High precision, low disturbance calibration of the High Voltage system of the CMS Barrel Electromagnetic Calorimeter
Outline

• LHC and CMS description
• ECAL description
• Readout electronics
• ECAL Barrel HV system
• Calibration Description
Compact Muon Solenoid (CMS)

- Multi-purpose detector
  - length: 21 m; height: 15 m; weight: >10 kt

- Subdetectors:
  - Tracker (+pixel)
  - Calorimeters: e.m. and hadronic
  - Solenoid magnet: 3.8 Tesla
  - Muon chambers
Electromagnetic Calorimeter

- The electromagnetic calorimeter of CMS (ECAL) is a hermetic homogeneous calorimeter made of 61200 lead tungstate (PbWO$_4$) crystals mounted in the central barrel part, closed by 7324 crystals in each of the two endcaps.

- Barrel is divided in 36 Supermodules of 1700 crystals each (two sides EB+ and EB-)
- Endcaps divided into Dees (138 5x5 matrices of crystals)
Lead Tungstate Crystals

- The PbWO₄ has been chosen for its particular characteristics:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$ [g/cm$^3$]</td>
<td>8.28</td>
</tr>
<tr>
<td>Molière radius [cm]</td>
<td>2.2</td>
</tr>
<tr>
<td>Radiation Length [cm]</td>
<td>0.89</td>
</tr>
<tr>
<td>Wavelength [nm]</td>
<td>420-430</td>
</tr>
<tr>
<td>p.e. emission [MeV$^{-1}$]</td>
<td>4.5</td>
</tr>
</tbody>
</table>

- Low p.e. emission $\Rightarrow$ photodetector with internal gain (gain=50) needed
Detection System

- Each crystal is coupled to one (Endcap) or two (Barrel) photodetectors:
  - Barrel: 2 Avalanche Photodiodes (APD)
  - Endcap: 1 Vacuum Phototriodes (VPT)

![Diagram of PbWO₄ Crystal](image_url)

**Figure 18:** Schematic representation of a PbWO₄ crystal, showing the approximate dimensions to be used in CMS, the position of the APD and the directions of incidence of light and/or particles for various tests.

Undoped crystals have difficulty transmitting light below 450nm, resulting in a loss of scintillation light. If the crystals are doped with an element such as niobium, lanthanum or lutetium then some absorption bands are removed, increasing the transmission at low wavelengths. Figure 19 shows transmission curves for undoped and doped crystals.

![Transmission curves](image_url)

**Figure 19:** Transmission curves for undoped and niobium-doped crystals. The solid line shows the longitudinal transmission whilst the data points are transverse transmission measured at various points along the crystal.

The transmission edge for the niobium-doped crystals is much steeper, and the longitudinal transmission (light passes through 23cm of crystal) is virtually the same as the transverse transmission in this case.

These dopants are particularly important for the control of induced absorption (after irradiation), as demonstrated in figure 20 which shows the induced absorption as a function of wavelength for four full-size Russian crystals. The doped crystals are between a factor of 2 and 5 better (longer absorption length) than the undoped crystal.

**Longitudinal Uniformity**

The tapered shape of the crystals has a focussing effect on any light inside a crystal: light produced at the front of the crystal (farthest from the photodetector) is focussed more, and thus has more chance of being detected by the photodetector, than light produced towards the back of the crystal. However, if the absorption length of the crystal is relatively short, light produced at the front of the crystal has more chance of being absorbed than that produced at the back. The light collection efficiency is thus a function of position along the crystal, as illustrated in figure 21. The shape of the longitudinal light collection curve can contribute to the constant term.

The ideal shape is shown in figure 22.

The most important region is around the shower maximum. This region should have a flat response. It is useful for the curve to show an increase towards the back of the crystal such that late developing showers are enhanced - this reduces low energy tails.

Recent crystals have shown a marked increase in their absorption lengths, resulting in the light collection curves...
Energy Resolution

• Three contributions in the energy resolution:
  - stochastic
  - noise
  - constant

\[
\frac{\sigma(E)}{E} = \frac{a_{stoc}}{\sqrt{E}} \oplus \frac{b_n}{E} \oplus c
\]

• The HV system affects the constant (c) term
  - to have 3% gain sensitive, we need better than 60mV HV stability to keep small contribution to energy resolution constant term
Power supply scheme

- All the 122400 APDs need a stable and accurate High Voltage power supply to guarantee a correct response of the calorimeter
- Each HV channel is connected with a ~150m long cable (equipped also with a ‘sense’ line) to the detector

- 144 boards of 8 or 9 HV ch.
  “CAEN A1520PE 9-channels”
- 8 boards are inserted in a “CAEN SY4527 Mainframe” (# 18, divided into 3 racks EB+ side and 3 racks EB- side)
HV channel characteristics

- Each channel specifications are:

<table>
<thead>
<tr>
<th></th>
<th>Voltage range</th>
<th>high freq. noise (&gt;100 kHz)</th>
<th>&lt; ±20 mV</th>
</tr>
</thead>
<tbody>
<tr>
<td>programmable steps</td>
<td>20 mV</td>
<td>operating temperature</td>
<td>15-40 °C</td>
</tr>
<tr>
<td>DC regulation</td>
<td>&lt; ±20 mV</td>
<td>current limit</td>
<td>15 mA</td>
</tr>
<tr>
<td>DC stability (3 months)</td>
<td>&lt; ±20 mV</td>
<td>max ramp rate</td>
<td>50V/s</td>
</tr>
<tr>
<td>low freq. noise (&lt;100 kHz)</td>
<td>&lt; ±20 mV</td>
<td>external calibration</td>
<td>&lt; ±20 mV</td>
</tr>
</tbody>
</table>

