Prospects for a precision timing upgrade of the CMS PbWO crystal electromagnetic calorimeter for the HL-LHC

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on behalf of the CMS collaboration

CHEF 2017
Calorimetry for the High Energy Frontier
CALORIMETERS: Today and for future projects
2 - 6 October 2017, Lyon
The High-Luminosity LHC: HL-LHC

Phase 1

Phase 2: HL-LHC
High-Luminosity LHC

High luminosity up to 3000 fb^{-1}

High pile-up
~ 140 – 200 interactions per bunch crossing

L_{1} = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}

L = 2 \times L_{1}

L = 5 \times L_{1}

300/500 fb^{-1}

we are here

current ECAL qualification

Year

2010  2013  2015  2019  2021  2024  2026  2036
The Electromagnetic Calorimeter of CMS (ECAL)

- Homogeneous, compact, hermetic, fine grain PbWO$_4$ crystal calorimeter
- Goal is excellent energy resolution

Present ECAL in a glance

**Barrel:** $|\eta| < 1.48$, APD readout, **61200** crystals

**Endcap:** 1.48 < $|\eta|$ < 3.0, VPT readout

**Preshower:** 1.65 < $|\eta|$ < 2.6

Performance of the CMS precision electromagnetic calorimeter at the LHC Run II and prospects for high-luminosity LHC by Zhicai Zhang

Electronics to be replaced

To be replaced with silicon calorimeter

Barrel (EB) supermodule

Pb/Si Preshower (ES)

Endcap (EE)
**Trigger**

- Accommodate HL-LHC **trigger** requirements
- Provide **1x1 crystal info** to **trigger** instead of present 5x5. Better isolation and also better spike rejection

<table>
<thead>
<tr>
<th></th>
<th>Max Level 1 Accept Rate</th>
<th>Max Latency</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECAL Phase 1</td>
<td>100 kHz</td>
<td>6.4 μs</td>
</tr>
<tr>
<td>Trigger Phase 2</td>
<td>750 kHz</td>
<td>12.5 μs</td>
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**Energy resolution**

- **Cool photodetectors** and **crystals** (18 → 9° C) to reduce increase noise in APD due to radiation damage

**Time resolution**

- Change **pre-amp** for more optimal noise filter and **30 ps timing @50 GeV** to suppress spikes and pileup and improve physics performances
The crystals and the present readout

- Original design requirements on ECAL timing to ensure good **energy resolution**: 0.1% energy stability in reconstruction for 1 ns

- PbWO$_4$ is a **fast** scintillator
  - 90% of light within 25 ns
  - ~10% contribution from Cherenkov

- Current pulse: optimized for LHC, different conditions for HL-LHC
  - 43 ns electronics CR-RC shaping time
  - sampling at 40 MHz → one sample every 25 ns
  - Using assumption about **pulse shape** to derive time information
What time is it?

- Time information extracted exploiting the universal character of the pulse shape
- Time from ratios of consecutive samples
Several ingredients determine the time resolution of an electromagnetic shower in a homogeneous crystal calorimeter

- **Intrinsic EM shower fluctuations**
  - longitudinal shower fluctuations
  - optical transit time spread: scintillation rise/decay time, light propagation

- **Photodetector + electronics**
  - photodetector: rise time, transit time
  - noise: dark current, electronic noise

- **DAQ**
  - clock distribution

Simulation of the CMS electromagnetic calorimeter response at the energy and intensity frontier
By Alexander Ledovskoy
Results from test beams and pp collision data at LHC:

- $A_{\text{eff}}$ effective amplitude, $\sigma_n = \text{noise}$
- $A_{\text{eff}} = A_1 A_2 / \sqrt{A_1^2 + A_2^2}$, $A_1$ and $A_2$ crystals amplitudes

Constant term of resolution:

- $\sim 20\text{ ps}$ in test beam
- $\sim 70\text{ ps}$ in situ, $Z \rightarrow \text{ee}$, same clock (close-by crystals)
- $\sim 150\text{ ps}$ in situ, $Z \rightarrow \text{ee}$, different regions of clock distribution
Pile-up

LHC

High pile-up run
78 vertices
Benefits of precision timing

- Timing as mitigation of pile-up
  - Subtraction of **neutral energy from pile-up** in electron and photon clusters
  - Identification of **pile-up jets**
  - **Vertex** assignment in high **pile-up** environment

HL-LHC

Simulated event: 140 interactions
Time precision and vertexes

- Time used to triangulate the vertex
- Vertex assignment in high pile-up environment
- $H \rightarrow \gamma\gamma$: correctly assign vertex $\rightarrow m_{\gamma\gamma}$ peak resolution
- ECAL has no longitudinal segmentation, no pointing
- Vertexes spread 5 cm along beam axis
- $\sim 20/30$ ps $\rightarrow \sim$ 1 cm resolution on vertex

$$\frac{\Delta m_{\gamma\gamma}}{m_{\gamma\gamma}} = \frac{1}{2} \left[ \frac{\Delta E_{\gamma 1}}{E_{\gamma 1}} \oplus \frac{\Delta E_{\gamma 2}}{E_{\gamma 2}} \oplus \frac{\Delta \theta_{\gamma\gamma}}{\tan(\theta_{\gamma\gamma}/2)} \right]$$

