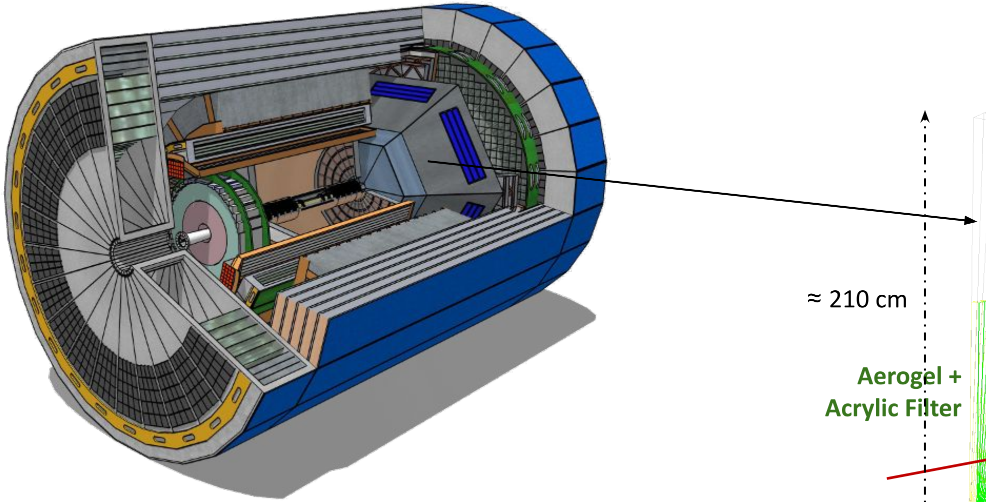
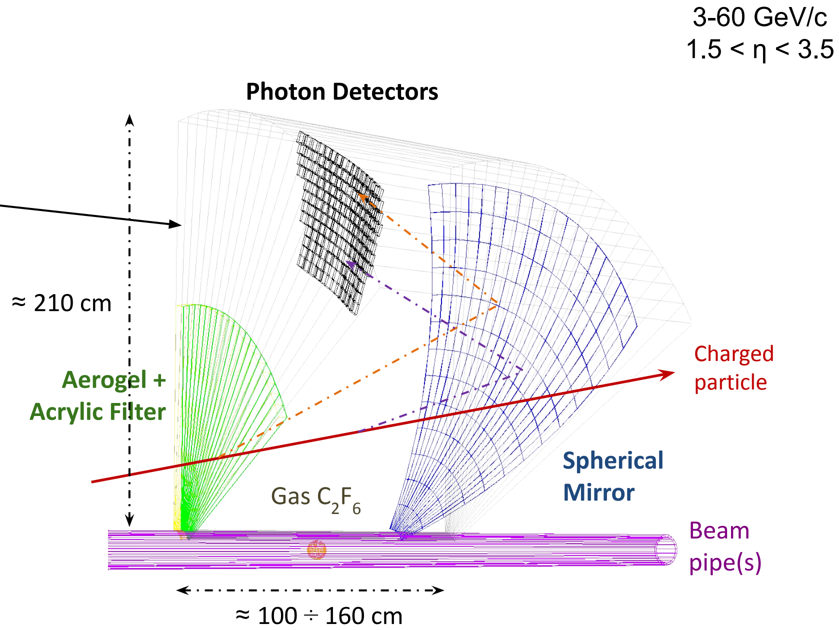
Status of SiPM photosensor technology

Roberto Preghenella

The dual-radiator (dRICH) for forward PID

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
  - ~ 3m^2 surface with photosensors (~ 300 k channels)
  - single-photon detection inside high B field (~ 1 T)
  - outside of acceptance, reduced constraints

SiPM readout option

no dedicated SiPM R&D for EPIC backward RICH
work being done within dRICH activities can in principle be applied on the e-side

SiPM option for RICH optical readout

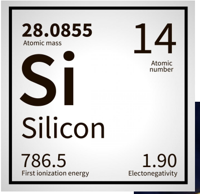
- **pros**
  - cheap
  - high photon efficiency
  - excellent time resolution
  - insensitive to magnetic field

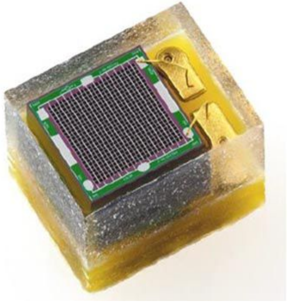
- **cons**

large dark count rates

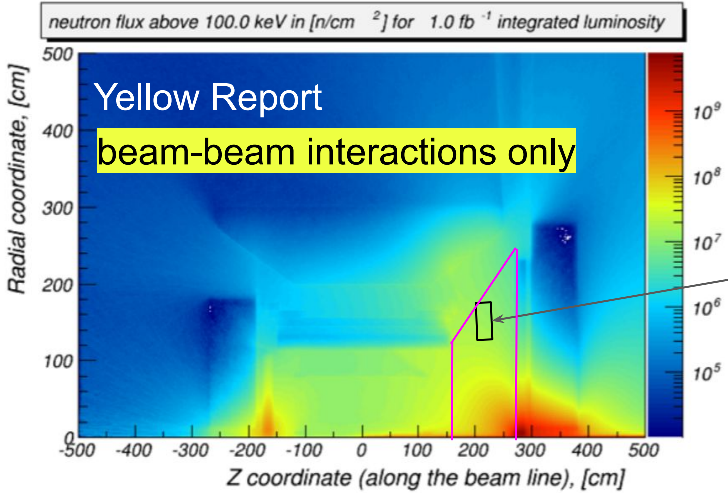
not radiation tolerant

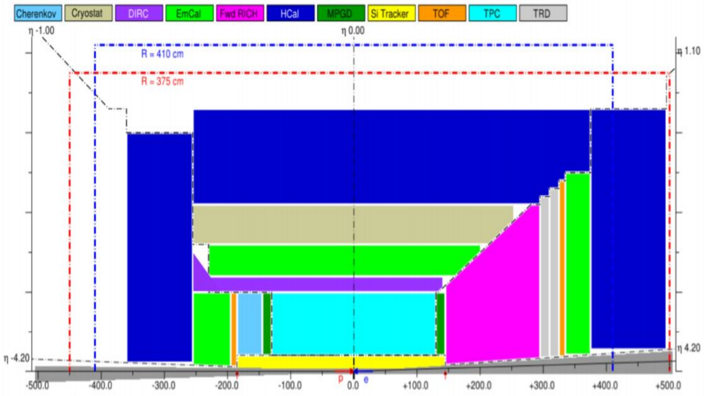
R&D focus on risk-mitigation strategies





Neutron fluxes and SiPM radiation damage





Most of the key physics topics discussed in the EIC White Paper [2] are achievable with an integrated luminosity of 10 fb^{-1} corresponding to 30 weeks of operations. One notable exception is studying the spatial distributions of quarks and gluons in the proton with polarized beams. These measurements require an integrated luminosity of up to 100 fb^{-1} and would therefore benefit from an increased luminosity of $10^{34}\text{cm}^{-2}\ \text{sec}^{-1}$.

possible location of dRICH photosensors
neutron fluence for 1 fb^{-1} → 1-5 10^7 n/cm^2 (> 100 keV ~ 1 MeV n_{eq})

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

is radiation load at e-side RICH similar?
looks like it is not larger, need to look at

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

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

→ better do study in smaller steps of radiation load

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

SiPM radiation damage and mitigation strategies

Radiation damages increase currents, affects V_{bd} and increase DCR
With very high radiation loads can bring to baseline loss, but…
does not seem to be a problem up to 10^{11} n_{eq}/cm^2 (if cooled, T = -30 C)

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

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

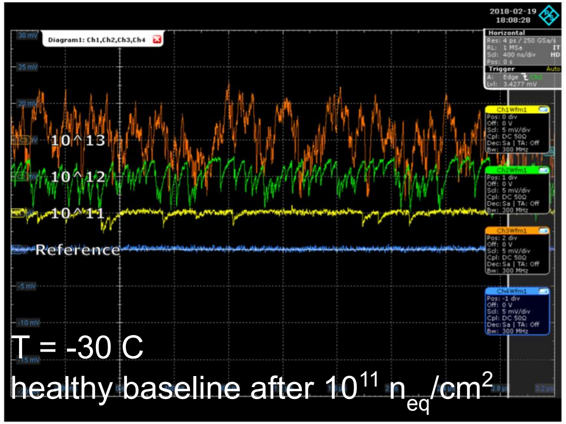
Key point for R&D on RICH optical readout with SiPM:

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

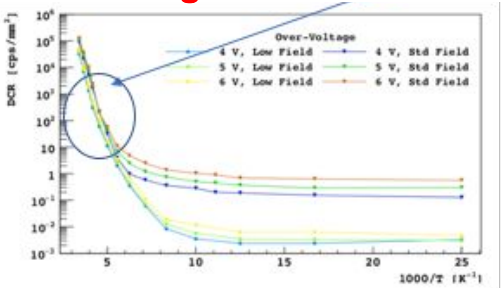
despite radiation damages

Calvi, NIM A 922 (2019) 243

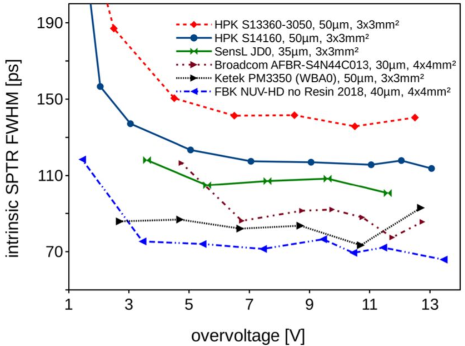
10^{11}

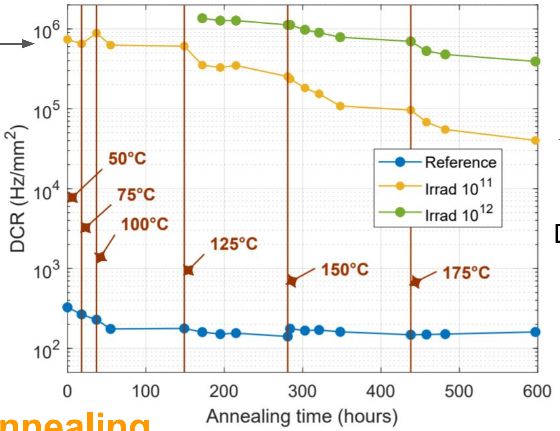


cooling



timing





20x less DCR

annealing

Open R&D questions before CD-3

- **sensor cooling**
  - mitigation of high DCR
  - decide type of cooling approach
    - thermoelectric
    - liquid / hybrid
  - critical for layout of detector plane
    - cooling / electronics on the back
    - dead area between sensor modules
  - also critical for engineering
    - material budget
    - space and services
- **high-temperature annealing**
  - mitigation of radiation damage
  - definition of annealing protocol
    - in-situ approaches
    - oven annealing needs unmounting
  - critical for engineering
    - services for Joule annealing (power)
    -
- **high data-rate readout**
  - mitigation of required bandwidth
  - usage of dedicated electronics
    - fast bunch-crossing gating / inhibit
    - online data reduction / interaction tagger (~ trigger)

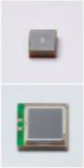
R&D status

Milestones FY 2022

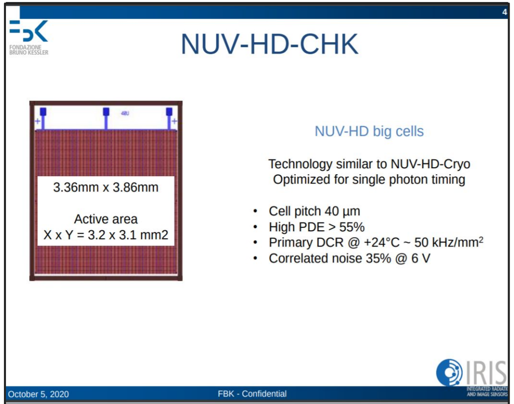
- **[COMPLETED]** automated setup for SiPM characterization in climatic chamber (9/2022)
- **[PARTIAL]** Comparative assessment of commercial (and prototypes not yet available on the market) of SiPM performance after irradiation (2/2023)
- **[PARTIAL]** Definition of an annealing protocol (2/2023)

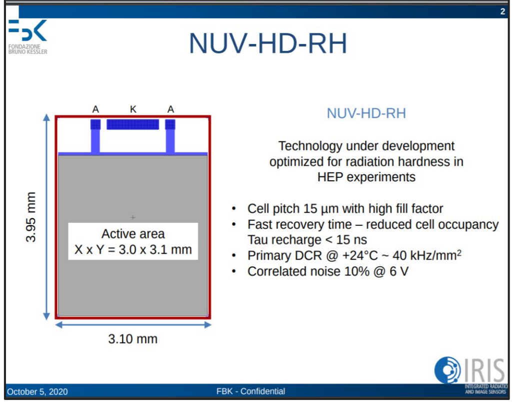
- **acquired SiPM samples**
  - from different manufacturers
  - and of different types
- **developed electronic boards**
  - SiPM carrier boards
  - adapter boards
  - ASIC readout board
- **irradiation campaign(s)**
  - with proton beams
  - increasing NIEL: 10^9 10^{10} and 10^{11} neq
- **high-temperature annealing**
  - with industrial oven
  - up to T = 150 C
  - exploring alternative solutions
- **characterisation and operation**
  - low temperature operation
  - I-V characterisation
  - DCR and signal sampling
  - readout with ALCOR ASIC
  - pulsed LED light response

