Photosensors and Front-End Electronics

Roberto Preghenella
INFN Bologna

preghenella@bo.infn.it

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Outline

slides for the PID review talk

1. title
2. outline
3. dual-RICH reminder with focus on photosensor surface
4. SiPM option requirements for dRICH readout and cons
5. neutron fluxes at the dRICH location in EIC
6. irradiation studies of radiation damage
7. high-temperature annealing recovery
8. online annealing
9. repeated annealing
10. radiation ageing model
11. technical solution: online annealing
12. technical solution: SiPM cooling
13. technical solution: space and readout with the photodetector unit
14. services
15. power consumption
16. ALCOR front-end ASIC
17. preliminary time resolution and overall SNR considerations
18. SiPM SPAD size
19. 75 micron SiPM sensors
20. new Hamamatsu SiPM prototypes
21. SiPM run with FBK
22. steps towards TDR

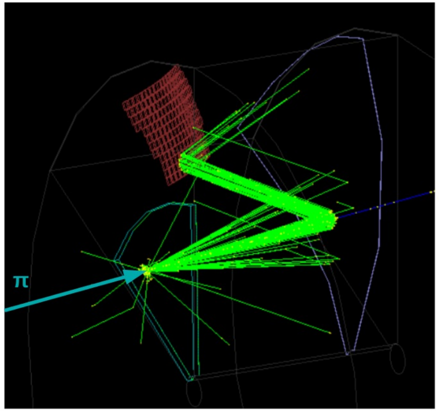
Items 3–5 → Specifications

Items 18–22 → Optimization

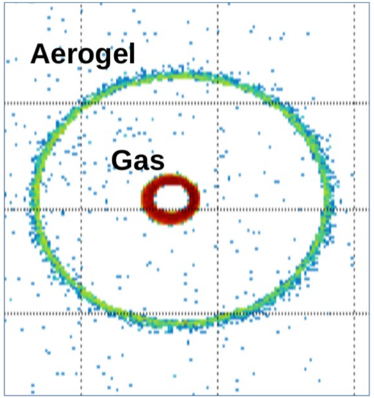
The dual-radiator (dRICH) for forward PID at EIC

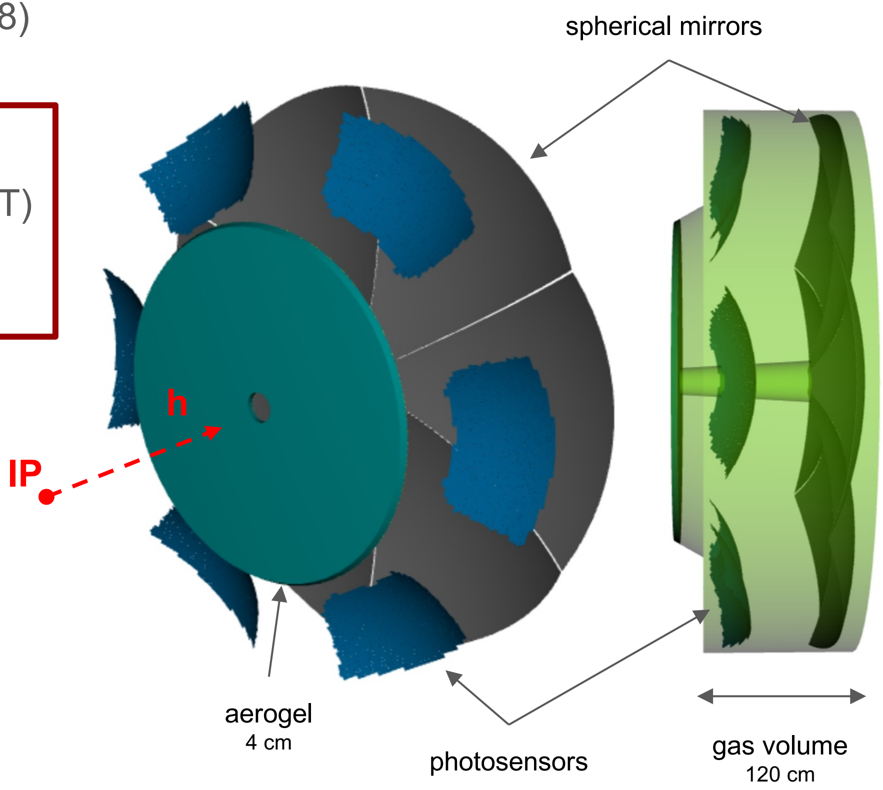
compact and cost-effective solution for broad momentum coverage at forward rapidity

- **radiators:** aerogel (n ~ 1.02) and C_2F_6 (n ~ 1.0008)
- **mirrors:** large outward-reflecting, 6 open sectors
- **sensors:** 3x3 mm² pixel, 0.5 m² / sector
  - single-photon detection inside high B field (~ 1 T)
  - outside of acceptance, reduced constraints
  - best candidate: SiPM option



example event (accumulated hits)



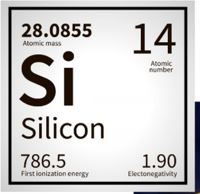


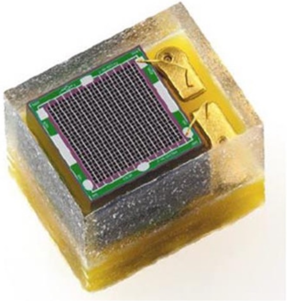
SiPM option and requirements for RICH optical readout

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

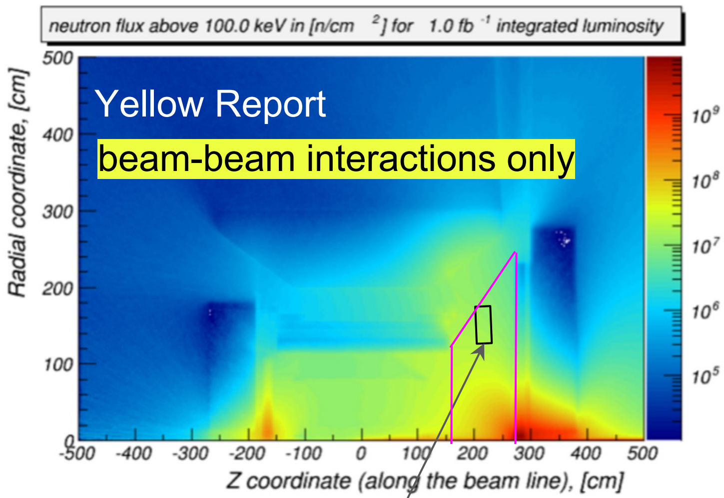
large dark count rates
not radiation tolerant

technical solutions and mitigation strategies
🐧 cooling
⏱ timing
🔥 annealing





Neutron fluxes at the dRICH location in EIC



location of dRICH photosensors
neutron fluence ~ 1-5 10^7 n / cm^2 / fb^{-1}

(> 100 keV ~ 1 MeV n_{eq})

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

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}cm^{-2} sec^{-1}.

