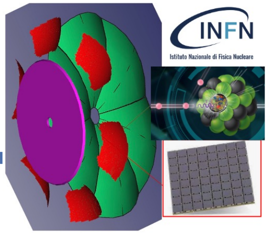
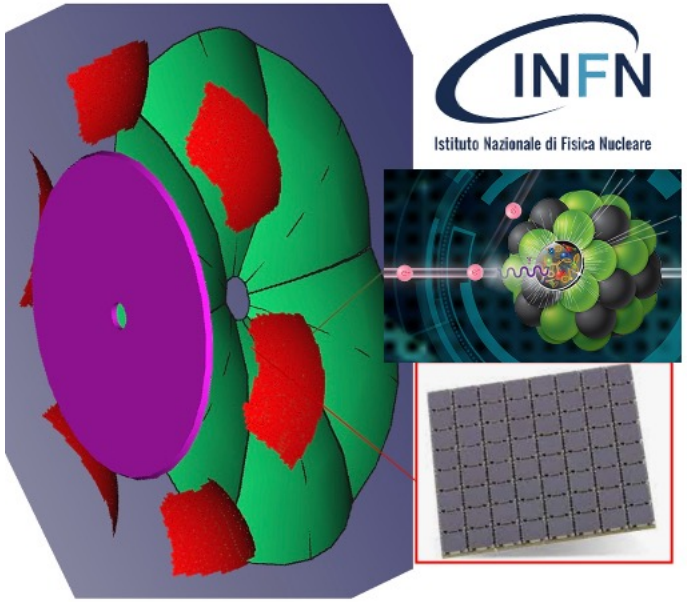
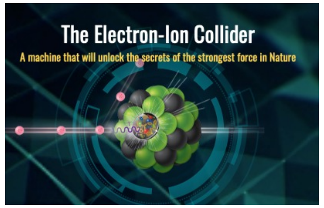



CPAD Workshop 2022



# R&D studies forward a SiPM-based readout for the dRICH detector at the EPIC experiment

eRD-110

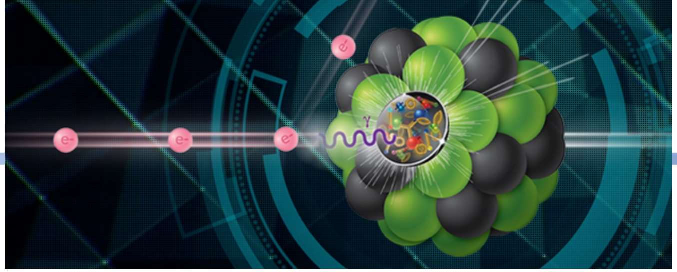


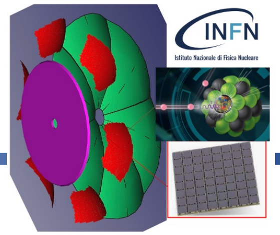

Advancement and Innovation for Detectors at Accelerators

P. Antonioli – INFN Bologna

on behalf of the EIC_NET INFN dRICH Collaboration

# ( EIC physics in one slide )





Parton Distributions in nucleons and nuclei

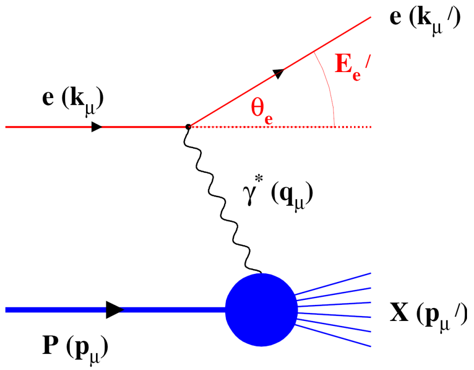
QCD at high parton density Saturation

Spin and Flavor structure of nucleons and nuclei

Tomography Transverse Momentum Dist.

QCD at high parton density Saturation

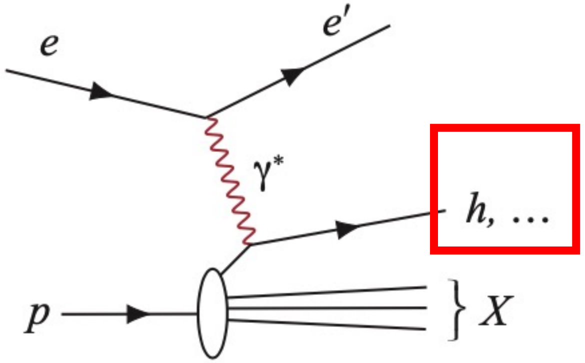
Tomography: Spatial Imaging




inclusive DIS

e-measurement!
→ e/h PID
→ EM calorimetry

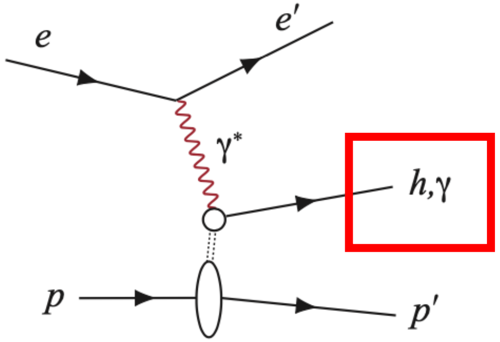
$\int$**Ldt:** **1 fb$^{-1}$**




semi-inclusive DIS (SIDIS)

electrons and hadrons
→ **hadron PID**

**10 fb$^{-1}$**



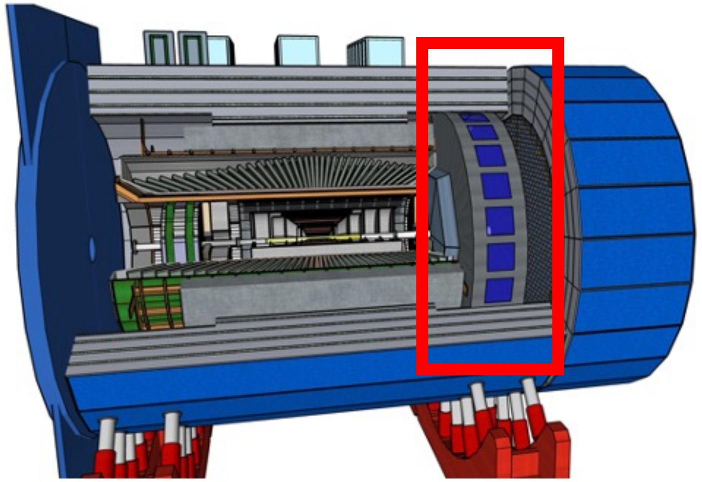

exclusive processes
get all particles
→ hermeticity
→ IR design + forward region

**10 - 100 fb$^{-1}$**

EIC extra-bonus: DIS in nuclei
- nPDF modifications
- gluon saturation A-dependent [jets]
- hadronization in CNM

(see T. Ulrich talk this morning)

# EIC and the EPIC detector: the forward dRICH

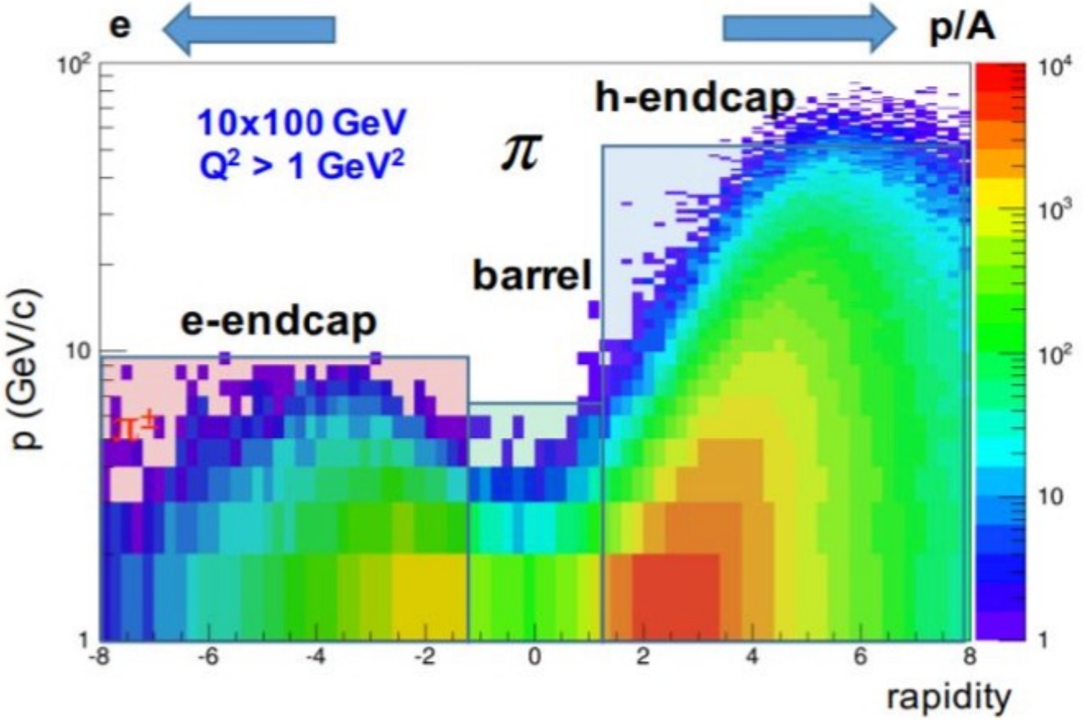


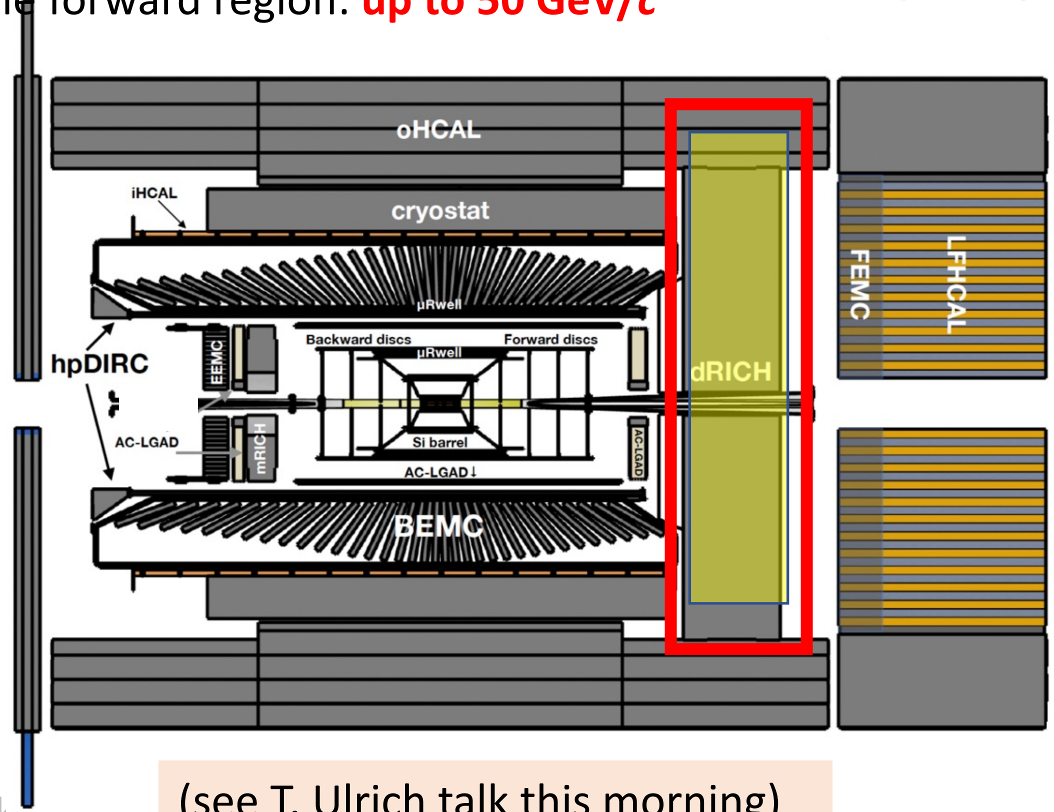
The EPIC Collaboration (born in July 2022) will build the first EIC detector at IP6

Hadron PID is key capability to match the physics goals of the EIC program

π/K/p over wide rapidy range ($|\eta| \leq 3.5$)

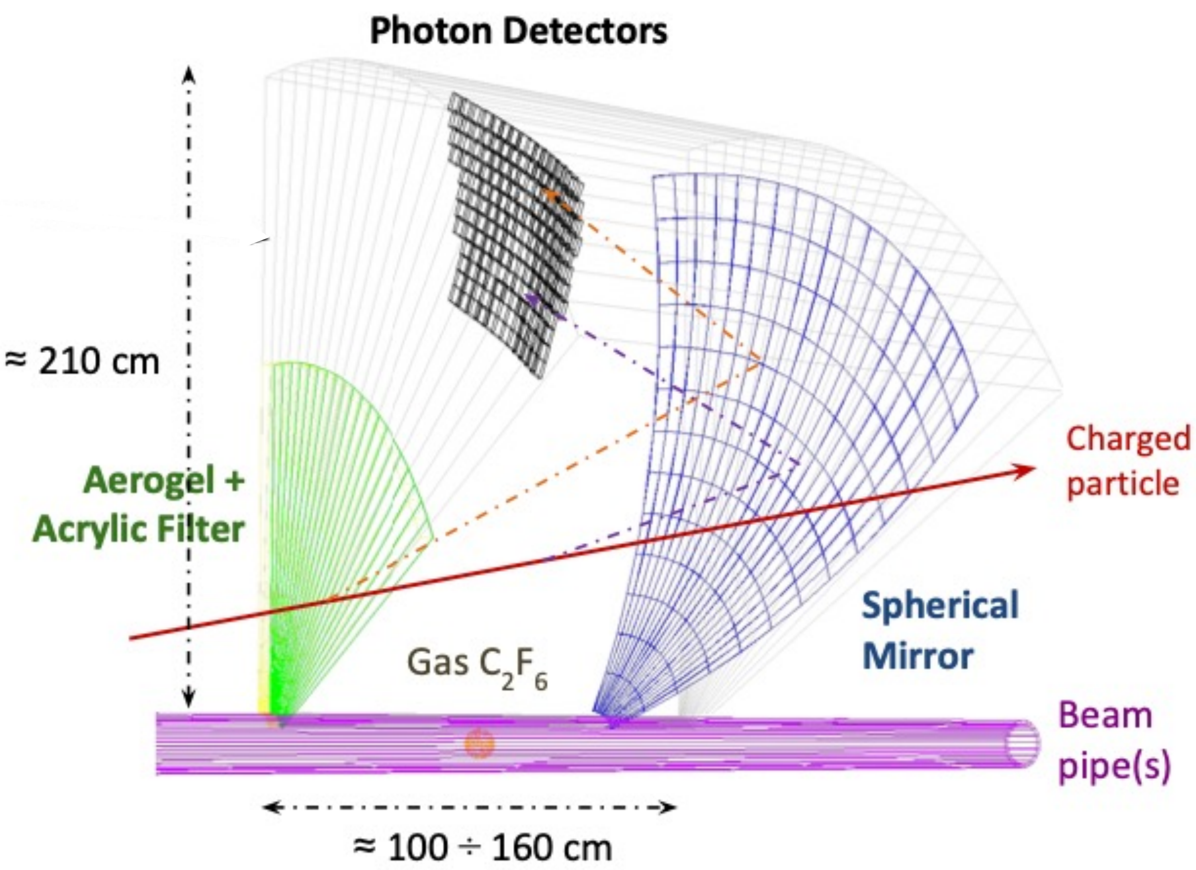
Momentum-rapidty coverage in the forward region: **up to 50 GeV/*c***



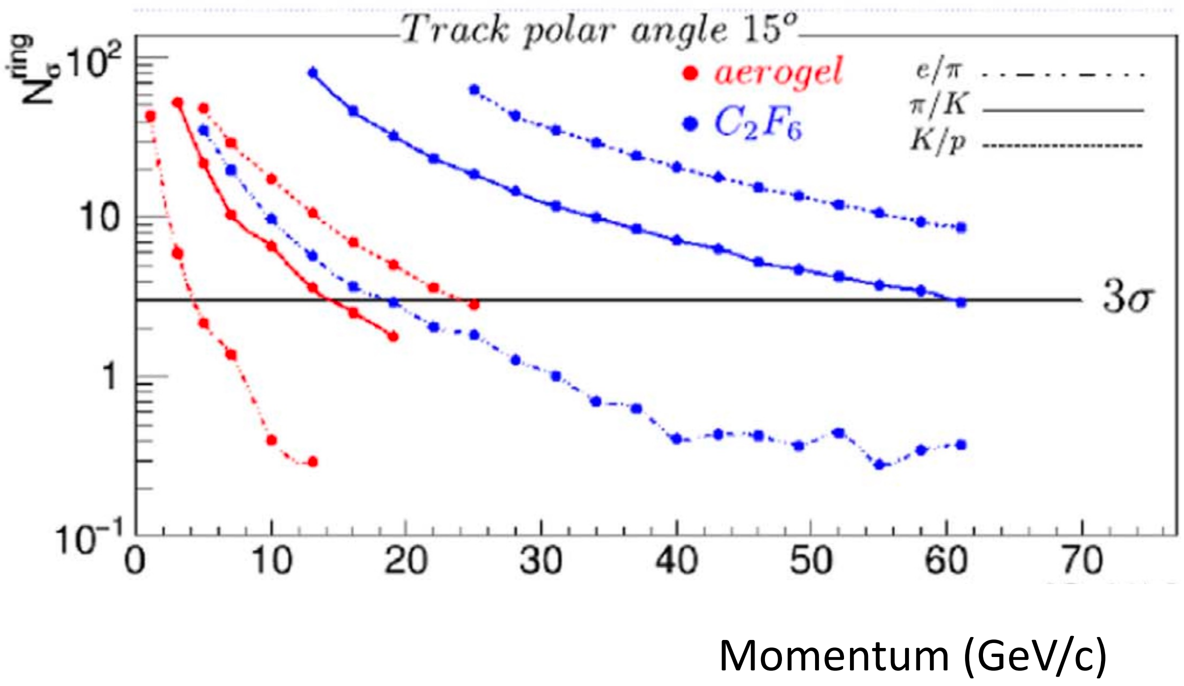




(see T. Ulrich talk this morning)

# EIC and the EPIC detector: the forward dRICH




[A. Del Dotto et al., NIM A876 (2017) 237-240]



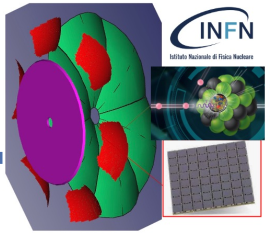

Radiators: Aerogel (n=1.02) and $C_2F_6$ (n=1.008)
Mirrors: CFRP spherical mirror array (6 mirrors)
Sensors: 3x3 mm$^2$ pixel, 0.5 m$^2$ / sector

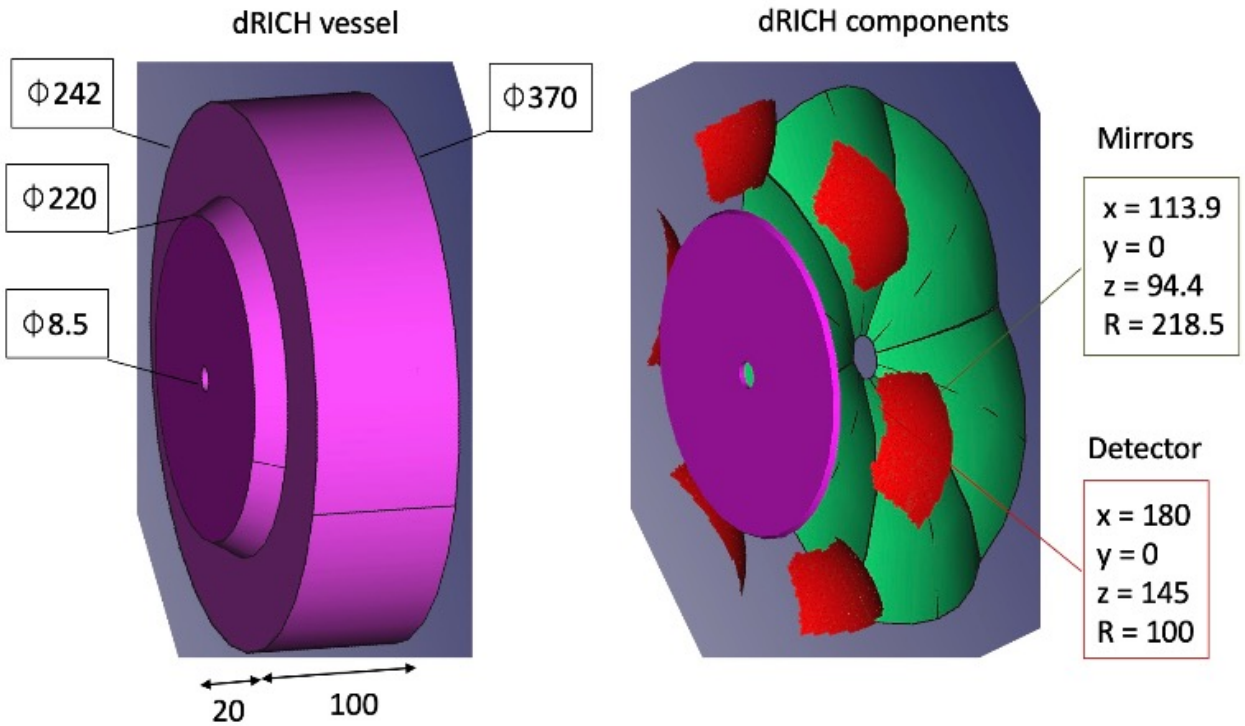
→

- 3 m$^2$ photosensor-surface
- inside magnetic field (~ 1 T)

Exploit a dual-radiator scheme to cope with the wide momentum range to be covered

# A SiPM readout for a RICH detector?






**Silicon photomultipliers**

✓ Insensitive to magnetic field

✓ Cheap / Integrated arrays

✓ Time resolution within requirements (< 200 ps RMS)

✓ Commercially available

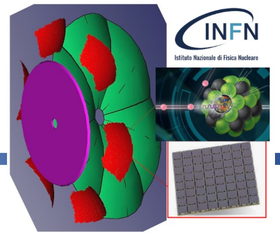
? Single Photon resolution needed!

