THE CMS ECAL UPGRADE FOR PRECISION CRYSTAL CALORIMETRY AT THE HL-LHC

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ON BEHALF OF THE CMS COLLABORATION
THE CMS ELECTROMAGNETIC CALORIMETER (ECAL)

Homogeneous Scintillating Crystal Calorimeter made of Lead tungstate (PbWO$_4$) crystals

Photon in CMS: Cluster of energy deposits in crystals

- EB = 36 super-modules (SM) of 1700 crystals each
- EB scintillation light read out by Avalanche Photodiodes (APDs)
- EE scintillation light read out by Vacuum Phototriodes (VPTs)

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<tr>
<th>η REGION</th>
<th># CRystals</th>
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<tbody>
<tr>
<td>BARREL (EB)</td>
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<tr>
<td>ENDCAPS (EE)</td>
<td>$1.48 &lt;</td>
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<tr>
<td>Pb/Si PRESHOWER (ES)</td>
<td>$1.65 &lt;</td>
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ECAL CURRENT PERFORMANCE

- ECAL energy resolution crucial for Higgs boson and many other CMS analysis
  - \( H \rightarrow \gamma \gamma \): Resolution on \( m_{\gamma\gamma} \sim 1\% \)

- Performance affected by Pile Up (PU) = Overlapping interactions for single bunch crossing (BX)

- Improved techniques for LHC Run II (2015-2018) to cope with higher PU (x2 wrt Run I)

**Excellent performance of ECAL @13 TeV**

**Photon Energy resolution:** 1-3\% in EB, 2.5-4.5\% in EE

Can we maintain this performance for the future?
Higher instantaneous and annual integrated luminosity
- Much higher levels of overlapping events: pile-up (PU)
- Radiation levels will be 6x higher than for LHC
CMS ECAL CHALLENGE DURING HL-LHC

The HL-LHC conditions = significant challenge to both detector longevity and performance

- **EE difficult challenge** ➔ radiation levels change by a factor of 100 between $|\eta| = 1.48$ and $|\eta| = 3.0$

- Dose & fluence levels result in significant loss to the crystal light transmission and VPT performance ➔ replacement of the Endcap (EE) calorimeter for HL-LHC

- EB: radiation damage not a serious problem
  - increase in APD dark current ➔ dominant effect for $L_{int} > 1000/fb$
  - higher PU
  - increased photodetector (APD) noise
ECAL EB UPGRADE: MOTIVATION

ACCOMODATE PHASE II TRIGGER

- Current FE and OD readout inconsistent with L1 Phase II requirements

<table>
<thead>
<tr>
<th>TRIGGER PHASE II</th>
<th>L1 ACCEPT RATE</th>
<th>L1 LATENCY</th>
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<tr>
<td></td>
<td>750 kHz</td>
<td>12.5 µs</td>
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<tr>
<td>ECAL PHASE I</td>
<td>150 kHz</td>
<td>6.4 µs</td>
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SPIKES MITIGATION

- Improved trigger granularity: 1x1 crystal trigger primitive (TP) vs legacy 5x5 (FE/OD)
- Timing: Spikes have different time evolution if compared with scintillation (VFE/OD)

MAINTAIN PERFORMANCE

- APD noise increase will significantly degrade EM resolution at HL-LHC
- MANDATORY to mitigate this by cooling the APDs, and optimising pulse shaping (new VFE)

Performance of current L1 spike killer will degrade significantly
ECAL BARREL (EB)

36 SUPERMODULES (SM)

All the SMs will be removed for the electronics upgrade MAJOR EFFORT

2448 TRIGGER TOWERS (TT)
basic readout unit 5x5 crystals matrix
1 SM = 68 TTs

61200 PbWO₄ CRYSTALS

12240 VERY FRONT END Cards
pulse amplification, shaping, digitisation

61200 APD pairs

2448 FRONT END Cards
data pipeline and transmission, TP formation, clock/control

PbWO₄ crystal

APD

VFE

FE
ECAL EB UPGRADE: OVERVIEW

- **PbWO₄ crystals, APDs, mother boards, & overall mechanical structure will not change**

- **APD dark current strongly dependent on temperature** → by operating **EB colder from 18°C to 8°C** → reduce noise by 35% and dark current by a factor of 2.5

- The **FE and VFE electronics readout will be replaced**:
  - to satisfy the increased **trigger latency** (up to 12.5 μs) and **L1 accept rate** (750 kHz) requirements
  - to cope with HL-LHC conditions (increased APD dark current, anomalous APD signals, higher PU)

- **VFE** maintains similar purpose, but **reduce shaping time + digitisation** → reduce out-of-time PU contamination, electronics noise and spikes

