dRICH photosensors and electronics

Roberto Preghenella
INFN Bologna
on behalf of the dRICH Collaboration

preghenella@bo.infn.it

Outline

- The dual-radiator (dRICH) for forward PID at EIC
- SiPM option and requirements for RICH optical readout
- Neutron fluxes at the dRICH photosensor surface
- Studies of radiation damage on SiPM
- Commercial SiPM sensors and FBK prototypes
- High-temperature annealing recovery
- Comparison between different sensors
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- SiPM photodetector unit – PDU
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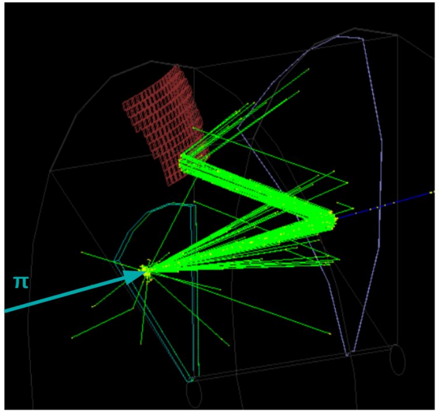
- Laser timing measurements with ALCOR
- Current & future plans: sensor optimisation and risk mitigation

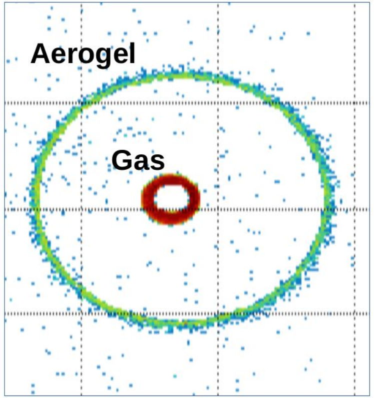
The dual-radiator (dRICH) for forward PID at EIC

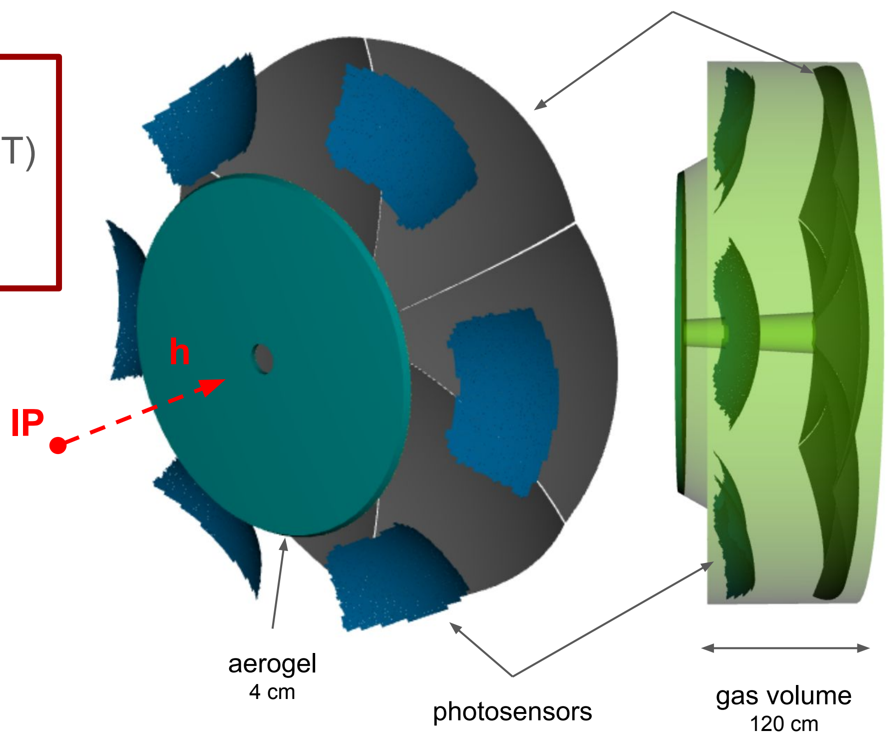
compact and cost-effective solution for broad momentum coverage at forward rapidity

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



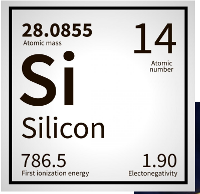
example event (accumulated hits)





SiPM option and requirements for RICH optical readout

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

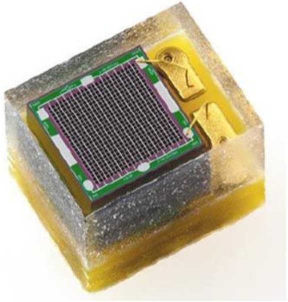


- **cons**

large dark count rates
not radiation tolerant

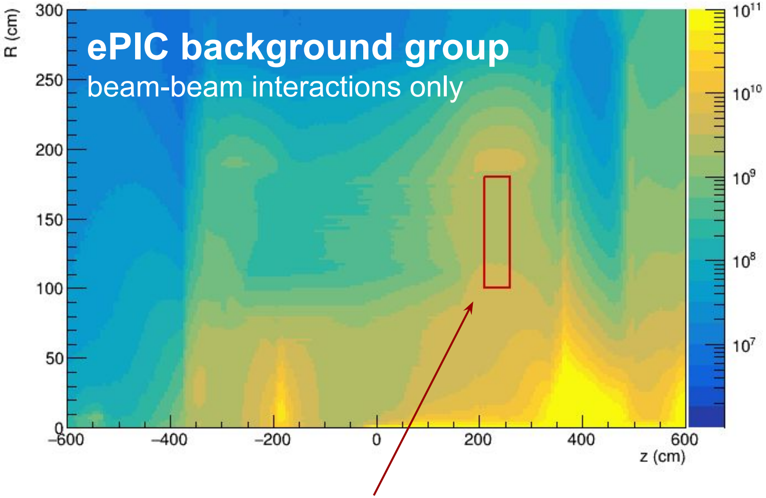
technical solutions and mitigation strategies

🐧 cooling
⌚ timing
🔥 annealing



Neutron fluxes at the dRICH photosensor surface

neutron (> 100 keV) fluence for 6 months at 500 kHz



location of dRICH photosensors

mean fluence: 1.75 10^{7} n / cm^{2} / fb^{-1}

max fluence: 2.25 10^{7} n / cm^{2} / fb^{-1}

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

- radiation level is moderate

assume fluence: 4.5 10^{7} n / cm^{2} / fb^{-1}

conservatively assume max fluence and 2x safety factor

> 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 $10^{34} cm^{-2} sec^{-1}$.

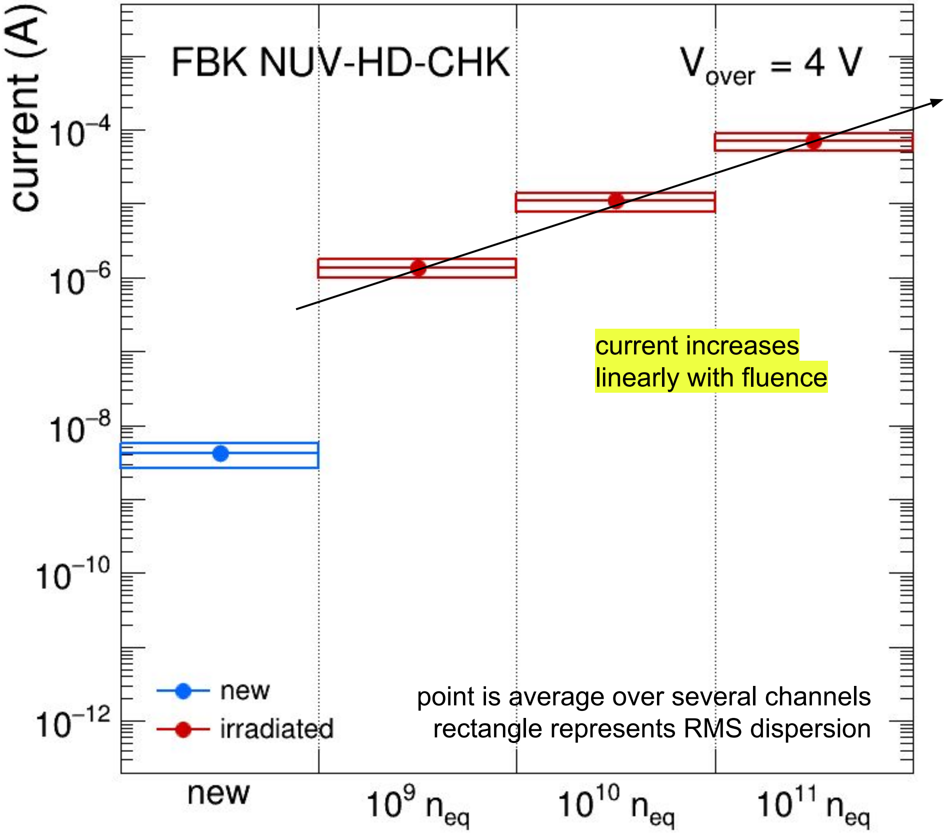
R&D on SiPM as potential photodetector for dRICH, main goal
study SiPM usability for Cherenkov up to 10^{11} 1-MeV n_{eq}/cm^{2}