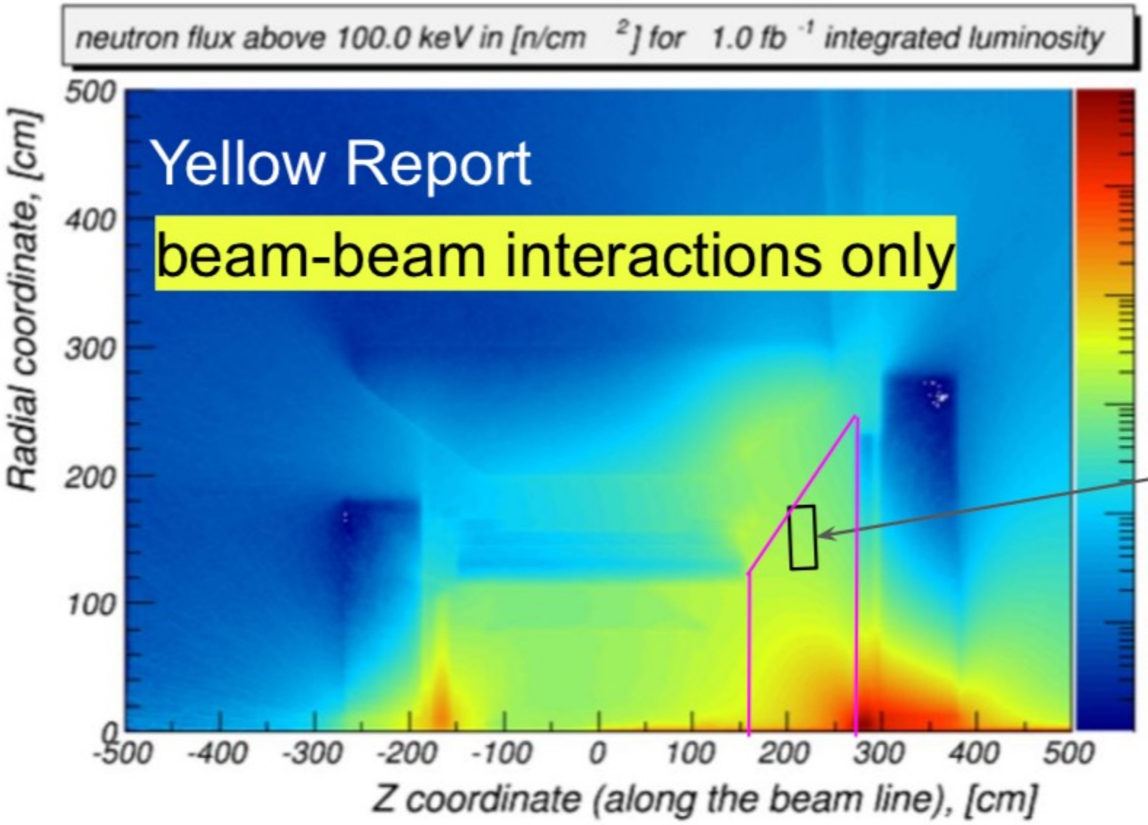
? DCR vs temperature → cooling

? Not radiation tolerant: DCR increases!

**Our R&D:** evaluate radiation tolerance and mitigation procedures (annealing)
- → test large O(10-100) samples of different commercial (HPK/OnSemi) and prototypes (FBK)
- → establish annealing protocol, evaluate DCR after repeated annealing cycles
- → characterize sensors and test them on beam conditions
- → use/test realistic readout with ALCOR ASIC

# How much radiation?






potential location of photosensors:
≈ **1-5 $10^7$ n/cm² every 1 fb⁻¹**

$10^{11}$ n/cm² 1-MeV $n_{eq}$ is a "true maximum"

- 30 weeks @ $10^{34}$ cm⁻² s⁻¹= 100 fb⁻¹ → 1-5 $10^9$ n/cm²
- $10^{11}$ n/cm² would be reached in O(10+) years at full $\mathcal{L}$!

A moderately hostile environment:

$10^9$ 1-MeV $n_{eq}$/cm² → most of the key physics topics
$10^{10}$ 1-MeV $n_{eq}$/cm² → GPD and more statistically eager topics
$10^{11}$ 1-MeV $n_{eq}$/cm² → may be we will never go here…

Can we use SiPM for a Cherenkov detector up to $10^{11}$ 1-MeV $n_{eq}$ /cm² fluence?

# How much radiation damage? How mitigate it? (I)

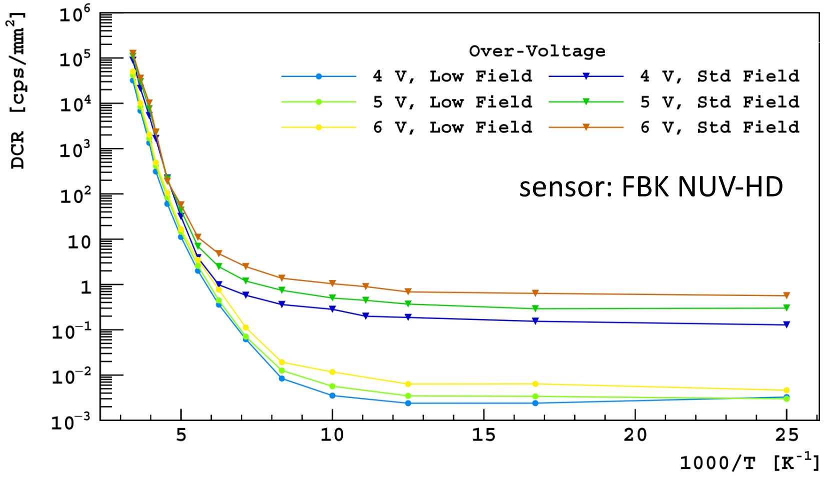
During last 10 years growing studies/ literature on SiPM radiation damage, see review from
E. Garutti and Y. Musienko, NIMA 926 (2019) 69

Up to $10^{11}$ 1-MeV $n_{eq}$ /$cm^2$ radiation damages increase currents and DCR (and affects $V_{bd}$) **but the baseline is still there** (with proper cooling)

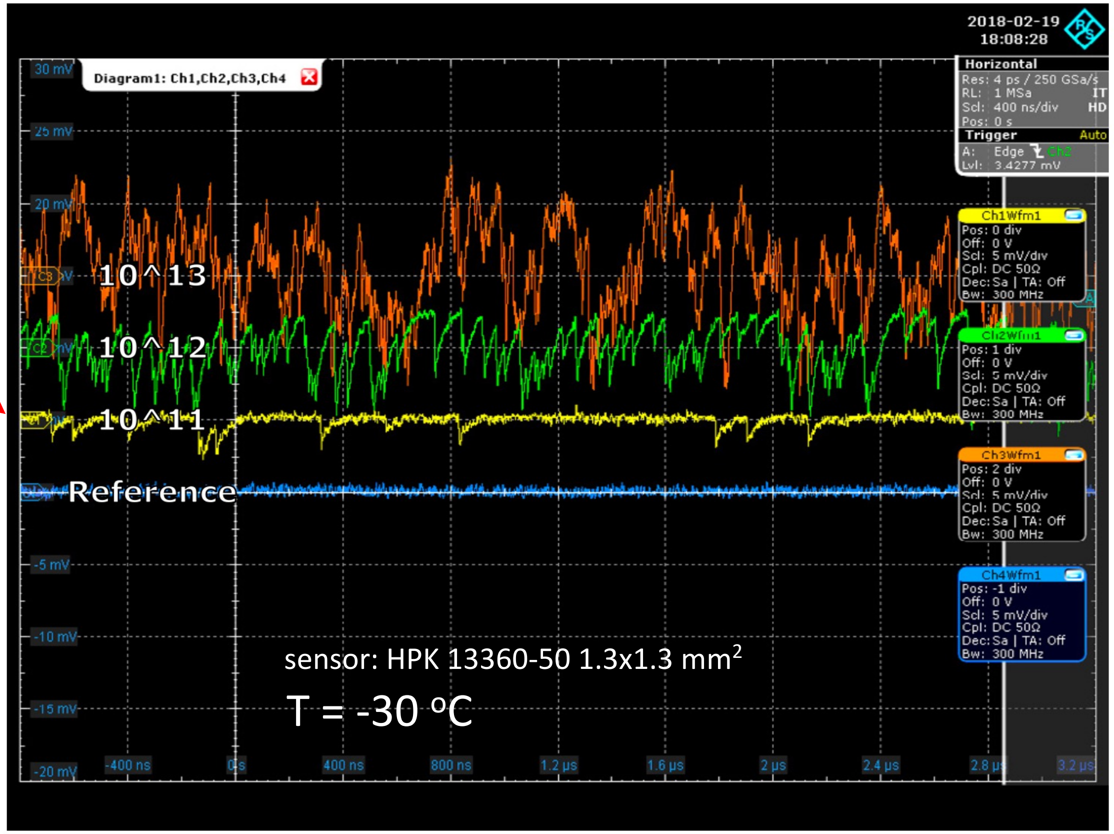
For a RICH we need to demonstrate that:

- we can maintain single photon detection
- we can keep DCR "under control" to still get rings!

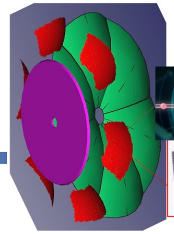
Acerbi F. et al., IEEE Trans. On El. Devices 64 (2017) 521




M. Calvi et al., NIMA 922 (2019) 243

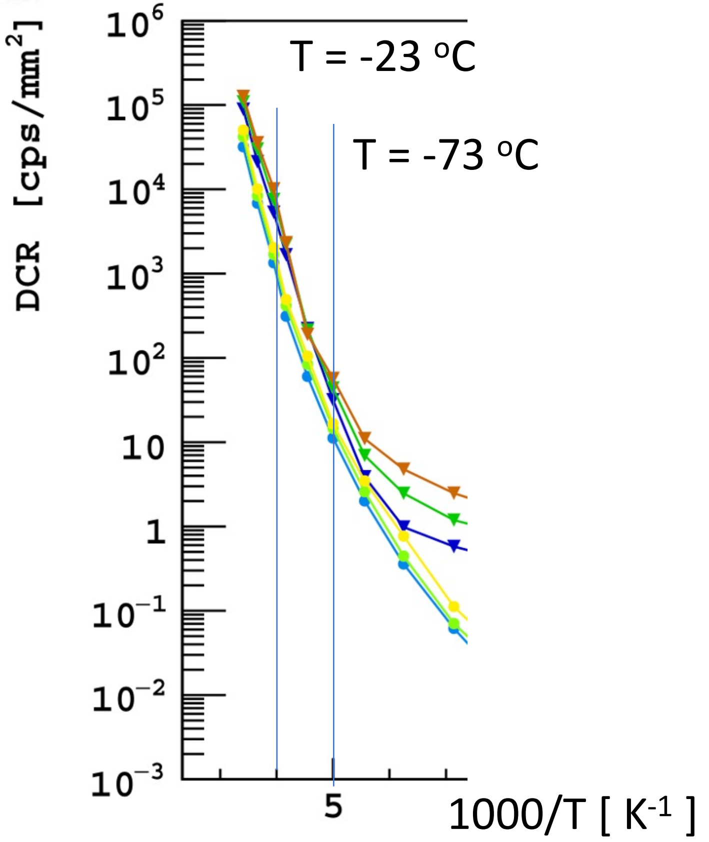


# How mitigate it? (II)



## cooling

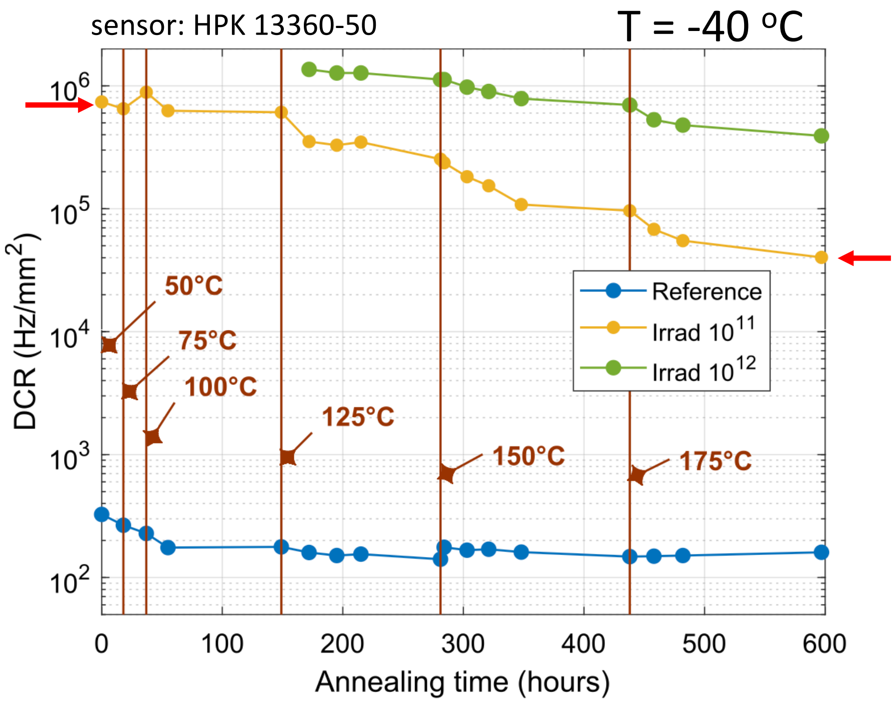
"DCR decreases by a factor 2-2.5 every 10 degrees"


Acerbi F. et al., IEEE Trans. On El. Devices 64 (2017) 521

## annealing

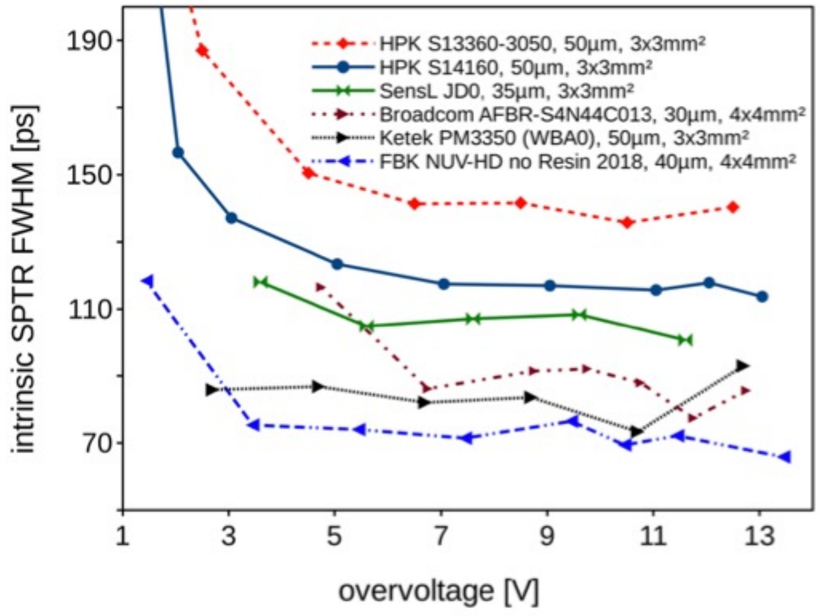
"DCR decreases by a **factor 20** after an annealing cycle up to 175 °C"




M. Calvi et al., NIMA 922 (2019) 243

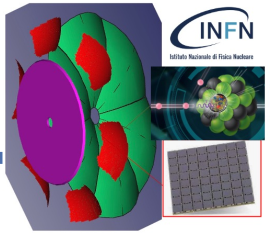
## timing

- Timing resolution below 100 ps are nowadays achieved by SiPM
- A 3σ cut based on interaction time will further reduce DCR in a RICH

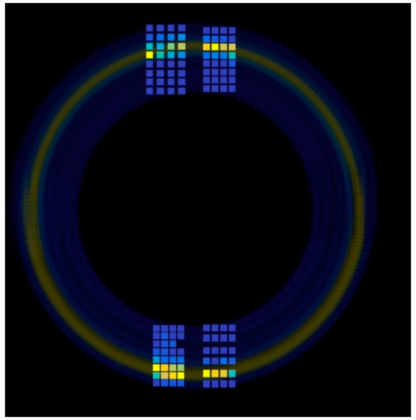



S. Gundacker et al., Phys. Med. Biol. **65** (2020) 025001

# The R&D program so far (an outline)




- **SiPM**
  - selection by manufacturer, $V_{bd}$, SPAD cell
- **Electronics**
  - SiPM carriers and adapters
  - readout cards with ALCOR ASIC
- **Irradiation**
  - 2021 and 2022 campaigns with proton beams ( 140 MeV)
  - fluences from $10^9$ to $10^{11}$ 1-MeV $n_{eq}/cm^2$
- **Annealing**
  - High-temperature cycles (oven)
  - Exploring "in-situ" alternatives
- **Characterization**
  - I-V, DCR, LED pulse in climatic chamber
- **Test beam**
  - test on dRICH prototype irradiated & annealed sensors



# SiPM under test

## Commercial:

| board | sensor | uCell (µm) | $V_{bd}$ (V) | PDE (%) | DCR (kHz/mm$^2$) | window | notes |
|---|---|---|---|---|---|---|---|
| HAMA1 | S13360 3050VS | 50 | 53 | 40 | 55 | silicone | legacy model Calvi et. al |
| | S13360 3025VS | 25 | 53 | 25 | 44 | silicone | legacy model smaller SPAD |
| HAMA2 | S14160 3050HS | 50 | 38 | 50 | | silicone | newer model lower $V_{bd}$ |
| | S14160 3015PS | 15 | 38 | 32 | 78 | silicone | smaller SPADs radiation hardness |
| SENSL | MICROFJ 30035 | 35 | 24.5 | 38 | 50 | glass | different producer and lower $V_{bd}$ |
| | MICROFJ 30020 | 20 | 24.5 | 30 | 50 | glass | the smaller SPAD version |
| BCOM | AFBR S4N33C013 | 30 | 27 | 43 | 111 | glass | commercially available FBK-NUVHD |

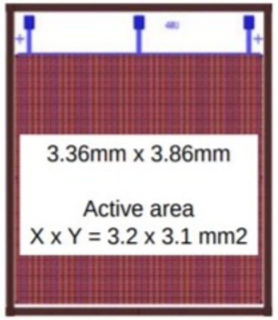
HAMAMATSU PHOTON IS OUR BUSINESS

ON Semiconductor

BROADCOM

## Prototypes

### NUV-HD-CHK

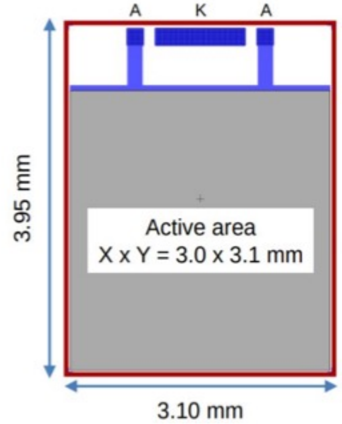



NUV-HD big cells

Technology similar to NUV-HD-Cryo
Optimized for single photon timing

- Cell pitch 40 µm
- High PDE > 55%
- Primary DCR @ +24°C ~ 50 kHz/mm$^2$
- Correlated noise 35% @ 6 V

### NUV-HD-RH

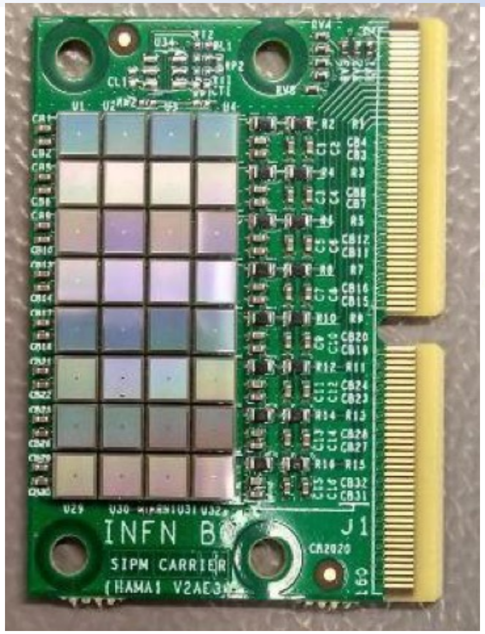



NUV-HD-RH

Technology under development optimized for radiation hardness in HEP experiments

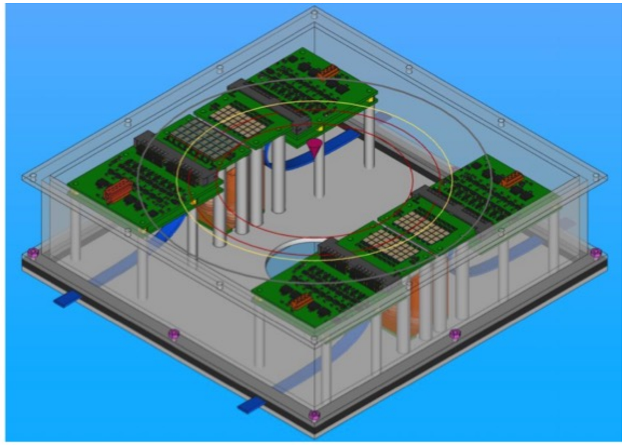
- Cell pitch 15 µm with high fill factor
- Fast recovery time – reduced cell occupancy Tau recharge < 15 ns
- Primary DCR @ +24°C ~ 40 kHz/mm$^2$
- Correlated noise 10% @ 6 V

