Development and performance of the dRICH SiPM-based photodetector for the ePIC experiment at the EIC

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On behalf of the ePIC-dRICH collaboration

22/09/2025

The Electron-Ion Collider

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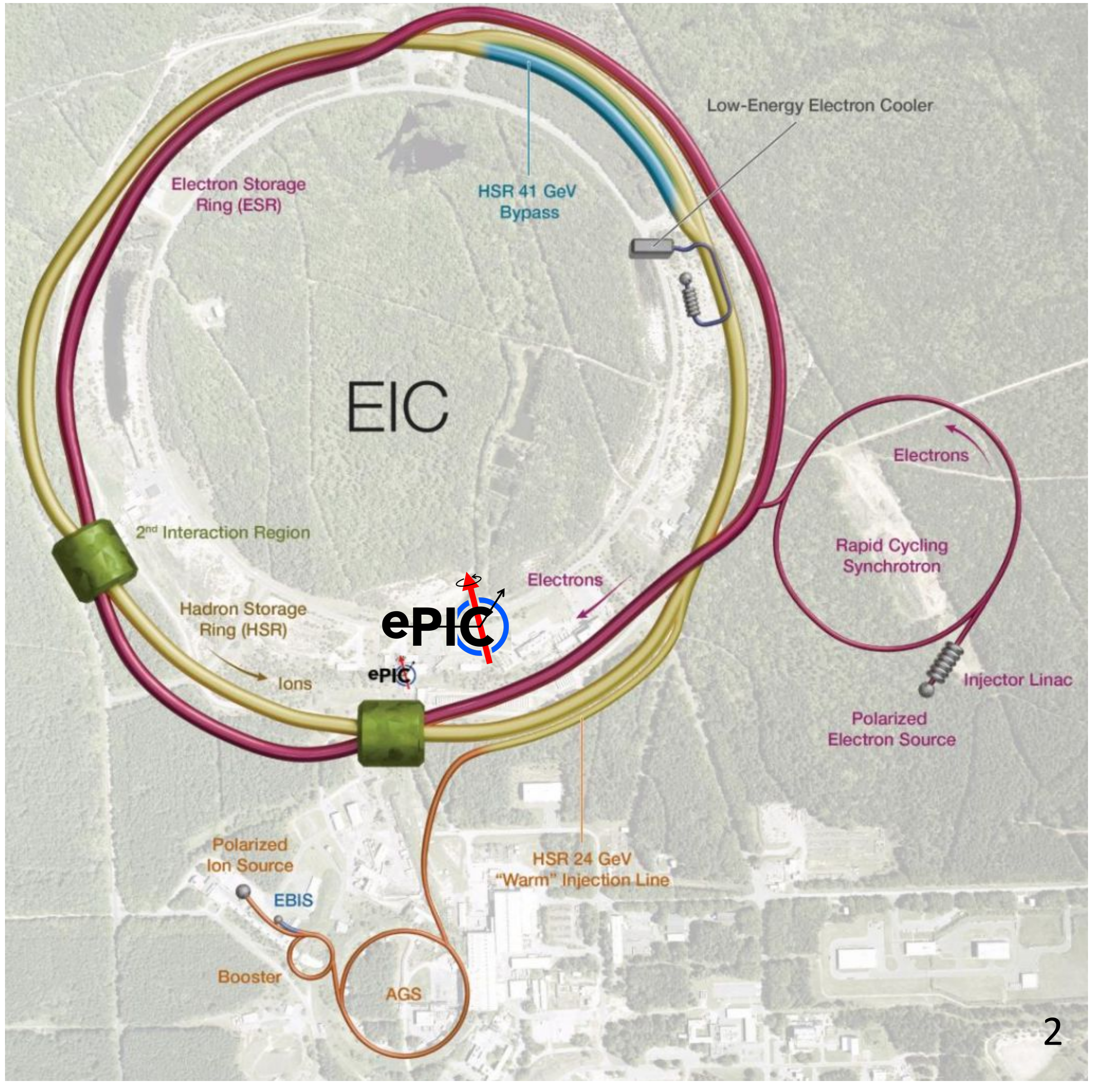
Next generation electron-proton and electron-ion collider machine planned at Brookhaven National Laboratory **BNL** (USA):

- Operations will start in early 2030's
- Designed to probe the secrets of the strong force

Key Features and goals

- First collider providing:
  - Polarized electron-proton (and light ion) beams
  - electron-nucleus collisions
- Precision tests of Quantum Chromodynamics (QCD):
  - Origin of nucleon mass & spin from quarks and gluons
  - 3D mapping of nucleon and nuclear structure
  - Deeper understanding of quark-gluon confinement into hadrons



*http://www.bnl.gov/eic

The ePIC experiment

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Physics requirements for PID:

- pion, kaon and proton ID
- cover a wide range in pseudo-rapidity, $|\eta| \leq 3.5$
- with better than 3σ separation
- significant pion/electron suppression

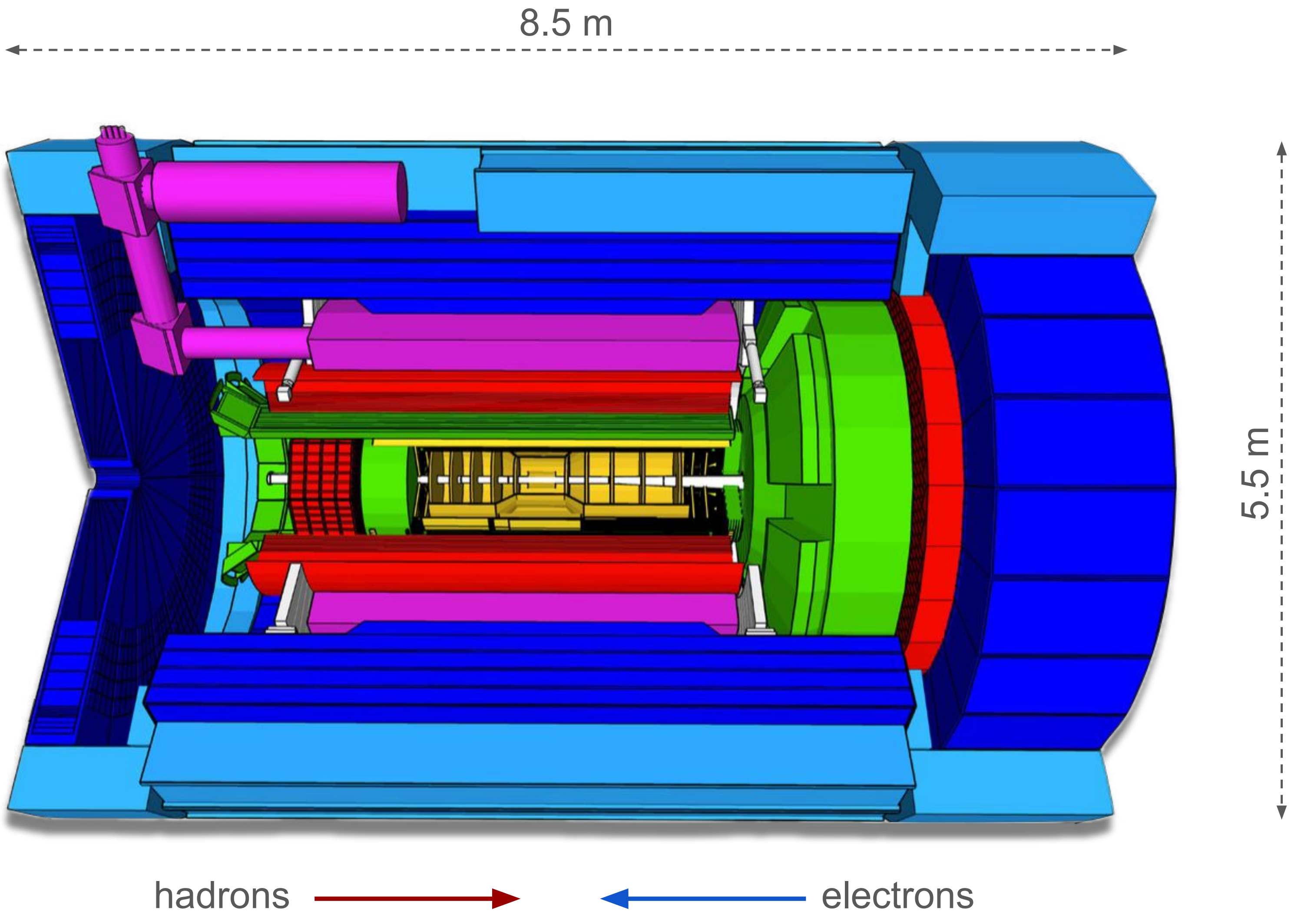
Hadronic Calorimeters

Particle Identification

Solenoid Magnet

Tracking

Electromagnetic Calorimeters



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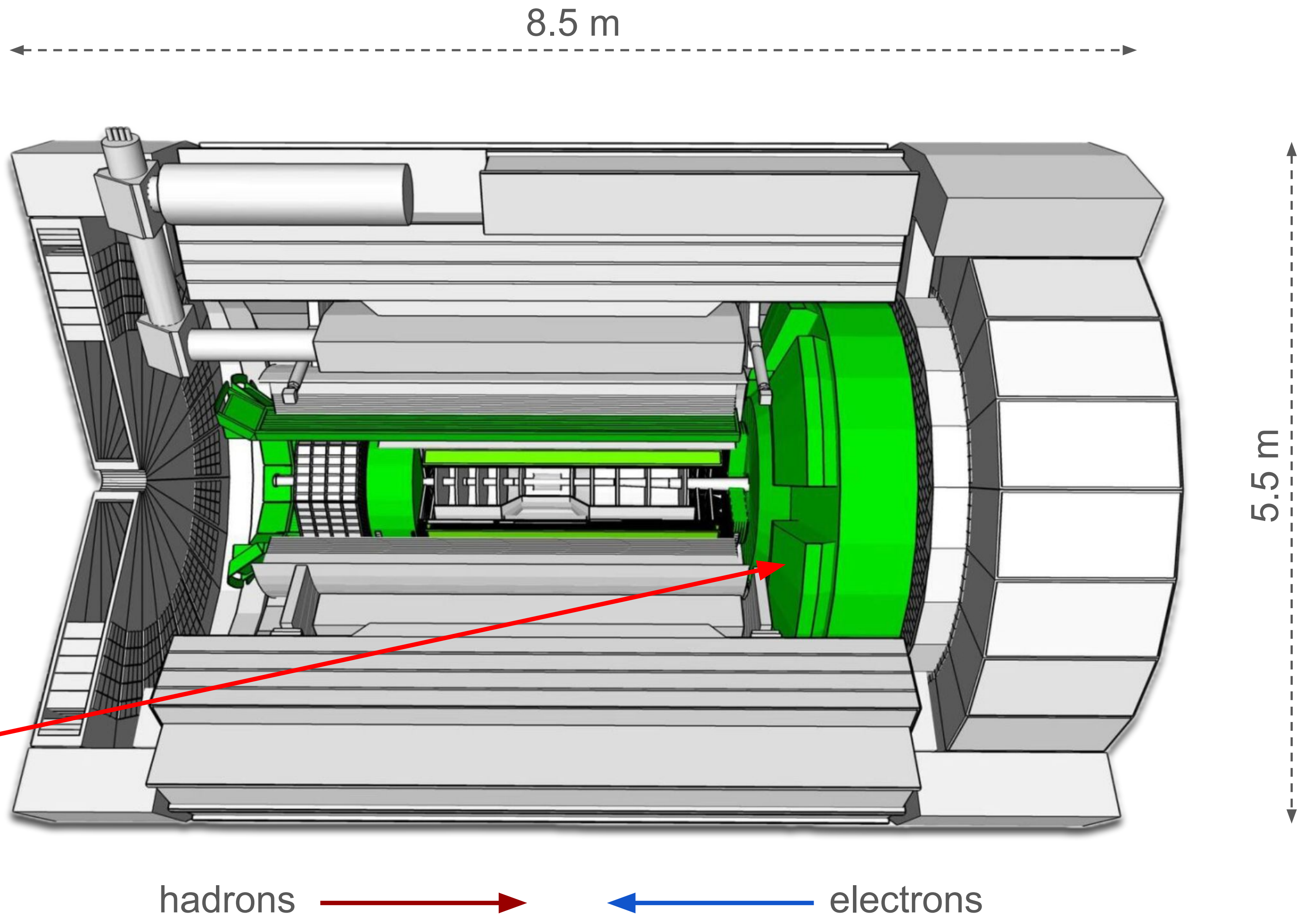
- **particle ID**
  - AC-LGAD TOF
  - pfRICH
  - hpDIRC
  - **dRICH**

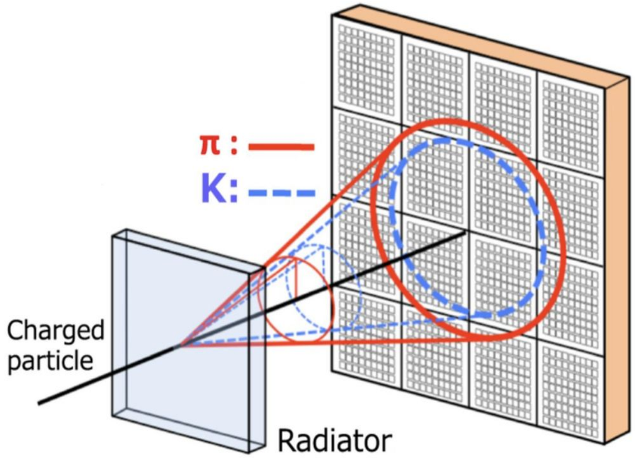


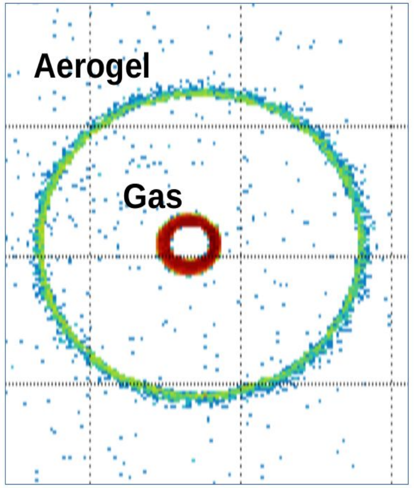
The ePIC dRICH

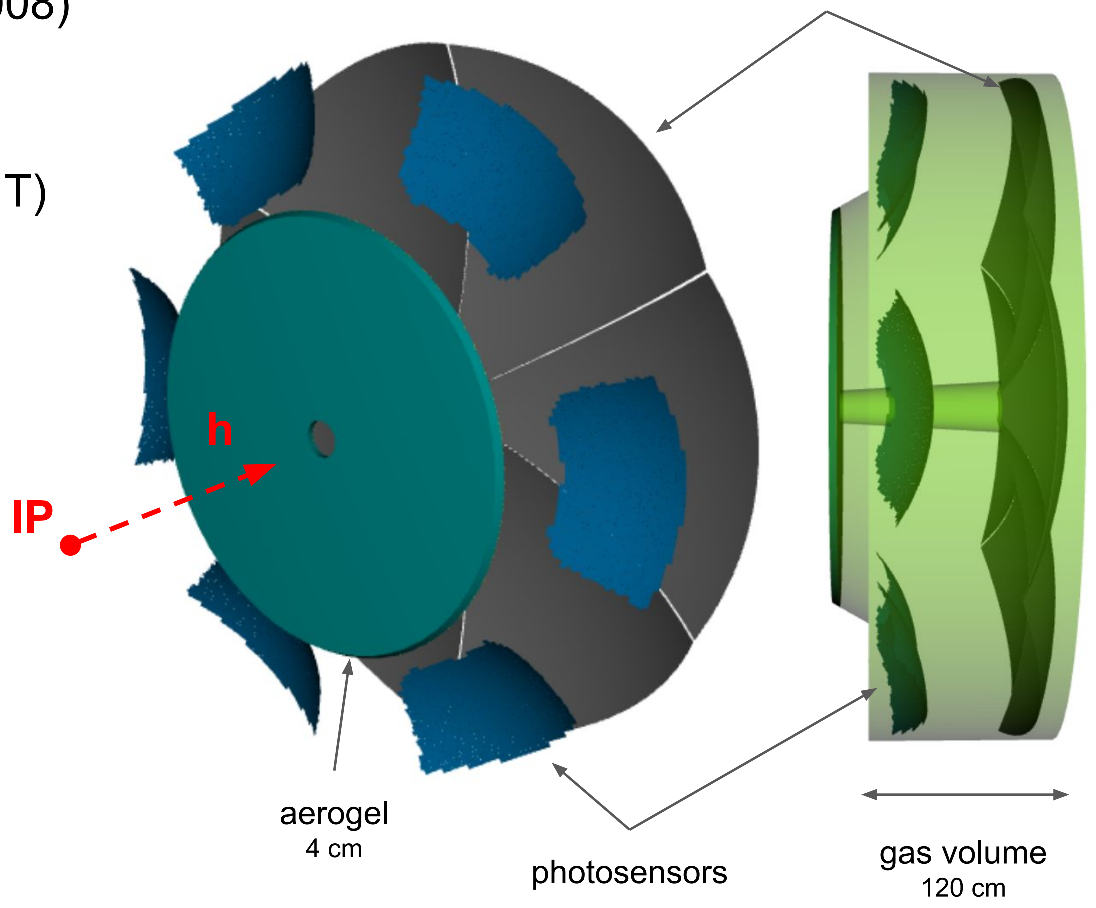
p = [3.0, 50] GeV/c
η = [1.5, 3.5]
e-ID up to 15 GeV/c

The ePIC dual-radiator (dRICH) will perform forward PID at the EIC

- **two 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
  - optical readout: **SiPM**