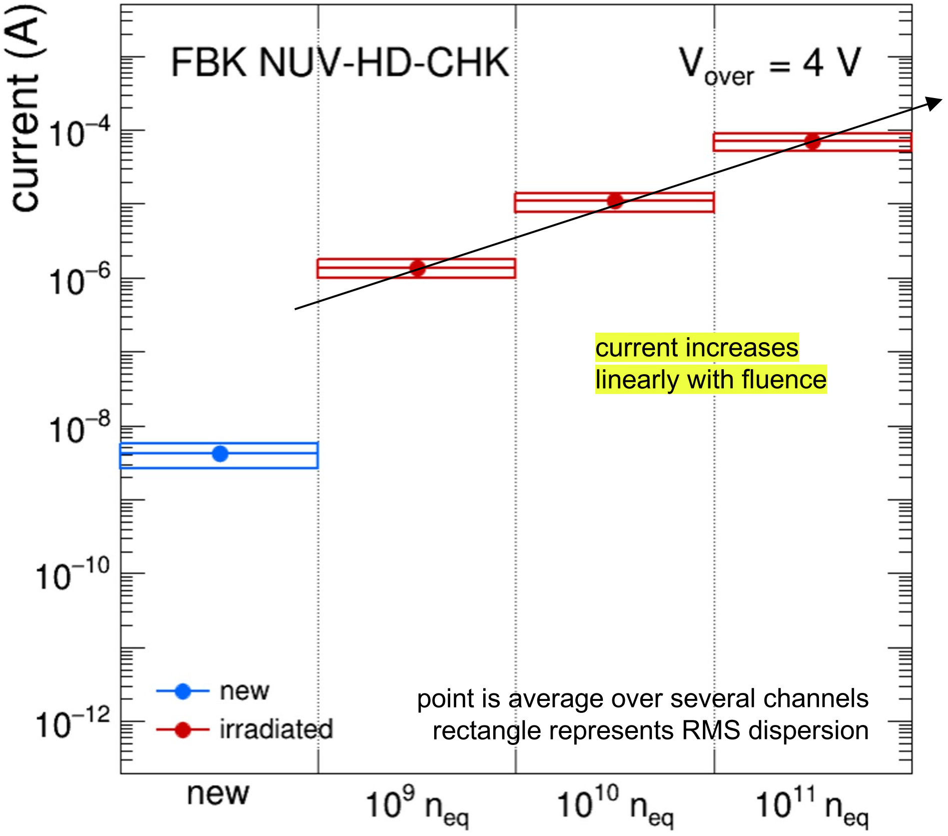
R&D on SiPM as potential photodetector for dRICH, main goal
study SiPM usability for Cherenkov up to 10^{11} 1-MeV n_{eq}/cm^2

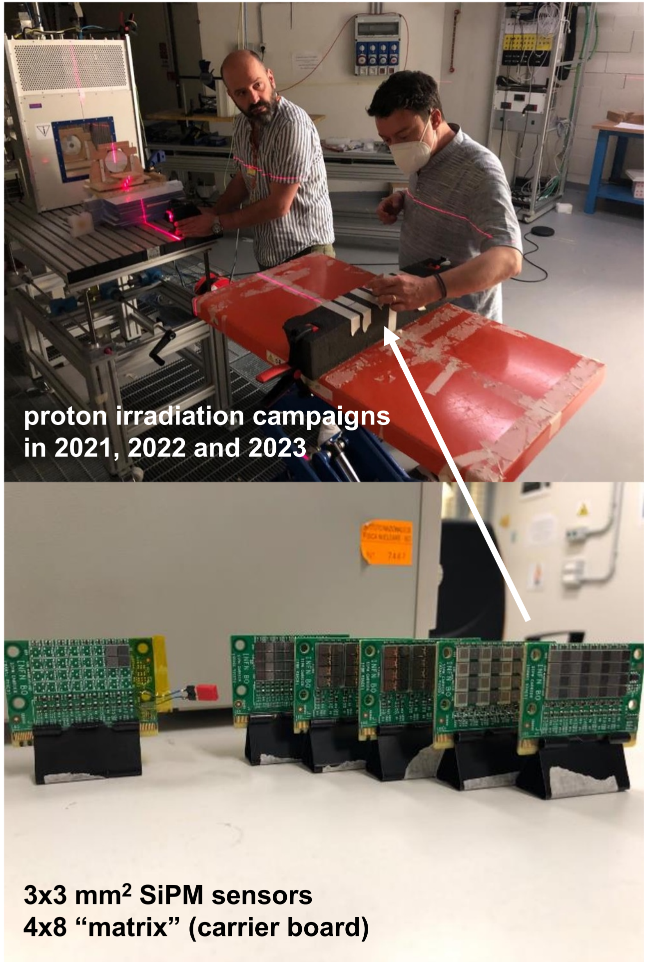
notice that 10^{11} neq/cm^2 would correspond to 2000-10000 fb^{-1} integrated $\mathcal{L}$
quite a long time of EIC running before we reach there, if ever
it would be between 6-30 years of continuous running at $\mathcal{L} = 10^{34}$ s^{-1} cm^{-2}

→ radiation damage studied in smaller steps of radiation load

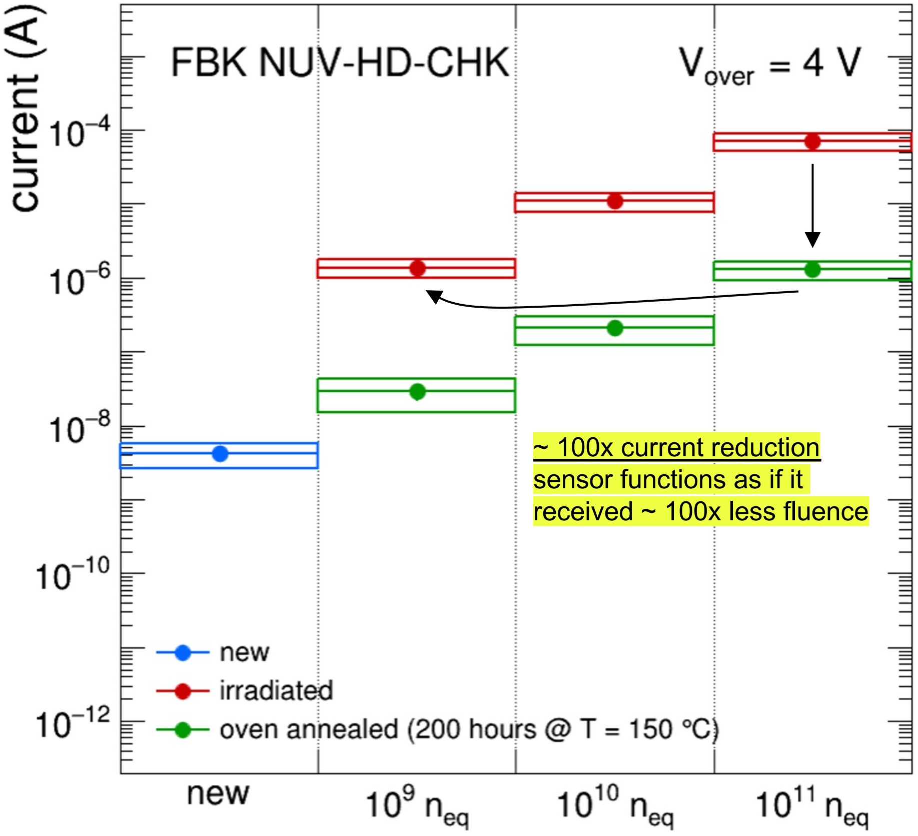
10^9 1-MeV n_{eq}/cm^2	*most of the key physics topics*
10^{10} 1-MeV n_{eq}/cm^2	*should cover most demanding measurements*
10^{11} 1-MeV n_{eq}/cm^2	*possibly never reached*