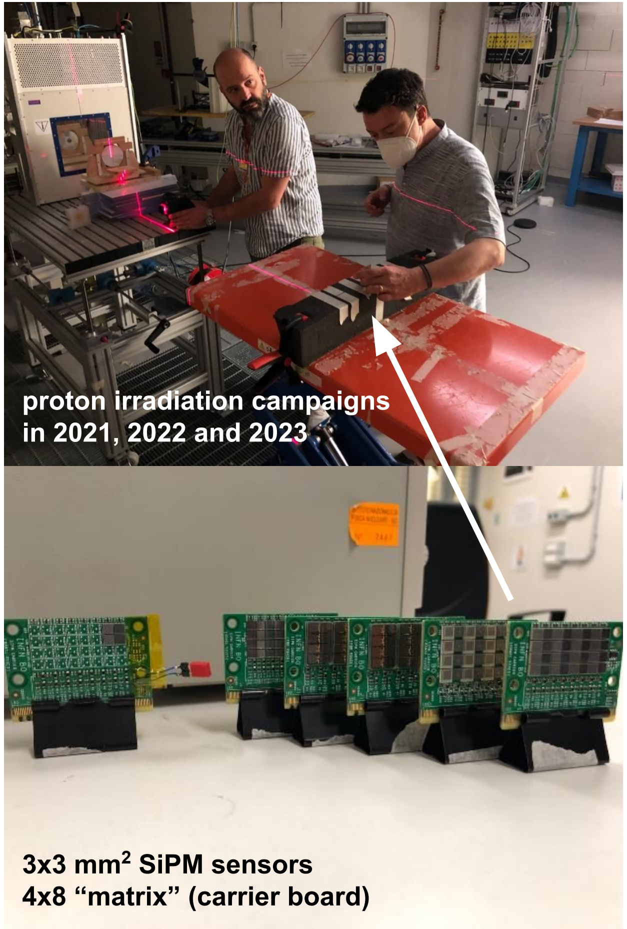
notice that 10^{11} neq/cm^{2} would correspond to 2000 fb^{-1} integrated $\mathcal{L}$
it would be 12 years of 6-months/year (160 fb^{-1}/year) running at top lumi $\mathcal{L} = 10^{34}\ s^{-1}\ cm^{-2}$
quite a long time of EIC running before we reach there, if ever

→ 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}	*might never be reached*

Studies of radiation damage on SiPM

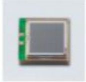




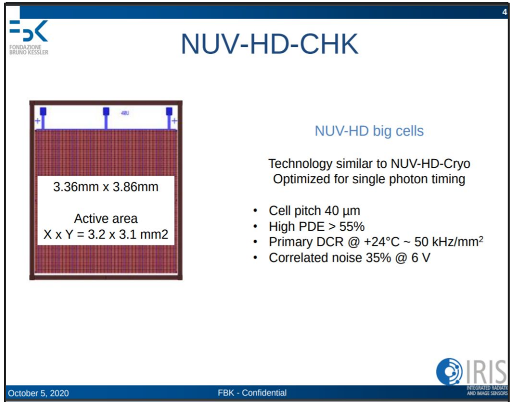
all results are reported at T = -30 C

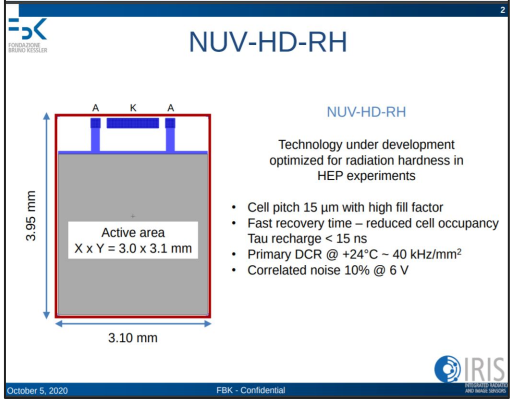
Commercial SiPM sensors and FBK prototypes





