The CMS electromagnetic calorimeter barrel upgrade for High-Luminosity LHC

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From LHC to HL-LHC

- LHC → 300 fb\(^{-1}\) by end of 2022
- Detectors originally designed for 500 fb\(^{-1}\)
- HL-LHC: \(5 \cdot 10^{34}\text{cm}^{-2}\text{s}^{-1}\). 300 fb\(^{-1}\) per year
  → 3000 fb\(^{-1}\) by end of 2035
Homogeneous PbWO$_4$ calorimeter. 26 $X_0$

Two readout streams:
- For level-one trigger decision. 2448 channels @40MHz $\Delta\eta \Delta\phi = 0.087 \times 0.087$
- For level-one-selected event: 61200 channels @100kHz ~poissonian; $\Delta\eta \Delta\phi = 0.0174 \times 0.0174$; 10 time samples.

Scintillation light is read out with APDs

ECAL barrel made up of 36 Supermodules
Crystal transparency

- Irradiation induced crystal transparency change
- Transparency monitored online with a laser (every 40 mn)

- Barrel: top red curve
  - Small transparency loss in Run 1
  - Suitable for HL-LHC
**APD operation**

**Dark current**
- Leakage current in the bulk due to irradiation damages → noise = $\alpha \sqrt{I_d}$
- Extrapolation from Run 1 → acceptable level (~400 MeV at end of HL-LHC)
- Complementary irradiation test on-going to confirm the extrapolations
- Operation at lower temperature (8~10°C) to mitigate the effect under study

**Anomalous event**
- Energy deposit directly in the bulk of the APD produces a signal → Faster signal than real signal
  → Isolated channel
  → Rate proportional to instantaneous luminosity
Data Readout

- **LHC:**
  - Two levels of trigger: L1 electronics based, HLT software based.
  - Current ECAL electronics allows for L1A rate up to 100~150kHz and trigger latency up to 6.3 μs

- **HL-LHC:**
  - Same architecture but with x10 L1 rate: 1MHz → larger detector readout throughput
  - Tracker included in the trigger → larger L1 latency: 20 μs

- **Pile-up in HL-LHC:**
  - large pile-up, 140 events per bunch crossing

→ Electronics needs to be changed
ECAL barrel upgrade overview

**Detector**
- The detector itself and the light readout (APDs) do not require an upgrade.
  → upgrade limited to the electronics.

**Electronics upgrade**
- Mandatory changes
  - Data pipeline depth
  - Data readout bandwidth
  - Anomalous event filter in the trigger
  - Front-end electronics of crystal transparency monitoring system
- Highly desirable changes
  - Signal preamplifier and shaping (“VFE” boards)
  - ADC encoding
    ➔ Optimisation for new conditions, noise level, pile-up and for anomalous event rejection
  - Full granularity read out for trigger decision
- Possibly operate the ECAL barrel at a lower temperature, 8-10°C, to mitigate the APD dark current increase.
4 types of cards: data concentration (DCC), trigger data concentration (TCC), controls and clock distribution (CCS), intelligent data reduction (SRP)

Readout unit (FE + VFEs)
Signal shaping, digitization, pipeline, serialization, trigger primitive

25 APDs

25 Crystals
Readout

Lead-Tungsten crystals

APDs

Multi-Gain Pre-Amplifier chip (MGPA)

AD41240 ADC

Clock & Control chip (CCU)

VFE card

FE card

FENIX chip in “STRIP” mode

FENIX chip in “DAQ” mode

FENIX chip in “TCP” mode

Gigabit Links (GOH)

Readout Data

Trigger Data

Clock & Control
Electronics architecture for HL-LHC

One single type of card

One single data stream. 40MHz sync
Versatile link

GBT.
Re-Optimization of signal shaping and encoding

Readout unit
Signal shaping, digitization, serialization, trigger primitive

25 APDs

25 Crystals

1 single type of cards: data, trigger data, controls and clock distribution, intelligent data reduction

off-detector

on detector

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Off-detector readout card option

- Considered option: build a new MP7' more suitable for ECAL FE

10 x 12-way miniPod receiver sites

2 x 12-way miniPod transmitter sites

Xilinx Virtex N?

2 x 36 data links

1 x 48 data links

1 x 24 control links

OK for Version FE3
Would need 2 MP7' per SM
Upgrade of data pipelines and data links

- Increase of trigger latency → longer data pipeline
- Data links from the detector to the readout cards (in service cavern) will be changed
  → Plan to use the Versatile link with GBT (GigaBit Transceiver) chipset developed at CERN [1].

- GBT bandwidth allows a full-granularity readout for the trigger
  - A unique readout at 40MHz
  - Four fibres per readout units: 4 x 2448 links.
  - All trigger logic moved to off-detector
  - Better trigger performance
  - Allowing for more advanced topological filtering of anomalous events

- Off-detector: trigger, data and controls is planned to be grouped in a single card.

Upgrade of preamplifier and shaping

- Gain expected from re-optimizing pre-amplification to HL-LHC conditions
  - Shorter shaping time to integrate less noise and less pile-up
  - Investigating other approaches:
    - e.g. integrate charge on one clock (25ns). See QIE (Charge integrate and Encoder) [1] developed for CMS HCAL.
    - complement with a precise timing measurement (→ pile-up and anomalous event rejection)
- Discrimination of anomalous and real signals can be taken into account in the new design
- Encoding of digital signal will be revised: e.g. coarser quantification

Laser monitoring of crystal transparency

- 1/72th of detector flashed at a time
- Continuous measurement during data taking. One complete measurement every ~40 mn.
- Reference measured with PN diodes. Electronics on-detector. Same readout as for APDs
Upgrade of Laser monitoring of crystal transparency

Light reference measurement done upstream outside the detector

- We expect that for HL-LHC light reference can be measured on the main fibres
  - can be done off-detector
  - a low cost solution
  - will be tested during run 2, in parallel to current system
Upgrade logistics

- Electronics upgrade will require extraction of the 36 ECAL barrel super modules
  → Time required for the intervention: 18 months. Fits in the 30 months of the Long Shutdown 3.
Conclusions

- The ECAL barrel detector elements (crystals and APDs) will still be highly performant throughout HL-LHC
- Minimal upgrade of transparency monitoring system. A low cost option will be studied in situ during run 2
- Readout downstream the APD is foreseen to be upgraded
  - Support for a longer trigger latency and a higher trigger rate
  - Full granularity for trigger decision: information from each crystal
  - Optimization for noise, pile-up and anomalous events