The SiPM readout plane for the ePIC-dRICH detector at the EIC: overview and beam test results

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on behalf of the dRICH collaboration
[(1)]INFN Bologna

17 September 2025

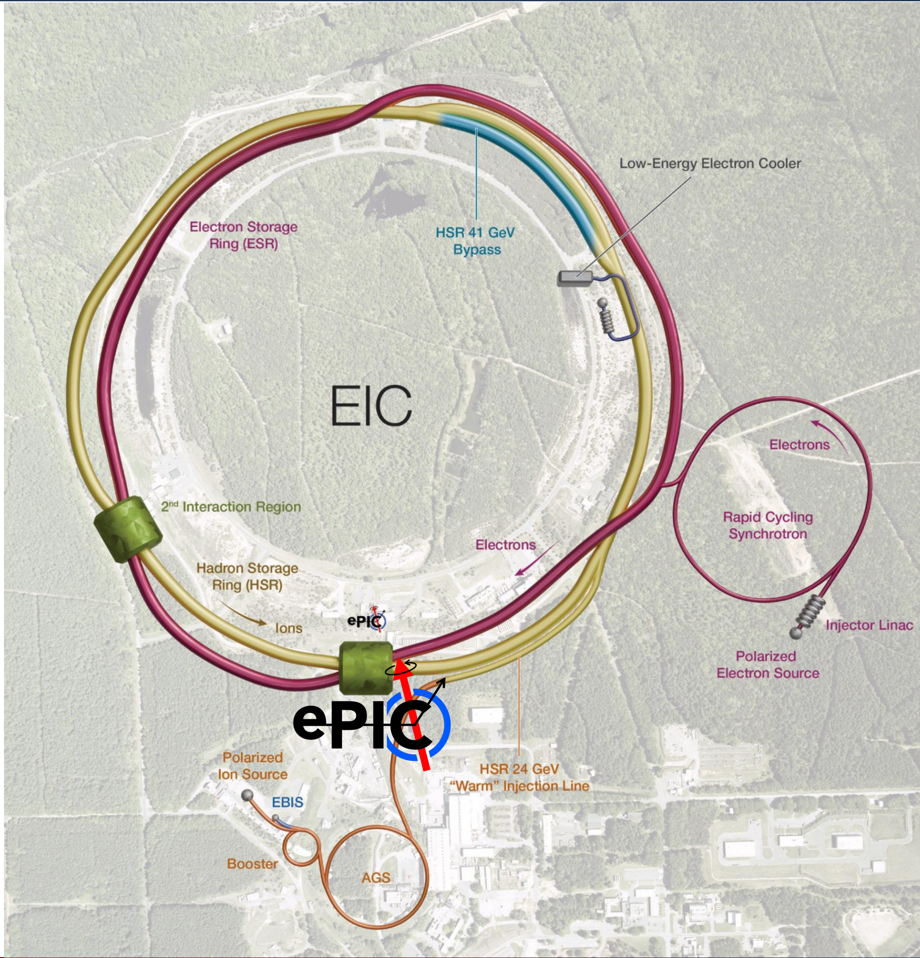
ePIC experiment at EIC

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

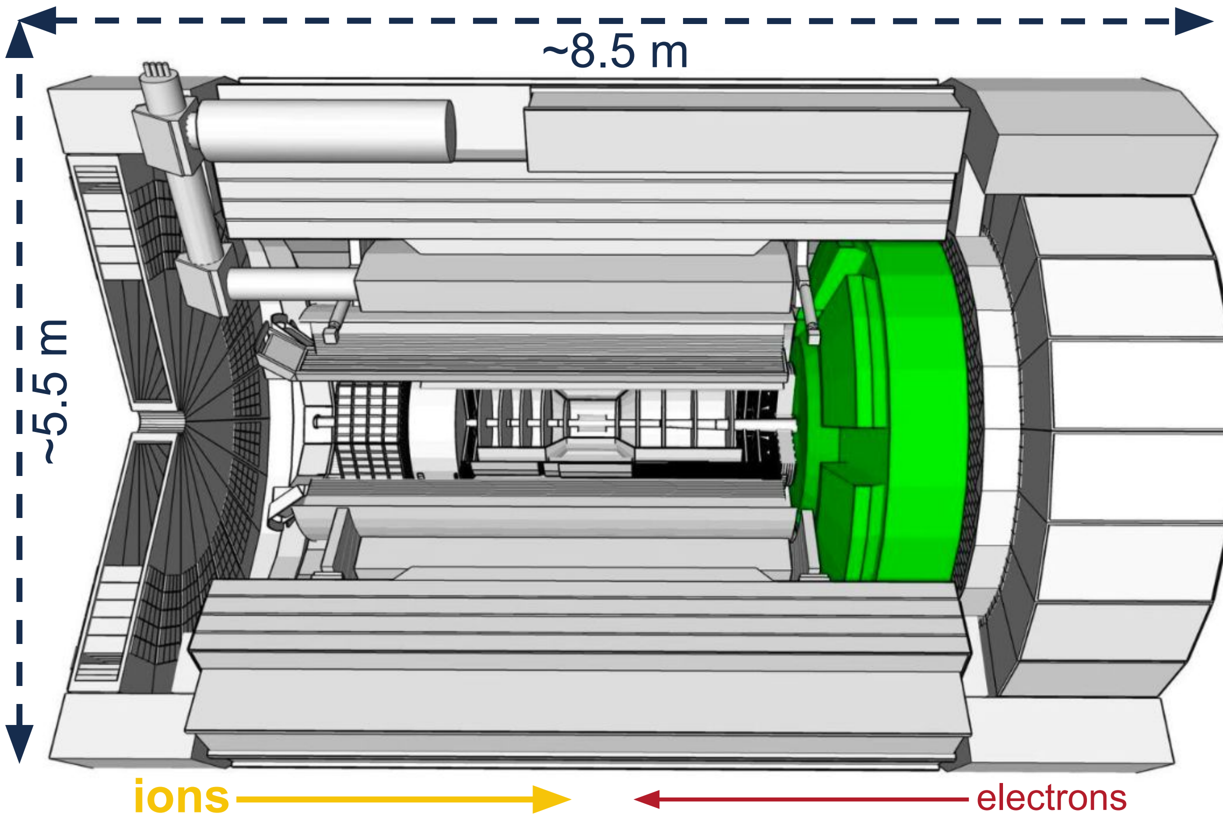
- Collision of e^- and ions from proton to uranium
- Center-of-mass energy from 20 to 140 GeV
- Highly polarised beams: ~70%
- High luminosity 10^{33} $cm^{-2}s^{-1}$
- One foreseen experiment: ePIC
- Start of operations in the early 2030s

Physics goals:

- Precise measurements in non-perturbative QCD
- Origin of mass & spin of the nucleons
- 3D imaging of the nuclear structure



ePIC detector layout



Tracking:

1.7 T magnet
Si-MAPS + MPGDs

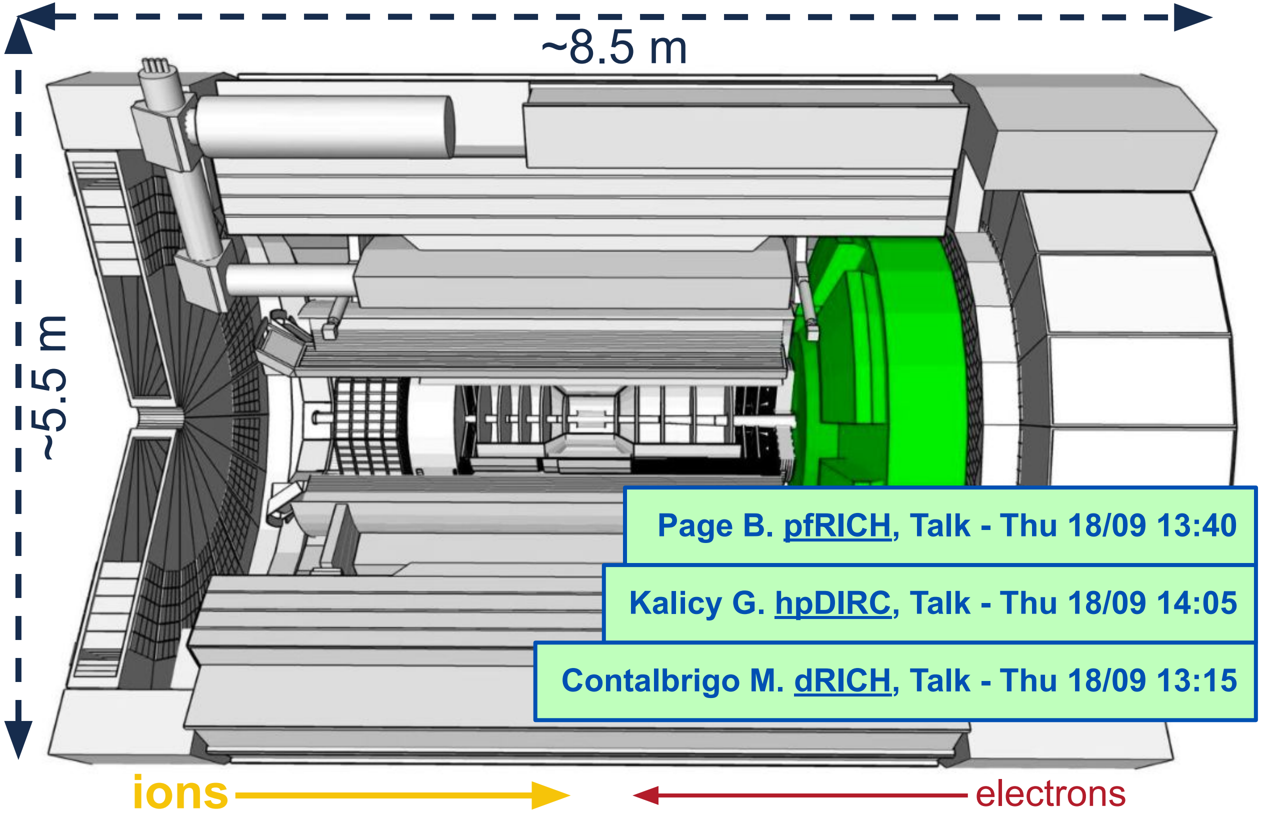
Calorimetry:

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

PID:

AC-LGAD TOF
pfRICH
hpDIRC
dRICH

ePIC detector layout



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AC-LGAD TOF
pfRICH
hpDIRC
dRICH

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

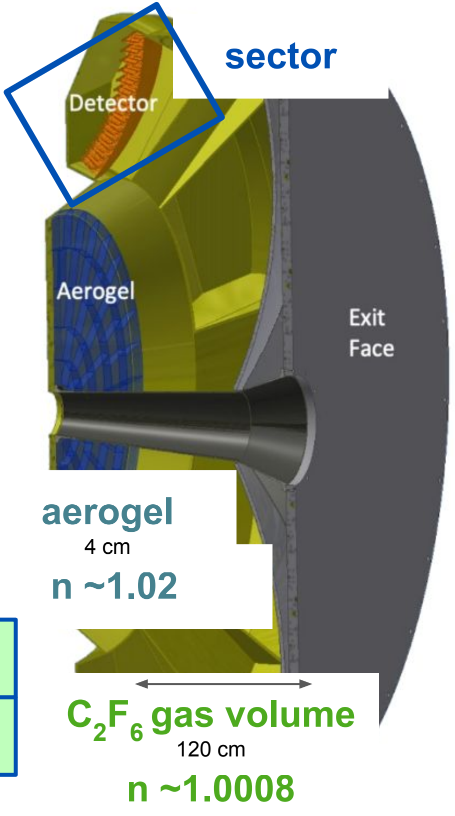
PID

p ~ 3-50 GeV/c

η ~ 1.5-3.5 GeV/c

e ~ up to 15 GeV/c

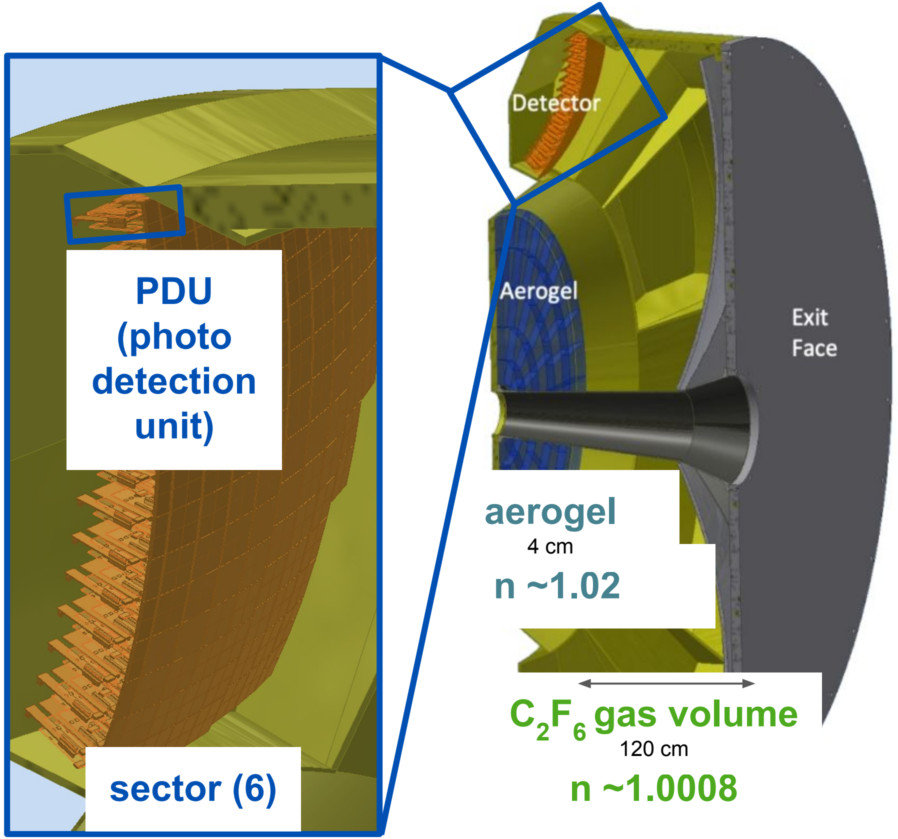
Broad momentum coverage thanks to two radiators



Boasso T. dRICH Performance Simulation, Poster

Tessarotto F. dRICH radiator gas, Talk - Fri 19/09 09:10

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



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

Photosensors:

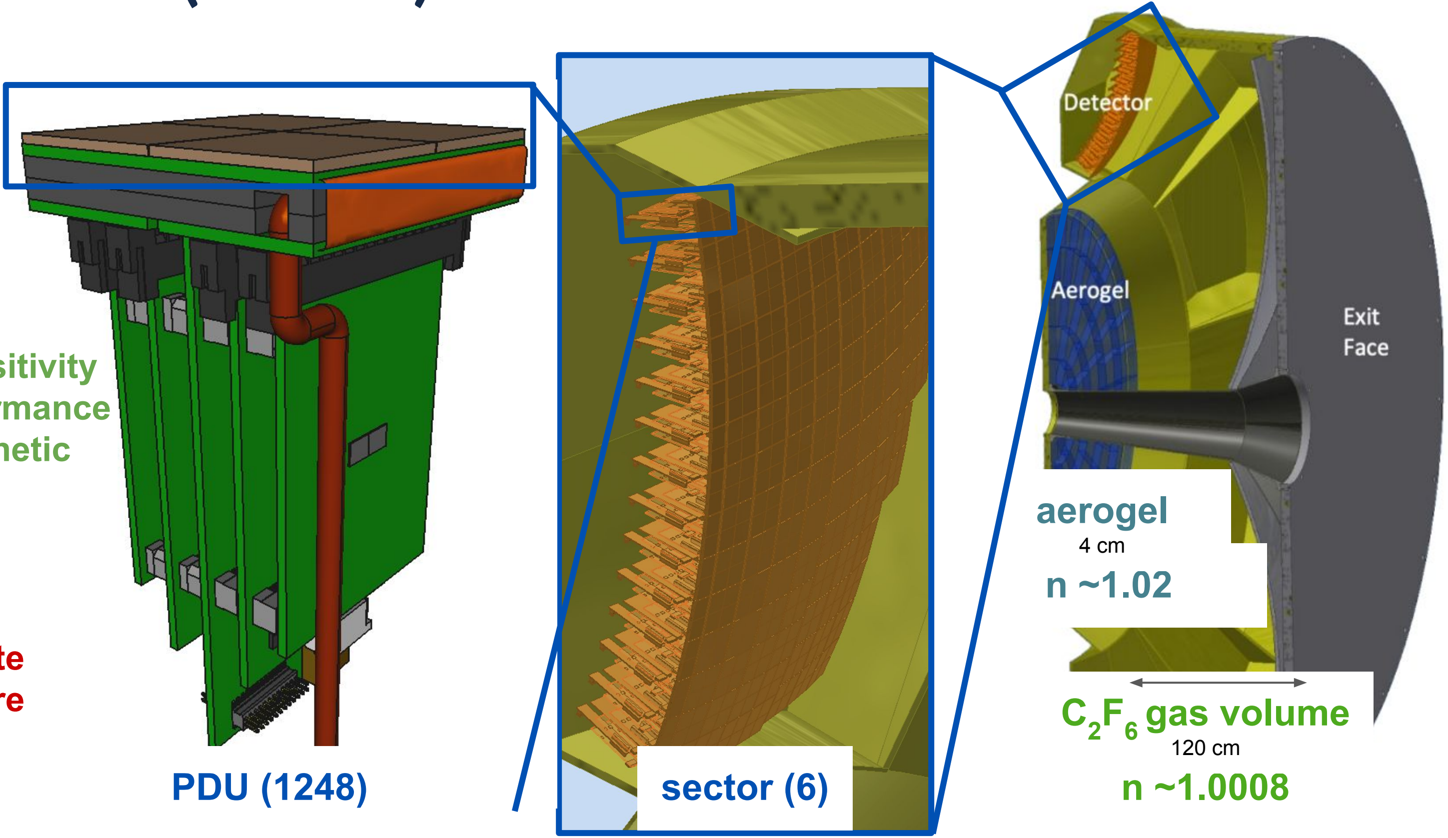
- $3x3\ mm^2$ pixels
- $0.5\ m^2$ per sector
- SiPM chosen

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



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

Ripoli C. SiPM radiation hardness, Poster

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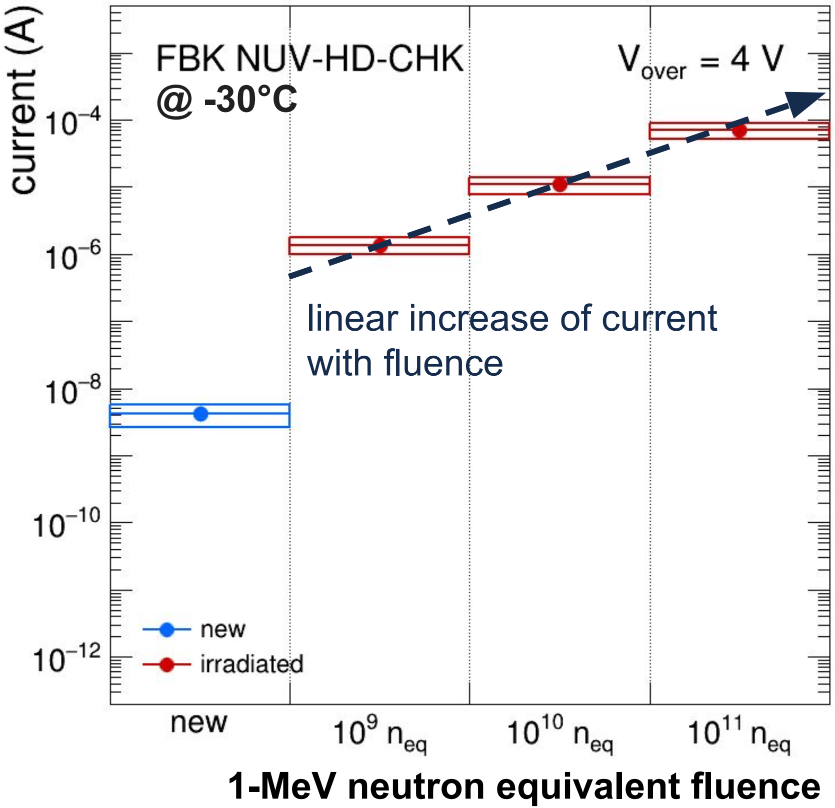

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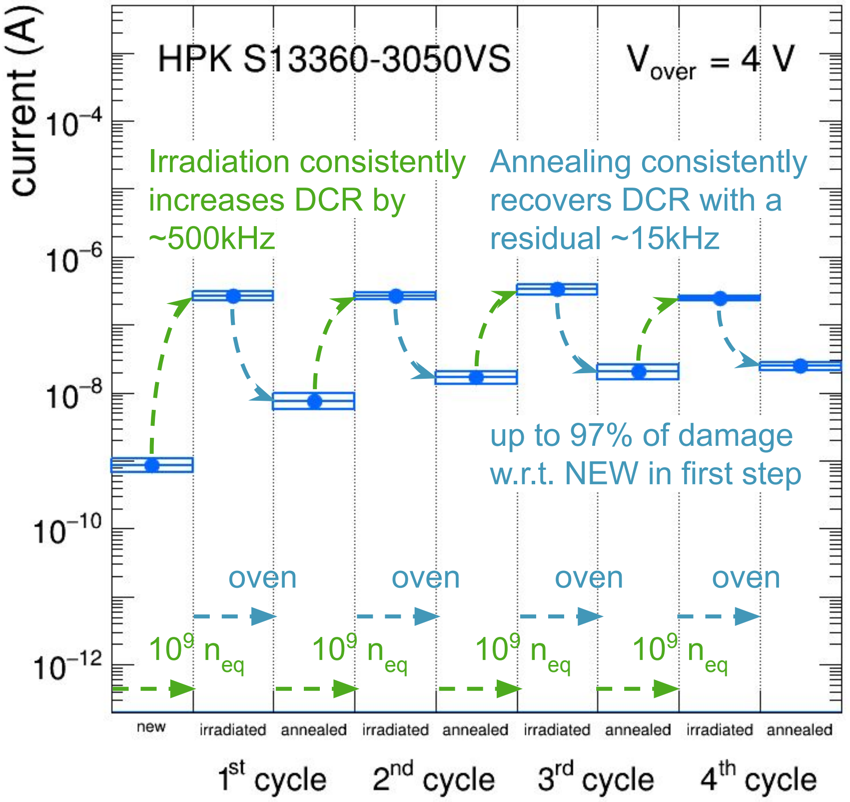

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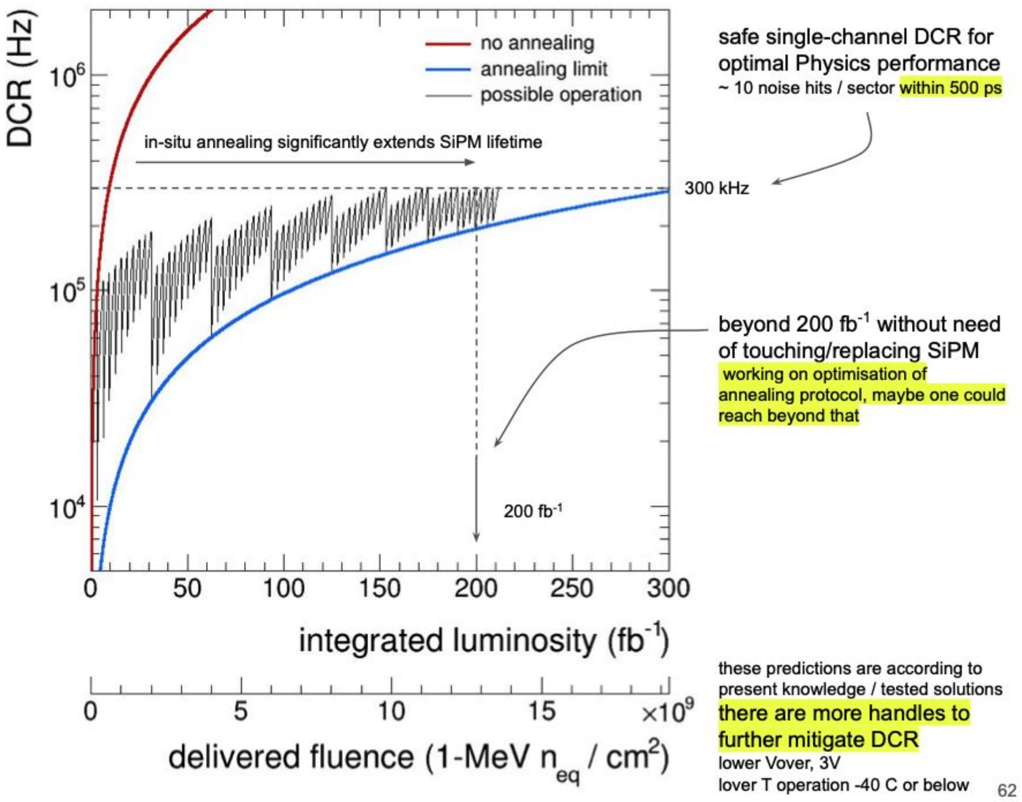


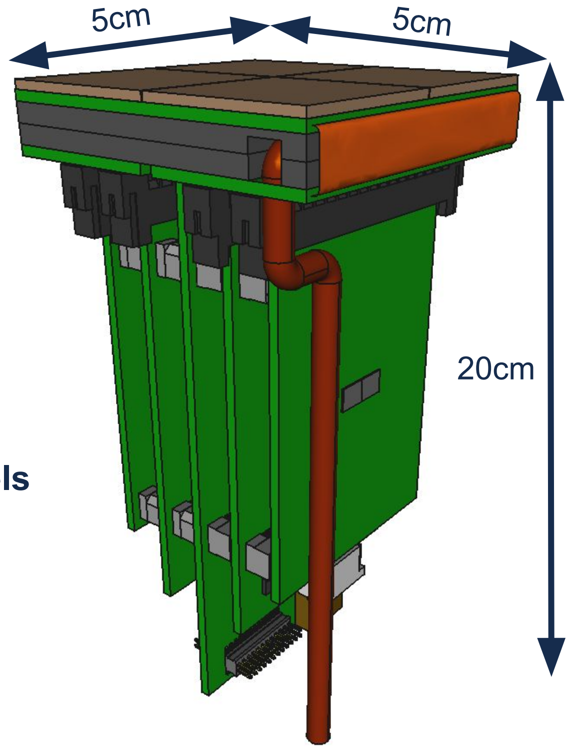
The dRICH Photo Detection Unit (PDU)

Photosensors:

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

Specifics

1. Each PDU holds 4 matrices
2. Each matrix is 8x8 sensors
3. Total of 256 channels



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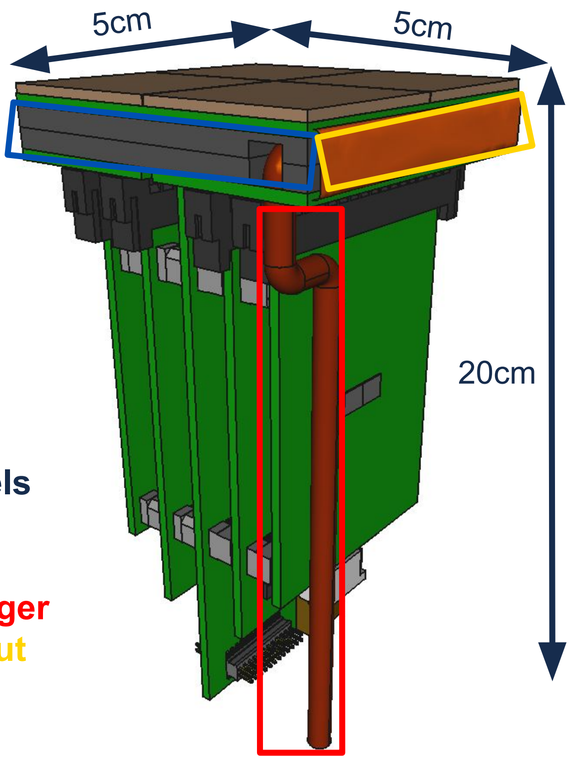
The dRICH Photo Detection Unit (PDU)

Photosensors:

- $3 \times 3\ mm^2$ pixels
- $0.5\ m^2$ per sector
- SiPM chosen

Specifics

1. Each PDU holds 4 matrices
2. Each matrix is 8x8 sensors
3. Total of 256 channels
4. Cold plate / heat exchanger
5. Liquid heat exchanger
6. Flex PCB for readout



The dRICH Photo Detection Unit (PDU)

Photosensors:

- **3x3 mm² pixels**
- **0.5 m² per sector**
- **SiPM chosen**

Specifics

1. **Each PDU holds 4 matrices**
2. **Each matrix is 8x8 sensors**
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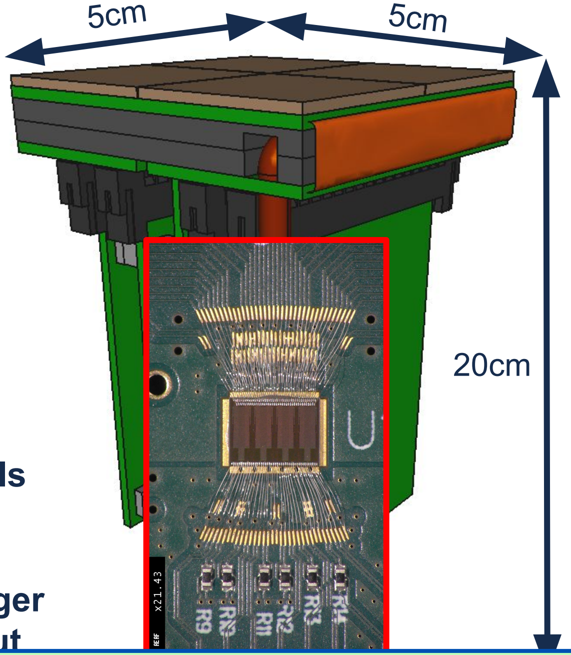

