SiPM for the ePIC-dRICH detector at the EIC

Roberto Preghenella
INFN Bologna

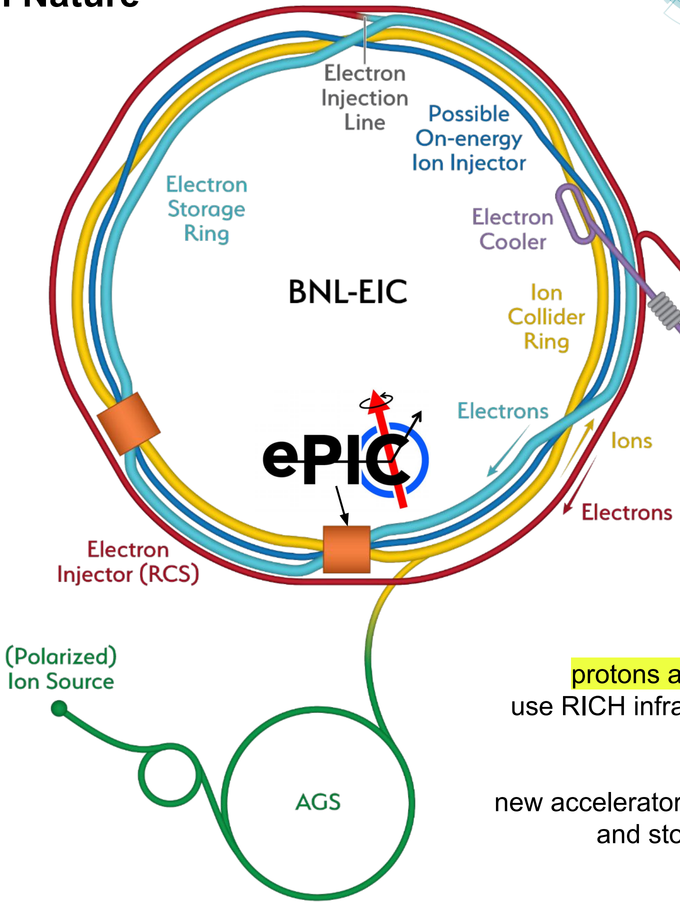
PHOSE 2023
Workshop on "Photodetectors and sensors
for particle identification and new physics searches"
22 November 2023, CERN

preghenella@bo.infn.it

The Electron-Ion Collider

a machine that will unlock the secrets of the strongest force in Nature
is a future electron-proton and electron-ion collider at BNL (USA)
foreseen to start operation in early 2030's

- **the major US project in the field of nuclear physics**
  - one of the most important scientific facilities for the future of nuclear and subnuclear physics
- **the world's first collider for**
  - polarised electron-proton (and light ions)
  - electron-nucleus collisions
- **will allow to explore the secrets of QCD**
  - understand origin of mass & spin of the nucleons
  - extraordinary 3D images of the nuclear structure



protons and nuclei
use RICH infrastructure

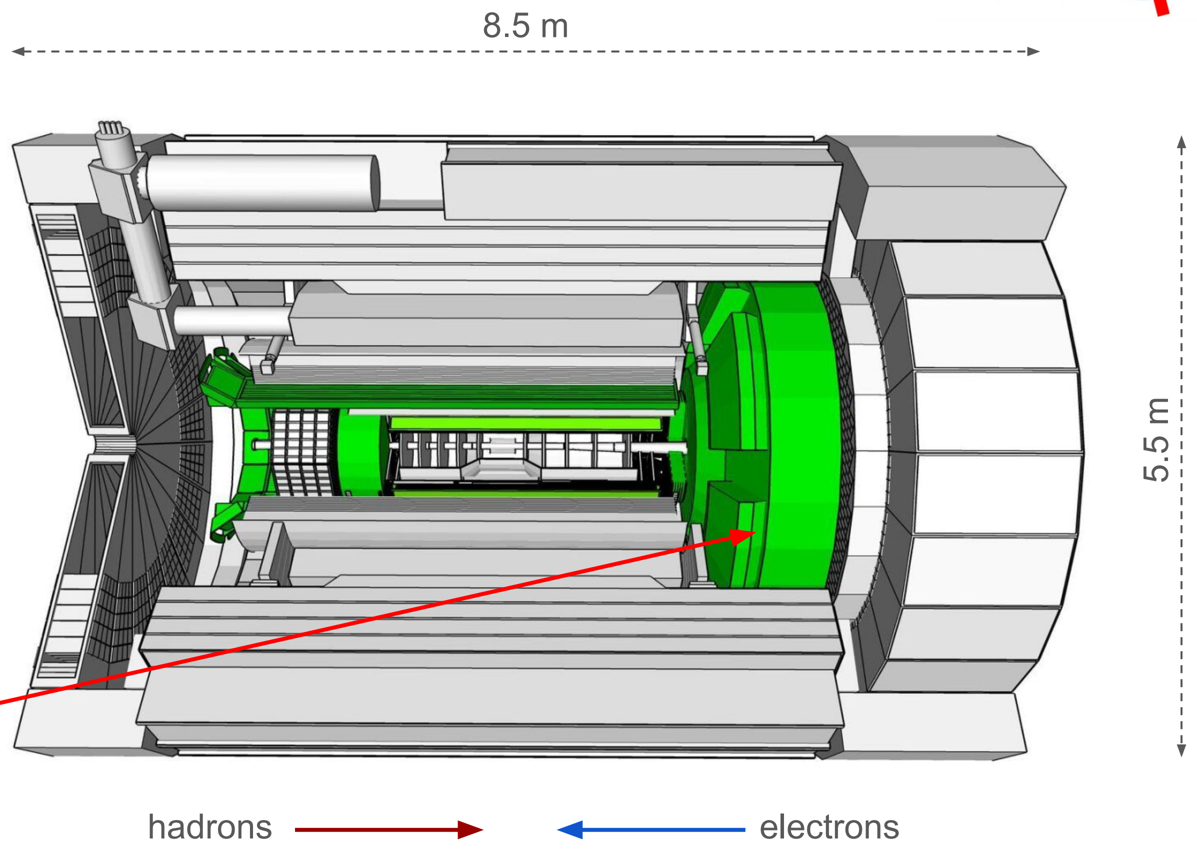
electrons
new accelerator complex
and storage ring

www.bnl.gov/eic

The ePIC experiment

layout of the barrel detector

- **tracking**
  - new 1.7 T magnet
  - Si-MAPS + MPGDs
- **calorimetry**
  - e-side: $PbWO_4$ EMCal
  - barrel: imaging EMCal
  - h-side: finely segmented
  - outer barrel HCal
- **particle ID**
  - AC-LGAD TOF
  - pfRICH
  - hpDIRC
  - **dRICH**

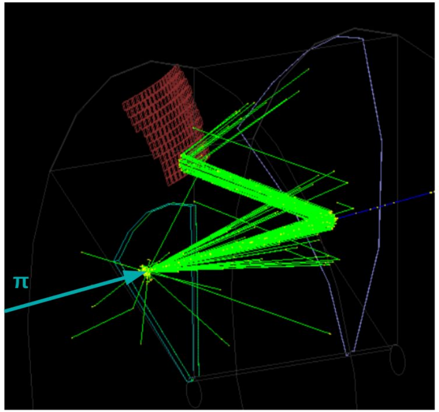


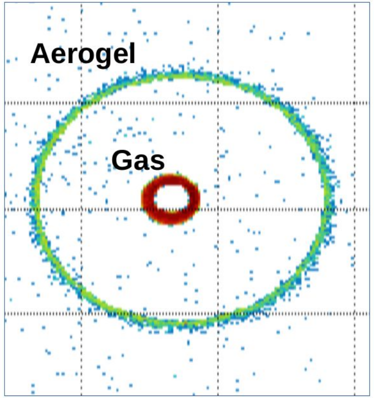
The dual-radiator (dRICH) for forward PID at EIC

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

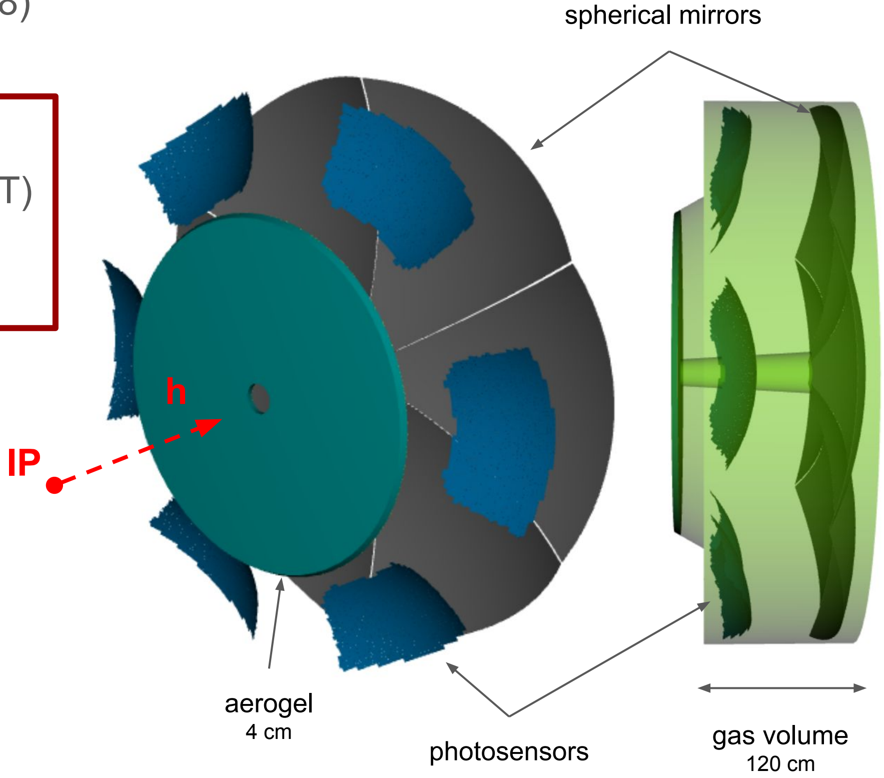
p = [3.0, 50] GeV/c
η = [1.5, 3.5]
e-ID up to 15 GeV/c

- **radiators:** aerogel (n ~ 1.02) and C_2F_6 (n ~ 1.0008)
- **mirrors:** large outward-reflecting, 6 open sectors
- **sensors:** 3x3 mm^2 pixel, 0.5 m^2 / sector
  - single-photon detection inside high B field (~ 1 T)
  - outside of acceptance, reduced constraints
  - SiPM optical readout





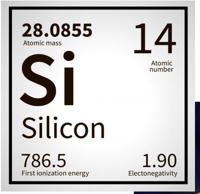
example event (accumulated hits)



SiPM option and requirements for RICH optical readout

INFN

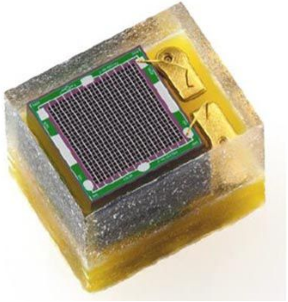
- **pros**
  - cheap
  - high photon efficiency
    requirement
  - excellent time resolution
    requirement
  - insensitive to magnetic field
    requirement



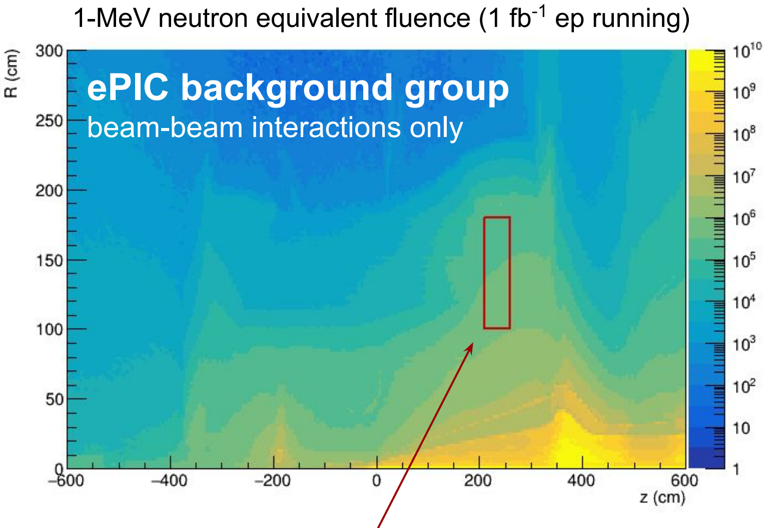
- **cons**

large dark count rates
not radiation tolerant

technical solutions and mitigation strategies
🐧 cooling
⏱️ timing
🔥 annealing



Neutron fluxes at the dRICH photosensor surface



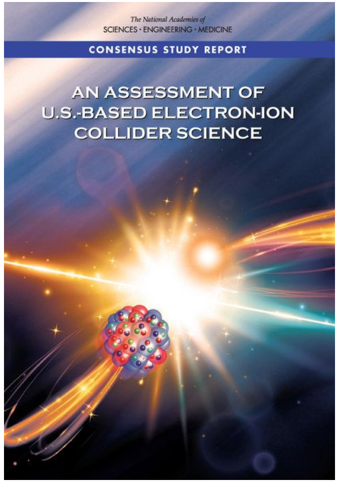
location of dRICH photosensors
mean fluence: 3.9 10^5 neq / cm^2 / fb^{-1}
max fluence: 9.2 10^5 neq / cm^2 / fb^{-1}

- radiation level is moderate

assume fluence: ~ 10^7neq / cm^2 / fb^{-1}
conservatively assume max fluence and <u>10x safety factor</u>

Most of the key Physics goals defined by the NAS require an integrated luminosity of 10 fb^{-1} per center of mass energy and polarization setting

The nucleon imaging programme is more luminosity hungry and **requires 100 fb^{-1} per center of mass energy and polarization setting**



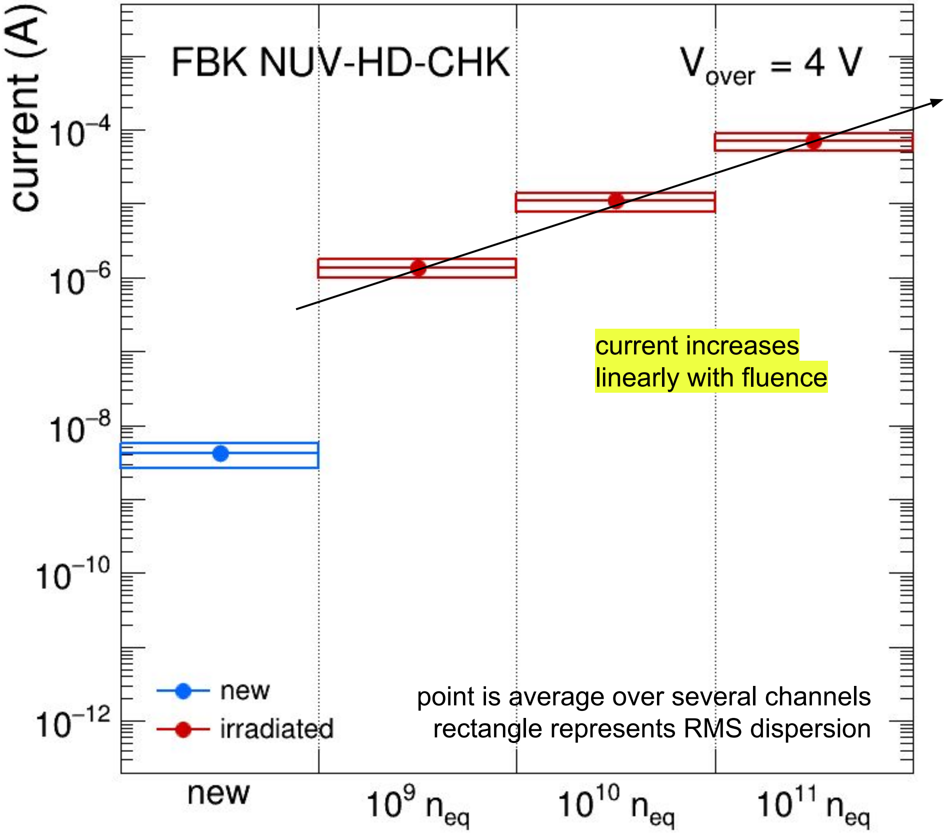
in 10-12 years the EIC will accumulate 1000 fb^{-1} integrated $\mathcal{L}$ corresponding to an integrated fluence of ~ 10^{10} n_{eq}/cm^2

study the SiPM usability for single-photon Cherenkov imaging applications in moderate radiation environment

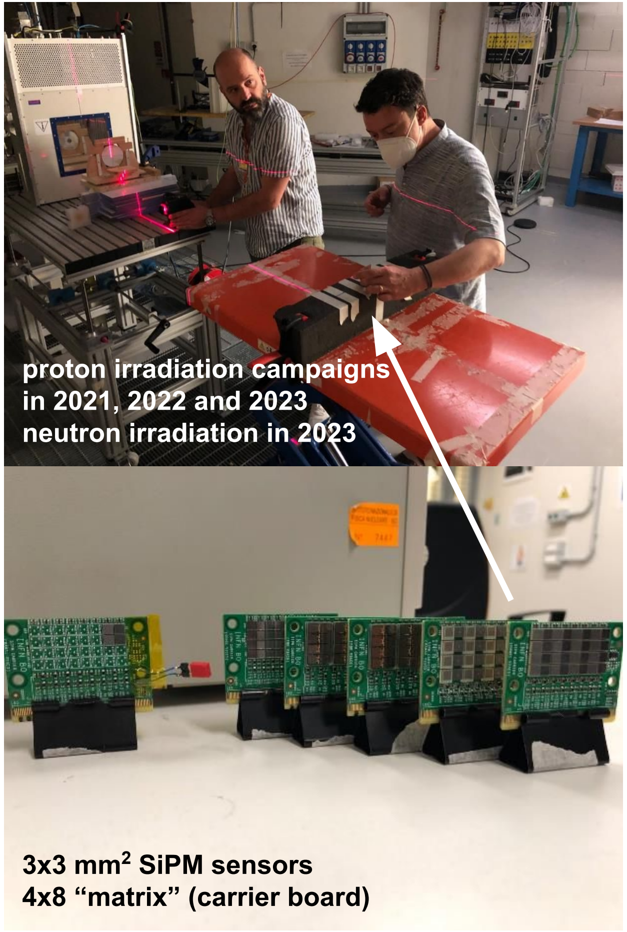
→ radiation damage studied in steps of radiation load

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	*might never be reached*

Studies of radiation damage on SiPM

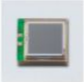


all results are reported at T = -30 C



Commercial SiPM sensors and FBK prototypes



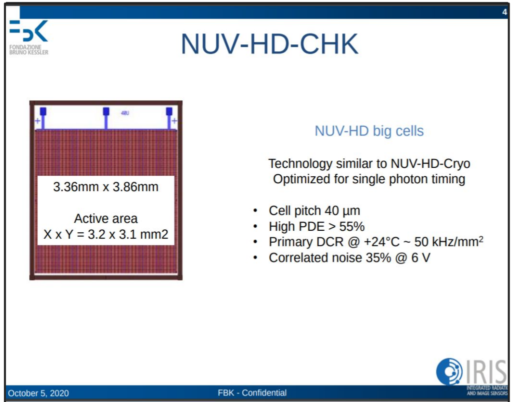


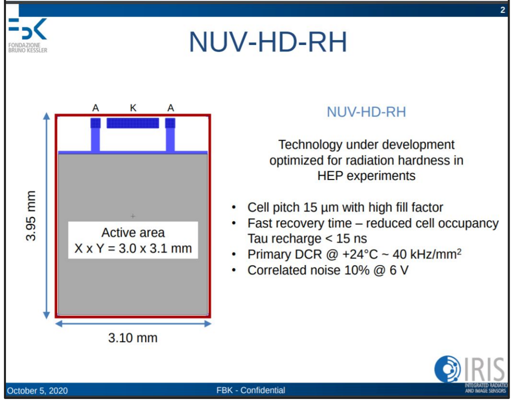
board	sensor	uCell (µm)	V_{bd} (V)	PDE (%)	DCR (kHz/mm^2)	window	notes
HAMA1	S13360 3050VS	50	53	40	55	silicone	legacy model Calvi et. al
	S13360 3025VS	25	53	25	44	silicone	legacy model smaller SPAD
HAMA2	S14160 3050HS	50	38	50		silicone	newer model lower V_{bd}
	S14160 3015PS	15	38	32	78	silicone	smaller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

