TREDI24

20-22 February 2024

Studies of radiation damage and mitigation strategies for the SiPM of the ePIC-dRICH detector at EIC

Nicola Rubini[1][2]

on behalf of the dRICH collaboration

[1]INFN Bologna, [2]University of Bologna

20 February 2024

The Electron-Ion Collider

Major US project in nuclear physics, one of the most important future facilities in the field

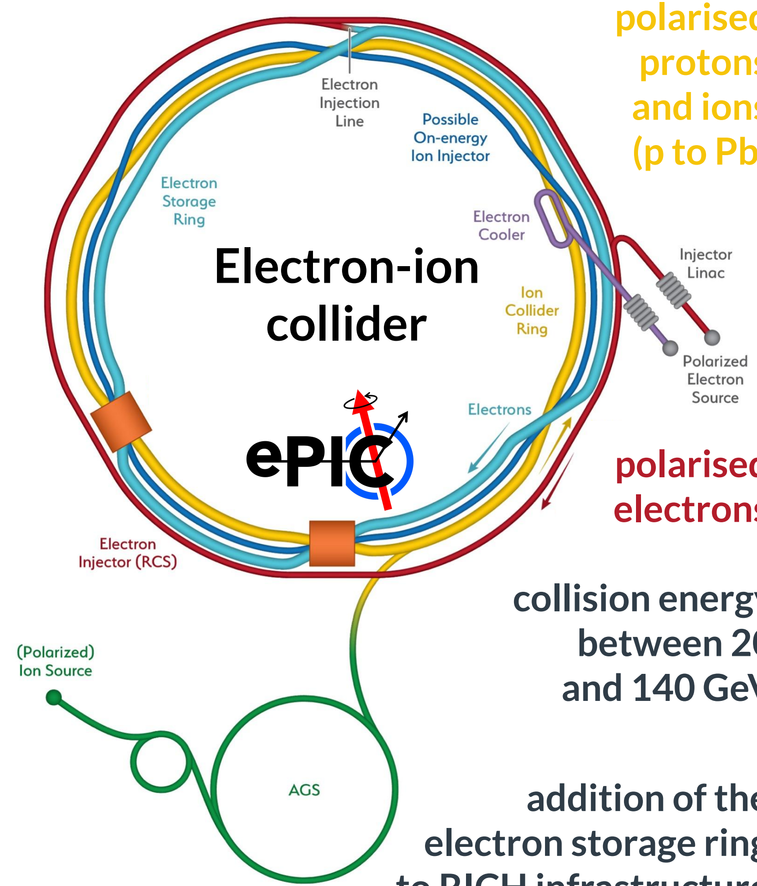
World's first collider for polarised electrons and protons, ions

Will allow to explore the secrets of QCD:

- Origin of the mass & spin of the nucleus
- 3D images of the nuclear structure

The collider will start in the **early 2030s**

One experiment foreseen for now, **ePIC**



polarised protons and ions (p to Pb)

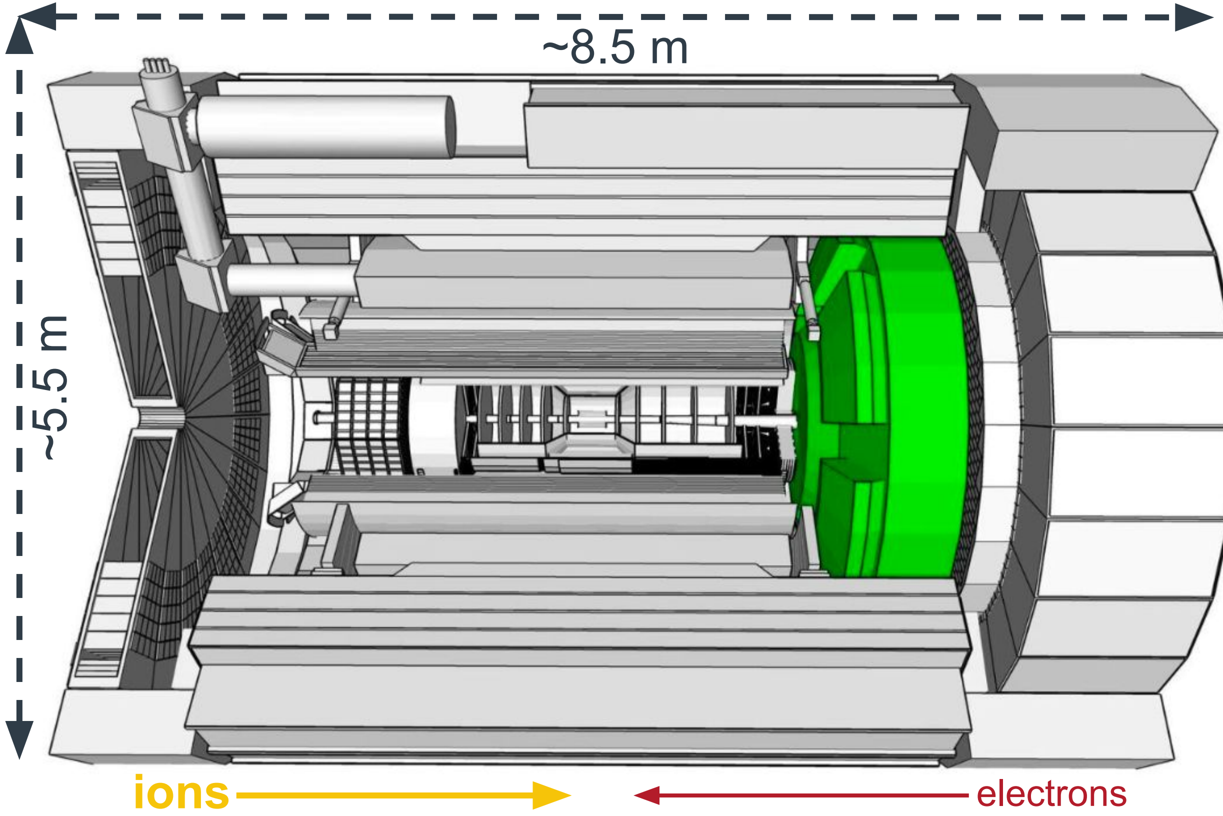
polarised electrons

collision energy between 20 and 140 GeV

addition of the electron storage ring to RICH infrastructure

https://www.bnl.gov/eic/

ePIC detector layout



Tracking:

1.7 T magnet
Si-MAPS + MPGDs

Calorimetry:

e-endcap: $PbWO_4$ EMCal
barrel: imaging EMCal
outer barrel: HCal
h-endcap: finely segmented

PID:

AC-LGAD TOF
pfRICH
hpDIRC
dRICH

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

Photosensors:

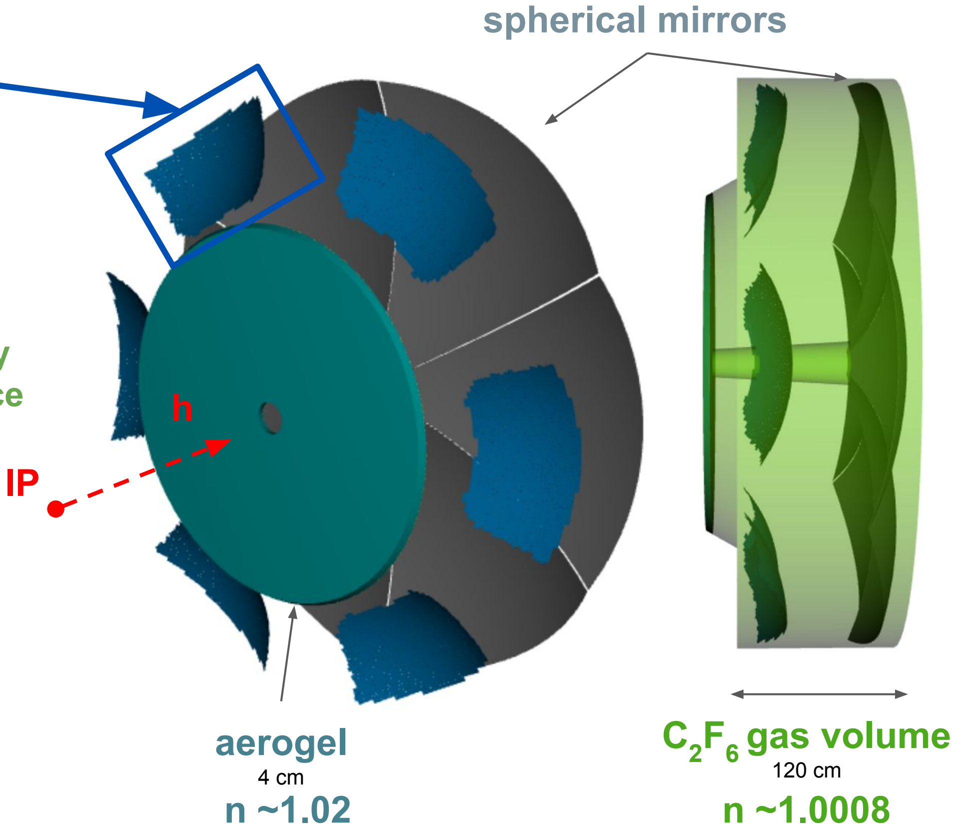
- 3x3 mm^2 pixels
- 0.5 m^2 per sector
- SiPM chosen

Pros

1. Single photon sensitivity
2. Good timing performance
3. Insensitive to magnetic fields
4. Cheap

Cons

1. High dark count rate at room temperature
2. High radiation sensitivity



PID

p ~ 3-50 GeV/c
η ~ 1.5-3.5 GeV/c
eID up to 15 GeV/c

Broad momentum coverage thanks to two radiators

nicola.rubini@bo.infn.it - Nicola Rubini

SiPMs and neutron equivalent fluence for dRICH sensors

Cons

1. **High dark count rate at room temperature**
2. **High radiation sensitivity**

What can be done?

