Radiation Damage Study and Performance Evaluation of SiPM for the Dual-Radiator RICH Detector in the ePIC Experiment

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2nd European School on the Physics of the EIC and Related Topics
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The dual-radiator RICH Detector for forward PID at ePIC

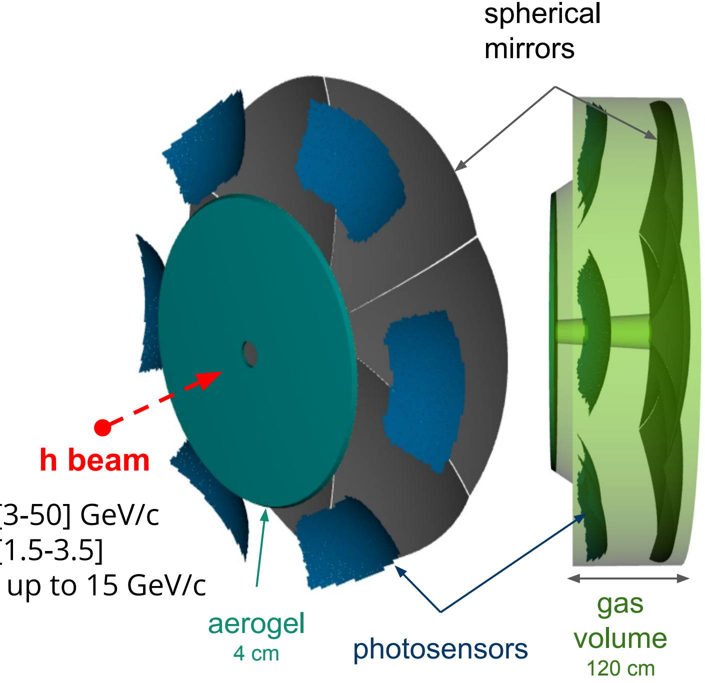
- **Radiators:** **aerogel (n ~ 1.02)** and **C_2F_6 (n ~ 1.0008)**
- **Mirrors:** large outward-reflecting, 6 open sectors
- **Sensors:** **3x3 mm² pixels of SiPM, ~ 3 m² of photodetectors**
  - Pros:
    - Single photon sensitivity
    - Good timing performance
    - Resistive to high B field (~ 1 T)
    - Compact and cost effective
  - Cons:
    - High dark count rate
    - Not radiation tolerant

    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**

Technical solutions and mitigation strategies

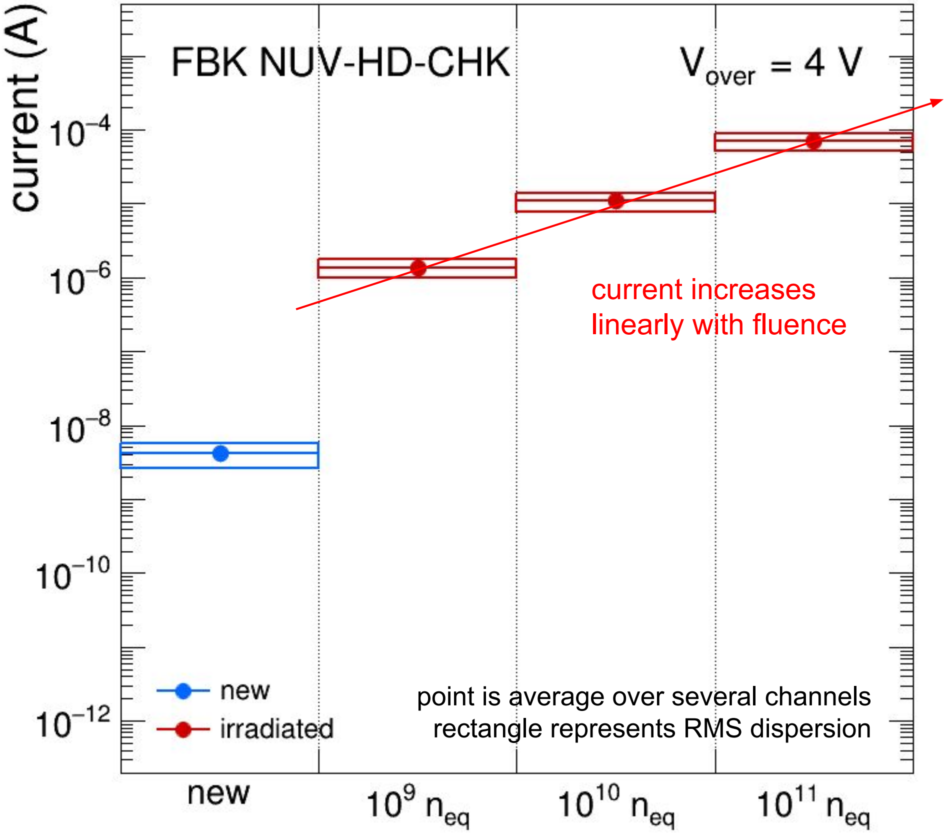
🐧Cooling: reduces DCR by a factor of 2 every ~8°C
⌚Timing: cut down the background
🔥Annealing: recover from radiation damage

Compact and cost-effective solution for broad momentum (3-50 GeV/c) coverage at forward rapidity