HAMAMATSU PHOTON IS OUR BUSINESS

ON Semiconductor

BROADCOM

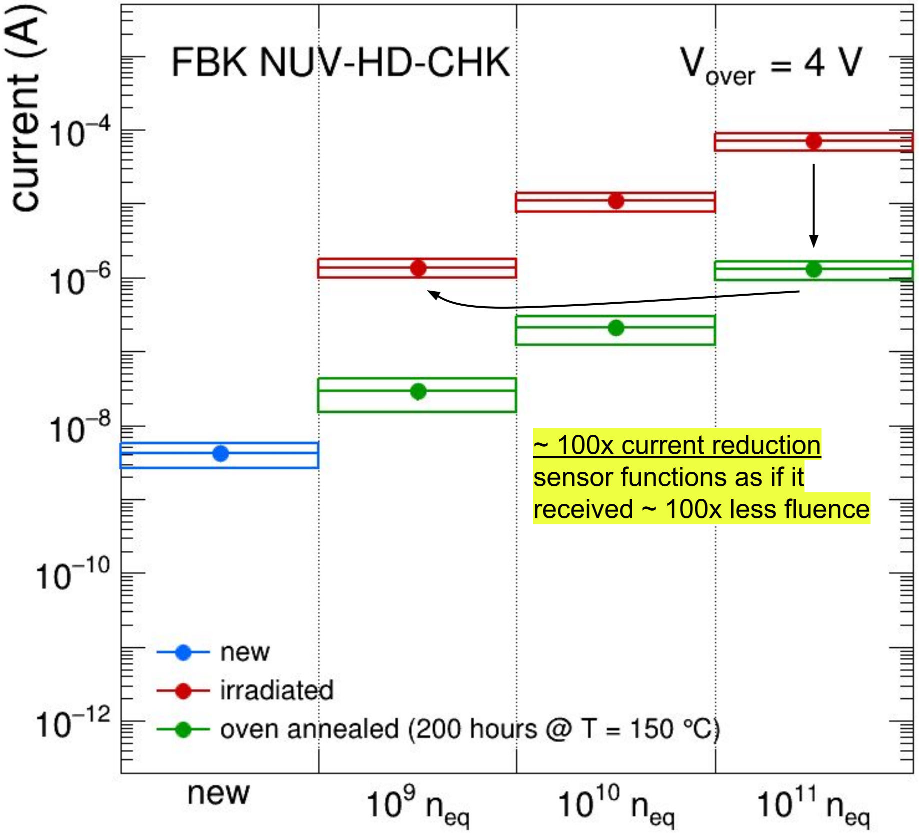




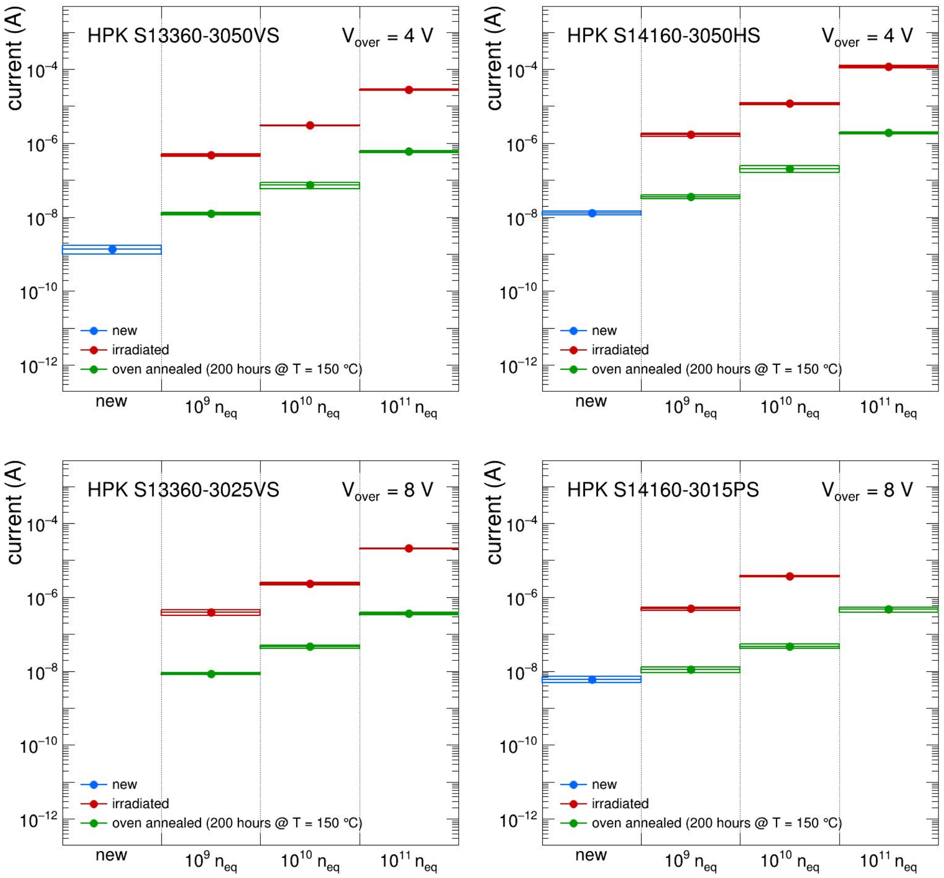
multiple producers: different technologies, SPAD dimensions, V_{bd}, electric field …

High-temperature annealing recovery

oven annealing
~ 1 week at 150 C



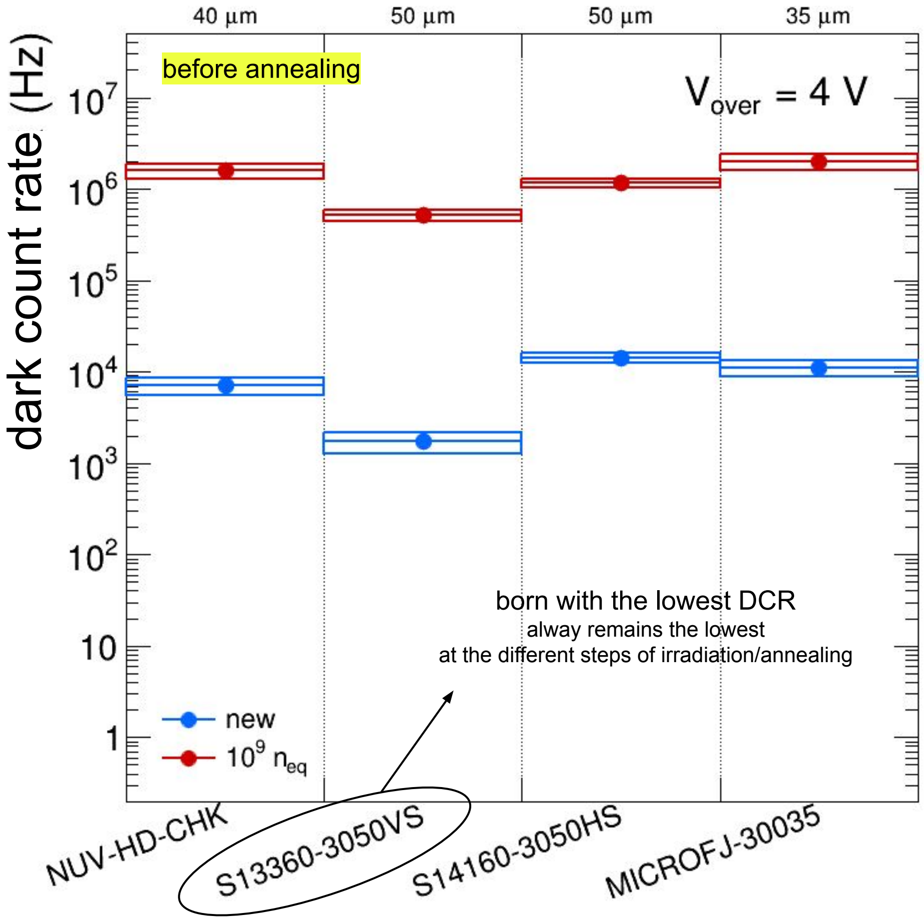
~ 100x current reduction
sensor functions as if it
received ~ 100x less fluence

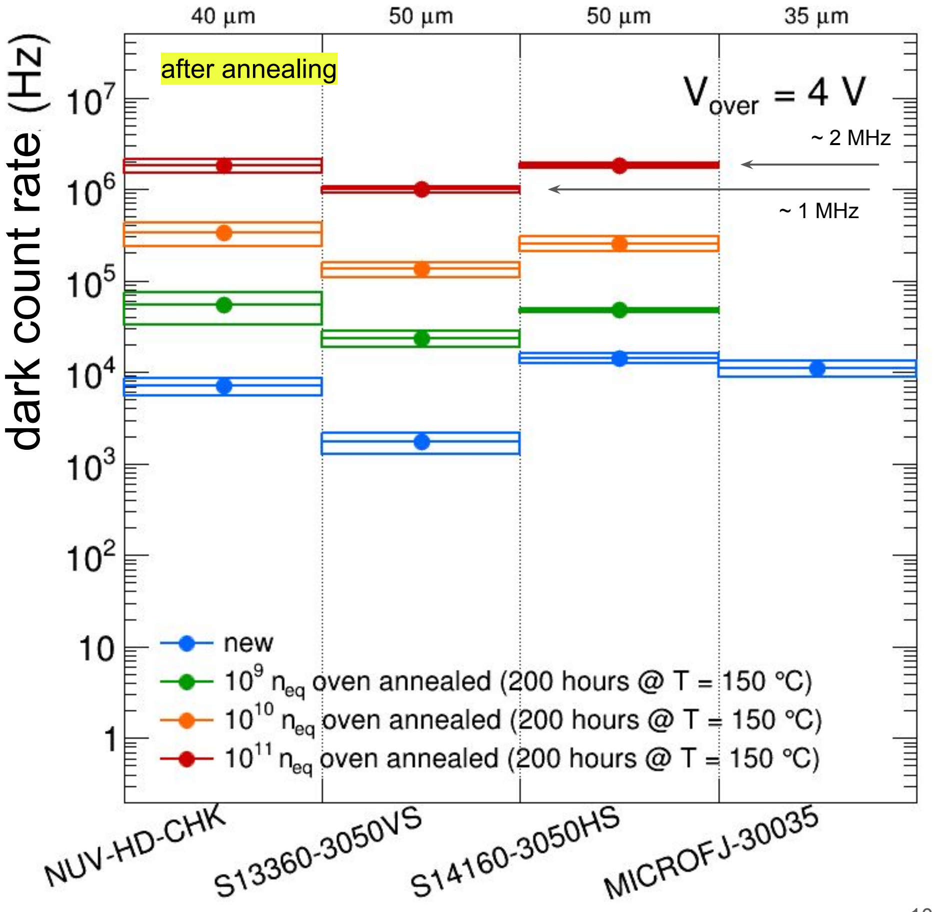


similar observation with various types of Hamamatsu sensors

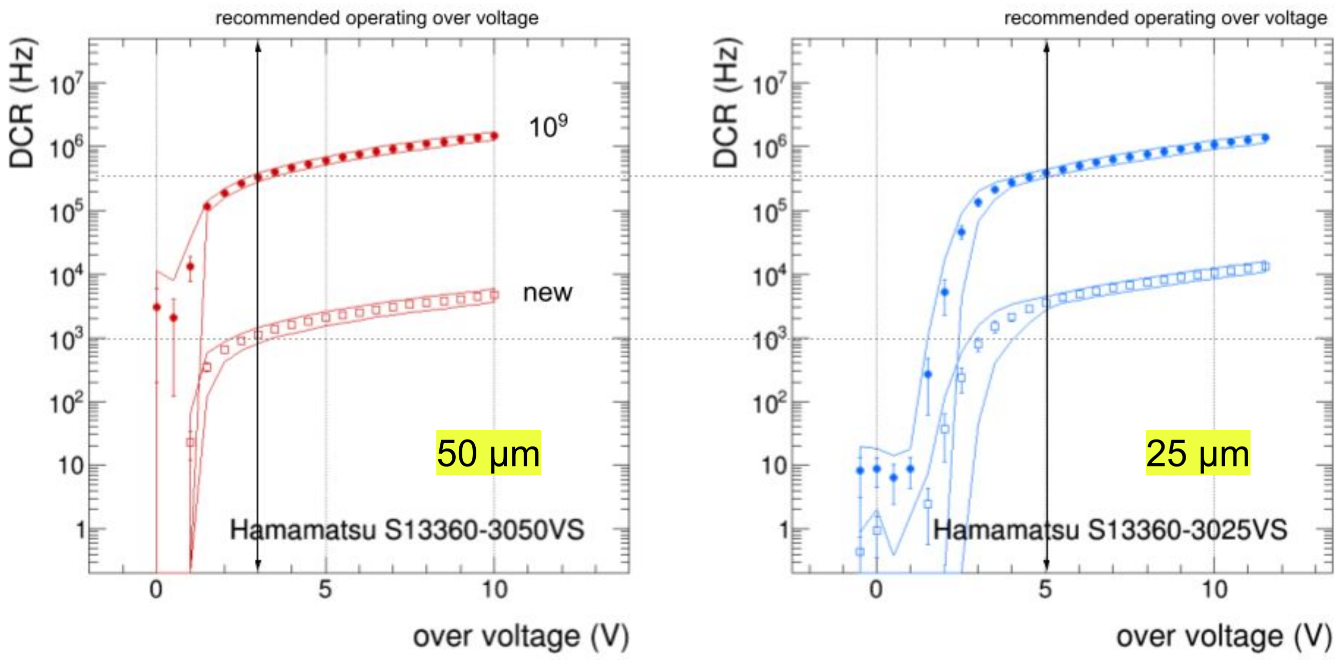
Comparison between different sensors

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





Small vs. large SPAD sensors



sensors with **small SPADs have lower SNR** also after irradiation

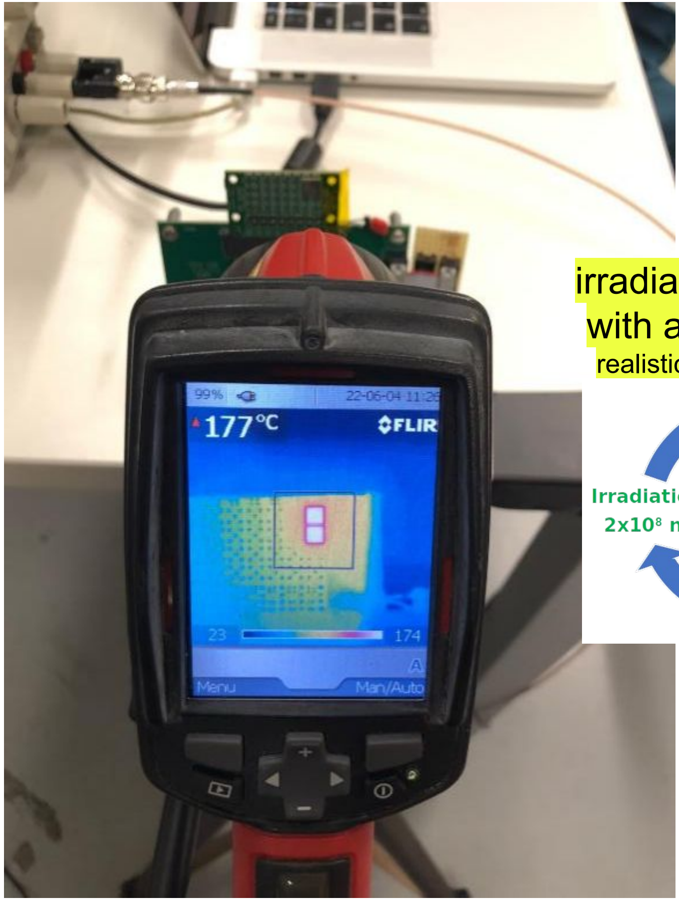
small SPAD sensors are not radiation harder for single-photon applications (RICH)

- **sensors operated at Hamamatsu recommended over-voltage**
  - [datasheet] 50 µm sensors have 40% PDE, 25 µm have 25%
  - [measured] 50 µm sensors have lower DCR than 25 µm when new
  - [measured] both sensors have similar DCR after irradiation

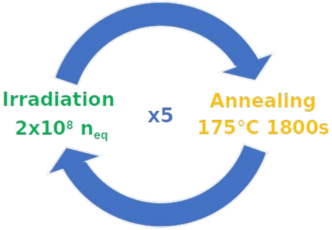
similar results and conclusions obtained with SENSL sensors

