PROCEEDINGS OF SCIENCE

SiPM photosensors for the ePIC dual-radiator RICH detector at the EIC

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SiPMs are the baseline photodetector technology for the dual-radiator Ring-Imaging Cherenkov (dRICH) detector of the ePIC experiment at the future Electron-Ion Collider (EIC). SiPMs offer significant advantages being cheap devices, highly efficient and insensitive to the high magnetic field ($\sim$ 1 T) at the expected location of the sensors in the experiment. However, they are not radiation tolerant and one has to test whether the increase in dark count rate (DCR) can be mitigated to maintain single-photon performance with current SiPM technology in a moderately hostile radiation environment of $< 10^{11}$ 1-MeV equivalent neutrons/cm^2 (n_{eq}). Several options are available to maintain the DCR to an acceptable rate (below $\sim$ 100 kHz/mm^2) by reducing the SiPM operating temperature and by recovering the radiation damage with high-temperature annealing cycles. Moreover, by utilising high-precision TDC electronics the use of timing information can effectively reduce background due to DCR. We present the current status of the R&D and the results of studies performed on significant samples of commercial and prototype SiPM sensors. The devices have undergone proton irradiation in two campaigns aimed at studying the device performance with increasing NIEL doses up to 10^{11} 1-MeV n_{eq}, the device recovery with long high-temperature annealing cycles and the reproducibility of the performance in repeated irradiation-annealing cycles. In October 2022 the sensors were mounted inside the dRICH detector prototype and successfully tested with particle beams at the CERN PS accelerator. The results are obtained with a complete chain of front-end and readout electronics based on the first 32-channel prototypes of the ALCOR chip, a new ASIC designed for SiPM readout.

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1. Introduction

The Electron-Ion Collider (EIC) [1] is a forthcoming collider that will be built in the USA within this decade. It is anticipated to commence operations in the early 2030s. The EIC will be groundbreaking in its ability to provide polarised electron-proton (and light ion) collisions, as well as electron-nucleus collisions. These capabilities will enable us to explore the details of Quantum Chromodynamics (QCD), the strongest force in nature, and gain insights into the origin of mass and spin of nucleons. One of the primary challenges faced by the ePIC detector at the EIC pertains to particle identification (PID) [2]. EIC physics demands identification of pions, kaons, and protons across a wide pseudorapidity range ($|\eta| \leq 3.5$) with separation between kaons and pions better than 3σ up to momenta of 6, 10, and 50 GeV/c at central, backward, and forward rapidity, respectively. Various detector technologies are necessary to meet these PID requirements at the EIC.

A dual-radiator Ring Imaging Cherenkov (dRICH) detector [3] has been identified as a compact and cost-effective solution for the extensive momentum coverage needed at forward rapidity. It achieves 3σ separation between kaons and pions from a few GeV/c up to 50 GeV/c. The detector comprises aerogel and gaseous (C_2F_6) Cherenkov radiators with refractive indices of $\sim$ 1.02 and 1.0008, respectively. To focus the emitted Cherenkov radiation and form rings on the sensor surface, large outward-reflecting mirrors are arranged in 6 open sectors. The readout surface, covering approximately 3 m^2 and equipped with 3x3 mm^2 photosensor pixels (around 300000 channels), must ensure efficient single-photon detection within a high magnetic field ($\sim$ 1 T). The photosensors are positioned outside the detector acceptance, offering the opportunity to use silicon photomultiplier sensors (SiPM) for Cherenkov light readout [4]. While SiPMs present advantages such as affordability, high photodetection efficiency, and excellent time resolution [6], they are susceptible to large dark count rates (DCR) and radiation damage [5], leading to increased currents and DCR. Current projections from simulations of the ePIC experiment indicate that at the location of the dRICH photosensors there will be a particle fluence ranging from 3.9 to 9.2 10^5 1-MeV equivalent neutrons/cm^2 (referred to as n_{eq} hereafter) for each fb^{-1} of delivered luminosity. At the present, the largest value of 9.2 10^5 n_{eq} (for sensors closer to the beamline) is taken with a 10x safety factor to define a conservative limit of $\sim 10^7$ n_{eq}/fb^{-1} for the dRICH SiPM radiation damage. The nucleon imaging measurements at the EIC are the most luminosity hungry, requiring an integrated luminosity of up to 100 fb^{-1} (corresponding to a fluence of $\sim 10^9$ n_{eq}) for each centre-of-mass energy and polarisation setting. It is expected that in 10-12 years of operations the EIC will accumulate an integrated luminosity of $\sim$ 1000 fb^{-1}, leading to an integrated fluence of $\sim 10^{10}$ n_{eq} on the dRICH photosensors.