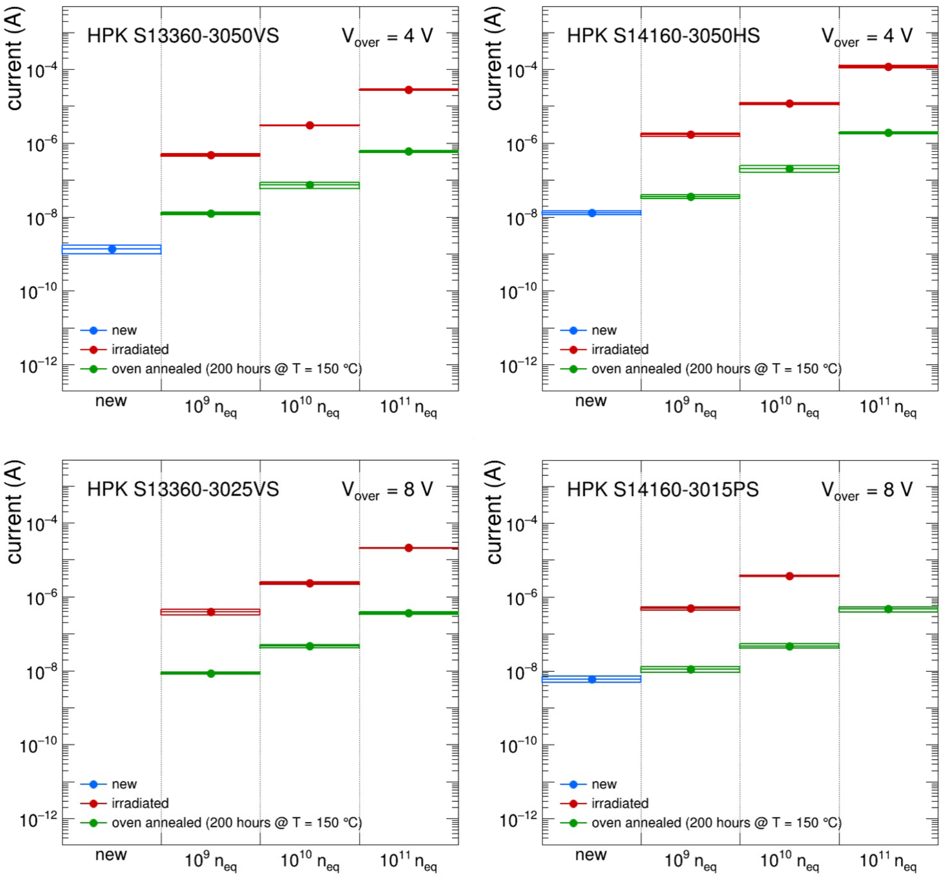
Studies of radiation damage on SiPM





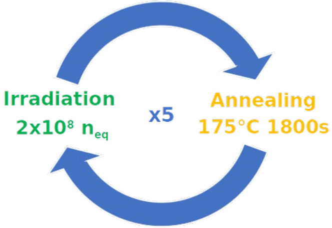
High-temperature annealing recovery

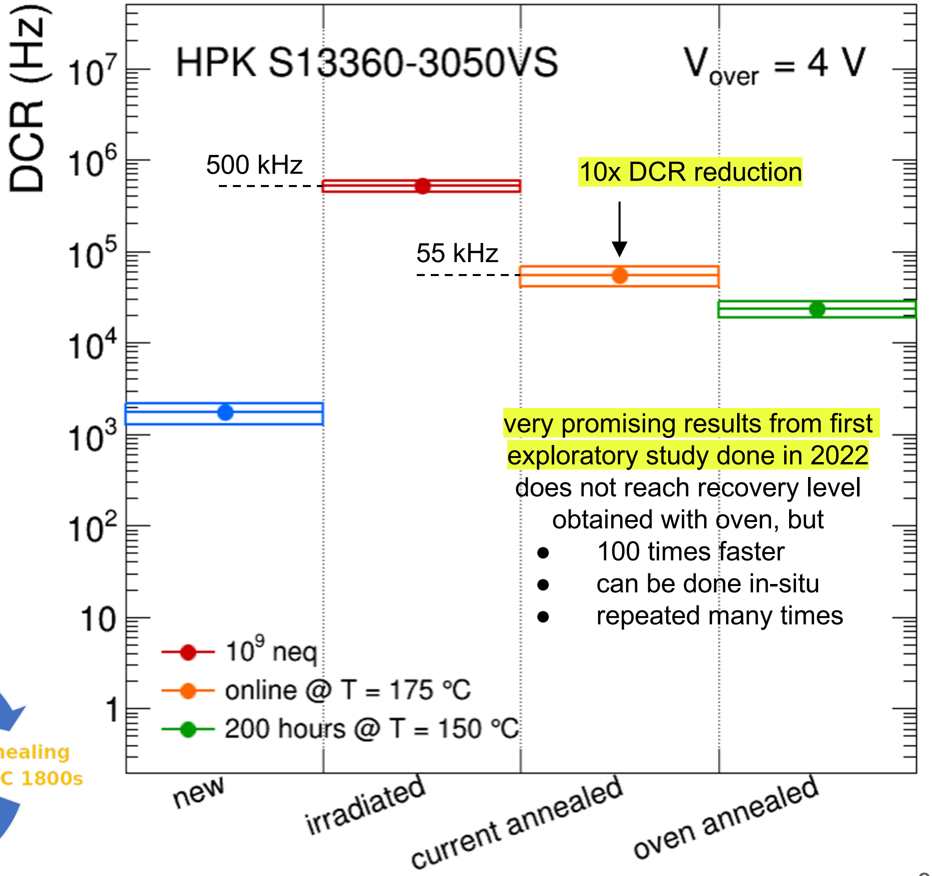




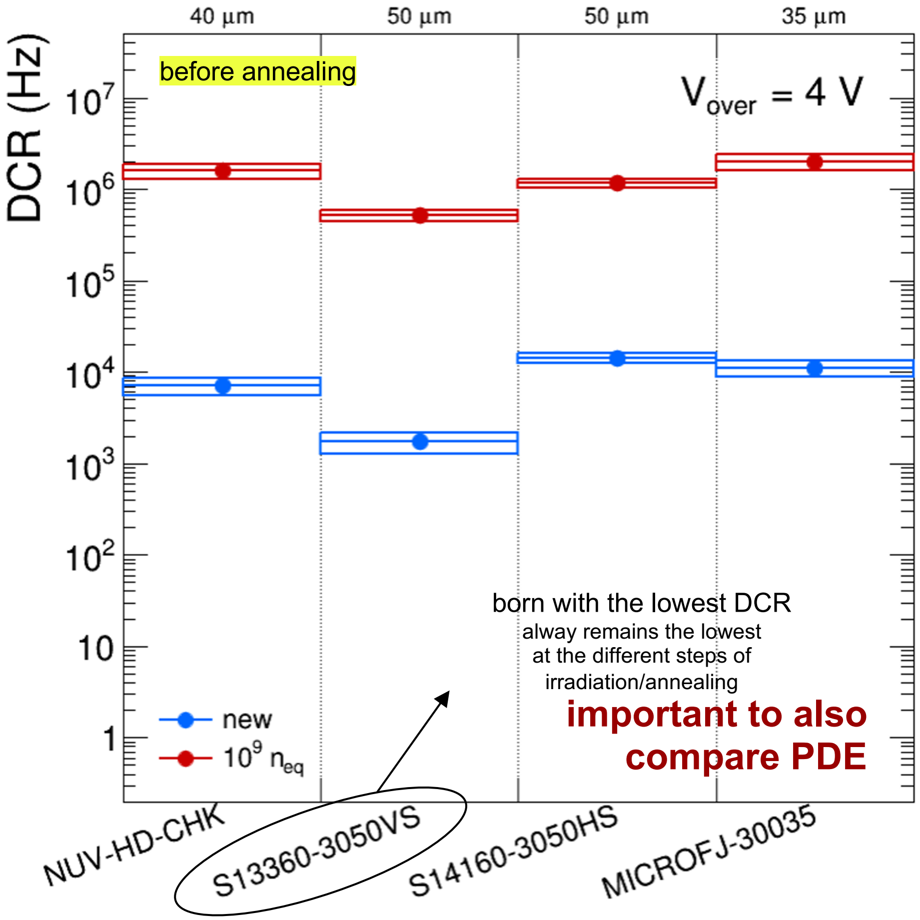
similar observation with various types of Hamamatsu sensors