**CMSProjection**

$H \rightarrow \gamma\gamma$

- fiducial volume:
  - $p_T^{\text{gen}}(\gamma_{1,2}) > \frac{1}{3} \left( \frac{1}{4} \right) m_{\gamma\gamma}$
  - $|\eta^{\text{gen}}(\gamma_{1,2})| < 2.5$
  - $\text{Iso}_{H=0.3}^{\text{gen}}(\gamma_{1,2}) < 10$ GeV
- S2 (90% Vertex Efficiency)
- S2+ Optimistic (75% Vertex Efficiency)
- S2+ Intermediate (55% Vertex Efficiency)
- S2+ Pessimistic (40% Vertex Efficiency)

- S/(S+B)-weighted signal models
- $\sigma_{\text{eff}}^{S2} = 1.71$ GeV

**CMSProjection**

$H \rightarrow \gamma\gamma$

- fiducial volume:
  - $p_T^{\text{gen}}(\gamma_{1,2}) > \frac{1}{3} \left( \frac{1}{4} \right) m_{\gamma\gamma}$
  - $|\eta^{\text{gen}}(\gamma_{1,2})| < 2.5$
  - $\text{Iso}_{H=0.3}^{\text{gen}}(\gamma_{1,2}) < 10$ GeV
- stat. $\oplus$ exp.
- stat. only

- S2
  - $\pm 0.014$ (stat.) $\pm 0.029$ (exp.)
- S2+ (Opt.)
  - $\pm 0.015$ (stat.) $\pm 0.031$ (exp.)
- S2+ (Med.)
  - $\pm 0.016$ (stat.) $\pm 0.031$ (exp.)
- S2+ (Pes.)
  - $\pm 0.017$ (stat.) $\pm 0.030$ (exp.)
Time precision upgrade

- Intrinsic EM shower fluctuations
  - longitudinal shower fluctuations
  - optical transit time spread: scintillation rise/decay time, light propagation
- Photodetector + electronics
  - photodetector: rise time, transit time
  - noise: dark current, electronic noise
- DAQ
  - clock distribution

Where we can work to improve the time precision

Upgrade Very Front End (VFE) based on dual gain

**Trans Impedence Amplifier (TIA)**

- Preserve a fast signal to optimize time resolution

- ADC sampling rate increased @ **160 MHz**

- Clock distribution has a crucial role: need to ensure clock stability <10 ps on a large distributed system

The front-end data conversion and readout electronics for the CMS ECAL upgrade by Gianni Mazza

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**Spikes mitigation**

- Discrimination between scintillation and signals generated by hadron interactions in the APD, **spike**
  - Spike → more prompt pulse
  - Time information to distinguish

*Current readout*

*New TIA readout*

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**Figure:**

- Left graph: Time [ns] vs. amplitude (a.u.)
  - APD spike
  - Signal

- Right graph: Sample # vs. amplitude (a.u.)
  - APD spike
  - Signal
Test beam results

- Test beams performed in 2015, 2016 and 2017 @ CERN SPS H4 to study **intrinsic PbWO$_4$ timing** capabilities and **new electronics**
  - 5x5 matrix of ECAL barrel crystals + APDs
  - Different VFE electronics configuration
  - Signals readout by a fast digitizer (CAEN V1742, 5 GHz)
  - Time extracted from a fit to the pulse shape
  - Micro-Channel Plate (MCP) detectors used as time reference ($\sigma_t \sim 20$ ps)

A modern and versatile data-acquisition package for calorimeter prototypes test-beams: H4DAQ by Andrea Carlo Marini
APD + VFE electronics with standard (43 ns) and **reduced** (21.5 ns) **shaping time**
- 21.5 ns shaping time almost x2 \( A/\sigma \) noise
- Additional noise from test beam custom electronics
  - in CMS: \( A/\sigma \) noise ~800 for a 50 GeV shower

Readout using 2 SiPMs from the front face
- Resolution with different readout dominated by longitudinal shower fluctuations (~80 ps constant term)
- Prototype **VFE with TIA** implemented using discrete components
  - 30 ps resolution for $A/\sigma = 250$
    - 25 GeV @ HL-LHC start (100 MeV noise)
    - 60 GeV @ HL-LHC end (240 MeV noise)
  - Signals readout by a fast digitizer 5 GHz
  - Optimal performance already with 160 MHz sampling
  - Test beam with advanced prototype **TIA ASIC + integrated ADC** in June 2017
ECAL Barrel upgrade: timing resolution of $\sim 30$ ps for high energy photons and electrons

Needed to maintain and improve performances for precision physics: exploit 3 ab$^{-1}$ at HL-LHC

New readout electronics for ECAL Barrel Phase II

- Trans Impedence Amplifier (TIA) $\to$ high energy and time precision
- Improved spike rejection

Test beams for characterization:

- Intrinsic crystal time resolution
- Crystals + new electronics

New and undiscovered physics is waiting for us to be found!
backup
ECAL structure

- Barrel
- APD
- Endcap
- VPT
The target performance for the EB upgrade is a clock distribution system with a stability better than 10 ps.