2. Irradiation and annealing

The ongoing R&D effort for the ePIC-dRICH focuses on investigating radiation damage in SiPM sensors and their suitability for Cherenkov imaging applications in a moderate radiation environment (up to 10^{11} n_{eq}). Various approaches are being explored to maintain the Dark Count Rate (DCR) at an acceptable level. These methods include reducing the operating temperature of SiPMs (cooling), utilising timing information with high-precision Time-to-Digital Converter (TDC) electronics (gating), and mitigating radiation damage through high-temperature annealing cycles

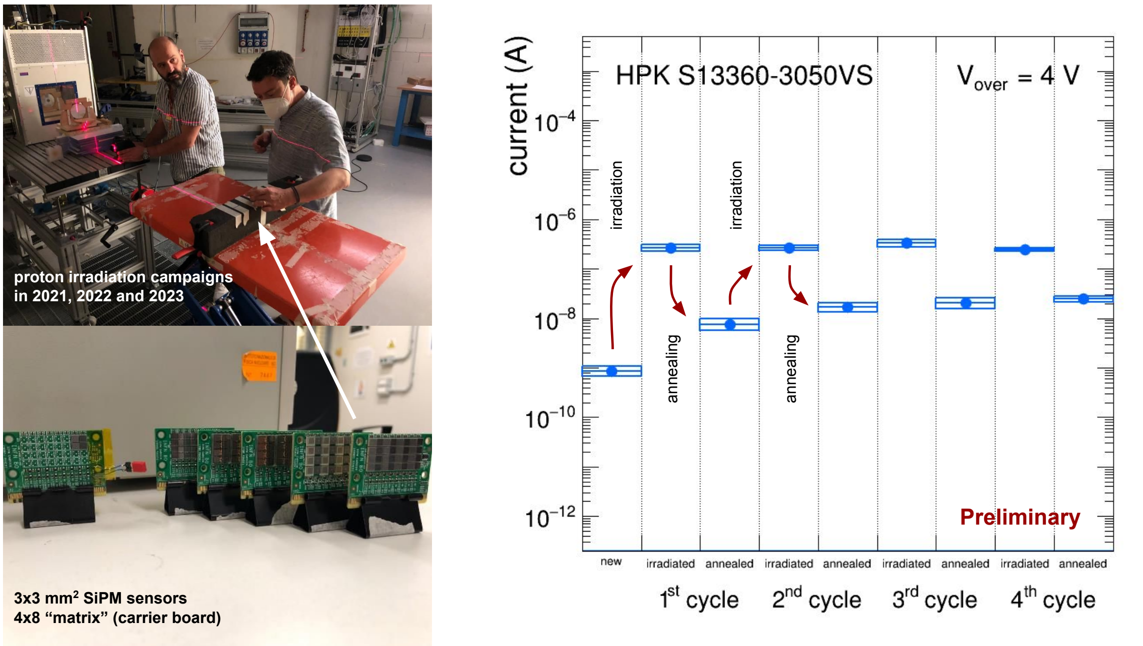

Figure 1: Positioning of one SiPM carrier board on the TIFPA proton beam line (top left). The custom SiPM carrier boards being irradiated (bottom left). Preliminary results obtained on the DCR of Hamamatsu S13360 sensors following repeated cycles of irradiation and annealing procedures (right).

(curing). Positive outcomes have been reported regarding the performance of cooled SiPMs after irradiation and subsequent annealing cycles, as documented in previous publications [7]. However, the applicability of SiPM sensors is contingent upon various factors and should be assessed for each specific application.

Specialized custom boards (Figure 1, bottom left) have been designed to accommodate SiPM photosensors and to withstand various irradiation and high-temperature annealing cycles. Their design with SiPM matrix arrangement was chosen to enable their use for imaging in beam tests (Figure 3, right). Several types of boards and SiPM sensors were subjected to irradiation using 145 MeV protons from the TIFPA experiemental room [8] at the Trento Proton Therapy facility (Figure 1, top left). To mitigate radiation damage, the SiPM sensor boards underwent annealing with a high-temperatures cycle of 150 hours up to 150 °C. This annealing process was conducted using a temperature-controlled climatic chamber and is also referred to as "oven annealing" in the following. Characterisation measurements have been taken before irradiation, after irradiation and after annealing operating the SiPM boards in a temperature-controller climatic chamber at T = −30°C. Previous results are reported in [11]. Here we focus on measurements performed in 2022 to test the reproducibility of repeated irradiation-annealing cycles to simulate a realistic experimental situation. Figure 1 (right) shows results obtained on Hamamatsu S13360-3050 sensors that underwent four repeated cycles of irradiation, each delivering a fluence of 10^9 n_{eq}, followed by the "oven annealing" procedure. A consistent irradiation damage is observed after each irradiation cycle with a consistent residual damage left after annealing. Measurements of the DCR are also performed to quantify the damage. A consistent DCR increase of ~ 500 kHz (at 4 V of overvoltage) is measured after each irradiation cycle and residual DCR of ~ 15 kHz after annealing, regardless

