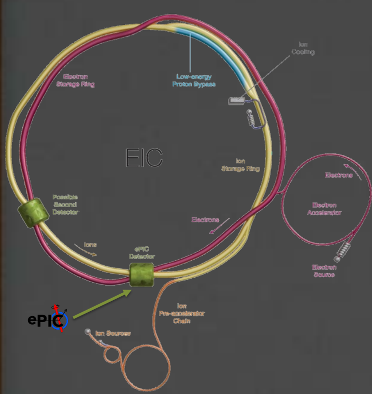
M. Ruspa (Univ Piemonte Orientale and INFN-Torino) on behalf of the ePIC-dRICH Collaboration

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

Introduction

The dual-radiator RICH (dRICH) detector of the electron-Proton/Ion Collider (ePIC) experiment at the future Electron-Ion Collider (EIC) will make use of silicon photomultiplier (SiPMs) sensors for the detection of the Cherenkov light emitted by particles crossing its radiators. This will be the FIRST APPLICATION OF SiPMs FOR SINGLE-PHOTON DETECTION IN A HEP EXPERIMENT



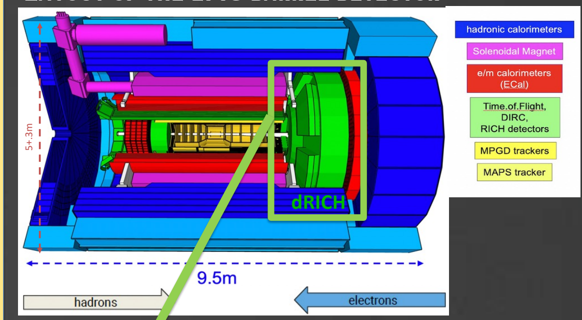
Electron-Ion Collider (EIC)

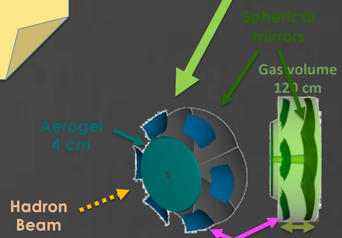
World's first collider for polarised electrons with polarised protons and ions (collision energy between 20 GeV and 140 GeV), foreseen to start operation in early 2030's at BNL (USA). Will allow one to

- understand the origin of nucleon mass and spin
- extraordinary 3D images of the nucleare structure

www.bnl.gov/eic
www.bnl.gov/eic/epic.php
www.eicug.org

Layout of the ePIC barrel detector





The dRICH detector is designed to provide continuous hadron identification

- in a broad momentum range (3 GeV/c to 50 GeV/c)
- in the forward region (1.5 < η < 3.5)

~3 m² surface
~300000 channels
single photon detection

SiPMs were chosen for their low cost and immunity to high magnetic field (~1 T). However, they are susceptible to radiation, demanding careful testing and attention to preserve single-photon counting capabilities and to maintain the dark count rates (DCR) under control over the years of running of the ePIC experiment.

Mitigation strategies were explored in R&D studies:

- ❄ operating at low temperature
- 🔥 recovery of radiation damage via high-temperature annealing cycles
- ⏰ precise timing with fast TDC electronics

Over the years the EIC will accumulate 100 fb^{-1} integrated luminosity corresponding to an integrated fluence of ~6 x 10^{10} n_{eq}/cm^{-2}

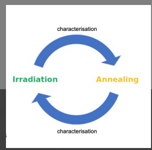
Radiation damage and annealing studies

Sensors exposed to various radiation doses up to 1 x $10^{11} n_{eq}/cm^2$

- Proton irradiation (2021, 2022, 2023,2024)
- Neutron irradiation (2023, 2024)

Sensor characterisation at T = -30 °C in temperature-controlled climatic chambers

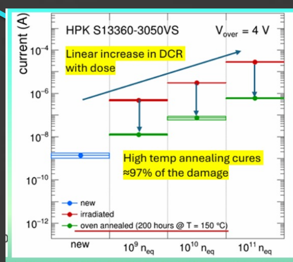
- before irradition
- after irradiation
- after annealing



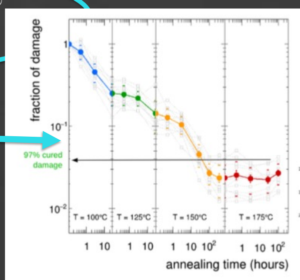
Two annealing procedures

1 Oven annealing: long (~ 200 hours) cycles up to 150 °C using a temperture-controlled climatic chamber

→ Linear trend with dose
→ 97-98% recovery of dark current generated by the radiation
→ Similar with various type s of sensors



2 Online in-situ tecnique using Joule effect to heat up the sensors, exploiting internal power dissipation of the SiPMs under forward bias
Temperature calibrated as a function of the applied forward current



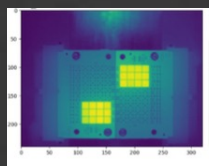


Image taken with the infrared thermal monitoring camera during annealing

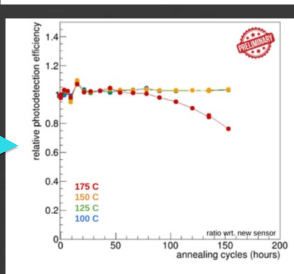
Study of dark current reduction

Data taken at increasing annealing temperature (different colors)
Multiple SiPMs subject to identical annealing treatment (averaged)

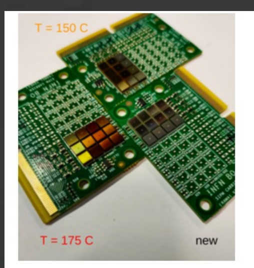
→ Consistent behaviour
→ Annealing at 150 °C for 100 hours is sufficient to recover approx 97% efficiency, while going beyond this temperature after 300 h has no further improvement

Relative photo detection efficency (PDE)

Laser light (attenuated to ensure single-photon conditions) directed to the SiPMs:: laser outpu remains constant hence # of detected photon events provides an estimate of PDE, relative to non-irradiated sensors



→ Yellow discolouration after 500 h of annealing at 175 °C, correlated with drop in PDE (not observed at lower temperatures and in sensors annealed in oven at the same temperature). Possivble reaction of air or residual huminidy with resin at high T. New annealing setup under development with SiPMs in a sealed chamber with zero humidity



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Conclusions

- Significant progress made in radiation damage mitigation with in-situ forward bias annealing – up to 97% recovery of dark current achieved
- Method validated accross a range of temperature and duration

Contribution to EPS-HEP Conference, Marseille July 7-11 2025