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

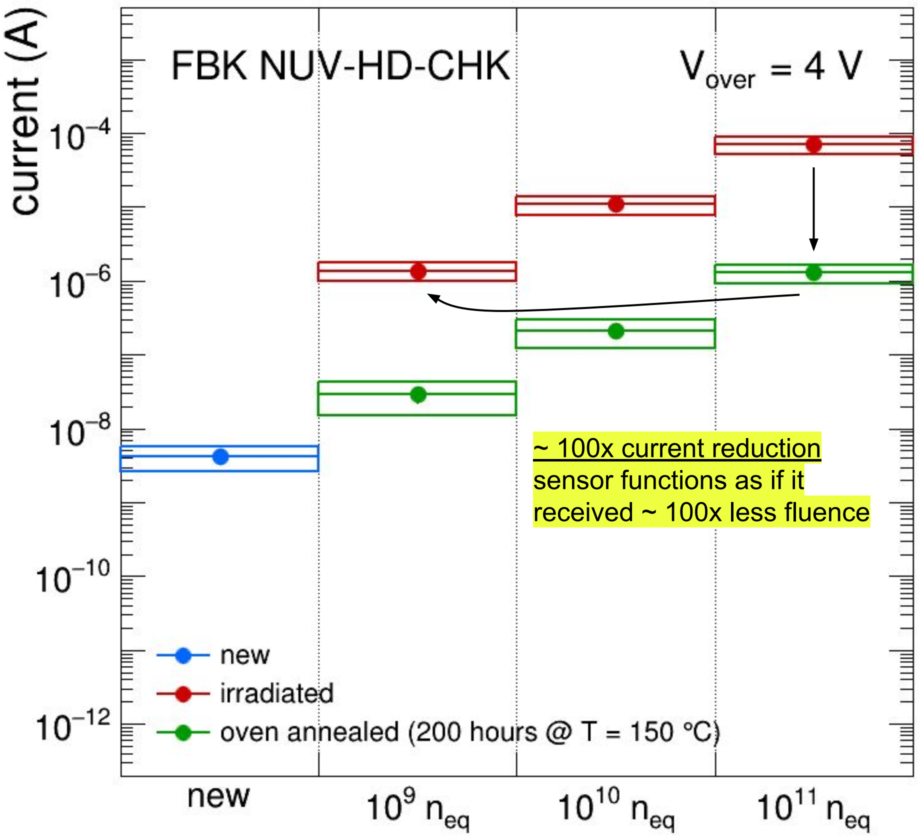


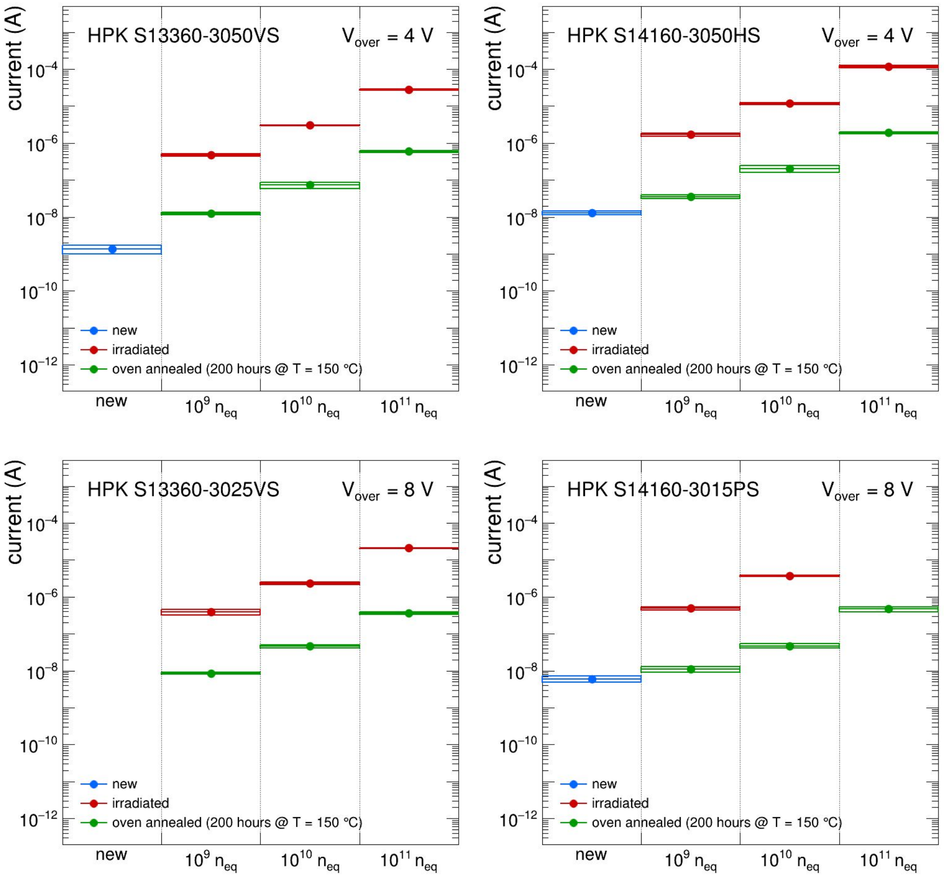


multiple producers: different technologies, SPAD dimensions, V_{bd}, electric field …