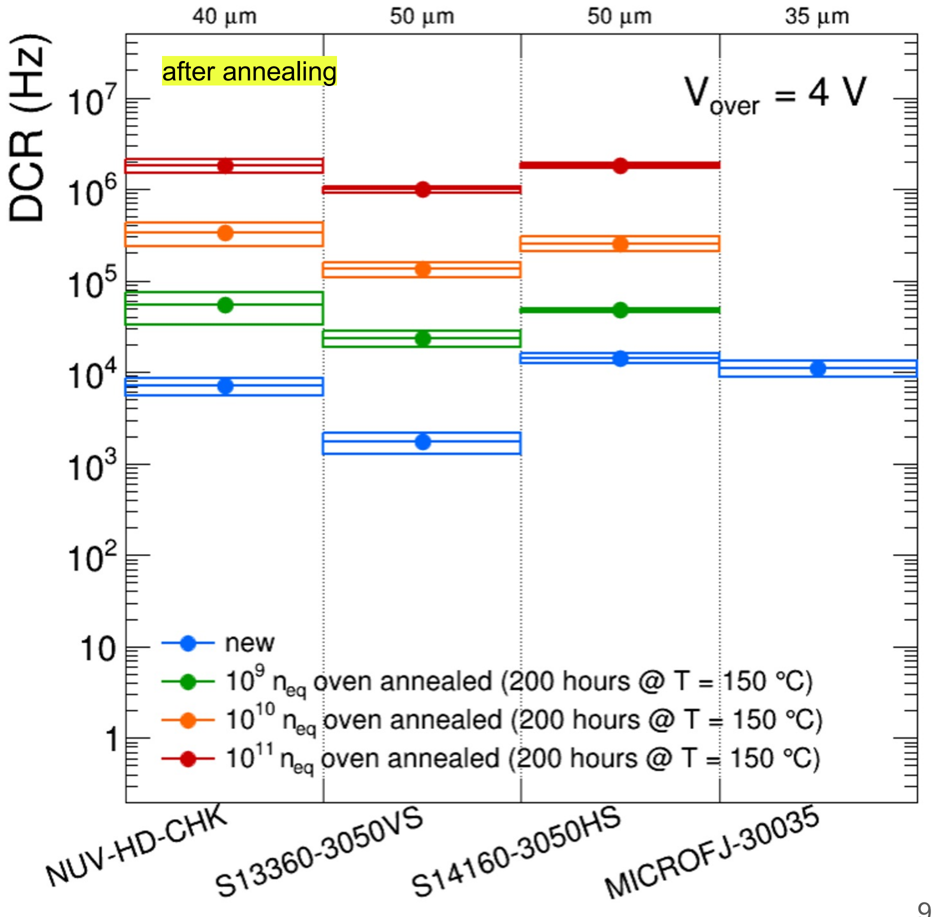
“Online” self-induced annealing for in-situ recovery



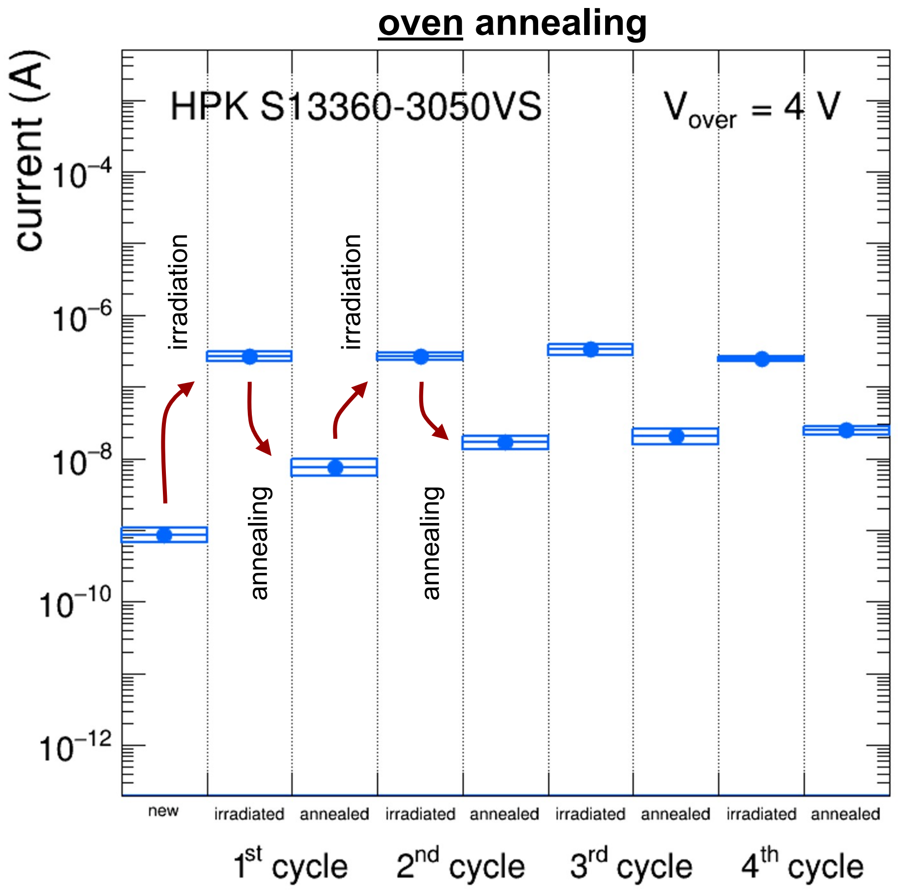


DCR after irradiation and annealing





Repeated irradiation-annealing cycles



test reproducibility of repeated irradiation-annealing cycles

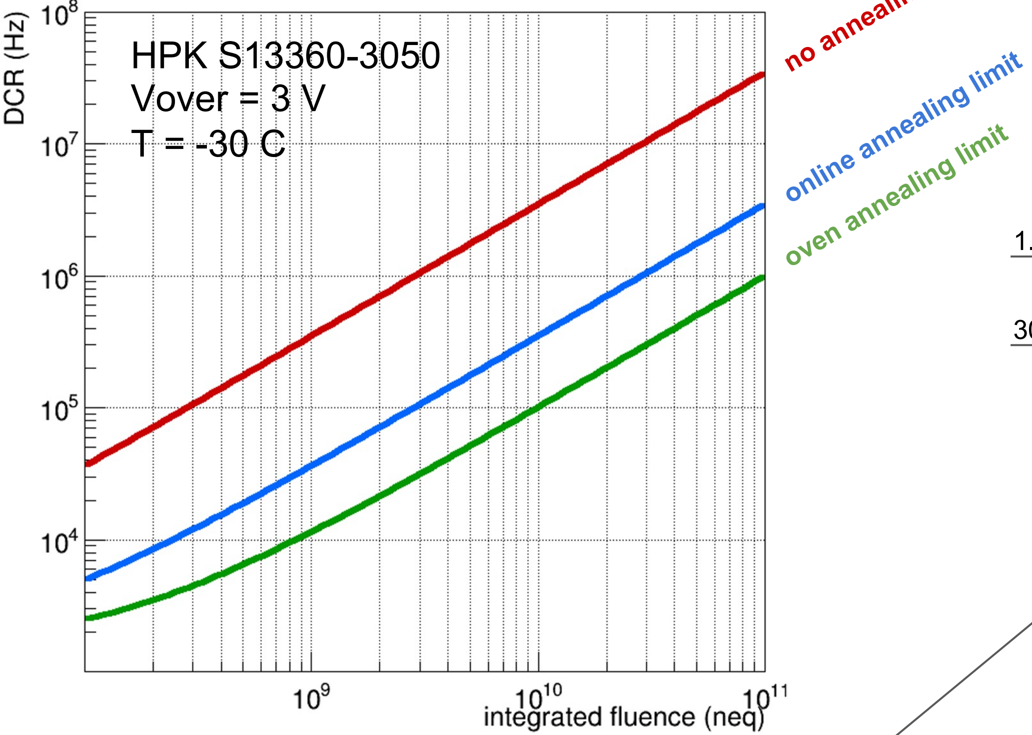
simulate a realistic experimental situation