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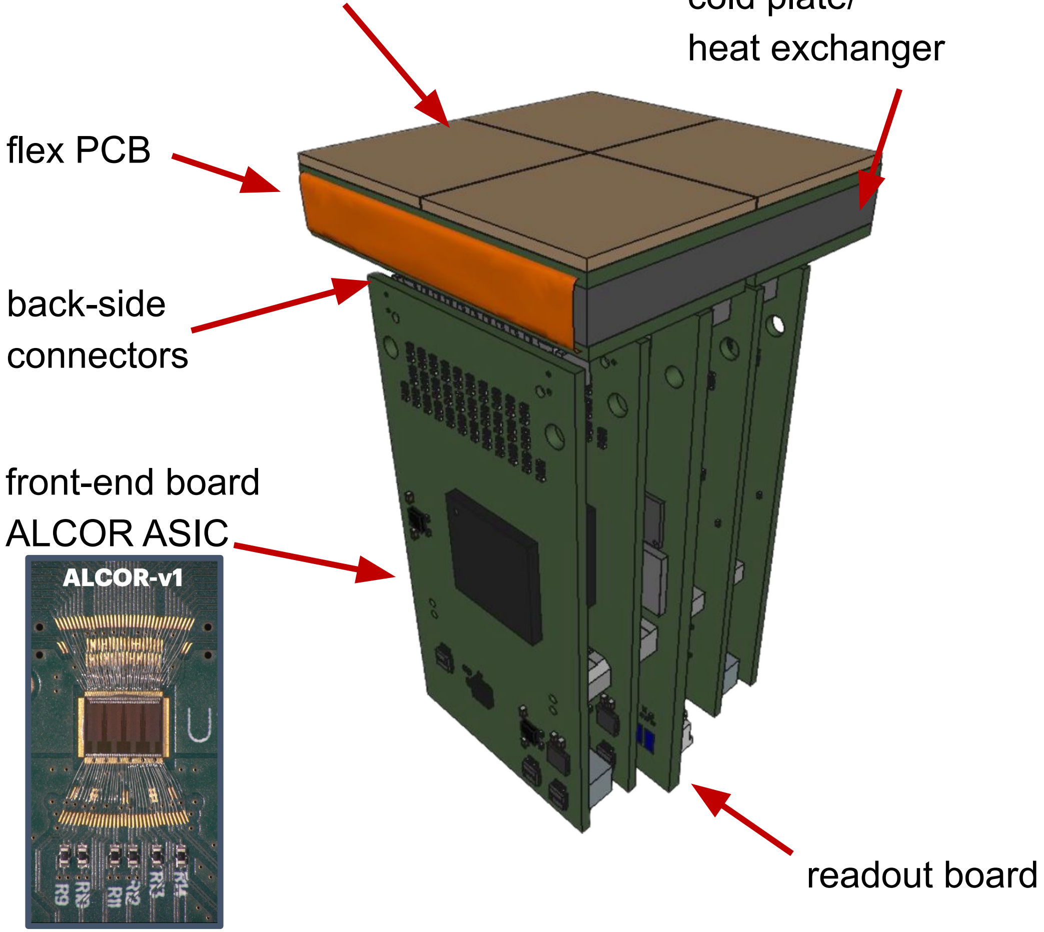
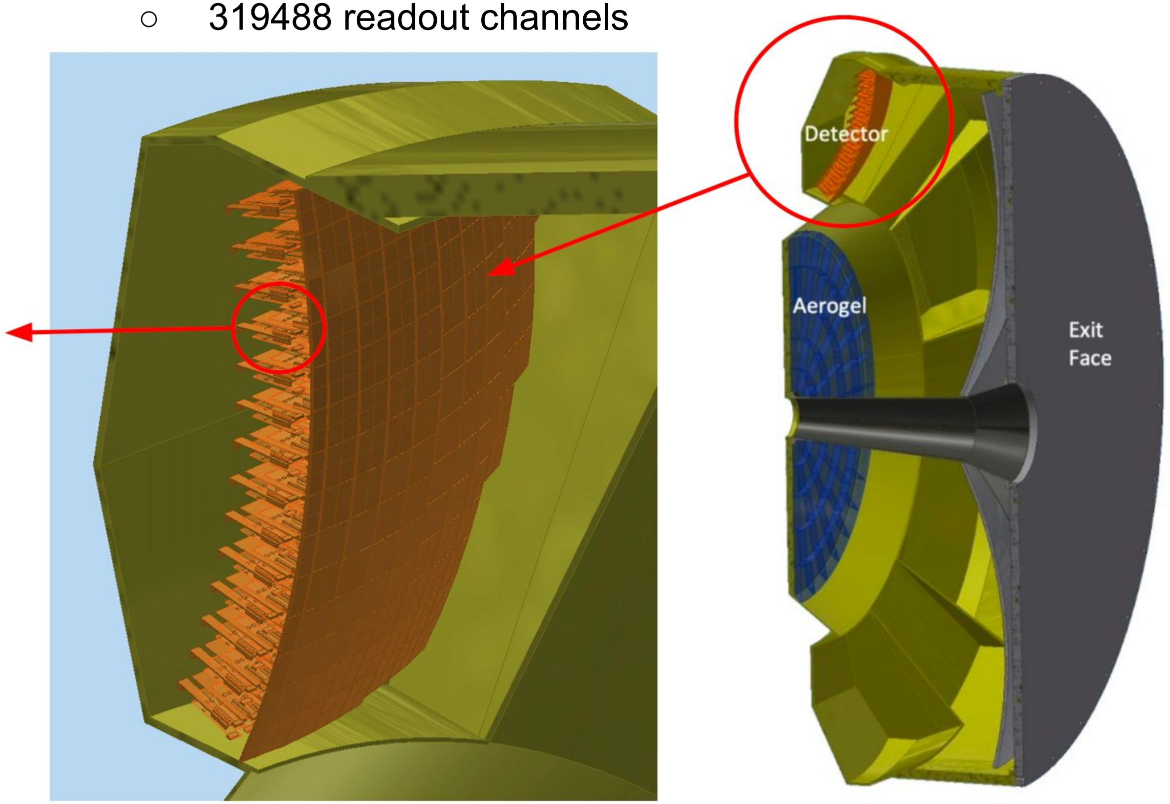
Detector integration and electronics

Photodetector unit (PDU) - conceptual design



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



SiPM for the dRICH optical readout

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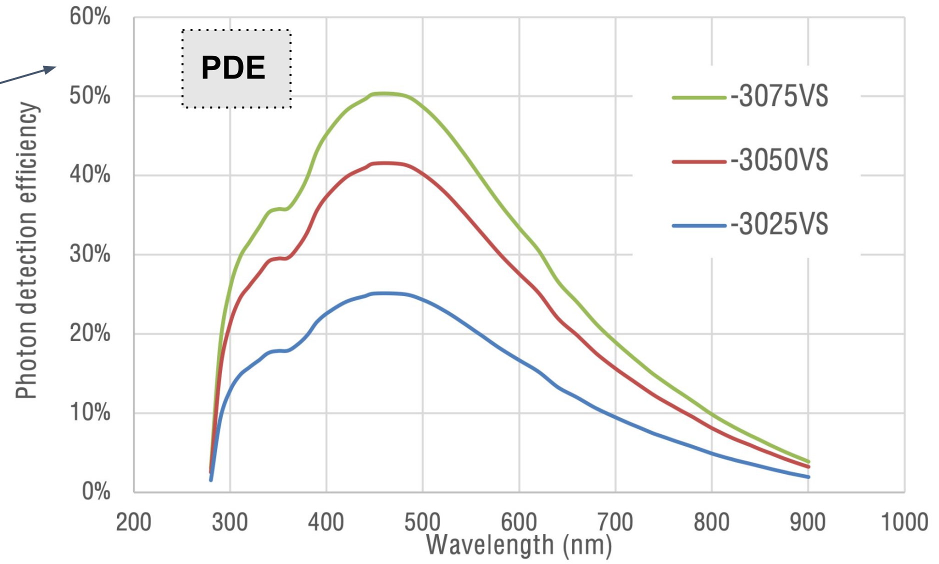
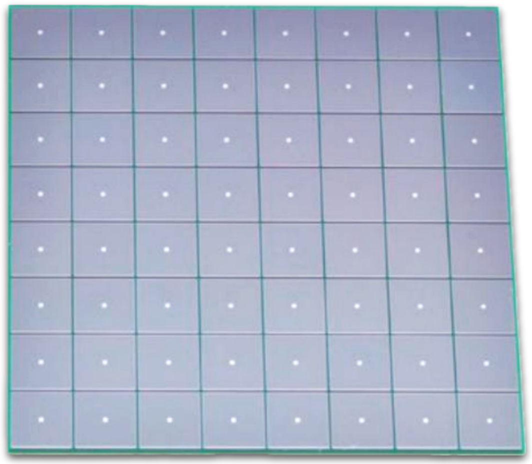
Silicon Photomultiplier (SiPM) tecnology:

- Cheap
- High Photon Detection Efficiency (PDE)
- Excellent time resolution
- Insensitive to Magnetic field
- baseline device: 64
  (8x8 channel SiPM array)

- Large dark count rates
- Low radiation tolerance

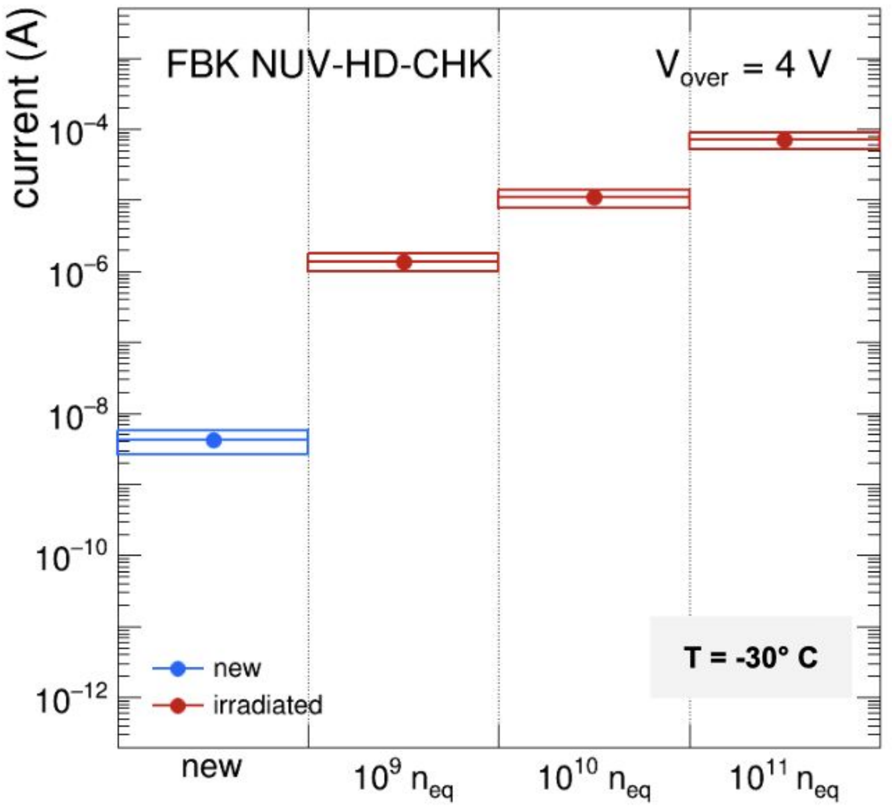
Solutions and mitigation strategies:
Cooling, **Timing** & **annealing**



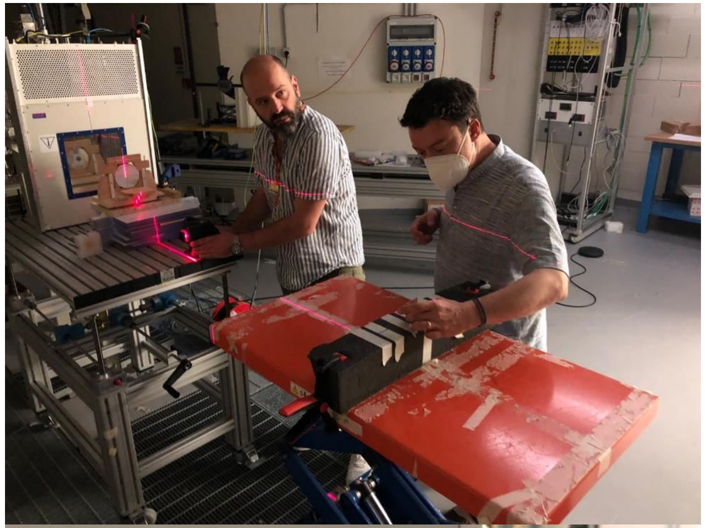


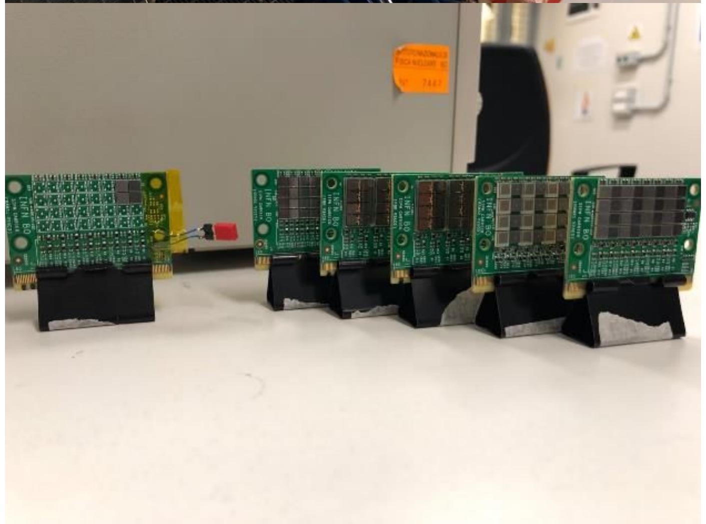
Example device that fulfills requirements
(Hamamatsu TSV S13361 - 3050/75NE-08)

SiPM - studies of radiation damage



- current increases linearly with fluence
- point is the average over several channels
- rectangle represents RMS dispersion





- Proton irradiation campaigns (2021, 2022, 2023 and 2024)
- Neutron irradiation in 2023 and 2024

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

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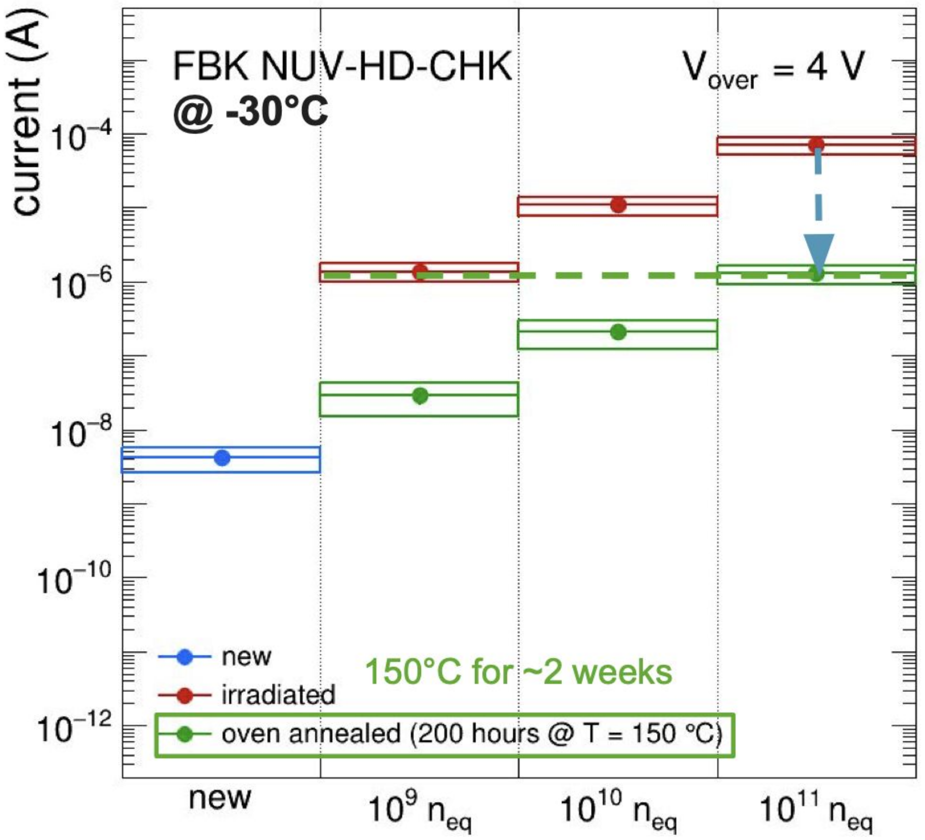
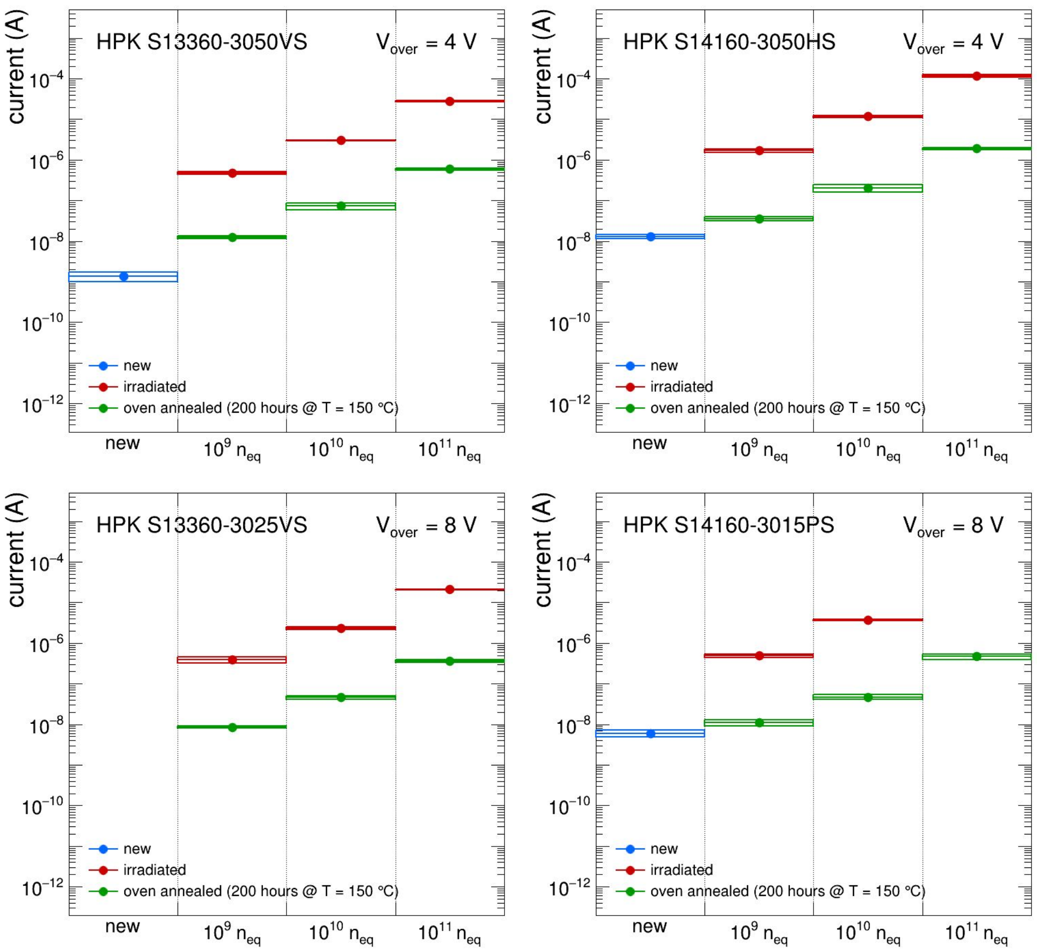
SiPM - high temperature annealing recovery