# Carrier boards and "detector box"

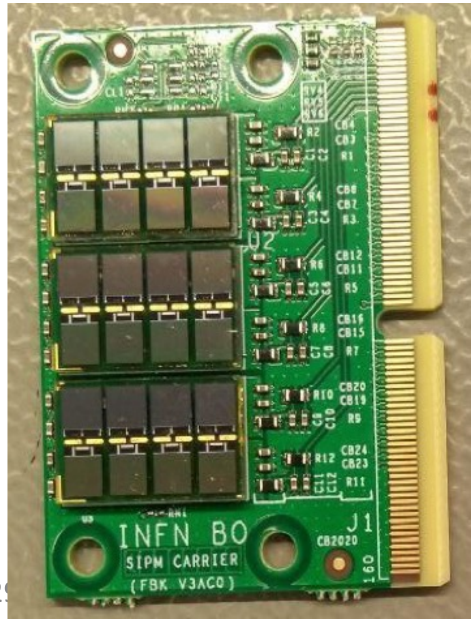



8x4 HPK matrix

Peltier cooling from the back
PCBs design with many vias to favour cooling



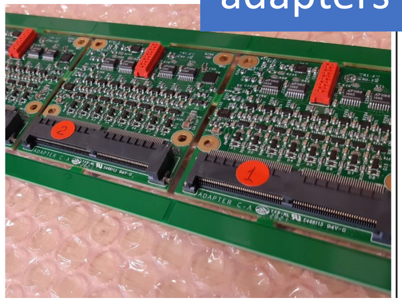
Build a SiPM carrier able to go through:
- annealing cycles (150 $^{o}$C)
- irradiation
- cooling at low T (- 30 $^{o}$C)
- suitable for test beams

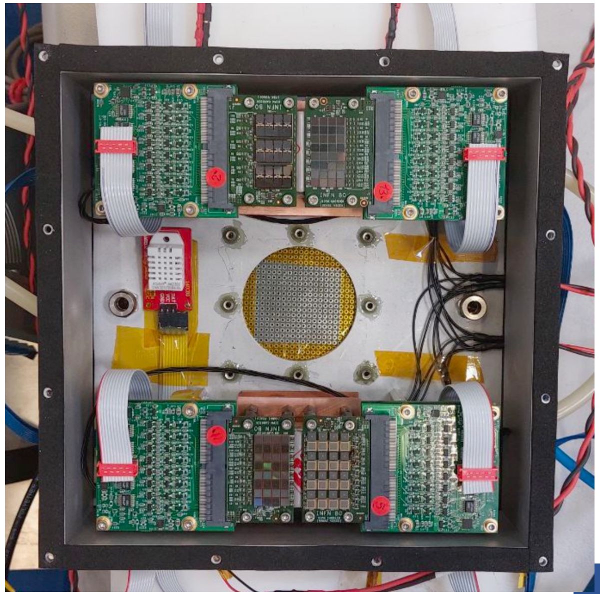



8x4 FBK matrix

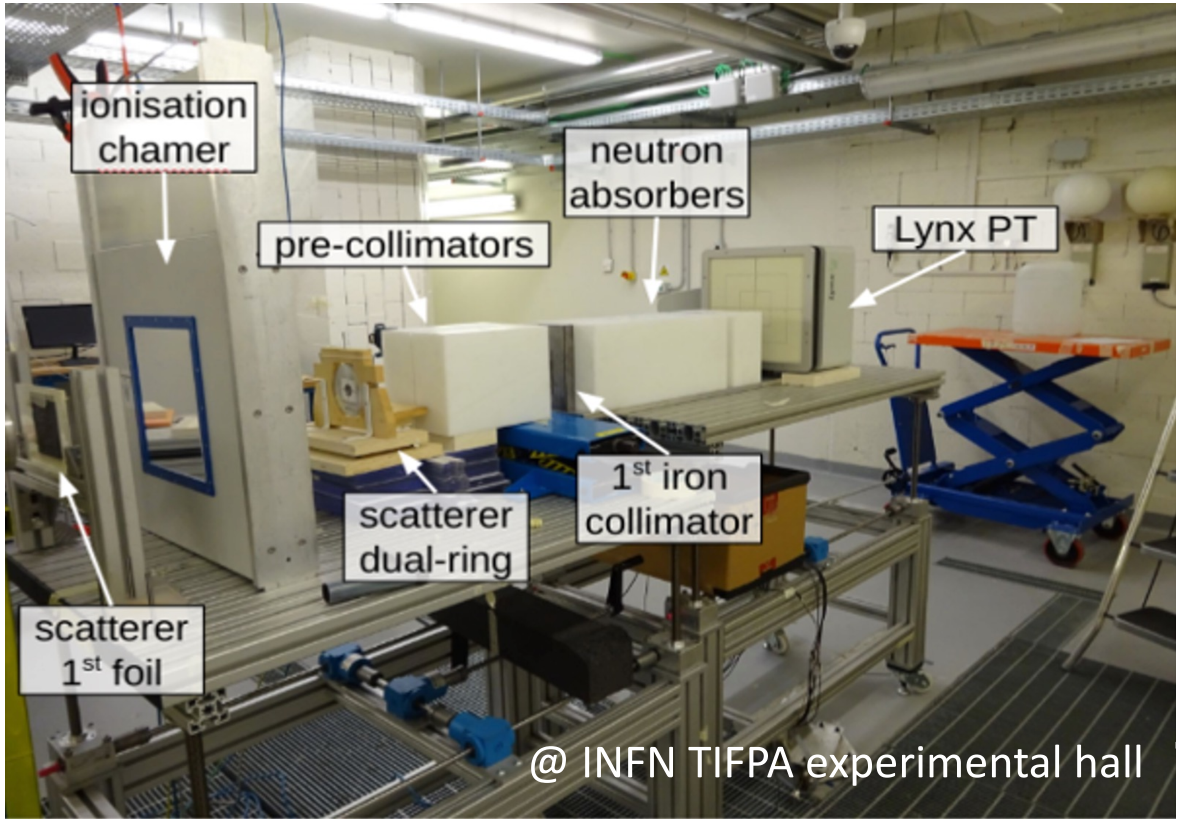
high T-grade FR4 (up to 180 $^{o}$C)
edge connector (high T tolerant)

adapters

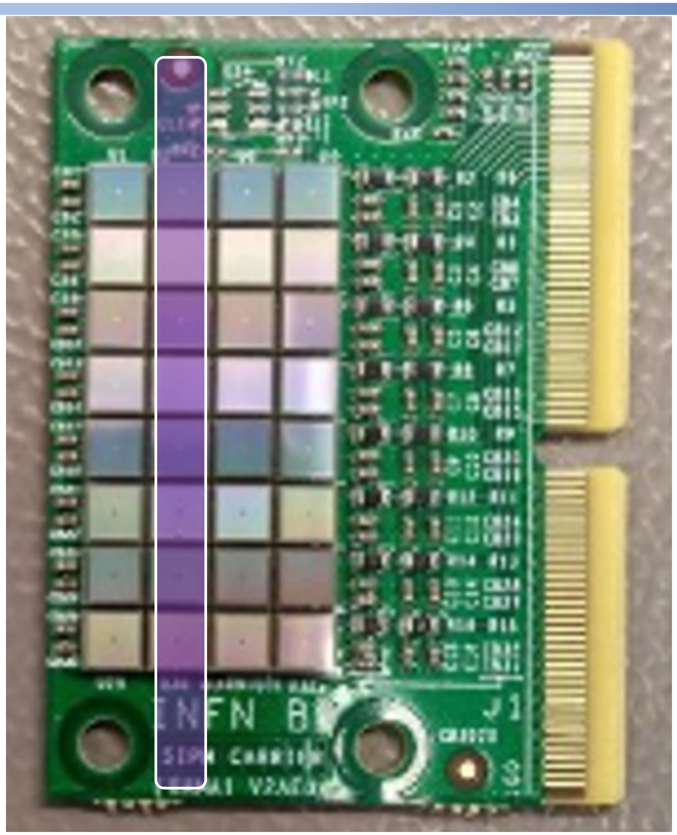




# Irradiation at Trento protontherapy center



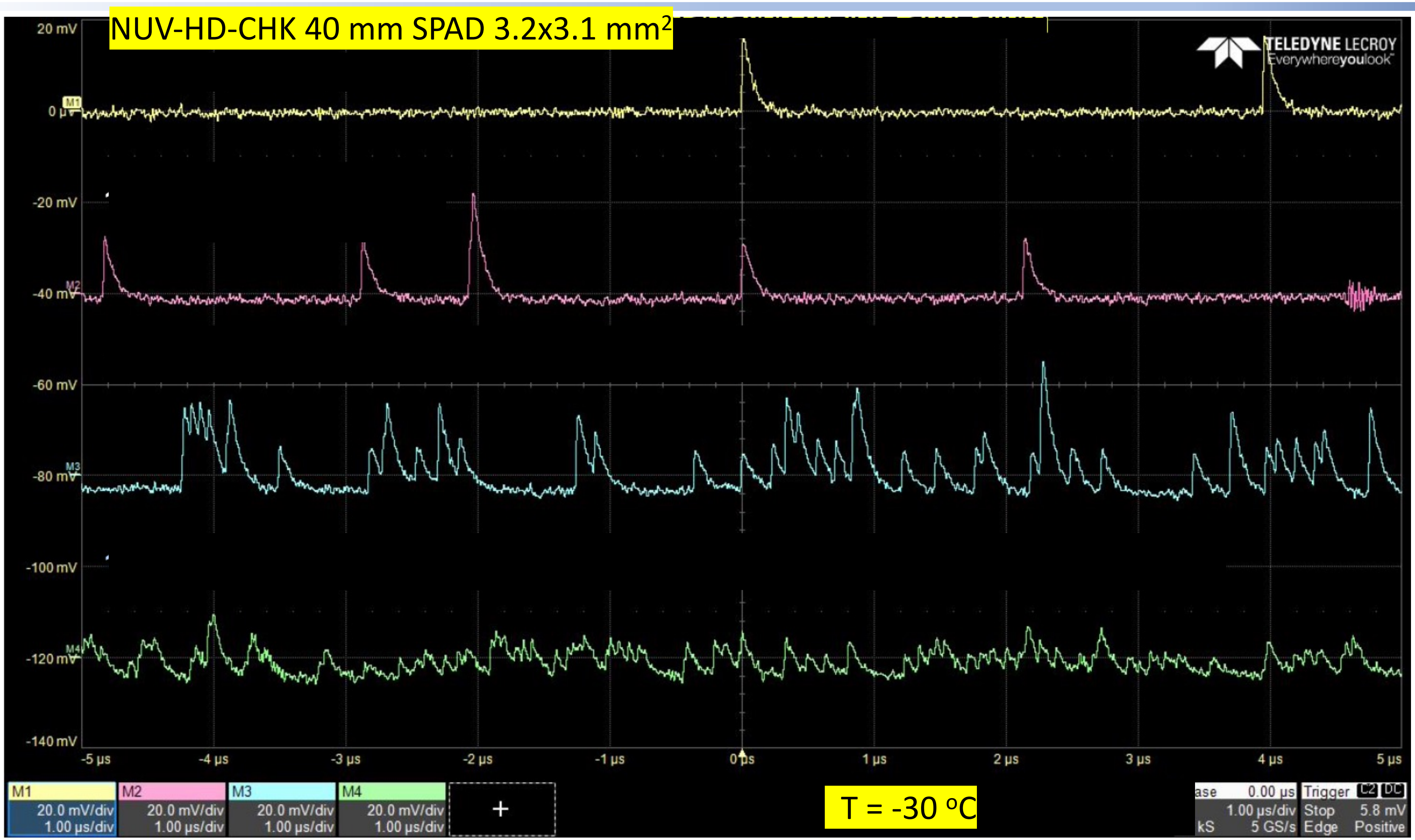





2021 campaign: irradiation of carriers "by column" at $10^9$, $10^{10}$, $10^{11}$ 1-MeV $n_{eq}/cm^2$
2022 campaign: repeated irradiation at $10^9$ 1-MeV $n_{eq}/cm^2$ and annealing cycles on same sensors

148 MeV proton beam (fix pencil beam/uniform 6 cm diameter spot)
On the beam line facility: F. Tommasino et al., NIMA 869 (2017) 15 and F. Tommasino et al., Phys. Med. 58 (2019) 99

# First check signals on the scope.... (before annealing)




$10^8$ $n_{eq}$ ok

$10^9$ $n_{eq}$ still ok

$10^{10}$ $n_{eq}$ challenging

$10^{11}$ $n_{eq}$ baseline lost

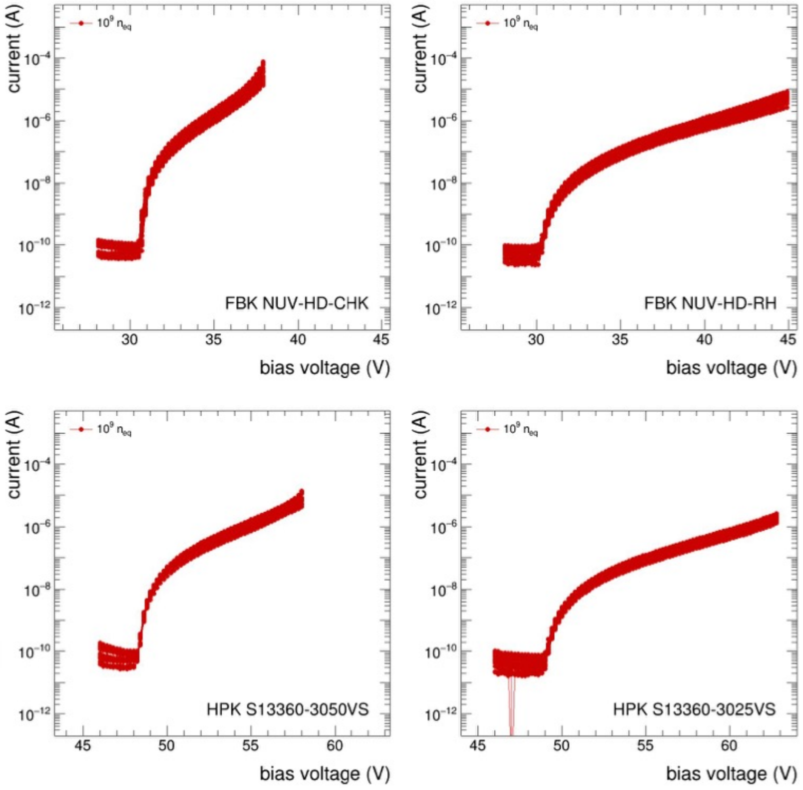
[since now on for fluences: $n_{eq}$ = 1-MeV $n_{eq}/cm^2$]

# Characterization setup (@INFN-BO)

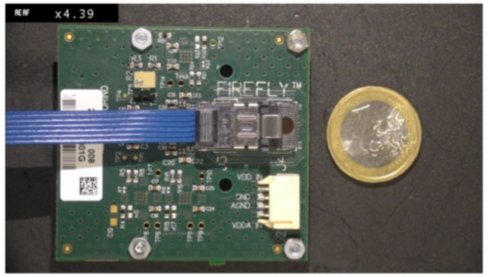
climatic chamber Memmert CTC256
measurements at T=-30 °C


I-V

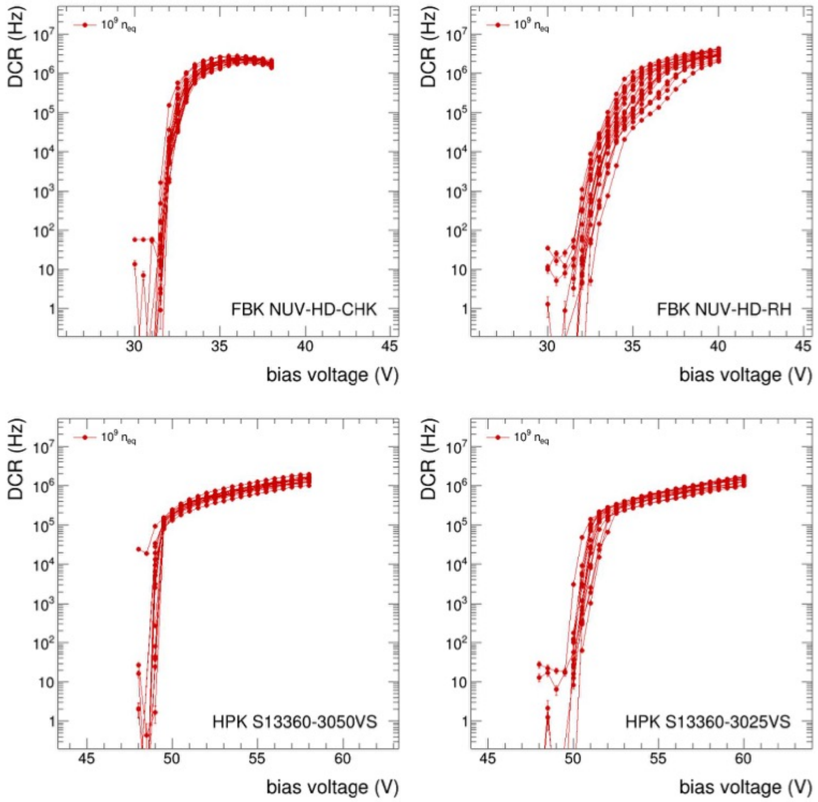
2x40 ch multiplexers → 2 carrier boards



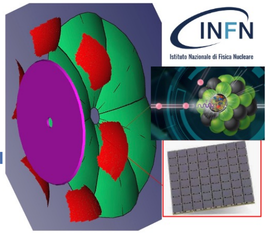

DCR

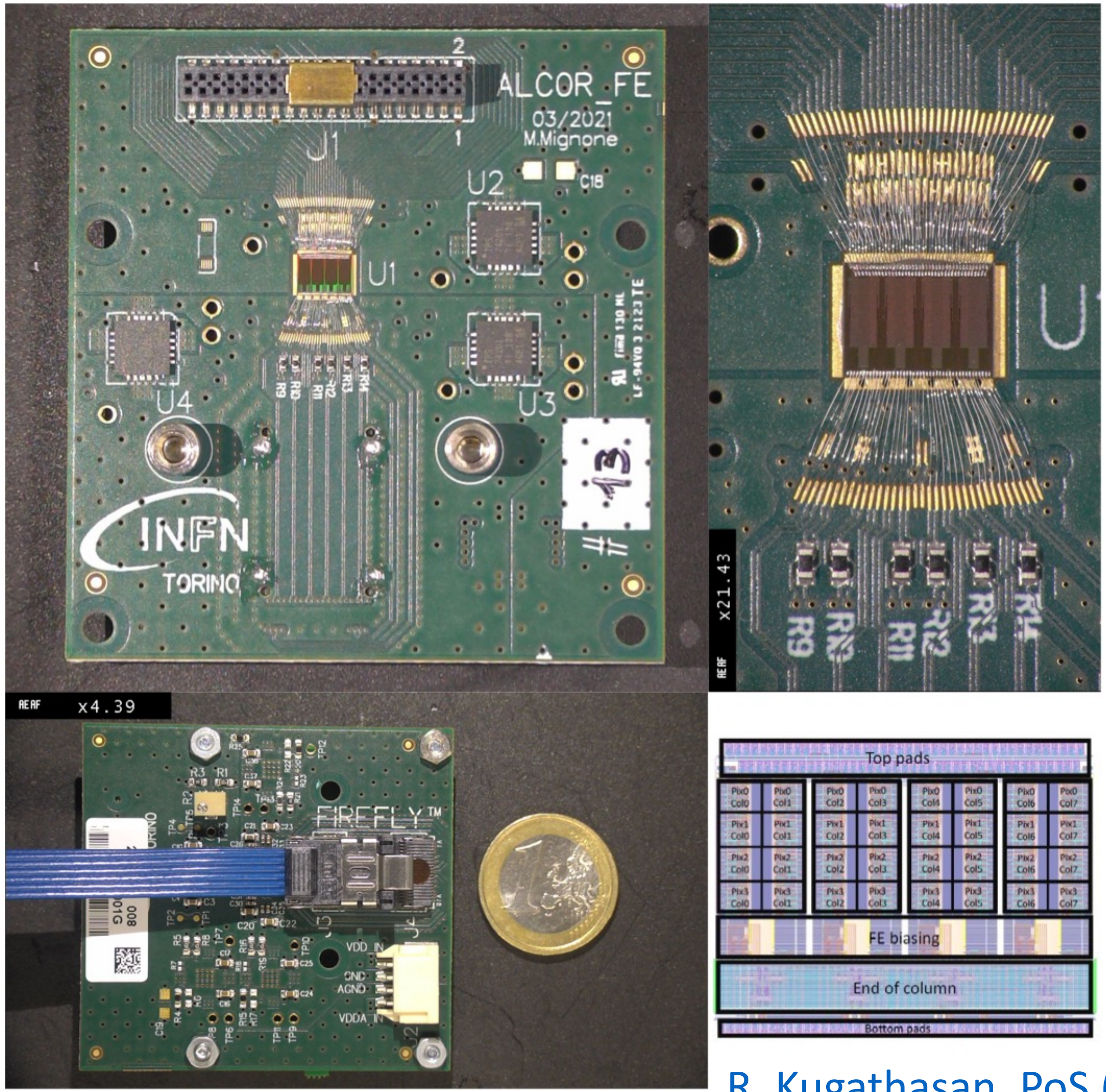



ALCOR readout board (32 ch)
FPGA-based readout (Xilinx Kintex)



# ALCOR ASIC: A Low Power Chip for Optical sensor Readout






- developed at INFN-TO for cryogenic operations (DarkSide)
- planned branching to an EIC optimized version (64 ch)

➤ 32-pixel matrix mixed-signal ASIC.

