A SiPM-based optical readout system for the EIC dual-radiator RICH

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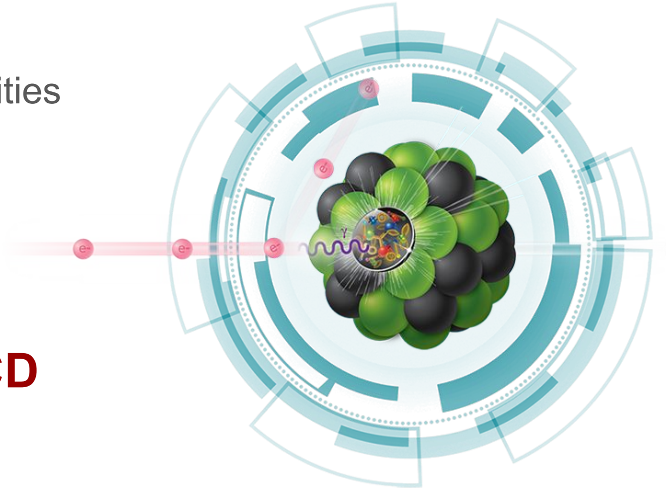
The Electron-Ion Collider

a machine that will unlock the secrets of the strongest force in Nature

is a future electron-proton and electron-ion collider to be constructed
in the United States in this decade and foreseen to start operation in 2030

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

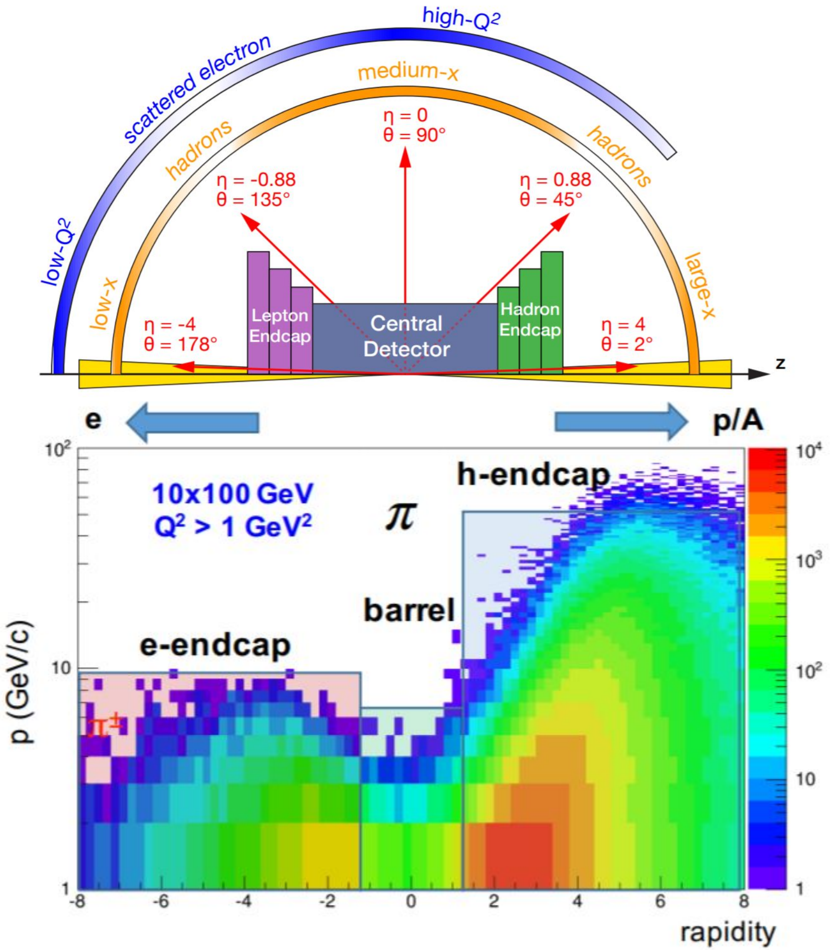


www.bnl.gov/eic

Particle identification at EIC

one of the major challenges for the detectors

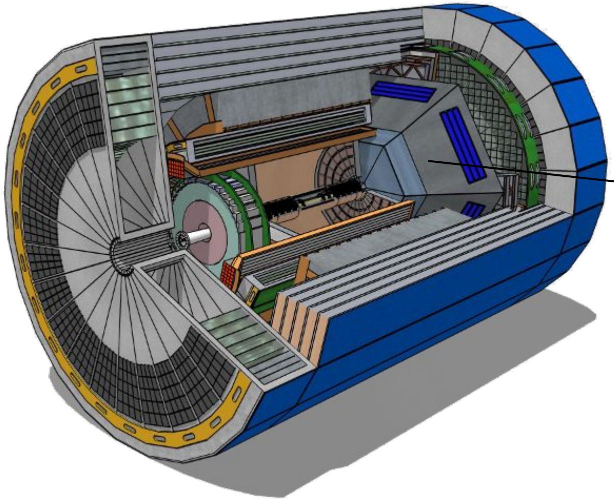
- **physics requirements**
  - pion, kaon and proton ID
  - over a wide range $|\eta| \leq 3.5$
  - with better than 3σ separation
  - significant pion/electron suppression
- **momentum-rapidity coverage**
  - forward: up to 50 GeV/c
  - central: up to 6 GeV/c
  - backward: up to 10 GeV/c
- **demands different technologies**

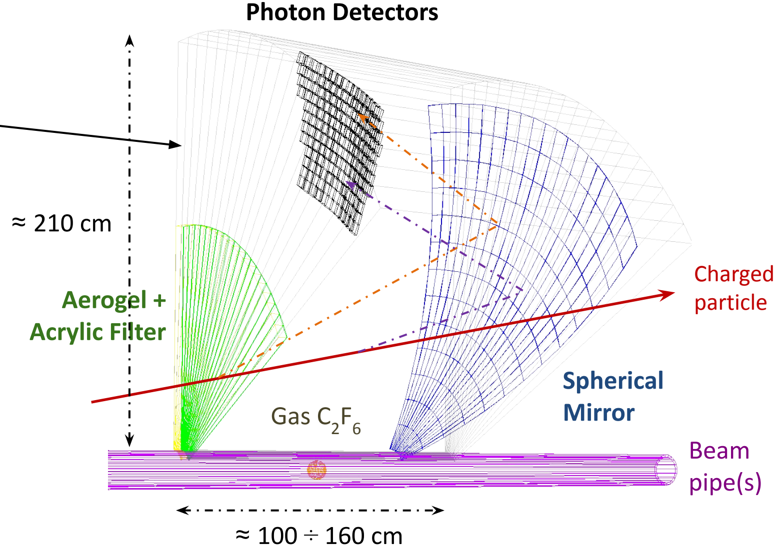


The dual-radiator (dRICH) for forward PID

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

3-60 GeV/c
$1.5 < \eta < 3.5$



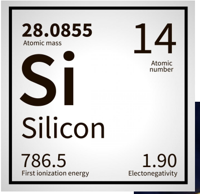


- **radiators:** aerogel (n ~ 1.02) and C_2F_6 (n ~ 1.0008)
- **mirrors:** large outward-reflecting, 6 open sectors
- **sensors:** 3x3 mm^2 pixel, 0.5 m^2 / sector
  - ~ $3m^2$ surface with photosensors (~ 300 k channels)
  - single-photon detection inside high B field (~ 1 T)
  - outside of acceptance, reduced constraints

explore SiPM readout option

SiPM option for RICH optical readout

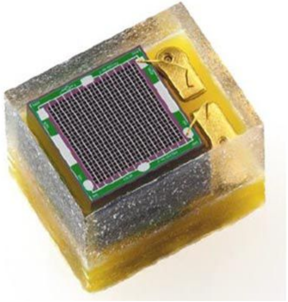
- **pros**
  - cheap
  - high photon efficiency
  - excellent time resolution
  - insensitive to magnetic field



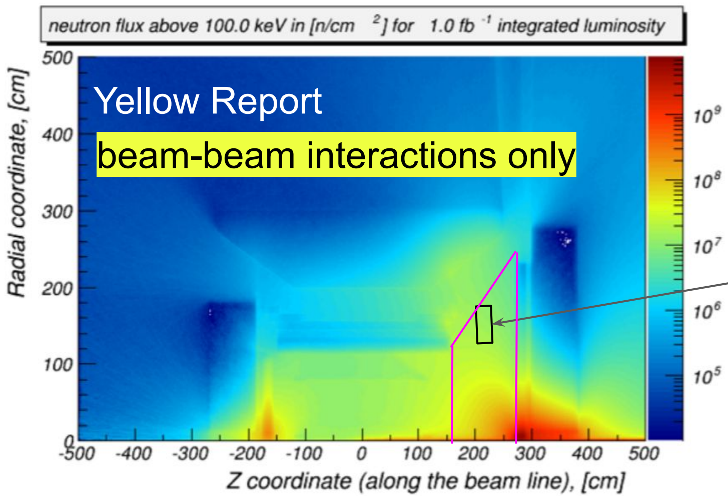
- **cons**

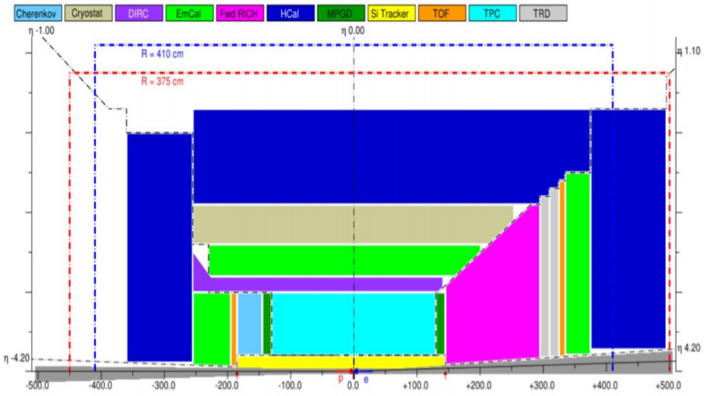
large dark count rates

not radiation tolerant



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

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)

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 $\mathcal{L} = 10^{34}$ s^{-1} cm^{-2}

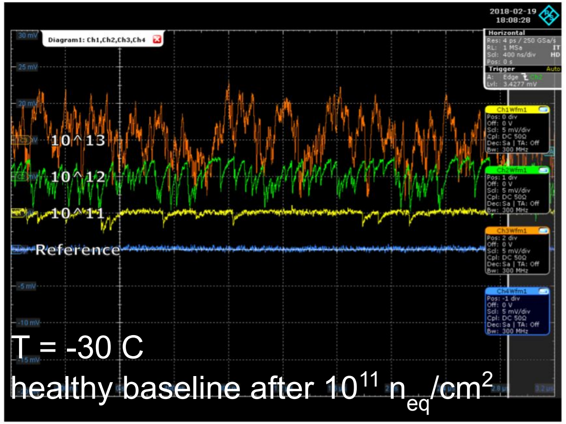
→ better do study in smaller steps of radiation load

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)

Calvi, NIM A 922 (2019) 243



10^{11}

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

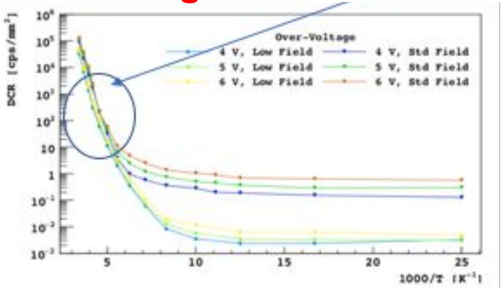
- Reduce operating temperatures (**cooling**)
- Use **timing**
- High-temperature **annealing** cycles

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

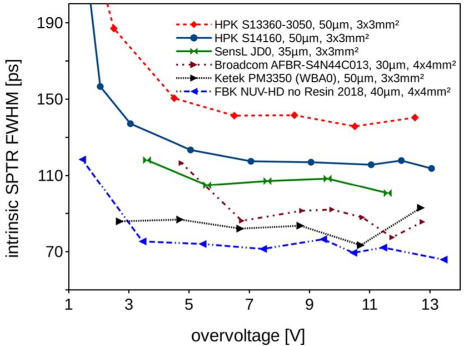
- demonstrate capability to measure Single Photon
- keep DCR under control (ring imaging background)

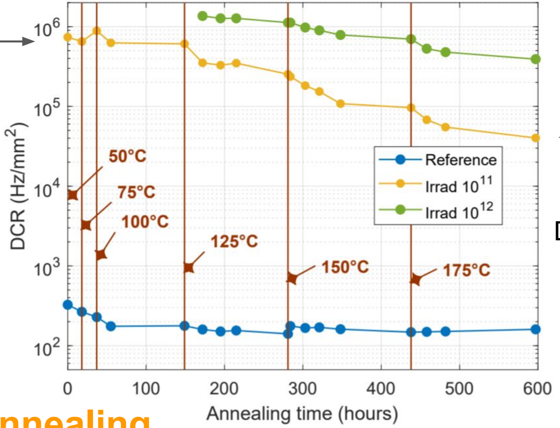
despite radiation damages

cooling



timing





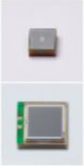
20x less DCR

annealing

[Garutti et al] Due to the increased DCR, the single photoelectron separation from noise is lost already at relatively low fluences Φ_{eq} ~ 10^{10} cm^{-2}. This limit depends on many factors related to the SiPM design and the operation conditions, so it should be tested for each specific application.

- **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

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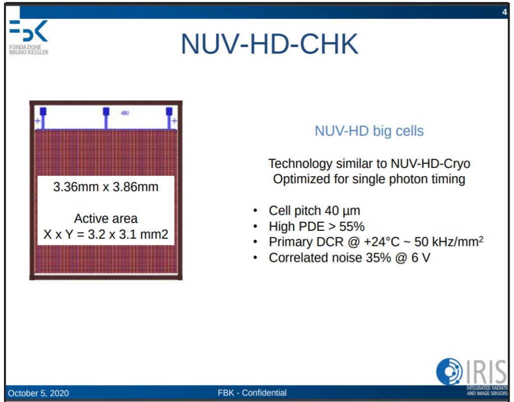
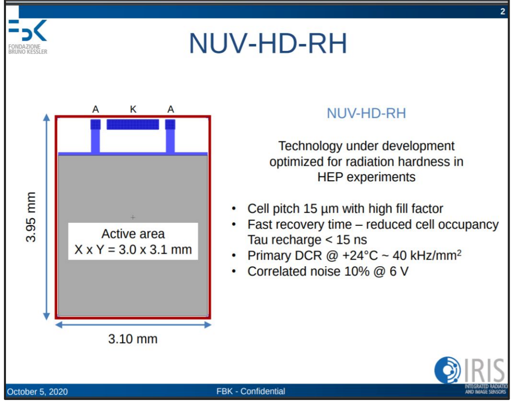
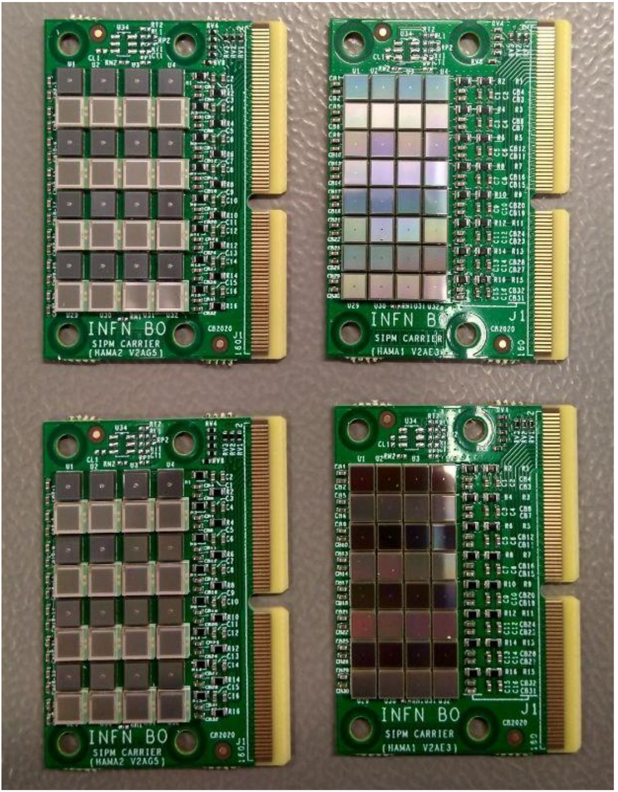




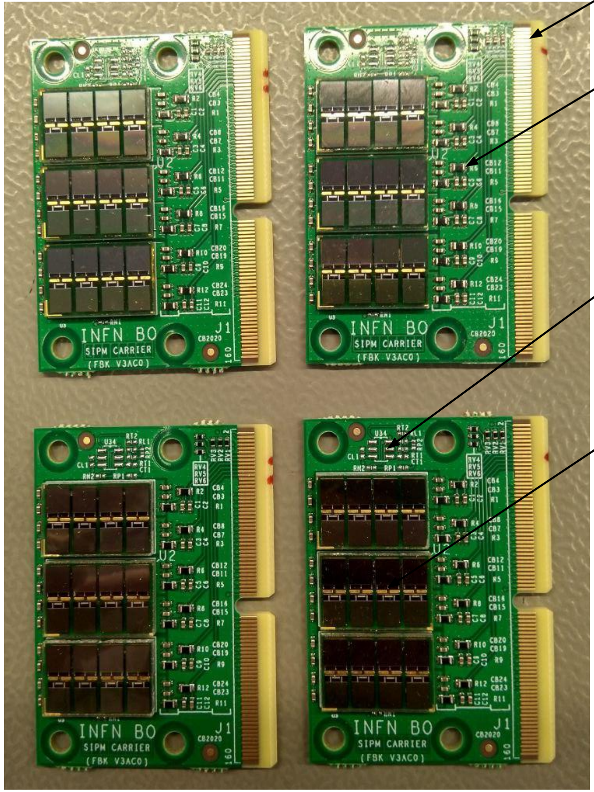
multiple producers: different technologies, SPAD dimensions, V_{bd}, electric field …

SiPM custom carrier boards

8x4 matrices with commercial Hamamatsu



6x4 matrices with prototype FBK sensors



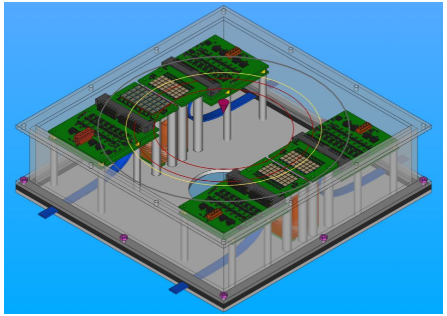
high-density edge connector

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 in beam tests

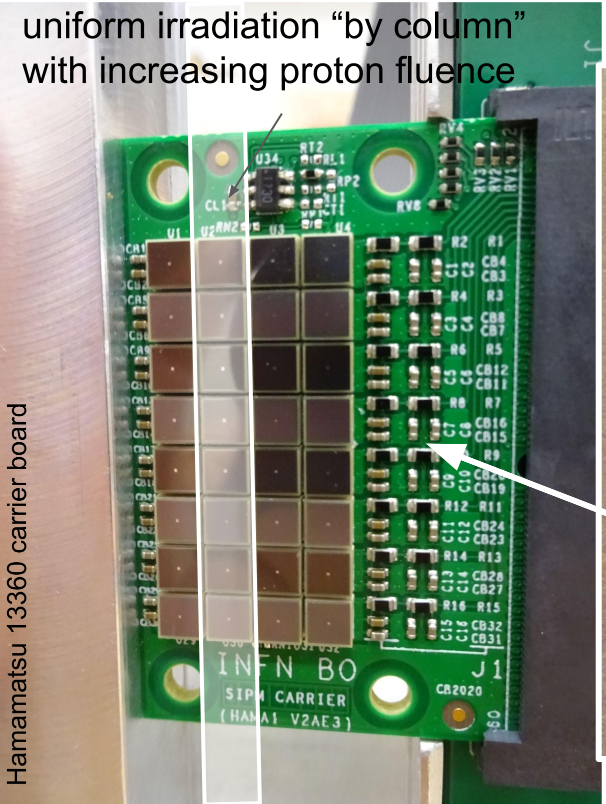
Irradiation at Trento Proton-Therapy hall (TIFPA)

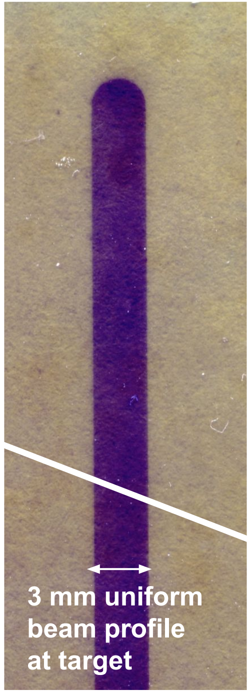
3x3 mm^2 SiPM sensors
4x8 “matrix” (carrier board)

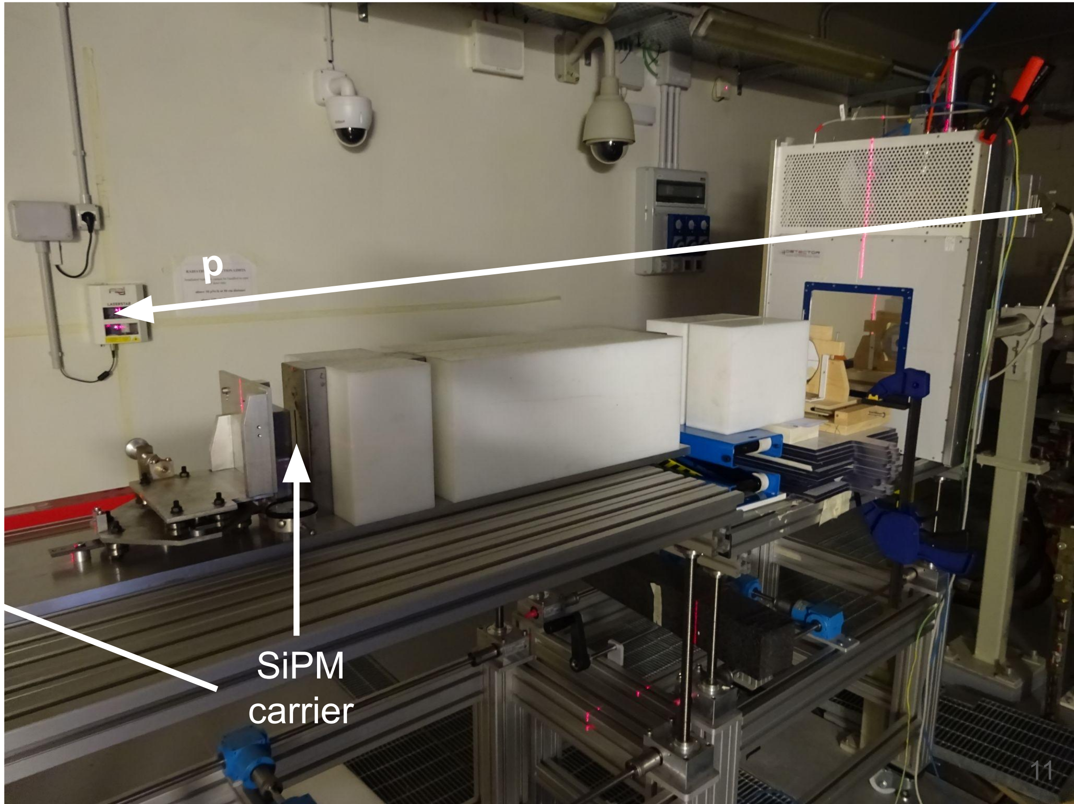
multiple types of SiPM: **Hamamatsu** commercial (13360 and 14160)
FBK prototypes (rad.hard and timing optimised)