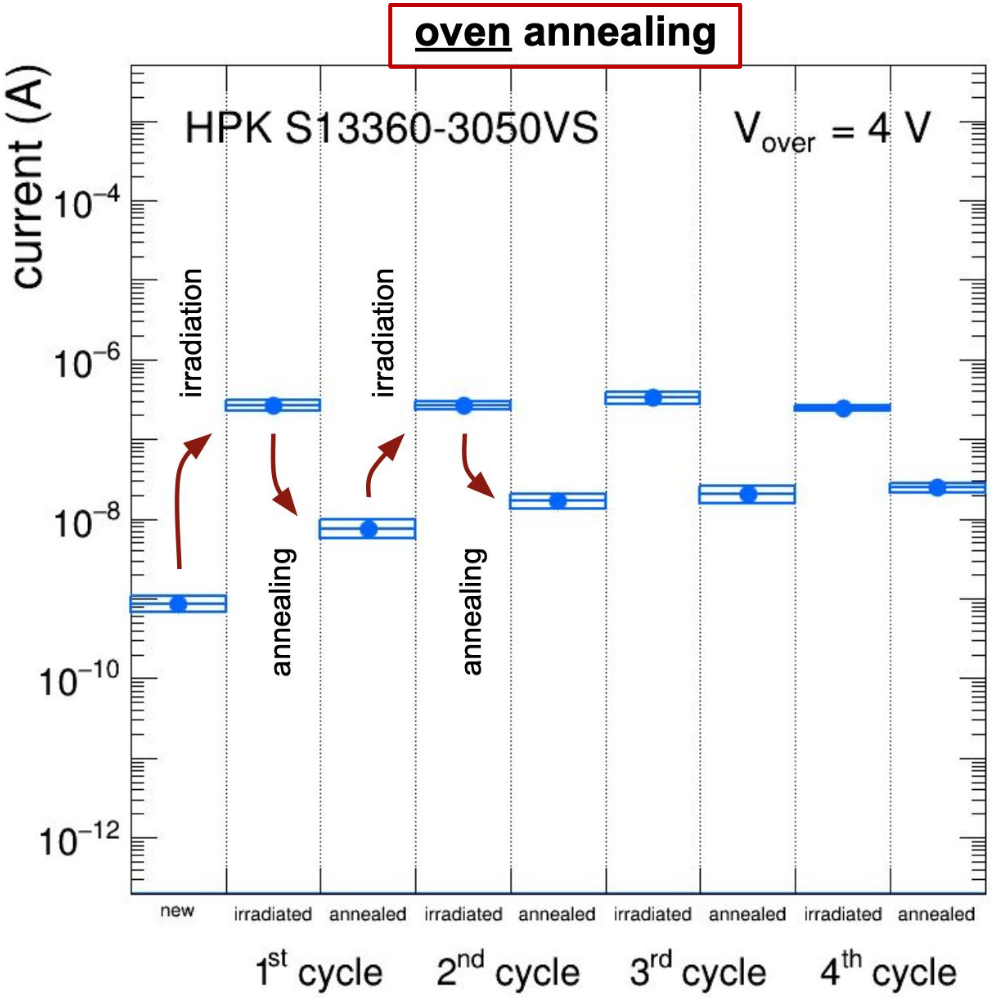
- ~ 100x current reduction
- sensor works as if it received ~ 100x less fluence

Oven annealing: ~ 1 week at 150 C



similar observation with various types of Hamamatsu sensors

Repeated irradiation-annealing cycles

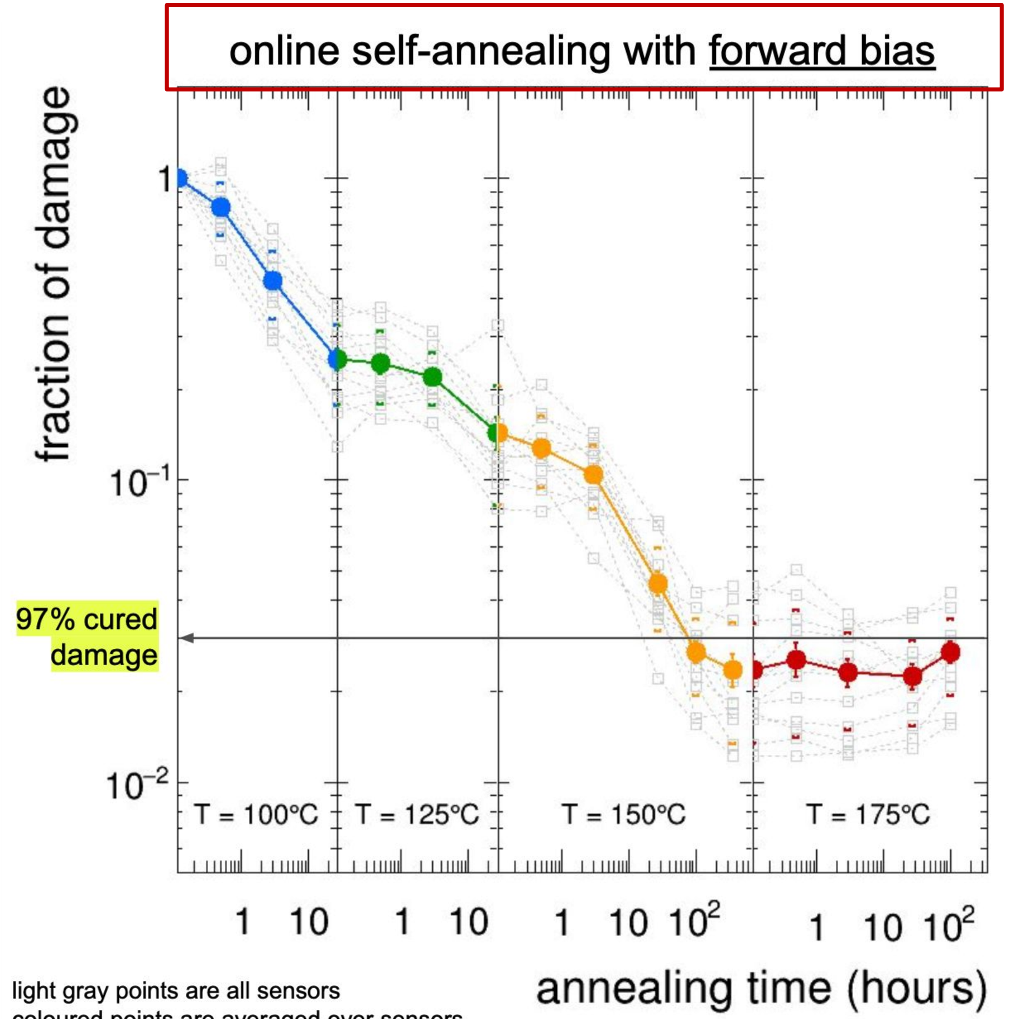


Goal: Test reproducibility of repeated irradiation-annealing cycles **to simulate a realistic experiment** situation

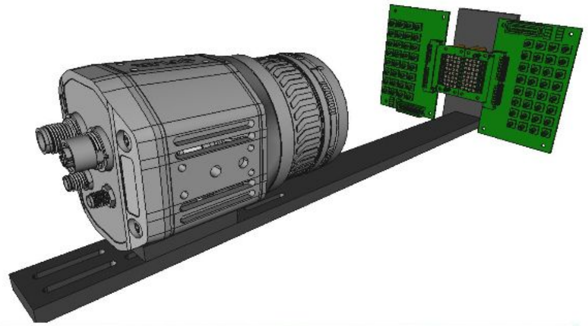
- **consistent irradiation damage**
  - DCR increases by **~ 500 kHz** (@ Vover = 4)
  - after each shot of 10^9 n_{eq}
- **consistent residual damage**
  - **~ 15 kHz** (@ V_{over} = 4) of residual DCR
  - builds up after each irradiation-annealing

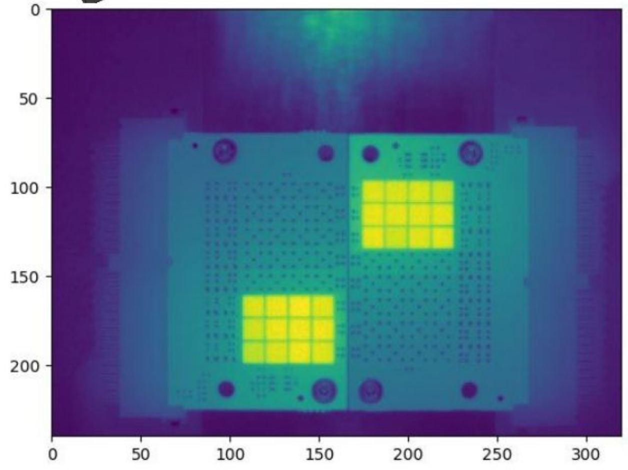
recovering about ~97% in terms of in DCR

SiPM - self induced annealing



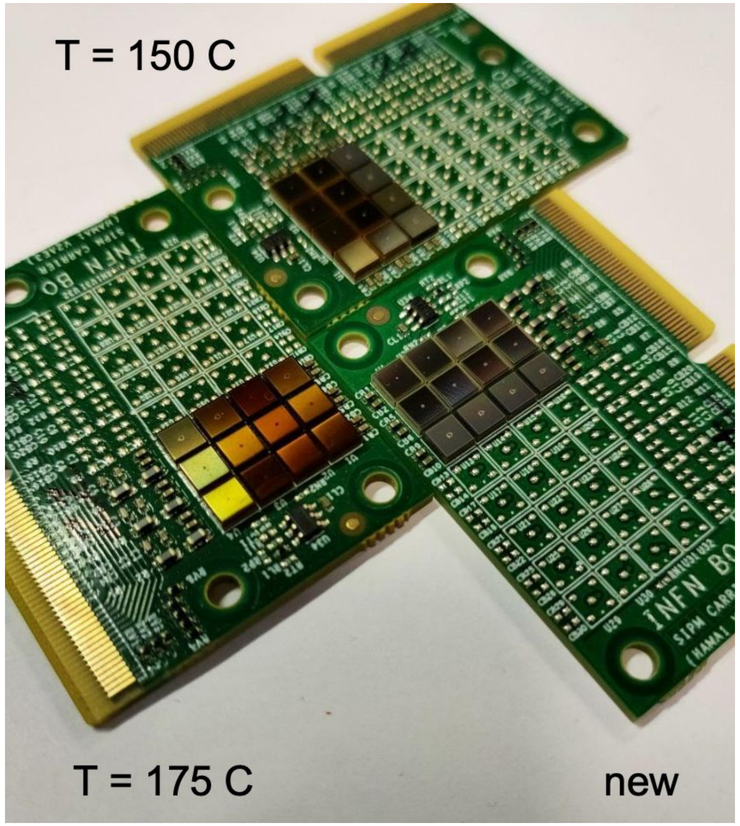
light gray points are all sensors
coloured points are averaged over sensors
coloured brackets is the RMS

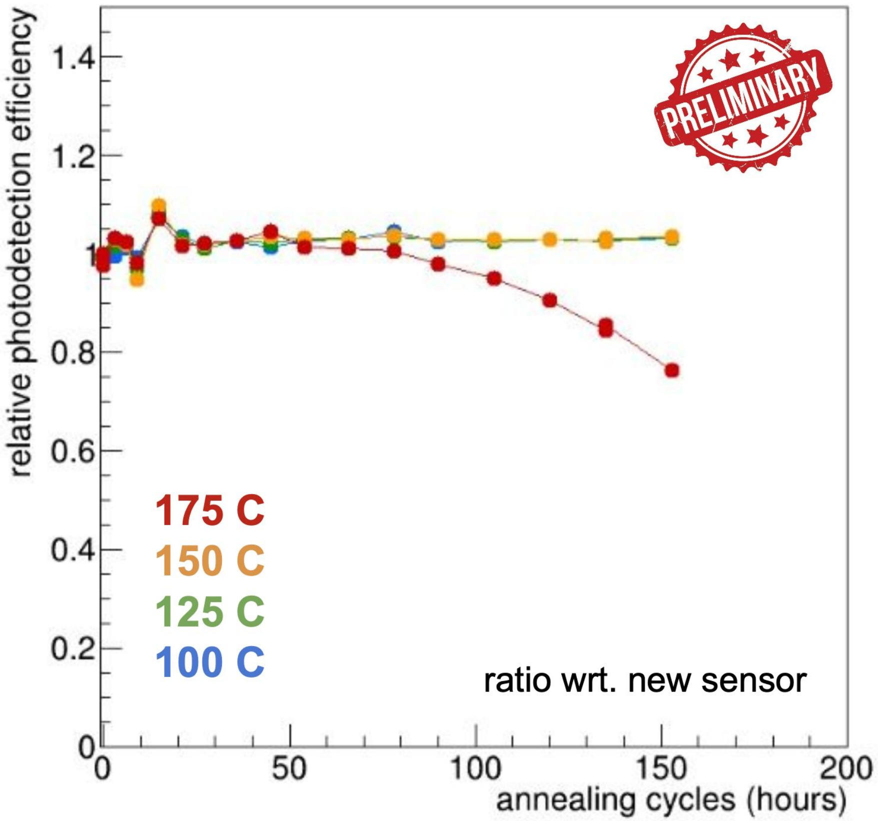




- **detailed studies on a large sample of sensors**
  how much damage is cured as a function of temperature and time
- **fraction of residual damage seems to saturate**
- **at 2-3% after ~ 300 hours at T = 150 C**
  continuing at higher T = 175 C seems not to help curing more

Detailed study on self induced annealing



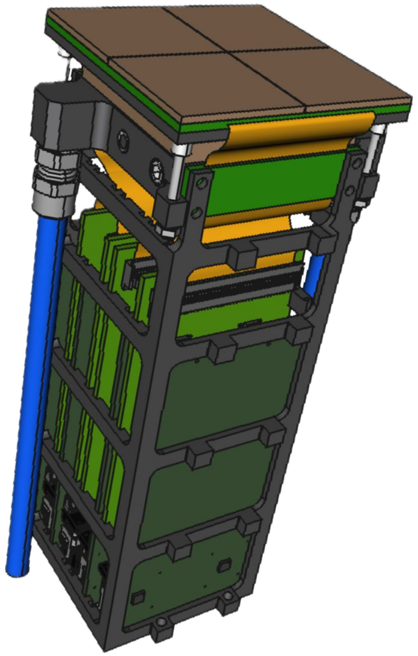


After many hours of online annealing → noticed alterations on the SiPM windows in particular in one board that underwent **500 hours of online annealing at T = 175 C** → the sensors appear "yellowish" when compared to new

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

ePIC dRICH prototype

PDU prototype
4x SiPM matrix arrays
(256 channels)



Front-end electronics
(ALCOR ASIC inside)

2024 dRICH prototype:

- 20x20x20 cm^3
- 8 Photon Detection Units (PDU)
- Each PDU fully equipped with 4 matrix arrays of 64 SiPMs.
- **256** channels for each PDU.