1. Cooling can lower DCR of a factor ~2 every ~8°C
2. Timing can discard background
3. Annealing can recover DCR resulted from radiation damage

10^9 n_{eq}/cm^2 fluence:

Requirement for the key physics goals is 10 fb^{-1} per center of mass energy and polarization setting

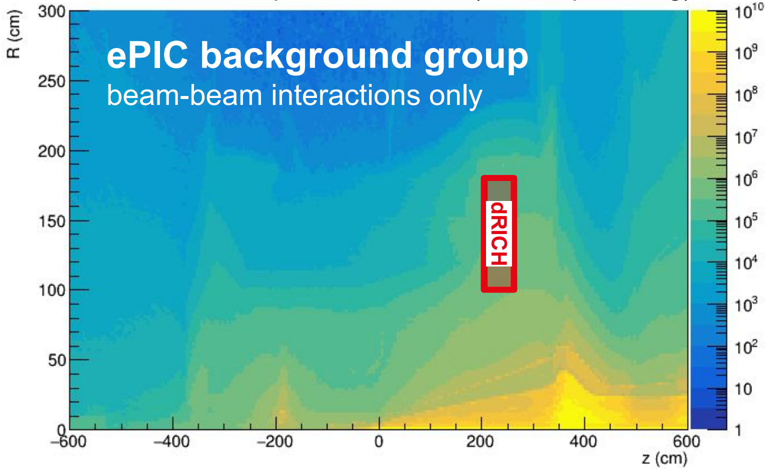
10^{10} n_{eq}/cm^2 fluence:

Requirement for the nucleon imaging programme is 100 fb^{-1} per center of mass energy and polarization setting

10^{11} n_{eq}/cm^2 fluence:

Expected fluence over 10-12 years of operation, might never be reached

1-MeV neutron equivalent fluence (1 fb^{-1} e-p running)



Expected fluence:

average: ~4 10^5 n_{eq} / cm^2 fb^{-1}

maximum: ~ 10^6 n_{eq} / cm^2 fb^{-1}

assumed: ~ 10^7 n_{eq} / cm^2 fb^{-1}

x10 safety factor

SiPMs and neutron equivalent fluence for dRICH sensors

Cons

1. **High dark count rate at room temperature**
2. **High radiation sensitivity**

What can be done?

1. Cooling can lower DCR of a factor ~2 every ~8°C
2. Timing can discard background
3. Annealing can recover DCR resulted from radiation damage

10^9 n_{eq}/cm^2 fluence:

Requirement for the key physics goals is 10 fb^{-1} per center of mass energy and polarization setting

10^{10} n_{eq}/cm^2 fluence:

Requirement for the nucleon imaging programme is 100 fb^{-1} per center of mass energy and polarization setting

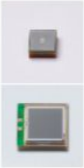
10^{11} n_{eq}/cm^2 fluence:

Expected fluence over 10-12 years of operation, might never be reached

We need to study the SiPM response to this moderately irradiated environment

We started with irradiations with these three levels of dose

SiPMs tested as dRICH sensors

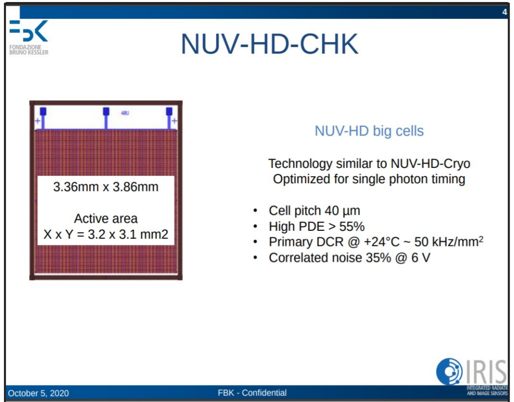



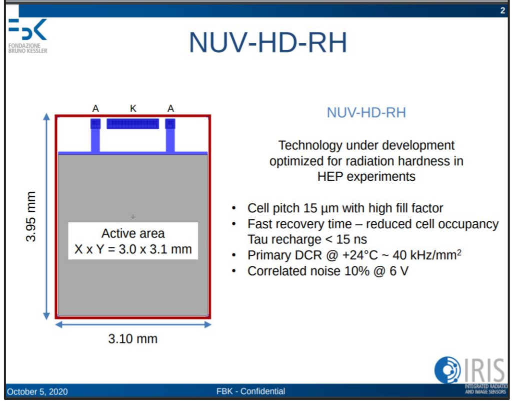
board	sensor	uCell (µm)	V_{bd} (V)	PDE (%)	DCR (kHz/mm^2)	window	notes
HAMA1	S13360 3050VS	50	53	40	55	silicone	legacy model Calvi et. al
HAMA1	S13360 3025VS	25	53	25	44	silicone	legacy model smaller SPAD
HAMA2	S14160 3050HS	50	38	50		silicone	newer model lower V_{bd}
HAMA2	S14160 3015PS	15	38	32	78	silicone	smaller SPADs radiation hardness
SENSL	MICROFJ 30035	35	24.5	38	50	glass	different producer and lower V_{bd}
SENSL	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