For each pixel:

- signal amplification, conditioning, discrimination and event digitisation
- dual-polarity front-end amplifier
- low input impedance
- programmable gain settings
- leading-edge discriminators
- 4 TDCs TAC-based

➤ 25 ps LSB (@ 320 MHz)

➤ single-photon time-tagging mode or ToT

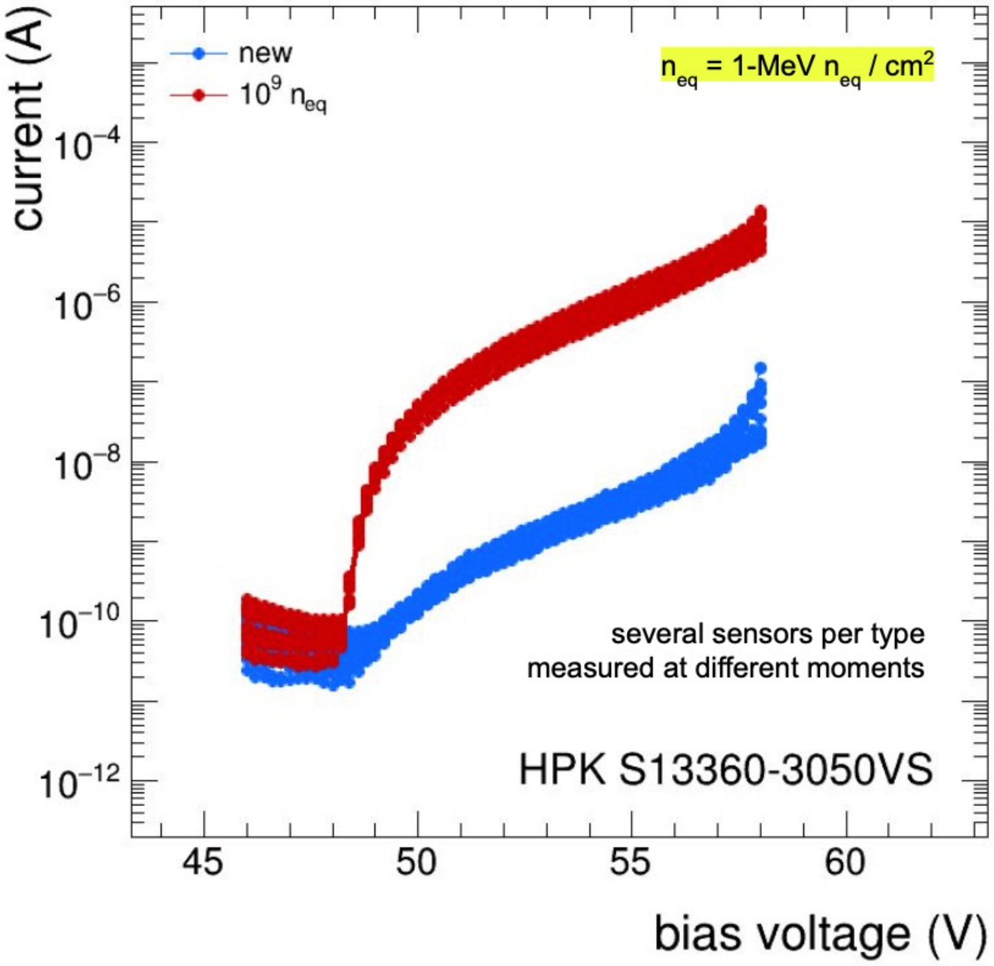
➤ power consumption < 5 mW/ch

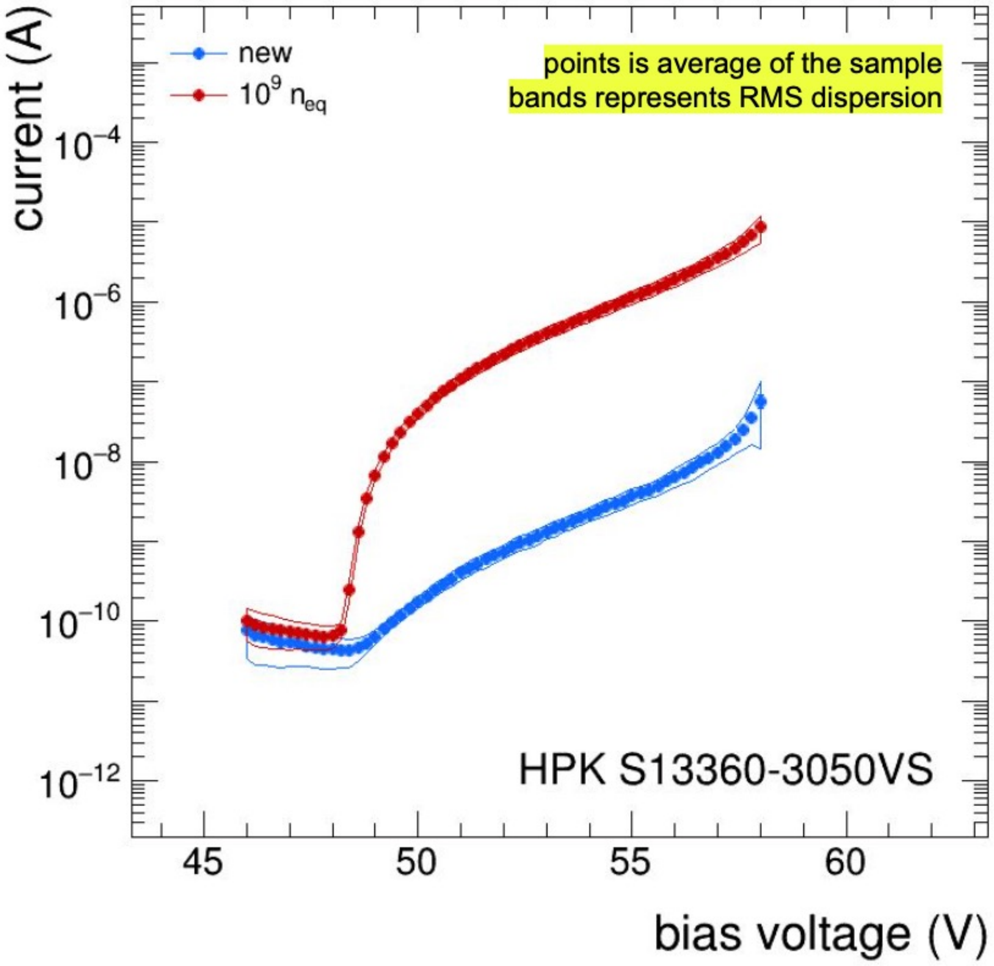
➤ digital output: 4 LVDS TX data links (1 for each colum = 8 pixels)

R. Kugathasan, PoS (TWEPP2019) 011

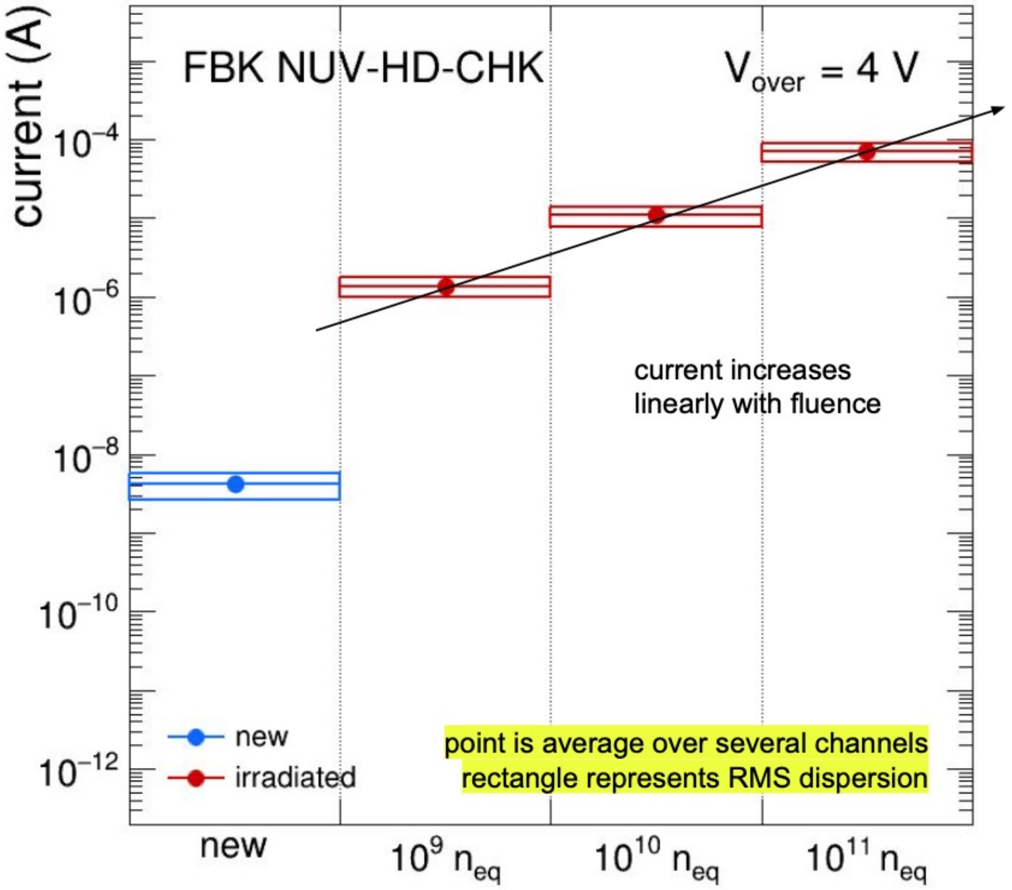
# I-V measurements

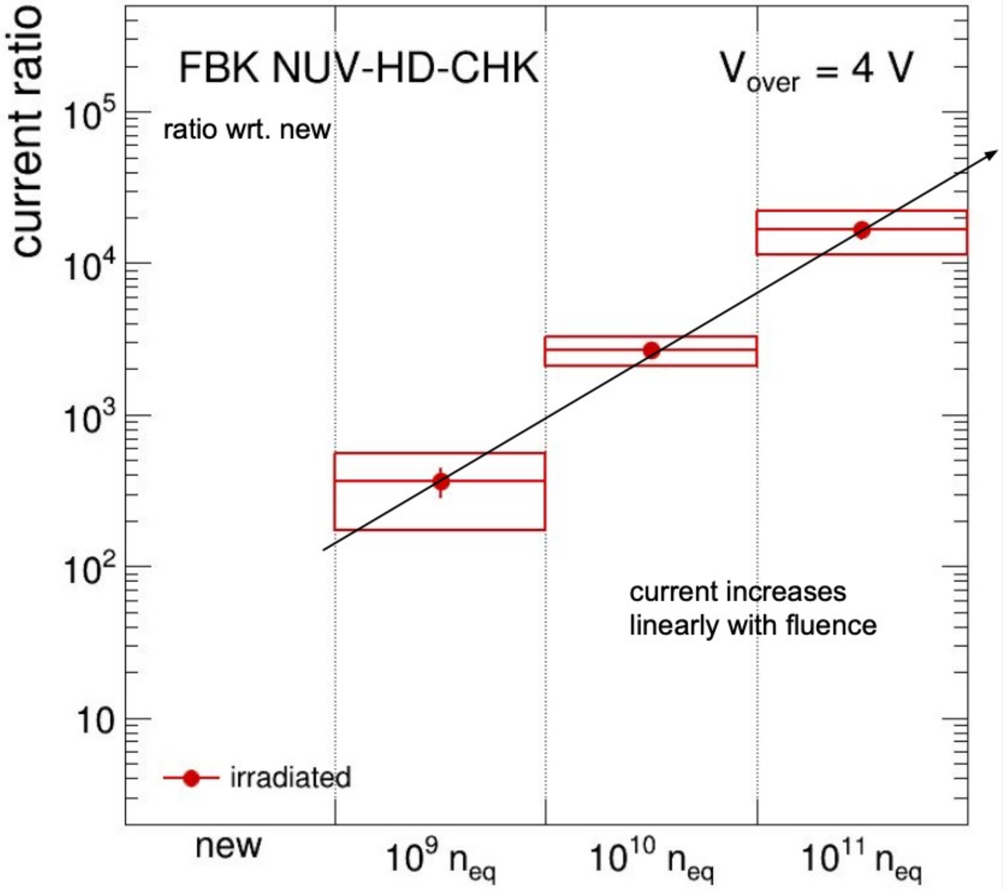
- the "carrier" scheme allows testing large O(10) sensors of a given type
- good uniformity seen



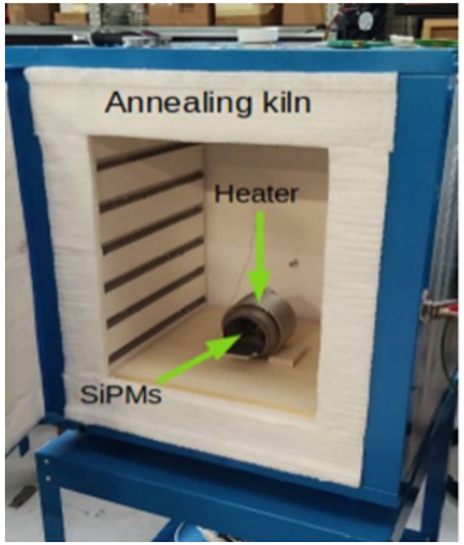
# Current vs fluence after irradiation

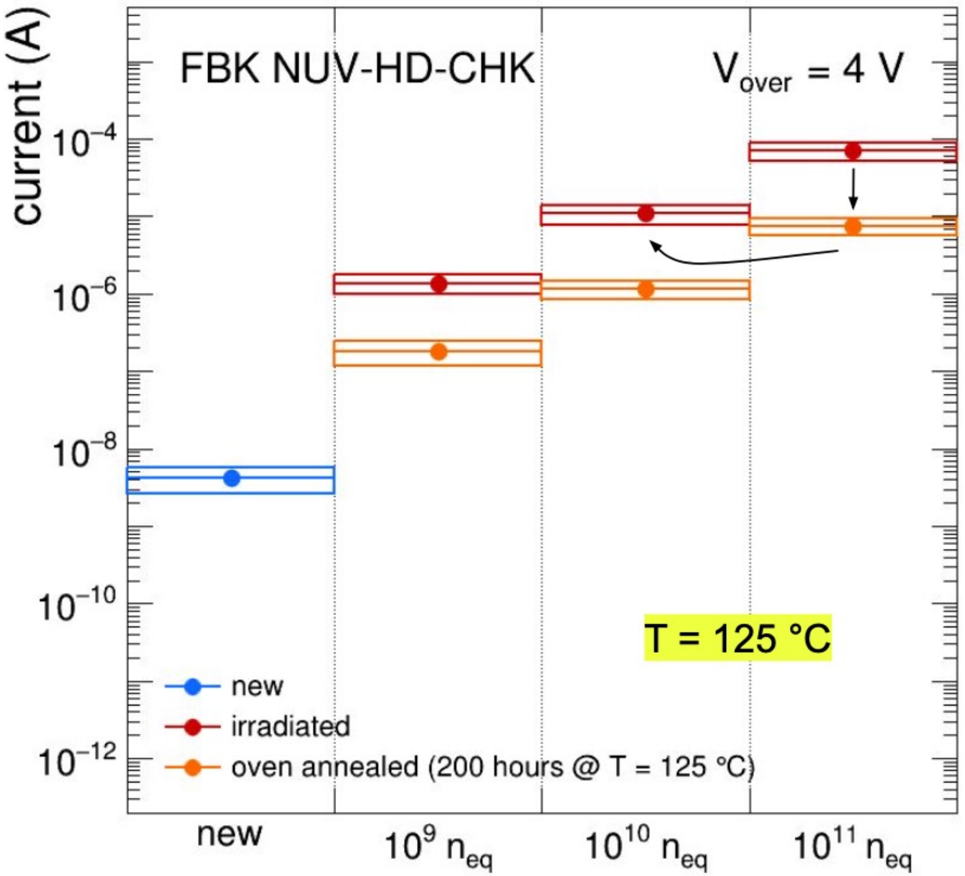


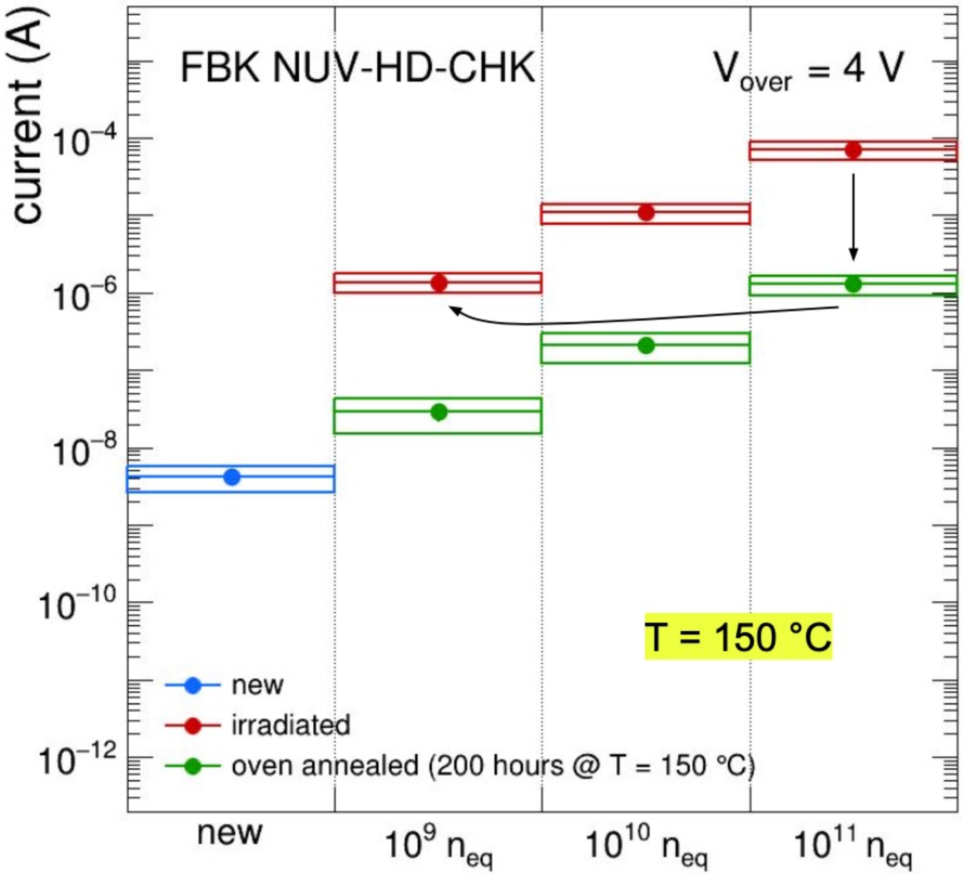



# Recovery post-annealing (I)

@INFN-FE



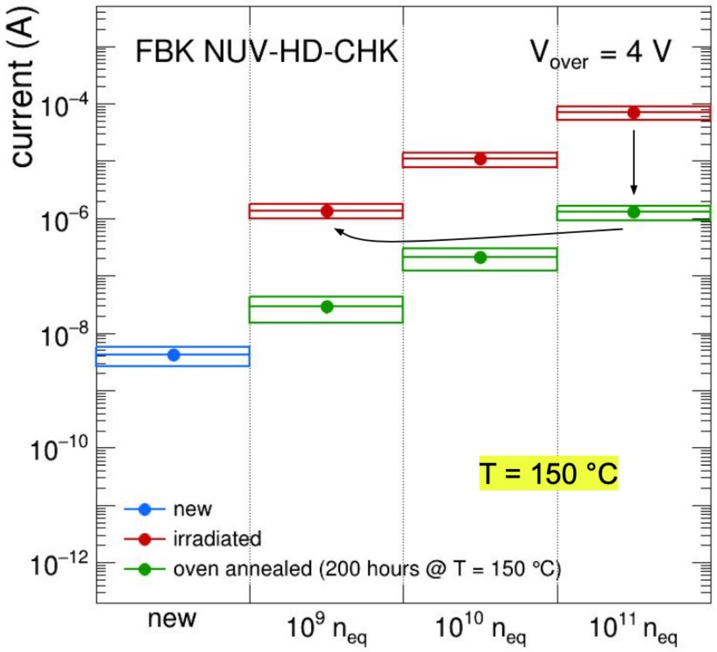



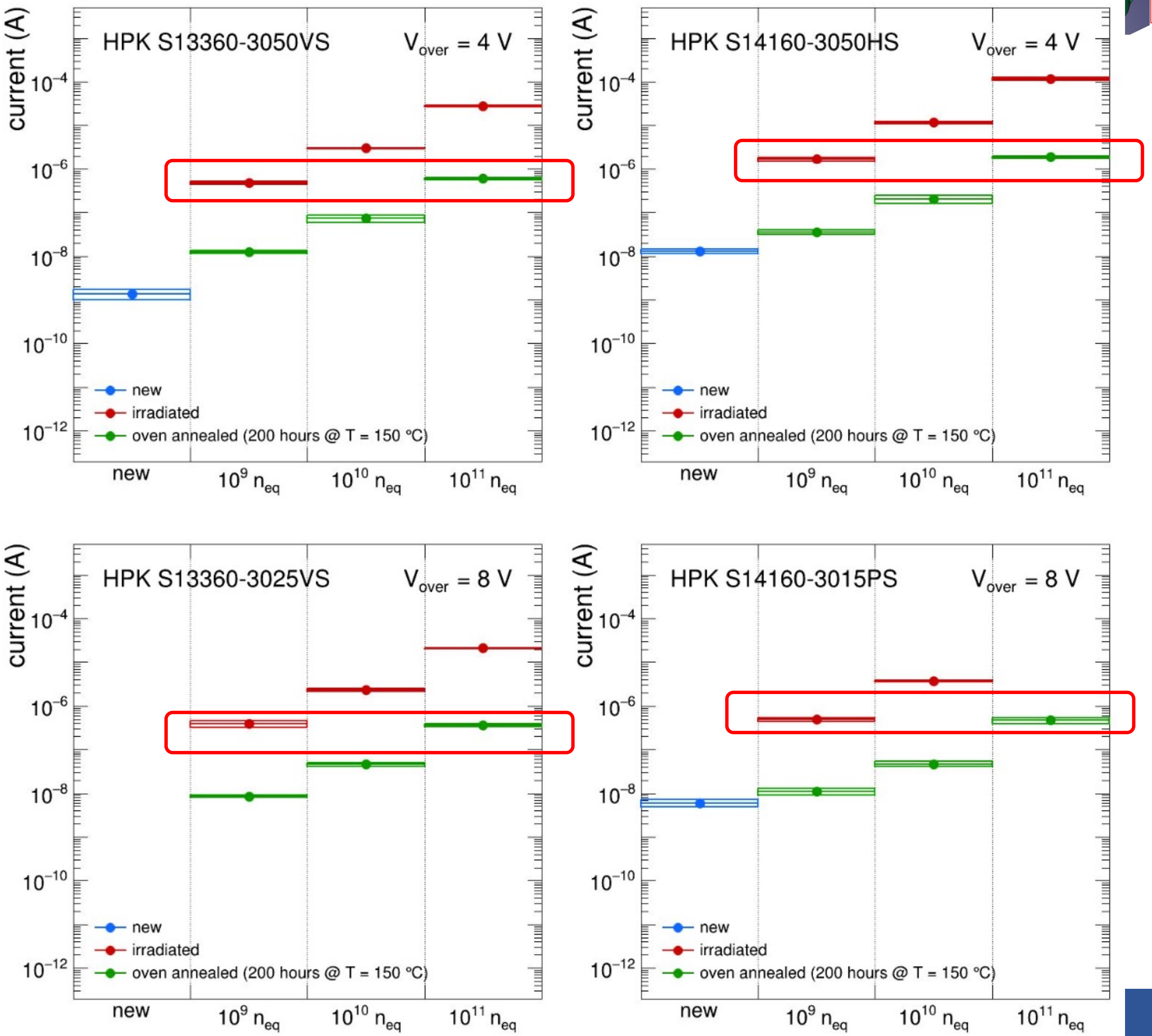




At 150 $^{o}$C we recover the sensor as it would have received 100 times less fluence