The jitter and phase stability (skew) must be maintained below 10 ps during transmission across the detector and over long LHC running periods.
Crystal **transparency loss** and VPT (endcap readout) **conditioning** under **irradiation** corrected by **laser system**

- Monitor with laser light at 447 nm (close to max of scintillation spectrum)
- During no irradiation periods transparency partially recovers
**ECAL energy reconstruction**

Energy of **electrons/photons**

- $A_i = \text{amplitude response}$
- $S_i(t) = \text{time-dependent corrections}$
- $C_i = \text{inter-calibration among crystals}$
- $G = \text{ADC to GeV}$
- $E_{ES} = \text{preshower energy}$
- $F_{e,\gamma} = \text{cluster corrections}$

$$E_{e,\gamma} = F_{e,\gamma} \left[ G \times \sum_{i=\text{crystals}} (C_i \times S_i(t) \times A_i) + E_{ES} \right]$$
Run II pulse reconstruction: Multi-Fit

Estimates the in-time signal amplitude and up to 9 out of time amplitudes by means of a minimization of $\chi^2$

$$\chi^2 = \sum_{i=1}^{10} \frac{\left( \sum_{j=1}^{M} A_j \times p_{ij} - S_i \right)^2}{\sigma_{S_i}^2}$$

- $S_i$: digitized amplitudes
- $A_j (\geq 0)$: amplitudes from pulse at bunch cross $j$
- $p_{ij}$: the pulses. All identical and shifted by $j \times 25$ns
- $\sigma_{S_i}$: noise covariance matrix

Current ECAL
New TIA readout electronics

CMS simulation, $\sqrt{s}=13$ TeV
PU=20/BX, 25 ns

Observed signal
Total pulse
In-time pulse
Out-of-time pulses

0 1 2 3 4 5 6 7 8 9
Time sample

0 0.05 0.1 0.15
amplitude (GeV)

time sample

0 5 10 15

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A. Massironi - CMS ECAL
Laser and transparency loss: monitor

- **Laser** response vs “electrons” response
  - $S/S_0 = (R/R_0)^\alpha$
- Check with electron response:
  - energy from ECAL / momentum from tracker

![Graph showing Laser response vs electron response](image)

$S/S_0 = (R/R_0)^\alpha$

![Graph showing energy from ECAL vs tracker momentum](image)

**CMS Preliminary 2012**

\[ \sqrt{s} = 8 \text{ TeV} \quad L = 19.6 \text{ fb}^{-1} \]

**ECAL barrel**

- Mean: 1
- RMS: 0.0009
- Mean: 0.95
- RMS: 0.011
Inter-calibration and transparency corrections

- Impact on the $Z \rightarrow e^+e^-$ of energy scale and resolution
- Inter-calibrations: energy scale corrections to account for the intrinsic spread in crystal and photodetector response
- LM (laser monitoring): time-dependent corrections to compensate for channel response loss

![Graph showing CMS Preliminary 2012 data for ECAL endcap with $\sqrt{s} = 8$ TeV, $L = 19.6$ fb$^{-1}$]
ECAL timing

- ECAL sensitive to **time** of energy deposit
- Time resolution ~ **100 ps** for energies > 10 GeV
- Time information extracted exploiting the **reproducibility of the pulse shape**
- Time resolution measured in data
  - Comparing in $Z \rightarrow ee$ events the time from energy deposit from the **two leptons**
  - Comparing the time differences between **two neighbor crystals** in a photon cluster

![Graphs showing time resolution](image)
**EB VFE and FE**

- **New electronics: VFE and FE**
- Avalanche Photodiode (APD): from light to electric pulse
- Very Front End (VFE): pre-amplifier and ADC
- Front End (FE): data for trigger and data for full event reconstruction
EB upgrade and energy resolution

CMS Simulation Preliminary

Energy resolution, $\sigma_{\text{eff}}(E)/E$

- Energy (5x5) resolution
- $<\text{PU}> : 50$, int lumi: 0fb$^{-1}$
- $<\text{PU}> : 140$, int lumi: 1000fb$^{-1}$
- $<\text{PU}> : 140$, int lumi: 3000fb$^{-1}$
- $<\text{PU}> : 140$, 1000fb$^{-1}$, EB upgrade

Prompt, unconverted photons (H-$\gamma\gamma$)
ECAL Endcap upgrade

- Complete replacement of current ECAL Endcap
- **HGC**: High Granularity Calorimeter
  - 10 layers: 0.65 $X_0$ thickness absorber followed by a plane of silicon
  - 10 layers: 0.88 $X_0$ thickness absorber followed by a plane of silicon
  - 8 layers: 1.26 $X_0$ thickness absorber followed by a plane of silicon