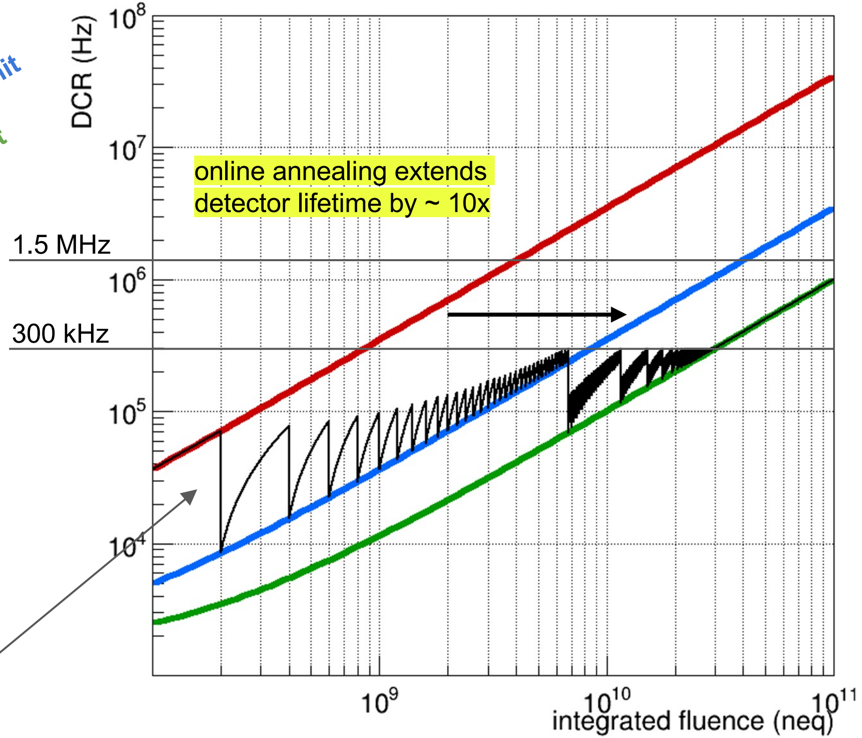
- consistent irradiation damage
  - DCR increases by ~ 500 kHz (@ Vover = 4)
  - after each shot of 10^9 n_{eq}
- consistent residual damage
  - ~ 15 kHz (@ Vover = 4) of residual DCR
  - builds up after each irradiation-annealing

annealing cures same fraction of newly-produced damage

~ 97% for HPK S13360-3050 sensors

Radiation damage model





online annealing every 2 10^8 neq (many times)
oven annealing when DCR > 300 kHz (few times)

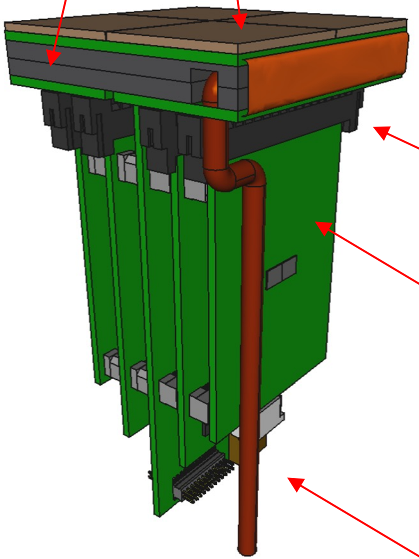
NOTE 300 kHz limit assumes there is a bandwidth limitation from electronics
using ASIC shutter/strobe capabilities could increase limit by ~ 5x
BUT the one needs to know what is the limit of from physics performance

depending on the actual DCR limit the photosensors could survive "untouched" up to 4 10^{10} neq fluence

we might have more handles to increase lifetime:
lower temperature, more aggressive annealing

SiPM photodetector unit – PDU

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



photosensors

cooling

electronics

services

~ 15-20 cm

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

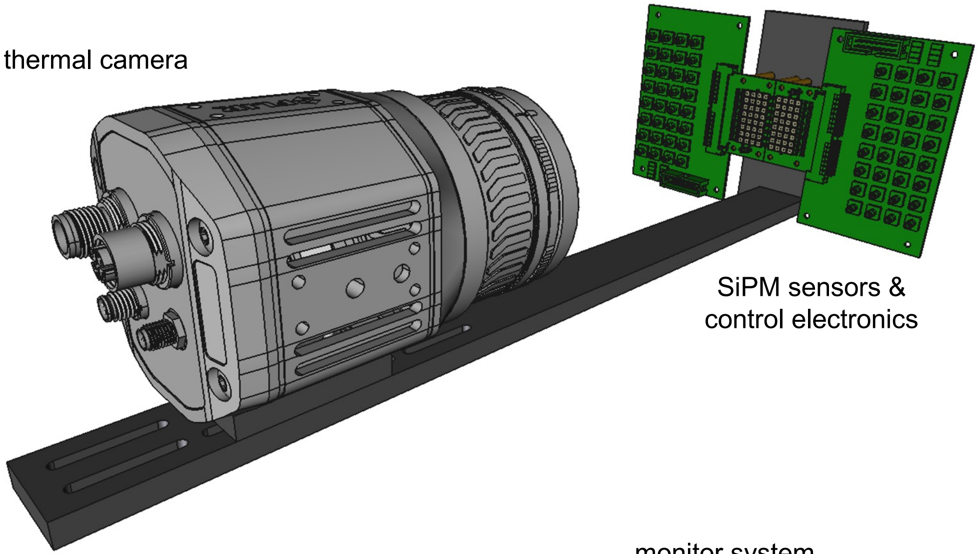
General & Temperature Control

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

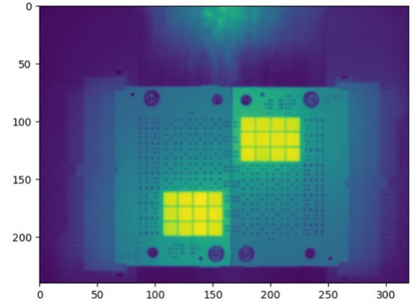
Automated multiple SiPM online self-annealing



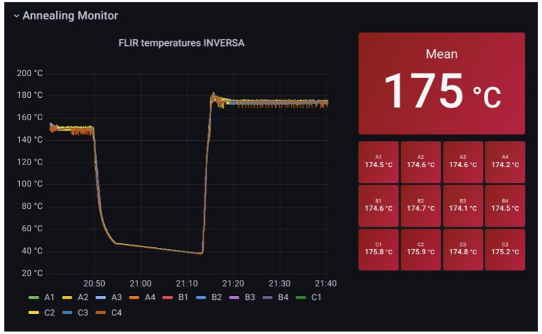
demonstrator system for online temperature monitor and control of each individual SiPM