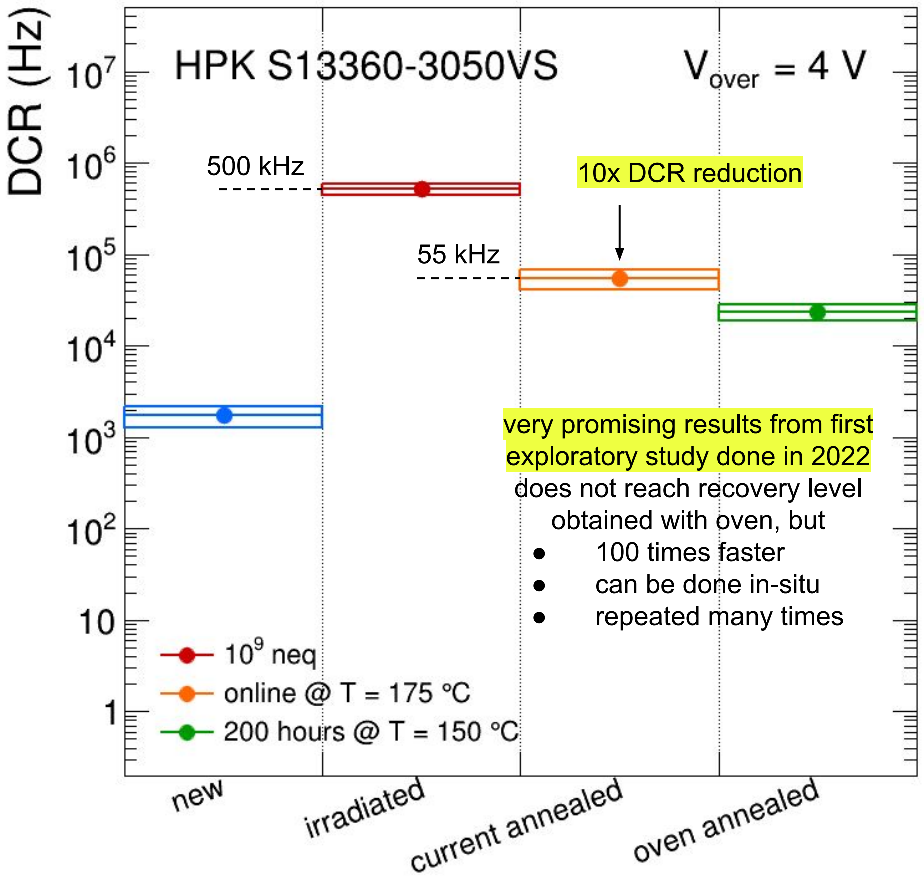
“Online” self-induced annealing

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

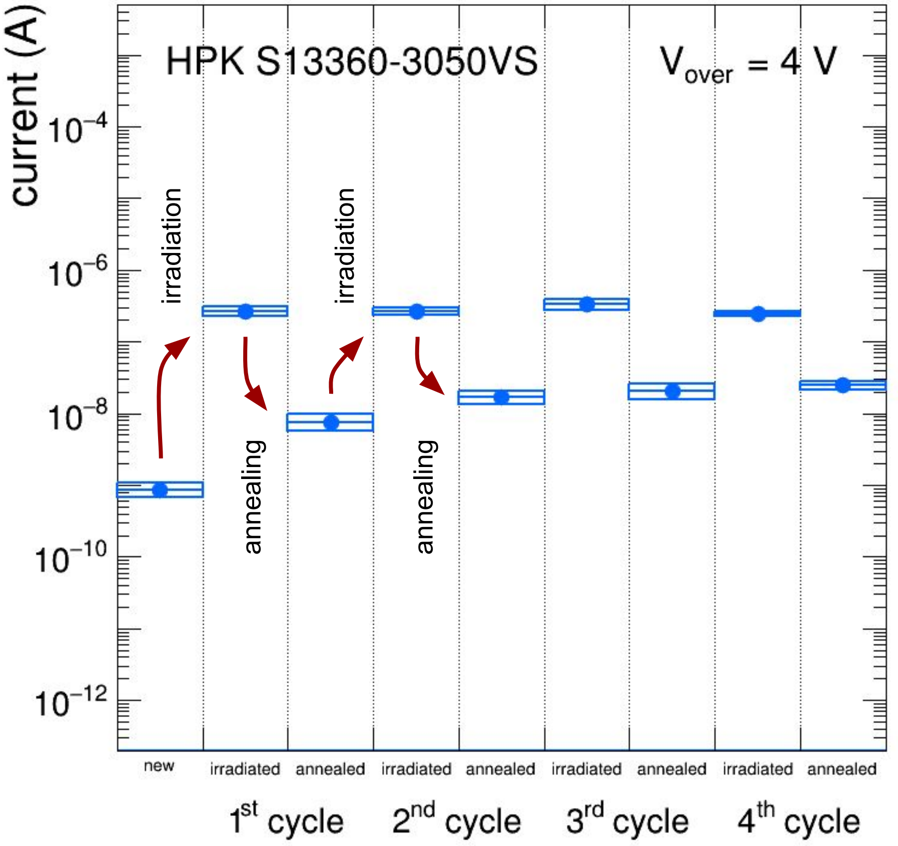




very promising results from first exploratory study done in 2022
does not reach recovery level obtained with oven, but
- 100 times faster
- can be done in-situ
- repeated many times

Repeated irradiation-annealing cycles

oven annealing



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

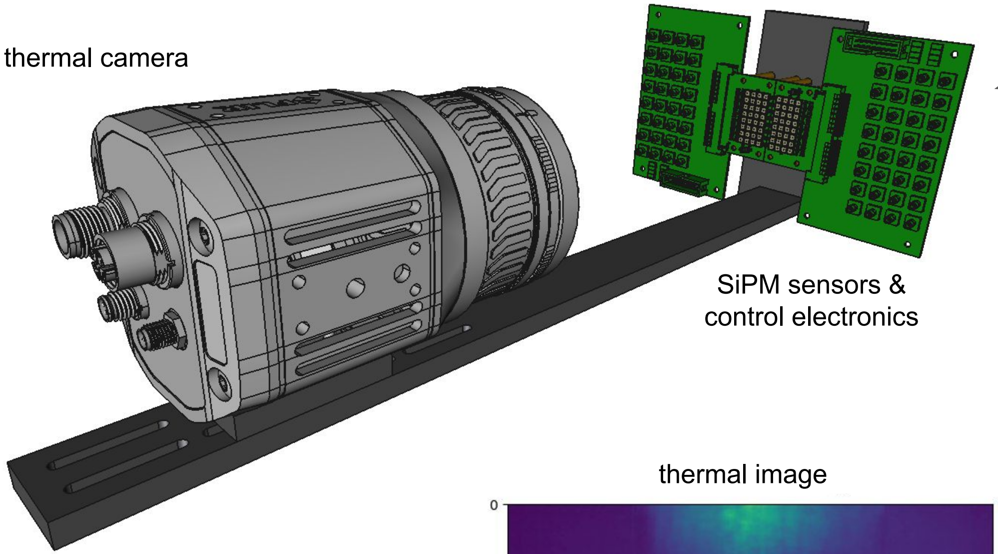
annealing cures same fraction of newly-produced damage

~ 97% for HPK S13360-3050 sensors

Automated multiple SiPM online self-annealing

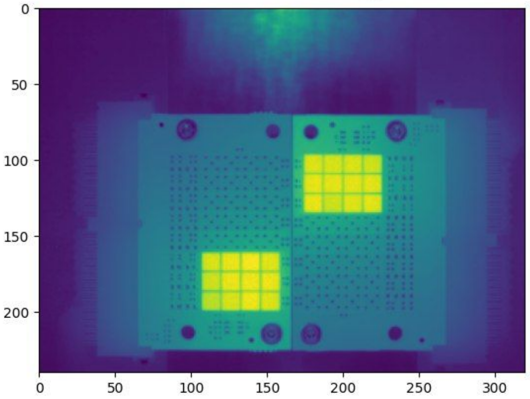
system for online self-annealing with temperature monitor and control of each individual SiPM

thermal camera

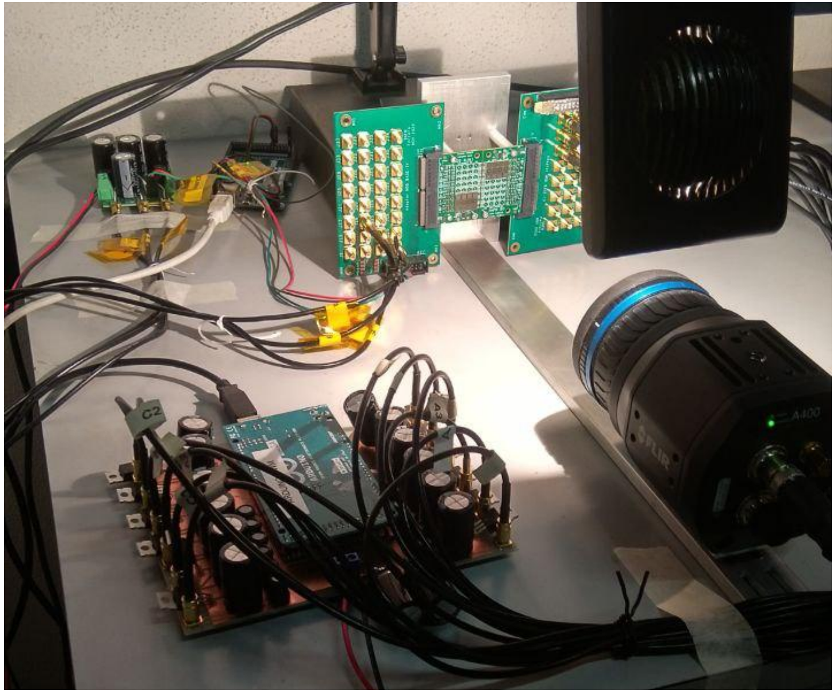


SiPM sensors & control electronics

thermal image

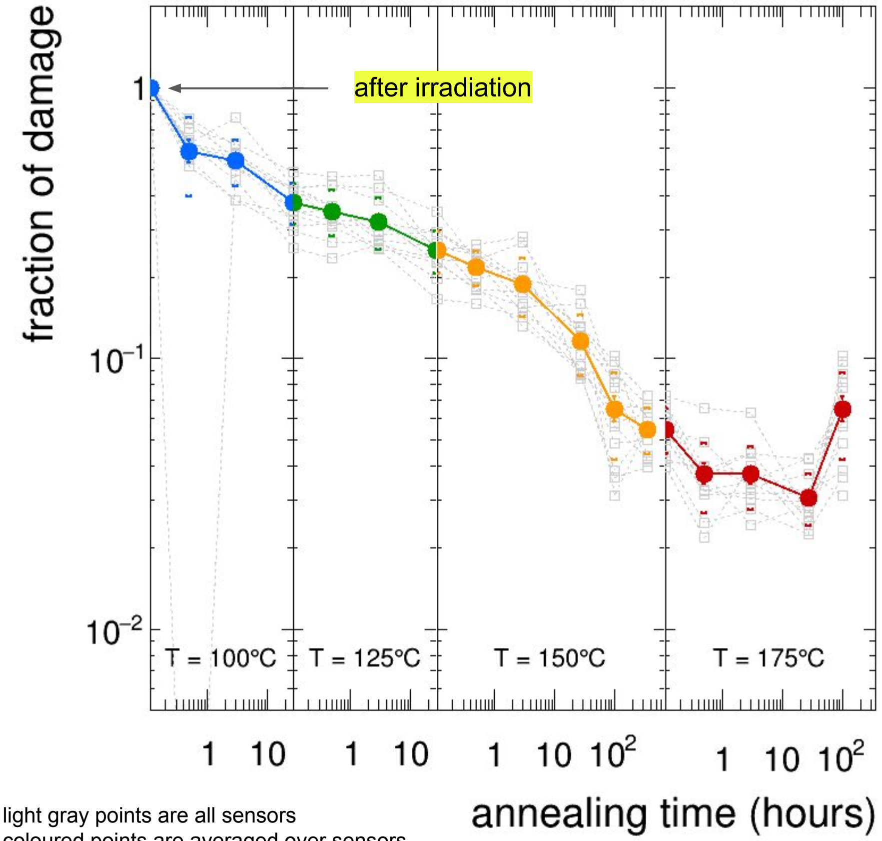


monitor and logging system



Detailed studies of SiPM online self-annealing

online self-annealing with reverse bias



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

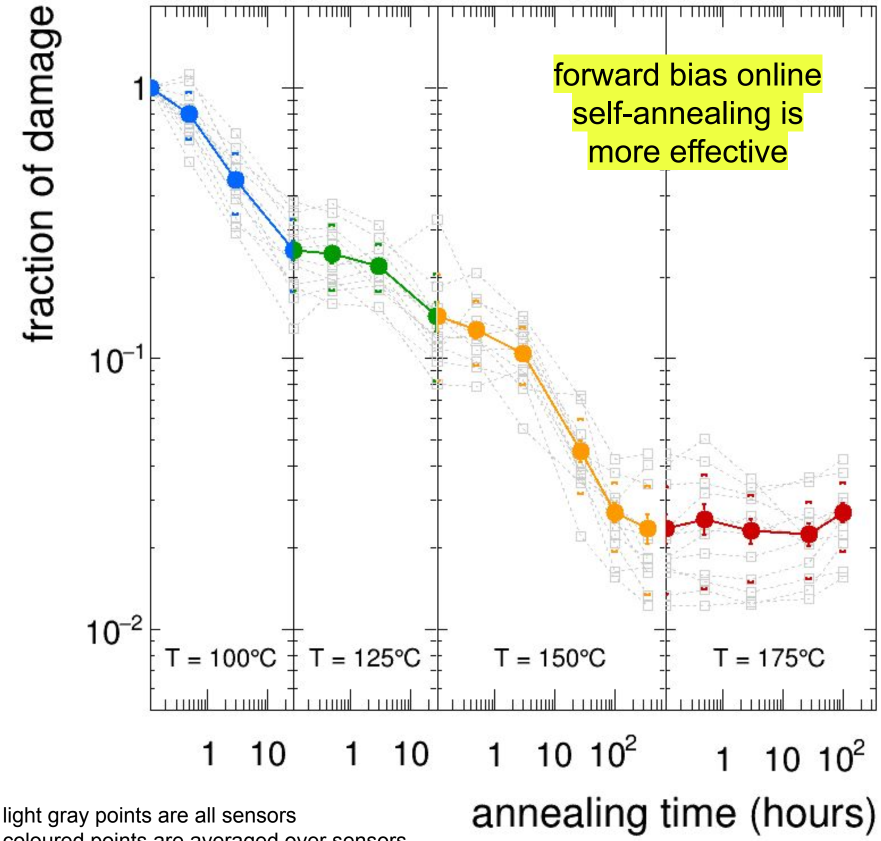
test on a large number of proton irradiated sensors how much damage is cured as a function of temperature and time

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

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

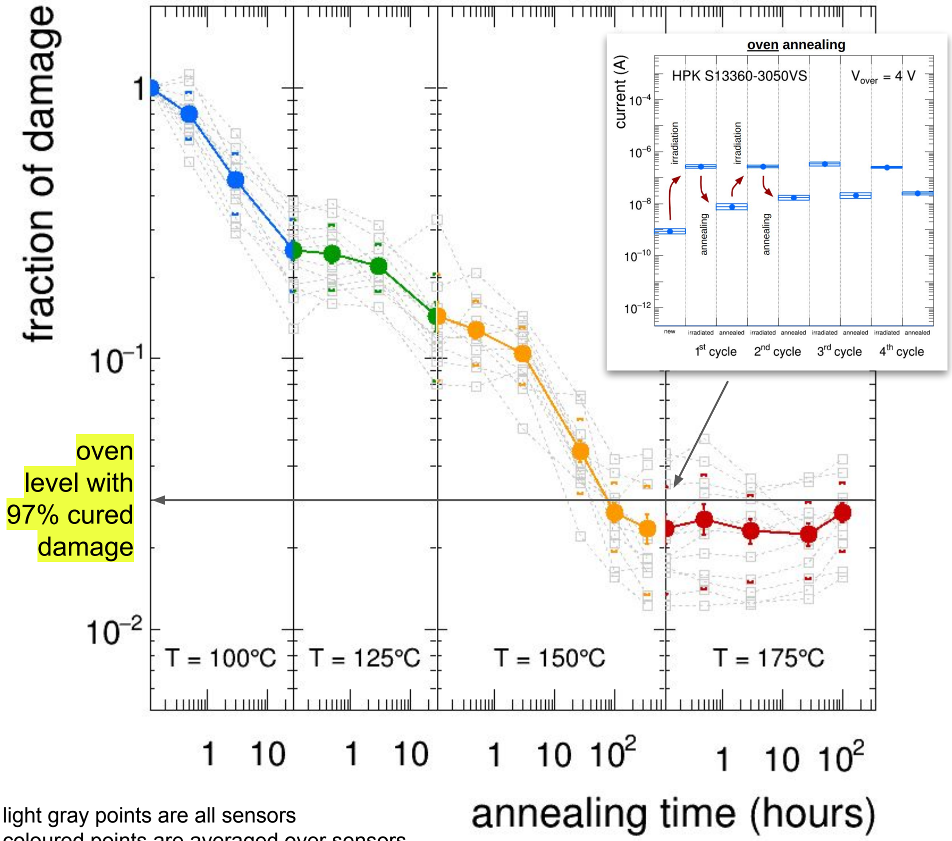
in this study, the same sensors have undergone self-annealing in increasing temperature steps and increasing integrated time steps

- 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

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

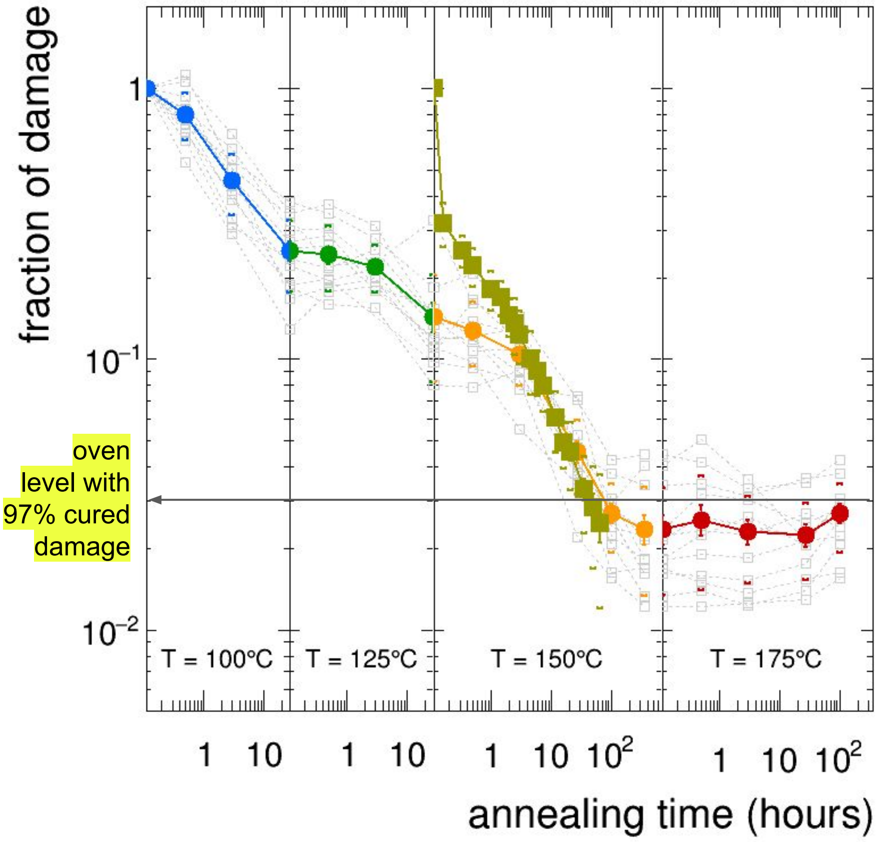
in this study, the same sensors have undergone self-annealing in increasing temperature steps and increasing integrated time steps

- 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

online self-annealing with forward bias



oven level with 97% cured damage

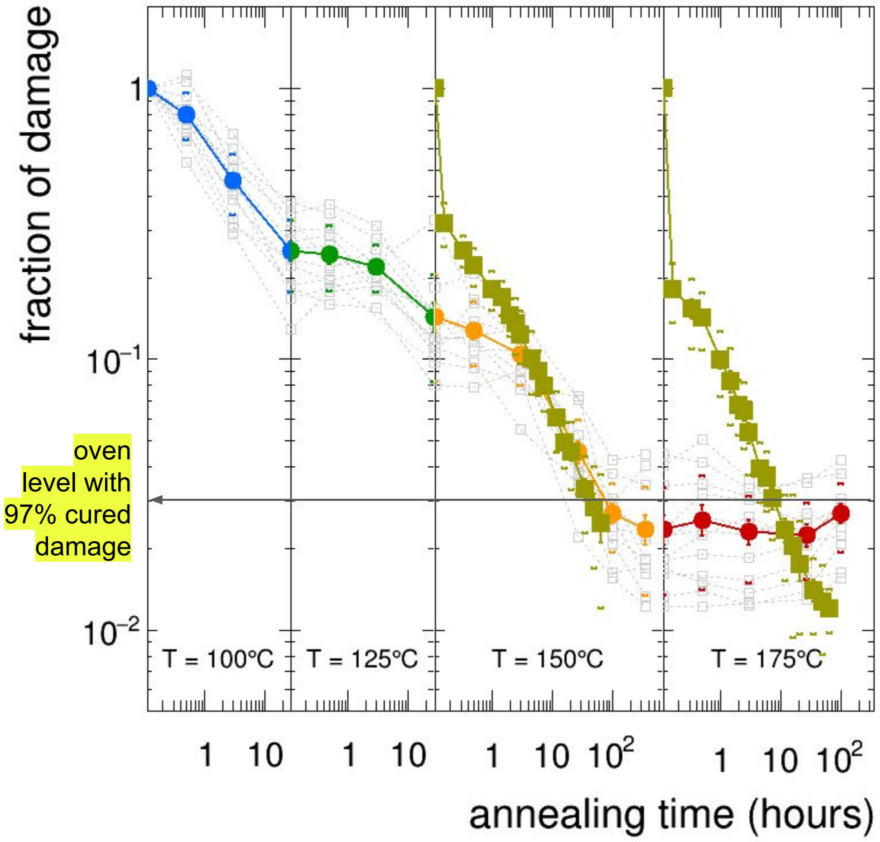
tested on a number of neutron irradiated sensors the details of annealing curve at fixed temperature

