Performance degradation of SiPM sensors under various irradiation fields and recovery via high-temperature annealing

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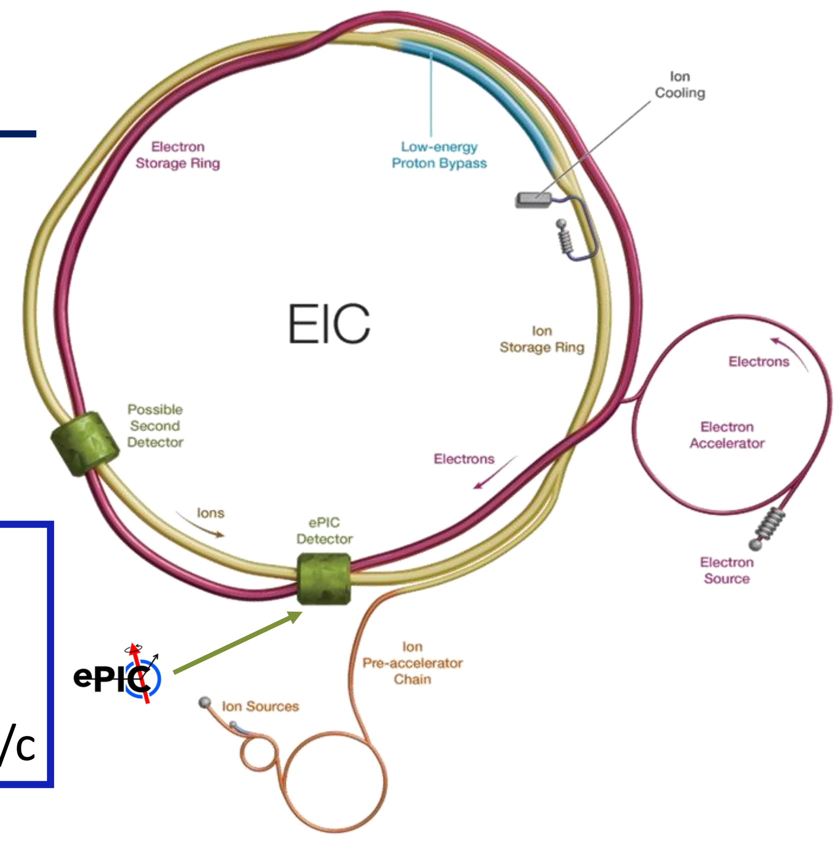
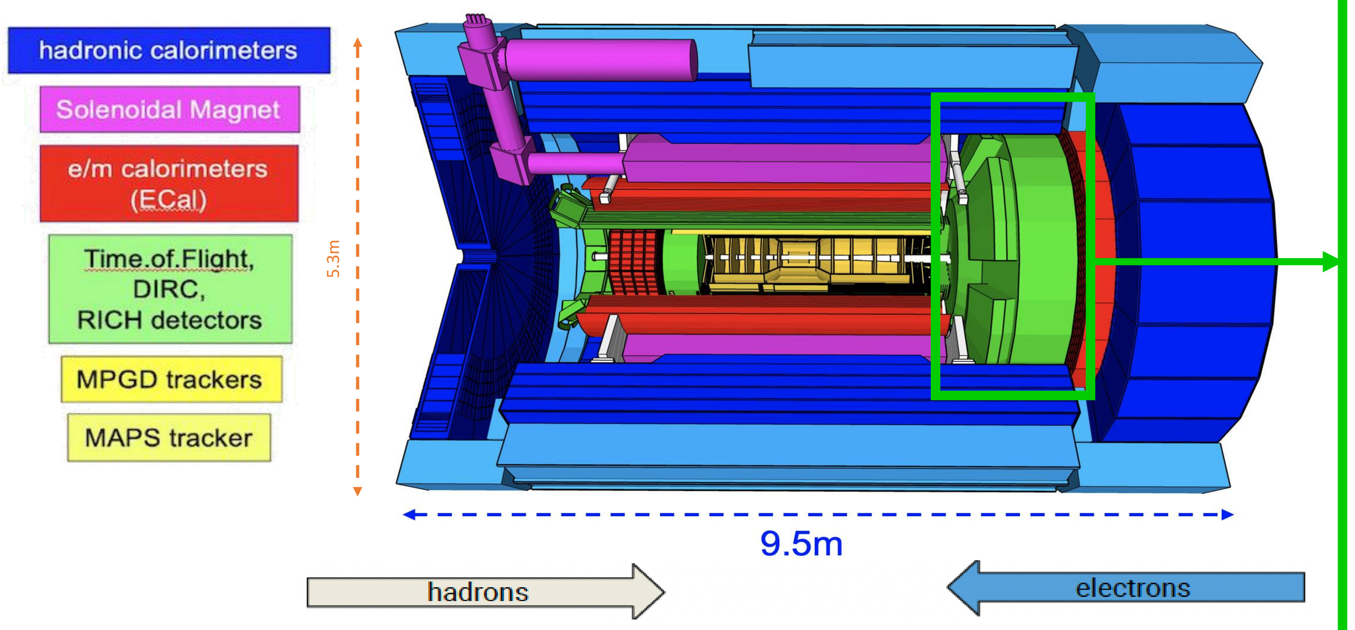
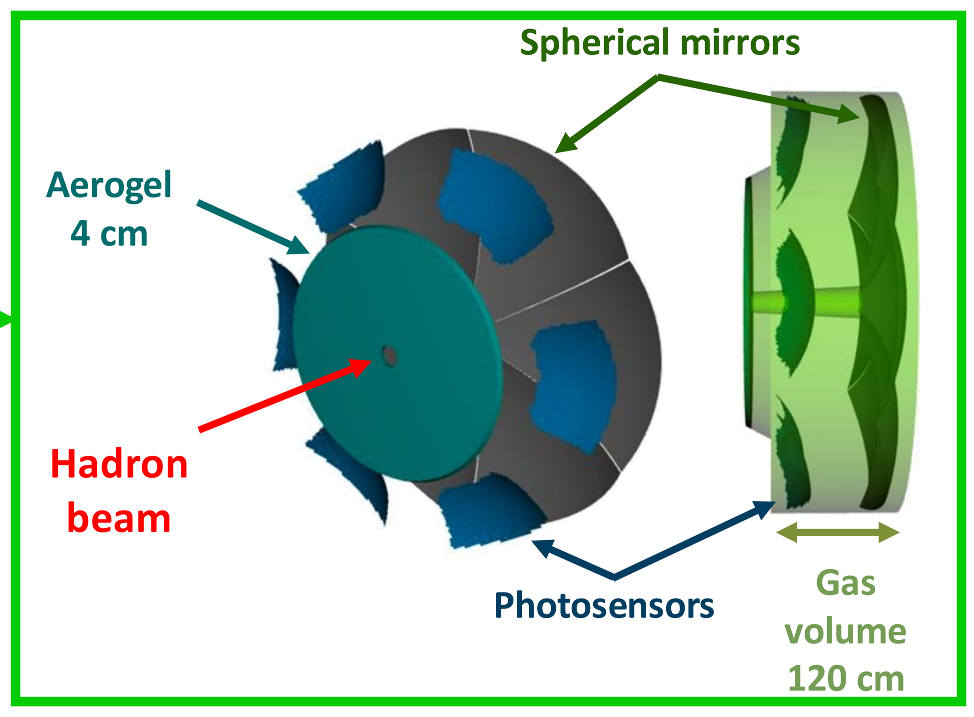
ePIC experiment

