Available on CMS information server

CMS CR -2024/310

The Compact Muon Solenoid Experiment

Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

13 November 2024 (v4, 02 December 2024)

Radiation Testing of New Readout Electronics for the CMS ECAL Barrel

Nico Härringer, Günther Dissertori, Tomasz Gadek, Wojciech Hajdas, Christian Haller, Nikitas Loukas, Werner Lustermann, Ljiljana Morvaj, Alexander Singovski, Krzysztof Stachon on behalf of the CMS ECAL collaboration

Abstract

In preparation of the operation of the CMS electromagnetic calorimeter (ECAL) barrel at the High Luminosity Large Hadron Collider (HL-LHC) the entire on-detector electronics will be replaced. The new readout electronics comprises 12240 very front end (VFE), 2448 front end (FE) and low voltage regulator (LVR) cards arranged into readout towers (RTs) of five VFEs, one FE and one LVR card. The results of testing one RT of final prototype cards at CERN′s CHARM mixed field facility and PSI′s proton irradiation facility are presented. They demonstrate the proper functioning of the new electronics in the expected radiation conditions.

Presented at *TWEPP2024 Topical Workshop on Electronics for Particle Physics*

Prepared for submission to JINST

Radiation Testing of New Readout Electronics for the CMS ECAL Barrel

Nico Härringer[a] , Günther Dissertori[a] , Tomasz Gadek[a] , Wojciech Hajdas[b] , Christian Haller[a] , Nikitas Loukas[c] , Werner Lustermann[a] , Ljiljana Morvaj[b] , Alexander Singovski[c] , Krzysztof Stachon[a] on behalf of the CMS ECAL collaboration

[a]*ETH Zürich, Institute for Particle Physics and Astrophysics (IPA), Switzerland*
[b]*Paul Scherrer Institute (PSI), Switzerland*
[c]*University of Notre Dame, Department of Physics and Astronomy, United States*

E-mail: nico.harringer@cern.ch

Abstract: In preparation of the operation of the CMS electromagnetic calorimeter (ECAL) barrel at the High Luminosity Large Hadron Collider (HL-LHC) the entire on-detector electronics will be replaced. The new readout electronics comprises 12240 very front end (VFE), 2448 front end (FE) and low voltage regulator (LVR) cards arranged into readout towers (RTs) of five VFEs, one FE and one LVR card. The results of testing one RT of final prototype cards at CERN's CHARM mixed field facility and PSI's proton irradiation facility are presented. They demonstrate the proper functioning of the new electronics in the expected radiation conditions.

1 The CMS Electromagnetic Calorimeter (ECAL)

The Compact Muon Solenoid (CMS) experiment at CERN's Large Hadron Collider (LHC) [1] has a dedicated subsystem to measure the energies of electromagnetic objects like electrons and photons. The Electromagnetic Calorimeter (ECAL) [2] is divided into two parts: the Barrel (EB), covering $0 < |\eta| < 1.4442$, and the Endcap (EE), covering $1.566 < |\eta| < 3$. The EB consists of 2448 trigger towers organized into 36 supermodules (SM), which collect energy from electromagnetic objects in significant events. Each SM holds 1700 lead tungstate (PbWO4) crystals, each connected to an Avalanche Photodiode (APD) capsule containing two sensors collecting the scintillation light emitted by the crystal during excitation by a passing particle. 25 capsules connect to a single motherboard that provides bias voltage and houses the readout electronics. This readout tower includes five Very-Front-End (VFE) cards, one Low-Voltage-Regulator (LVR) card, and one Front-End (FE) card [3].

1.1 The Upgrade

During the Long Shutdown 3 (LS3) scheduled to start in 2026, the LHC will be upgraded to the High Luminosity LHC (HL-LHC) [4, 5], which will increase its annual delivery to about 1.5 times the Run 2 dataset (138 fb^{-1}). Over its lifetime, it will produce roughly 10 times the total LHC's integrated luminosity (4000 fb^{-1}) collected to date. This upgrade will result in higher radiation levels and event rates, with pileup rising to 140-200 interactions per bunch-crossing (up from 40-60) [6], and the Level-1 trigger rate increasing to 750 kHz (from 100 kHz). Enhanced granularity and timing resolution will be necessary to identify primary vertices amid this higher pileup. Additionally, radiation-hard on-detector electronics will be required. In the upgraded system, the APD signal is amplified by the Calorimeter transimpedance amplifier (CATIA, [7]) chip on the VFE cards. This pulse is digitized by the Lisbon-Torino ECAL Data Transmission Unit (LiTE-DTU, [8]), with data from each chip collected by four low power Gigabit transmission (lpGBT, [9]) chips on the FE card and transmitted via optical links with 10.26 Gbps to the off-detector Barrel Calorimeter Processor (BCP, [10]) for digital processing and trigger generation.