High-temperature annealing recovery

oven annealing
~ 1 week at 150 C

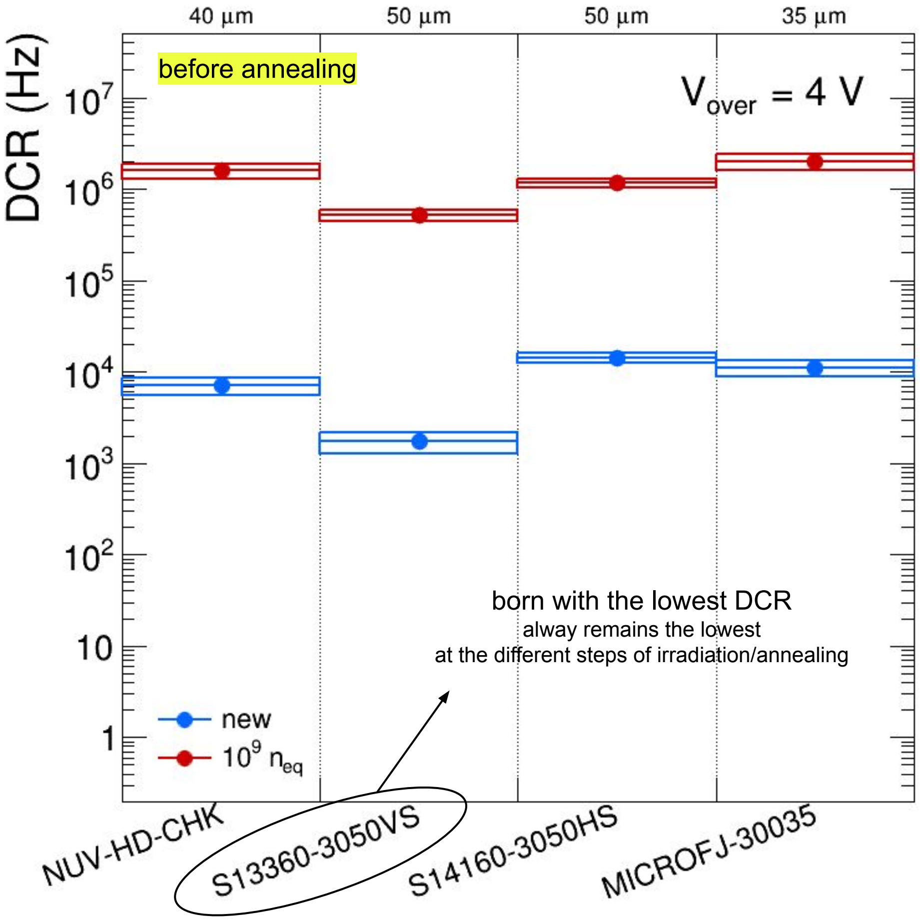


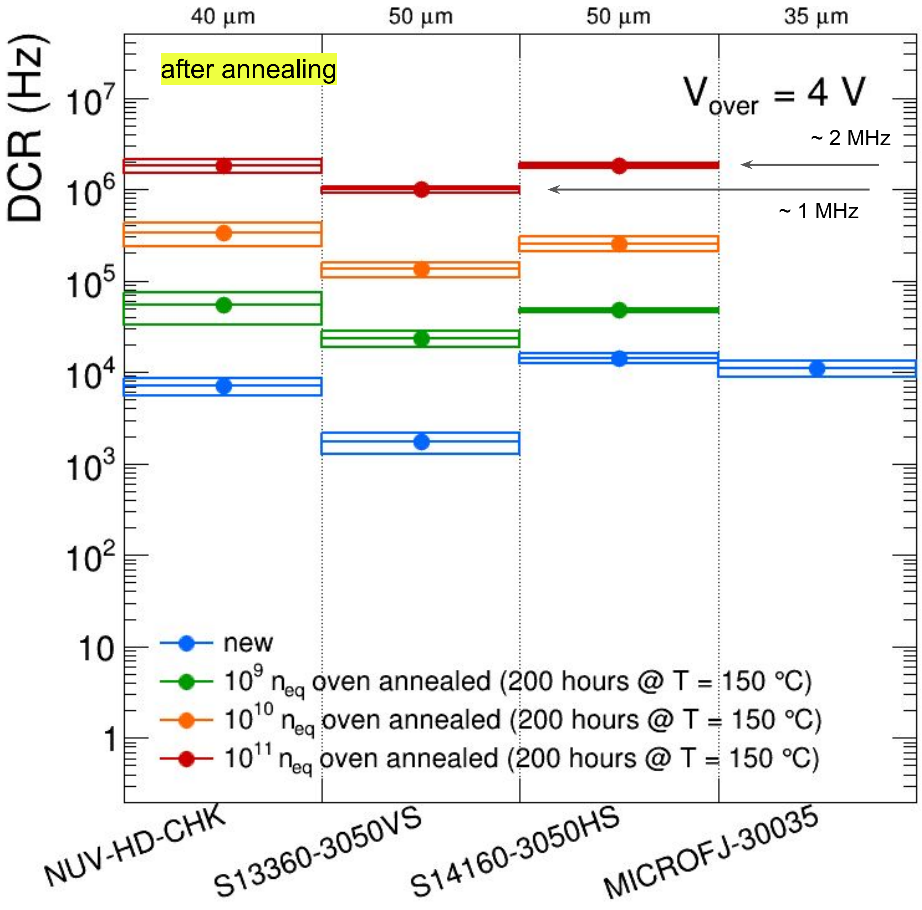


similar observation with various types of Hamamatsu sensors

Comparison between different sensors

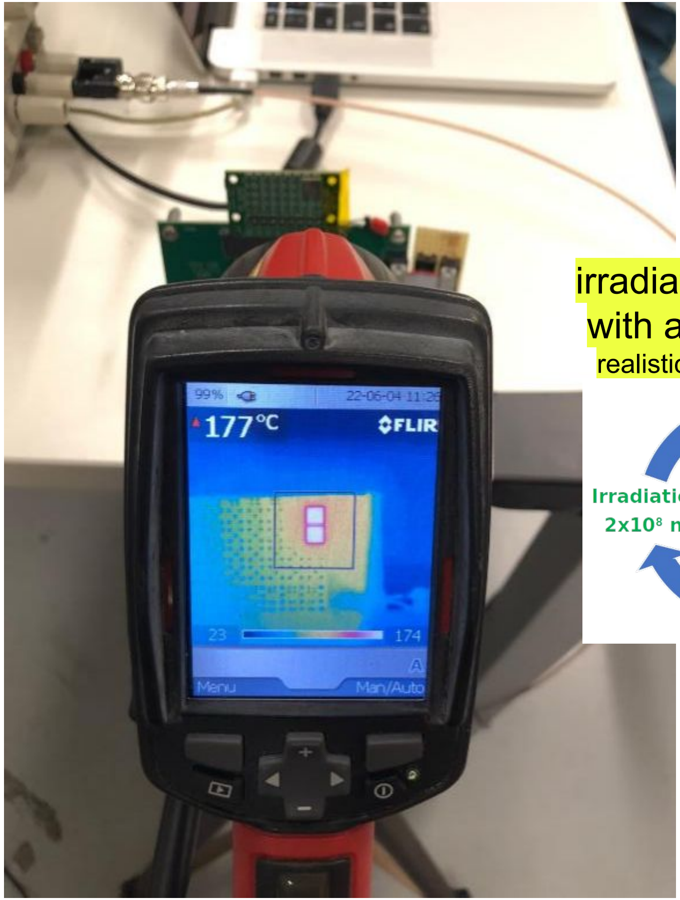
comparison at same Vover not totally fair
important to consider PDE (and SPTR) → SNR ~ PDE / DCR
unlikely 2x larger DCR is matched by 2x larger PDE



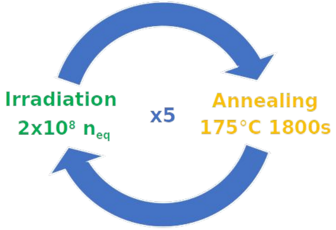


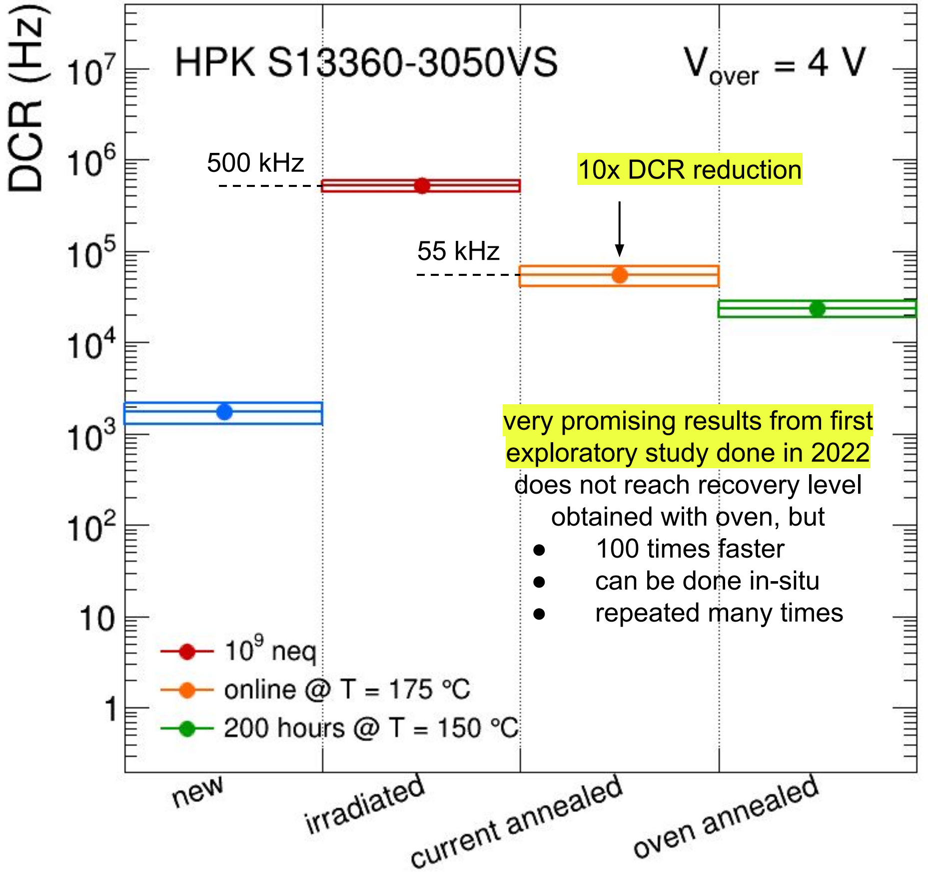
“Online” self-induced annealing

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



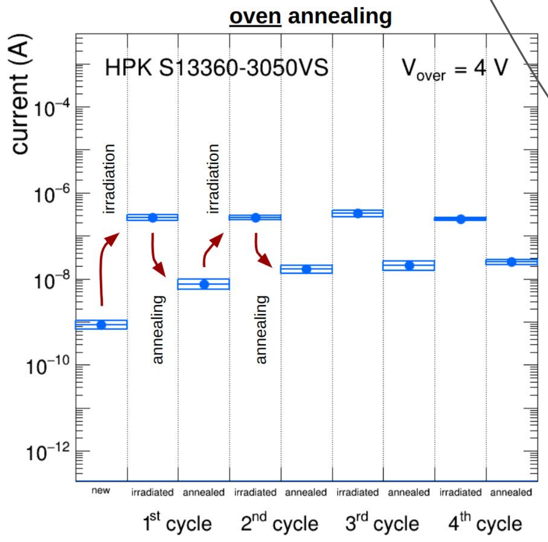


very promising results from first exploratory study done in 2022
does not reach recovery level obtained with oven, but

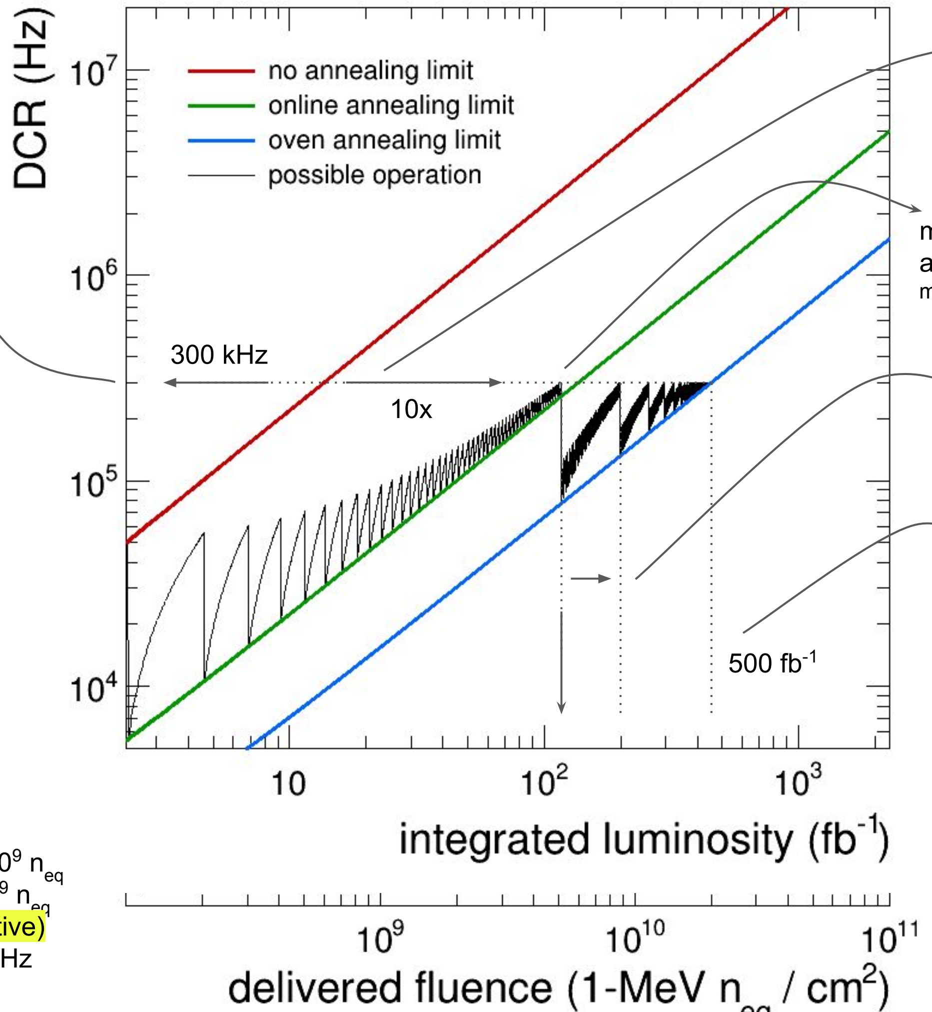
- 100 times faster
- can be done in-situ
- repeated many times