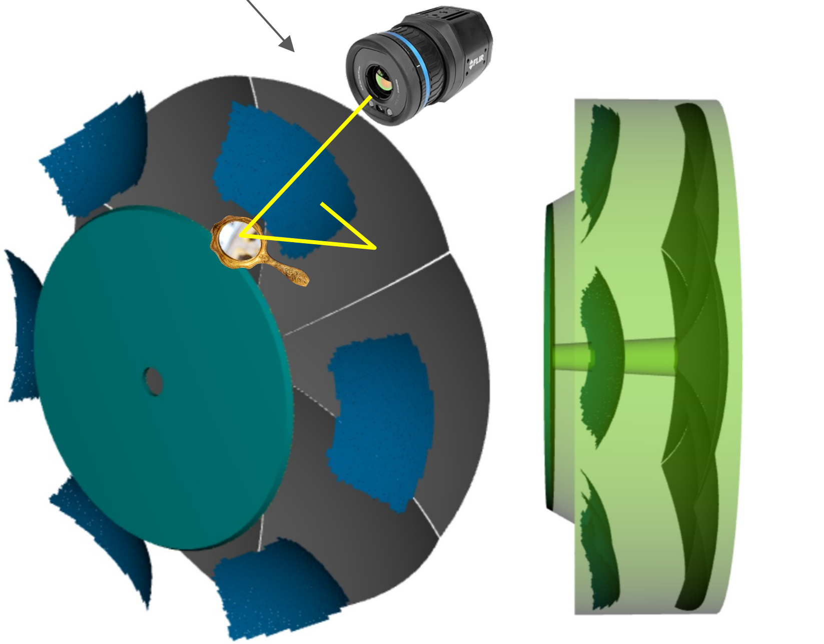
technical feasibility and implementation in the experimental environment to be studied in details

thermal image

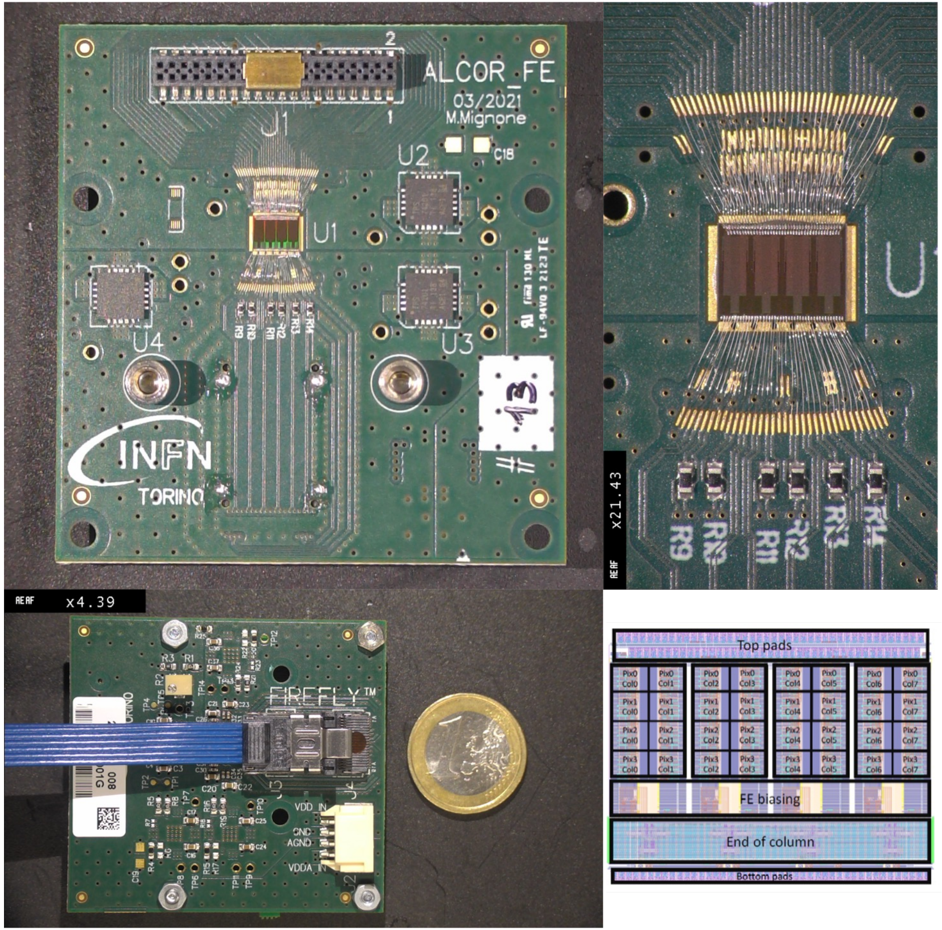


monitor system





ALCOR: A Low Power Chip for Optical sensor Readout

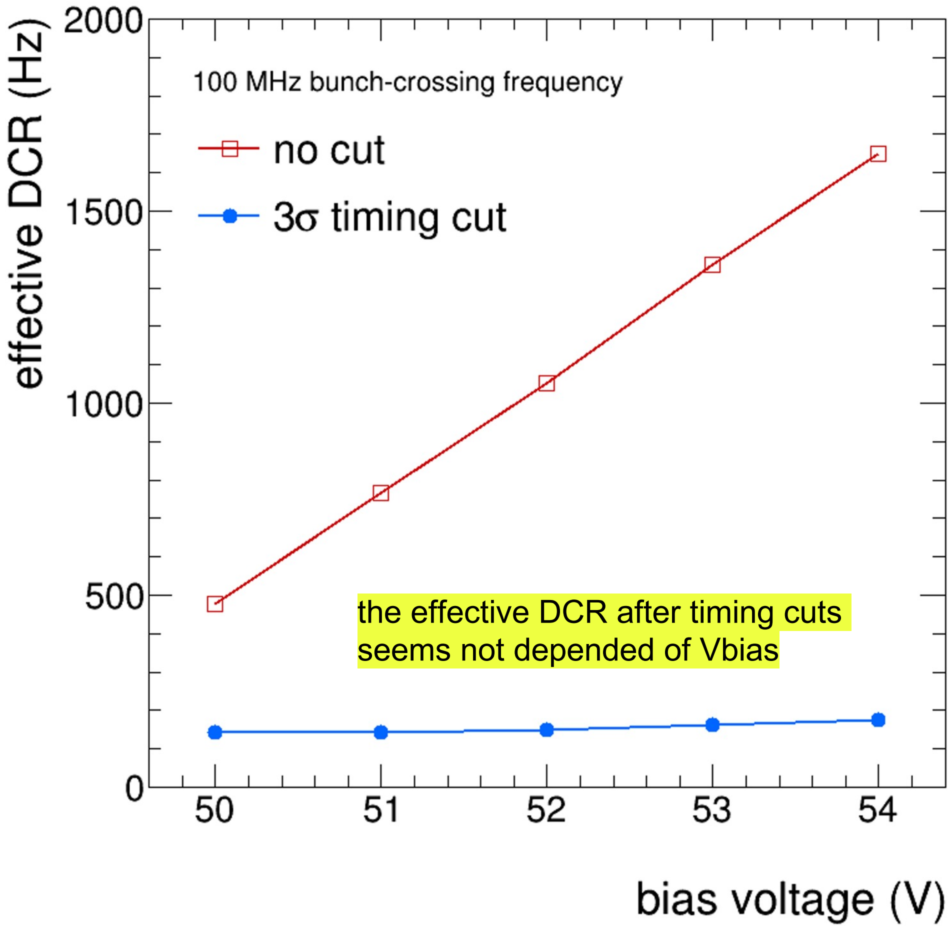


developed by INFN-TO for DarkSide

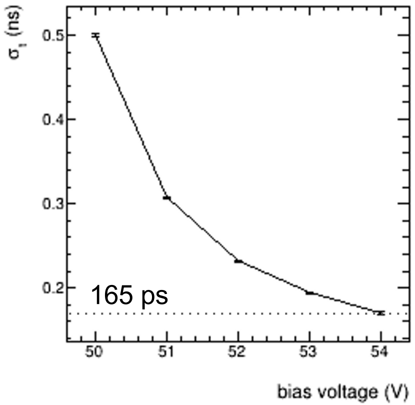
32-pixel matrix mixed-signal ASIC

- **the chip performs**
  - signal amplification
  - conditioning and event digitisation
- **each pixel features**
  - dual-polarity front-end amplifier
    - low input impedance
    - 4 programmable gain settings
  - 2 leading-edge discriminators
  - 4 TDCs based on analogue interpolation
    - 25 or 50 ps LSB (@ 320 MHz)
- **single-photon time-tagging mode**
  - continuous readout
  - also with Time-Over-Threshold
- **fully digital output**
  - 4 LVDS TX data links