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

uniform irradiation “by column”
with increasing proton fluence

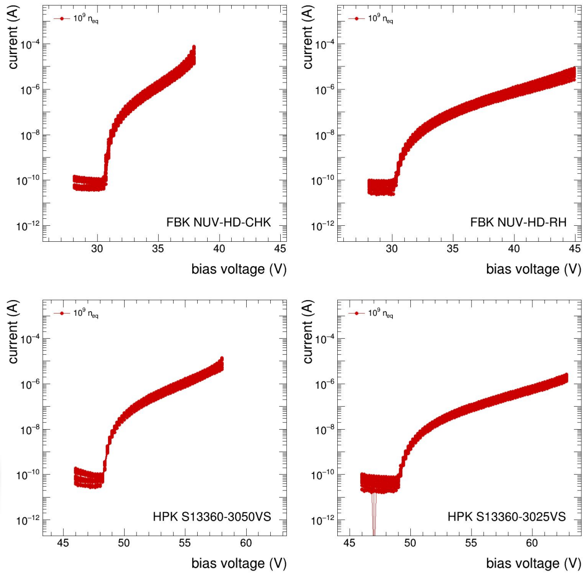


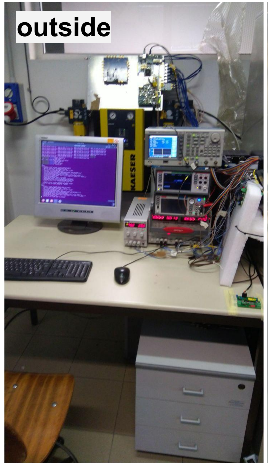


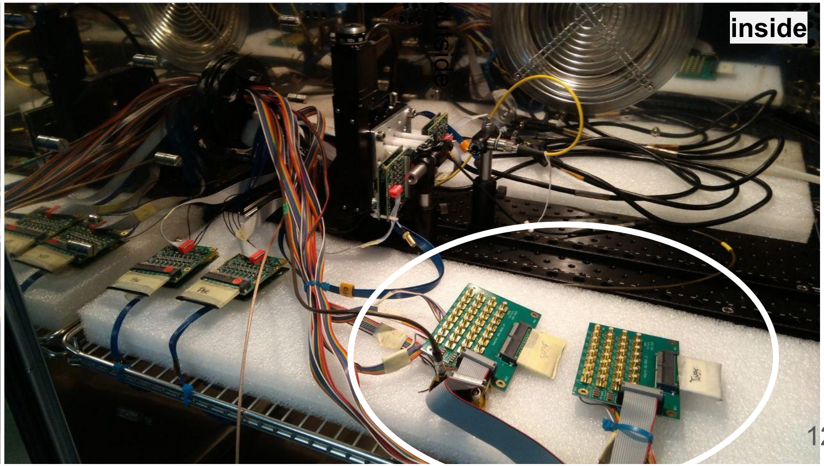


Current measurements

- **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**



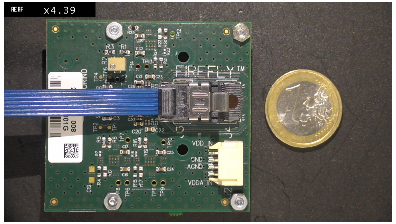


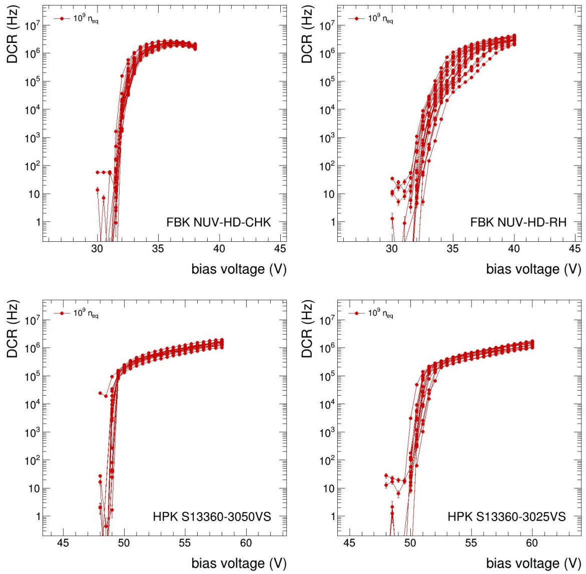


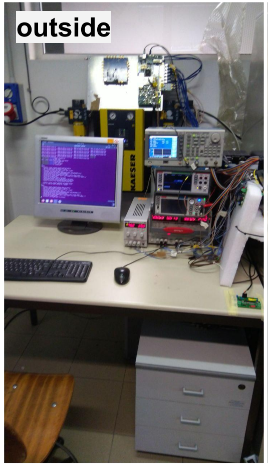
INFN

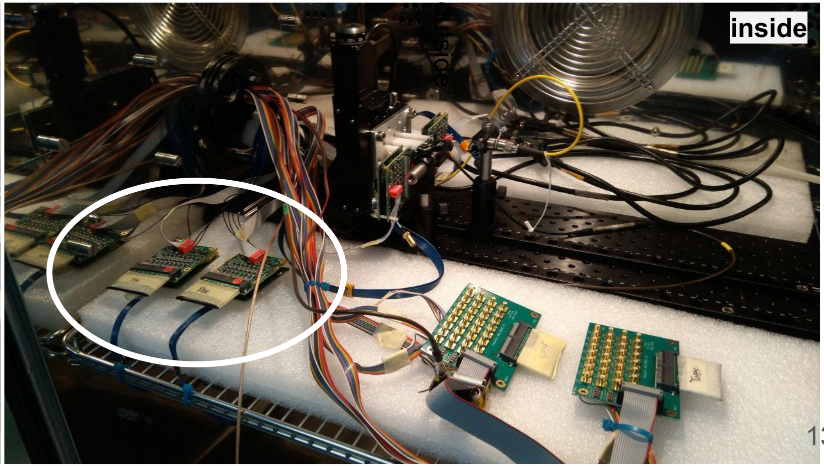
DCR measurements

- **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**

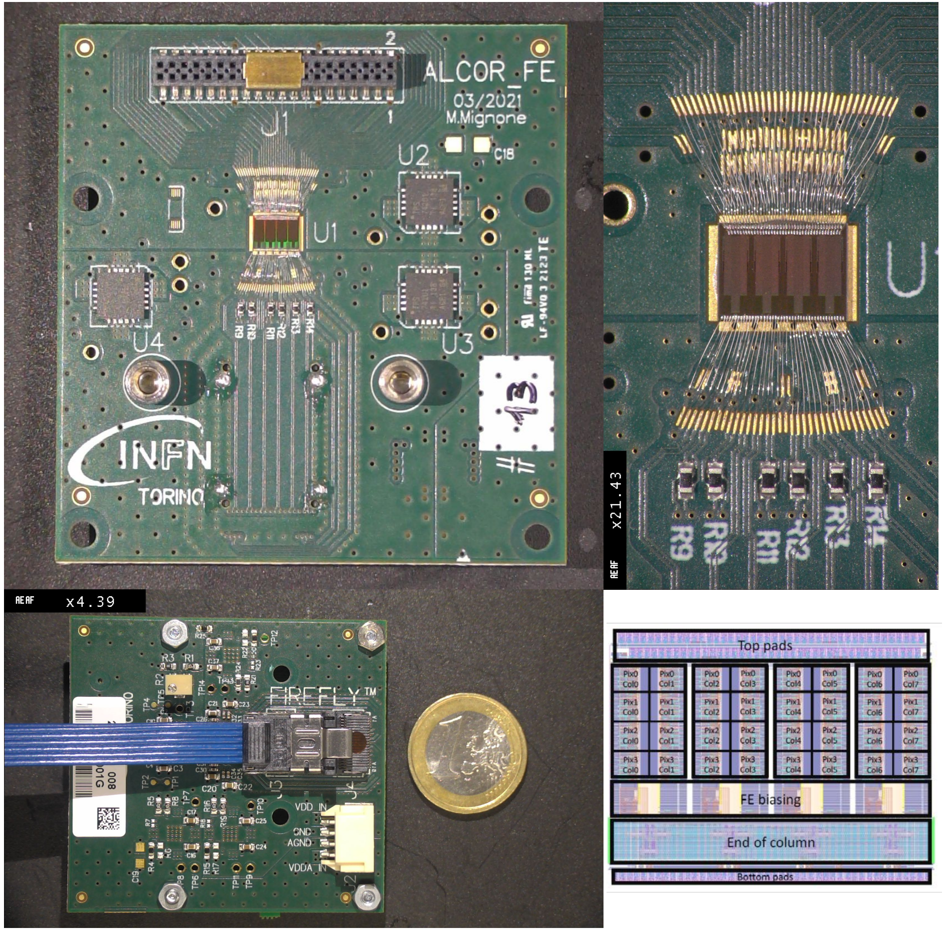








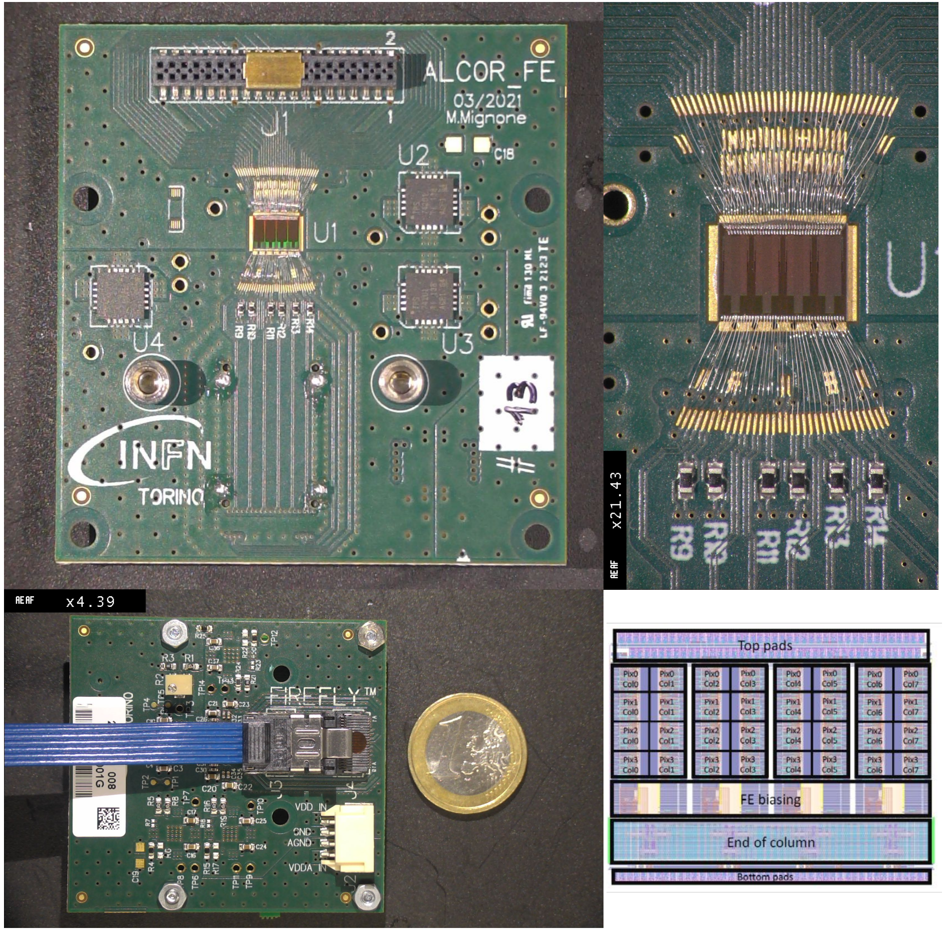
ALCOR: A Low Power Chip for Optical sensor Readout

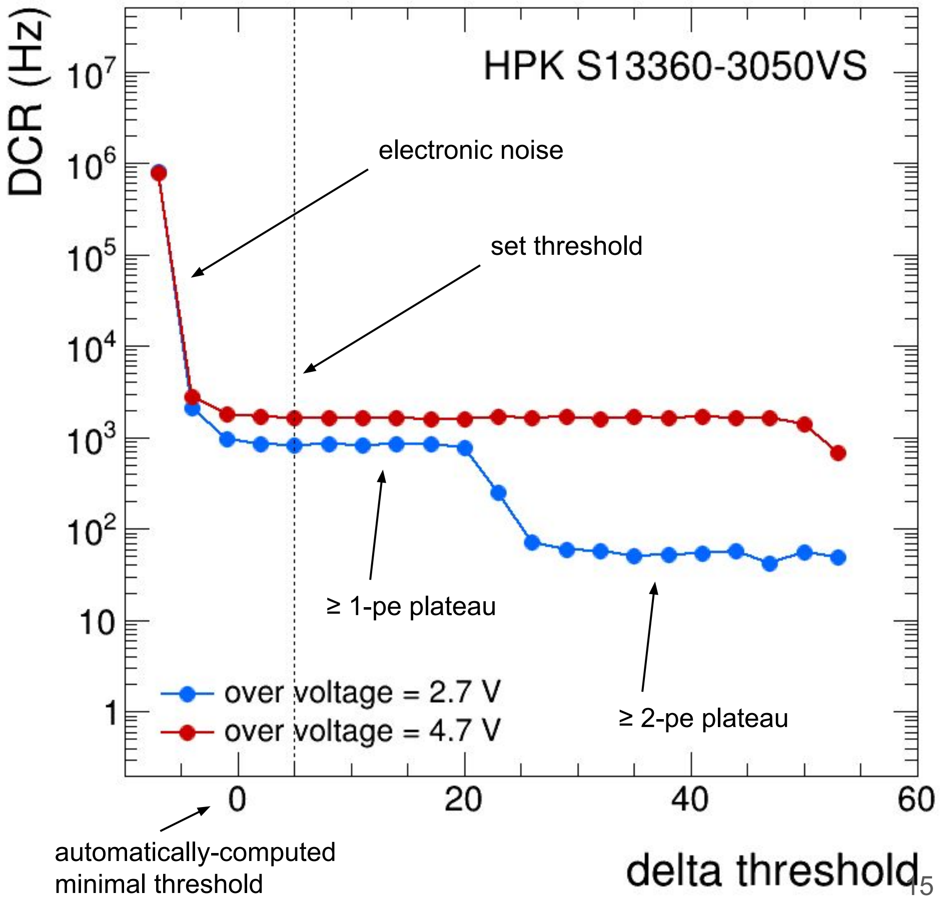


developed by INFN-TO for DarkSide

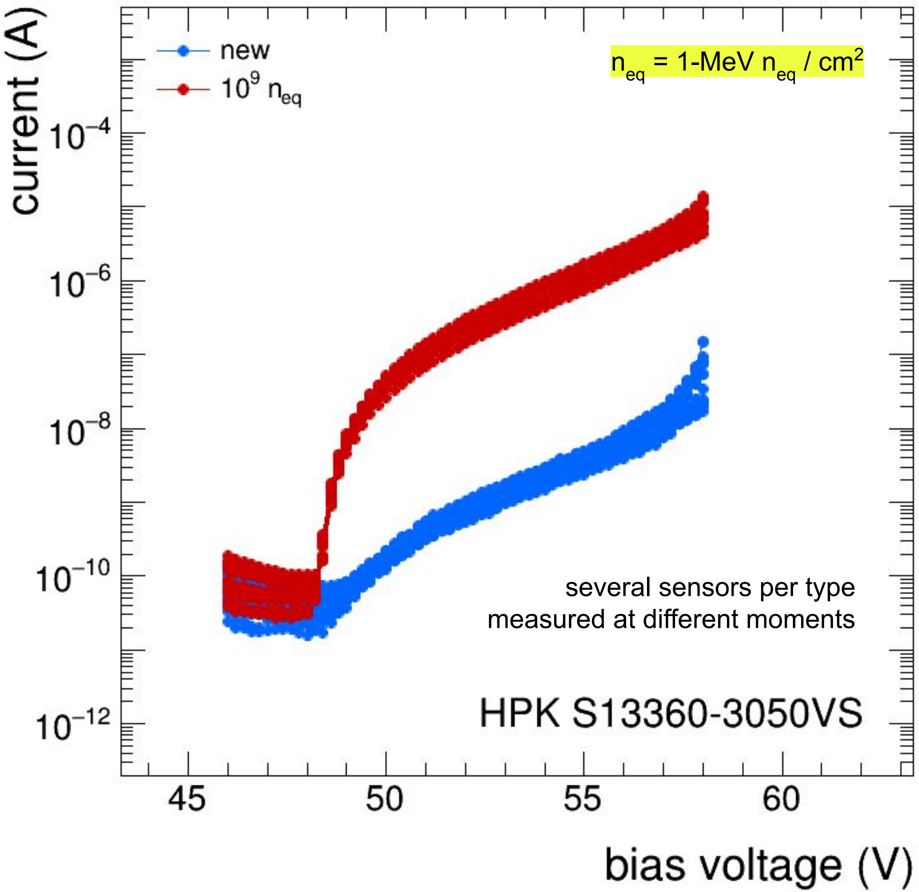
- 32-pixel matrix mixed-signal ASIC
- the chip performs
  - signal amplification
  - conditioning and event digitisation
- each pixel features
  - dual-polarity front-end amplifier
    - low input impedance
    - 4 programmable gain settings
  - 2 leading-edge discriminators
  - 4 TDCs based on analogue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

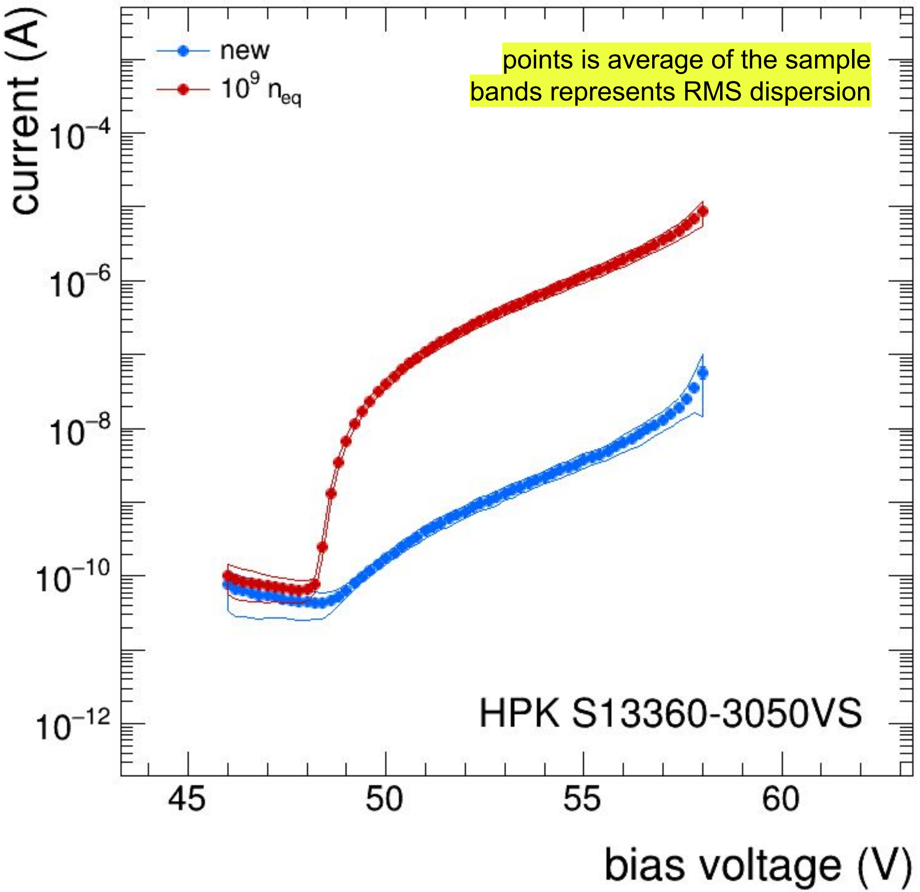
Photon counting with ALCOR



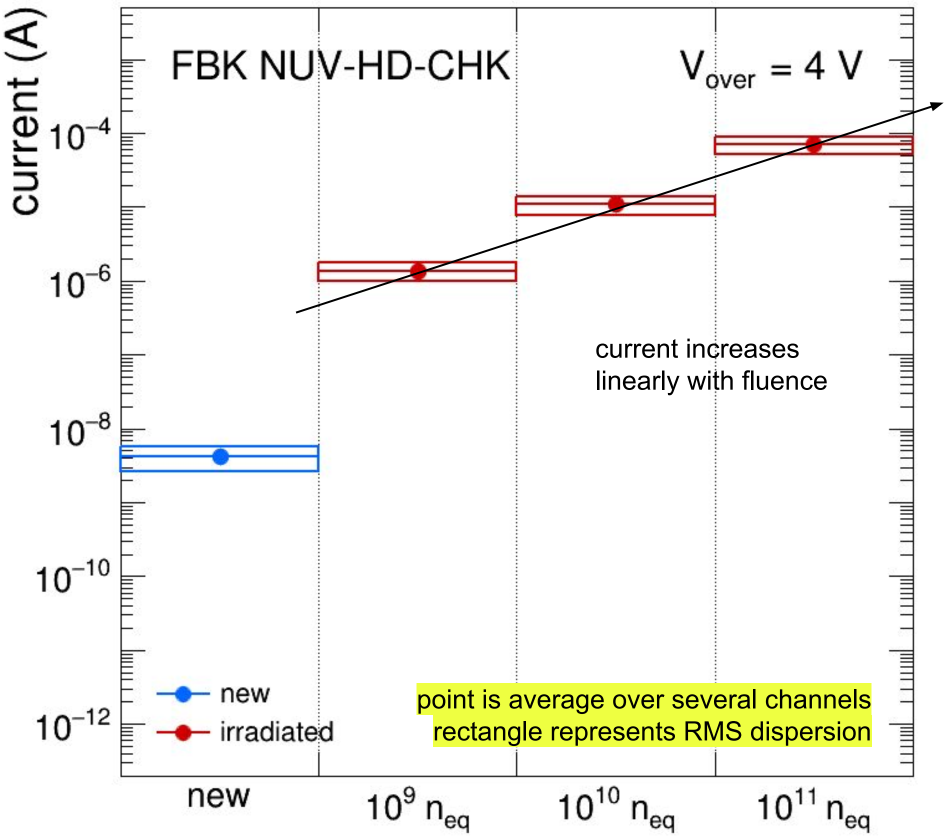


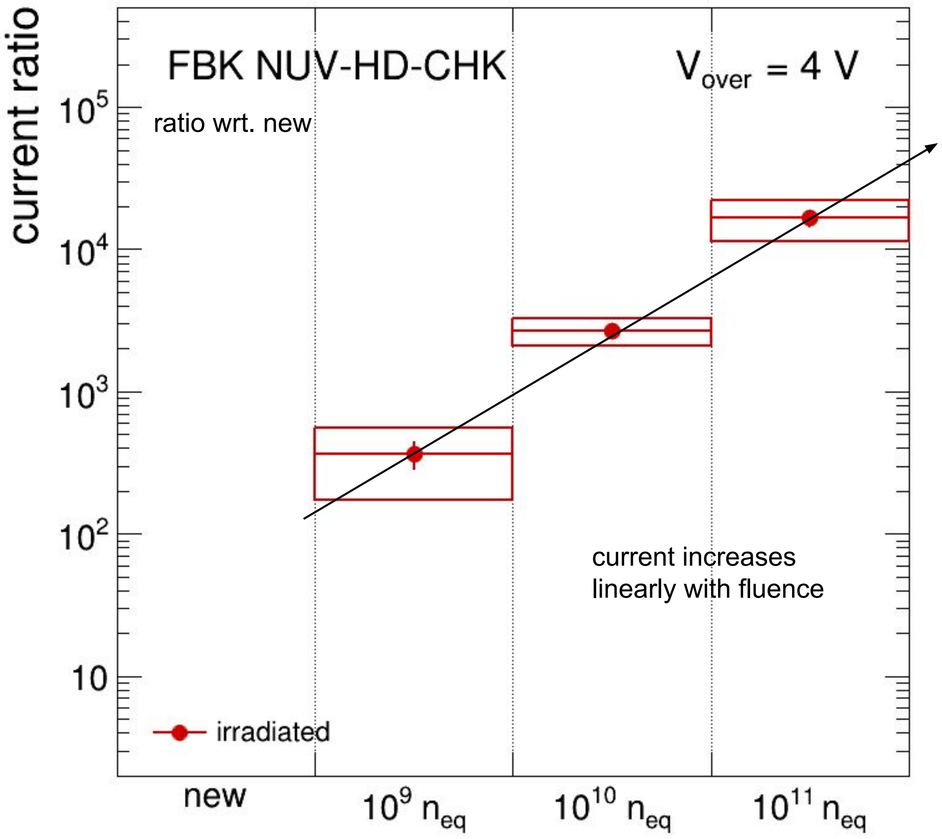
Measurements over large sensor samples



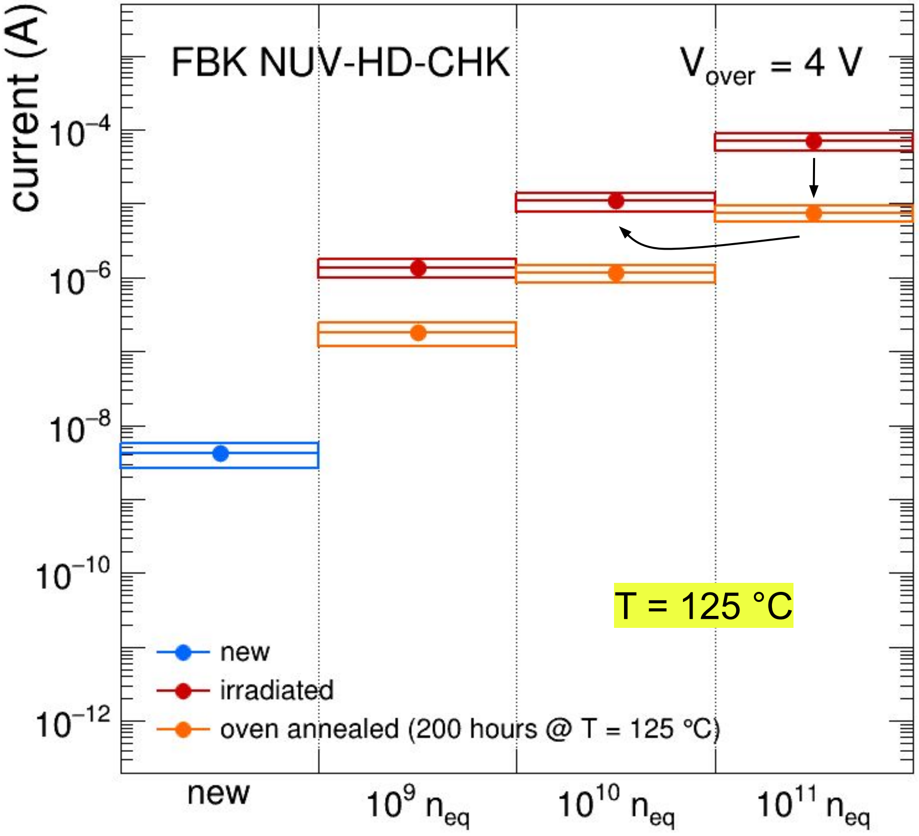


Current vs. delivered fluence



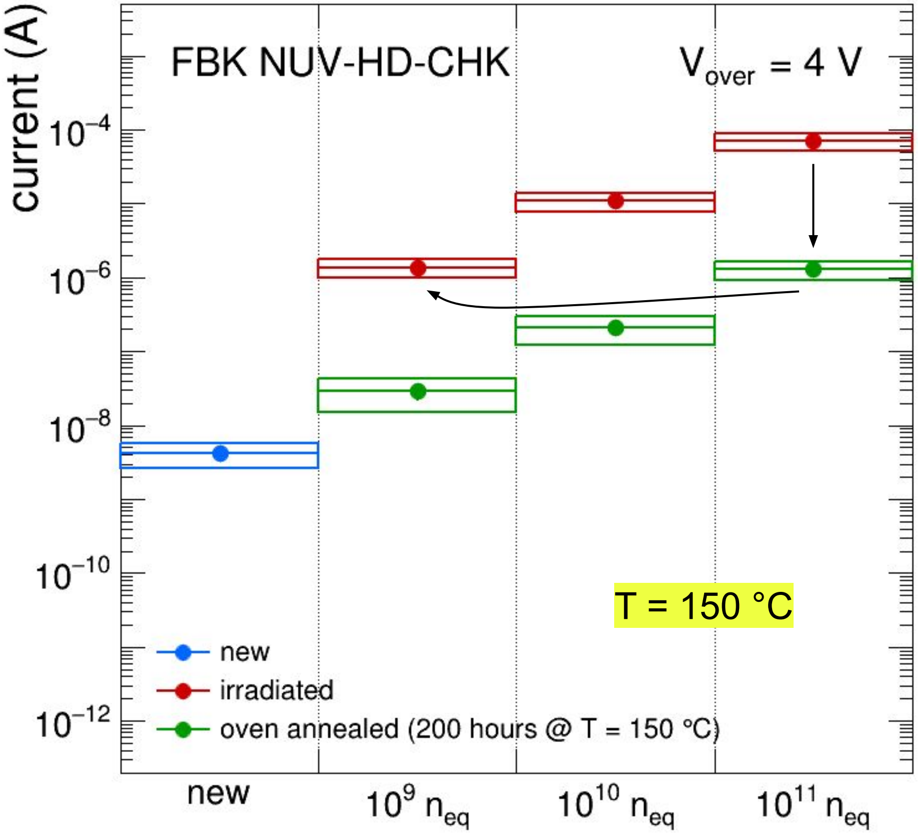


High-temperature annealing recovery (cycle #1)



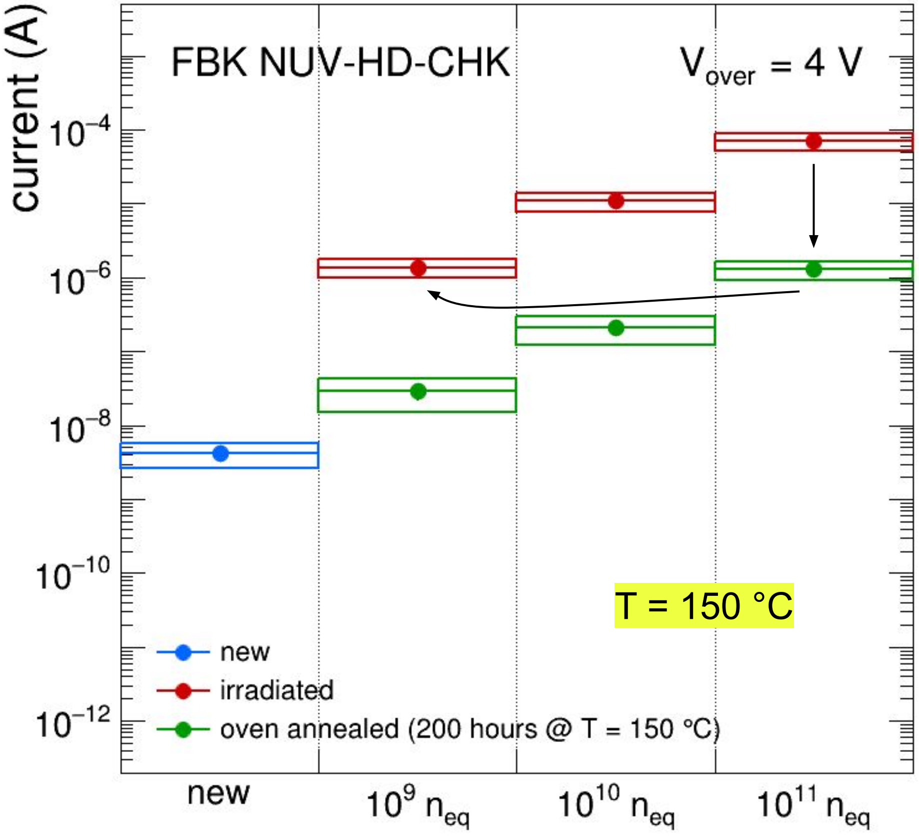
~ 10x current reduction
sensor functions as if it received ~ 10x less fluence

