SiPM readout plane for the ePIC dual-radiator RICH at the EIC

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PD24
The 6th International Workshop on new Photon-Detectors
19 – 21 November 2024, Vancouver

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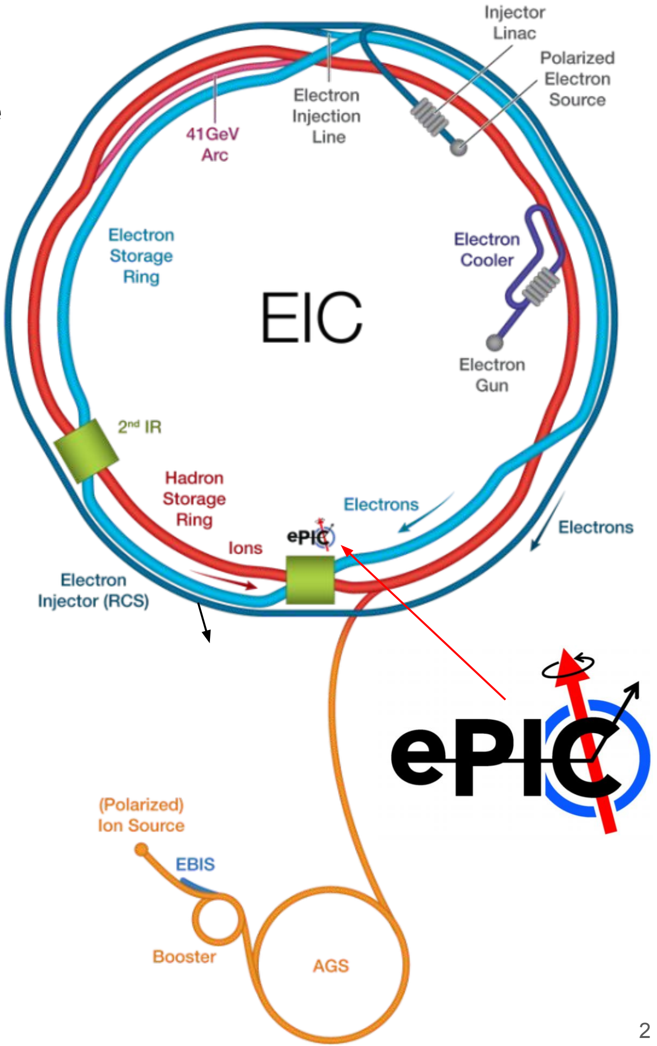
The Electron-Ion Collider

a machine that will unlock the secrets of the strongest force in Nature
is a future electron-proton and electron-ion collider at BNL (USA)
foreseen to start operation in early 2030’s

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

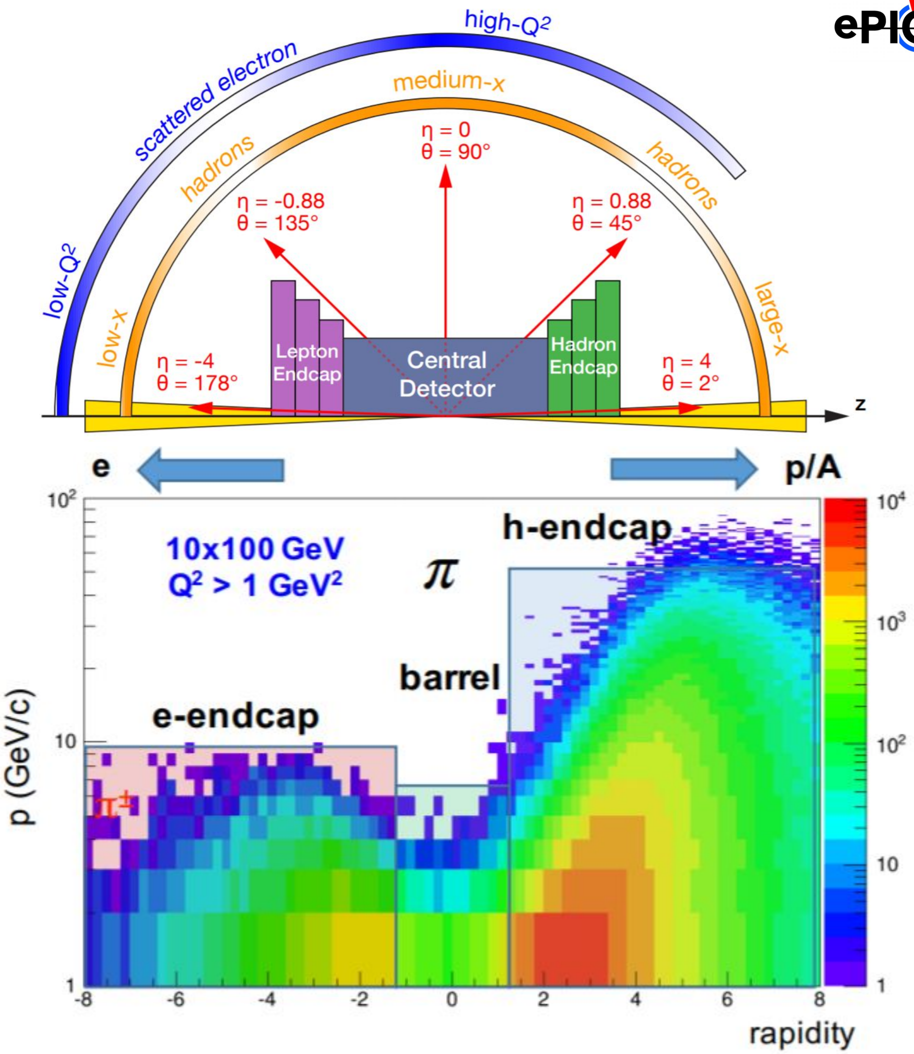


www.bnl.gov/eic

Particle identification at the EIC

one of the major challenges for the detector

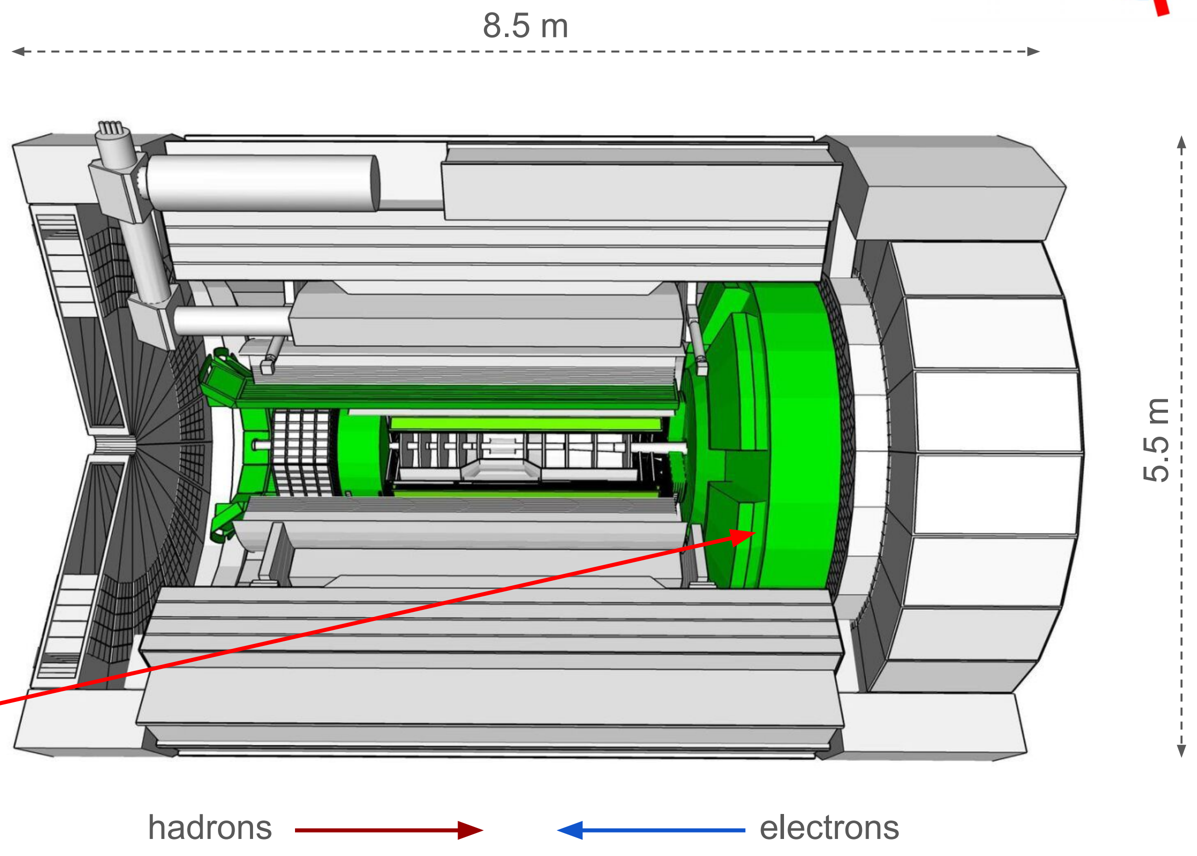
- **physics requirements**
  - pion, kaon and proton ID
  - over a wide range $|\eta| \leq 3.5$
  - with better than 3σ separation
  - significant pion/electron suppression
- **momentum-rapidity coverage**
  - forward: up to 50 GeV/c
  - central: up to 6 GeV/c
  - backward: up to 10 GeV/c
- **demands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



The ePIC experiment

layout of the barrel detector

- **tracking**
  - new 1.7 T magnet
  - Si-MAPS + MPGDs
- **calorimetry**
  - e-side: $PbWO_4$ EMCal
  - barrel: imaging EMCal
  - h-side: finely segmented
  - outer barrel HCal
- **particle ID**
  - AC-LGAD TOF
  - pfRICH
  - hpDIRC
  - **dRICH**

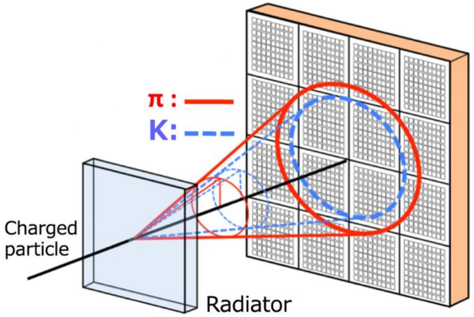


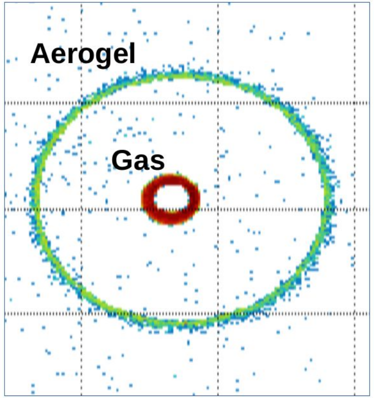
The dual-radiator (dRICH) for forward PID at EIC

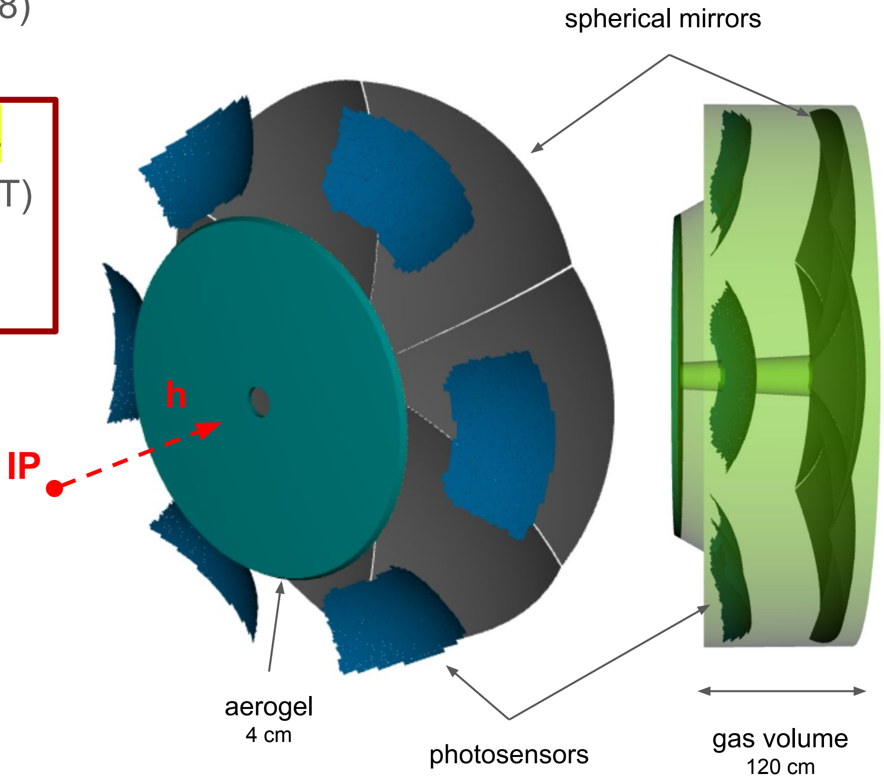
compact and cost-effective solution for broad momentum coverage at forward rapidity

p = [3.0, 50] GeV/c
η = [1.5, 3.5]
e-ID up to 15 GeV/c

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

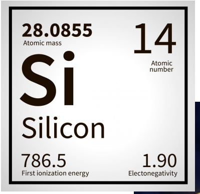






SiPM option and requirements for RICH optical readout

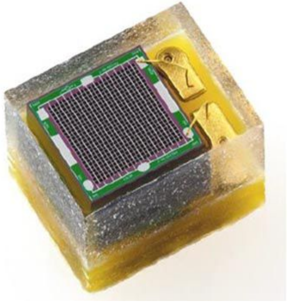
- **pros**
  - cheap
  - high photon efficiency
    requirement □
  - excellent time resolution
    requirement □
  - insensitive to magnetic field
    requirement □



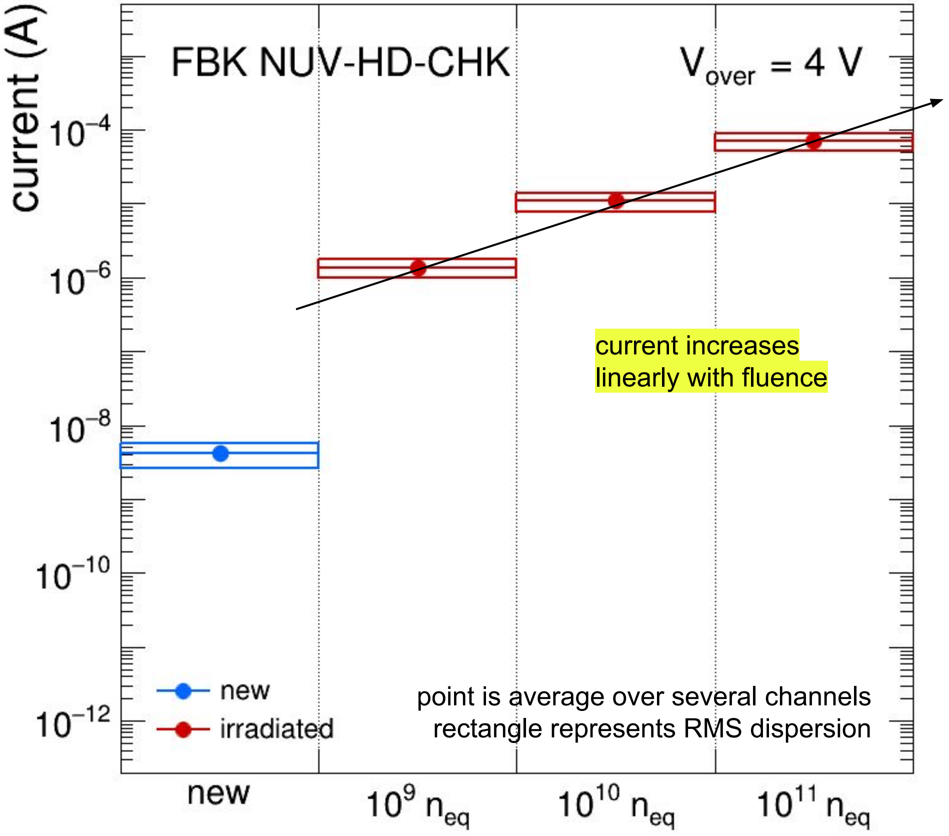
- **cons**

large dark count rates
not radiation tolerant

technical solutions and mitigation strategies
🐧 cooling
⌚ timing
🔥 annealing



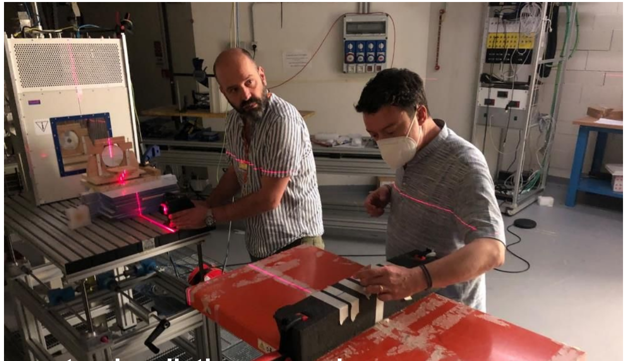
Studies of radiation damage on SiPM



current increases
linearly with fluence

point is average over several channels
rectangle represents RMS dispersion

all results are reported at T = -30 C

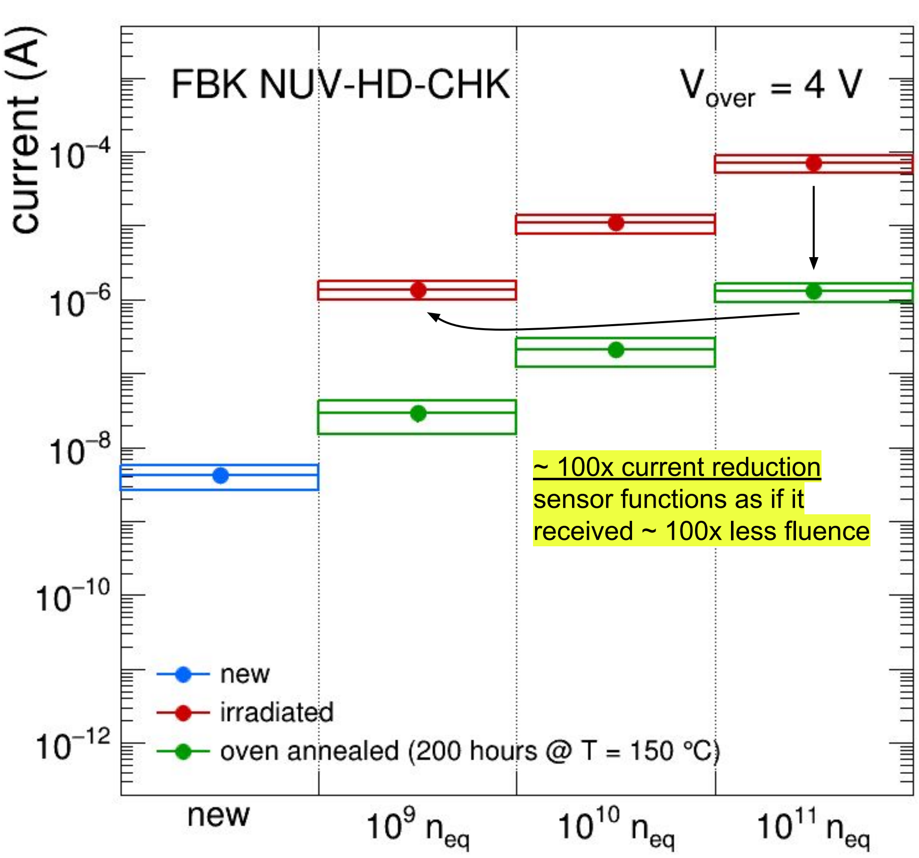


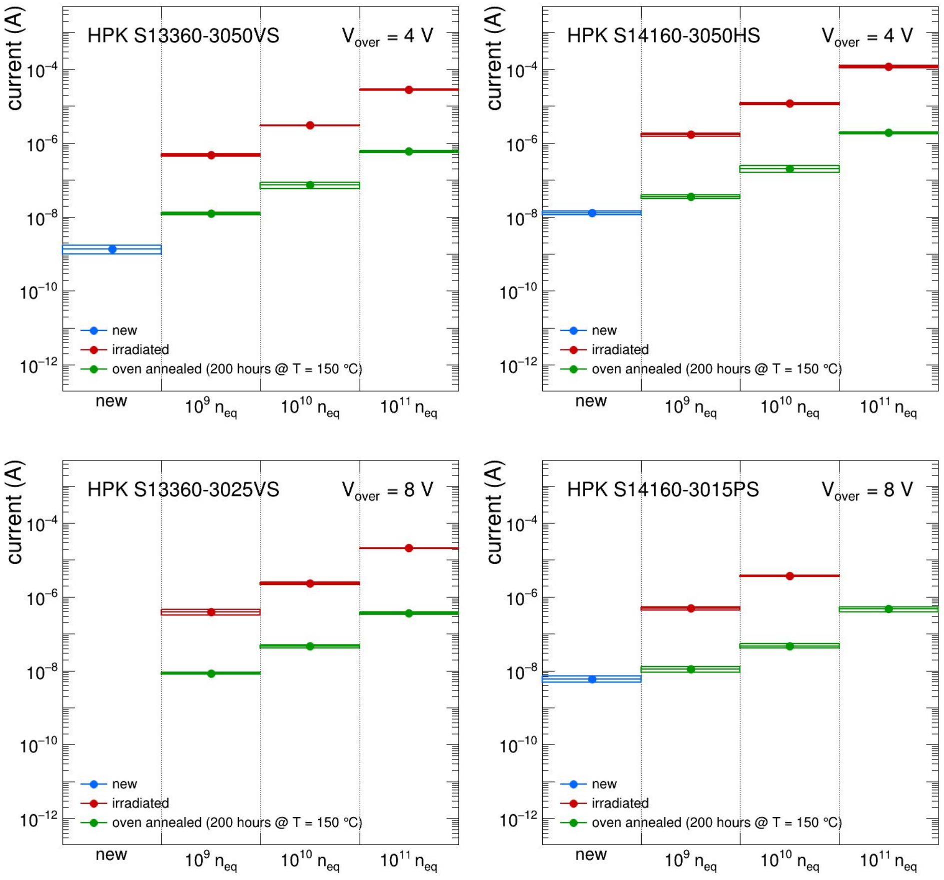
proton irradiation campaigns
in 2021, 2022, 2023 and 2024
neutron irradiation in 2023 and 2024

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

High-temperature annealing recovery

oven annealing
~ 1 week at 150 C



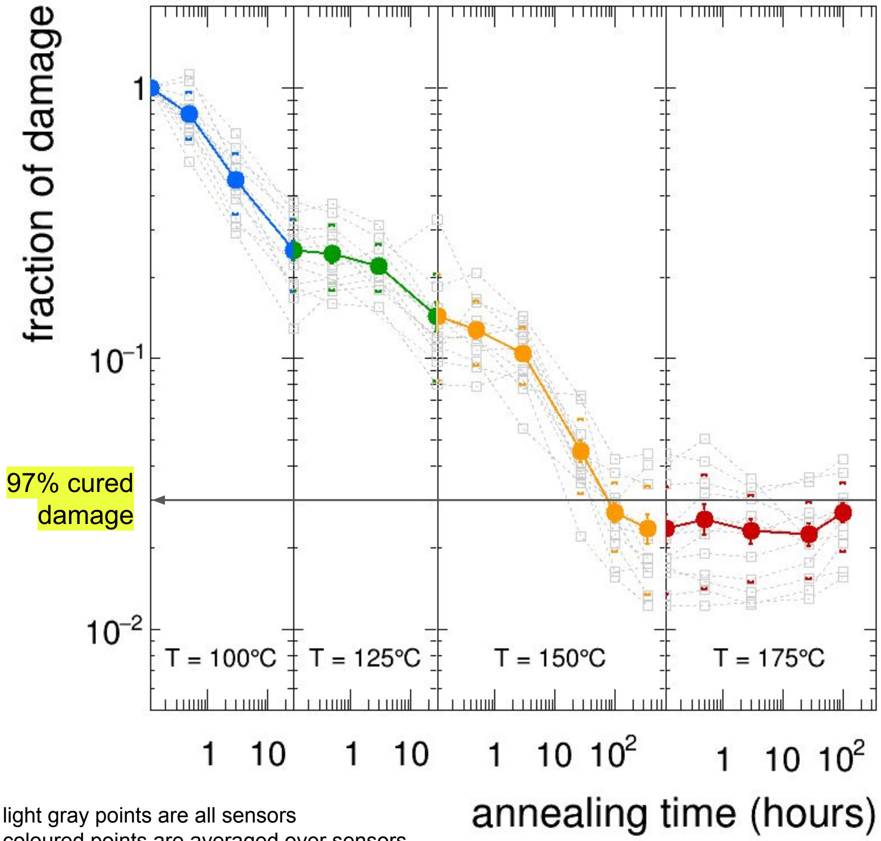


similar observation with various types of Hamamatsu sensors

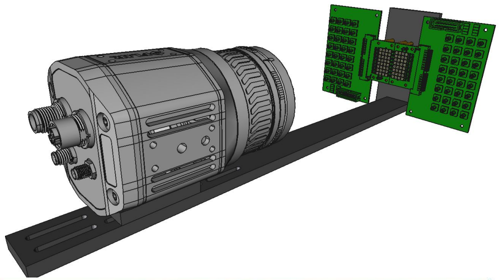
“Online” self-induced annealing

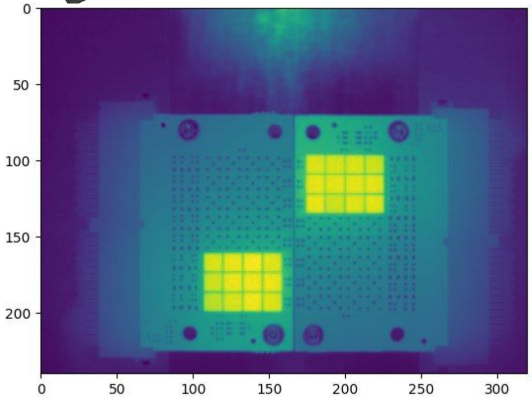
thermal studies for “in-situ” SiPM recovery
sensors heated with up to 1 W power/sensor

online self-annealing with forward bias



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





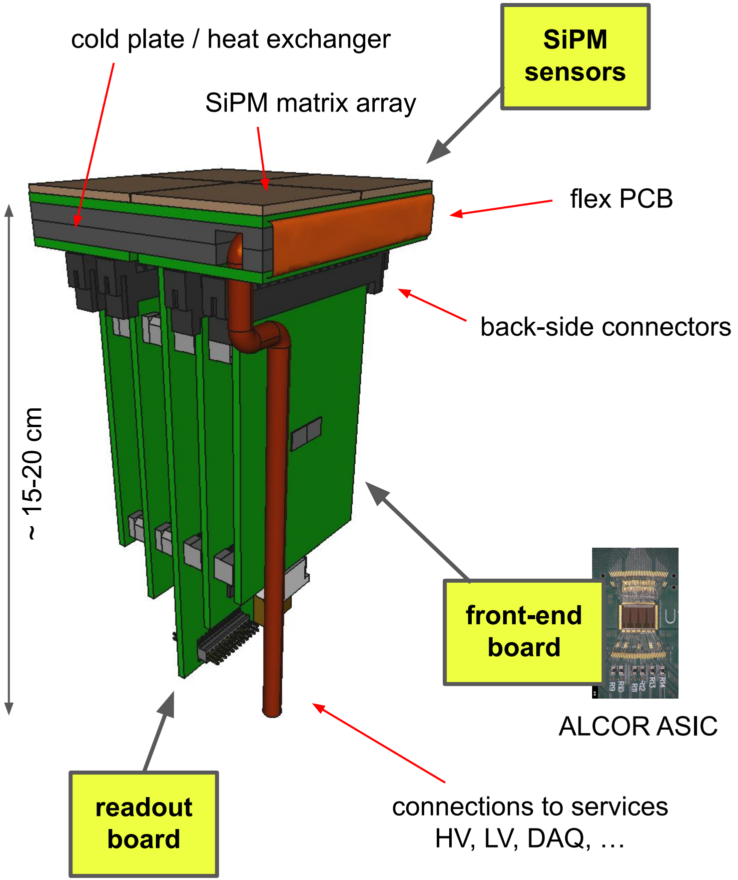
detailed studies on a large sample of sensors
how much damage is cured as a function of temperature and time

fraction of residual damage seems to saturate at 2-3% after ~ 300 hours at T = 150 C
continuing at higher T = 175 C seems not to help curing more

detector integration and electronics

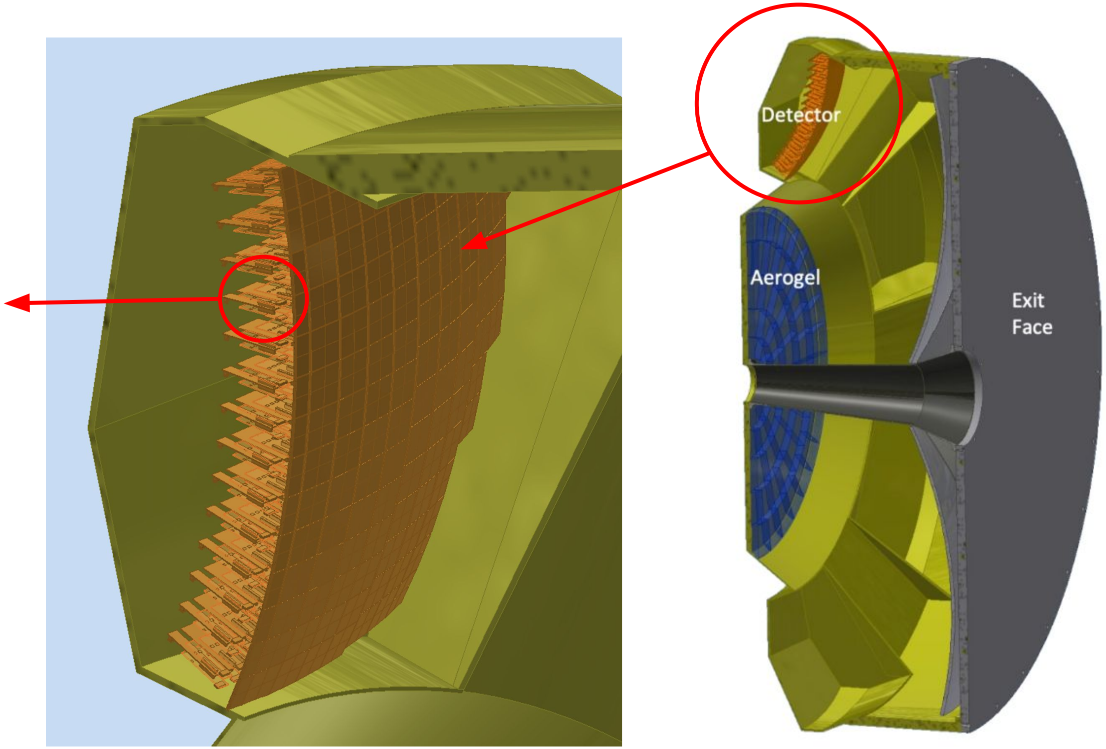
Photodetector unit

conceptual design of PDU layout

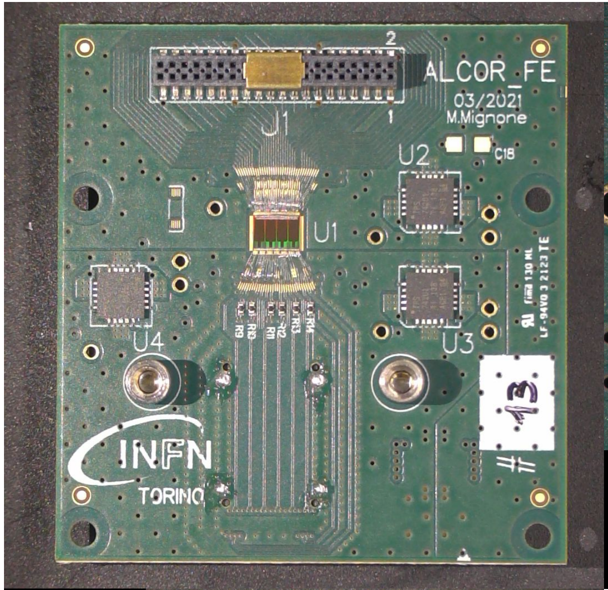


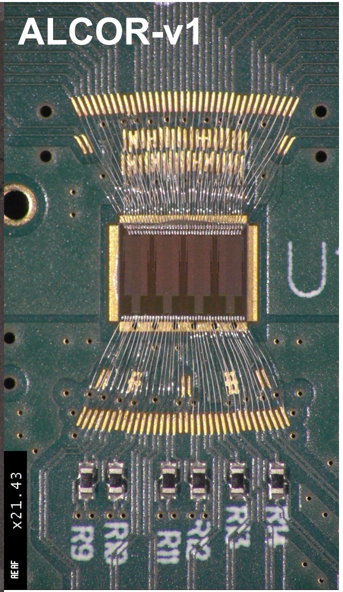
SiPM sensor matrices mounted on carrier PCB board

