Upgrade of the CMS Electromagnetic Calorimeter for High-Luminosity LHC Operation

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CMS Collaboration

EPS-HEP, Stockholm, 17-23 July 2013
• The CMS electromagnetic calorimeter (ECAL)
• The role of the ECAL in CMS physics
• The HL-LHC program
• The challenges of the detector at the HL-LHC
• The upgrade of the ECAL
The CMS electromagnetic calorimeter

The energy resolution for photons from $H \rightarrow \gamma \gamma$ in EB is 1.1% to 2.6% and in EE 2.2% to 5%. Timing resolution is 190 ps and 280 ps in EB and EE.
• Excellent energy resolution led to the discovery of the H boson in the $\gamma\gamma$ decay mode
• Electrons and photons are used in many other searches ($H \rightarrow WW, ZZ^*, Z'$) and SM physics analyses ($W, Z, \text{top } ...$)
• Precision timing used in search for long lived SUSY particles
A new machine, for high luminosity, to measure the H couplings, H rare decays, HH, Vector boson scattering, other searches and difficult SUSY benchmarks, measure properties of other particles eventually discovered in Phase1.
Detector challenges

- Number of events per bunch crossing (pile-up) $\sim 140$

- Radiation levels will be 6 times higher than for the nominal LHC design.

- Strong $\eta$ dependence in the endcaps (at $\eta=2.6$ hadron fluence $2 \cdot 10^{14}$ /cm$^2$, gamma radiation: 30 Gy/h, total:300kGy)

MARS calculations,
P.C. Bhat et al., CERN-CMS-NOTE-2013-001
Radiation damage to crystals

**Gamma irradiation** damage is spontaneously recovered at room temperature.

**Hadron** damage creates clusters of defects which cause light transmission loss. The damage is permanent and cumulative at room temperature.
Extensive test-beam studies with proton-irradiated crystals

Reduction of light output causes:
- Worsening of stochastic term
- Amplification of the noise
- Light collection non-uniformity (impact on the constant term)

\[
\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c
\]

Progressive deterioration of energy resolution and trigger efficiency, with strong \(\eta\) dependence

Performance for e/y is acceptable up to 500 fb\(^{-1}\)

ECAL endcaps should be replaced after 500 fb\(^{-1}\) (during LS3)
Possible design options for the endcap calorimeters:

- ECAL plan is to replace the Endcap calorimeters in LS3
- Hadron calorimeter endcaps (HE) may need to replace the active material in LS3.

**Two possible scenarios:**

1. **HE absorber is left, only active material is replaced:**
   New EE will be a standalone calorimeter

2. **HE is fully replaced**
   This opens the possibility of a more coherent redesign of the endcaps calorimeters.
Scenario 1: standalone EE

- **Sandwich calorimeter** in a sampling configuration with inorganic scintillator (LYSO or CeF₃, which are rad-hard) and Pb or W as absorber.
- Possibilities for light readout via wavelength shifting fibers (WLS) in a shashlik configuration or with photon sensors on the sides.
- Light path is short $\rightarrow$ rad-hard
- **Challenges:** rad-hard fibers, photo-detectors, mechanical mounting (tolerances)
Scenario 2: Dual Readout Calorimeter

- **Dual Readout**: simultaneous measurement of the Cerenkov and scintillation signal in the calorimeter in order to correct for intrinsic fluctuations in the hadronic and e.m. component ($\gamma, \pi^0, \eta$) of the hadronic showers (RD52 Collaboration)

- Other ideas: inorganic crystal fibers, e.g. LuAG

- **Challenges**: rad-hard fibers, photo-detectors

See presentations in this session by R. Wigmans and CALOR 2010-12 E. Auffray et al.
Scenario 2: Imaging calorimeter

- **Imaging calorimeters**: measure charged particle momentum with the inner tracker, and neutrals in the calorimeter.

- Key point: resolving/separating showers through a finely granulated and longitudinally segmented calorimeter.

- High rates in CMS in the endcaps region drive the detector choice.