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

online self-annealing with forward bias

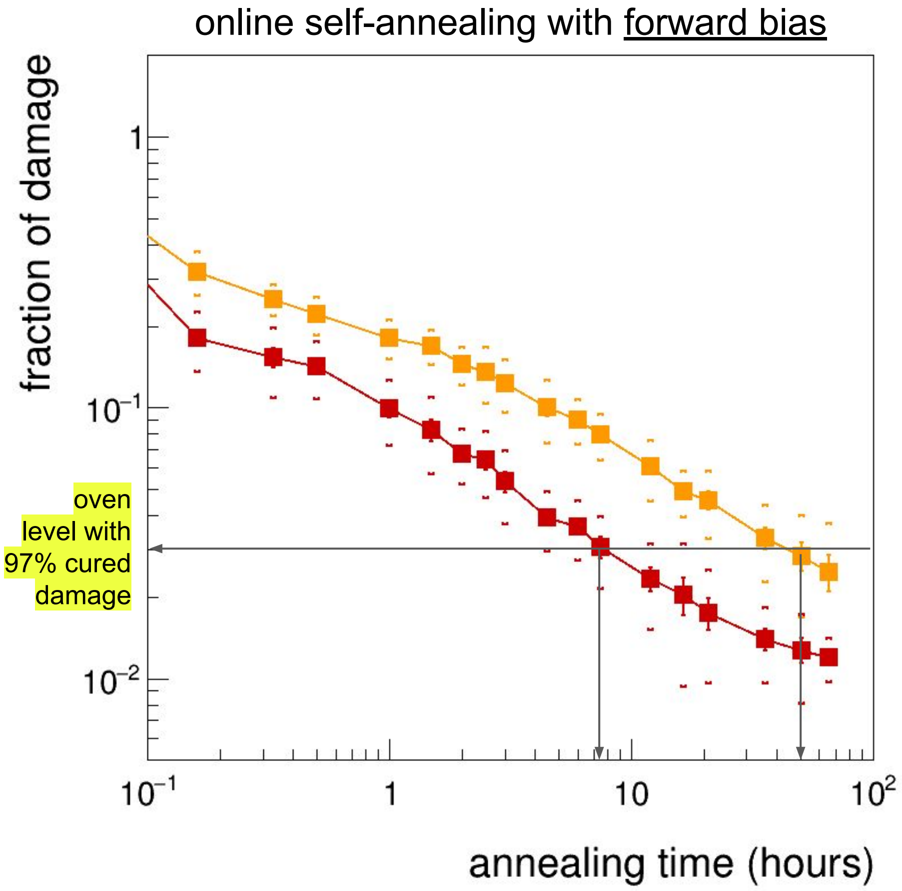


tested on a number of neutron irradiated sensors the details of annealing curve at fixed temperature

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

- at T = 175 C
  - faster sudden decrease in short time
  - followed by a faster rate decrease
  - exceeding the oven performance
  - still decreasing, might reach plateau soon
    - measurements are in progress

Automated multiple SiPM online self-annealing



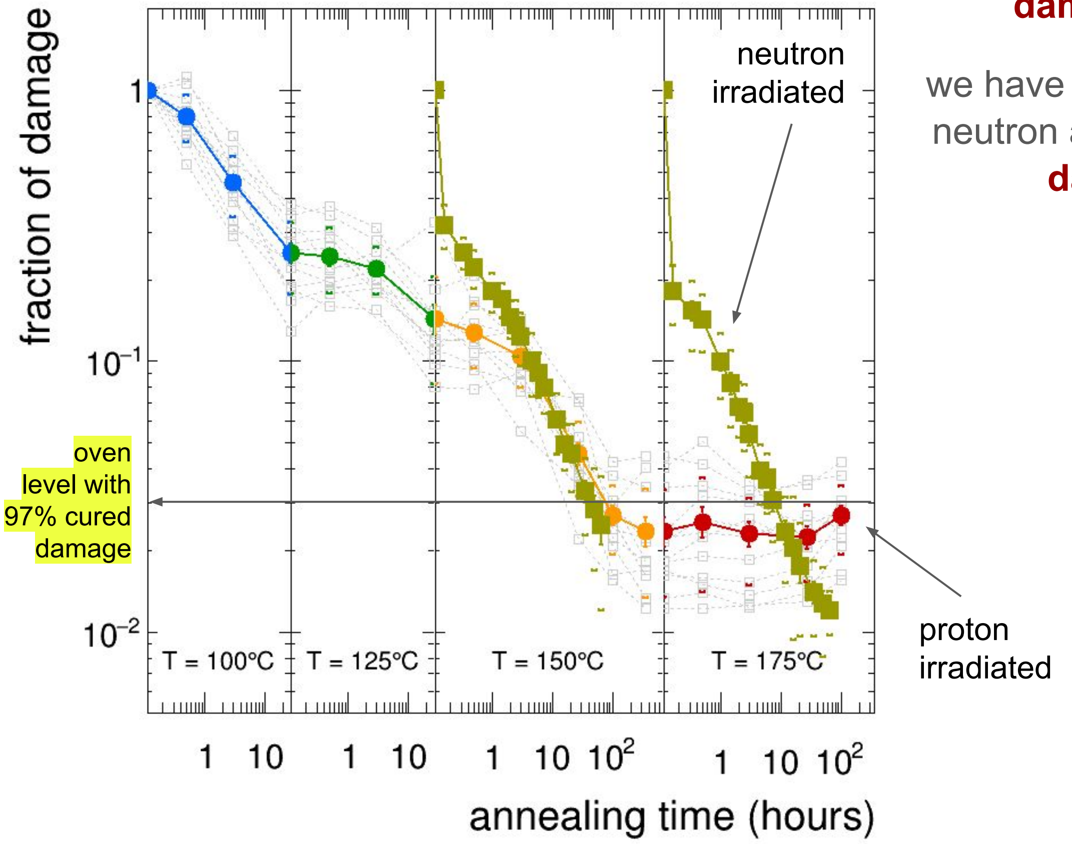
comparison between two annealing temperatures

both reach and exceed 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 reached at T = 150 C
  - < 100 hours integrated

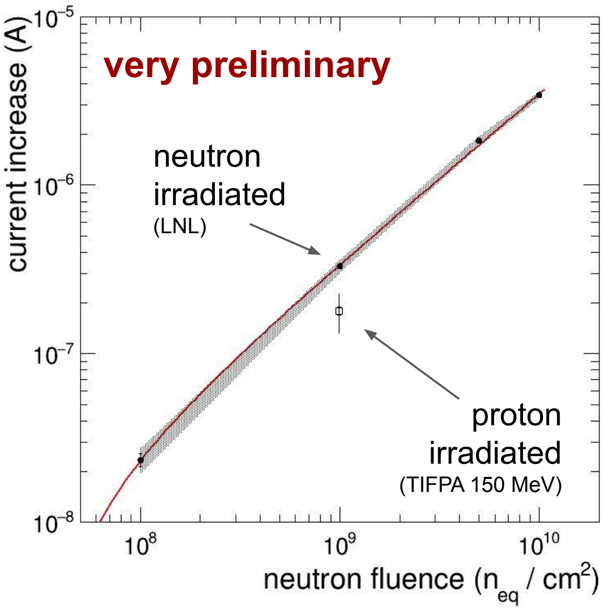
Very preliminary neutron damage caveat

online self-annealing with forward bias



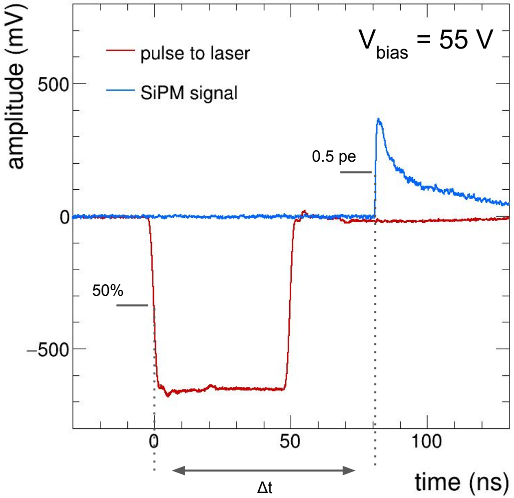
looking at these results there is an indication that **neutron damage is cured more than proton damage**

we have very preliminary results on comparison between neutron and proton damage which indicate that **neutron damage is larger after same n_{eq} fluence**
using NIEL scaling for normalisation

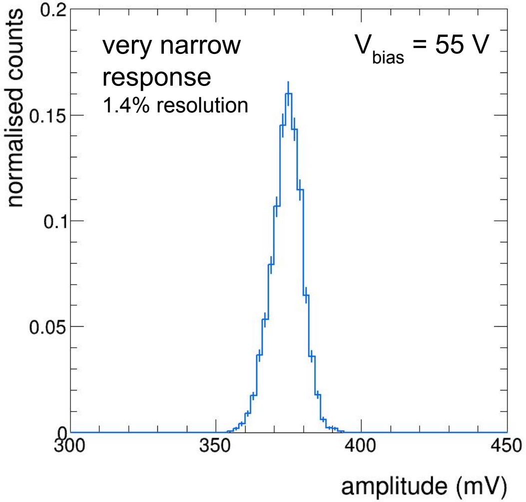


Laser timing measurements with oscilloscope

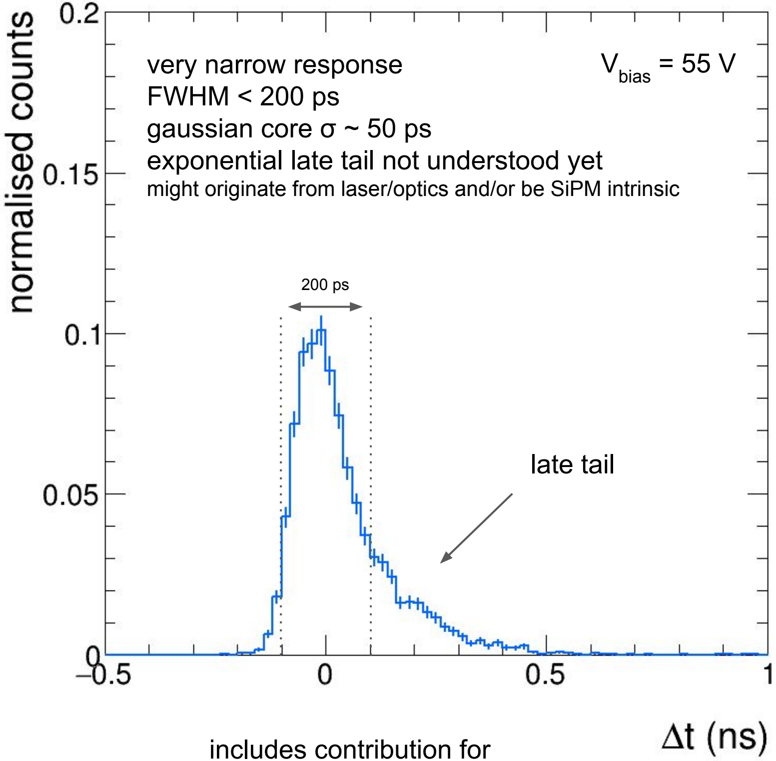
acquired oscilloscope traces



SiPM signal amplitudes (1pe)



laser-SiPM correlations (time-walk corrected)



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

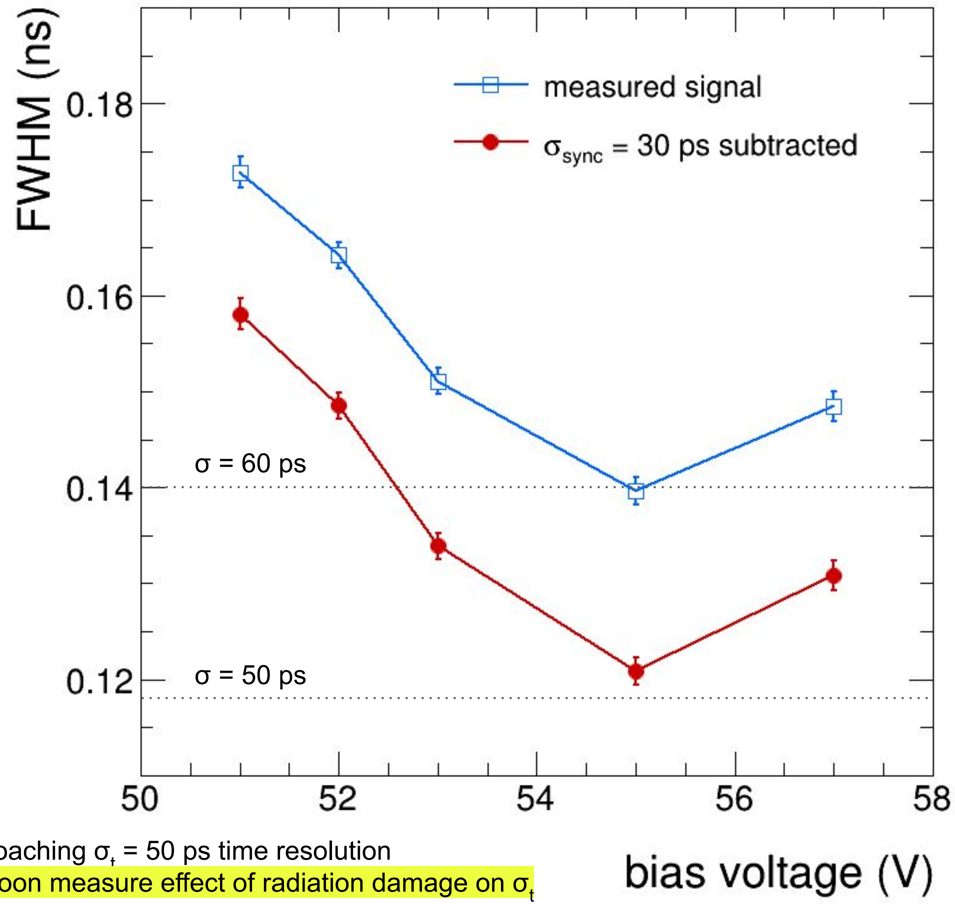
measurements performed at T = -30 C with
- Lecroy Waverunner 40186 oscilloscope
- Cividec Broadband amplifier (40 db)

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

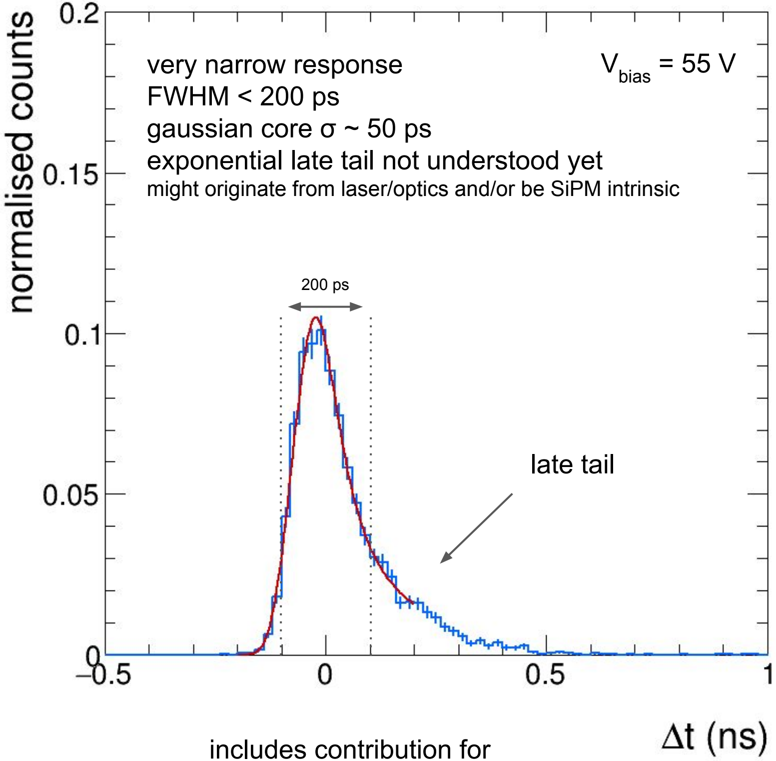
Hamamatsu S13360-3075



approaching σ_t = 50 ps time resolution

will soon measure effect of radiation damage on σ_t

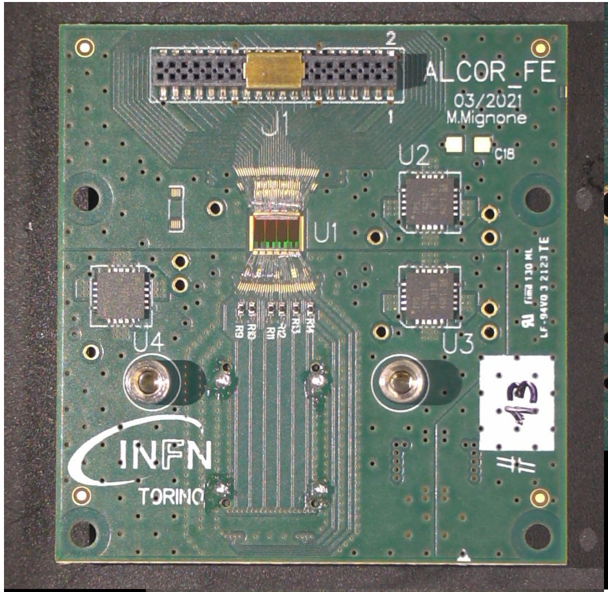
laser-SiPM correlations (time-walk corrected)

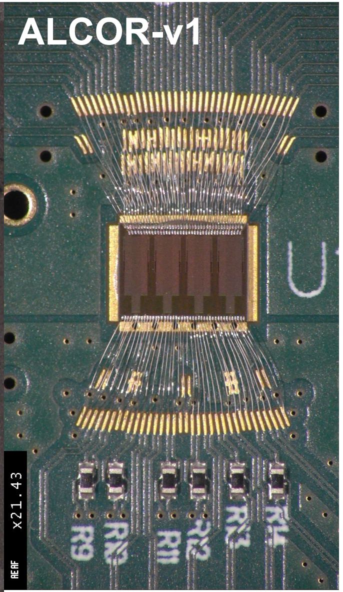


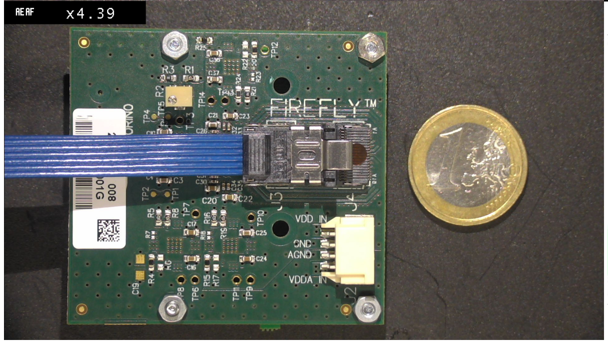
includes contribution for
laser-oscilloscope synchronization
measured to be σ_{sync} = 30 ps