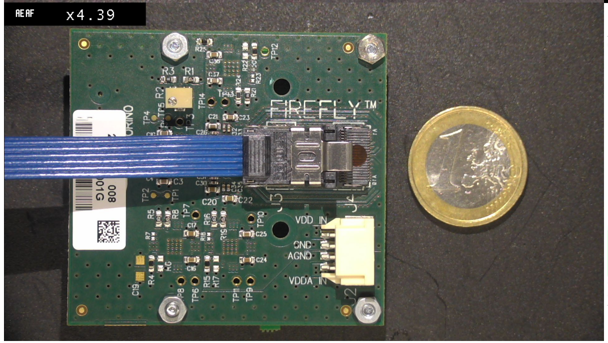
- 4x 64-channel SiPM array device (256 channels) for each unit
  - need modularity to realise curved readout surface
- 1248 photodetector units for full dRICH readout
  - 4992 SiPM matrix arrays (8x8)
  - 319488 readout channels

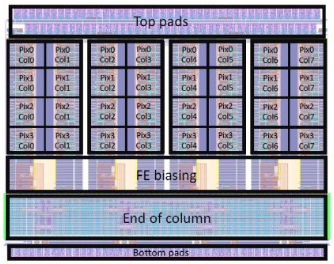


ALCOR ASIC: integrated front-end and TDC









developed by INFN-TO

64-pixel matrix mixed-signal ASIC

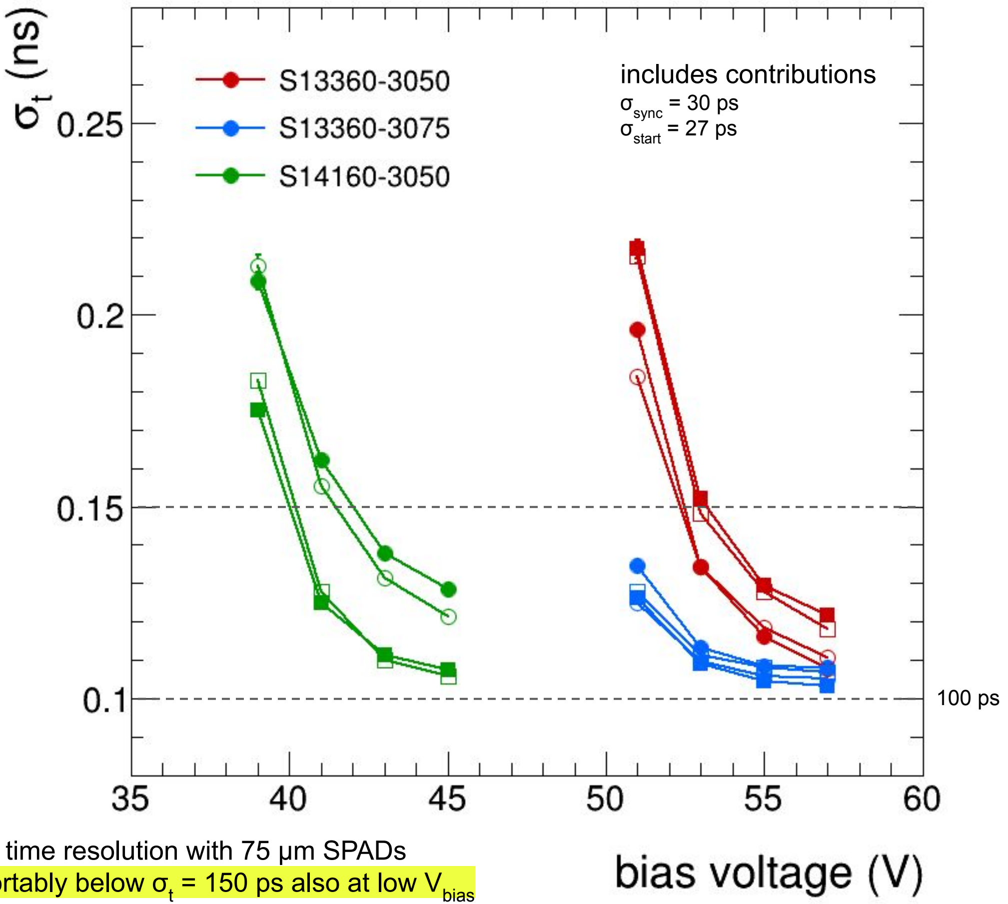
current versions (v1,v2,v2.1) have 32 channels, wirebonded

final version will have 64 channels, BGA package, 394.08 MHz clock

- **the chip performs**
  - signal amplification
  - conditioning and event digitisation
- **each pixel features**
  - 2 leading-edge discriminators
  - 4 TDCs based on analogue interpolation
    - 20 or 40 ps LSB (@ 394 MHz)
  - digital shutter to enable TDC digitisation
    - suppress out-of-gate DCR hits
    - 1-2 ns timing window
    - programmable delay, sub ns accuracy
- **single-photon time-tagging mode**
  - continuous readout
  - also with Time-Over-Threshold
- **fully digital output**
  - 8 LVDS TX data links

Timing performance measurements with ALCOR

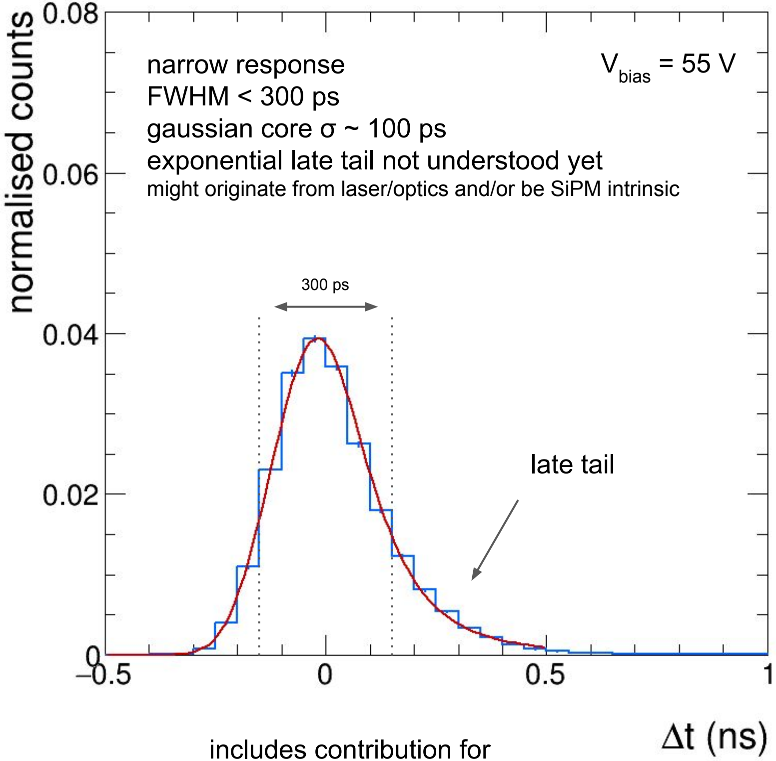
standard ALCOR front-end bias configuration



better time resolution with 75 μm SPADs

comfortably below σ_t = 150 ps also at low V_{bias}

laser-SiPM correlations (time-walk corrected)



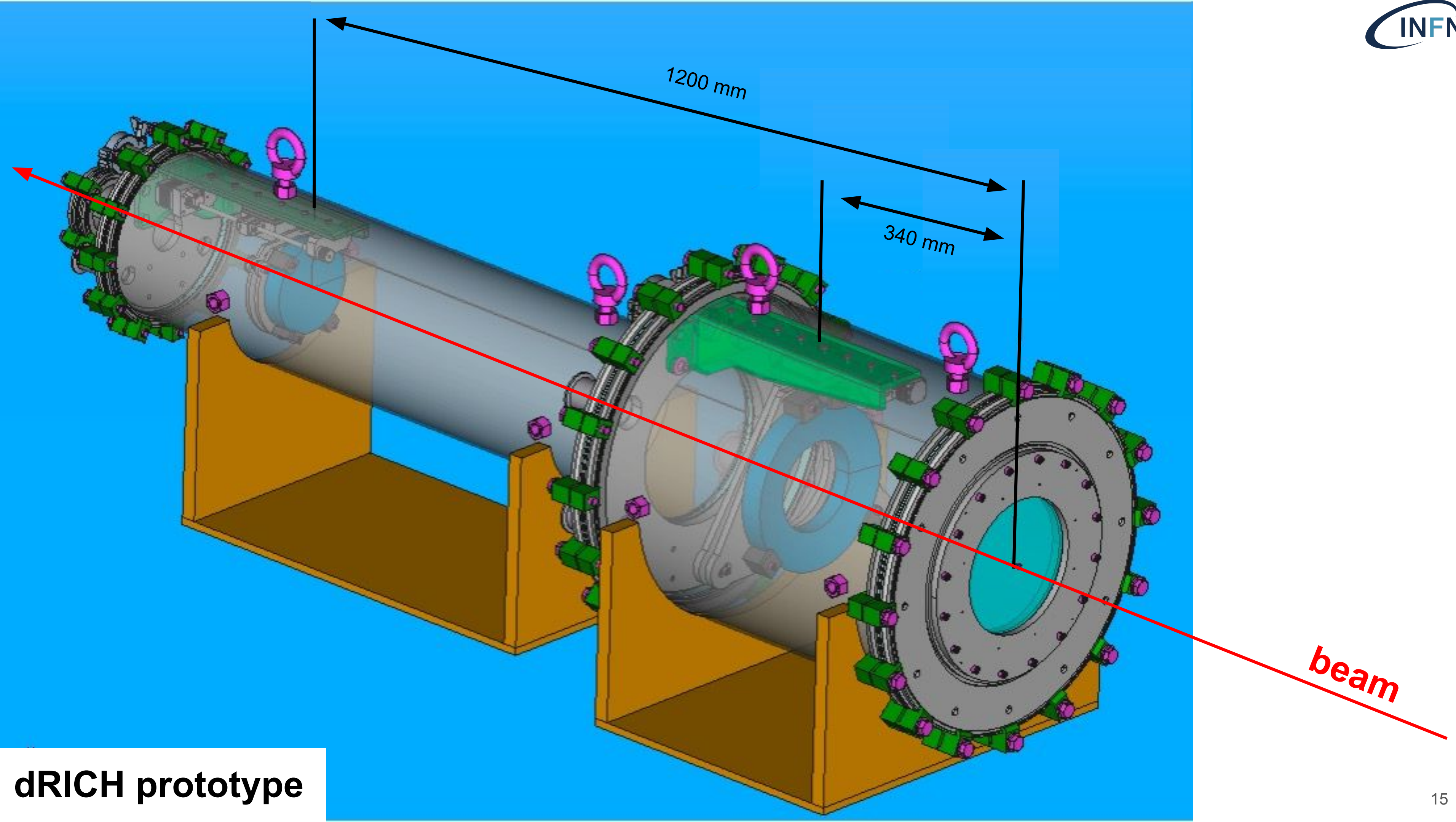
includes contribution for laser-ALCOR synchronization

measured to be σ_{sync} = 30 ps

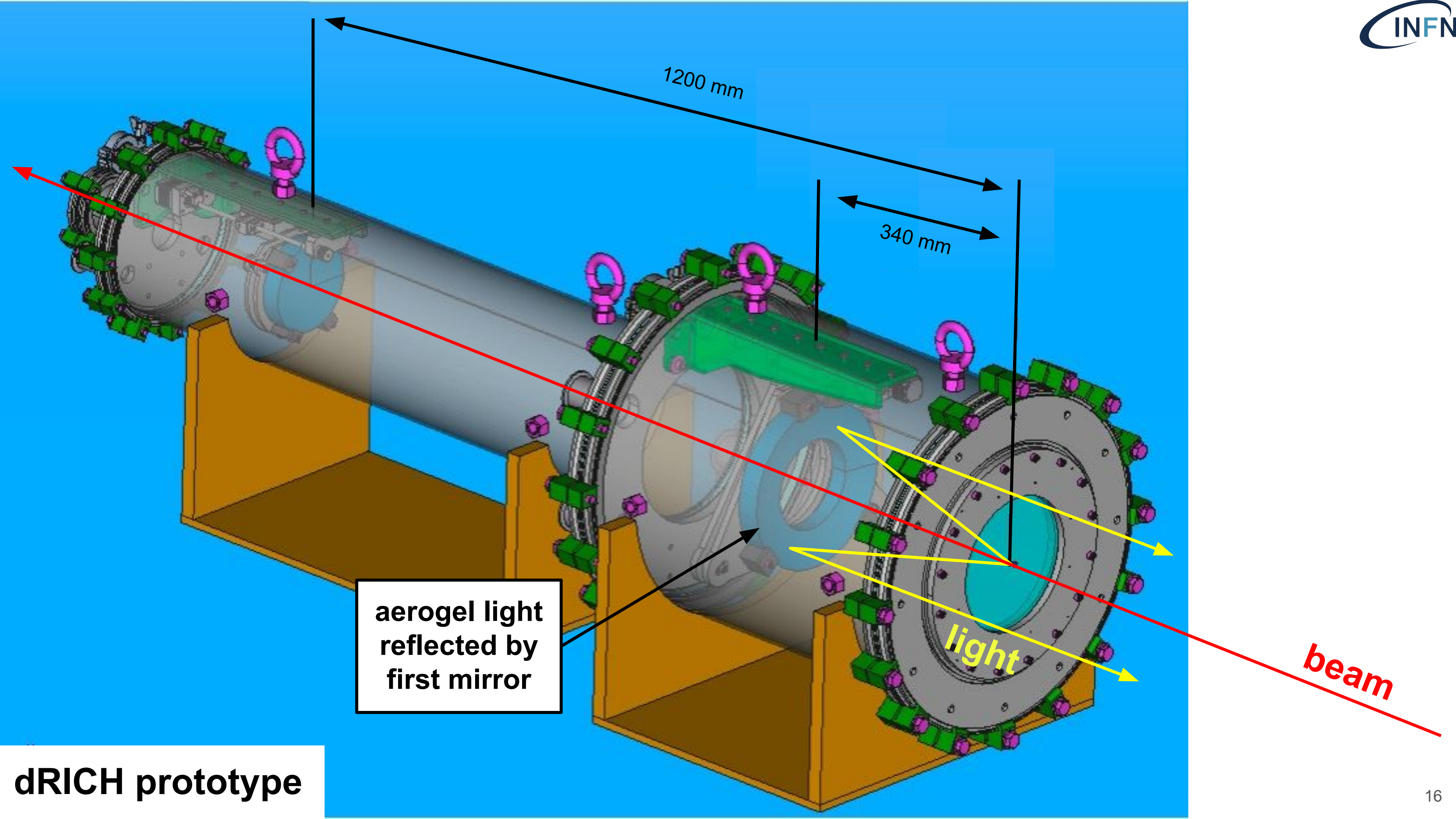
and reference time resolution

measured to be σ_{start} = 27 ps

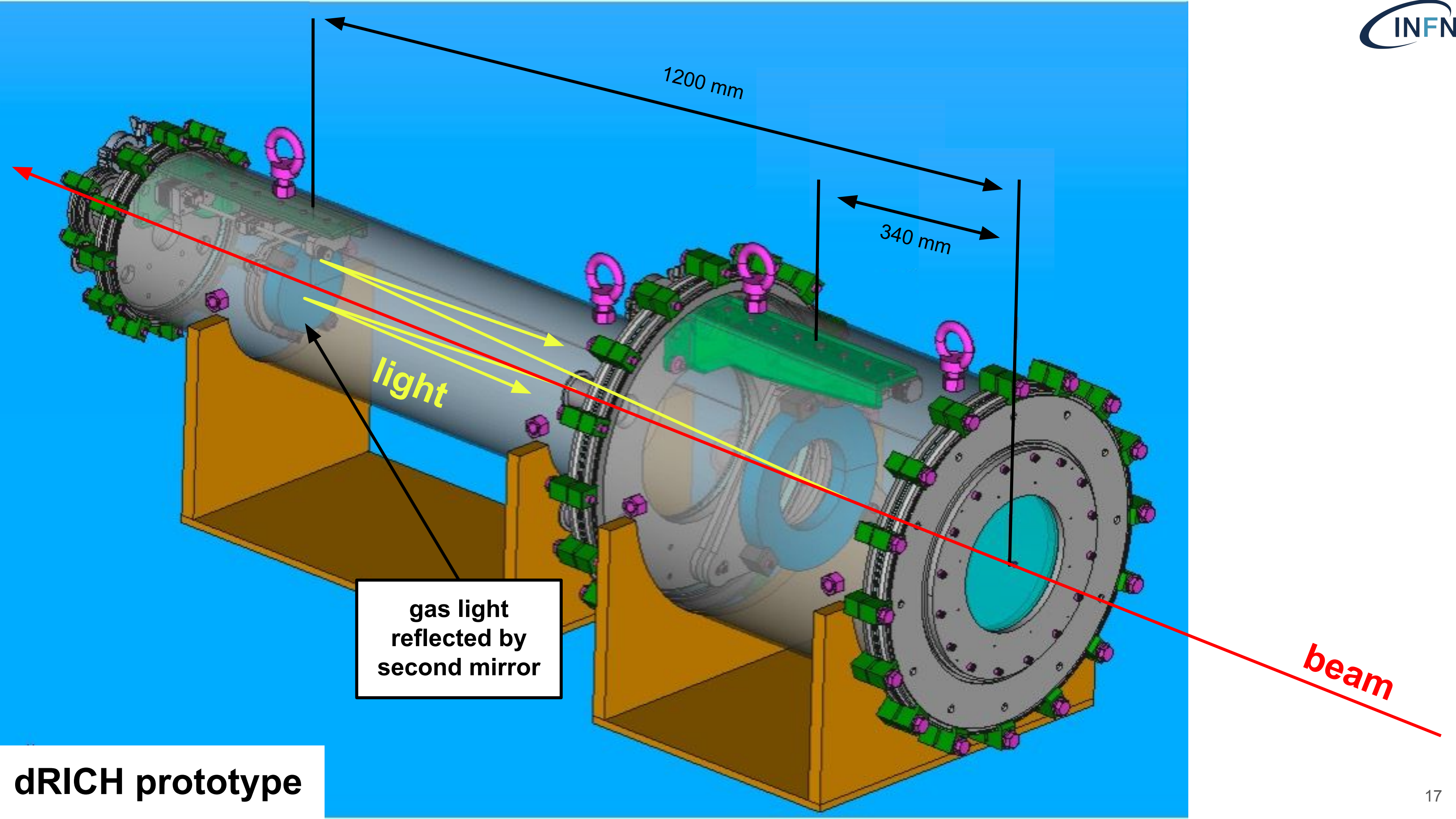
detector prototype and beam tests



dRICH prototype



dRICH prototype



dRICH prototype

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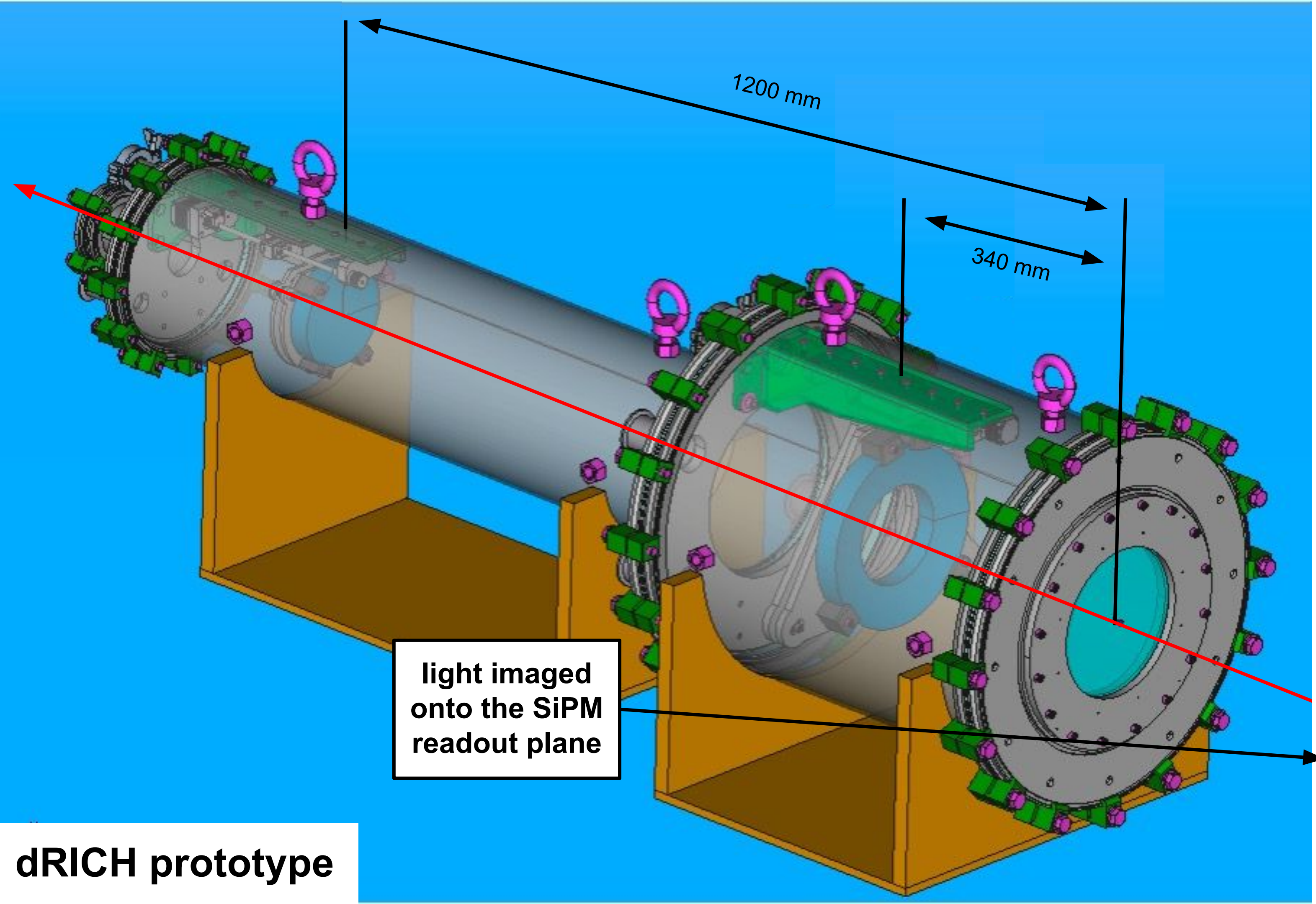
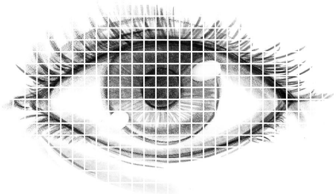
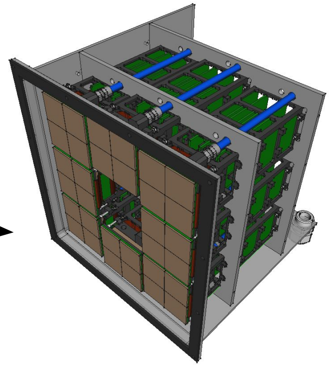