- **2048** Hamamatsu S13361 SiPMs, ≈ 400 cm^2 optical surface (1/10 of a dRICH sector)
- 2 different SPAD sizes (50 and 75 um)
- 2 mm dead layer between PDUs
- **64 ALCOR** v2 ASICS
- 2048 TDC channels electronics
- Automatically controlled temp down to -40 °C
- 10 °C water cooling

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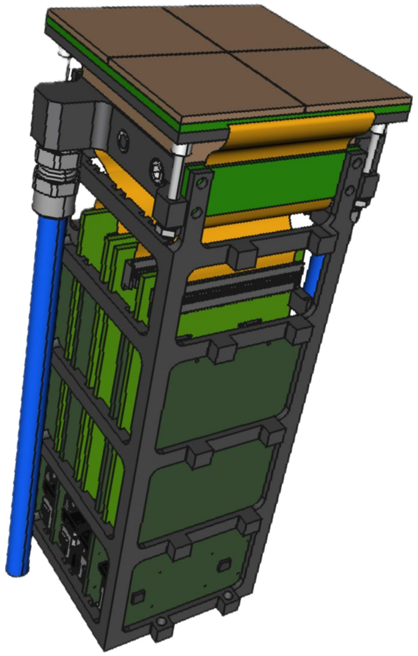
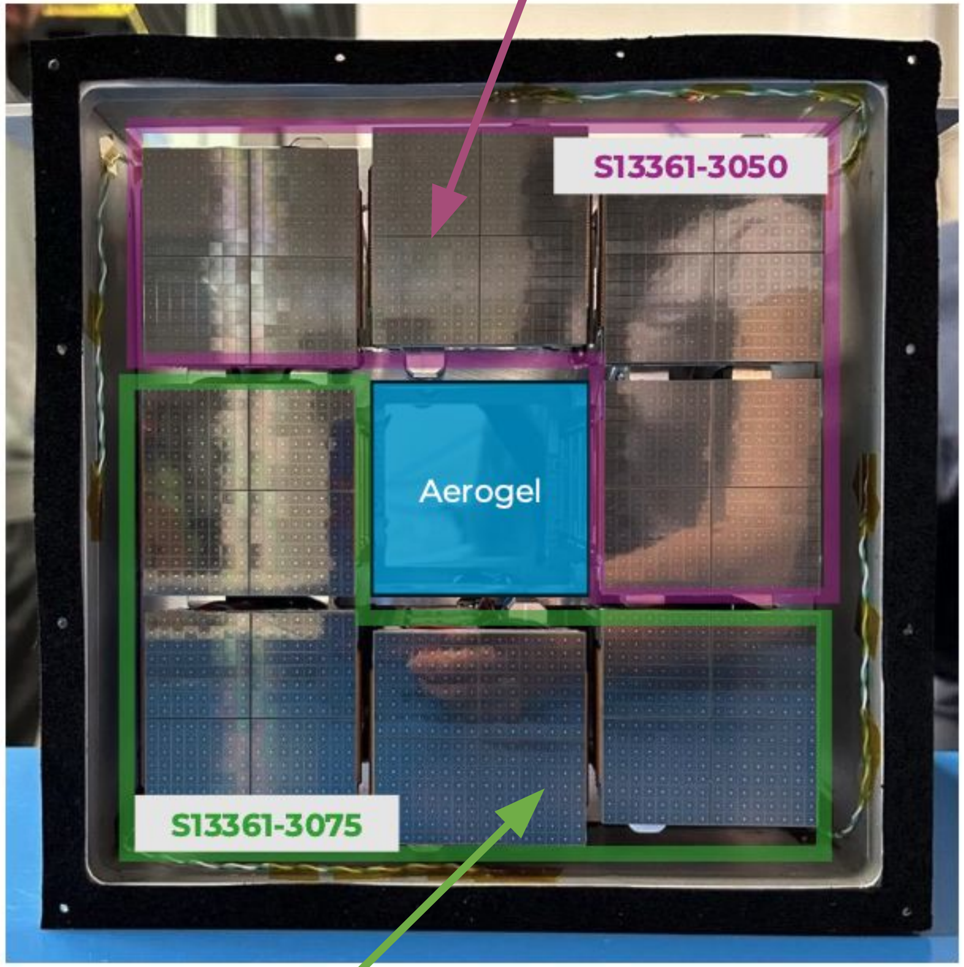
PDU prototype
4x SiPM matrix arrays
(256 channels)



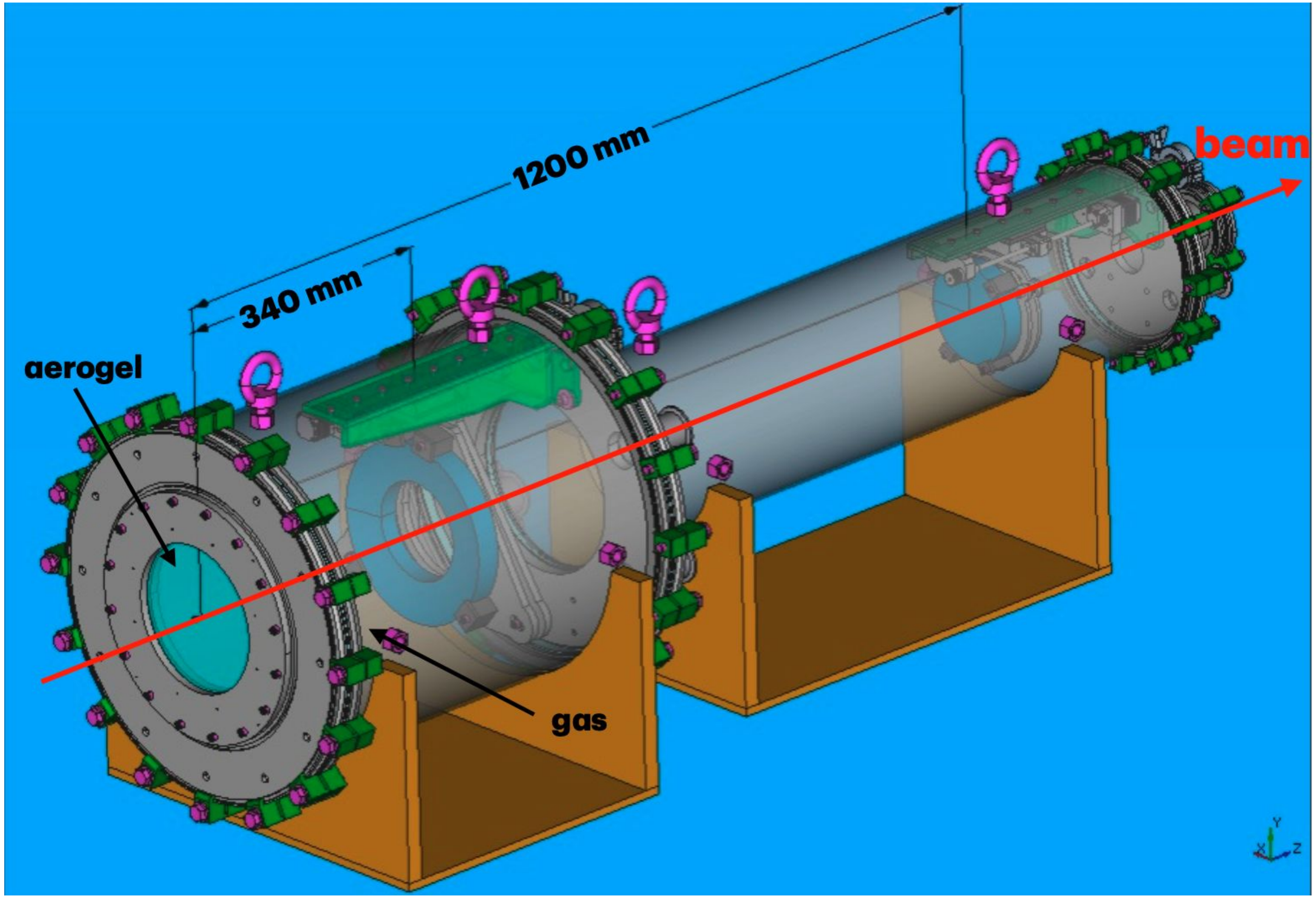
Front-end electronics
(ALCOR ASIC inside)

50 µm SPAD

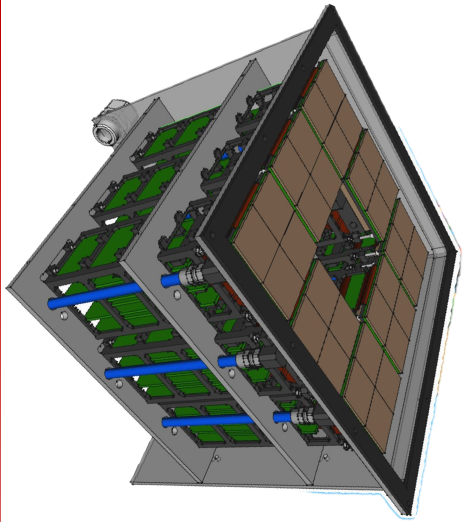


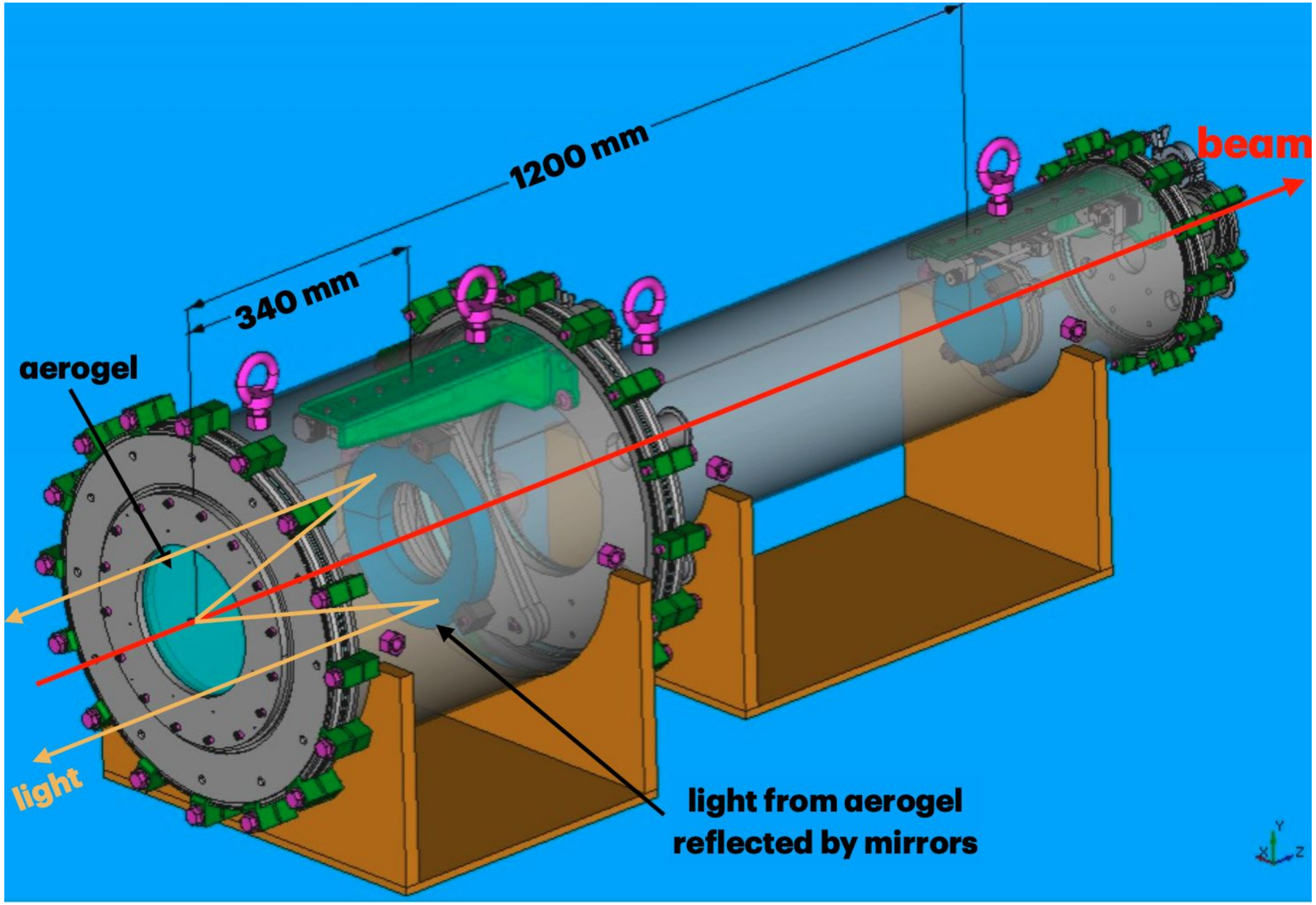
75 µm

Beam test setup



Beam test at CERN PS T10





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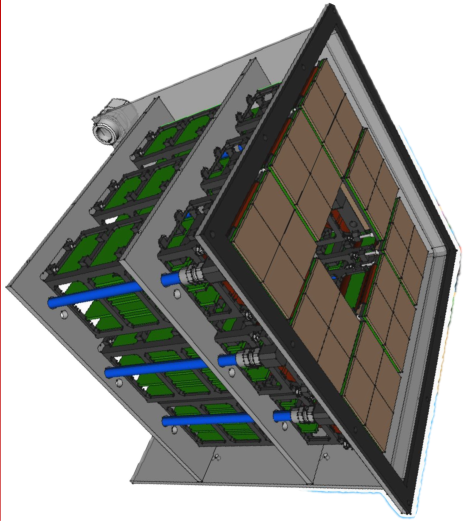
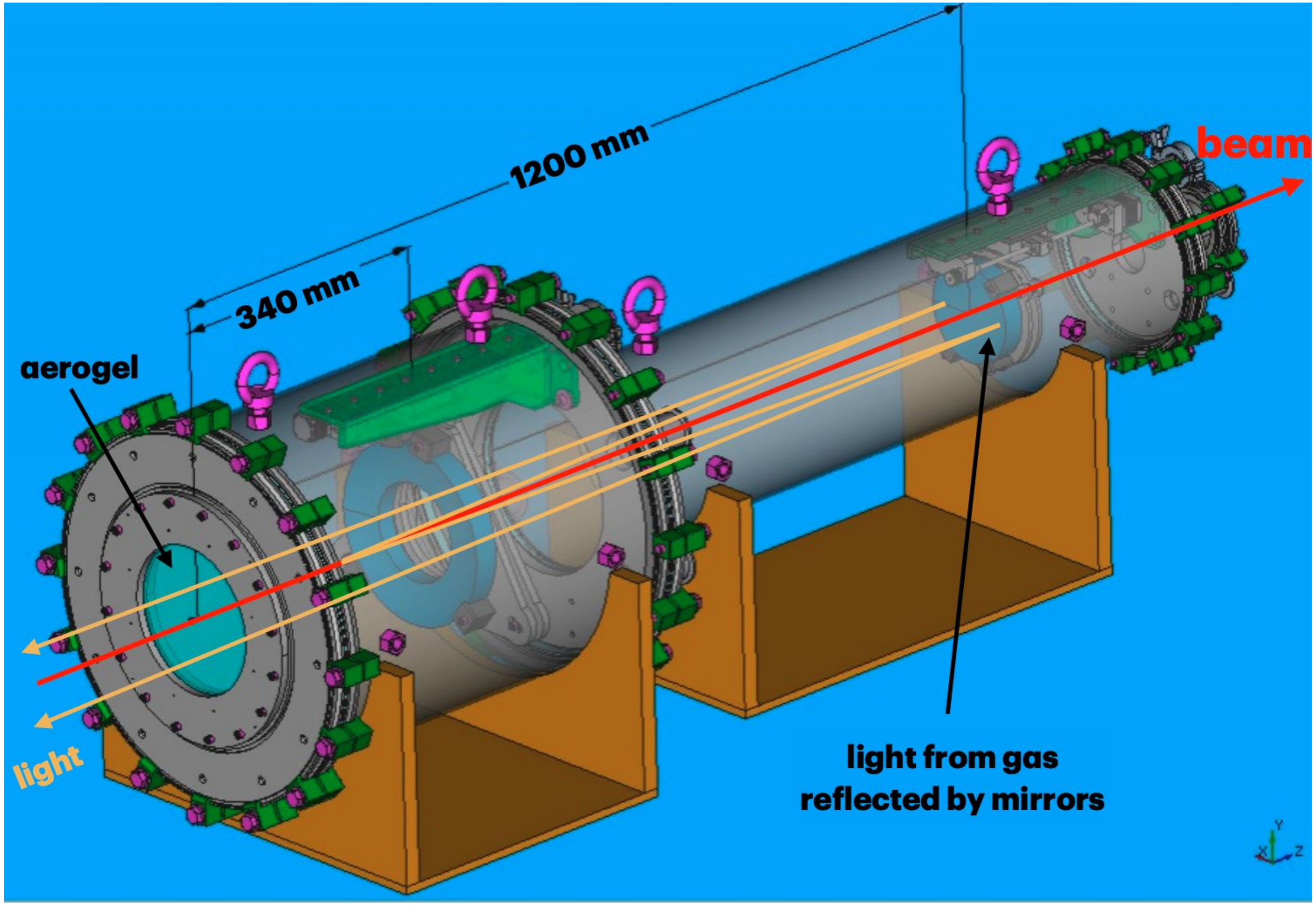
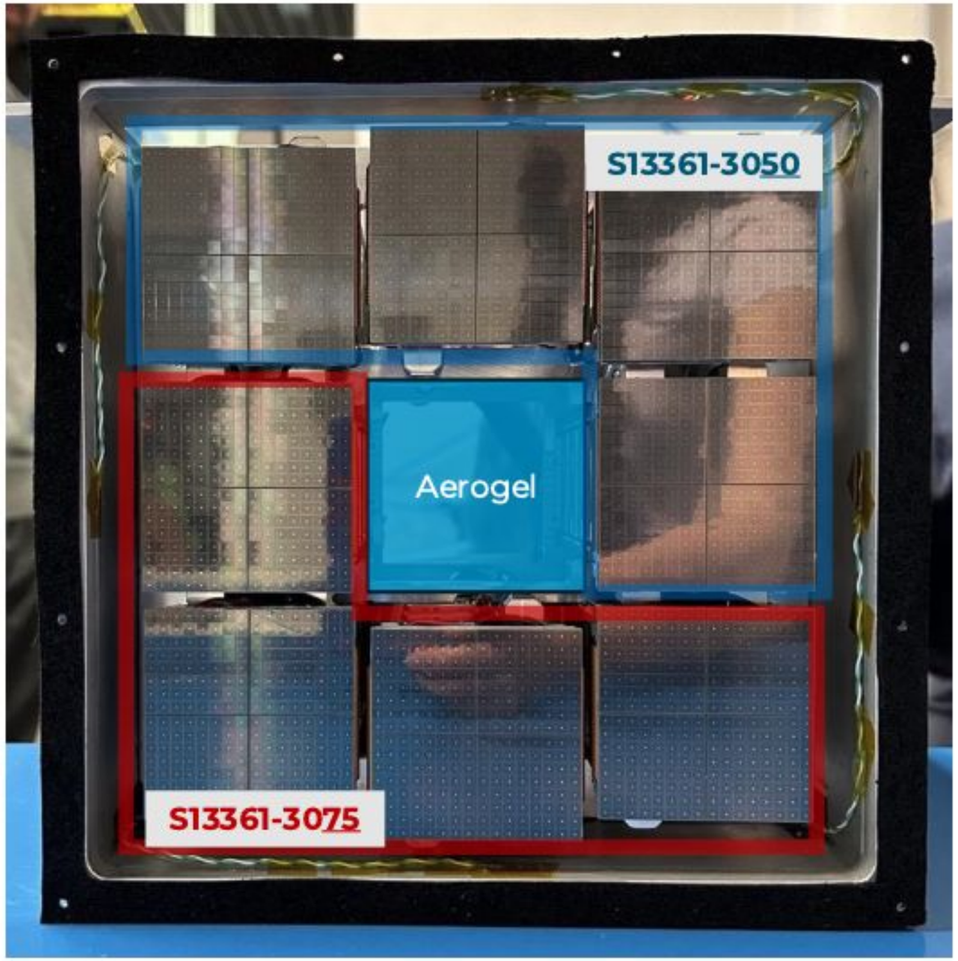
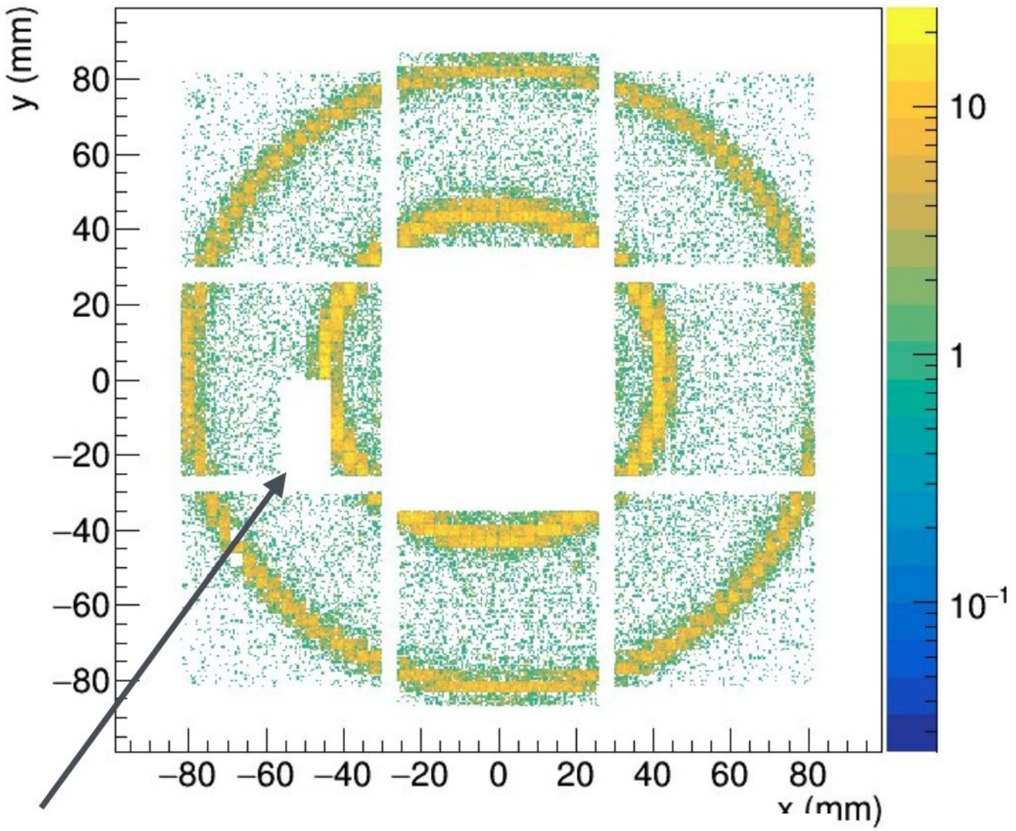