- In total the ECAL Barrel HV system consists in 1224 HV channels that must provide a stable and accurate voltage to the APDs of the detector which operate at **Gain 50**
The calibration is currently done **once per year** (Jan. - March after the LHC Winter shutdown) - to maintain the same response of the detector

Each channel is calibrated with a fixed load of 33 kΩ using 10 voltage points:
- each Digital MultiMeter (DMM) reading is written in the channel buffer
- an internal interpolation is done ⟹ the channel extrapolates the calibration corrections changing its internal settings

In the following two calibrations will be described: “old” used since 2008 and “new” introduced in 2017;
- **this fw procedure is common for both calibrations**
Old calibration procedure

- It was a fully-manual procedure

- Hardware used (for each EB± side):
  - 1 digital multimeter (6 digis)
  - 1 9-ch. calibration board developed by CAEN
  - HV board-to-calibration board-to-DMM connectors

- Expert operations:
  - unscrew one HV board and replace it with the calibration one
  - connect the cables to the DMM and the board that has to be calibrated
  - launch the calibration program (loaded in the fw)
  - launch a “verify” routine (check the channel after calibration)
  - calibrate the HV board unplugged

Internal view of the calibration board
Old procedure pros&cons

• Pros:
  - fully validated procedure
  - machinery and steps very well known by experts

• Cons:
  - time consuming (>3 weeks)
  - a lot of manpower needed (>10 people - 2 FTE shifts)
  - could stress the hardware: all the procedures and steps have to be performed plugging and unplugging delicate boards thus stressing their backplanes
  - the value of the verify and the one written in the channel buffer is taken after a fixed delay time. In principle the channel could be stable in less time (can we improve this?)
  - the plugging and unplugging procedures prevent us to perform periodically verify or calibration during Technical Stops of LHC
New calibration procedure (HW)

- During 2015 a new set of hardware equipment has been installed in USC to permit new procedures of calibration.

- **Multiboxes** have been designed and tested at CERN by the CMS Rome group.
  - HV and High Current resistant relays that can decouple the HV system from the ECAL detector (the HV can be ON with the LV OFF without damaging the APDs).

### New Calibration HW scheme connections

- Multiboxes
  - To the DMM
    - 33 kΩ resistor with a copper plate to dissipate heat
    - 8 1/2 digis DMM
  - CMS ON: HV to detector
  - CMS OFF: HV to DMM

- Multiboxes
  - to ECAL

- Cytec Multiplexer
The multiplexer enables us to use only one DMM (for each side) and without unplugging any of the HV boards
- made of many boards containing one channel (just a switch) corresponding each to a HV one (latched=HV ch. connected; unlatched= HV ch. disconnected)

All the multiplexers are connected in a “star” configuration
- one (central module) multiplexer is connected to the DMM
- the other multiplexers “common channel” are connected to a board of the central module (each to a different channel)

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**common ch.**
- it is a short circuit connected to all the cytec channels that are latched
- latched channel and connection

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**Rear view of the Multiplexer**

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**Rack connections**

- **Rack 1**
  - DMM
  - R=33kΩ
- **Rack 2**
  - cytec
- **Rack 3**
  - cytec
New calibration procedure

• It uses a C++ program with the CAEN HWrapper.h and visa/r232 libraries to communicate with the whole system

• Sequence of the calibration:
  - Set the Multiboxes on CMS OFF (decouple the detector): this is the **only** manual operation
  - enter which rack/crate/board/channel number to calibrate
  - launch the calibration (the system automatically checks the status of the calibration apparatus and running protection routines to verify that the HV is completely OFF preventing any possible short-circuit and checking the network connection)
  - it calibrates a channel if it differs from the correct value by 10 mV

• How does it decides when the channel is stable?

  “signal follower routine”

  If the channel readings are in a 40 mV window for 10 seconds, **it is stable**

  the value is written in the buffer
We calibrated the same channel with the two different calibration procedures. The mean shift from 0 is due to the use of two different DMMs, whose calibration is compatible at the 30 mV level, which reflects in a 0.1% systematic error on the APD gain. Almost 100% of the channels within ± 0.5% maintaining the same energy resolution. The two methods are fully compatible.
New procedure pros&cons

• Pros:
  - very fast (no need of “manual” operations; overall time used < 1 week) and less manpower needed (3-4 people; 2 FTE shifts)
  - procedure very intuitive (instructions appear on the screen) and configurable (no need to recompile if settings/hw addresses are changed)
  - no stress to the board screws as they are not unplugged for this calibration
  - introduction of the “signal follower” routine speeds up the procedures
  - it uses a 8 1/2 digis DMM (the 6 digis is just a backup)
  - detector safe (multiboxes decouple the system from ECAL)
  - a “verify” scan can be run during LHC Technical Stops
  - fully compatible with the old calibration results

• Cons:
  - it needs a machine (also a VM) connected to the CMS service network
Conclusions

- Described the ECAL Barrel HV system of CMS
  - excellent stability is needed to maintain very good energy resolution

- Showed the Calibration procedure used from 2008
  - firstly what has been called “old” calibration used since the beginning of the experiment
  - the “new” calibration used this year showing the new hardware and techniques used

- The responses of the two calibration are fully compatible

- Major pros of the “new” calibration
  - less time consuming
  - completely automatic and configurable
Large Hadron Collider

- Length = 27 km
- c.m. energy ≈ 13 TeV
- $\Delta t_{\text{bunches}} = 25 \text{ ns}$
- Protons & heavy ions