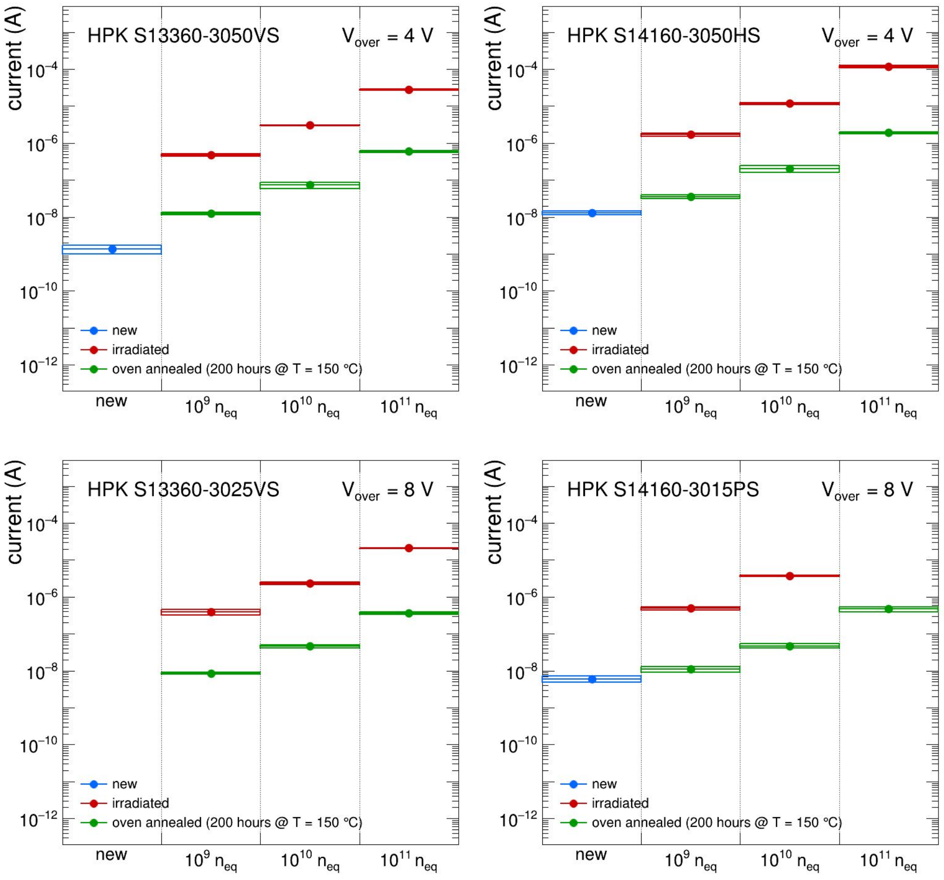
High-temperature annealing recovery (cycle #2)



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

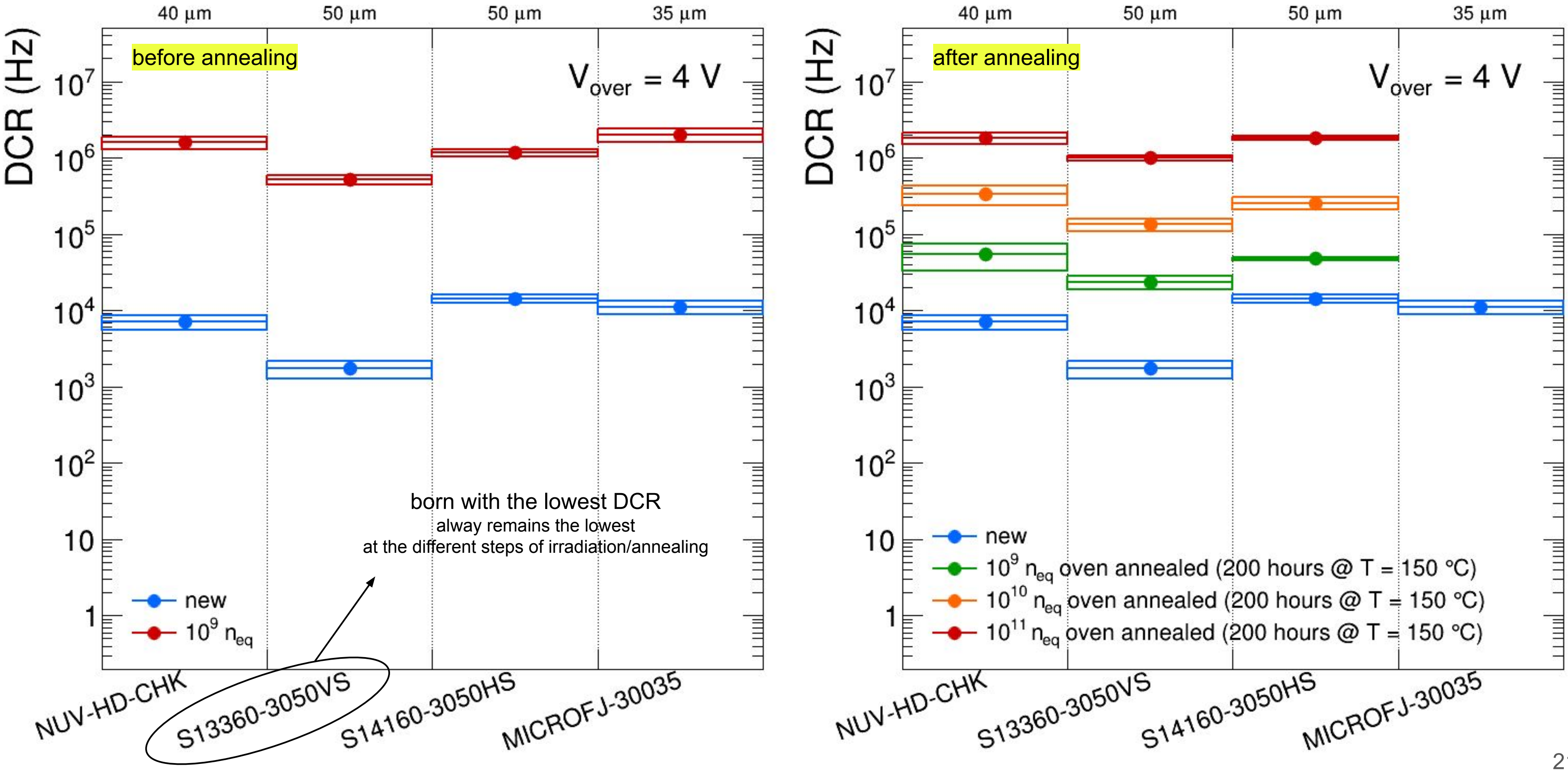
High-temperature annealing recovery (cycle #2)



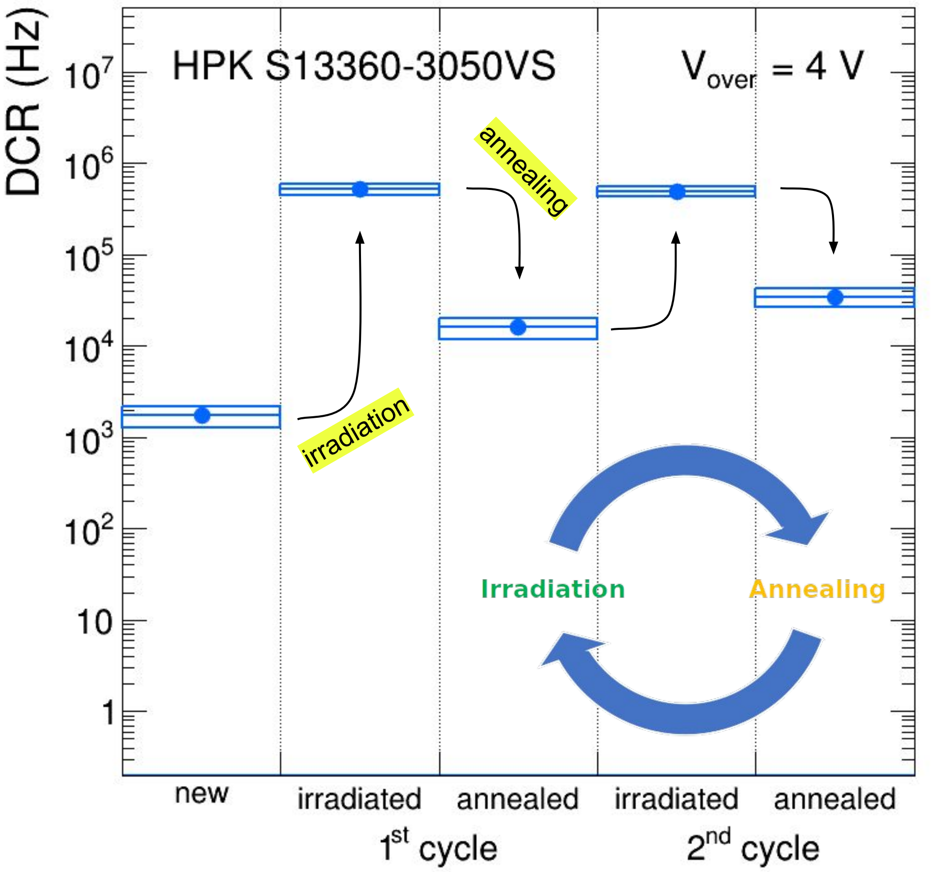


similar observation with different Hamamatsu sensors

DCR after irradiation and annealing



Repeated irradiation-annealing cycles

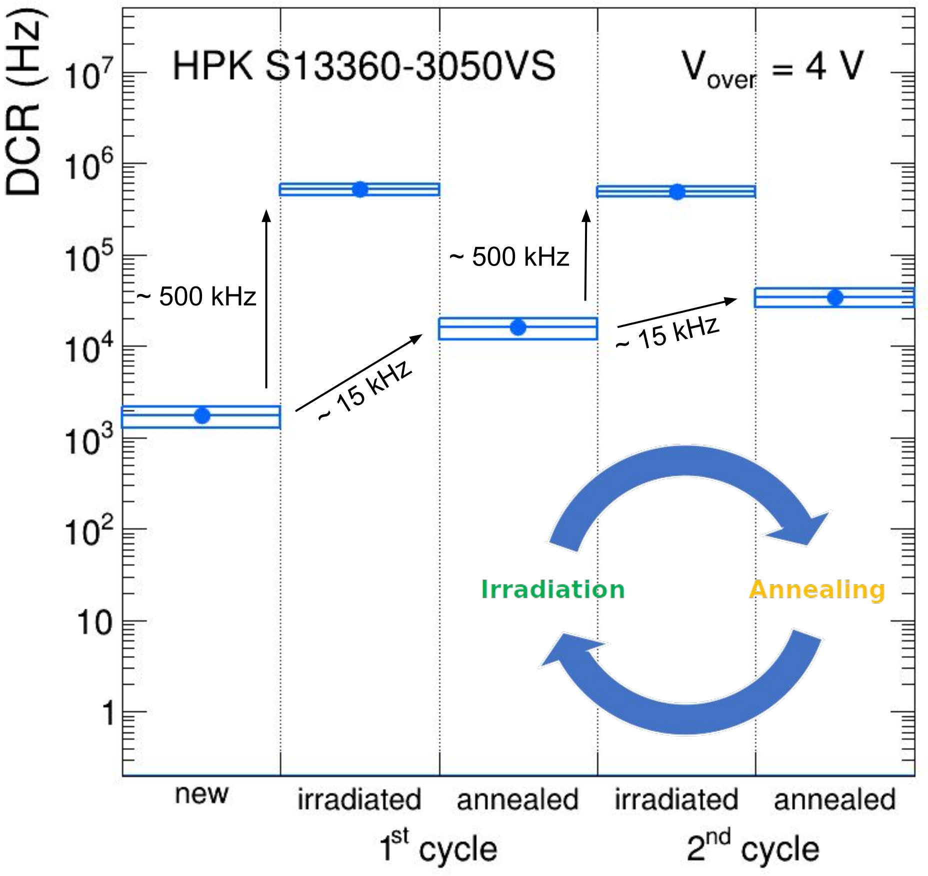


test reproducibility of repeated irradiation-annealing cycles

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

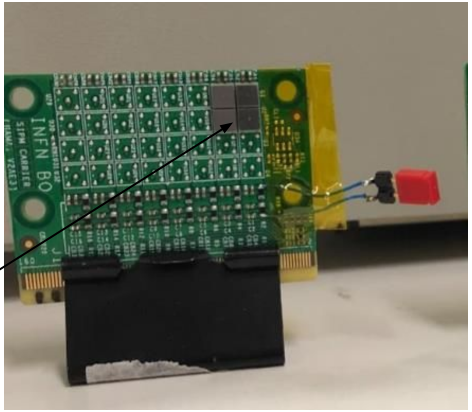
simulate a realistic experimental situation

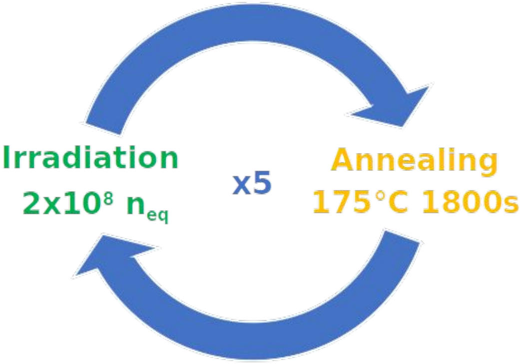
- consistent irradiation damage
  - DCR increases by ~ 500 kHz (@ Vover = 4)
  - after each shot of 10^9 n_{eq}
- consistent residual damage
  - ~ 15 kHz (@ Vover = 4) of residual DCR
  - builds up after each irradiation-annealing

annealing cures same fraction of newly-produced damage

~ 97% for HPK S13360-3050 sensors

Online annealing

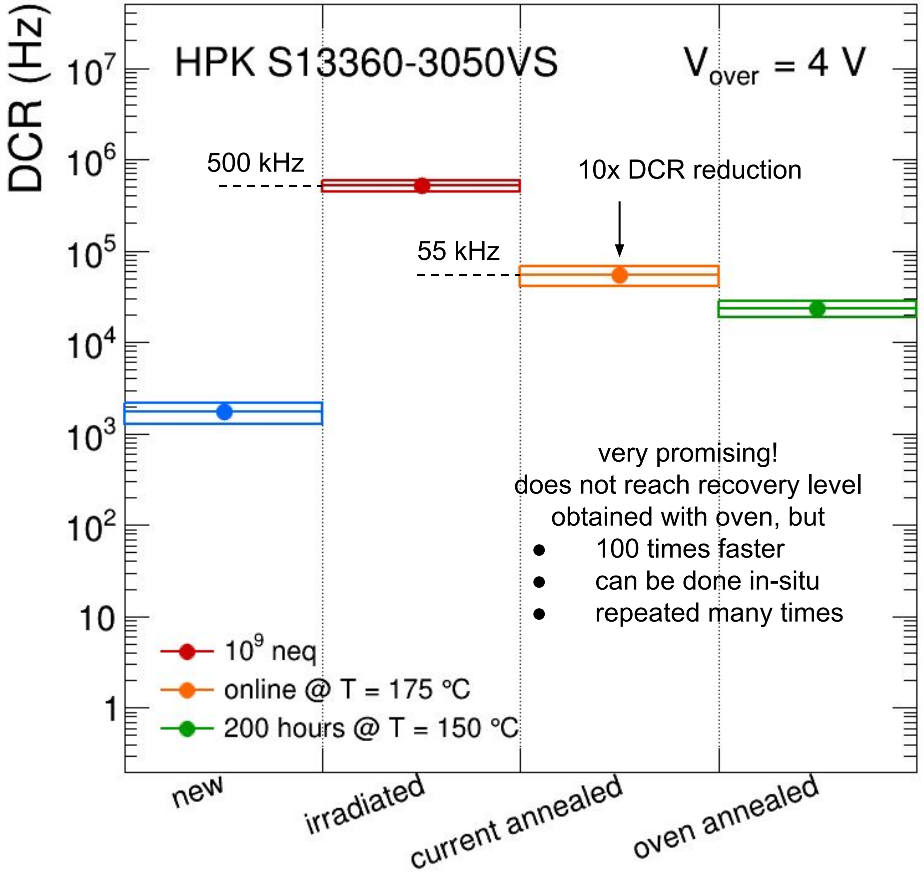




explore solutions for in-situ annealing

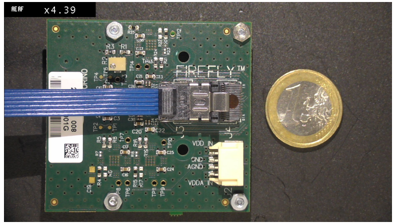
- total fluence of $10^9\ n_{eq}$
  - delivered in 5 chunks
  - each of $2\ 10^8\ n_{eq}$
- interleave by annealing
  - forward bias, ~ 1 W / sensor
  - T = 175 °C, thermal camera
  - 30 minutes
- preliminary tests
  - Hamamatsu S13360-3050