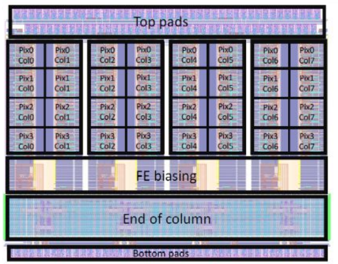
front-end electronics

ALCOR ASIC: integrated front-end and TDC









developed by INFN-TO

64-pixel matrix mixed-signal ASIC

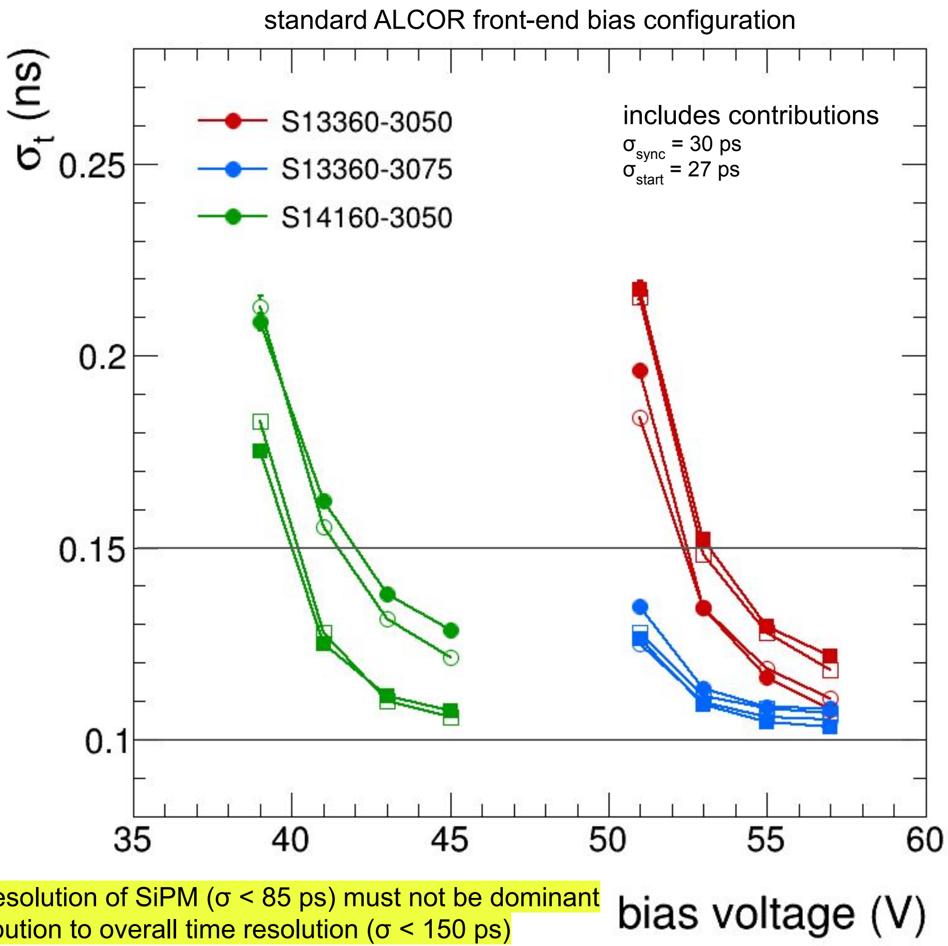
current versions (v1,v2) have 32 channels, wirebonded

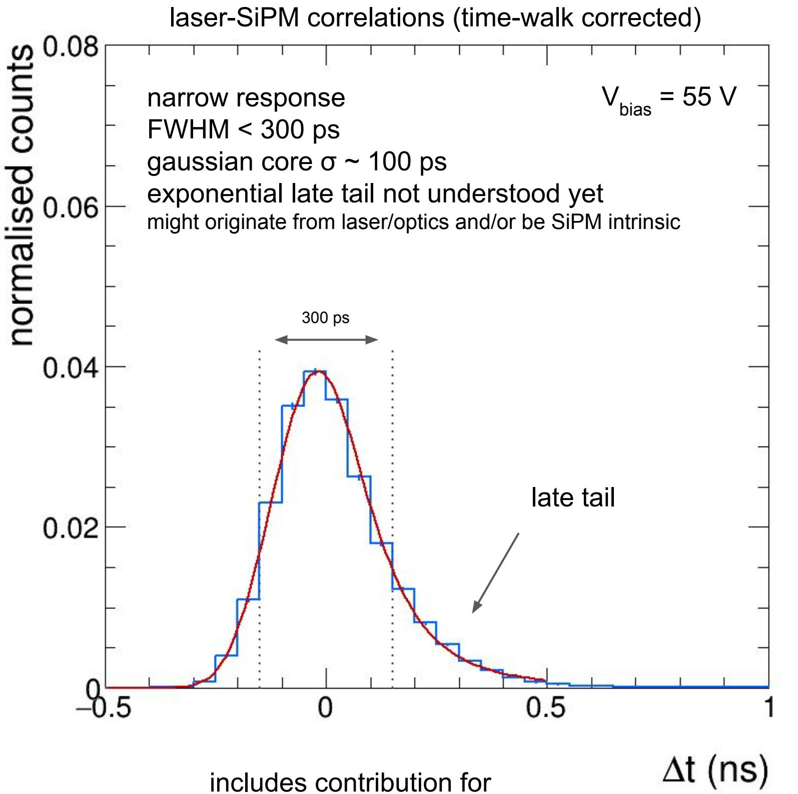
final version will have 64 channels, BGA package, 394.08 MHz clock

- **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

Timing performance measurements with ALCOR

Hamamatsu S13360-3075

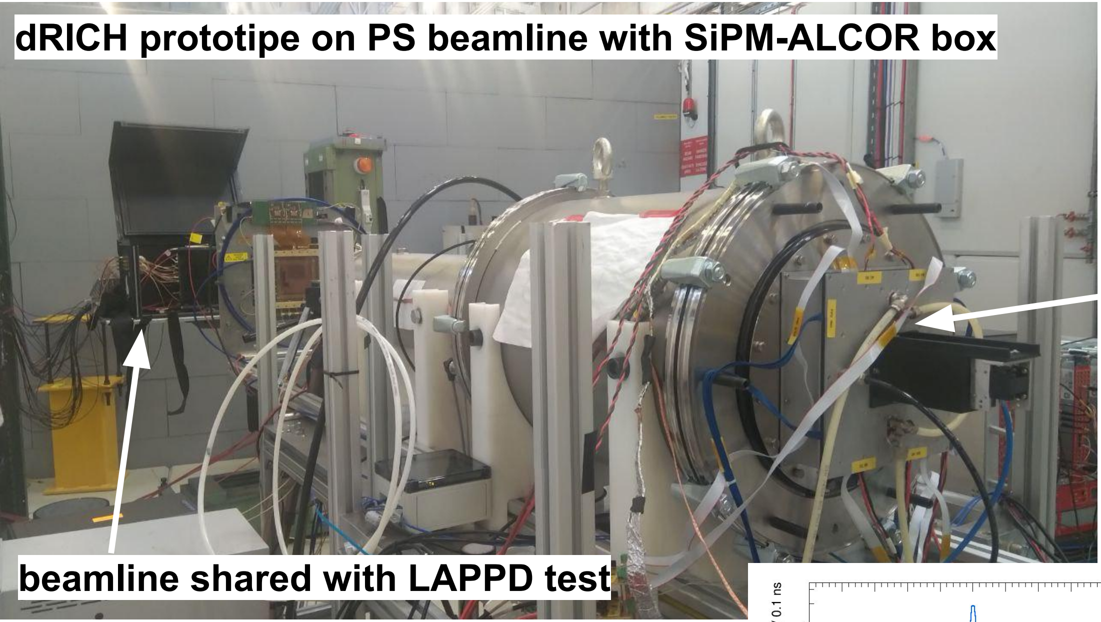


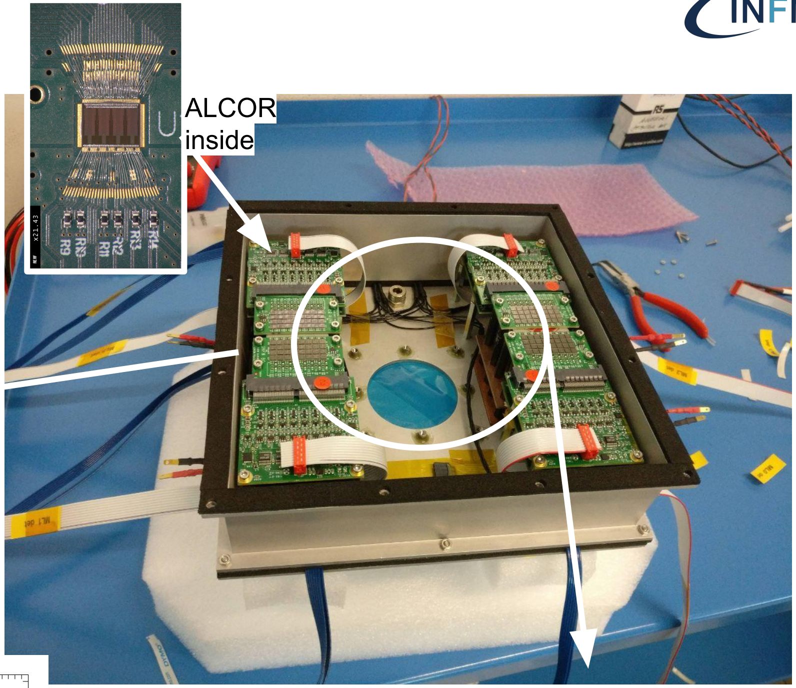


includes contribution for
laser-ALCOR synchronization
measured to be σ_{sync} = 30 ps
and reference time resolution
measured to be σ_{start} = 27 ps

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

2022 test beam at CERN-PS

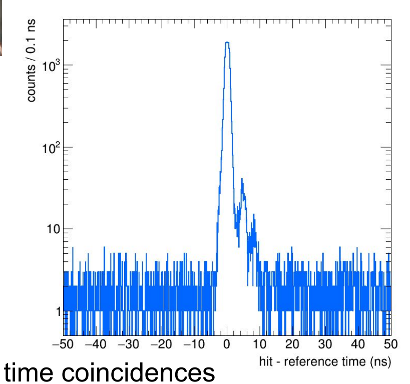




successful operation of SiPM

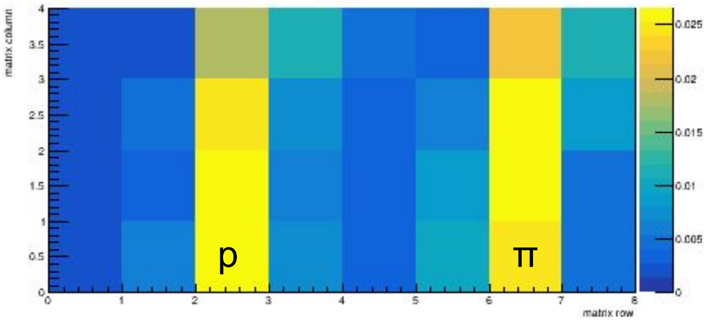
irradiated (with protons up to 10^{10})

and annealed (in oven at 150 C)

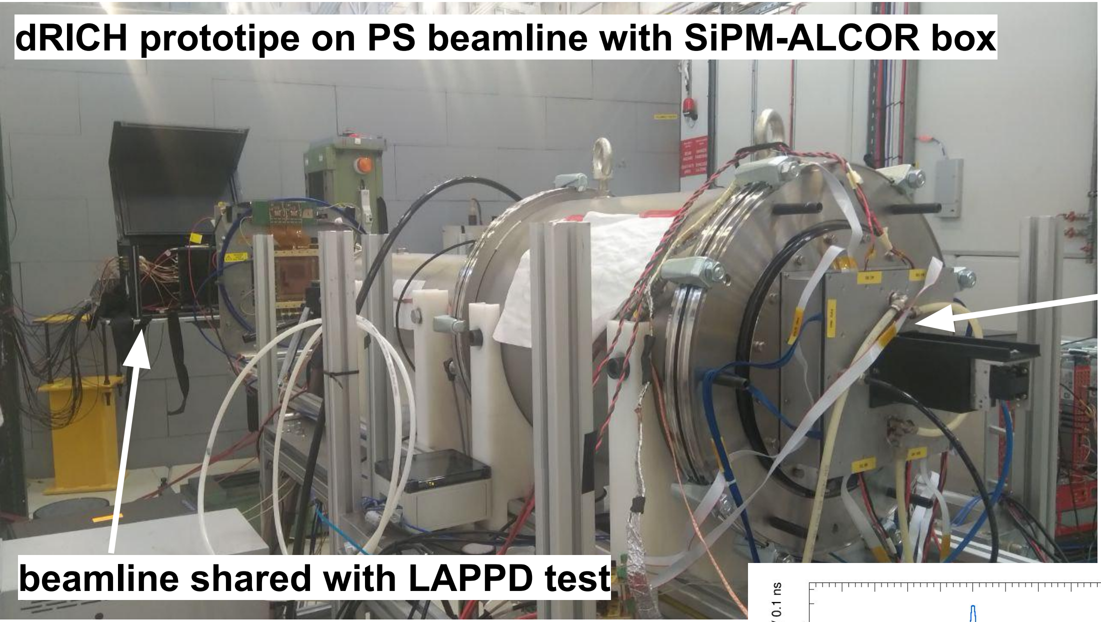


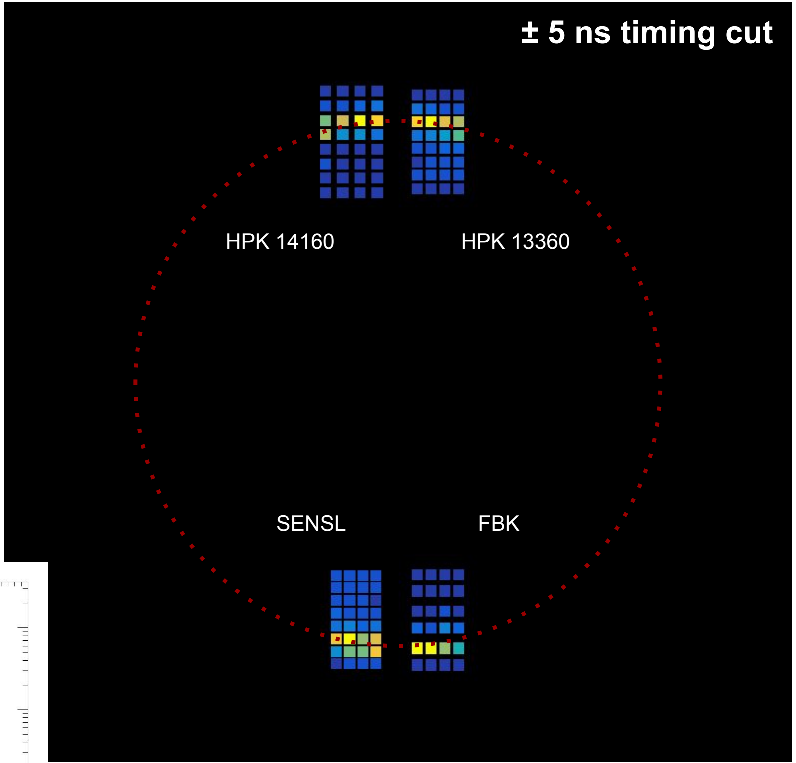
time coincidences

8 GeV positive beam (aerogel rings)



2022 test beam at CERN-PS



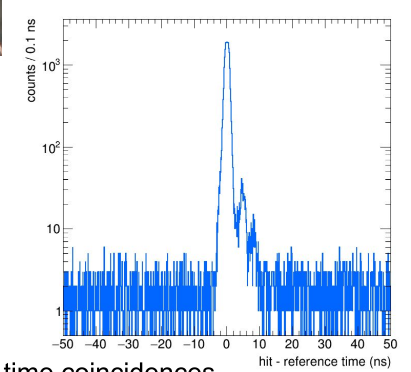


8 GeV negative beam (aerogel rings)

successful operation of SiPM

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

and annealed (in oven at 150 C)

