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Performance of H2GCROC3, the readout ASIC of SiPMs for the back hadronic sections of the CMS High Granularity Calorimeter.

Jose David Gonzalez Martinez for the CMS Collaboration

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Abstract: H2GCROC is the 130nm CMOS ASIC designed to read out the SiPMs coupled to the scintillating tiles of the back hadronic sections of CMS HGCAL. Each of its 72 channels comprises a current conveyor, a high-gain preamplifier, a shaper, an ADC to read the energy, and two discriminators connected to TDCs for time-of-arrival and time-over-threshold information, respectively. This work presents the ASIC architecture and its characterization in lab and test beam, proving good adaptability in calibration, radiation tolerance, and capacity to measure SiPM single-photon-spectrum and MIP's energy with high resolution.

Keywords: CMS, HGCAL, ASIC, SiPM

1 Introduction

The CMS experiment's High Granularity Calorimeter (HGCAL) is currently in development and is expected to be fully operational by 2026 [1]. Two ASICs have been designed: HGCROC for reading the Silicon sensors in the front part of the calorimeter and H2GCROC for reading the SiPM-on-tile in the back hadronic section. During the conceptual phase, it was determined that using a similar or identical ASIC for both sensor types on the detector would be advantageous. However, this decision posed a significant challenge for the development of H2GCROC. SiPM sensors offer advantages, including higher gain and lower cost than Silicon sensors. Nevertheless, they are less radiation-tolerant and exhibit larger detector capacitances that increase with sensor size. In terms of charge, the input signal at H2GCROC is expected to be approximately 30 times larger than the maximum expected from Silicon sensors.

2 H2GCROC Architecture

H2GCROC is a radiation-hardened CMOS chip fabricated using 130nm CMOS technology. This chip features 78 channels, each consuming approximately 15mW of power. Among these channels, 72 serve as standard cell readouts, two function as readout calibration cells, and the remaining four channels are not connected to any sensor cells, serving for common-mode noise estimation. Figure 1 presents the overview of its architecture and structure.

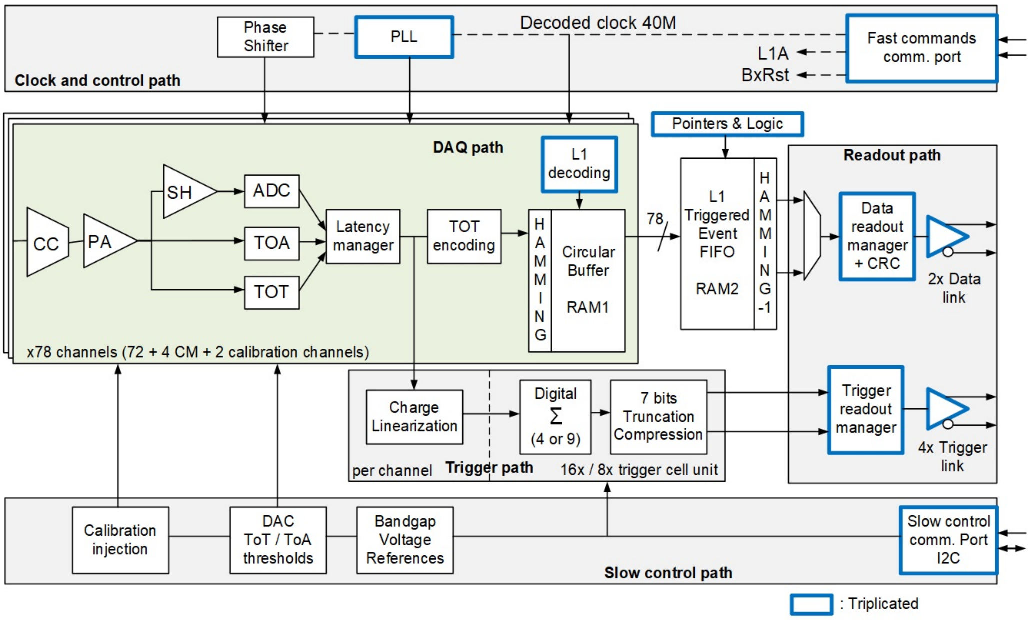

Figure 1: Front-end Architecture of H2GCROC ASIC version 3.