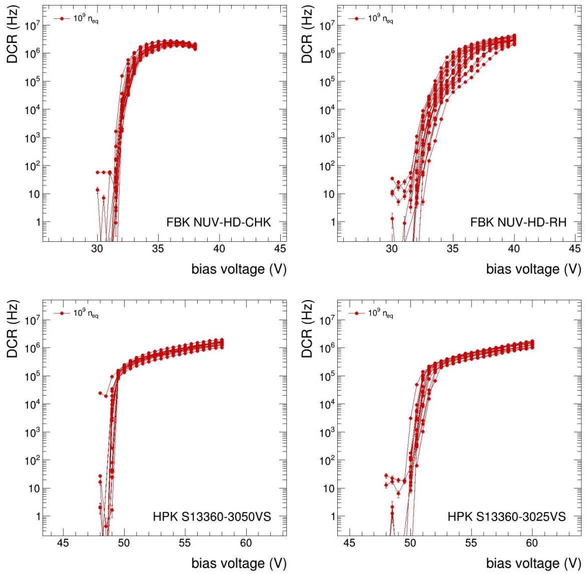
Online annealing

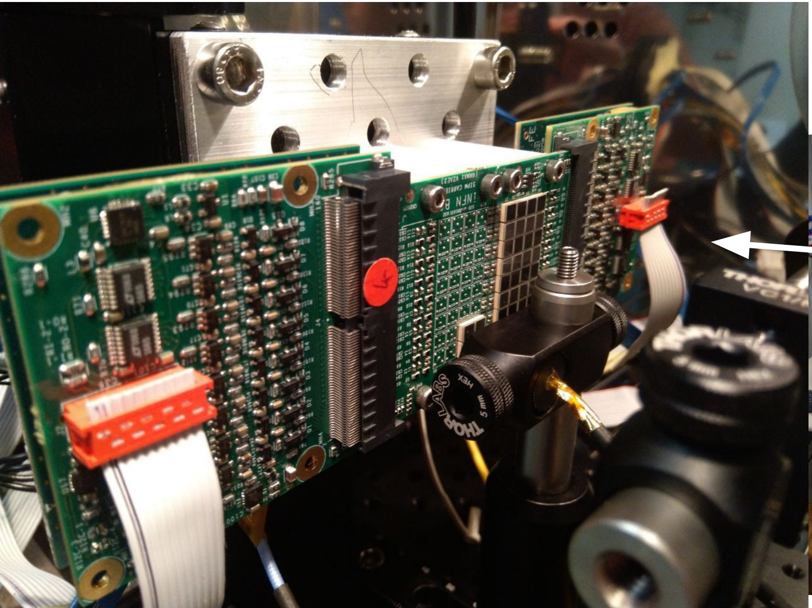


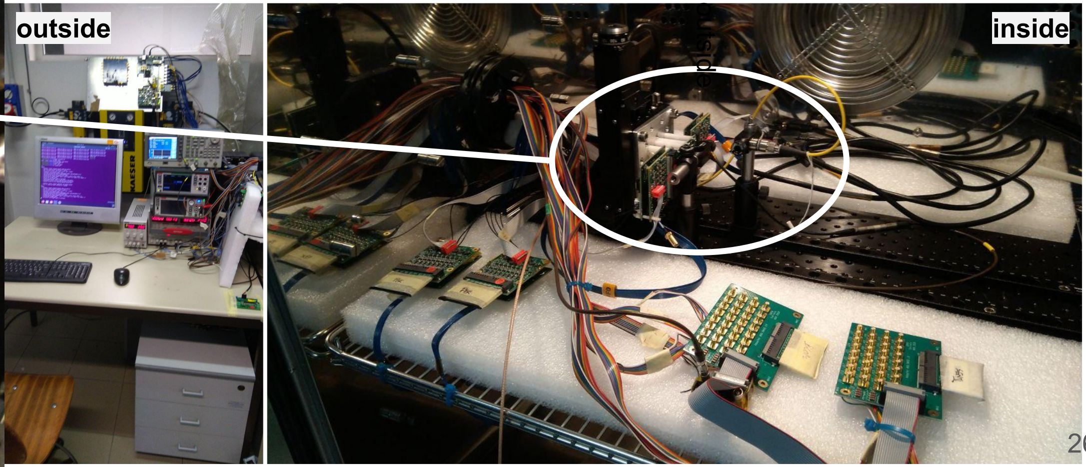
LED measurements

- **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**

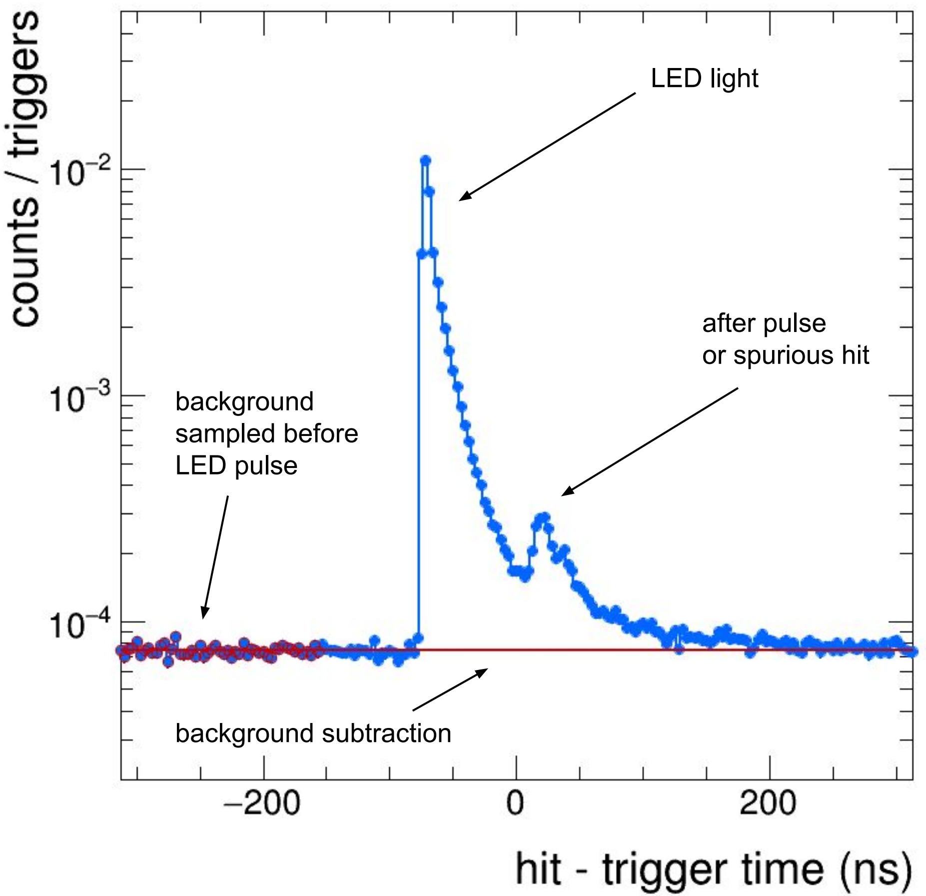




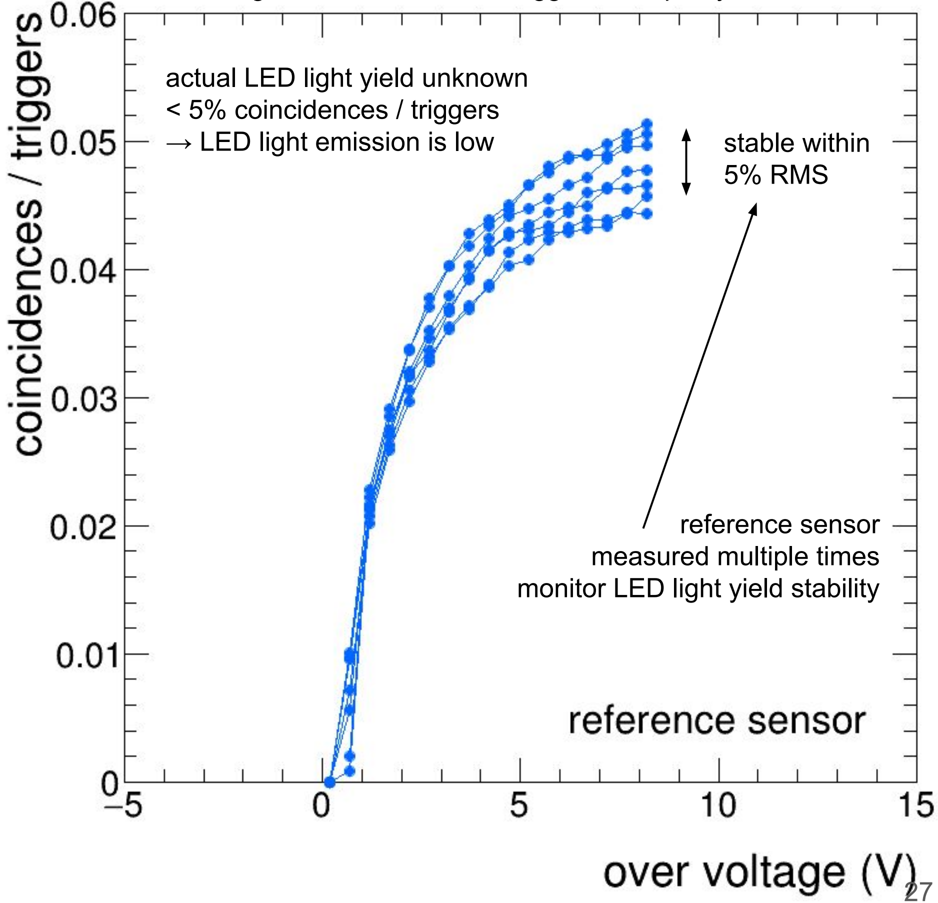




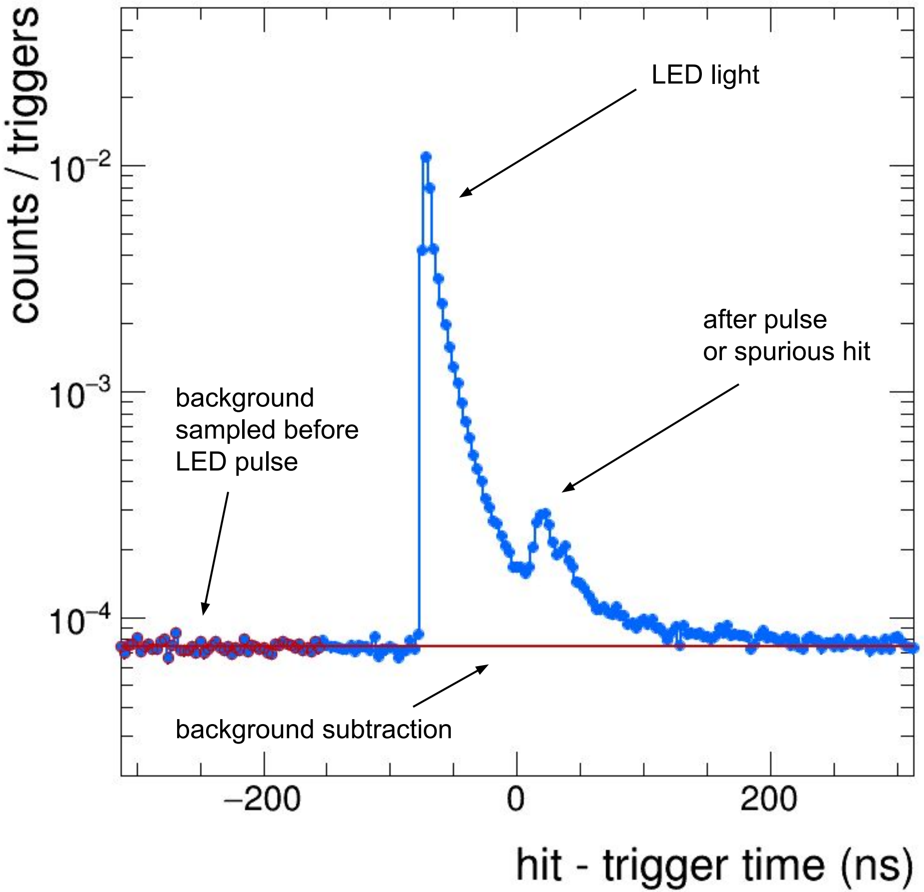
Light response with pulsed LED



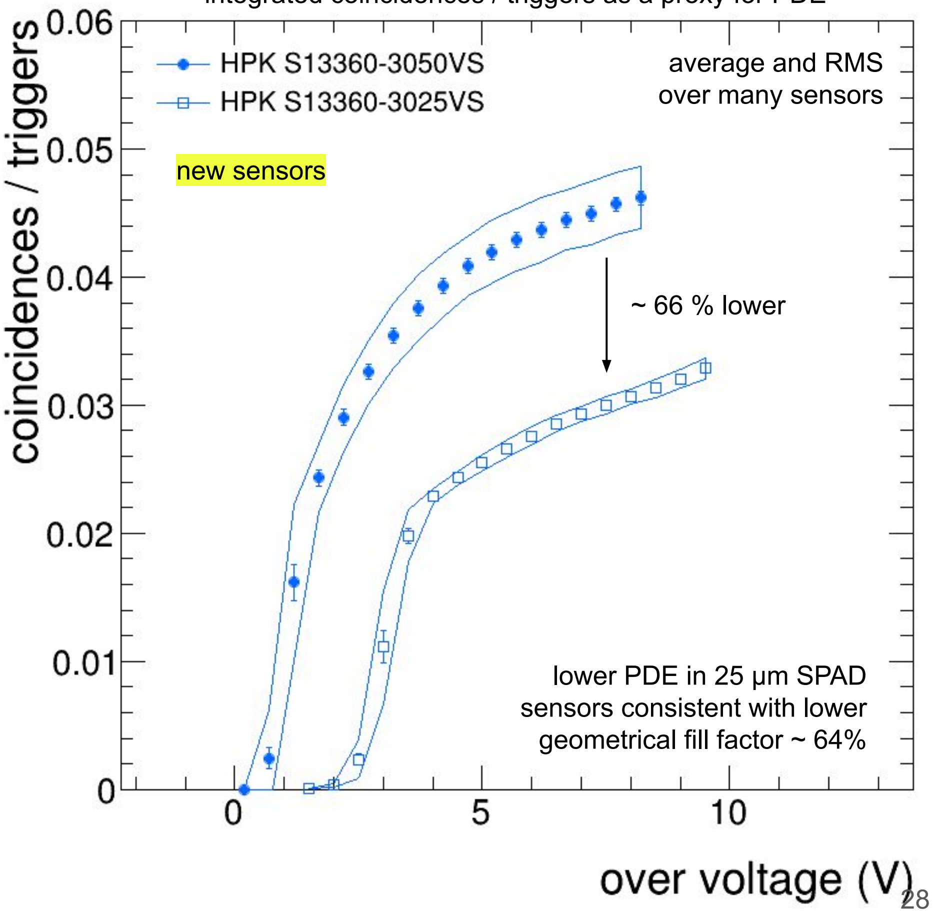
integrated coincidences / triggers as a proxy for PDE



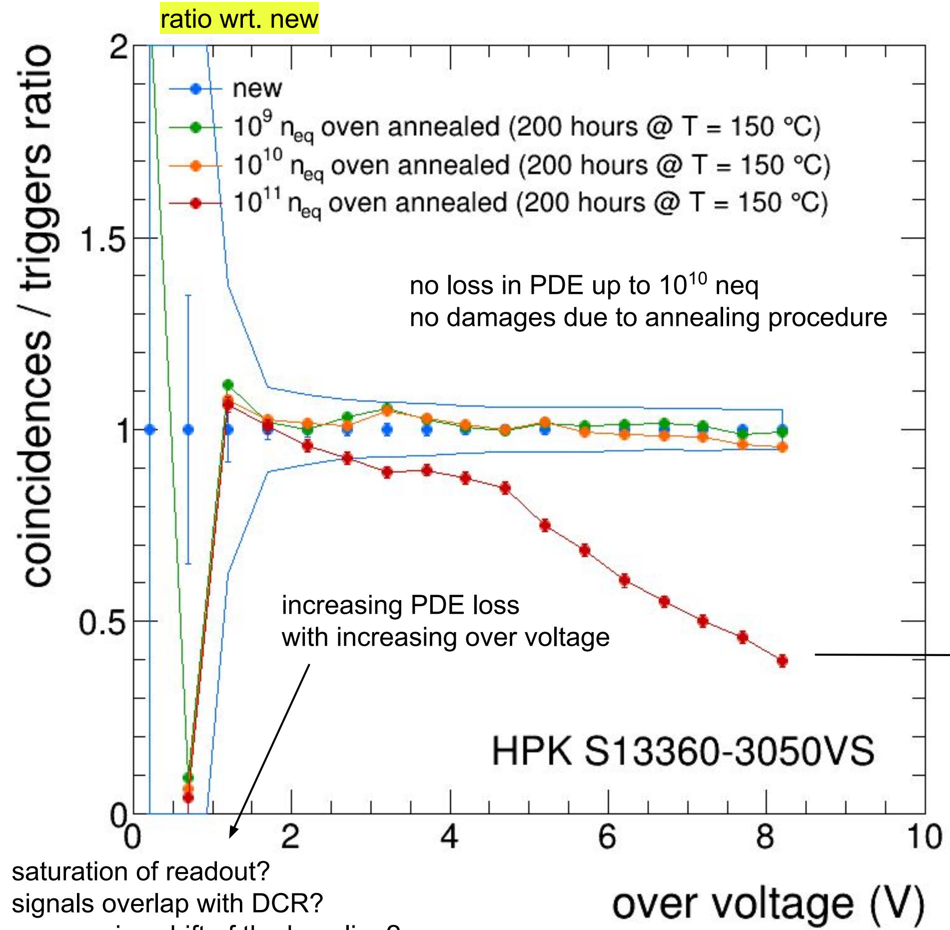
Light response with pulsed LED



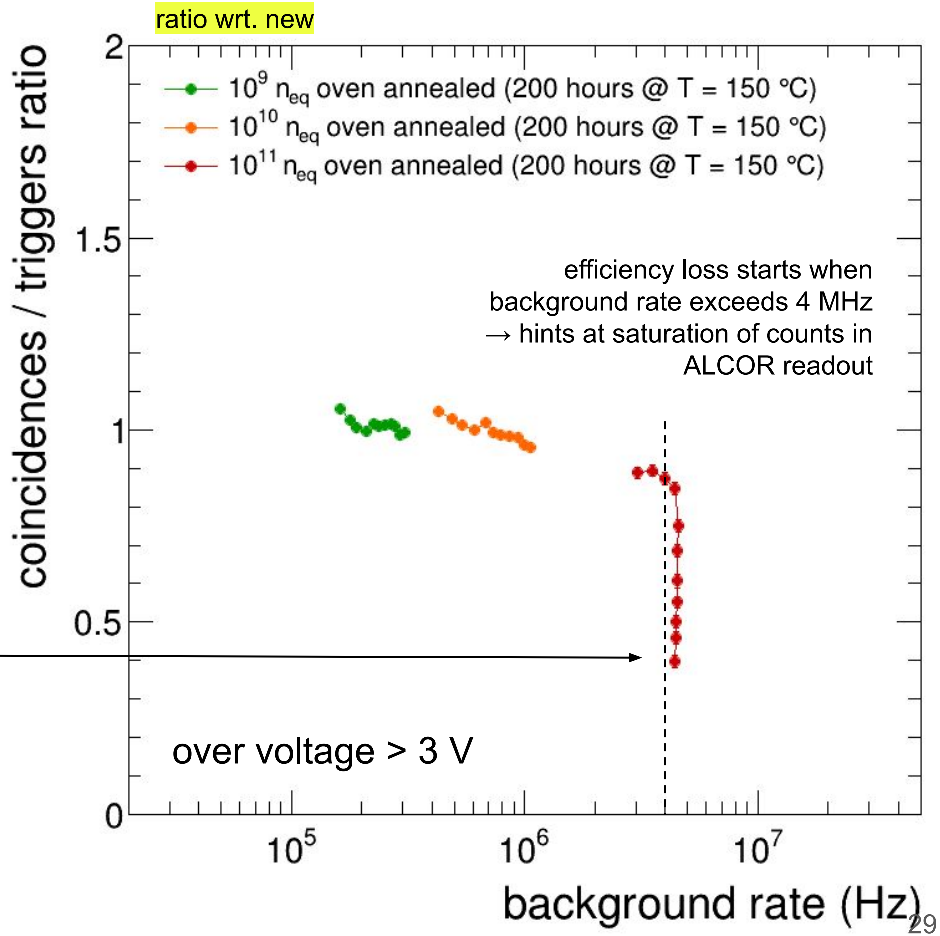
integrated coincidences / triggers as a proxy for PDE



Light response after irradiation and annealing



saturation of readout?
signals overlap with DCR?
progressive shift of the baseline?

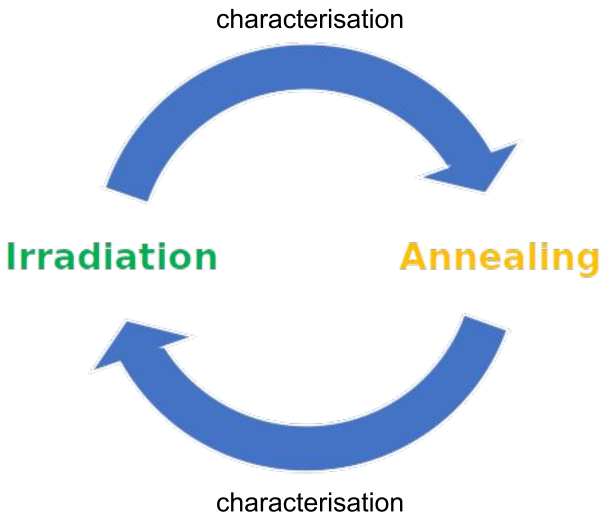


Summary

R&D to explore use of SiPM as baseline for the EIC-dRICH optical readout

in conjunction with prototype chain of electronics based on the ALCOR front-end ASIC
important to test details for this specific application

- **results on irradiation and high-T annealing**
  - over a large sample of devices
    - HPK S13360: lowest DCR at all stages
  - repeated irradiation and annealing procedure ongoing
    - experimental scenario in a more realistic way
- **promising results with online annealing**
  - valuable method for “in-situ” recovery
  - “continuous” effective reduction of delivered fluence
- **single-photon light detection efficiency**
  - unaffected by irradiation and annealing up to 10^{10} neq
  - efficiency loss at 10^{11} likely due to saturation of electronics
    - will be investigated in coming months

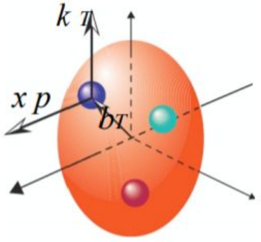


END

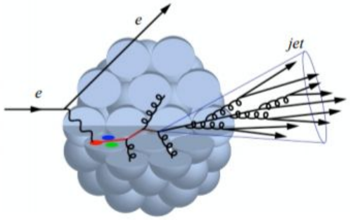
The Physics of EIC

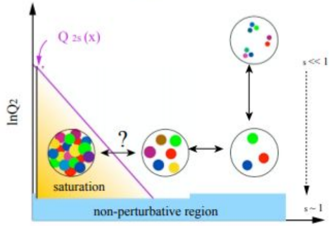
is precision QCD Physics

investigate universal dynamics of gluons
understand the emergence of hadronic matter and its properties



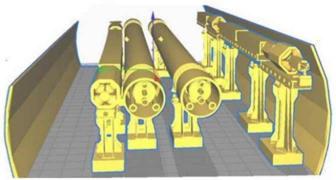
- **how are sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?**
  - how do the nucleon properties emerge from them and their interactions?
- **how do colour-charged quarks and gluons, and colorless jets, interact with a nuclear medium?**
  - how do confined hadronic states emerge from these quarks and gluons?
  - how do the quark-gluon interactions create nuclear binding?
- **what happens to the exploding gluon density at low-x in hadronic matter?**
  - does it saturate at high energy, giving rise to a gluonic matter with universal properties?





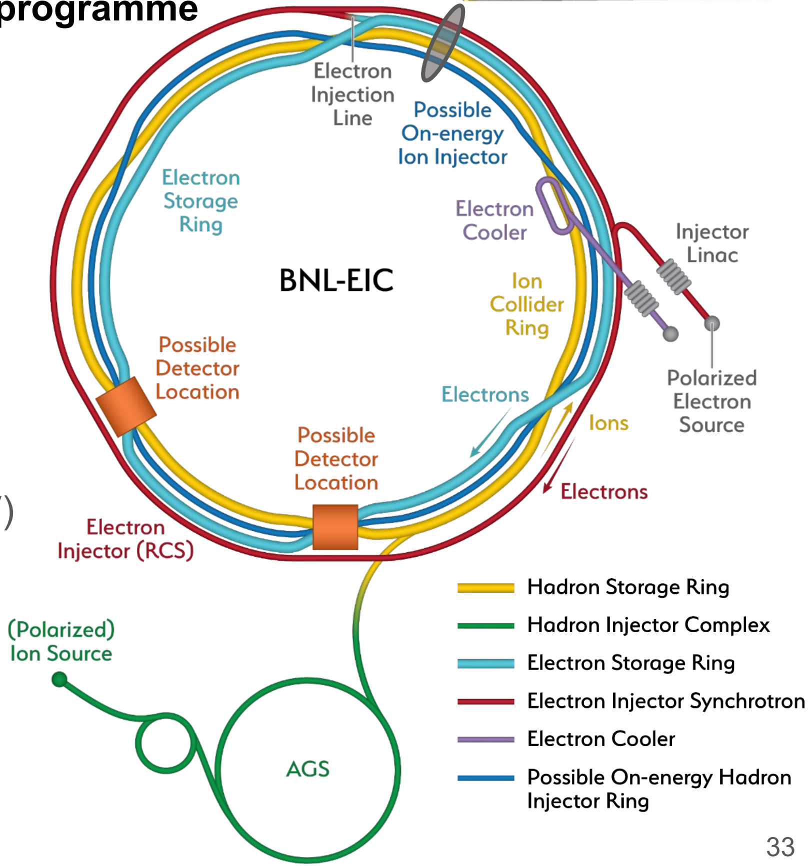
The Electron-Ion Collider aim is to <u>answer central questions in QCD</u> Physics

Accelerator overview



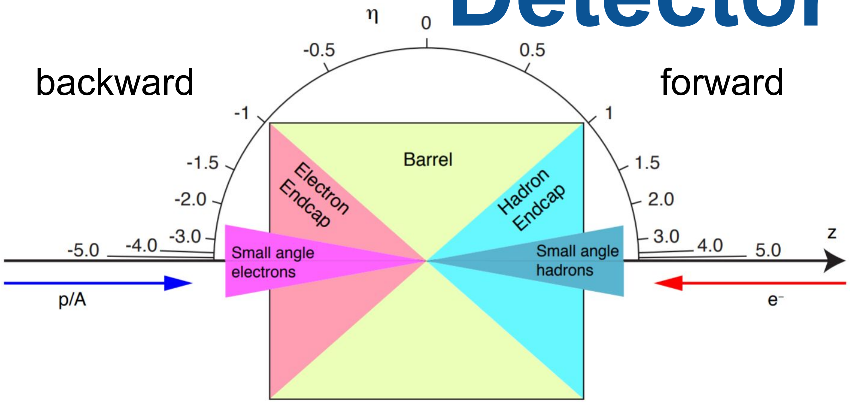
$\sqrt{s}$	20 – 141 GeV
$\mathcal{L}_{max}$	10^{34} cm^{-2} s^{-1}
P(e⁻)	80%
P(h)	80%
A	p – U

BNL-EIC satisfies the requirements
to fulfill the rich physics programme



- **design using much of the RICH facility**
  - three accelerator rings
    - existing RHIC ring (275 GeV)
    - new Rapid Cycling Electron Synchrotron (18 GeV)
    - new Electron Storage Ring (18 GeV)
  - two injector complexes
    - existing Hadron Injectors
    - new Electron Injectors
  - two detector halls
  - hadron cooling facility

Detector requirements



main challenges
forward PID
EM cal at < 2% / √E %

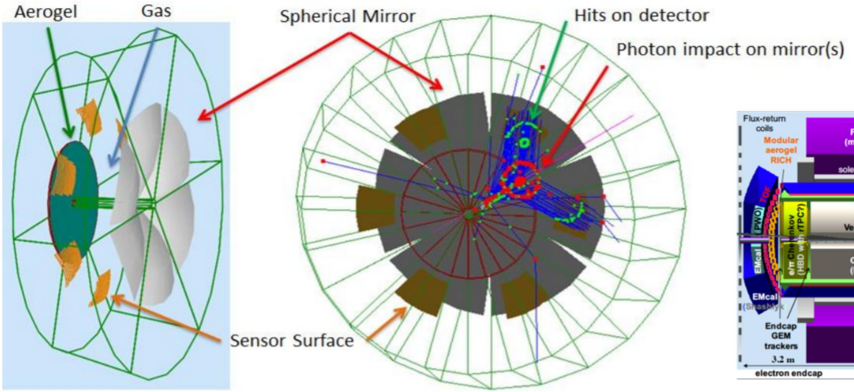
- **hermetic detector**
  - with low-mass inner tracker
  - moderate radiation hardness
- **good momentum resolution**
  - central: $\sigma_p/p = 0.05 \oplus 0.5$ %
  - forward: $\sigma_p/p = 0.1 \oplus 0.5$ %
- **and impact parameter resolution**
  - $\sigma = 5 \oplus 15 / p \sin^{3/2}$ μm
- **electron and jets**
  - $-4 < \eta < 4$

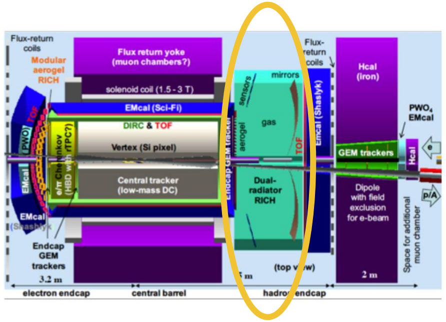
- **excellent EM resolution**
  - central: $\sigma_E/E = 10 / \sqrt{E}$ %
  - backward: $\sigma_E/E < 2 / \sqrt{E}$ %
- **good hadronic energy resolution**
  - forward: $\sigma_E/E \approx 50 / \sqrt{E}$ %
- **excellent PID for π, K, p**
  - forward: up to 50 GeV/c
  - central: up to 8 GeV/c
  - backward: up to 7 GeV/c

dRICH proposal for forward PID

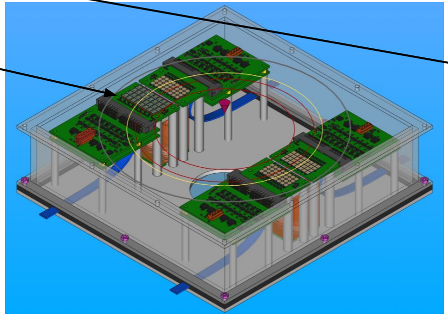
- **dual-radiator RICH (dRICH)**
  - aerogel (n ~ 1.02) + gas (n ~ 1.0008)
  - for PID in the hadronic endcap
    - 3 < *p* < 50 GeV/c
    - 1.5 < η < 3.5
  - 6 sectors x 0.5 m^2/sector photosensors
    - ~ 1 T magnetic field
    - sensors out of acceptance

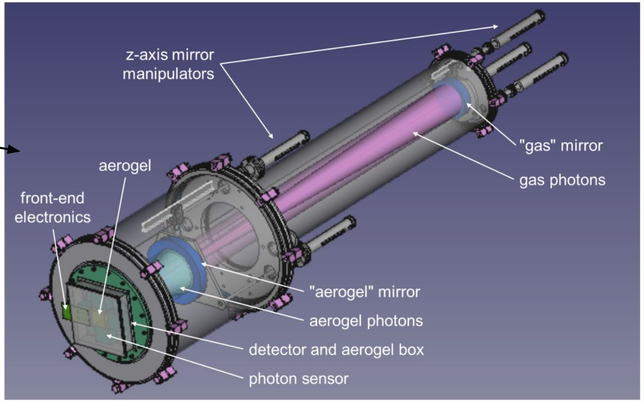
explore SiPM readout option





- **realisation of dRICH prototype, test beams**
  - design of electronics boards
  - SiPM studies
    - irradiation tests (@ Trento)
    - annealing at high T ~ 170°
    - operation at low T ~ −40°
  - DAQ for front-end readout
    - front-end based on ALCOR

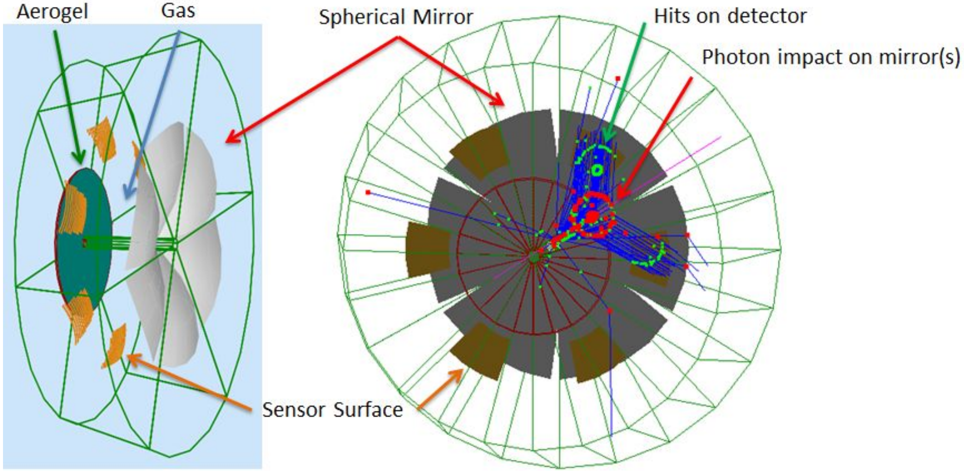


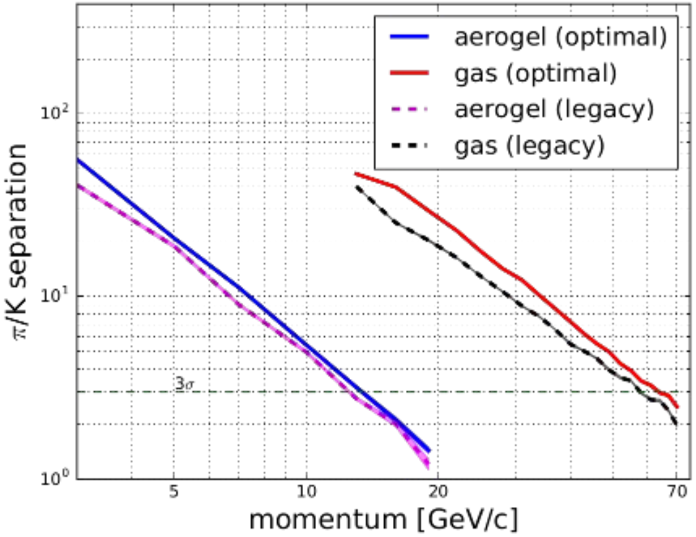


The dual-radiator (dRICH) for forward PID

3-60 GeV/c
1.5 < η < 3.5

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



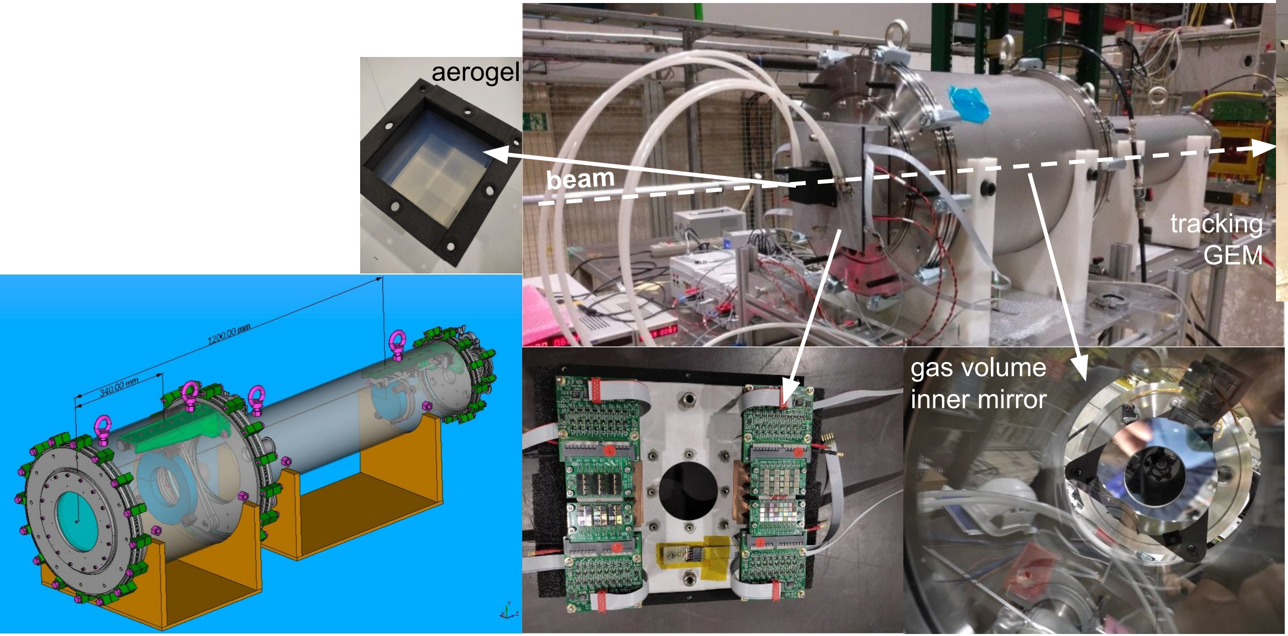


- **radiators:** aerogel (n ~ 1.02) and C_2F_6 (n ~ 1.0008)
- **mirrors:** large outward-reflecting, 6 open sectors
- **sensors:** 3x3 mm^2 pixel, 0.5 m^2 / sector
  - ~ 3m^2 surface with photosensors (~ 300 k channels)
  - single-photon detection inside high B field (~ 1 T)
  - outside of acceptance, reduced constraints
- **full Geant4 simulation studies**
  - with bayesian optimisation of layout
  - and analytic parameterisations

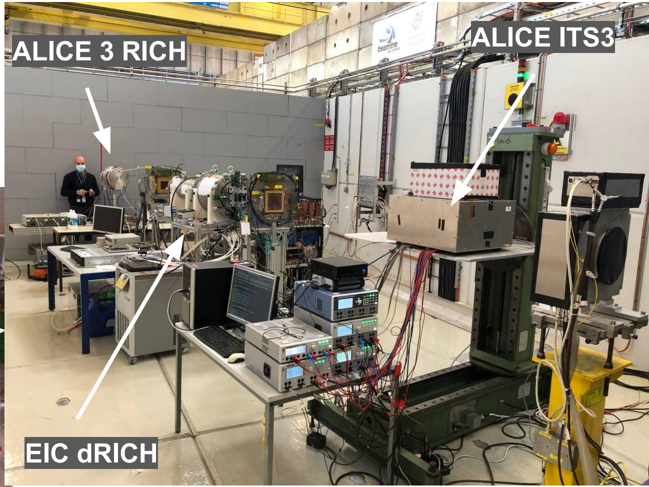
SiPM tested with beams at CERN

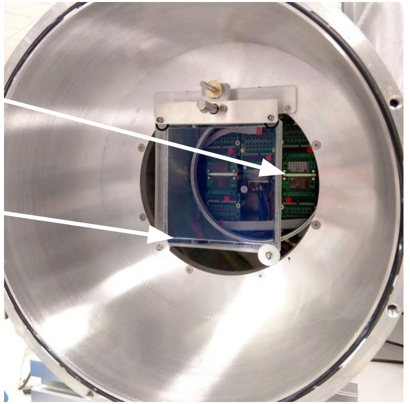
first test-beams in September (SPS) and October 2021 (PS, in synergy with ALICE) at CERN

dRICH prototype @ CERN-SPS



ALICE and EIC at CERN PS T10 October 2021





perhaps too optimistic / ambitious for the program of 2021
some troubles with electronics, not really a successful beam test for the SiPM readout
but we have anyway learned something, stay positive for 2022!