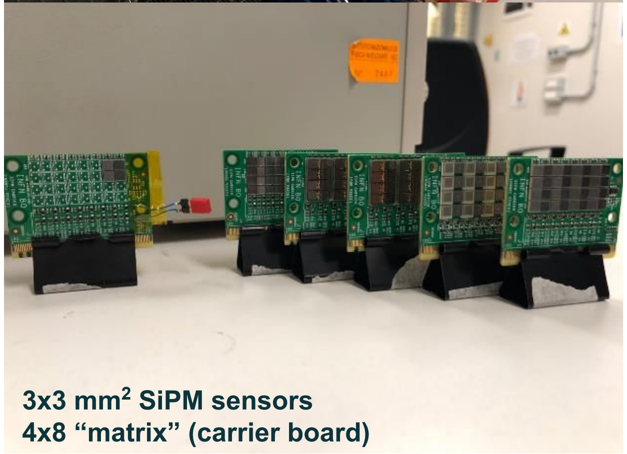


PID:
p = [3-50] GeV/c
η = [1.5-3.5]
e-ID up to 15 GeV/c

Studies of radiation damage on SiPM

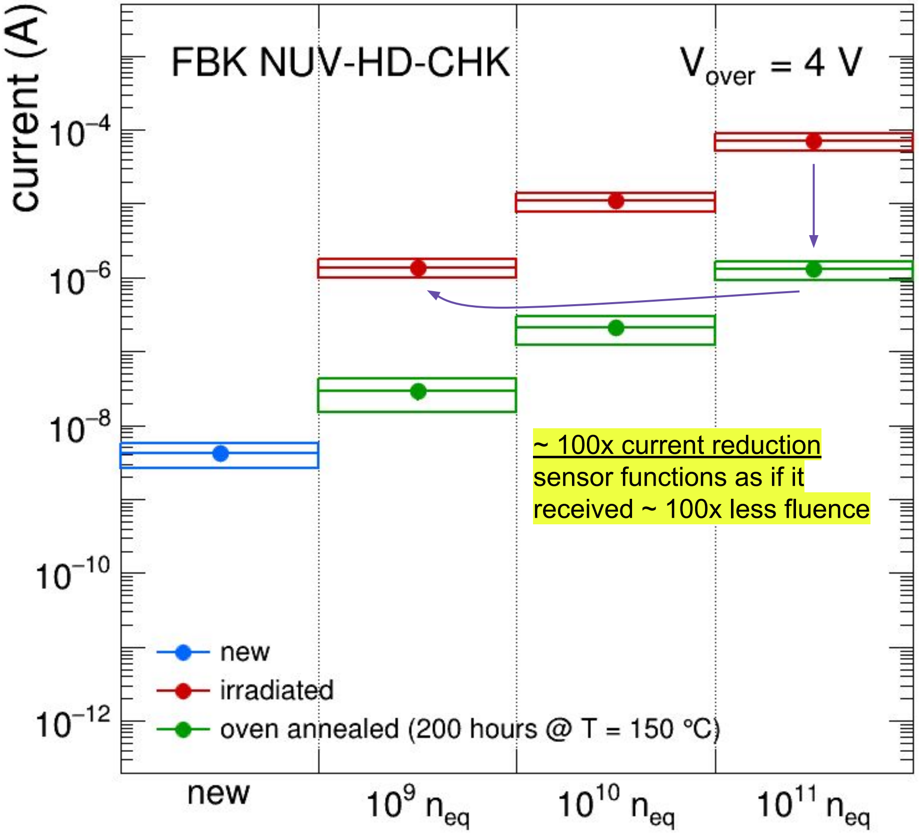


all results are reported at T = -30 C

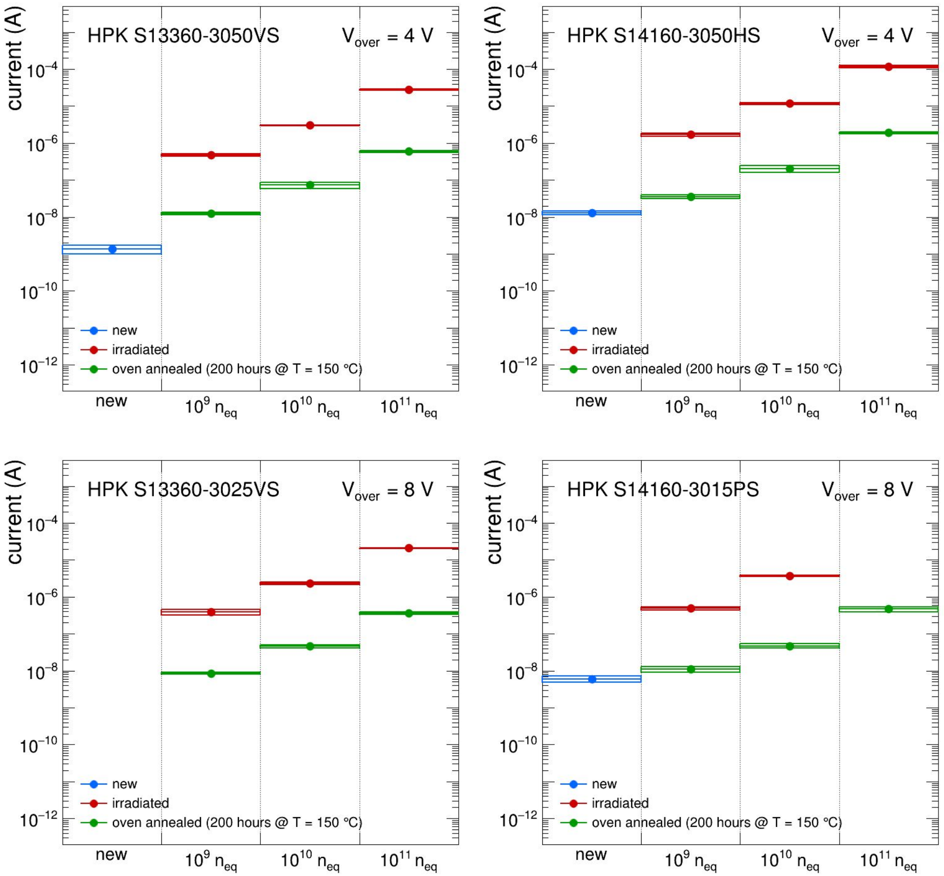


Damage recovery of SiPMs: offline annealing

oven annealing
~ 1 week at 150 C



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

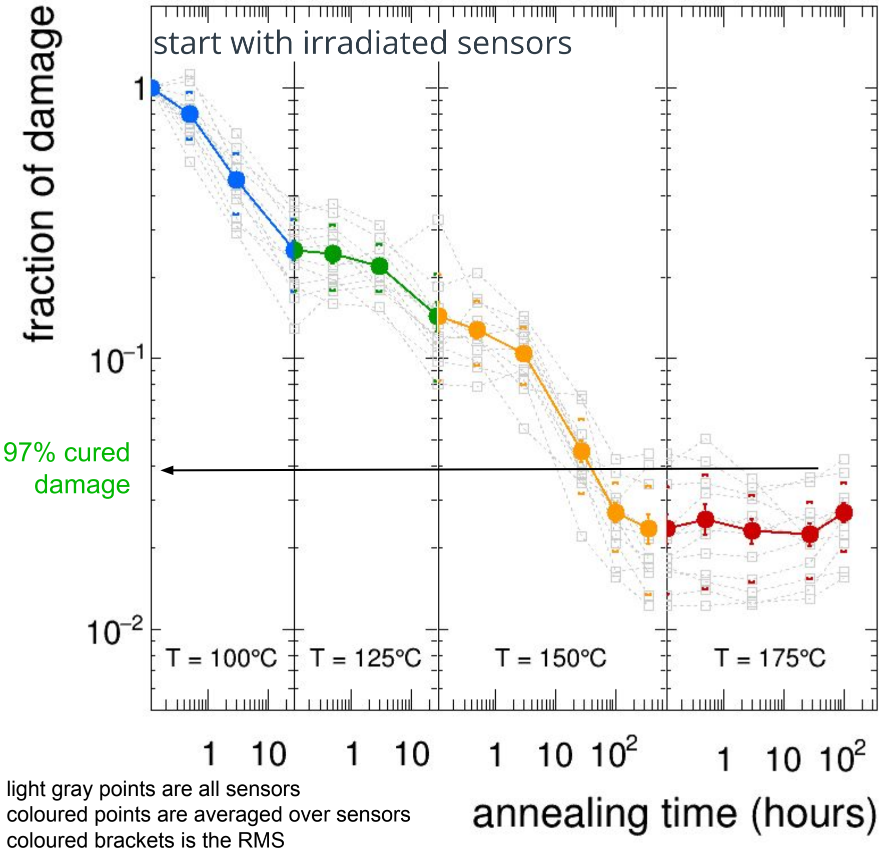


similar observation with various types of Hamamatsu sensors

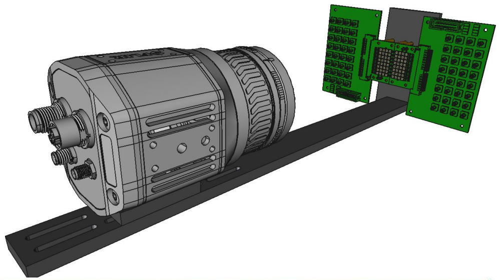
"Online" self-induced annealing

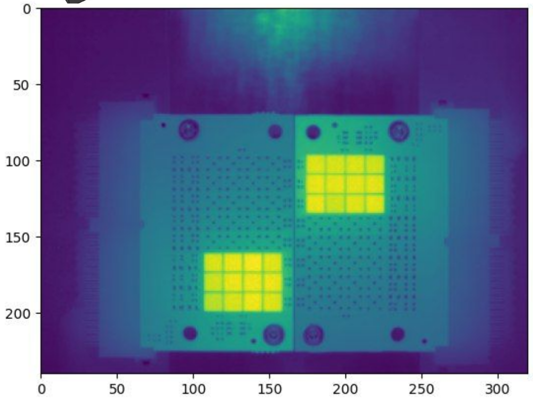
thermal studies for "in-situ" SiPM recovery
sensors heated with up to 1 W power/sensor

forward-bias annealing



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

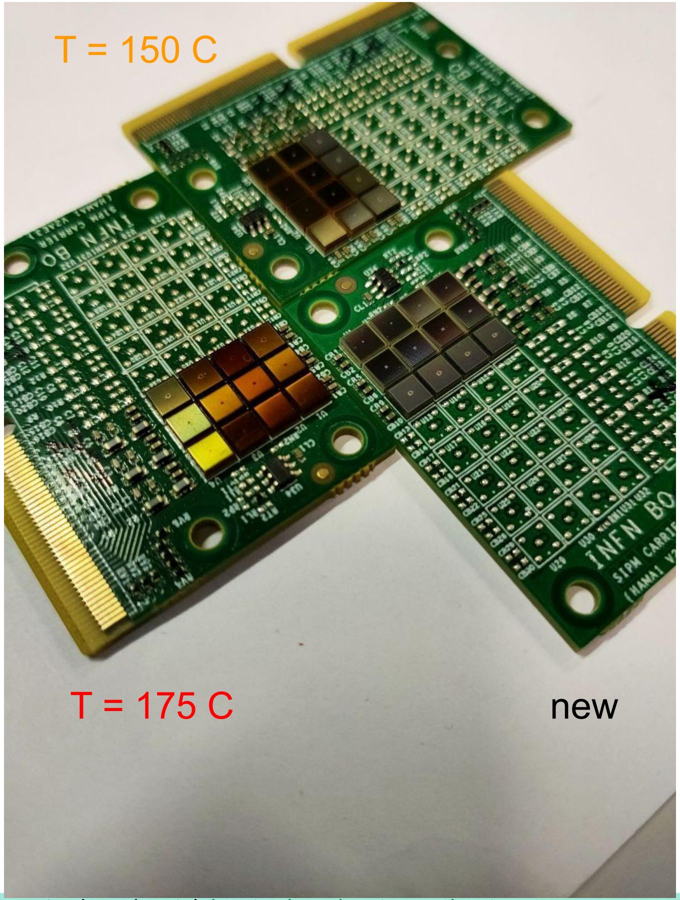




detailed studies on a large sample of sensors
how much damage is cured as a function of temperature and time