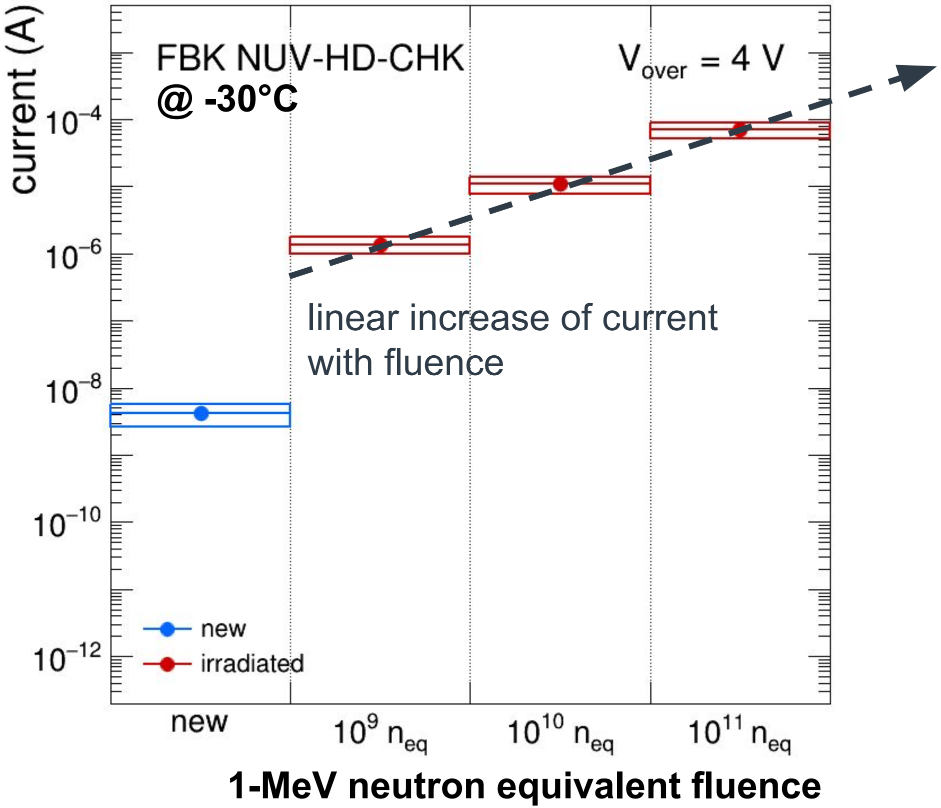
ON Semiconductor

BROADCOM

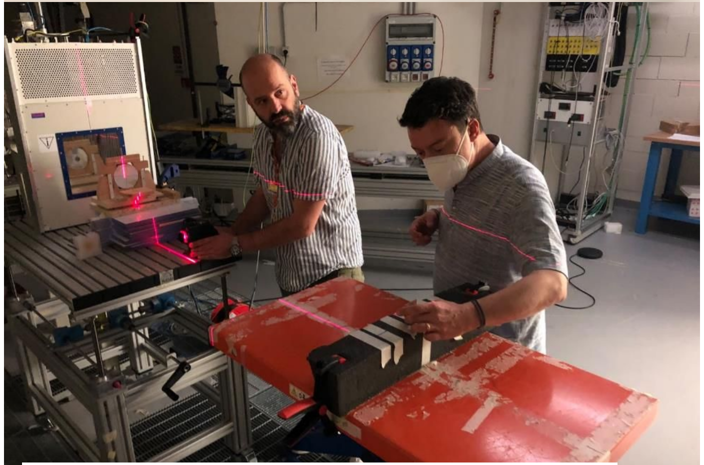




Radiation damage of SiPMs with protons at TIFPA

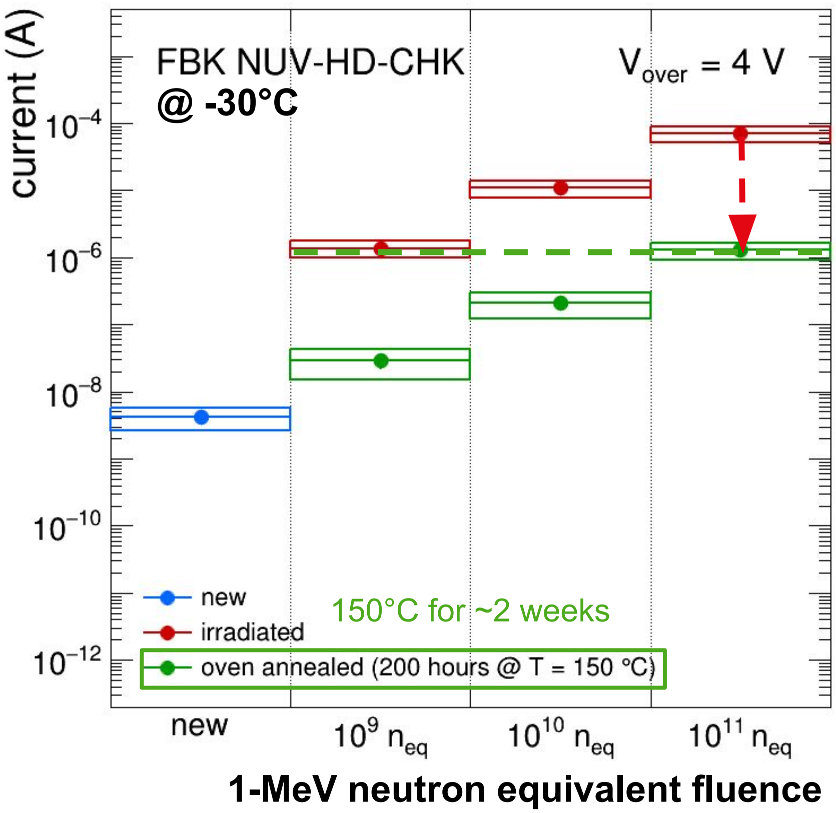


4x8 carrier boards w/ 3x3mm^2 sensors



2021, 2022, 2023 campaigns set-up

Damage recovery of SiPMs: offline annealing

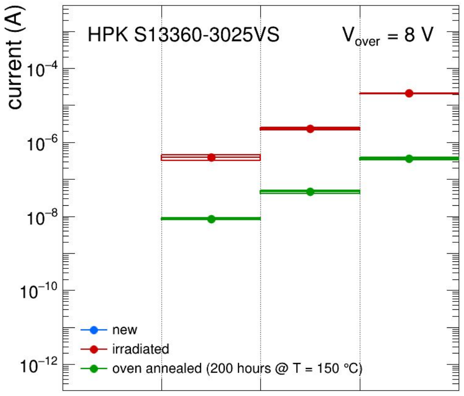


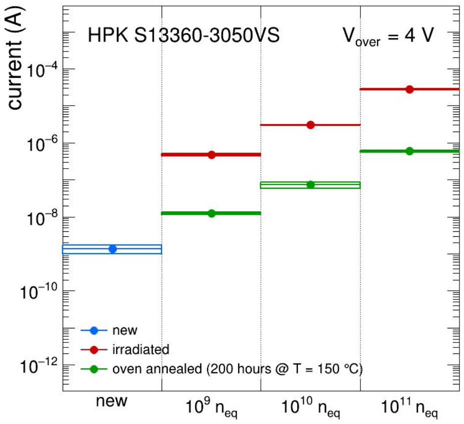
~ 100x reduction of dark current

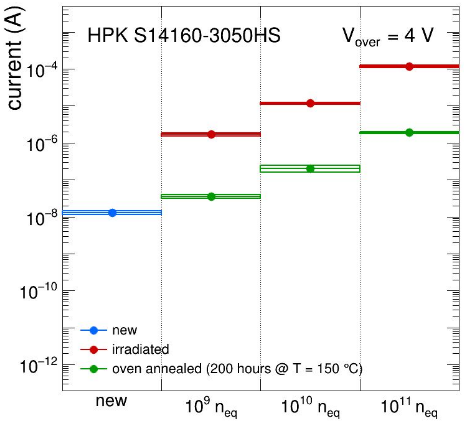
behaves as if it had received ~100x less fluence

Offline annealing done with sensors in oven

Hamamatsu sensors show very similar behaviours



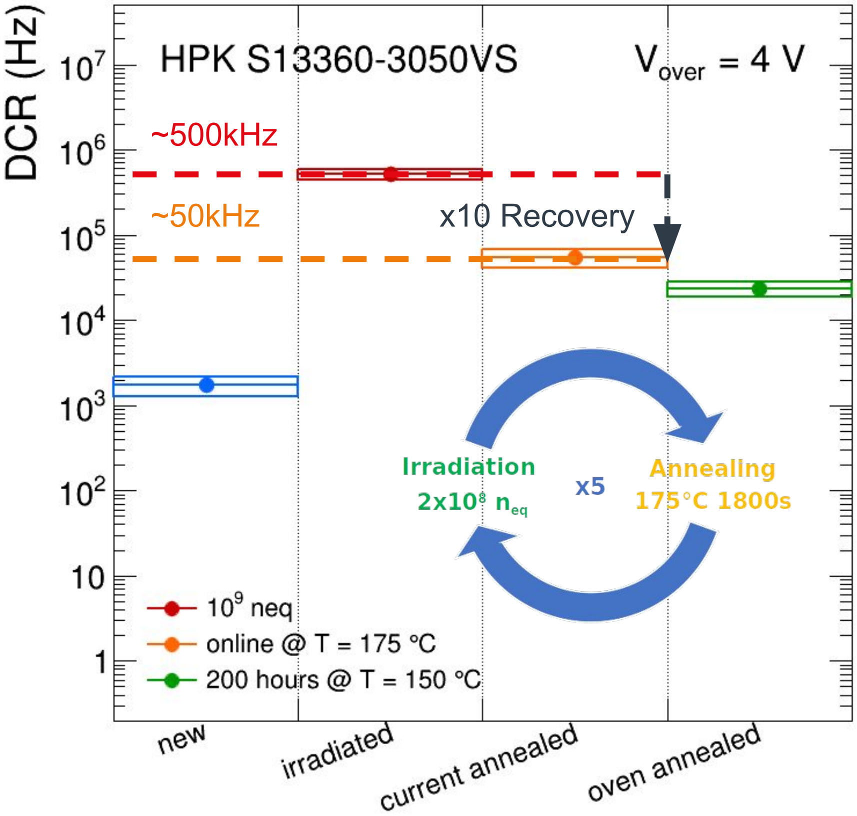




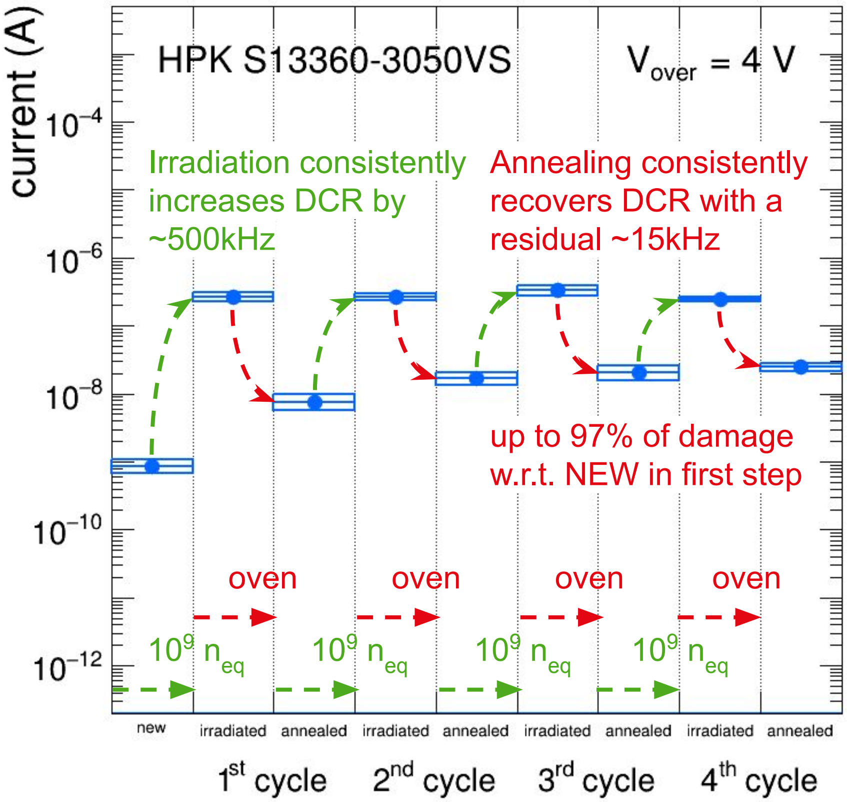
Damage recovery of SiPMs: online self-annealing