The Front-End design of the chip directly reads the current generated by the SiPM detectors at a 40 MHz frequency. Each channel includes a current conveyor (CC), which is based on the input stage of the KLauS chip from Heidelberg University [2], a low-noise preamplifier (PA) and a shaper connected to a 10-bit 40 MHz SAR-ADC, enabling charge measurement within the linear range of the preamplifier. Additionally, the ASIC incorporates a discriminator and a TDC to provide charge information based on time-over-threshold (ToT) within a dynamic range of 200 ns in the preamplifier's saturation zone. A fast discriminator and TDC also supply timing information with an accuracy of 25 ps. The chip employs a DRAM memory to store charge and timing data, and it performs data processing to select and compress relevant data for trigger formation. The chip's configuration can be adjusted using an I^2C protocol for slow control and communicates with the chip using fast commands at a rate of 320 MHz.

The current conveyor is designed with a 25 Ω input impedance to efficiently capture the sensor's charge signal. It can automatically compensate for offset variations on a chip level through the common-mode channel. Radiation can increase dark currents in SiPMs, resulting in leakage currents of up to 1 mA. A 6-bit DAC can inject an opposite current to compensate for up to 1.3 mA. Moreover, a dedicated DAC of the ASIC can mitigate fluctuations in the SiPM gain by configuring the input's DC voltage.

3 H2GCROC Performance

Two different configurations will be employed for HGCAL. The 'Calibration' configuration is intended for measuring the single-photon spectrum (SPS) of the SiPM for in-situ calibration. This configuration requires a high gain with a good signal-to-noise ratio to detect the separation of photons and read the gain of the SiPM connected to each channel. The 'Physics' configuration is designed to measure the required dynamic range of charges (ranging from 160fC to 320pC) with minimal noise during regular operation. It aims for optimal linearity in charge measurements and the highest achievable resolution for time measurements.

The ASIC characterization was performed with two SiPM detectors. Firstly, the Hamamatsu S14160-1315PS [3], a commercial 2mm^2 SiPM with characteristics similar to those intended for use in HGCAL. Secondly, the S16713 Hamamatsu pre-series SiPMs were explicitly developed for HGCAL and available in three sizes (2mm^2, 4mm^2, and 9mm^2). The 9mm^2 detector was selected as it presents a more challenging scenario for the ASIC due to its larger capacitance.

The injection of photons at the laboratory was carried out using a laser with the SiPM connected to one of the channels of the ASIC, referencing [4]. The goal is first to attenuate the light and measure injection from 0 to a few photons using the oscilloscope. Figure 2 illustrates the oscilloscope responses to photon injections from the 2mm^2 and 9mm^2 SiPMs, respectively. The voltage output indicates photon events in green. The event counting is presented in yellow, highlighting the photon separation achieved. Three main effects are observable: a larger SiPM area decreases the rising and falling times of the signal, increases the rms noise, and reduces the amplitude, leading to a decreased gain and a diminished separation of photons during SPS measurements.