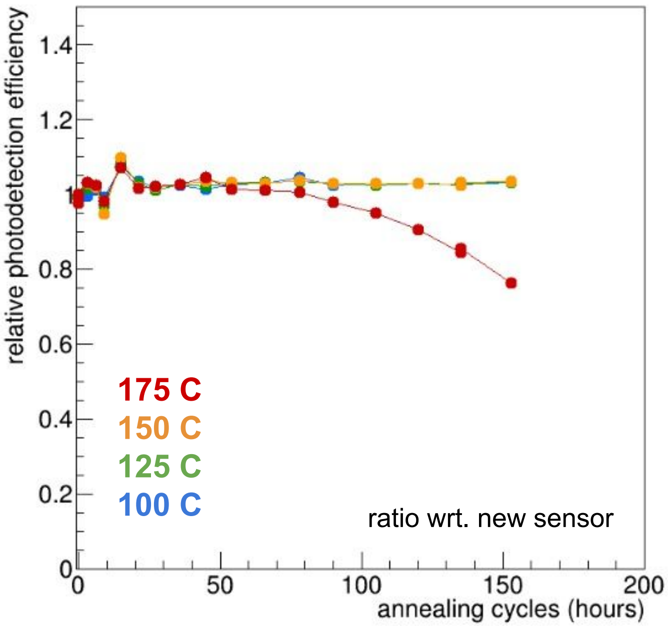
fraction of residual damage seems to saturate at 2-3% after ~ 300 hours at T = 150 C
continuing at higher T = 175 C seems not to help curing more

Detailed 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

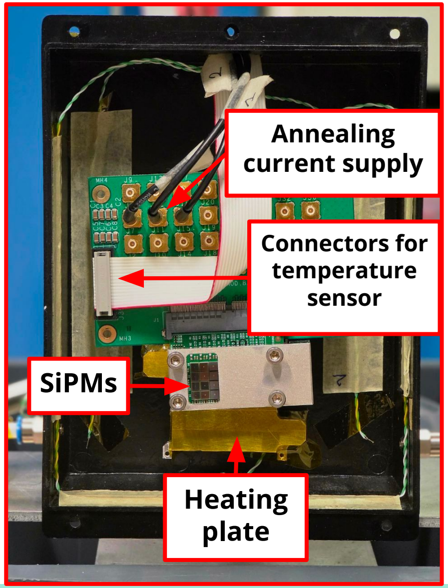


detailed studies are ongoing, preliminary results indicate efficiency loss after 100 hours of annealing at T = 175 C. lower temperatures unaffected up to 150 hours

Hybrid annealing

Different approach for annealing:

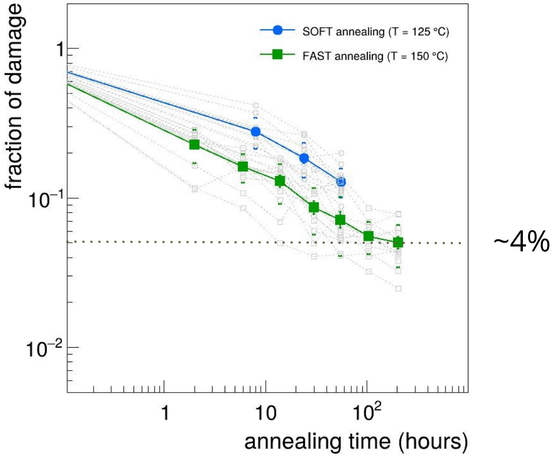
1. **Humidity** will always be kept **at 0%** by flushing **dry air** in a closed a box.
2. It uses **a external heating source and forward current** to heat up the sensors upto the desired temperatures.
3. The goal now was to **go upto 100 ℃ with heating plate** and **remaining temperatures with forward bias current**.

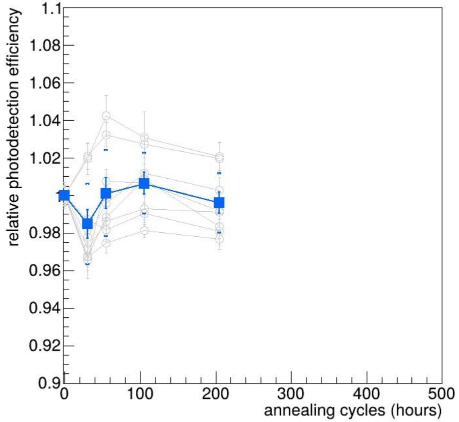


The SiPM board is attached on the surface of a heating plate where liquid flows through it to maintain at 100 ℃.

The LM73 sensor measures the ambient temperature near SiPM region.

There are two main calibrations needed:
1. Variations of LM73 with chiller temperatures.
2. SiPM temperature with supplied power in forward bias.

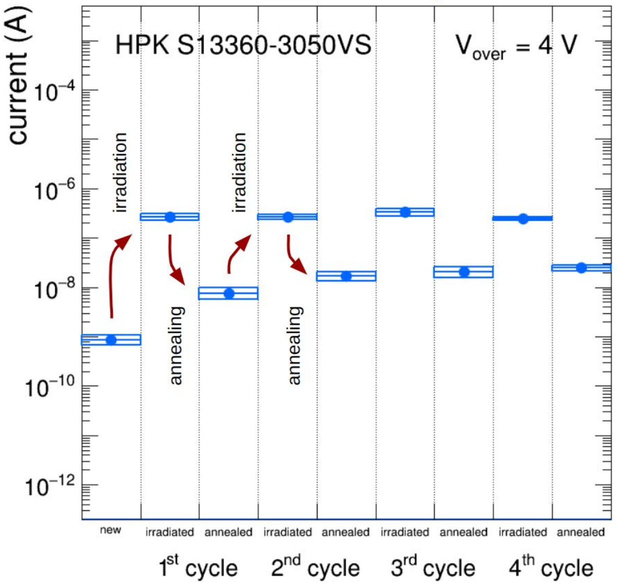




Ageing model

repeated irradiation-annealing cycles

simulate realistic experimental situation



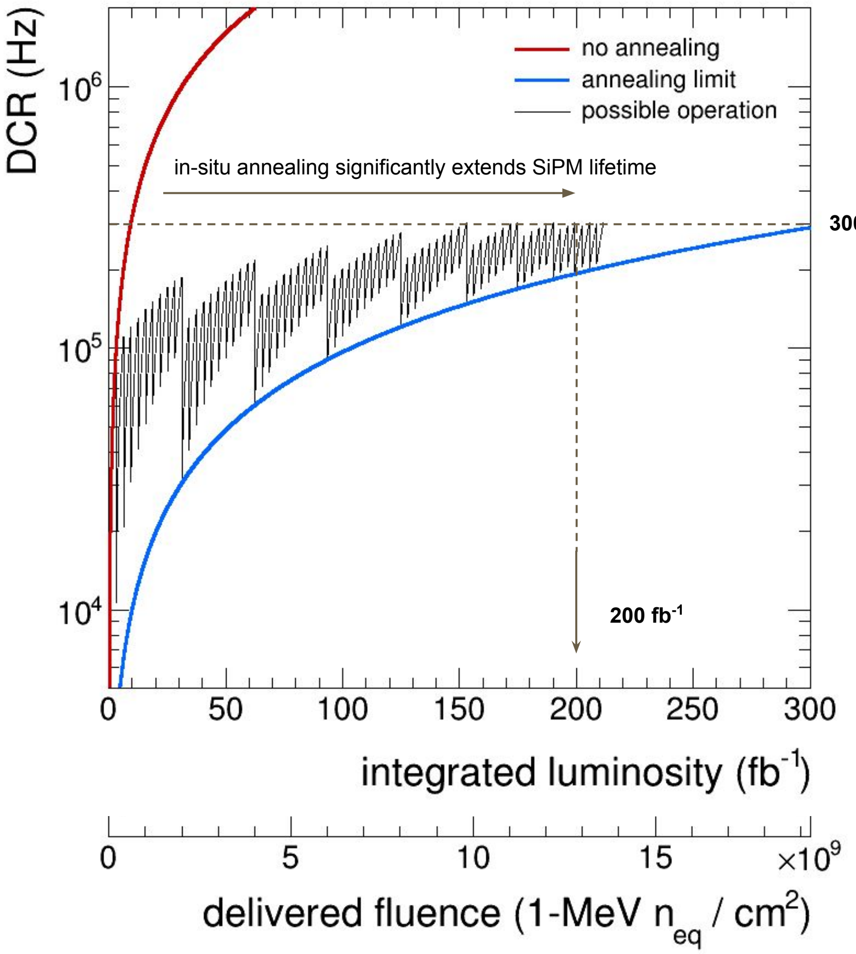
model input from R&D measurements done in 2022

