followed by T = 125, 150 and 175 C

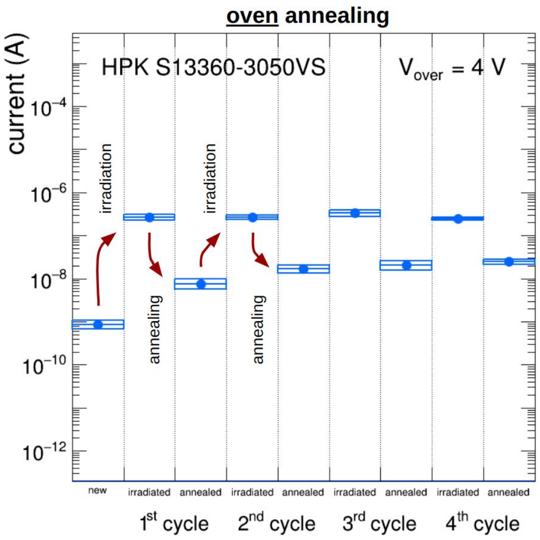
fraction of residual damage seems to saturate at 2-3%
after ~ 300 hours at T = 150 C
continuing at higher T = 175 C seems not to cure more than that

Automated multiple SiPM online self-annealing

remember oven annealing at T = 150 C
“annealing cures same fraction of newly-produced damage
~ 97% for HPK S13360-3050 sensors”



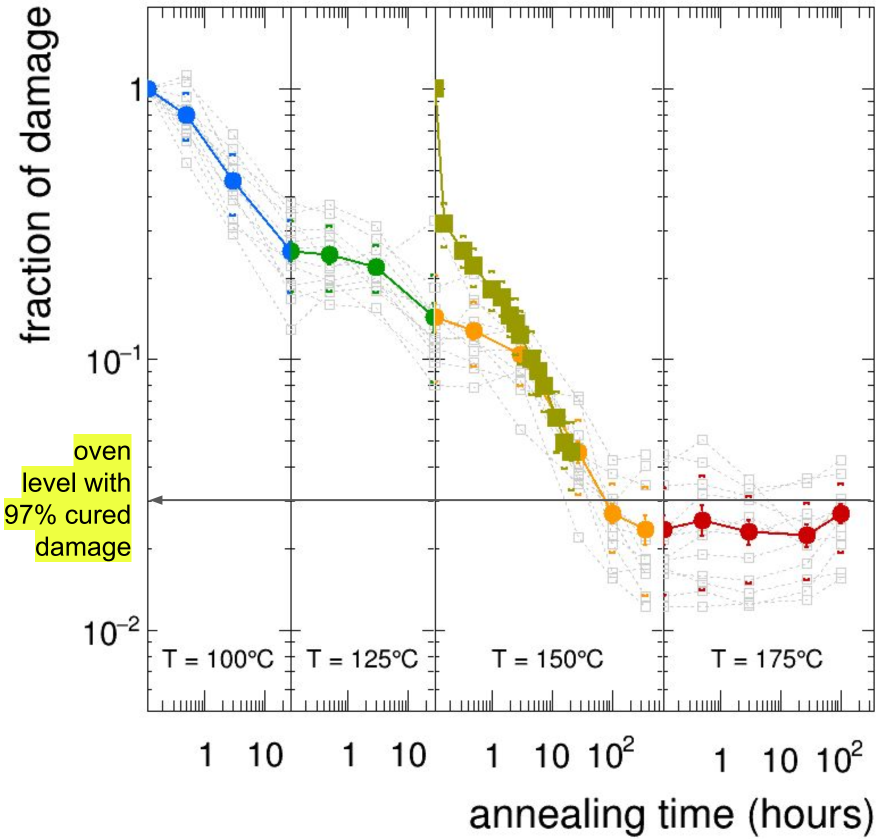
oven level with 97% cured damage



fraction of residual damage seems to saturate at 2-3%
after ~ 300 hours at T = 150 C

we eached the oven limit (aggressive annealing)
with an online self-anneling process

Automated multiple SiPM online self-annealing

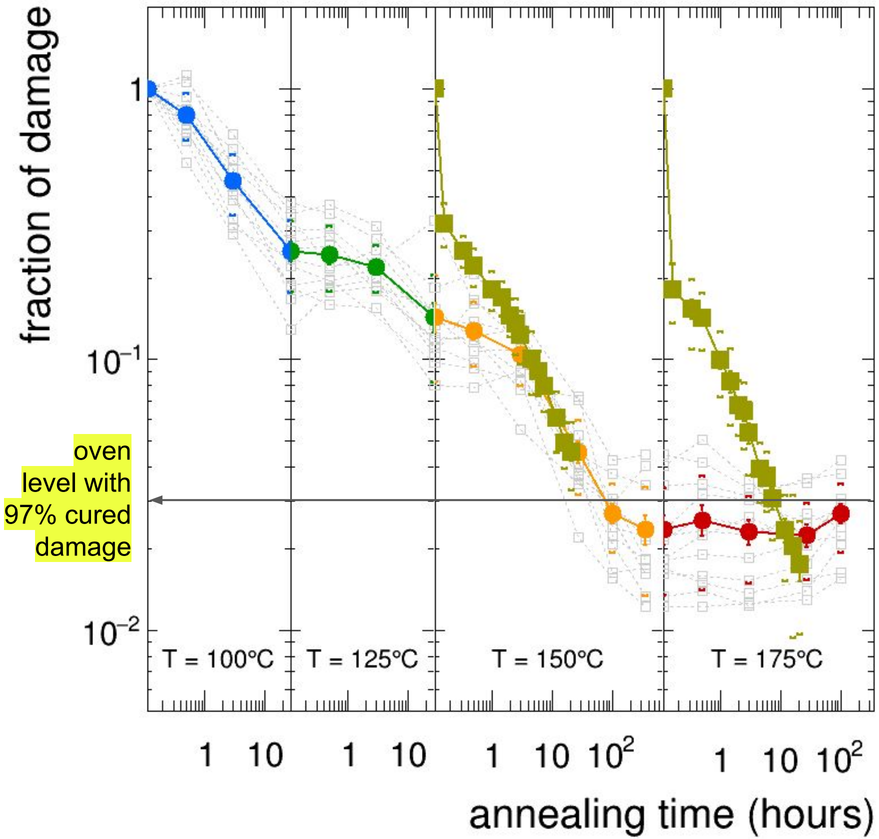


tested on a number of neutron irradiated sensors the details of annealing curve at fixed temperature

annealing at same temperature with increased number of steps to highlight the details of the damage decreasing trend

- at T = 150 C
  - sudden decrease of damage in short time
  - followed by a slower rate decrease
  - eventually meeting the orange curve
  - and decreasing at ~ same rate

Automated multiple SiPM online self-annealing

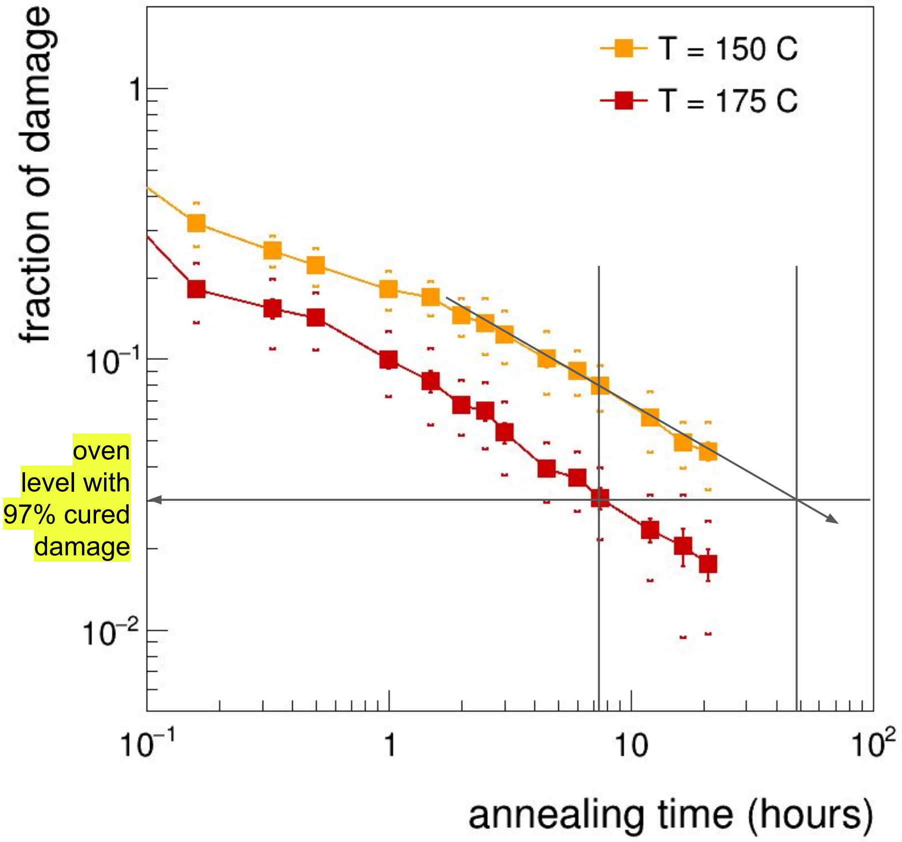


tested on a number of neutron irradiated sensors the details of annealing curve at fixed temperature

annealing at same temperature with increased number of steps to highlight the details of the damage decreasing trend

- at T = 175 C
  - faster sudden decreasein short time
  - followed by a faster rate decrease
  - eventually reaching the plateau

Automated multiple SiPM online self-annealing



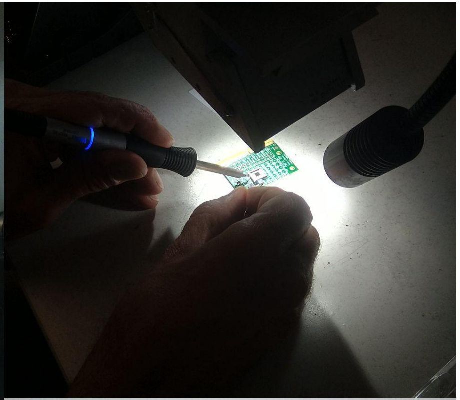
oven level with 97% cured damage

comparison between two annealing temperatures

we know both reach the oven limit of ~ 2-3% residual damage

- at T = 175 C
  - there seems to be a faster “sudden” cure
  - followed by a similar rate of reduction with time
- oven-level annealing reached faster at T = 175 C
  - < 10 hours integrated
- oven-level annealing not yet reached at T = 150 C
  - we are still running the setup
  - prediction it will be reached < 100 hours integrated