The SPS was measured using two sets for the Calibration configuration (Figure 3). The configurated gain was adjusted to compensate for the gain decrease in the 9mm^2 SiPM. The changes included reducing the attenuation of the Current Conveyor from 0.3 on the 2mm^2 SiPM to the minimum possible (0.375) on the 9mm^2 SiPM and reducing by half the feedback capacitance of the preamplifier to accelerate the rising and falling times of the 9mm^2 SiPM response. This configuration led to similar gains in both SiPMs. To compensate for the increment in noise, the 9mm^2 SPS was measured with three datasets configured with a different pedestal setting on the

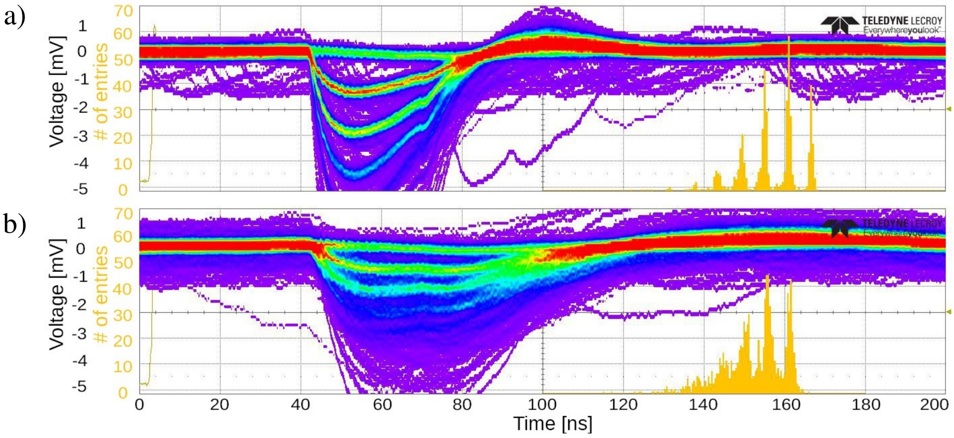

Figure 2: SiPM response to injecting 0 to 5 photons using an oscilloscope and an extra 20dB gain. a) 2mm^2 SiPM. b) 9mm^2 SiPM.

ASIC. Figure 3 b) presents the aligned data minus pedestal from the three datasets. This technique is not time-consuming and will be feasible during the in-situ calibration of HGCAL.

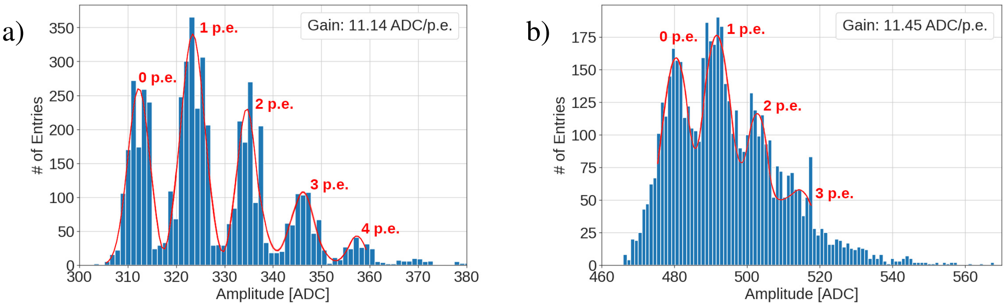

Figure 3: SPS response using injection with a laser to the H2GCROC ASIC. a) SPS of 2mm^2 SiPM. b) SPS of 9mm^2 SiPM with three datasets configured with a different ADC pedestal.

In the Physics configuration, the ADC measures the small charge injection. Figure 4 a) presents the difference in ADC gain for different detector capacitances. The measured charge ranges were 12.8 pC for the 2mm^2 SiPM, 14.4 pC for the 4mm^2 SiPM, and 18.4 pC for the 9mm^2 SiPM. The output exhibits a linearity of 99.94%, calculated with a linear fit. The rms noise measured from the ADC corresponds to 21 fC, 26 fC, and 35 fC for the different SiPM sizes, respectively.

As the preamplifier enters the saturation region, the signal duration becomes proportional to the injected charge. The ToT technique reads charge by comparing the preamplifier output to a defined threshold voltage via a discriminator. Upon crossing the threshold, a TDC measures the time until the signal drops below the threshold again. The ASIC subtracts the time measured by the ToT TDC from the time of the time-of-arrival (ToA) TDC. The resulting time corresponding to the signal's duration is sent to the output data. Figure 4 b) illustrates ToT measurement with the Physics configuration, reading charges from ~ 15 pC to ~ 200 pC.

