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The Compact Muon Solenoid Experiment

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Upgrade of the high voltage system for the Avalanche Photodiodes of the CMS ECAL for the High Luminosity phase of the LHC

Federica De Riggi for the CMS Collaboration

Abstract

The electromagnetic calorimeter (ECAL) of the CMS experiment at the Large Hadron Collider is a homogeneous calorimeter made of 75848 lead tungstate crystals. The scintillation light is detected by avalanche photodiodes (APD) in the barrel and vacuum phototriodes in the endcaps. One of the drawbacks of the APDs is the challenging requirement on the stability of the high voltage source. Indeed, for the CMS ECAL APDs, which are operated at a gain of 50, the variation of the gain as a function of the voltage is 3%/V. The excellent ECAL energy resolution is ensured thanks to the achieved stability of high voltage, temperature and crystal transparency monitoring, whose individual contribution are required to not exceed 0.2%. Therefore, the high voltage system stability must be within 60 mV during a period of one month, the typical period over which calibration of the crystals with physics channels can be performed. The legacy high voltage system was developed by CAEN s.p.a. and it is based on the board A1520PE. The system has provided excellent stability and reliability. The APDs are silicon devices and therefore are subject to radiation damage and particularly their leakage current will increase during the high luminosity phase of the LHC as much as 10 times the present value. Therefore, a new HV system has been developed. Stability tests were performed on these new HV boards, as well as noise measurement, using prototypes of the front-end electronics mounted on a spare ECAL supermodule.

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Upgrade of the CMS ECAL barrel HV system for HL-LHC

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I. INTRODUCTION

The Electromagnetic Calorimeter (ECAL) of the Compact Muon Solenoid (CMS) detector at the Large Hadron Collider at CERN (LHC) is a hermetic homogeneous calorimeter [1] made of 61200 lead tungstate (PbWO4) crystals mounted in the barrel part, closed by 7324 crystals in each of the two endcaps. The calorimeter is designed to perform precision measurements aiming to reach 0.5% energy resolution at high energy. The relatively low light yield of PbWO4 (about 100 photons/MeV) and the presence of a very intense magnetic field inside CMS ($3.8\,T$) have led to the choice of Avalanche Photo-Diodes (APDs) as photon sensors in the barrel.

The APDs were manufactured by Hamamatsu Photonics, these silicon-based APDs offer internal signal amplification and are installed in pairs on each crystal, operating with a typical gain of 50. However, their performance is highly sensitive to fluctuations in the bias voltage, as changes in gain directly affect the calorimeter's constant term in energy resolution. To mitigate this effect, a custom high-voltage power supply system, designed in collaboration with CAEN, ensures a stable power source for the APDs. The system has to be upgraded in preparation for the new high-luminosity phase of the LHC (HL-LHC) [2]. In fact, the High-Voltage system (HV) is part of the Phase-2 detector upgrade project, where enhancing long-term stability and minimizing operational noise are key requirements.

II. HV SYSTEM

To safeguard the HV power supply from radiation damage during LHC operations, the HV system for ECAL is installed in the service cavern, away from the detector. This remote placement is essential to protect the delicate electronics from the intense radiation environment near the detector. Due to logistical constraints, such as limited cabling and space within the patch panels, multiple APD pairs must share the same HV source. Consequently, 50 APD capsules (100 APDs) are connected to a single HV channel. The APDs are carefully grouped according to their operating voltage into 5 V bins, ensuring that each pair maintains an average gain of 50.

As depicted in Fig. 1, each APD capsule is powered through an RC filter network and protected by two resistors (68 kΩ) that limit the bias current to 3 mA in case of an APD failure. The HV system is designed to provide a variable voltage, a sense wire is used to monitor the delivered voltage and adjust it if necessary, in order to account for possible voltage drops along the length of the cable

The CMS ECAL HV system is based on a standard control crate (SY1527), which accommodates 8 A1520E boards (HVBOARD), purpose-built for this application. The SY1527 contains a microcomputer that interfaces with the board controller via an internal bus, with multiple interface options available to integrate the system into the ECAL Detector Control System (DCS). The modular design allows each HV channel to function as an independent module providing flexibility in the event of channel failure. The complete system consists of 18 SY1527 crates and 144 A1520E boards, with a bias voltage ranging from 0 to 500 V and a maximum current of 15 mA. This capability allows the HV channel to continue operating even in the event of a short circuit in several APDs.

The ECAL barrel is divided into 2×18 supermodules, each containing 1700 crystals. All connections are routed through a patch panel located at the outer end of each supermodule. Each supermodule requires 34 HV channels, distributed across four boards (with one spare channel available per two boards).

Custom 9-channel multiwire cables, designed to meet ECAL specifications and manufactured by Pansystem, connect the boards in the service cavern to the patch panels. On the opposite side, bundles of 8 or 9 multiwire cables link the patch panels to motherboards, which distribute the bias voltage to the APD capsules and handle connections to the Very Front End (VFE) electronics.