2 Irradiation at CHARM

Positioned in front of the Hadronic Calorimeter [11], ECAL will be exposed to high-energy hadrons (HEH) like protons, neutrons, and pions. By the end of its lifetime, the most affected readout tower in a SM, located at $|\eta| = 1.431$, is expected to experience a HEH fluence of $4.5 \times 10^{13}\ \text{cm}^{-2}$ and a total ionizing dose (TID) of about 7.65 kGy [12]. All HL-LHC key figures discussed here refer to this specific position. The ideal facility for the test offers a uniform radiation field with a sufficient dose rate and particle fluence. For these reasons, the CERN High Energy Accelerator Mixed Field (CHARM) facility [13] was chosen. CHARM uses the Proton Synchrotron (PS) beam, which provides protons with energies up to 24 GeV [14]. The total time spent at CHARM including the access times was 17 days.

2.1 Data taking and results

During the test, the readout tower remained powered and operational most of the time. A comprehensive system test of the new EB electronics, simulating HL-LHC operation with the appropriate number of power cycles and full reconfigurations, and performing stability studies on baselines (pedestals), CATIA test pulse amplitudes, and the CATIA RMS noise evolution is conducted. For a dark current readout with the GBT-SCA chip, the APDs are biased with +400V. Every six hours the tower was power cycled and every hour a reconfiguration was performed. Every twelve seconds, data including pedestals, CATIA test pulses, various status flags, power consumption of the LVR (V_{1P2}, V_{2P5}, and V_{in}), the dark current of the APDs and the Single Event Upset (SEU) counter of CATIA and the lpGBTs are taken. Each pedestal and CATIA test pulse is collected with a 129 bunch crossing acquisition window, totaling 3.225 μs. The CATIA test pulse feature is used to simulate physics signals. The LiTE-DTU's gain switch feature automatically adjusts the gain when the signal exceeds a predefined threshold. To test this, pulses are taken for both gains. Current injection is controlled by a 12-bit register in CATIA, with approximately 0.24 mA for high gain and 0.72 mA for low gain.

Every reconfiguration cycle the VFEs were calibrated. During this step, the CATIA digital-to-analog (DAC) converter register (6-bit) and the baseline subtraction register (12-bit) of the LiTE-DTU were adjusted so that mean pedestal values fall between 20 and 40 ADC counts, ideally around 30 ADC counts. The exact pedestal value may vary with each tower reconfiguration. The pedestals and CATIA test pulses were disentangled from the baseline set during VFE calibration and categorized based on their baseline subtraction value. During the first week at CHARM, both cooling fans malfunctioned and were replaced in the following maintenance window, resulting in a loss of over 100 fb^{-1}. The second downtime window was shorter as the fans were successfully restarted. In CHARM plots, fan downtime is marked in red. Data collected over 17 days (up to 1384 Gy / 673 fb^{-1}) suggests that pedestal values for all channels are stable, except for channel 3, which showed a slight negative drift. The average median distributions remained constant with respect to integrated luminosity for a given CATIA / LiTE-DTU configuration. Test pulse amplitude stability was also assessed. Test pulses in high and low gain were alternated, with CATIA chips set to reference voltages of 1.355V. A drift in amplitude indicate possible radiation effects on the channel. The relative drifts of test pulse amplitudes were calculated. Channels with CATIA v2.1 performed well, showing no significant drift with relative deviations from the average test pulse amplitude under 1% for both gains.