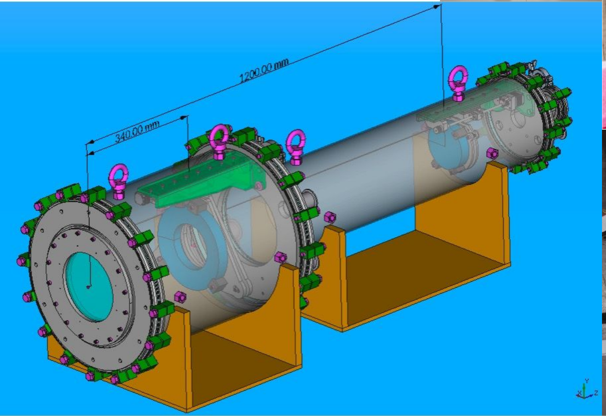
dRICH: dual-radiator RICH

first test-beams in September (SPS) and October 2021 (PS, in synergy with ALICE) at CERN

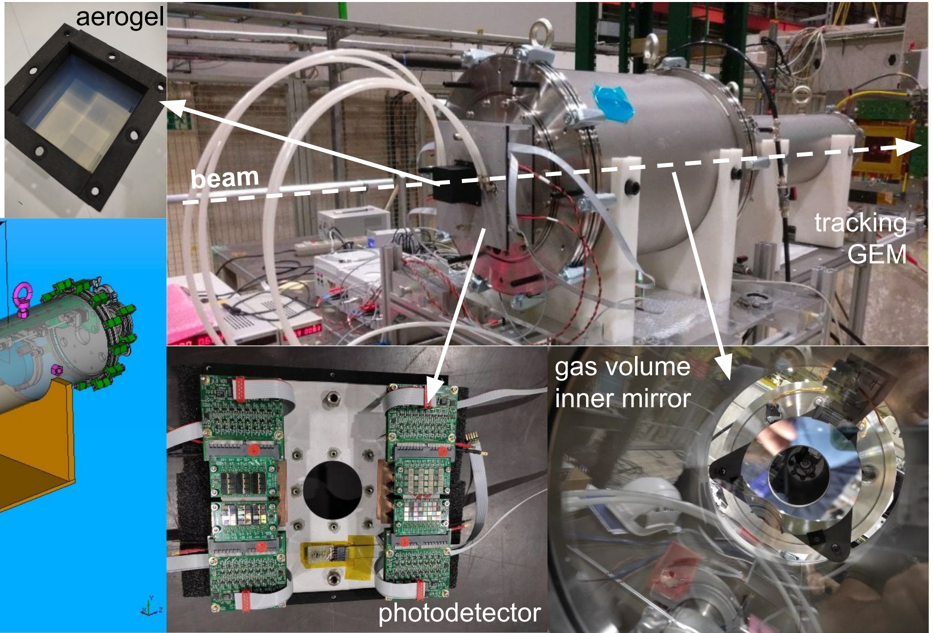
- **goals**
  - study dual radiator performance and interplay
  - study specifications and alternatives for optical components
  - test alternate single-photon detection systems

dRICH prototype

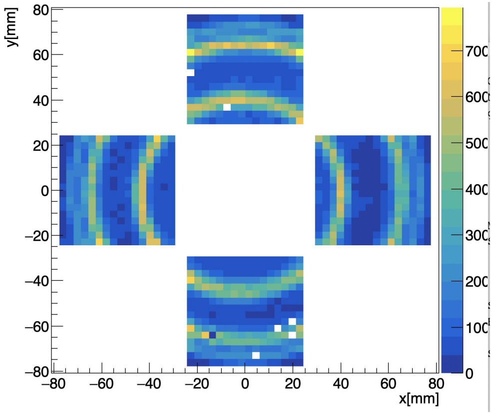
- dual-radiator imaging
- vessel for gas and n tune
- sensor & readout friendly

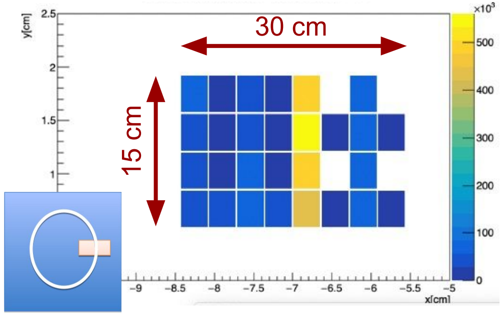


dRICH prototype @ CERN-SPS



working principle + optical performance
with H13700 PMT and MAROC readout

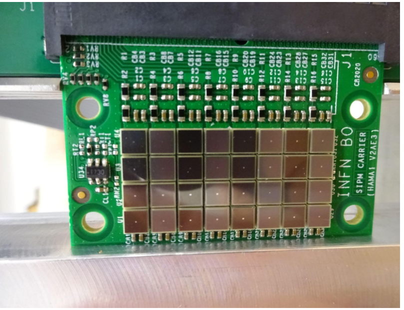




test of SiPM Cherenkov application
with new ALCOR chip (ToT, streaming)

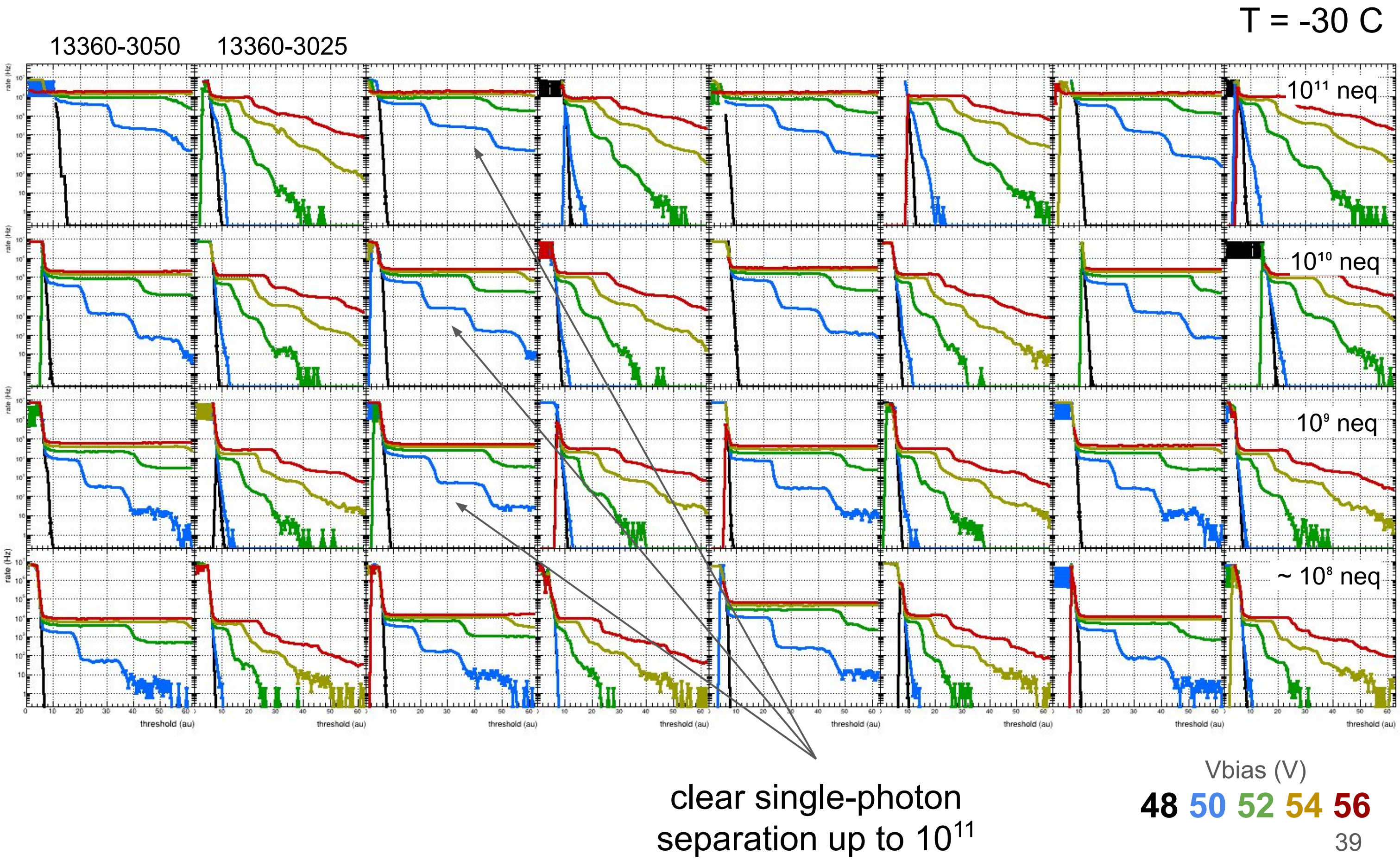
dRICH online monitor results

Hamamatsu (HAMA1 #2) threshold scans



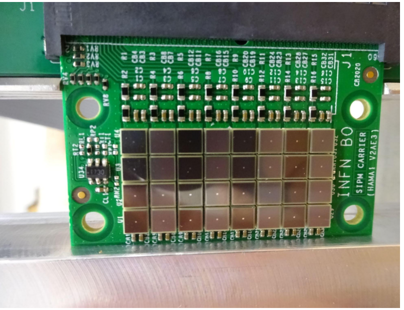
irradiated board after annealing

still working!



Hamamatsu (HAMA1 #2) threshold scans

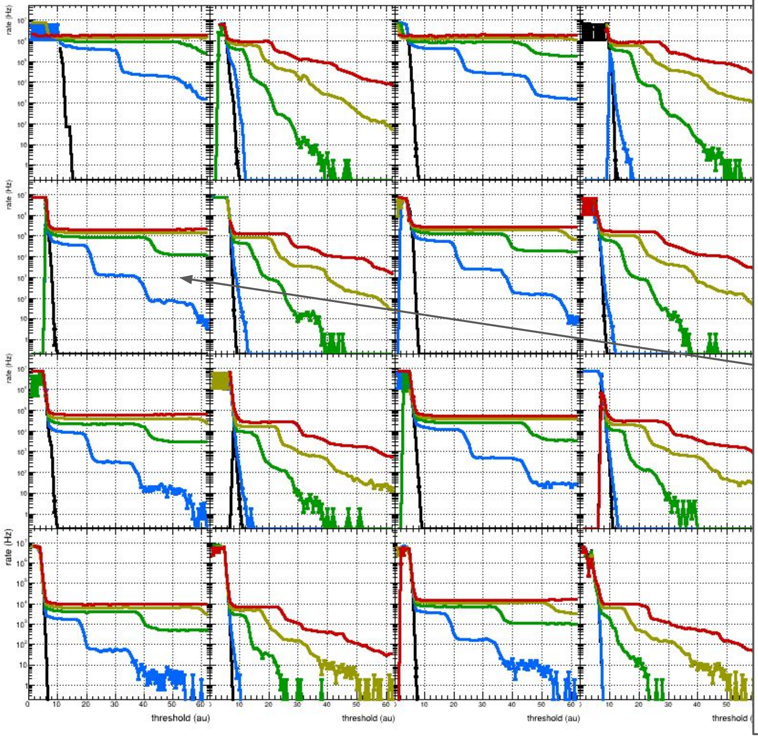
T = -30 C



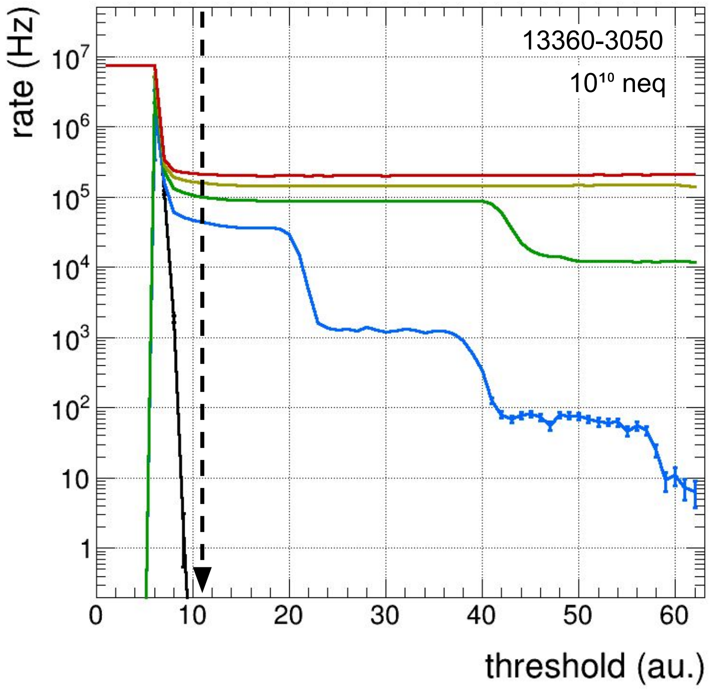
irradiated board after annealing

still working!

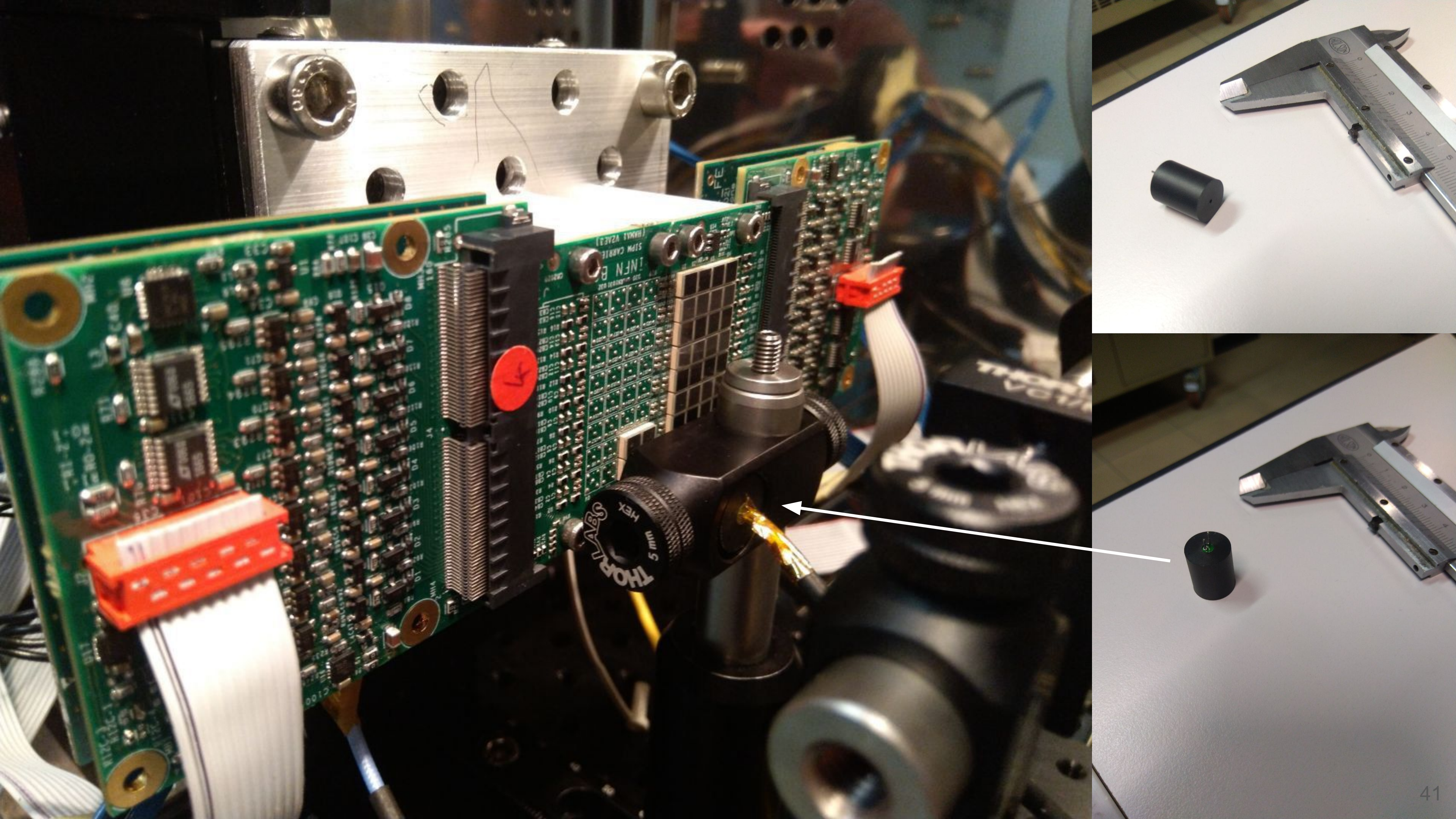
13360-3050 13360-3025



selected threshold value automatically optimised

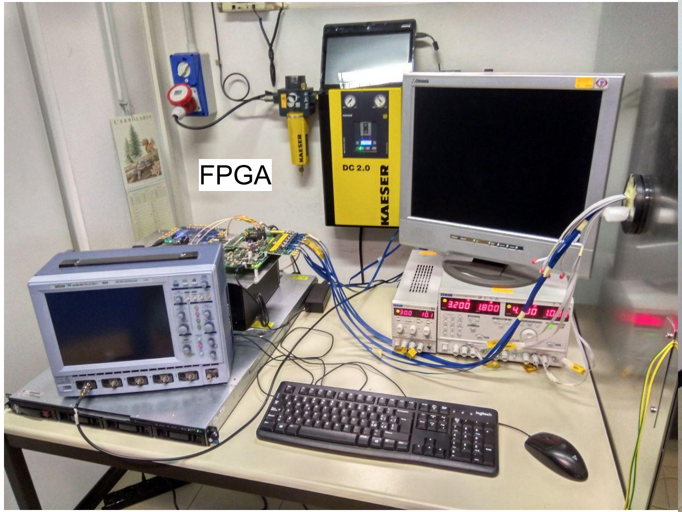


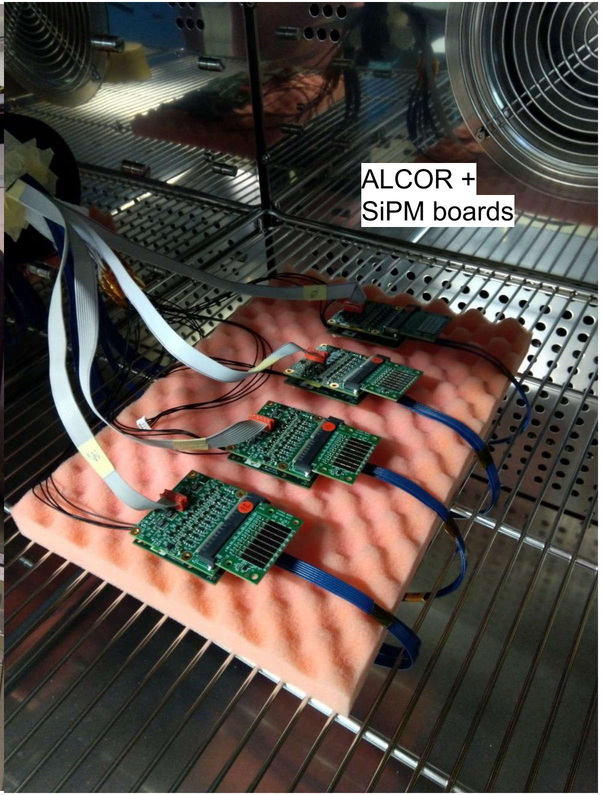
Vbias (V)
48 50 52 54 56


THORLABS
HEX
5 mm

SiPM+ALCOR setup in Bologna

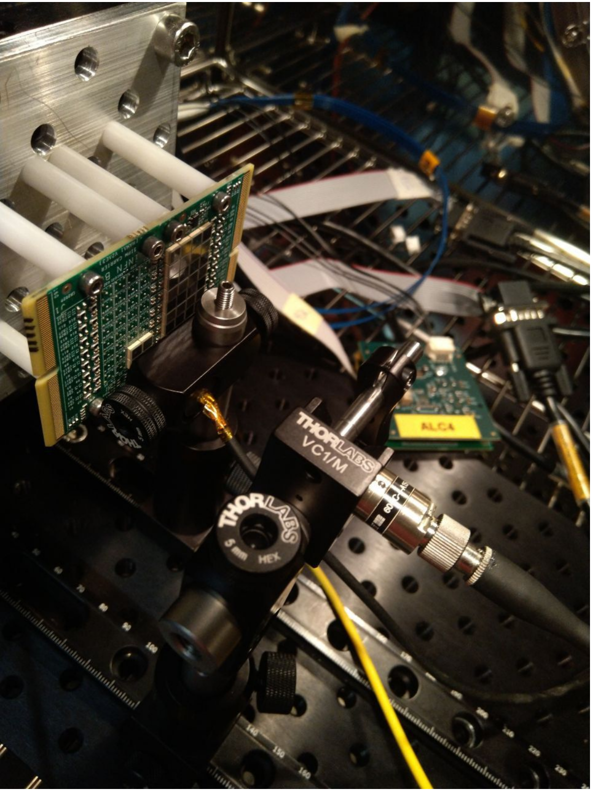
permanent EIC SiPM setup in the INFN Bologna Silicon Labs
characterisation of performance of SiPM with full (ALCOR) readout system
measure many SiPM in one go!