New Hamamatsu SiPM prototypes



newly-developed Hamamatsu SiPM sensors

based on S13360 series

few samples of 50 μm and 75 μm SPAD sensors

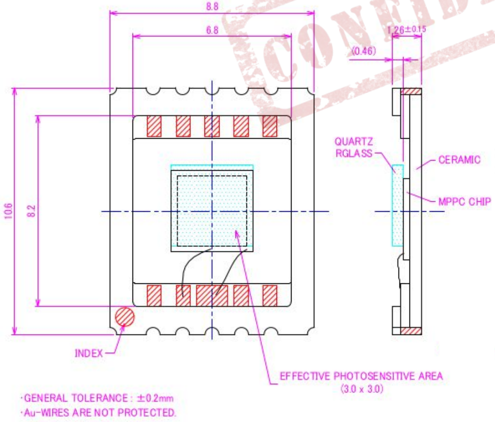
on paper they look VERY promising

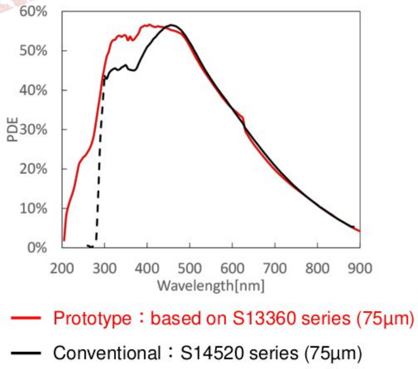
- improved NUV sensitivity
- improved signal shape
- improved recharge time

mounted on EIC SiPM test boards

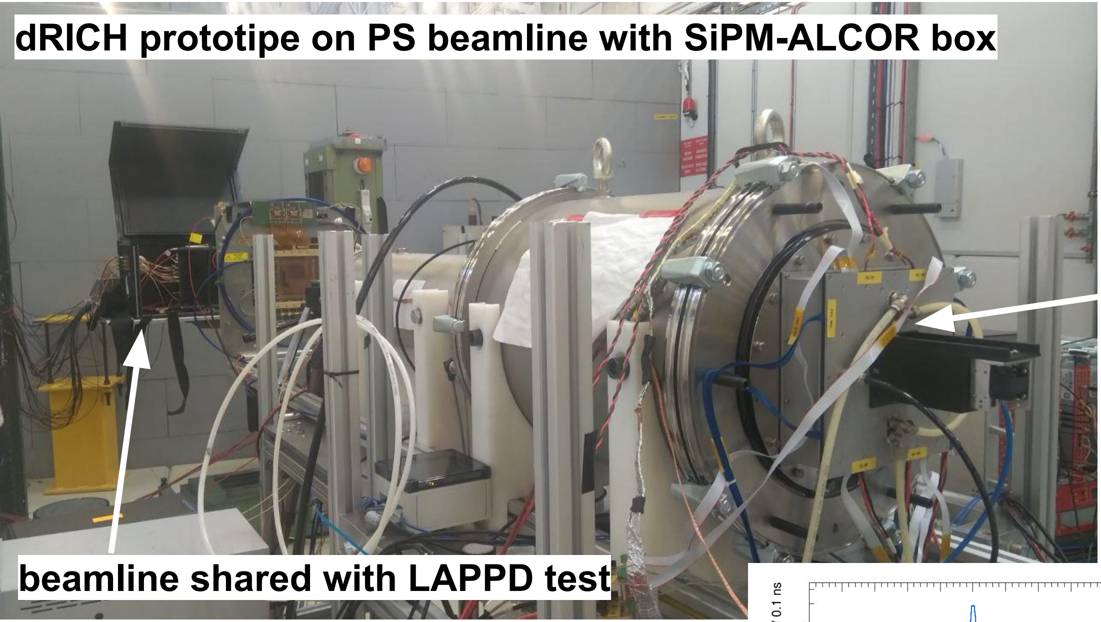
we will characterise and test them in full

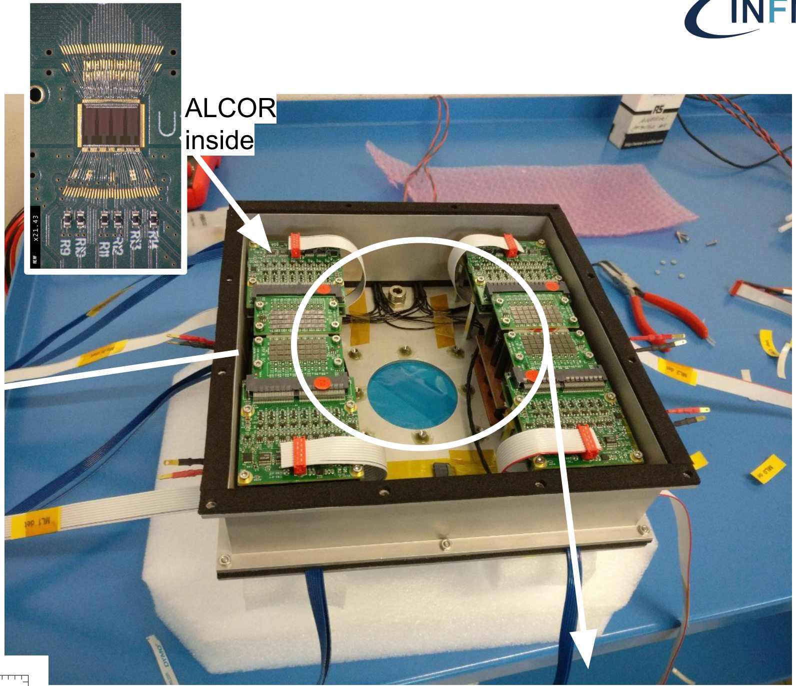
irradiation, annealing, laser, …





2022 test beam at CERN-PS

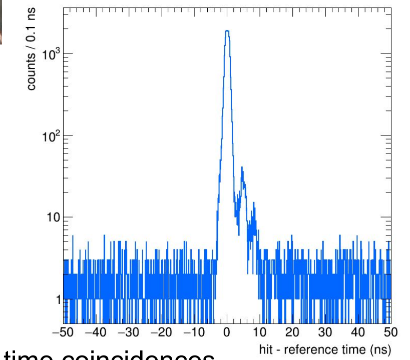




successful operation of SiPM

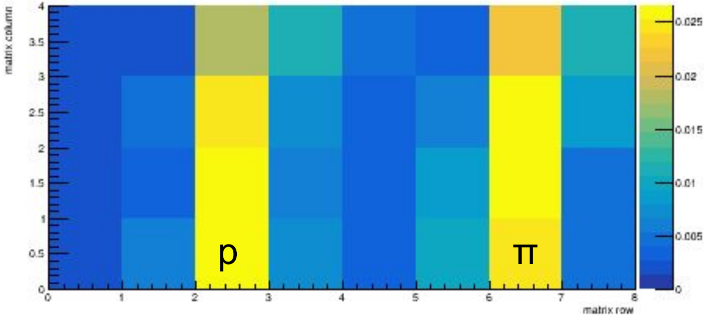
irradiated (with protons up to 10^{10})

and annealed (in oven at 150 C)

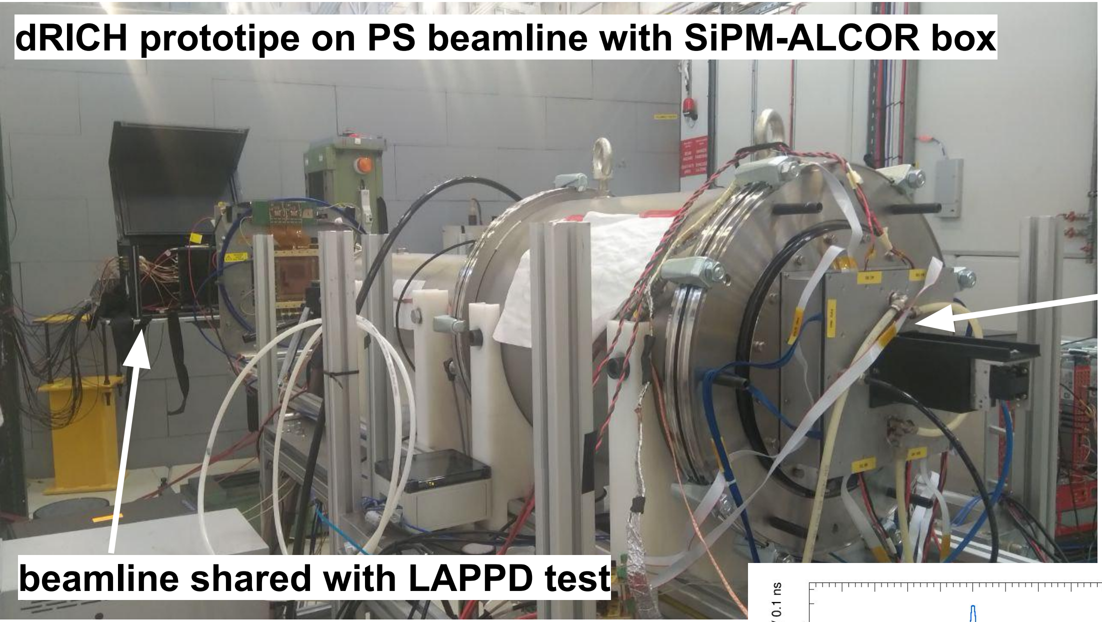


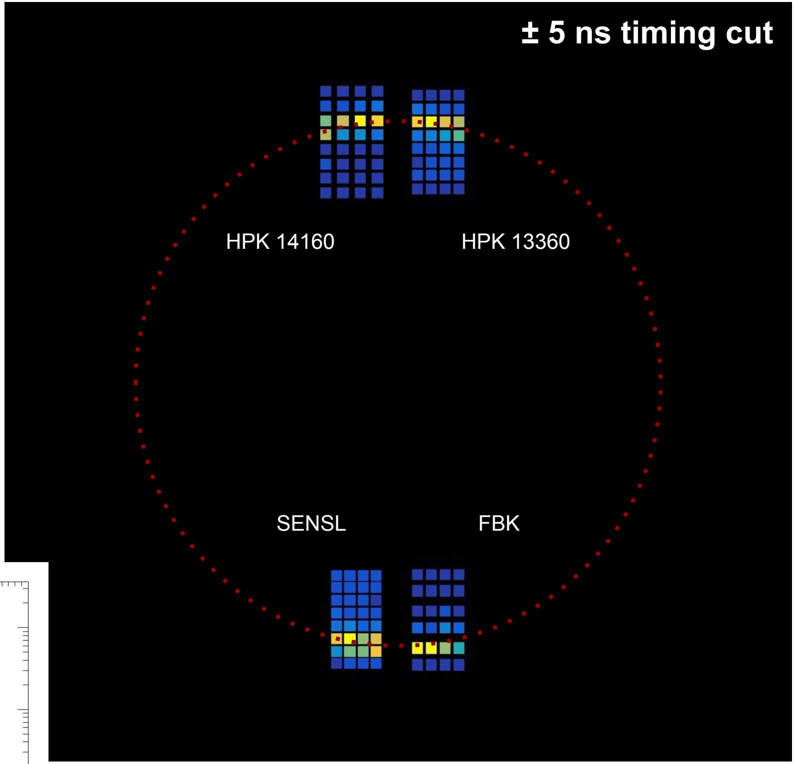
time coincidences

8 GeV positive beam (aerogel rings)



2022 test beam at CERN-PS



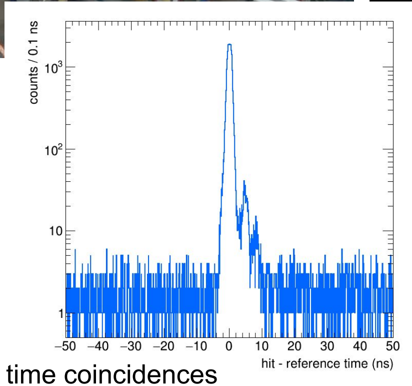


8 GeV negative beam (aerogel rings)

successful operation of SiPM

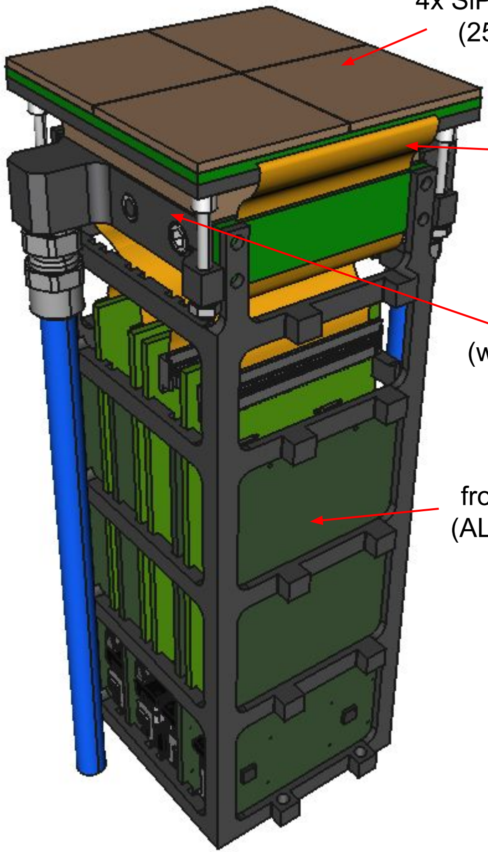
<u>irradiated</u> (with protons up to 10^{10})

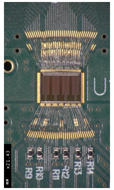
and <u>annealed</u> (in oven at 150 C)