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



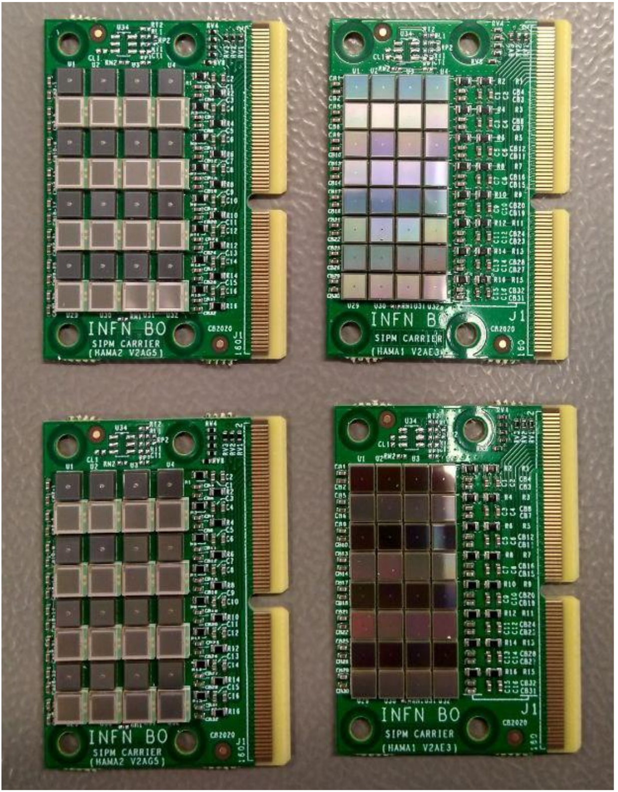


multiple producers: different technologies, SPAD dimensions, V_{bd}, electric field …

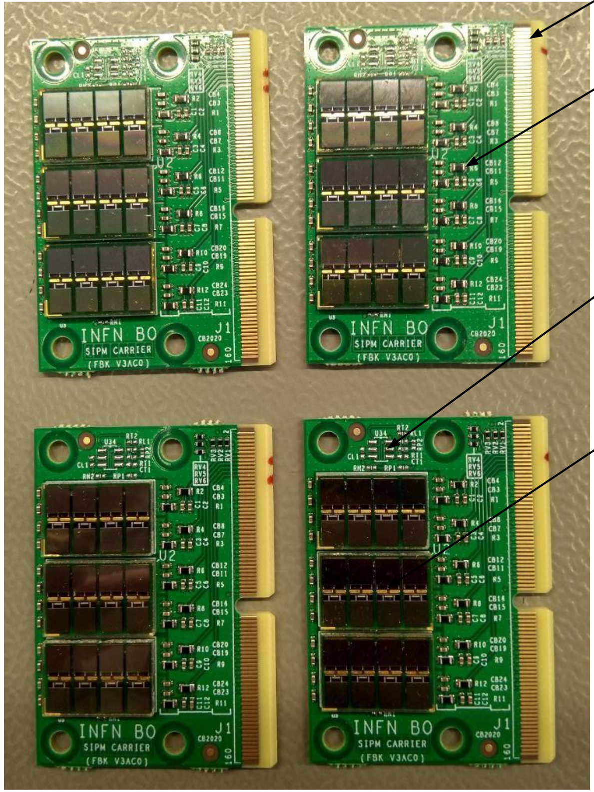
in collaboration with FBK since inception

SiPM custom carrier boards

8x4 matrices with commercial Hamamatsu



6x4 matrices with prototype FBK sensors



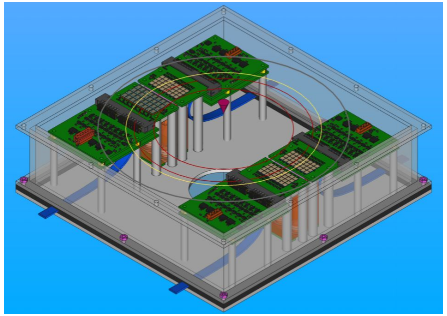
high-density edge connector

high-T grade FR4 for annealing up to 180 °C

temperature sensor for
operation with Peltier cooling

many metallic vias for heat conductivity
(Peltier cooling from the back)

prototype SiPM readout box



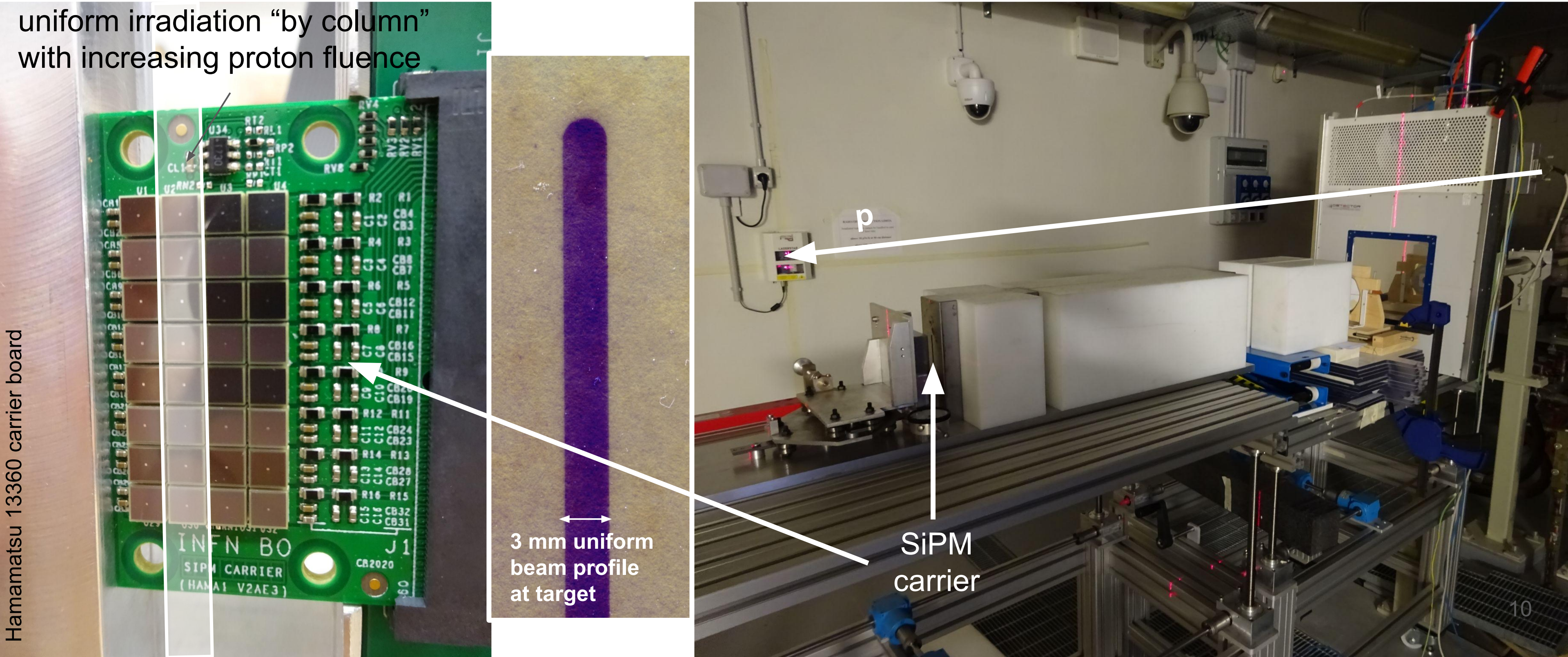
withstand irradiation, high-T annealing and low-T operation in form-factor usable for imaging in beam tests

Irradiation at Trento Proton-Therapy hall (TIFPA)

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

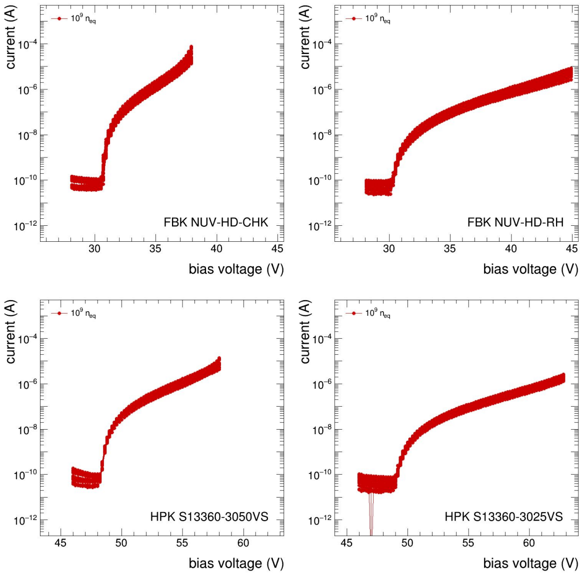
multiple types of SiPM: **Hamamatsu** commercial (13360 and 14160)
FBK prototypes (rad.hard and timing optimised)

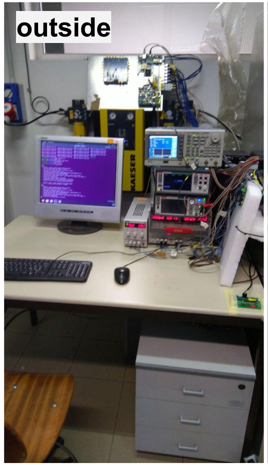
148 MeV protons → scattering system → collimation system → carrier board

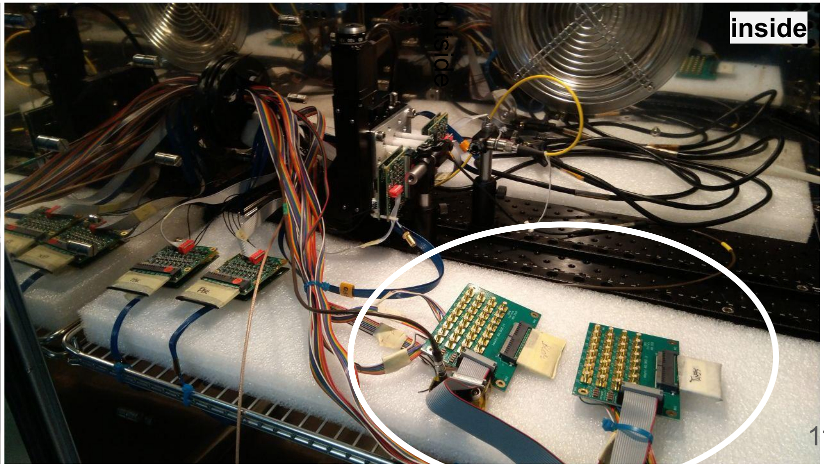


Current measurements

- **climatic chamber**
  low-temperature operation
  all reported measurements at T = -30 °C
- **2x 40-channel multiplexers**
  automatic measurement of 2x SiPM boards (64 channels)
- **source meter**

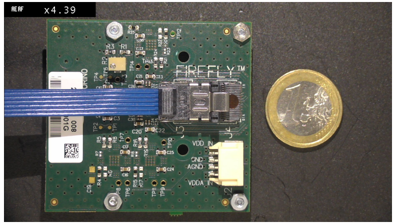


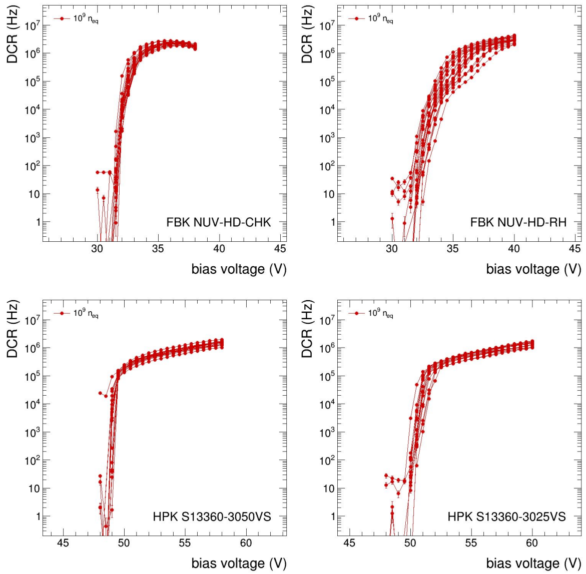


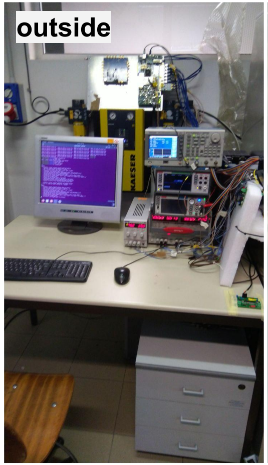


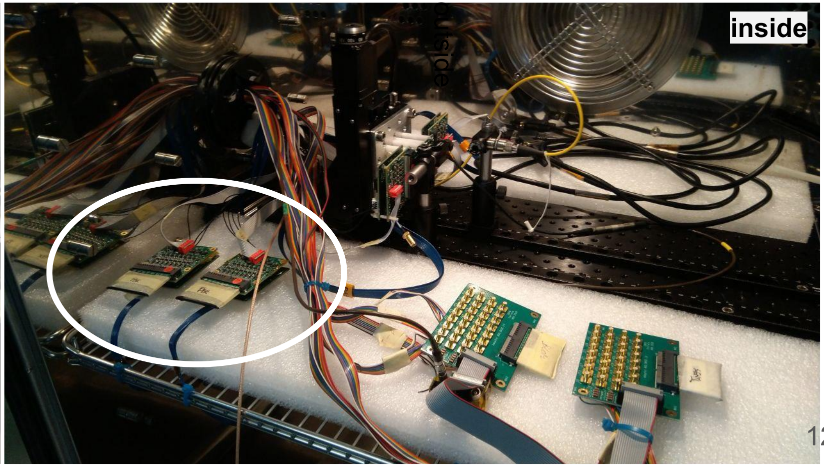
DCR measurements

- **climatic chamber**
  low-temperature operation
  all reported measurements at T = -30 °C
- **2x ALCOR-based front-end chain**
  automatic measurement of 2x SiPM boards (64 channels)
- **FPGA (Xilinx) readout**