Preghenella R. ALCOR chip, Poster

Rossi C. dRICH Data Reduction, Talk - Tue 16/09 15:05

developed by INFN Torino, 64-channel 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
  - 2-3ns 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

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The PDU prototype

4x matrices of 8x8 SiPMs
3x3 mm^2, total 256 channels

2 peltier cells for subzero operating temperatures

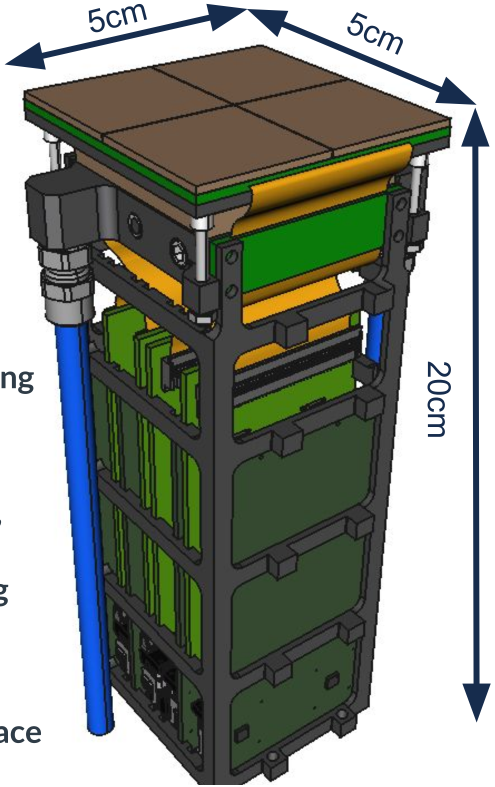
Temperature sensors both under the sensors and on the peltiers

light-weight aluminium structure

Front-end electronics featuring the ALCOR ASIC chip

Externally provided:
High voltage bias for sensors, low voltage power supply for electronics, T sensors piloting and read-out

liquid heat exchange for temperature control of hot-face of peltiers



The PDU proto

4x matrices of 8x8 SiPMs
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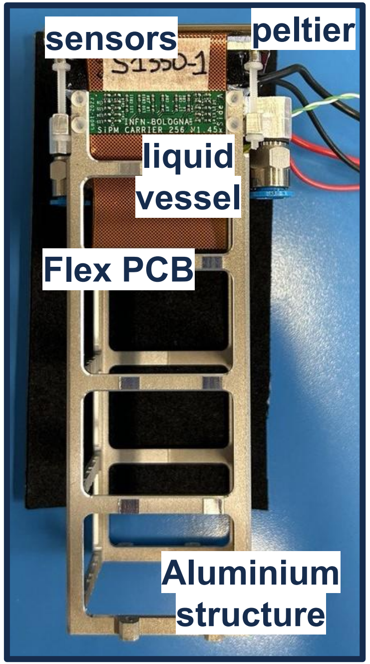

The PDU prot

- 4x matrices of 8x8 SiPMs 3x3 mm^2, total 256 channels
- 2 peltier cells for subzero operating temperatures
- Temperature sensors both under the sensors and on the peltiers
- light-weight aluminium structure
- Front-end electronics featuring the ALCOR ASIC chip
- Externally provided: High voltage bias for sensors, low voltage power supply for electronics, T sensors piloting and read-out
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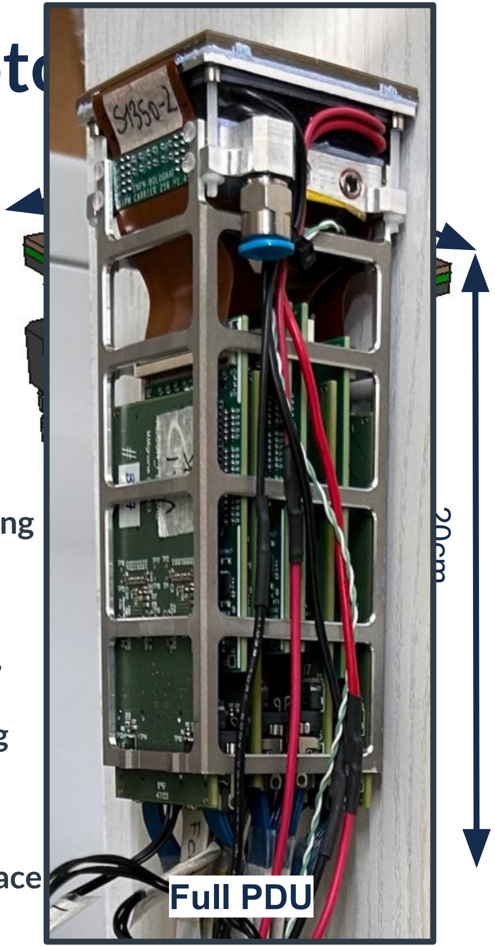
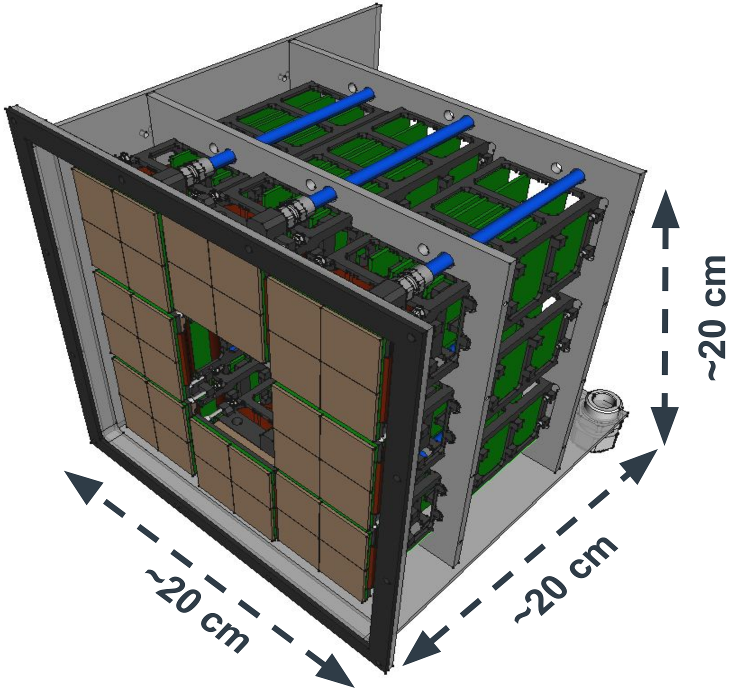


Detector prototype

Compact solution for a ~18 cm^2 of active area, reading 2048 channels



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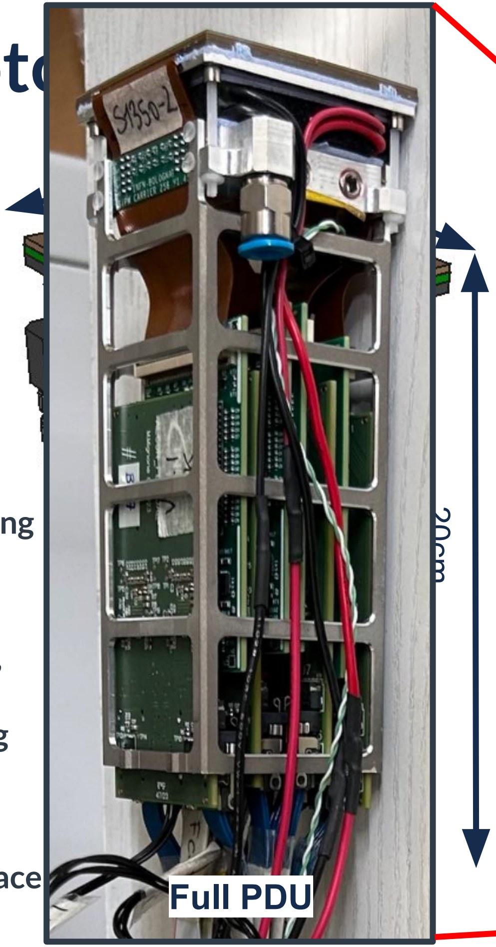
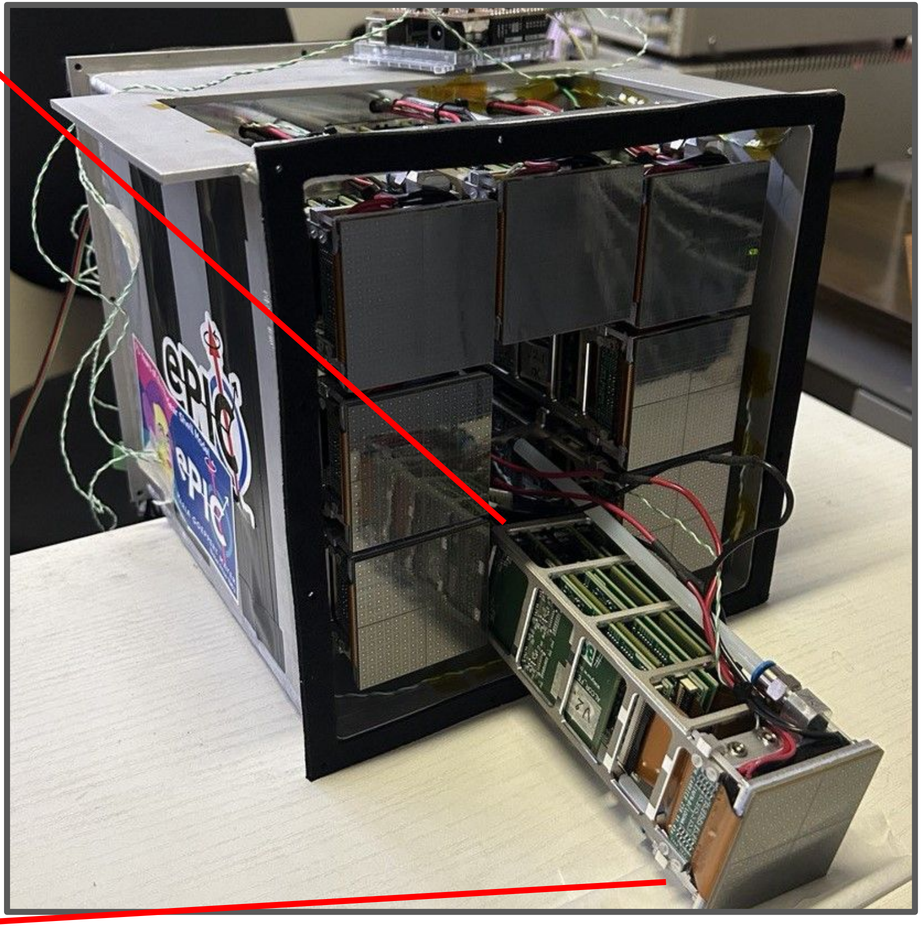
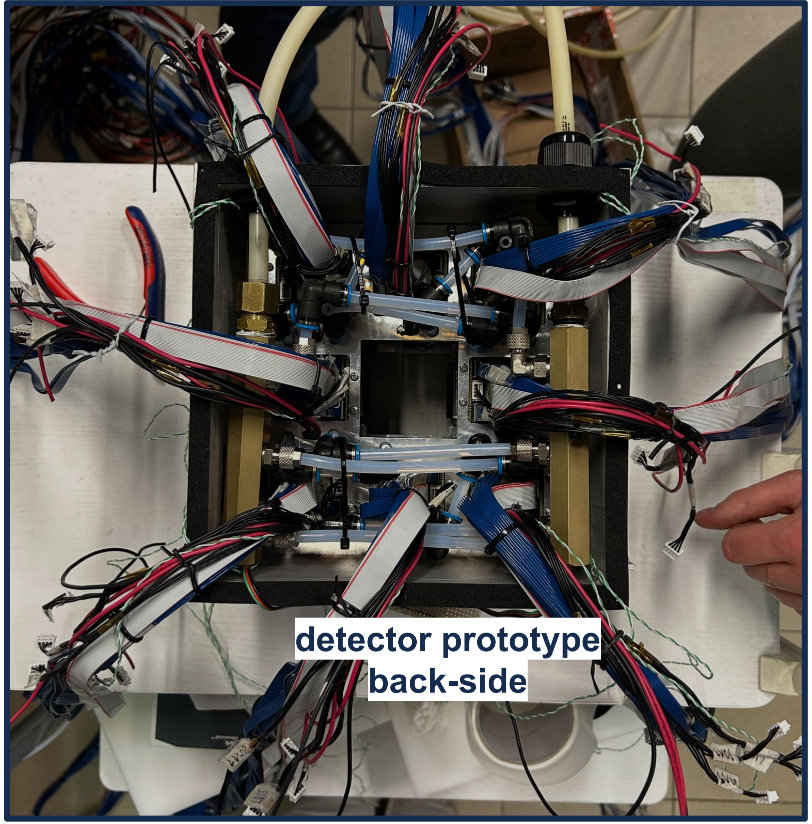
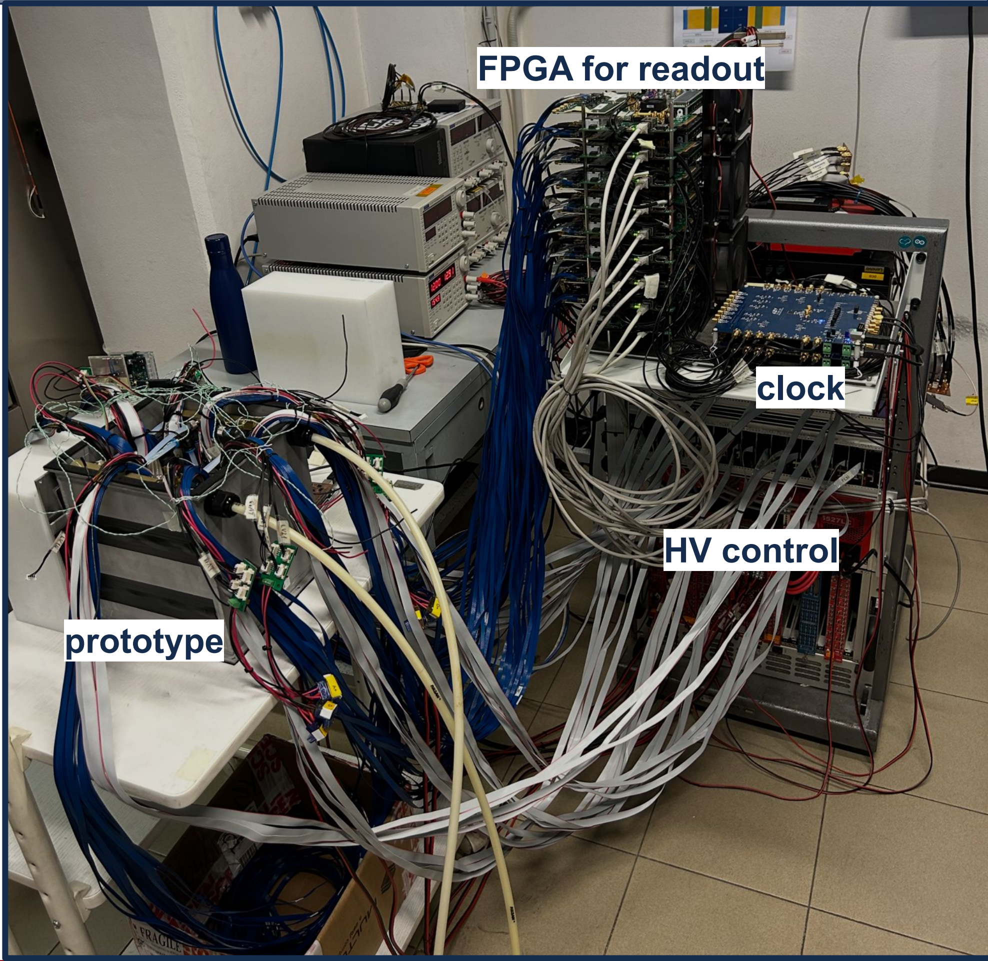