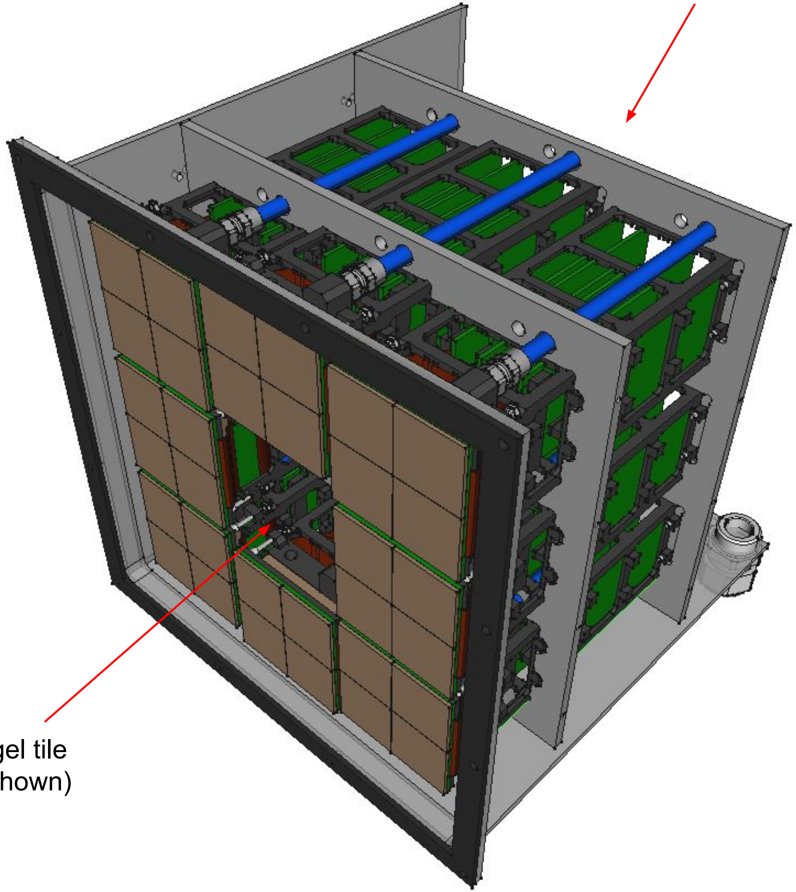
time coincidences

EIC ePIC-dRICH SiPM photodetector prototype

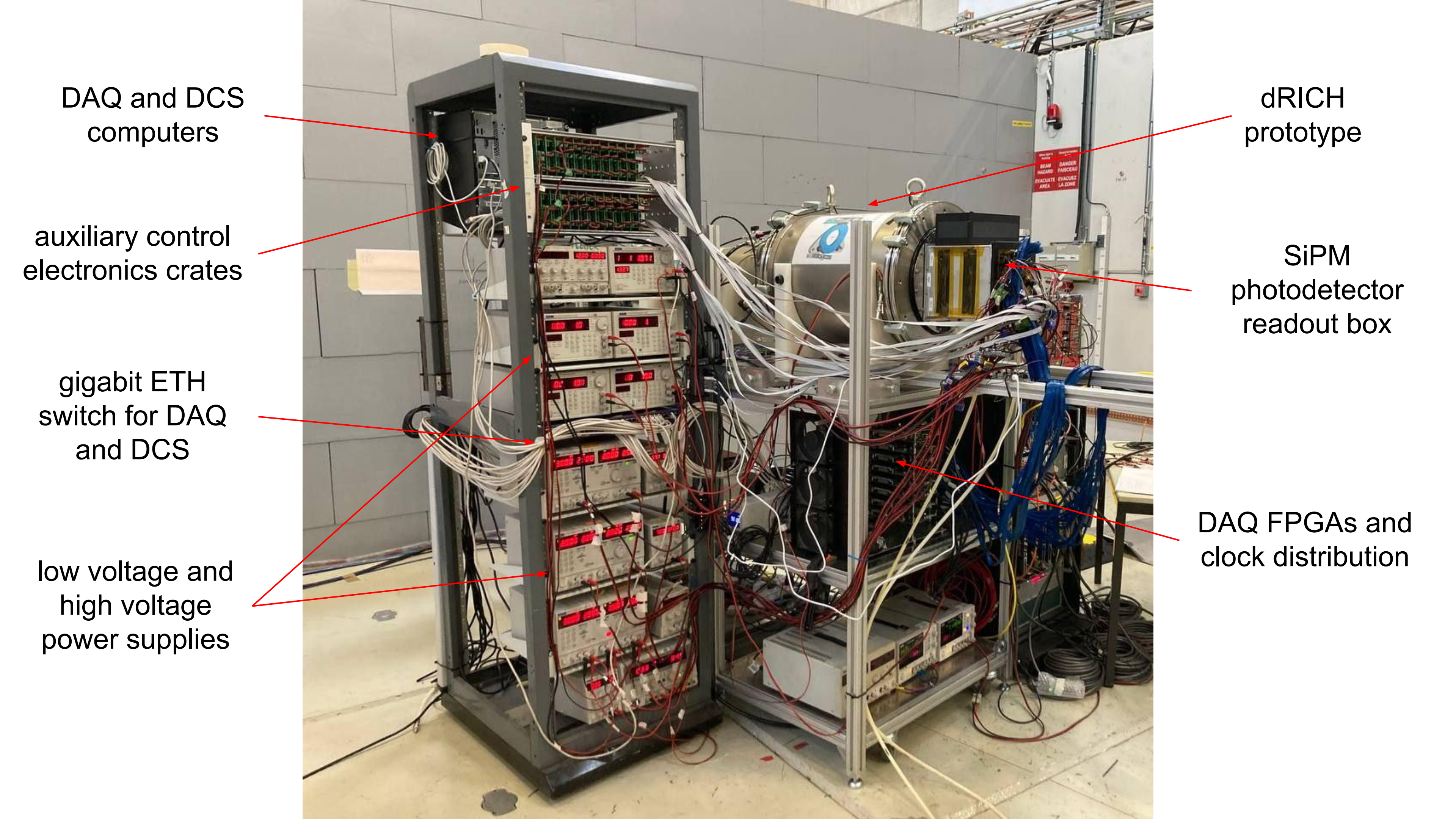




PhotoDetector Unit (PDU)

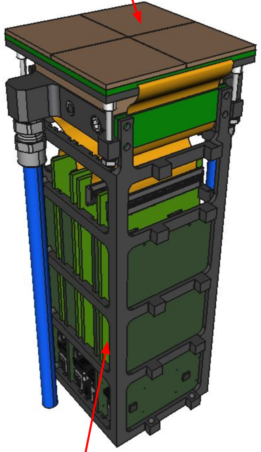


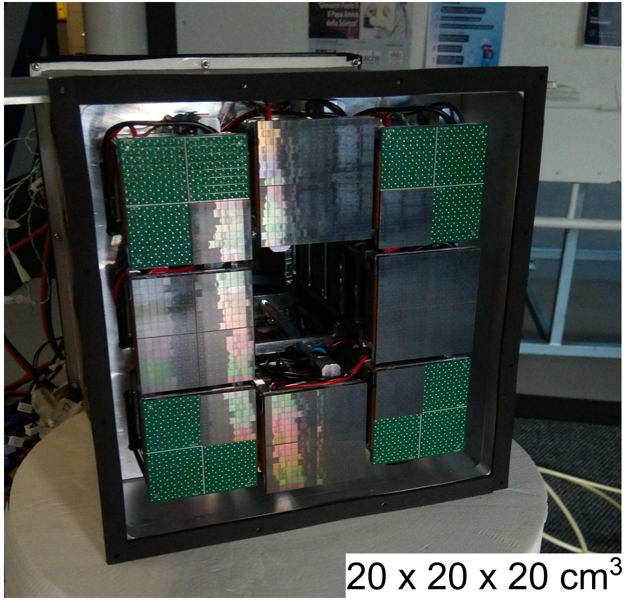
Readout Box

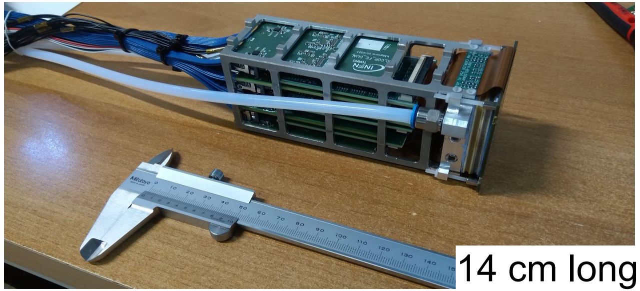

DAQ and DCS computers
auxiliary control electronics crates
gigabit ETH switch for DAQ and DCS
low voltage and high voltage power supplies
dRICH prototype
SiPM photodetector readout box
DAQ FPGAs and clock distribution
BEAM HAZARD
DANGER FAISCEAU
EVACUATE AREA
EVACUEZ LA ZONE

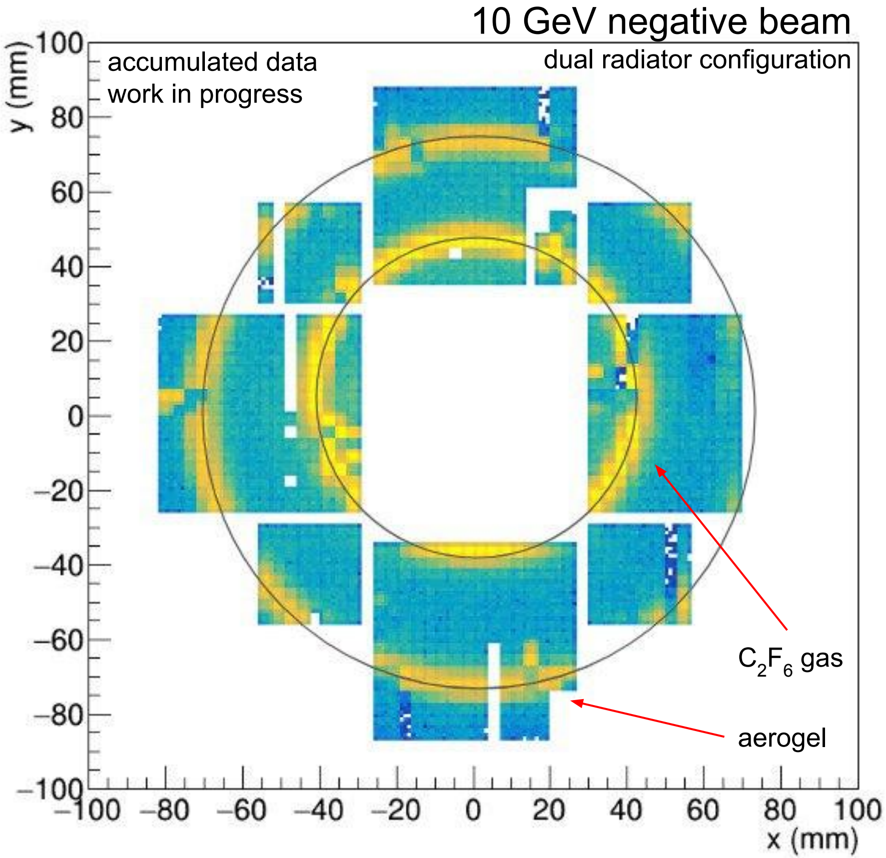
2023 test beam at CERN-PS

successful beam test with prototype SiPM photodetector units (CERN-PS, ended on 18th October)