- 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

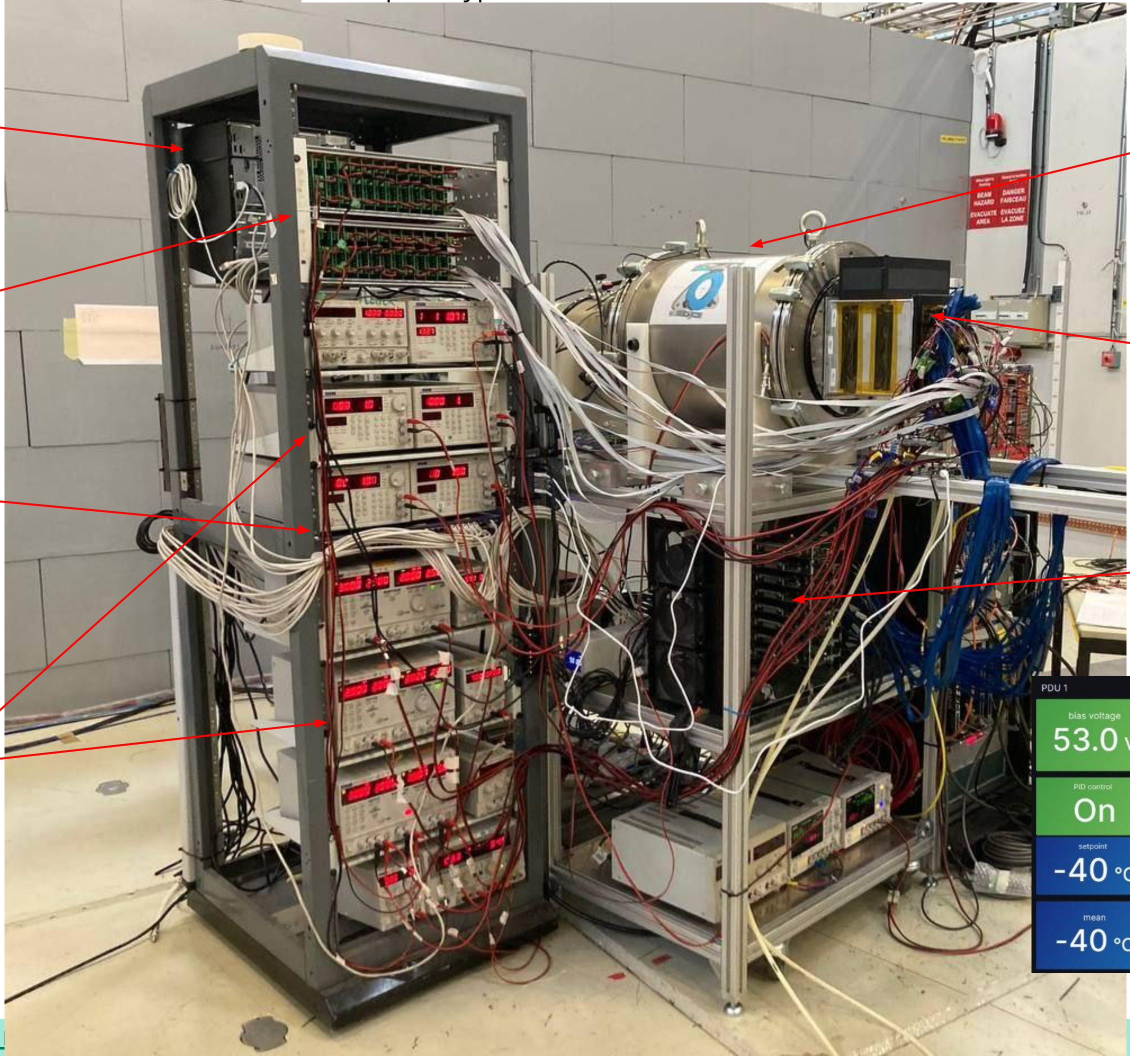
these predictions are according to present knowledge / tested solutions
there are more handles to further mitigate DCR
lower Vover, 3V
lower T operation -40 C or below

Now we know how the sensors work!

What about the real experimental condition?

Can they able to identify different hadrons (p, pions and kaons) in a large momentum range (3 - 50 GeV/c)?