The future Electron-Ion Collider (EIC) will explore the internal structure of nucleons using deep inelastic scattering.
The electron-Proton/IonCollider (**ePIC**) detector is designed to provide precise tracking, calorimetry and PID capabilities.
The dual-Ring Imaging Cherenkov (**dRICH**) is designed to provide continuous hadron identification in a broad momentum range (3 GeV/c to 50 GeV/c) and in the forward region ($1.5 < \eta < 3.5$).



Layout of the ePIC barrel detector





PID:
p = [3-50] 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 mm² pixel, 0.5 m² / sector

- single-photon detection inside high B field (~ 1 T)
- outside of acceptance, reduced constraint
- Silicon photomultiplier (**SiPM**) optical readout

dRICH optical readout

The **dRICH** detector will make use of **SiPM** sensors for the detection of the Cherenkov light emitted by particles crossing its radiators.
The photodetector will cover 3 m² with (3x3) mm² pixels, for a total of more than 300k readout channels.

SiPM as photo-detection units:

- ☺ Ability to detect light at the single photon level
- ☺ Insensitive in high-magnetic field
- ☺ High photon detection efficiency
- ☺ Excellent time resolution
- ☹ High sensitivity to radiation damage
- ☹ Large Dark Count Rate (**DCR**)

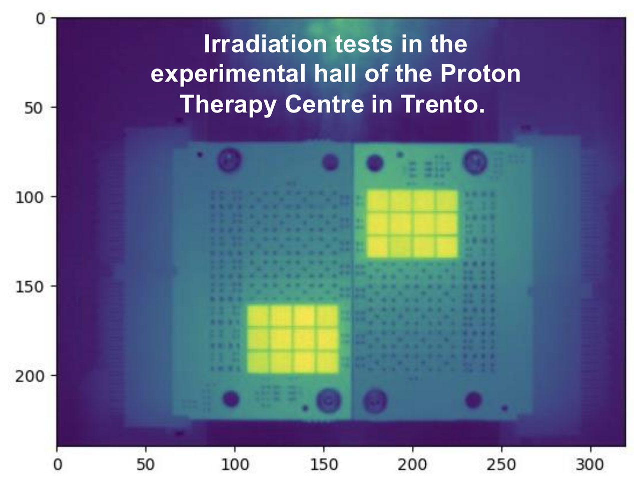
First application of SiPMs for single-photon detection in a HEP experiment

Custom SiPM carrier boards hosting several types and models of SiPM sensors

Irradiation and damage

SiPMs were subjected to fluences up to ~ 10^{10} n_{eq}/cm^2 corresponding to the expected cumulative dose over a decade of EIC operation

- **Proton:** Trento Proton Therapy Centre, delivering integrated fluences up to 10^{11} 1-MeV n_{eq}/cm^2 to the SiPMs and studying different proton energies from 18 to 138 MeV.
- **Neutron:** CN accelerator of the INFN Legnaro National Laboratories at integrated fluences up to 10^{10} 1-MeV n_{eq}/cm^2.
- **Gamma:** CERN GIF++ facility up to 1 krad.



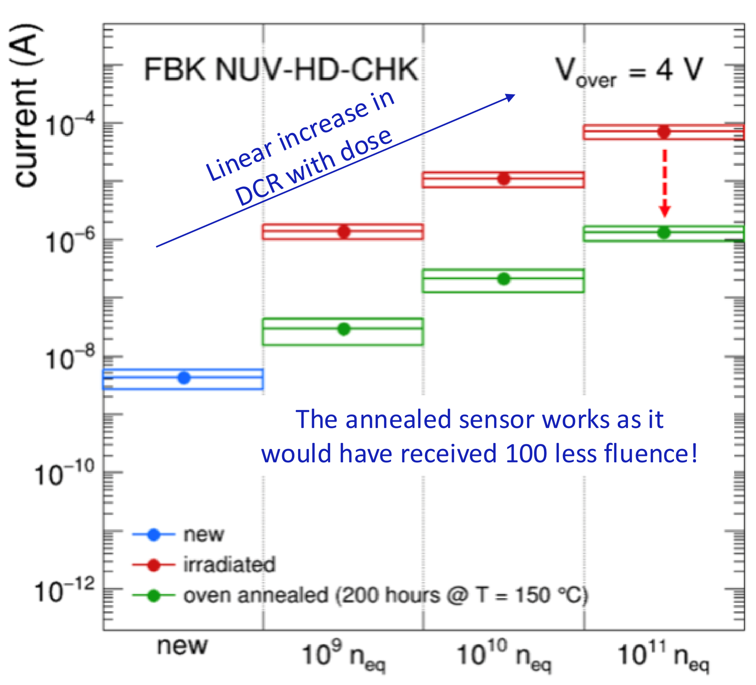
Technical solution and mitigation strategy