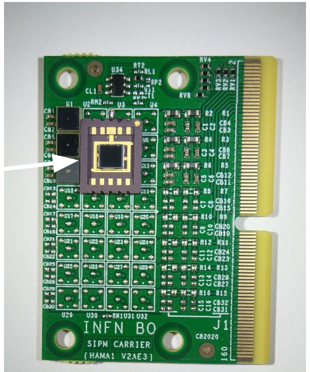
Risk and mitigation

- **radiation damage**
  - using estimates from ePIC background group
  - increasing the expected fluence by a 10x safety factor
- **dark count rate mitigation**
  - measurements are by default performed at T = -30 C
    - lower operation in ePIC should be possible
  - acquire equipment for lower temperature cooling
    - operation at T = -40 C would give a further 2x DCR suppression
- **higher efficiency SiPM sensors**
  - most of the measurements performed on S13360-3050 (50 μm SPAD) sensors
  - preliminary tests on commercial 75 μm SPAD SiPM very promising
    - better time resolution at lower Vover
    - higher PDE at same Vover
    - (or alternatively) lower DCR at same PDE
  - prototype SiPM sensors from Hamamatsu in house (both 50 and 75 μm SPAD)
    - improved NUV sensitivity, improved signal shape and recharge time
    - we will test them with irradiation soon
- **annealing protocol**
  - preliminary online self-annealing results (2022) set the 10x lifetime increase mentioned in reviews
  - recent detailed studies show that a further 3x lifetime increase is accessible
  - gearing up towards engineering of the process for TDR
    - ideas in place, to be integrated with electronics

Current & future plans: sensor optimisation and risk mitigation

This list is not exhaustive and only contains the most important items and steps towards the TDR

- **characterisation measurements**
  - measurements of time resolution after irradiation and annealing
  - define SiPM performance and comparisons based on SNR (DCR, PDE, SPTR)
  - full evaluation of 75 μm SPAD sensors (ie. Hamamatsu S13360-3075)
    - PDE is larger than 50 μm, SPTR is better, DCR is similar
  - full evaluation of new Hamamatsu SiPM prototypes (based on S13360 technology)
    - improved NUV sensitivity, improved signal shape and recharge time
    - already received 50 μm and 75 μm samples
- **operation and annealing**
  - test low-temperature (down to T = -40 C) operation with fluid-based chiller
    - evaluate possibility of using the system in heating mode for annealing
  - study the details of “in-situ” online self-induced annealing
    - forward (safer, but larger currents) vs. reverse (less safe, lower currents) bias operation
    - recovery vs. annealing temperature and time
    - refine technical solutions (and electronics) for monitor and control in the experiment
- **engineering run with FBK**
  - optimisations for the EIC of the already-mature NUV-HD technology (lower field / shaping to improve DCR)
  - development of single-die multi-channel SiPM sensor (achieve high fraction of active area with a low-cost process)



S13360-3050UVE

Current & future plans: electronics

This list is not exhaustive and only contains the most important items and steps towards the TDR

- **front-end electronics**
  - full test and evaluation of improved ASIC (ALCOR-v2, 32-channels, wirebonded)
    - recently received chips from MPW production
    - will be mounted on electronics for beam test of dRICH prototype (October 2023)
  - developments toward final ASIC version (ALCOR-v3, 64-channels, BGA package)
    - upgrade front-end to improve time resolution
    - include digital shutter, hysteresis to discriminator and other optimisations
    - optimise chip layout for “flip-chip” BGA packaging
- **readout electronics**
  - design and develop first prototype RDO
    - target is a beam test in 2024
- **radiation tolerance**
  - measure radiation damage / tolerance of susceptible components
    - ALCOR
    - FPGA
  - measure SEU rates
    - and latch-ups
    - verify monitor watchdogs are effective to protect

END

SiPM cooling for low-temperature operation (−30 °C or lower)

external chiller with fluid recirculation (ie. siliconic oil)

the chiller here one is just a commercial example

cooling and heating capacity

could use heating capability for annealing? must be demonstrated to be feasible

cooling capacity at -40 C is large (1.5 kW)

huber

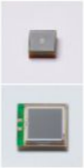
General & Temperature Control

Temperature range	-55...250 °C
Temperature stability	±0,01 K

Heating / cooling capacity

Heating capacity	6 kW								
Cooling capacity	250	200	100	20	0	-20	-40	-50	°C
	6	6	6	6	6	4,2	1,5	0,65	kW

Commercial SiPM sensors and FBK prototypes

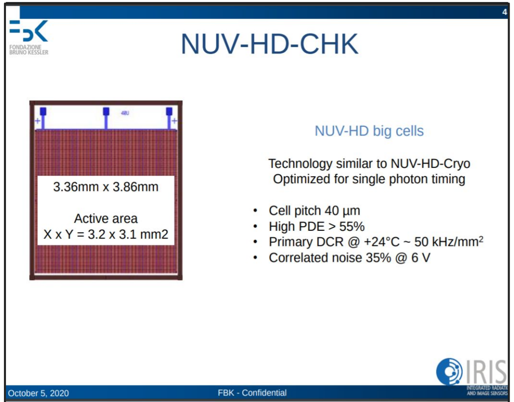



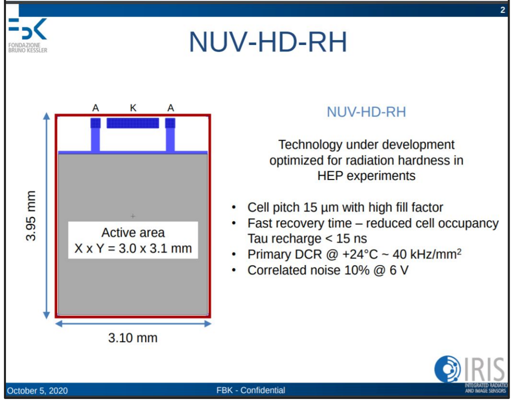
board	sensor	uCell (µm)	V_{bd} (V)	PDE (%)	DCR (kHz/mm^2)	window	notes
HAMA1	S13360 3050VS	50	53	40	55	silicone	legacy model Calvi et. al
	S13360 3025VS	25	53	25	44	silicone	legacy model smaller SPAD
HAMA2	S14160 3050HS	50	38	50		silicone	newer model lower V_{bd}
	S14160 3015PS	15	38	32	78	silicone	smaller 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

PHOTON IS OUR BUSINESS

ON Semiconductor

BROADCOM

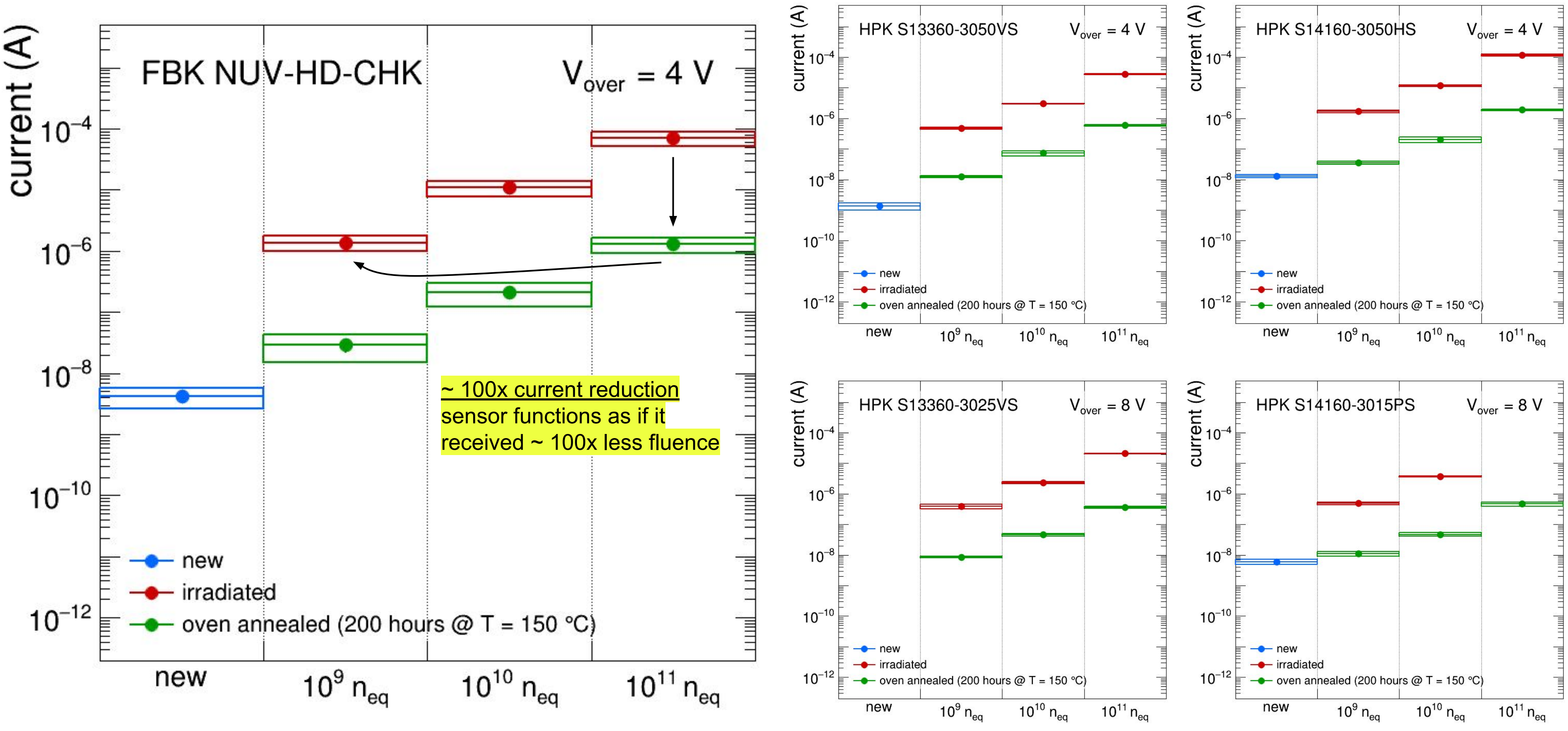




multiple producers: different technologies, SPAD dimensions, V_{bd}, electric field …