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



DAQ and DCS computers

auxiliary control electronics crates

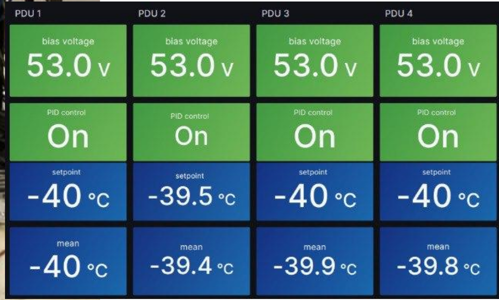
gigabit ETH switch for DAQ and DCS

low voltage and high voltage power supplies

dRICH prototype

SiPM photodetector readout box

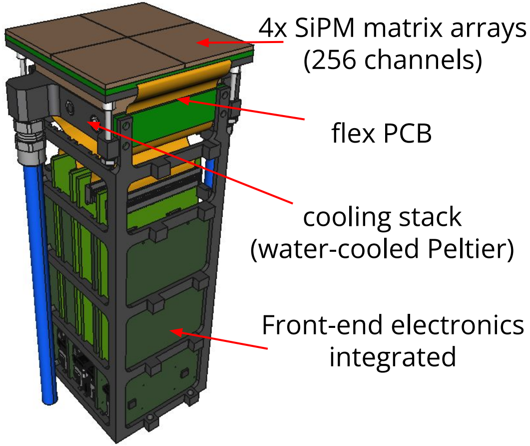
DAQ FPGAs and clock distribution



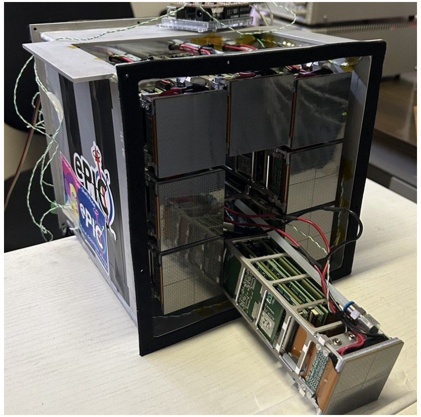
SiPM at low temperature

dRICH Prototype

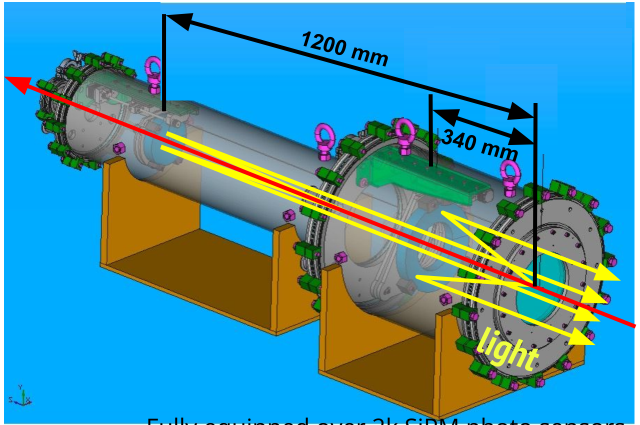
Full PDU

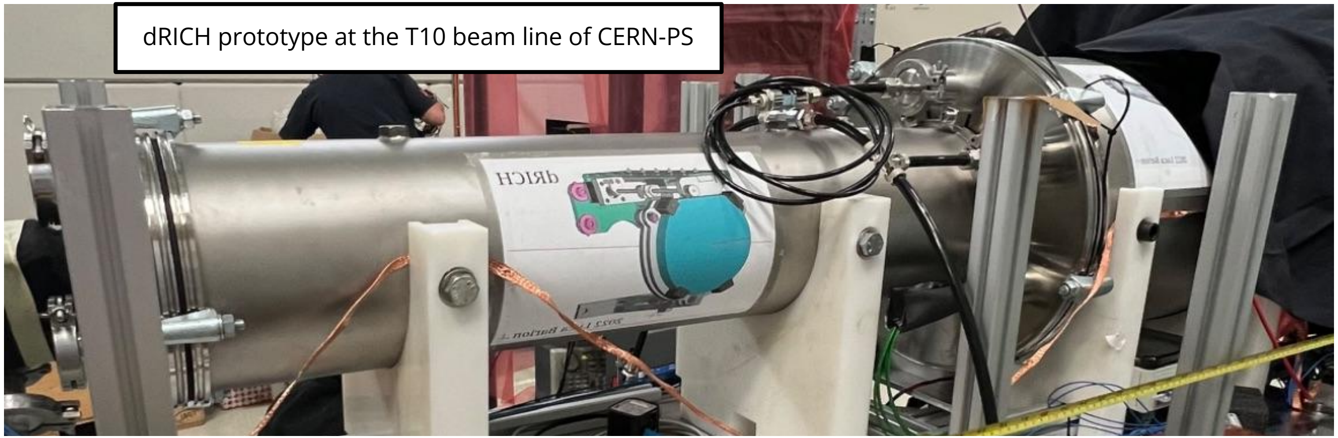


Prototype readout box



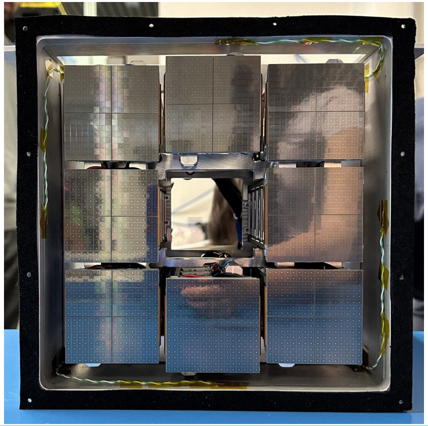
Schematic of the dRICH prototype





dRICH prototype at the T10 beam line of CERN-PS

Fully equipped over 2k SiPM photo sensors



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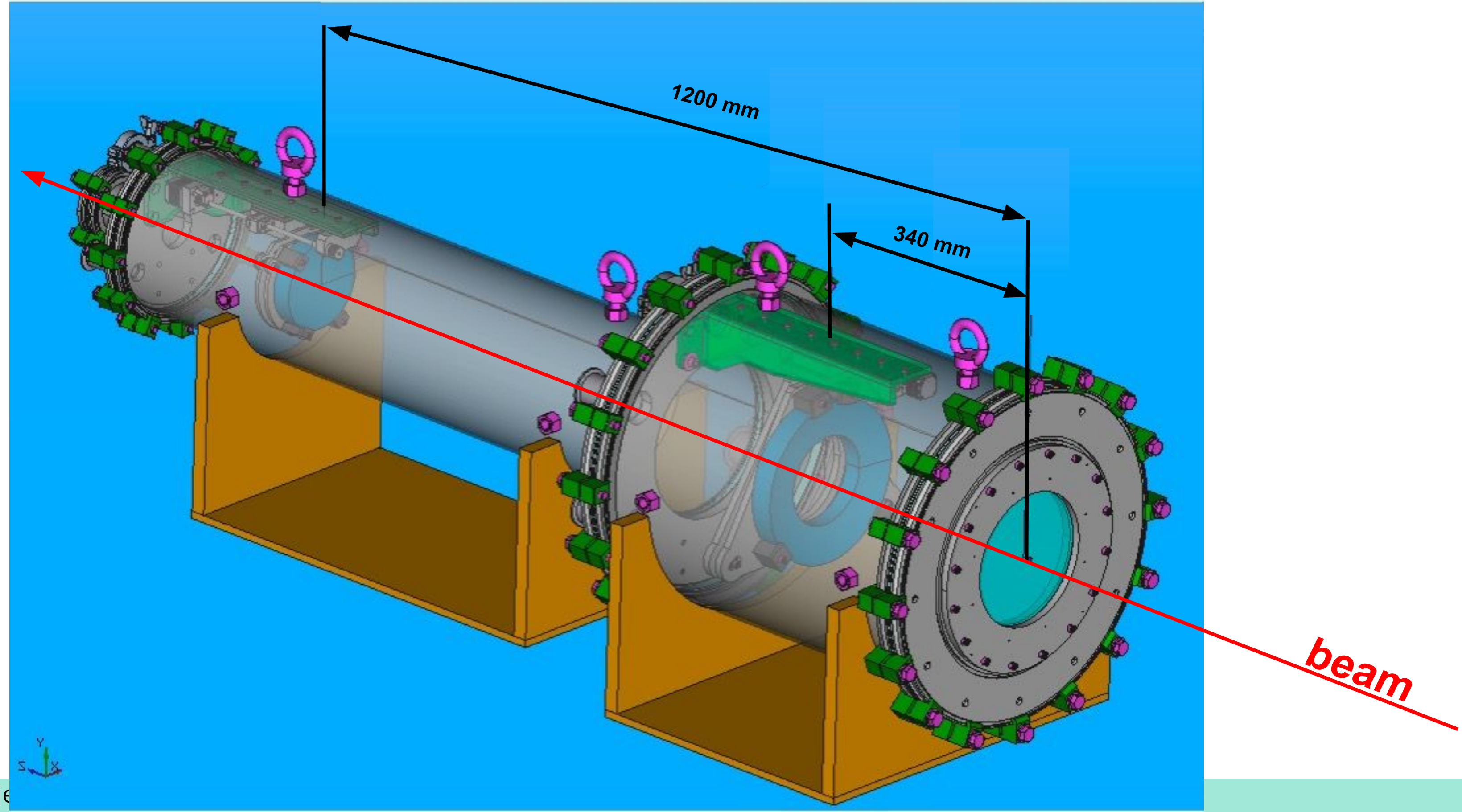

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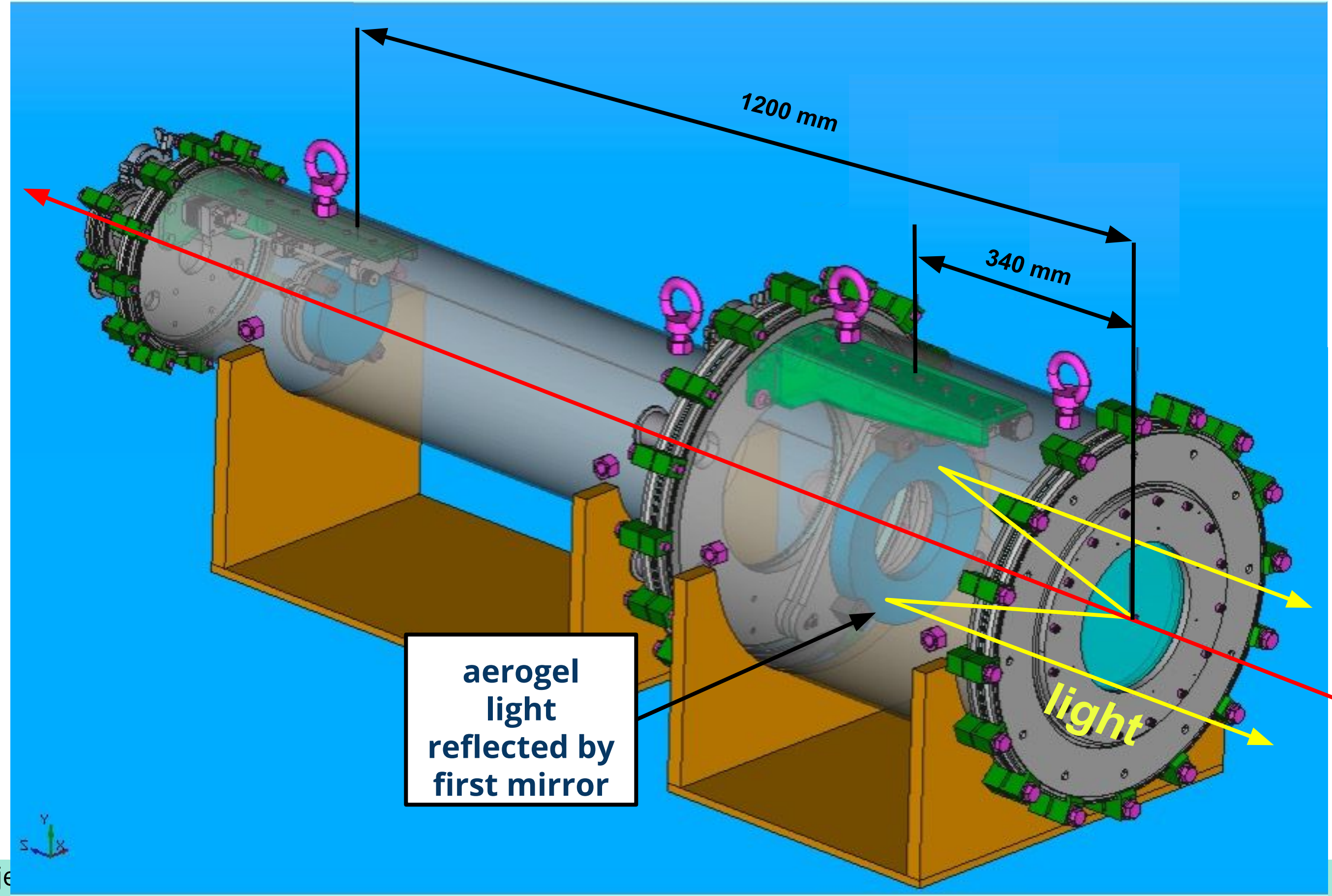