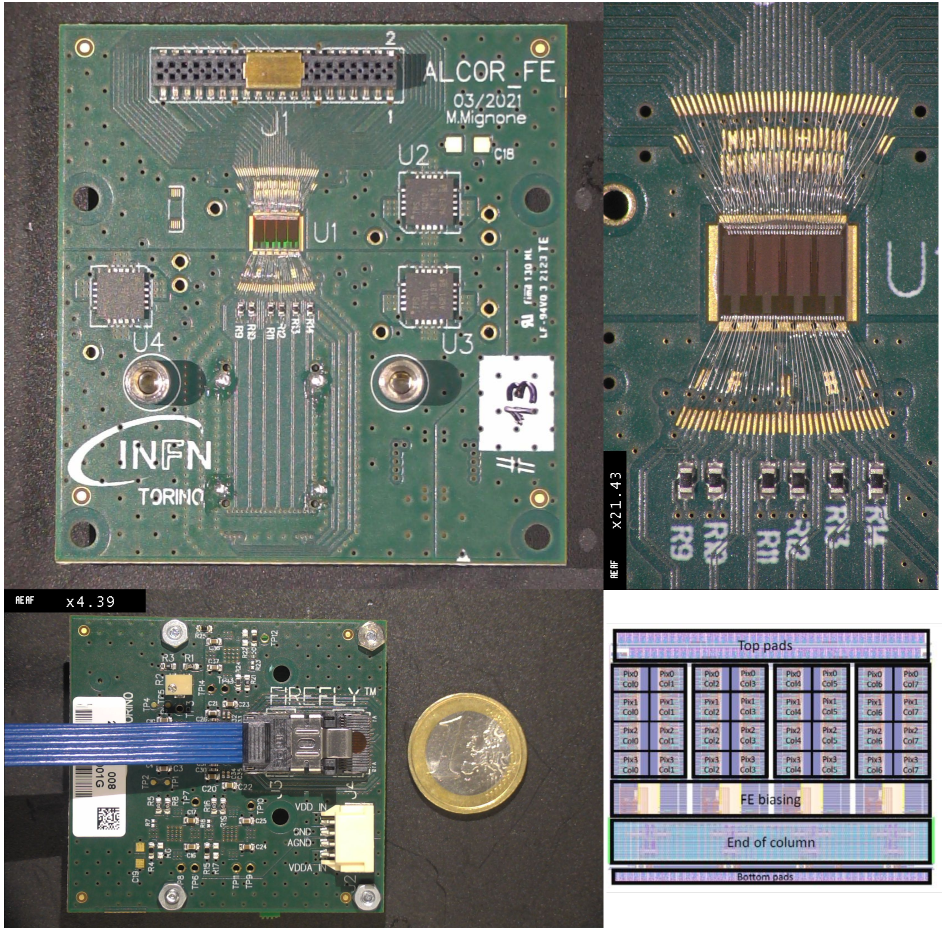






INFN

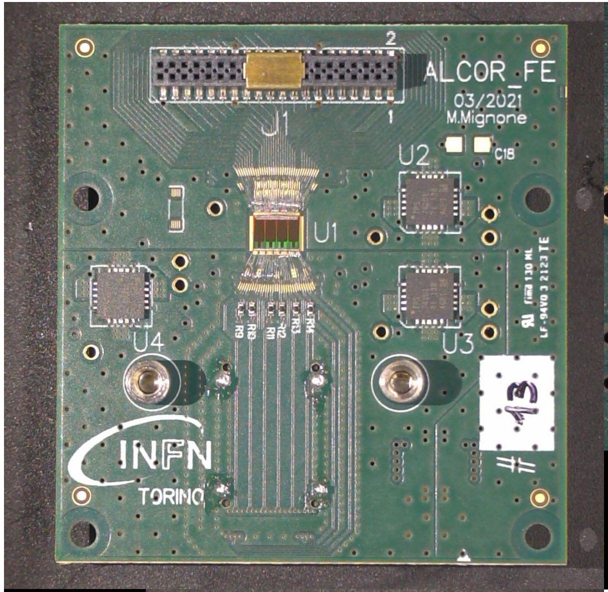
ALCOR: A Low Power Chip for Optical sensor Readout

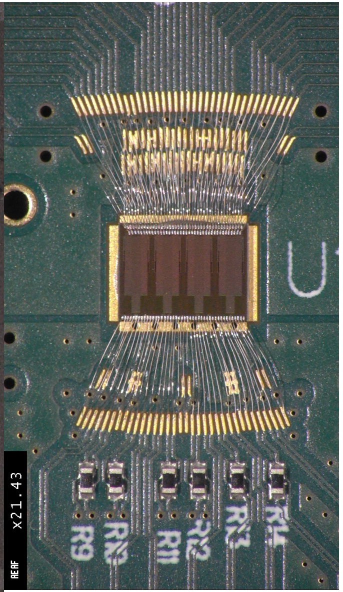


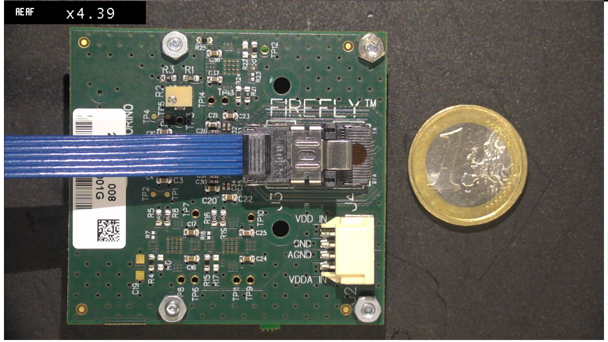
developed by INFN-TO for DarkSide

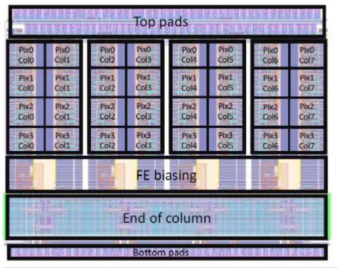
- 32-pixel matrix mixed-signal ASIC
- the chip performs
  - signal amplification
  - conditioning and event digitisation
- each pixel features
  - dual-polarity front-end amplifier
    - low input impedance
    - 4 programmable gain settings
  - 2 leading-edge discriminators
  - 4 TDCs based on analogue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