Ageing model

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



Hamamatsu S131360-3050 @ 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 200 fb^{-1} with only one oven annealing cycle

could reach 500 fb^{-1} with optimisation of online annealing protocol
to approach oven performance

model input from R&D measurements

- 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}

neutron fluence from background group (conservative)

- 7 10^9 1-MeV n_{eq}/cm^2 for 6 months at 500 kHz
- corresponds to 4.5 10^7 n_{eq} / fb^{-1}

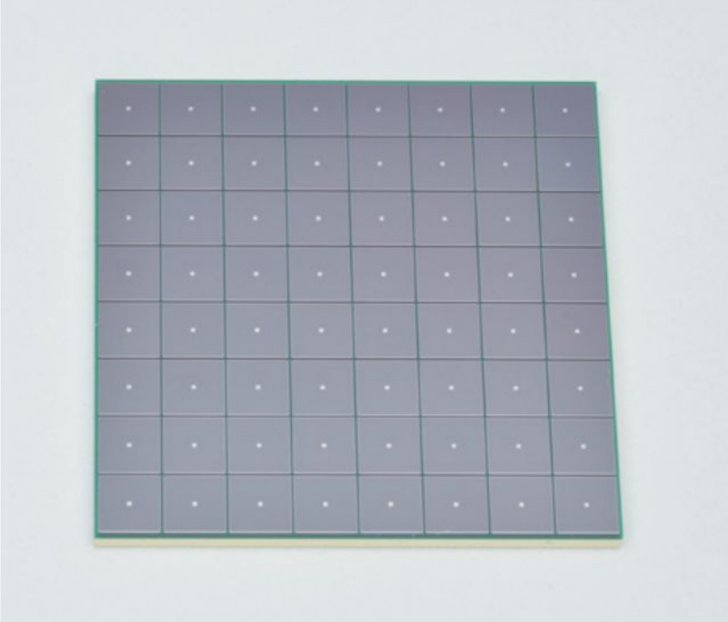
these predictions are according to present knowledge / tested solutions
there are more handles to further mitigate DCR
lower Vover, 3V
lover T operation -40 C or below

SiPM technical specs

baseline sensor device

64 (8x8) channel SiPM array

3x3 mm^2 / channel



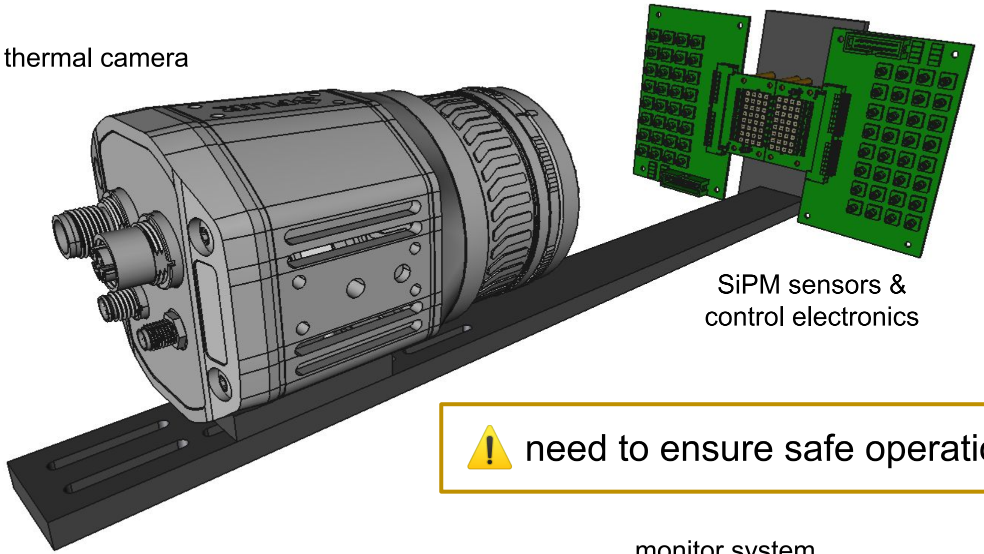
Parameters (at Vop, T = 25 C, unless specified)	Symbol	Value	Notes
Package type		SiPM array	
Mounting technology		surface mount	wire bonding also acceptable
Number of channels		64 (8 x 8)	8 (2 x 4) also acceptable
Effective photosensitive area / channel		3 x 3 mm^2	
Package dimension		< 26 x 26 mm^2	
Fraction of active area in package		> 85 %	
Microcell pitch		50 or 75 um	
Number of microcells	Nspad	> 1500	
Protective window material		Silicone resin	radiation / heat resistant
Protective window refractive index		1.55 - 1.57	
Spectral response range		300 to 900 nm	
Peak sensitivity wavelength	Lambda	400 - 450 nm	
Photon detection efficiency at Lambda		> 40%	
Breakdown voltage	Vbreak	< 60 V	
Operating overvoltage	Vover	< 5 V	
Operating voltage	Vop	Vbd + Vover	
Max Vop variation between channels		< 100 mV	at T = -30 C
Dark count rate	DCR	< 500 kHz	
DCR at T = -30 C		< 5 kHz	at T = -30 C
DCR increase with radiation damage		< 500 kHz / 10^9 neq	at T = -30 C
Residual DCR after annealing		< 50 kHz / 10^9 neq	at T = -30 C
Terminal capacitance		< 500 pF	
Gain		> 1.5 10^6	
Recharge time constant	Tau	< 100 ns	
Crosstalk	CT	< 5%	
Afterpulsing	AP	< 5%	
Operating temperature range		-40 C to 25 C	
Single photon time resolution	SPTR	< 200 ps FWHM	