High-temperature annealing recovery

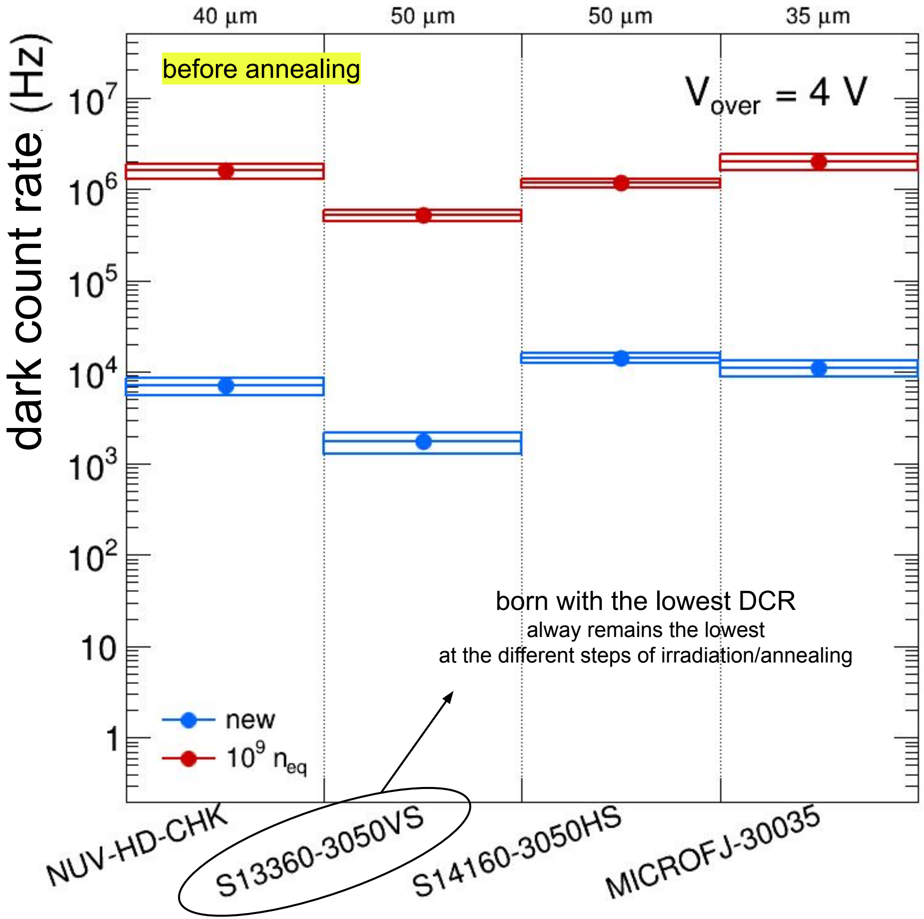
oven annealing
~ 1 week at 150 C

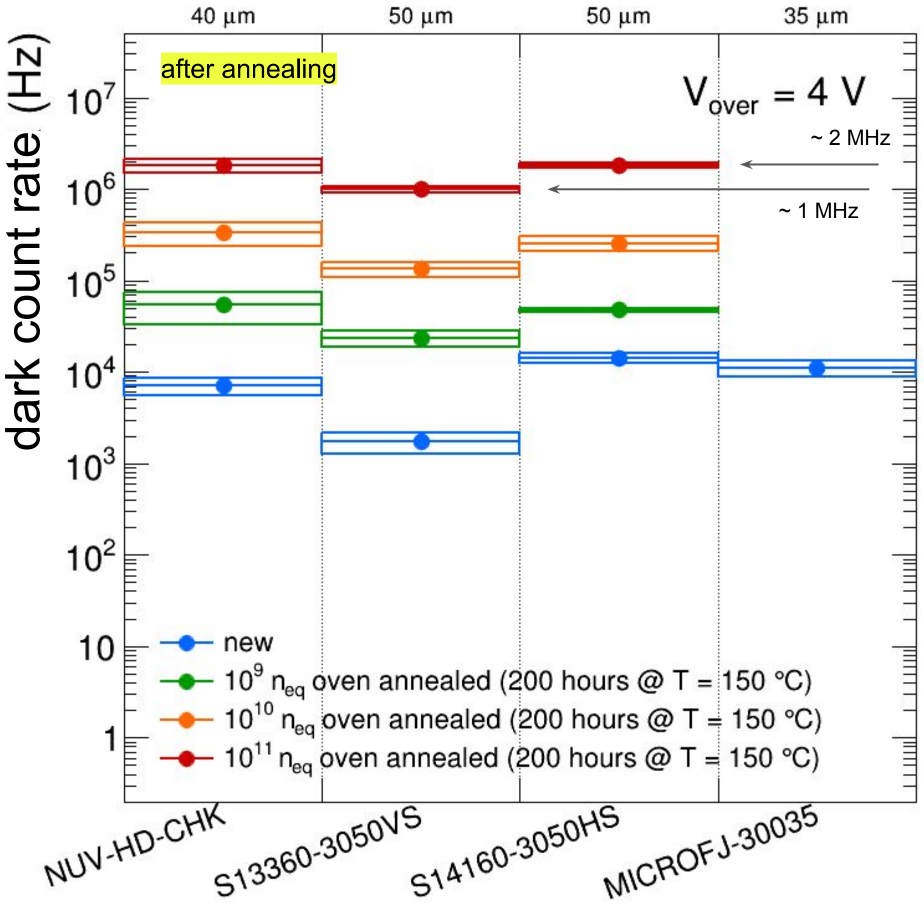


similar observation with various types of Hamamatsu sensors

Comparison between different sensors

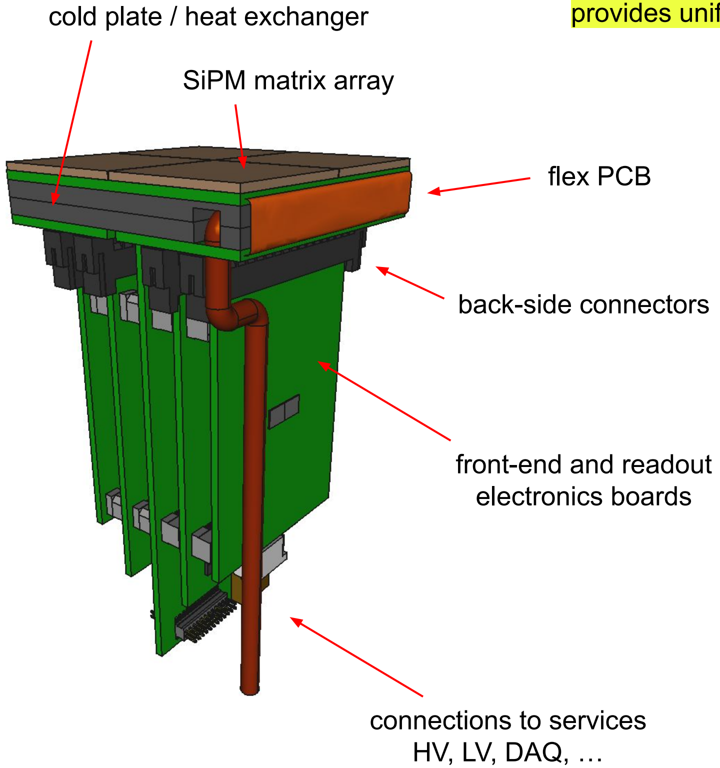
comparison at same Vover not totally fair
important to consider PDE (and SPTR) → SNR ~ PDE / DCR
unlikely 2x larger DCR is matched by 2x larger PDE

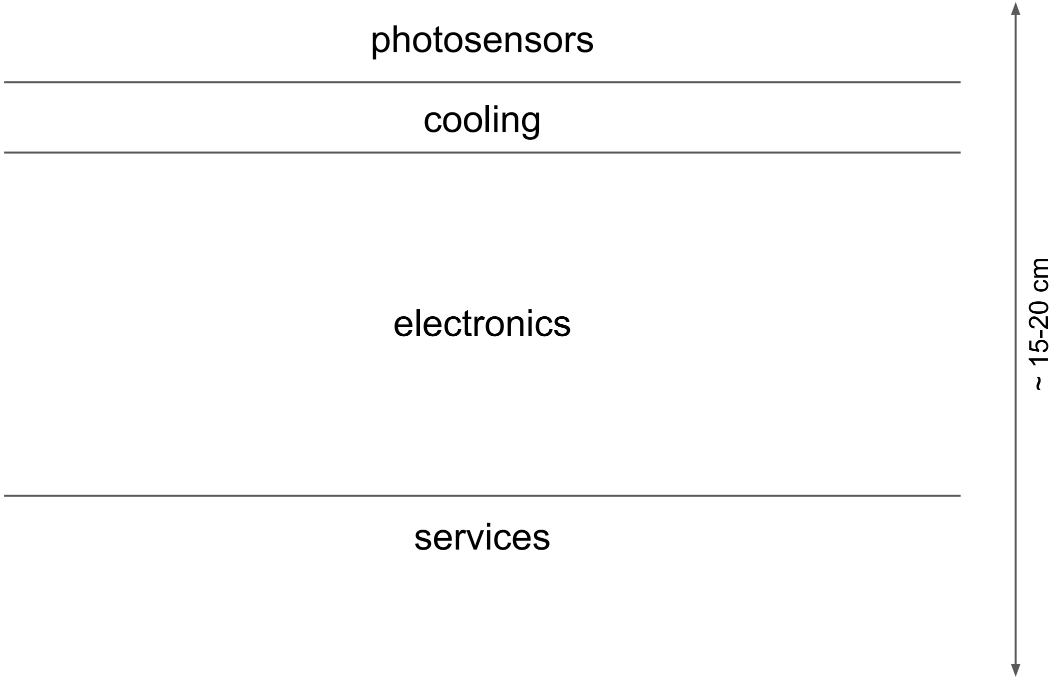




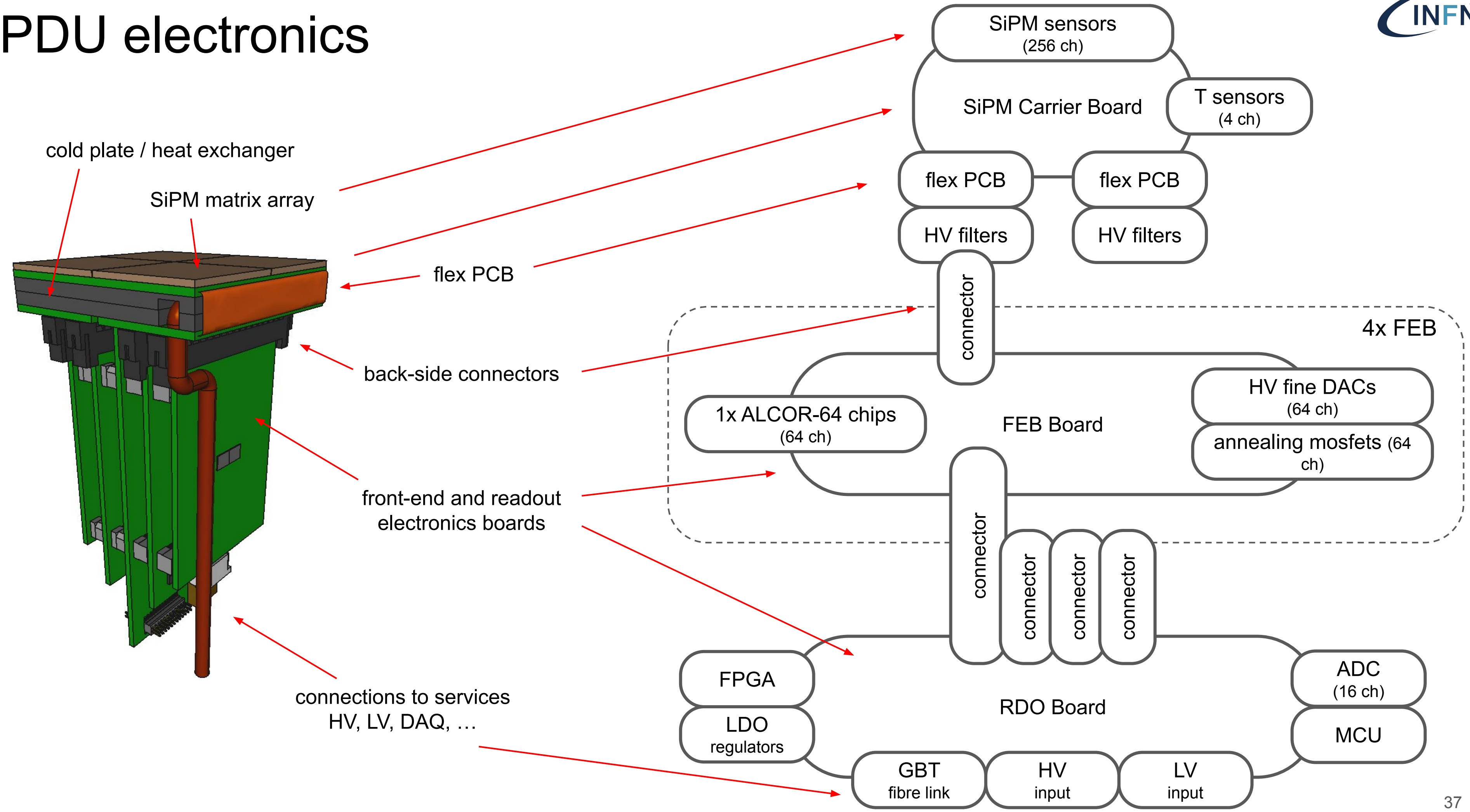
SiPM photodetector unit – PDU

technical solution using cold plate and flex-PCB circuit
provides uniform sensor cooling with no loss of active area