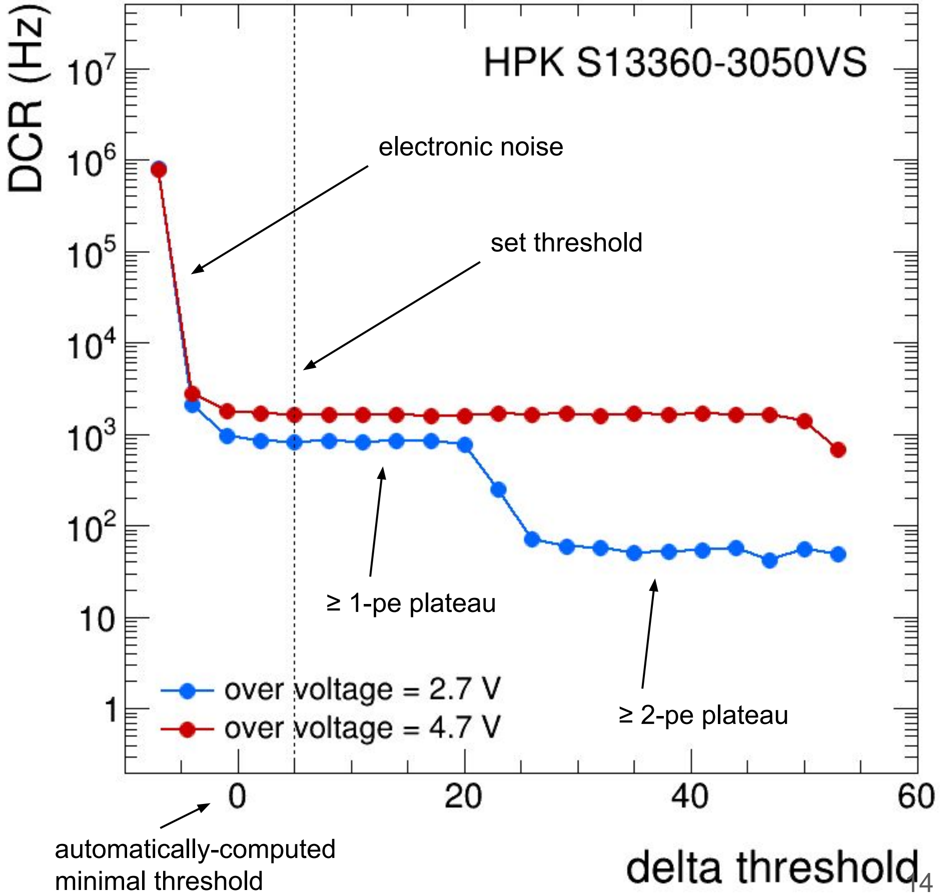
Photon counting with ALCOR



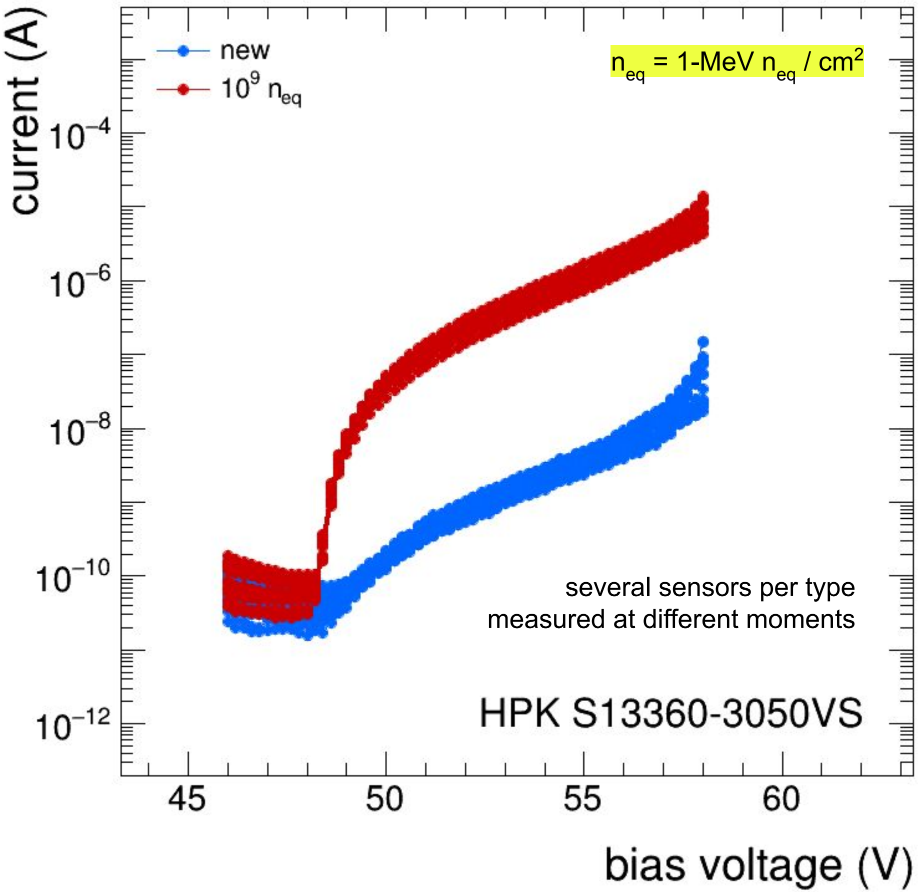


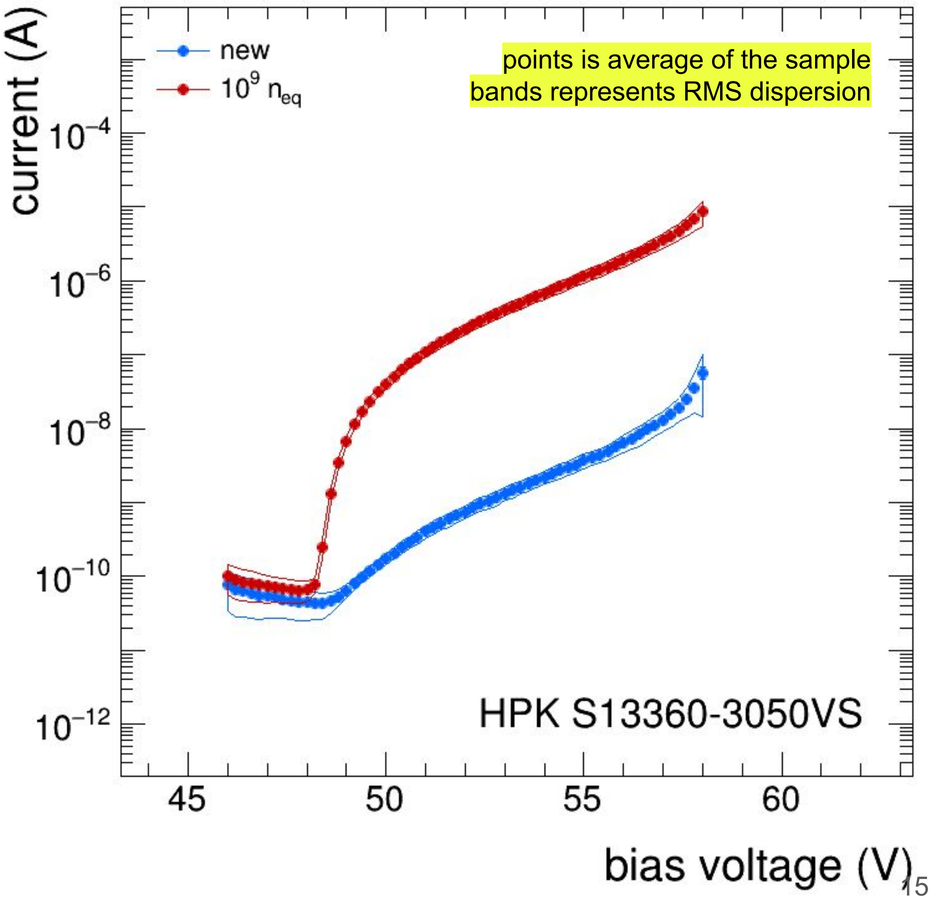




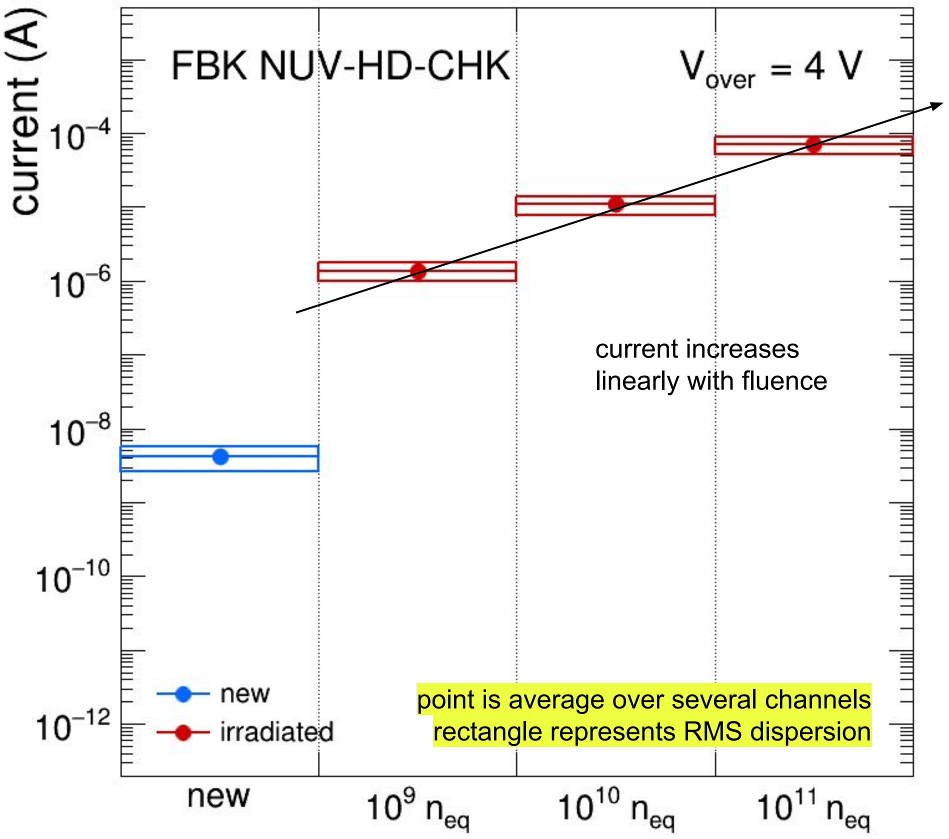


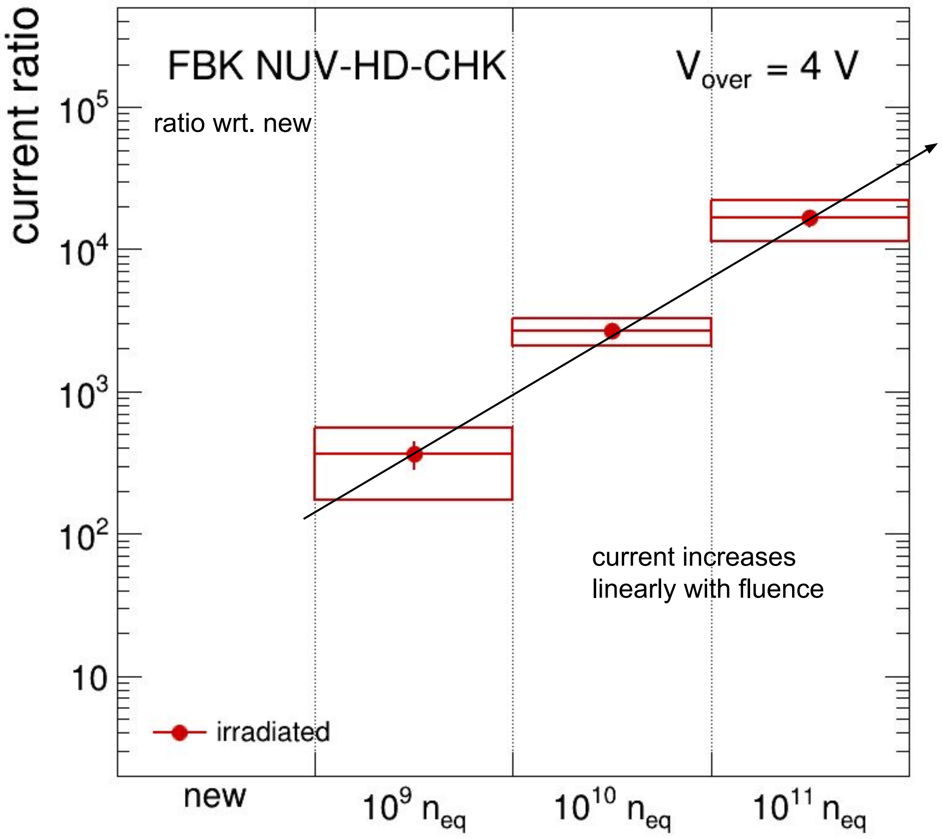
Measurements over large sensor samples



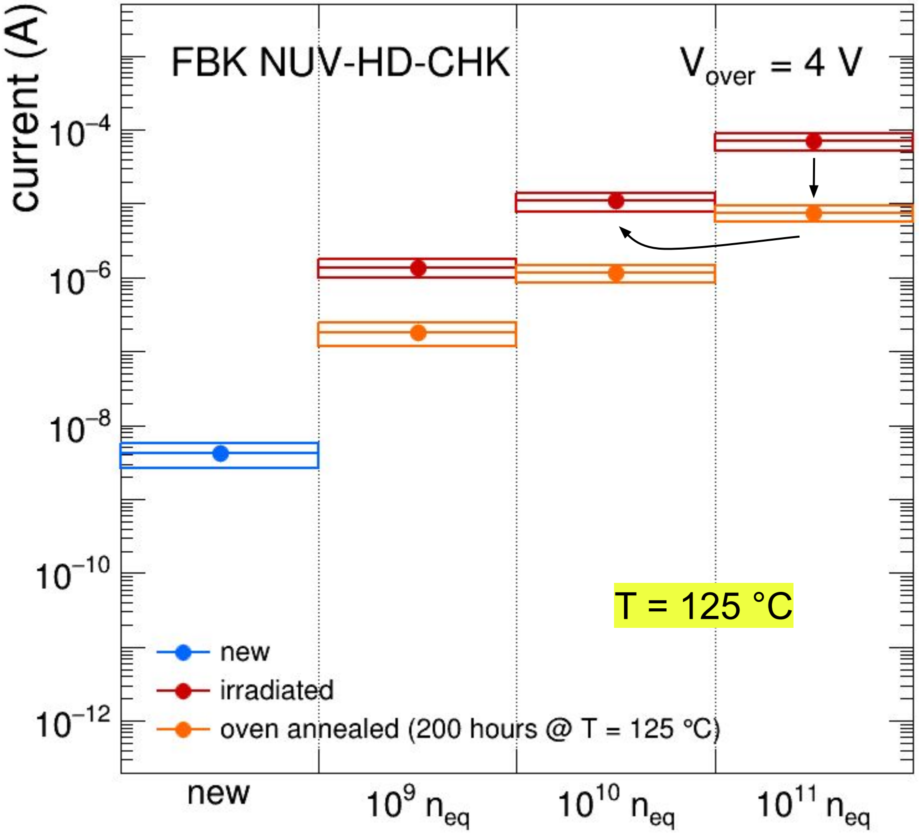


Current vs. delivered fluence



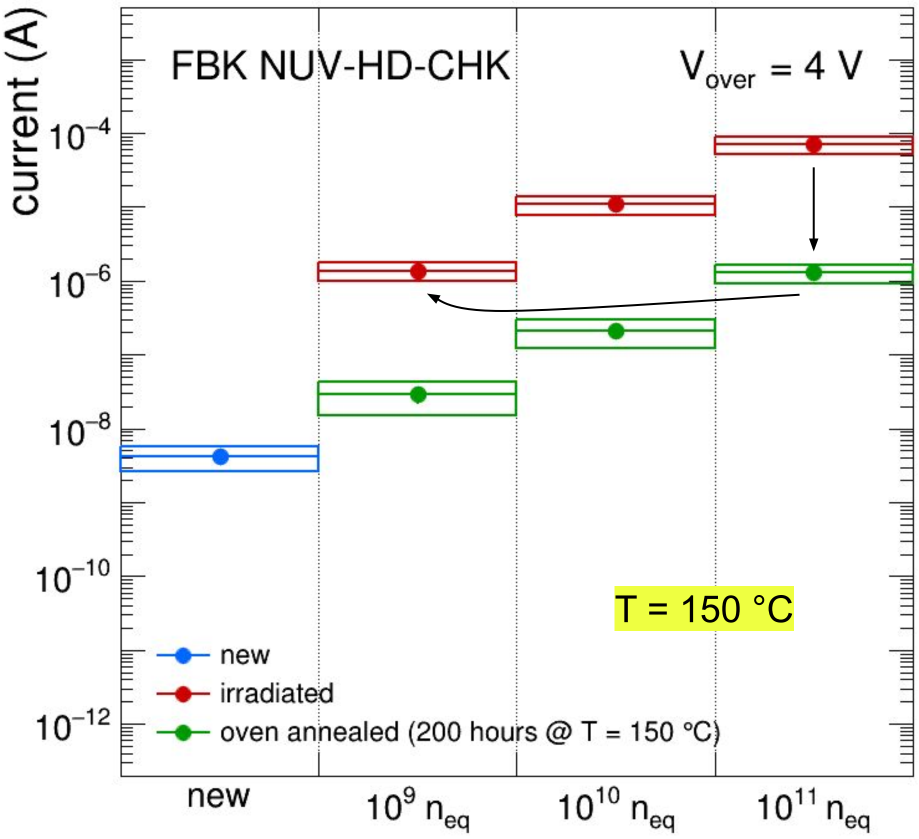


High-temperature annealing recovery (cycle #1)