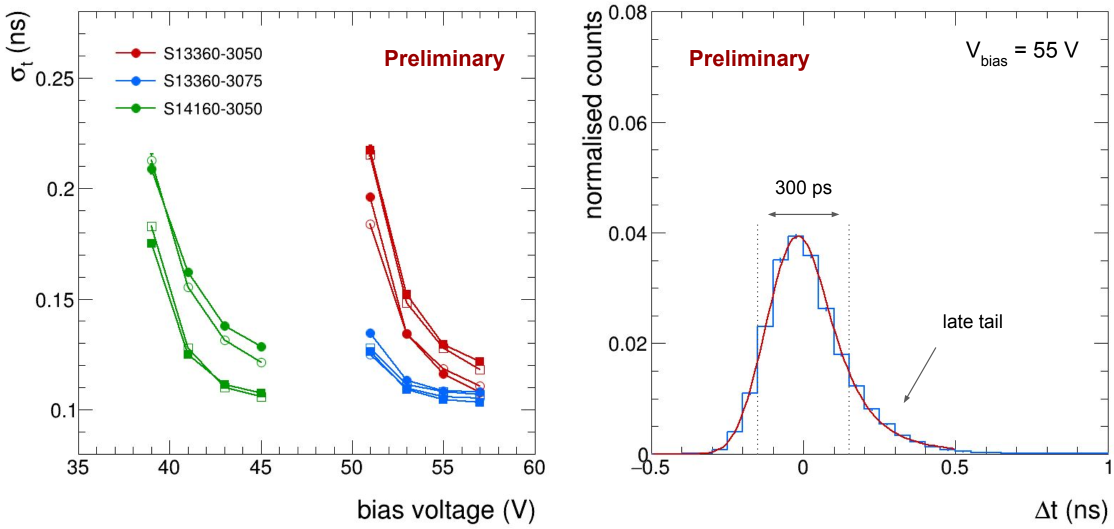

Figure 2: The resolution measured with a pulsed laser system and full readout electronics chain based on the ALCOR chip (left). Time coincidences between the recorded photon hits and the laser trigger pulse (right).

the irradiation-annealing cycle. It is noticeable that a 15 kHZ residual DCR increase measured after irradiation and annealing builds up after each cycle.

3. Timing performance

As previously mentioned, high-precision TDC electronics exploiting the excellent timing capabilities of SiPM can be of help in effectively reducing background due to DCR in the dRICH. A complete customly-developed prototype electronics chain, based on the ALCOR chip is employed to test the timing capabilities in the ePIC-dRICH configuration. ALCOR [10] is a prototype 32-pixel low-power mixed-signal ASIC developed to readout silicon photomultipliers at low temperature and performing single photon time-stamping. The chip is chosen as the baseline front-end ASIC for SiPM reaodut of the ePIC-dRICH detector. Configuration and readout of the ALCOR chip is achieved via an FPGA (Xilinx Kintex-7 FPGA KC705 evaluation board) which is controlled by a Linux PC. A pulsed-laser setup is used to study the timing response Hamamatsu SiPM sensors coupled to the prototype ALCOR-based electronics. The laser light is directed onto the SiPM which are located inside a climatic-chamber operated at T = −30°C. The laser light is attenuated by a neutral-density filter system to deliver single photons events, to a level such that no more than 1% of the laser pulses leads to a detected signal in the sensor. An example of the the time coincidences between the recorded photon hit on the sensor and the laser pulse trigger are shown in Figure 2 (right) after time-walk correction for a Hamamatsu S1336-3075 sensor. The correlation shows a narrow response with a FWHM smaller that 300 ps. A late tail in the timing response is also observed. Measurements of the time resolution of the SiPM-ALCOR system are performed on several Hamamatsu sensors of different types as a function of the bias voltage. The results are shown in Figure 2 (left) which shows that the time resolution improves with bias voltage for all sensors. The timing performance measured on the S13360-3075 sensors is the best, showing a