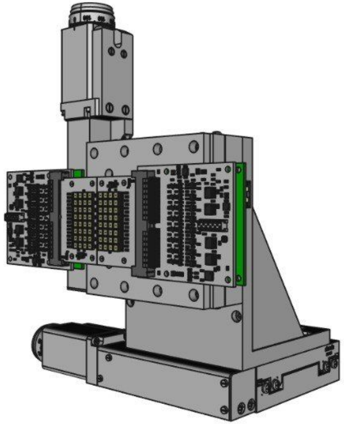




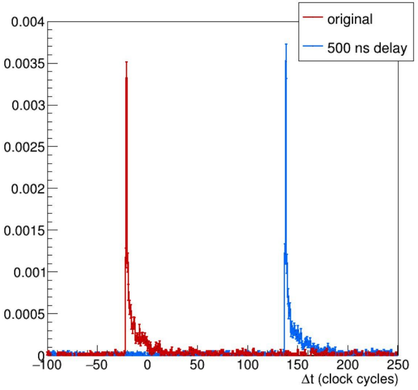
the following results have been obtained with this setup

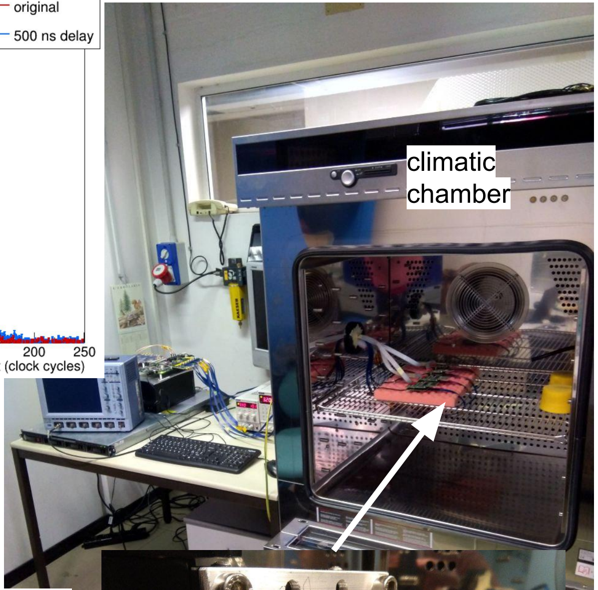
SiPM+ALCOR setup in Bologna

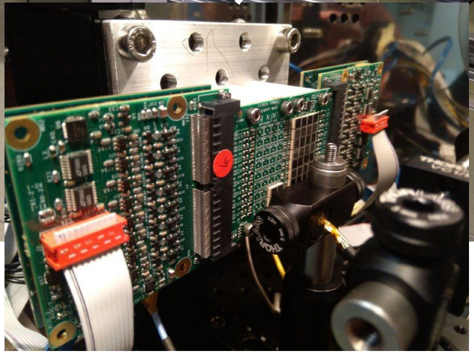




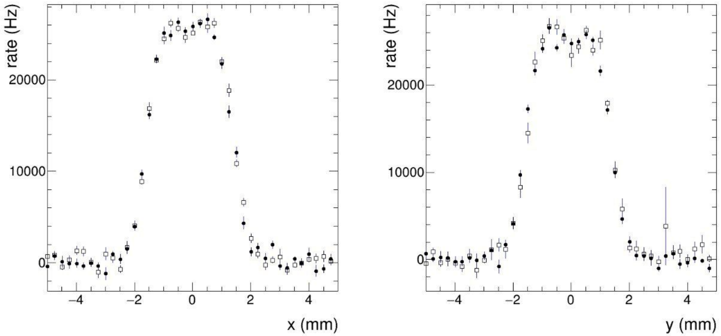
time correlations



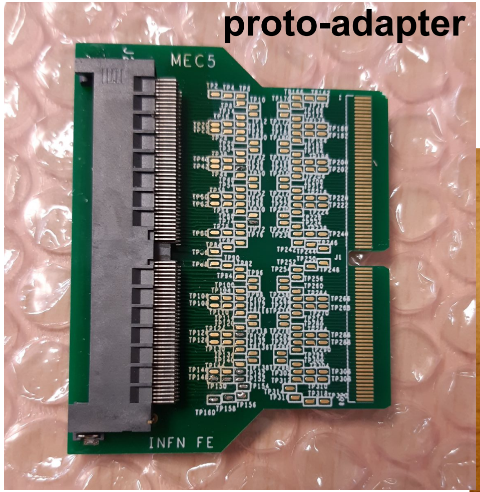




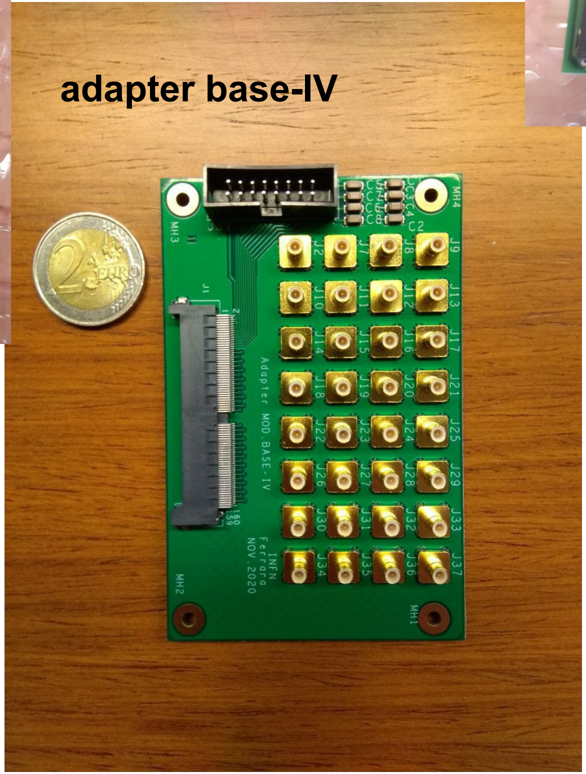
position scan



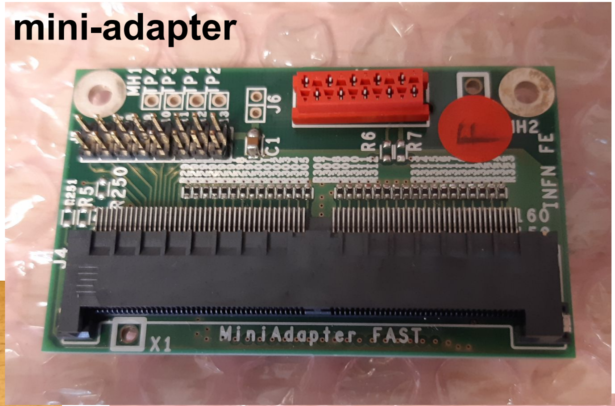
Bologna setup **upgraded** with pulsed LED and movimentation inside the climatic chamber



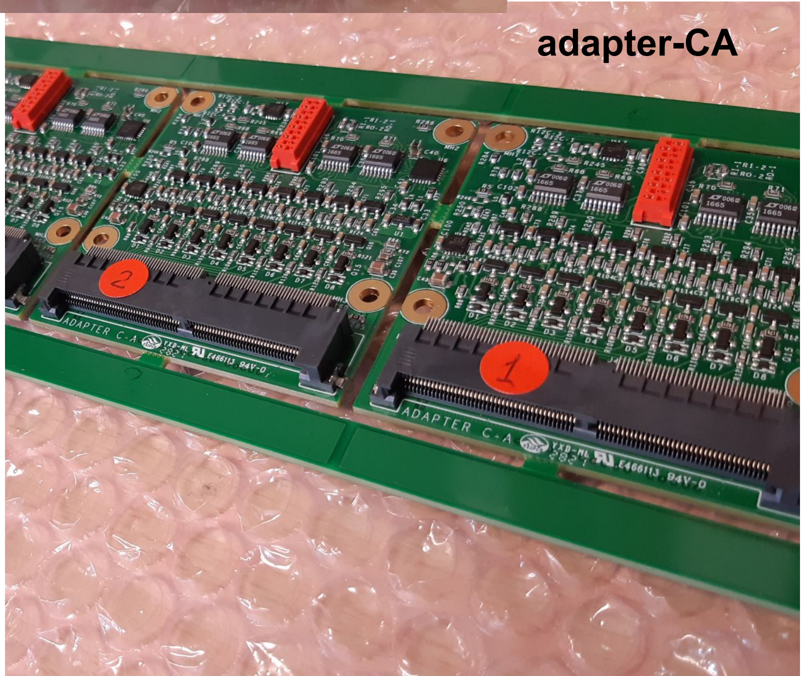
proto-adapter



adapter base-IV



mini-adapter

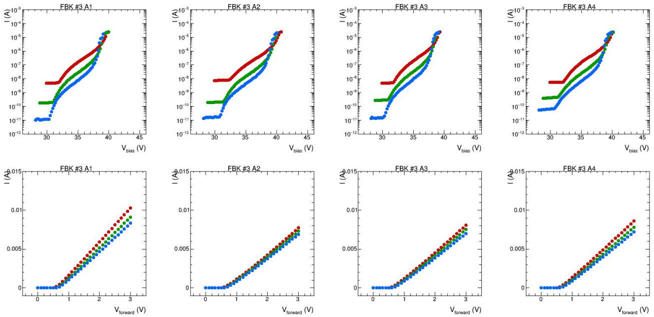


adapter-CA

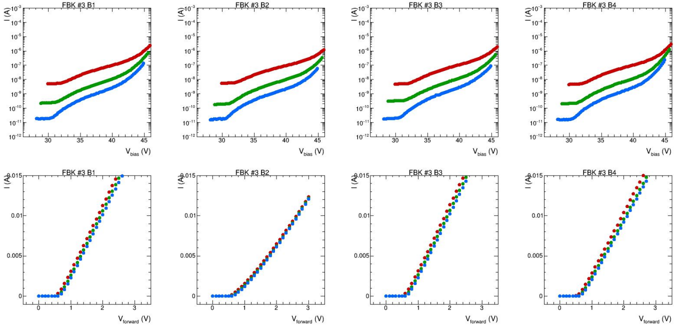
IV characteristics at different T

+20 C
−10 C
−30 C

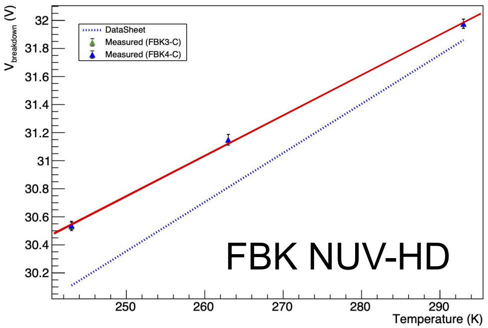
FBK NUV-HD-CHK

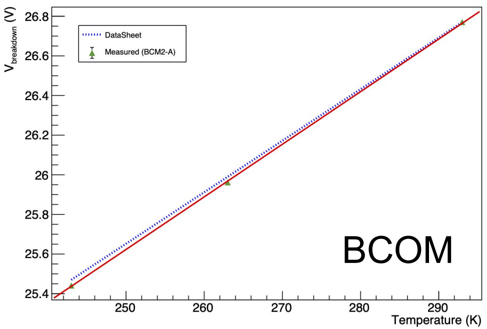


FBK NUV-HD-RH

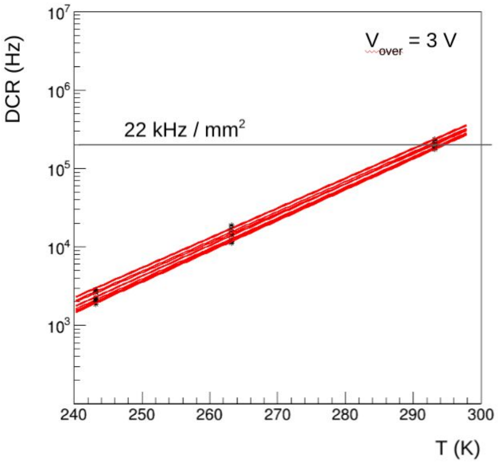


breakdown voltage vs. temperature



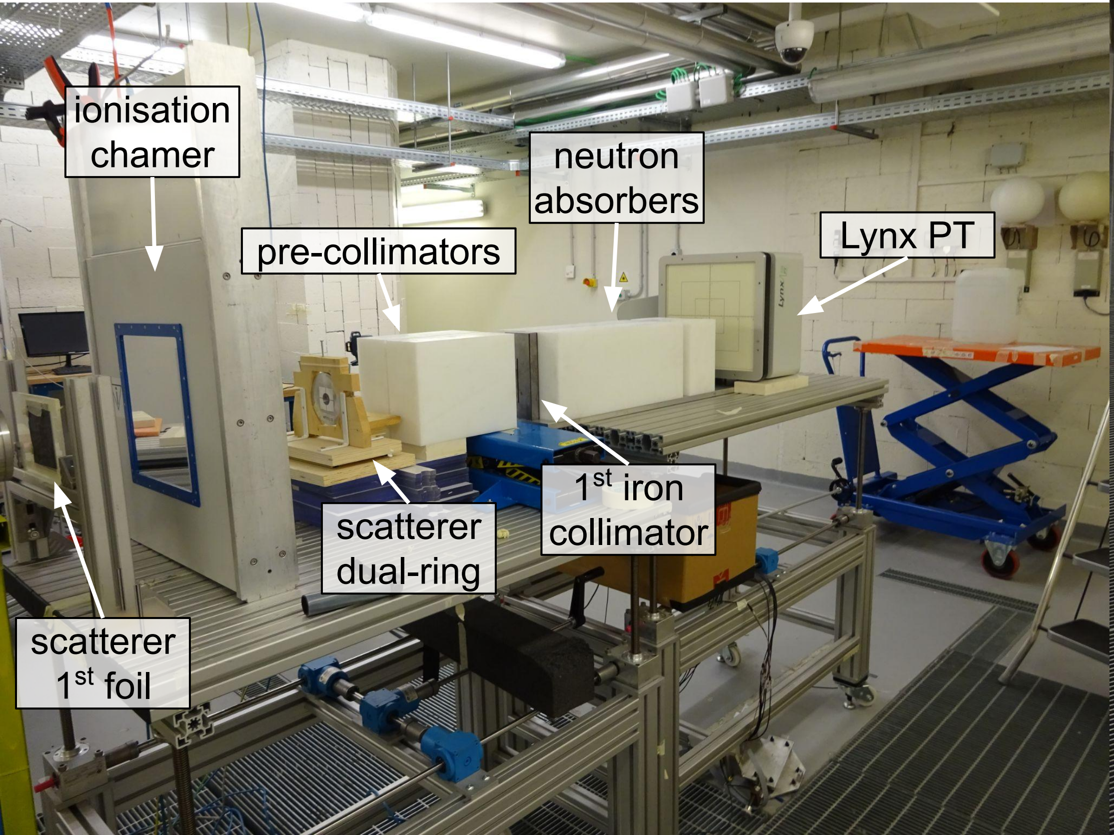


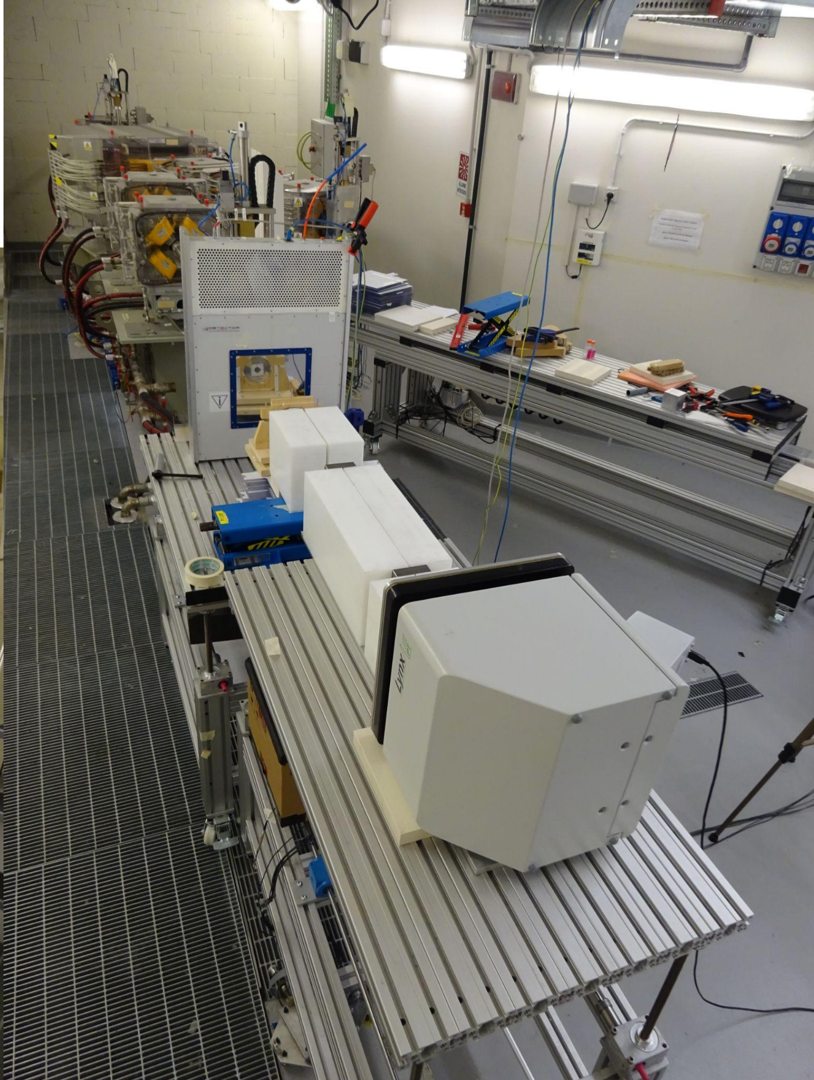
dark count rate vs. temperature



only a little fraction of the large amount of data collected shown

Collimator setup: intensity calibration





Photosensors: SiPM

pros

B-field insensitive

cheap, robust, fast-evolving

cons

(mitigation options)

high dark-count rate

(cooling, time resolution)

limited radiation tolerance

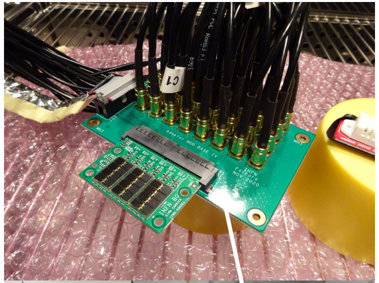
(design, high-T annealing)

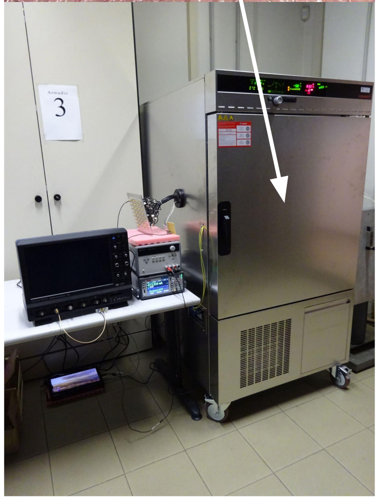
single-photon performance after 10^{11} 1-MeV n_{eq} dose

commercial Hamamatsu

FBK prototypes

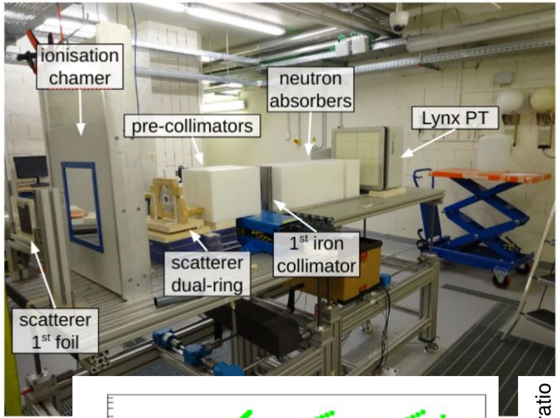
characterisation in lab



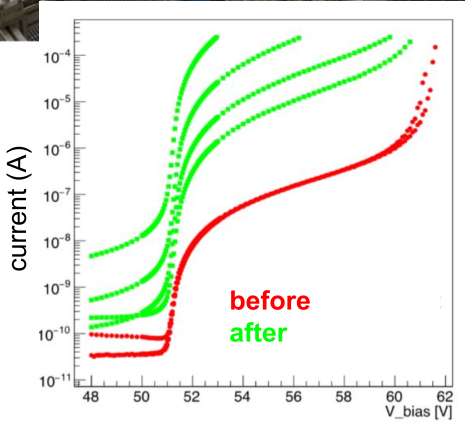


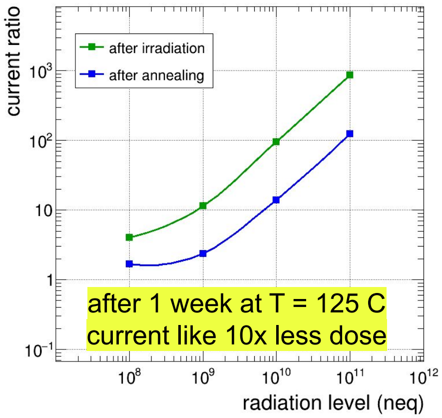
climatic chamber, low-T operation

TIFPA proton beam facility
collimated beam, 10^{9}-10^{11} 1-MeV n_{eq}

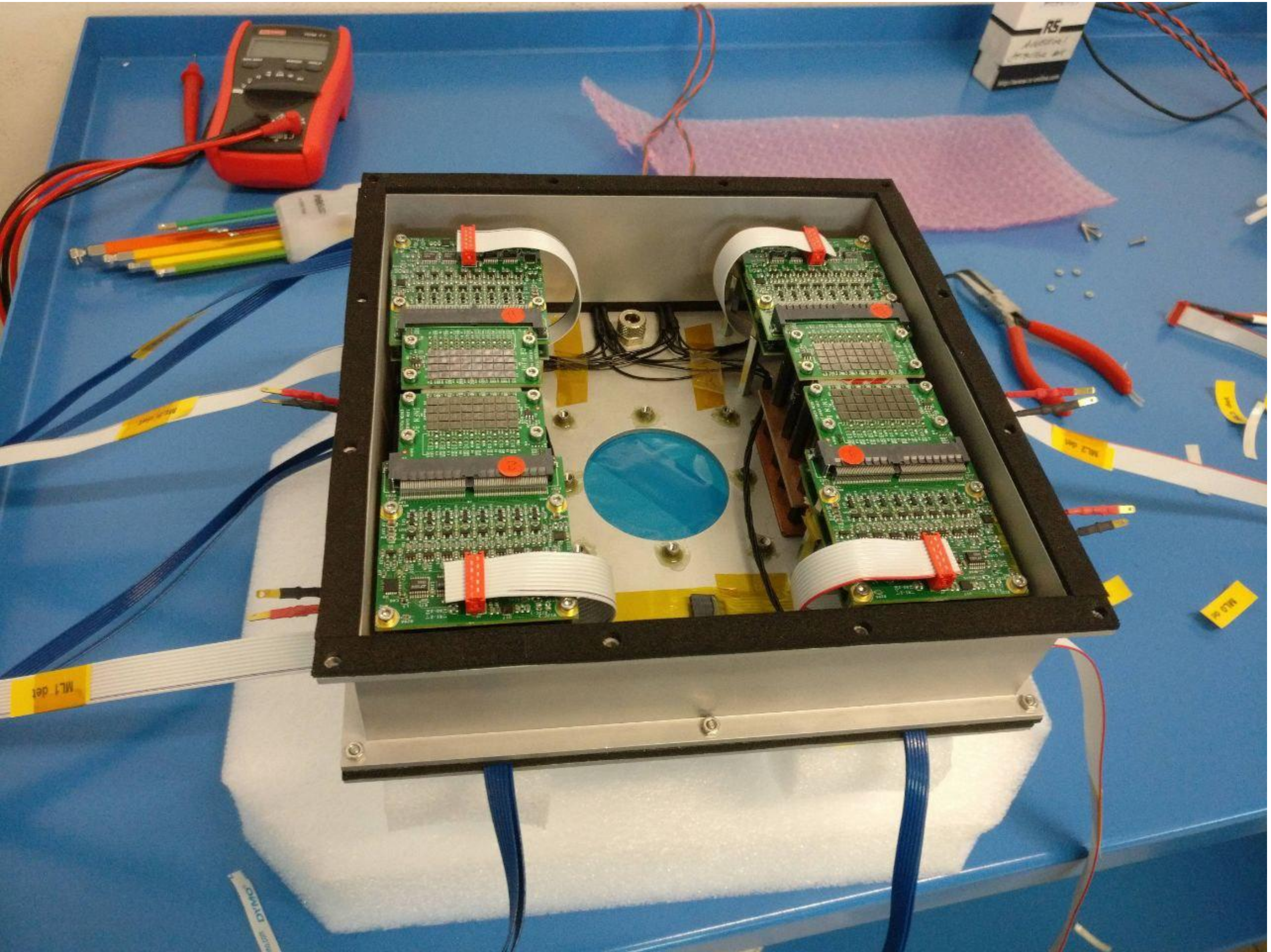


high-T annealing





dRICH prototype SiPM readout box in Bologna



thanks to Luca the dRICH prototype SiPM readout box is in Bologna

currently being equipped with services
- water
- dry air
- power
- computing

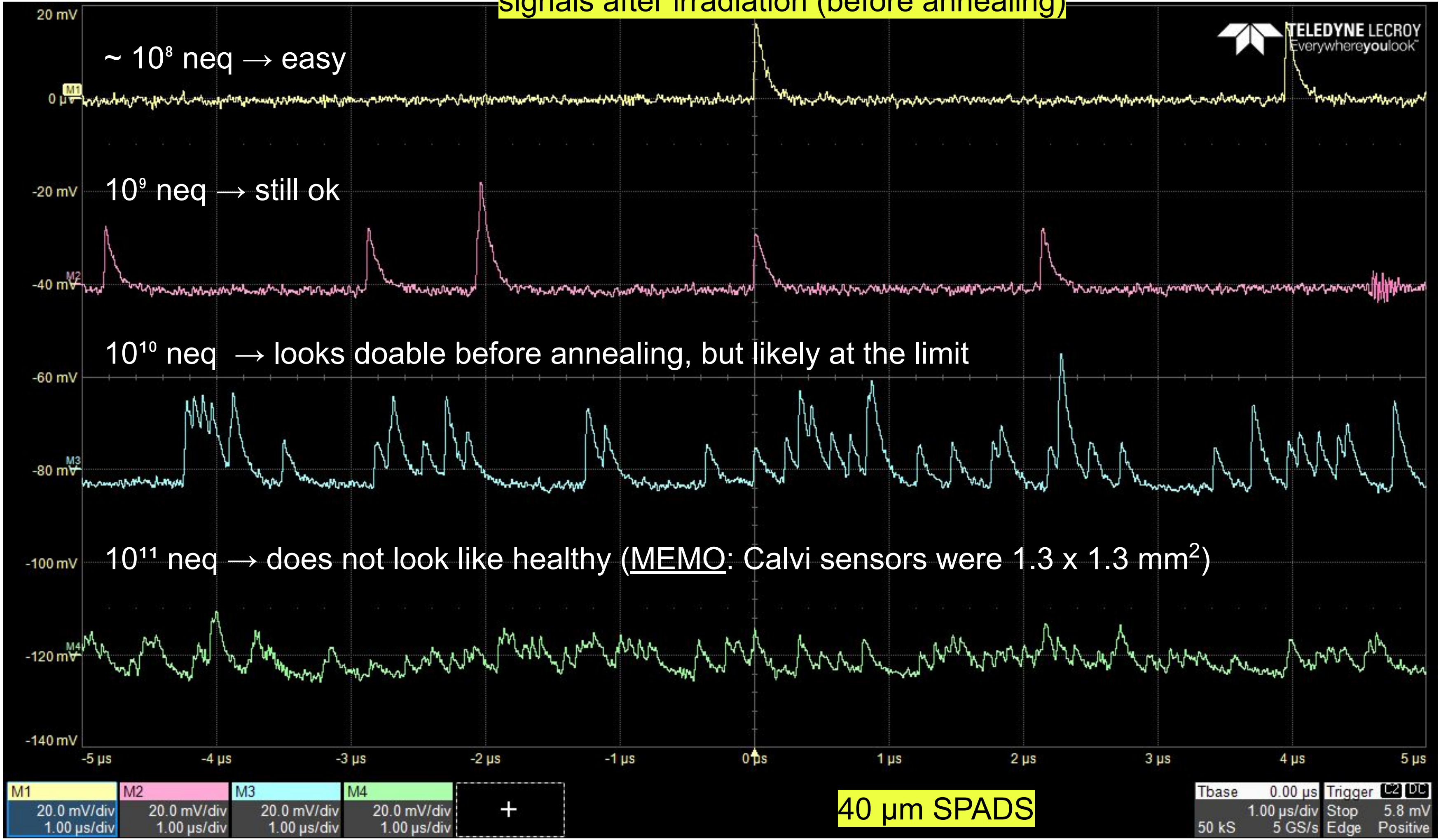
few adapter boards damaged fixed by Roberto M

a new setup for operation of SiPM in realistic conditions in preparation for test beams

expected to be fully operative by end of May, **help is welcome**

signals after irradiation (before annealing)

FBK #3 (T = -30 C)
NUV-HD-CHK (row A)