- **FE card becomes streaming readout**, moving most processing **off-detector**

- **Off-detector electronics will be upgraded** to accommodate higher transfer rates and to generate trigger primitives → **Trigger will use single crystal information for spike rejection**
**ECAL EB UPGRADE: PRECISION TIMING**

- **PRECISION TIMING** will improve the vertex localisation for high energy photons:
  - Vertex resolution for $H \rightarrow \gamma \gamma$ decays benefits from precise timing
    - current efficiency of localising vertex ($|dz| < 1$ cm) is $\sim 70$-$80\%$
    - reduced to $< 30\%$ at 200 PU with current EB timing precision
    - improves to $\sim 70\%$ for photons with $|\Delta \eta| > 0.8$ for 30 ps timing resolution

- Goal: VFE ASIC design, sampling rate, clock distribution should be designed to approach 30 ps timing precision for high energy EM signals

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**Figure 13:** Distribution of the distance between the virtual vertex and the true vertex position, for the HL-LHC baseline optics, and for a hypothetical beam optics providing a collision time spread as short as 50 ps. Results for diphoton mass resolution vs accuracy of determining vertex location.

- Diphoton mass resolution improves to $\sim 70\%$ for photons with $|\Delta \eta| > 0.8$
- Crab-smacking: 50 ps
- Baseline HL-LHC: 160 ps

**Table 17:** Photon EB resolution at HL-LHC $\sim 1.7$-$1.8\%$

- Diphoton mass resolution vs accuracy of determining vertex location.

**Swagata Mukherjee et al.**

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**Vertex location accuracy at PU=200 assuming 30ps timing resolution**

**Diphoton mass resolution vs accuracy of determining vertex location**

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**see Adolf Bornheim talk**
**ECAL EB UPGRADE: VFE**

- **New VFE boards with re-designed ASICs:**
  - Optimise shaping time and sampling rate to reduce impact of noise, out-of-time PU, spikes
  - **Precision timing desired:** with **30 ps resolution** H vertex efficiency from 30% to 70% (at 200 PU), PU mitigation removing neutral particles

- **Pulse shaper/preamplifier ASIC option:**
  - **TIA (Trans-impedance Amplifier):** Digital design, using trans-impedance amplifiers, focused on achieving **optimal time resolution** (as much as allowed by kapton connections): **160 MHz sampling**

- **ADC:** Require multi-channel ADC with ~12 bit resolution and ability to sample up to 160 MHz
TIA: AMPLIFIER FOR ECAL EB @HL-LHC

TIA (Trans-impedance Amplifier):

- No shaping time
- Look directly at APD analog signal with high bandwidth
- Optimised for precision timing measurement of EM shower in ECAL

Performance confirmed @CERN during 2016 Test Beam

- High energy electrons (20 < Ee < 250 GeV) and pions
- PbWO₄ crystal matrix read out with prototype VFE with discrete component TIA
- Different sampling frequencies can be emulated
- APD timing extracted through template fit to pulse shape

SPIKE REJECTION

- Pulse reconstruction with fast VFE electronics can flag trigger information
- Spike pulse shape is faster and can be rejected

TIME RESOLUTION

Promising results:

- At 160 MHz σ ~ 30 ps @A/σ=250
  - 25 GeV photon with 100 MeV noise (HL-LHC start)
  - 60 GeV photon with 240 MeV noise (HL-LHC end)
ECAL EB UPGRADE: FE & OFF-DETECTOR

- REQUIREMENTS:
  - Read data from all crystals
  - Increased trigger latency (12.5 μs) ➔ need longer data pipeline

- FE Changes:
  - Move L1A pipeline off-detector with arbitrary trigger latency
  - Move trigger primitive generation off-detector

- Data links from detector to readout cards (in service cavern) to be updated to Versatile links w/ GigaBit Transceiver (GBT) chipset
  - GBT bandwidth allows a full-granularity readout for the trigger
  - Potential for more advanced topological filtering of anomalous events

- Off-detector: trigger, data & controls may be grouped in single card
TRIGGER PRIMITIVE GENERATION OFF-DETECTOR

LEGACY 5X5 CRYSTAL TP

Before Upgrade

Electron

Photon

After Upgrade

Electron

Photon

TP NOW 1X1 CRYSTAL
Tracks matched to cluster

Electromagnetic Shower

TRIGGER RESOLUTION
w/wo single crystal upgrade

ΔR(reconstructed-true)

see Fanbo Meng poster

Before Upgrade

AFTER UPGRADE

global view and full granularity of calorimeters

single crystal information should also allow more efficient track/cluster matching for track trigger
CONCLUSIONS