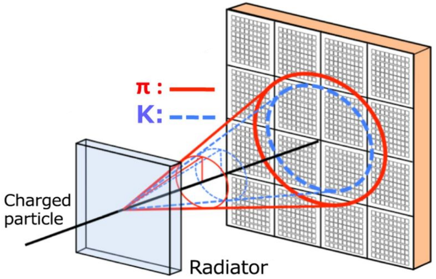

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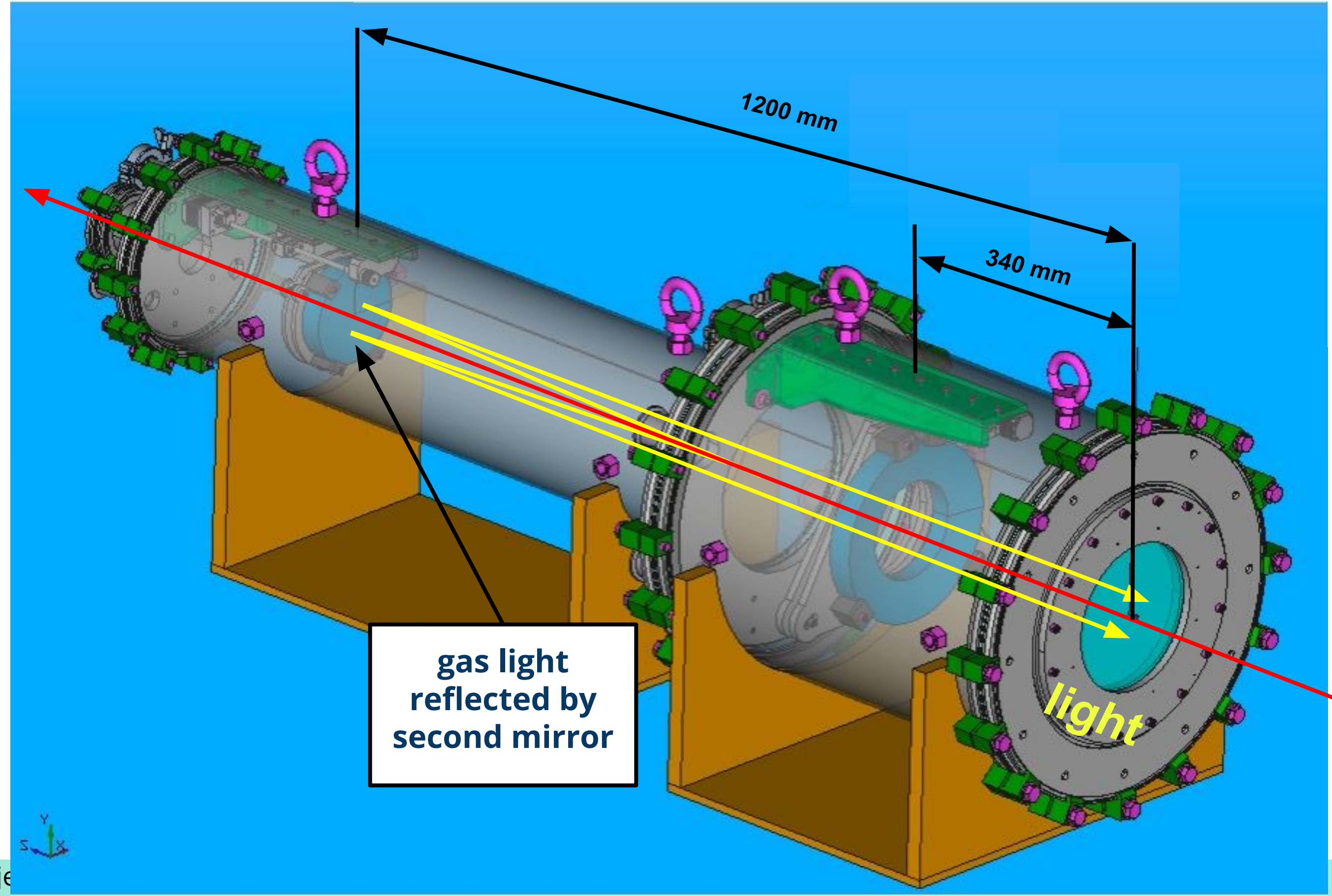

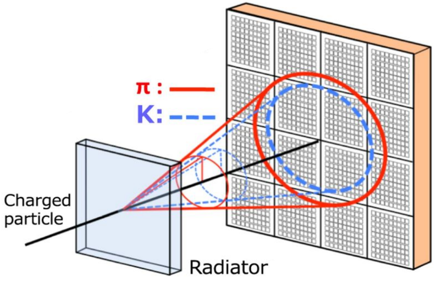

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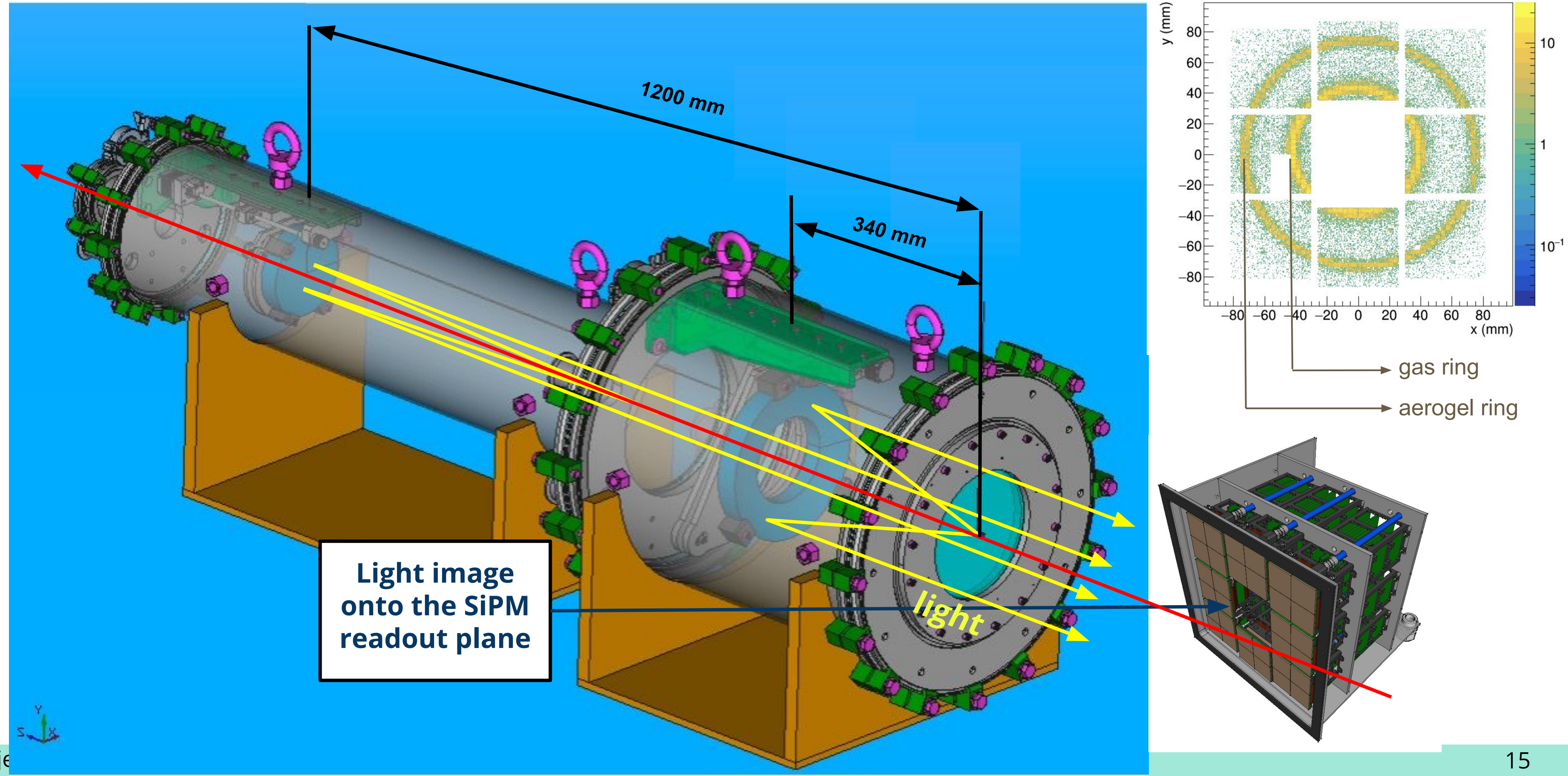
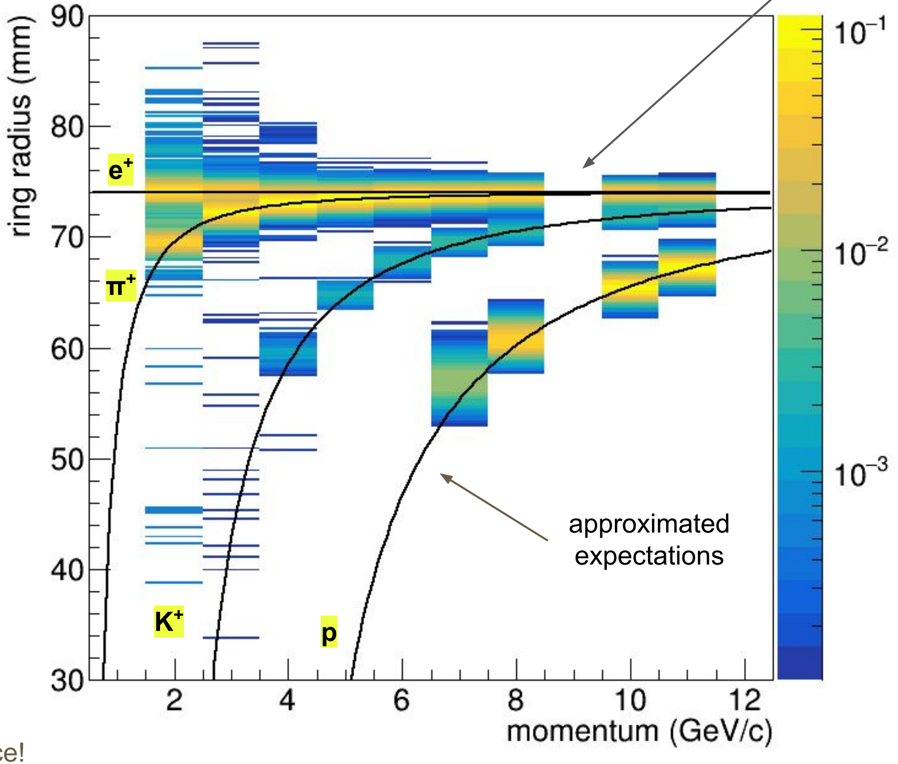