To determine the raw Root Mean Square (RMS) noise, the median value ped_i was calculated for each channel in a pedestal dataset i. By subtracting ped_i from every data point ADC_i^j in the pedestal dataset i, the distribution $n_i^j := ADC_i^j - \text{ped}_i$ was obtained. The standard deviation of n_i^j is referred to as the raw RMS noise, denoted as $\sigma_{\text{rawnoise},i}$. The objective of this study was to verify the stability of $\sigma_{\text{rawnoise},i}$ with respect to radiation. The evolution of the raw RMS noise in relation to the TID for all 25 channels was calculated. When APDs are connected, the raw RMS noise can be influenced by the increasing dark current of the APDs. Therefore, channels 0-4 which are connected to APDs are not suitable for estimating the raw RMS noise and were thus excluded from this analysis. The data shows that the raw RMS noise of channels equipped with CATIA v2.1 remained very stable with respect to radiation up to 673 fb^{-1}. The mean value of the RMS noise standard deviation distribution is 5.24 ± 0.92%, while the mean of the RMS noise mean distribution is 1.17 ± 2.84%. This indicates that the newest generation of CATIA chips exhibit excellent resilience to radiation in terms of maintaining consistent RMS noise levels.

During the CHARM test, the GBT-SCA chip on the FE card reliably read the dark current at all times. Figure 1 shows the dark current's evolution with integrated luminosity.

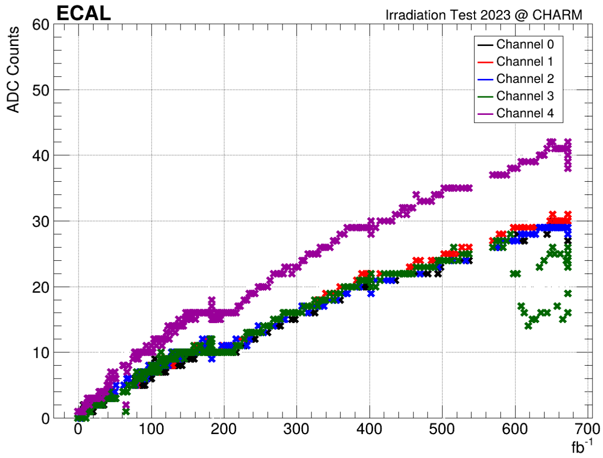

Figure 1: The dark current of channels 0-4 as a function of the equivalent integrated luminosity. Each channel carries a previously not irradiated APD capsule, constantly biased with +400V. For visibility reasons, only every 375th datapoint is shown.

The APD capsules in channels 0-3 were uniformly irradiated (see Fig. 1). However, channel 4 displayed a different behavior, likely due to its capsule being positioned unfavorably within the beam box, leading to uneven radiation exposure. Alternatively, the capsule could be inherently more susceptible to radiation. APD 3 experienced contact issues near the test's end, causing the readings to oscillate.

2.1.1 Single Event Upsets (SEU)

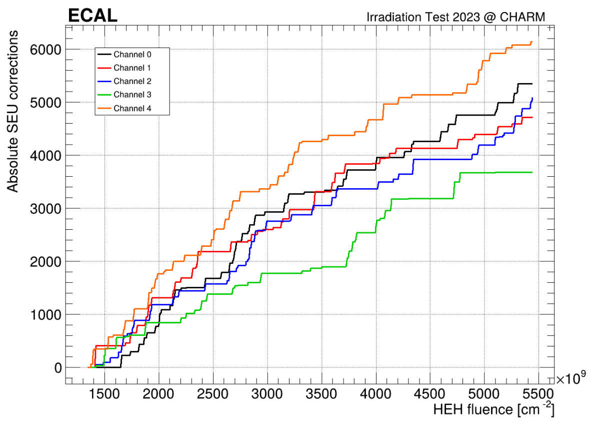

Figure 2: Absolute SEU corrections as function of the high energy hadron (HEH) fluence of VFE 0.

Due to the architecture of the FE v3.1 used in the CHARM test (the master lpGBT communicates with three slave lpGBTs) most SEU corrections (63.6%) occurred in the master lpGBT, which is expected given this setup. Since CATIA SEU data is available only for channels with CATIA v2.1, the study includes ten channels. Figure 2 shows the absolute SEU corrections for VFE 0 (channels 0-4, with APDs).