~ 10^8 neq → easy

10^9 neq → still ok

10^{10} neq → looks doable before annealing, but likely at the limit

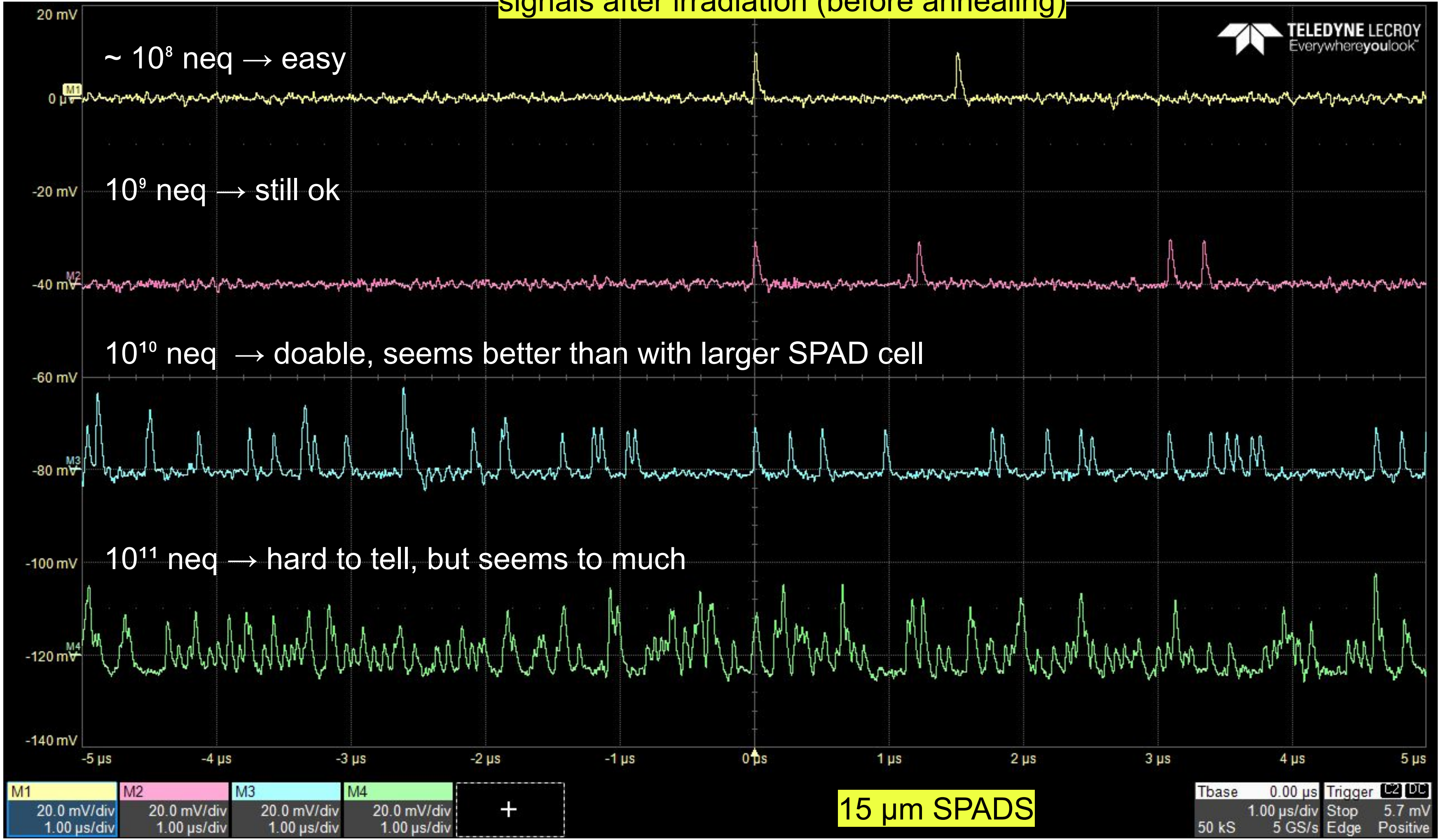
10^{11} neq → does not look like healthy (<u>MEMO</u>: Calvi sensors were 1.3 x 1.3 mm^2)

40 µm SPADS

signals after irradiation (before annealing)

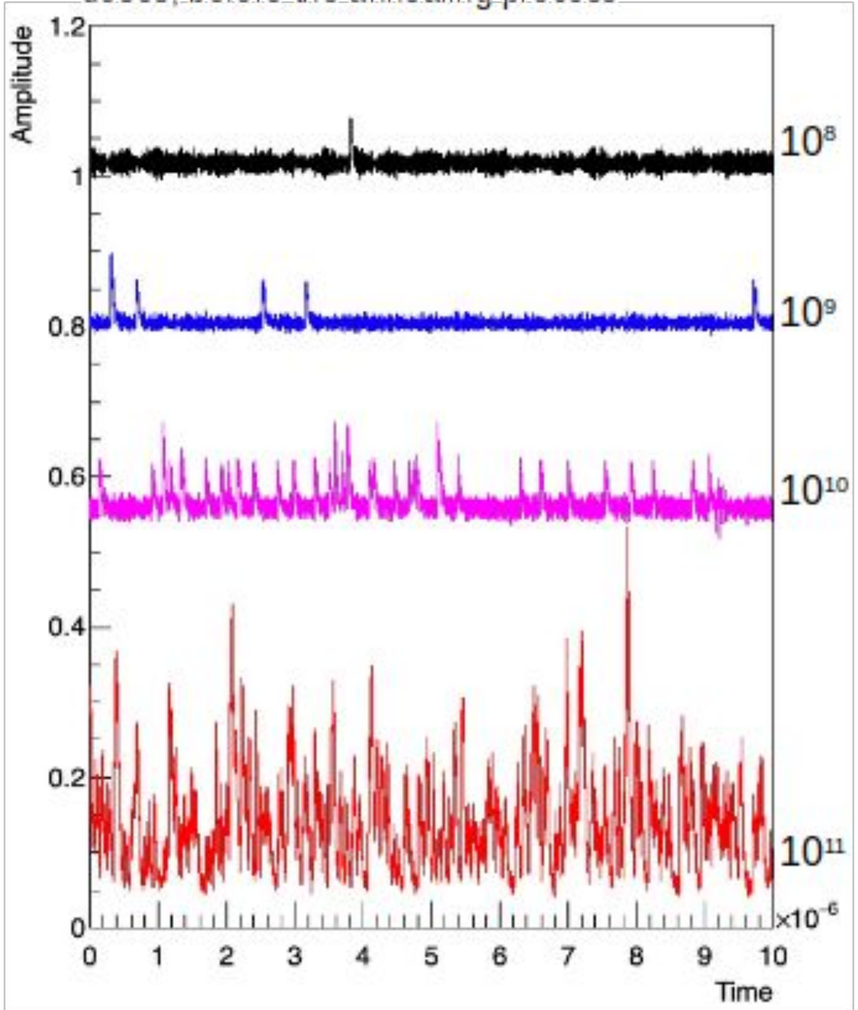
FBK #3 (T = -30 C)

NUV-HD-RH (row B)



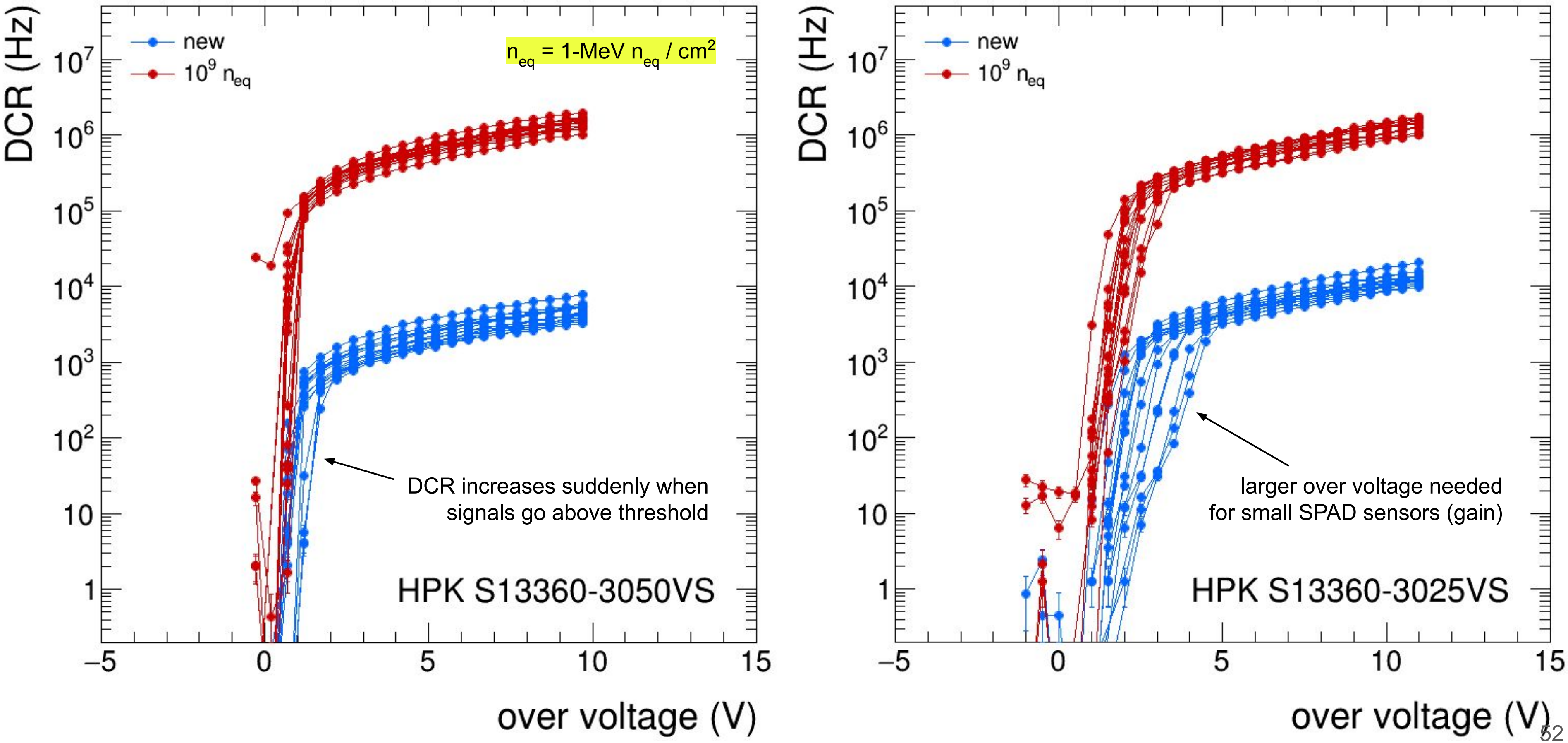
15 µm SPADS

Signals of SiPMs irradiated with different doses, before the annealing process

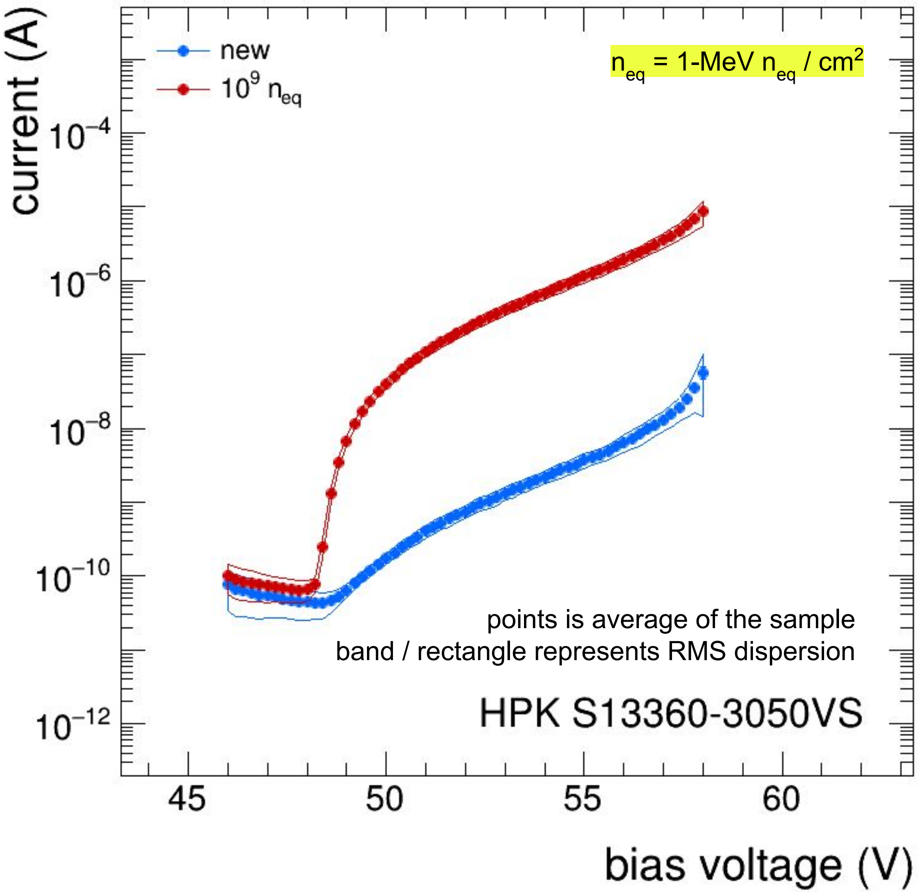


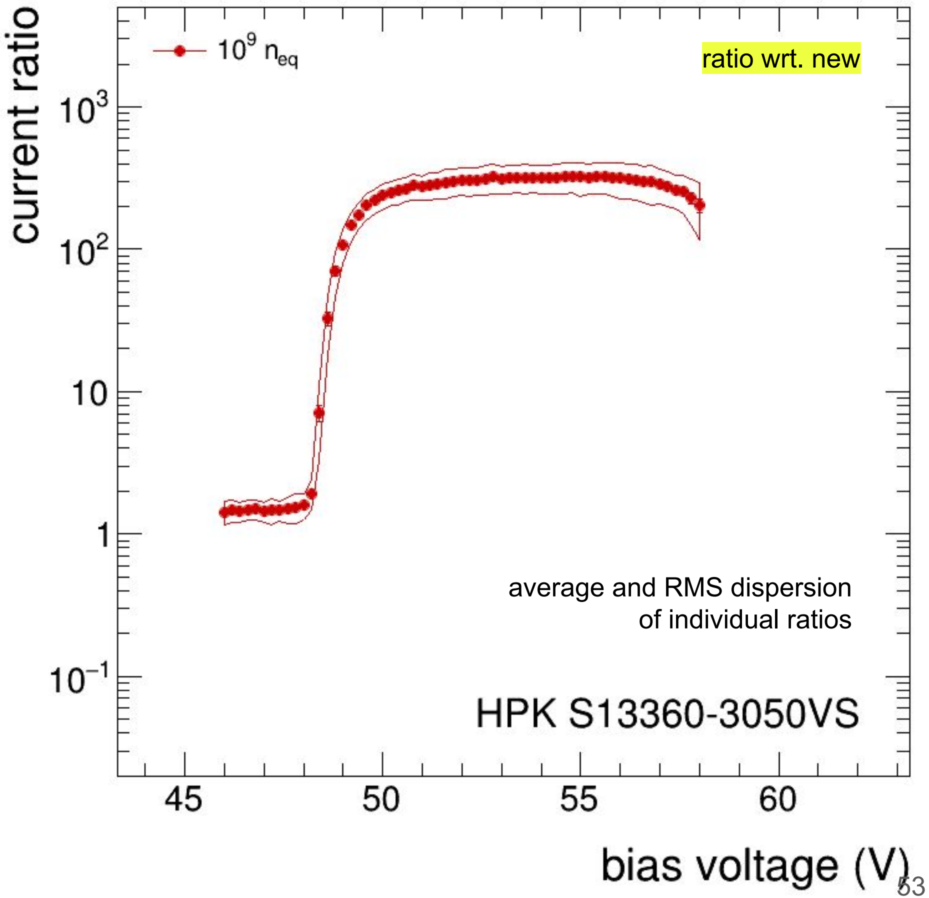
also Hamamatsu sensors seem to be doing ok up to 10^{10} neq

Photon counting at fixed ALCOR threshold

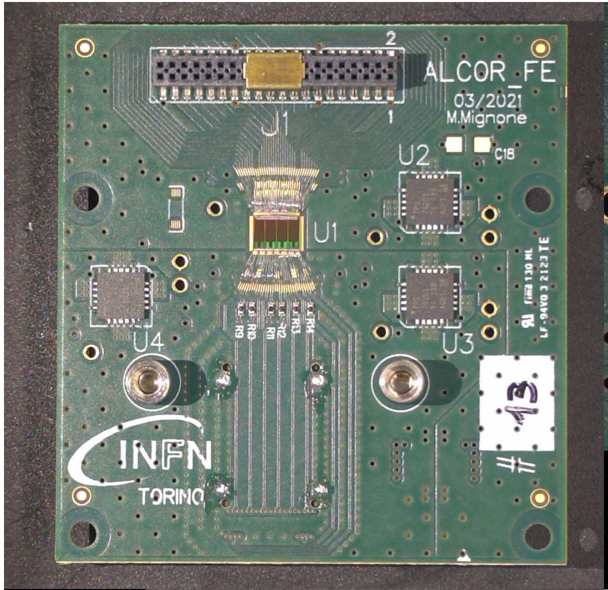


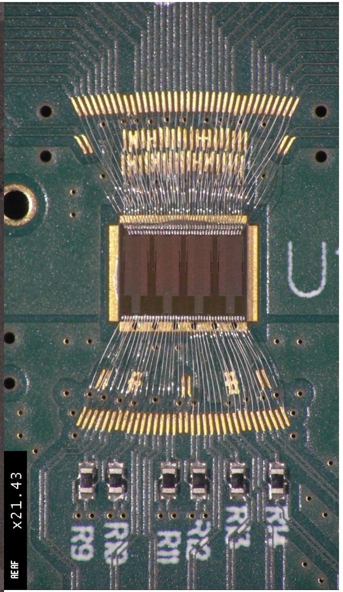
Averages and RMS dispersion of the sample

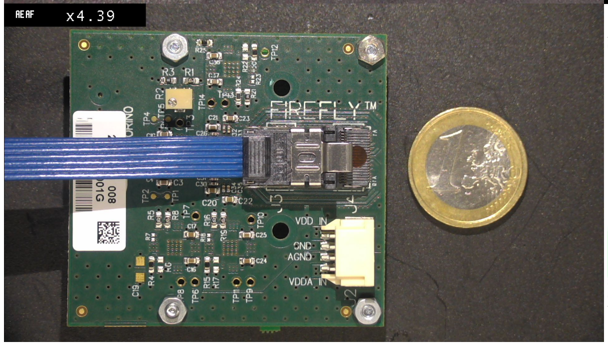


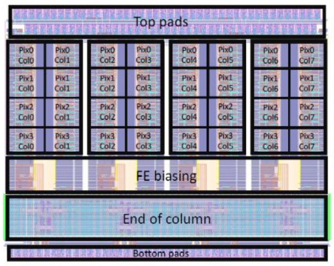


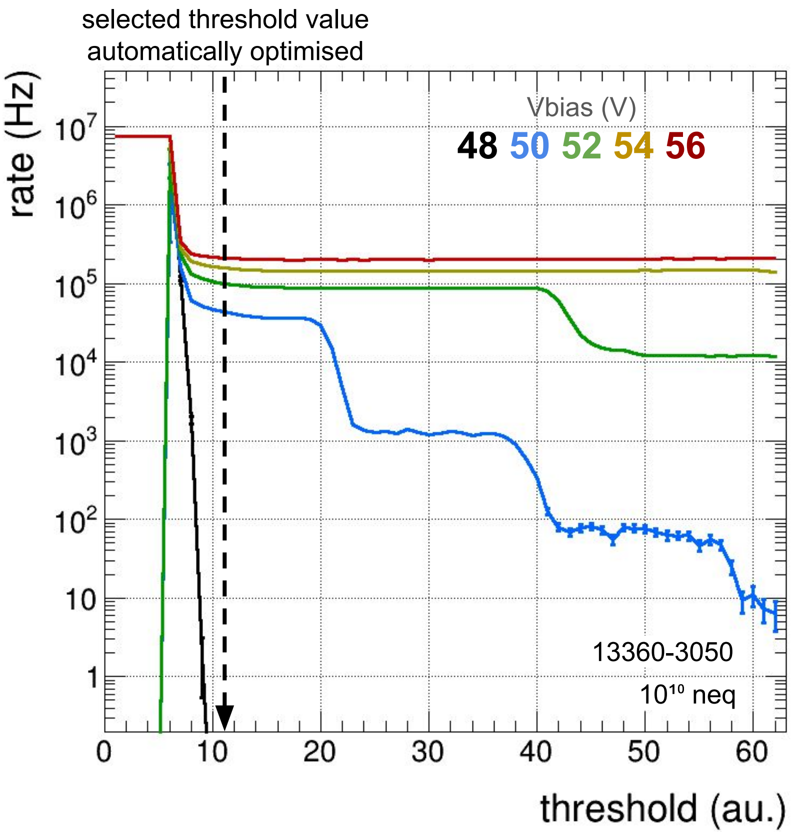
Photon counting with ALCOR



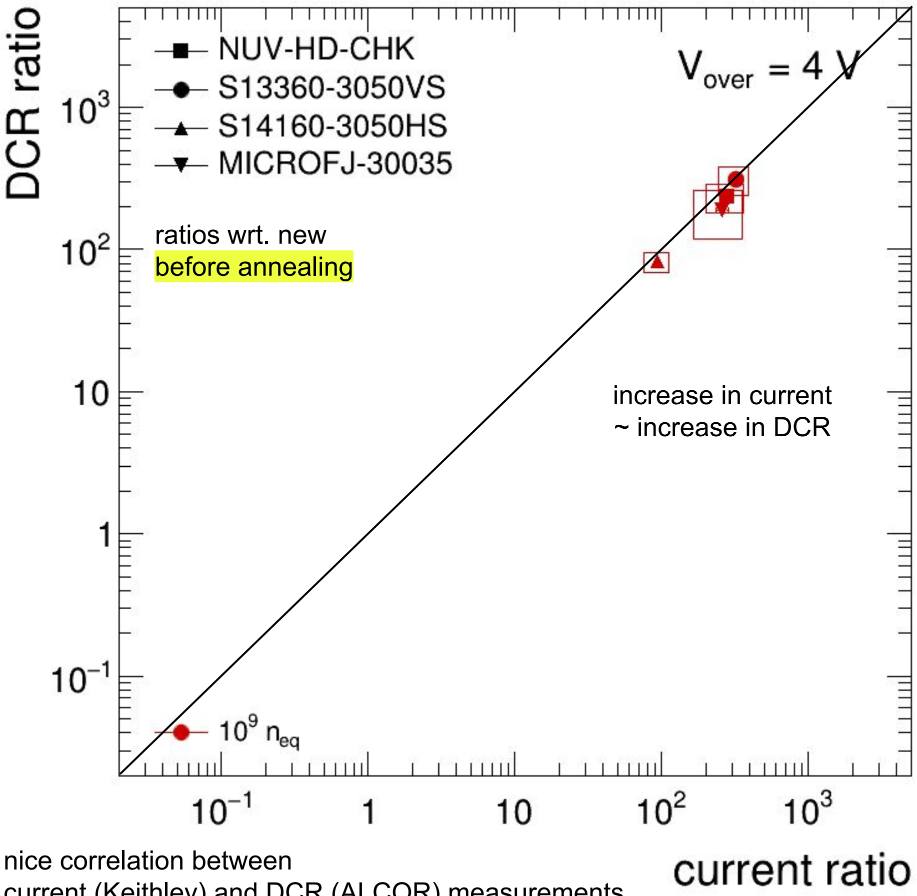


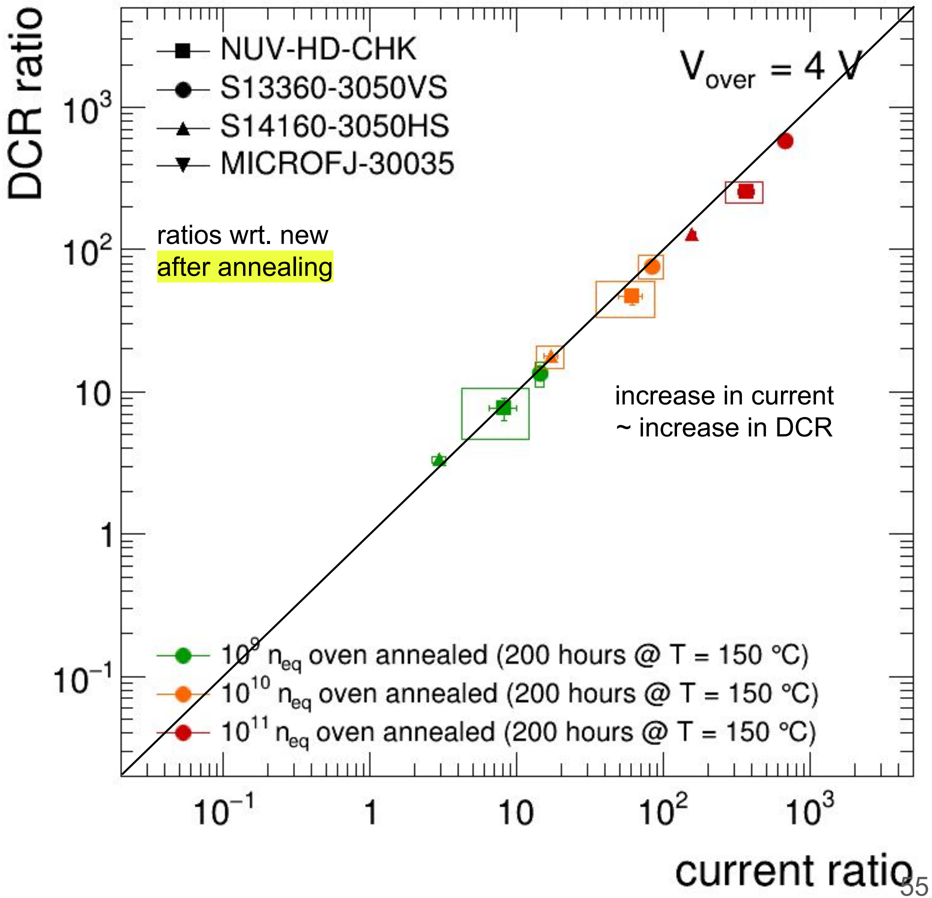






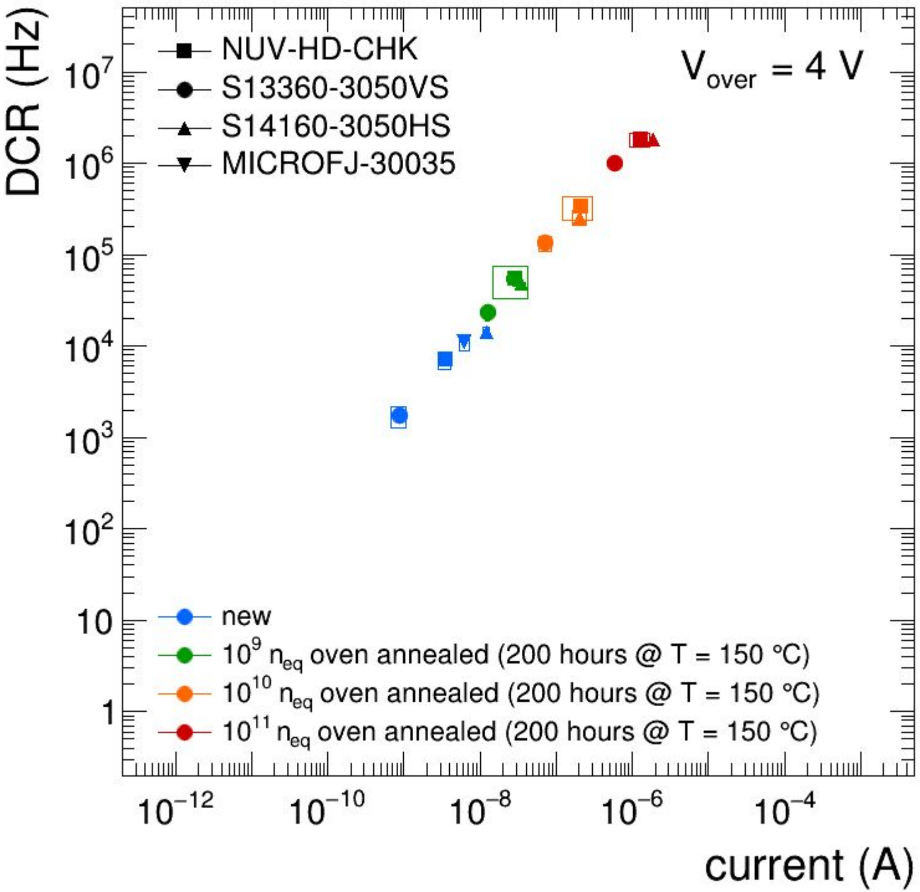
DCR increases with current at the same rate