Beam momentum scan

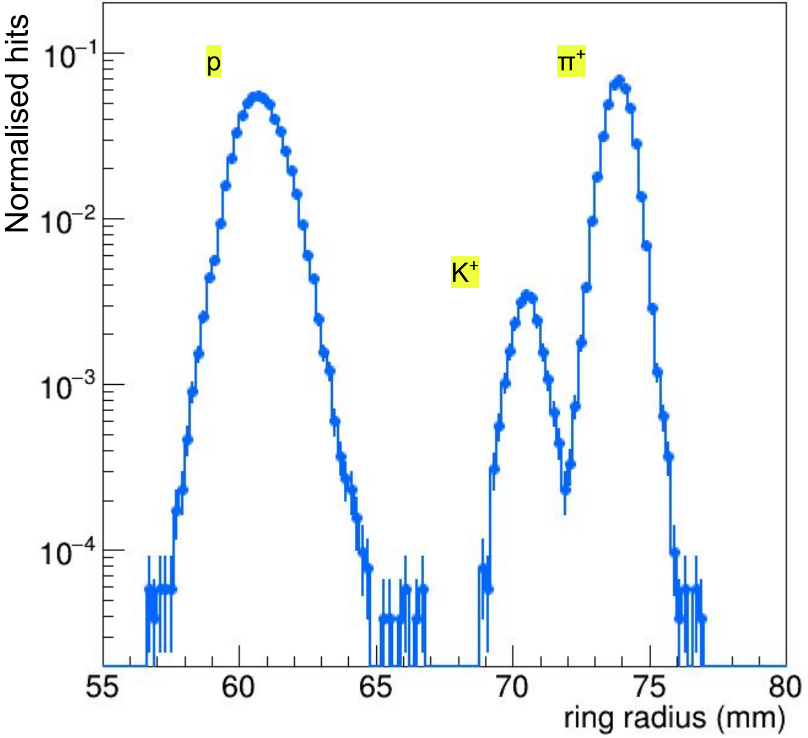
positive particles, aerogel only

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

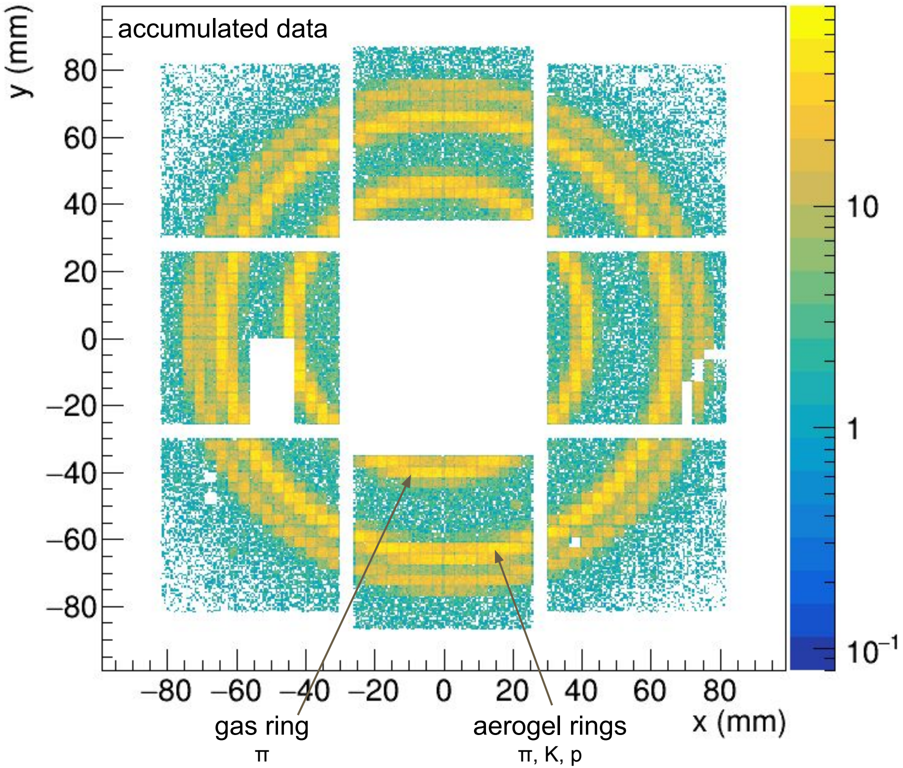


nice!

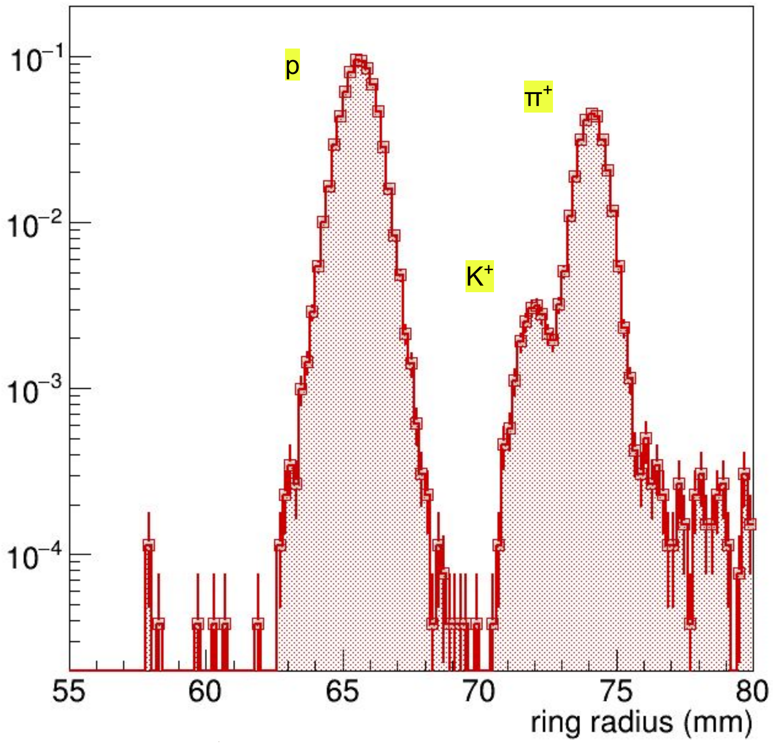
Interplay between aerogel and gas radiators