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

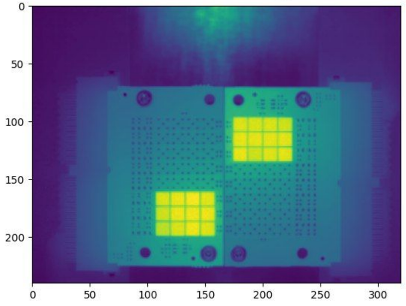
thermal camera



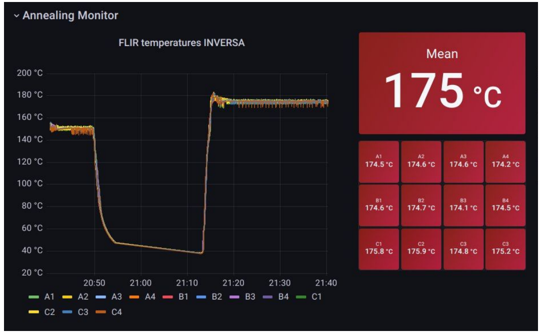
SiPM sensors &
control electronics

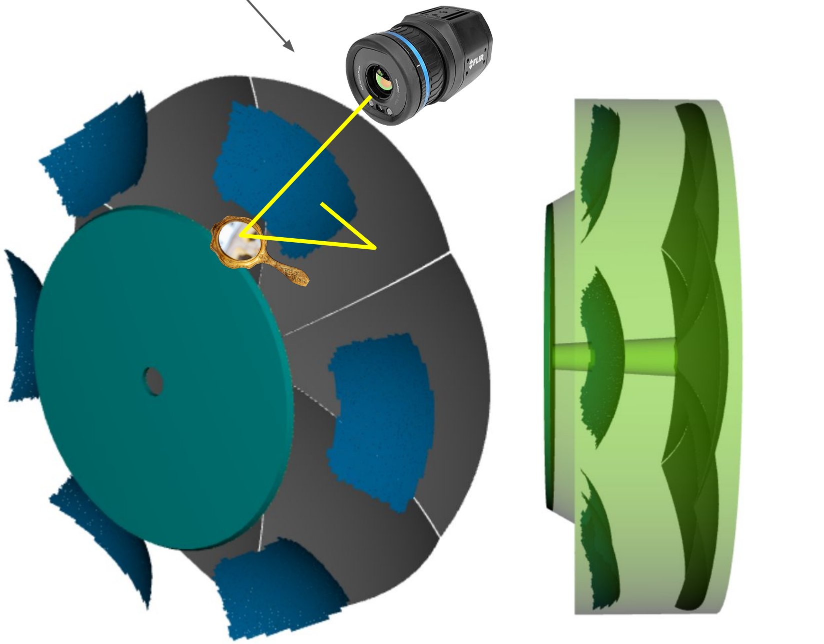
⚠️ need to ensure safe operation

thermal image



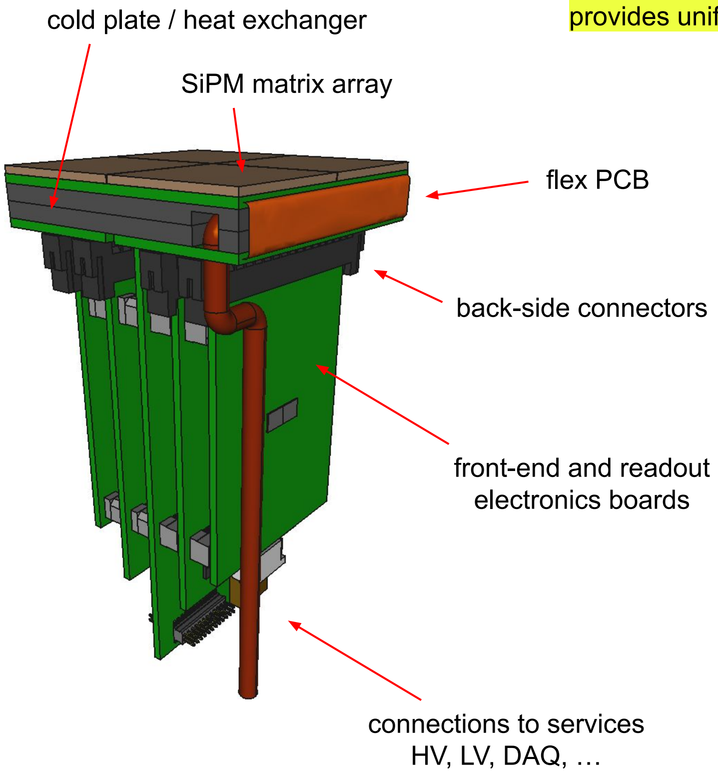
monitor system

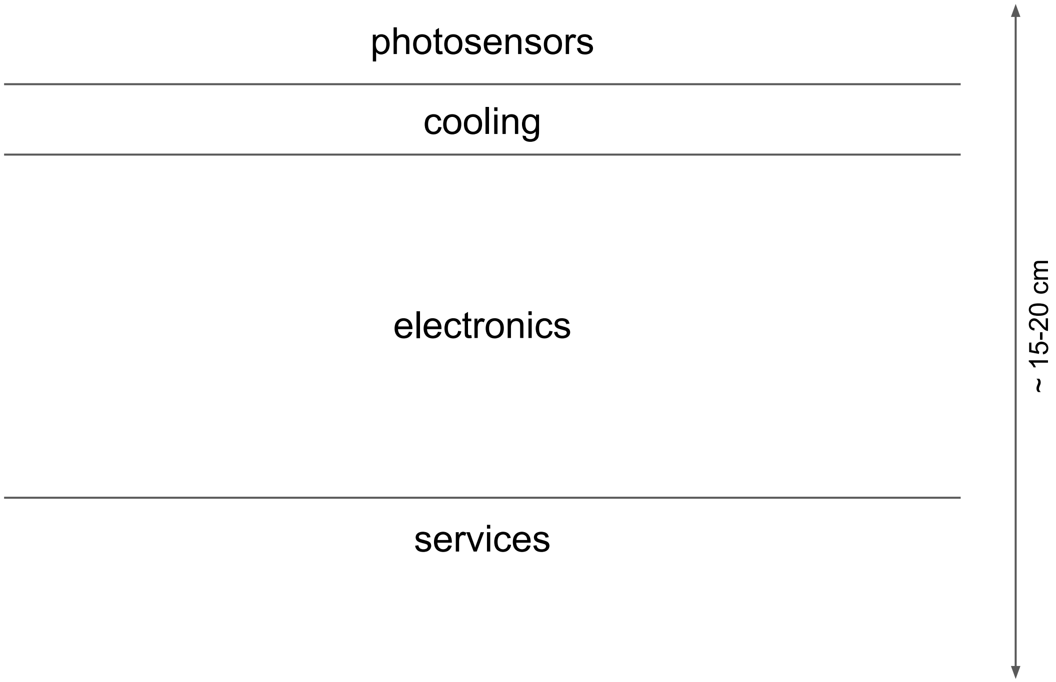




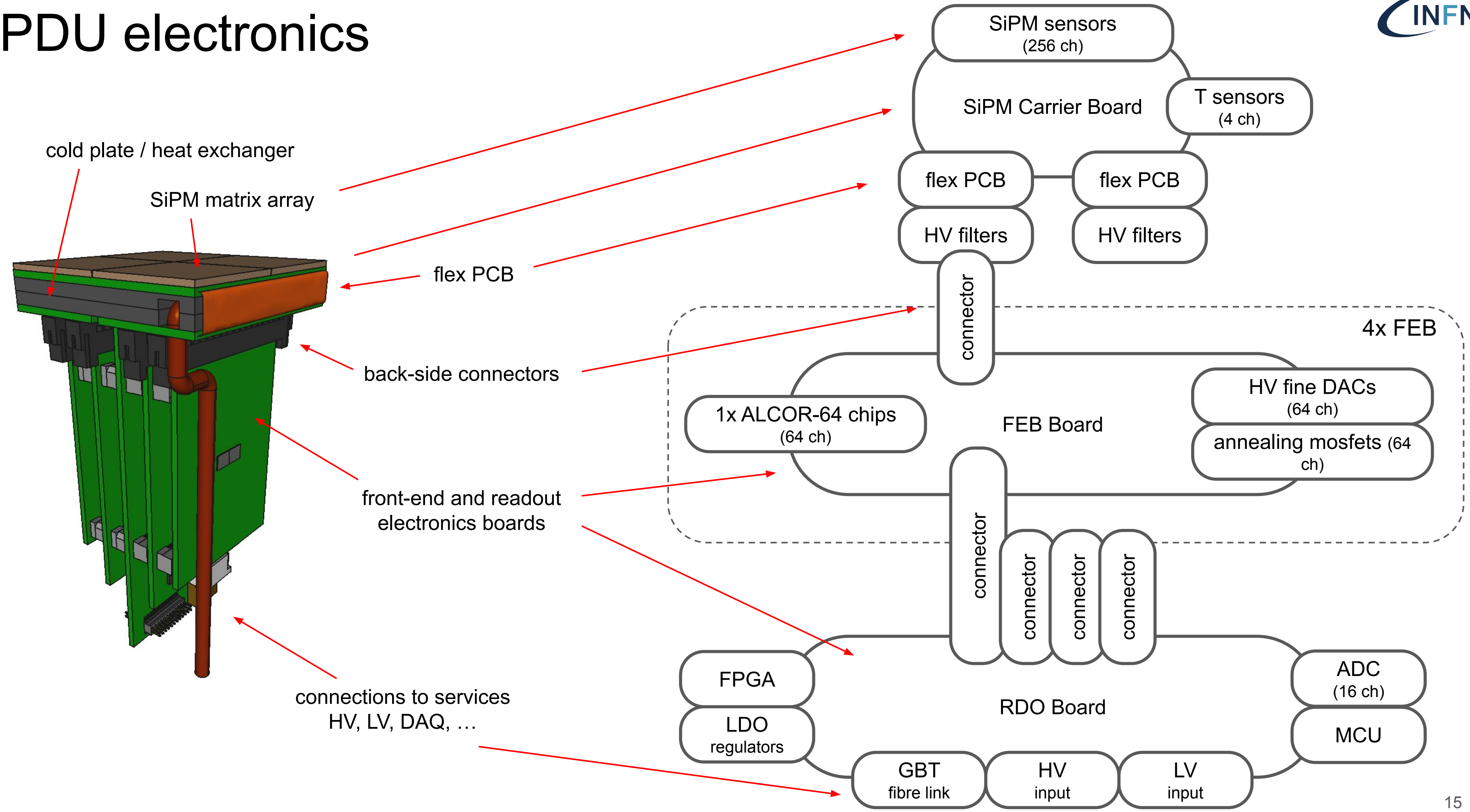
SiPM photodetector unit – PDU