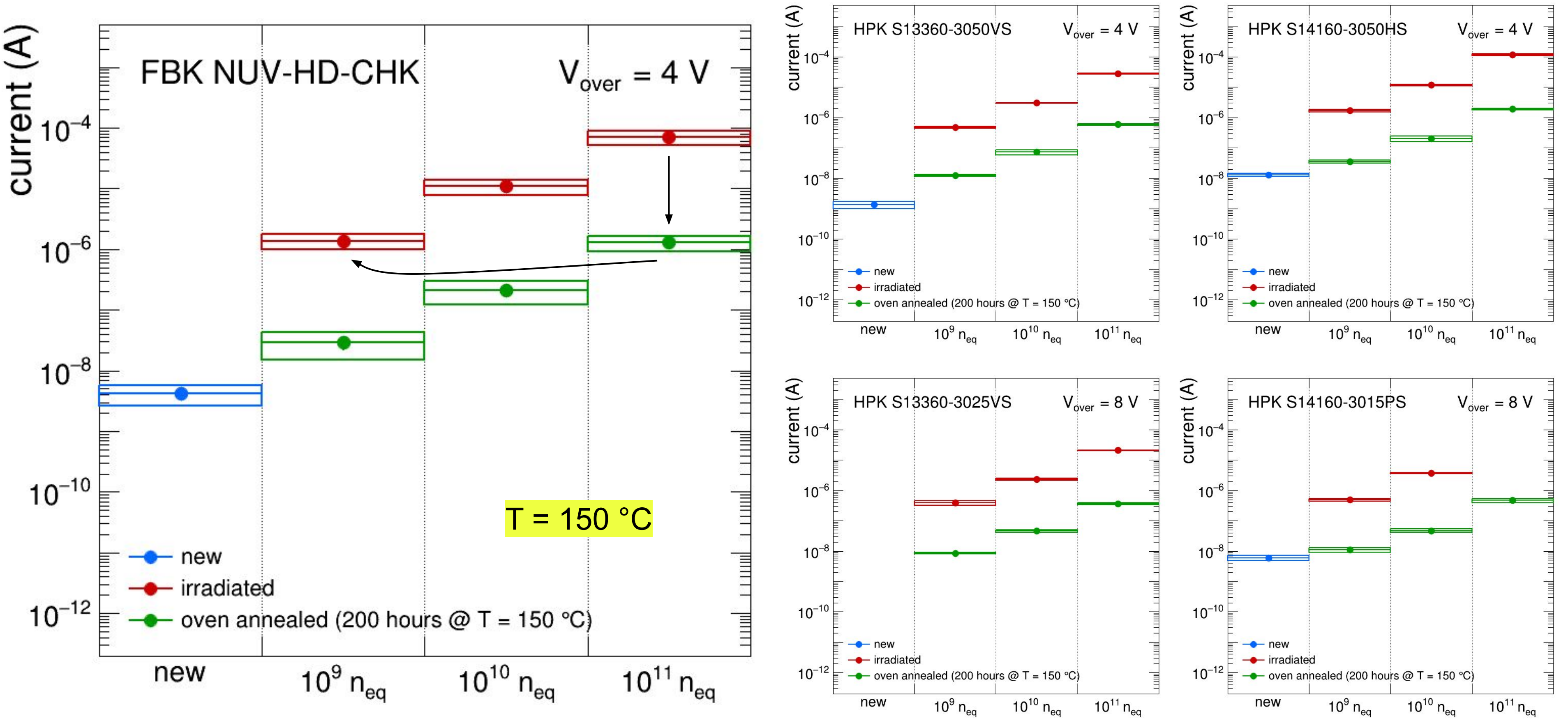
~ 10x current reduction
sensor functions as if it
received ~ 10x less fluence

High-temperature annealing recovery (cycle #2)



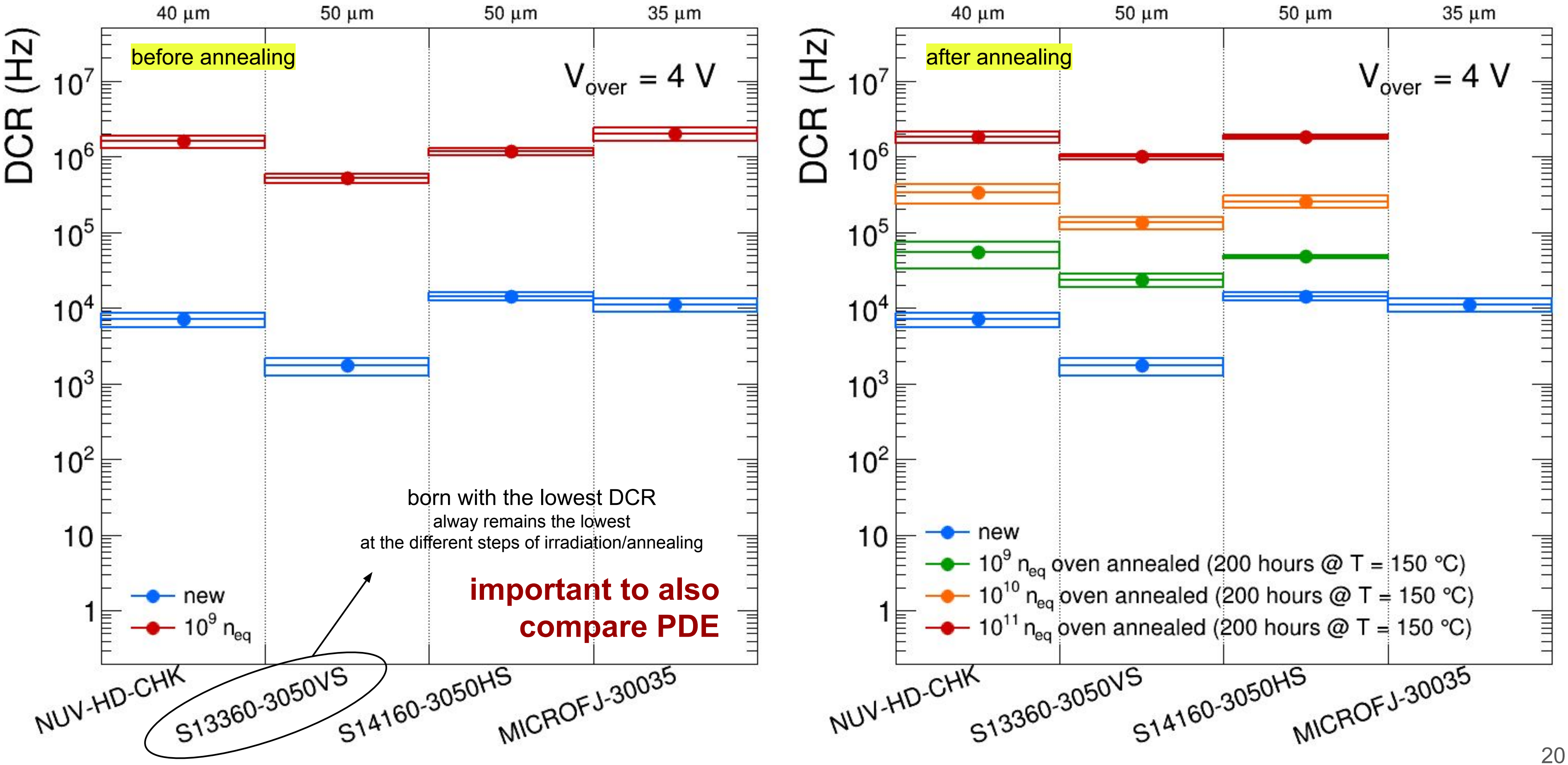
<u>~ 100x current reduction</u>
sensor functions as if it received ~ 100x less fluence

High-temperature annealing recovery (cycle #2)

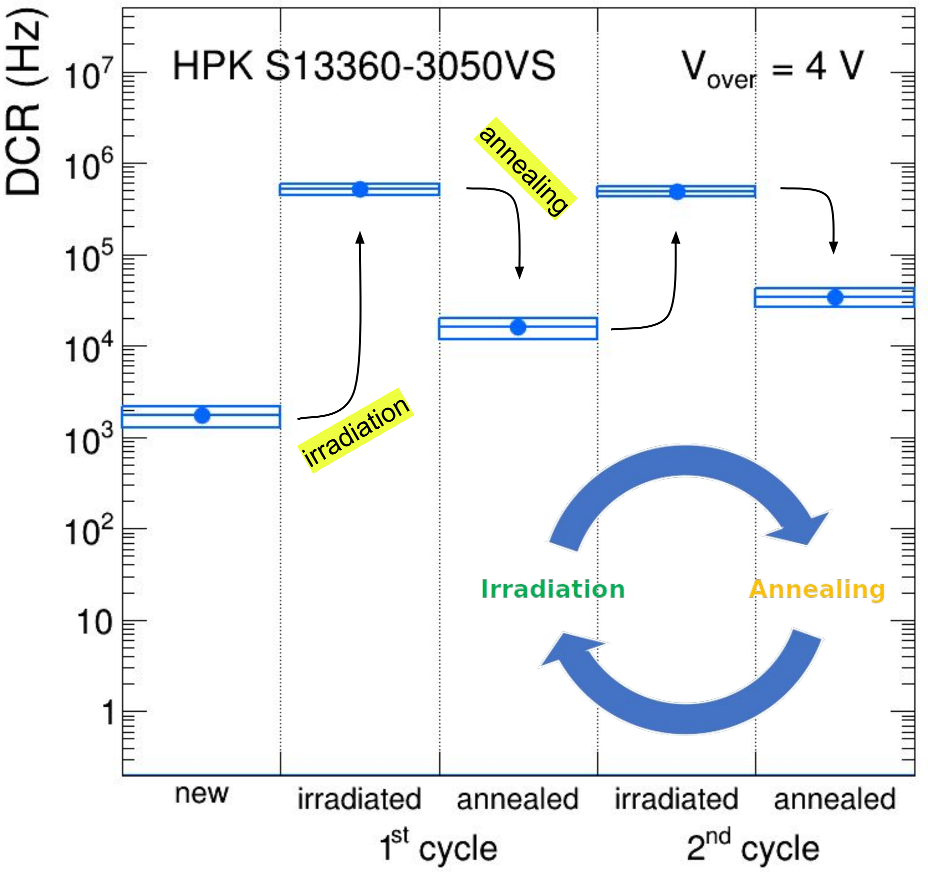


similar observation with different Hamamatsu sensors

DCR after irradiation and annealing



Repeated irradiation-annealing cycles

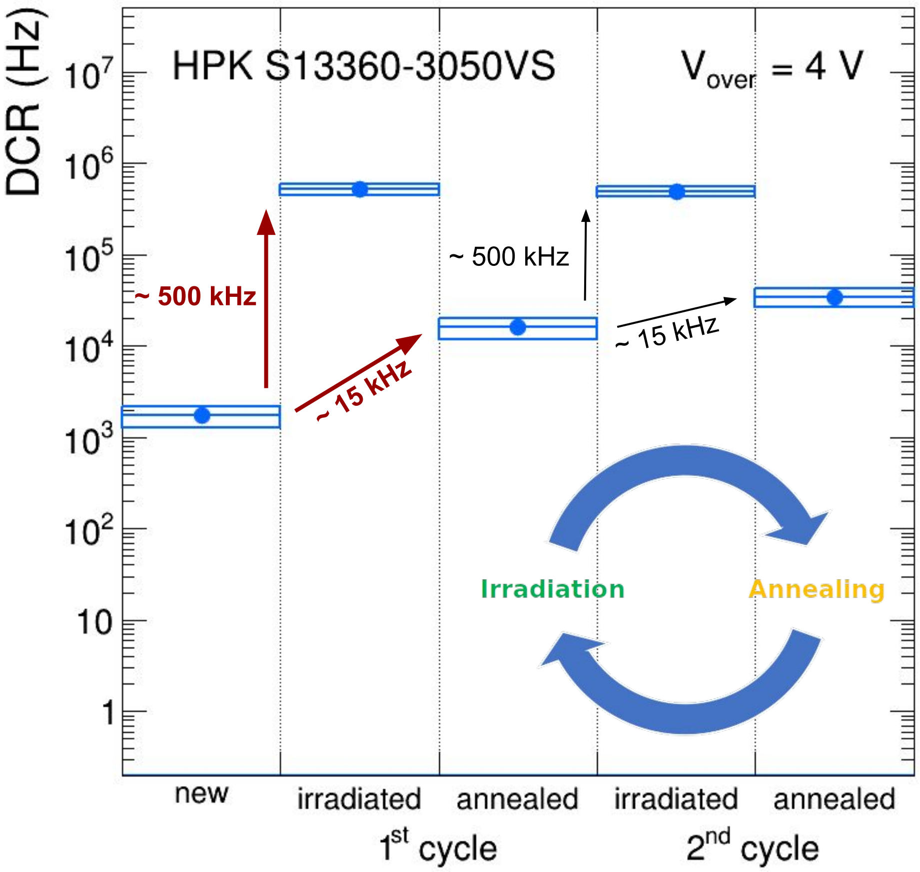


test reproducibility of repeated irradiation-annealing cycles

simulate a realistic experimental situation

- campaign is ongoing
  - partial results reported here
- 2 cycles performed so far
  - irradiation fluence/cycle of 10^9 n_{eq}
  - annealing in oven for 150 hours at 150 °C
- interleaved with full characterisation
  - new
  - after each irradiation
  - after each annealing

Repeated irradiation-annealing cycles



test reproducibility of repeated irradiation-annealing cycles

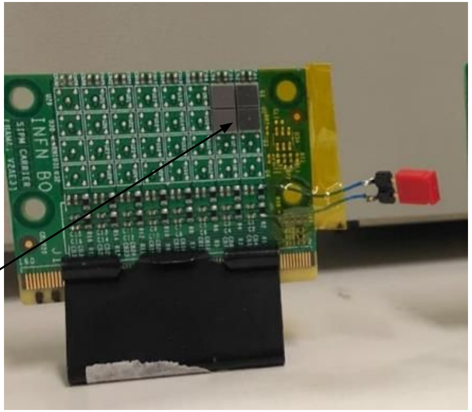
simulate a realistic experimental situation