dRICH prototype on the T10 beam line at CERN-PS in October 2023

DAQ and DCS computers

auxiliary control electronics crates

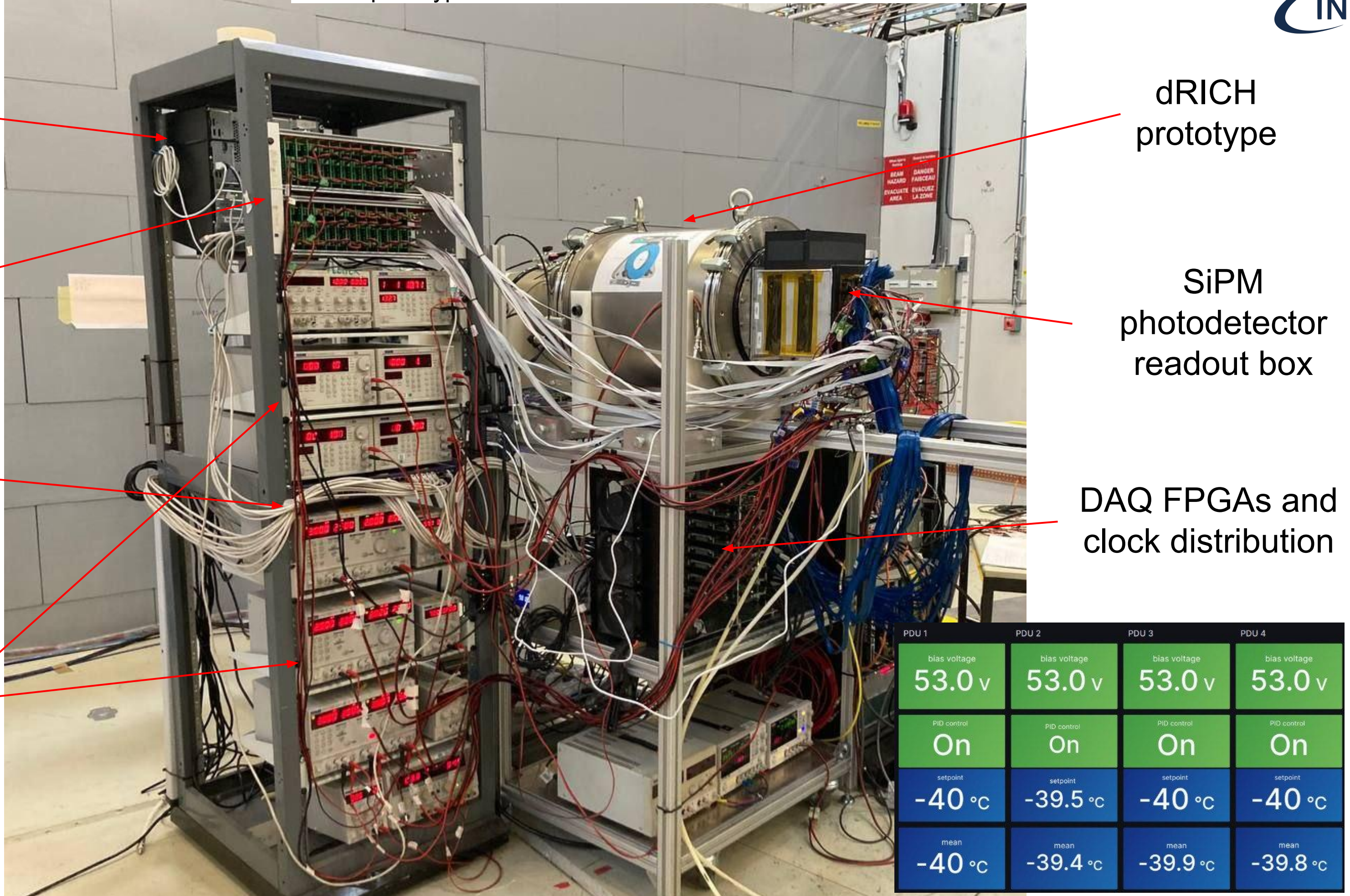
gigabit ETH switch for DAQ and DCS

low voltage and high voltage power supplies

dRICH prototype

SiPM photodetector readout box

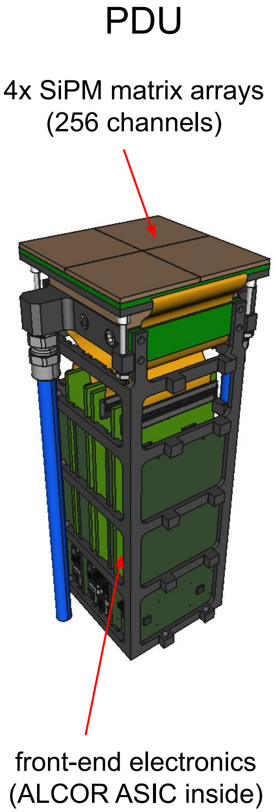
DAQ FPGAs and clock distribution

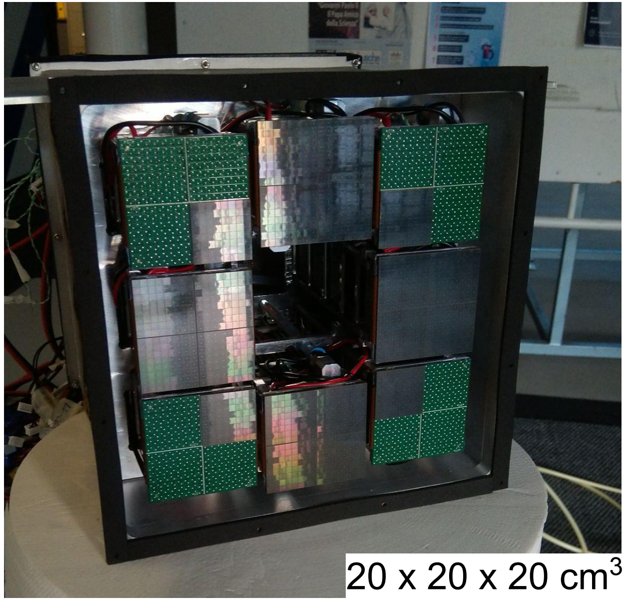


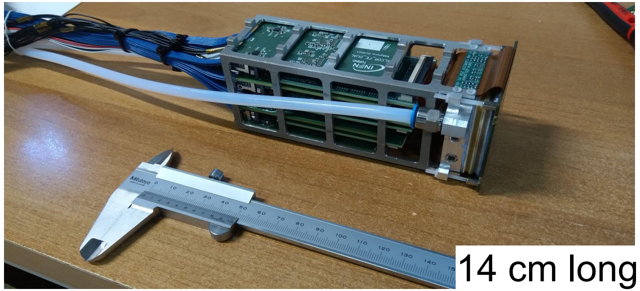
SiPM at low temperature

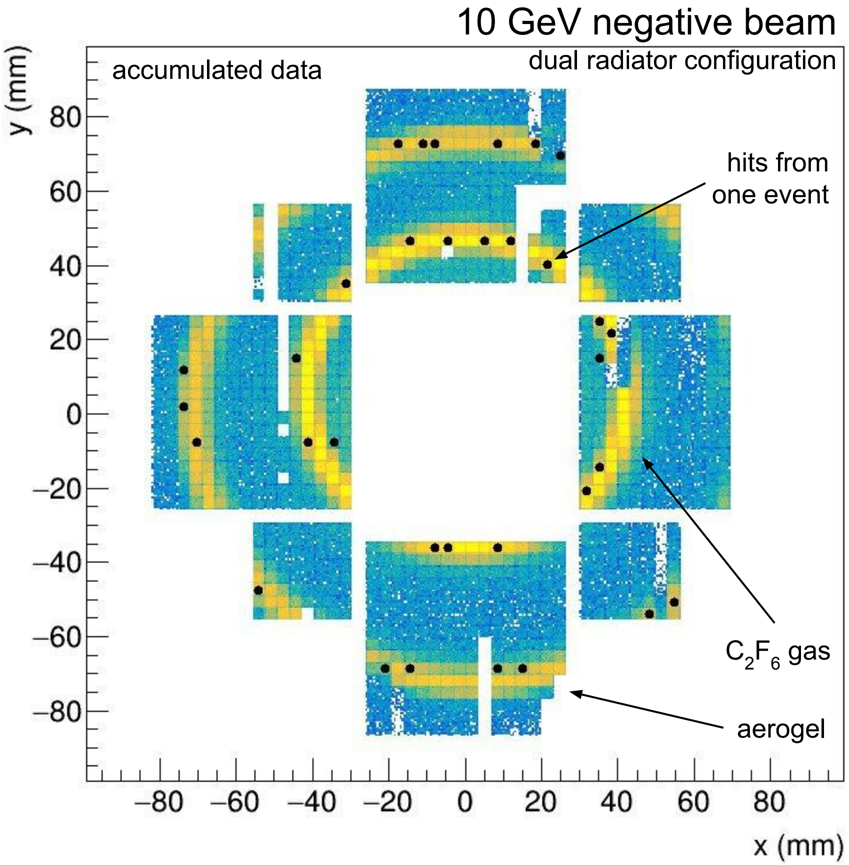
2023 test beam at CERN-PS

successful beam test with prototype SiPM photodetector units (CERN-PS, ended on 18th October)



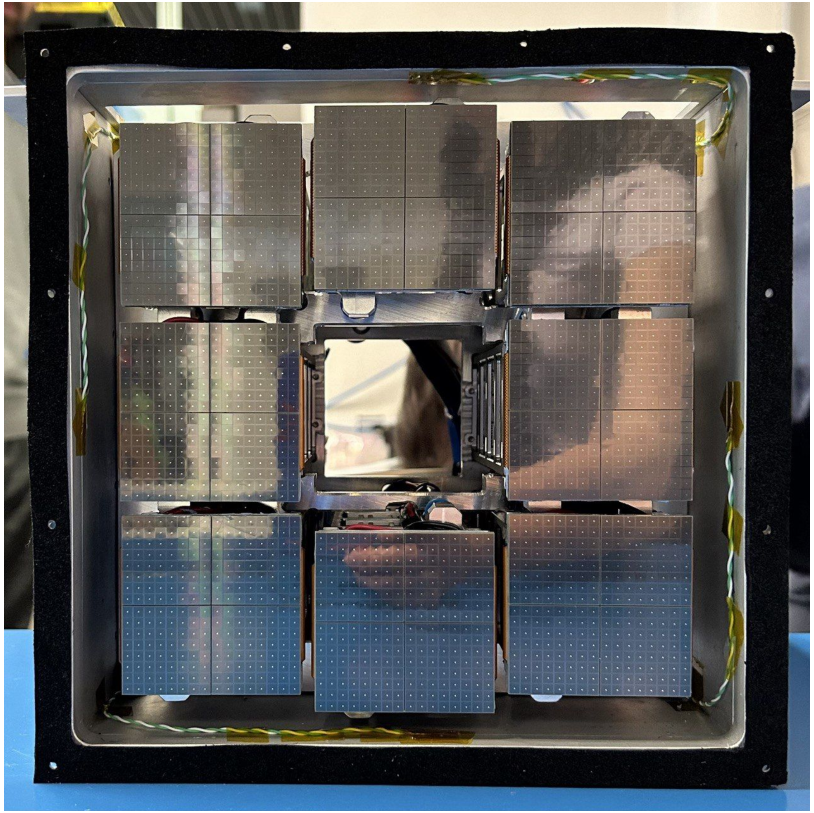


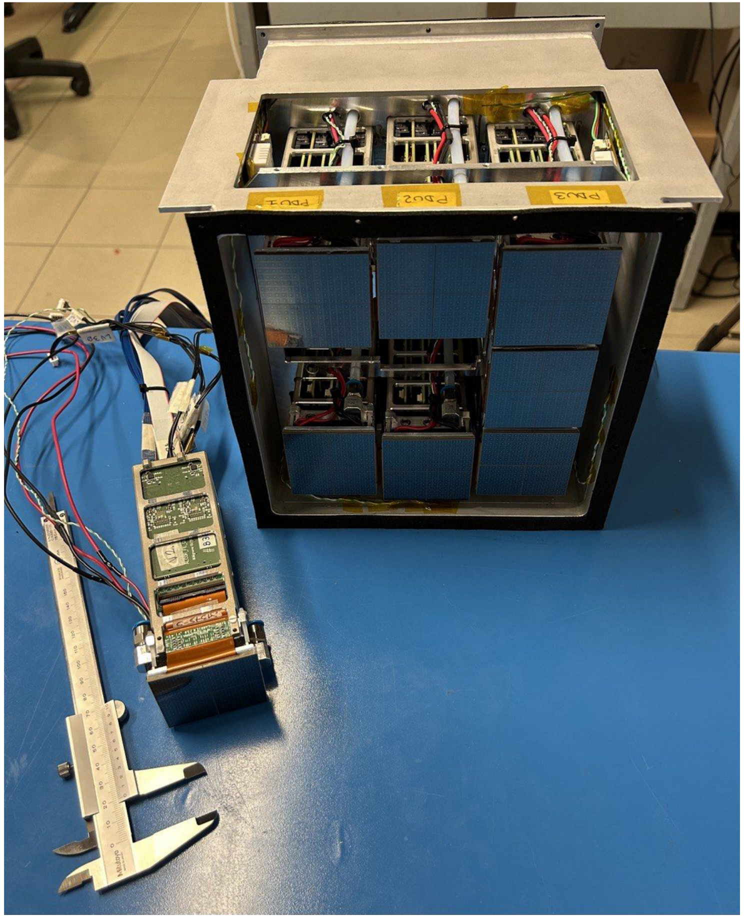




Upgraded in 2024 with 2k channels

Hamamatsu S13360-3050/3075 8x8 MPPC arrays





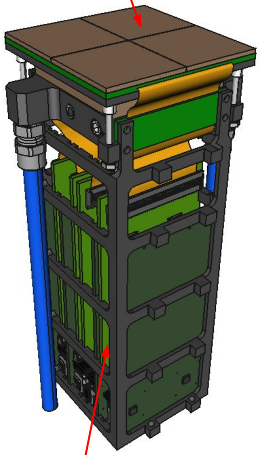
fully-equipped, 2048-channels SiPM readout surface with cooling and TDC electronics

2024 test beam at CERN-PS

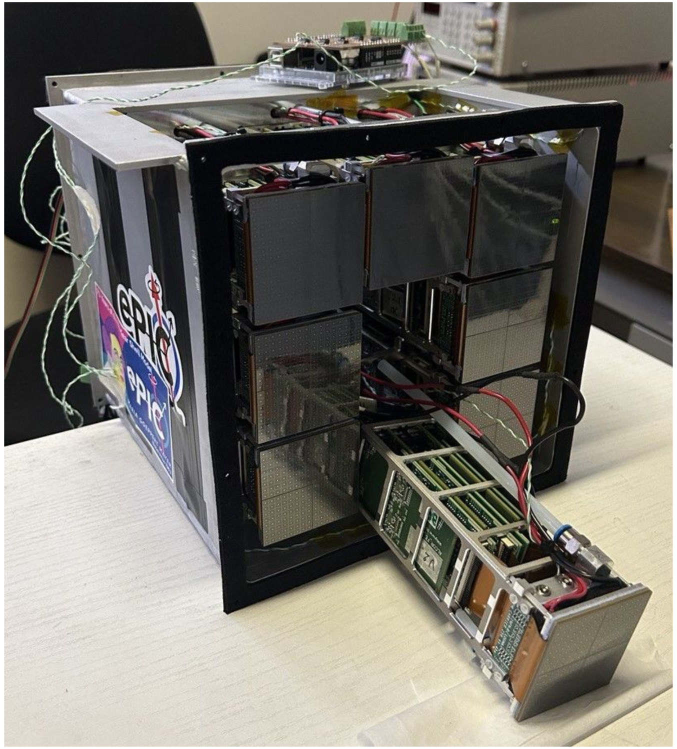
another successful beam test with prototype SiPM photodetector units (CERN-PS, ended on 5th June)

PDU

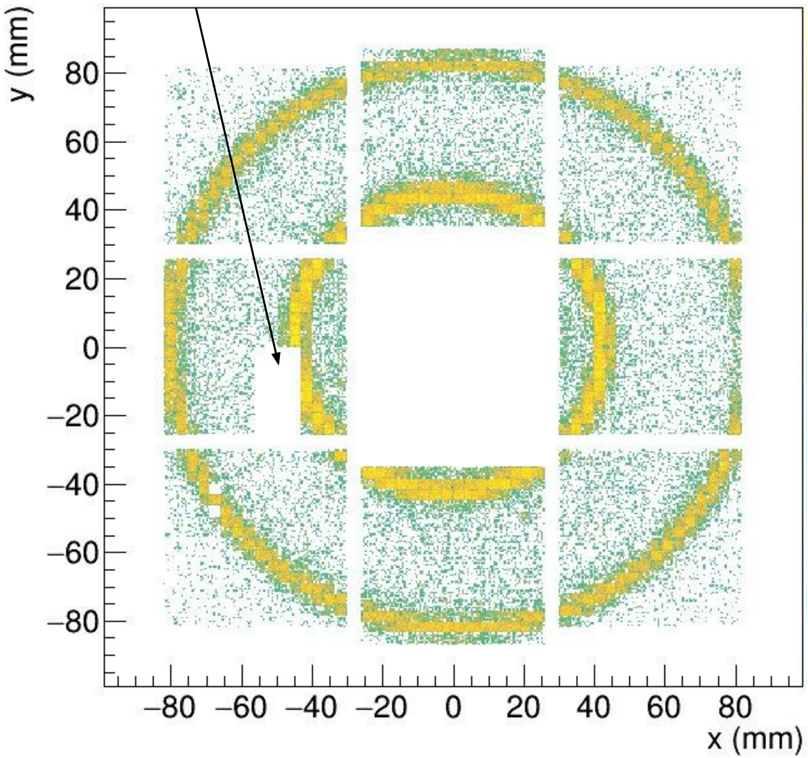
4x SiPM matrix arrays
(256 channels)



front-end electronics
(ALCOR ASIC inside)



unfortunately one ASIC chip (32 ch) had some front-end problems



all the rest was rather full of photons

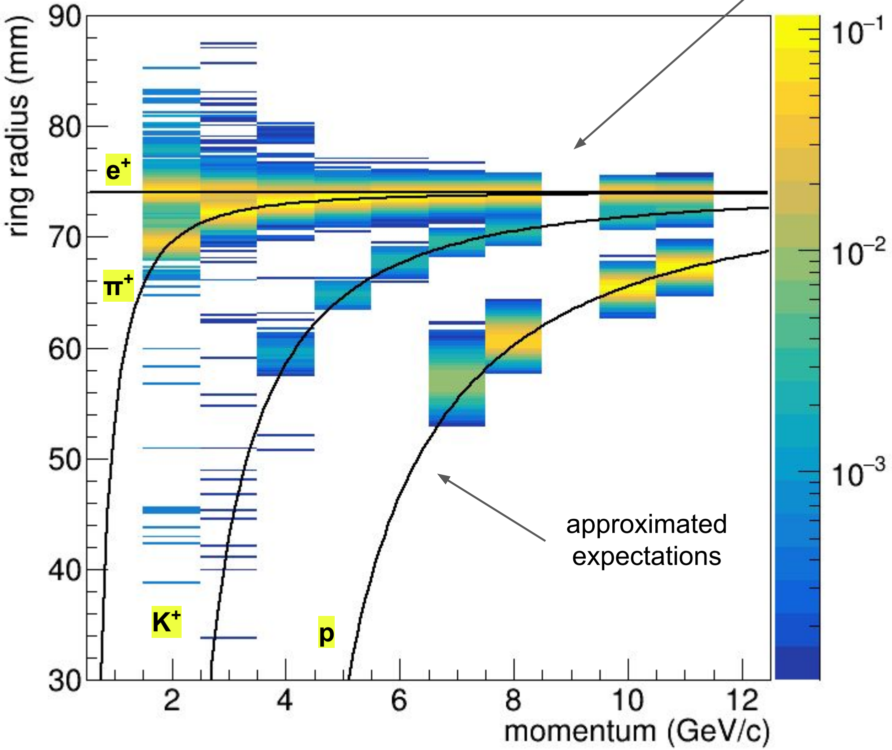
> 2000 SiPMs with TDC readout at work

Beam momentum scan

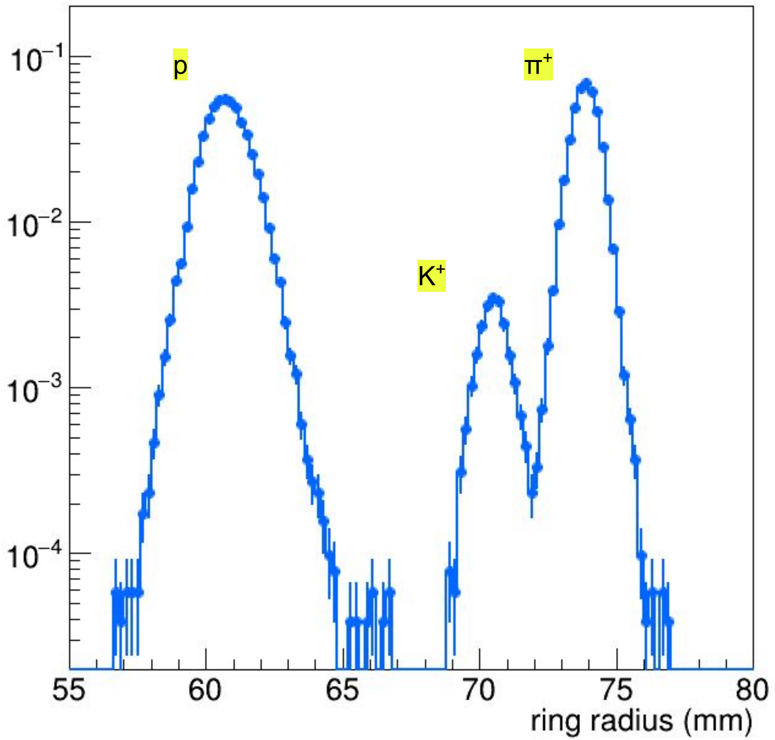
positive particles, aerogel only

something went wrong with the beam configuration for 9 GeV
(that's a pity, data seems not good)

reconstructed radii vs. beam momentum



reconstructed ring radius at 8 GeV/c beam momentum

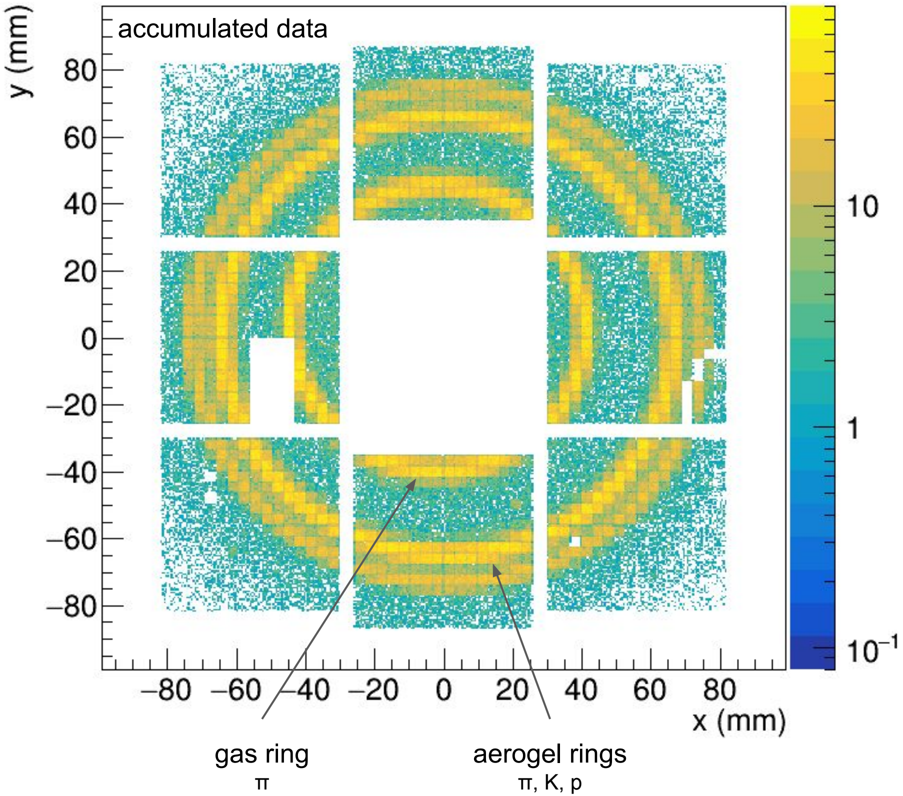


nice!

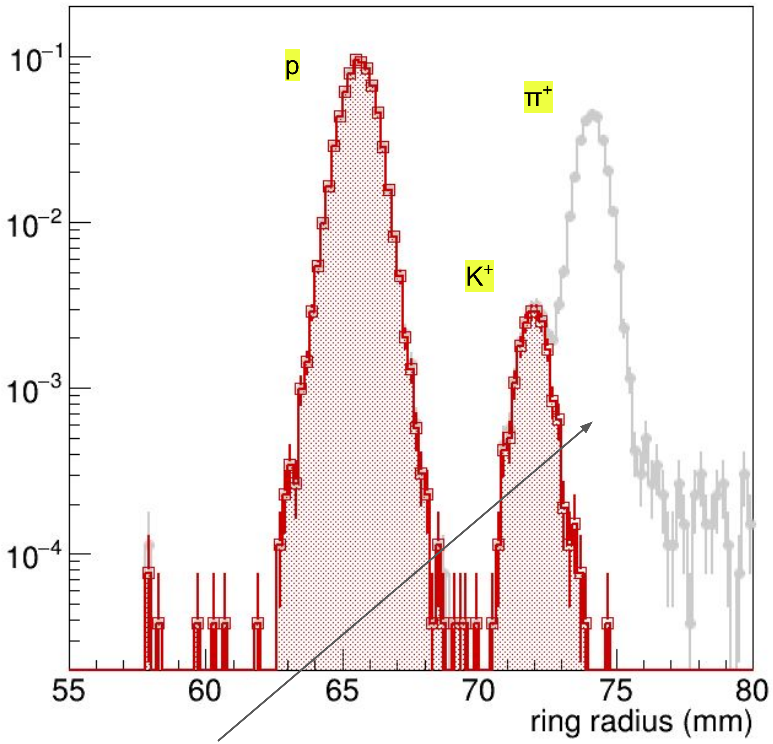
Interplay between aerogel and gas radiators

gas ring tags pions, at 10 GeV/c kaons and protons are below C_2F_6 gas threshold

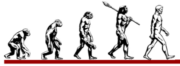
10 GeV/c positive beam with no selection applied



reconstructed ring radius at 10 GeV/c with gas veto

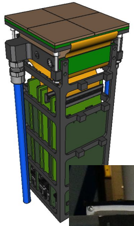


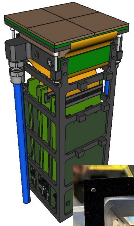
gas-ring veto removes pions, clean kaon identification at 10 GeV/c

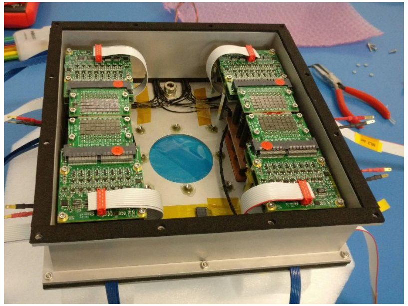


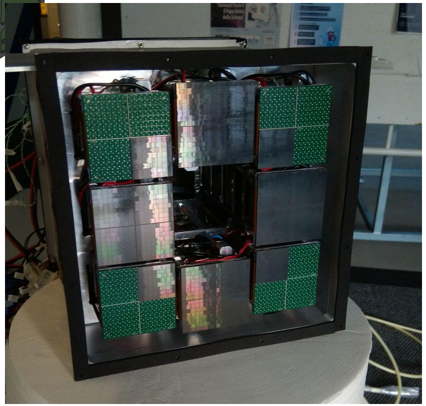
towards construction

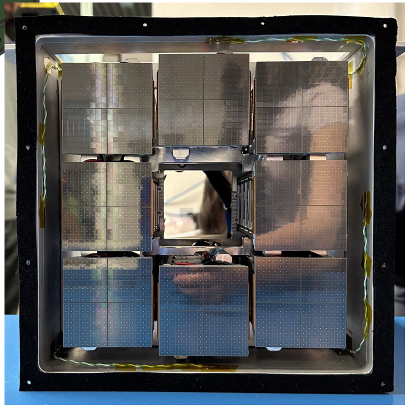
2022	2023	2024	2025
electronics v1	electronics v2	electronics v2.1	electronics v3 final prototype

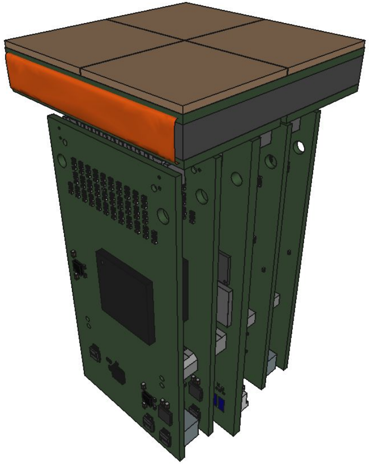


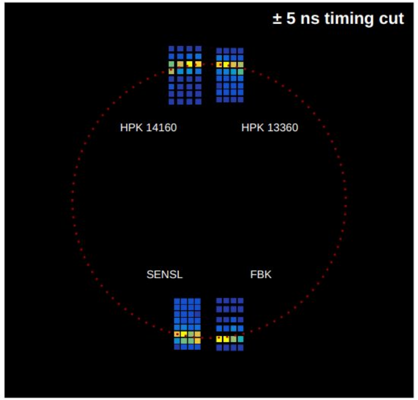


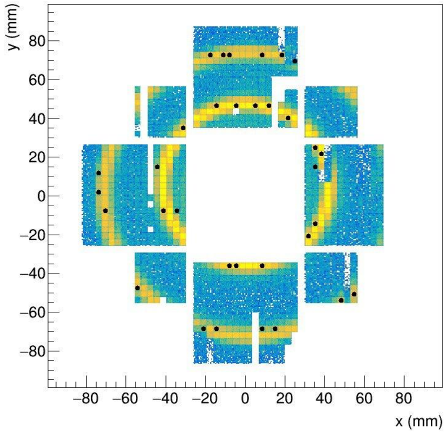


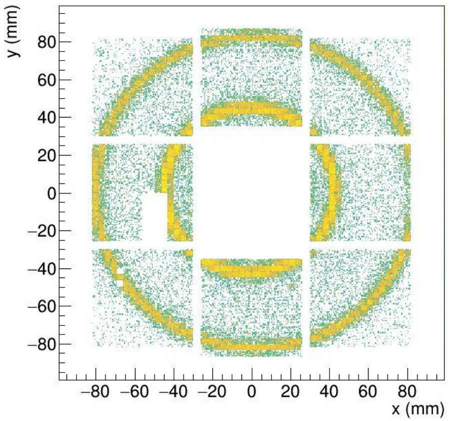












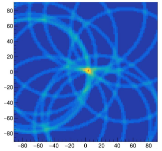
Summary

- **dRICH SiPM option fulfills dRICH requirements**
  - magnetic field limitations
  - excellent timing and efficiency
- **technical solutions to mitigate radiation damage**
  - low temperature operation
  - online “in-situ” self-annealing
  - extend lifetime of good detector performance for Physics
    - present solutions can be optimised/improved to extend it further
- **SiPM readout with full electronics chain**
  - based on ALCOR ASIC
  - successful beam tests at CERN-PS in 2022, 2023 and 2024
  - overall 1-pe time resolution approaching 100 ps
  - ring-imaging, particle-identification and more
  - beam test data-analysis ongoing
- **clear path for optimisation towards TDR and beyond**
  - refinements, engineering and SiPM sensor selection in 2025 and 2026
  - SiPM readout mass production in 2027-2029
  - dRICH detector installation in the ePIC experiment in 2030