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

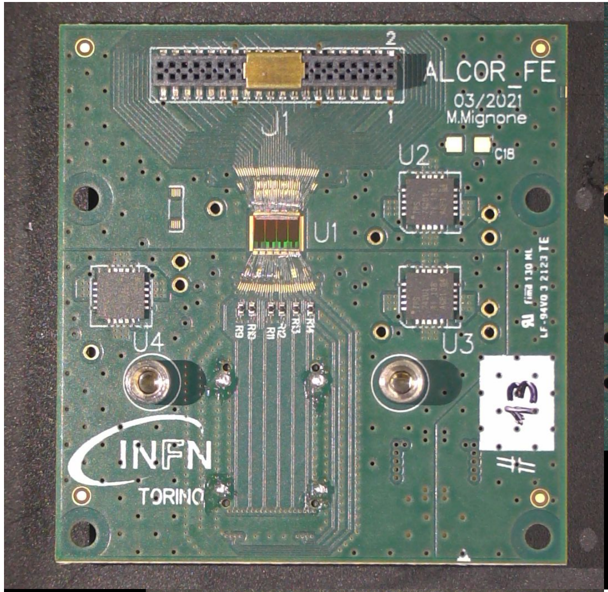


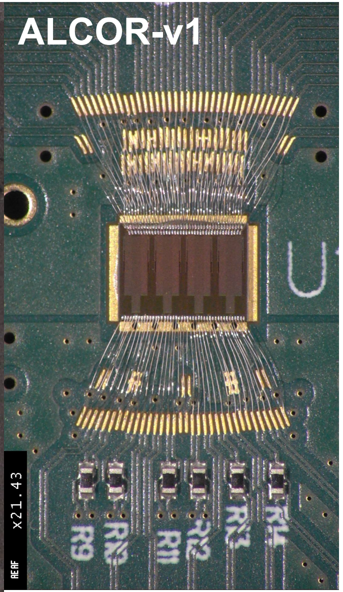


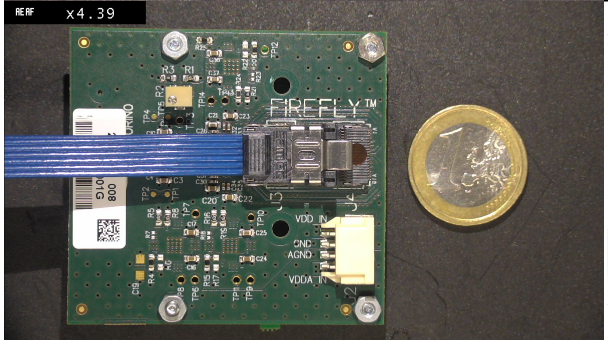
PDU electronics

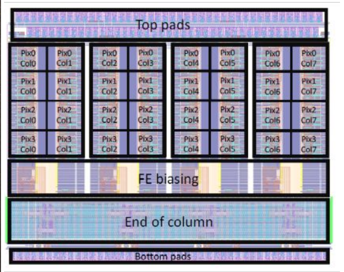


ALCOR ASIC: integrated front-end and TDC









developed by INFN-TO

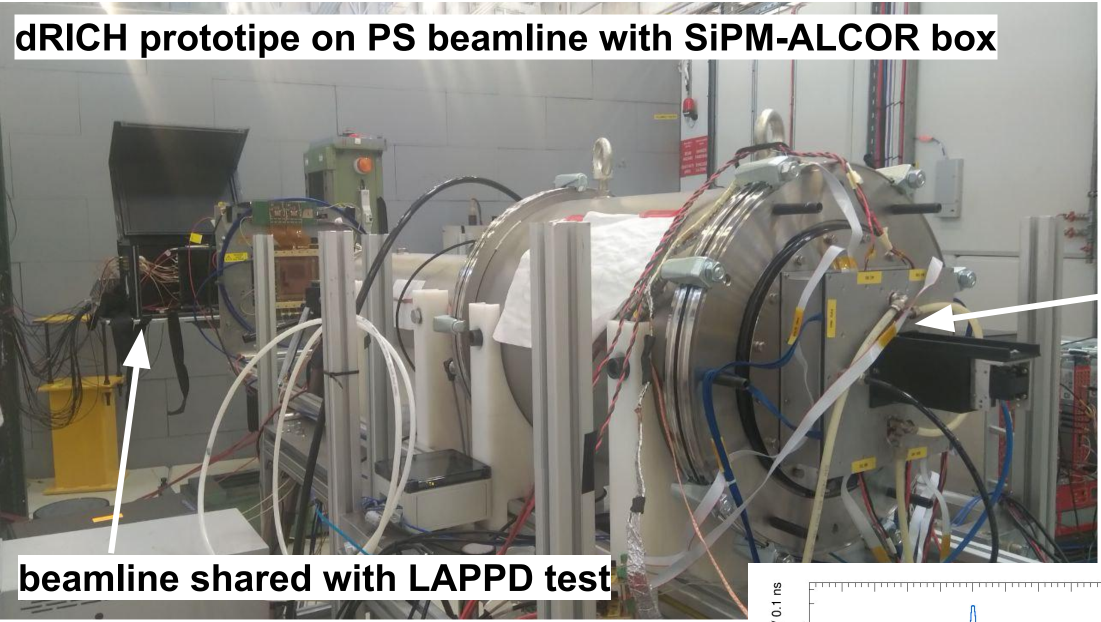
64-pixel matrix mixed-signal ASIC

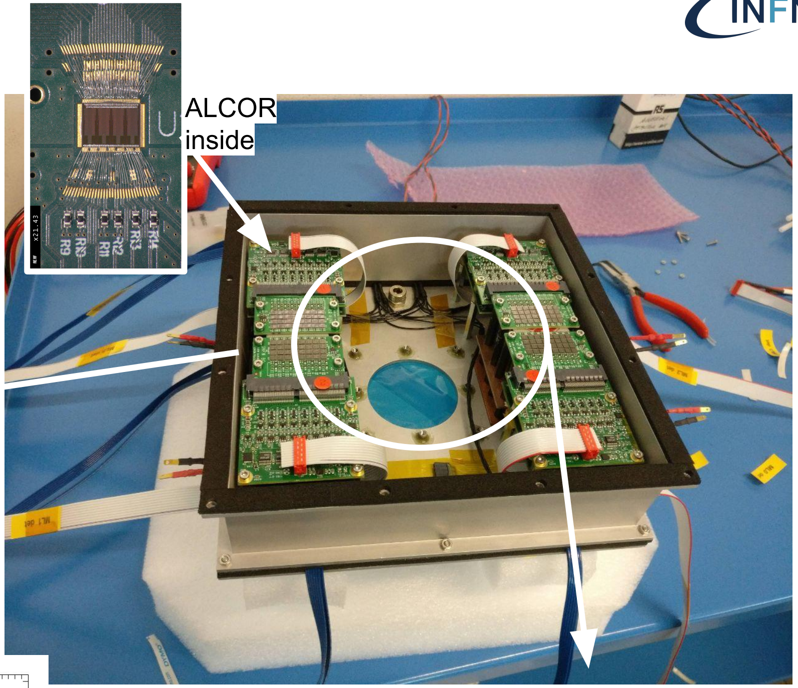
current versions (v1,v2) have 32 channels, wirebonded