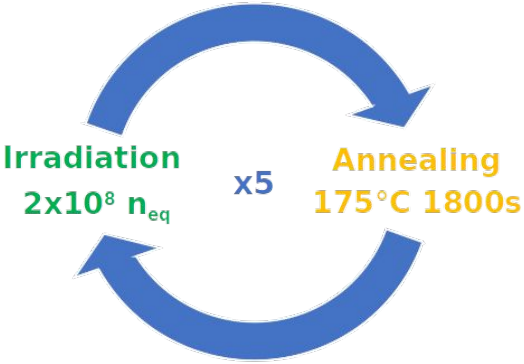
- consistent irradiation damage
  - DCR increases by ~ 500 kHz (@ Vover = 4)
  - after each shot of 10^9 n_{eq}
- consistent residual damage
  - ~ 15 kHz (@ Vover = 4) of residual DCR
  - builds up after each irradiation-annealing

annealing cures same fraction of newly-produced damage

~ 97% for HPK S13360-3050 sensors

Online annealing

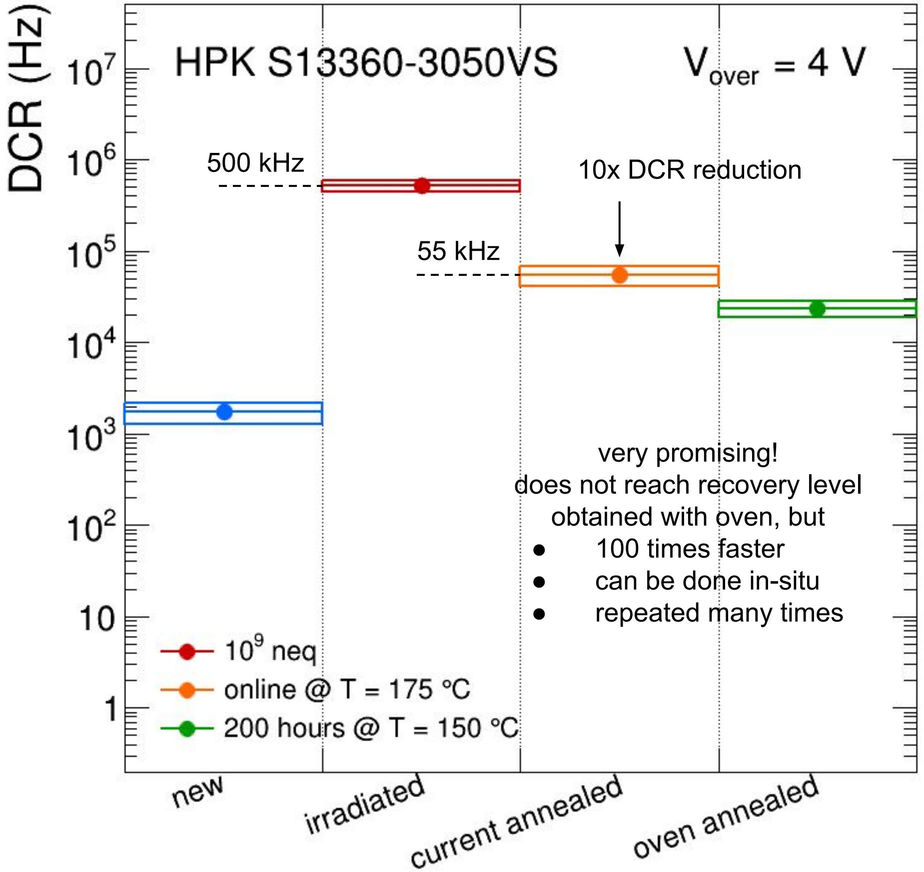




explore solutions for in-situ annealing

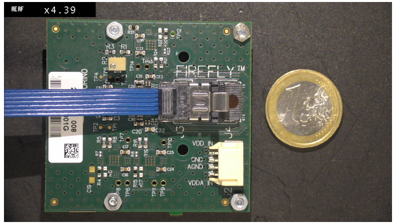
- total fluence of 10^9 n_{eq}
  - delivered in 5 chunks
  - each of 2 10^8 n_{eq}
- interleave by annealing
  - forward bias, ~ 1 W / sensor
  - T = 175 °C, thermal camera
  - 30 minutes
- preliminary tests
  - Hamamatsu S13360-3050

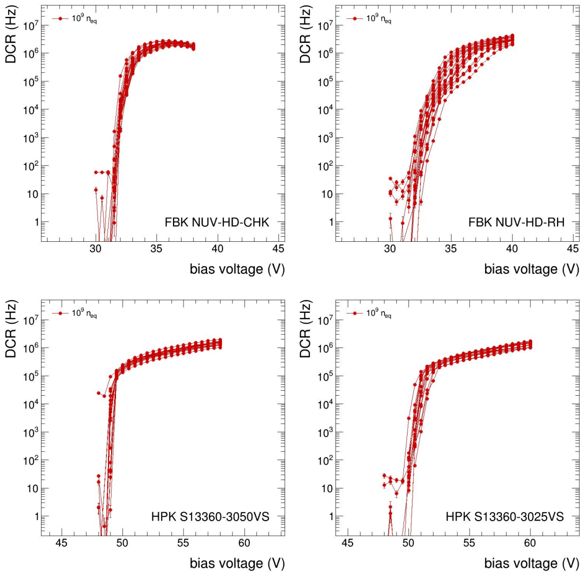
Online annealing

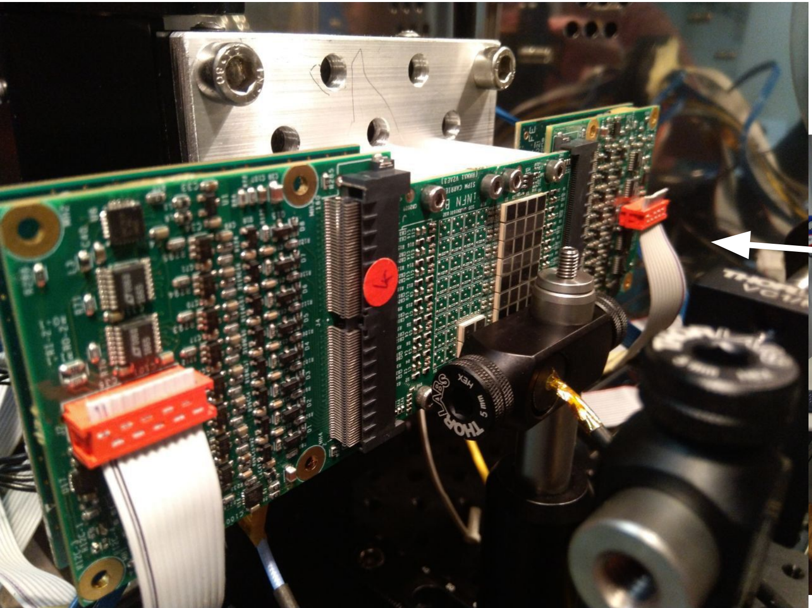


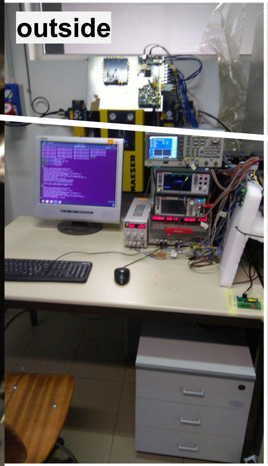
LED measurements

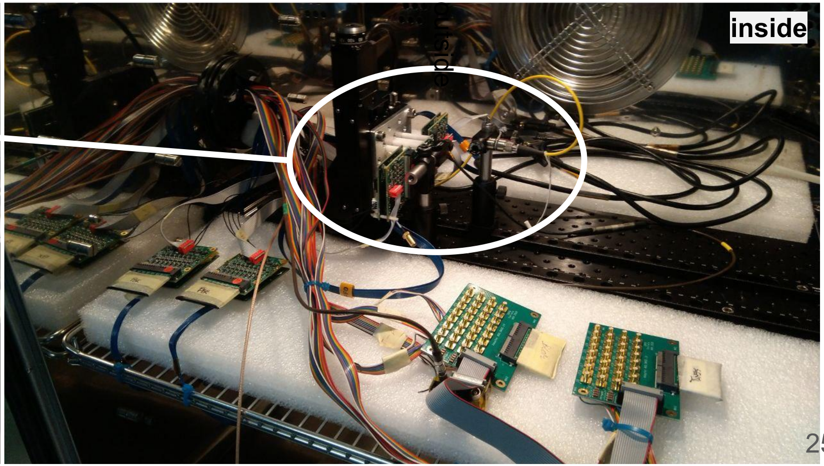
- **climatic chamber**
  low-temperature operation
  all reported measurements at T = -30 °C
- **arbitrary function generator**
  pulse to LED and readout (trigger)
- **2x ALCOR-based front-end chain**
  automatic measurement of 2x SiPM boards (64 channels)
- **FPGA (Xilinx) readout**