Another discriminator, linked to a dedicated Preamplifier output, records ToA data of charge injections. Figure 5 presents the time walk and jitter performance of the ToA measurements.

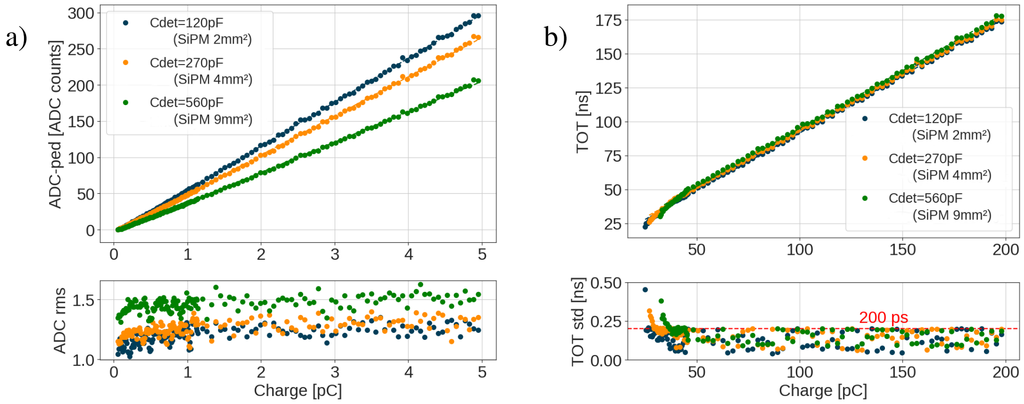

Figure 4: Charge measurement for different detector capacitances C_{det}. a) ADC response for small charge injection. b) Time over threshold measurement for large charge injection.

The increase in noise due to larger detector capacitances impacts the minimum threshold value available for configuration and significantly affects the resolution of small charge injections. Figure 6 illustrates the ToA efficiency for a charge injection scan, displaying the minimum charge with ToA data for the different detector capacitances. The three SiPM sizes allow us to measure ToA data from a minimal charge of around 230 fC, 280 fC, and 420 fC, respectively. The system maintains a resolution of less than 100 ps for the total charge dynamic range, reaching a floor of 25 ps.

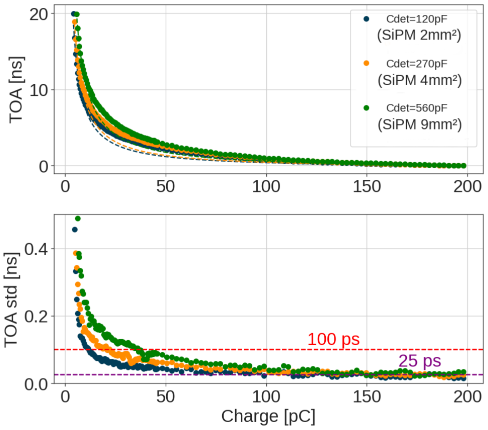

Figure 5: Time of Arrival time walk and jitter for different detector capacitances C_{det}.

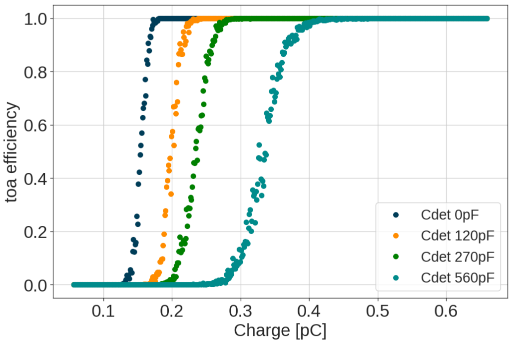

Figure 6: ToA efficiency for different charge injections, showing the minimum charge with ToA data for different detector capacitances C_{det}.