Beam test results

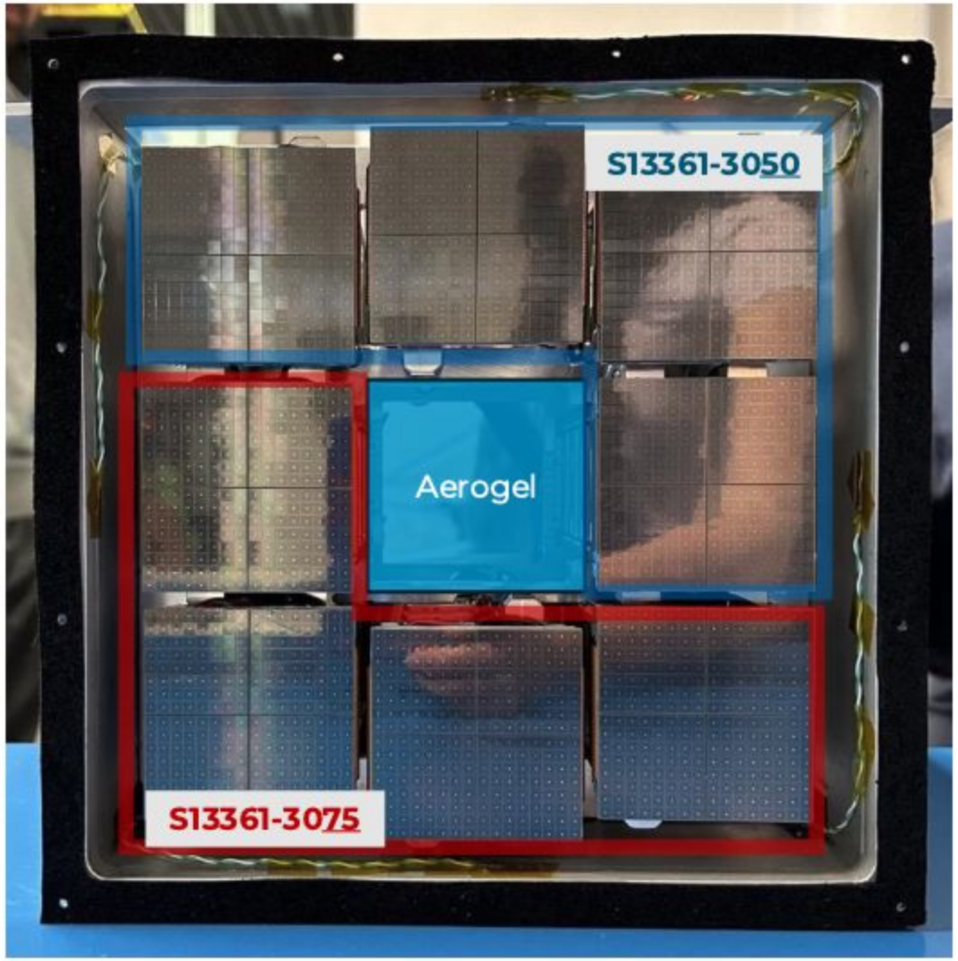


Dual radiator (both aerogel and C_2F_6)

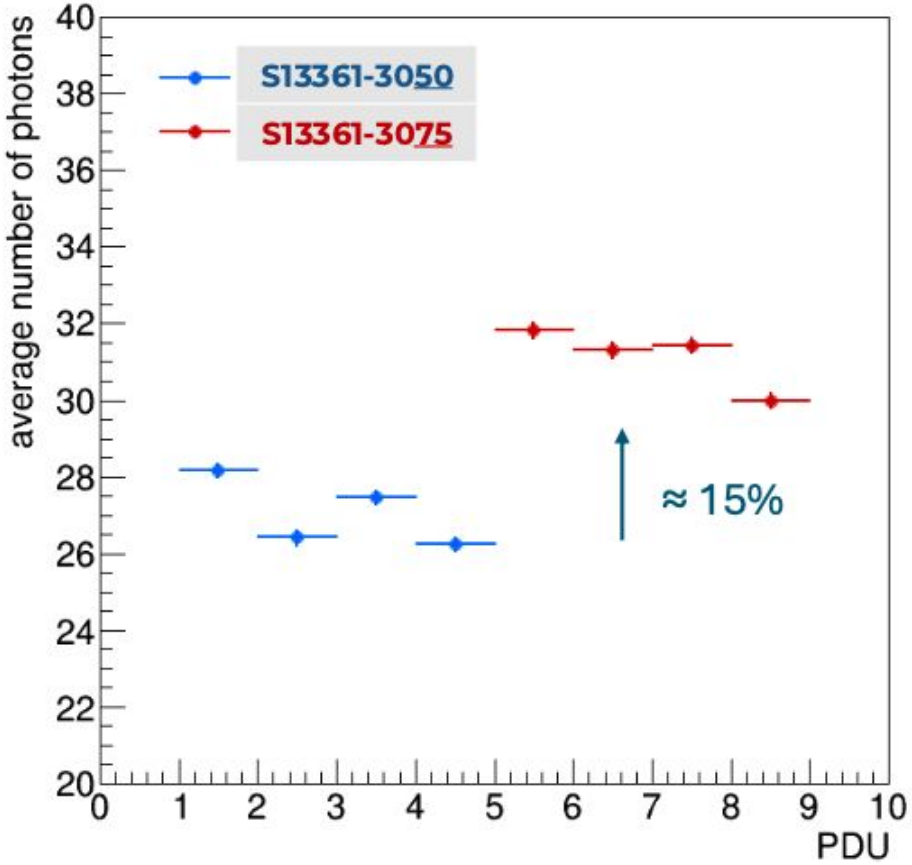


32 channels not available due to readout issues with one ASIC

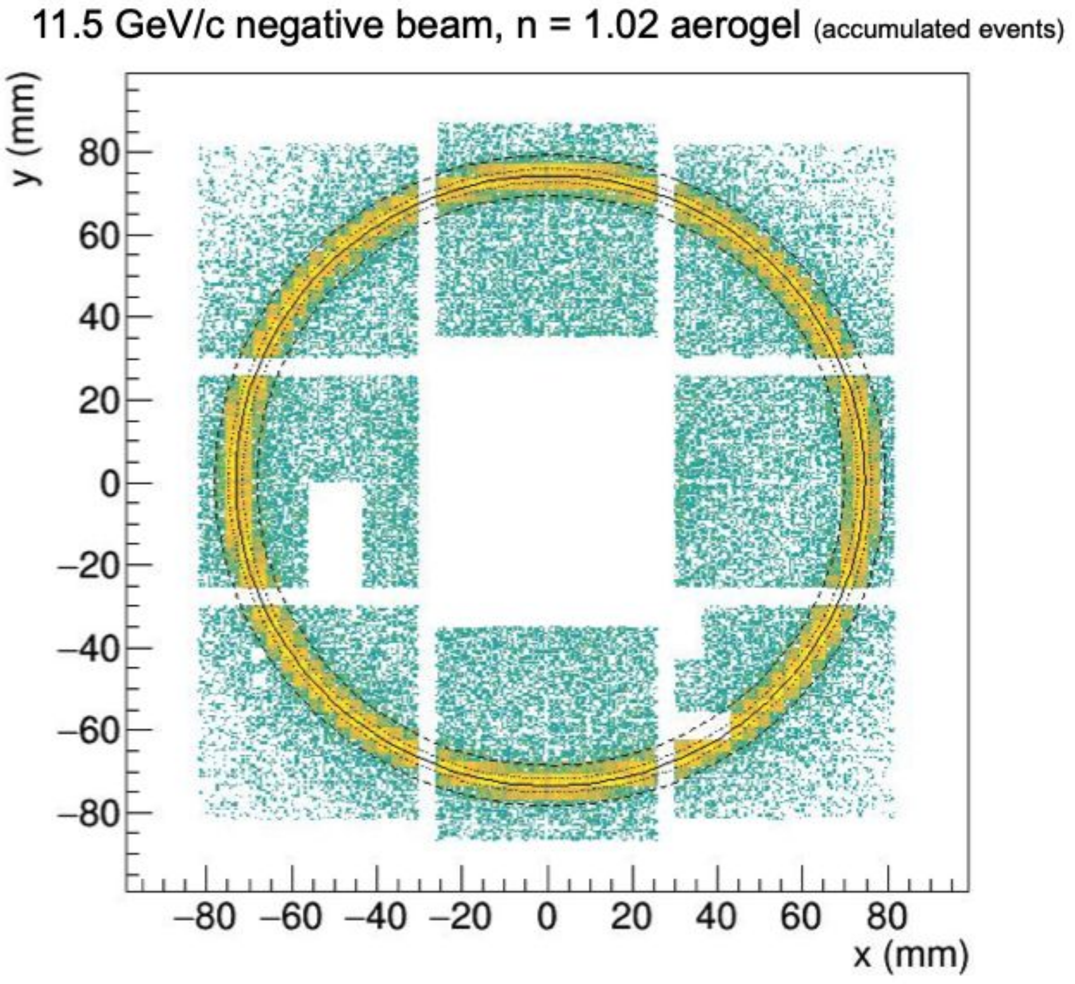
Comparison between different SiPM sensors



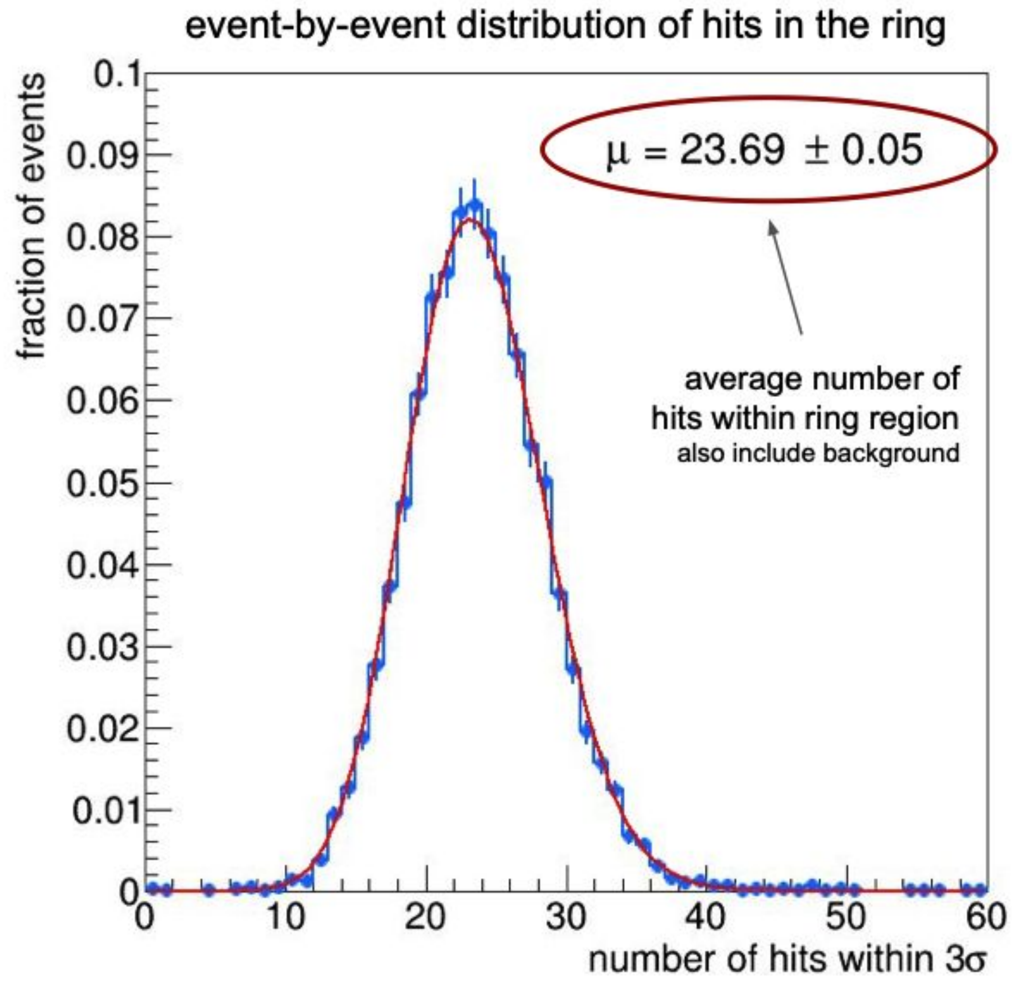
15% increase in number of detected photons wrt to 25% increase in PDE



Number of photoelectrons



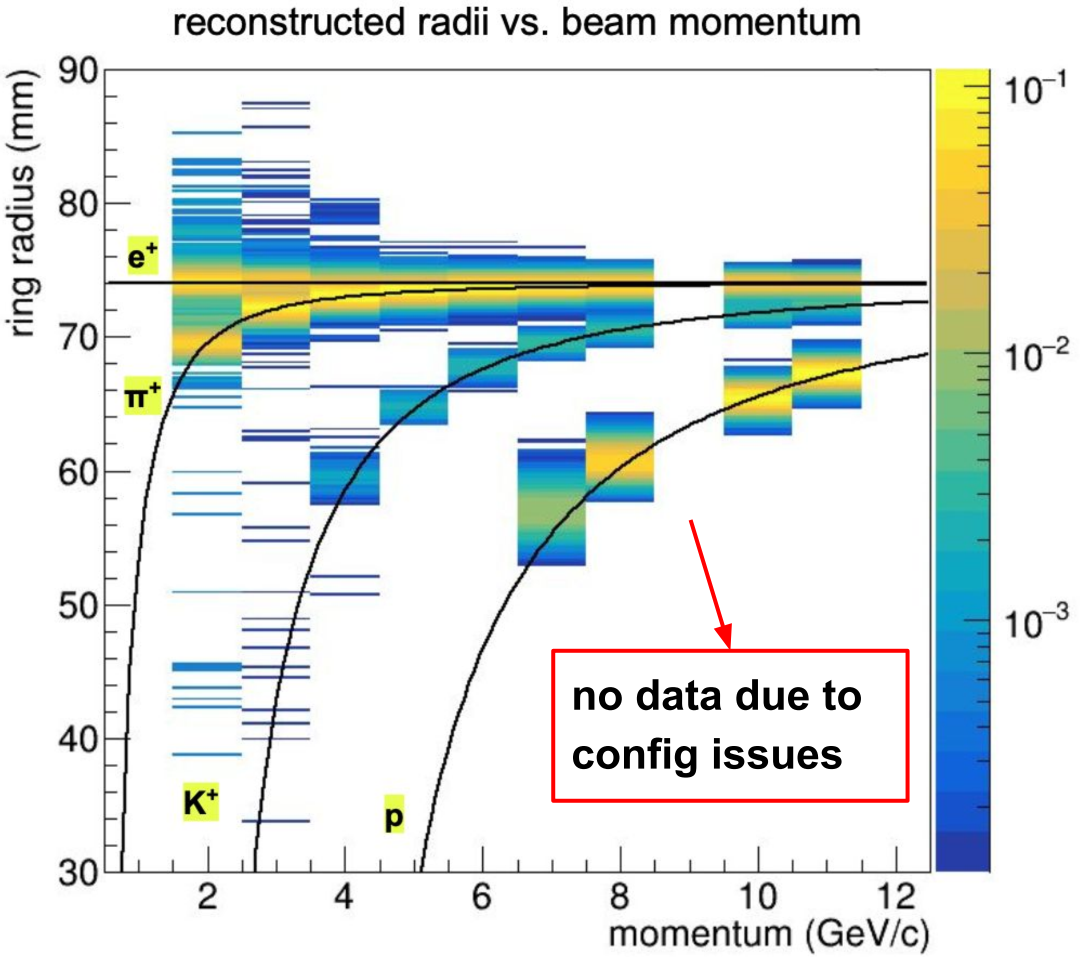
2D fit to accumulated data with realistic model (ring + background)