The dRICH prototype





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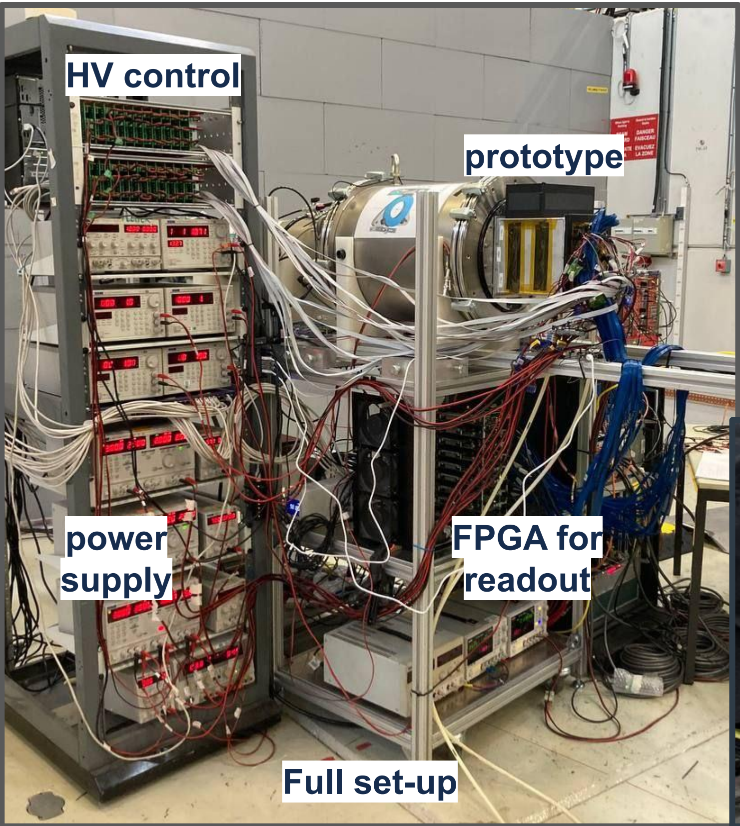
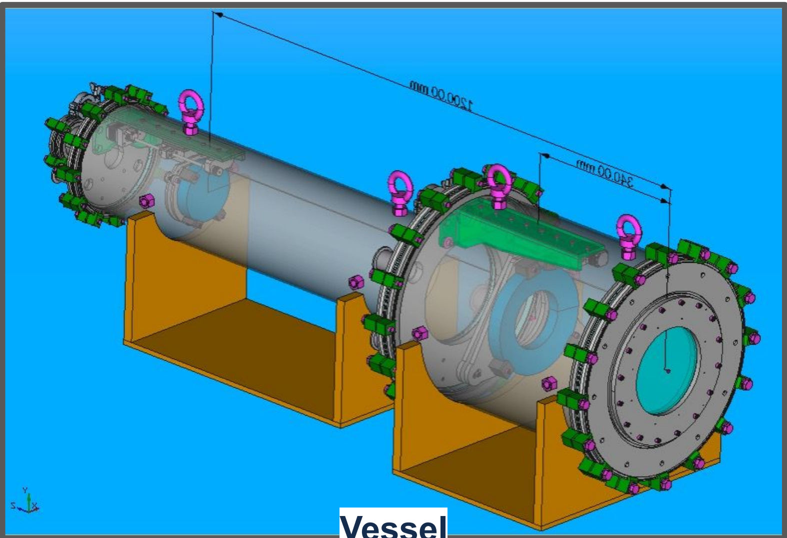
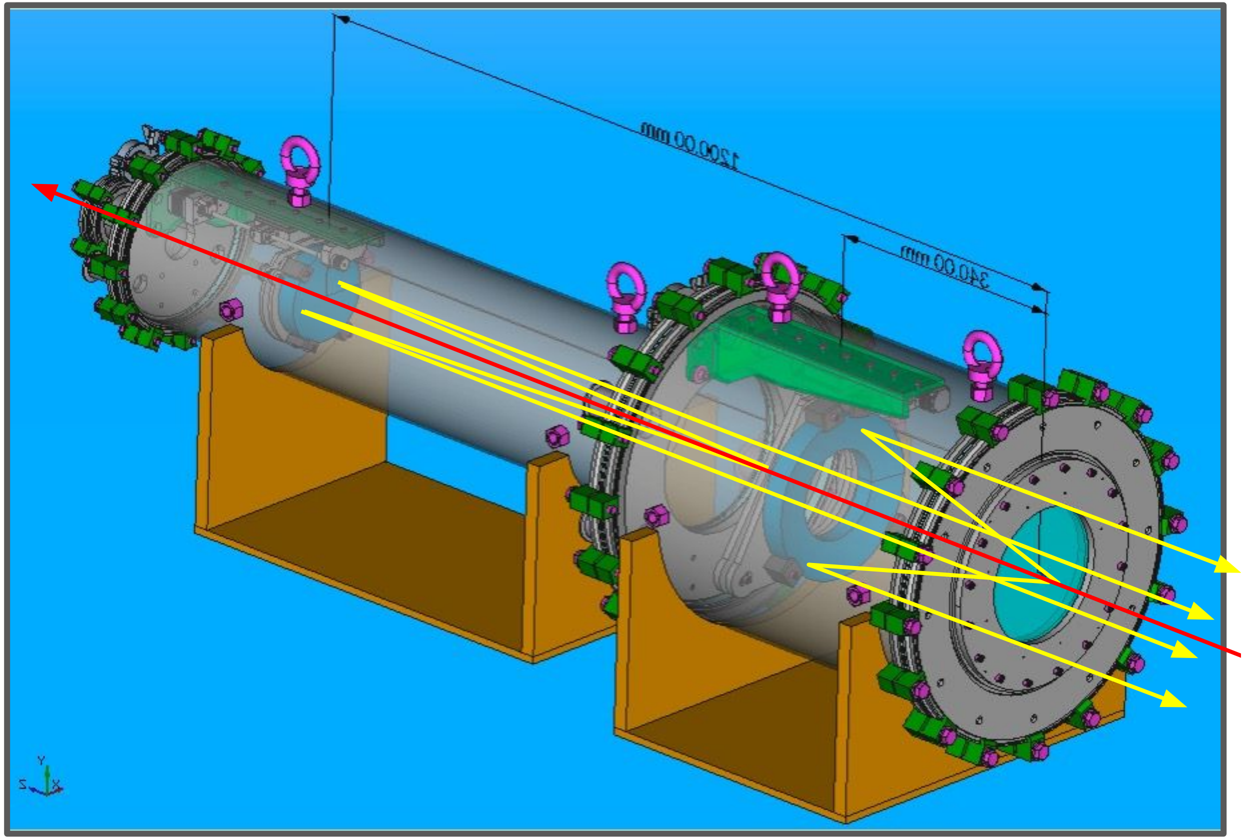
Beam test