**EE COMPLETE REPLACEMENT + EB PARTIAL UPGRADE**

- **EE crystals** will suffer large transparency losses ➔ must be replaced in LS3
- **EB crystals** will perform well during HL-LHC (< 50% transparency loss)
- **APDs** remain operational but will have increased noise

**MOTIVATION FOR EB UPGRADE**

- **Increased Trigger rate** compared to LHC Run II ➔ replace VFE, FE and off-detector electronics
  - **Main motivation**: Phase II requirements: 750 kHz L1 accept rate & 12.5 μs latency (currently 100 kHz & 5 μs)
- **Mitigation of APD noise** (dark current increase due to higher neutron fluence)
  ➔ Cooling temperature reduced to 10 or 8°C (now 18°C)

**ADDITIONAL IMPROVEMENTS**

- **Improved spike rejection** ➔ single crystal information in trigger + VFE fast shaping
- **Precision timing for vertex determination & PU mitigation** ➔ new design for VFE electronics
  ➔ With precise time-of-flight measurement of photons (σ~30 ps) same angular resolution in H(→γγ) analysis as in Run II
BACKUP
**RADIATION DAMAGE IN PbWO₄ CRYSTALS**

**IONIZING RADIATION DAMAGE**

- It recovers at room temperature (~20°C)
- Light transmission of crystals is constantly monitored in ECAL using laser light
- Evolution of the response is in agreement with expectations

**HADRON RADIATION DAMAGE**

- No recovery at room temperature
- Shift of transmission band edge: cumulative effect
- Will dominate at HL-LHC
Defects inside the crystals, due to high-radiation environment, lead to **stronger induced light absorption**.

Induced absorption causes a **light output loss**.

Damaged crystals show a **non-linear response** to electromagnetic showers.

The constant term of energy resolution increases with higher $\mu_{\text{ind}}$ (irradiation dose expressed in terms of the radiation induced absorption coeff. $\mu_{\text{ind}}(\lambda)$).
TEST BEAM: DOUBLE-ENDED READ-OUT TECHNIQUE

Experimental setup

- 9 PbWO$_4$ crystals with different levels of $\mu_{\text{ind}}$ (from 0 to 20 m$^{-1}$)
- Each crystal is instrumented with a front and a rear photodetector
- Study of crystal response to electrons of 20-250 GeV energy

Additional photodetector on the front face of the crystal would provide:

- Information on shower maximum position and event-by-event shower fluctuations
- Better reconstruction of the electron energy by combination of both signals $S_{\text{corr}} = \sqrt{R_{\text{sh}}F_{\text{sh}}}$
LIGHT COLLECTION AND SHOWER FLUCTUATIONS

LIGHT COLLECTION UNIFORMITY

- First measurement of light collection efficiency curves for highly damaged crystals
- Exponential-like behaviour with attenuation coefficients proportional to the level of induced absorption $\mu_{\text{ind}}$

LONGITUDINAL SHOWER FLUCTUATIONS

- In non-damaged crystals the ratio of front/rear signal is rather constant for each event at all beam energies
- Longitudinal shower fluctuations become visible in damaged crystals due to non-uniformity of light collection efficiency

![Light collection efficiency curve](image1)

![Longitudinal shower fluctuations](image2)
LINEARITY & ENERGY RESOLUTION

LINEARITY

- **Linearity:** $E_{\text{reco}}/E_{\text{beam}}$ (normalized at 50 GeV) is entirely restored if front and rear signals are properly combined \[ S_{\text{corr}} = \sqrt{R \cdot F} \]

- The non-linear response due to $\mu_{\text{ind}}$ can be isolated from longitudinal leakage effects by comparison with a non-irradiated crystal.

- **non-linearity estimator** can be defined as the change of linear response between 50 and 250 GeV.

ENERGY RESOLUTION

- Increase of constant term $C$ is $\propto \mu_{\text{ind}}$ but the combination of front and rear signals allows to strongly mitigate the degradation of constant term $C$.

- Increase of constant term due to radiation damage is defined as \[ \Delta C = \sqrt{C_1^2} - C_{\text{ni}}^2 \]

- Strong mitigation of the constant term also for high levels of $\mu_{\text{ind}}$ (from 11% to 3%).
Anomalous signals (spikes) are energy deposits directly into APD bulk ➔ create fake EM-like pattern

- Deposited in a single APD compared to EM shower spread over several crystals
- Arrive earlier in time + shorter pulse than EM shower

**Spike rejection:**
- Currently rejected offline at L1 using coarse topological algorithm
- Efficiency will degrade to unacceptable levels at HL-LHC due to higher noise & PU
- VFE/FE will be upgraded for better spike rejection, optimising pulse shaping & using finer granularity (single crystal data) @ L1

Charge deposited directly in the APD results in pulses that are shorter in time than pulses generated by scintillation light.