- **Cooling** operating at low temperature (down to −30 °C)
- **Timing** precise timing with fast TDC electronics helps to reduce the effect of **DCR** as background signal
- **Annealing** recovery of radiation damage via high-temperature annealing cycles

Annealing and recovery studies

Oven annealing

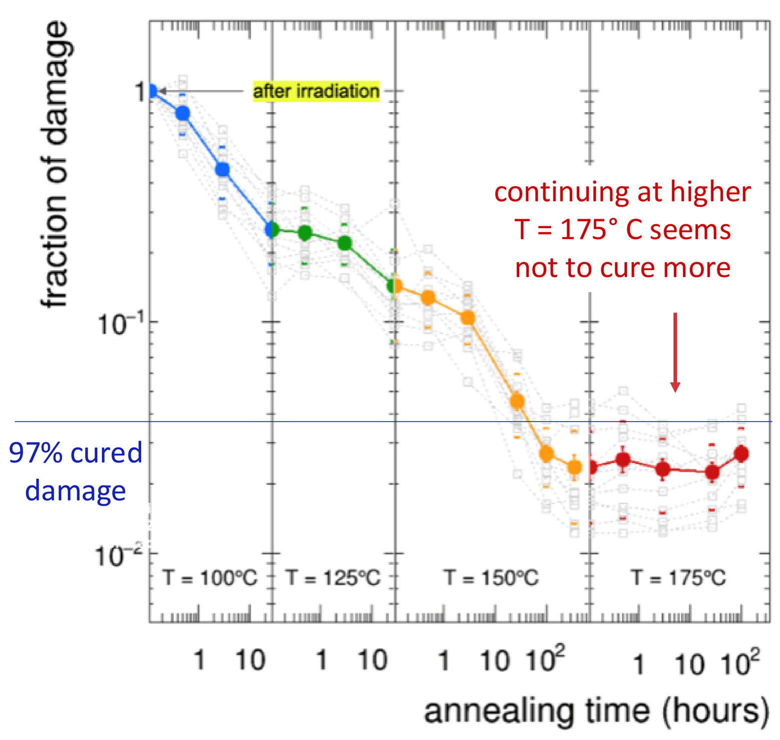
- 200 hours up to 150 °C
- Linear trend with dose
- A factor 100 of damage reduction



Oven annealing recovers ~97–98% of dark current damage.

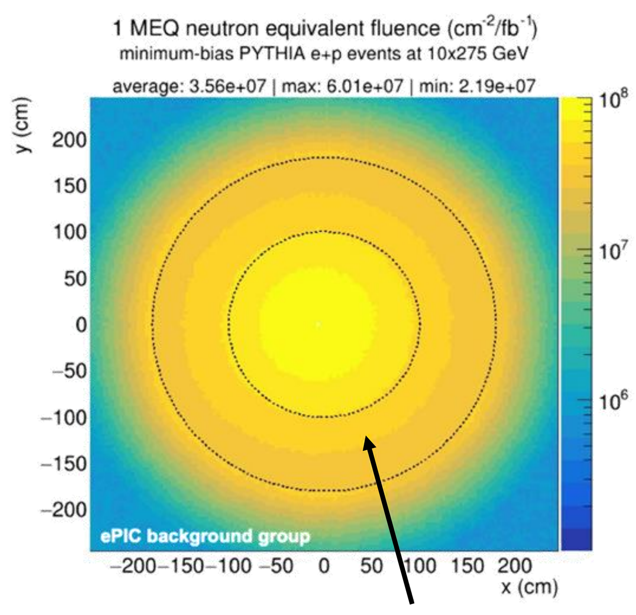
In-situ self-induced annealing

- Started at 100 °C
- 4 steps up to 30 hours integrated
- Followed by 125,150,175°C annealing