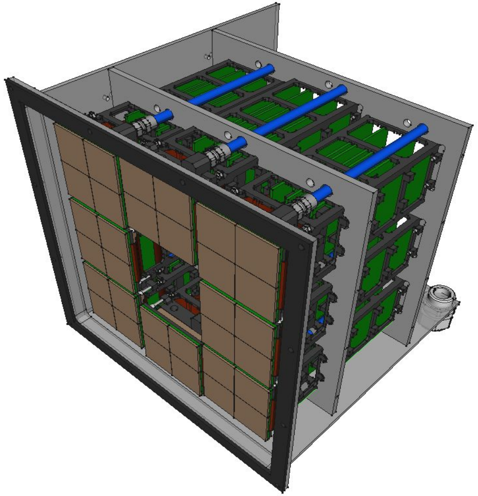




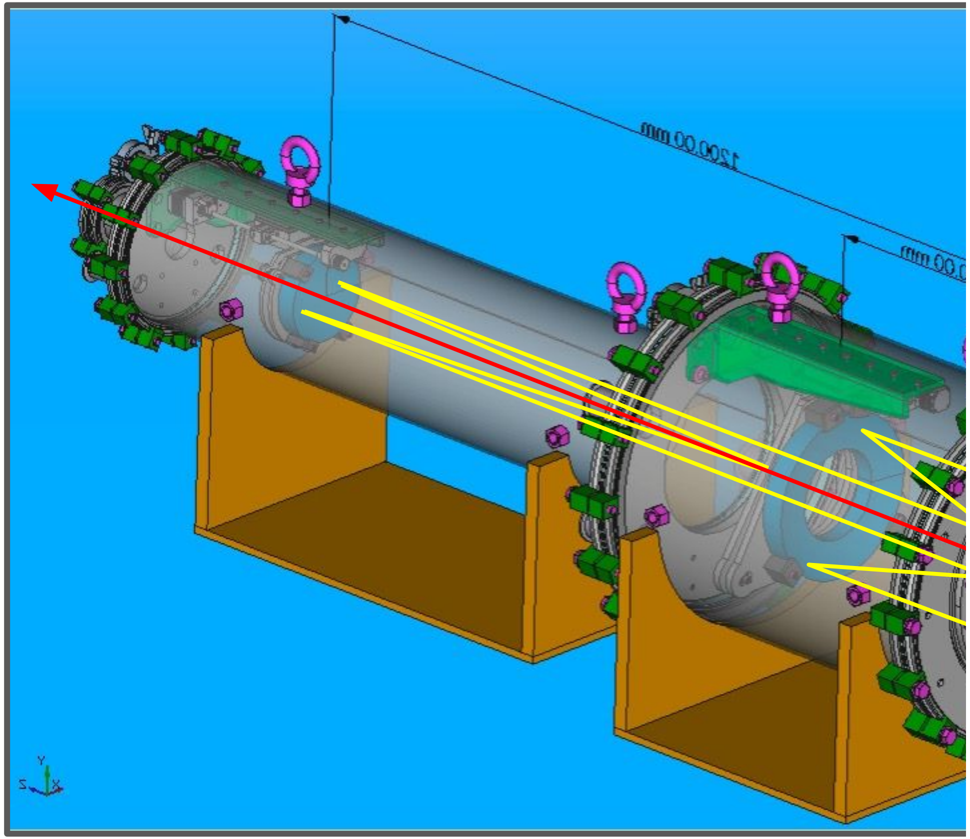
Vessel

Beam test

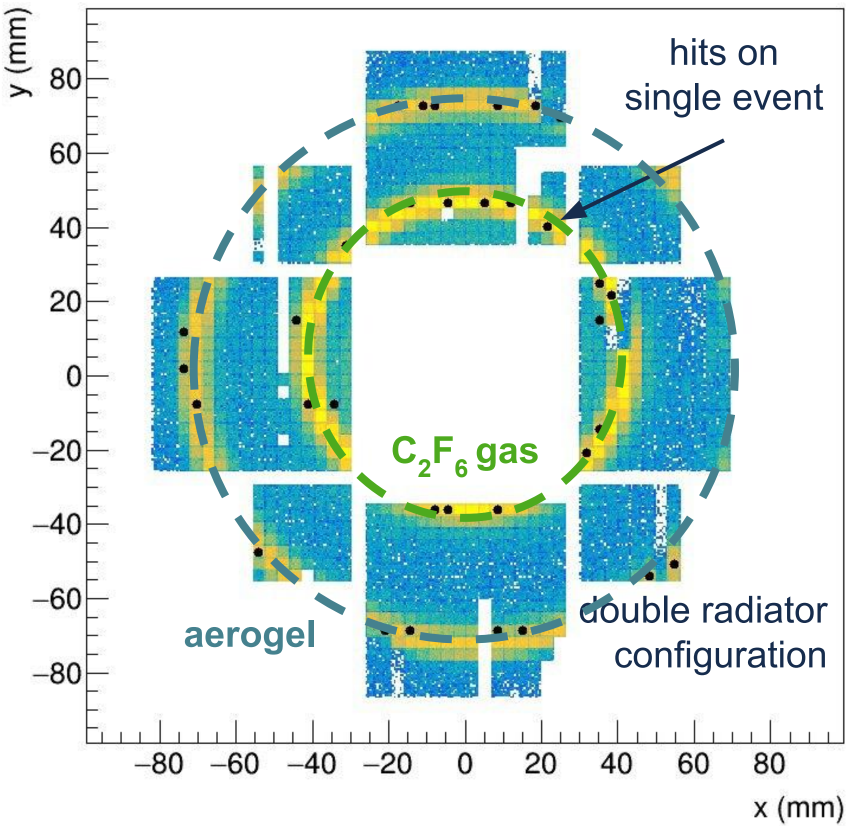




Beam test



10GeV negative beam



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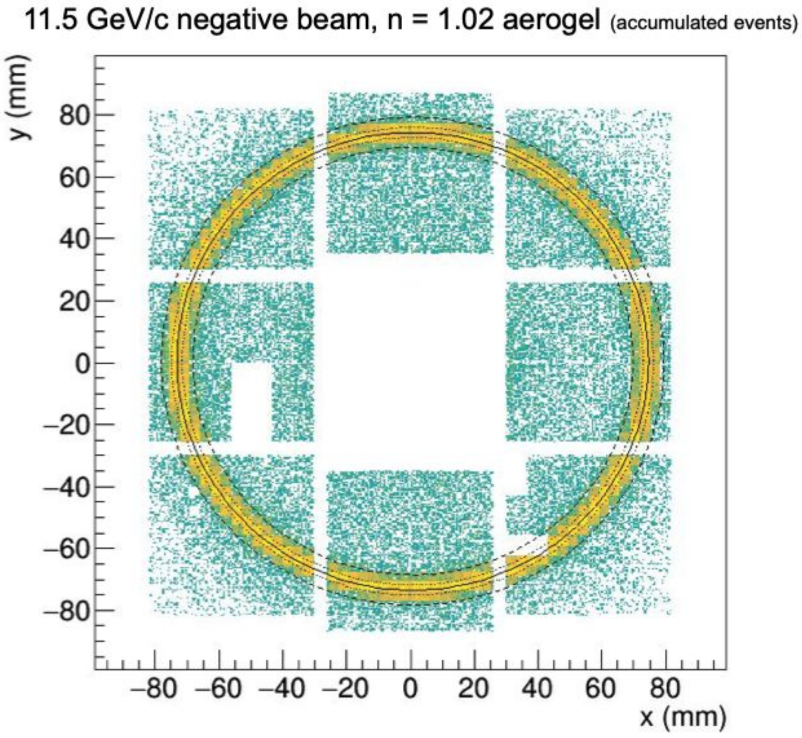
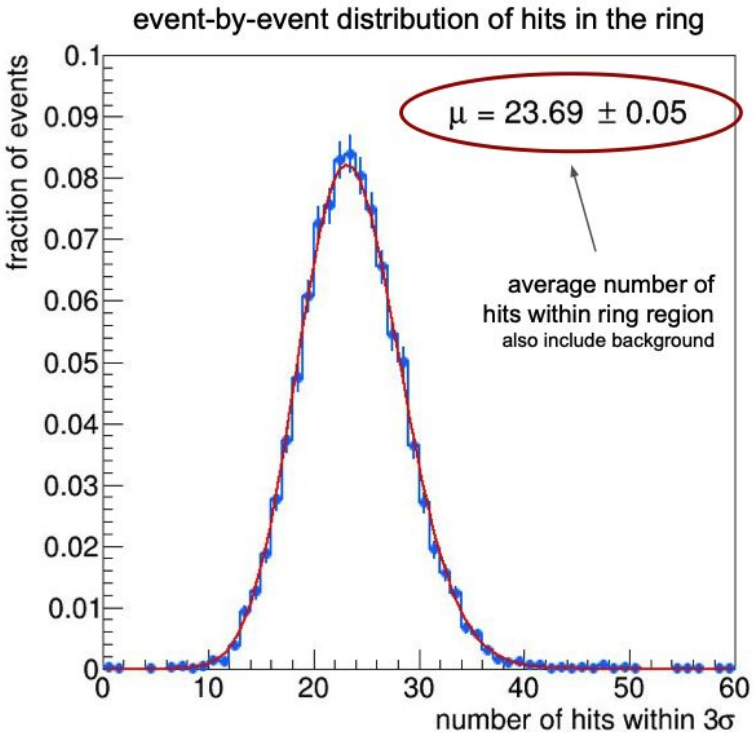
Aerogel



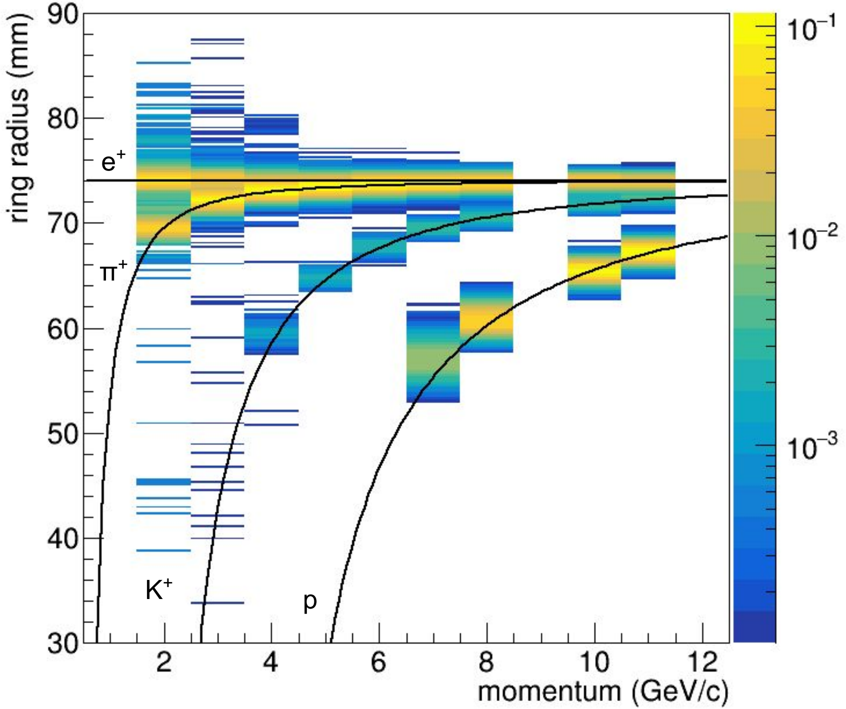
2D fit to accumulated data with realistic model (ring + background)



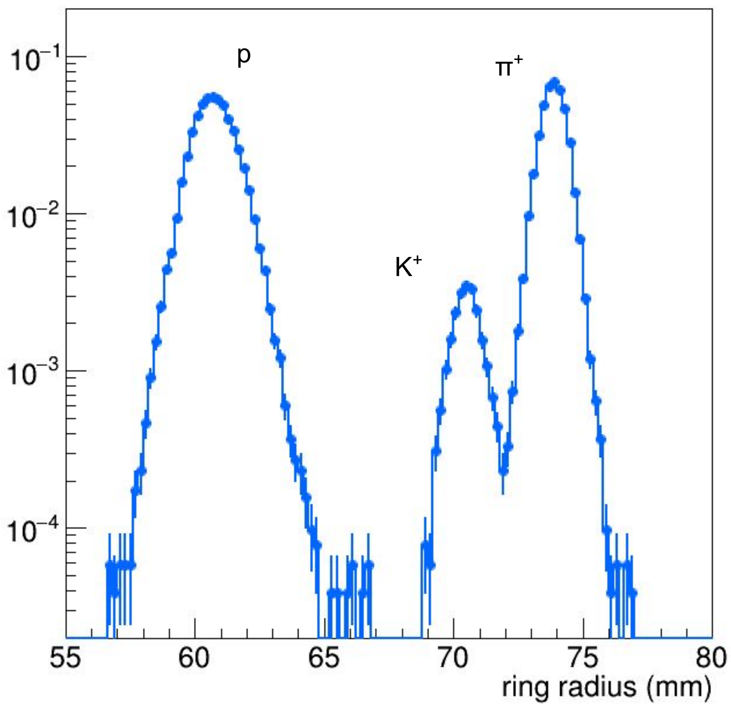
Poisson fit to data, average number of hits is large

Momentum scan

reconstructed radii vs. beam momentum

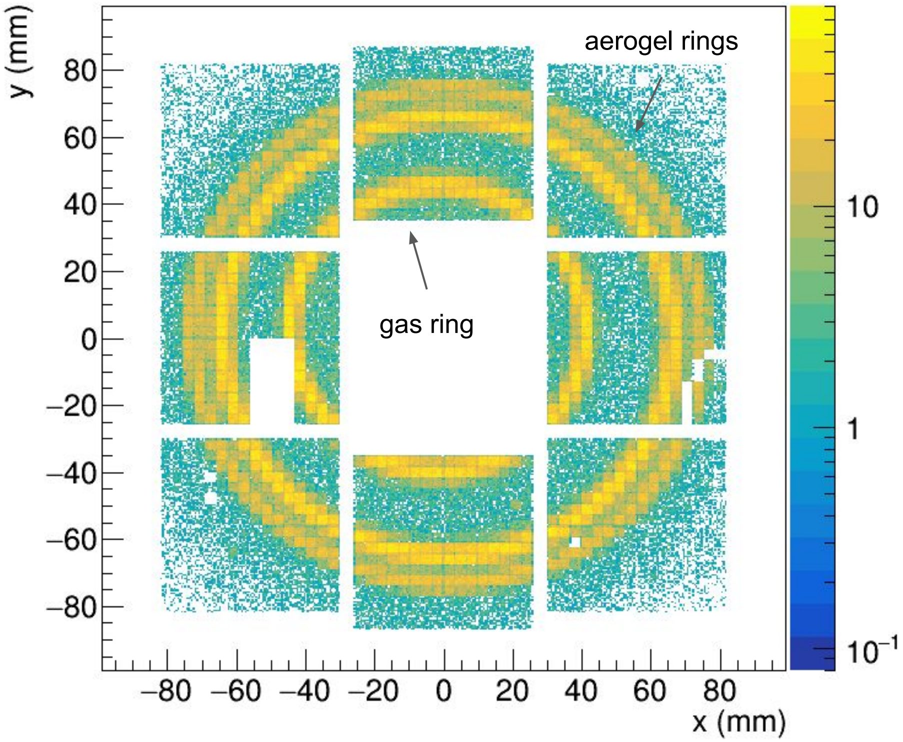


reconstructed radii at 8 GeV/c beam momentum

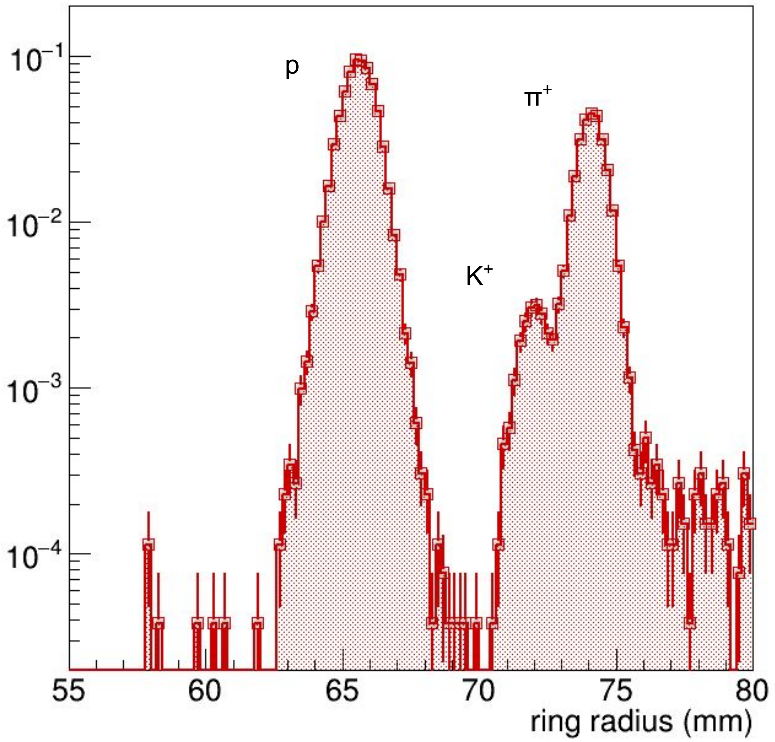


PID w/ Gas & Aerogel

10 GeV/c positive beam with no selection applied

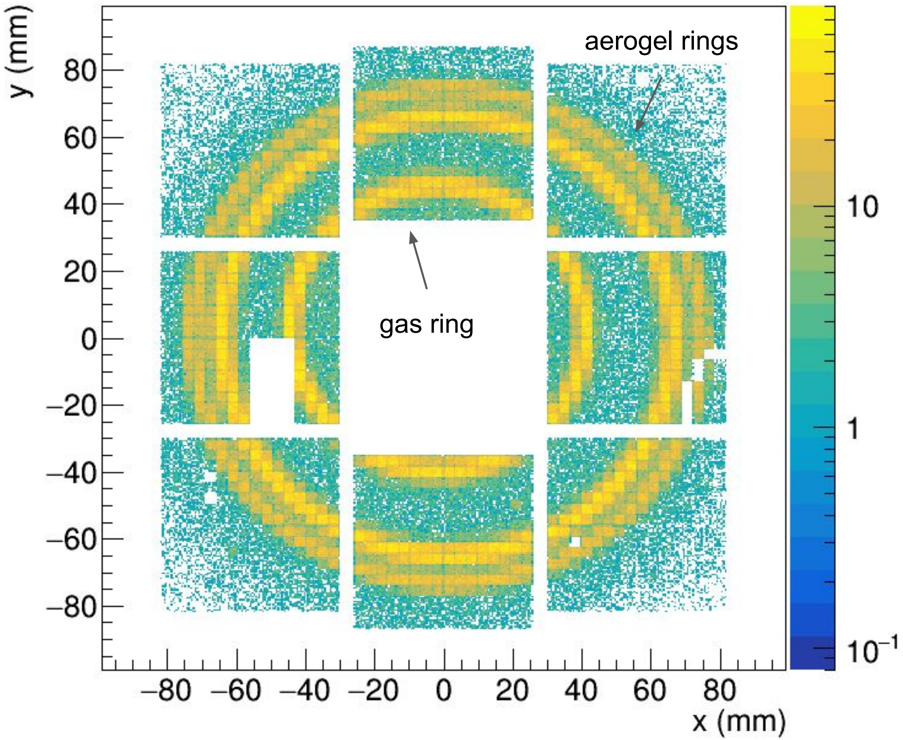


reconstructed radii at 10 GeV/c with no selection applied

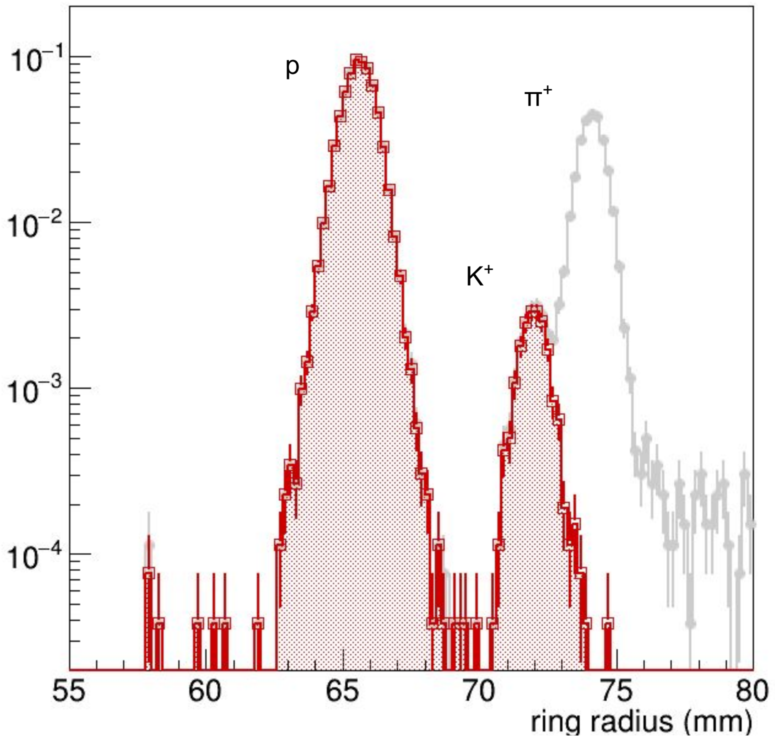


PID w/ Gas & Aerogel

10 GeV/c positive beam with no selection applied

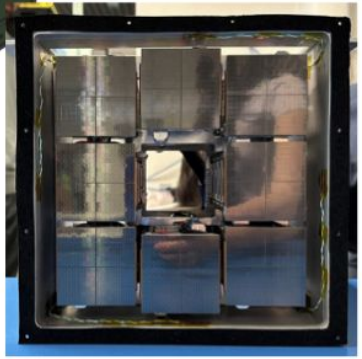


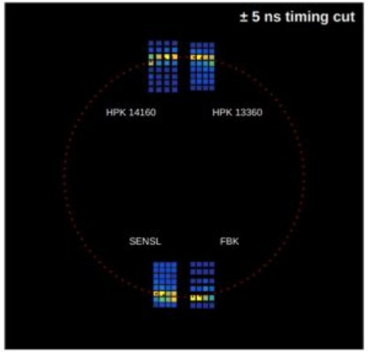
reconstructed radii at 10 GeV/c with gas veto applied