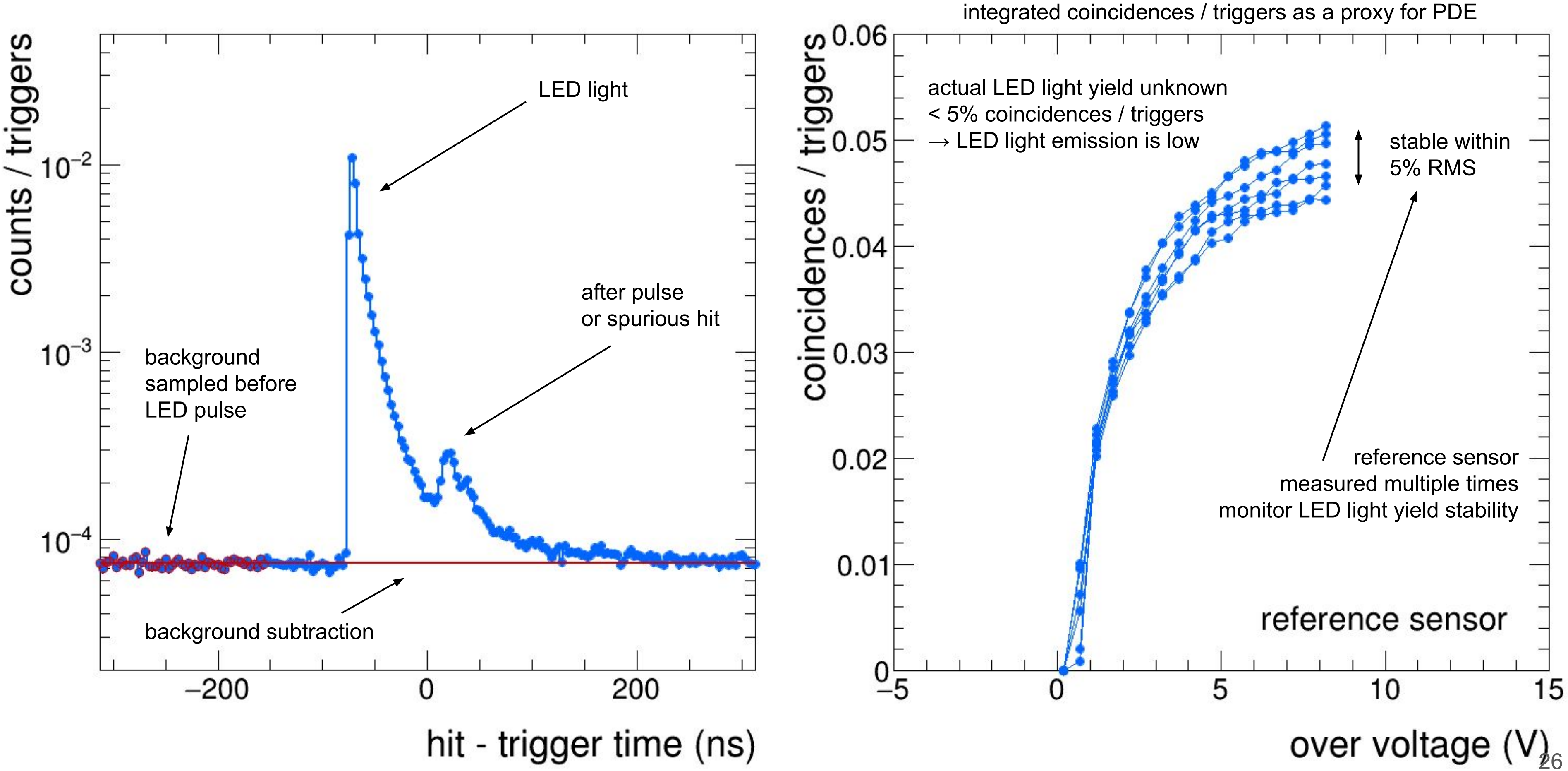




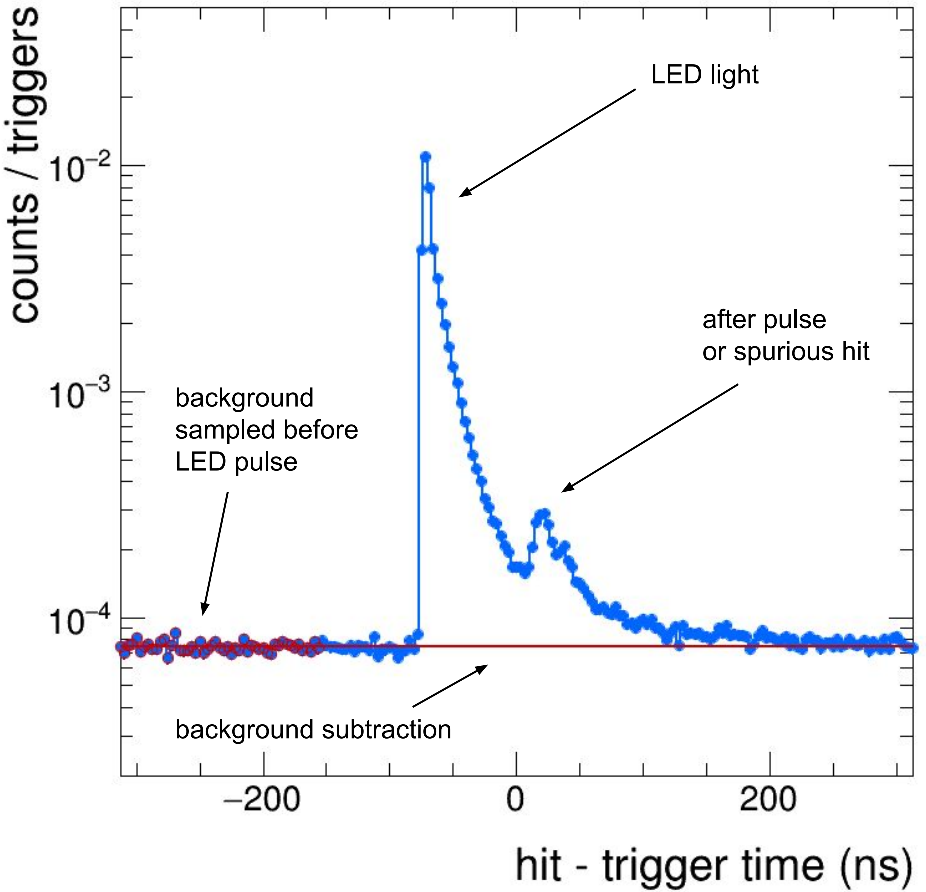


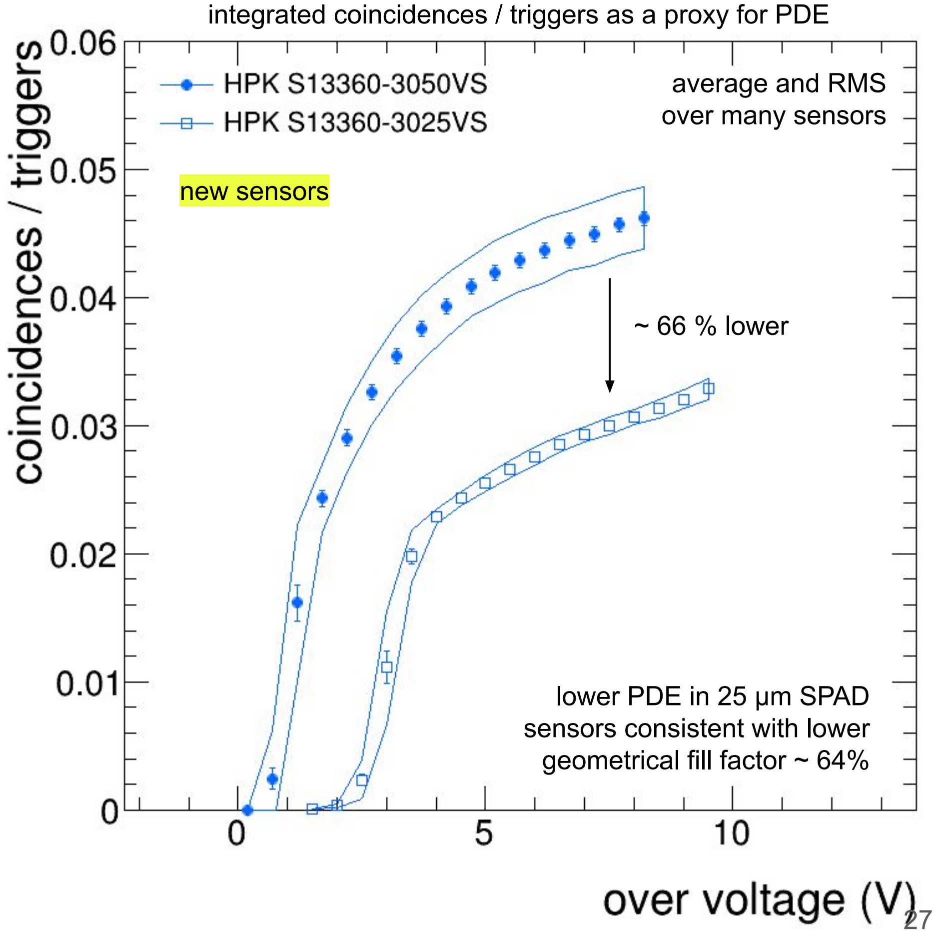


Light response with pulsed LED

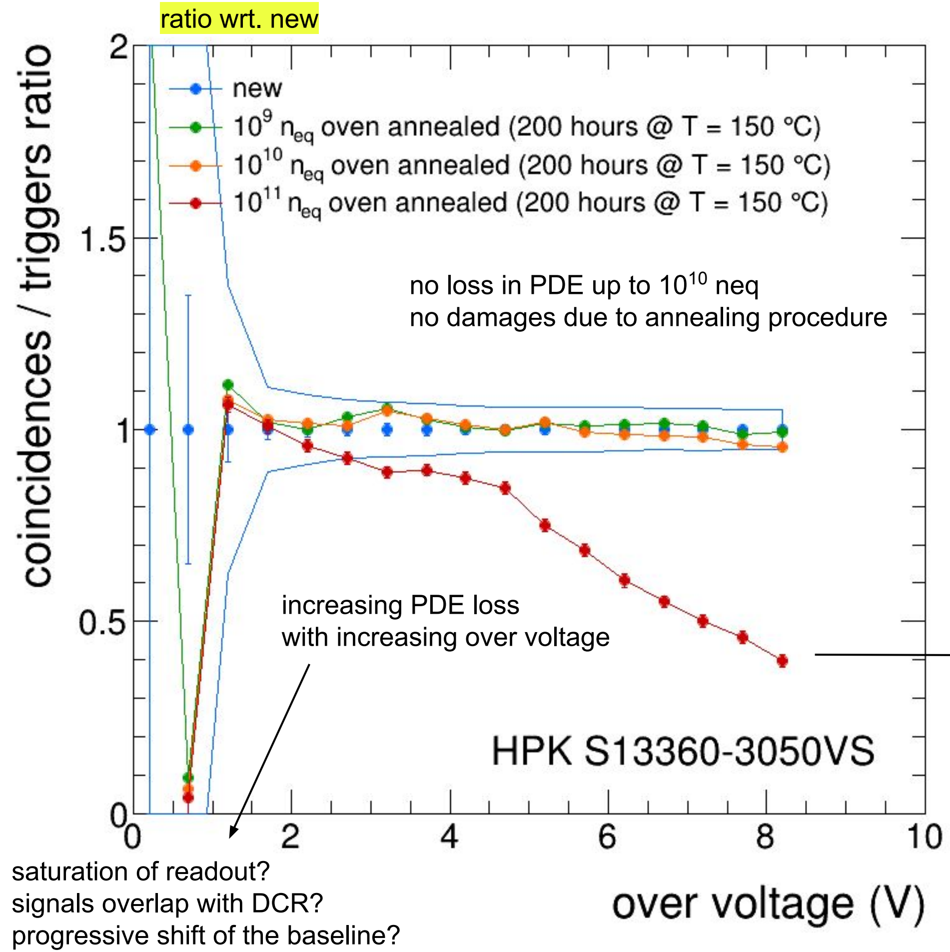


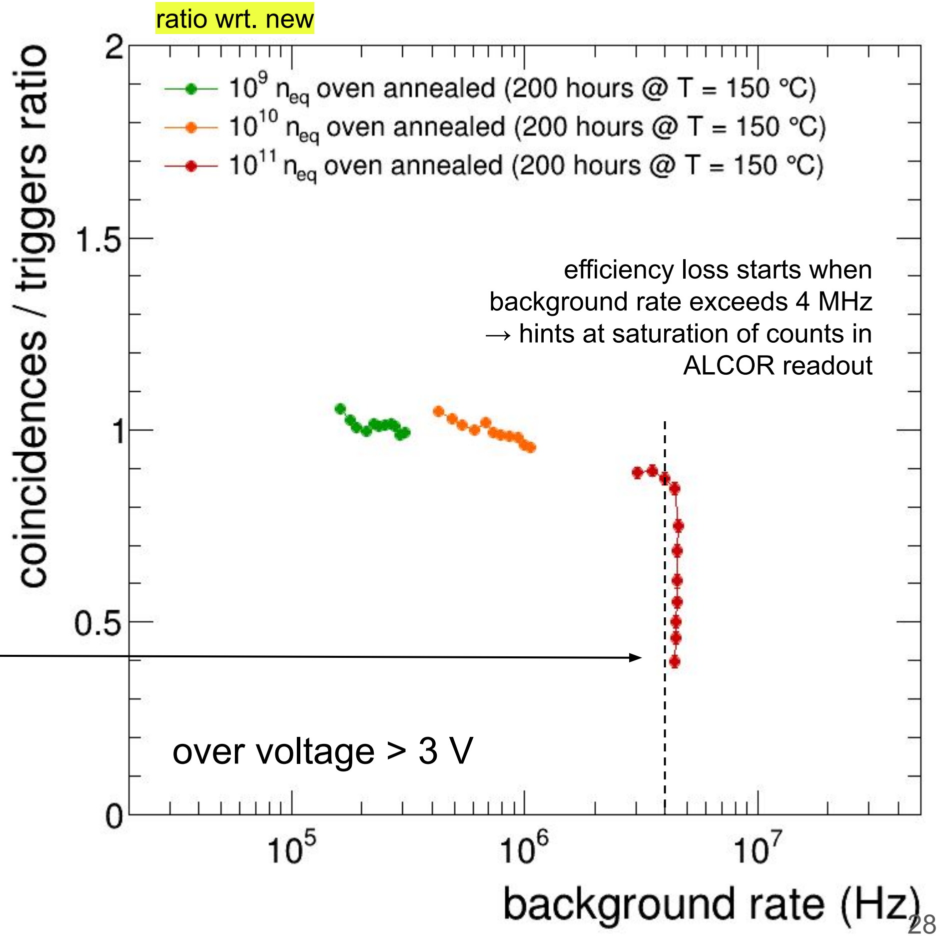
Light response with pulsed LED



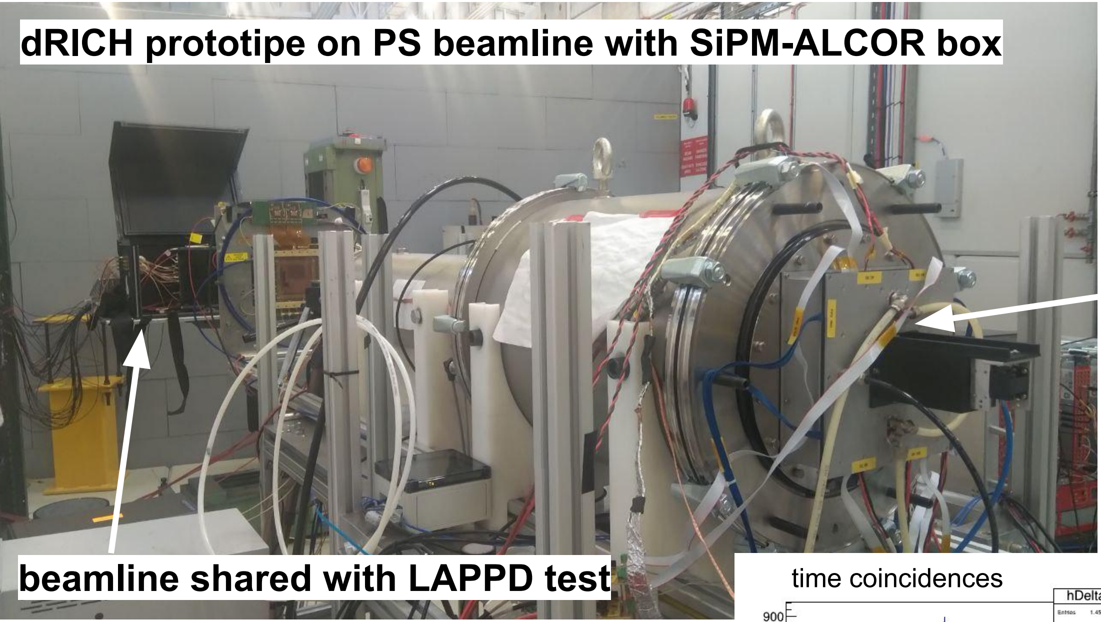


Light response after irradiation and annealing

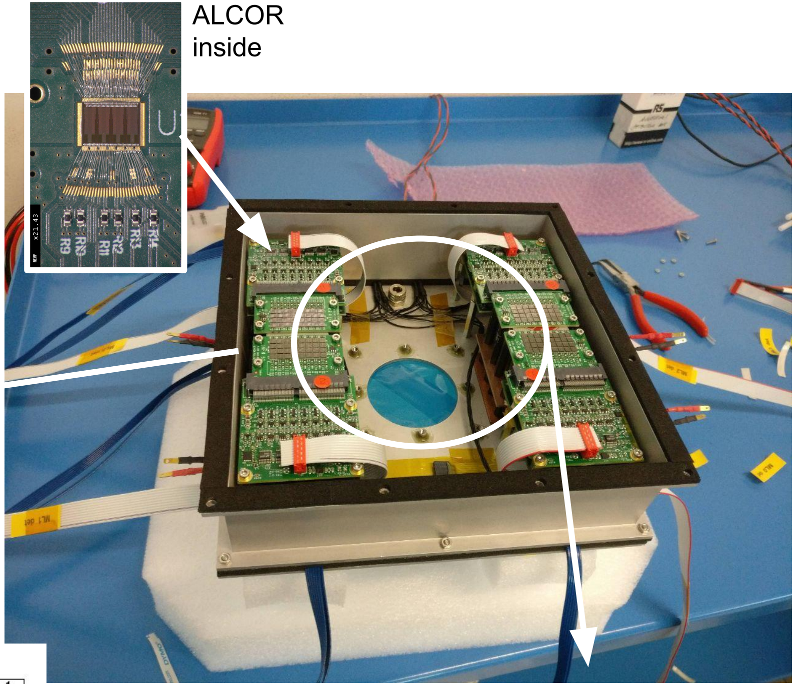




Test beam at CERN just concluded



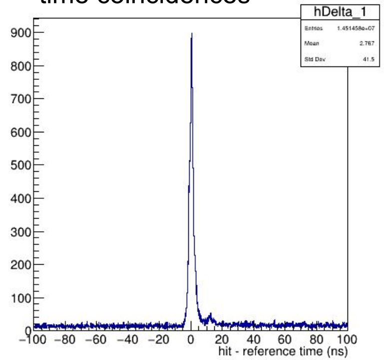
ALCOR
inside



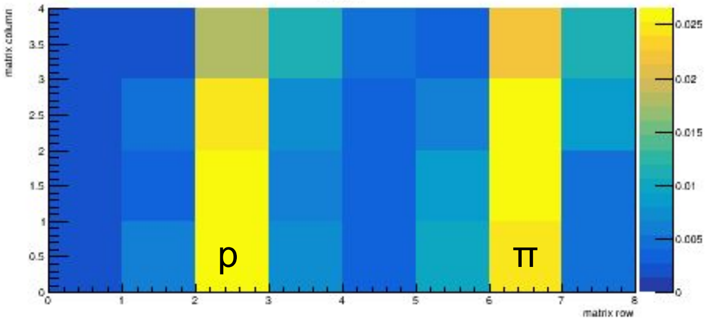
successful operation of SiPM

- all sensors were irradiated (up to 10^{10}) and annealed (oven)
- complete prototype readout chain based on ALCOR-v1

time coincidences



8 GeV positive beam (aerogel rings)



Plans for FY 2023

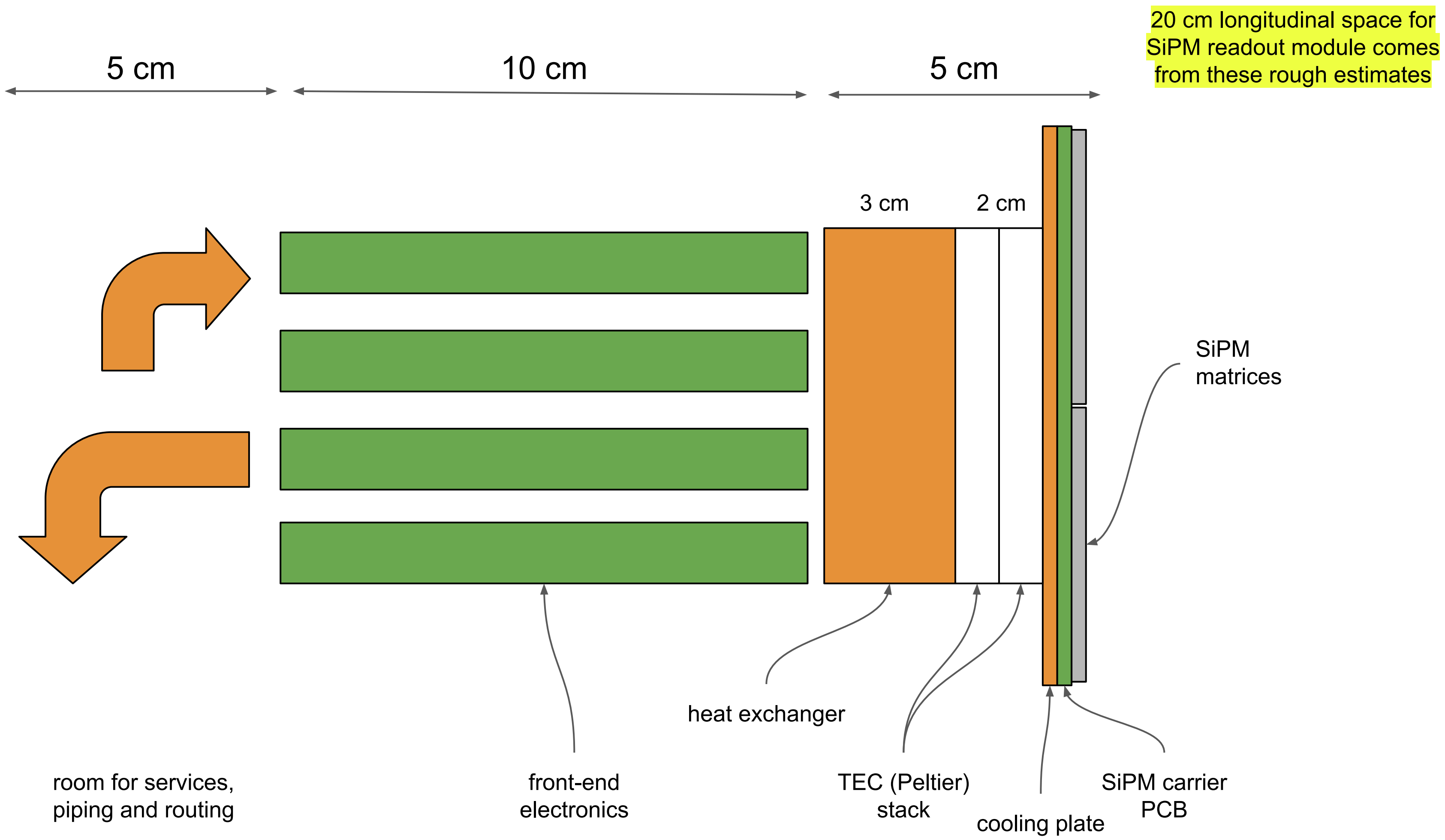
Milestones FY 2023

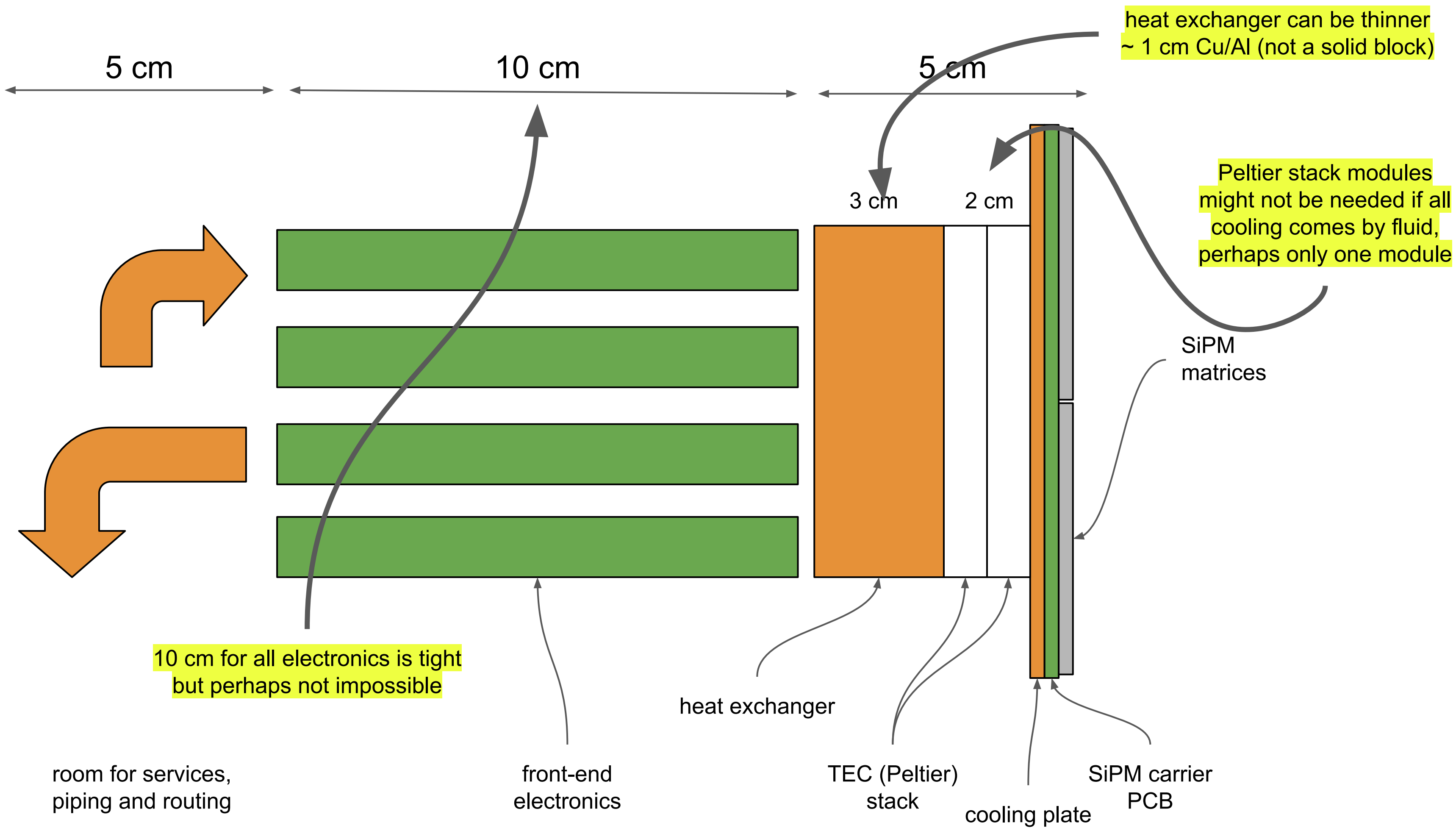
critical results for pre-TDR

- Timing measurement of irradiated (and annealed) sensors (6/2023)
- Comparison of the results achieved with proton and neutron irradiation sources (8/2023)
- Study of annealing in-situ technique with a proposed model selected as baseline for the pre-TDR (9/2023)

- **single-photon time resolution**
  - of full SiPM-ALCOR readout chain
    - no capacity to measure it so far
  - critical to set performance simulation
- **alternative annealing solutions**
  - so far done with industrial oven (days)
  - address ideas for faster / in-situ recovery
    - exploration started, promising