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



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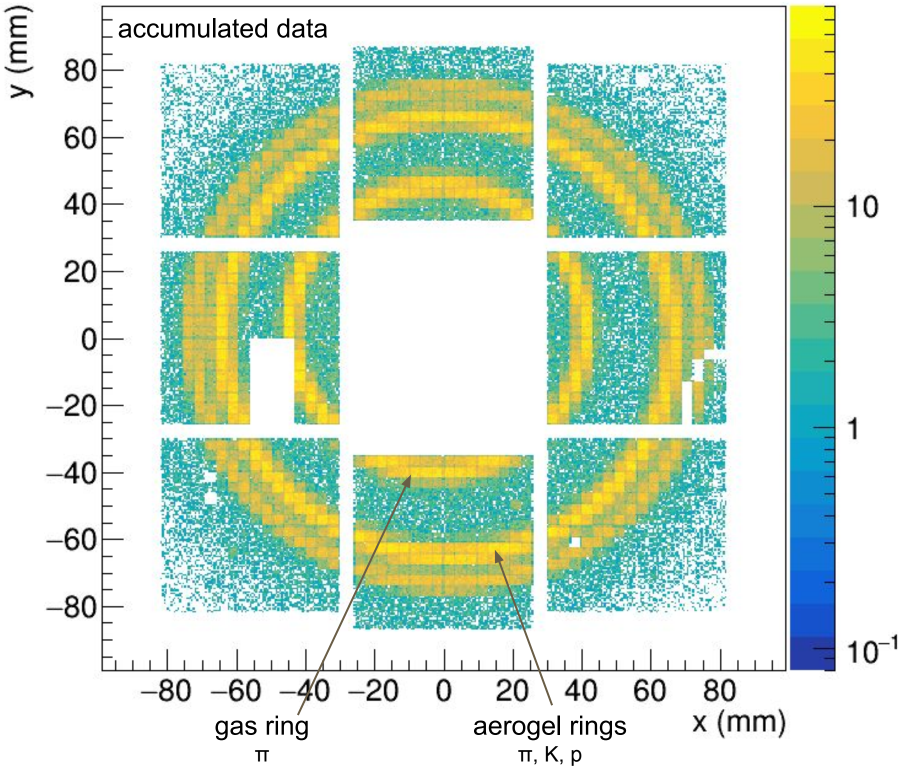
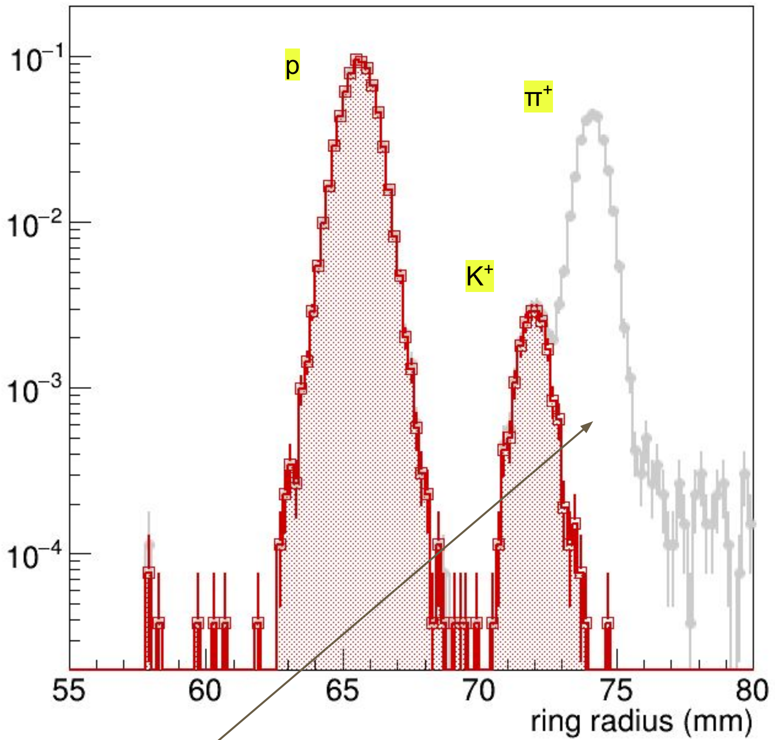
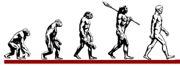


reconstructed ring radius at 10 GeV/c with gas veto

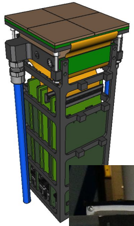


gas-ring veto removes pions, clean kaon identification at 10 GeV/c towards construction



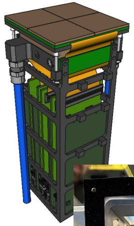
2022

electronics v1



2023

electronics v2



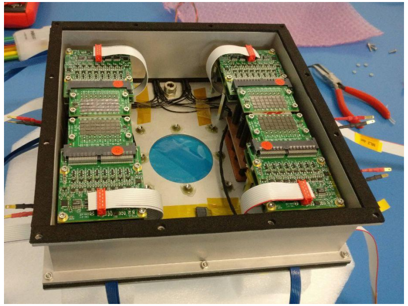
2024

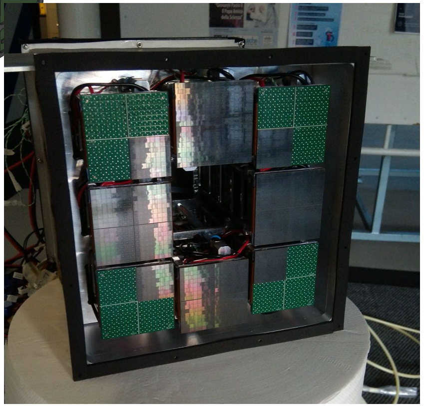
electronics v2.1

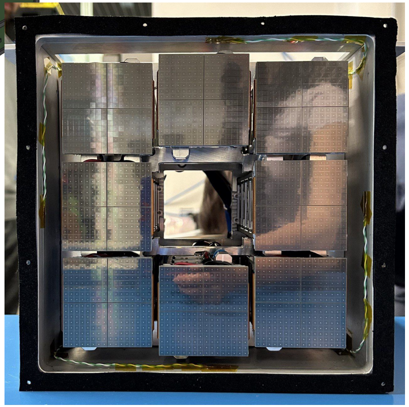
2025

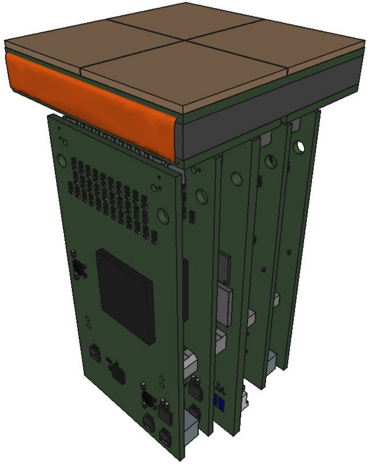
electronics v3

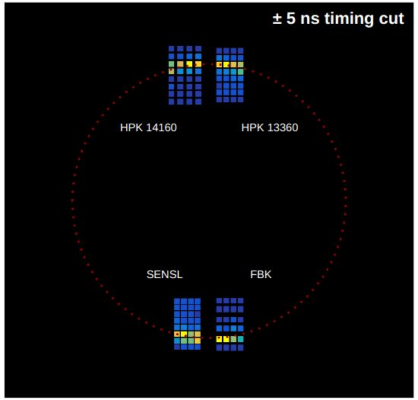
final prototype

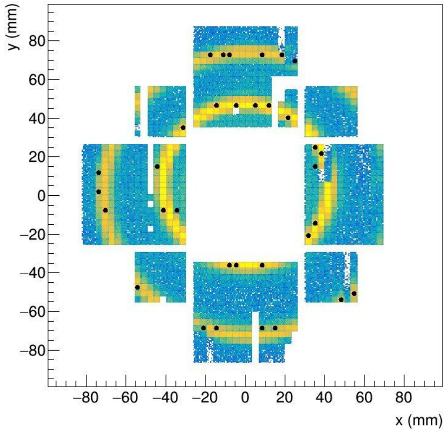


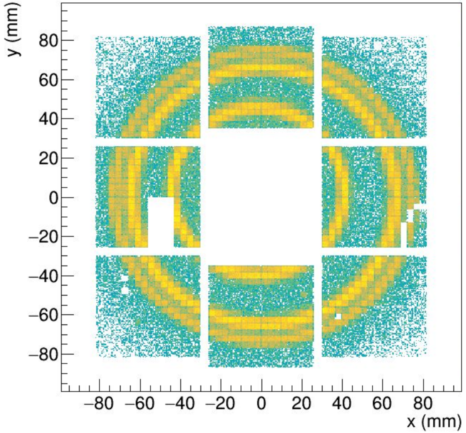












Conclusion and Outlook

- **SiPMs fulfills the dRICH requirements:**
  - Single photon detection
  - Magnetic field limitations
  - Excellent timing and efficiency
- **Technical solutions to mitigate radiation damage**
  - Low temperature operations
  - Online “in-situ” self annealing and hybrid annealing
- **SiPM readout with full electronics chain**
  - 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
- **Upcoming approach 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

Thank you!