END

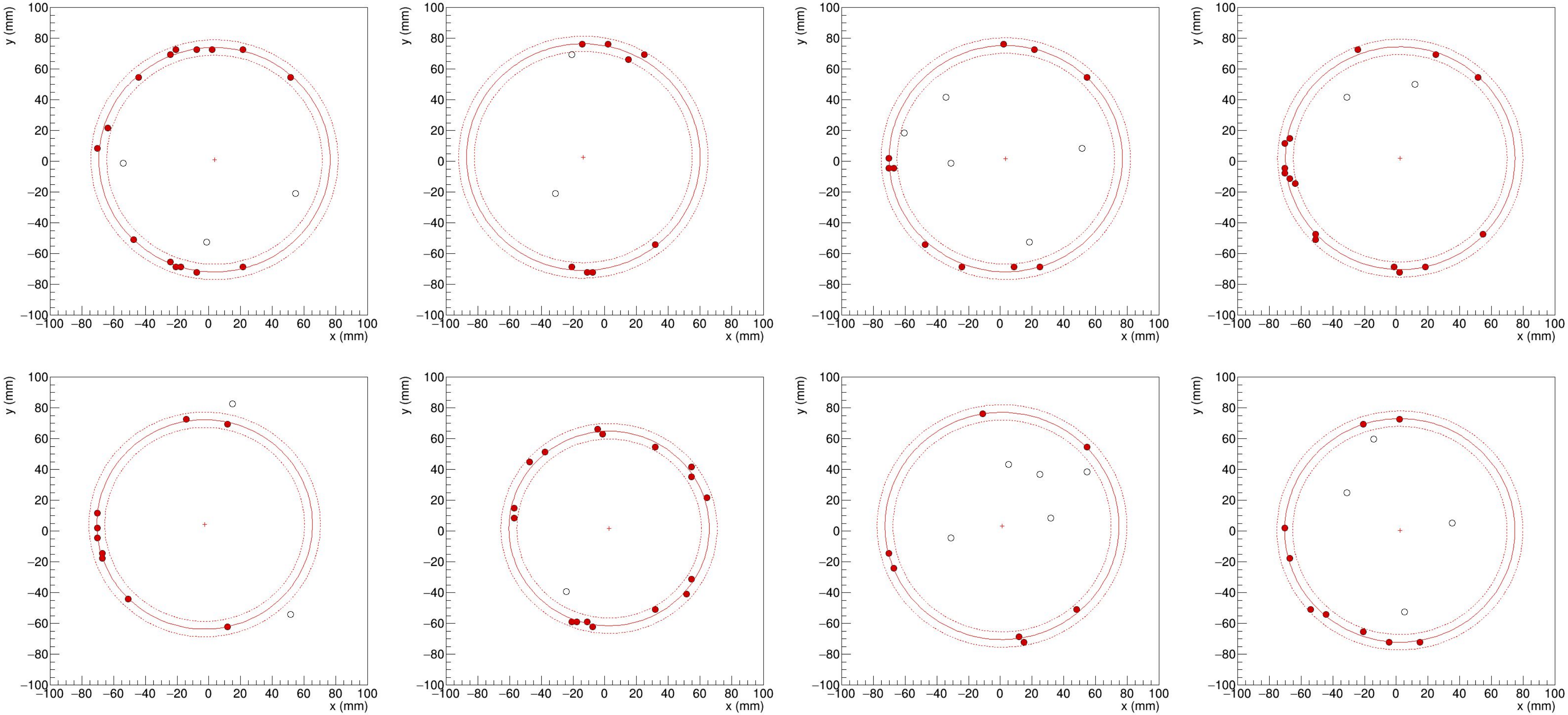
2023 test beam data analysis ongoing

event-by-event ring reconstruction: Hough Transform Method



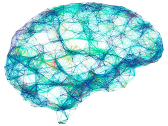
10 GeV negative beam

only aerogel radiator



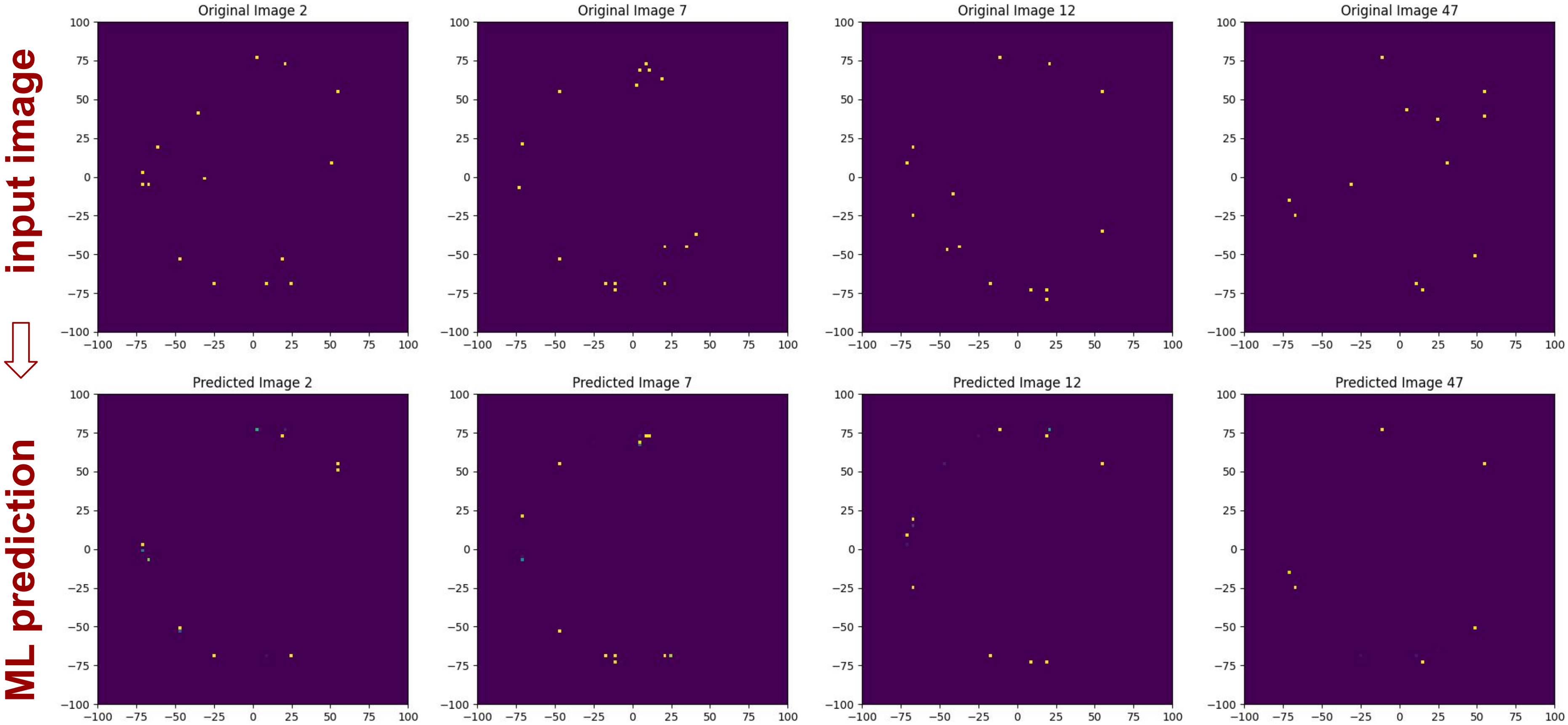
2023 test beam data analysis ongoing

event-by-event ring reconstruction: Machine Learning



10 GeV negative beam

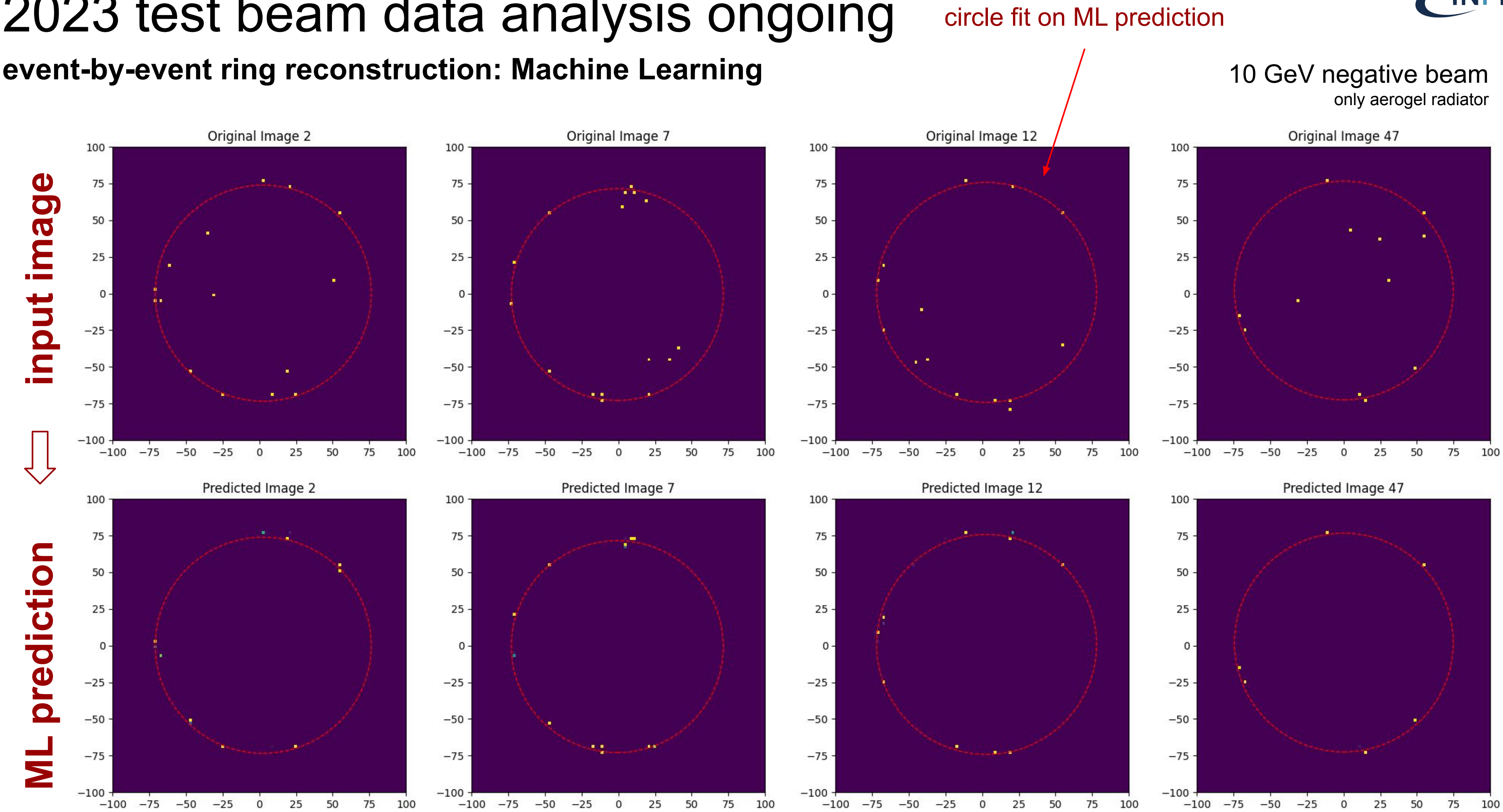
only aerogel radiator



2023 test beam data analysis ongoing

event-by-event ring reconstruction: Machine Learning

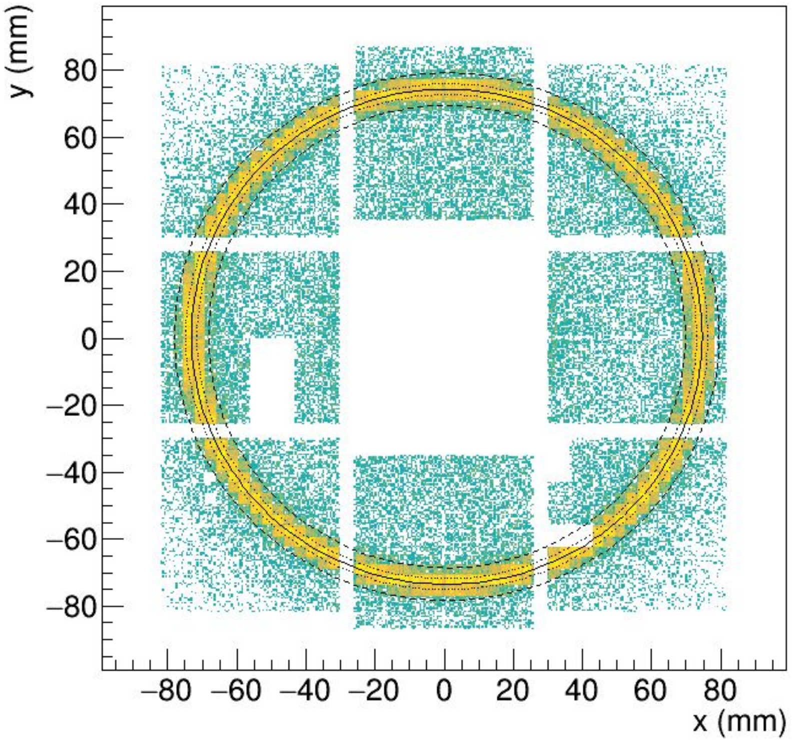
10 GeV negative beam
only aerogel radiator



Number of photoelectrons

is large as expected

11.5 GeV/c negative beam, n = 1.02 aerogel (accumulated events)



$X_0 = 0.75 \pm 0.01$ mm

$Y_0 = 0.45 \pm 0.01$ mm

$R = 73.87 \pm 0.00$ mm

$\sigma_R = 1.63 \pm 0.00$ mm

$N_{sig} = 29.13 \pm 0.07$

$N_{bkg} = 8.47 \pm 0.05$

average number of signal photons for 100% acceptance
includes SiPM efficiency

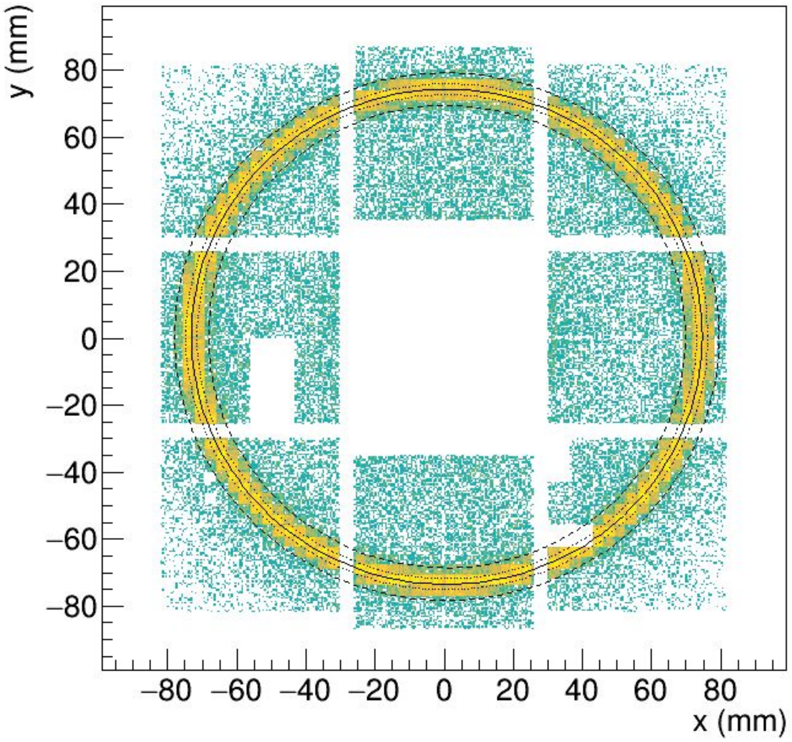
2D fit to accumulated data with realistic model (ring + background)

global ring parameters and performance, running also online

Number of photoelectrons

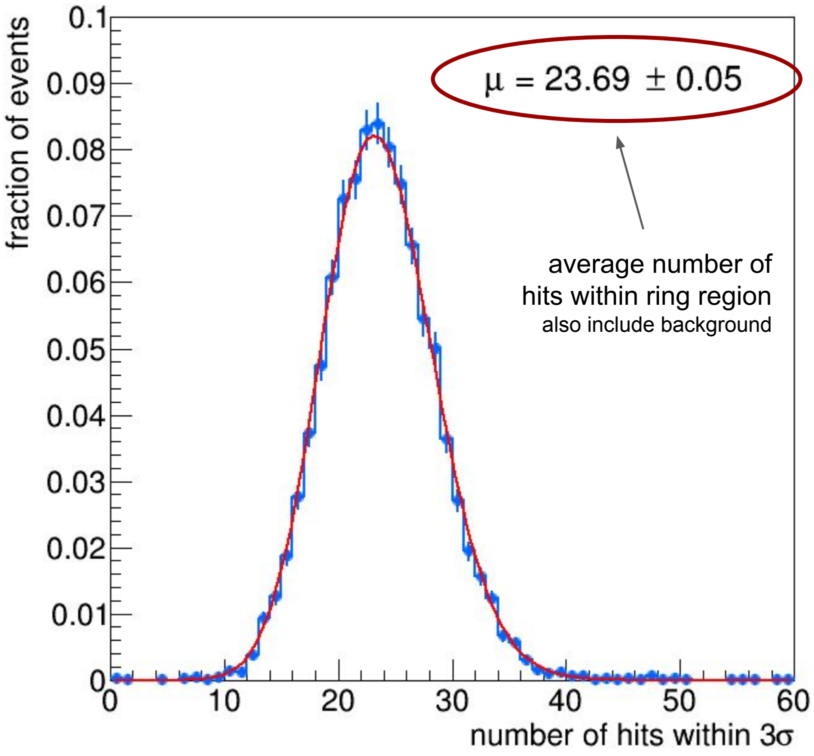
large as expected

11.5 GeV/c negative beam, n = 1.02 aerogel (accumulated events)



2D fit to accumulated data with realistic model (ring + background)

event-by-event distribution of hits in the ring

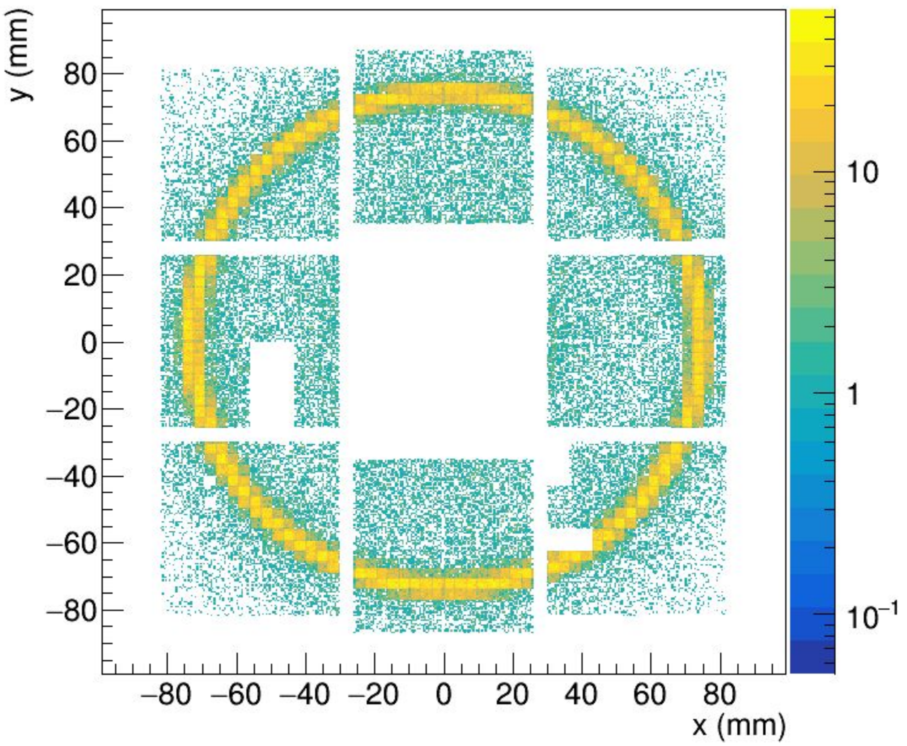


Poisson fit to data, average number of hits is large

Background studies

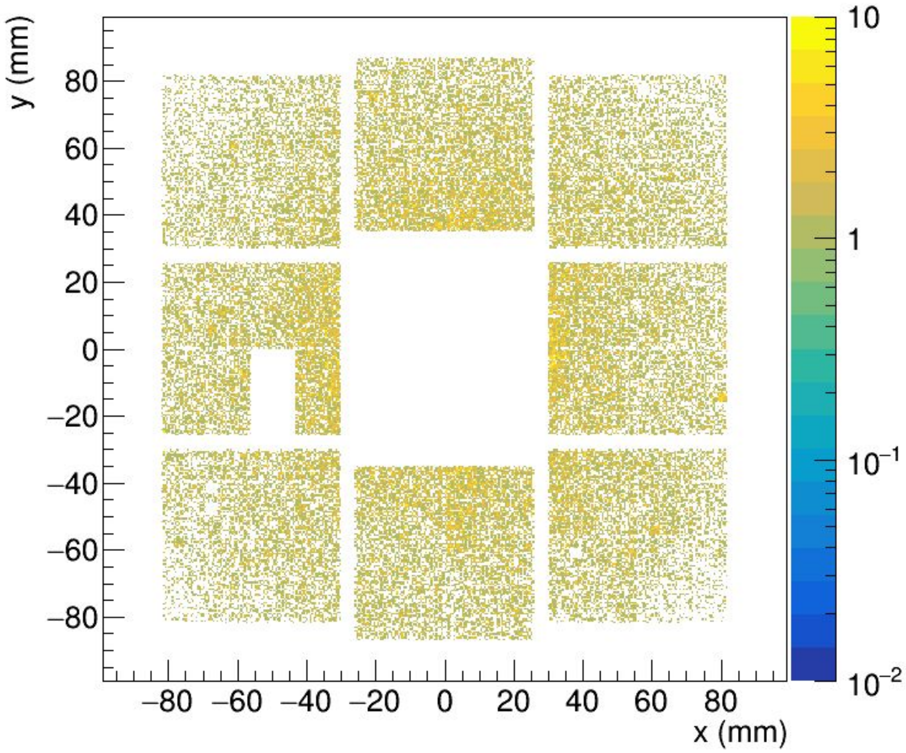
data taken without aerogel radiator

with two n = 1.02 aerogel tiles (accumulated events)



with timing cuts applied, large background as seen in past years

without aerogel (accumulated events)

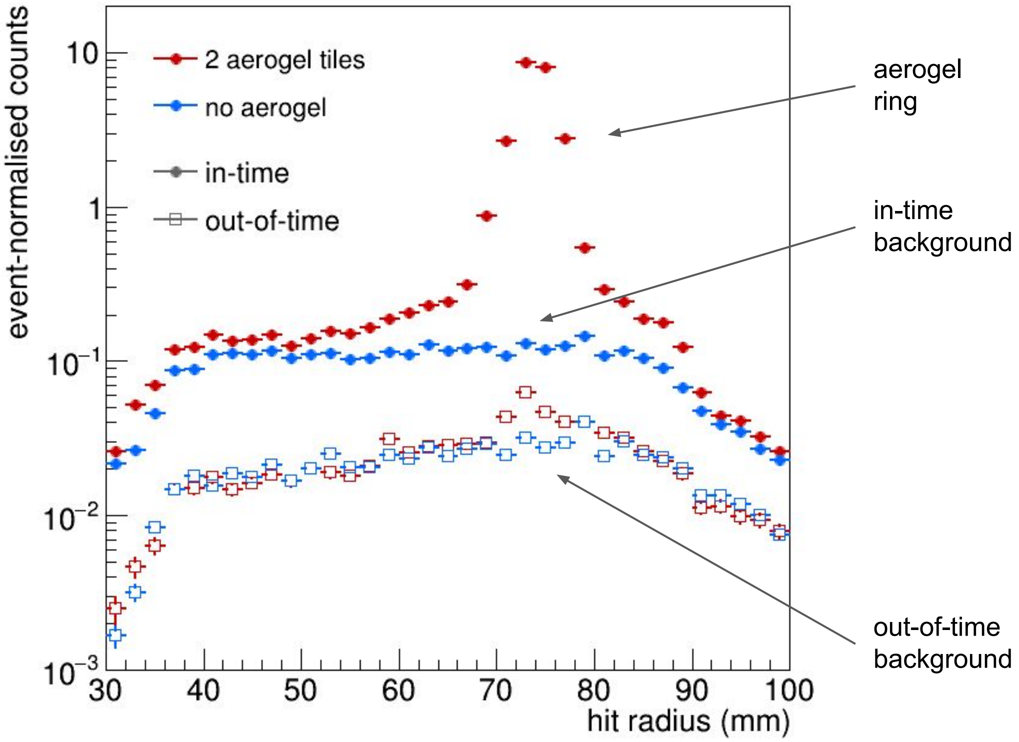


removed the aerogel tile, background remains

Background studies

basically all the background remains after removing aerogel, not from DCR

distribution hit radii with and without aerogel

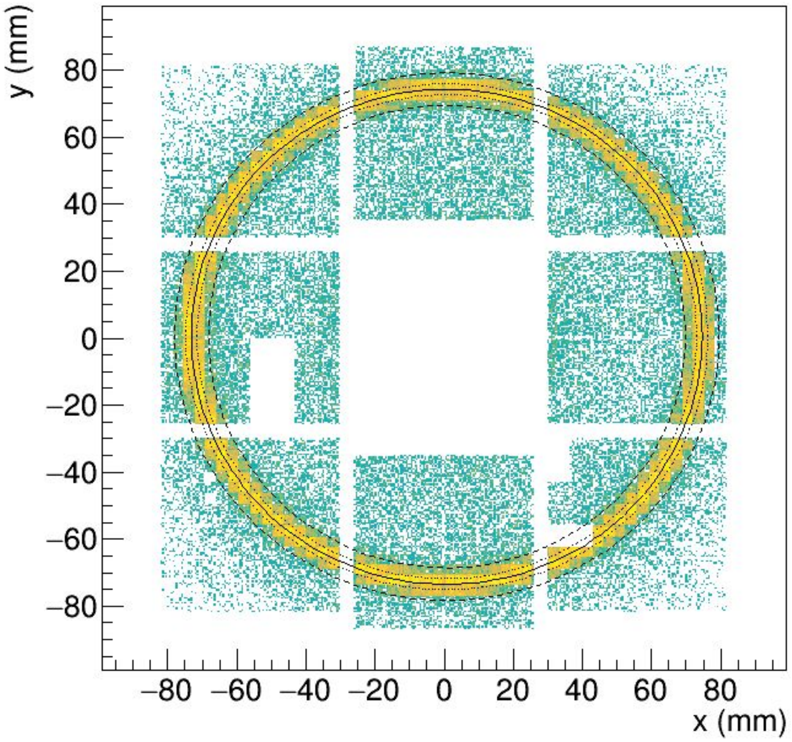


in-time (40 ns window) background is ~ 10x larger than out-of-time (40 ns window) background (mostly DCR) | origin still unclear | to be understood

Background studies

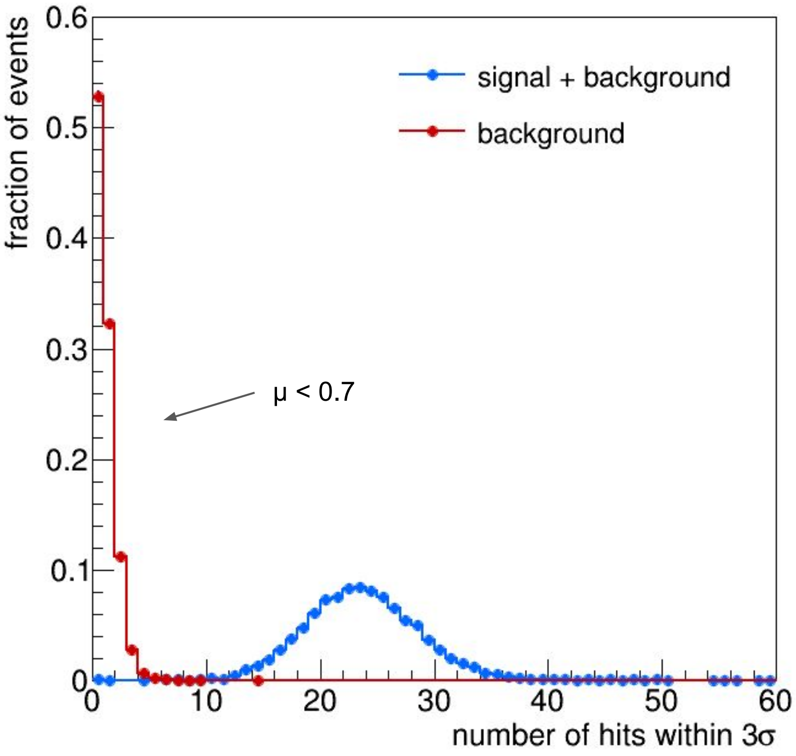
there is often one background hit in the ring, this will impact resolution