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

2022 test beam at CERN-PS

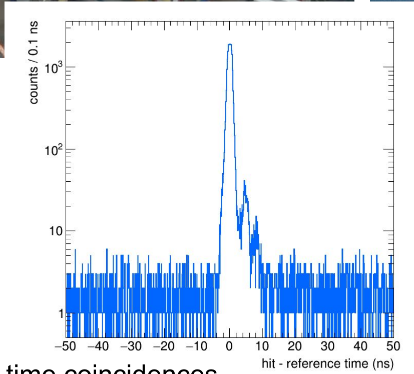




successful operation of SiPM

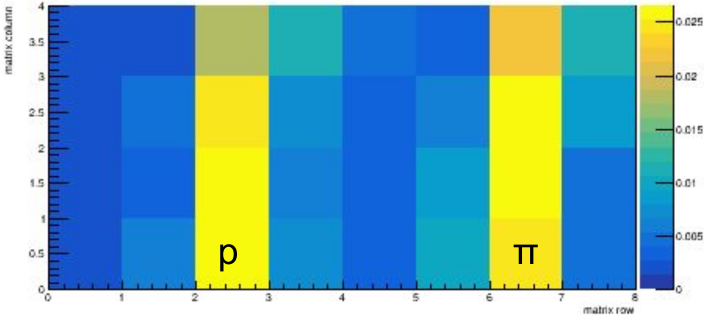
<u>irradiated</u> (with protons up to 10^{10})

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



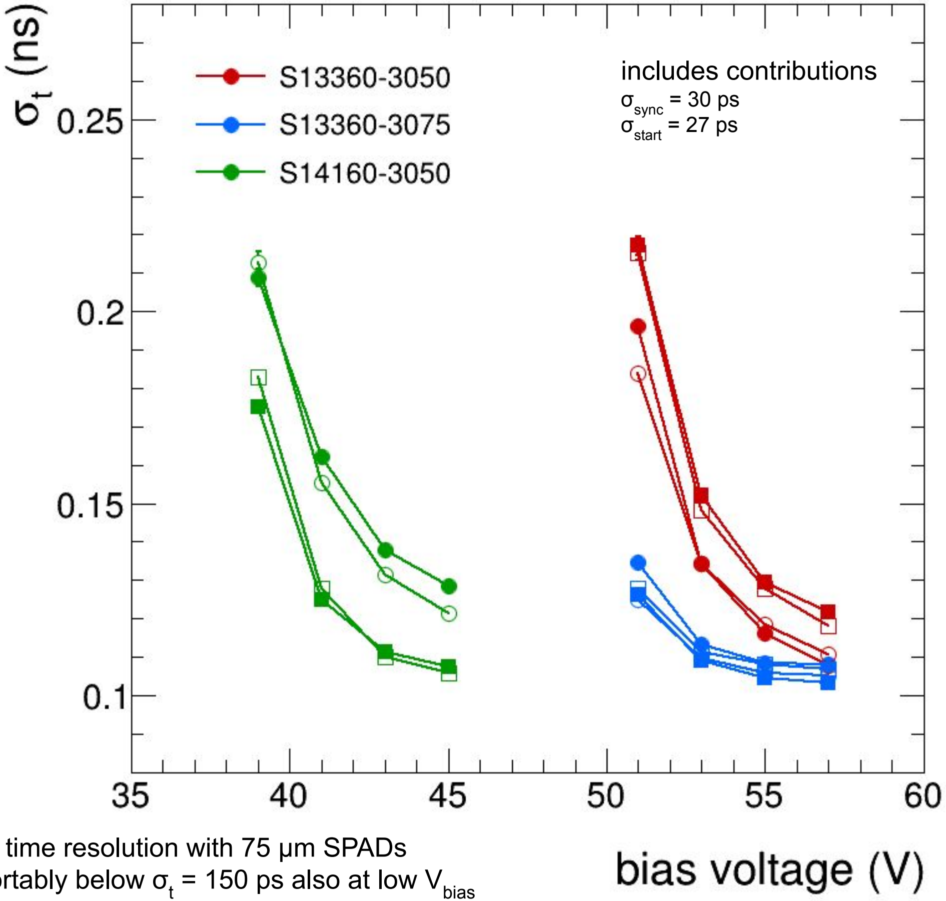
time coincidences

8 GeV positive beam (aerogel rings)

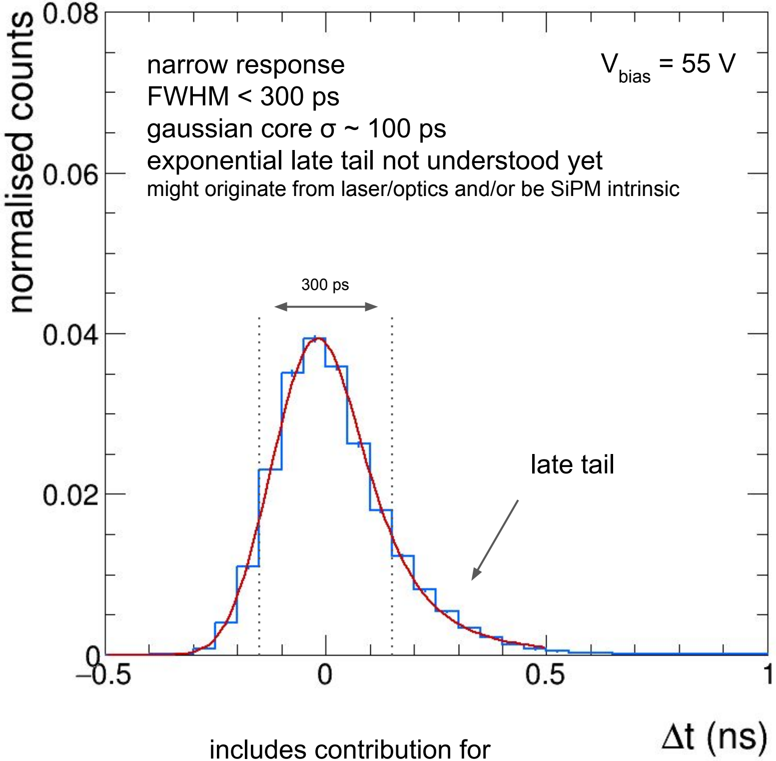


Laser timing measurements with ALCOR

standard ALCOR front-end bias configuration



laser-SiPM correlations (time-walk corrected)



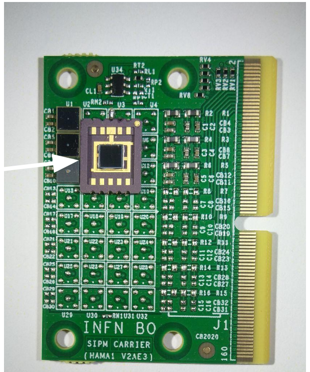
better time resolution with 75 μm SPADs
comfortably below σ_t = 150 ps also at low V_{bias}

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

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

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
  - 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