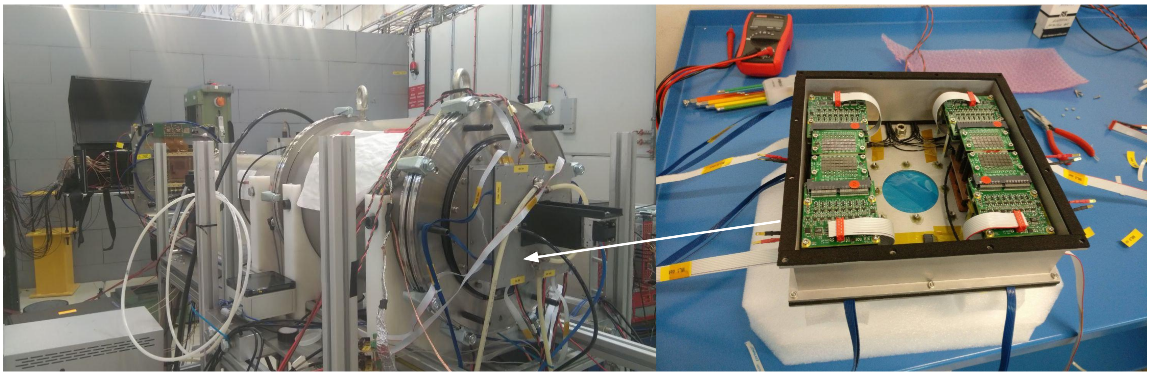

Figure 3: The dRICH detector prototype with the SiPM readout box installed on the CERN-PS T10 beam line in October 2022 (left). The SiPM readout box opened in the laboratory, showing its inner layout and the arrangement of the SiPM boards and front-end electronics.

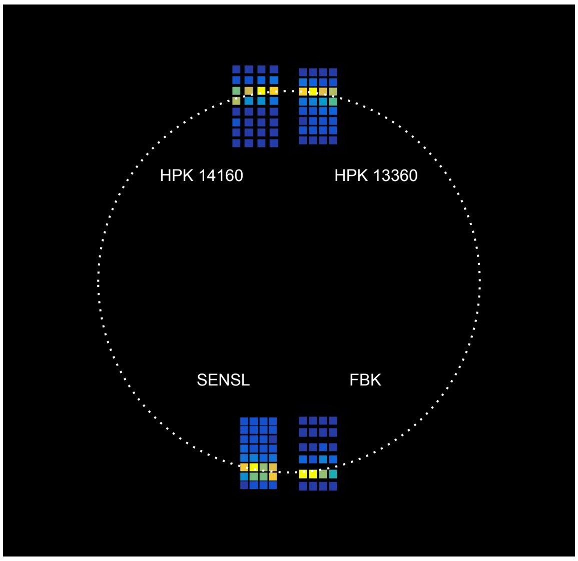

Figure 4: The reconstructed Cherenkov partial ring onto the dRICH prototype SiPM readout surface in the 2022 beam test at CERN with a negative beam.

RMS time resolution comfortably below $\sigma = 150$ ps also at low bias voltages.

4. Beam test

A beam test has been performed in October 2022 at the CERN-PS T10 experimental hall with the SiPM sensors and the ALCOR-based front-end prototype electronics mentioned before. The dRICH detector prototype [12] was equipped with a SiPM photosensor readout box and it is shown in Figure 3 (left) on the beam line. The inner details of the readout box and the arrangement of the four SiPM prototype boards installed are shown in Figure 3 (right). The beam test was successful and partial Cherenkov rings could be reconstructed despite the limited acceptance offered by the SiPM prototype readout system, as demonstrated by Figure 4.

5. Conclusions

The ePIC dRICH will use SiPM sensors for the optical readout and an R&D effort has been carried out to study the details of their performance in conjunction with a prototype chain of electronics based on the ALCOR front-end ASIC. Irradiation and high-temperature annealing studies have been performed in repeated cycles to simulated the experimental environemnt. Measurements of the timing performance of the prototype readout chain based on the ALCOR front-end ASIC shows that the system is adequate for the dRICH requirements, with an RMS time resolution below 150 ps. A beam test has been succesfully performed in October 2022 utilising the SiPM prototype sensor boards readout by a complete chain of electronics based on the ALICE prototype chips.

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