11.5 GeV/c negative beam, n = 1.02 aerogel (accumulated events)



2D fit to accumulated data with realistic model (ring + background)

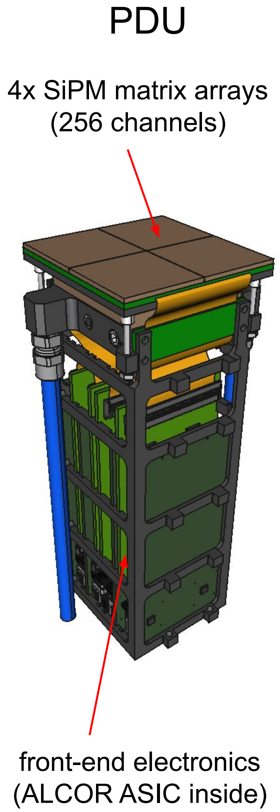
event-by-event distribution of hits in the ring

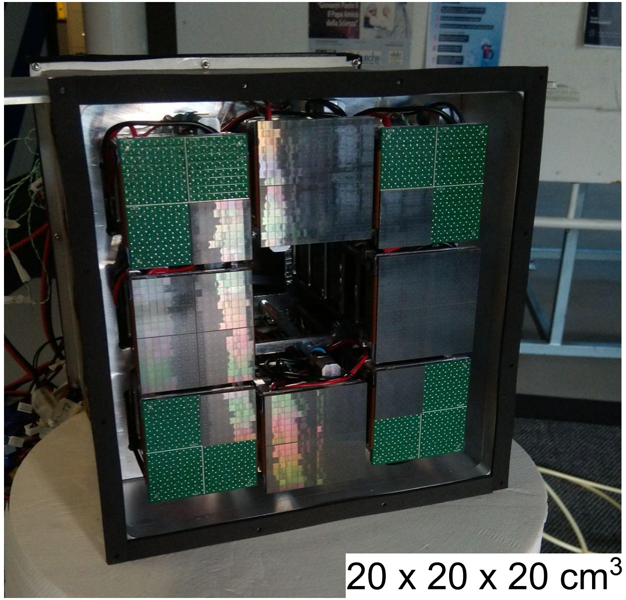


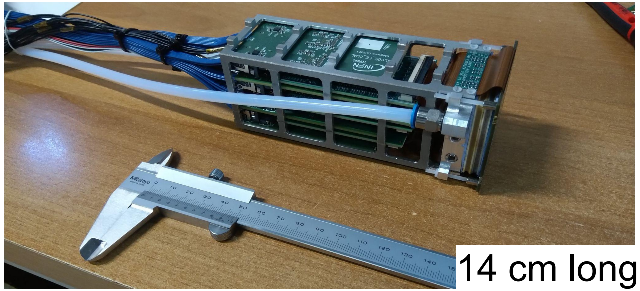
background in ring region estimated with data taken without aerogel

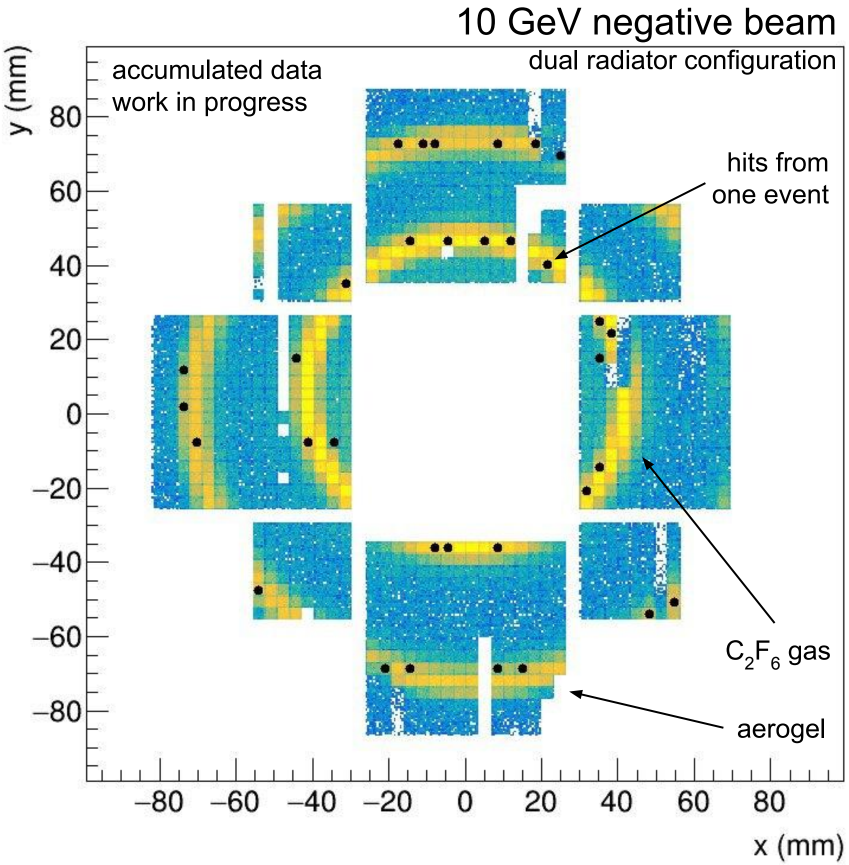
2023 test beam at CERN-PS

successful beam test with prototype SiPM photodetector units (CERN-PS, ended on 18th October)

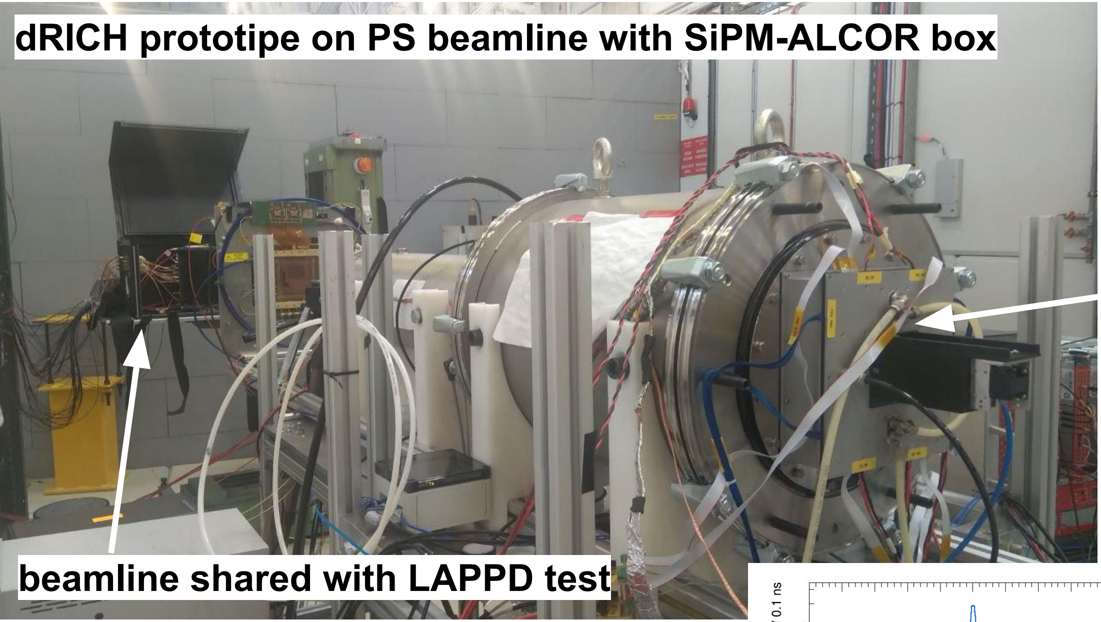


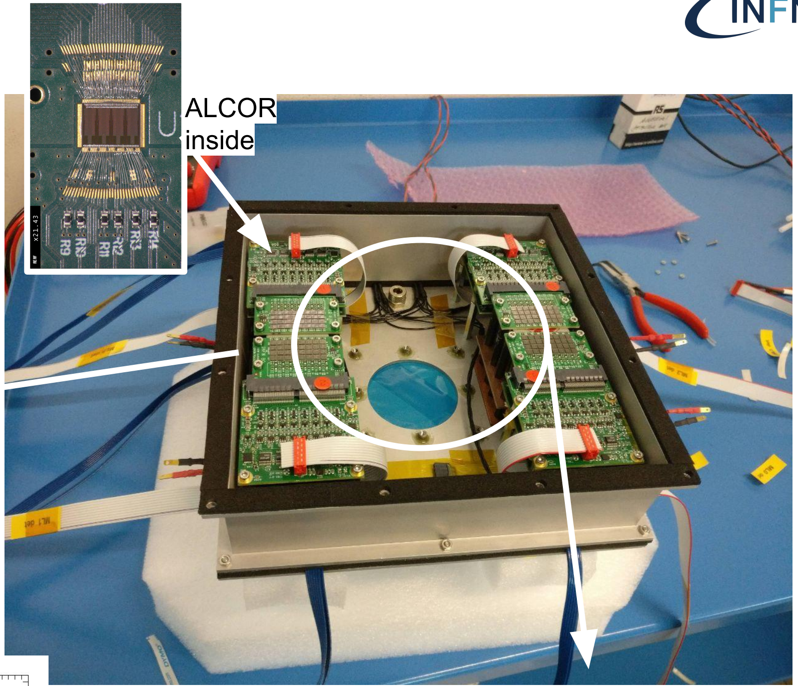






2022 test beam at CERN-PS

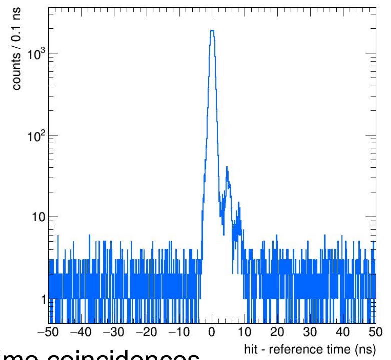




successful operation of SiPM

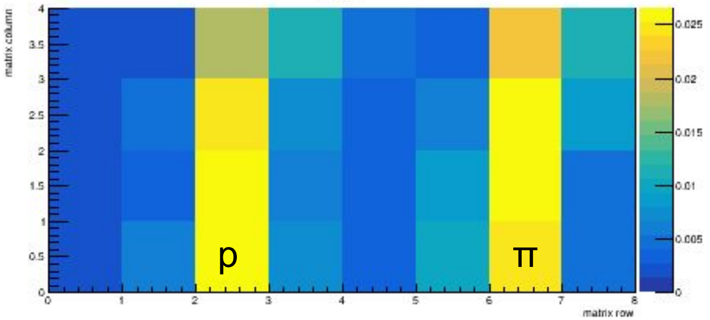
irradiated (with protons up to 10^{10})

and annealed (in oven at 150 C)

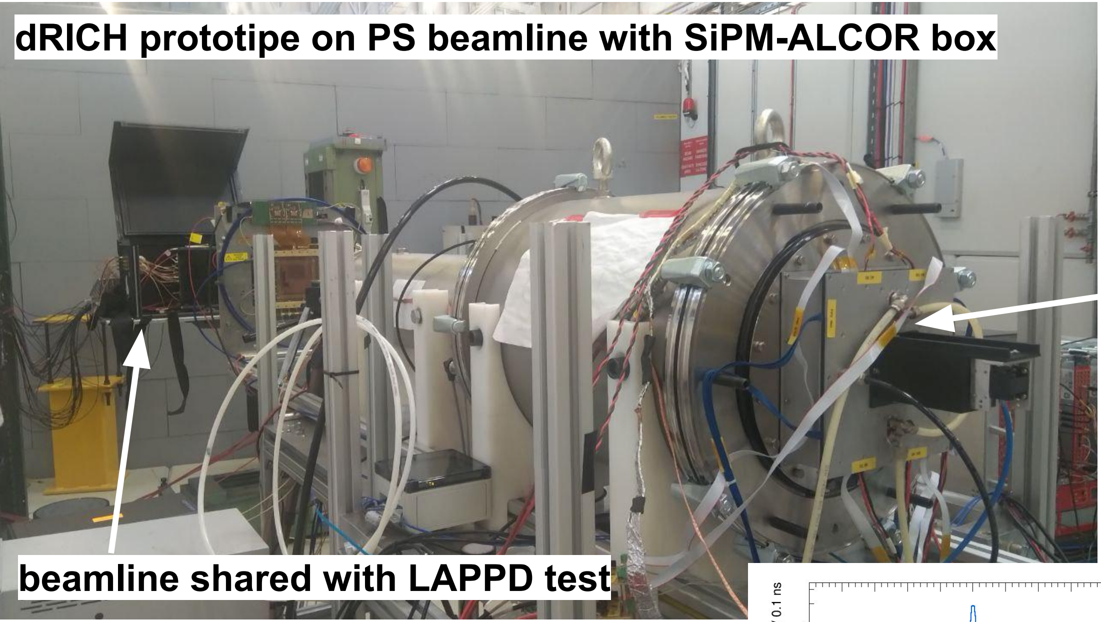


time coincidences

8 GeV positive beam (aerogel rings)



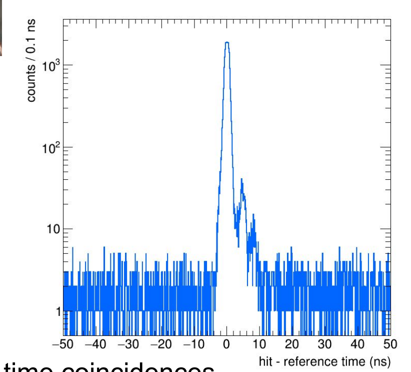
2022 test beam at CERN-PS



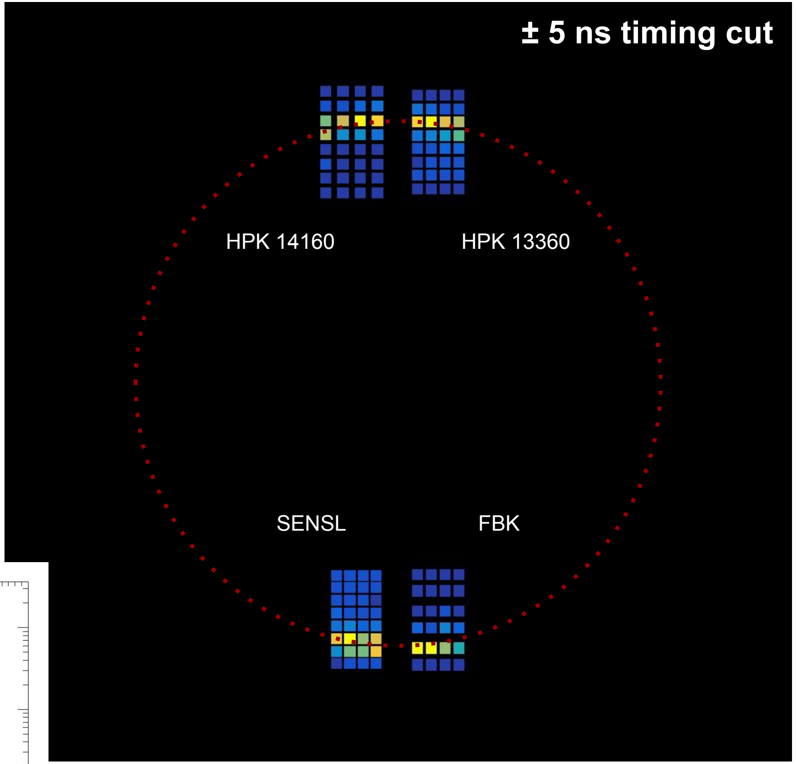
successful operation of SiPM

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

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



time coincidences

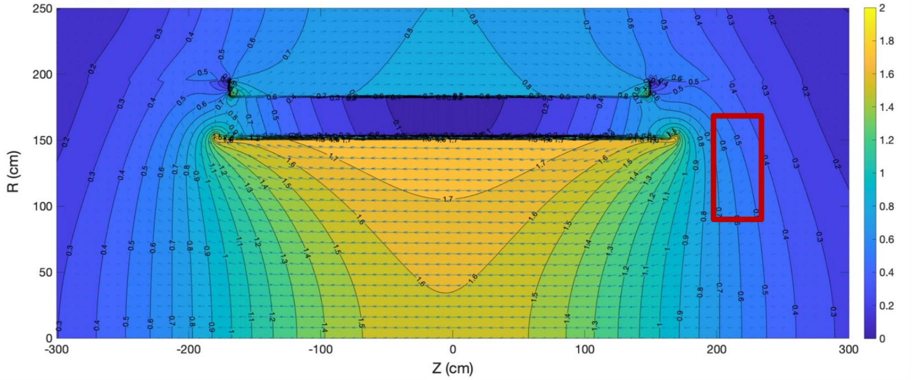


8 GeV negative beam (aerogel rings)

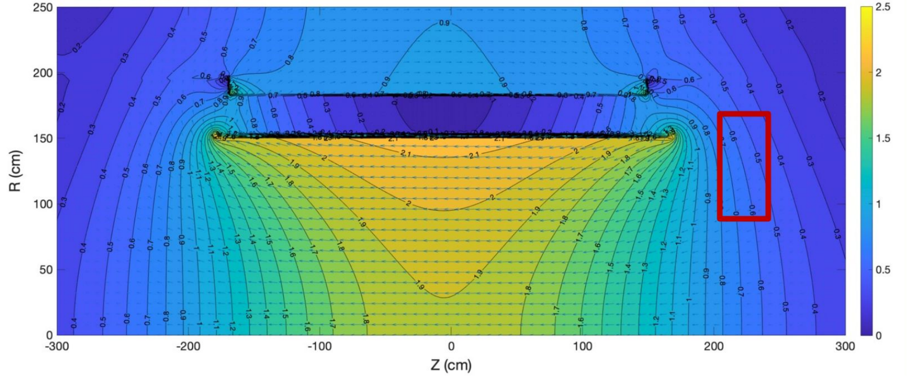
Environment

MARCO magnetic field maps

1.7 T field



2.0 T field



non-uniform, strong magnetic field ~ 0.7 T
field lines ~ parallel to photodetector surface

SiPM cooling for low-temperature operation (−30 °C or lower)

external chiller with fluid recirculation (ie. siliconic oil)

the chiller here one is just a commercial example

cooling and heating capacity

could use heating capability for annealing? must be demonstrated to be feasible

cooling capacity at -40 C is large (1.5 kW)

huber

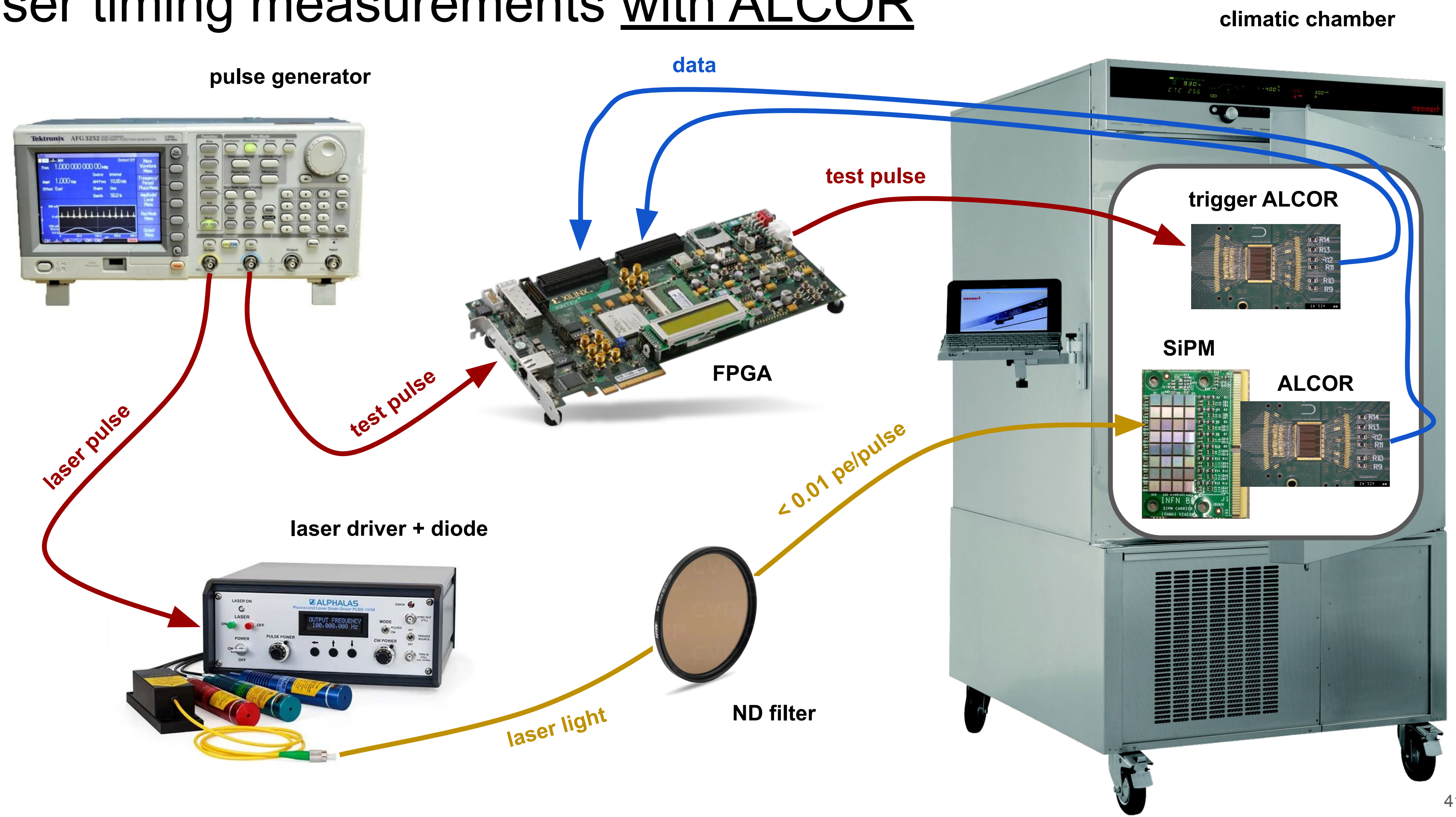
General & Temperature Control

Temperature range	-55...250 °C
Temperature stability	±0,01 K

Heating / cooling capacity

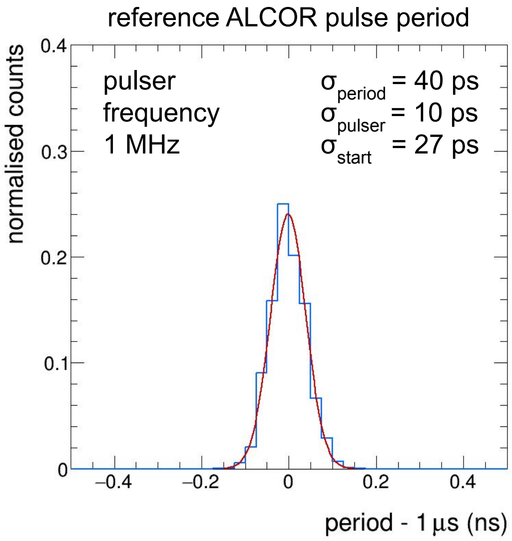
Heating capacity	6 kW								
Cooling capacity	250	200	100	20	0	-20	-40	-50	°C
	6	6	6	6	6	4,2	1,5	0,65	kW

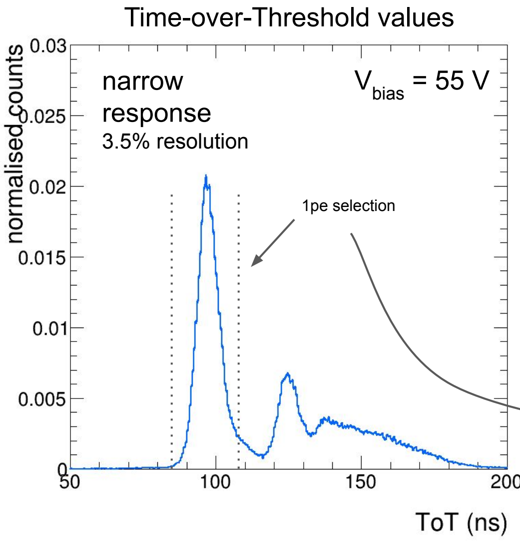
Laser timing measurements with ALCOR

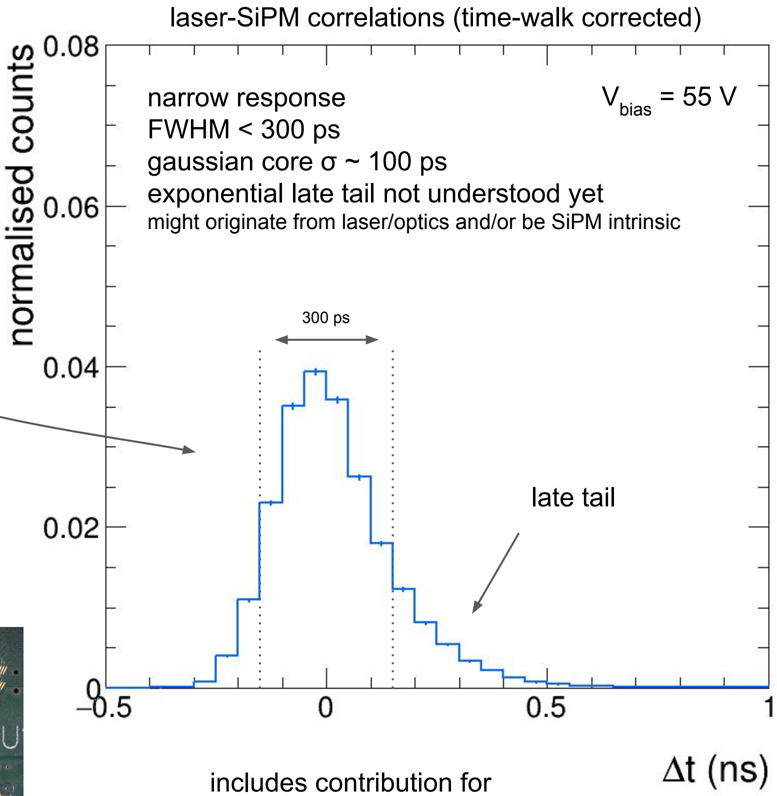


Laser timing measurements with ALCOR

Hamamatsu S13360-3075



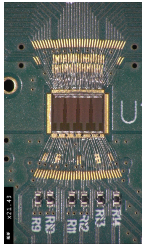




laser-SiPM signal synchronisation by sending test pulse to reference ALCOR

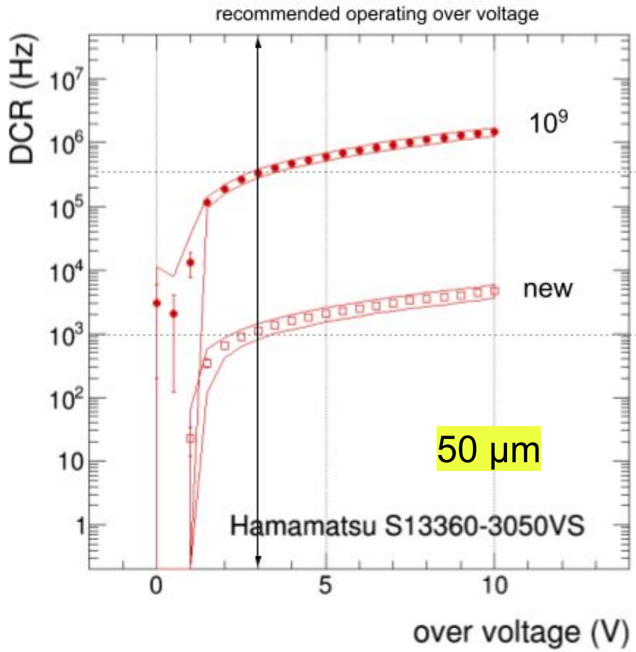
- to measure laser pulse t_{start}
- with 50 ps LSB TDC
- in synch with ALCOR readout

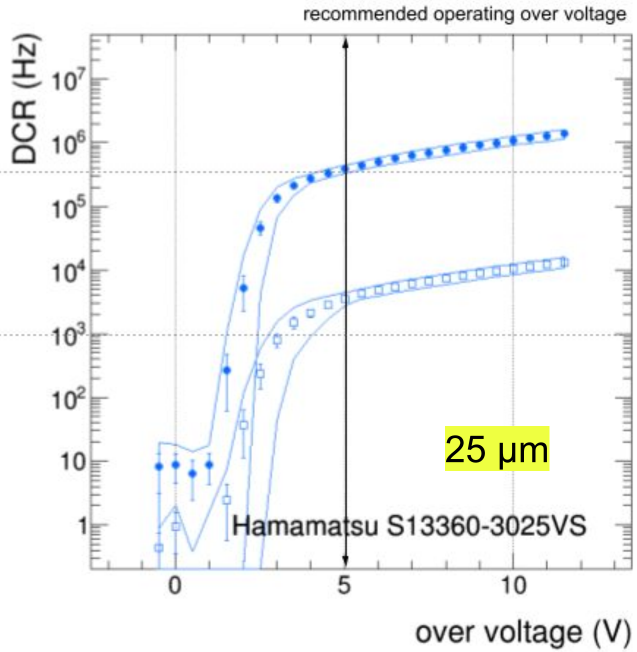
measure time coincidences Δt between reference and ALCOR reading SiPM