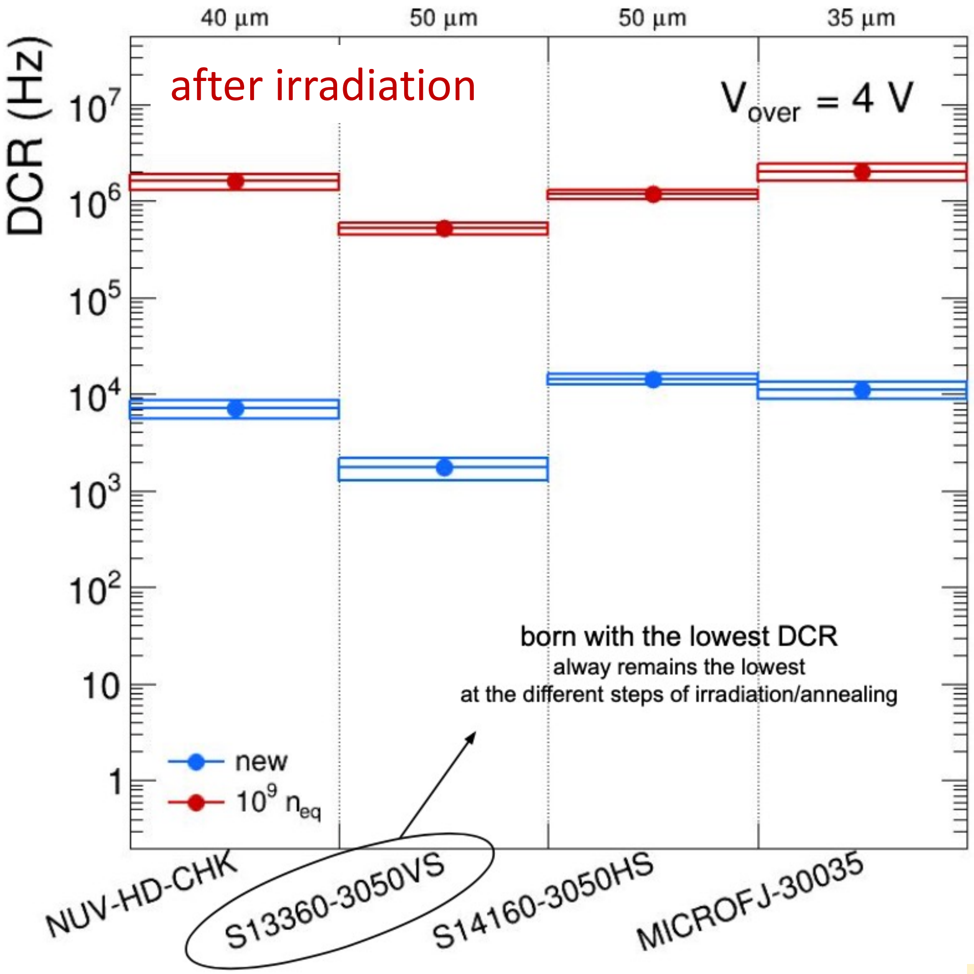
# Recovery post-annealing (II)

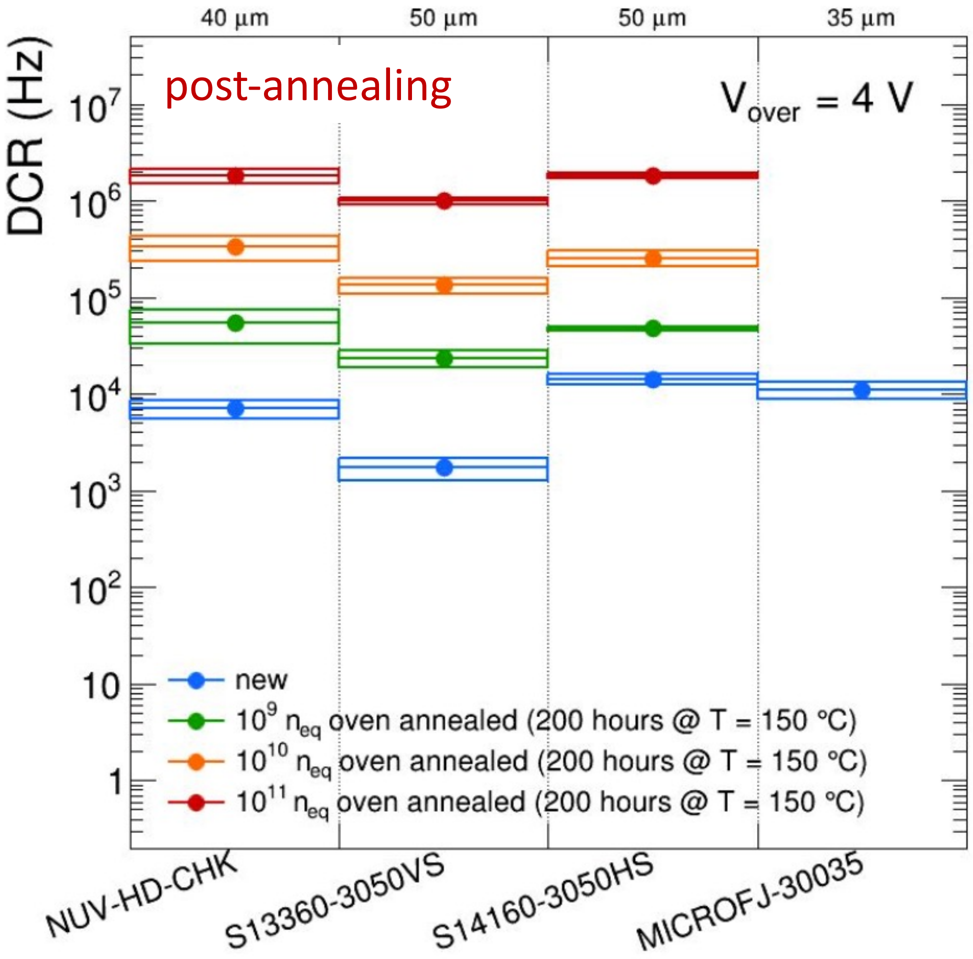
very similar results with HPK sensors



# DCR: after irradiation and post-annealing

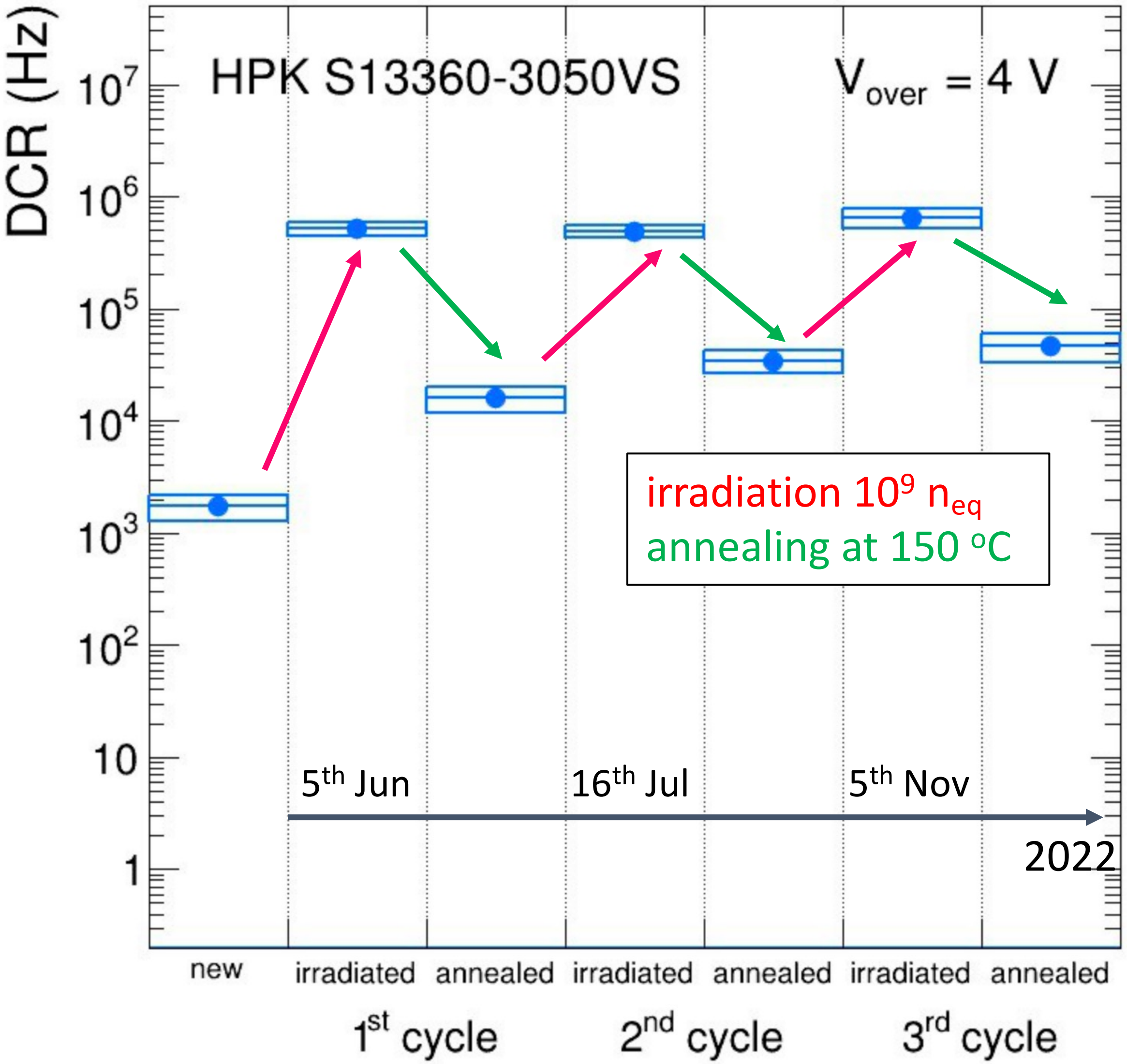



O(100) DCR increase after $10^{11}$ $n_{eq}$

O(10) DCR recovery post-annealing

# 2022 campaign: irradiation + annealing cycles




"getting closer to the experimental setup"

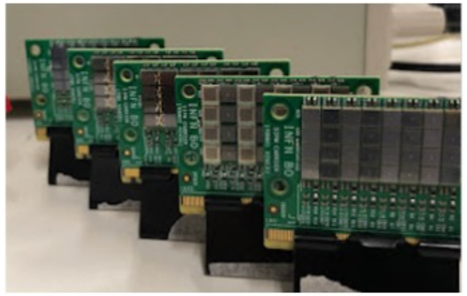
- test reproducibility of repeated irradiated/annealing cycles on the same sensors. **On-going campaign**: next shot 3rd December!
- each shot is $10^9$ $n_{eq}$ (remember: 0.2/1 year EIC at max lumi)
- extract parameters (sensor and $V_{over}$ specific!) to shape annealing cycles in the experiment:
  - $f_d$ : every $10^9$ $n_{eq}$ increases by 500 kHz DCR pixel rate (3x3 mm$^2$)
  - $f_a$ : each annealing leaves 15 kHz of additional DCR rate

$$DCR_r\,(k) = DCR_0 + f_d + (k-1)f_a$$

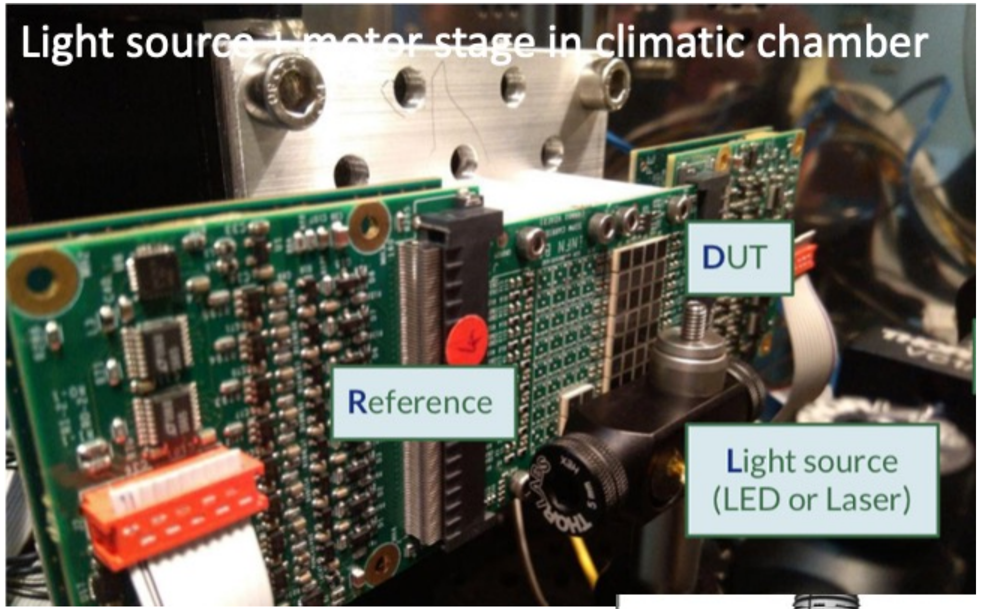
DCR after k irradiation and k-1 annealing cycles

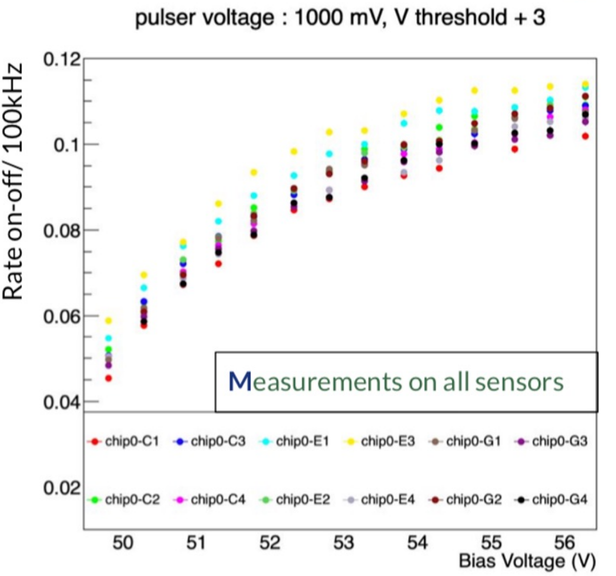
- damage and recovery remain additive
- annealing repairs $f_a/f_d$ of a given sensor (97% here)