Online annealing done with sensor in forward bias, delivering ~1 W/sensor

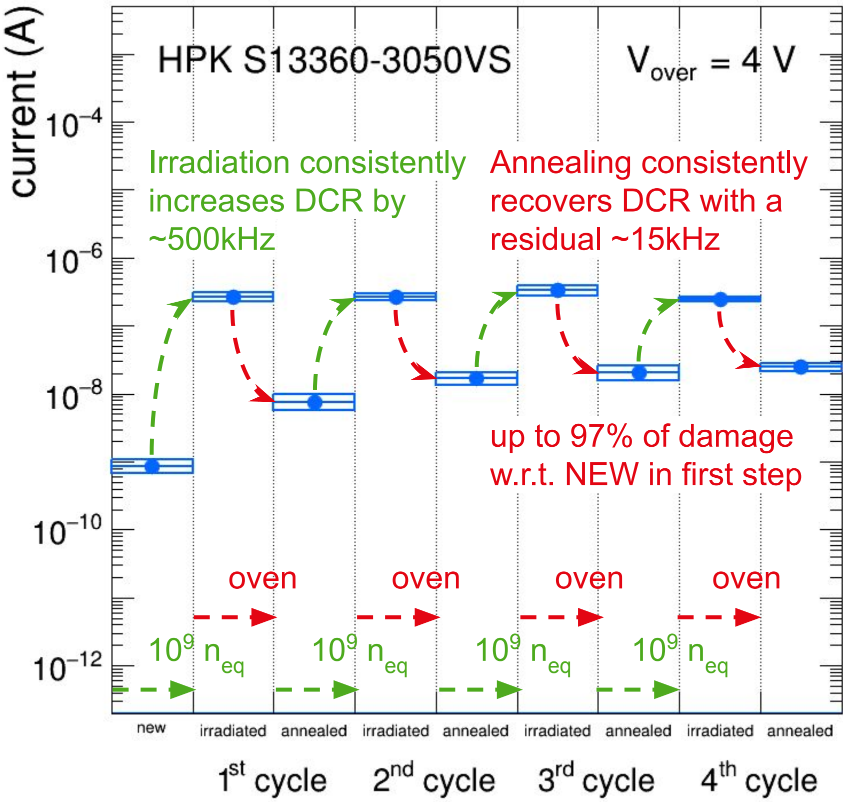
Exposure to radiation is interleaved with annealing cycles as could be the case in the experiment

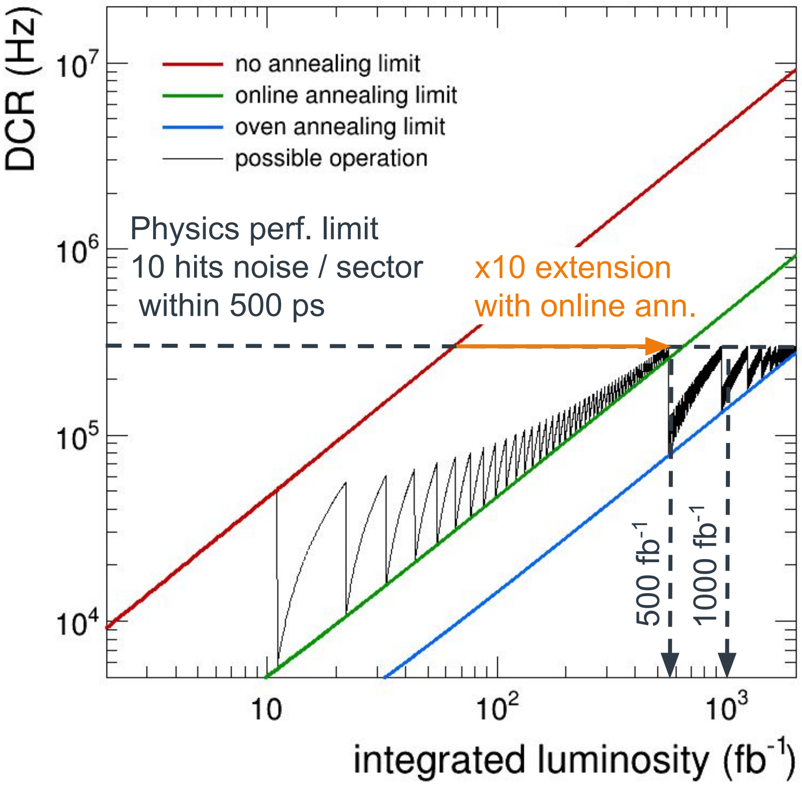


Damage recovery of SiPMs: multiple offline annealing



Damage recovery of SiPMs: multiple offline annealing

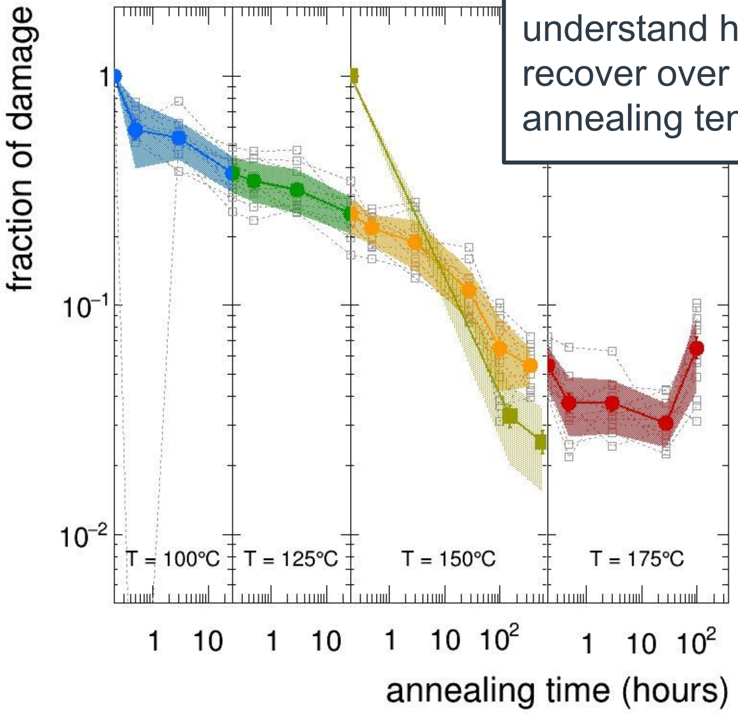




At the 500 fb^{-1} mark a more aggressive annealing is required (oven)

It makes it possible to stay within the limit with 1000 fb^{-1} luminosities

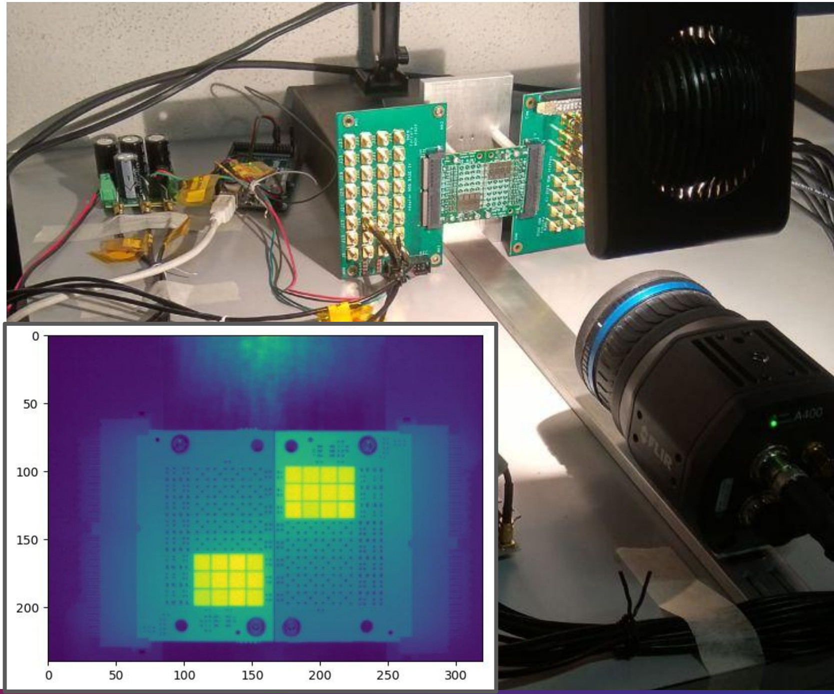
Damage recovery of SiPMs: self-annealing