Self-annealing reduces damage saturating at 2–3% after ~300h at 150 °C

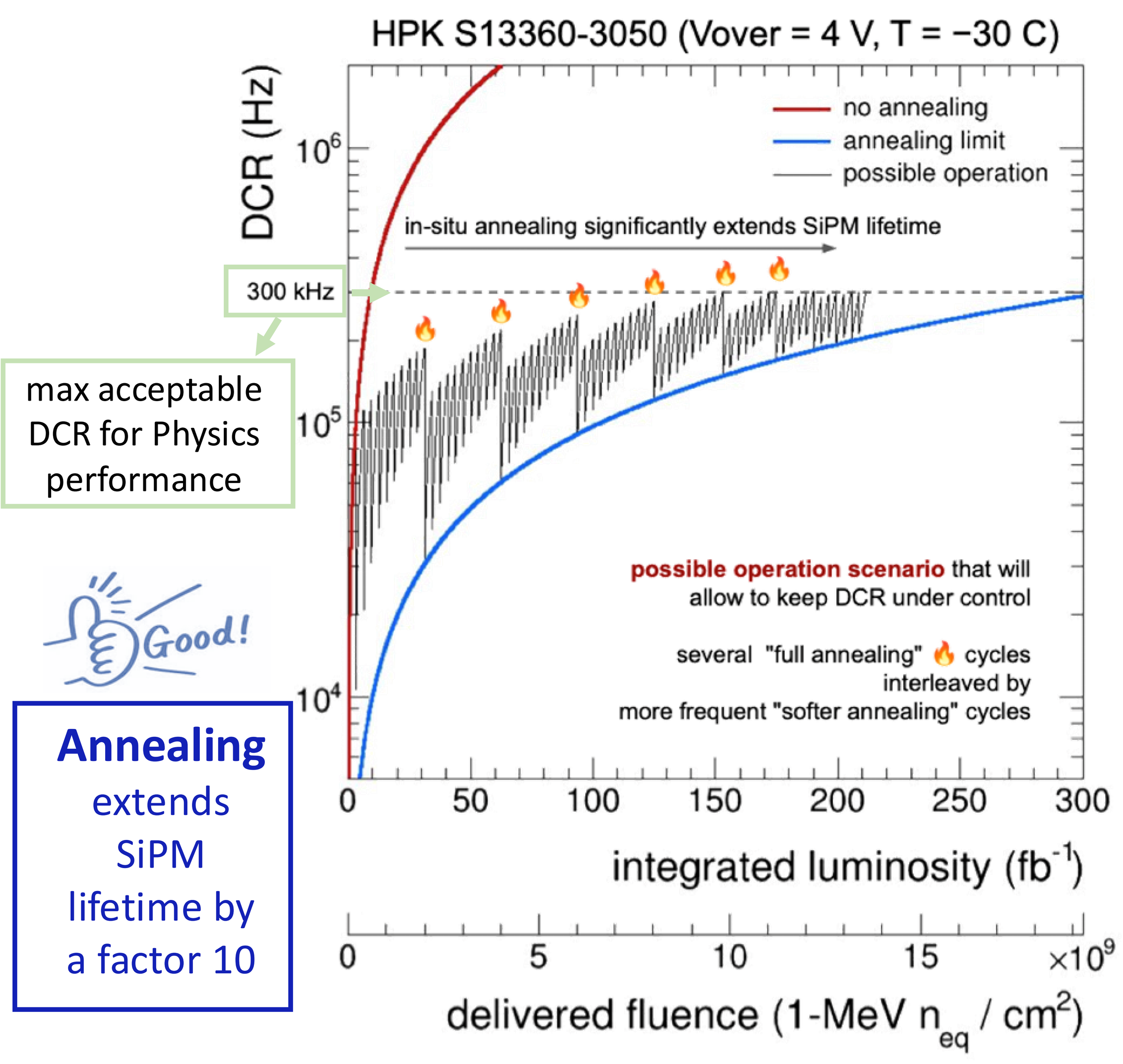
Radiation level Estimates Update



Max fluence = 6.38 x 10^7 n_{eq}/fb^{-1} at the location of the dRICH photosensors