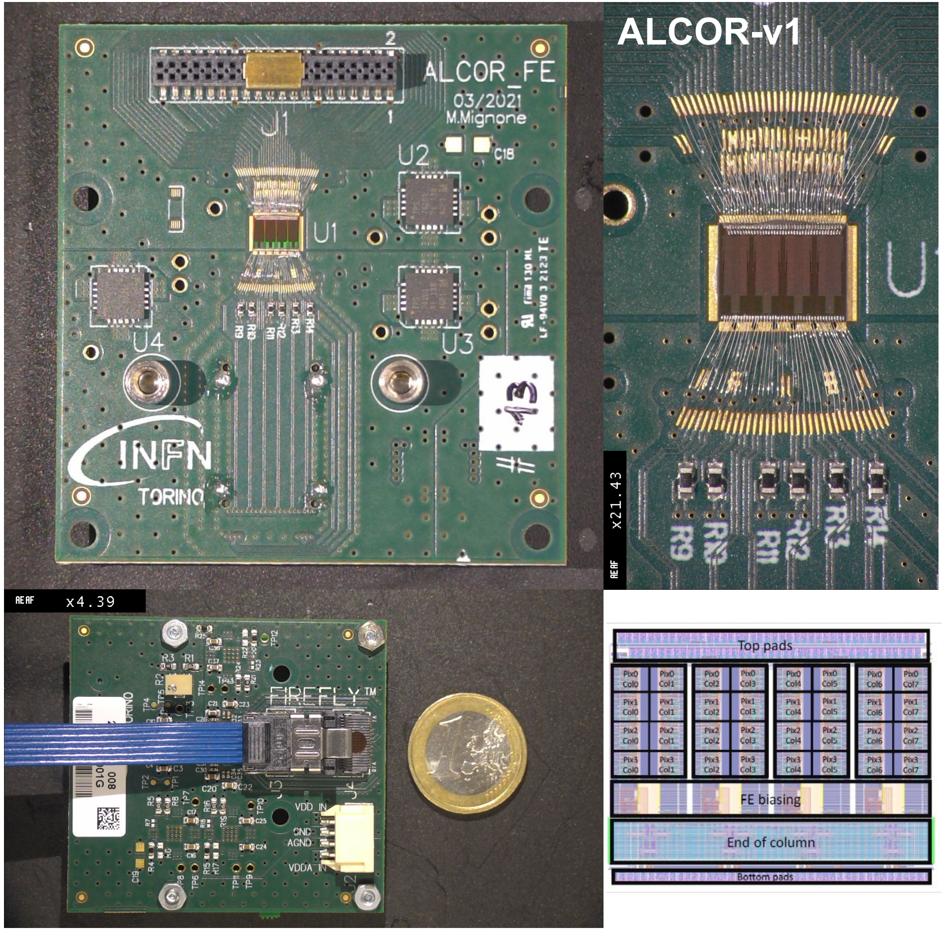




PDU electronics



ALCOR ASIC: integrated front-end and TDC



developed by INFN-TO

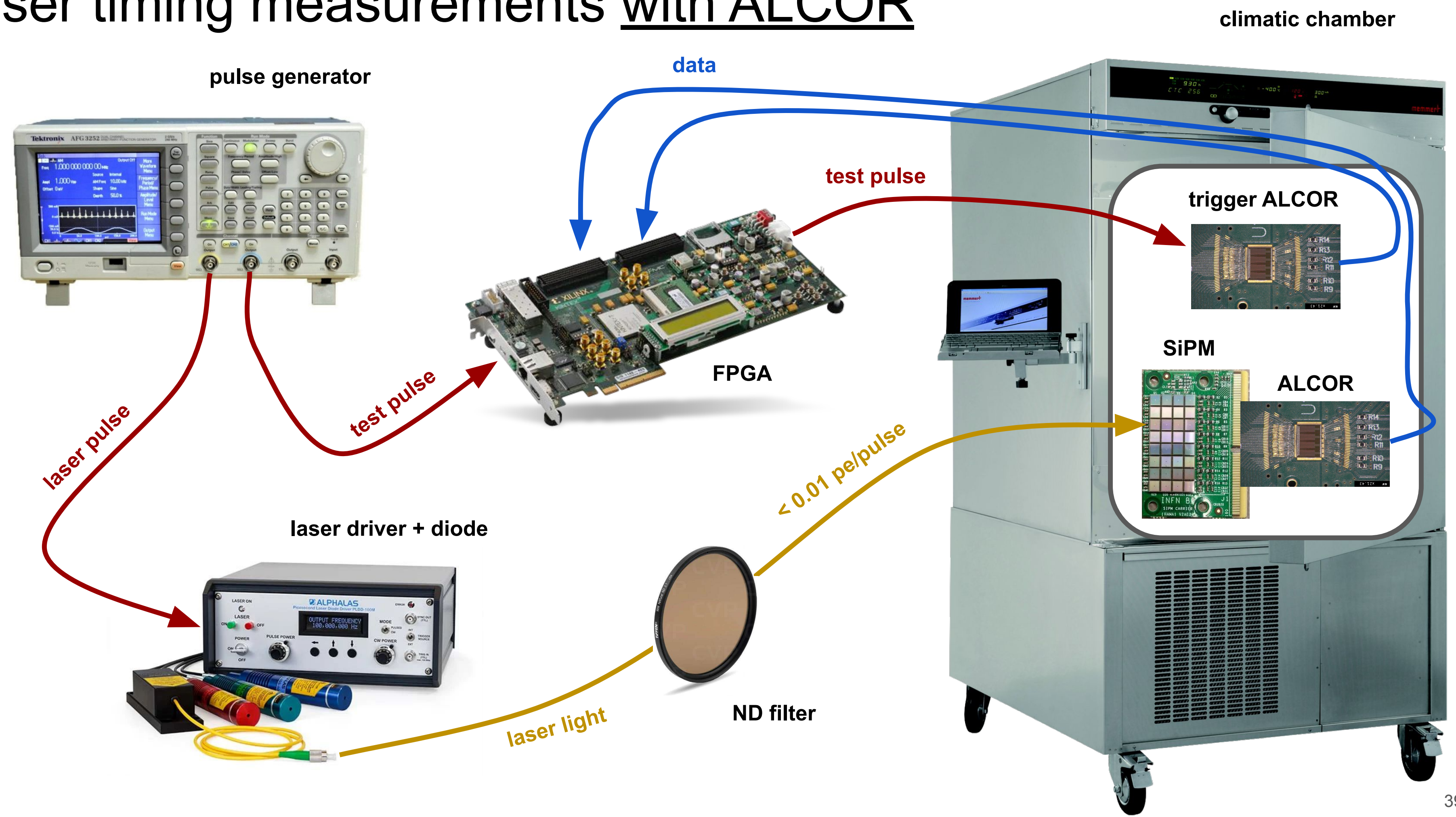
64-pixel matrix mixed-signal ASIC

current versions (v1,v2) have 32 channels, wirebonded

final version will have 64 channels, BGA package, 394.08 MHz clock

- **the chip performs**
  - signal amplification
  - conditioning and event digitisation
- **each pixel features**
  - 2 leading-edge discriminators
  - 4 TDCs based on analogue interpolation
    - 20 or 40 ps LSB (@ 394 MHz)
  - digital shutter to enable TDC digitisation
    - suppress out-of-gate DCR hits
    - 1-2 ns timing window
    - programmable delay, sub ns accuracy
- **single-photon time-tagging mode**
  - continuous readout
  - also with Time-Over-Threshold
- **fully digital output**
  - 8 LVDS TX data links

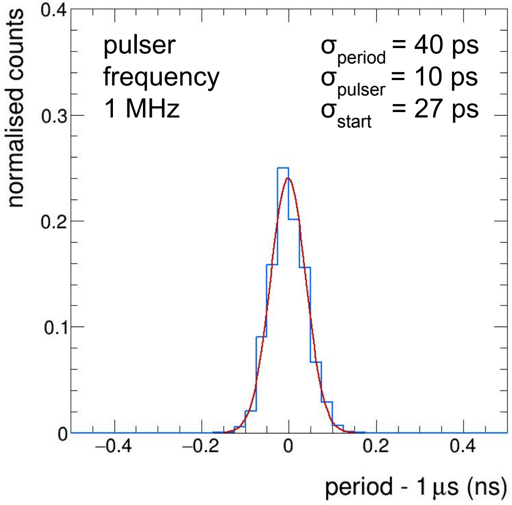
Laser timing measurements with ALCOR



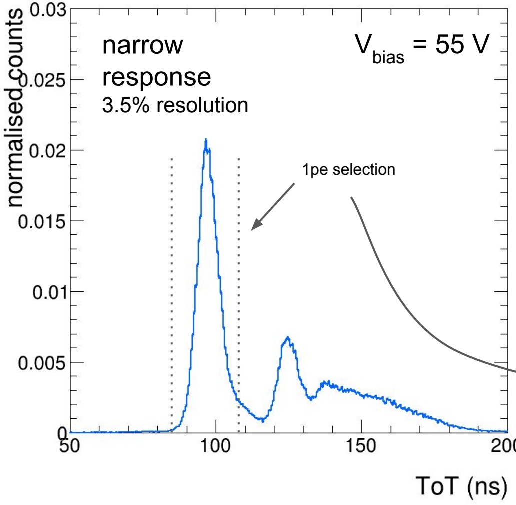
Laser timing measurements with ALCOR

Hamamatsu S13360-3075

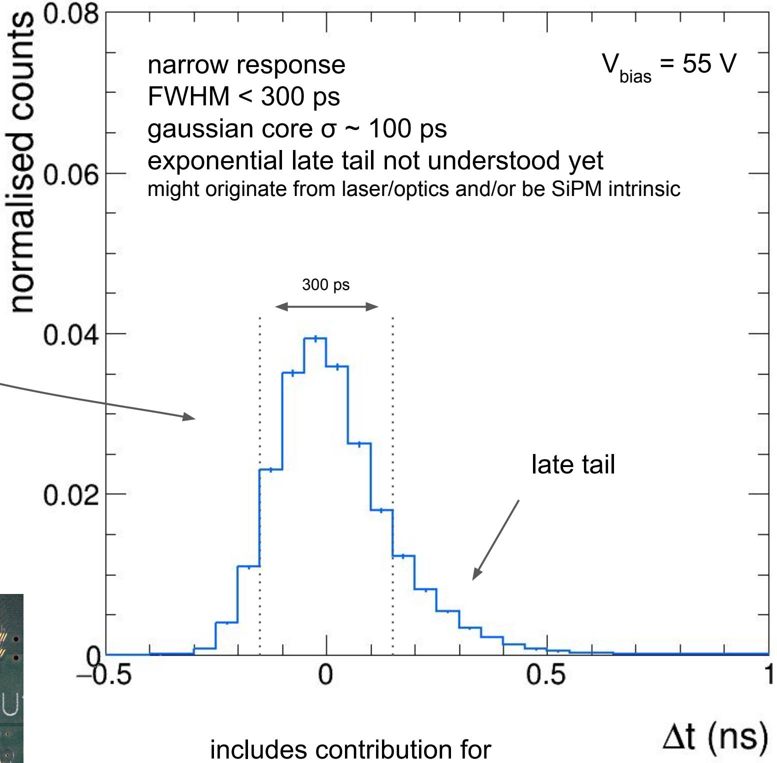
reference ALCOR pulse period



Time-over-Threshold values



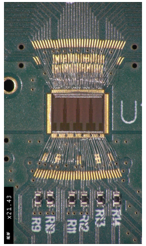
laser-SiPM correlations (time-walk corrected)



laser-SiPM signal synchronisation by sending test pulse to reference ALCOR

- to measure laser pulse t_{start}
- with 50 ps LSB TDC
- in synch with ALCOR readout