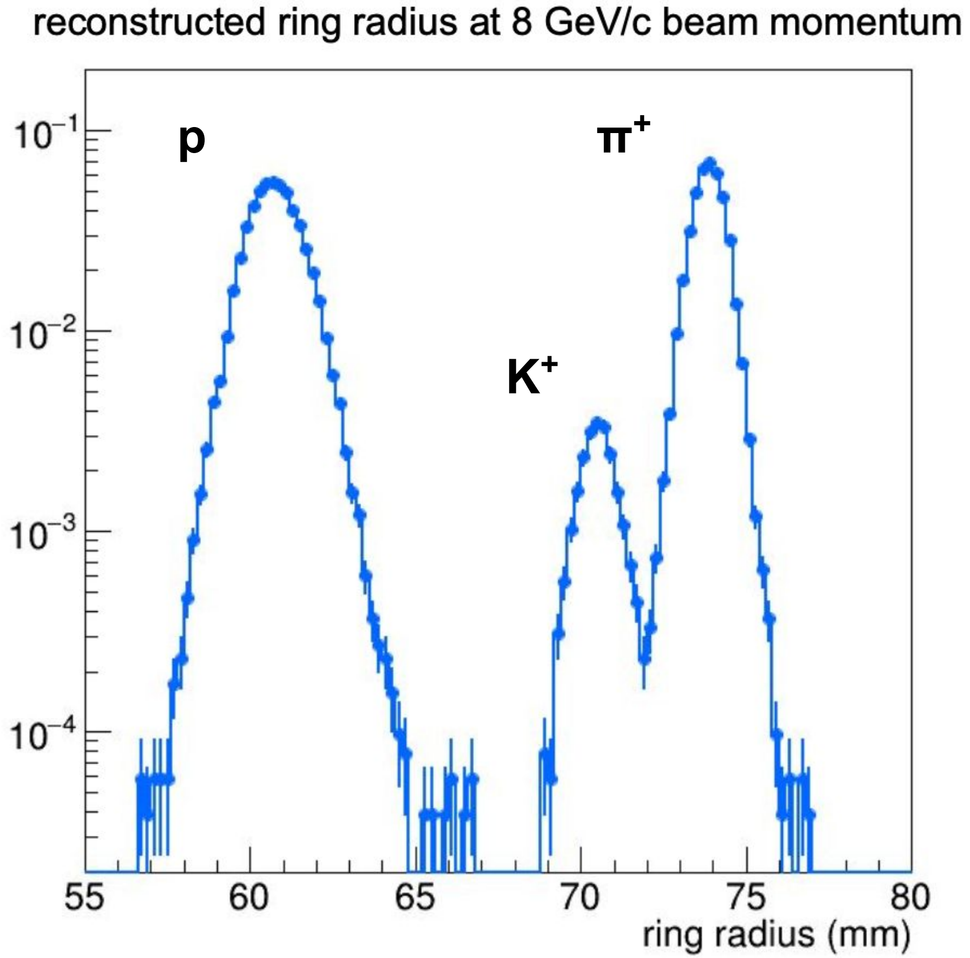


Poisson fit to data, average number of hits is large

Beam test results - CERN PS 2024

positive particles, aerogel only

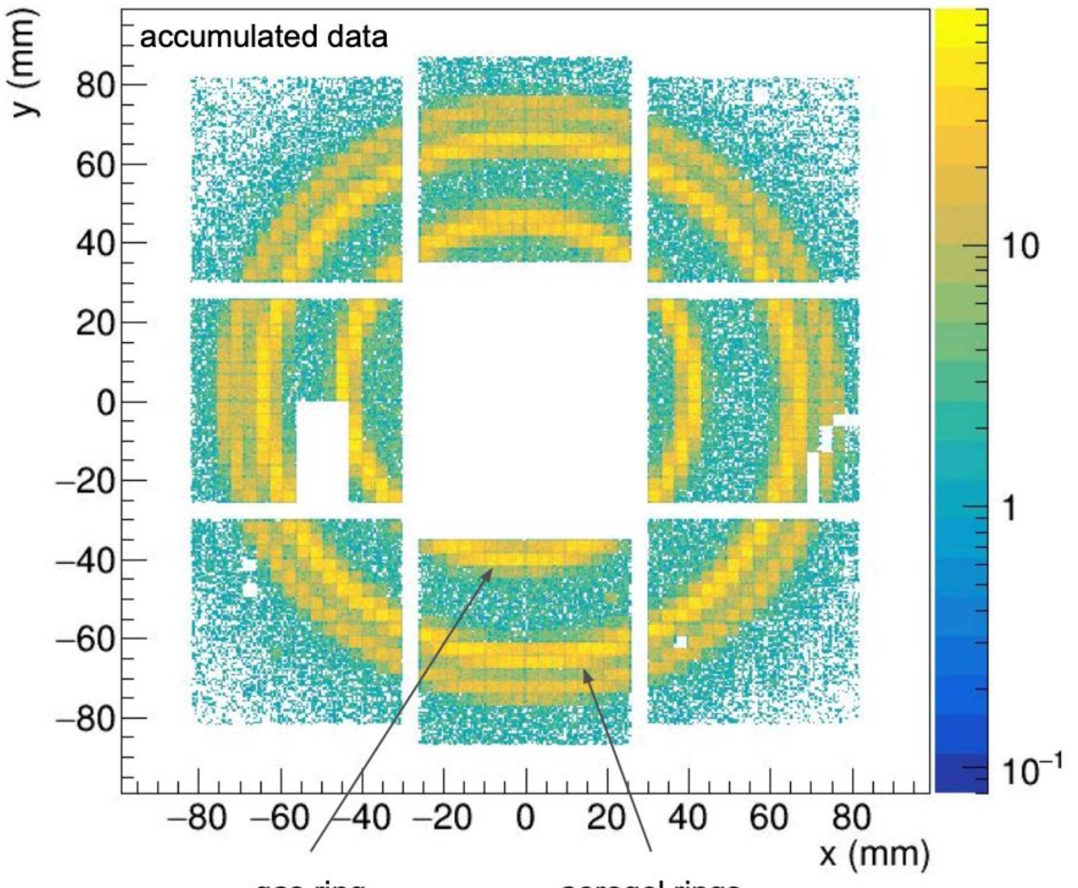




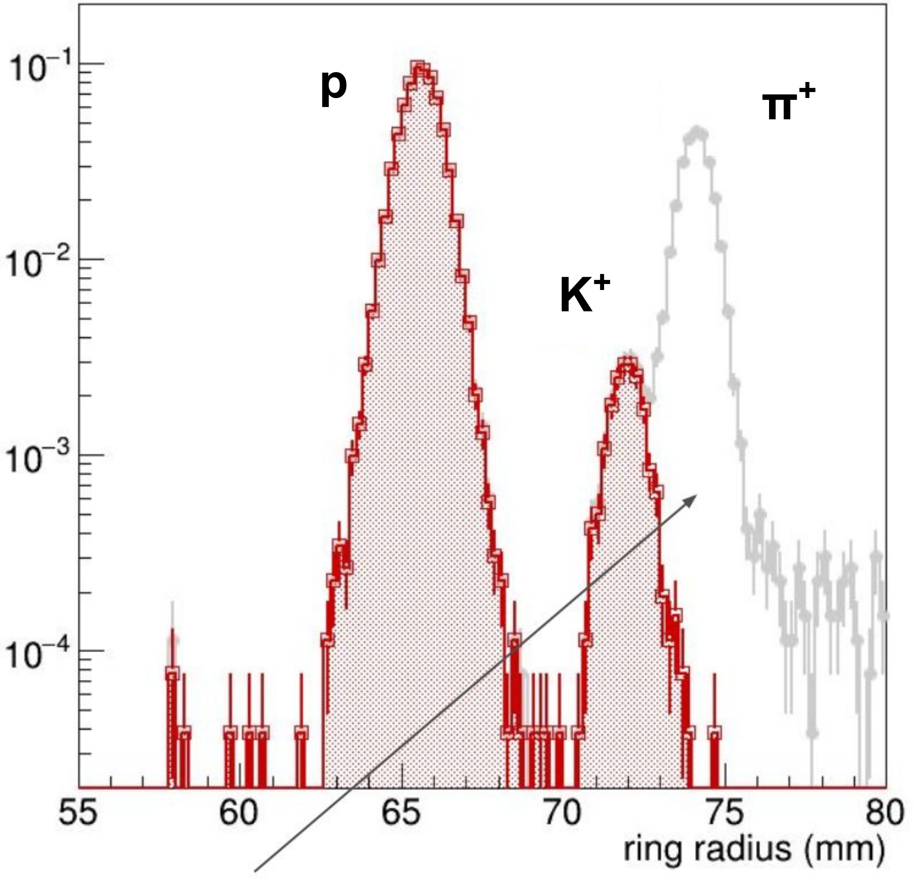
Beam test results - CERN PS 2024

Gas ring tags only **π**, at 10 GeV/c K and p are **below** the C2F6 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

Summary and conclusions

- The SiPM technology has been chosen for the ePIC-dRICH experiment at the EIC
- R&D activities to study and perfectionate radiation damage mitigation strategies have been done and are still going on to define the SiPMs annealing procedures

- The 2024 dRICH prototype has been assembled and tested at CERN PS
- From the results observed from beam tests:
  - First PID study for the ePIC dRICH with both aerogel & gas
  - Efficiently observed Cherenkov rings and identified the passing particle
  - The gas veto efficiently extends PID range excluding under-threshold pions

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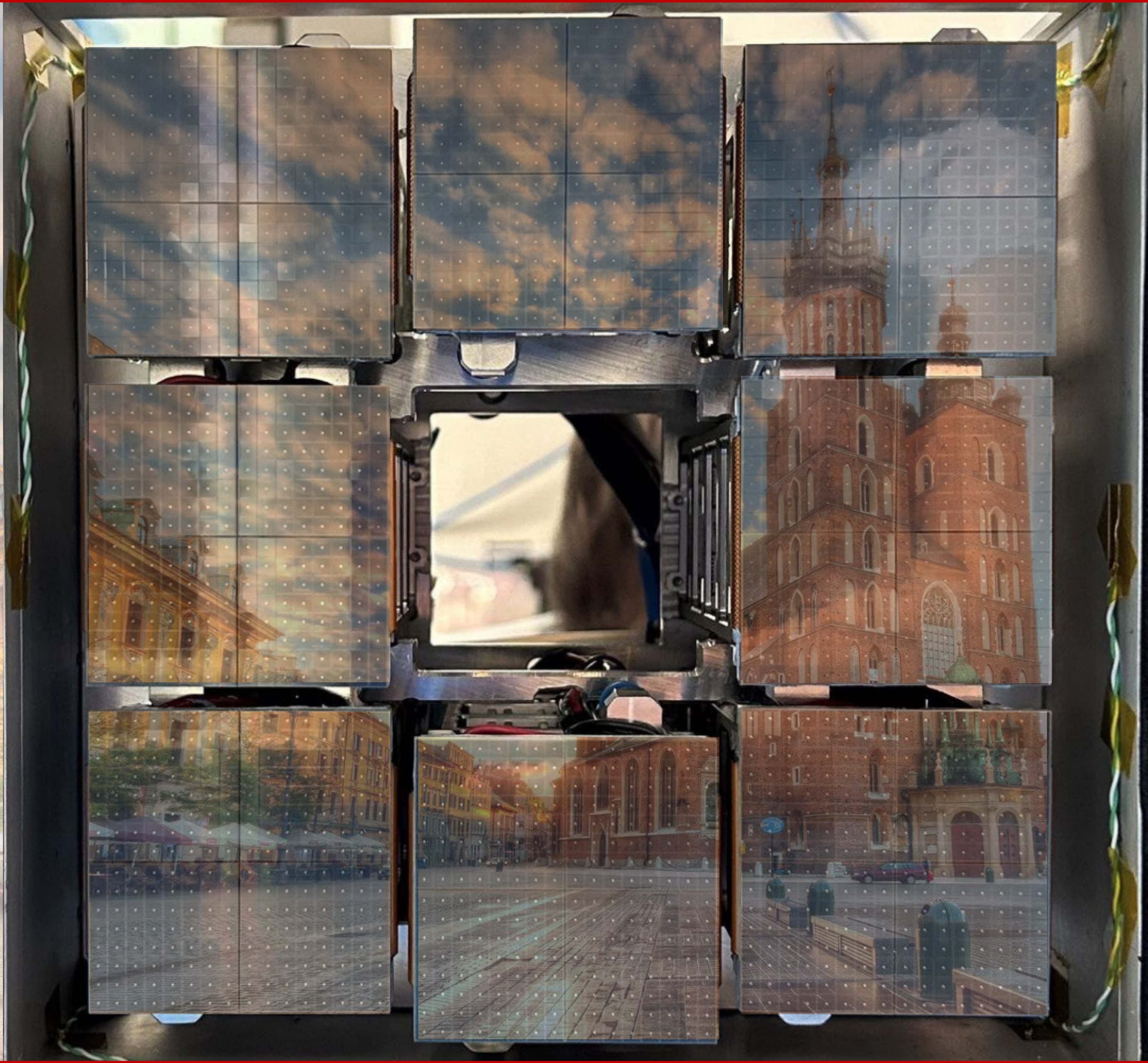
Thank you!



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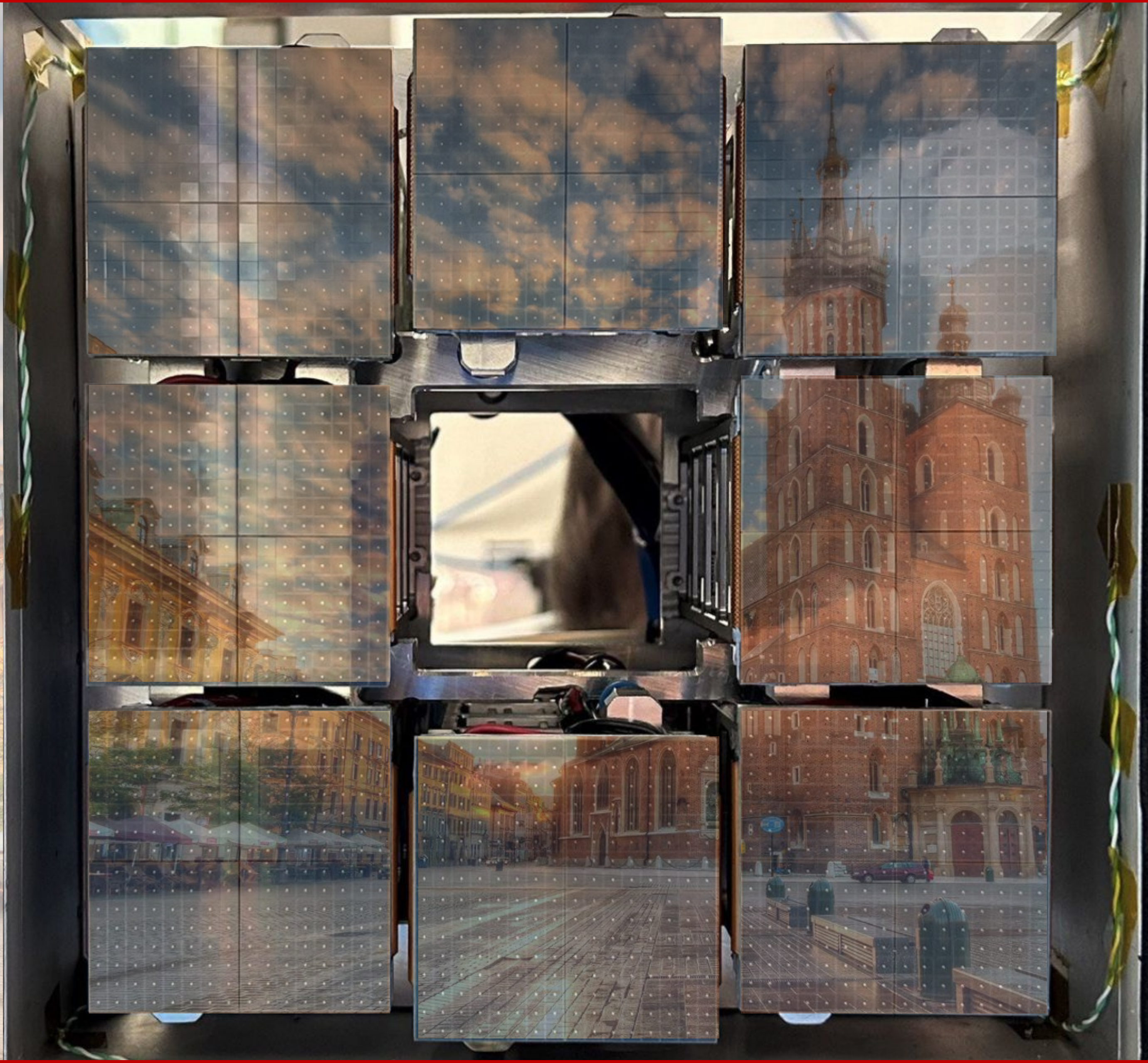
Backup