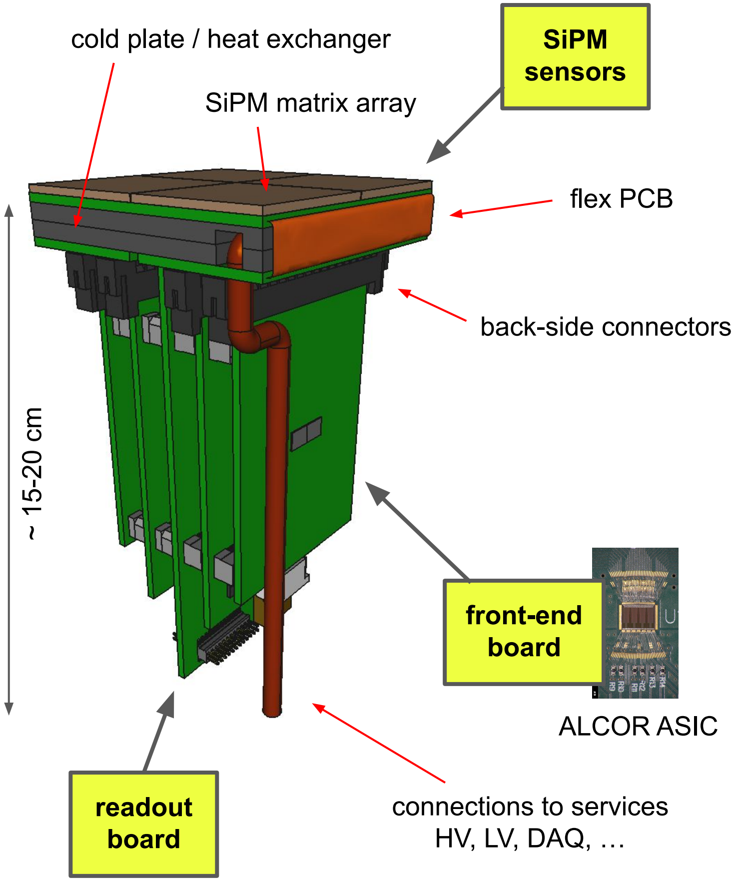


time coincidences

detector integration

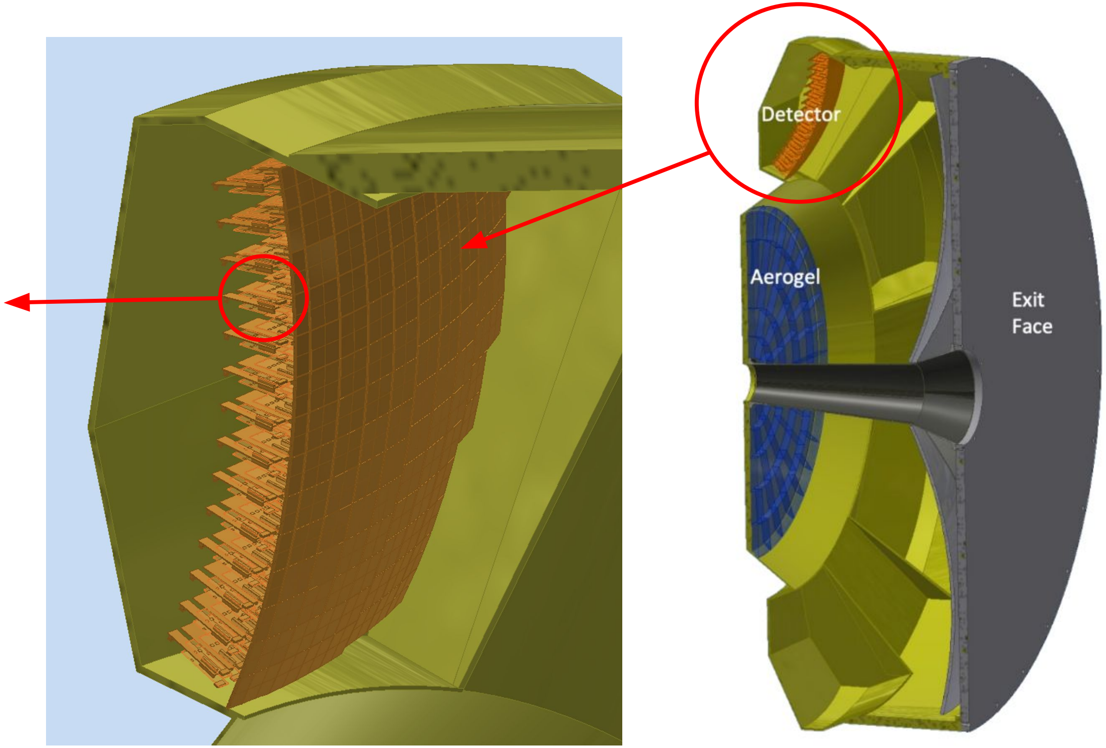
Photodetector unit

conceptual design of final layout

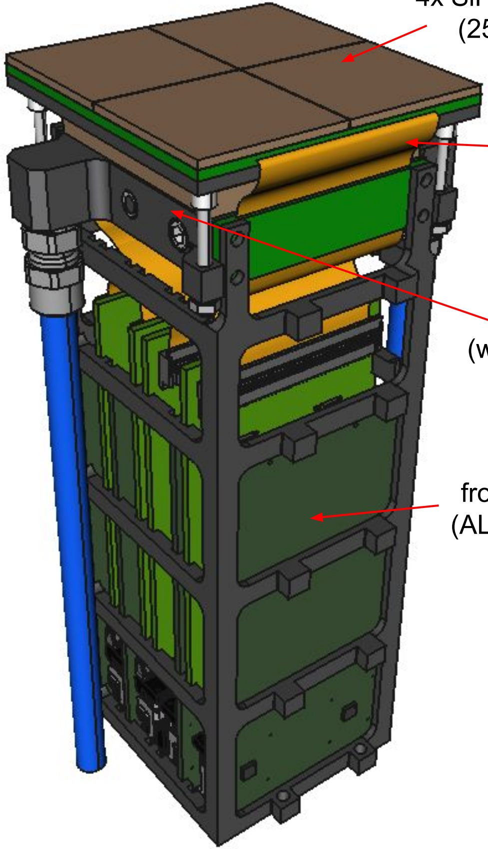


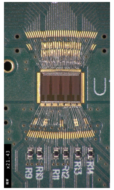
SiPM sensor matrices mounted on carrier PCB board

- 4x 64-channel SiPM array device (256 channels) for each unit
  - need modularity to realise curved readout surface
- 1248 photodetector units for full dRICH readout
  - 4992 SiPM matrix arrays (8x8)
  - 319488 readout channels

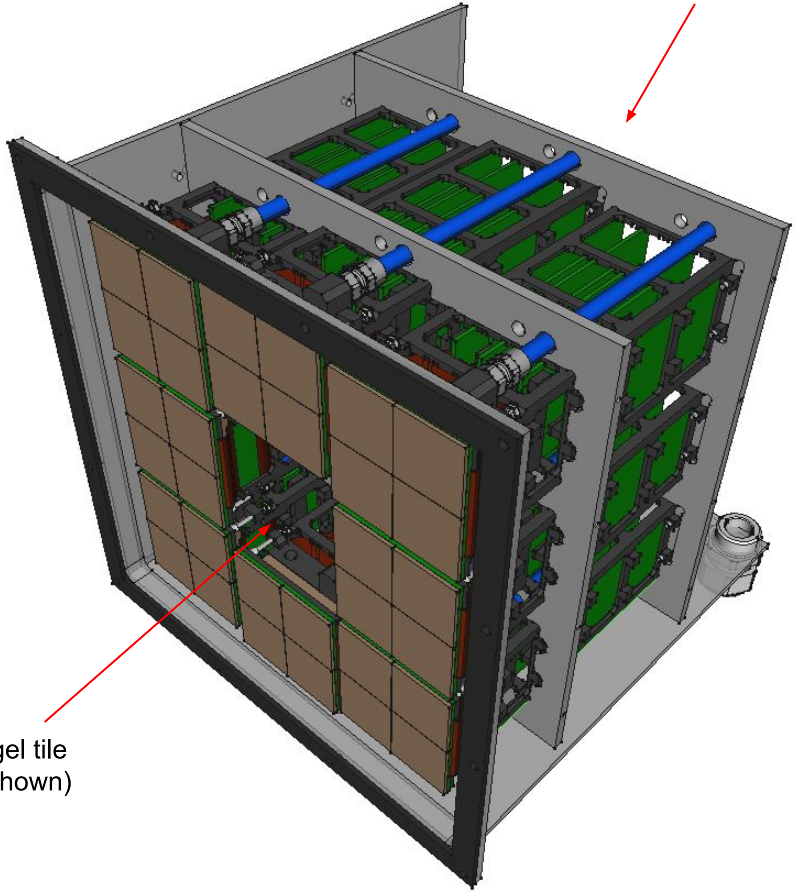


EIC ePIC-dRICH SiPM photodetector prototype





PhotoDetector Unit (PDU)

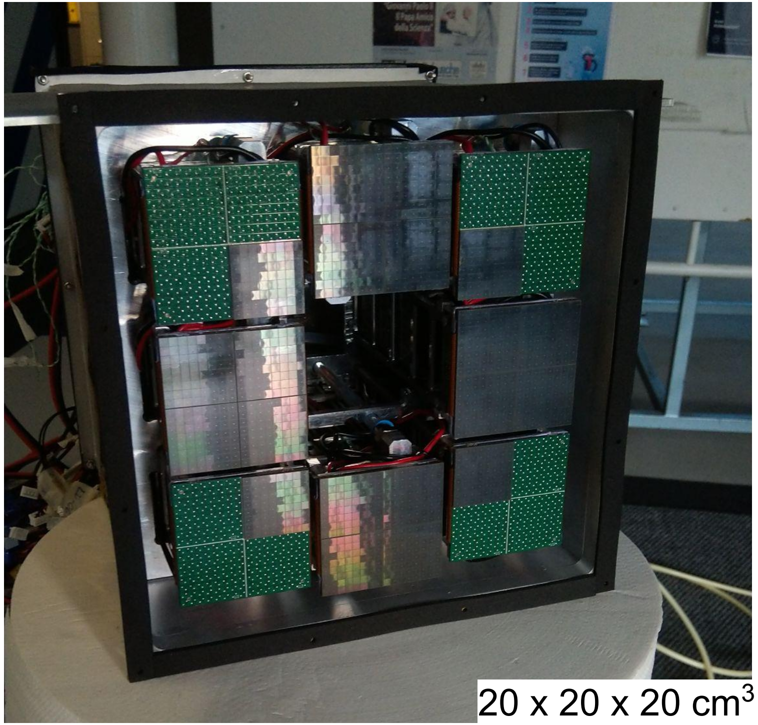


Readout Box

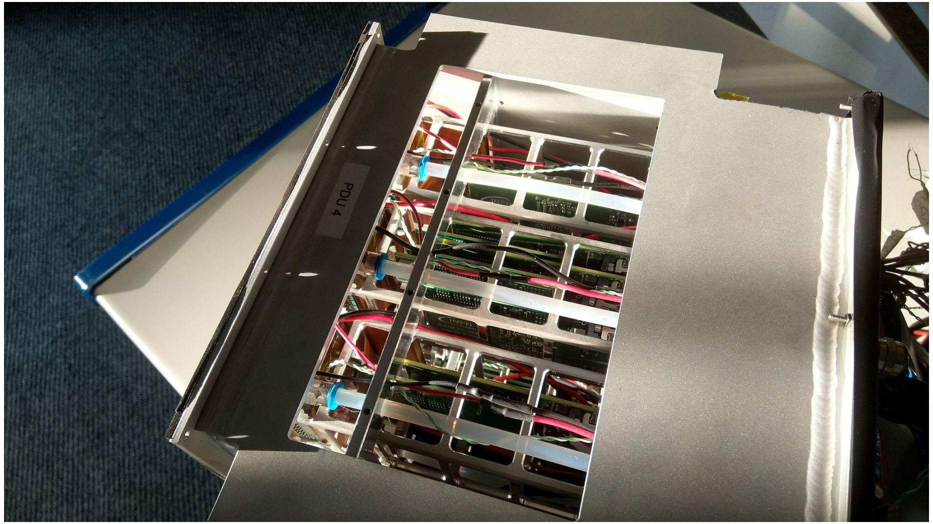
EIC ePIC-dRICH SiPM photodetector prototype

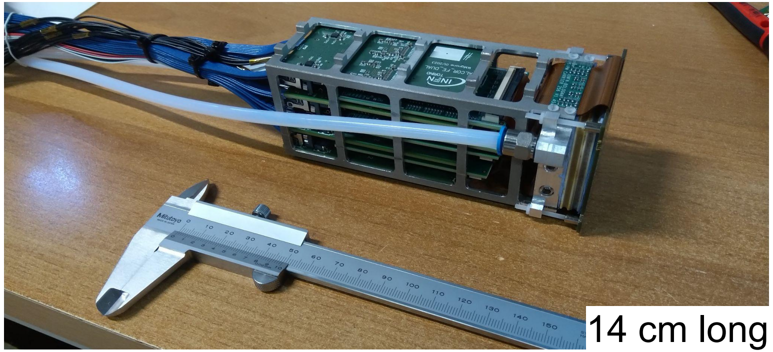
Readout Box (top)

Readout Box (front)



20 x 20 x 20 cm^3





PDU

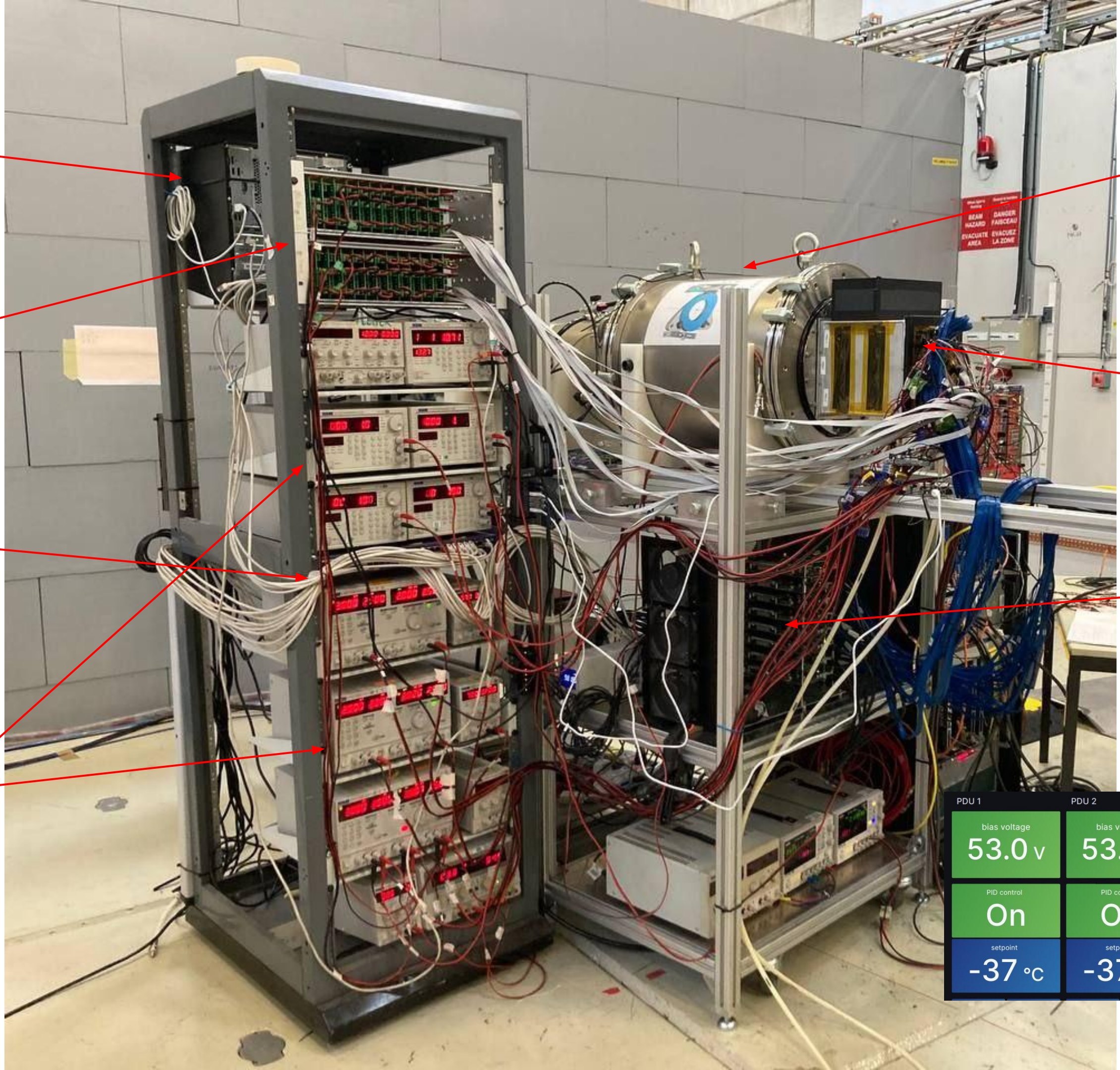
14 cm long

DAQ and DCS computers

auxiliary control electronics crates

gigabit ETH switch for DAQ and DCS

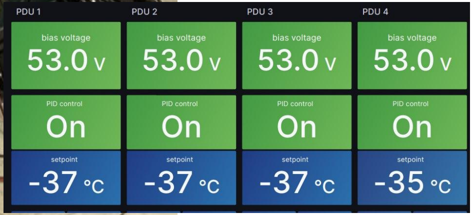
low voltage and high voltage power supplies



dRICH prototype

SiPM photodetector readout box

DAQ FPGAs and clock distribution



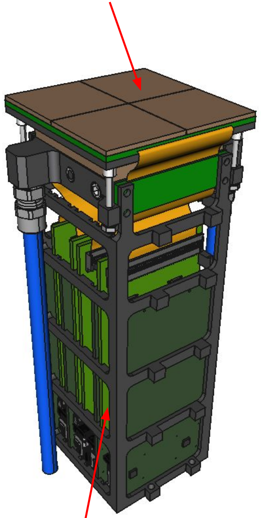
SiPM at low temperature

2023 test beam at CERN-PS

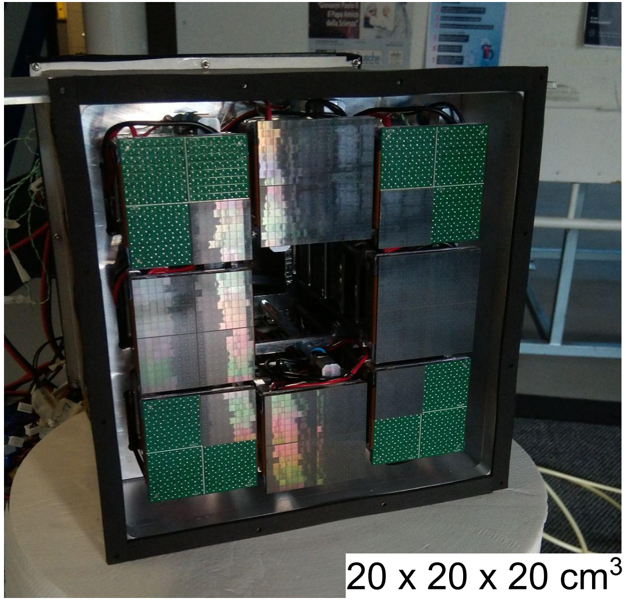
successful beam test with prototype SiPM photodetector units (CERN-PS, ended on 18th October)

PDU

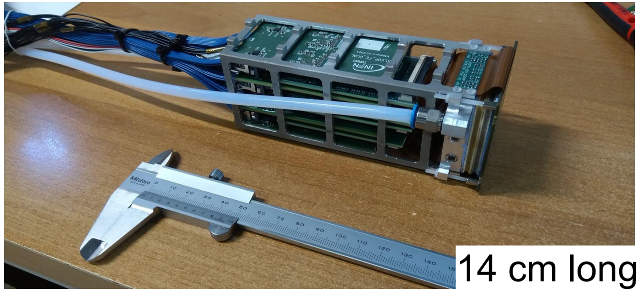
4x SiPM matrix arrays
(256 channels)



front-end electronics
(ALCOR ASIC inside)

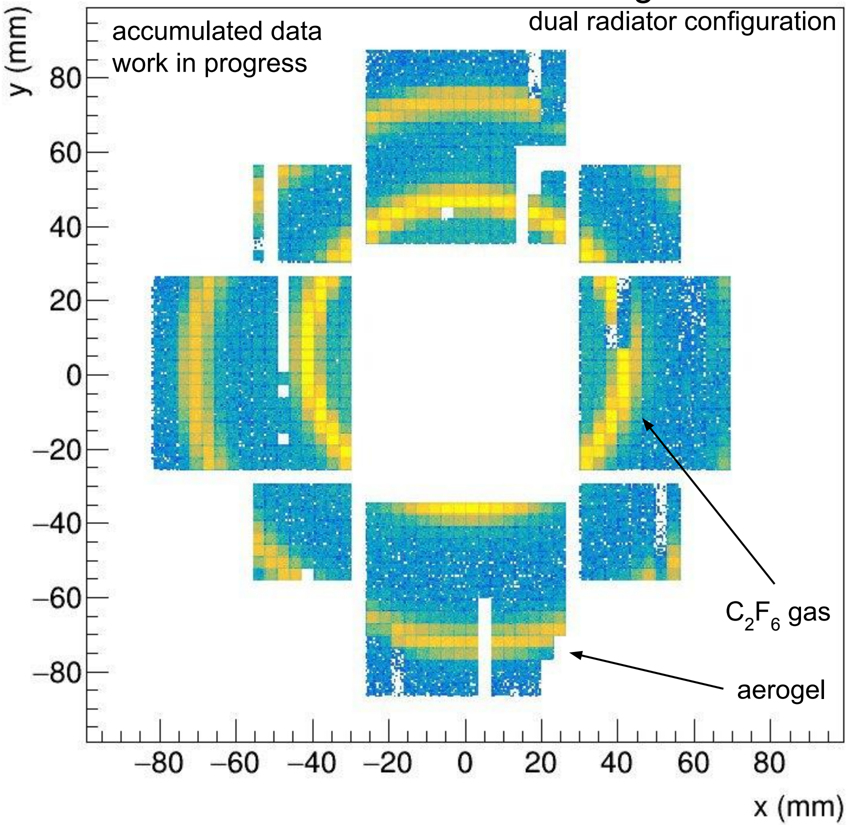


$20 \times 20 \times 20$ cm^3



14 cm long

10 GeV negative beam

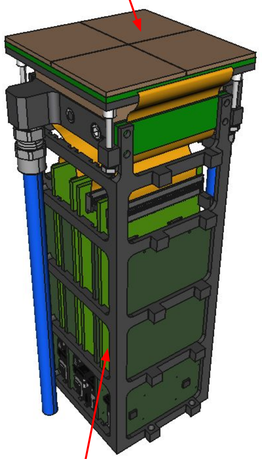


2023 test beam at CERN-PS

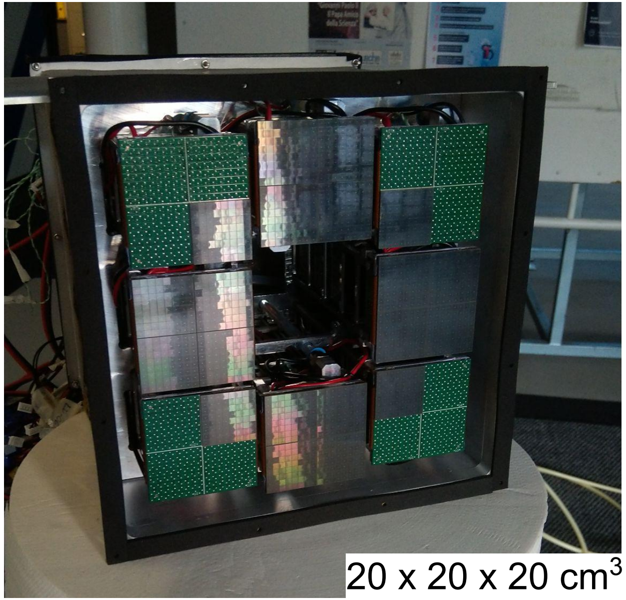
successful beam test with prototype SiPM photodetector units (CERN-PS, ended on 18th October)