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

Small vs. <u>large</u> SPAD sensors





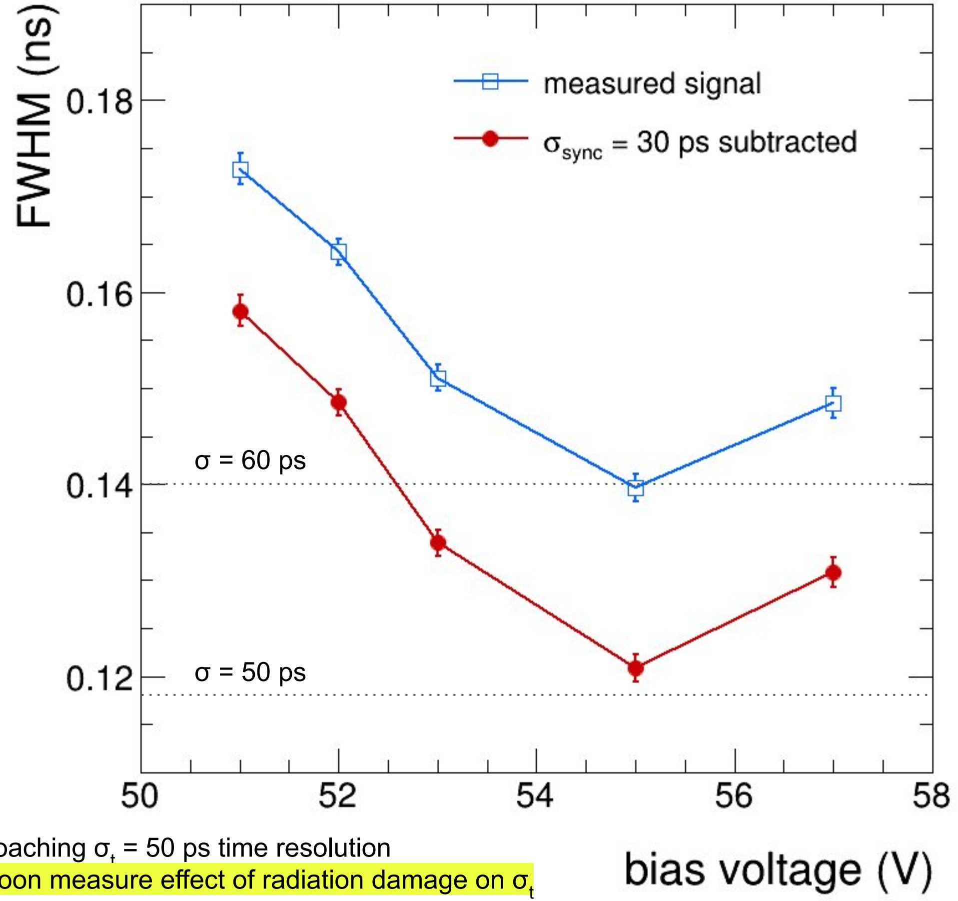
sensors with **small SPADs have lower SNR** also after irradiation

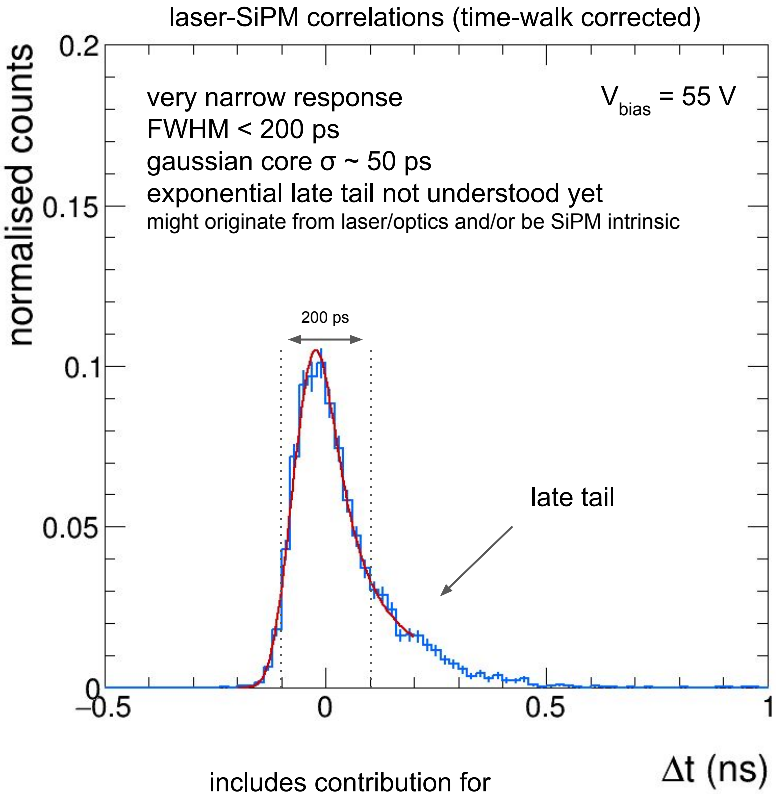
small SPAD sensors are not radiation harder for single-photon applications (RICH)

- **sensors operated at Hamamatsu recommended over-voltage**
  - [datasheet] 50 µm sensors have 40% PDE, 25 µm have 25%
  - [measured] 50 µm sensors have lower DCR than 25 µm when new
  - [measured] both sensors have similar DCR after irradiation

similar results and conclusions obtained with SENSL sensors

Laser timing measurements with oscilloscope

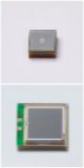




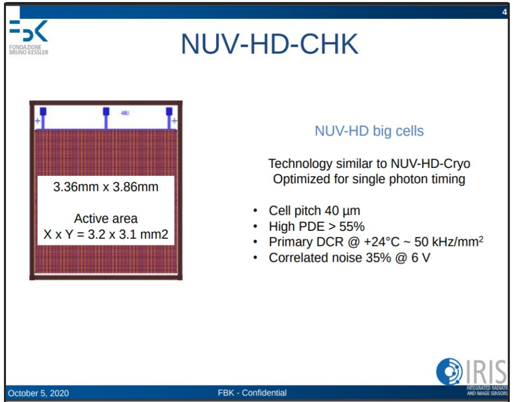
includes contribution for
laser-oscilloscope synchronization
measured to be σ_{sync} = 30 ps

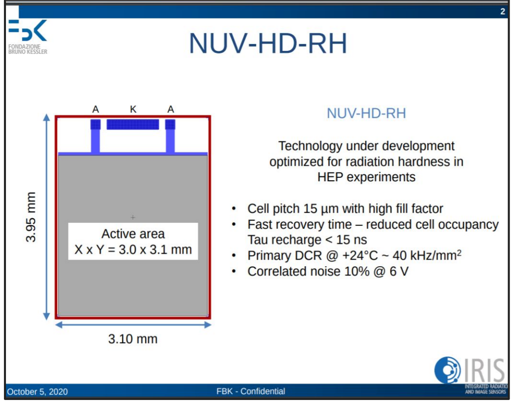
approaching σ_t = 50 ps time resolution
will soon measure effect of radiation damage on σ_t

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

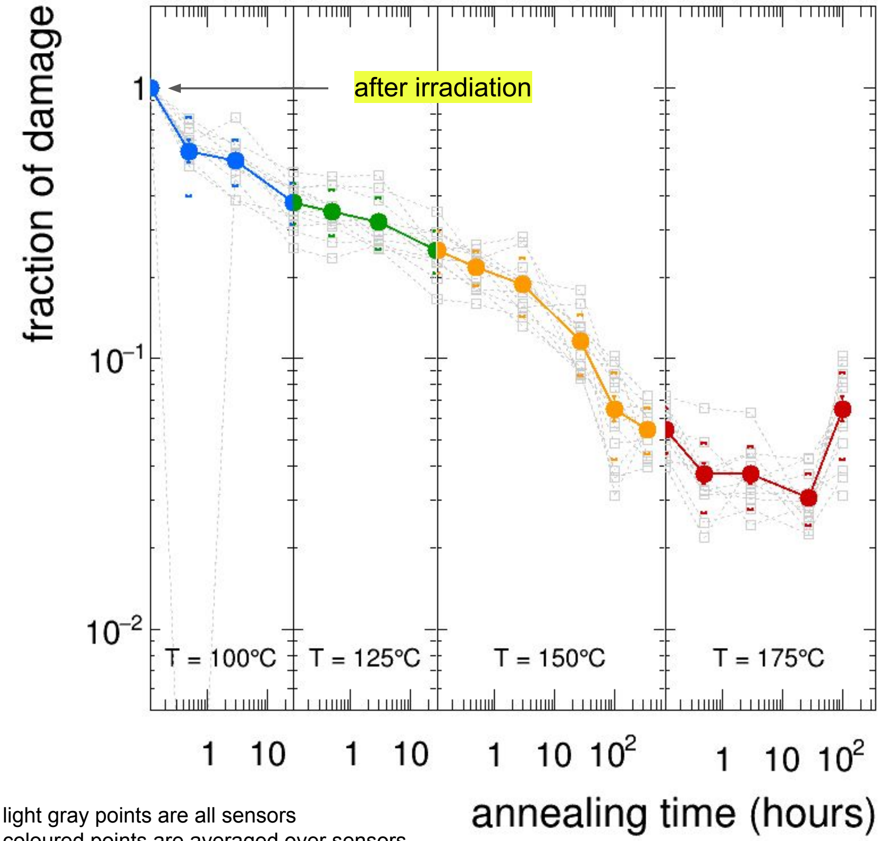




multiple producers: different technologies, SPAD dimensions, V_{bd}, electric field …

Detailed studies of SiPM online self-annealing

online self-annealing with reverse bias



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

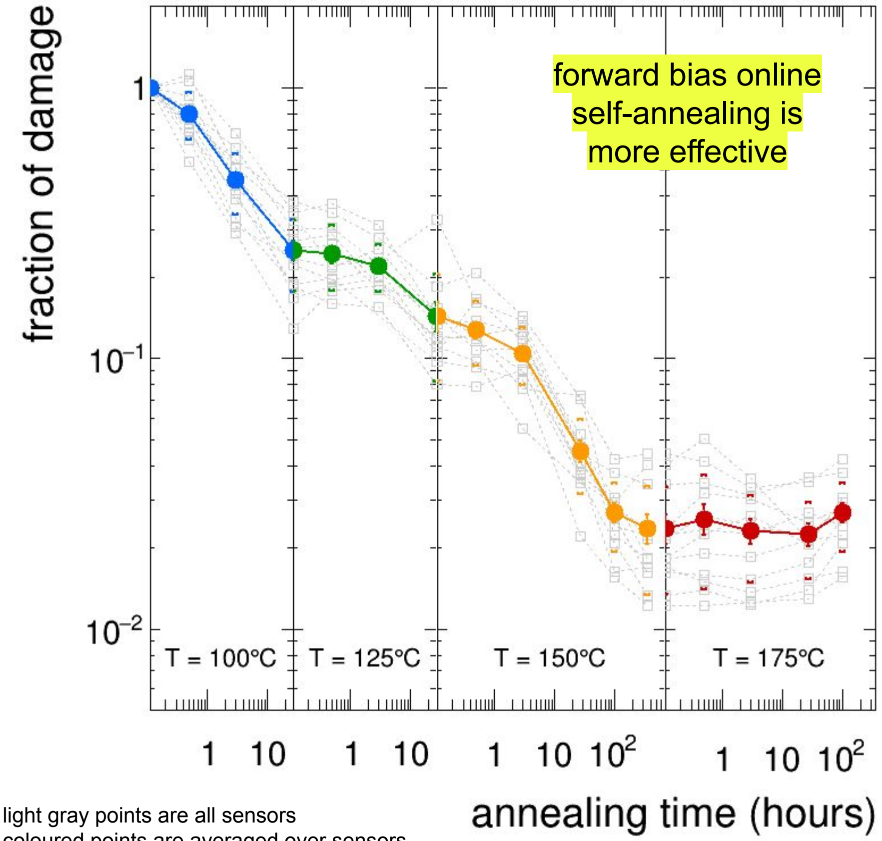
test on a large number of proton irradiated sensors how much damage is cured as a function of temperature and time

in this study, the same sensors have undergone self-annealing in increasing temperature steps and increasing integrated time steps

- started with T = 100 C annealing
  - performed 4 steps up to 30 hours integrated
- followed by T = 125, 150 and 175 C

Detailed studies of SiPM online self-annealing

online self-annealing with forward bias



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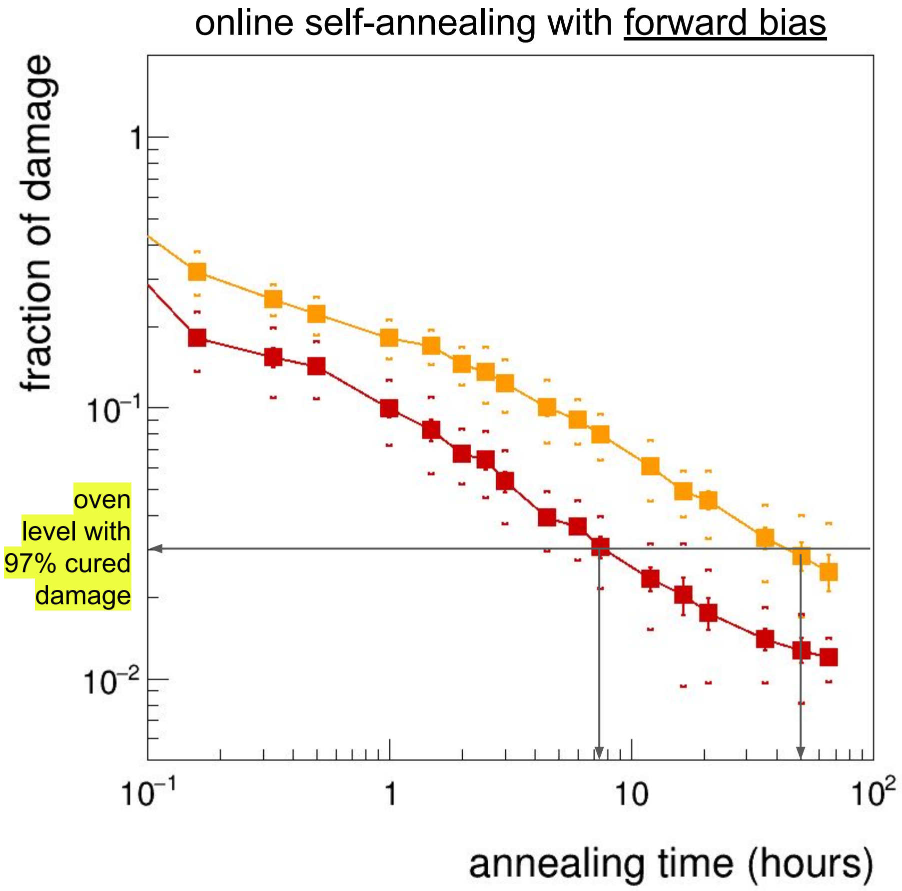
- started with T = 100 C annealing
  - performed 4 steps up to 30 hours integrated
- followed by T = 125, 150 and 175 C

fraction of residual damage seems to saturate at 2-3%
after ~ 300 hours at T = 150 C

continuing at higher T = 175 C seems not to cure more than that

Automated multiple SiPM online self-annealing



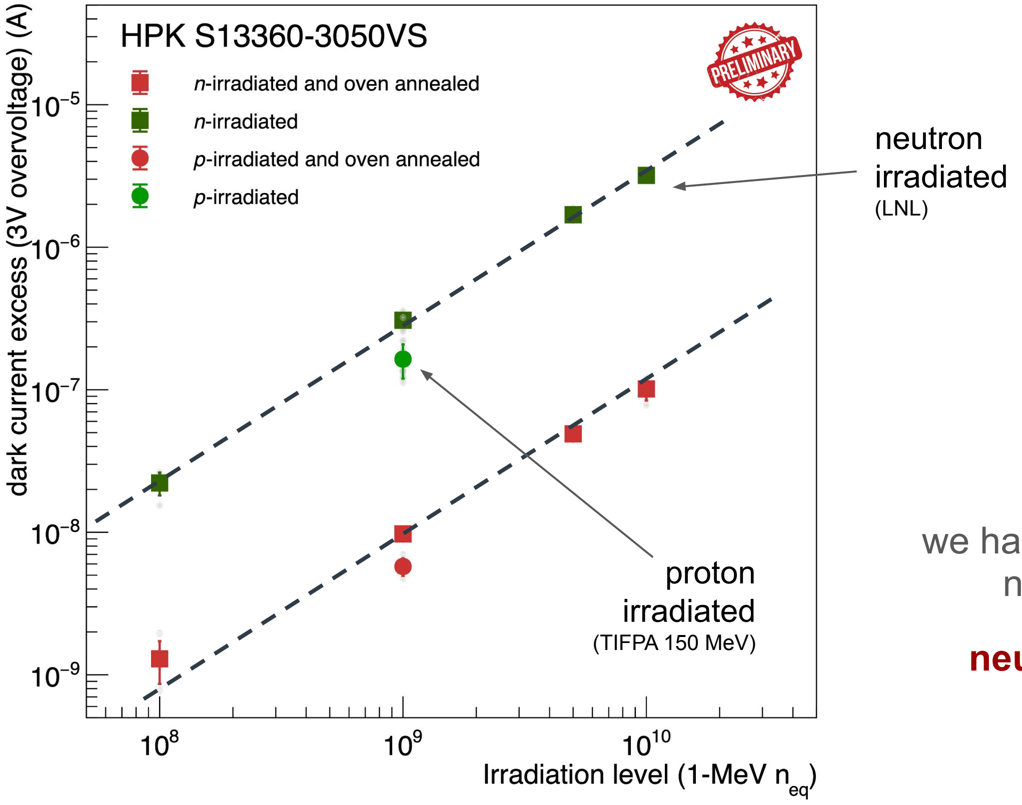
comparison between two annealing temperatures

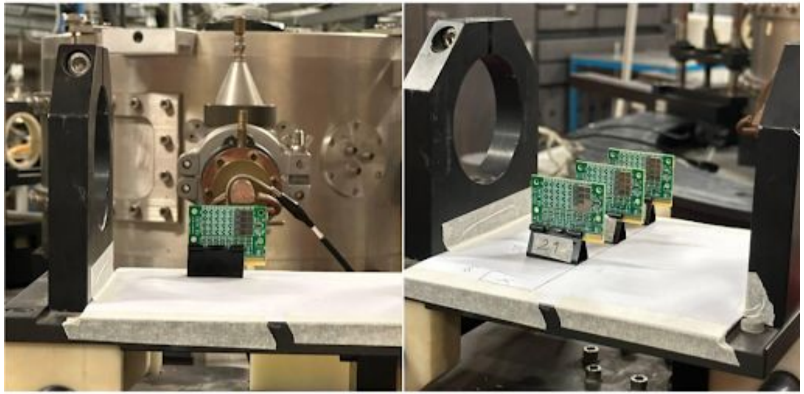
both reach and exceed the oven limit of ~ 2-3% residual damage

- at T = 175 C
  - there seems to be a faster "sudden" cure
  - followed by a similar rate of reduction with time
- oven-level annealing reached faster at T = 175 C
  - < 10 hours integrated
- oven-level annealing reached at T = 150 C
  - < 100 hours integrated

Preliminary comparison of neutron vs. proton damage

neutrons from Be(d,n) reaction with 4 MeV deuteron beam



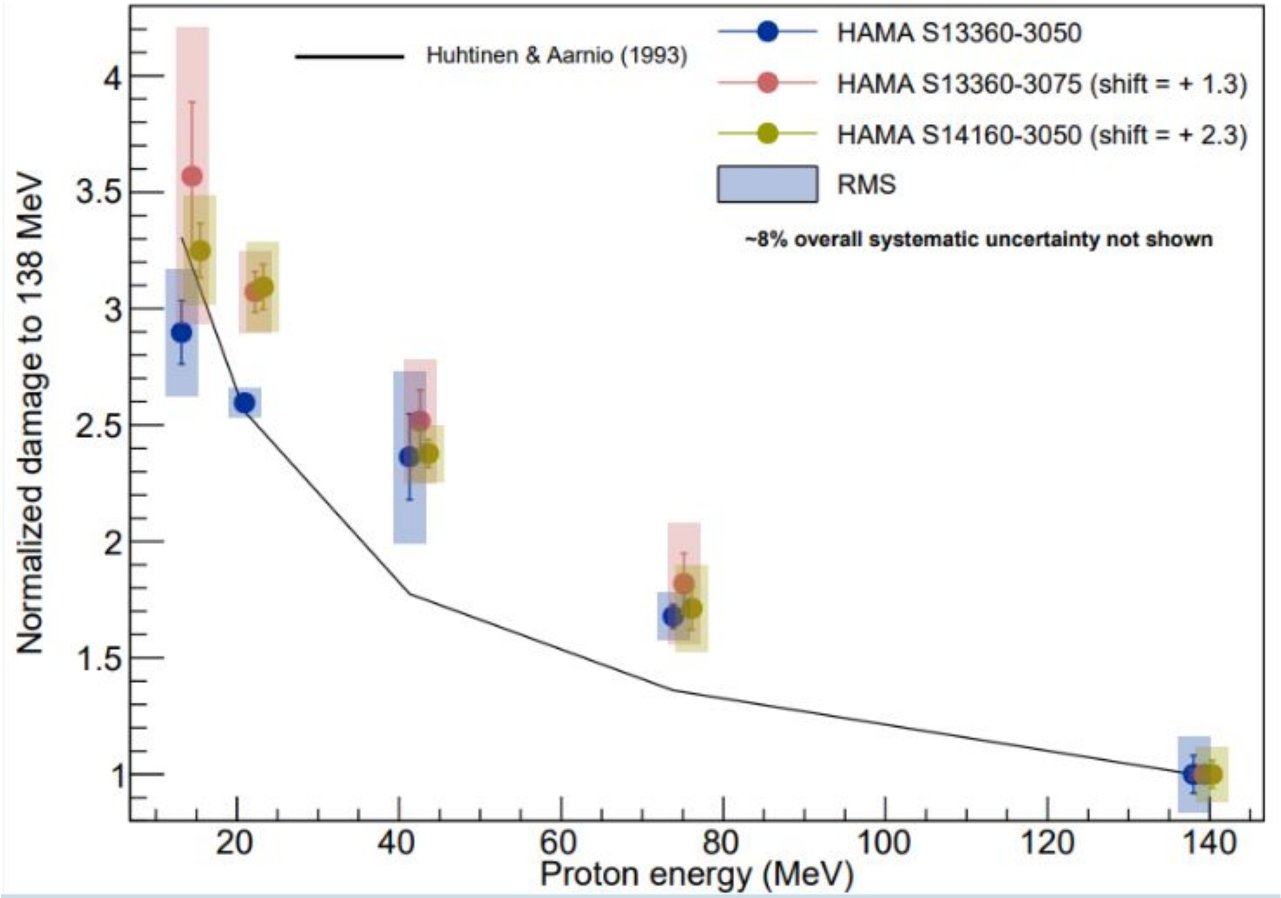


we have very preliminary results on comparison between neutron and proton damage which indicate that

neutron damage is larger after same n_{eq} fluence
using NIEL scaling for normalisation

by approximately a factor of 2x
we use a 10x safety factor for radiation damage estimates

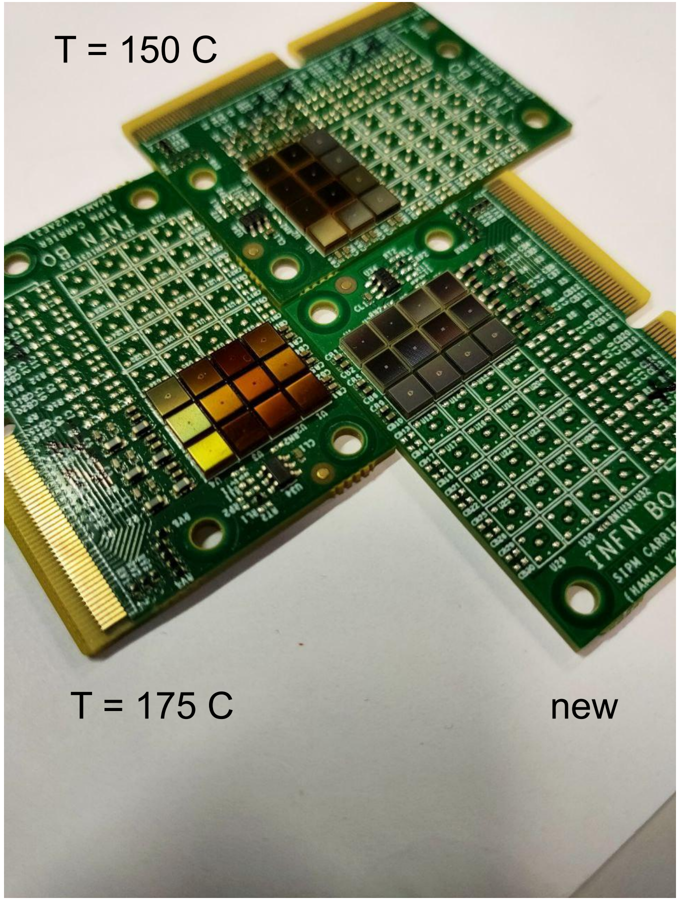
Preliminary proton vs. energy damage



we have very preliminary results on comparison between of proton damage vs. proton energy to NIEL hypothesis which indicate that the scaling is valid within 30-50%

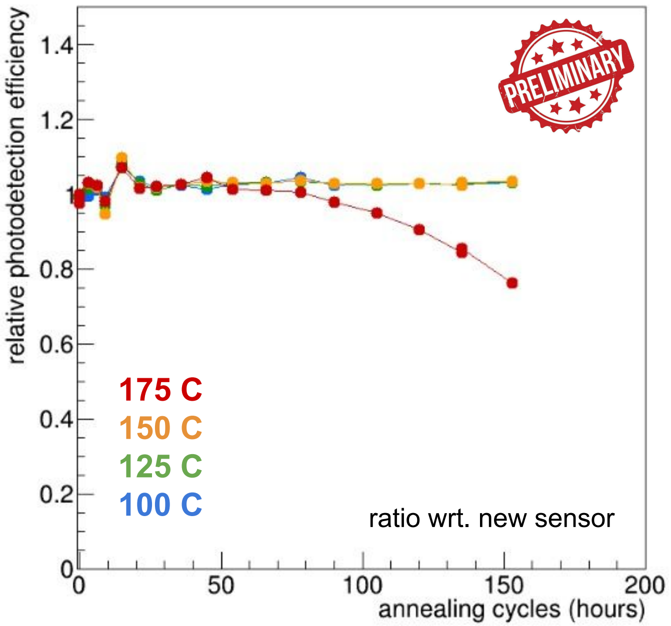
using NIEL scaling for normalisation

Detailed studies of SiPM online self-annealing



after many hours of online annealing

we noticed alterations on the SiPM windows
in particular in one board that underwent
500 hours of online annealing at T = 175 C
the sensors appear "yellowish" when compared to new

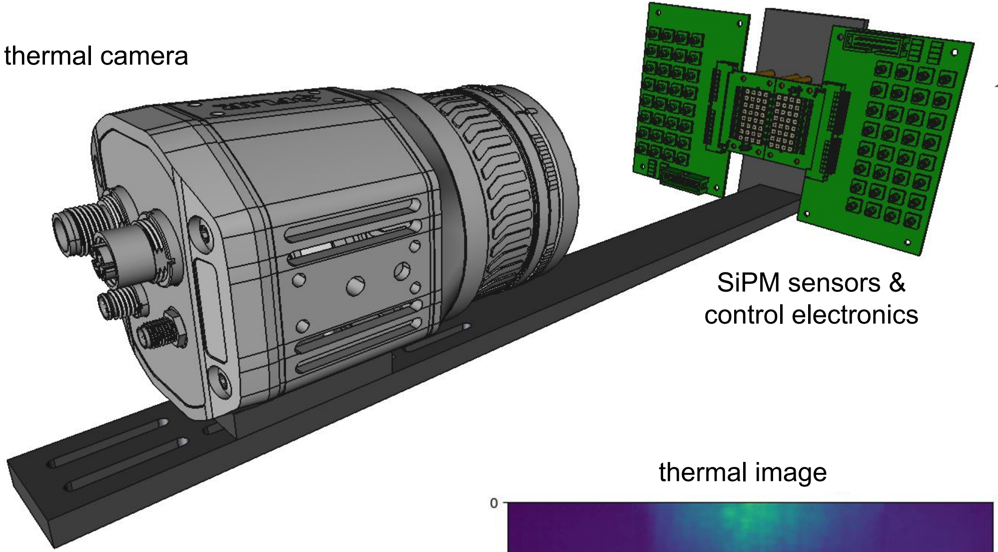


detailed studies are ongoing, preliminary results indicate efficiency loss after 100 hours of annealing at T = 175 C. lower temperatures unaffected up to 150 hours