- **Challenges**: number of channels, compact and inexpensive electronics, trigger, cooling, performance in high pile-up, linearity
Pile-up Mitigation

- Pile-up is most critical in the forward region, so upgrades should aim at optimizing the forward detector for high pile-up conditions.
- Two areas of study:
  - **Increased granularity and segmentation** may help to separate out pile-up activity from primary event physics objects.
  - **High precision (pico second) timing** may help in pile-up mitigation. The subdetector providing the precision timing may best be associated to precise and finely segmented detector ⇒ ECAL.
    - Object reconstruction
    - Object-to-vertex attribution
    - \( H \rightarrow \gamma\gamma \) vertex
- Studies on precision timing are ongoing for pile-up mitigation through time-of-flight. Desired resolution is 20-30 ps.
Conclusions

• The HL-LHC poses severe requirements to detectors in terms of performance and rad-hardness.
• ECAL endcaps should be replaced at the end of the LHC phase1 (after 500 fb$^{-1}$).
• New calorimeter options are being studied. Key points are rad-hardness, granularity and segmentation.
• Timing resolution may add important information for pile-up mitigation.
Backup
Radiation levels in the detector

<table>
<thead>
<tr>
<th></th>
<th>L (cm$^{-2}$ s$^{-1}$)</th>
<th>Lint (fb$^{-1}$)</th>
<th>EB</th>
<th>gamma dose rate (Gy/h)</th>
<th>Protons/cm$^2$</th>
<th>EE (eta=2.6)</th>
<th>gamma dose rate (Gy/h)</th>
<th>Protons/cm$^2$</th>
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<tbody>
<tr>
<td>design</td>
<td>1x10$^{34}$</td>
<td>500</td>
<td></td>
<td>0.3</td>
<td>4x10$^{11}$</td>
<td>6.5</td>
<td>3x10$^{13}$</td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>7x10$^{33}$</td>
<td>30</td>
<td></td>
<td>0.2</td>
<td>2.4x10$^{10}$</td>
<td>4.5</td>
<td>2x10$^{12}$</td>
<td></td>
</tr>
<tr>
<td>HL-LHC</td>
<td>5x10$^{34}$</td>
<td>3000</td>
<td></td>
<td>1.5</td>
<td>2.4x10$^{12}$</td>
<td>30</td>
<td>2x10$^{14}$</td>
<td></td>
</tr>
</tbody>
</table>
Energy resolution of hadron-irradiated crystals

Test-beam setup with hadron-irradiated crystals

Induced absorption $\mu_{\text{IND}}$:

$$\frac{LT_0(\lambda)}{LT_0(\lambda)} = e^{-\mu_{\text{IND}}(\lambda) \times E}$$

Transparency deterioration $\rightarrow$

Light output loss (affects the stochastic term and noise term)

Light collection non-uniformity impacts the constant term

\[ \frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c \]
Hadron damage consequences

\[ \frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c \]

Non-uniformity of light collection deteriorates the constant term
• Progressive deterioration of the energy resolution and trigger efficiency, with strong $\eta$ dependence
• Performance for e/y is acceptable up to 500 fb$^{-1}$
• ECAL endcaps will have to be replaced after 500fb$^{-1}$ (during LS3)
R&D on new scintillators

- R&D on new crystal materials and new growing techniques are ongoing.

- Key points are:
  - radiation hardness, especially for hadron damage
  - Light emission spectrum matching to WLS fibers or rad-hard photo-detectors
ECAL electronics

- CMS L1 trigger will require an upgrade for the HL-LHC.
- One of the critical points to be added to the system is some **track and momentum** information already at the L1 trigger level.
- L1 track information will also be beneficial for the e/γ triggers (e / π⁰ in jets» separation, track-cluster matching, better isolation, primary vertex match for multiple triggers: e+jets)

**ECAL front-end electronics cannot meet with the HL-LHC L1 trigger requirement and will need to be replaced.**
APD dark current grows linearly with neutron fluence. As a consequence there is an increase in noise in EB. The dark current can be mitigated cooling the EB. A reduction of 2-2.5 in current cooling EB to 8 C.

At lower temperature PWO decay time is slower, and e.m. damage spontaneous annealing is less effective. An optimization of the temperature may be needed.