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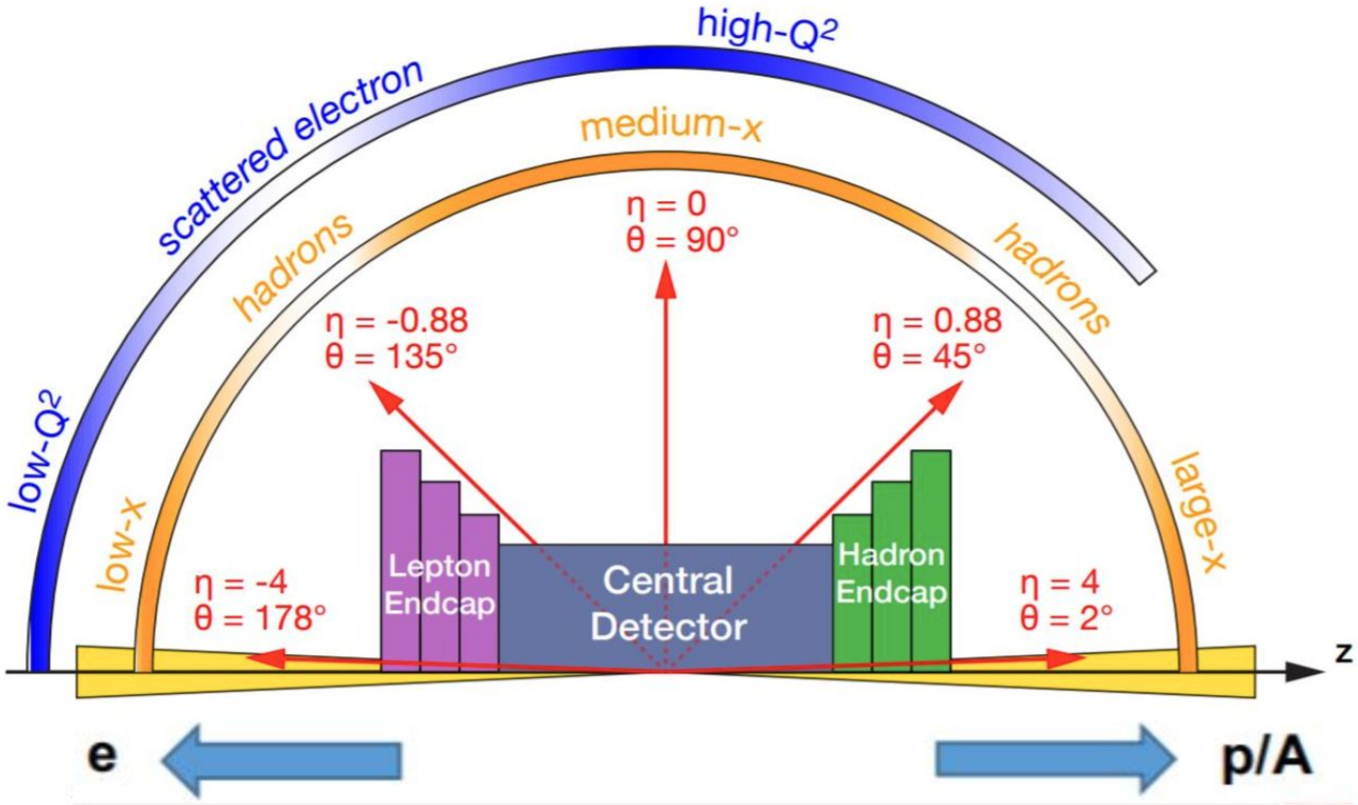


SiPM option and neutron fluence for dRICH sensors

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:

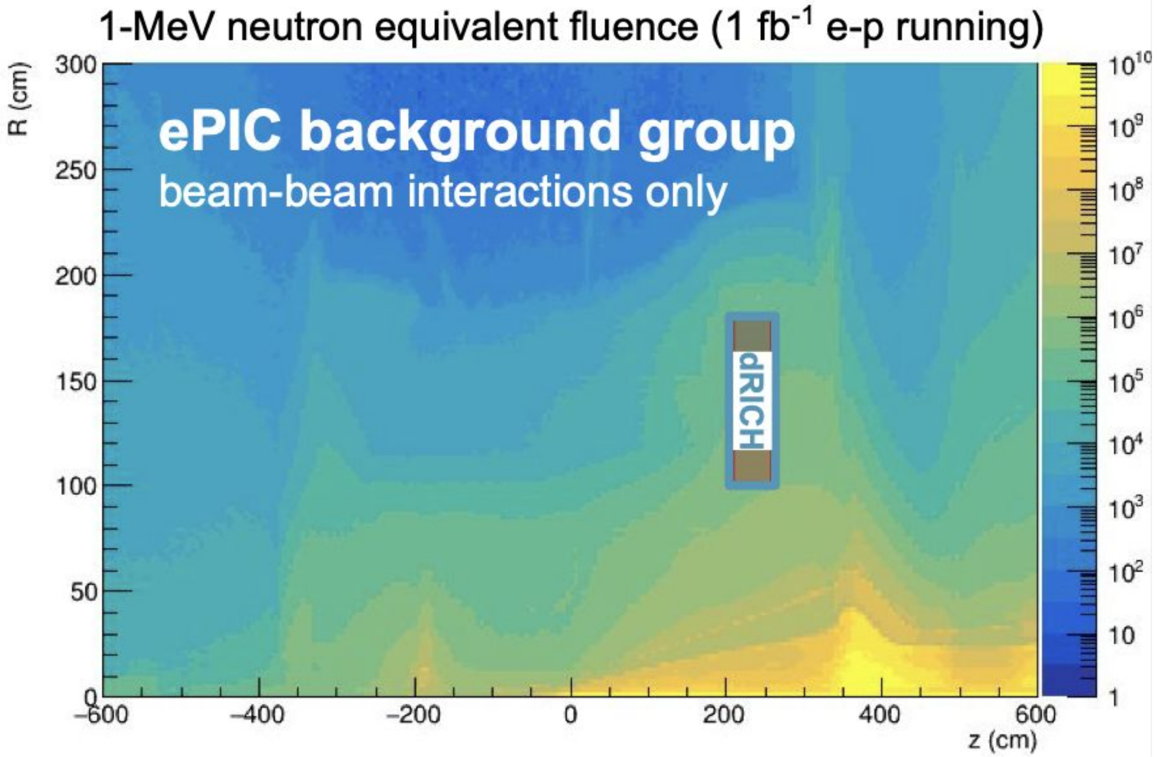
Requirement for the key physics goals is 10 fb^{-1} per center of mass energy and polarization setting

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



Expected fluence:

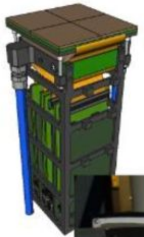
average: ~4 10^5 n_{eq} / cm^2 fb^{-1}

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

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

x10 safety factor

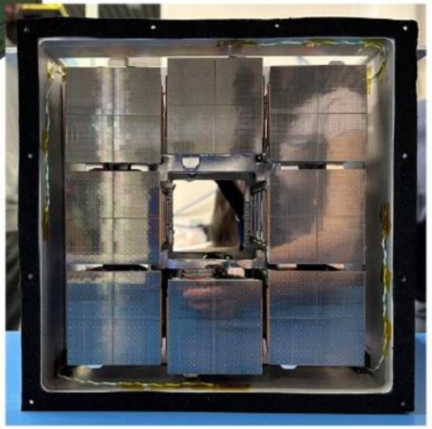
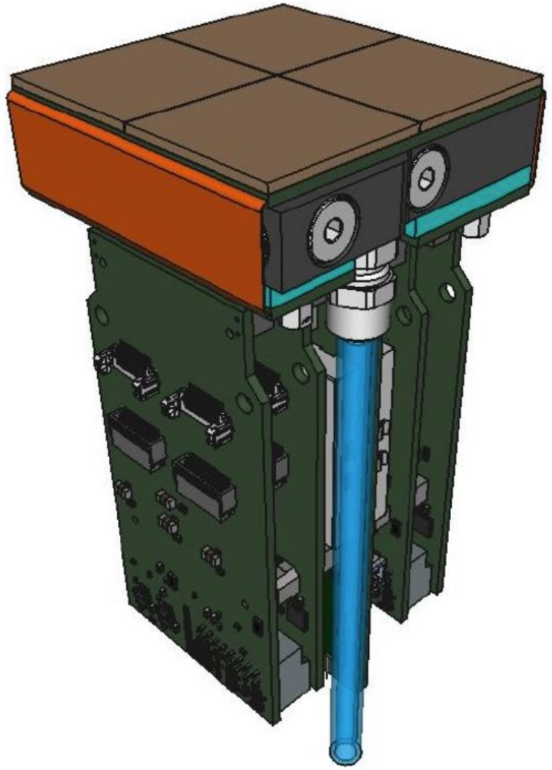
Prototype evolution

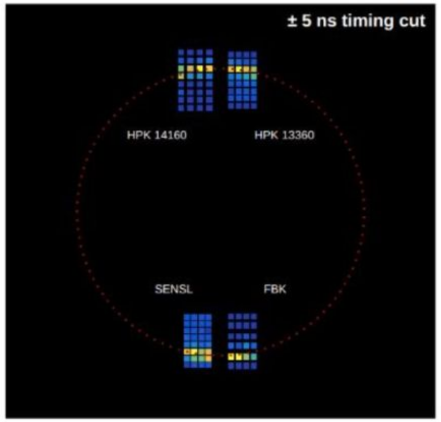


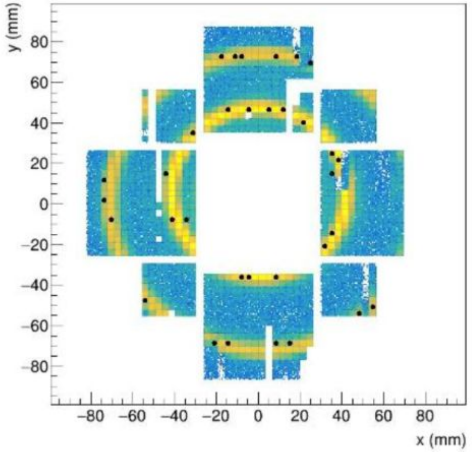

towards construction

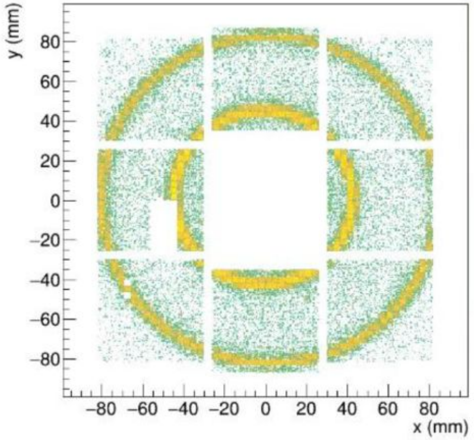
2022	2023	2024	2025
electronics v1	electronics v2	electronics v2.1	electronics v3 final prototype









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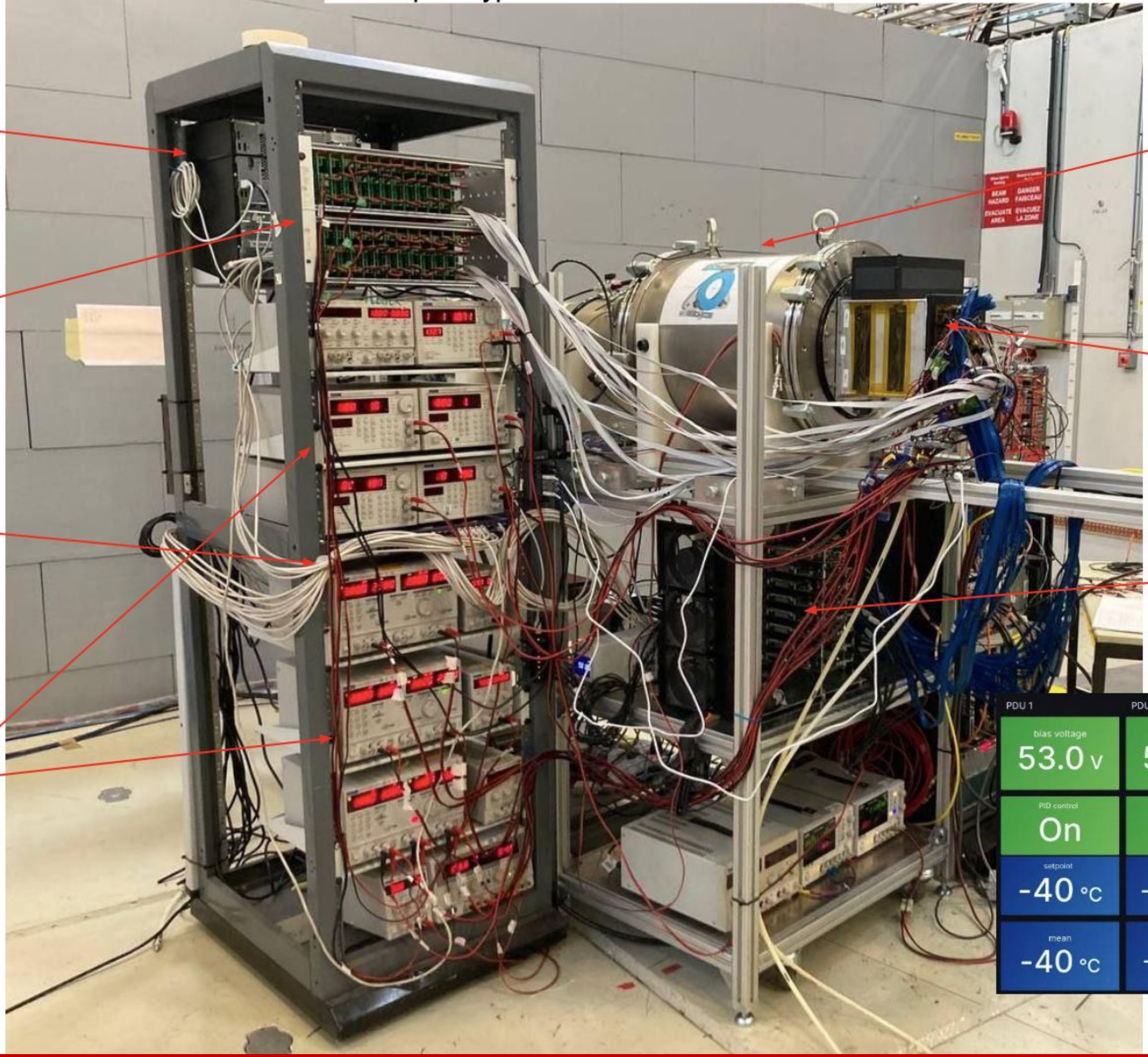
Beam test setup (CERN PS 2023)

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



SiPM at low temperature

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ALCOR ASIC

- Developed by INFN-TO
  - 64-pixel matrix mixed-signal ASIC;
  - current versions (v1,v2,v2.1) with 32 channels, wire-bonded;
  - final version with 64 channels, BGA package, 394.08 MHz clock;
- Chip features:
  - signal amplification
  - conditioning and event digitisation
- Single 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 with sub ns accuracy
- Single-photon time-tagging mode:
  - continuous readout
  - also with Time-Over-Threshold
- Fully digital output

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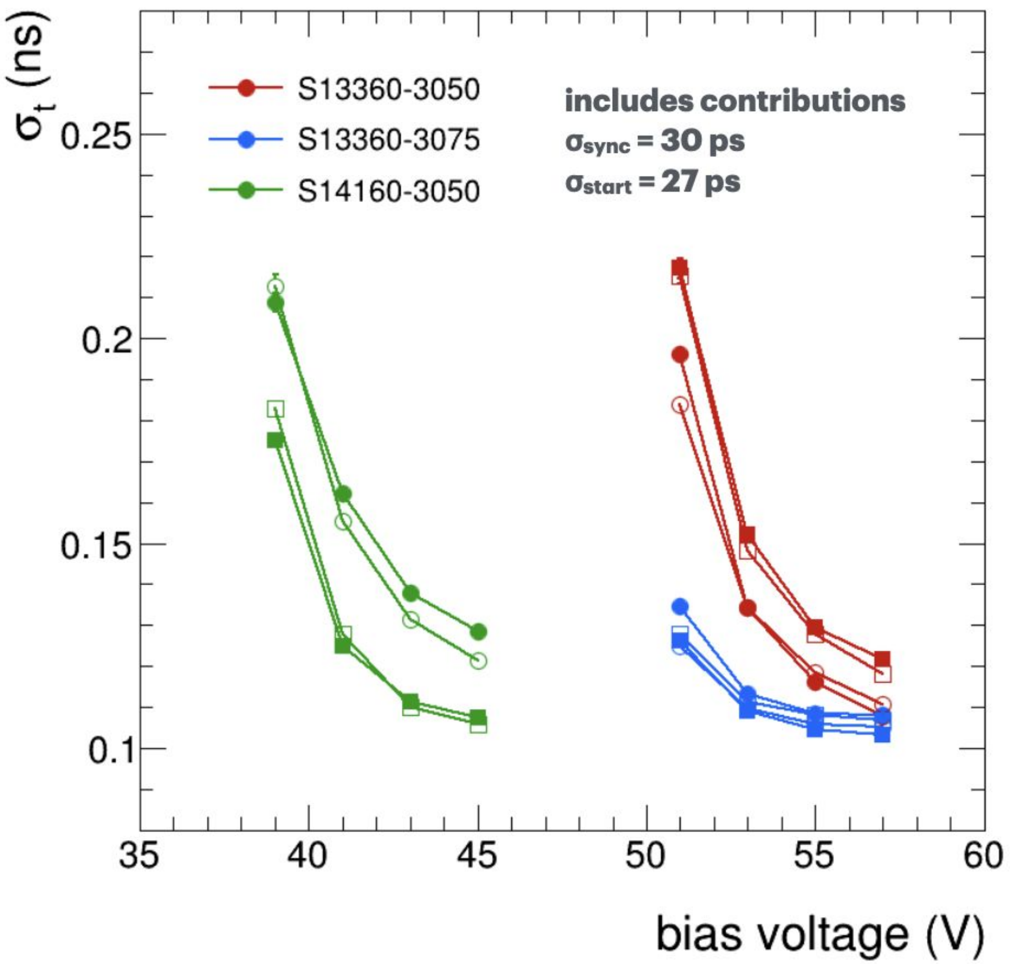
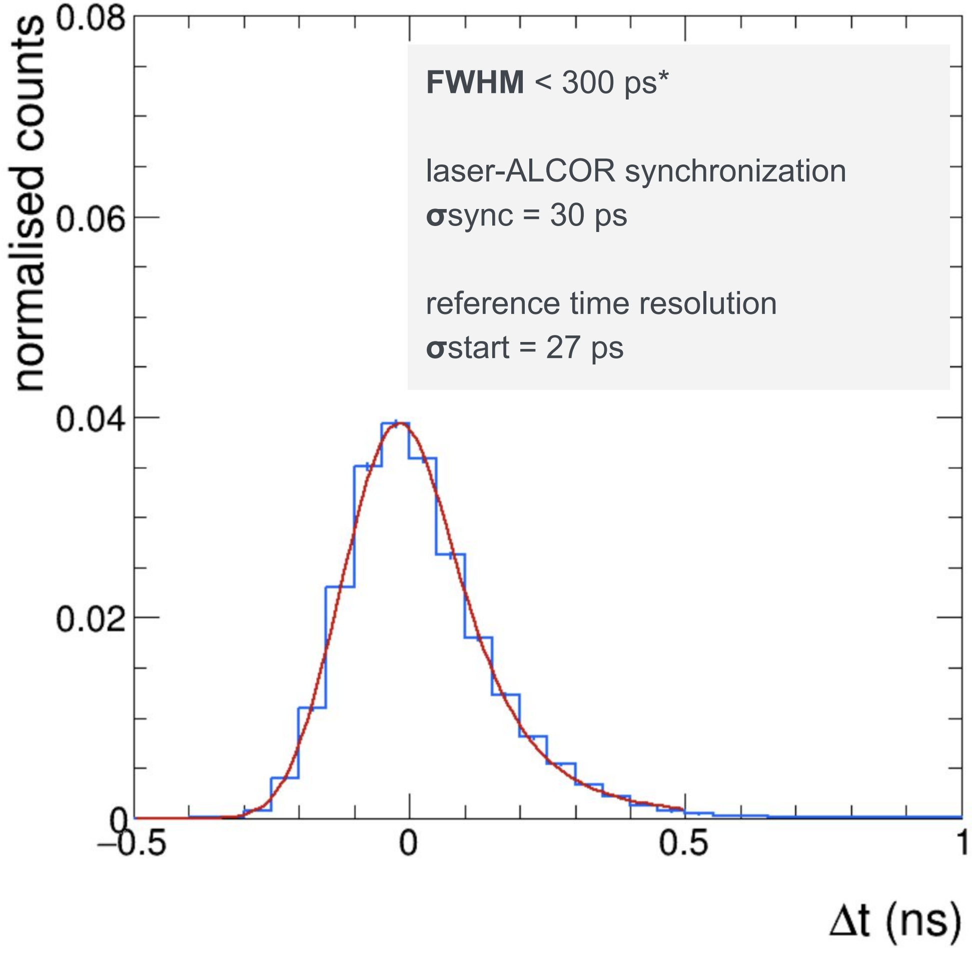
ALCOR timing performance