3 Irradiation at PSI

To achieve the target dose of 5.7 kGy (3000 fb^{-1}) and potentially 7.65 kGy (4000 fb^{-1}), a more intense particle source was required. The Proton Irradiation Facility (PIF) at the Paul Scherrer Institute (PSI) in Switzerland provides directed high-energy protons from the COMET cyclotron [15]. 74 MeV protons were used, yielding a proton flux of 8.70×10^7 $\text{cm}^{-2}\text{s}^{-1}$. With a stopping power of $\frac{dE}{dx} = 7.326\ \frac{\text{MeV cm}^2}{\text{g}}$ in silicon, the expected TID per hour is about 356 Gy, with a proton fluence of 3.13×10^{11} cm^{-2}. In over four night shifts (16.19 hours), a TID of 5.77 kGy was accumulated, with an average dose rate of 99.0 mGy/s. For the PSI test, the newest version of the FE card was used (v3.3) which decreases the configuration time by the use of the External Control feature (EC) of the lpGBT chips to less than five minutes. The VFE cards were exposed tangentially with respect to the beam.

3.1 Data taking and results

The data taking routine used was almost identical to CHARM. Due to the short period at PSI, the power cycle feature was removed. Every 30 minutes the tower was reconfigured. Combined with the dose from CHARM, a cumulated TID of 7.15 kGy (93.40% of the 4000 fb^{-1} dose target) and a proton fluence of 4.92×10^{12} cm^{-2} was achieved. Similarly, the proton fluence target was reached by 83.40%, and the 4.42×10^{12} cm^{-2} target for 3000 fb^{-1} by 111.3%. The tower collected a high-energy hadron fluence of 5.44×10^{12} cm^{-2} from the CHARM test. Due to tighter time constraints at PSI, fewer data points were collected. Channels 7 and 12 received the highest radiation exposure, approximately 98.5 mGy/s, owing to the Gaussian beam profile of COMET at PSI.

Each pedestal dataset was binned in up to 100 luminosity bins and categorized according to different CATIA DAC and LiTE-DTU baseline tuning register values. Test pulse stability was assessed using the same procedure as in CHARM. For CATIA v2.1, the relative drift of the test pulse amplitude remained within 2% in both gains. Specifically, channel 7 showed a relative drift of 1.7% in high gain (see Fig. 3) and 1.5% in low gain, while channel 12 had a drift of 5% in high gain and 4% in low gain. The mean value of the RMS noise distribution is $0.52 \pm 2.66\%$, while the mean of the RMS noise standard deviation distribution is $4.54 \pm 1.13\%$.

4 Discussion

Both the CHARM and PSI irradiation campaigns confirmed that the on-detector electronics for the CMS ECAL upgrade for HL-LHC can withstand extreme conditions. The communication between the readout tower and backend was flawless, with a bit error rate of 2.87×10^{-14} over a 1-hour test across all four lpGBTs. Throughout both tests, the GBT-SCA chip consistently read out the dark current without any SEU issues, ensuring continuous channel monitoring. Four months post-irradiation, a re-evaluation at CERN (without beam) over 17 days showed no channel drift, with pedestals remaining stable (Fig. 4). CATIA v2.1 demonstrated high precision in handling

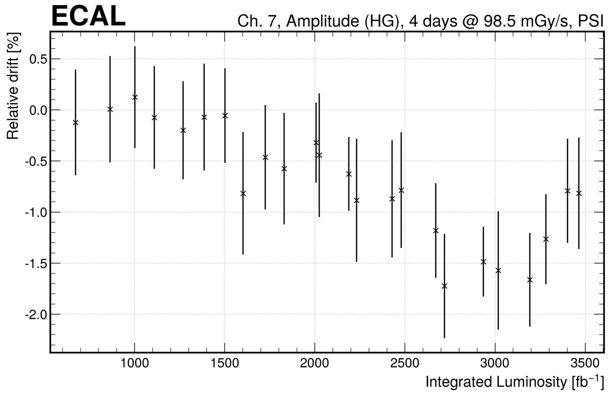

Figure 3: The relative drift of the test pulse amplitude of channel 7 during the PSI test as a function of the equivalent integrated luminosity. The used reference voltage was 1.355V. The data set was not categorized.

injected test pulses, even under dose rates up to 98.5 mGy/s. The raw RMS noise analysis indicated that relative drifts remained within 5‰. These results suggest that the upgraded readout electronics will perform reliably throughout the HL-LHC's operational period.