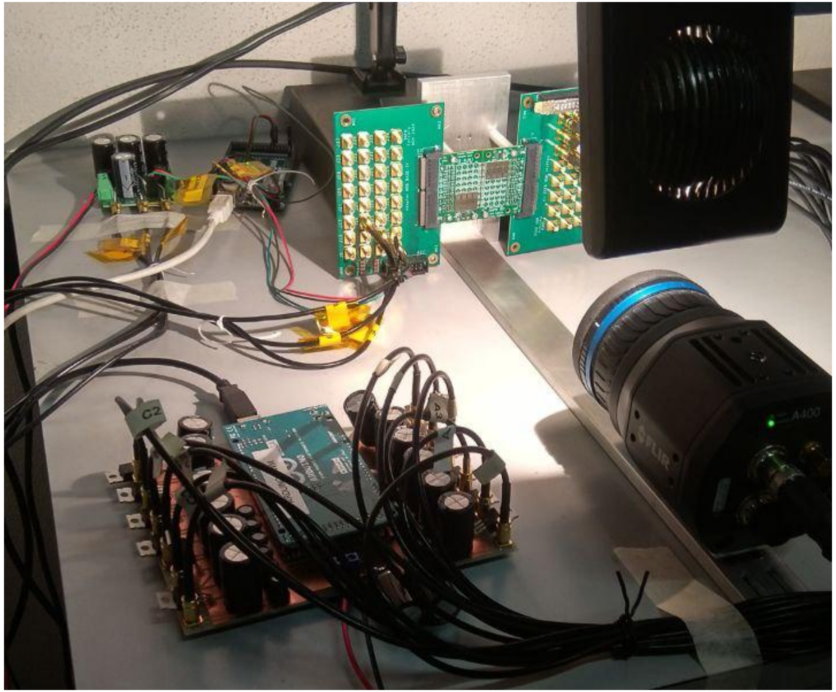
Automated multiple SiPM online self-annealing

system for online self-annealing with temperature monitor and control of each individual SiPM

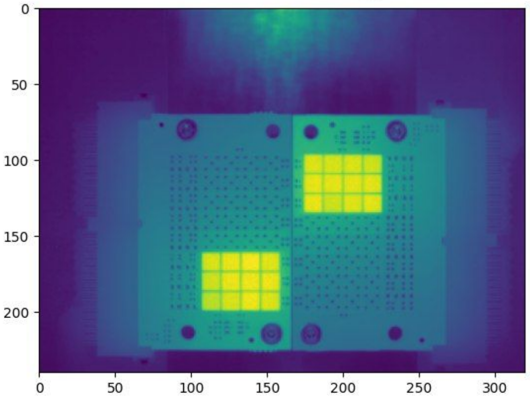
thermal camera



SiPM sensors & control electronics



thermal image



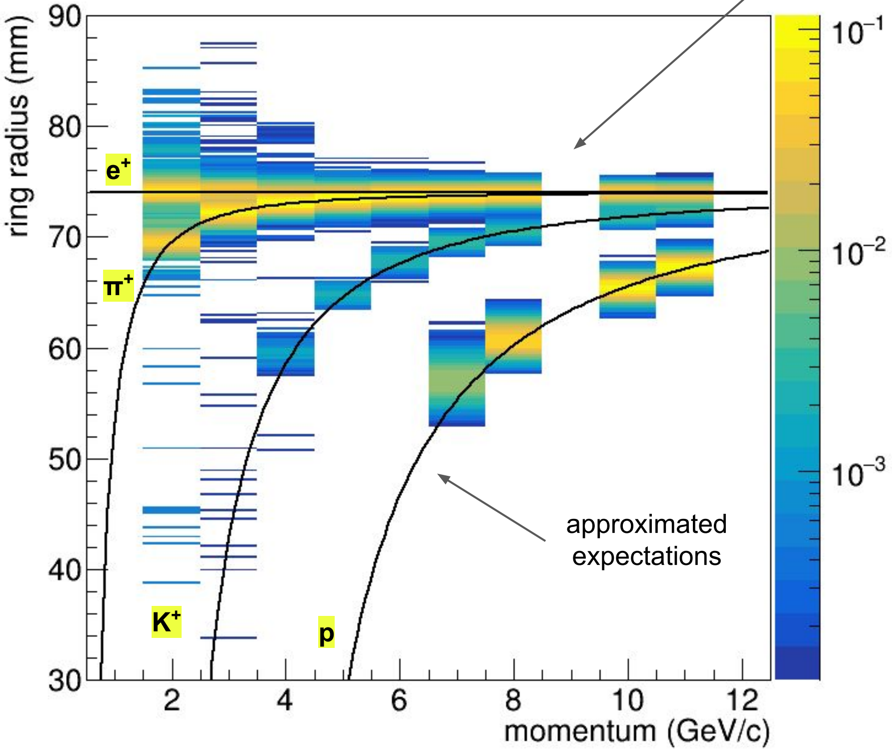
monitor and logging system

Beam momentum scan

positive particles, aerogel only

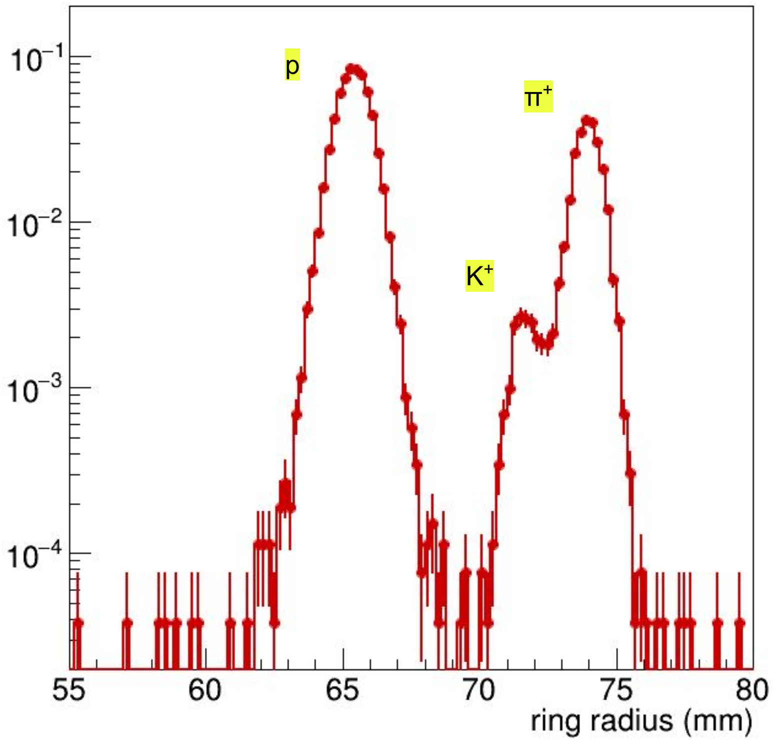
something went wrong with the beam configuration for 9 GeV
(that's a pity, data seems not good)

reconstructed radii vs. beam momentum



approximated expectations

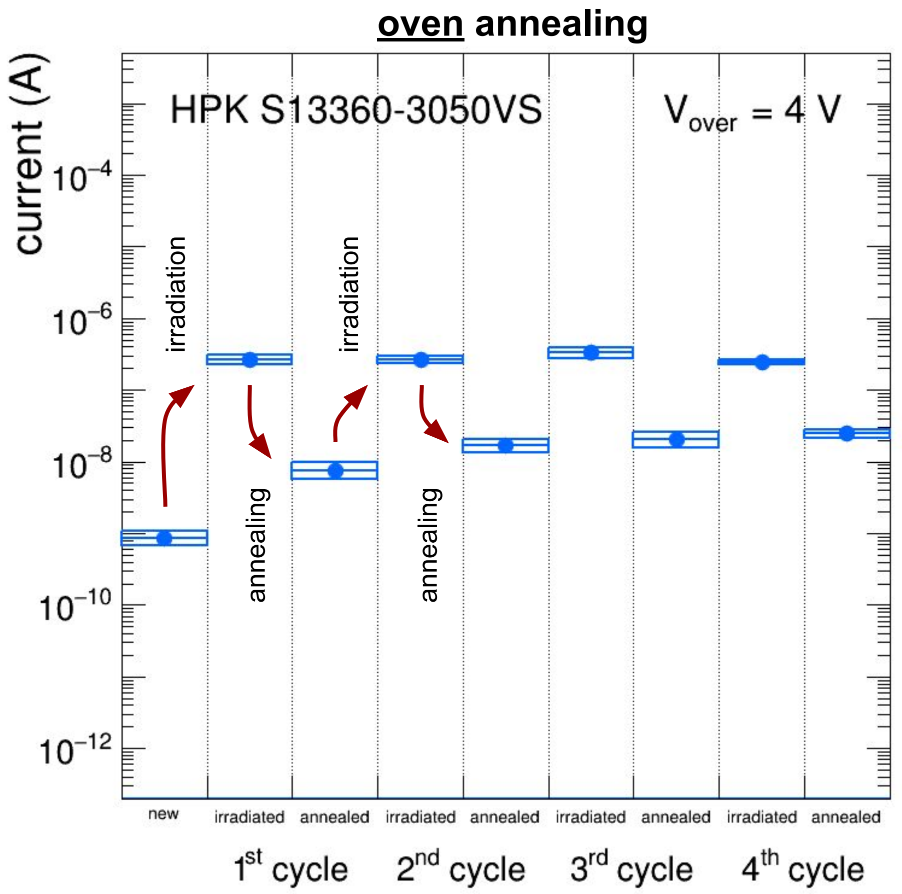
reconstructed ring radius at 10 GeV/c beam momentum



nice!

asdasdasd

Repeated irradiation-annealing cycles



test reproducibility of repeated irradiation-annealing cycles

simulate a realistic experimental situation

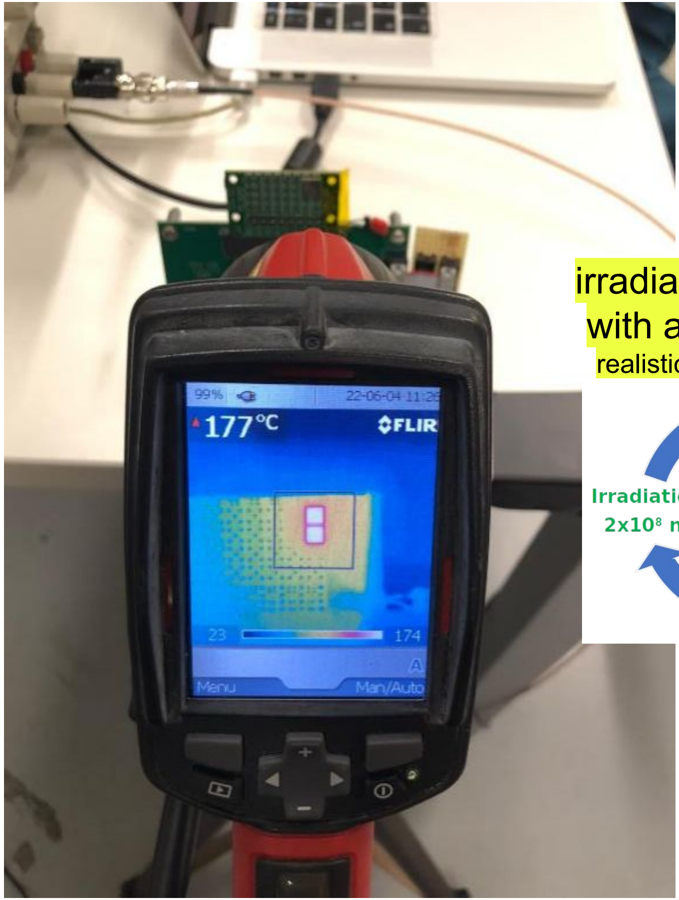
- consistent irradiation damage
  - DCR increases by ~ 500 kHz (@ Vover = 4)
  - after each shot of 10^9 n_{eq}
- consistent residual damage
  - ~ 15 kHz (@ Vover = 4) of residual DCR
  - builds up after each irradiation-annealing

annealing cures same fraction of newly-produced damage

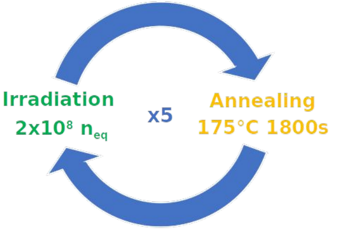
~ 97% for HPK S13360-3050 sensors

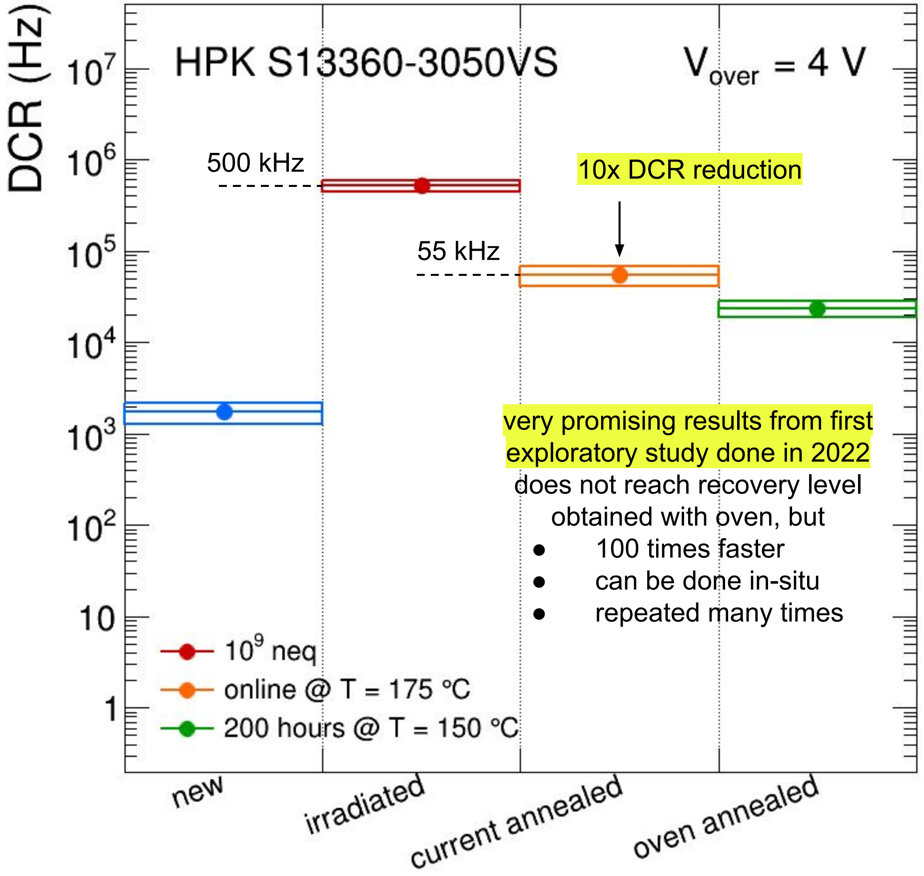
"Online" self-induced annealing

studies for "in-situ" SiPM recovery
multiple cycles: 30 minutes at 175 C
~ 1 W power/sensor delivered with forward bias voltage



irradiation interleaved with annealing cycle
realistic experimental case

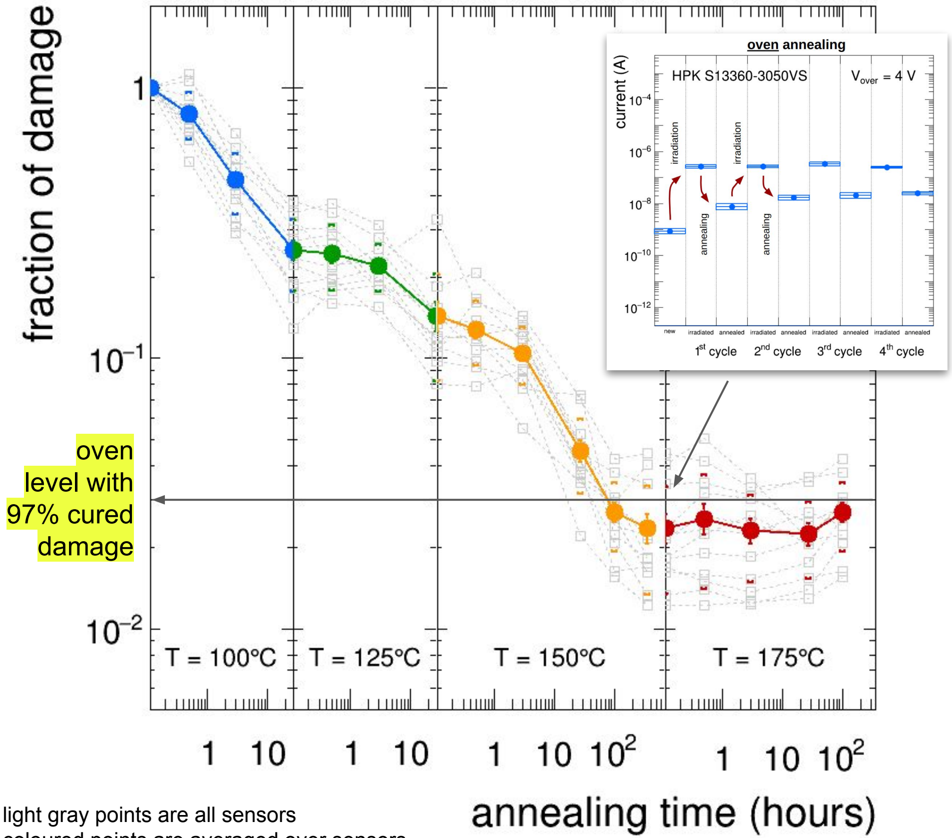




very promising results from first exploratory study done in 2022
does not reach recovery level obtained with oven, but
- 100 times faster
- can be done in-situ
- repeated many times

Detailed studies of SiPM online self-annealing

online self-annealing with forward bias



light gray points are all sensors
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coloured brackets is the RMS

test on a large number SiPM sensors how much damage is cured as a function of temperature and time

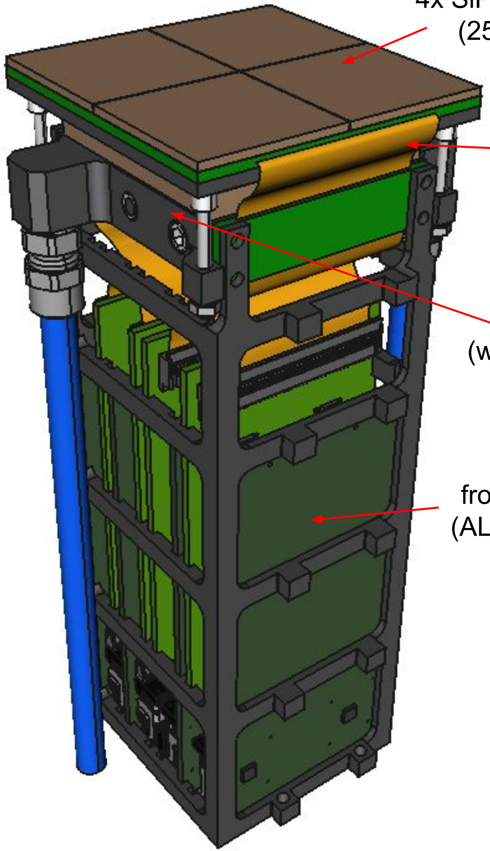
the same sensors have undergone self-annealing
increasing temperature steps
increasing integrated time steps

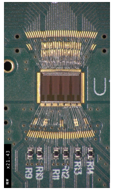
- started with T = 100 C annealing
  - performed 4 steps up to 30 hours integrated
- followed by T = 125, 150 and 175 C

fraction of residual damage seems to saturate at 2-3% after ~ 300 hours at T = 150 C

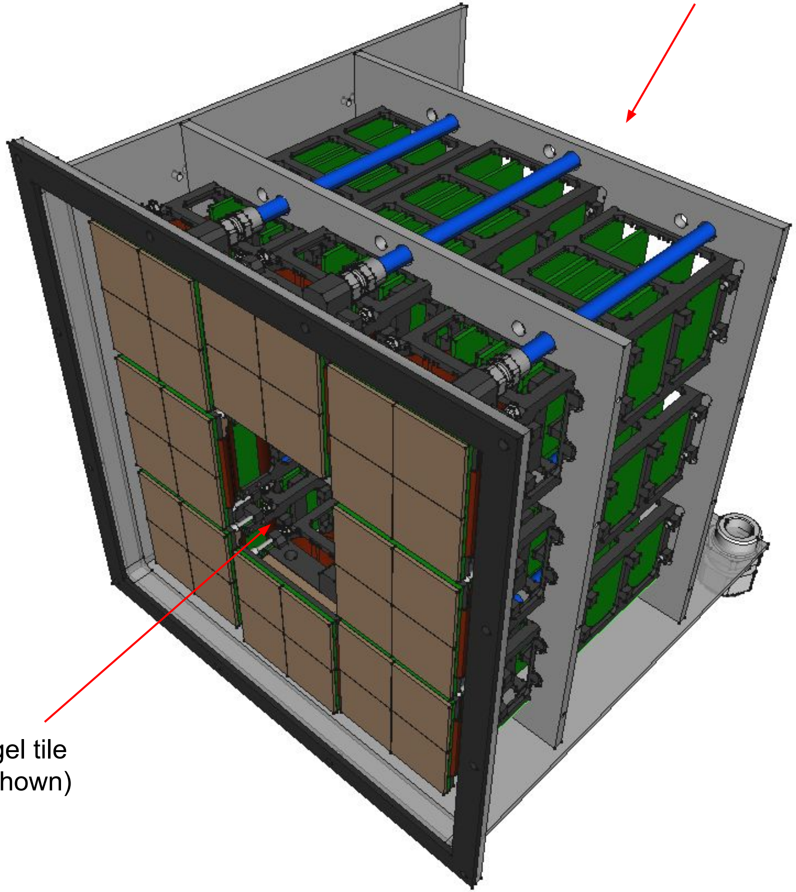
continuing at higher T = 175 C seems not to cure more than that

EIC ePIC-dRICH SiPM photodetector prototype





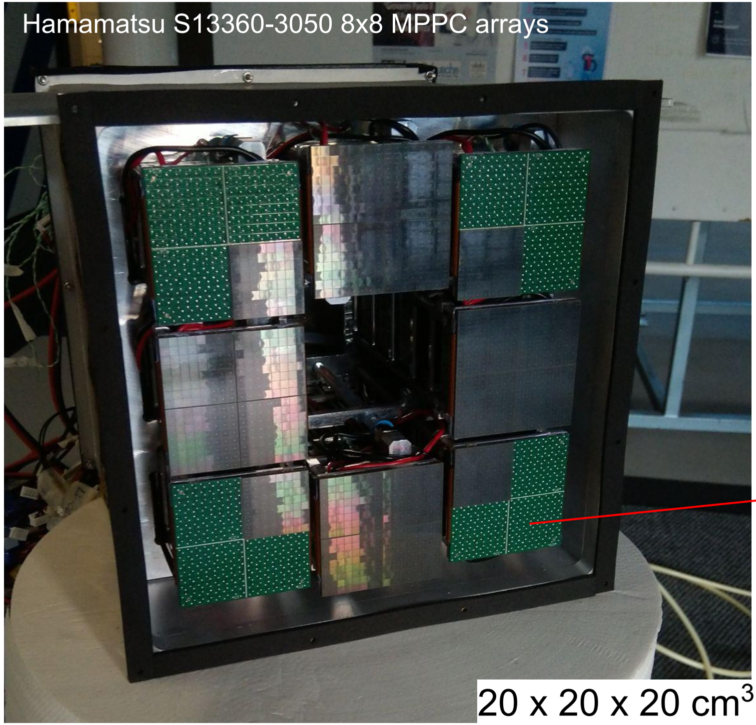
PhotoDetector Unit (PDU)



Readout Box

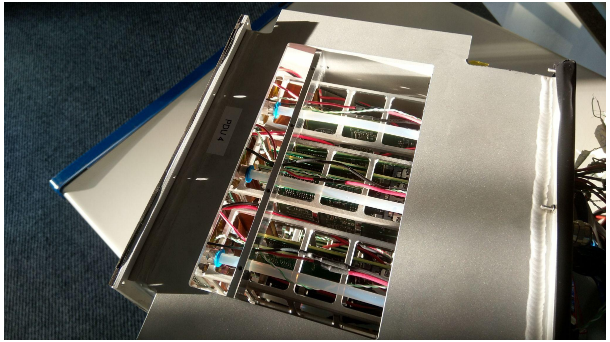
dRICH SiPM photodetector prototype in 2023

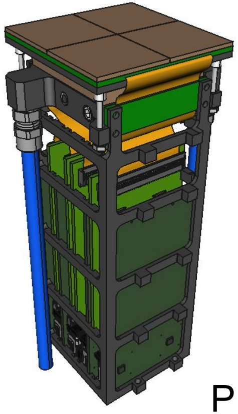
Readout Box (front)



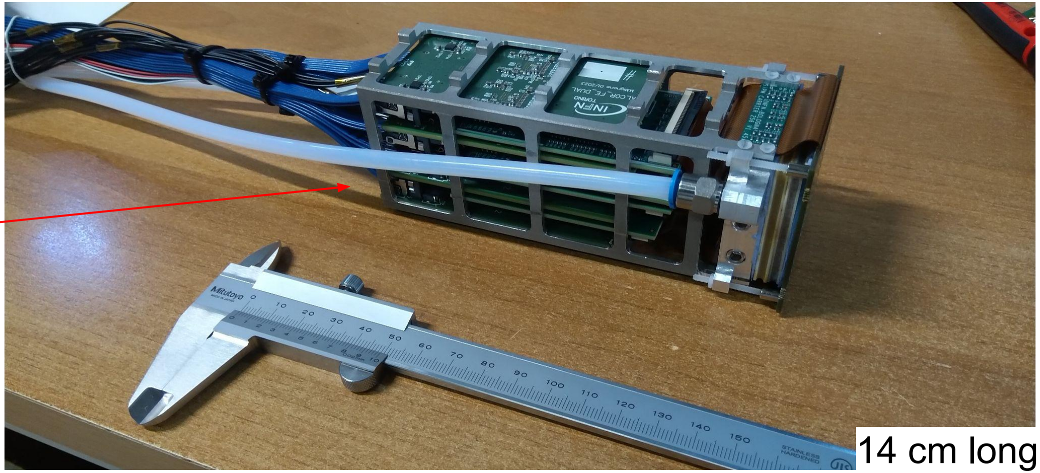
20 x 20 x 20 cm^3

(top)





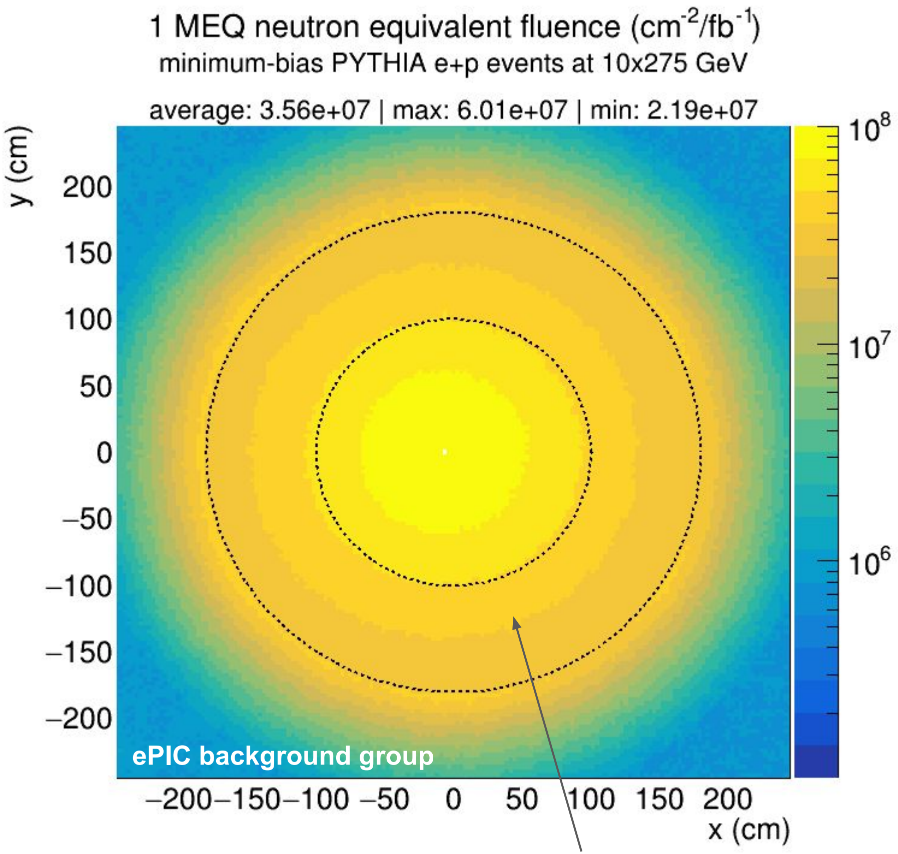
PDU



14 cm long

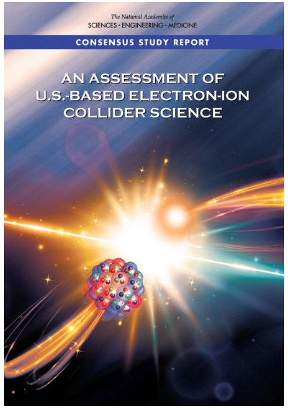
partially-equipped, 1280-channels SiPM readout surface with cooling and TDC electronics