standard ALCOR front-end bias configuration



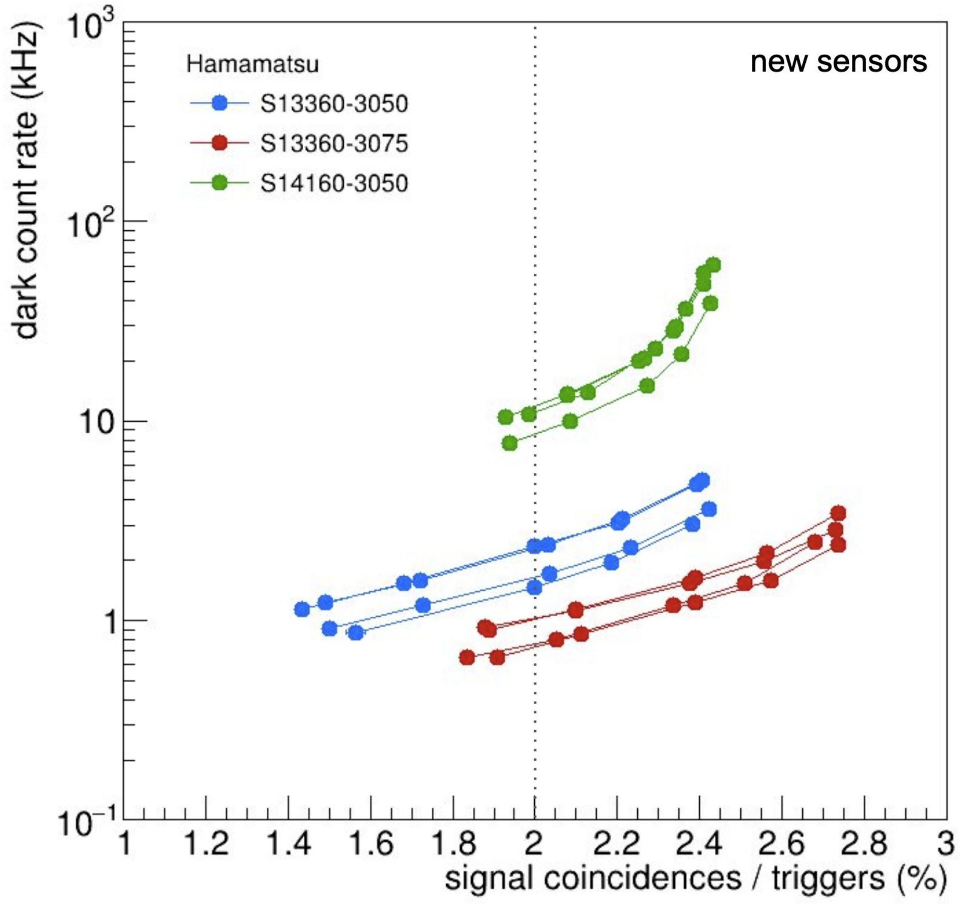
laser-SiPM correlations (time-walk corrected)



*exponential late tail not understood yet, might originate from laser/optics and/or be SiPM intrinsic contributions

Riccardo Ricci | INFN Bologna

DCR vs PDE - comparison between sensors



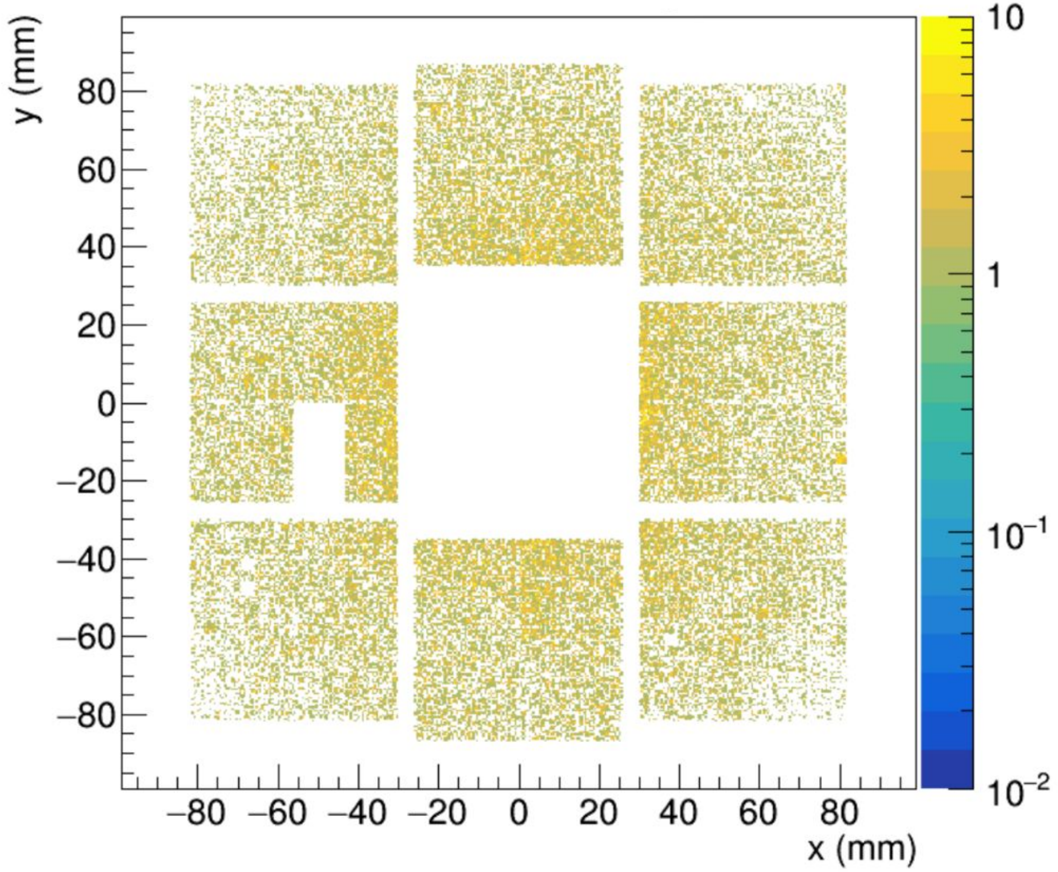
proxy for photodetection efficiency

- **DCR at the same level of detection efficiency (**namely, the probability to detect light from laser pulse)

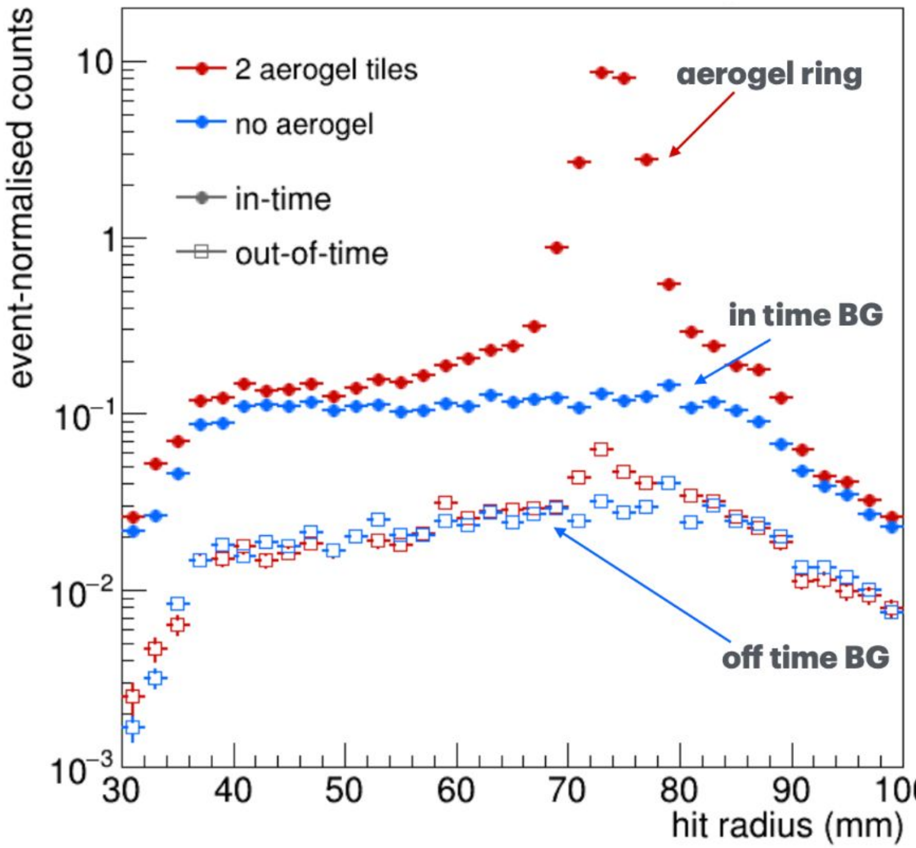
- **different sensors have different DCR level**
  - **best: S13360-3075** → most promising sensors, large pitch SPADs (75 μm)
  - second: S13360-3050 **(**same technology, medium pitch SPADs, 50 μm)
  - worst**: S14160-3050 (**different technology, medium pitch SPADs, 50 μm)

Beam test results - background studies

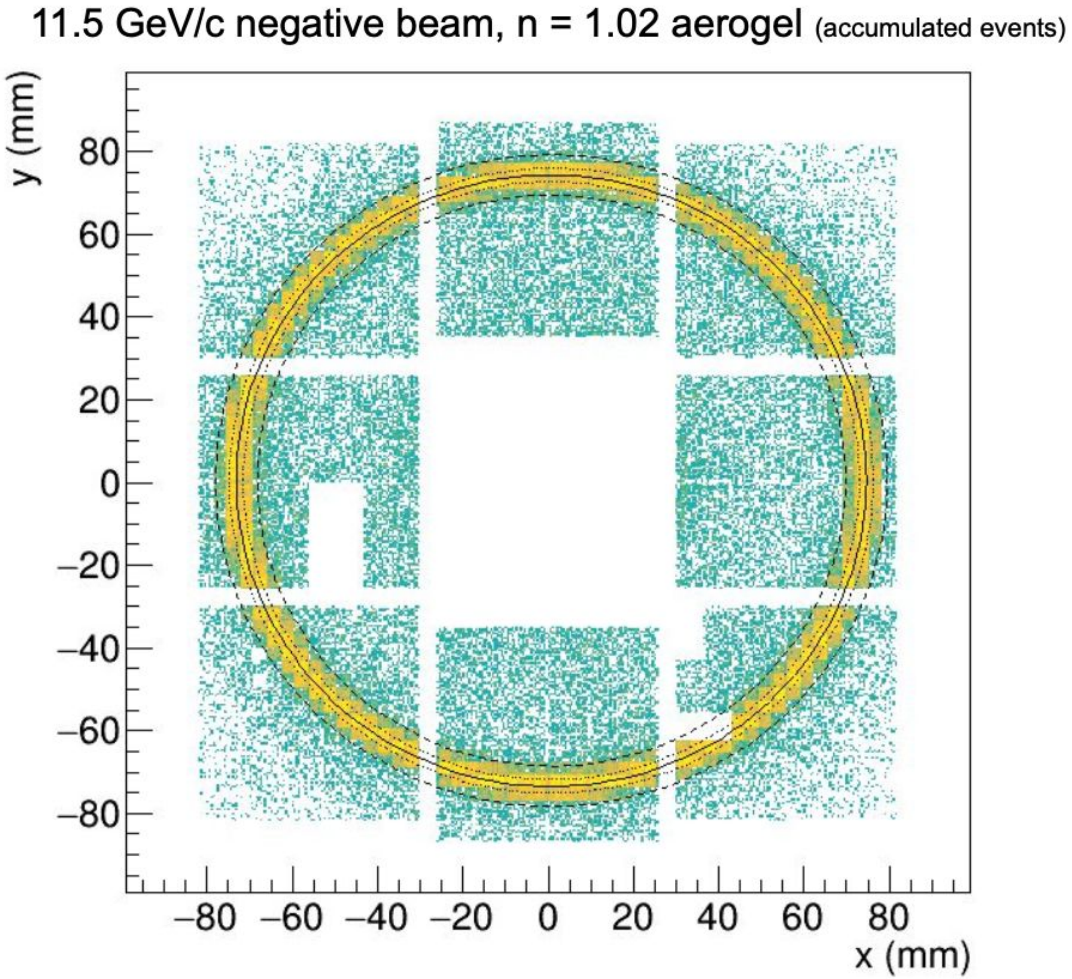
Events taken w/o aerogel tiles



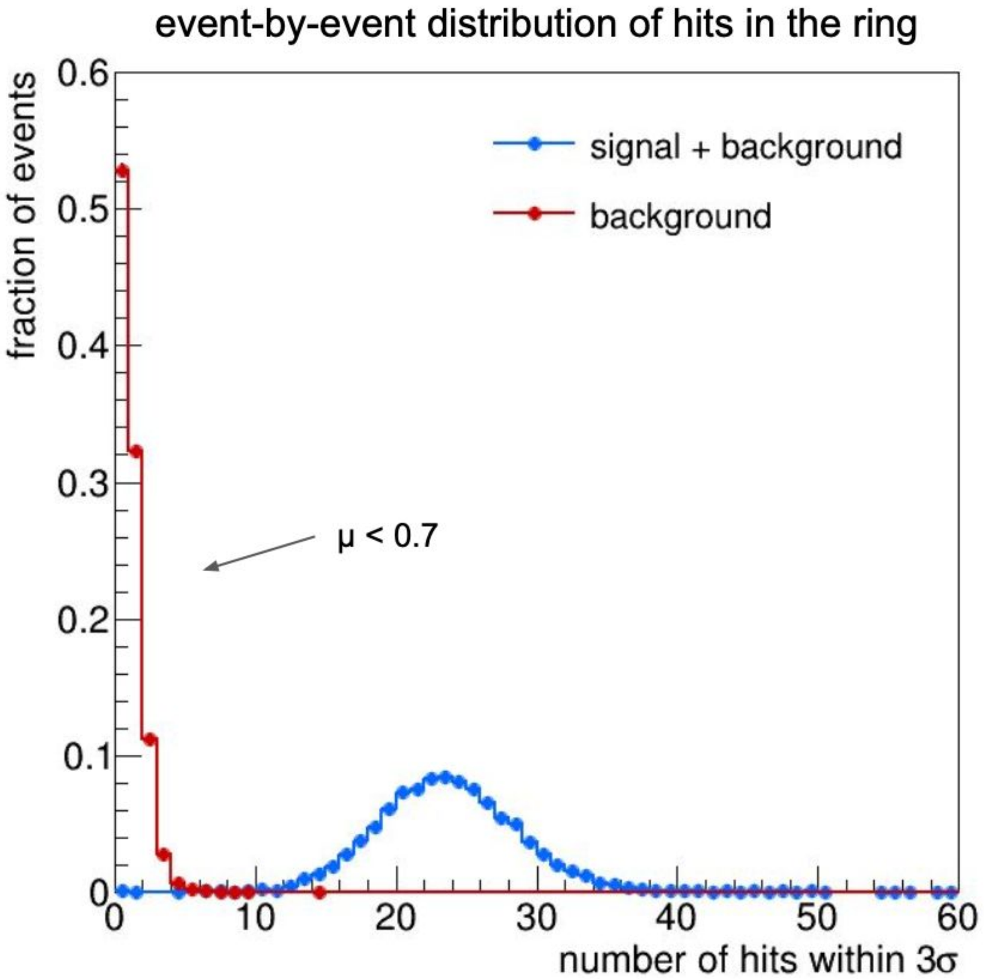
Hit distribution with and w/o aerogel tiles



Beam test results - background studies



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



background in ring region estimated with data taken without aerogel