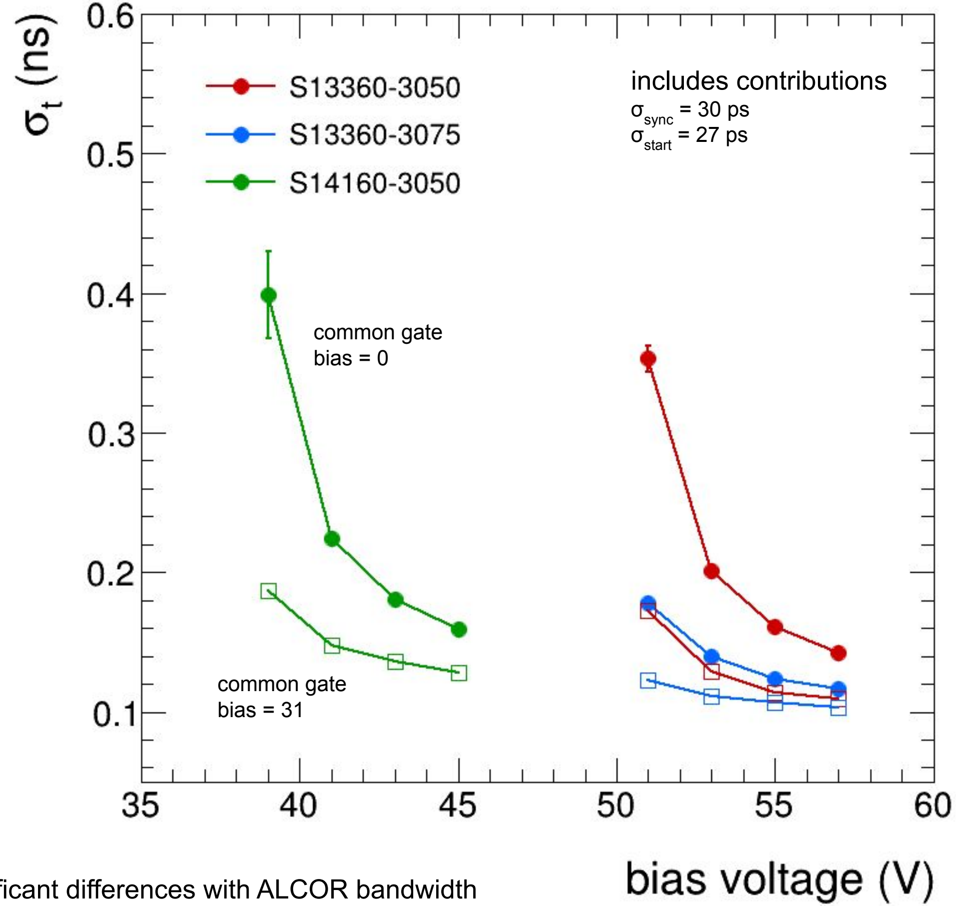
measure time coincidences Δt between reference and ALCOR reading SiPM



includes contribution for
laser-ALCOR synchronization
measured to be σ_{sync} = 30 ps
and reference time resolution
measured to be σ_{start} = 27 ps

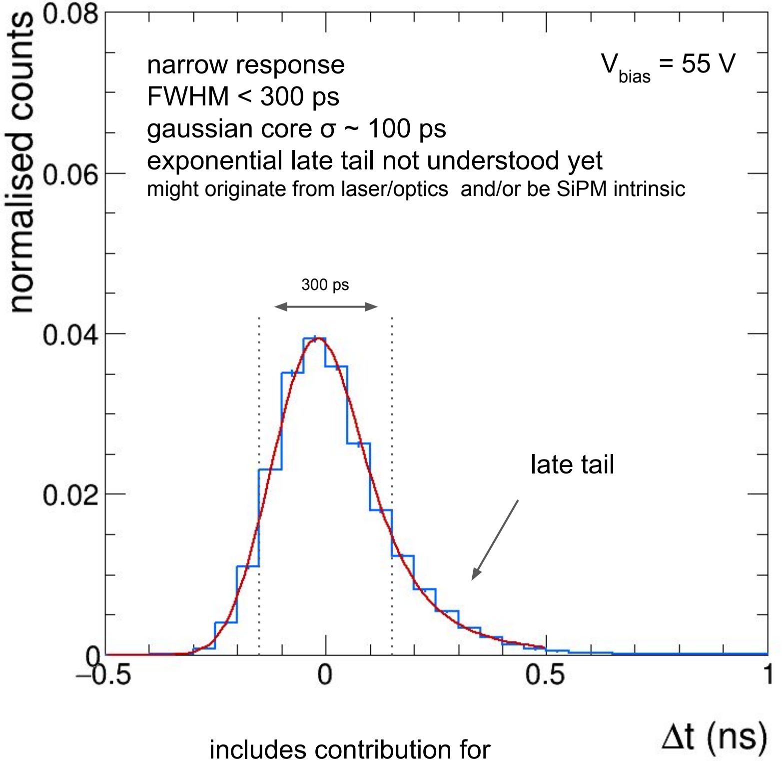
Laser timing measurements with ALCOR

the two extremes of ALCOR front-end bias configuration



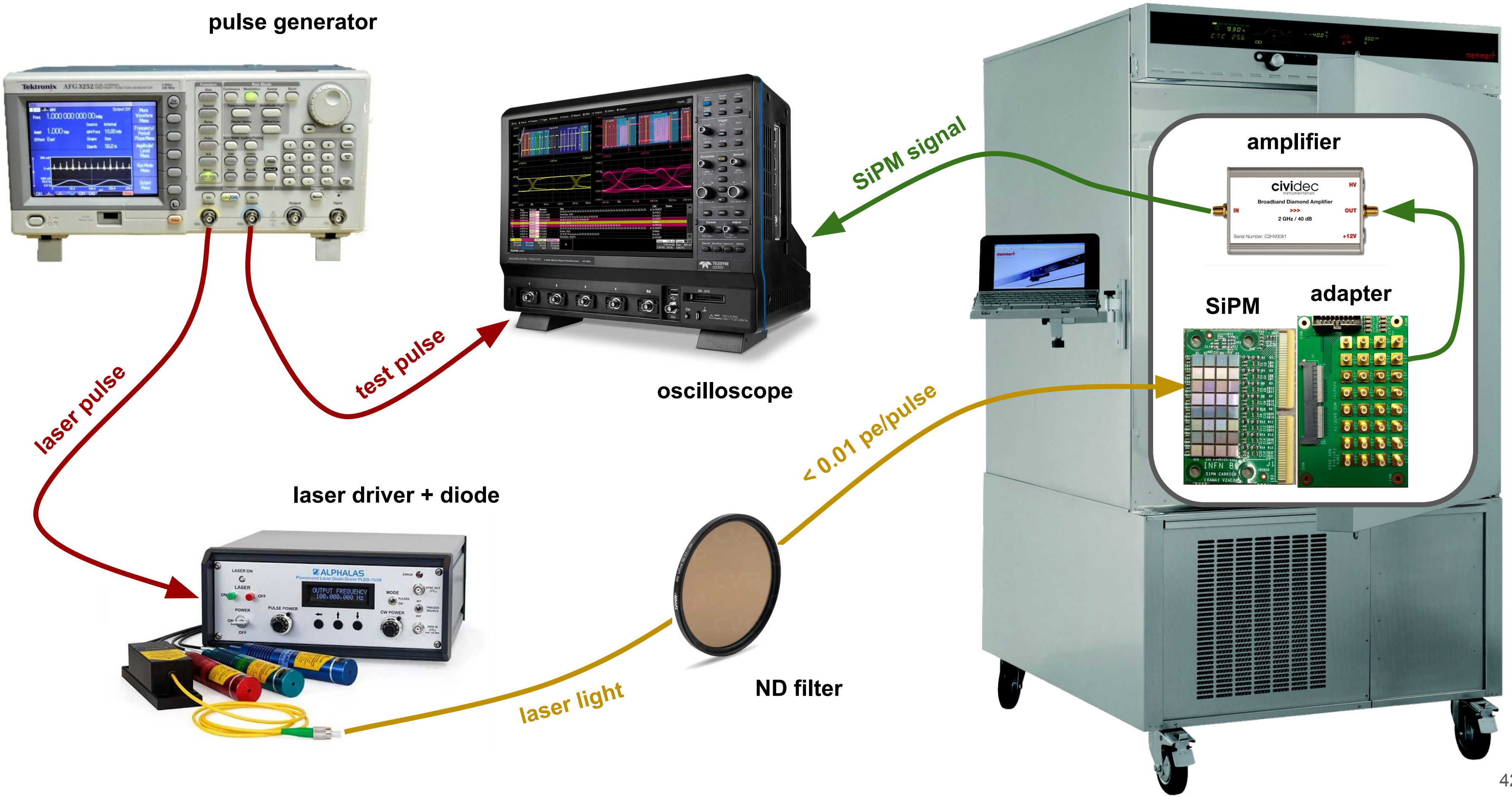
significant differences with ALCOR bandwidth

laser-SiPM correlations (time-walk corrected)



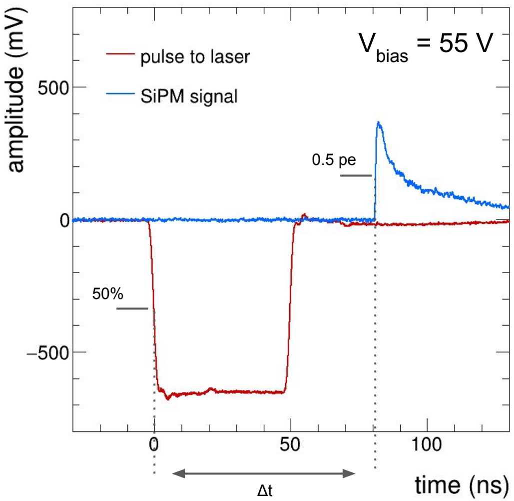
includes contribution for laser-ALCOR synchronization
measured to be σ_{sync} = 30 ps
and reference time resolution
measured to be σ_{start} = 27 ps

Laser timing measurements with oscilloscope

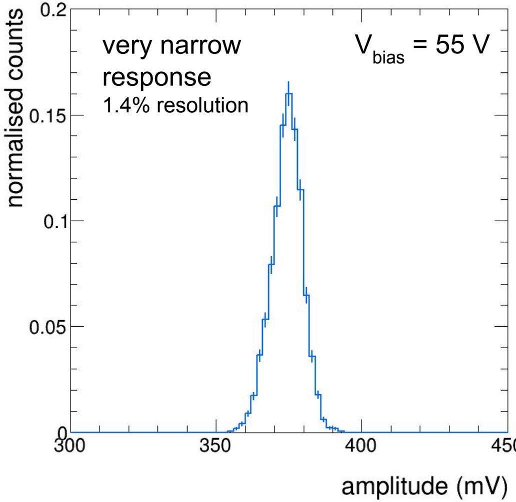


Laser timing measurements with oscilloscope

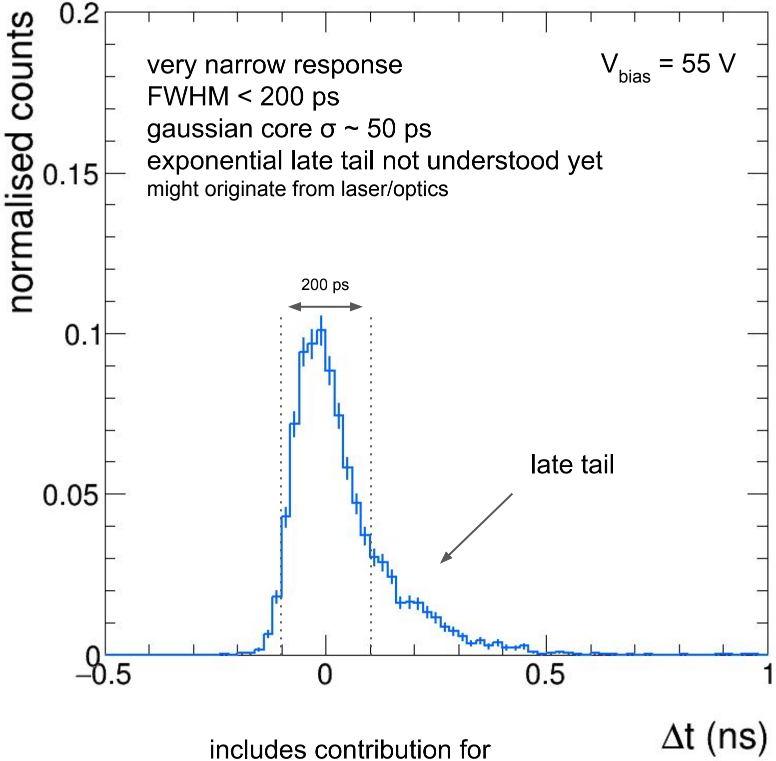
acquired oscilloscope traces



SiPM signal amplitudes (1pe)



laser-SiPM correlations (time-walk corrected)