Study the SiPM feasibility for single-photon Cherenkov imaging application in moderate radiation environment

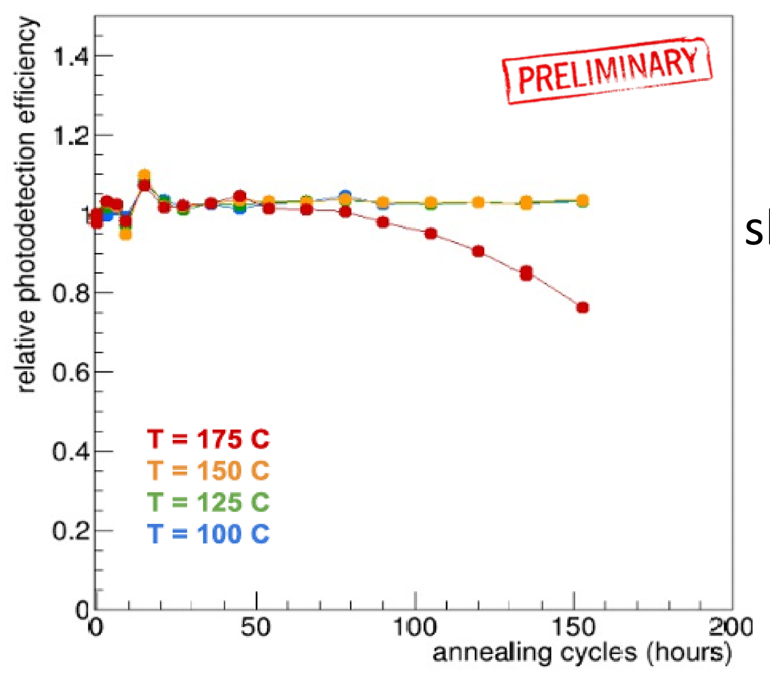
SiPM aeging



Annealing extends SiPM lifetime by a factor 10

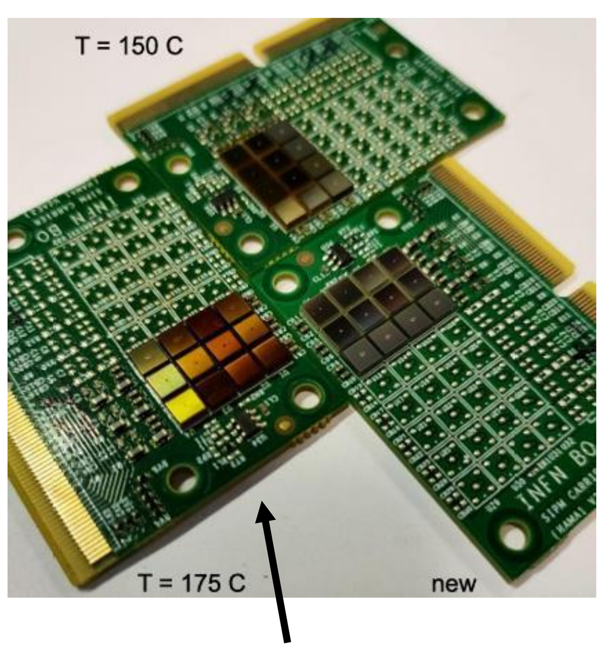
Relative Photo Detection Efficency (PDE)

The efficiency variation as a function of the annealing temperature and integrated time indicate an efficiency loss after 100 hours of annealing at 175 °C.



The SiPM entrance window shows changes after ~500 h of online annealing at 175 °C.

no alterations observed at lower temperatures up to 150 h



The annealed sensors exhibit a yellowish coloration compared to new ones.

Conclusions

- SiPMs meet the requirements of the dRICH detector in the ePIC experiment at EIC
- A large number of SiPMs for usability in single-photon applications in a moderate radiation environment were tested
- Radiation mitigation strategies were implemented to extend detector lifetime and stability
- Significant progress made in radiation damage mitigation with annealing were achieved
- Method validated accross a range of temperature and duration
- Further improvements and sensor selection will continue

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