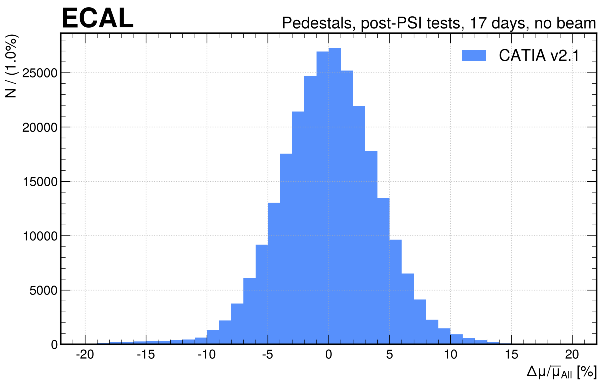

Figure 4: The relative deviation of the mean values of the pedestals of all CATIA v2.1 channels after PSI from the mean of the complete dataset. In total 260945 datapoints were collected. The mean of the histogram is 0 ± 4.07‰.

Acknowledgments

The authors would like to thank Giacomo Cucciati, Tanja Gisler and the ECAL community for their valuable help and expertise in making these irradiation test campaigns work. A big thank you also the PSI beam operators, as well as to the staff from CHARM.

References

[1] CMS Collaboration, *The CMS experiment at the CERN LHC. The Compact Muon Solenoid experiment*, *JINST* **3** (2008) S08004.

[2] CMS Collaboration, *The CMS electromagnetic calorimeter project: Technical Design Report*, Technical design report. CMS, CERN, Geneva (1997).

[3] A. Dolgopolov, C. Jessop, N. Loukas, A. Singovski and on behalf of the CMS collaboration, *CMS ECAL Upgrade Front End card: design and prototype test results*, *Proceedings of Science* **343** (2018) .

[4] O. Aberle, I. Béjar Alonso, O. Brüning, P. Fessia, L. Rossi, L. Tavian et al., *High-Luminosity Large Hadron Collider (HL-LHC): Technical design report*, CERN Yellow Reports: Monographs, CERN, Geneva (2020), 10.23731/CYRM-2020-0010.

[5] CMS Collaboration, *Development of the CMS detector for the CERN LHC Run 3*, *Journal of Instrumentation* **19** (2024) P05064.

[6] CMS Collaboration, *The Phase-2 Upgrade of the CMS Barrel Calorimeters*, Tech. Rep. CERN-LHCC-2017-011, CMS-TDR-015, Geneva (2017).

[7] F. Guilloux, *CATIA APD Readout ASIC for the CMS phase 2 ECAL electronics upgrade*, Tech. Rep. CMS-CR-2019-196, Geneva (2019).

[8] G. Mazza, S. Argirò, C. Borca, S. Cometti, F. Cossio, M. Dejardin et al., *A Data Conversion and Compression ASIC for the Readout of the CMS Electromagnetic Calorimeter*, *IEEE Transactions on Nuclear Science* **70** (2023) 1215.

[9] P. Moreira, S. Baron, S. Biereigel, J. Carvalho, B. Faes, M. Firlej et al., *lpGBT documentation: release* (2022).

[10] N. Loukas, S. Goadhouse, T. Anderson, A. Belloni, T. Gorski, T. Grassi et al., *The CMS Barrel Calorimeter Processor demonstrator (BCPv1) board evaluation*, *Journal of Instrumentation* **17** (2022) C08005.

[11] CMS Collaboration, *The CMS hadron calorimeter project: Technical Design Report*, Technical design report. CMS, CERN, Geneva (1997).

[12] CMS Collaboration, *FLUKA Simulations for Radiation Levels in Tracker and ECAL Regions for Phase II*, 2024 (Note in preparation).

[13] A. Thornton, *CHARM Facility Test Area Radiation Field Description*, Tech. Rep. CERN-ACC-NOTE-2016-12345, CERN, Geneva (2016).

[14] E. Regenstreif, *The CERN Proton Synchrotron*, CERN Yellow Reports: Monographs, CERN, Geneva (1962), 10.5170/CERN-1962-003.

[15] W. Hajdas, L. Adams, B. Nickson and A. Zehnder, *The Proton Irradiation Facility at the Paul Scherrer Institute*, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* **113** (1996) 54.