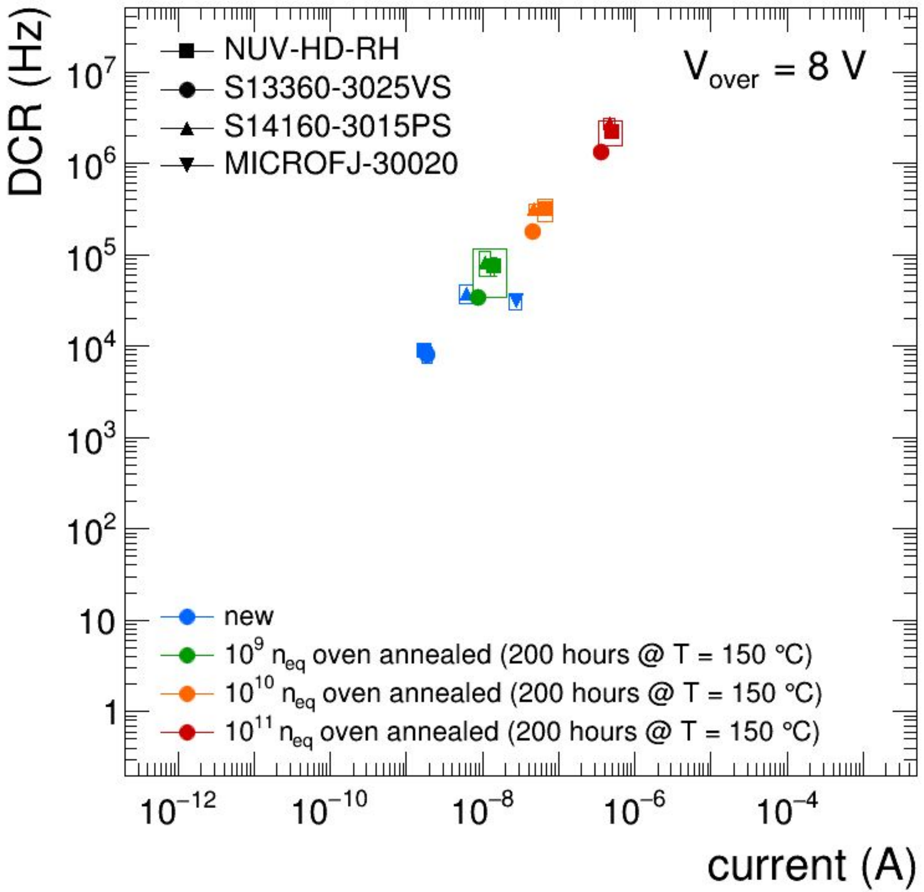




nice correlation between
current (Keithley) and DCR (ALCOR) measurements

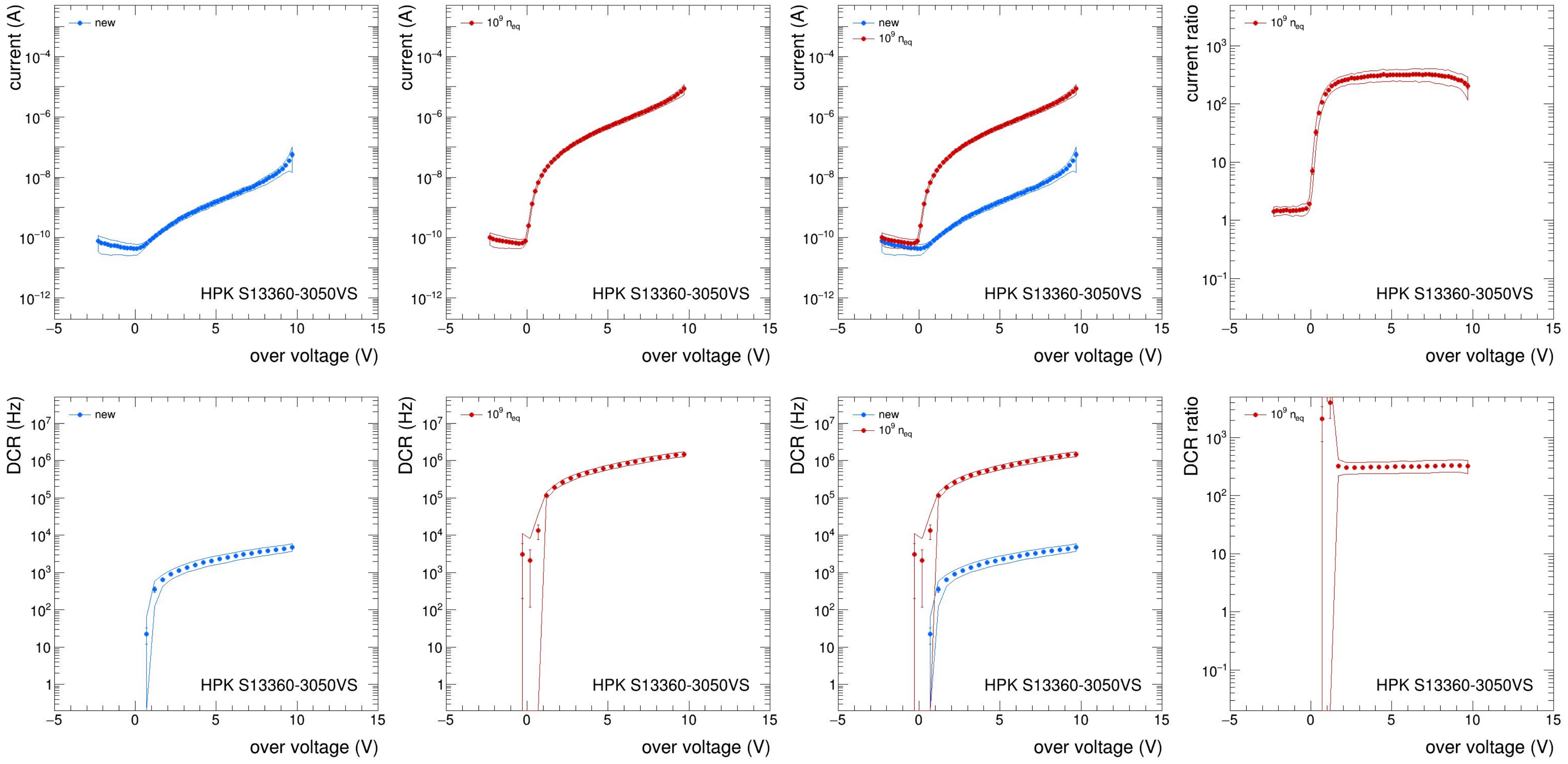
DCR vs. current



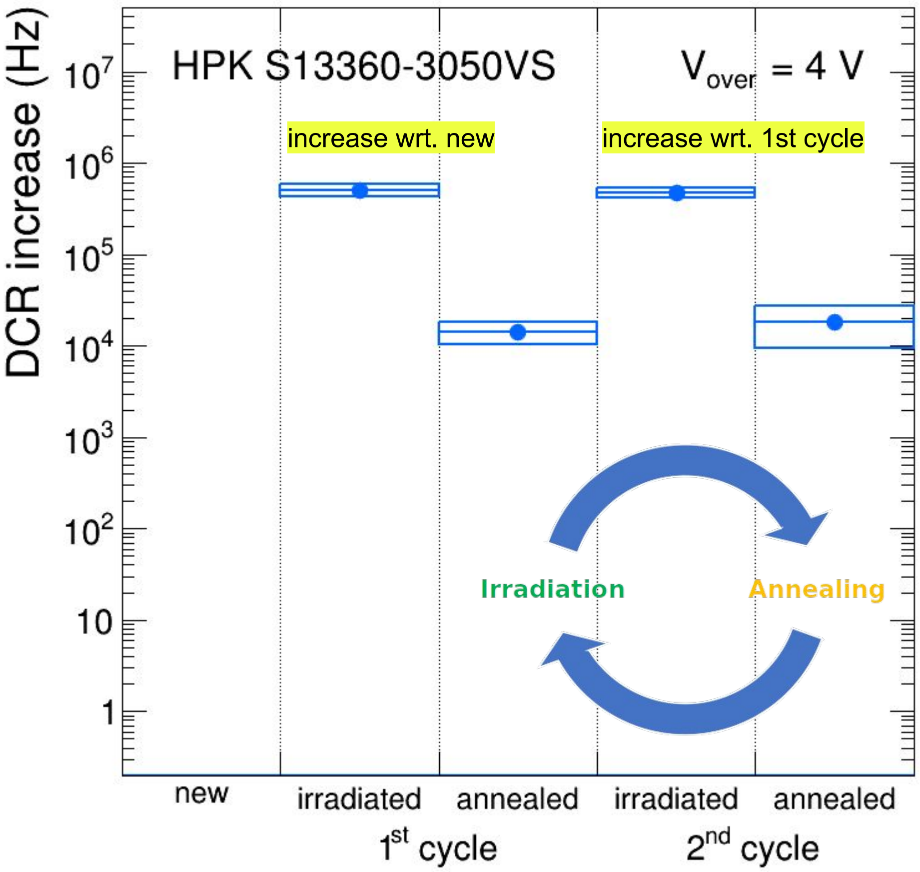


HPK 13360-3050VS

2022
over voltage



Repeated irradiation-annealing cycles



test reproducibility of repeated irradiation-annealing cycles

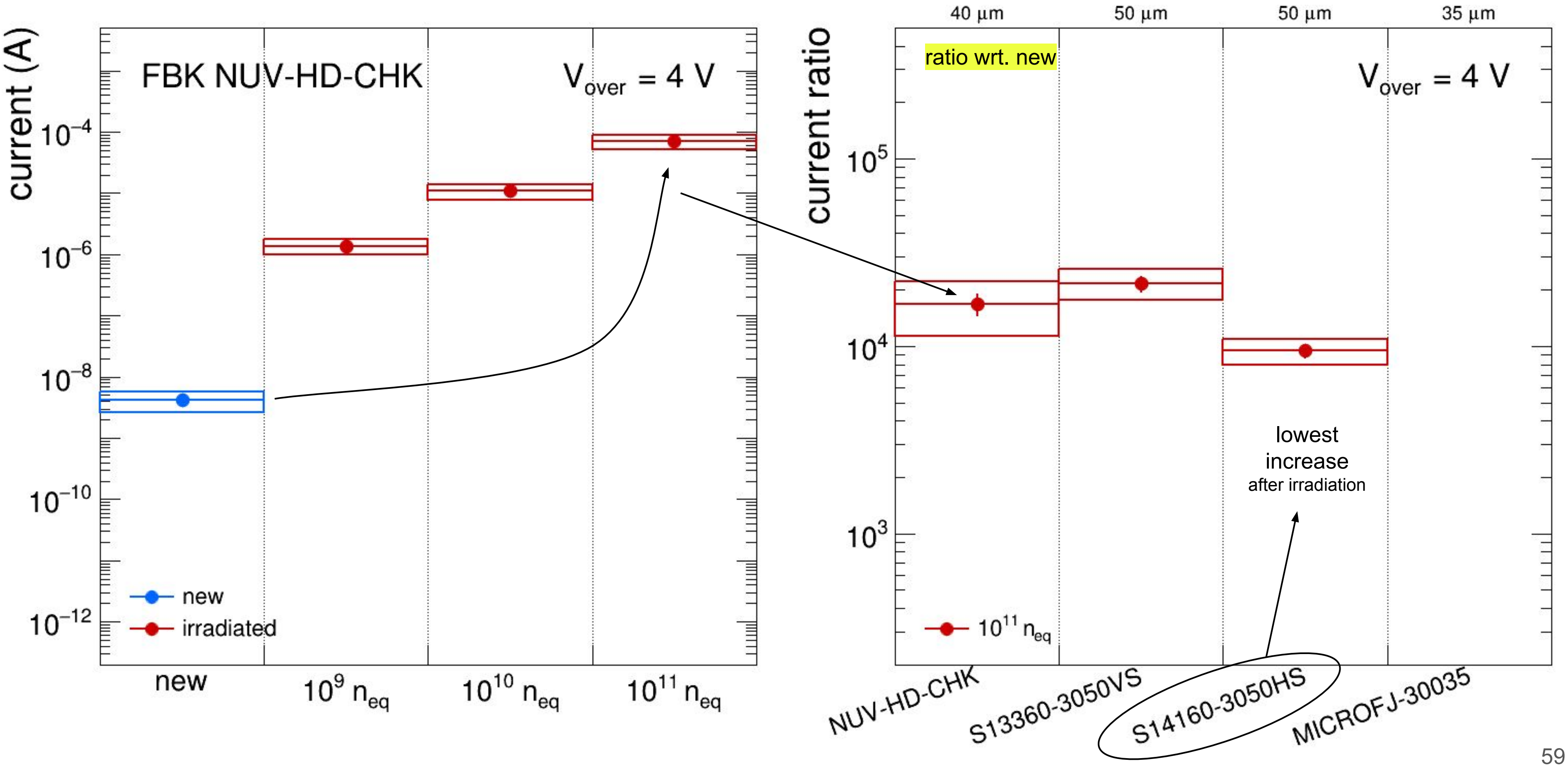
simulate a realistic experimental situation

- 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

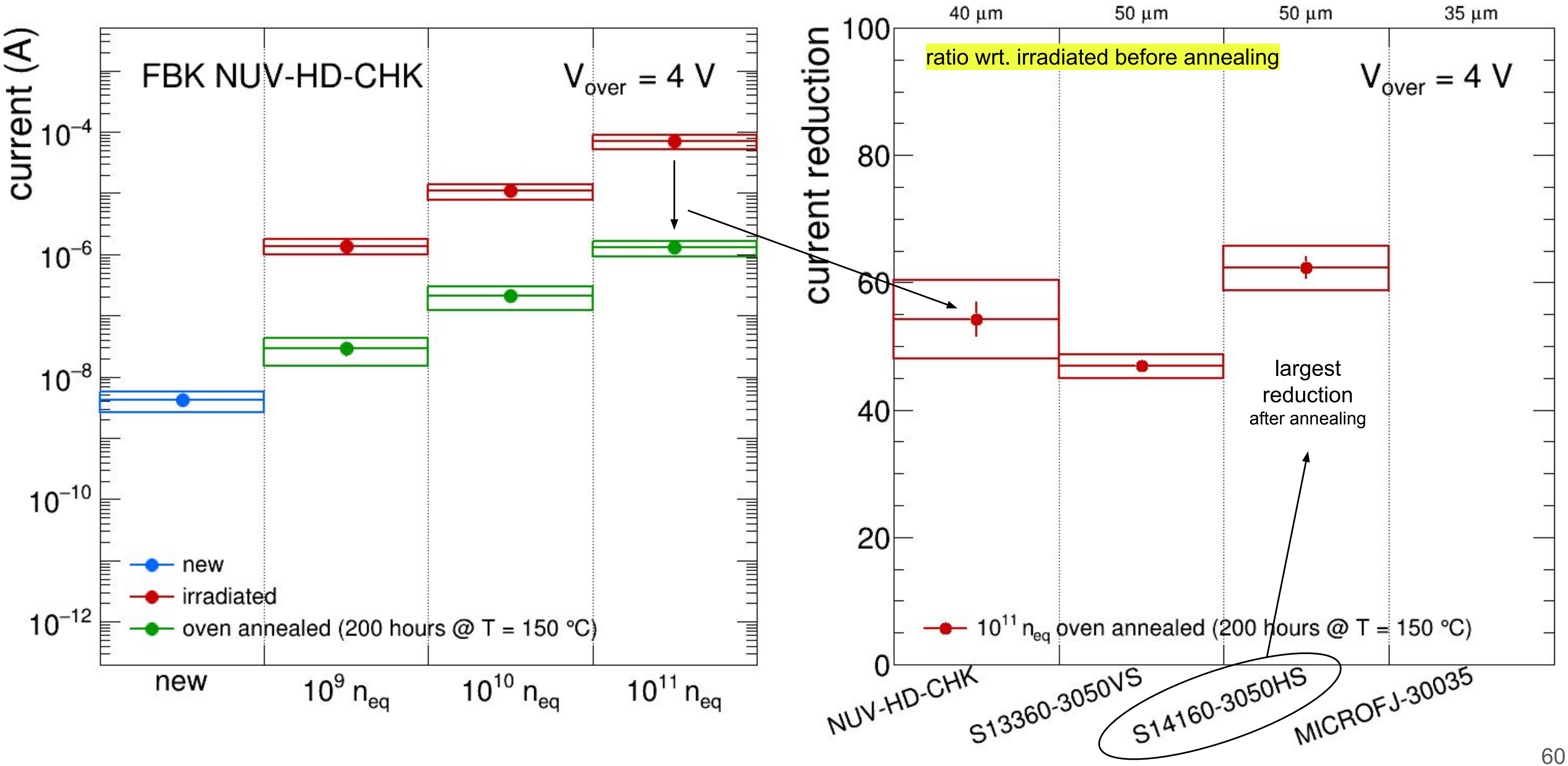
annealing cures same fraction of newly-produced damage

~ 97% for HPK S13360-3050 sensors

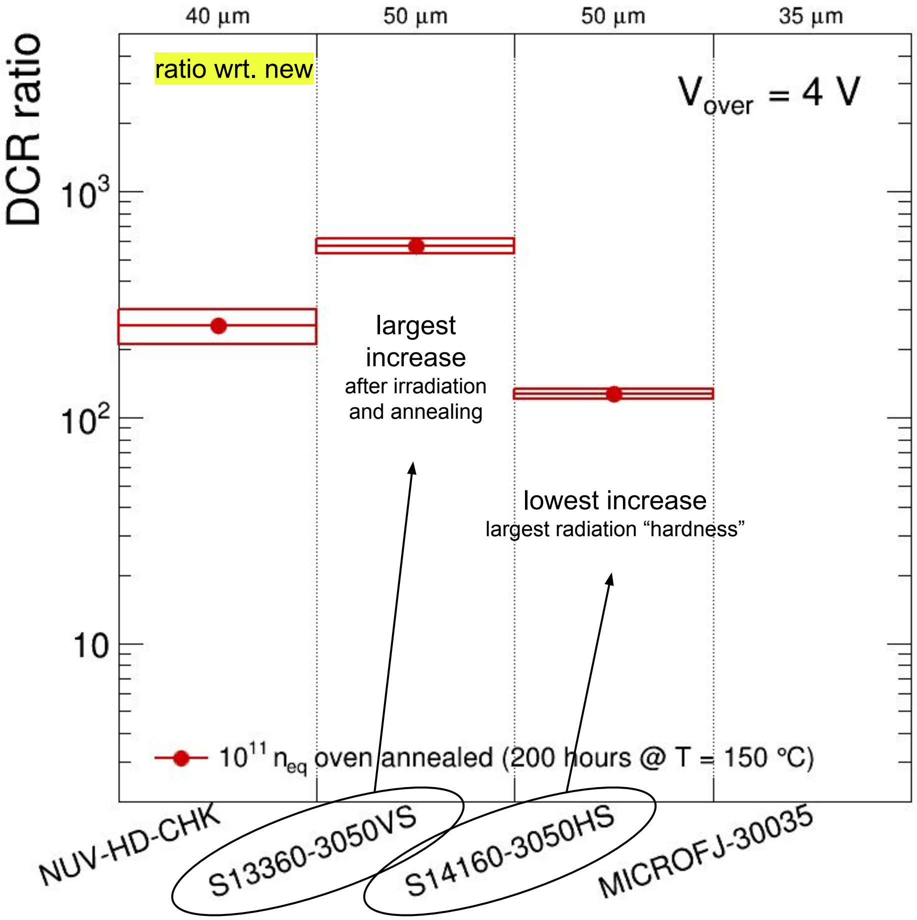
Current increase by irradiation in different sensors

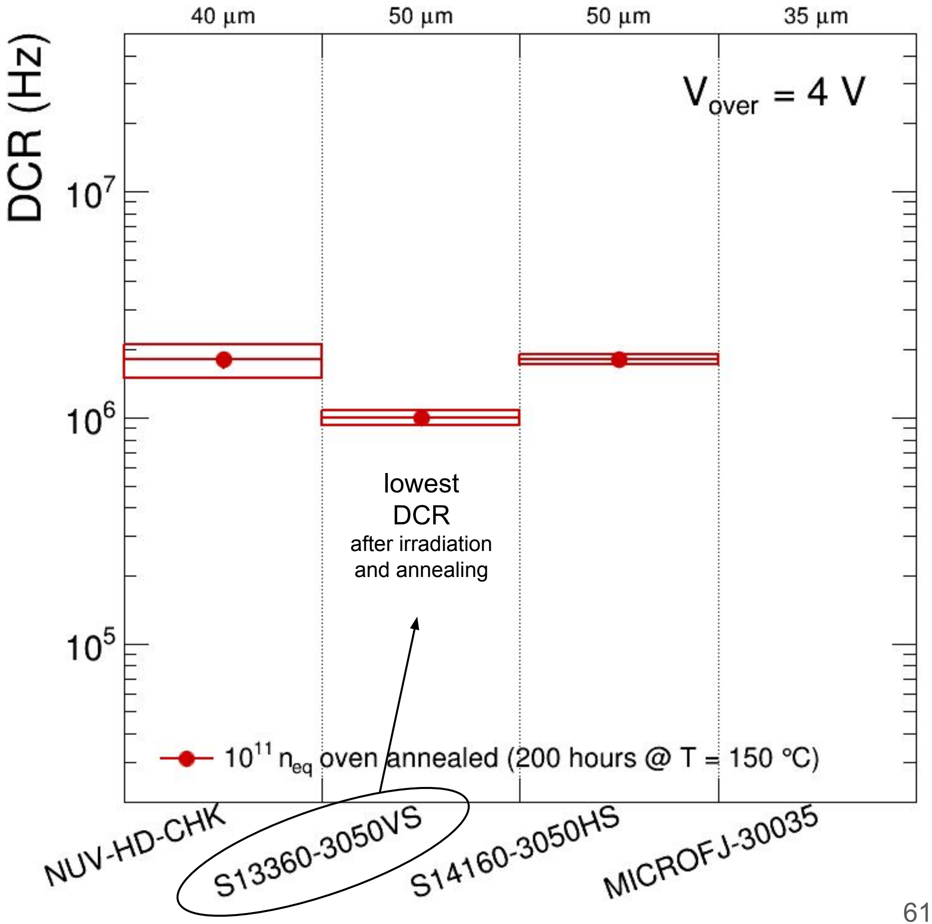


Current reduction by annealing in different sensors

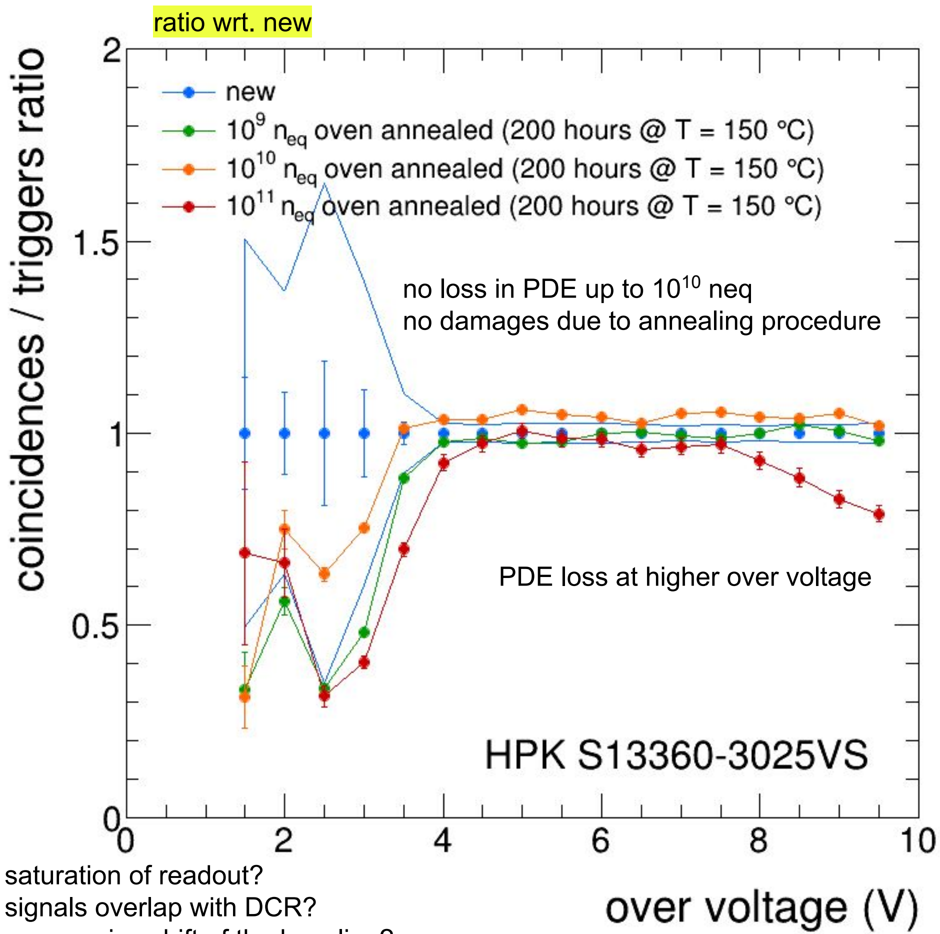


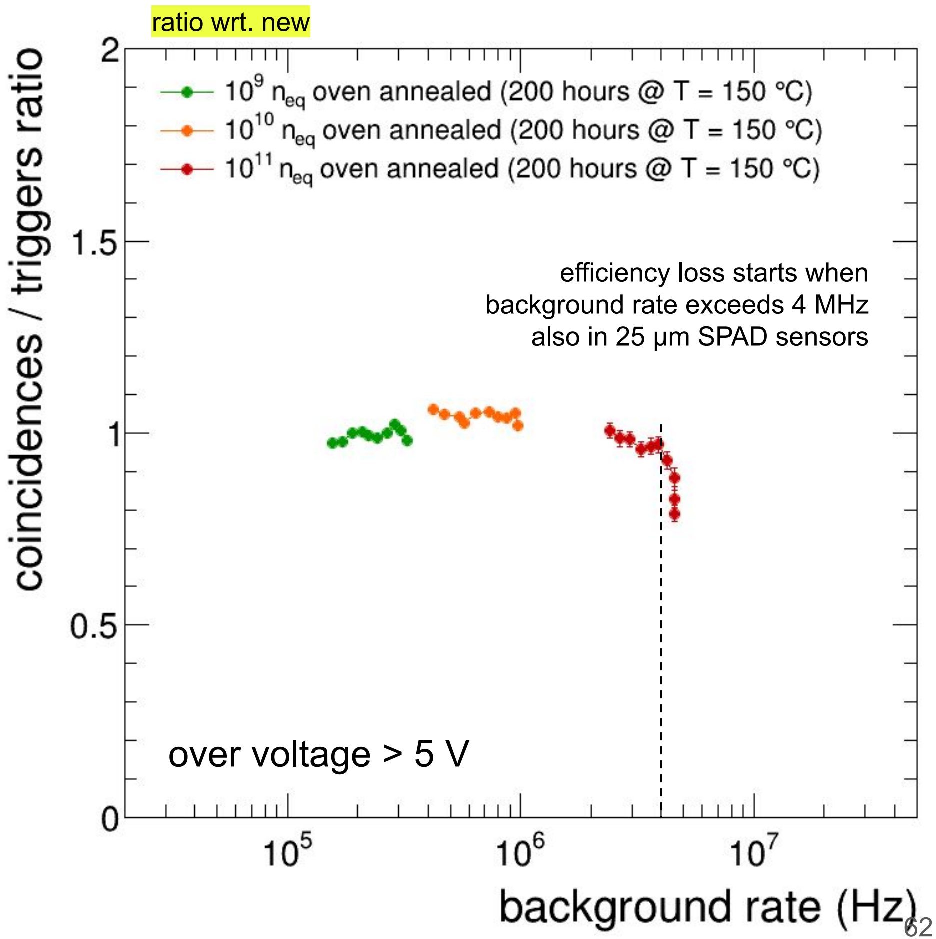
DCR after irradiation and annealing





Light response after irradiation and annealing





saturation of readout?
signals overlap with DCR?
progressive shift of the baseline?

Measurements over large sensor samples