We can take many measurements to understand how the damage recover over time and annealing temperature

New self-annealing station in Laboratory

Both direct and reverse polarisations possible

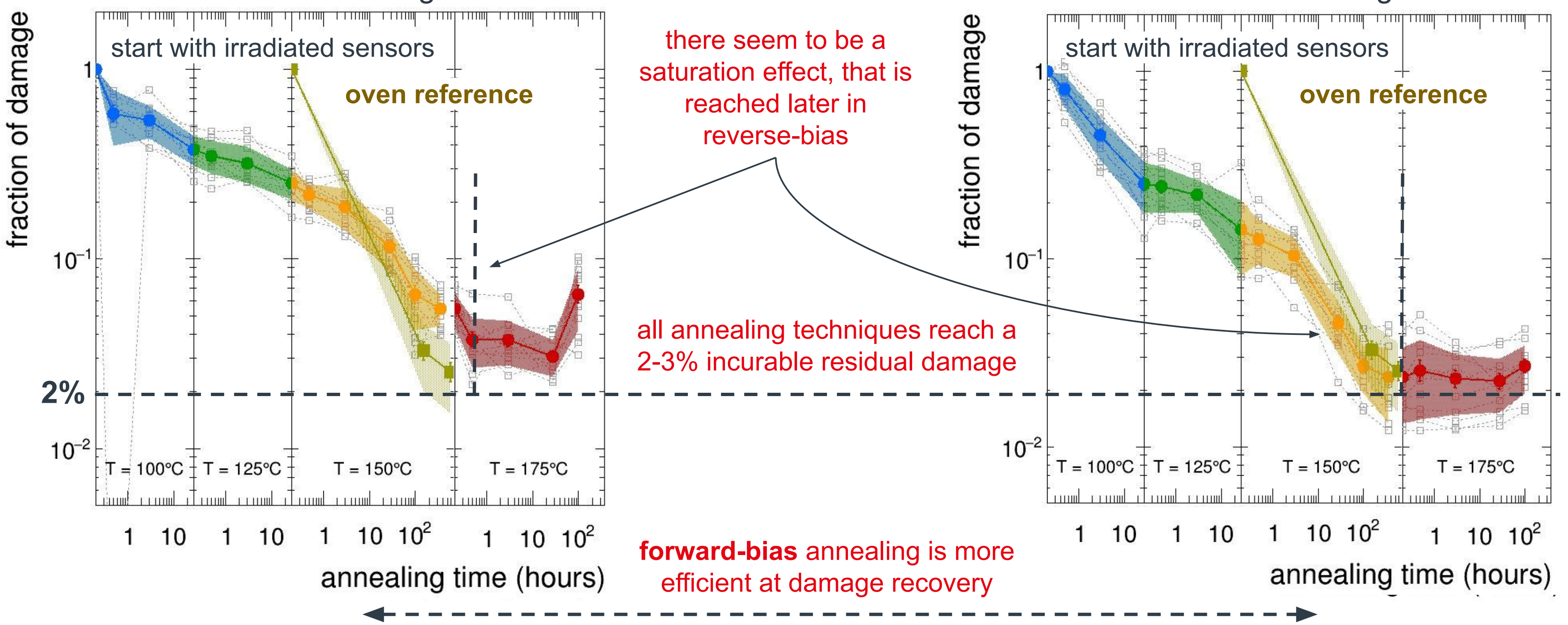


 nicola.rubini@bo.infn.it - Nicola Rubini

Damage recovery of SiPMs: self-annealing

light gray points are all sensors
coloured points are averaged over sensors
coloured area is the RMS

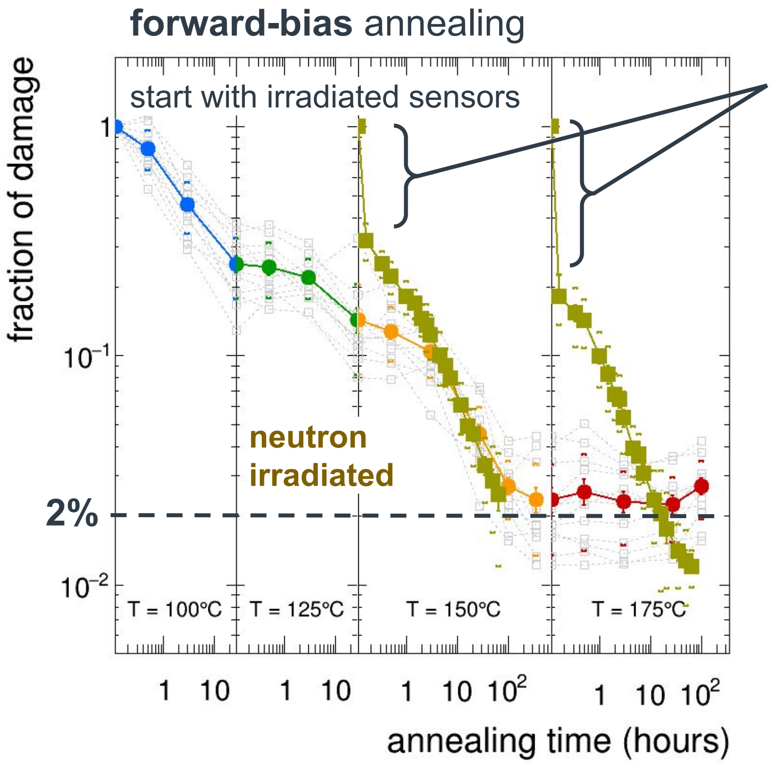
reverse-bias annealing | **forward-bias** annealing



forward-bias annealing is more efficient at damage recovery

Damage recovery of SiPMs: self-annealing

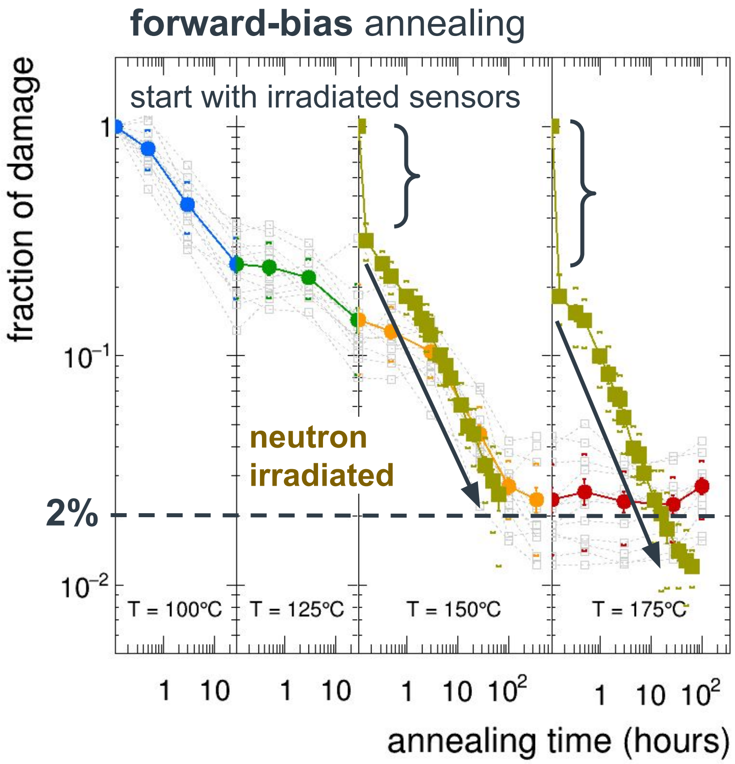
light gray points are all sensors
coloured points are averaged over sensors
coloured brackets is the RMS



Both annealing samples show a substantial recovery (70/80%) in a small time (10 min)

Damage recovery of SiPMs: self-annealing

light gray points are all sensors
coloured points are averaged over sensors
coloured brackets is the RMS

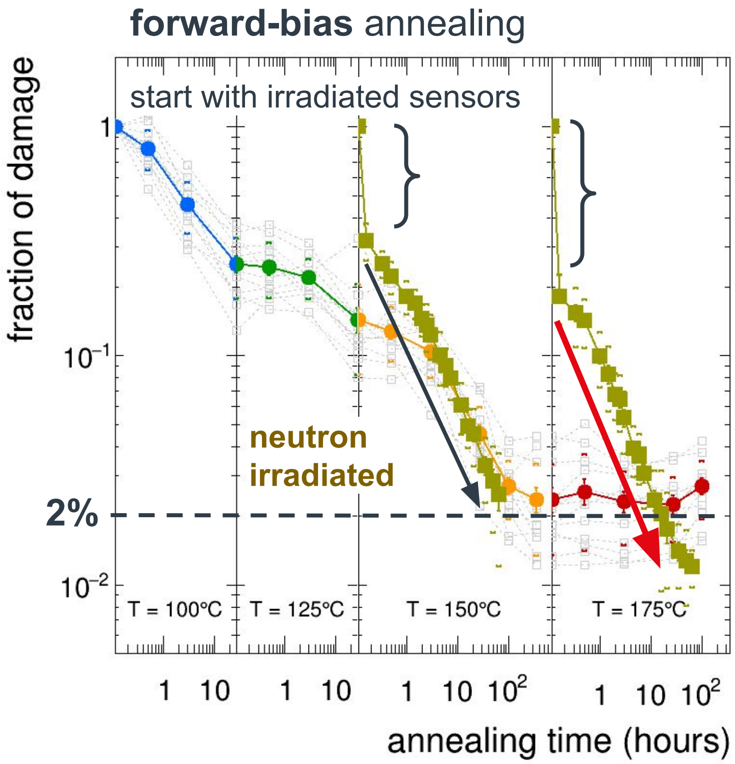


Both annealing samples show a substantial recovery (70/80%) in a small time (10 min)