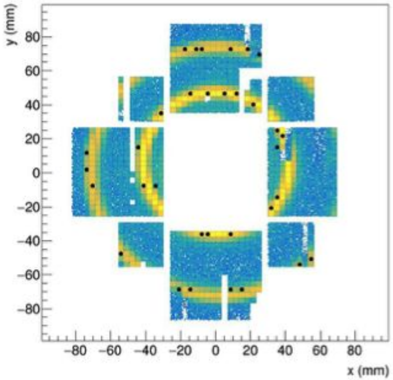


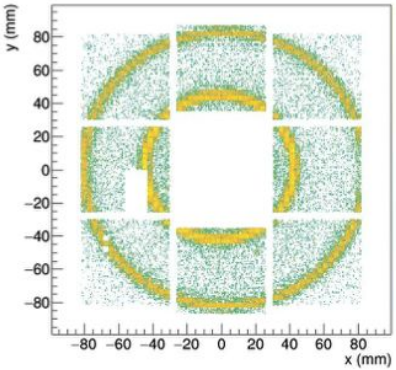
towards construction

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









Summary

SiPMs meet dRICH requirements

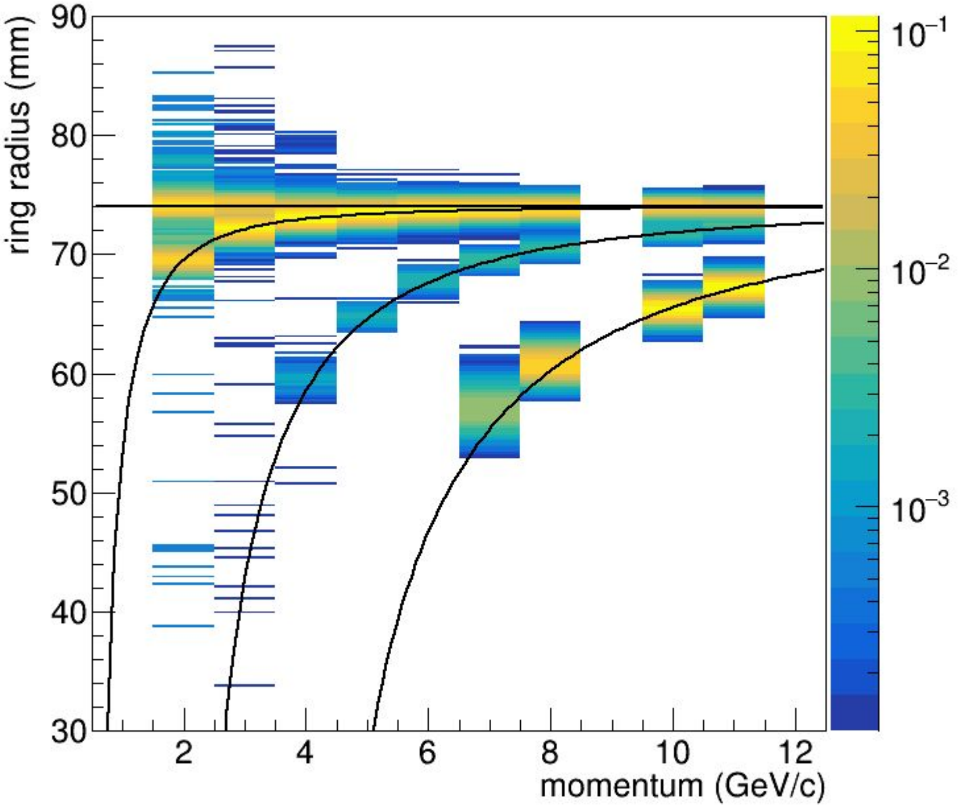
- excellent timing + efficiency, B insensitive

Technical solutions for SiPMs rad damage

- in-situ annealing provides sensors lifetime extension to experiment lifetime

Full readout chain of SiPMs

- We tested full readout chain based on ALCOR w/ multiple successful beam tests



Thank you!

Back-up

The SiPM option and neutron fluence for dRICH sensors

Cons

1. **High dark count rate at room temperature**
2. **<u>High radiation sensitivity</u>**

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:

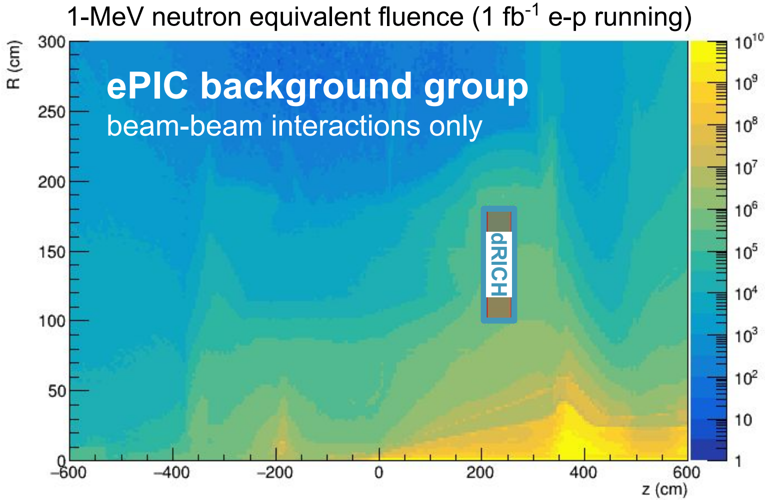
Requirement for the key physics goals is 10 fb^{-1} per center of mass energy and polarization setting

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

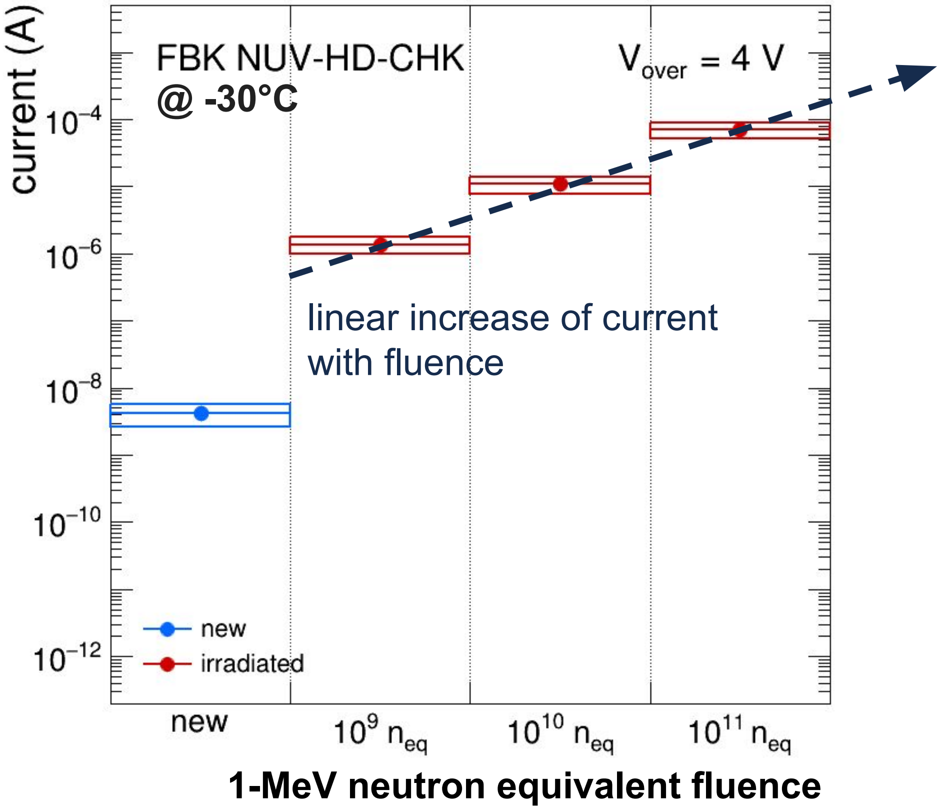
10^{11} n_{eq}/cm^2 fluence:

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

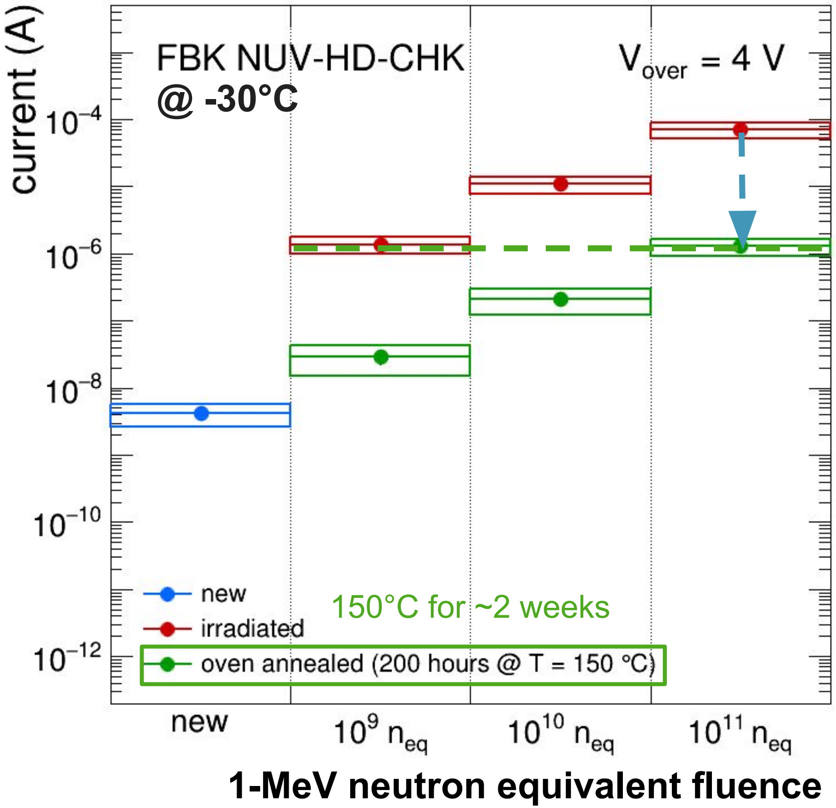
Radiation damage of SiPMs with protons at TIFPA



4x8 carrier boards w/ 3x3mm^2 sensors

2021, 2022, 2023 campaigns set-up

Radiation damage recovery of SiPMs with offline annealing

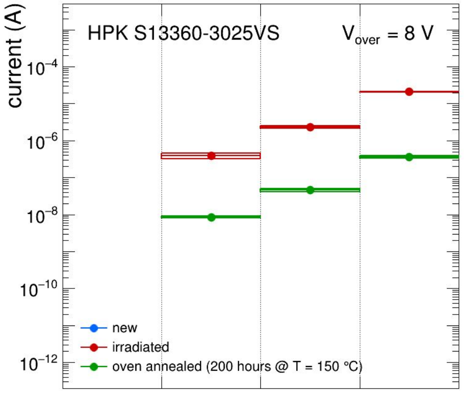


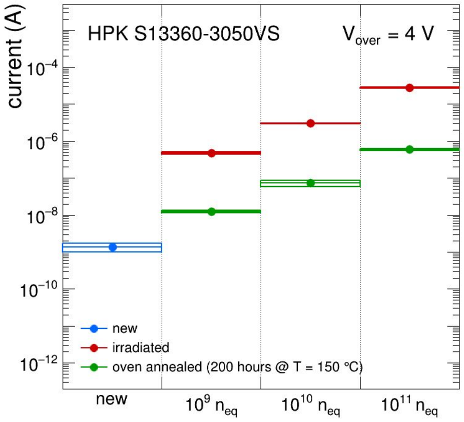
~ 100x reduction of dark current

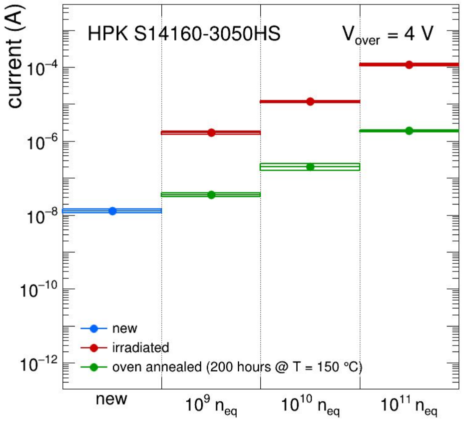
behaves as if it had received ~100x less fluence