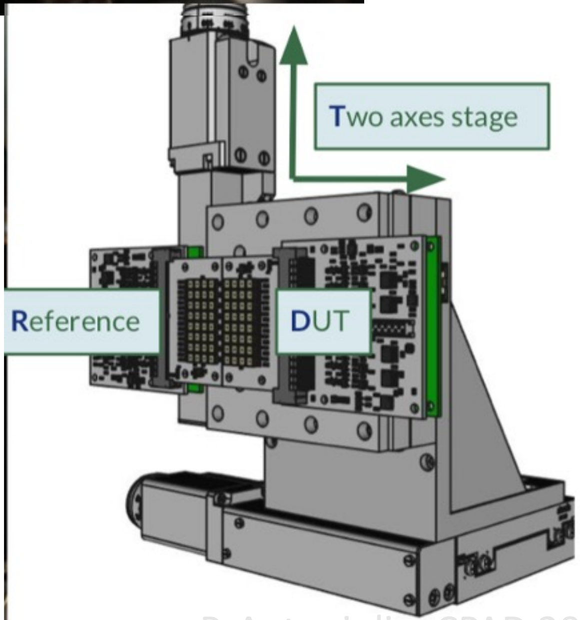
Total of 134 sensors under test



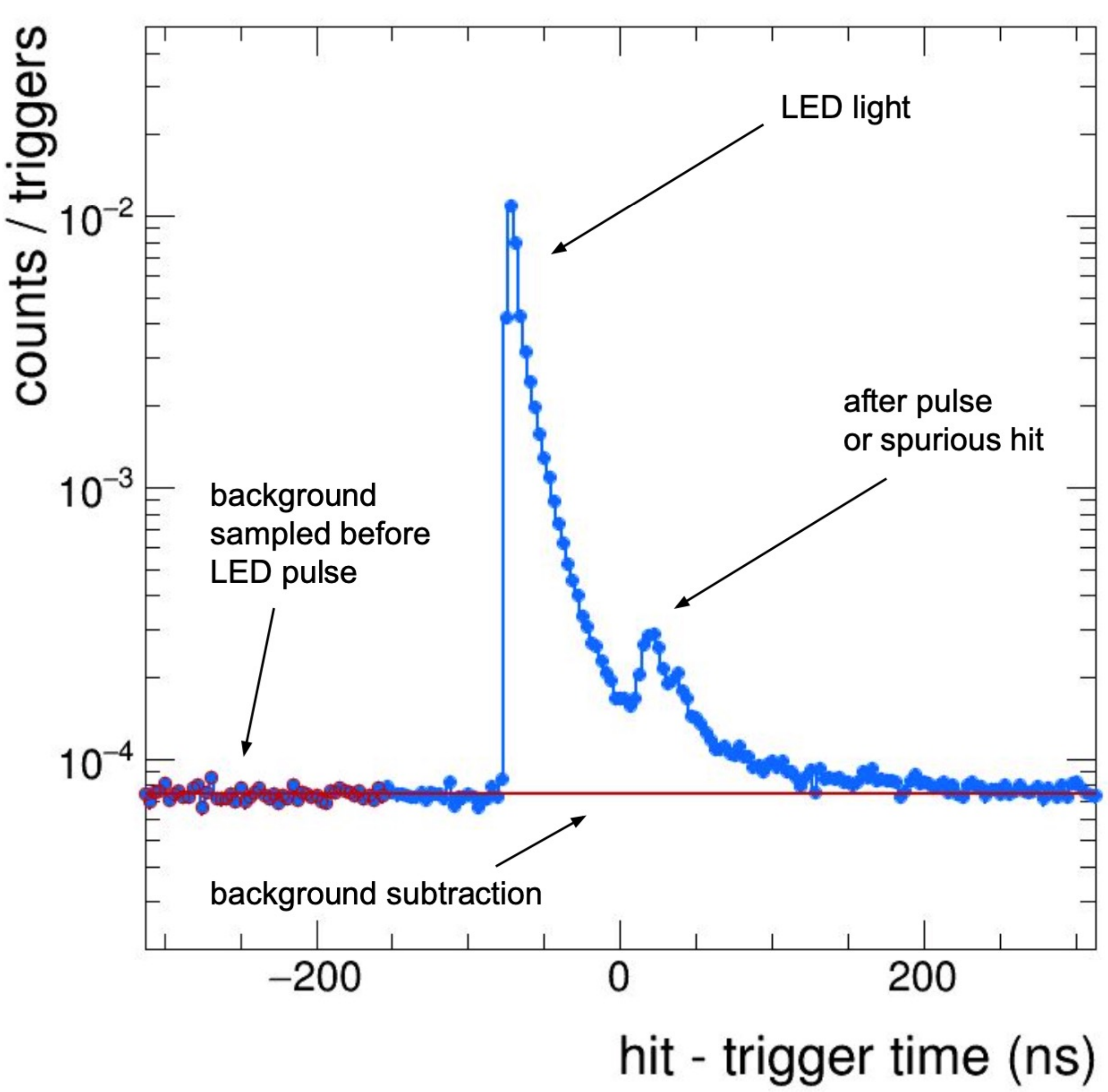
# Light response with pulsed LED



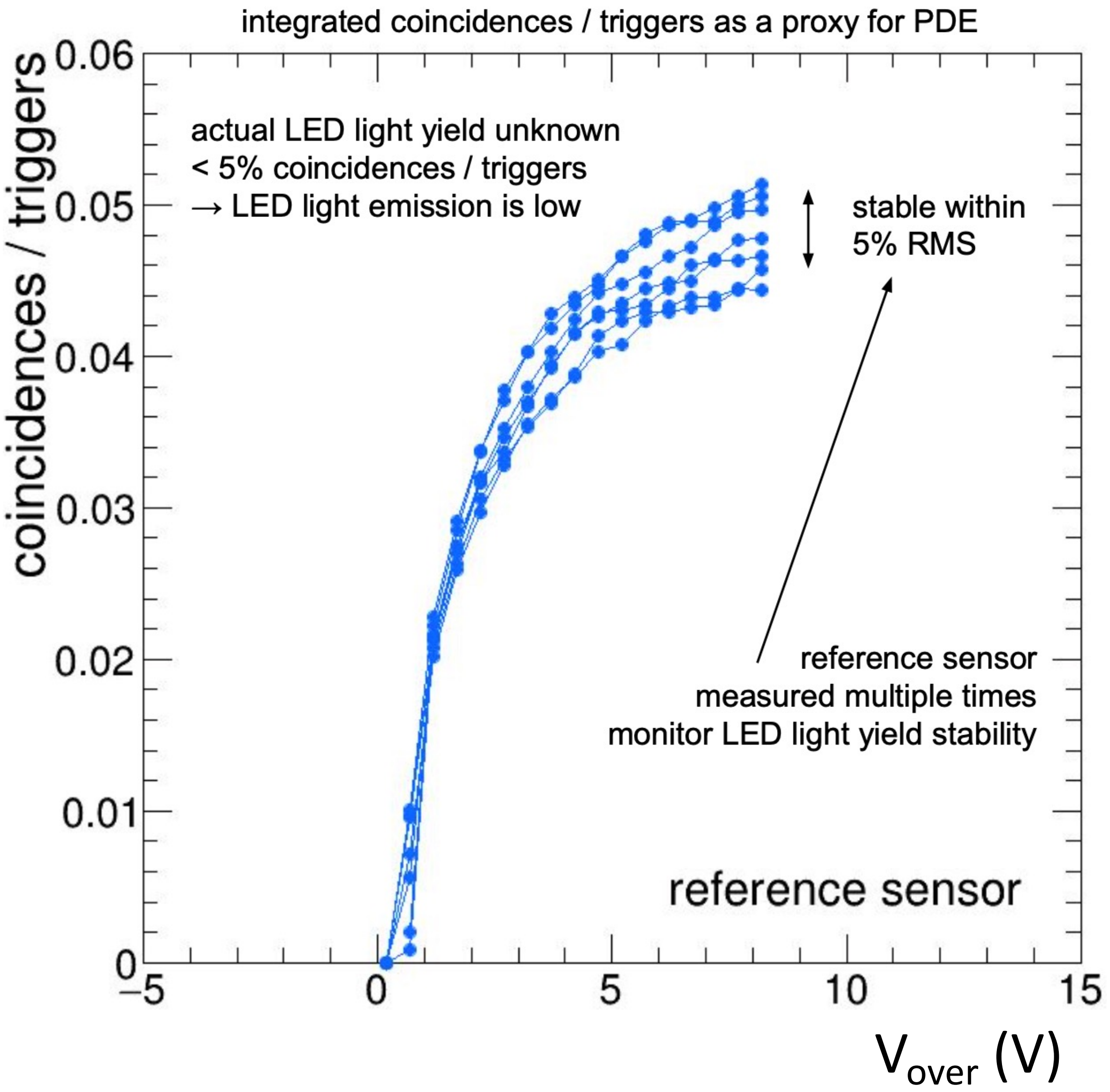



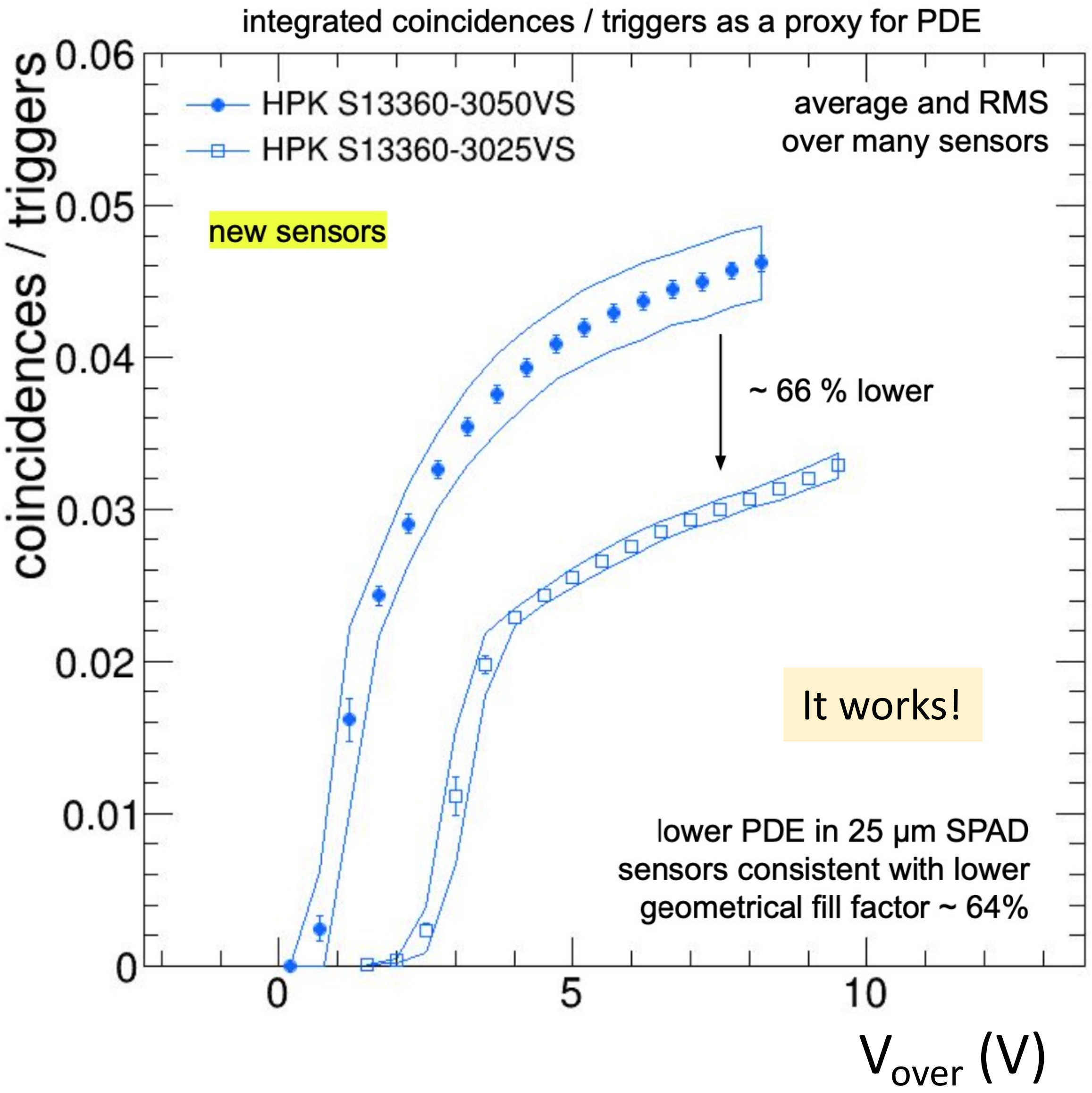




the basic measurement

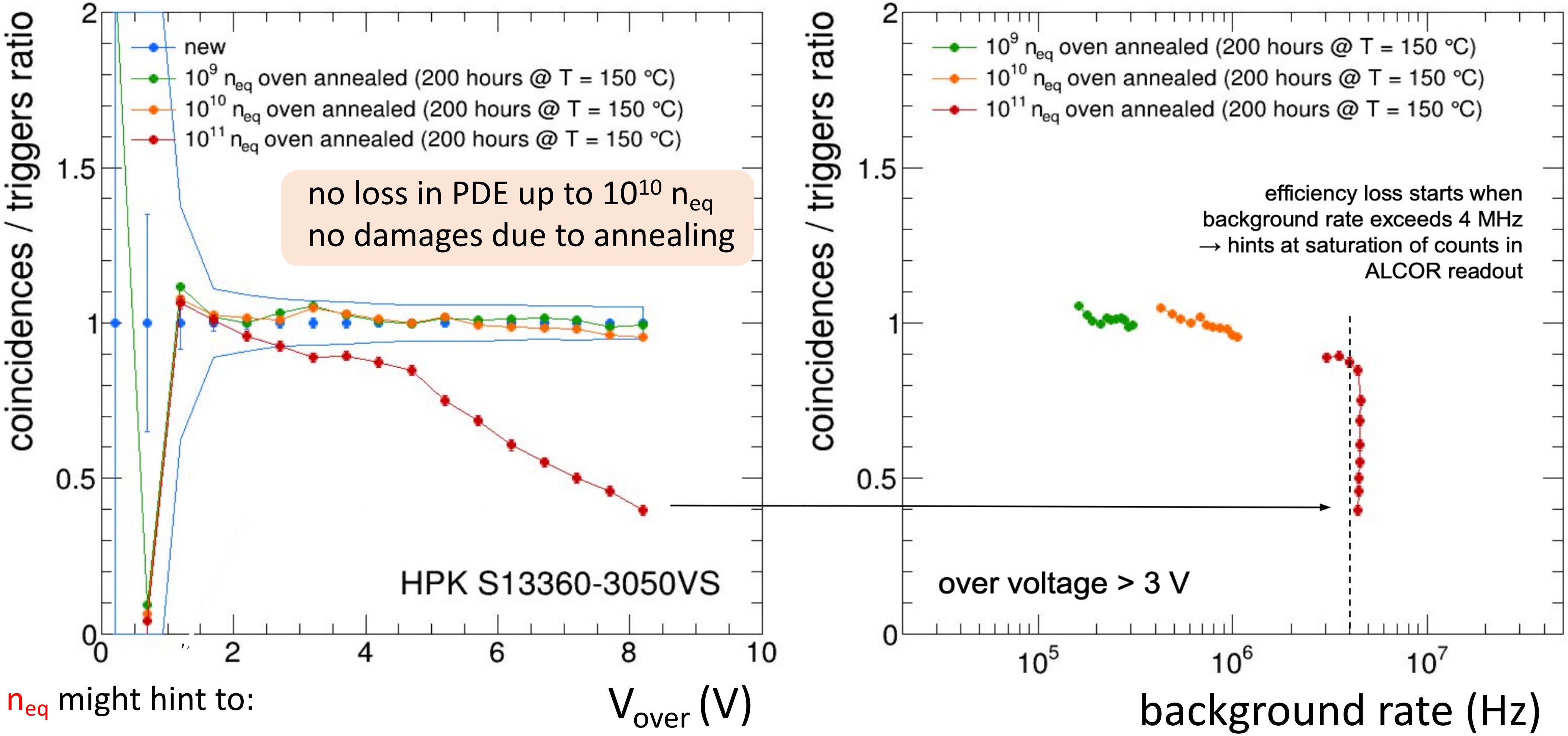


# Light response with LED (II)



# Efficiency after irradiation and annealing



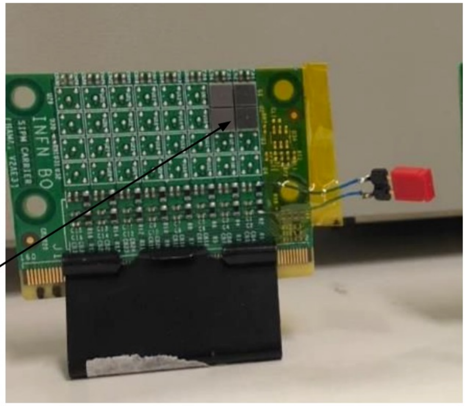

loss in PDE @ $10^{11}$ $n_{eq}$ might hint to:

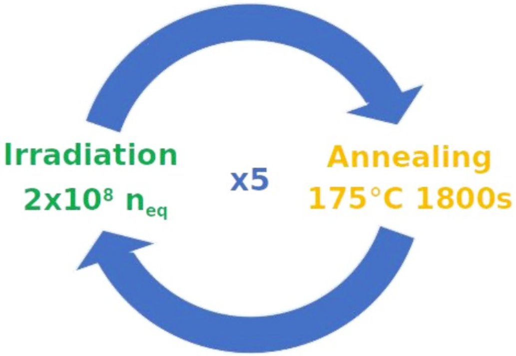
- baseline loss
- readout saturation

loss in PDE @ $10^{11}$ $n_{eq}$ consistent with known ALCOR limitations

# "Getting closer to the experimental setup"

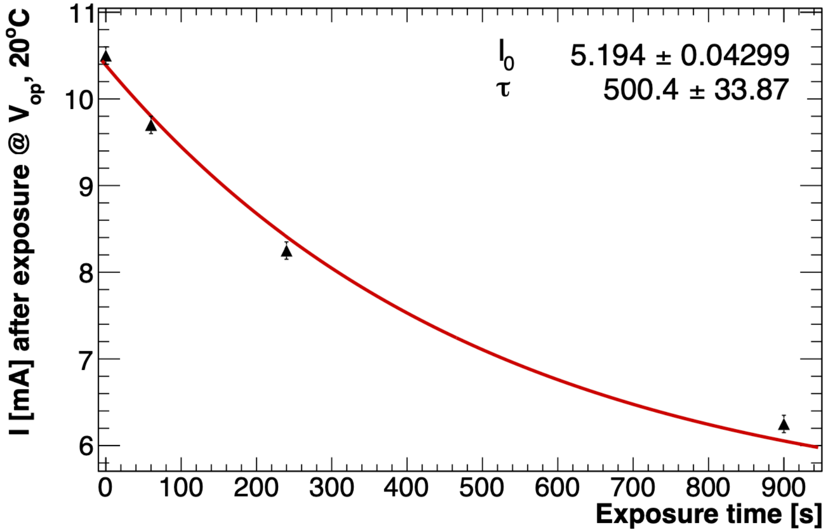
testing online annealing solutions ("in situ")


- preliminary test on electrical annealing techniques
- forward bias + Joule effect: ~ 1 W / sensor → T = 175 °C
- could pave the way to more frequent (and without dismounting sensors) annealing cycles

→ we "split" the irradiation fluence ($10^9$ $n_{eq}$) in five shots, interleaved by 30 minutes annealing




M. Cordelli *et al* 2021 *JINST* **16** T12012 results on HPK and SensL (OnSemi) sensors, both forward and inverse bias

# Electrically induced annealing techniques

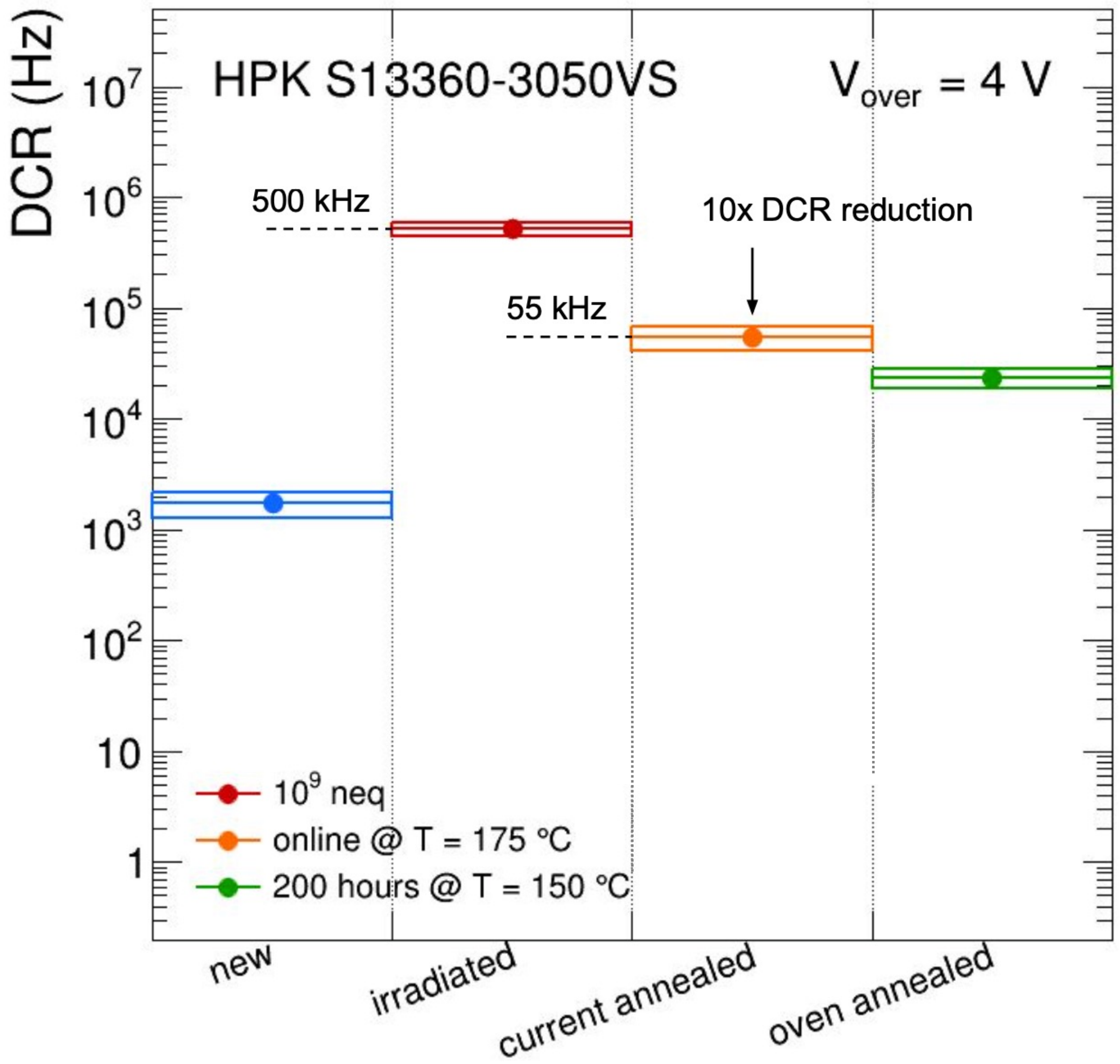
The sensors current-annealed found at 55 kHz

Residual DCR not good as in oven (15 kHz) but:

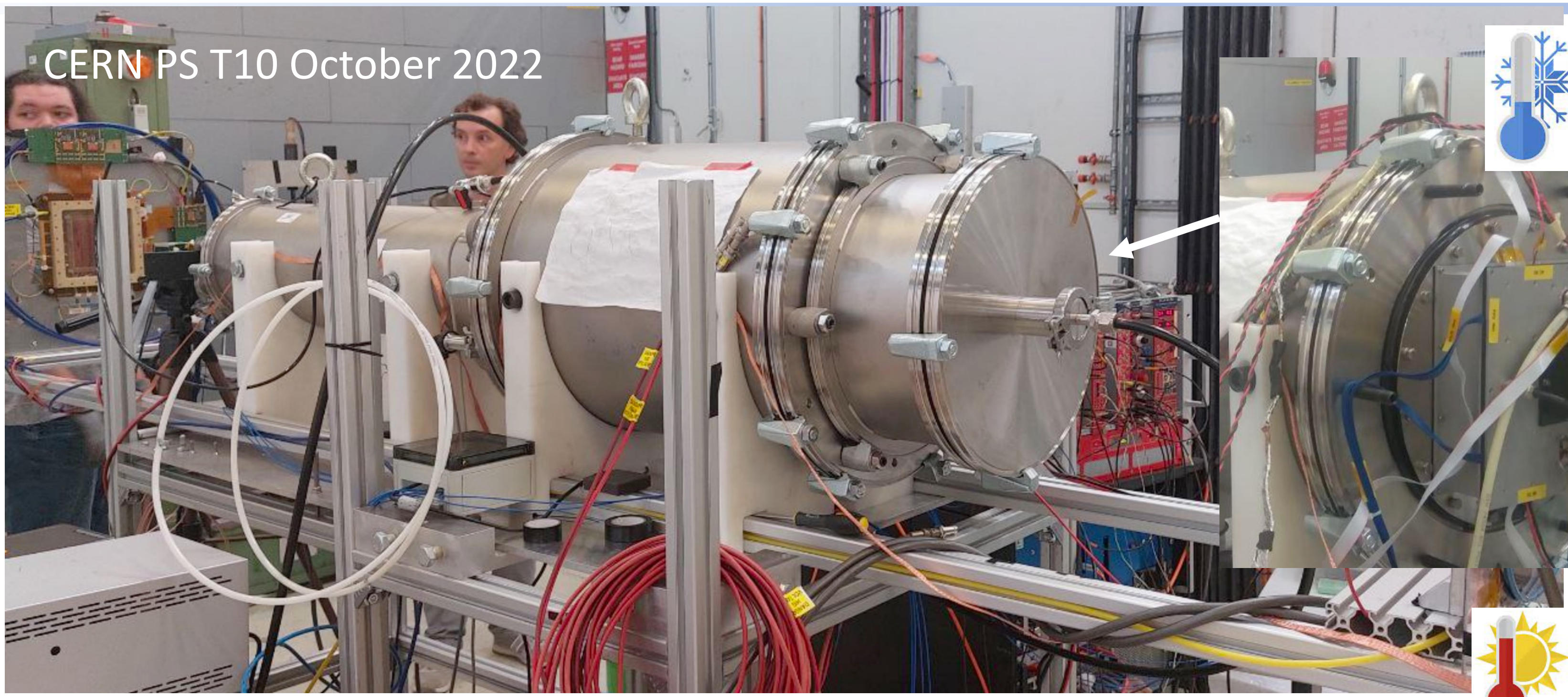
- 100 times faster!! (2.5 hours vs 200 hours!)
- can be done in-situ
- can be done more frequently

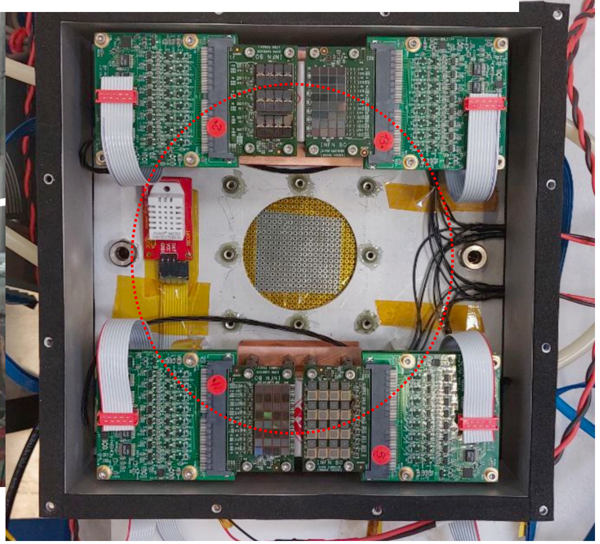
It looks very promising!