The motherboards serve groups of 5×5 crystals, forming a trigger tower. Two motherboards are connected in parallel to the same HV channel. Recent upgrades have focused on optimizing the connection architecture to reduce noise and improve performance during the HL-LHC, supporting the continued operation of the ECAL in high-luminosity conditions.

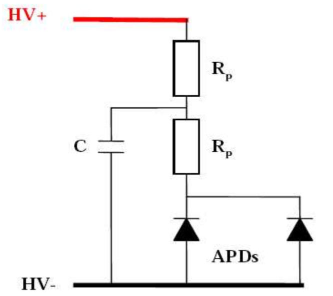

Fig. 1. CMS ECAL APDs loading electrical scheme. Rp = 68 kΩ are the protection resistors. C = 10 nF is a ceramic capacitor.

III. HV System Upgrades

The legacy High Voltage system [4] was produced in 2003. The maintenance contracts will cease at the end of the LHC program. Some of the components are becoming obsolete and a new system will be prepared for Phase-2. The specifications for the Phase-2 system in terms of ripple, noise and stability are unchanged. However, the maximum current and voltage must be increased, as shown in the second column in Tab. I.

Because of irradiation, the APD dark current will increase, to 200 μA per capsule at 18 °C at $|\eta|$ = 1.5, after 3000 fb^1. To bias the APDs at 18 °C through to the end of the HL-LHC program, the HV channels must be able to supply up to 10 mA.

If one capsule line goes into short, the HV channel draws an additional current of about 3.5 mA. Currently there are $<$ 10 such channels in the detector. If one capacitor goes into short, the HV channel draws an additional current of about 7 mA and there is currently one such channel in the detector. In both cases, only one of the 50 crystals cannot be read out. For HL-LHC, the specification for the maximum current for each HV channel will be 20 mA, to have a safety margin.

It should be noted that these values were calculated at a temperature of 18°C. However, with the upcoming Phase-2 of the LHC, the ECAL barrel cooling temperature will be lowered from the Phase-1 temperature of 18 °C to 9 °C, which will in turn decrease the noise current values by approximately the same factor.

The APD bias voltage required to provide a gain of 50 will increase with radiation by about +30 V at $|\eta|$ = 1.5 after 3000 fb^{-1}. The bias resistors (136 kΩ in total) will create a voltage drop, which will grow with increasing APD dark current up to a maximum of 27 V at 200 μA. The maximum required voltage, for the channels with the highest V50, will approach the legacy system specification of 500 V.

A safety margin of at least 50–100 V is therefore required for the new system specification.

The ramp-up and ramp-down voltage rates must be configurable from a minimum of 2 V/s to a maximum of 50 V/s. The voltage must never turn off abruptly. In the legacy system this has been implemented by reprogramming the KILL and INTERLOCK functionality of the channels as a normal turn off command achieved at the ramp-down rate. The HV system must measure the current drawn by each channel to better than 5%, and it must be possible to check the calibration of the channels periodically to ensure the required stability during LHC operation.

TABLE I
The characteristics of the legacy High Voltage system and of the new High Voltage system for the CMS ECAL barrel APDs.

Parameter	**Legacy HV system**	**HL-LHC HV system**
Output voltage range	0–500 V	0–600 V
Programmable setting step	1 mV	1 mV
External calibration	± 20 mV	± 20 mV
DC regulation at load	± 20 mV	± 20 mV
DC stability at load (over 90 days)	± 70 mV	± 70 mV
Low freq. noise at load (f $<$ 100 KHz)	± 20 mV	± 20 mV
High freq. noise at load (f $>$ 100 KHz)	± 20 mV	± 20 mV
Operating temperature at supply	15-40 C	15-40 C
Current limit	15 mV	20 mV
On and off ramp rate	2-50 V/s	2-50 V/s
Current measurement (from 1 μA)	5%	5%

A. *stability test*

Two preliminary boards of the upgraded board (A7420PE) produced by CAEN were tested for about a month in the Rome laboratory to check the stability requirements. The Rome laboratory setup consists of a SY1527 crate, containing the two boards connected to resistors (to simulate the APDs), a multimeter, and a computer with the LabVIEW program installed to control the devices via a graphical interface and for data acquisition. Two prototype boards provided by CAEN were tested over a 20 day period. The nominal voltage for all nine channels was set to 380 V, with no prior calibration, as it was not required for the purpose of this analysis, which focused on evaluating the boards' stability. As shown in Fig. 3, most channels exhibited a temperature dependence, with some showing a positive correlation between voltage (V) and temperature (T), while others displayed a negative correlation. The temperature was measured using an internal sensor on the board. Despite this dependence, the boards met the stability criteria, maintaining a standard deviation of less than 60 mV.