PDU

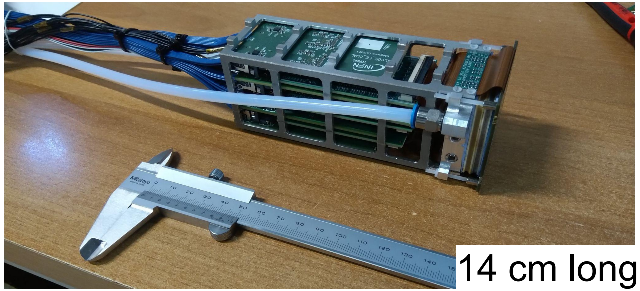
4x SiPM matrix arrays
(256 channels)



front-end electronics
(ALCOR ASIC inside)

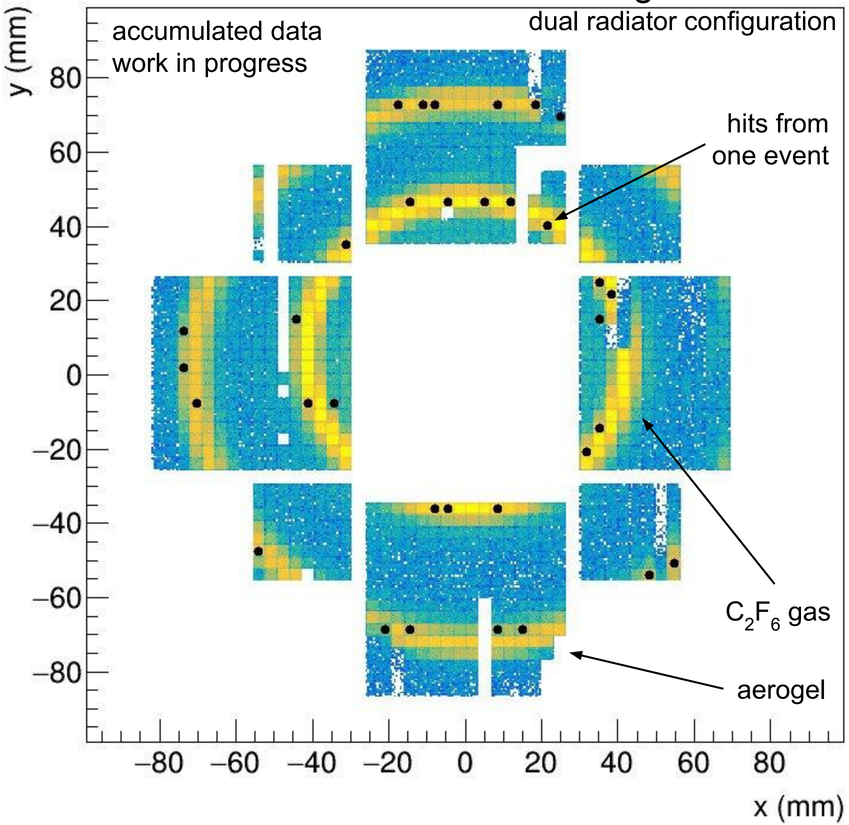


20 x 20 x 20 cm^3



14 cm long

10 GeV negative beam



Summary

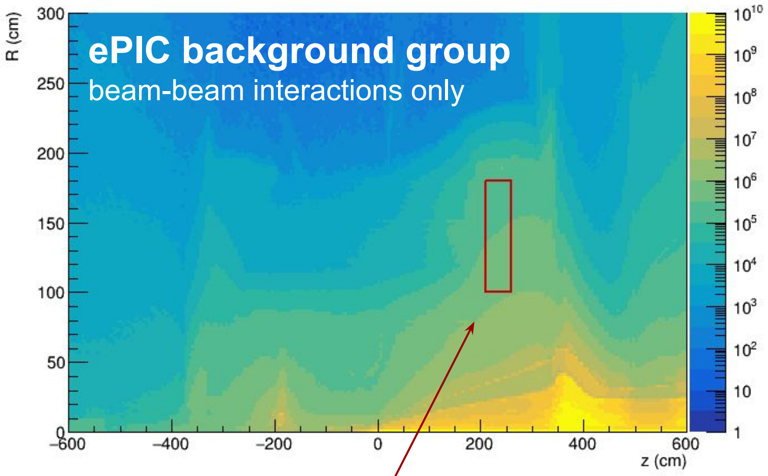
- **dRICH SiPM option fulfills dRICH requirements**
  - magnetic field limitations
  - excellent timing and efficiency
- **technical solutions to mitigate radiation damage**
  - low temperature operation
  - online “in-situ” self-annealing
  - extend lifetime of good detector performance for Physics
    - present solutions can be optimised/improved to extend it further
- **SiPM readout with full electronics chain**
  - based on ALCOR ASIC
  - successful beam test at CERN-PS in 2022 and in 2023
  - overall 1-pe time resolution approaching 100 ps
- **clear path for optimisation towards TDR**
  - good feeling on 75 μm SPAD sensors
  - new Hamamatsu prototypes and FBK developments
  - development of RDO
  - ALCOR-v3, optimisation and final packaging

END

Environment

radiation damage estimates

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



location of dRICH photosensors

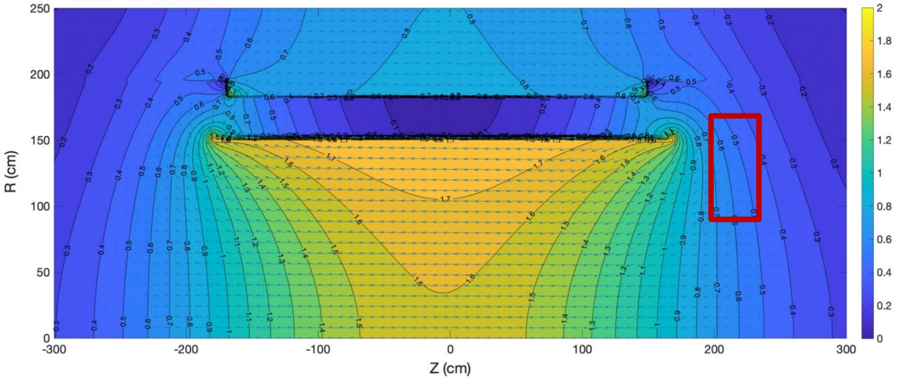
assume fluence: ~ 10^7neq / cm^2 / fb^{-1}

conservatively assume max fluence and 10x safety factor

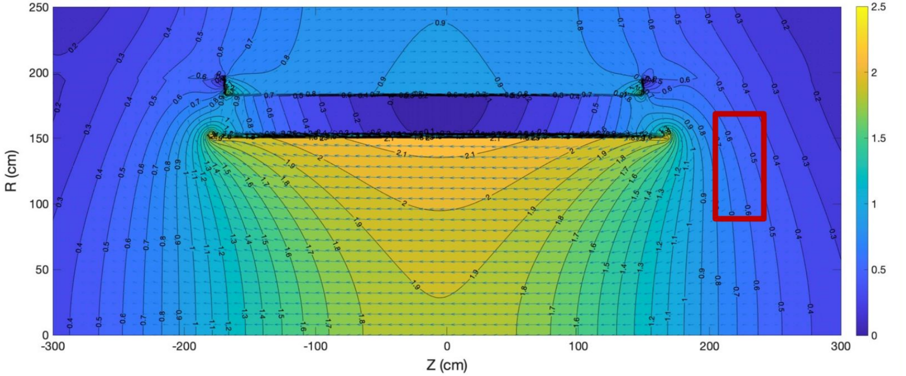
moderate radiation, 1000 fb^{-1} integrated $\mathcal{L}$ corresponds to ~ 10^{10} n_{eq}/cm^2

MARCO magnetic field maps

1.7 T field



2.0 T field



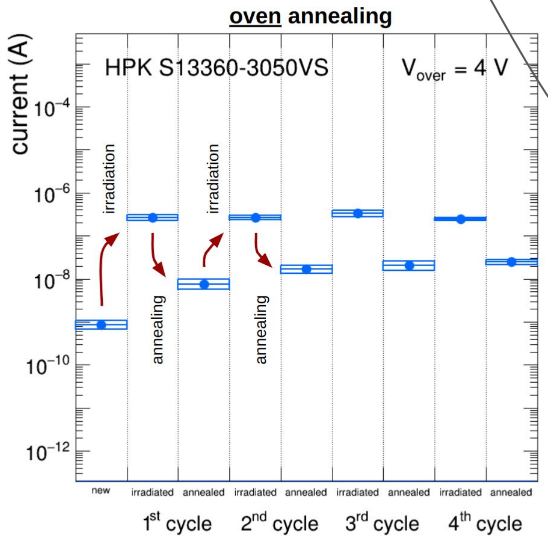
non-uniform, strong magnetic field ~ 0.7 T

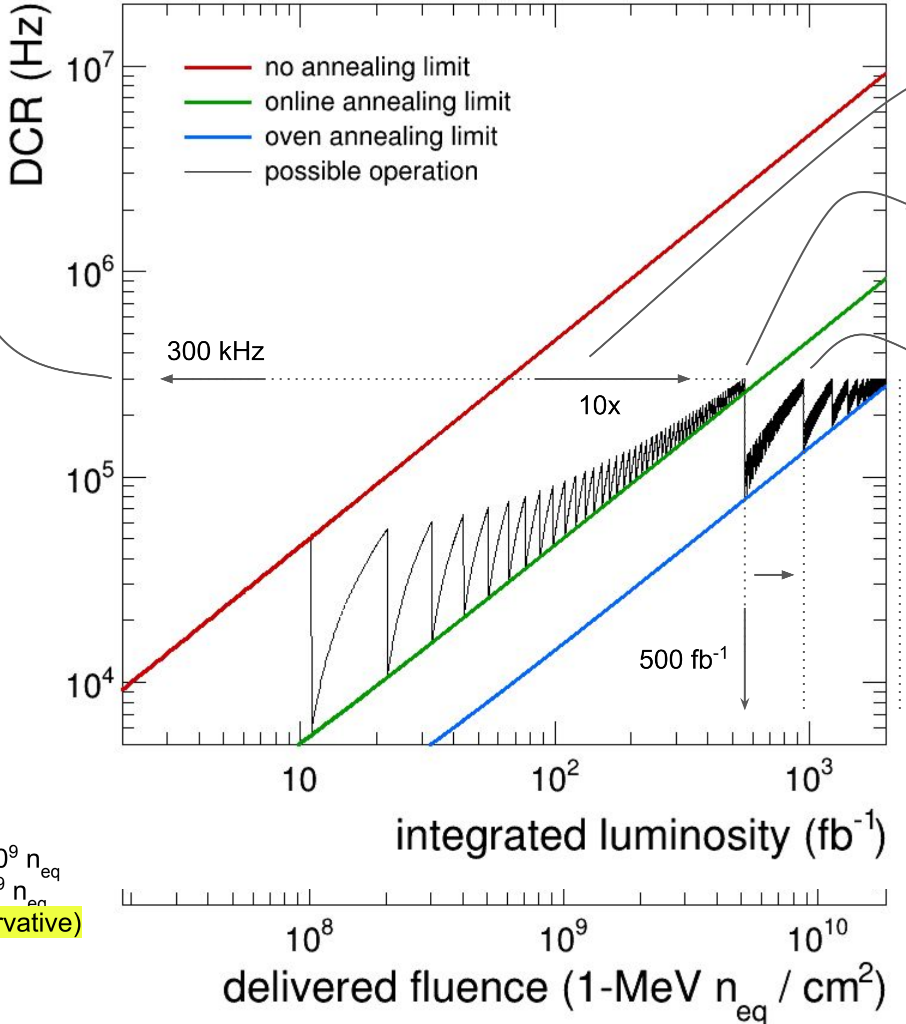
field lines ~ parallel to photodetector surface

Ageing model

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

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





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

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}

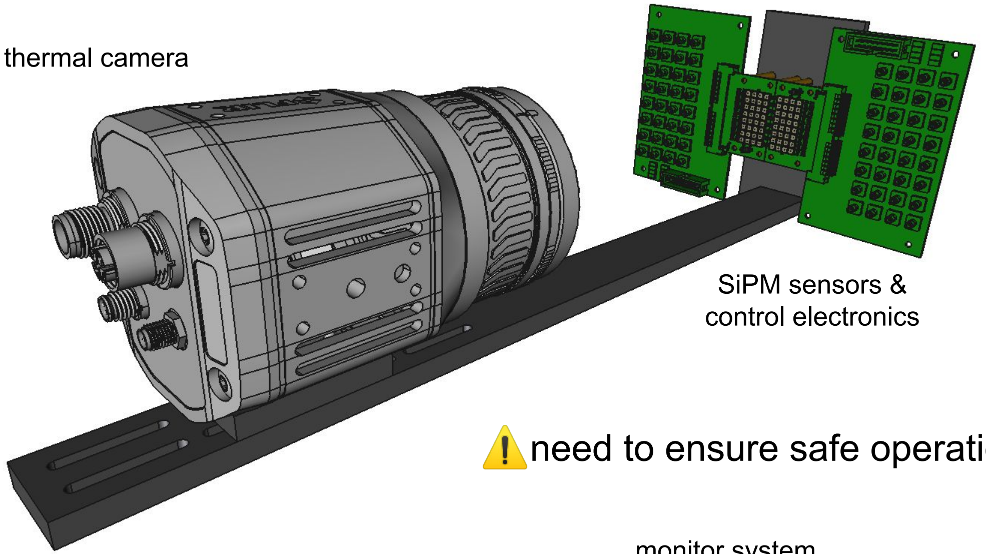
1-MeV neq fluence from background group (conservative)

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

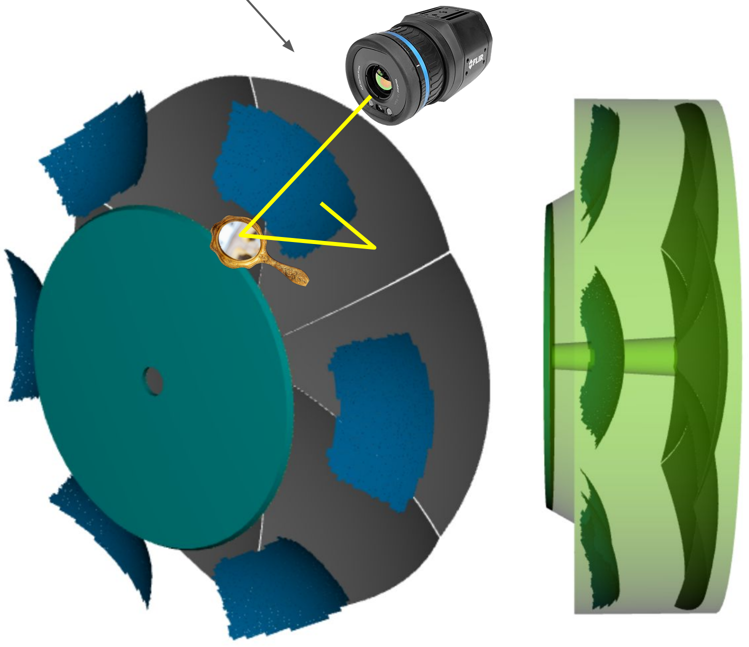
these predictions are according to present knowledge / tested solutions
there are more handles to further mitigate DCR
lower Vover, 3V
lover T operation -40 C or below

Automated multiple SiPM online self-annealing

demonstrator system for online temperature monitor and control of each individual SiPM

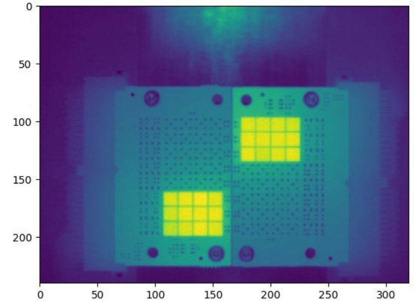


technical feasibility and implementation in the experimental environment to be studied in details