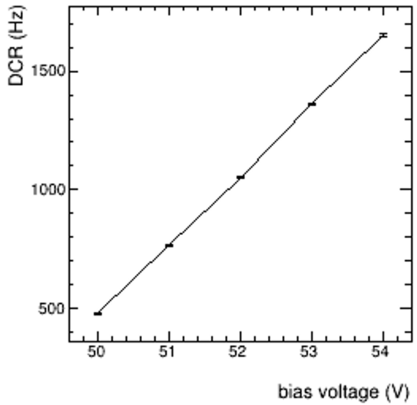
Preliminary first results with timing laser

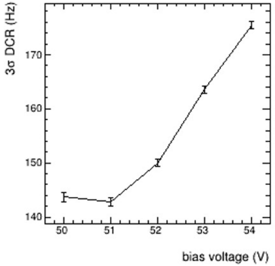


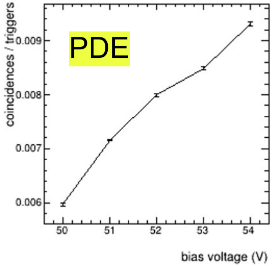
σ_t decreases with Vbias

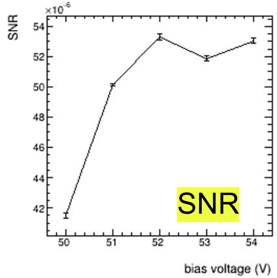


DCR increases with Vbias





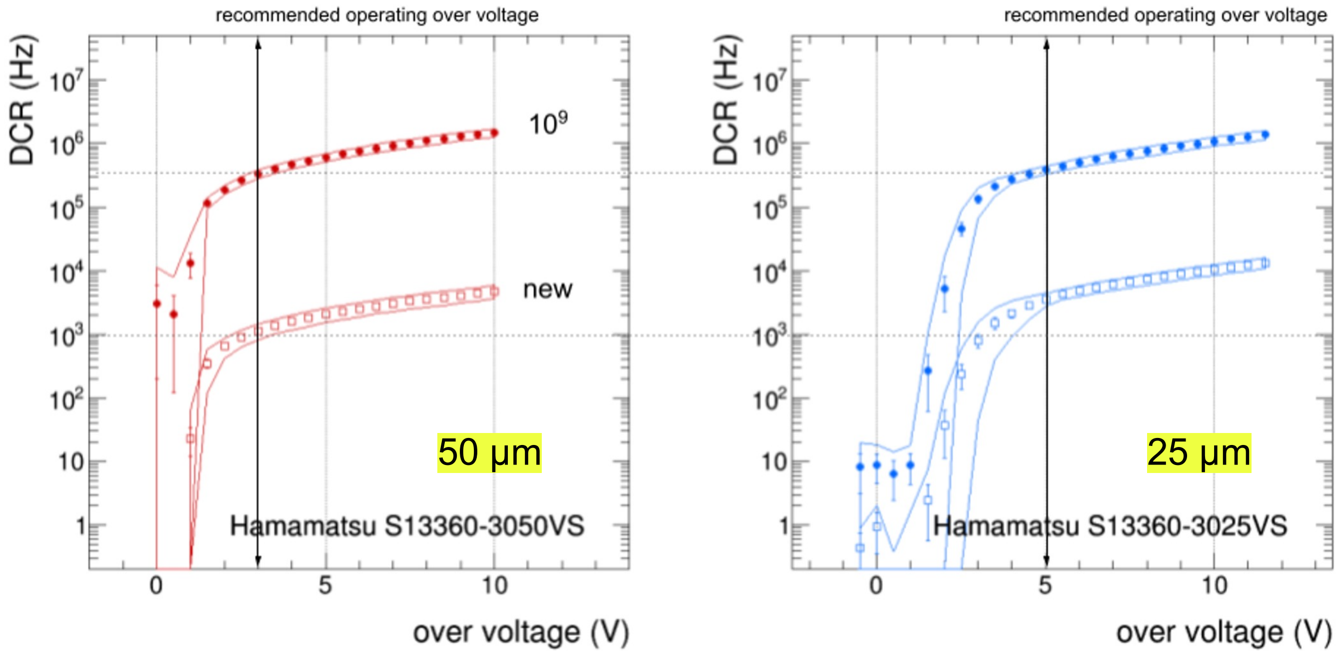




measured PDE increases with Vbias
eventually the SNR also increases with Vbias
→ low Vbias seems NOT the best working point

important to evaluate FBK sensors, because they are know to have higher PDE and better time resolution

Small vs. large SPAD sensors



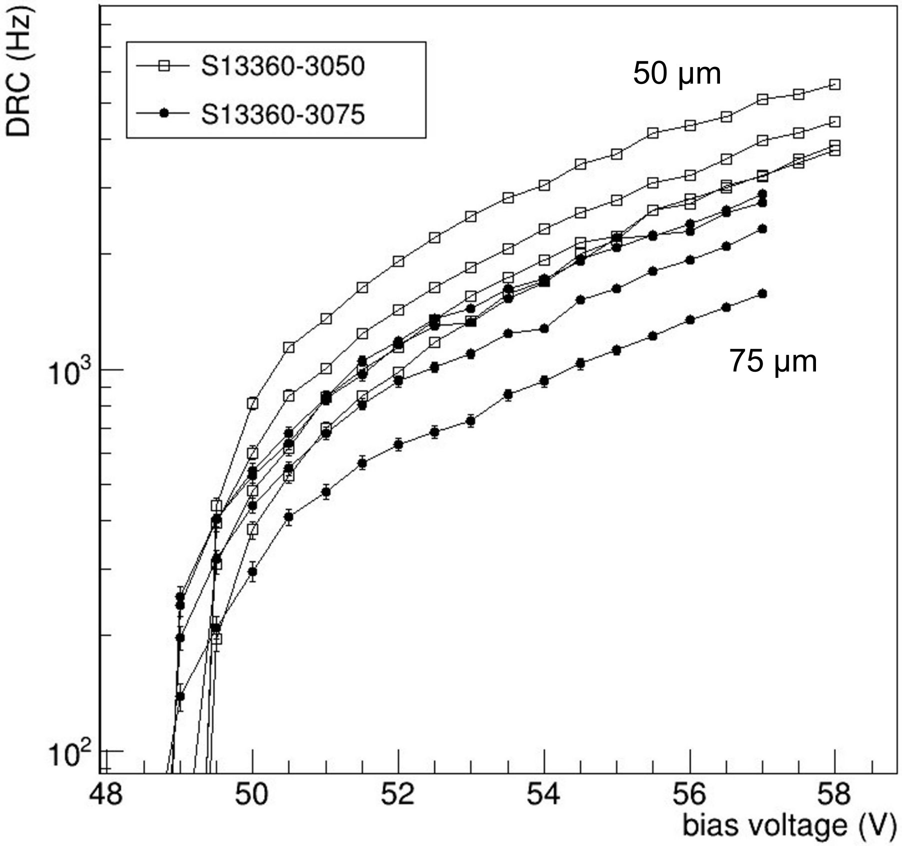
sensors with **small SPADs have lower SNR** also after irradiation