The boards were subsequently returned to CAEN for improvements and then reanalyzed in the Rome laboratory for a month. As shown in Fig. 3, the updated boards no longer show temperature dependence and meet the stability requirement of a standard deviation (STD) of the output voltage of less than 60 mV (STD $<$ 60 mV).

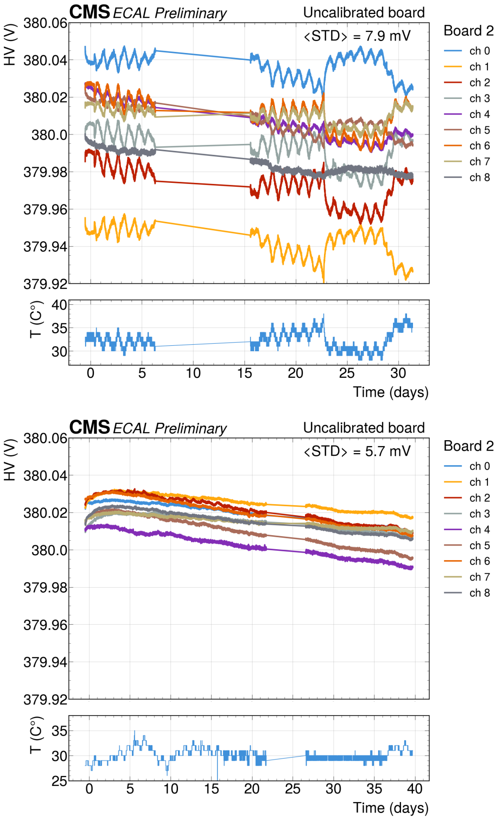

Fig. 2. The plots show the output voltage over a 30-day period, with measurements taken every 3 minutes across nine channels of two boards: A7420PE (top) and A7420PE after improvements (bottom). The nominal voltage during the test was set to 380V, and both boards were uncalibrated. Day–night variations are visible in the upper plot, likely due to temperature dependencies affecting the output voltage, as indicated by the temperature plot below. The straight line in the center suggests a data collection error. The $< STD >$ value shown in the graph is the average of the standard deviations across the various channels. Both boards met the stability requirements, with standard deviations below 60 mV.

B. *Noise measurement with phase-2 ECAL electronics*

To handle the extreme conditions of up to 200 collisions per bunch crossing and the resulting increased data rates, the on- and off-detector electronics of the CMS barrel electromagnetic calorimeter will be upgraded. In order to test the new electronics, trials were conducted at Prevèssen using a supermodule tester (SM36) containing four different readout units.

Each readout unit consists of 25 crystals, all connected to a shared motherboard. The data from each tower are processed by five VFE electronics boards, each managing five channels. The grounding of the boards is directly attached to the supermodule patch panel via a small cable.

The electronic noise is measured by analyzing baseline fluctuations in the absence of energy deposits, comparing both new and old boards. Data from all four readout units are acquired at a frequency of 160 MHz. Channels with poor RMS distributions or abnormally high means—caused by suboptimal pedestal calibration—were excluded from the analysis. As shown in Fig. 3, the noise distributions of the old and new boards are comparable.

C. *Summary*

The HV system upgrade is needed to meet the rising radiation levels and increased operational demands. While the current system is reliable, enhancements are required to support higher voltages and currents, ensuring long-term stability and improved performance under more challenging conditions.

Final tests on the new HV boards showed they successfully met the stability criteria, maintaining voltage variations within the required 60 mV over a month, which is essential to preserve the energy resolution of the ECAL. Additionally, noise measurements conducted with the upgraded electronics showed comparable performance to the legacy system.

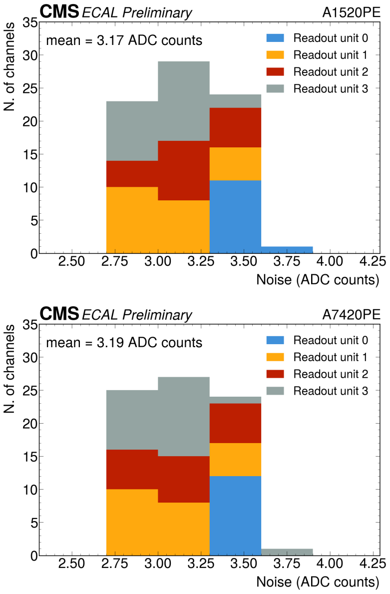

Fig. 3. The plots show the distributions of electronic noise fluctuations across various ECAL channels in 4 different readout units for the A1520PE (top) and A7420PE (botton) boards. The data were collected using SM36, with the signal amplified by a factor of 10. The ground state of the boards is connected to the supermodule path panel. The plot reports the mean value of the noise, computed from the unbinned distribution.

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