    - critical to become structured R&D
- **irradiation campaigns**
  - so far only with 150 MeV protons
  - critical to test neutron damage
    - might be topologically different
    - effectiveness of annealing
    - test NIEL damage hypothesis
  - irradiation needed to test new annealings
- **operation at low temperature**
  - so far characterisation in climatic chamber
    - compare results with TEC (Peltier) cooling
  - explore alternative solution to TEC
    - liquid, hybrid (liquid + TEC) approaches
- **development of new sensors**
  - within INFN-FBK collaboration agreement
    - critical for procurement risk mitigation
  - reduction of DCR
    - field / thickness optimisation
    - exploration of advanced microlensing
  - development of “monolithic” SiPM sensor array
    - wire bonded, cost reduction

preliminary notes on dimensions of SiPM readout unit


20 cm longitudinal space for
SiPM readout module comes
from these rough estimates
5 cm
10 cm
5 cm
3 cm
2 cm
SiPM
matrices
heat exchanger
room for services,
piping and routing
front-end
electronics
TEC (Peltier)
stack
cooling plate
SiPM carrier
PCB


heat exchanger can be thinner
~ 1 cm Cu/Al (not a solid block)
5 cm
10 cm
5 cm
3 cm
2 cm
Peltier stack modules
might not be needed if all
cooling comes by fluid,
perhaps only one module
SiPM
matrices
10 cm for all electronics is tight
but perhaps not impossible
heat exchanger
room for services,
piping and routing
front-end
electronics
TEC (Peltier)
stack
cooling plate
SiPM carrier
PCB