During the conception of HGCAL, the radiation expected from the increased luminosity of 3000fb^{-1} was simulated considering a 10-year lifetime of the detector [5]. A maximum accumulated dose of 300 kRad is expected in the back part of the Hadronic calorimeter. Several tests were conducted to demonstrate the radiation resistance of the HGCROC ASICs. Total Ionizing Dose (TID) campaigns were carried out at CERN, injecting high particle doses at cold or room temperature to simulate the expected radiation damage at the end of the detector's lifetime. H2GCROC proved to be radiation tolerant up to at least 19 Mrad, maintaining its ADC, TDCs, memories, I^{2}C, and PLL performance. The chip's performance and noise levels remain stable without visible effects for an accumulated dose of up to 300 kRad. However, Figure 7 presents a slight increment in the ADC rms noise after an accumulated dose of 19 Mrad.

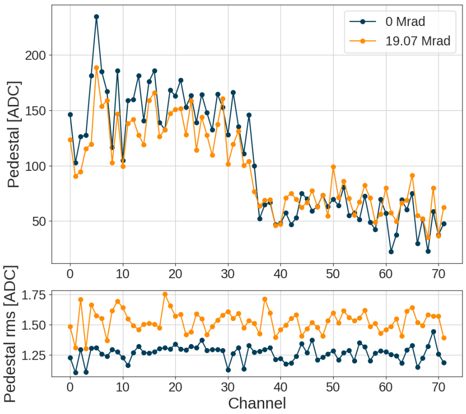

Figure 7: Measured pedestals of H2GCROC before and after irradiation up to 19 Mrad.

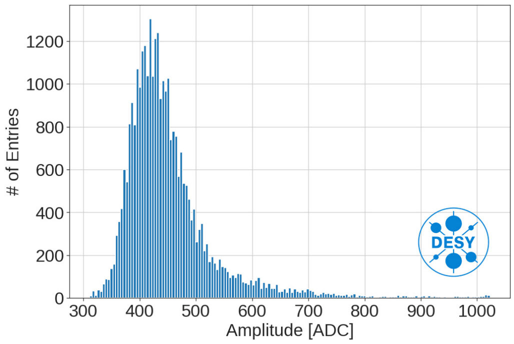

Figure 8: MIP histogram with pedestal subtraction of one channel of a Tileboard equipped with a 4mm² SiPM, using the Physics Mode configuration of H2GCROC.

The radiation fluence produces radiation damage induced by a single particle to electronic devices, which is non-cumulative. This type of radiation produces what is known as Single Event Effects (SEE), which can occur any time from the start of HGCAL's operation. Different particles induce damage in various parts of the electronics. They significantly affect the memories, treatment of data, and PLL. Since those blocks do not present any change from the two versions of the ASIC, the SEE campaigns were performed only in the Si version of HGCROC. Two tests were performed by injecting heavy ions and protons. The results indicated that the triplicated part of the ASIC (See Figure 1) compensates for those particle effects. However, the PLL was significantly affected by SEE, so an increase in its triplicated parts was applied to the next version of the ASIC.

Finally, several beam tests occurred at DESY in Hamburg, Bahrenfeld. DESY II [6], the electron-positron synchrotron, was used to inject electrons at 3 GeV using a Tileboard equipped with one H2GCROCv3 ASIC and 64 4mm^2 SiPMs from the S16713 Hamamatsu pre-series. Figure 8 displays the MIP response of one of the 4mm^2 SiPM-on-tile with the Physics configuration. This histogram has the pedestal subtracted to display only the MIP spectrum.

4 Conclusions

The results obtained with the complexity of all the modules included in the H2GCROC ASIC indicate a good chip performance for the new HGCAL of CMS. The H2GCROC is currently in its third printed version, and minor corrections have been prepared for the next and final version of the ASIC for HGCAL.

Acknowledgments

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