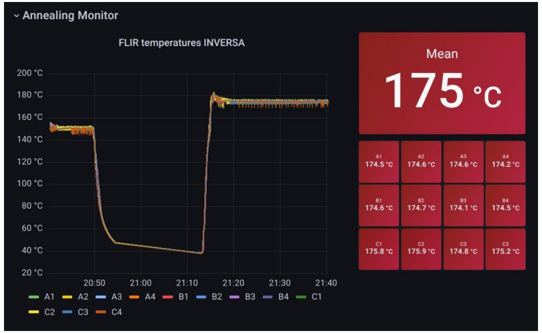


⚠️ need to ensure safe operation

thermal image



monitor system



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

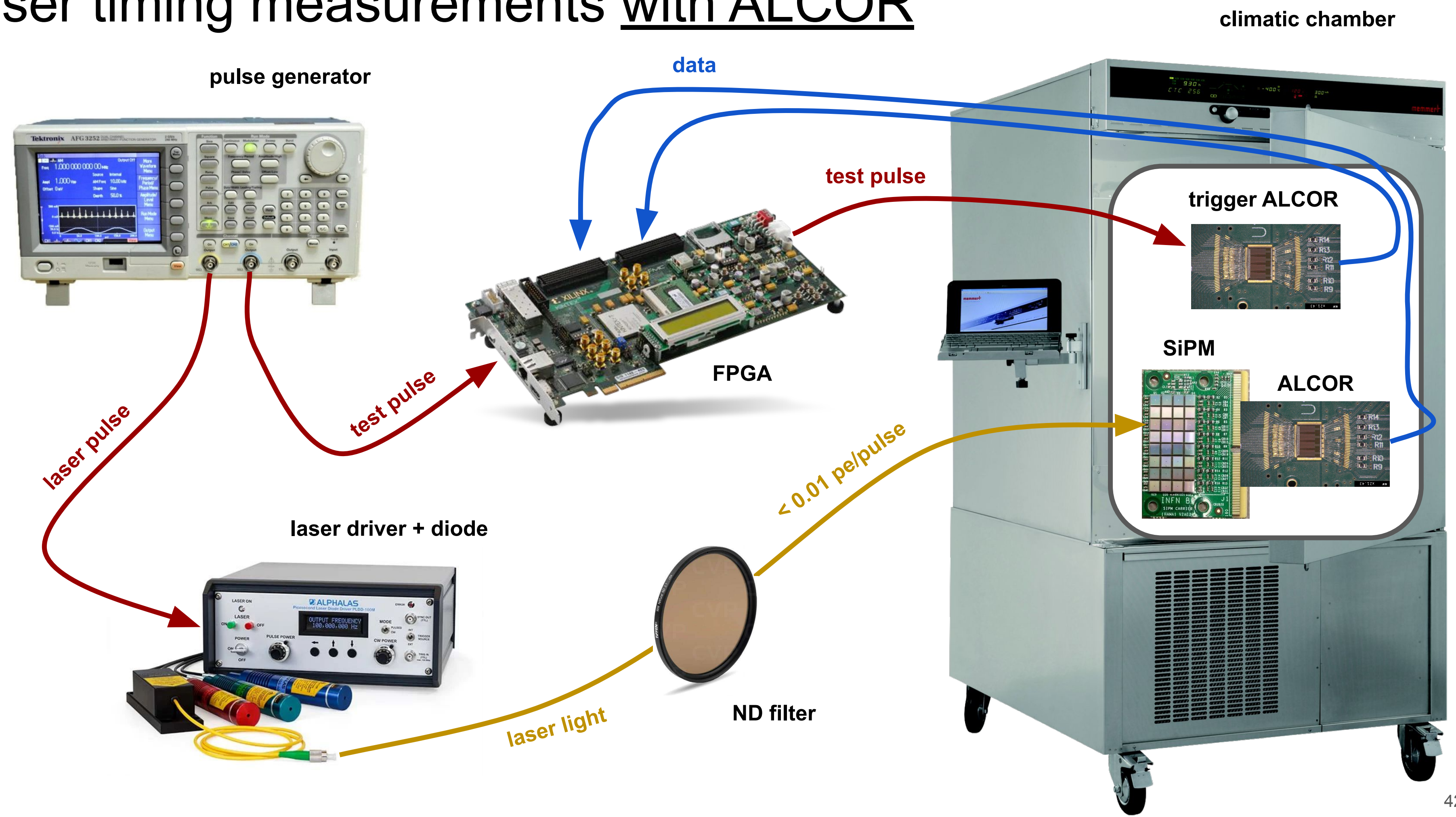
Heating / cooling capacity

Heating capacity	6 kW

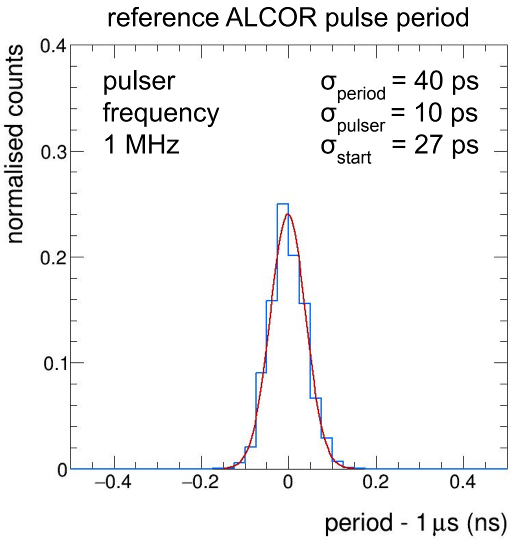
Cooling capacity

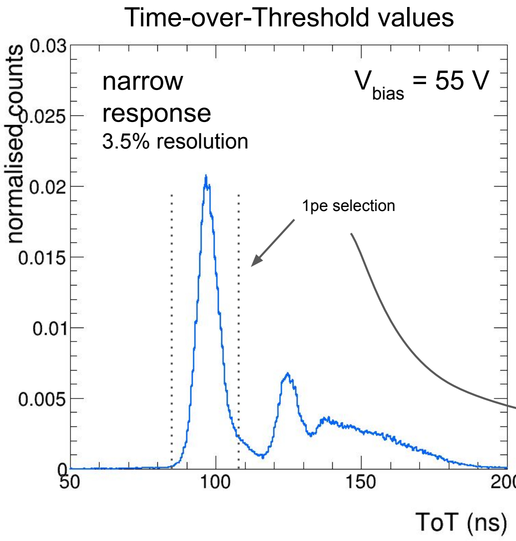
250	200	100	20	0	-20	-40	-50	°C
6	6	6	6	6	4,2	1,5	0,65	kW

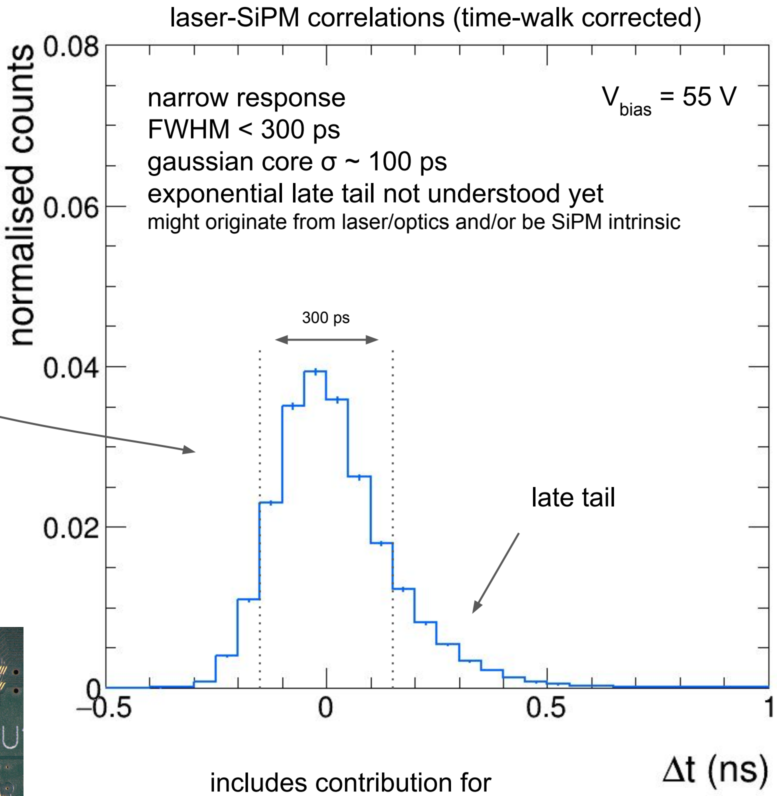
Laser timing measurements with ALCOR



Laser timing measurements with ALCOR



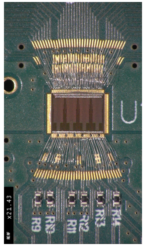




laser-SiPM signal synchronisation by sending test pulse to reference ALCOR

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

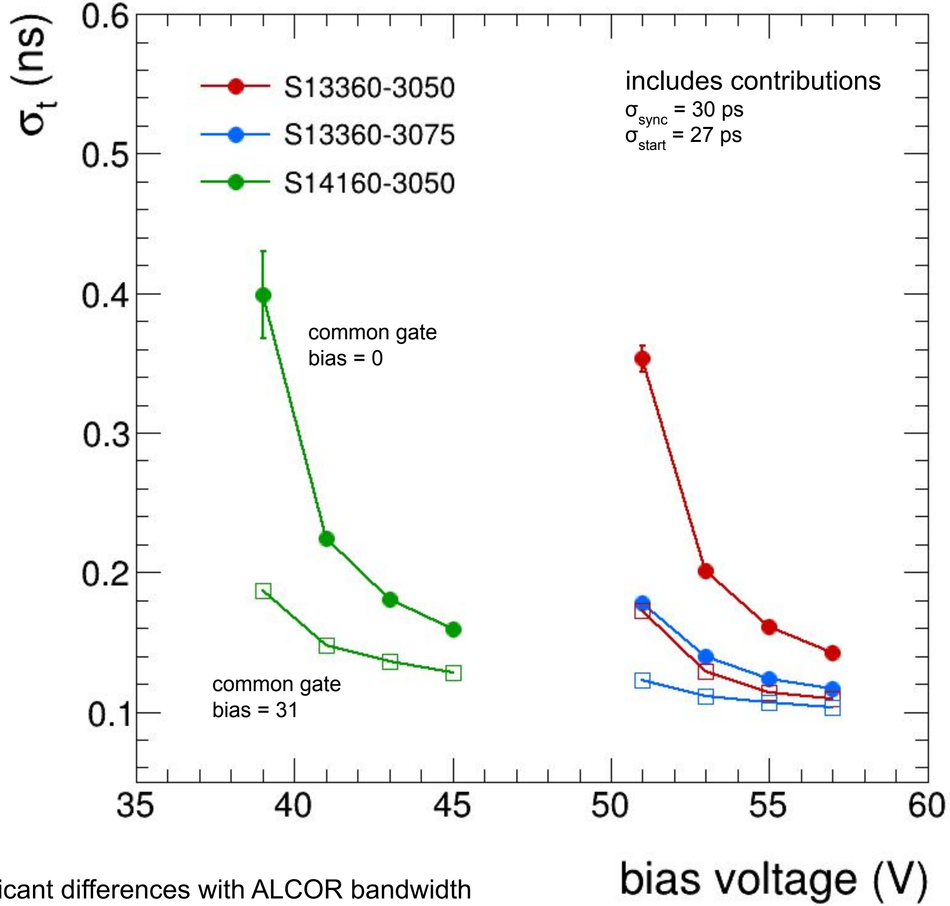
measure time coincidences Δt between reference and ALCOR reading SiPM



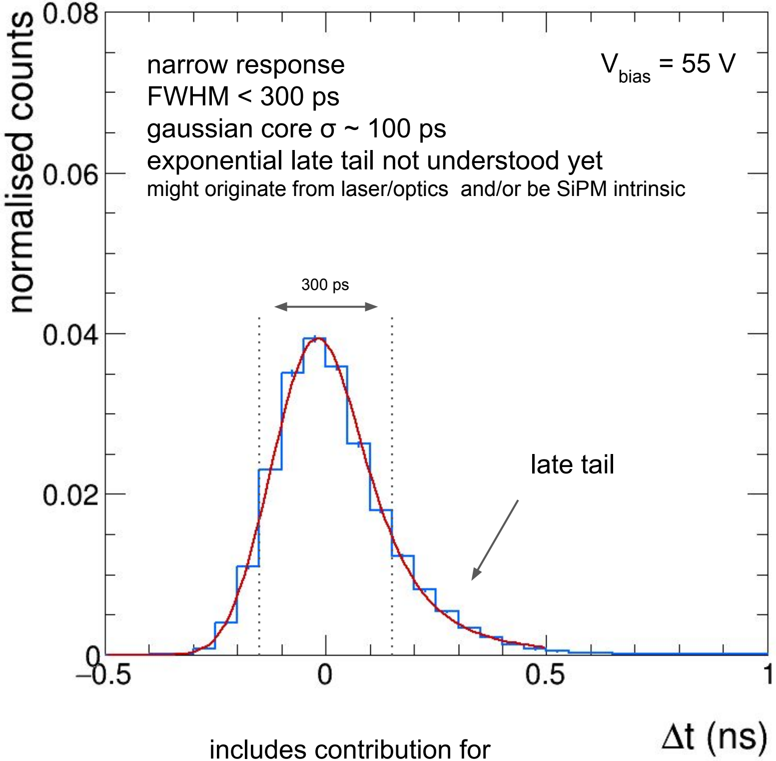
includes contribution for laser-ALCOR synchronization measured to be σ_{sync} = 30 ps and reference time resolution measured to be σ_{start} = 27 ps

Laser timing measurements with ALCOR

the two extremes of ALCOR front-end bias configuration



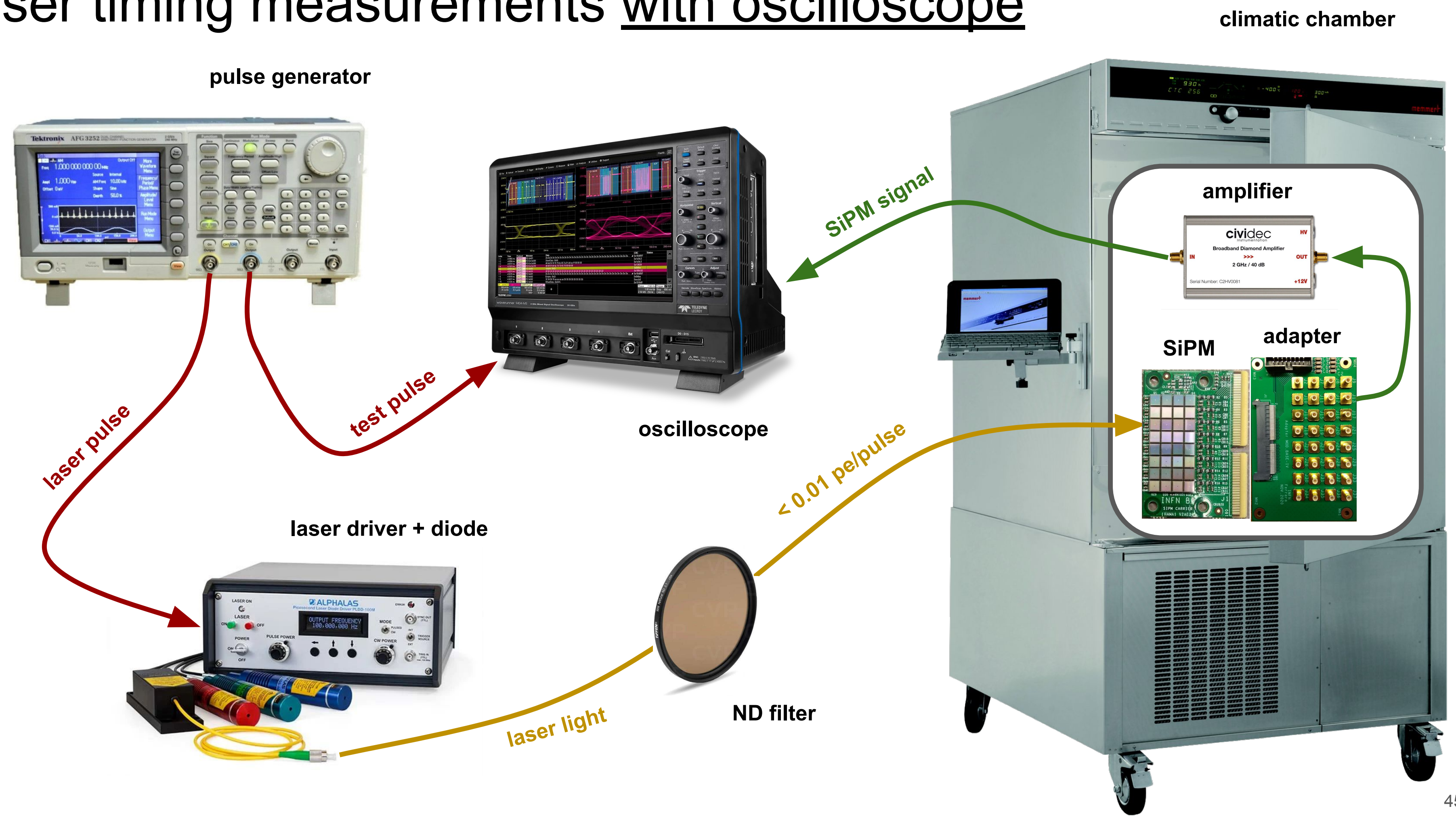
laser-SiPM correlations (time-walk corrected)



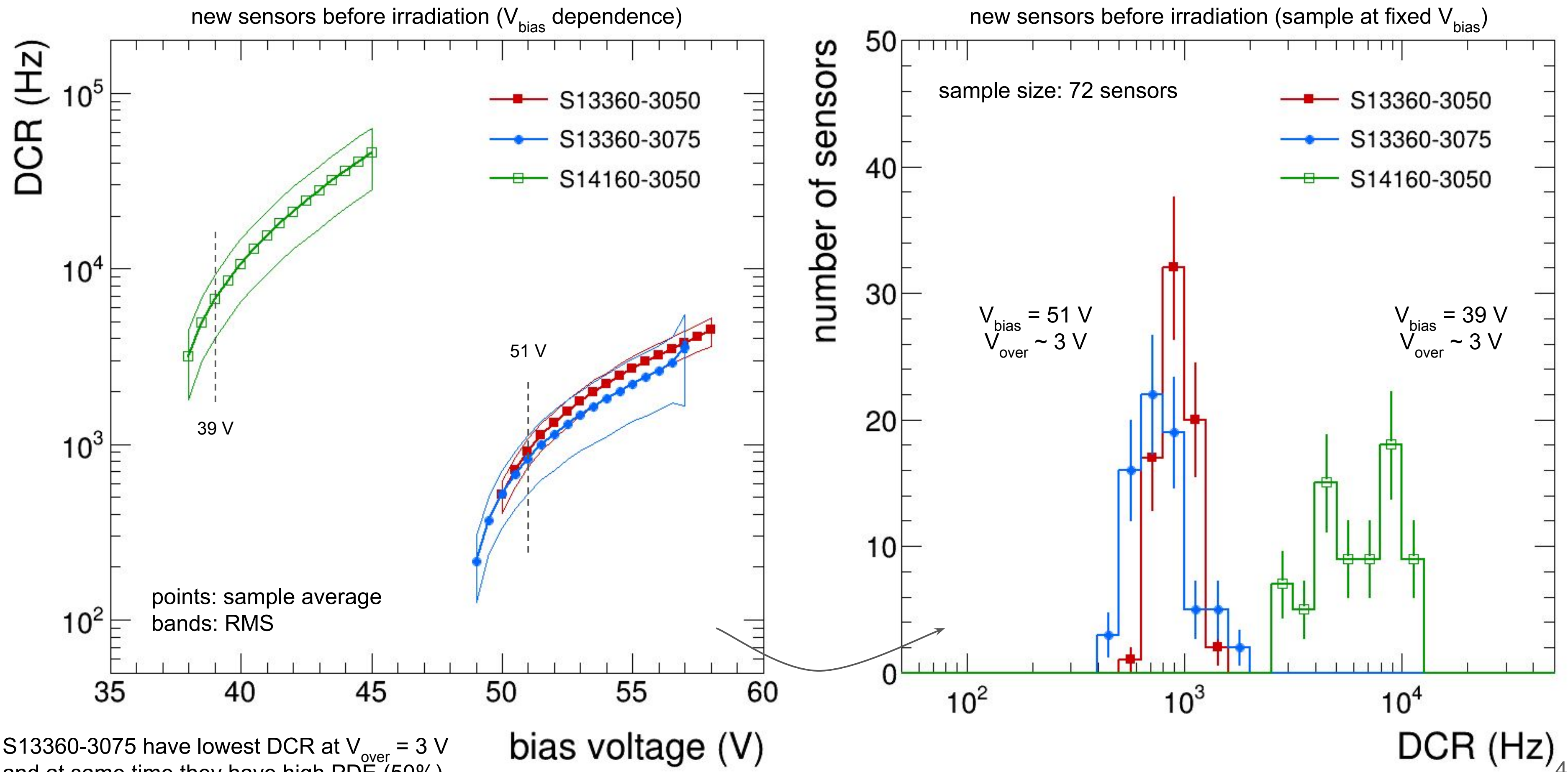
significant differences with ALCOR bandwidth

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



Characterisation of new SiPM boards



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