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

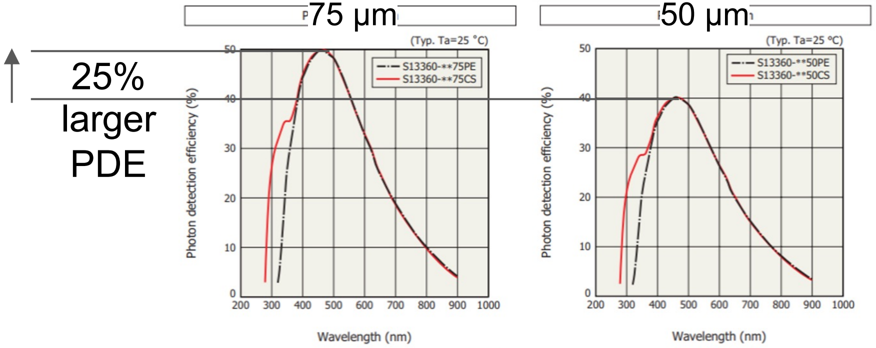
Hamamatsu 75 μm SPAD sensors



first preliminary comparison between NEW sensors
Hamamatsu S13360-3050 (50 μm SPADs)
Hamamatsu S13360-3075 (75 μm SPADs)
identical technology, different SPAD size
we knew already that 50 μm are better that 25 μm for us
preliminary results show that 75 μm are better that 25 μm
averaged over the 4 sensors tested here
75 μm sensors have sensibly lower DCR than 50 μm
and it is known that 75 μm sensors have larger PDE
→ 75 μm SPADs might soon become the baseline

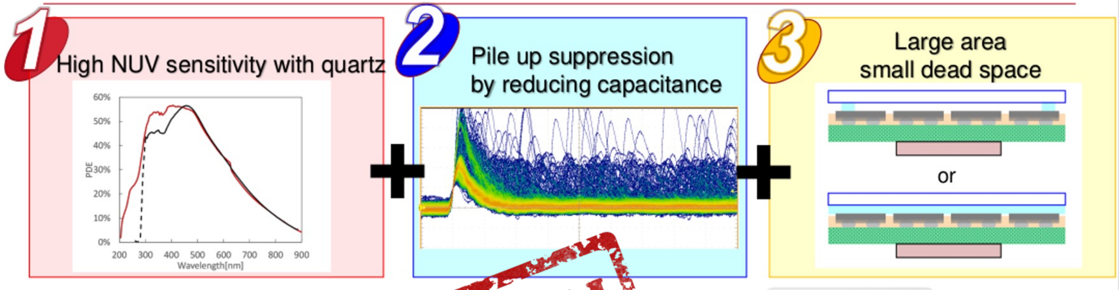
we need of course to characterise and test them deeply
with irradiation, annealing and everything else
this is our plan for 2023, this is R&D

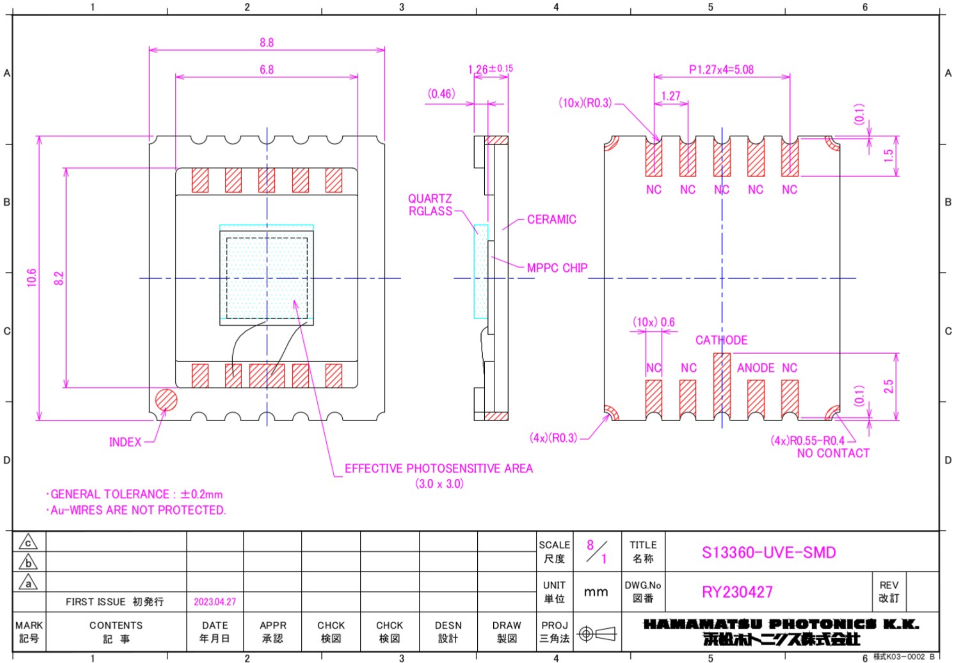
for 2024 we need to buy 75 μm arrays to equip the dRICH
prototype and confirm they might be the best choice
(but keep in mind FBK)



New Hamamatsu prototype samples

samples of newly-developed Hamamatsu SiPM
samples based on S13360 series
on paper they look VERY promising
being shipped to Bologna (arriving soon)
we will characterise and test them in full
irradiation, annealing, laser, whatever…





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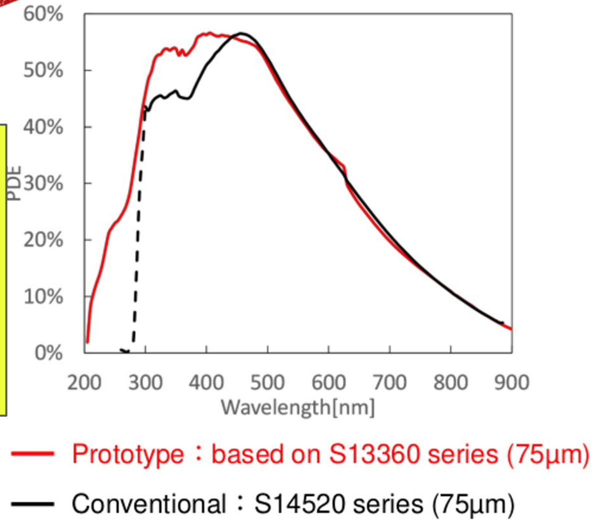
we will receive next week samples of these prototype SiPMs with 50 µm and 75m µ SPADs



SiPM run with FBK

sipm4eic project

funded and approved within
INFN-FBK Collaboration agreement

start of run October 2023

1) Sintesi del progetto di ricerca

Ring Imaging Cherenkov applications at the EIC require sensors with single-photon detection capabilities with high efficiency and excellent time resolution. High dark count rates (DCR) in SiPM can be counteracted with low-temperature operation and radiation damage can be partially cured with high-temperature annealing. Even small improvements towards reduction of DCR are helpful for a better exploitation of the detectors and to provide a strong alternative to commercially-available sensors. One of the goals of the R&D is to exploit the already-mature FBK NUV-HD technology to improve radiation tolerance and meet the needs for EIC. Increasing the fraction of the sensor active area over the total area while retaining a low-cost process (wire-bonding vs. TSV) is another important step to make FBK technology an even more attractive solution for EIC. These research goals are in line with the timeline for the initial operation of EIC and are targeted to the Technical Design Reports.

in line with initial operation of EIC

Another line of research aims to significantly reduce DCR and radiation vulnerability in SiPM by reducing their active area while maintaining photodetection efficiency. Such a study is exploratory and more ambitious, but has a high return potential. This part of the R&D is not targeted for the EIC initial operation phase, but might yield a new class of SiPM photosensors for the EIC RICH detector upgrades, for the ALICE3 RICH detector as well as future LHCb RICH upgrades.

might yield sensors for EIC RICH upgrades and for ALICE3 RICH