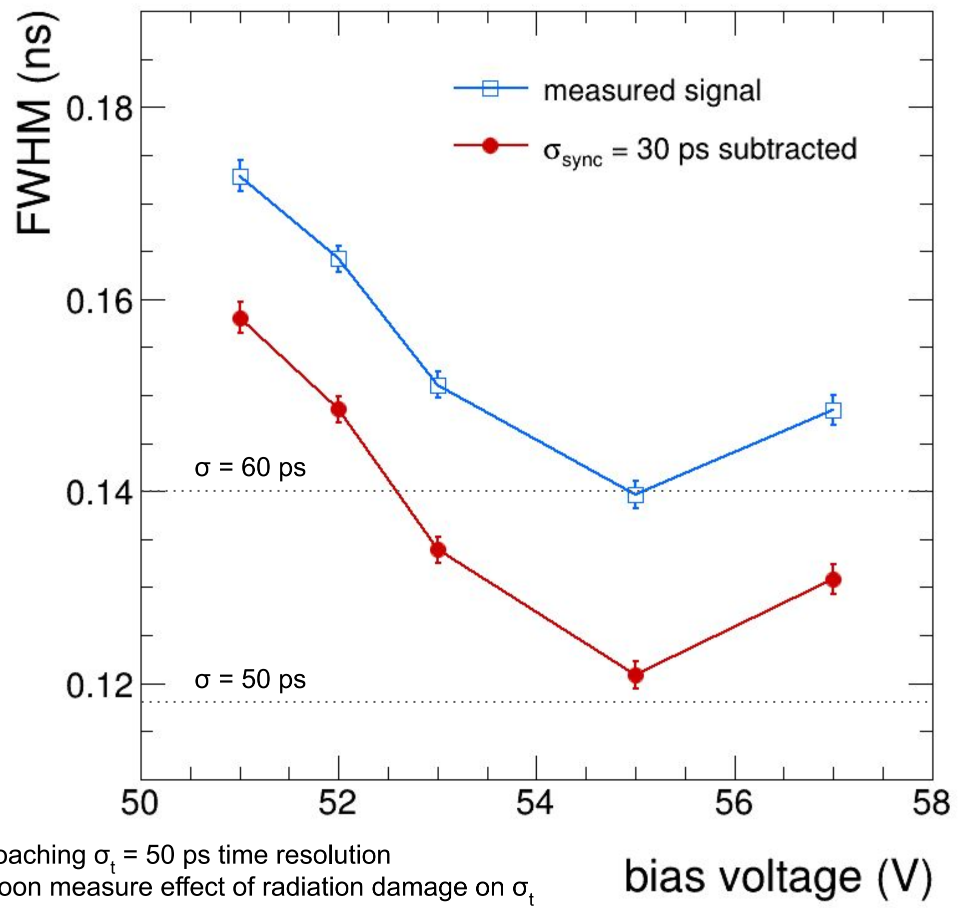
measurements performed at T = -30 C with
- Lecroy Waverunner 40186 oscilloscope
- Cividec Broadband amplifier (40 db)

timing defined with fixed thresholds
- laser pulse at 50% of signal
- SiPM signal at 0.5 pe (average amplitude)

time-amplitude correlation (walk) corrected

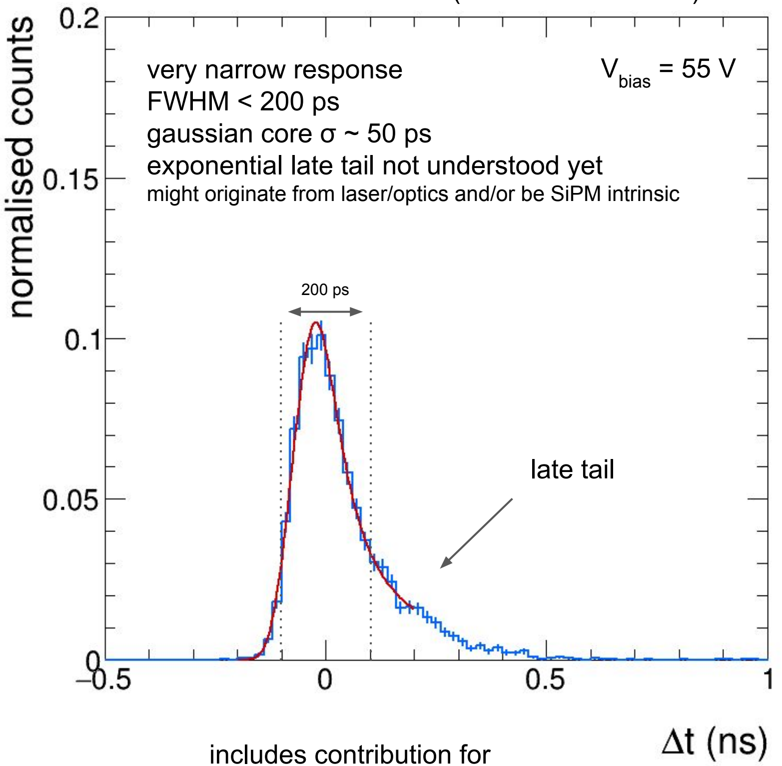
includes contribution for
laser-oscilloscope synchronization
measured to be σ_{sync} = 30 ps

Laser timing measurements with oscilloscope



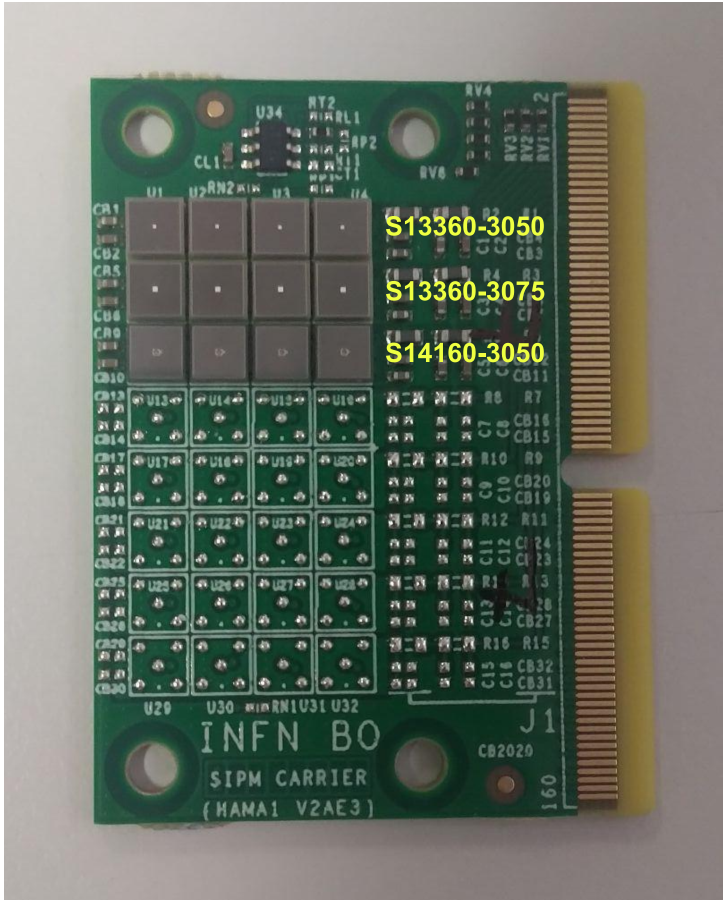
approaching σ_t = 50 ps time resolution
will soon measure effect of radiation damage on σ_t

laser-SiPM correlations (time-walk corrected)



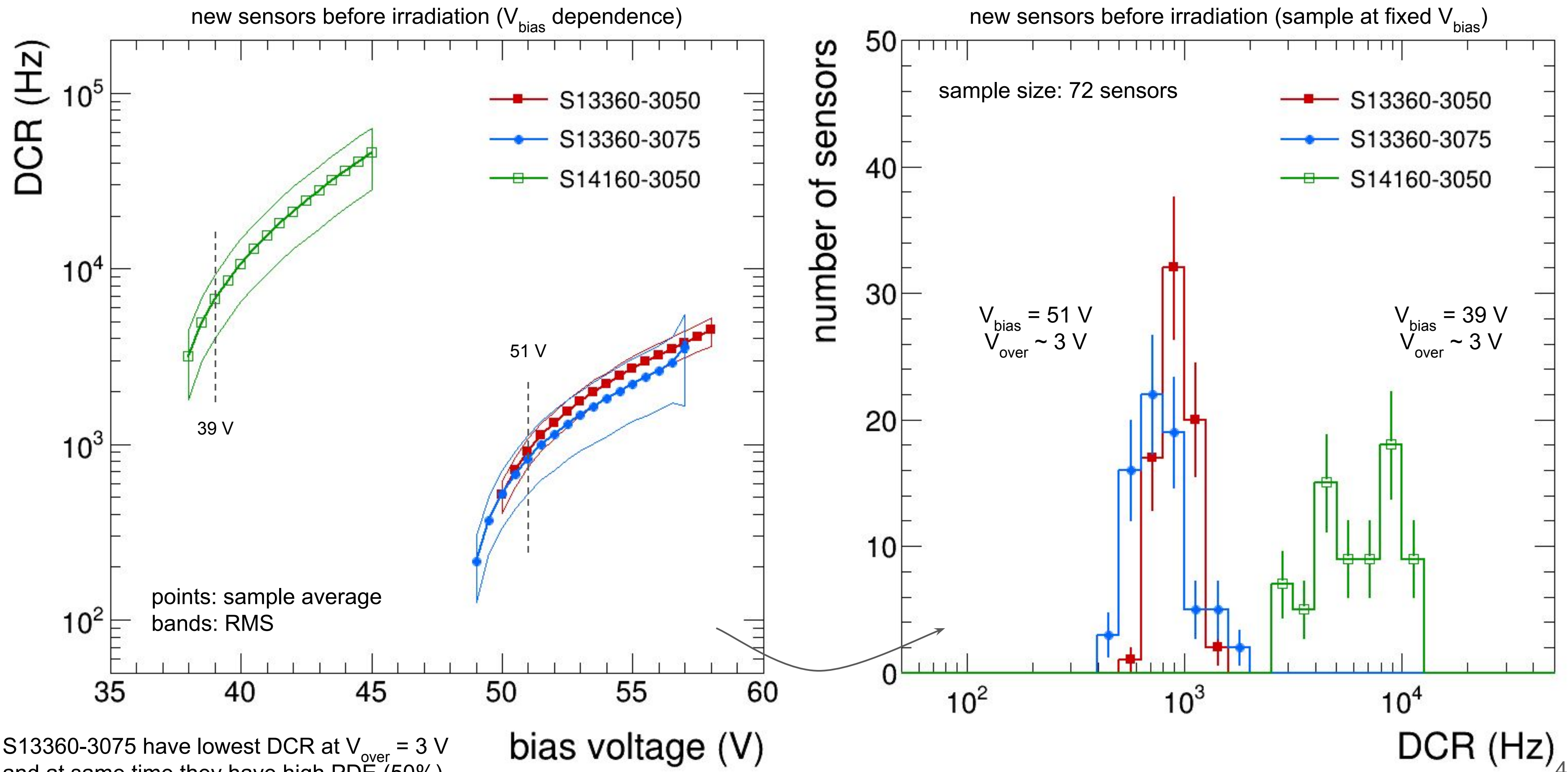
includes contribution for
laser-oscilloscope synchronization
measured to be σ_{sync} = 30 ps

New SiPM custom boards for characterisation (2023 program)



- **35 new boards have been produced**
  - same design from 2020
  - populate only 3 rows
    - 4 sensors, for minimal statistical sample
  - sensors from Hamamatsu
    - S13360-3050
    - S13360-3075
    - S14160-3050
  - replaced 50 Ω RC resistors with ferrite beads
    - allow to perform annealing
    - same components used for prototype
- **irradiation studies**
  - proton energy scan (TIFPA)
    - irradiation done in June 2023
  - neutron damage (LNL)
    - irradiation to be done in August 2023
  - more proton irradiation (TIFPA)
    - November - December 2023
- **annealing studies**
  - online annealing
    - forward and reverse bias
  - detailed studies of annealing techniques
    - time and temperature dependence
    - comparison of different techniques

Characterisation of new SiPM boards



S13360-3075 have lowest DCR at V_{over} = 3 V
and at same time they have high PDE (50%)