Specific R&D planned for 2023 on this item



# Bringing irradiated sensors on a dRICH (prototype)



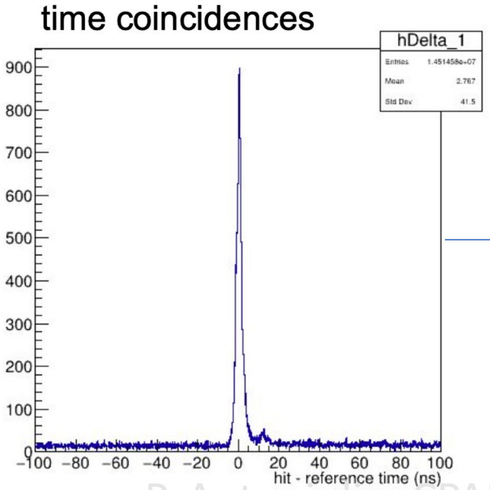



**cooling** keeps sensors at T= -30 °C

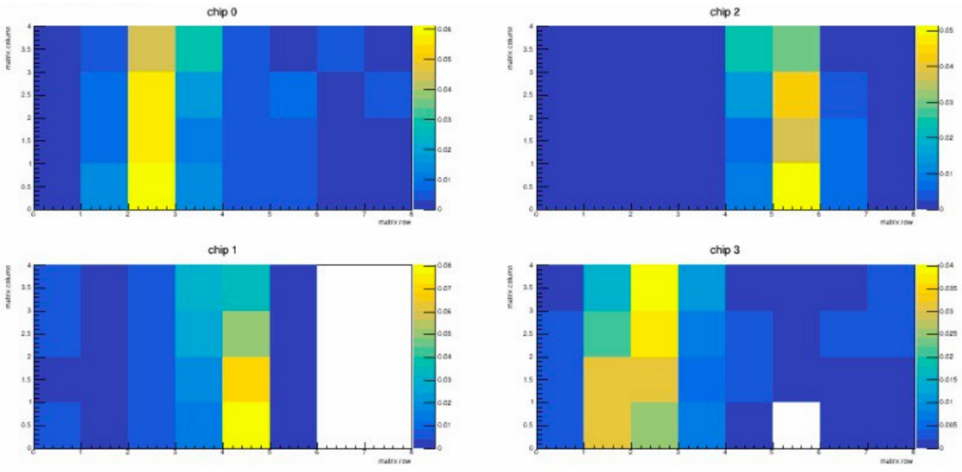
irradiated/**annealed** sensors

**timing**

ALCOR streaming readout
time tagger with scintillators

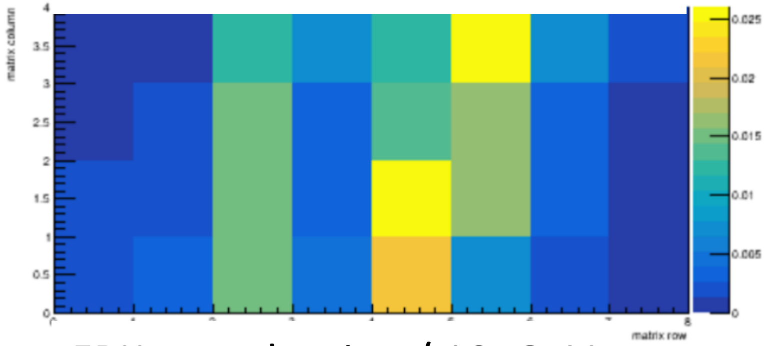



Cherenkov photons visible!

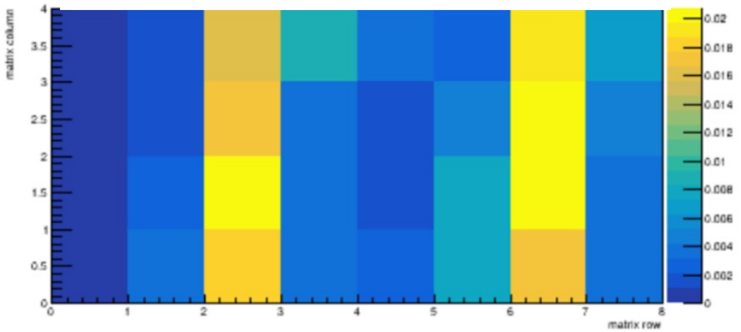


# Irradiated sensors on test beam/dRICH prototype (I)

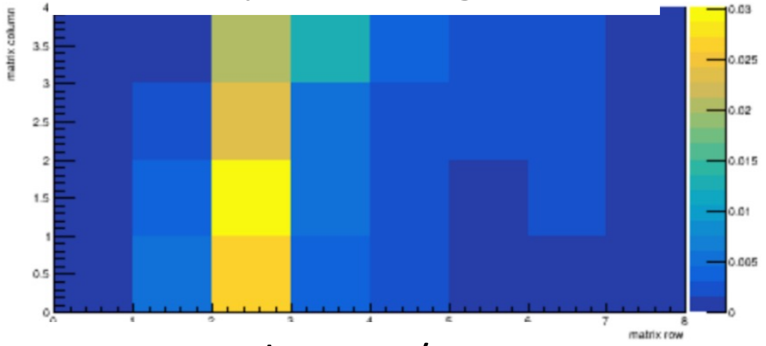
HAMA1: p and π ring / 10 GeV



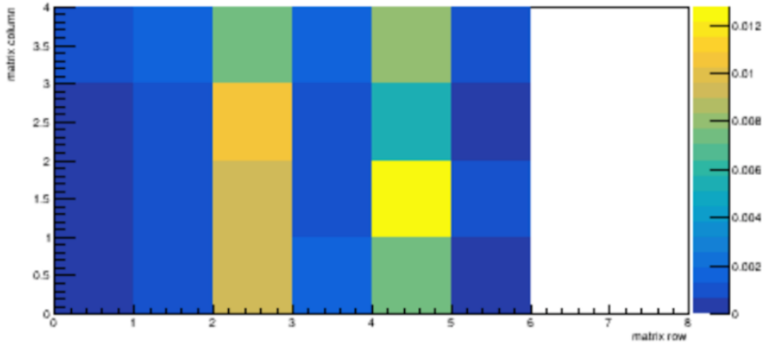

HAMA1: p and π ring / 8 GeV



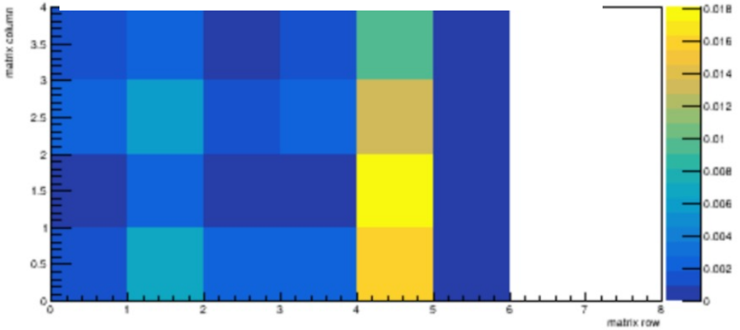

HAMA1: p and π ring / 6 GeV



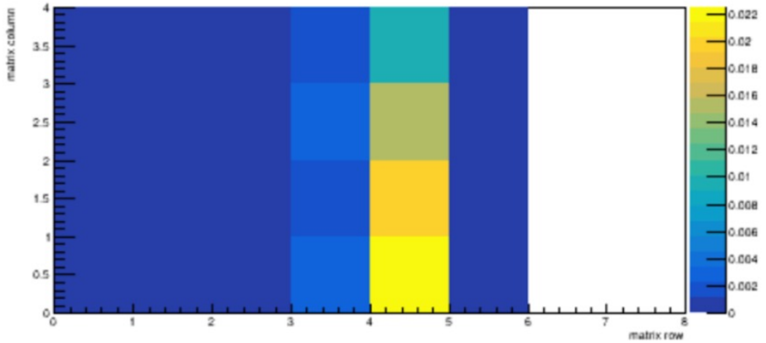

FBK: p and π ring / 10 GeV




FBK: p and π ring / 8 GeV

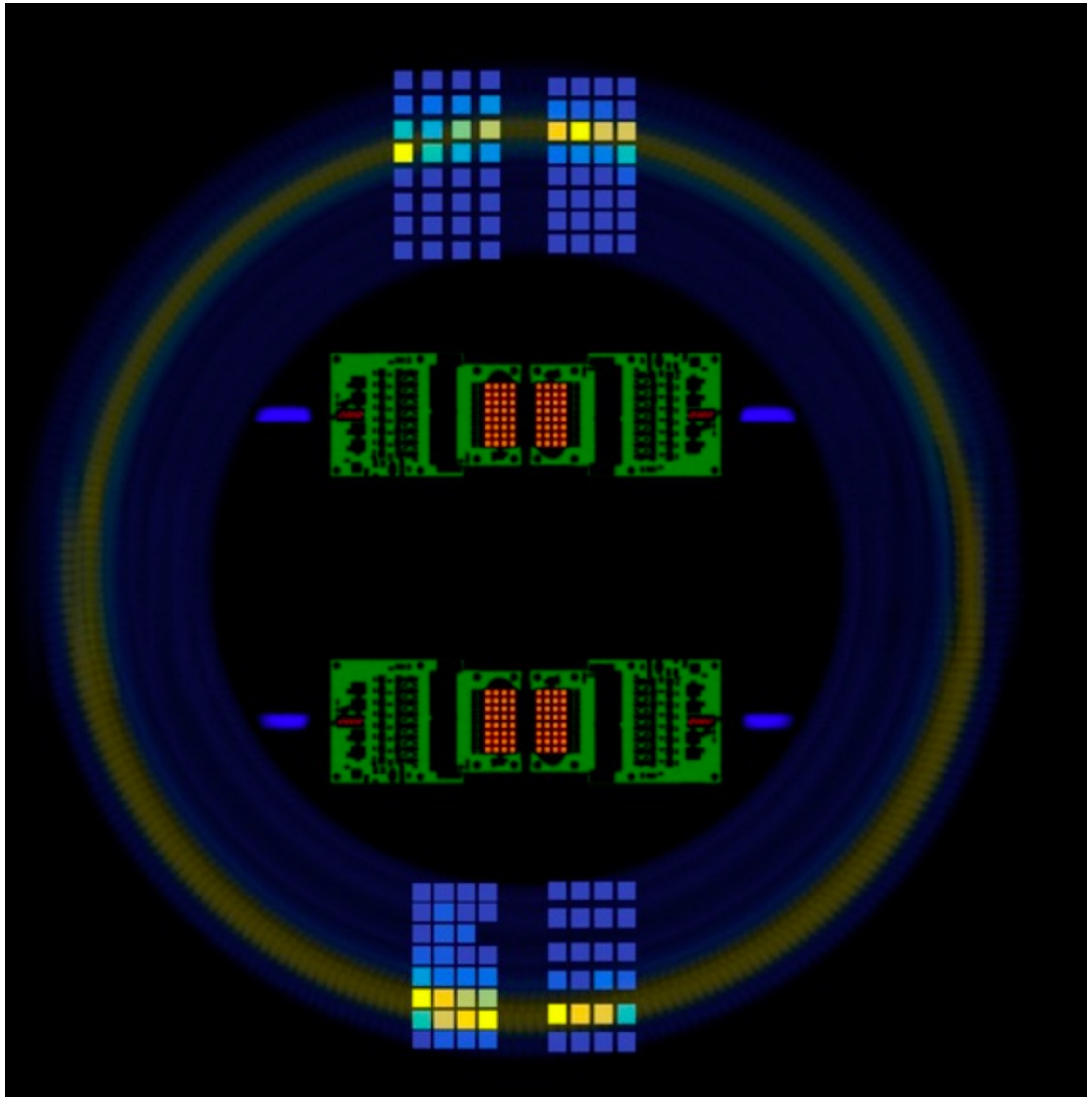



FBK: p and π ring / 6 GeV



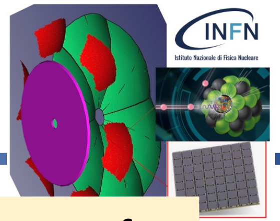

Basic checks show the system is working consistently
Single photon detection mantained

# Irradiated sensors on test beam/dRICH prototype (II)



taking into account actual dimensions "sharpness" of "rings" looks consistent

full analysis on-going



# Summary and outlook

R&D program started in 2020 to explore SiPM as baseline photosensor choice for dRICH @ EIC. Non-radiation hardness of these devices identified as main risk, however expected fluence is not high → dedicated study.

- results on **irradiation** and high-T **annealing**
  - observed DCR increase consistent with existing literature, tested different sensors
  - repeated *several* times mimicking real-life experiment on *large* number of sensors
  - allow us to proceed with SiPM as full optical readout for dRICH prototype (2023) [HPK S13360 as baseline]

- promising initial results using **electrically induced annealing** techniques → to be further explored in 2023

- **single photon detection efficiency**
  - unaffected up to $10^{10}$ $n_{eq}$
  - and likely up to $10^{11}$ $n_{eq}$ → to be investigated

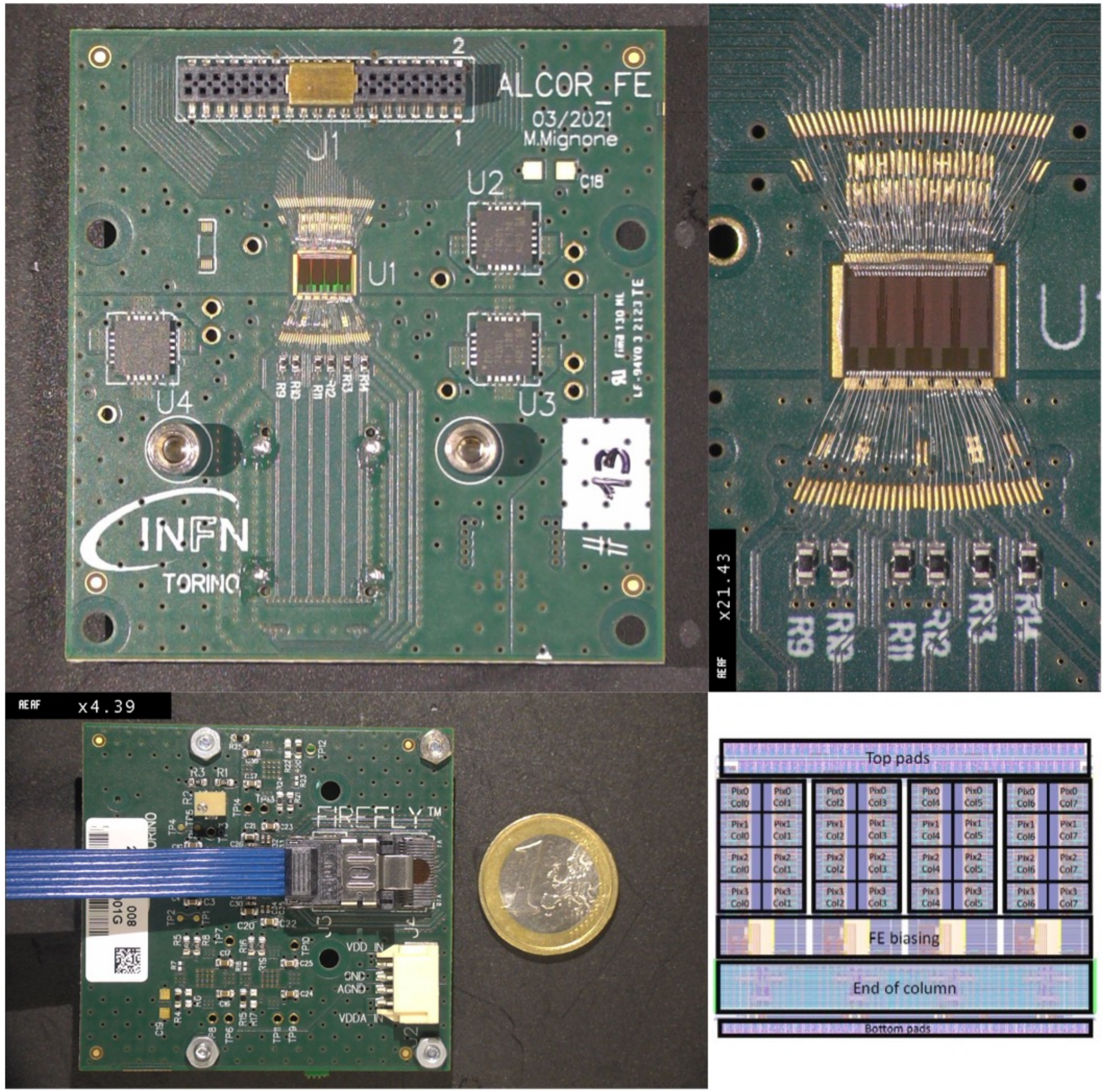
- **test beam** was successfull "proof-of-concept" of the three key ingredients

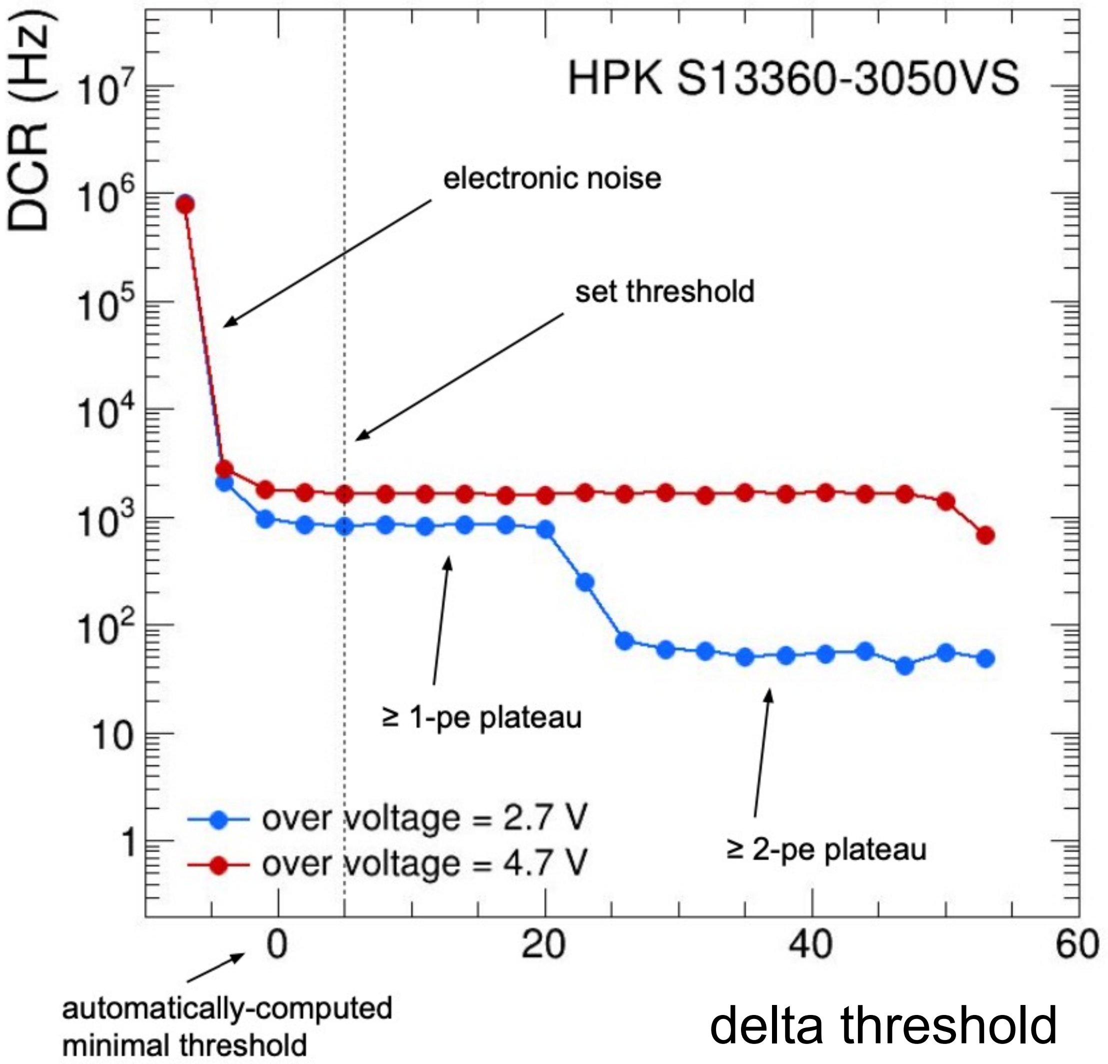
- All measurements/readout successfully operated with **ALCOR** ASIC