Both are followed by a slow rate of recovery, in the case of the 150° C curve the trend is compatible with the proton result

Damage recovery of SiPMs: self-annealing

light gray points are all sensors
coloured points are averaged over sensors
coloured brackets is the RMS



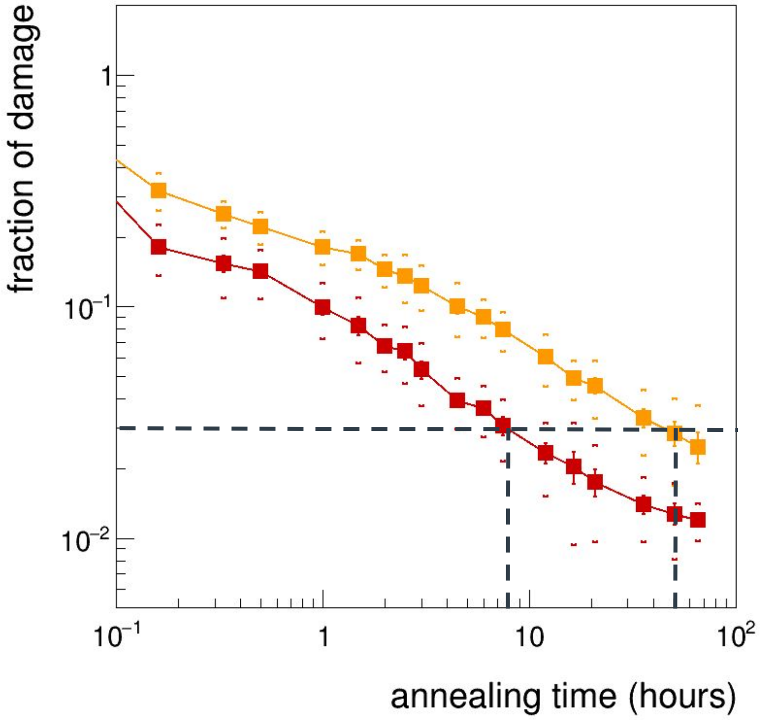
Both annealing samples show a substantial recovery (70/80%) in a small time (10 min)

Both are followed by a slow rate of recovery, in the case of the 150° C curve the trend is compatible with the proton result

The 175° C curve seem to cure more damage than the previously thought plateau

Damage recovery of SiPMs: self-annealing

forward-bias annealing



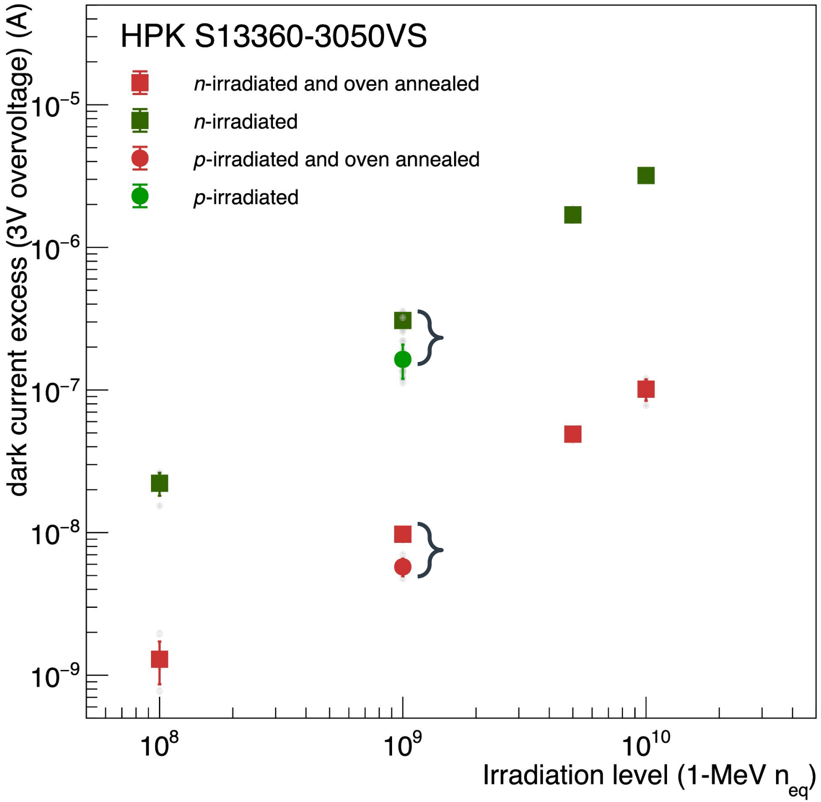
Both annealing samples show a substantial recovery (70/80%) in a small time (10 min)

Both are followed by a slow rate of recovery, in the case of the 150°C curve the trend is compatible with the proton result

The 175° C curve seem to cure more damage than the previously thought plateau

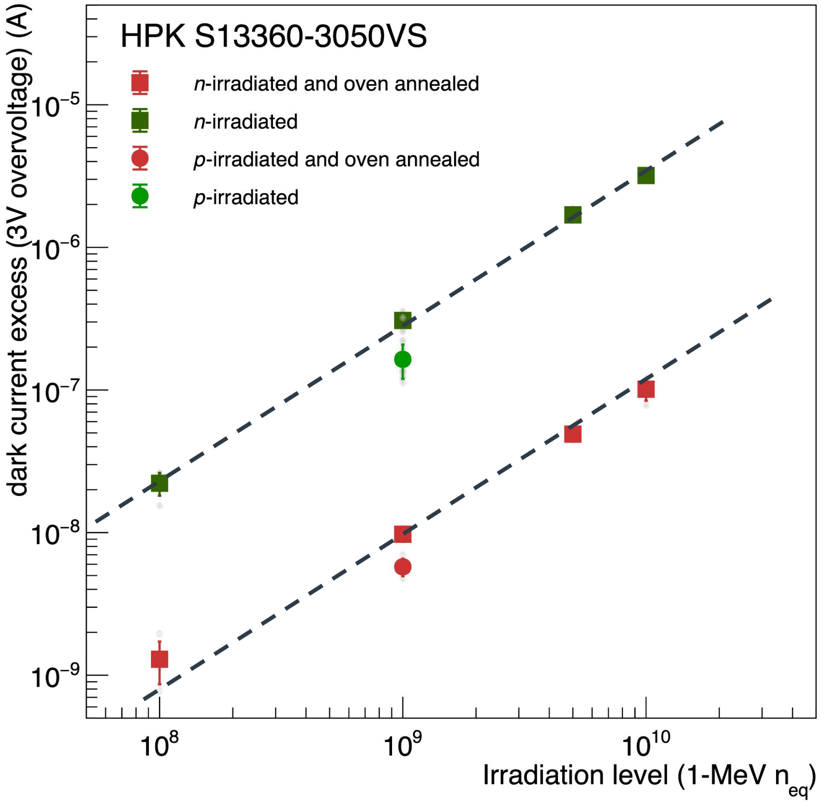
The 175° C curve is much faster than the 150° C in reaching 3% residual damage: a factor 6 in time!