Offline annealing done with sensors in oven

Hamamatsu sensors show very similar behaviours



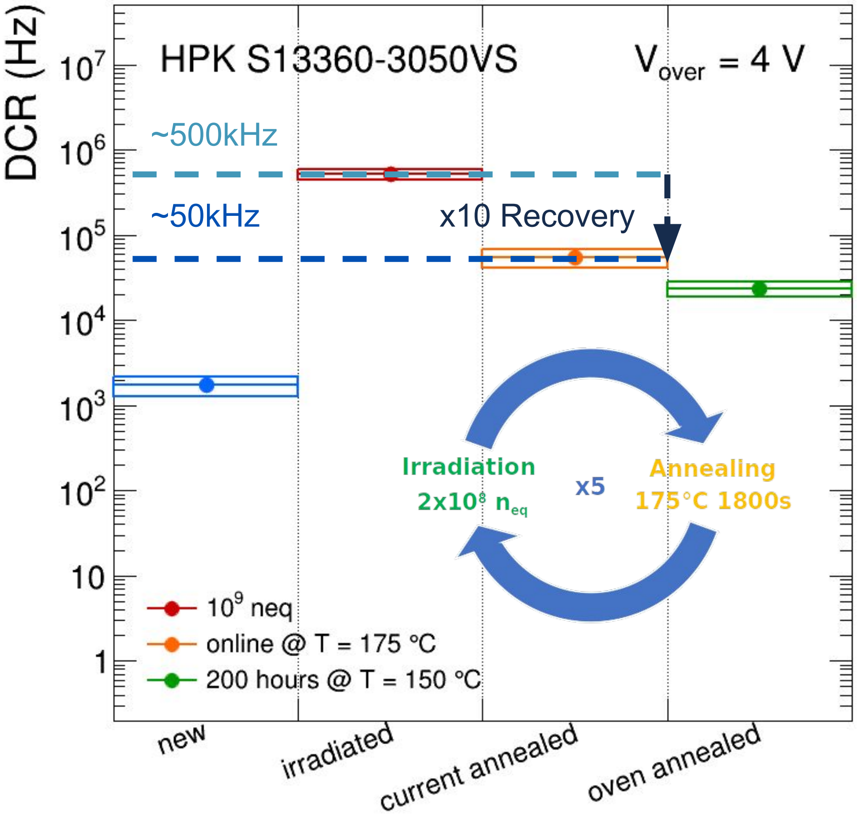




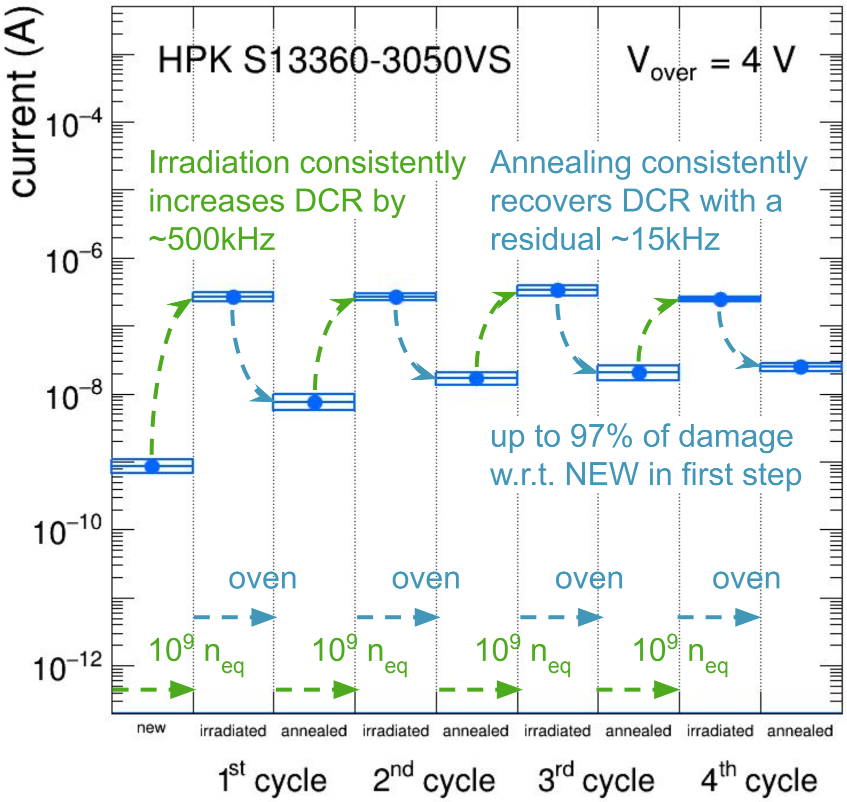
Radiation damage recovery of SiPMs with online anneling

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

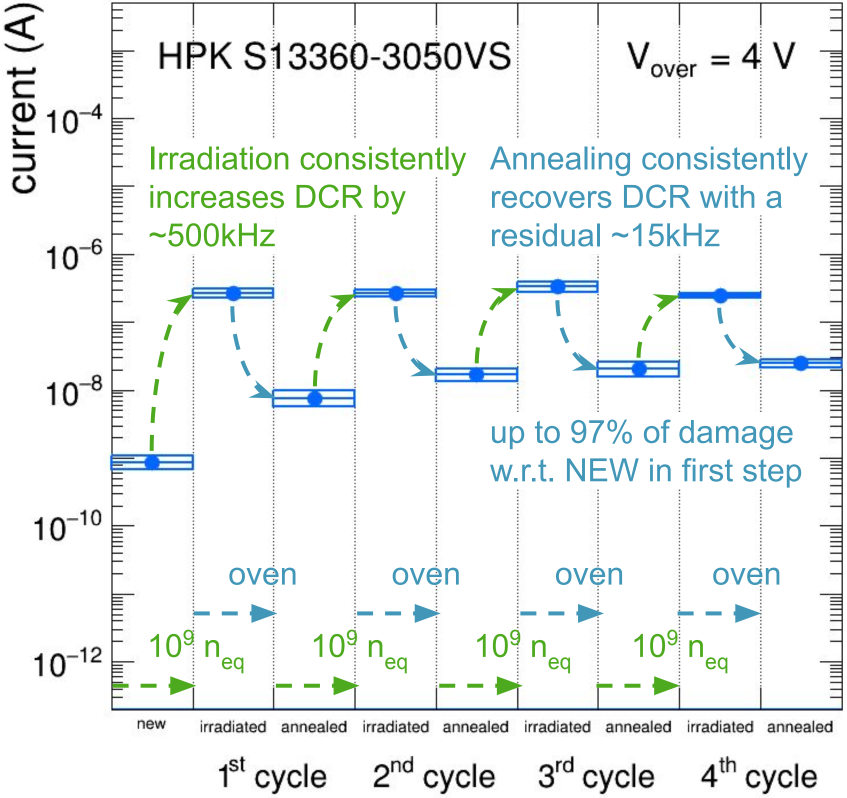
Exposure to radiation is interleaved with annealing cycles as could be the case in the experiment

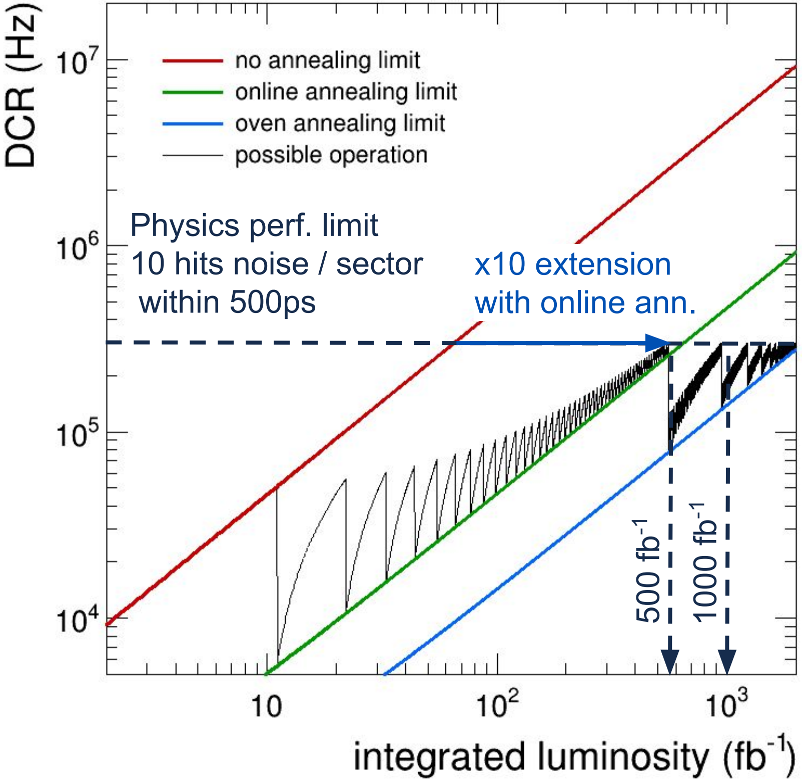


Damage recovery of SiPMs with multiple annealing cycles



Damage recovery of SiPMs with multiple annealing cycles

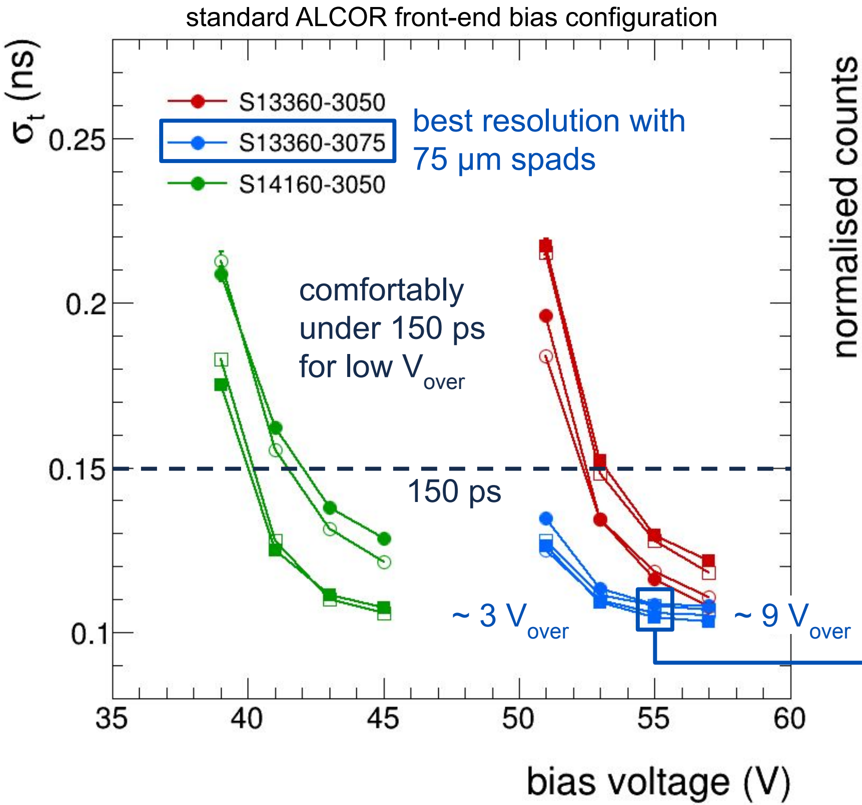


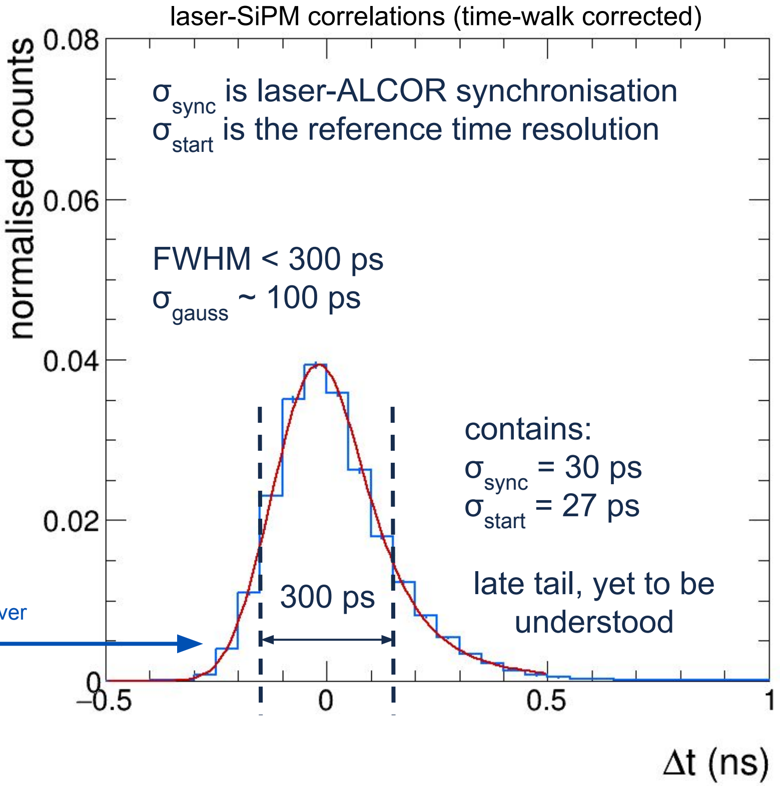


At the 500fb^{-1} mark a more aggressive annealing is required (oven)

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

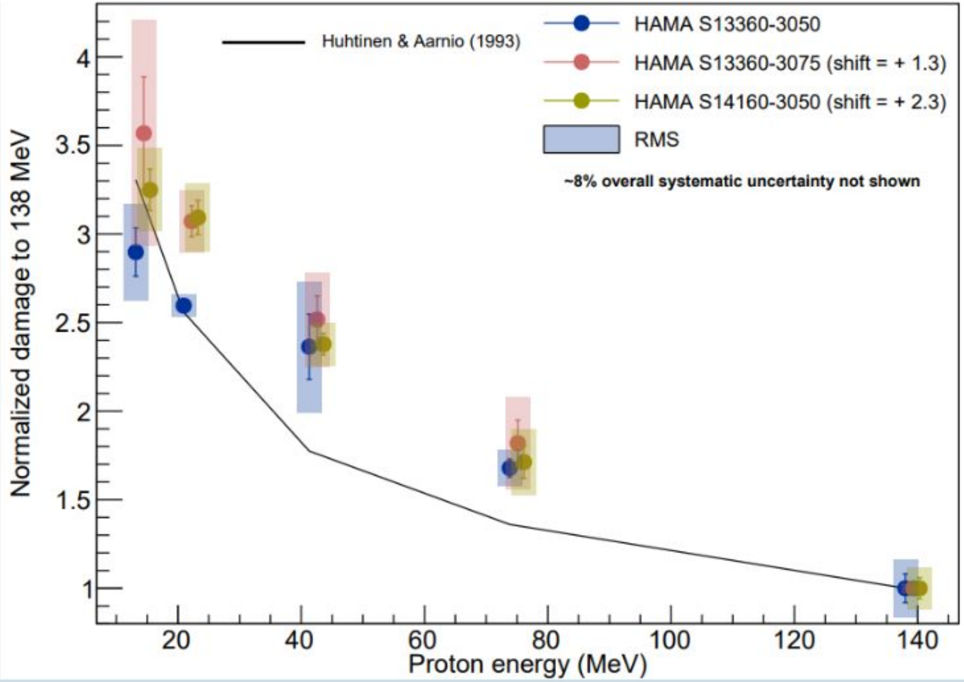
Laser timing w/ ALCOR





p-irr: energy scan

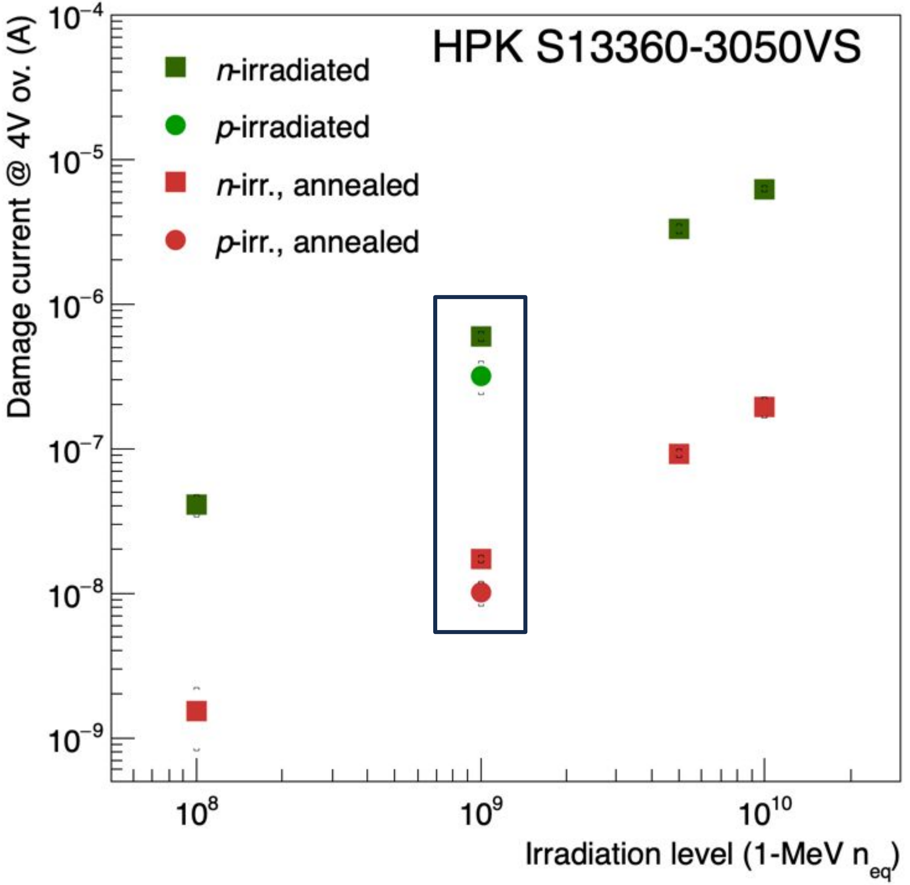
We also tested different incident proton energies.
The theoretical calculations refer to pure Silicon.