- **neutron** irradiations planned (so far only protons)
- study of impact of irradiation/annealing on **time resolution** planned

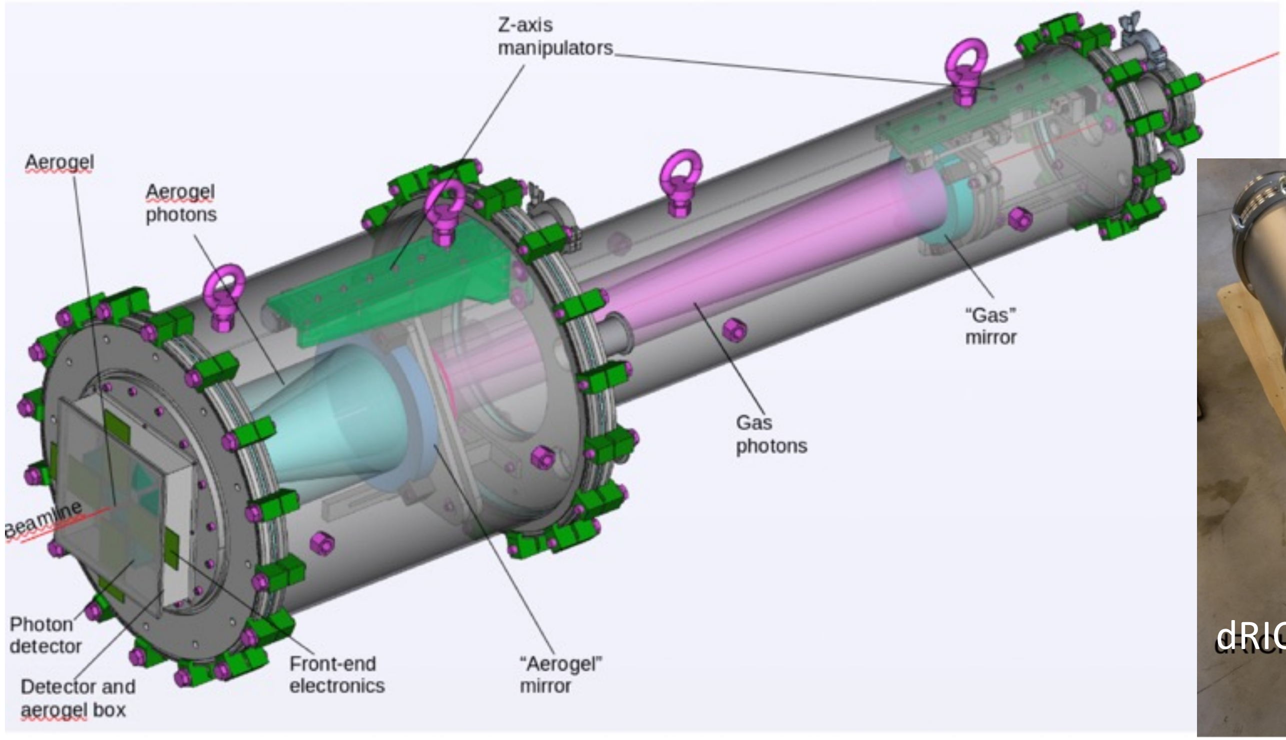
# Backup

# Photon counting with ALCOR

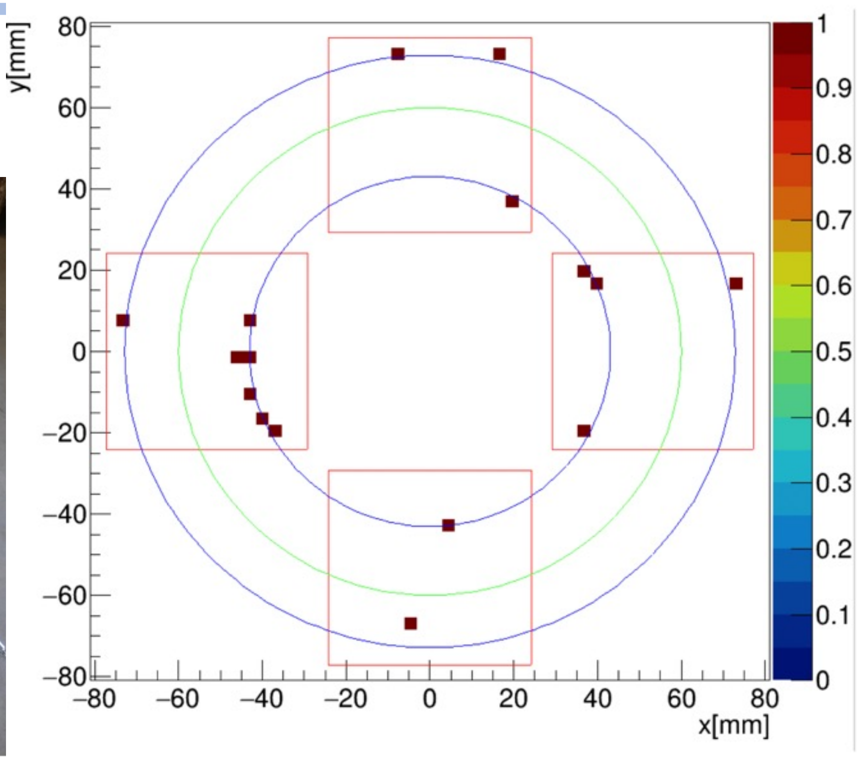


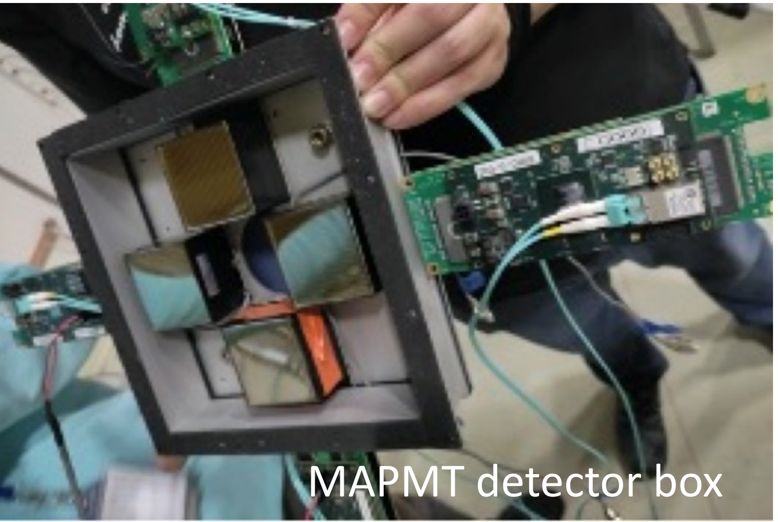



# dRICH prototype

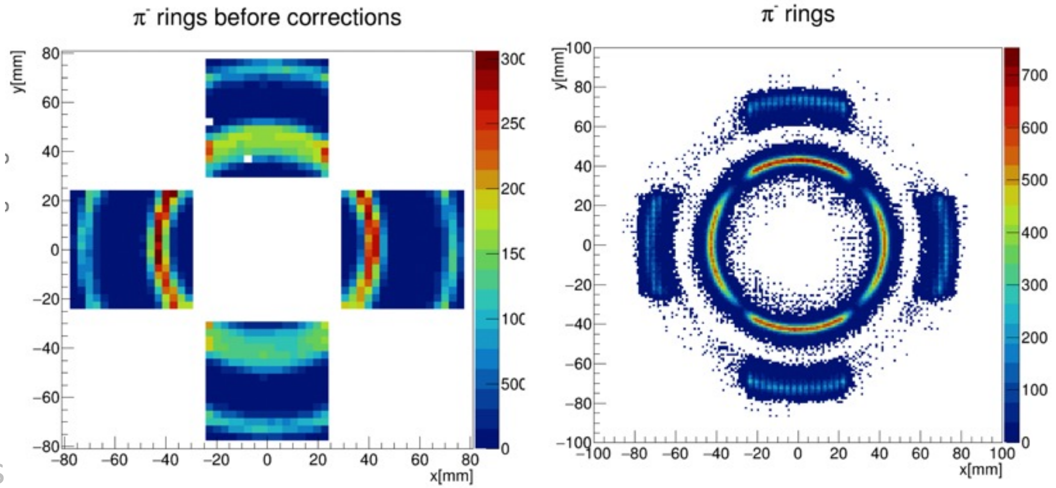




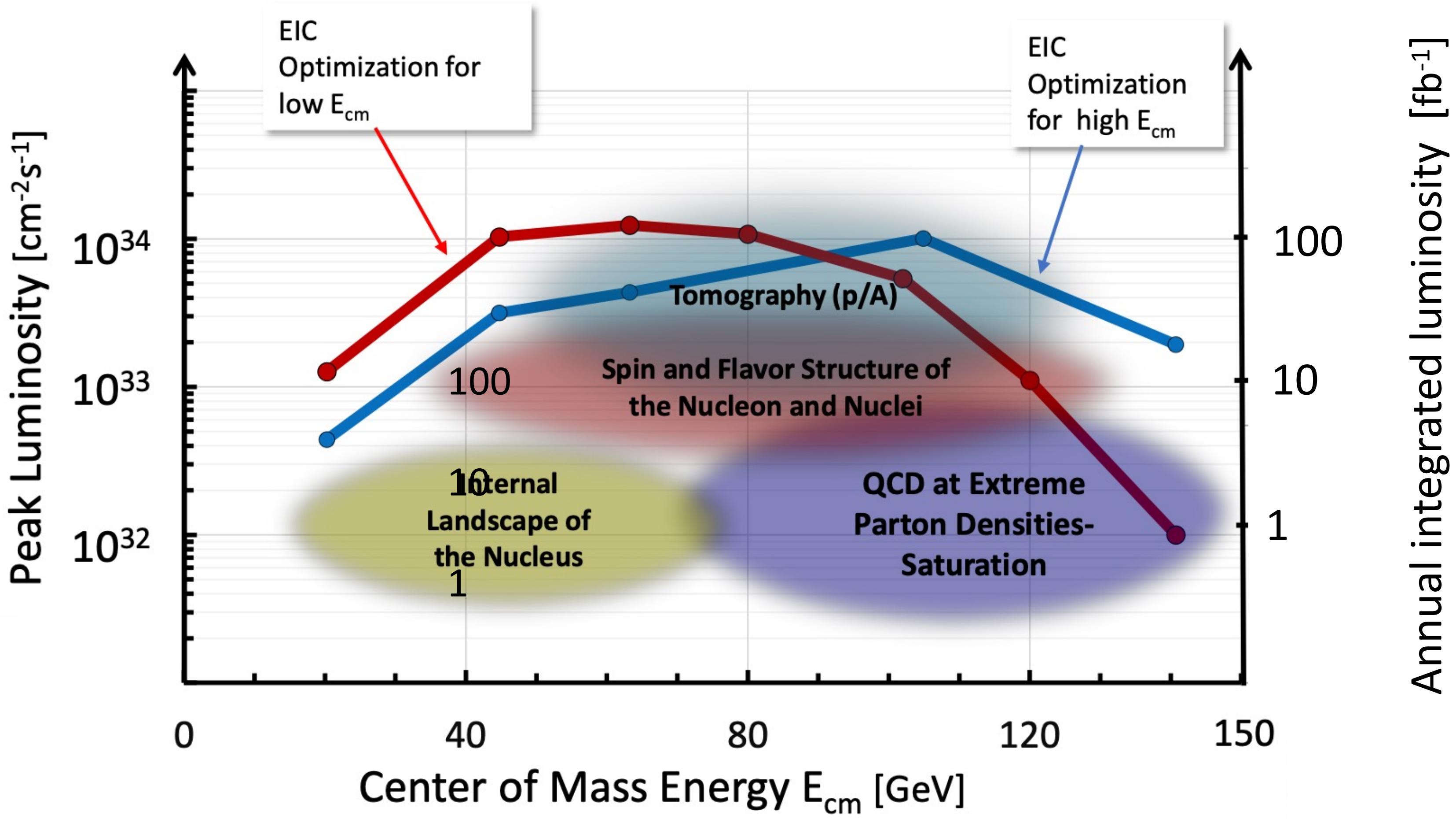


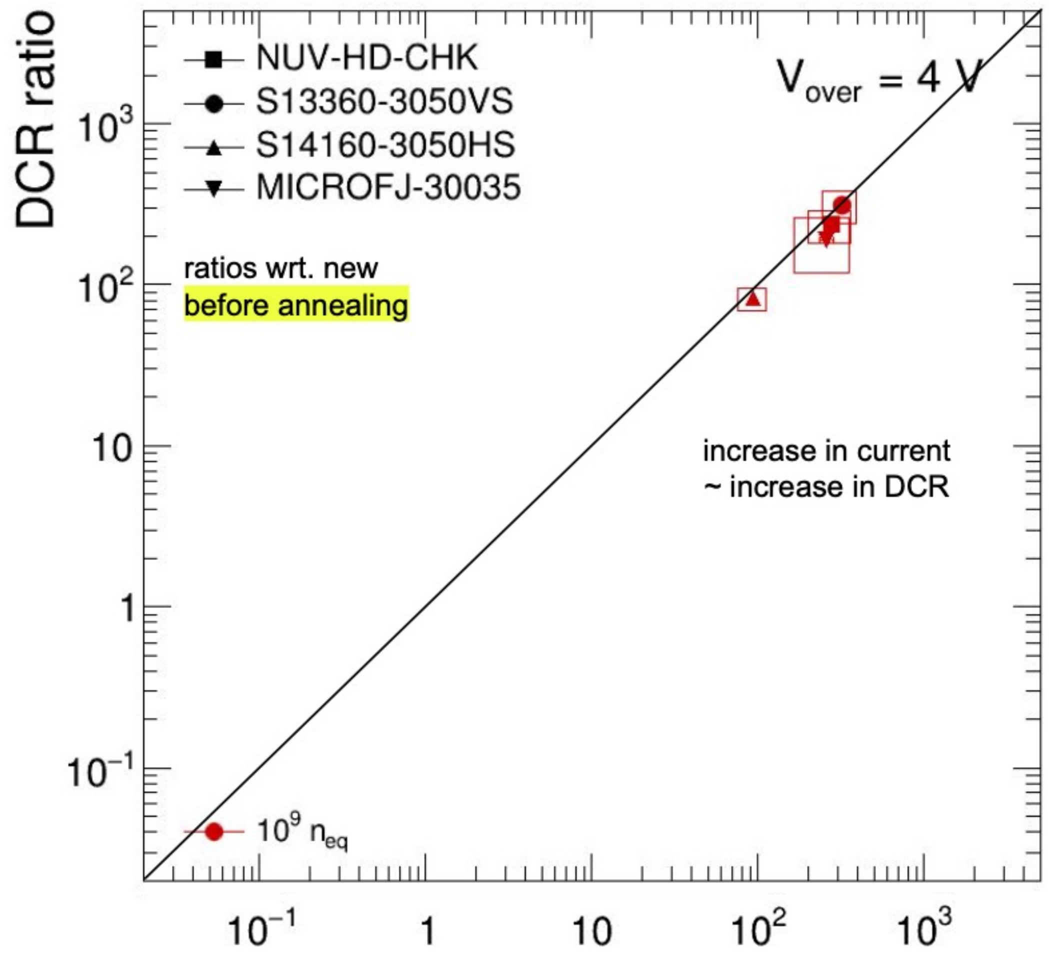

- Tracking with GEM
- Preliminary results on $\sigma_\theta$ resolution with aerogel and gas



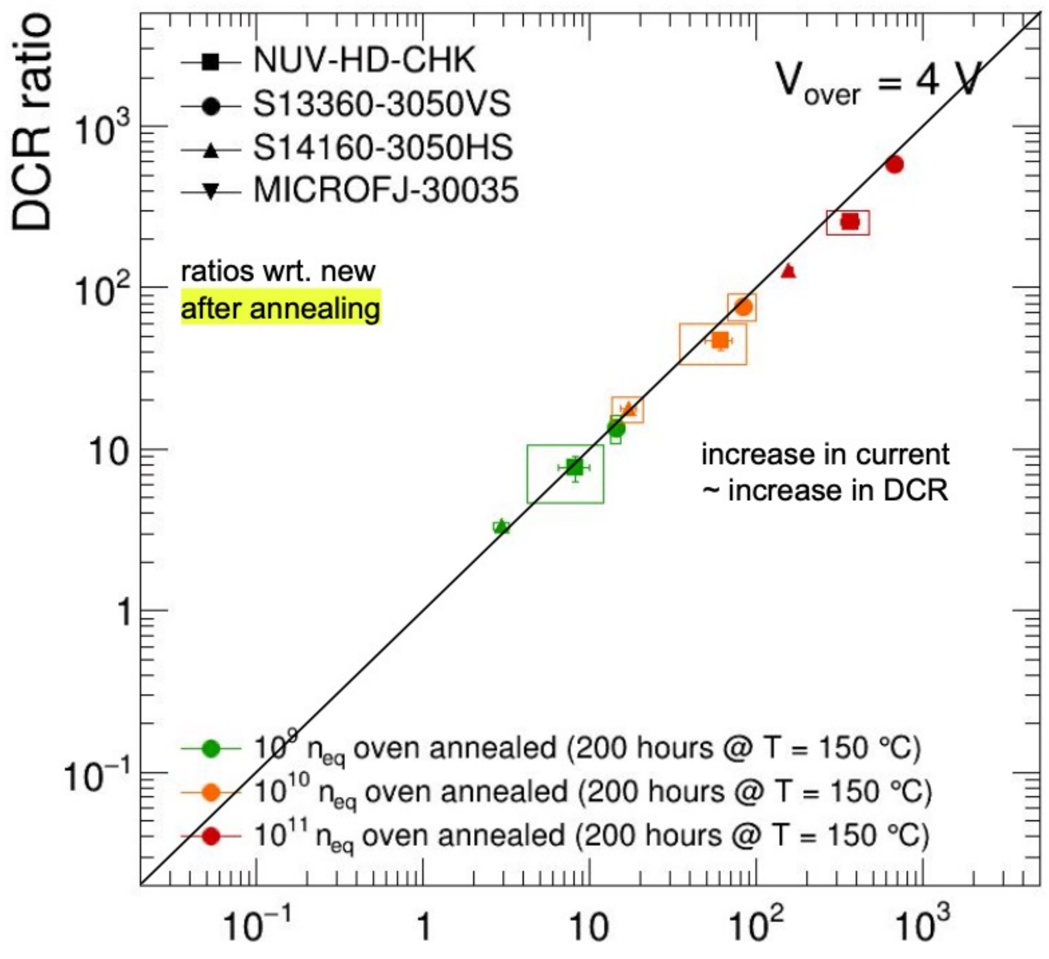
# EIC: physics & luminosity



# DCR and currents: irradiation & annealing




current ratio




current ratio

current increases are realiable proxy of DCR increases, as expected

# dRICH throughput estimates

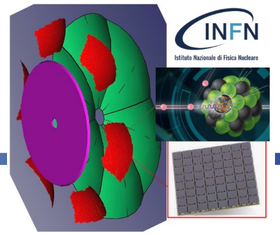


Table 2.5: Maximum data volume by detector. from ATHENA proposal

| Detector | Channels | DAQ Input (Gbps) | DAQ Output (Gbps) |
|---|---|---|---|
| B0 Si | 400M | <1 | <1 |
| B0 AC-LGAD | 500k | <1 | <1 |
| RP+OMD+ZDC | 700k | <1 | <1 |
| FB Cal | 4k | 80 | 1 |
| ECal | 34k | 5 | 5 |
| HCal | 39k | 5.5 | 5.5 |
| Imaging bECal | 619M | 4 | 4 |
| Si Tracking | 60B | 5 | 5 |
| Micromegas Tracking | 66k | 2.6 | .6 |
| GEM Tracking | 28k | 2.4 | .5 |
| µRWELL Tracking | 50k | 2.4 | .5 |
| dRICH | 300k | 1830 | 14 |
| pfRICH | 225k | 1380 | 12 |
| DIRC | 100k | 11 | 11 |
| TOF | 332k | 3 | .8 |
| Total | | 3334 | 62.9 |

ASSUMPTIONS in these estimates

- throughput @ average 300 kHz DCR per pixel MAX before moving to annealing cycles given limitations on ALCOR and DAQ bandwidth
- factor 3 reduction due to timing selection
- throughput assumed 64 bit per hit (TOT)

**Future developments and outlook**

- timing reduction could be factor 10 (shutter on ALCOR)
- cooling at T= 40 °C would help another factor 2
- TOT might not be necessary?
- frequent electrically induced annealing
- ....

Note: 1.8 Tbps (300 kHz/pixel) is after > 6 $10^8$ $n_{eq}$ (and no annealing and under above assumptions) but we will start @ 7.3 Gbps (2 kHz/pixel)