Damage recovery of SiPMs: *p* and *n*



A bit of care needs to be put in interpreting the results of the neutrons as a factor 2 in damage has been found between, using NIEL scaling normalisation

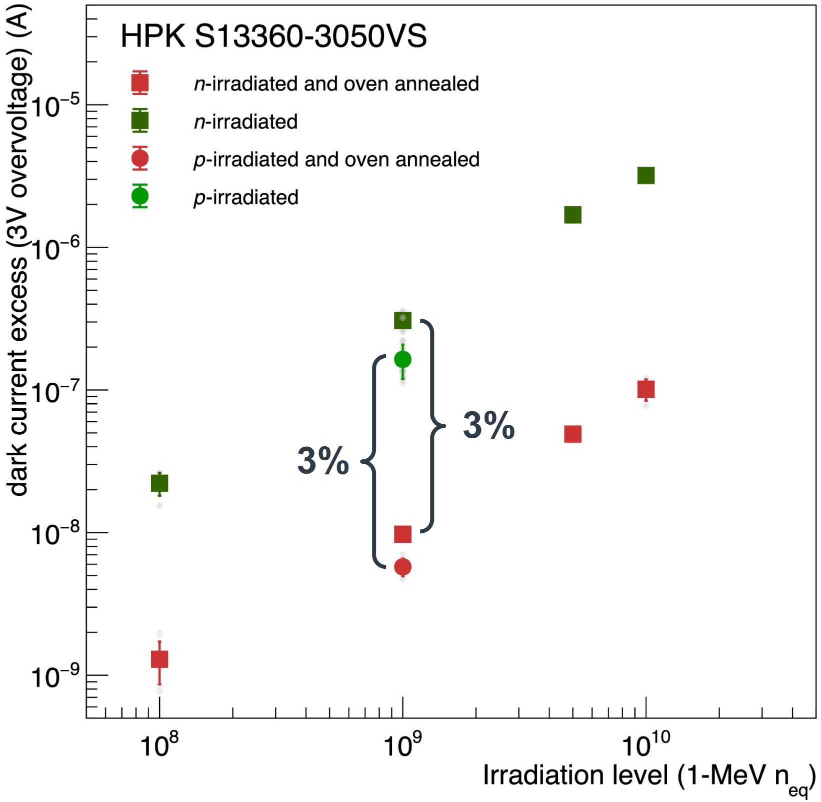
Damage recovery of SiPMs: *p* and *n*



A bit a care needs to be put in interpreting the results of the neutrons as a factor 2 in damage has been found between, using NIEL scaling normalisation

The damage is linear with n_{eq} fluence

Damage recovery of SiPMs: *p* and *n*



A bit a care needs to be put in interpreting the results of the neutrons as a factor 2 in damage has been found between, using NIEL scaling normalisation

The damage is linear with n_{eq} fluence

The recovery after 150 h of oven at 150 C is the same for both neutron- and proton-irradiated sensors

nicola.rubini@bo.infn.it - Nicola Rubini

ALCOR ASIC as front-end

developed by INFN Torino, 64-matrix mixed signal

The chip takes care of:

- Signal amplification
- Conditioning and event digitisation

Each pixel features:

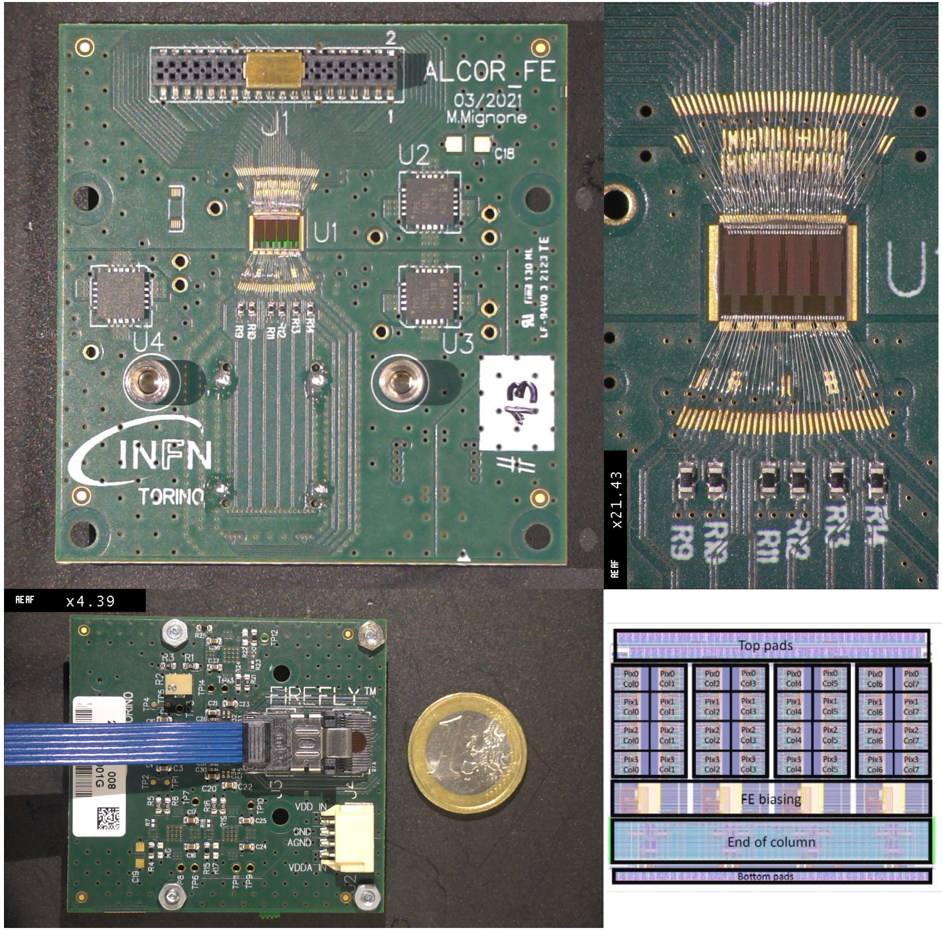
- 2 leading-edge discriminators
- 4 TDCs w/ analog interpolation
  - 20 or 40ps LSB @394MHz
- Digital shutter to allow TDC digitisation
  - Suppress out-of-gate DCR hits
  - 1 - 2ns timing window
  - programmable delay, sub ns accuracy

Single photon time-tagging mode:

- continuous readout
- possible time-over-threshold mode

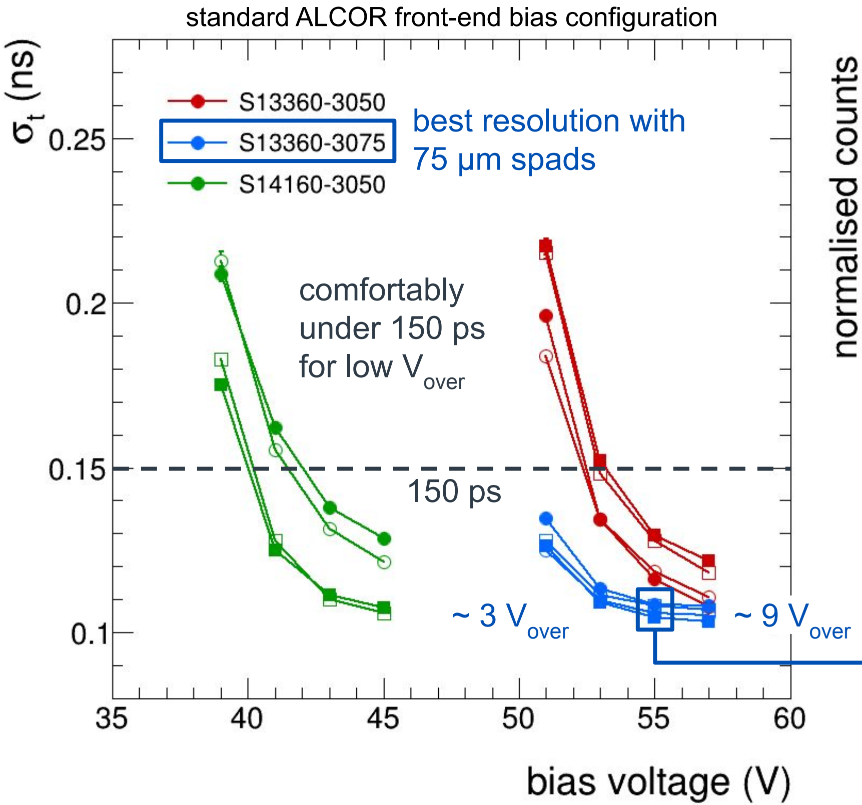
Fully digital output:

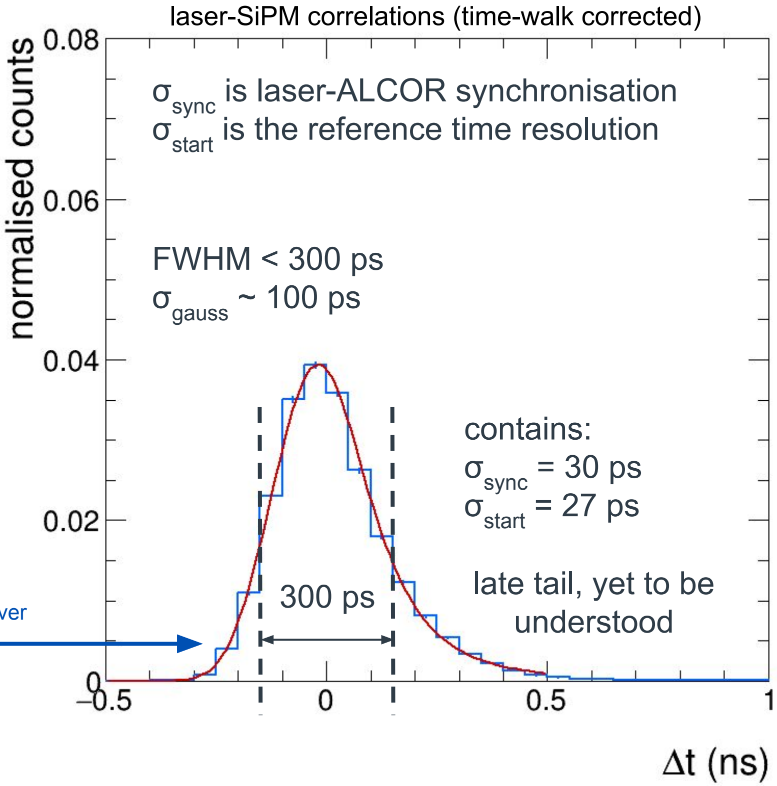
- 8LVDS TX Data Links



nicola.rubini@bo.infn.it - Nicola Rubini

Laser timing w/ ALCOR



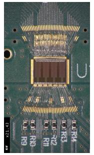


nicola.rubini@bo.infn.it - Nicola Rubini

Photodetector unit

conceptual design

ALCOR ASIC



SiPMs

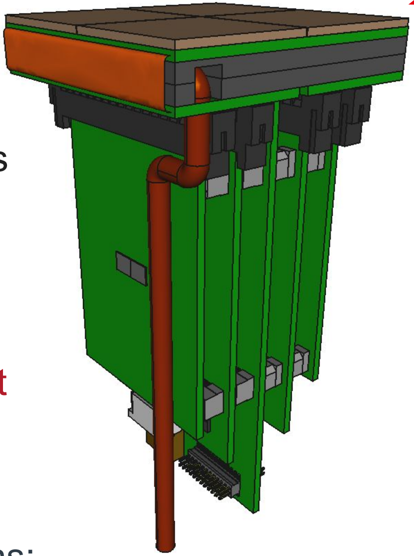
flex PCB

back-side connectors

front-end board

Water heat exchange

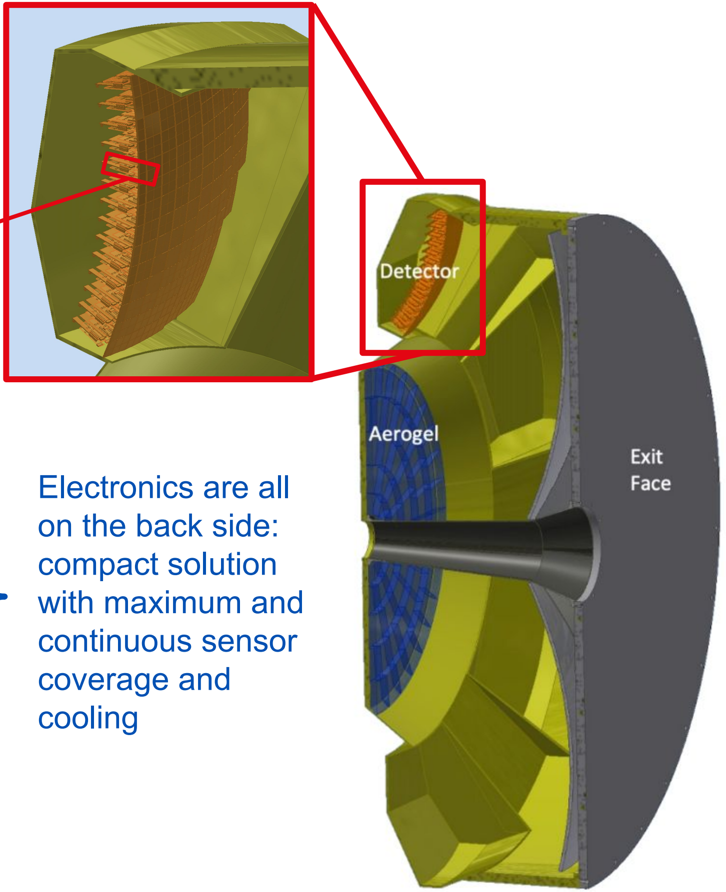
Services connections: LV, HV, DAQ



cold plate

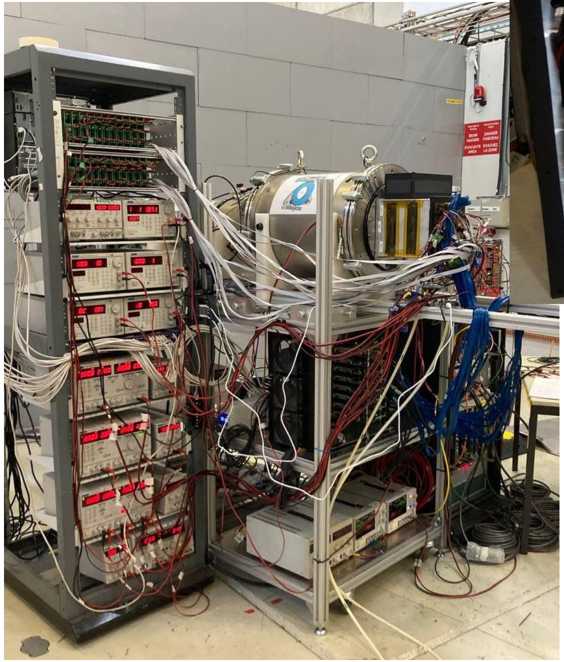
~ 15-20 cm

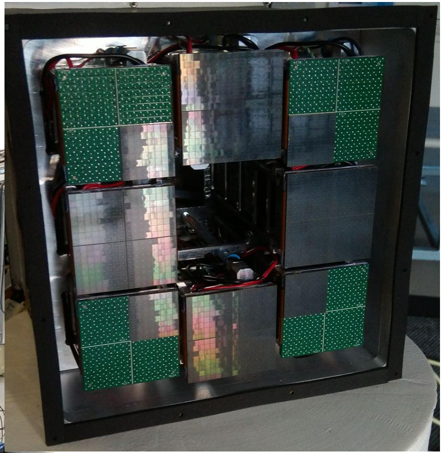
Electronics are all on the back side: compact solution with maximum and continuous sensor coverage and cooling

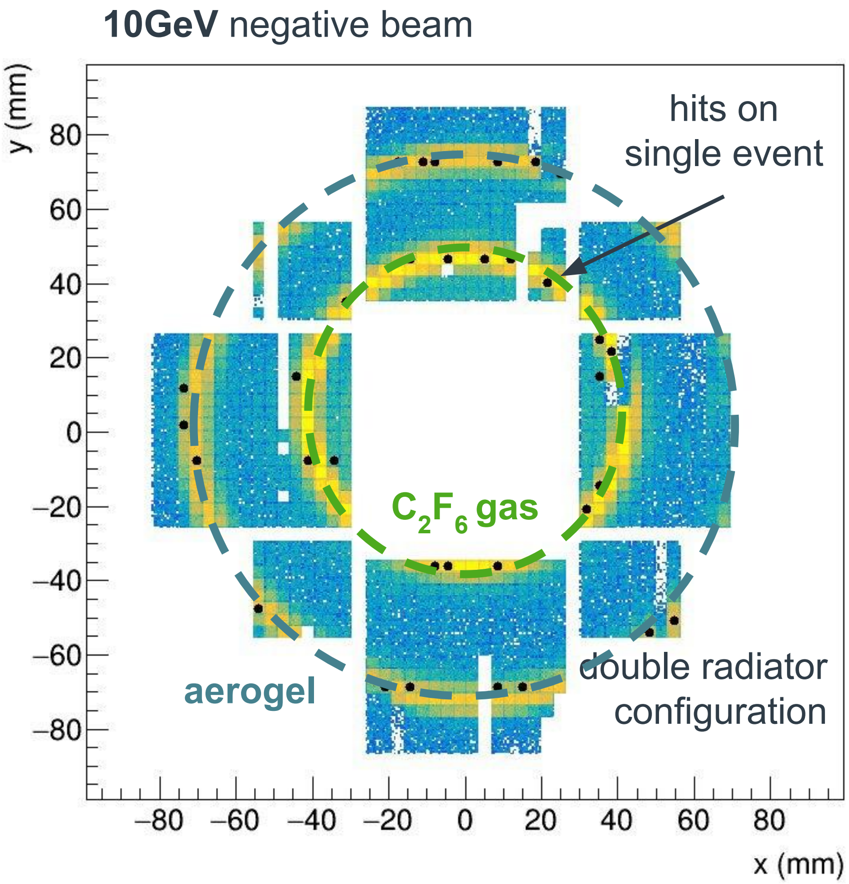


nicola.rubini@bo.infn.it - Nicola Rubini

2023 Test beam at CERN-PS







nicola.rubini@bo.infn.it - Nicola Rubini

Summary

SiPMs in ePIC-dRICH detector

- magnetic field limitations
- excellent timing and efficiency

Mitigation of the radiation damage

- low temperature operation
- online “in-situ” self-annealing
- they can extend lifetime of good detector performance for Physics

Full readout chain tested

- based on ALCOR ASIC
- successful beam test at CERN-PS in 2023
- 1-pe time resolution approaching 100 ps
- best candidate are the 75μm

What’s next

R&D and optimisation for the TDR

- new hamamatsu prototypes under scrutiny, together with possible FBK developments
- ALCOR-v3 optimisation and packaging

Thank you!

nicola.rubini@bo.infn.it - Nicola Rubini