Results are fitting nicely theoretical predictions within few tens of percent

n-irr: fluence scan

We covered a large range of different fluences with the *n*-irradiation. The most puzzling result was a factor 2 difference between *p*-irr and *n*-irr results, in violation of NIEL hypothesis.

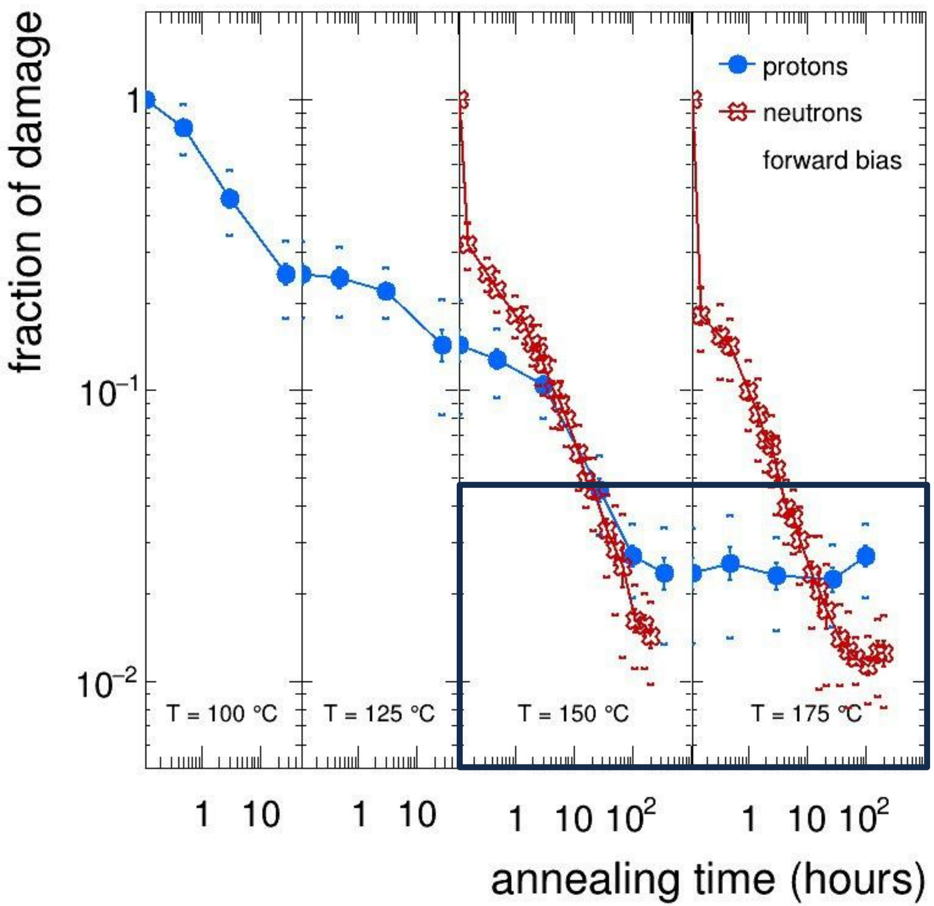


Puzzling factor 2 w.r.t. to *p*-irradiation

n-irr: forward annealing

We focused on fwd annealing for the *n*-irradiated boards at two different temperatures.
There seem to be a more significant recovery, that is due to the factor 2 in damage w.r.t. *p*-irradiated boards.

***p*- and *n*-irr. sensors show similar behaviours to annealing**



n-irr: forward annealing

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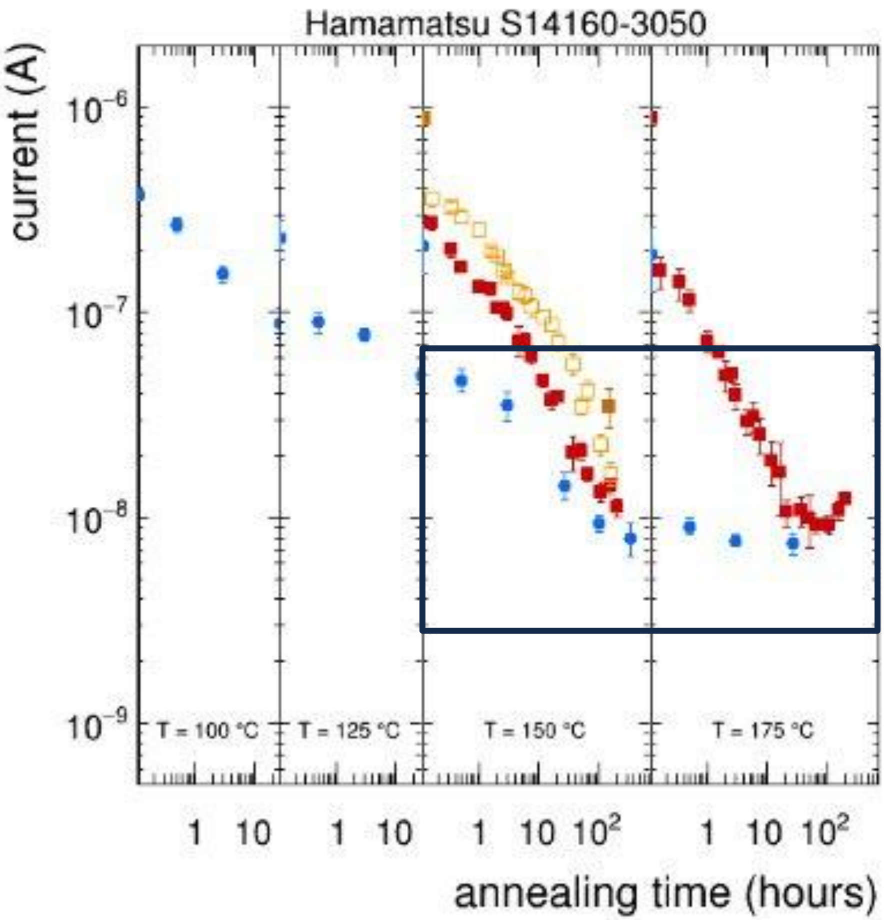
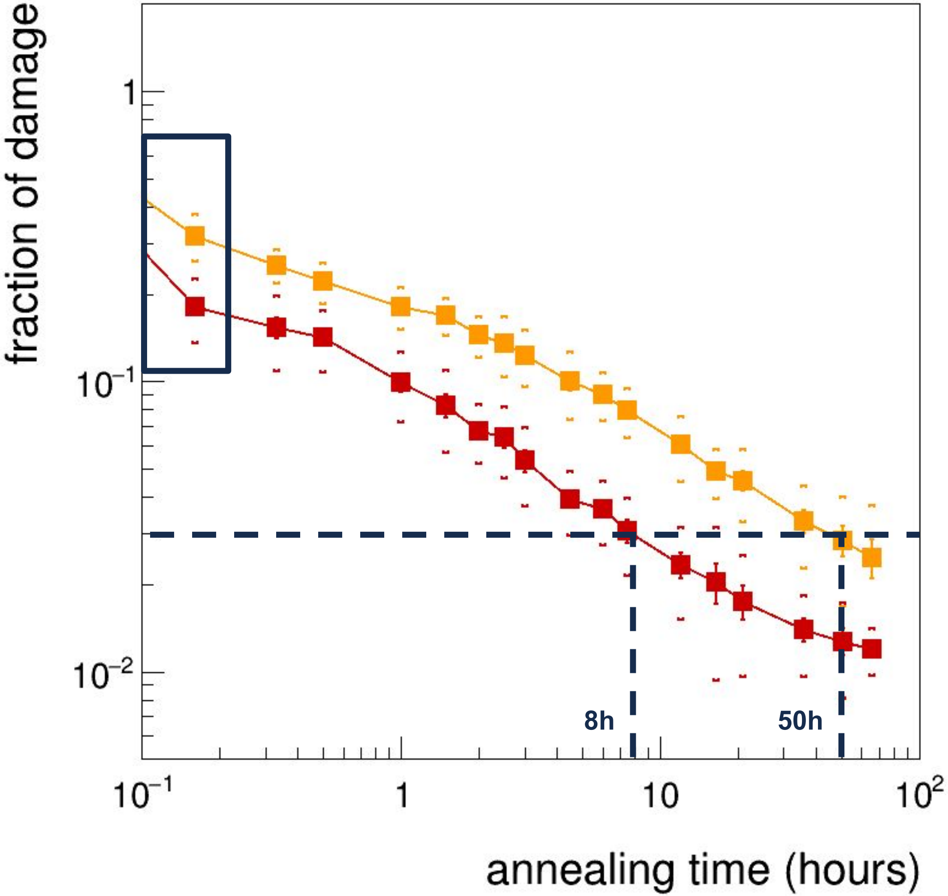


_p_- and _n_-irr. sensors show similar behaviours to annealing

n-irr: annealing temperature

Directly comparing 150C and 175C in forward annealing we see that we have an initial decrease that is proportional to the ann. temperature.
Moreover the speed of recovery is also greatly enhanced with a relatively small increase in ann. temperature.



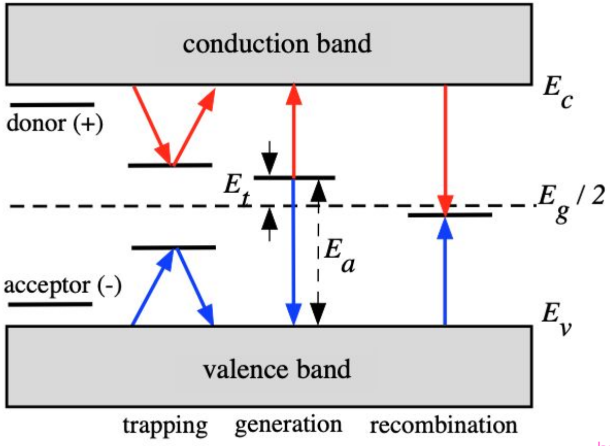
We reach the same cure level, but faster with higher temperatures. (*)

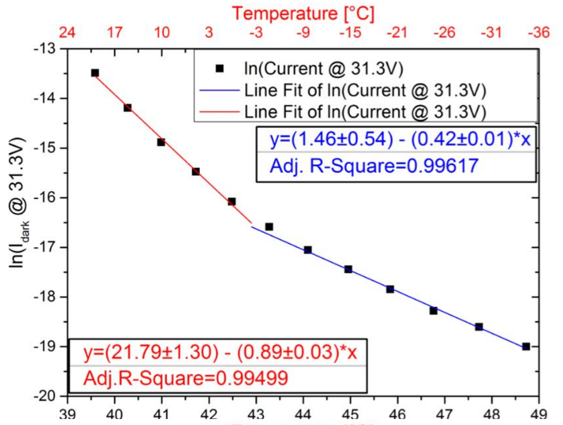
Activation energy

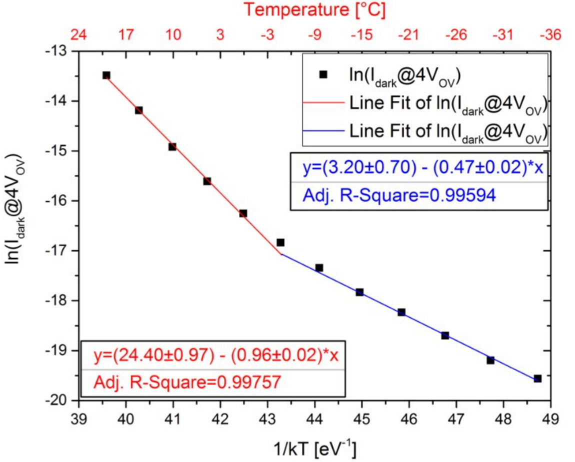
Activation energy can be measured with Arrhenius plots, DCR as a function of temperature at a given overvoltage or at a fixed voltages. The linear dependence of the dark current (log) dictates the activation energy and the dominant process for DCR generation:

high temperature:
thermal generation

low temperature:
trap assisted generation



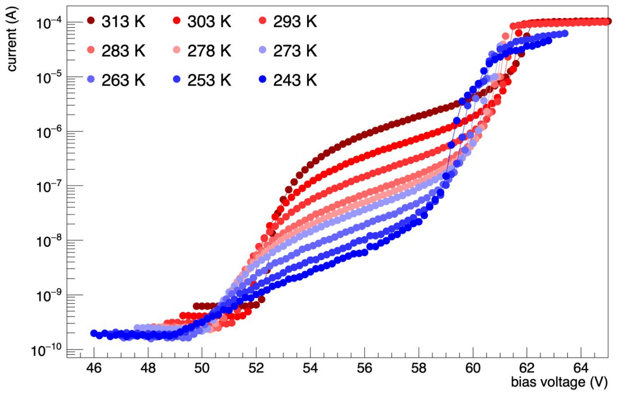




https://iopscience.iop.org/article/10.1088/1742-6596/675/4/042049/pdf

Activation energy

We measured the activation energy with the overvoltage method.



Results follow the expectations of a decrease of the act. en. in irr. sensors and an increase with annealing