Radiation damage estimates



max fluence = 6.38 10^7 neq/fb^{-1} at the location of dRICH photosensors

Most of the key Physics goals defined by the NAS require an integrated luminosity of 10 fb^{-1} per center of mass energy and polarization setting



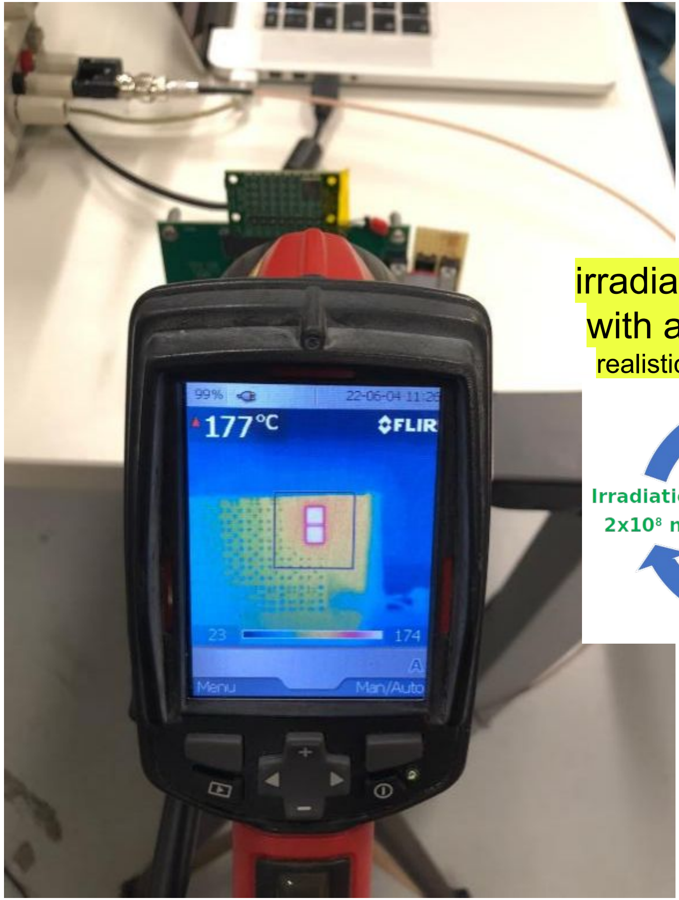
The nucleon imaging programme is more luminosity hungry and **requires 100 fb^{-1} per center of mass energy and polarization setting**

over the years the EIC will accumulate 1000 fb^{-1} integrated $\mathcal{L}$ corresponding to an integrated fluence of ~ 6 10^{10} n_{eq}/cm^2

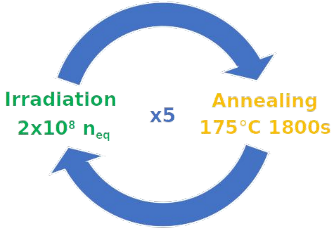
study the SiPM usability for single-photon Cherenkov imaging applications in moderate radiation environment

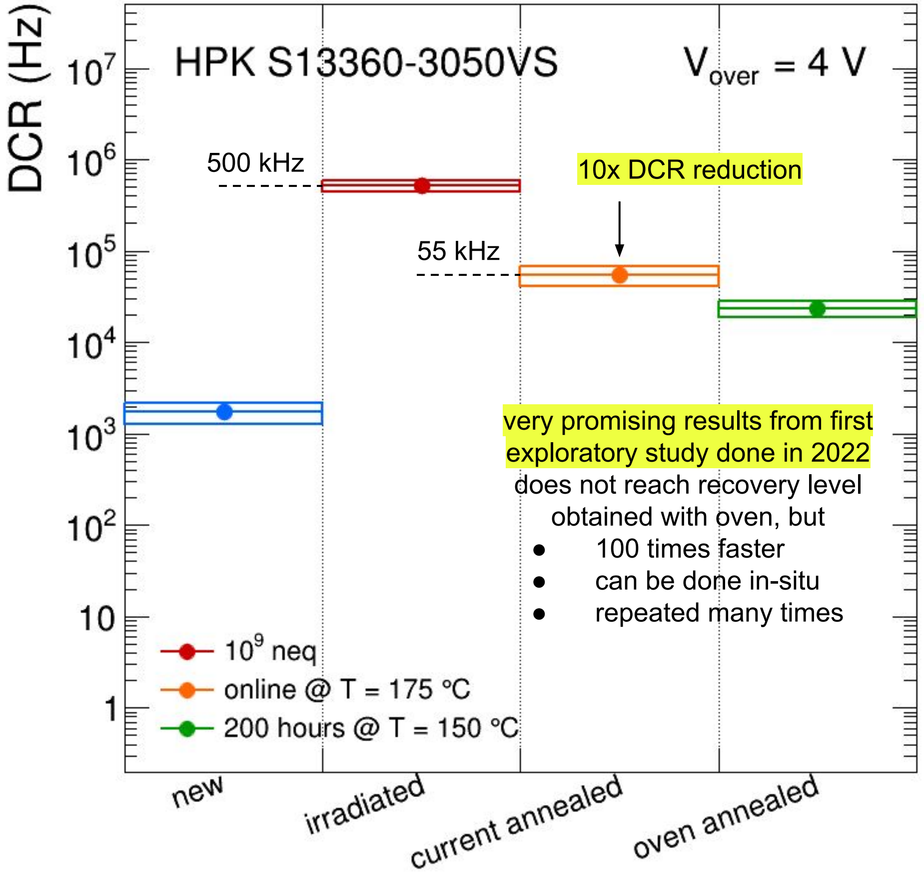
“Online” self-induced annealing

studies for “in-situ” SiPM recovery
multiple cycles: 30 minutes at 175 C
~ 1 W power/sensor delivered with forward bias voltage



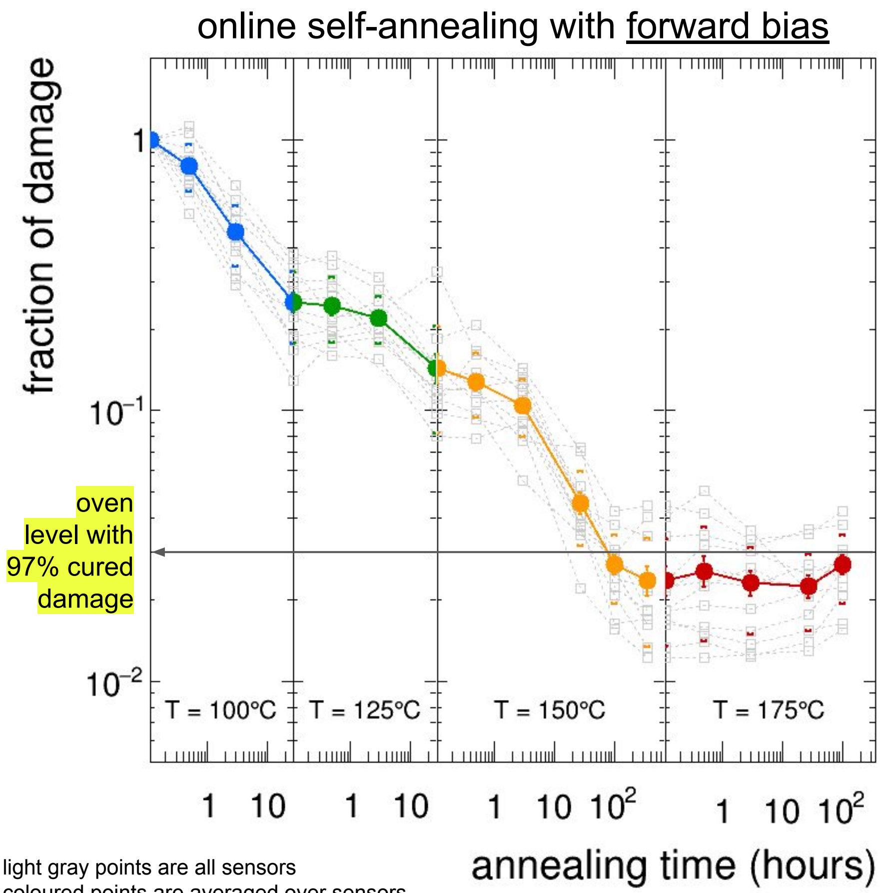
irradiation interleaved with annealing cycle
realistic experimental case





very promising results from first exploratory study done in 2022
does not reach recovery level obtained with oven, but
- 100 times faster
- can be done in-situ
- repeated many times

Detailed studies of SiPM online self-annealing



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

test on a large number SiPM sensors how much damage is cured as a function of temperature and time

the same sensors have undergone self-annealing
increasing temperature steps
increasing integrated time steps

- started with T = 100 C annealing
  - performed 4 steps up to 30 hours integrated
- followed by T = 125, 150 and 175 C

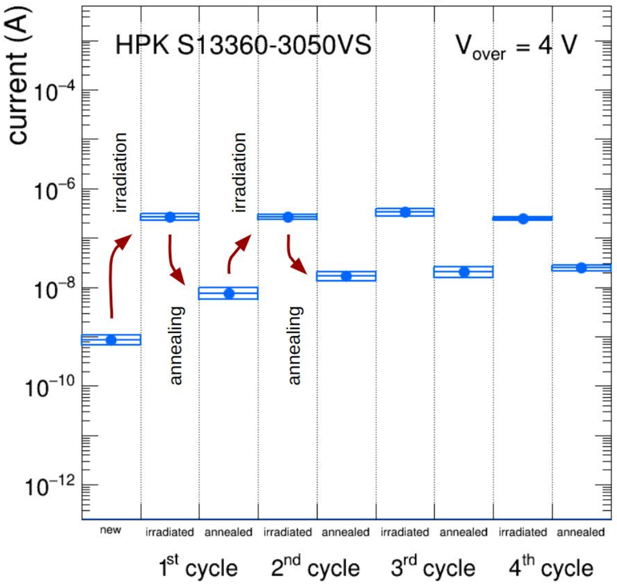
fraction of residual damage seems to saturate at 2-3% after ~ 300 hours at T = 150 C

continuing at higher T = 175 C seems not to cure more than that

Ageing model

repeated irradiation-annealing cycles

simulate realistic experimental situation



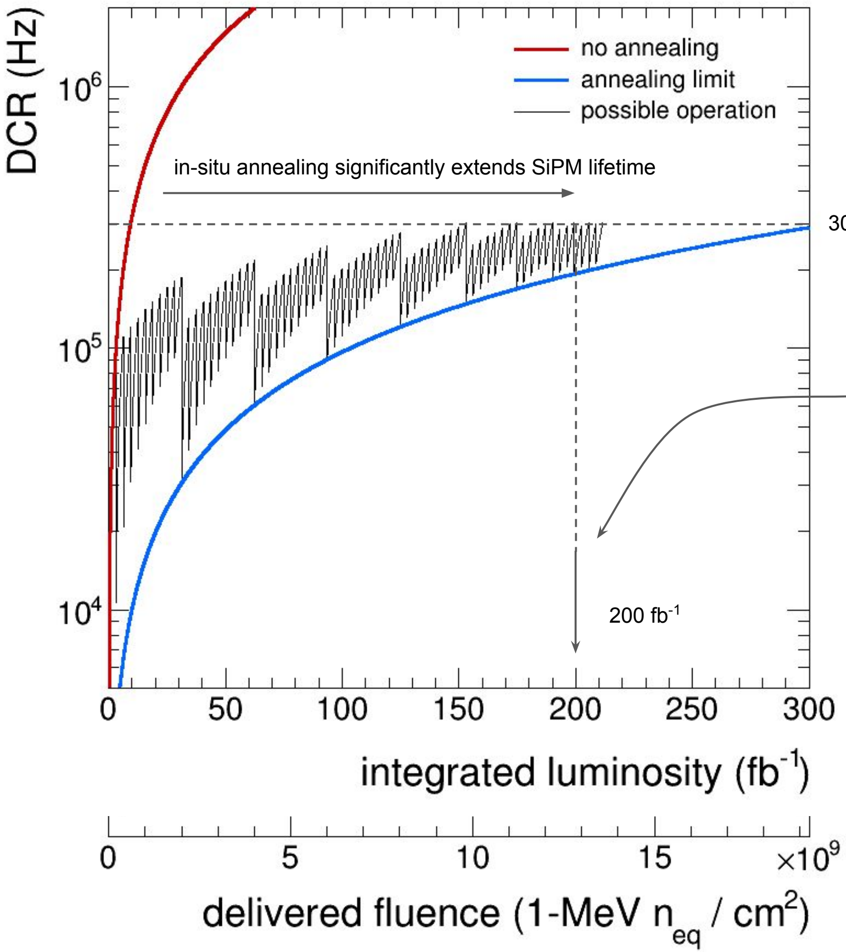
model input from R&D measurements done in 2022

- DCR increase: 500 kHz/10^9 n_{eq}
- residual DCR (fast annealing): 50 kHz/10^9 n_{eq}
- residual DCR (full annealing): 15 kHz/10^9 n_{eq}

1-MeV neq fluence from background group

- 6.38 10^7 n_{eq} / fb^{-1}

Hamamatsu S13360-3050 @ Vover = 4 V, T = -30 C



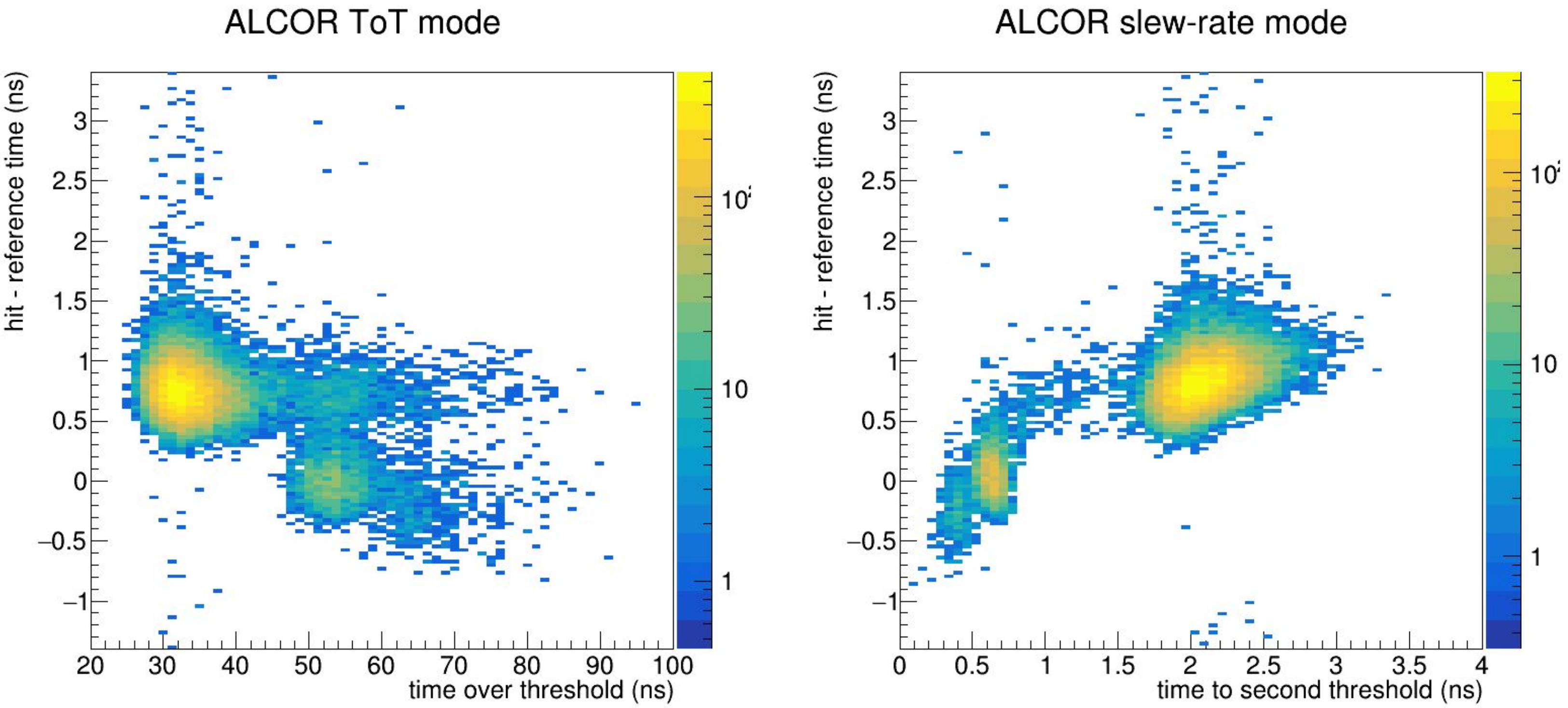
safe single-channel DCR for optimal Physics performance
~ 10 noise hits / sector within 500 ps

beyond 200 fb^{-1} without need of touching/replacing SiPM
working on optimisation of annealing protocol, maybe one could reach beyond that

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

Slew-rate vs. ToT mode

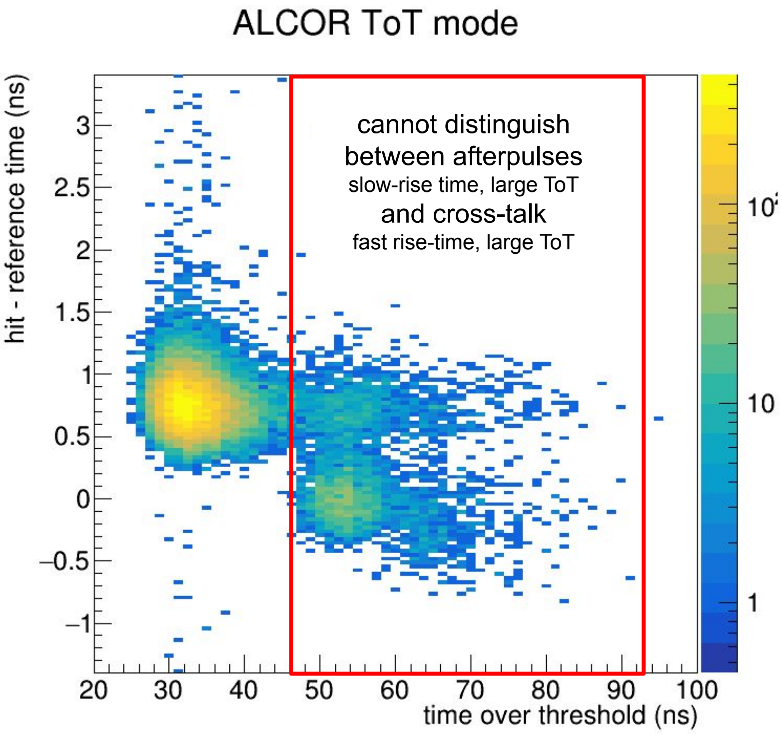
working with fixed threshold electronics

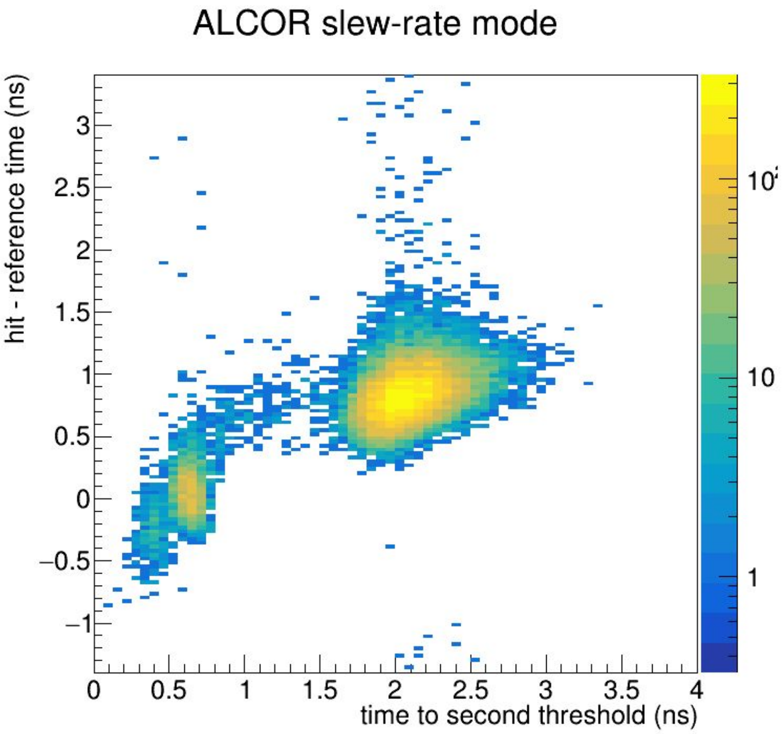


after correction for laser yield and background light, measurements of sensor under study are compatible

Slew-rate vs. ToT mode

working with fixed threshold electronics

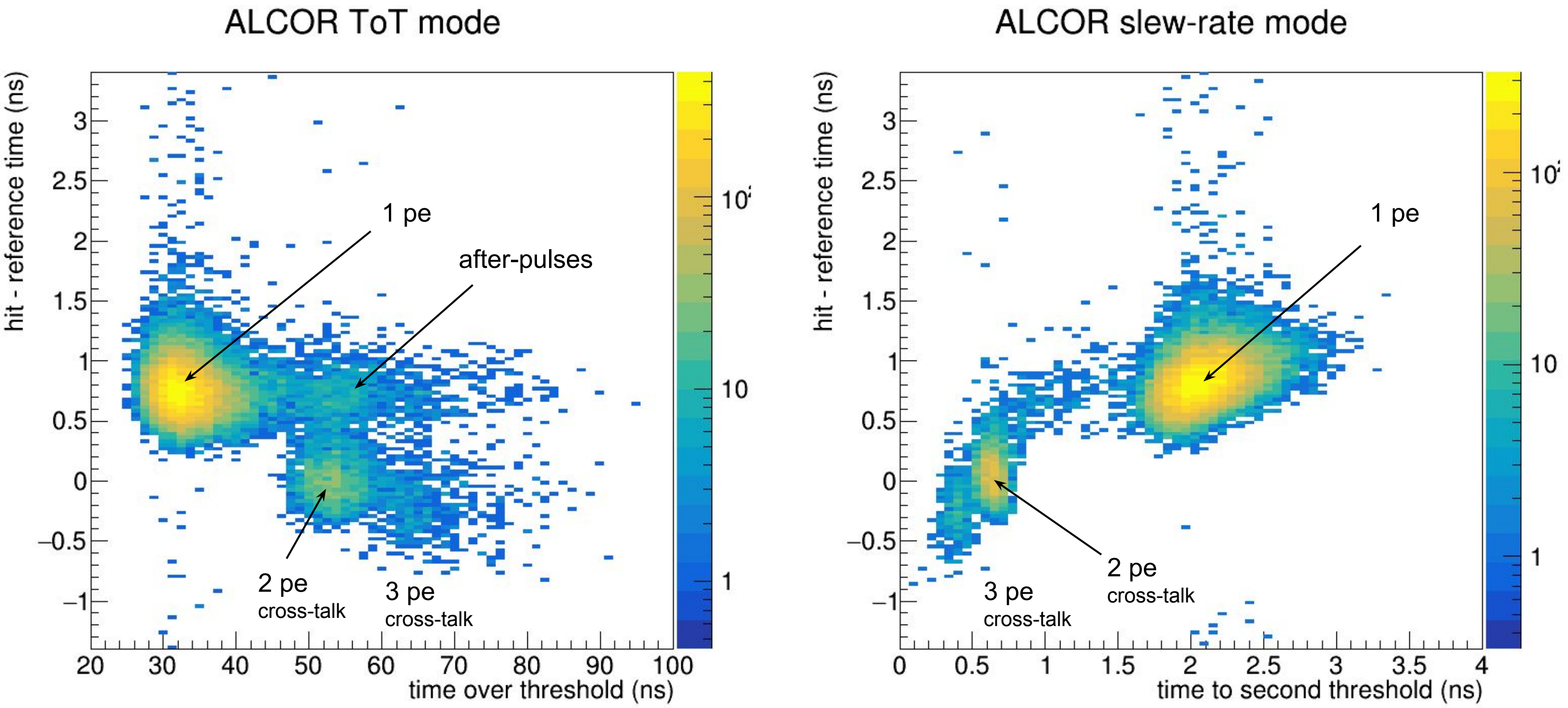




after correction for laser yield and background light, measurements of sensor under study are compatible

Slew-rate vs. ToT mode

several measurements repeated on the same NEW sensor

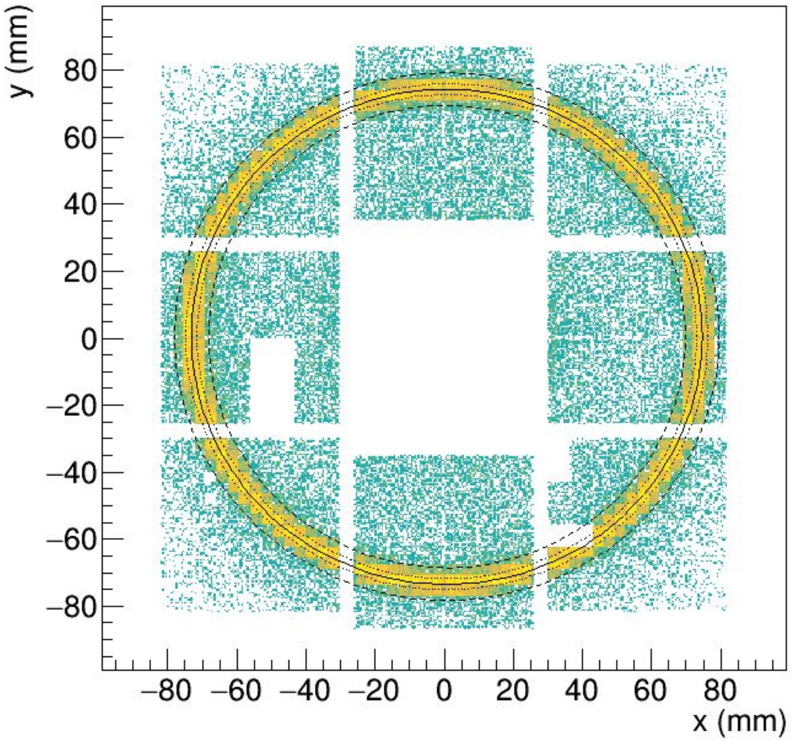


after correction for laser yield and background light, measurements of sensor under study are compatible

Number of photoelectrons

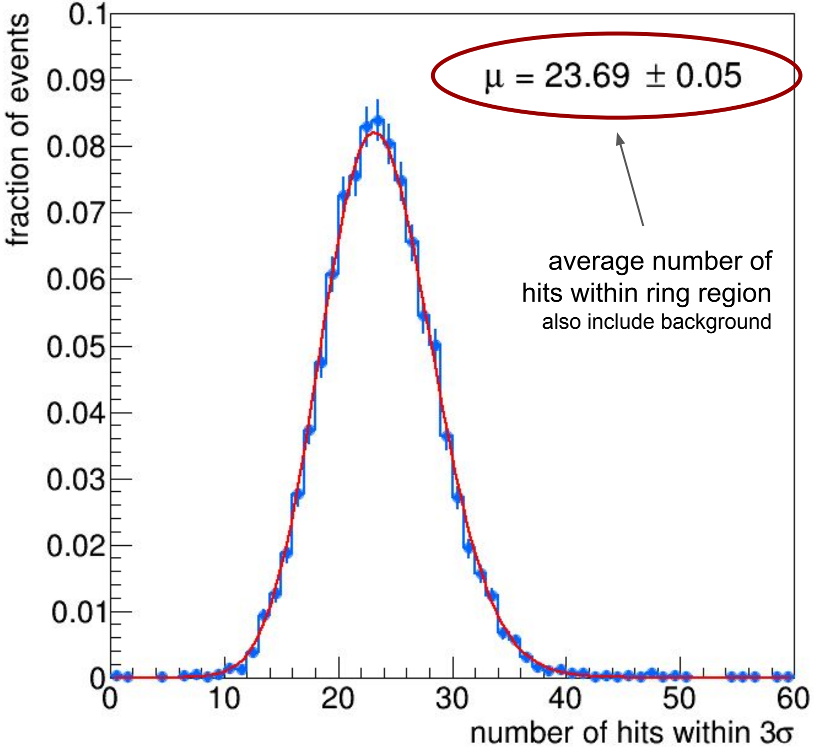
even-by-event photon counting in the ring

11.5 GeV/c negative beam, n = 1.02 aerogel (accumulated events)



2D fit to accumulated data with realistic model (ring + background)

event-by-event distribution of hits in the ring



Poisson fit to data, average number of hits is large